70 Years of Trapped Ions
- A brief review and introduction to ECTI 2025 –

Rainer Blatt[1,2,3]

[1]*Institute for Experimental Physics,*
University of Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
Rainer.Blatt@uibk.ac.at, www.quantumoptics.at
[2]*Institute for Quantum Optics and Quantum Information,*
Austrian Academy of Sciences, Otto-Hittmair-Platz 1, A-6020 Innsbruck, Austria
Rainer.Blatt@oeaw.ac.at, www.iqoqi.at
[3]*Alpine Quantum Technologies (AQT) GmbH,*
Technikerstrasse 17, A-6020 Innsbruck, Austria
www.aqt.eu

Ion trapping in Paul and Penning traps has been established for nearly seventy years. Initially developed primarily for mass spectrometry and trace analysis, ion traps evolved into powerful tools for precision spectroscopy during the 1960s. The advent of laser cooling in the 1970s enabled experiments with single confined ions, laying the foundation for fundamental quantum optics studies, including the observation of quantum jumps and non-classical correlation functions. In the 1990s, it was recognized that the interaction of laser light with a single trapped ion undergoing quantized motion can be described by the Jaynes–Cummings model, analogous to the coupling between an atom and a quantized cavity mode. This insight motivated the seminal proposal by Cirac and Zoller to employ trapped ions as a platform for quantum computation—an idea that has since initiated much of today's quantum information research. At present, ion traps play a central role in precision spectroscopy, quantum computing, quantum simulation, and quantum networking. In this talk, I will briefly review the historical development of the field, highlight key advances previously presented at ECTI conferences, and provide an outlook on the topics addressed at the ECTI 2025 meeting.

Digital quantum magnetism at the frontier of classical simulations

M. Foss-Feig[1]

[1]*Quantinuum*

The utility of near-term quantum computers for simulating realistic quantum systems hinges on the stability of digital quantum matter--realized when discrete quantum gates approximate continuous time evolution--and whether it can be maintained at system sizes and time scales inaccessible to classical simulations. Here, we use Quantinuum's H2 quantum computer to simulate digitized dynamics of the quantum Ising model and observe the emergence of Floquet prethermalization on timescales where accurate simulations using current classical methods are extremely challenging (if feasible at all). In addition to confirming the stability of dynamics subject to achievable digitization errors, we show direct evidence of the resultant local equilibration by computing diffusion constants associated with an emergent hydrodynamic description of the dynamics. Our results were enabled by continued advances in two-qubit gate quality (native partial entangler fidelities of 99.94(1)%) that allow us to access circuit volumes of over 2000 two-qubit gates. This work establishes digital quantum computers as powerful tools for studying continuous-time dynamics and demonstrates their potential to benchmark classical heuristics in a regime of scale and complexity where no known classical methods are both efficient and trustworthy [1].

[1] R. Haghshenas, E. Chertkov, et al., arXiv:2503.20870 (2025).

High fidelity quantum logic on two trapped-ion qubits without ground-state cooling

A. C. Hughes and Oxford Ionics team

Oxford Ionics, UK

We introduce the 'smooth gate' - a novel entangling gate method for trapped-ion qubits where residual motional errors are adiabatically eliminated by ramping the gate detuning. We combine the power of this technique with the robustness of electronic qubit control [1] to perform two-qubit gates with an estimated error of $< 10^{-4}$ without the use of ground-state cooling. We characterise the gate error using a new protocol (inspired by subspace randomised benchmarking [2]) which does not require the use of any single-qubit rotations. We further show that the error remains $< 5 \times 10^{-4}$ for Doppler-cooled ions with gate mode temperatures of up to $\bar{n} = 9.4(3)$. These results show that trapped-ion quantum computers can be operated above the Doppler limit, allowing for significantly faster device operation.

[1] C. M. Löschnauer et al., arXiv:2407.07694 [quant-ph] (2024)
[2] C. H. Baldwin et al., *Phys. Rev. Research* **2**, 013317 (2020)

Rovibrational Spectroscopy of State-selected HD+ Ions

Qian-Yu Zhang,[1] Wen-Li Bai,[1] Zhi-Yuan Ao,[1] Wen-Cui Peng,[1], Sheng-Guo He,[1] and
Xin Tong [1]

[1] *Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan, P. R. China*

We demonstrate a novel method that integrates the quantum state preparation of polar molecular ions and the detection of spatially resolved fluorescence in specific regions, for studying the high-precision spectroscopy of HD^+ molecular ions in traps. The detection technique not only enables real-time signal measurement, but also suppresses common-mode noise arising from fluorescence fluctuations and reduce the state redistribution induced by blackbody radiation. Thus, this method overcomes the key limitations encountered during quantum state preparation of polar molecules through resonance-enhanced threshold photoionization (RETPI). By utilizing this approach, we measured the (v, N): (0, 0) → (6, 1) rovibrational transition of HD^+ ions for the first time, with an unperturbed frequency of 303.3965067(20) THz. This value is in excellent agreement with the predictions of quantum electrodynamics (QED). Looking forward, our method could be extended to detect hot-band transitions of HD+ excited from highly excited rovibrational states. This provides high-precise tools for determining fundamental constants such as the proton-to-electron mass ratio and for exploring the unknown contributions of QED.

Quantum Control of a single H_2^+ molecular ion

D. Holzapfel,[1,2] F. Schmid,[1,2] Q. He,[1,2] N. Schwegler,[1,2] H. J. Kim,[1] O. Stadler,[1] M. Stadler,[1] A. Ferk,[1,2] J. P. Home,[1,2] and **D. Kienzler[1,2]**

[1] *Department of Physics, ETH Zürich, Zurich, Switzerland*
[2] *Quantum Center, ETH Zürich, Zurich, Switzerland*

I will present our latest results, implementing pure quantum state preparation, coherent manipulation, and non-destructive state readout of the hydrogen molecular ion H_2^+ [1]. The hydrogen molecular ion is the simplest stable molecule, and its structure can be calculated *ab initio* to high precision. However, challenging properties such as high reactivity, low mass, and the absence of rovibrational dipole transitions have thus far strongly limited spectroscopic studies of H_2^+.

We trap a single H_2^+ molecule together with a single beryllium ion using a cryogenic Paul trap apparatus, achieving trapping lifetimes of 11 h and ground-state cooling of the shared axial motion [2]. With this platform, we have recently implemented Quantum Logic Spectroscopy of H_2^+. We utilize helium buffer-gas cooling or 2+1 REMPI to prepare selected rotational states of H_2^+ in its vibrational ground state. We combine this with quantum-logic operations between the molecule and the beryllium ion for the preparation of single hyperfine states and non-destructive readout, achieving a combined state-preparation and readout fidelity of 66.5(8)%. We demonstrate Rabi flopping on several hyperfine transitions using stimulated Raman transitions and microwaves.

I will further present recent progress on high-precision hyperfine spectroscopy of ortho-H_2^+ (rotation L=1, vibration ν=0), where we achieve a precision of 50 mHz with a 6-minute averaging time and estimate a preliminary accuracy on the order of 100 mHz. This spectroscopy could provide a stringent test of state-of-the-art molecular theory and put an improved bound on a possible new tensor force between the two constituent protons of H_2^+ [3].

Our results pave the way for many high-precision spectroscopy studies of H_2^+, which would enable tests of QED, metrology of fundamental constants, and the implementation of an optical molecular clock based on the simplest molecule in nature.

[1] D. Holzapfel et al., Phys. Rev. X 15, 031009 (2025).
[2] N. Schwegler et al., Phys. Rev. Lett. 131, 133003 (2023).
[3] N. F. Ramsey, Physica 96A, 285 (1979).

Searching for parity violation in trapped chiral molecular ions

Yuval Shagam,[1]

[1]*Technion, Haifa, Israel*

Parity violating (PV) effects can be isolated in comparisons between the left and right-handed enantiomers of a chiral molecule. Commonly searches are designed to be sensitive to the Standard Model nuclear weak force, which is predicted to break the parity symmetry in chiral molecules. However, in principle any PV effect including new forces beyond the Standard Model, where there is observational evidence that suggests it is incomplete.

We are developing a chiral molecular ion version of the search for PV in molecules leveraging ion trapping to access long coherence times. Our isotopically chiral candidate molecule, $CHDBrI^+$ is predicted to exhibit a relatively large PV shifts of a few Hz between the two enantiomers for the C-H bend vibrational transition. Notably, the transition's computed natural linewidth is narrower than the predicted shift making it particularly promising for the search. Additionally, our candidate species is available for spectroscopic studies.

We aim to probe the PV signature in a mixed-handedness ensemble of trapped $CHDBrI^+$, using a variant of vibrational Ramsey spectroscopy. However, in order to conduct Ramsey spectroscopy on such complex polyatomic molecules, we must develop methods to prepare cold $CHDBrI^+$ and detect its internal state populations. We will present our preliminary results of neutral CHDBrI and discuss our progress toward selective preparation of $CHDBrI^+$ via photoionization in the VUV range.

Importantly, we will also show that chiral molecule radicals such as $CHDBrI^+$ can provide insights in the search for new inter-nuclear forces that violate parity symmentry.

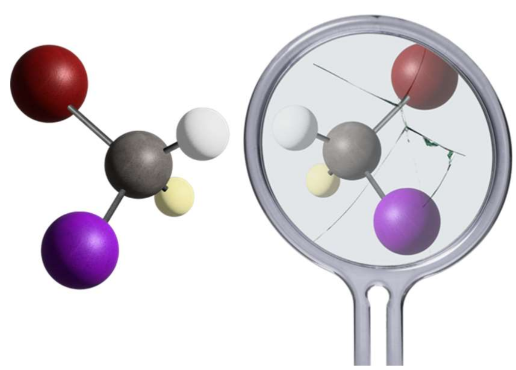


Figure 1: Mirror symmetry breaking between enantiomers

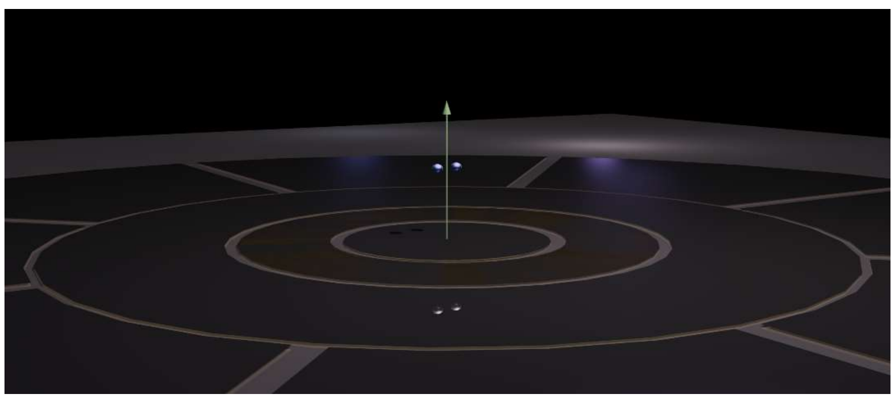
[1] A. Landau et al., J. Chem. Phys. 159, 114307 (2023)
[2] Eduardus et al. Chem. Communi. 59, 14579 (2023)
[3] Erez et al. Phys. Rev. X 13, 041025 (2023)
[4] Baruch et al. Phys. Rev. Research 6, 043115 (2024)

Coherent control of rotating ion strings: towards observing quantum statistics for always separated particles

Ryan Tollefsen, Yu-Lung Tang, Neil Glikin, **Hartmut Haeffner**

UC Berkeley, USA

Typically, the bosonic or fermionic nature of indistinguishable particles is either relevant at atomic scales or when the wavefunctions of the particles overlap. Two ions in an ion string, however, are always separated by several micrometers making it natural to identify them am individual particles. In order to demonstrate that the wavefunction of the two ions may need to properly symmetrized, we plan to interfere an ion string with itself rotated by 180 degrees. In view of this goal, we prepare ion strings rotating with angular momenta of thousands of quanta with a spread of as few as 10 quanta. The fast rotation allows for coherent control of the rotational degree-of-freedom. Using spin-echo sequences, we study the coherence properties of superpositions of two wavepackets with angular momenta differences of up to 4 quanta and find unusual scaling laws of the decoherence rate for small angles. Finally, we extend our measurements beyond small angles and observe interference of wavepackets for angles of up to 2π.



Magnetic gates for trapped ion quantum computing

D. H. Slichter

NIST Ion Storage Group, Boulder, CO, USA

Single-qubit and multi-qubit gates based on magnetic fields and magnetic field gradients can provide high fidelity control of hyperfine and Zeeman qubits in trapped ions. Generating these control fields and gradients using currents flowing through trap-integrated electrodes provides a natural way to perform the operations in a trapped ion quantum computer, with potentially favorable scaling properties.

I will describe our efforts to develop and demonstrate key features of a full mixed-species architecture for quantum computing based on high-fidelity magnetic gates. The use of mixed species presents both additional complications and additional opportunities, including the potential to operate the "data" species without any laser light required. Combining trap-integrated current-carrying electrodes for gate operations with other trap-integrated functionalities such as integrated photonics for light delivery and integrated photon detectors for fluorescence readout, especially if the data species does not require laser light, offers a path to large-scale ion traps with all control and readout integrated into the trap itself. The further addition of trap-integrated optical cavities to generate remote entanglement between traps could then offer a path to modular, distributed quantum computing.

A scale-up architecture for trapped ions quantum computing and simulation based on multi-qubit gates and optical tweezers

R. Ozeri,[1,2] N. Akerman,[1,2] Y. Shapira,[1,2] T. Manovitz,[1] D. Schwerdt, [1,2] A. Stern[1], R. Shaniv[1], L. Peleg[1,2], L. Gazit[1], J. Markov[1], N. Priel[2], Y. Florshaim[2], A. Gross[2], A. Zalic[2], G. Afek[2], and A. Ben Kish[2]

[1]*Weizmann Institute of Science, Rehovot, Israel*

[2]*Quantum Art, Nes Ziona, Israel*

One of the main advantages of trapped-ion qubits is their long-range Coulomb interaction and the all-to-all qubit connectivity it enables. In this talk I will present several experiments in which the global phonon spectrum of an ion crystal was used to generate programable couplings between qubits leading to non-trivial coupling schemes and quantum simulations of Hamiltonians with broken time-reversal symmetry [1-4]. Furthermore, I will show that tightly focused optical tweezer potentials are useful for ion crystal phonon spectrum engineering. I'll show how optical tweezers can generate a state-dependent phonon spectrum and can partition an ion crystal into a reconfigurable set of segments [5,6]. All these techniques culminate in a proposal for unique scale-up architecture for large-scale trapped-ion quantum computing [6].

[1] Manovitz et al., *Phys. Rev. X Quantum.* **1,** 020303 (2020).
[2] Shapira et al., *Phys. Rev. A.* **101,** 032330 (2020).
[3] Shapira et al., *Phys. Rev. X.* **13,** 021021 (2023).
[4] Shapira et al., *Phys. Rev. Lett.* **134,** 010602 (2025).
[5] Schwerdt et al., *arXiv 2506.08565* (2025).
[6] Schwerdt et al., *Phys. Rev. X.* **14,** 041017 (2024).

Quantum simulation of the Dicke model in a Penning ion trap

A.L. Carter,[1] B.B. Bullock,[1,2] S.R. Muleady,[2,3] Y. Zhang,[4] J.F. Lilieholm,[1] D.M. Nguyen,[1,2] K.A. Thompson,[1,2] A. Safavi-Naini,[5] R. Lewis-Swan,[4] A.M. Rey,[1,2] and J.J. Bollinger[1]

[1]*National Institute of Standards and Technology, Boulder, CO, USA*
[2]*University of Colorado, Boulder, CO, USA*
[3]*University of Maryland, College Park, MD, USA*
[4]*University of Oklahoma, Norman, OK, USA*
[5]*University of Amsterdam, Amsterdam, the Netherlands*

Penning traps allow for stable confinement and control of two-dimensional crystals of hundreds of ions, resulting in a system that is well-suited for quantum simulations with large qubit numbers. In this talk, I will discuss a recent quantum simulation of the Dicke model using ~100-200 Be^+ ions. The Dicke model describes a system of many spins coupled to a single quantum harmonic oscillator and predicts both a dynamical phase transition and quantum chaos [1,2]. The use of trapped ions for this simulation enables observation of the dynamics of this model in a regime not limited by boson dissipation.
We implement this model by simultaneously driving a transverse field using microwaves and a laser-based spin-dependent optical dipole force that couples the ion spins to the center-of-mass motional mode. Depending on the relative strengths of the transverse field and the spin-dependent force, we observe two phases: a “trapped” phase, where qubits remain aligned to a pole of the Bloch sphere, and an “untrapped” phase, where the transverse field drives oscillations of the spins. Additionally, I will present data showing non-equilibrium dynamics in a regime where the spin coupling and boson coupling are equal, leading to chaotic behavior. These data are consistent with predictions of quantum dynamics that cannot be explained by mean-field theory.

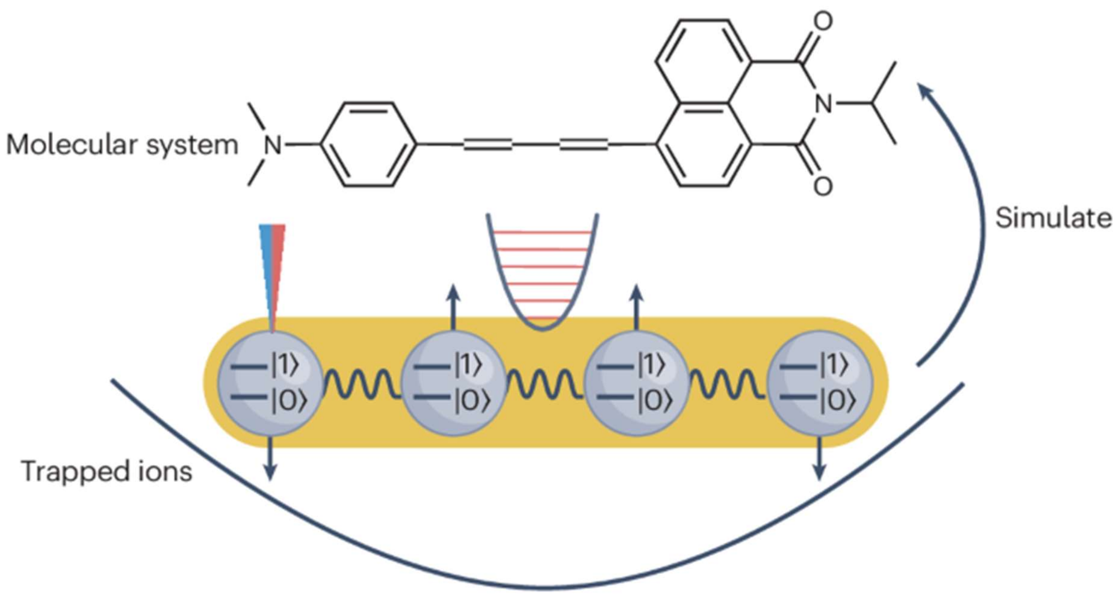
[1] R. Lewis-Swan et al., *Phys. Rev. Res.* **3**, L022020 (2021).
[2] A. Safavi-Naini et al., *Phys. Rev. Lett.* **121**, 040503 (2018).

Quantum simulation of spin-boson models with structured bath

K. R. Brown

[1]*Duke Quantum Center, Duke University, Durham, NC USA*

The spin-boson model, involving spins interacting with a bath of quantum harmonic oscillators, is a widely used representation of open quantum systems that describe many dissipative processes in physical, chemical and biological systems. Trapped ions present an ideal platform for simulating the quantum dynamics of spin-boson models, by accessing both the high-quality internal qubit states and the motional modes of the ions [1]. I will present our fully programmable method to simulate dissipative dynamics of spin-boson models using a chain of trapped ions, where the initial temperature and the spectral densities of the boson bath are engineered by controlling the state of the motional modes and their coupling with qubit states [2]. I will conclude with a discussion of future prospect for the simulation of chemical dynamics and dissipative phase transitions [3].



[1] M. Kang et al. *Nat. Rev. Chem.* **8**, 340 (2024).
[2] K. Sun et al., *Nat. Commun.* **16**, 4042 (2025).
[3] M. Kang, Y. Zhang, K. R. Brown, and T. Barthel, arXiv: 2507.07092

High dimensional quantum computing with trapped ions

Zichao Zhou[1]

[1]*Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing, PR China*

As one of the most promising systems to realize the universal quantum computer, trapped ions platform has achieved high fidelity state preparation and measurement, single qubit and two qubit gate, quantum error correction with better-than-physical error rates [1]. The current challenges include how to scale up the controllable qubit numbers to satisfy the practical quantum application requirements. Recently we have developed a cryogenic ion trap with 2D ion crystal [2] and dual-type qubit encoding protocol [3] in a species for quantum simulation and quantum computing. We successfully demonstrated sideband cooling a 2D crystal with 512 ions in a three-layer monolithic ion trap and realized quantum simulation of long-range quantum Ising model with 300 ions. We also realized the direct entangling gate between dual-type encoding qubits in $^{137}Ba^{+}$ ions [4]. In this talk, I will briefly introduce the recent experimental progresses in our lab.

[1] A. Paetznick et al., *arXiv: 2404.02280* (2024)
[2] S-A Guo et al., *Nature 630, 613-618*(2024).
[3] H.-X. Yang et al., *Nature Physics. 18, 1058* (2022).
[4] C.-X Wang et al., *Phys. Rev. Lett. 134, 010601*(2025).

Photon-based mass spectroscopy using two-ion Coulomb crystals in a Penning trap

A. Schupeta,[1] D. Yousaf,[1] and **D. Rodríguez[1]**

[1]*University of Granada, Granada, Spain*

Hybrid Coulomb crystals made of a spectroscopy and an auxiliary ion, have been implemented in radiofrequency traps to provide very accurate optical clocks using quantum logic (e.g. [1,2]). The use of such a crystal (but) in a Penning trap was proposed some years ago for mass spectroscopy based on the detection of photons as the most sensitive method, not only because of the single-ion sensitivity, but also because of the precise control of the spectroscopy (or target) and the auxiliary (or sensor) ion [3]. Such a system can give unique access to a broad frequency range but the Coulomb interaction, which contributes forming the crystal, prevents a precise motional-mode frequency determination due to the loss of linearity if the modes of the crystals are heated. Two scenarios are considered: when the crystal's modes are closed or at the Doppler limit and when they are near the ground state [4]. In this talk we will present some of the most important developments and results in this run towards establishing this method and improving precision, considering the different regimes, the two (pure photon-based) methods and the implications of this Penning-trap experiment in mass spectroscopy. Some results have been presented in Ref. [5,6], others are still unpublished.

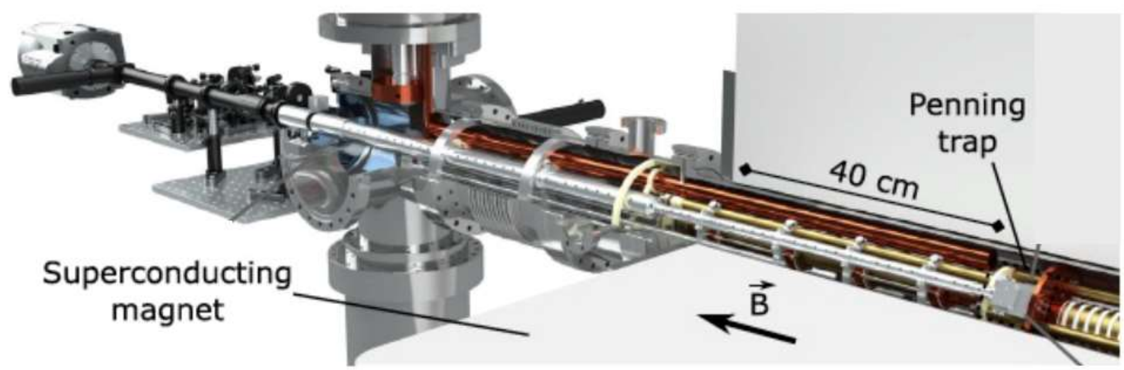


Figure 2: Three-dimensional drawing showing the in-vacuum optical system for the photons' detection of the sensor ion in a Penning trap [7].

[1] P.O. Schmidt et al., *Science* **309**, 749-752 (2005).
[2] S.M. Brewer et al., *Phys. Rev. Lett.* **123**, 033201 (2019).
[3] M.J. Gutiérrez et al., *Phys. Rev. A.* **100,** 063415 (2019).
[4] J. Cerrillo and D. Rodríguez, *EPL-Perspective* **134**, 38001 (2021).
[5] J. Berrocal et al., *Phys. Rev. Research* **6**, L012001 (2024).
[6] J. Berrocal et al., *Phys. Rev. A* **110**, 063107 (2024).
[7] J. Berrocal and D. Rodríguez, *EPJ Quantum Technol.* 12, **58** (2025).

High-precision ground-state hyperfine spectroscopy at μTEx

A. Mooser[1], S. Dickopf[1], A. Gramberg[1], P. Justus[1], A. Kaiser[1], A. Kauschik[1], M. Müller[1], S. Ulmer[2,3] and K. Blaum[1]

[1]Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany
[2]Heinrich-Heine University, Düsseldorf, Germany
[3]RIKEN, Wako, Japan

At our Penning-trap experiment μTEx in Heidelberg, Germany, we measure the ground-state hyperfine-structure splitting of light, hydrogenlike ions and nucleons in a magnetic field [1]. From the measured transitions, the bound electron and shielded nuclear g-factors as well as the hyperfine-structure constant are extracted. In comparison with theory calculations, this allows to test QED, to infer charge radii of nuclei and to precisely determine fundamental constants such as the electron mass and nuclear magnetic moments. Comparisons to additional lithiumlike measurements allow testing of nuclear magnetic shielding theory. The results of the latest 9Be campaign [2] as well as ongoing measurements and future plans will be presented.

[1] A. Schneider, Nature **606**, 878 (2022)
[2] S. Dickopf, Nature **632**, 757 (2024).

Nuclear laser spectroscopy of thorium-229 in trapped ions and ionic crystals

E. Peik

Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany

The challenge to control systematic frequency shifts in optical clocks at the sub-Hz level has led us to consider using a low-energy nuclear transition in Th-229 [1]. After more than 20 years of struggling with experimental difficulties, including the huge uncertainty in the transition wavelength, the first laser excitation signals have been observed with Th-doped calcium fluoride crystals in late 2023 [2]. This opens a new field for experiments that connect nuclear physics with atomic physics and quantum optics, and that extends beyond the application in a nuclear clock [3,4]. The topic is rich in cross connections that allow one to see familiar concepts in a different perspective, for example in atomic and nuclear structure, hyperfine interactions, and the interaction of nuclei with ionic crystals. I will give an overview of the history and the prospects of the field and will try to highlight some of these connections.

[1] E. Peik, Chr. Tamm., *Europhys. Lett.* **61**, 181 (2003)
[2] J. Tiedau, et al., *Phys. Rev. Lett*. **132**, 182501 (2024)
[3] K. Beeks, T. Sikorsky, T. Schumm, J. Thielking, M. V. Okhapkin, E. Peik, *Nature Reviews Phys.* **3**, 238 (2021).
[4] E Peik, T Schumm, M S Safronova, A Palffy, J. Weitenberg, P.G. Thirolf, *Quantum Sci. Technol*. **6**, 034002 (2021)

Precision Spectroscopy in Ion Coulomb Crystals and Search for New Physics

T.E.Mehlstäubler,[1,2] C.-H. Yeh,[1] L. Dreissen,[1] H. Fürst, [2] J. Keller,[1] N. Hausser,[1] J. Yu,[1] A. Prakash,[1,2] and I. Biswas[1]

[1]*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*
[2]*Leibniz University of Hannover, Hannover, Germany*

Trapped and laser-cooled ions allow for a high degree of control of atomic quantum systems. They are the basis for modern atomic clocks, quantum computers and quantum simulators. In our research we use ion Coulomb crystals, i.e. many-body systems with complex dynamics, for precision spectroscopy. This paves the way to novel optical ion frequency standards with ultra-high stability and accuracy for applications such as relativistic geodesy and quantum simulators in which complex dynamics become accessible with atomic resolution.

On the other hand, the high precision obtained in the spectroscopy of trapped cold ions enables sensitive tests of the Standard Model and the search for new physics. The long-lived F-state of the Yb^+-ion has a high sensitivity to both relativistic and nuclear effects. We use isotope-shift spectroscopy as a sensitive probe for nuclear structure and fifth forces mediated by a new boson that couples to electrons and neutrons. Deviations from a linear relation in the King-plot analysis can indicate new physics or higher-order SM effects. This powerful technique revealed large King-plot nonlinearities in Yb. We present two-orders-of-magnitude improved spectroscopic measurements in all five stable spinless isotopes of this element. The transition frequency of the forbidden $^2S_{1/2}$ to $^2D_{5/2}$ and $^2S_{1/2}$ to $^2F_{7/2}$ transitions are determined with an accuracy of 6 and 16 Hz, respectively, yielding isotope shifts with a relative precision as low as 10^{-9}. We combine these spectroscopic results with new mass measurements with a relative precision of a few 10^{-12}. With this, we can extract a new bound on the mass and coupling strength of the potential new bosons. The results are also used to investigate higher-order nuclear structure effects along a chain of Yb isotopes. In combination with ab initio nuclear structure calculations, this provides a window to nuclear deformation and nuclear charge distributions along isotopic chains towards exotic, neutron-rich nuclei. In my talk I will discuss the current state of the art regarding the search for new physics and the investigation of nuclear structure.

Novel developments in trapped ion clocks

M. S. Safronova

Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA

The development of atomic clocks with systematic uncertainties in the 10^{-18} range and below enabled searches for "new physics" beyond the Standard Model (BSM) of elementary particles and interactions. Highly charged ions (HCIs) offer narrow optical transitions that are among the most sensitive to the BSM effects. I will discuss recent theoretical developments in predicting properties of ions [1-5] with application to development of clocks and astrophysics. Results for highly charged ion computation in Ni [1], Ca [2], Os [3], and Fe ions and test of QED contributions [4] will be discussed.

I will also highlight recent relevant theory developments, including large-scale high-performance computing, the transformation of research codes into widely accessible software [6], the open sharing of data through a community portal [7], and the application of machine learning in atomic theory [8]. Recent results on the sensitivity of the 229Th nuclear clock to the variation of the fine structure constant and dark matter [9] will be presented.

[1] "Finding the ultra-narrow $^3P_2 \rightarrow {}^3P_0$ electric quadrupole transition in Ni^{12+} ion for an optical clock," C. Cheung et al., Phys. Rev. Lett. 135, 093002 (2025)
[2] L. J. Spieß et al., "Excited-state magnetic properties of carbon-like Ca^{14+}," Phys. Rev. Lett. 135, 043002 (2025).
[3] Nils-Holger Rehbehn et al., "Study of the elusive level crossing in highly charged osmium with optical transitions suitable for physics beyond the Standard Model searches", arXiv:2509.06710 (2025).
[4] Chintan Shah et al., "High-Precision Transition Energy Measurements of Neonlike Fe XVII Ions", The Astrophysical Journal 969, 52 (2024).
[5] H. Li et al., "The radium ion's metastable 6d $^2D_{3/2}$ and 6d $^2D_{5/2}$ state lifetimes", Phys. Rev. Lett. 135, 073001 (2025).
[6] C. Cheung et al., "pCI: a parallel configuration interaction software package for high-precision atomic structure calculations", Comput. Phys. Commun. 308, 109463 (2025).
[7] Amani Kiruga et al., "Portal for High-Precision Atomic Data and Computation", arXiv:2506.08170 (2025)
[8] Pavlo Bilous, Charles Cheung, Marianna Safronova, "A neural network approach to running high-precision atomic computations", Phys. Rev. A 110, 042818 (2024).
[9] K. Beeks et al., "Fine-structure constant sensitivity of the Th-229 nuclear clock transition," in press, Nature Communications (2025).

Non-invasive mid-circuit measurement and reset on atomic qubits

Zuo-Yao Chen,* Isabella Goetting,* George Toh, Yichao Yu, Mikhail Shalaev, Sagnik Saha, Ashish Kalakuntla, Harriet Bufan Shi, Christopher Monroe, Alexander Kozhanov, and **Crystal Noel**

Duke Quantum Center, Department of Electrical and Computer Engineering and Department of Physics,
Duke University, Durham, NC 27708

Mid-circuit measurement and reset of subsets of qubits is a crucial ingredient of quantum error correction and many quantum information applications. Measurement of atomic qubits is accomplished through resonant fluorescence, which typically disturbs neighboring atoms due to photon scattering. We propose and prototype a new scheme for measurement that provides both spatial and spectral isolation by using tightly-focused individual laser beams and narrow atomic transitions. The unique advantage of this scheme is that all operations are applied exclusively to the read-out qubit, with negligible disturbance to the other qubits of the same species and little overhead. In this letter, we pave the way for non-invasive and high-fidelity mid-circuit measurement and demonstrate all key building blocks on a single trapped barium ion.

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[1] https://arxiv.org/abs/2504.12538

Spectroscopy and reactions of cold trapped molecular anions of interstellar relevance

Roland Wester

Institut für Ionenphysik und Angewandte Physik, Universität Innsbruck,
Technikerstraße 25, 6020 Innsbruck, Austria
roland.wester@uibk.ac.at

Cryogenic radiofrequency ion traps are versatile tools to study molecular ions with high sensitivity and precision [1]. Of interest are fundamental two-body and three-body collisions [2,3,4], as well as the precise spectroscopy of rovibrational or electronic transitions [5]. Such processes are also of importance in the cold environment of interstellar molecular clouds, where more than 300 molecules and molecular ions have been observed by now. Using the free electron laser facility FELIX, we have studied the vibrational spectroscopy of the negatively charged molecular ions CN^-, C_2N^-, C_3N^- [6,7]. Recently, we have also obtained absolute rate coefficients for the reactions of several negative ions with atomic hydrogen, an important loss mechanism for interstellar anions [8,9]. Furthermore, new results on C_2^- will reported, a negative ion that possesses several excited electronic states below the detachment threshold. Using photodetachment spectroscopy we have determined a new value for the electron affinity of C_2 [10] and using optical pumping and electronic spectroscopy of the first excited vibrational level we have measured the ground state vibrational frequency [11], which provides a stringent benchmark for high level molecular structure calculations.

[1] R. Wester, *J. Phys. B* **42**, 154001 (2009)
[2] R. Wild, M. Nötzold, M. Simpson, T. D. Tran, R. Wester, *Nature* **615**, 425 (2023)
[3] M. Nötzold, R. Wild ,C. Lochmann, T. Rahim, S. Purushu Melath, K. Dulitz, B. Mant, J. Franz, F. A. Gianturco, R. Wester, *Phys. Rev. Lett.* **131**, 183002 (2023)
[4] C. Lochmann, M. Nötzold, R. Wild, M. Satta, E. Yurtsever, F. A. Gianturco, R. Wester, *J. Phys. Chem. A* **127**, 4919-4926 (2023)
[5] M. Nötzold, R. Wild, C. Lochmann, R. Wester, *Phys. Rev. A* **106**, 023111 (2022)
[6] F. Dahlmann, P. Jusko, M. Lara-Moreno, P. Halvick, A. N. Marimuthu, T. Michaelsen, R. Wild, K. Geistlinger, S. Schlemmer, T. Stoecklin, R. Wester, S. Brünken, *Mol. Phys.* **120**, e2085204 (2022)
[7] F. Dahlmann, D. Dinu, P. Jusko, C. Lochmann, T. Gstir, A. Marimuthu, K. Liedl, S. Brünken, R. Wester, *ChemPhysChem* **24**, e202300 (2023)
[8] C. Lochmann, S. Purushu Melath, R. Wild, E. Yurtsever, A. Martín Santa Daría, L. González-Sánchez, F. A. Gianturco, R. Wester, *Ap. J.* **976**,114 (2024)
[9] C. Lochmann, S. Purushu Melath, M. Hauck, R. Wild, R. Wester, *J. Phys. Chem. A* **129**, 103 (2025)
[10] S. Purushu *et al.*, in preparation
[11] M. Hauck *et al.*, in preparation

Tunable atom-ion Feshbach resonances and recombination pathways in a hybrid quantum system

T. Schaetz[1], F. Thielemann[1], J. Siemund[1], W. Wu[1], P. Weckesser[1], J. Grieshaber[1], M. Morita[2], M. Tomza[2], K. Jachymski[2]
[1] *University of Freiburg, Germany*
[2] *University of Warsaw, Poland*

Hybrid systems combining single, trapped ions with ultracold atomic ensembles are a versatile platform for exploring quantum-controlled few-body dynamics. The long-range atom-ion interaction allows access to complex scattering phenomena, including magnetically tunable Feshbach resonances, enabling control over elastic and inelastic processes in the ultracold regime [1].

We report on experiments where a single Ba^+ ion is immersed in a spin-polarized cloud of ultracold ^6Li atoms, prepared in their electronic ground state. By tuning the ion's kinetic energy, we resolve isolated s-wave Feshbach resonances and observe energy-dependent onset of resonant three-body loss. These signatures reflect enhanced recombination near specific resonances. We access higher-partial-wave resonances at elevated collision energies [2].

Preliminary results on state-dependent recombination compare fully polarized ensembles [3] with those containing controlled admixtures of the first excited hyperfine state. This aims to test a proposed two-step recombination pathway involving intermediate atom-ion dimer formation before relaxation via a third atom.

Looking ahead, our platform opens up opportunities to investigate polaron physics, where the ion acts as a localized impurity coupled to a quantum many-body bath. This system could provide controlled access to non-equilibrium dressing dynamics, and the study of the ion's effective mass in a medium - a regime at the intersection of few- and many-body physics.

Optical trapping of both species could eliminate excess micromotion, enabling recoil-limited resolution and controlled access to dressing and thermalization dynamics.

[1] P. Weckesser et al., *Nature* **600,** 429 (2021)
[2] F. Thielemann et al., *Phys. Rev. X* **15,** 011051 (2025).
[3] M. Morita et al, arXiv:2507.12936

Hybrid systems of trapped ions, molecules and nanooscillators

S. Willitsch[1]

[1]*University of Basel, Basel, Switzerlamd*

In the presentation, we will highlight recent developments in the realm of hybrid experiments involving trapped ions. First, we will introduce a new type of hybrid system in which single ions are coupled to an oscillating nanowire in a miniaturised RF trap. We demonstrate the successful coupling of the two systems and the mechanical manipulation of the ion by the nanoscillator in the classical regime.

Second, we will describe a novel platform for the simultaneous trapping of cold trapped neutral molecules with cold trapped ions aimed at studying cold ion-molecule interactions. In this approach, the cold neutral molecules are generated by Stark deceleration to be loaded into a cryogenic magnetic trap superimposed onto a RF ion trap. We will discuss the performance of this new hybrid experiment and present first results on cold collisions of magnetically trapped OH radicals with laser-cooled Ca^+ ions.

New pathway to universal quantum computing and entanglement generation

Arghavan Safavi-Naini[1,2]

[1]*University of Amsterdam, Amsterdam, the Netherlands*

[2]*Qusoft, Amsterdam, the Netherlands*

Trapped-ions are one of the most mature platforms for quantum computation and quantum simulation. I will show that optical tweezers can be used to generate spin-dependent optical forces. The tweezers can be used to both enhance the programmability of the quantum simulator and to create new quantum computing architectures. Next, I will discuss a new pathway to multi parameter sensing in trapped ion quantum simulators which can be readily implemented. Here, spin-dependent squeezing is used for the simultaneous sensing of x and p. I will discuss the advantages of this protocol compared to prior protocols which require phase-locking and/or two-mode squeezing.

Novel toolboxes for quantum information processing with ion crystals in Penning traps

Athreya Shankar,[1] Samarth Hawaldar,[2] Prakriti Shahi,[3] N. Nikhil,[4] Allison L. Carter[5], Ana Maria Rey[6] and John J. Bollinger[6]

[1]Indian Institute of Technology Madras, Chennai, India
[2]Institute of Science and Technology Austria
[3]Indian Institute of Technology Bombay, Mumbai, India
[4]Boston University, USA
[5]NIST Boulder, USA
[6]JILA Boulder, USA

In this talk, I will discuss two approaches to quantum information processing with ion crystals in Penning traps that go beyond the standard settings of 1D or 2D planar single-species crystals. First, I will show how Penning traps can be used to realize bilayer trapped ion crystals that open up new avenues in quantum simulation and sensing [1]. I will discuss how such a platform can be used to realize Ising models with tunable interlayer and intralayer coupling strengths as well as chiral spin exchange models. Subsequently, I will describe how the native features of the Penning trap can be used along with the co-trapping of two different ion species to realize quantum simulators with periodic boundary conditions [2]. I will show how such a platform can be used for exploring spin currents and the impact of disorder on their propagation. If time permits, I will also briefly discuss how coherent spin-motion coupling can be enhanced in general 3D crystals using the technique of parametric amplification [3].

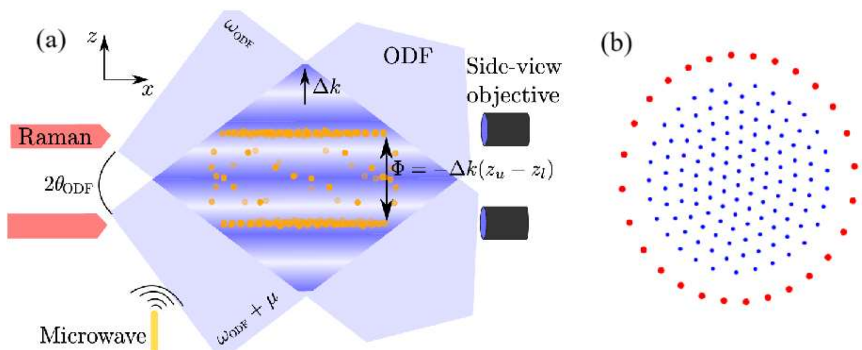


Figure 3: Novel paradigms for quantum information processing with Penning trap crystals. (a) A bilayer crystal of 200 ions in a traveling-wave optical lattice. (b) A dual-species 2D planar crystal of 127 $^9Be^+$ and 28 $^{24}Mg^+$ ions, with the Mg ions forming a ring at the crystal boundary.

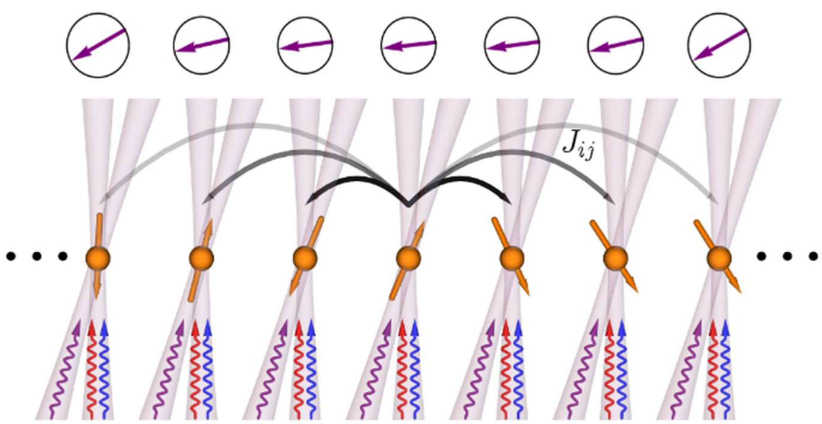
[1] S. Hawaldar, P. Shahi, A.L. Carter, A.M. Rey, J.J. Bollinger and A. Shankar, Phys. Rev. X **14**, 031030 (2024)
[2] P. Shahi, S. Hawaldar, A.M. Rey, J.J. Bollinger and A. Shankar, in preparation
[3] S. Hawaldar, N. Nikhil, A.M. Rey, J.J. Bollinger and A. Shankar, arXiv:2507.16741 (July 2025)

Quantum Simulations of The Mixed-Field Ising Model with Trapped Ions

O. Katz[1,2], D. Luo[2], F. Surace[3], A. De[2], A. Lerose[4], E. Bennewitz[5], B. Ware[5], A. Schuckert[5], Z. Davoudi[5], A. Gorshkov[5], C. Monroe[2]

[1]Cornell University, USA
[2]Duke University, USA
[3]California Institute of Technology, USA
[4]KU Leuven, Belgium
[5]University of Maryland/ NIST / Joint Quantum Institute, USA

Trapped-ion quantum simulators have long provided a versatile platform for exploring spin models and strongly correlated quantum dynamics. However, accessing phenomena such as confinement, string breaking, and first-order quantum phase transitions requires extensions beyond the standard transverse-field Ising model. In this talk, I will present recent theory and experiments [1-4] using a dual Raman beam array that enables independent, site-resolved control of both transverse and longitudinal fields, to realize the mixed-field Ising model. This capability allows observation of non-equilibrium string-breaking dynamics, signatures of a first-order phase transition including bubble nucleation, and future experiments of meson scattering. I will conclude by outlining ongoing efforts at Cornell to expand these capabilities and explore broader classes of spin models with trapped ion platforms.



Dual beam array for realizing mixed-field Ising models

[1] A. De, et al., arXiv 2410 13815 (2024).
[2] F. Surace, et al., arXiv 2411.10652 (2024).
[3] D. Luo, et al., arXiv 2505 09607 (2025).
[4] E. Bennewitz, et al., Quantum 9, 1773 (2025).

BASE – testing fundamental symmetries by high precision comparisons of the fundamental properties of protons and antiprotons

B. M. Latacz,[1] F. Abbass,[2] B. P. Arndt,[3,4] R. Czampiel,[2] S. Endoh,[5,6] S. Erlewein,[2] P. Geissler,[5] J. I. Jager,[3] T. Imamura,[7] M. Leonhardt,[2] P. Micke,[1,3] A. Mooser,[3] D. Schweitzer,[2] S. Stahl,[7] A. M. Thomas,[2] T. E. Tiemens,[8] F. Voelksen,[2] H. Yildiz,[3] K. Blaum,[3] J. A. Devlin,[9] Y. Matsuda,[6] C. Ospelkaus,[7,10] W. Quint,[4] A. Soter,[8] J. Walz,[11,12] Y. Yamazaki,[5] C. Smorra,[2] S. Ulmer,[2,5]

[1]*CERN, Geneva, Switzerland*
[2]*Heinrich Heine Universität, Duesseldorf, Germany*
[3]*Max-Planck-Institut fur Kernphysik, Heidelberg, Germany;* [4]*GSI, Darmstadt, Germany;* [5]*RIKEN, Ulmer Fundamental Symmetries Laboratory, Wako, Saitama, Japan;* [6]*University of Tokyo, Tokyo, Japan;* [7]*Leibniz Universitat, Hannover, Germany;* [8]*ETH-Zürich, Zürich, Switzerland;* [9]*Imperial College London, United Kingdom;* [10]*PTB, Braunschweig, Germany;* [11]*Institut fur Physik, Johannes Gutenberg-Universitat, Mainz, Germany;* [12]*Helmholtz-Institut Mainz, Johannes Gutenberg-Universitat, Mainz, Germany*

BASE – Baryon-Antibaryon Symmetry Experiment - is an international collaboration focused on testing CPT invariance by performing ultra-precise measurements of the fundamental properties of protons and antiprotons.
In this talk, we will focus on our flagship experiment at CERN, in which currently we are focusing on improving the measurements of the antiproton and proton magnetic moments. To date, these quantities were determined with a fractional resolution of 1.5 p.p.b. [1] and 300 p.p.t. [2], respectively, both by the BASE collaboration. We will report on the status of the current measurement campaign with the goal of improving the fractional accuracy of the antiproton magnetic moment by at least a factor of 10. We will summarize recent technical upgrades, like the implementation of a superconducting shimming system or a new cooling trap, which provides orders of magnitude improved cyclotron-mode cooling. The successful implementation resulted in error-free, non-destructive antiproton spin quantum transition spectroscopy [3]. These allowed us to implement the first coherent spin-state spectroscopy of a single antiproton spin, enabling measurements at 16-fold narrower linewidth than in previous experiments [4]. Finally, we will summarize the status of improved measurements.
Currently, the precision of our experiments is limited by magnetic noise in the accelerator hall. To overcome this limitation, we have developed an open Penning trap system, BASE-STEP [5], which will enable the transport of antiprotons to offline laboratories at Heinrich Heine University Dusseldorf and CERN, that are currently under development. In the stable environment, we aim to achieve measures with at least 100-fold improved precision.
Additionally, we are currently developing new measurement techniques that will allow us to continue operating the experiment in the accelerator hall. To that end, we will implement synchronized cyclotron frequency measurements on two-particles, simultaneously trapped on magnetron-locked orbits [6].

[1] C. Smorra, et al., *Nature* 550.7676 (2017): 371-374.
[2] G. Schneider, et al., *Science* 358.6366 (2017): 1081-1084
[3] B. M. Latacz, et al., *Phys. Rev. Lett.* 133.5 (2024): 053201
[4] B. M. Latacz, er al., Nature 644, 64–68 (2025)
[5] M. Leonhardt, et al., *Nature* 641(8064), 871-875 (2025)
[6] E. A. Cornell, et al., *Physical Review A* 45.5 (1992): 3049.

Highly charged isomeric qubits from antiproton annihilation

G Cerchiari[1,2], S Alfaro[2], L Panzl[2], J Zielínski[3], S Choudapurkar[1], Y Weiser[2], T Lafenthaler[2], T Monz[2], F P Gustafsson[4], M Germann[4], G Kornakov[3], M Doser[4] and the AEgIS Experiment

[1]*University of Siegen, Department of Physics, Siegen, Germany*
[2]*Universität Innsbruck, Institut für Experimentalphysik, Innsbruck, Austria*
[3]*Warsaw University of Technology, Faculty of Physics, Warsaw, Poland*
[4]*Experimental Physics Department, CERN, Switzerland*

We propose to utilize antiproton annihilation to produce synthetic qubits that may find application in quantum technology or for the study of excited nuclei. These qubits are based on the hyperfine transition of hydrogen-like highly charged ions (HCIs), which are emerging from the annihilation. The synthesis of HCIs via antiproton annihilation [1] differs from state-of-the-art techniques that are based on the acceleration of electrons onto atoms or on the acceleration of ions onto fixed targets because the annihilation is a reaction with much lower activation energy.
I will report on our theoretical investigation to suggest a list of nuclear candidates for a first experimental investigation. These candidates are selected HCIs that are found as products of the annihilation in an isomeric state and that have an excitation wavelength of the hyperfine transition in the infrared region of the electromagnetic spectrum [2]. Then, I will also report on how we are planning to control the annihilation reaction by co-trapping ions and antiprotons and the current status of our experiments.

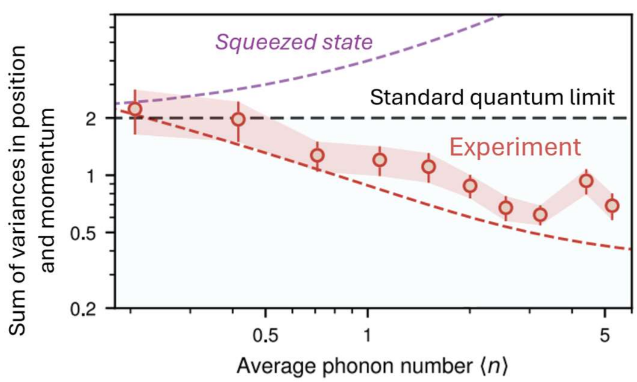
[1] G Kornakov et al., *Phys. Rev. C* **107**, 034314 (2023)
[2] S Alfaro et al., arXiv:2502.12832 (2025)

Quantum-enhanced multi-parameter sensing in a single mode [1]

T. R. Tan,[1] C. H. Valahu,[1] M. P. Stafford,[2] Z. Huang,[3] V. G. Matsos,[1] M. J. Millican,[1] T. Chalermpusitarak,[1] N. C. Menicucci,[4] J. Combes,[5] B. Q. Baragiola[4]

[1]University of Sydney, Australia
[2]University of Bristol, UK.
[3]Macquarie University, Australia
[4]RMIT University, Australia
[5]University of Melbourne, Australia

Measuring incompatible parameters is limited by fundamental constraints, exemplified by Heisenberg's uncertainty principle, which bounds the uncertainties when estimating position and momentum. Here, we demonstrate single-mode measurements of two incompatible parameters by instead measuring their modular counterparts [2]. By measuring modular position and modular momentum observables that commute, we demonstrate measurements of small displacements in position and momentum where the uncertainties are simultaneously reduced below the standard quantum limit (SQL), see Figure. This is achieved by using highly non-classical grid states (a variant of the Gottesman-Kitaev-Preskill logical qubits [3,4]) prepared in the motion of a single ion [1,5]. The measurement scheme ideally evades backactions, allowing the simultaneous parameter estimation of position and momentum displacements. Additionally, we investigate simultaneously estimating *number* and *phase*, which are the polar counterparts of position and momentum. This is performed by preparing a novel quantum resource---*number-phase* states [6]---and we demonstrate a metrological gain over their SQL.



Our experiment uses grid states to simultaneously reduce the variance of measuring small displacements in position and momentum below the standard quantum limit (SQL).

[1] C. H. Valahu, M. P. Stafford, Z. Huang, V. G. Matsos, M. J. Millican, T. Chalermpusitarak, N. C. Menicucci, J. Combes, B. Q. Baragiola, and T. R. Tan, arXiv:2412.04865 (2024).
[2] K. Duivenvoorden, B. M. Terhal, and D. Weigand, Phys. Rev. A **95**, 012305 (2017).
[3] D. Gottesman, A. Kitaev, and J. Preskill, Phys. Rev. A **64**, 012310 (2001).
[4] C. Flühmann, T. L. Nguyen, M. Marinelli, V. Negnevitsky, K. Mehta, and J. P. Home, Nature **566**, 513 (2019).
[5] V. Matsos, C. Valahu, T. Navickas, A. Rao, M. Millican, X. Kolesnikow, M. Biercuk, and T. Tan, Phys. Rev. Lett. **133**, 050602 (2024).
[6] A. L. Grimsmo, J. Combes, and B. Q. Baragiola, Phys. Rev. X **10**, 011058 (2020).

Trapped Rydberg ions

M. Hennrich[1], M. Mallweger[1], N. Kuk[1], R. Thomm[1], S. Schey[1,2], V. Shankar[1], H. Parke[1], I. Straka[1], W. Li[3], I. Lesanovsky[4]

[1] *Department of Physics, Stockholm University, Stockholm, Sweden*
[2] *Infineon Technologies Austria, Villach, Austria*
[3] *Centre of Mathematics and Theoretical Physics, University Nottingham, United Kingdom*
[4] *Institut für Theoretische Physik, University Tübingen, Germany*

Trapped Rydberg ions offer an alternative approach for quantum information processing [1,2]. This idea joins the advanced quantum computing toolbox developed for trapped ions with the strong dipolar interaction characteristic for Rydberg atoms. For trapped ions, this approach can significantly accelerate entangling gates and enable fast operations in larger ion crystals.
In this presentation, I will first describe the unique physics that arises when exciting ions into Rydberg states [2], including modifications to the trapping potential due to the Rydberg ions' large polarizability, and the tunable coupling between the ions' electronic and motional degrees of freedom. I will then summarize methods and results showing how strong Rydberg dipolar interactions can speed up entanglement operations with trapped ions [3]. Finally, I will present recent results on the state-dependent structural change of an ion crystal from linear to zigzag configuration induced by Rydberg excitation [4]. This represents a first step towards simulating molecular dynamics with the trapped Rydberg ion platform.

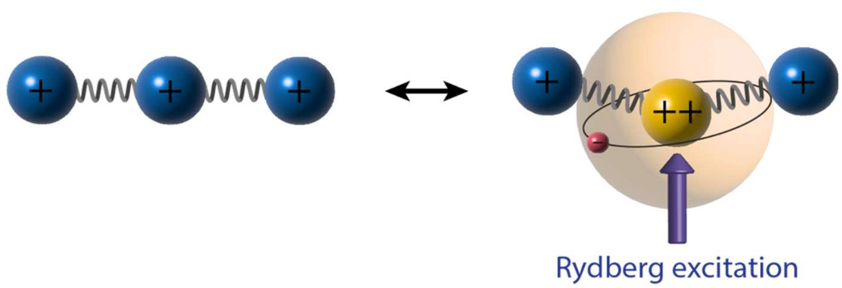


Figure 4: Schematic of the conformational change from linear to zigzag ion crystal induced by Rydberg excitation.

[1] M. Müller, L. Liang, I. Lesanovsky, and P. Zoller, *New J. Phys.* **10**, 093009 (2008).
[2] A. Mokhberi, M. Hennrich, and F. Schmidt-Kaler, *in Adv. At. Mol. Opt. Phys.* **69**, 233 (2020).
[3] C. Zhang, et al., *Nature* **580**, 345 (2020).
[4] M. Mallweger, et al., *arXiv:2507.23631* (2025).

Quantum Computing and Simulation with Qudits

M. Ringbauer,[1] M. Meth,[1] L. Gerster,[1] P. Tirler,[1] M. John,[1] K. Pareek,[1] T. Gollerthan,[1] L. Parigger,[1] T. Spalek,[1] R. Poloczek[1]

[1]*Universität Innsbruck, Institut für Experimentalphysik, Technikerstraße 25, 6020 Innsbruck, Austria*

The multi-level structure of trapped ions has long been recognized as a key advantage, enabling a wide range of techniques from cooling and dissipative processes for open system studies to spectroscopic decoupling for mid-circuit operations. Yet, despite increasing levels of control, information processing remained largely binary. Here, I discuss the potential and challenges for using the large Hilbert space for natively processing quantum information using qudits, rather than qubits [1]. Based on an established $^{40}Ca^{+}$-platform, we discuss various gate sets [1,2,3], suitable for different applications in qudit QIP, as well as first experimental demonstrations of the potential of this approach.

Distinguishing two classes of applications, we first discuss qudit-enhanced approaches, where the multilevel Hilbert space is used to achieve improvements in gate [4] and measurement complexity [5], as well as noise performance [6]. Second, native qudit QIP aims to completely abandon qubits and make full use of the available Hilbert space. In this context, we will discuss applications in the simulation of high-energy physics questions [3,7,8], where this approach appears particularly well suited.

[1] M. Ringbauer, et al., Nature Physics 18, 1053–1057 (2022)
[2] P. Hrmo, et al., Nature Communications 14, 2242 (2023)
[3] M. Meth, et al., Nature Physics 21, 570–576 (2025)
[4] X. Gao, et al., Quantum 7, 1141 (2023)
[5] R. Stricker, et al., PRX Quantum 3, 040310 (2022)
[6] M. Meth, et al., Phys. Rev. X 12, 041035 (2022)
[7] G. Calajo, et al., PRX Quantum 5, 040309 (2024)
[8] C. Edmunds, et al., PRX Quantum 6, 020349 (2025)

Rotational Doppler shifts measured with single ion probe

C.T. Schmiegelow,[1,2] N.A. Nuñez Barreto,[1,2] M. Bonetto,[1,2] M. A. Luda,[1,3] and C. Cormick,[4]

[1]Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, Buenos Aires, Argentina
[2]CONICET - Universidad de Buenos Aires, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina
[3] CEILAP, CITEDEF, Buenos Aires, 1603, Argentina
[4] Instituto de Física Enrique Gaviola, CONICET and Universidad Nacional de Córdoba, Ciudad Universitaria, X5016LAE, Córdoba, Argentina

Abstract: I will show a position-resolved measurement of the azimuthal Doppler shift of a structured beam[1]. These results reveal it's characteristic divergence at the center and it's scale-invariant nature. In the experiment we use two copropagating vortex laser beams. The setup isolates the azimuthal gradients of the fields, eliminating longitudinal and curvature effects. We provide a detailed characterization of the phenomenon by deterministically positioning a single ion across the beams and measuring fluorescence spectra with sharp "dark resonances" whose features depend on the angular velocity of the ion and the difference of optical orbital angular momentum between the two beams. The interpretation of the measurements is supported by numerical simulations and by a simplified analytical model. Our results reveal key properties of the rotational Doppler effect, showing that it increases approaching the center of the beam and that it is independent of the waist of the beam. This offers insights into the feasibility of superkicks or super-Doppler shifts for sensing and manipulating atomic motion transverse to the beams' propagation direction.

[1] Phys. Rev. Lett. 133, 183601 – Published 29 October, 2024 ,
https://doi.org/10.1103/PhysRevLett.133.183601

Coherent control of light from large ensembles of single-photon emitters

A. Kovalenko[1], D. Tran[1], K. Singh[1], T. Pham[2], A. Lešundák[1], A. Cidrim[3], R. Bachelard[3], R. Filip[1], L. Lachman[1], O. Číp[2], **L. Slodička[1]**
[1]*Department of Optics, Palacký University, Olomouc, Czechia*
[2]*Institute of Scientific Instruments of CAS, Brno, Czechia*
[3]*Departamento de Física, Universidade Federal de São Carlos, São Carlos, Brazil*

Achieving an efficient, coherent interface between atomic quantum emitters and light is crucial for advancing scalable quantum communication, distributed quantum information processing, or experimental observation of diverse cooperative quantum phenomena.
We demonstrate a free-space optical collection and coherent light control from large trapped ion crystals, enabling different paradigmatic regimes of photon emission from independent atomic emitters, including highly pure single photons or the largest photonic states with provably nonclassical statistics. The presented approach allows for an efficient single-mode coupling with simultaneous observation of phase coherence of light from several tens of trapped ions, applicable for the efficient photonic generation of atomic entanglement or the directional control of optical emission from trapped ions. The realized measurements demonstrate the emergence of super-Poissonian quantum statistics from many indistinguishable single-photon emitters [1], the enhancement of collection efficiency of nonclassical light scattered from linear ion strings [2], and the coherent control of the corresponding photon statistics [3].
The presented results suggest an alternative implementation of an efficient trapped ion-photon interface in free space by utilizing the optical coherence and scattering geometry that is inherent to most modern linear ion traps. Its effectiveness in a small collection solid angle regime offers a natural advantage of minimal wavefront aberrations of the collected light using simple paraxial collection optics. The potential to achieve collectively coupled ion crystals promises a feasible programmable platform for exploring cooperative quantum phenomena [4].

[1] A. Kovalenko et al., *Optica* **10**, 456-463 (2023)
[2] T. D. Tran et al., *npj Quantum Inf.* **11**, 117 (2025)
[3] K. Singh et al., *Phys. Rev. Lett.* **134**, 203602 (2025)
[4] M. Reitz et al., *PRX Quantum* **3**, 010201 (2022).

The Innsbruck Off-Campus Quantum Network and a Trapped-Ion Source of Multipartite Photonic Entanglement

F. Kodakkat[1], A.Winkler[1], F. Bernecker[1], T. Runggaldier[1], J. Bate[1], M. Canteri[1], I. Mishra[2], N. Friis[2], T. Northup[1], V. Krutyanskiy[1], **B. Lanyon[1]**

[1] *Institut für Experimentalphysik, Universität Innsbruck, Technikerstasse 25, 6020 Innsbruck, Austria.*

[2] *Technische Universität Wien, Atominstitut & Vienna Center for Quantum Science and Technology, Stadionallee 2, 1020 Vienna, Austria.*

I'll summarise two projects that use trapped ions in optical cavities to contribute to the development of long-distance quantum networks. In the first project, we establish a 17 km-long optical fiber link connecting a lab in Innsbruck to a village outside the city. Ion-entangled photons are distributed over the fiber, achieving a Bell-state fidelity of 0.89(3). Furthermore, we implement our recent quantum repeater node demonstration [1] over the long fiber, achieving remote entanglement of photon pairs with a Bell-state fidelity of 0.77(2). These results show that trapped-ion quantum repeater technology is compatible with real-world optical fiber networks. In the second project, we demonstrate a trapped-ion source of multipartite entangled photons. Specifically, three co-trapped ions are used to produce GHZ states of three photons. In the future, the trapped-ion source could be reprogrammed and extended to distribute arbitrary multipartite entangled states amongst the nodes of ion-based quantum networks.

[1] V. Krutyanskiy et al., *Phys. Rev. Lett.* **130,** 213601 (2023)

Hot topic talks

1. E. Iseke, Innovative fabrication of gold-filled through substrate vias for scalable ion trap quantum computing
2. T. Sägesser, A 3-dimensional trapped-ion scanning probe
3. B. Lekitsch, Scaling quantum computers to thousands of ions with high fidelity
4. A. Vazquez-Brennan, A universal four-qubit gate set using two trapped ions
5. J.J. Hope, All-to-all fast two-qubit gates for trapped ions
6. Aditya Kolhatkar, Light shift gates in ion traps with integrated optics
7. L. Hilico, Observation of a Doppler free two-photon transition in sympathetically cooled state selected H_2^+ ions
8. A. Shlykov, Quantum-logic spectroscopy of forbidden rovibrational transitions in single molecular ions
9. A. Ayyadevara, Structural transitions and stochastic dynamics of Coulomb clusters in a 3D Paul trap
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Innovative fabrication of gold-filled through substrate vias for scalable ion trap quantum computing

E. Iseke,[1,2] F. Giebel,[1,2] N. Krishnakumar,[1,2] N. Stahr,[1,3] K. Thronberens, [1,2] J. Stupp, [1,3] M. Billah, [2,3] and C. Ospelkaus[1,2,3]

[1] *Leibniz Universität Hannover, Institut für Quantenoptik, Hannover, Germany*

[2] *Physikalisch Technische Bundesanstalt, Quest Institut, Braunschweig, Germany*

[3] *Laboratorium für Nano- und Quantenengineering (LNQE), Hannover, Germany*

To solve real-world problems, quantum computers must be highly scalable. Achieving this scalability is a key challenge for ion trap quantum computers [1]. Traditional wire bonds, while commonly used for electrode connections, introduce limitations, such as blocking optical access and increasing complexity [2]. To overcome these challenges, Through Substrate Vias (TSVs) offer a superior alternative, enabling vertical electrical connections without obstructing critical areas. Classical TSVs use silicon as a substrate and copper as a filling material [3]. Silicon has high RF losses and copper can oxidize and affect stability. We address these issues by using gold-filled TSVs in dielectric substrates like fused silica or sapphire.

Our novel, patent-pending process minimizes processing steps and eliminates complex chemical additives or pulsed electroplating, ensuring high stability and reproducibility. The holes in the substrates are formed using the process of Selective laser-induced etching (SLE). SLE is a two-step process comprising laser modification and wet etching. This method allows a precise via shaping, including a cavity with an additional chamfer that optimizes subsequent metal deposition.

A thin titanium adhesion layer and a gold seed layer are deposited before electroplating. Then electroplating with a simple DC current is performed. The chamfer promotes current crowding, leading to an initial sealing of the cavity and void-free bottom-up filling. This results in highly reliable, defect-free gold-filled TSVs, as shown in Figure 1.

By integrating our gold-filled TSVs, ion trap architectures can transition away from wire bond-based connections towards a more scalable and robust interconnect solution. Additionally, these TSVs facilitate the use of interposer chips, replacing traditional filter boards and further enhancing system integration. Our results demonstrate a significant step towards more scalable and reliable quantum computing hardware.

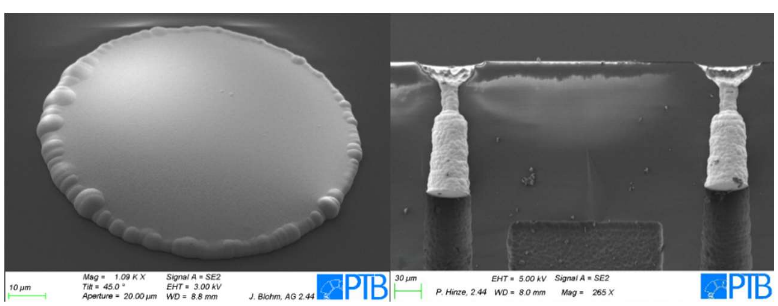


Figure 1 Defect-free gold-filled TSVs in fused silica. Left: Top view of a fully filled TSV. Right: Cross-section of two adjacent TSVs during the filling process.

[1] Bruzewicz et al., *Appl. Phys. Rev.* 6, 021314 (2019).
[2] Guise et al., *J. Appl. Phys*. 117, 174901 (2015)
[3] Wang et al., *Appl. Sci*. 13, 8301 (2023)

A 3-dimensional trapped-ion scanning probe

T. Sägesser,[1,2] S. Jain,[1,2] P. Hrmo,[1,2] A. Ferk,[1] M. Simoni,[1] Y. Cui,[1] C. Mordini,[1,3] D. Kienzler[1] and J. Home[1]

[1] *ETH Zürich, Zürich, Switzerland*

[2] *Present address: ZuriQ AG, Zürich, Switzerland*

[3] *Present address: Università degli Studi di Padova, Padova, Italy*

A wide range of quantum systems suffer from negative effects due to electric fields originating on close-by surfaces [1,2,3]. Among them, trapped ions are exceptionally sensitive to electric fields, which has allowed their use as sensors of noise stemming from surfaces with a diverse set of material compositions and surface treatments [4,5]. However, previous work was restricted in flexibility by the use of radio-frequency traps, limiting spatial positioning to linear translations and calling into question whether the observed results are connected to the radio-frequency fields [6]. Here, we instead use a micro-fabricated Penning trap [7] and demonstrate a single-ion probe which can be freely translated in three dimensions.

We position the ion at distances between 50 µm and 450 µm from a gold surface and above a 200 × 200 µm^2 area and measure static and time-varying electric fields at a grid of locations. From this data, the distribution of unwanted charge on the surface is reconstructed as well as the spatial dependence of the electric-field noise, in particular revealing the scaling behavior with respect to the ion-surface distance. Furthermore, the capability to resolve the fields in 3-d helps to distinguish noise originating on the surface from external contributions. The levels of surface noise observed in our apparatus are consistent with the lowest results obtained in radio-frequency traps to date.

The methods demonstrated here allow similar probing to be carried out on samples with a variety of materials, surface constitutions and geometries, providing a new tool for surface science and for the identification of materials and processes for low-noise performance.

[1] de Graaf et al., *Sci. Adv.* **6**, 5055(2020)
[2] Thiele et al., *Phys. Rev. A* **90,** 013414 (2014)
[3] Kim et al., *Phys. Rev. Let.* **115,** 087602 (2015)
[4] Brownnutt et al., *Rev. Mod. Ph.* **87,** 1419 (2015)
[5] Sedlacek et al., *Phys. Rev. A* **98,** 063430 (2018)
[6] Brown et al., *Nat. Rev. Mat.* **6,** 892–905 (2021)
[7] Jain et al., *Nature* **627,** 510–514 (2024)

Scaling quantum computers to thousands of ions with high fidelity

B. Lekitsch,[1] and J.Hilder[1]

[1]*neQxt GmbH, Erlenbach am Main, Germany*

We're discussing neQxt's approach to scaling trapped ion quantum computers while simultaneously increasing fidelities. To achieve this goal, we combine laser gates making use of individual addressing with ion shuttling and 3D ion traps. We can produce fully three-dimensional shaped trap electrodes on chips, uniformly coat them with metals and then precisely align and join multiple trap chips to make up 3D symmetric ion traps including X-junctions and more complex trap designs.

We make use of far detuned laser gates in combination with small individual addressing beams to achieve very high single and two qubit fidelities. Combined with integrated active waveguide control we attempt to build a quantum processor with more than a thousand ions and to combine multiple processors afterwards.

A universal four-qubit gate set using two trapped ions

A. Vazquez-Brennan,[1] J.D. Leppard[1], S. M. Decoppet[1], A.S. Sotirova,[2], W. R. Cutler[1], F. Pokorny[2], and C.J. Ballance[1,2]

[1] *University of Oxford, Oxford, United Kingdom*

[2]*Oxford Ionics, Oxford, United Kingdom*

Current quantum computing devices face the challenge of making the most efficient use of a small number of individual information carriers (e.g. individual trapped ions, superconducting resonator circuits, photons, etc.). One promising approach is to extend the accessible Hilbert space by using more than two energy levels per information carrier. Such schemes have often made use of qu*d*its to directly compute in base $d > 2$. While these approaches are naturally suited to certain problems, such as simulating quantum chemistry [1] and high-energy physics [2], quantum algorithms have been primarily developed for a binary qubit architecture. This makes a qubit-to-qudit translation step necessary for their implementation on qudit devices. Alternatively, an information carrier with 2^n accessible levels can be used to host n qubits [3-6]. This allows qubit algorithms to be implemented without modification, while requiring fewer information carriers for the same number of qubits in an equivalent two-level processor. Furthermore, existing techniques for qudit operations can be directly used to implement single- and two-qubit gates.

We present a system for manipulating four qubits stored in two trapped $^{137}Ba^+$ ions. Pairs of qubits are encoded within four atomic states distributed across the ground S1/2 and metastable $D_{5/2}$ levels of one ion. We extend the coherence time of the system by choosing states within the hyperfine structure with low relative magnetic field sensitivities. Single- and two-qubit gates on qubits within the same ion are implemented by driving quadrupole transitions between pairs of states using a narrow-linewidth 1762 nm laser. In addition, a pair of 532 nm lasers are used to drive two-ion gates via a light-shift mechanism [7, 8]. This novel gate scheme can be used to implement two-, three- and four-qubit gates, by using additional intra-ion gates that do not require motional coupling. These operations form a universal gate set on this system.

The physical requirements we use are the same as those found in many trapped-ion experiments with single qubits per ion. As such, this approach could be implemented in existing systems to double the number of qubits in a register without increasing the number of ions. This could reduce the complexity associated with controlling many ions, such as crowded motional mode spectra if the ions are stored in a single chain, or large numbers of shuttling operations in QCCD architectures.

[1] MacDonell, R. J. et al., *Chem. Sci.* **12**, 9794 (2021).
[2] Rico, E. et al., Ann. Phys. **393**, 466 (2018).
[3] Saumya, S. et al. (2024), preprint at http://arxiv.org/abs/2406.19332.
[4] Nikolaeva, A. S. et al, *Phys. Rev. A* **109**, 022615 (2024).
[5] Campbell, W. C. and Hudson, E. R. (2022), preprint at http://arxiv.org/abs/2210.15484.
[6] Bian, J. et al (2024), preprint at http://arxiv.org/abs/2407.01196.
[7] Sawyer, B.C. and Brown, K.R., *Phys. Rev. A* **103**, 022427 (2021).
[8] Hrmo, P. et al., *Nat. Commun* **14**, 2242 (2023).

All-to-all fast two-qubit gates for trapped ions

I. Savill-Brown[a], Z. Mehdi[a], P. Grosser[a], S.A. Haine[a], A.K. Ratcliffe[b], V.D. Vaidya[b], H. Liu[b], C.R. Viteri[b], and **J.J. Hope[a]**

[1]*Australian National University, Canberra, Australia*

[2]*IonQ Inc., College Park 20740, USA*

The ability to connect arbitrary pairs of qubits has a dramatic effect on the efficiency of quantum circuits. In trapped-ion systems, all-to-all connectivity can be achieved by resolving individual modes of collective motion, but at the cost of reduced fidelity and speed as the length of the ion chain increases. This motivates a range of approaches to scalable operations using shorter ion chains, such as shuttling, photonic interconnects and highly parallel operations. Fast gates, where the ions are subject to maximum possible state-dependent kicks (SDKs) from carefully timed laser pulses, do not require selective addressing of single motional modes. Previous studies have shown that such fast gate schemes are quicker, scale better for longer chains and allow more flexible trap geometry. However, they were only shown to be efficient for nearest-neighbor operations [1].

We present a theoretical study of fast all-to-all entangling gates in trapped-ion quantum processors. We demonstrate that impulsive spin-dependent excitation can be used to perform high-fidelity non-local entangling operations in quasi-uniform long chains. We identify a regime of phonon-mediated entanglement between arbitrary pairs of ions in the chain, where any two pairs of ions in the chain can be entangled at high fidelity in less than two centre-of-mass oscillation periods for chains of up to 30 ions. For longer chains, a subset of distant non-local solutions also exist. We assess the experimental feasibility of the proposed gate schemes, which reveals pulse error requirements that are independent of the length of the ion chain and the distance between the target qubits. Furthermore, we compare the performance of non-local fast gates to equivalent operations composed of sub-microsecond nearest-neighbor gate operations, as well as the achievable performance of spectroscopic protocols employed in existing QCCD and linear-trap architectures. These results suggest entangling gates based on impulsive spin-dependent excitation present new possibilities for large-scale computation in near-term ion-trap devices.

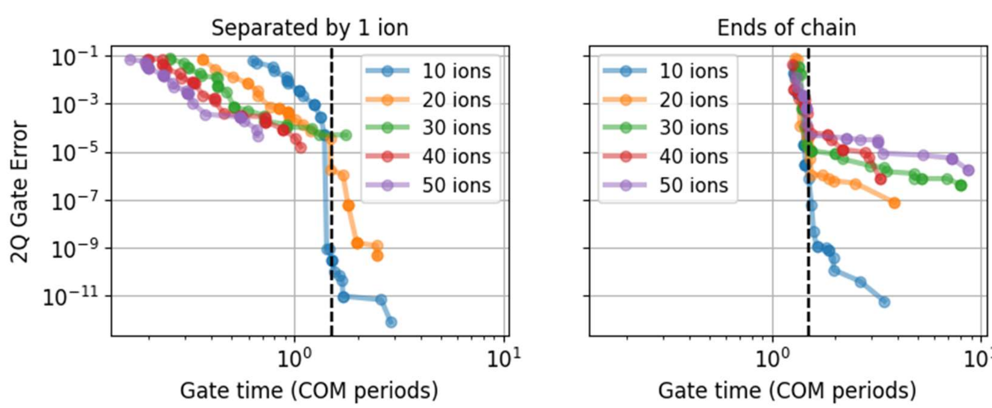


Figure 5: Gate fidelities using a maximum of 200 SDKs, showing feasible gates at minimum and maximum ion separation across long ion chains. Fast gates of two trap periods can be performed between arbitrary pairs of ions up to 30 ions.

[1] Z.Mehdi, A.K.Ratcliffe, and J.J.Hope, Phys. Rev. Research 3, 013026 (2021).

Light shift gates in ion traps with integrated optics

Aditya Kolhatkar,[1] Jack Xing,[1] Hamim Rivy,[1] Vighnesh Natarajan,[1] and Karan K. Mehta[1]

[1]*Cornell University, Ithaca, USA*

Surface traps with integrated optics stand to enable scalable control of trapped ion systems by permitting stable beam delivery and passive phase stability, and providing new opportunities for engineering laser-ion interactions. Previous work on two-qubit entangling operations with integrated photonics demonstrated a Mølmer-Sørensen gate on an optical qubit [1]. In pursuit of high-fidelity gates acting on long-lived ground-state qubits with favorable scaling of required power with gate duration, here we present trap designs for implementing light shift gates [2,3] with $^{40}Ca^{+}$ leveraging integrated optical delivery, for qubits encoded in $4S_{1/2}$ Zeeman sublevels. Spontaneous photon scattering limits gate fidelity in such a scheme, or equivalently, places a lower bound on the Raman detuning and laser power requirement for a target fidelity and gate duration [4]. We present an alternative geometry that yields an order-of-magnitude reduction in power required compared to the conventional two-beam configuration for realistic trap layouts, indicating potential for integrated light delivery to partially alleviate challenges faced with laser-based gates.

We will also present experimental work from our group on fast ground state cooling [5] with integrated photonics, towards realization of these gate schemes.

[1] Mehta, K.K., et al. Integrated optical multi-ion quantum logic. Nature 586, 533–537 (2020)

[2] Leibfried, Dietrich, et al. Experimental demonstration of a robust, high-fidelity geometric two ion-qubit phase gate. Nature 422.6930 (2003): 412-415

[3] Ballance, Christopher J., et al. High-fidelity quantum logic gates using trapped-ion hyperfine qubits. Physical review letters 117.6 (2016): 060504

[4] Ozeri, Roee, et al. Errors in trapped-ion quantum gates due to spontaneous photon scattering. Physical Review A—Atomic, Molecular, and Optical Physics 75.4 (2007): 042329

[5] Z. Xing, K.K. Mehta. "Trapped-ion laser cooling in structured light fields." arXiv:2411.08844 (2024)

Observation of a Doppler free two-photon transition in sympathetically cooled state selected H_2^+ ions

L. Hilico,[1,2] M. Leuliet,[1] D. Aboul Hosen, [1] A.O. Parada Flores, [1] B. Argence,[1] M. Panet, [1] H. Demattos Nogueira, [1] M. Salman, [1] J.-Ph. Karr[1,2]

[1]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL,*

Collège de France, 4 place Jussieu, F-75005 Paris, France

[2]*Université Evry Paris-Saclay, boulevard François Mitterrand, F-91000 Evry, France*

Hydrogen molecular ions have long been identified as promising species for high precision fundamental constant determination [1] since they are calculable systems [2] and are amenable to high precision measurements. Since 2022, HD^+ spectroscopy is included in the CODATA fundamental constant adjustment [3,4,5,6].

We report on the first observation of the (v=0,L=2)←(v=1,L=2) Doppler-free two-photon transition in H_2^+ at 9.166 µm. We present the experimental setup focusing on the sympathetically cooled state selected molecular ions source [7] and the spectroscopy laser frequency control with respect to the *Système International* of units using a frequency comb referenced to the REFIMEVE ultrastable signal [8].

We also discuss the future impact of H_2^+ spectroscopy on the determination of fundamental constants and search for new physics beyond the standard model [9,10].

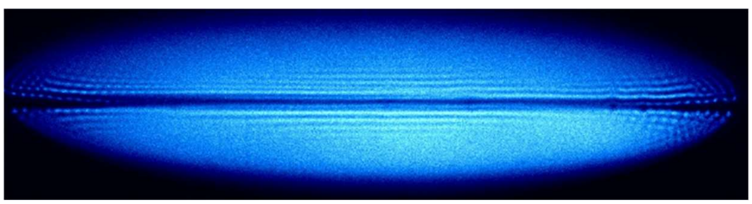


Figure 6: Be^+ coulomb crystal containing state selected H_2^+ ions.

[1] W.H. Wing et al., *Phys. Rev. Lett*. 36, 1488 (1976).
[2] V.I. Korobov et al., *Phys. Rev. Lett*. 118, 233001 (2017).
[3] S. Patra et al., *Science* **369**, 1238 (2020).
[4] S. Alighanbari et al., *Nature* 581, 7807 (2020).
[5] I.V. Kortunov et al., *Nature Physics* 17, 569 (2021).
[6] S. Alighanbari et al, *Nature Physics* 19, 9 (2023).
[7] J. Schmidt et al., *Phys. Rev. Appl*. **14**, 024053 (2020).
[8] https://www.refimeve.fr/index.php/en/
[9] C. Delaunay et al., *Phys. Rev. Lett.* **130**, 121801 (2023).
[10] S. Schiller, *Phys. Rev. A* **109**, 042825 (2024).

Quantum-logic spectroscopy of forbidden rovibrational transitions in single molecular ions

A. Shlykov,[1] M.L. Diouf,[1] R. Karl,[1] M. Roguski,[1] and S. Willitsch[1]

[1]*Department of Chemistry, University of Basel, Klingelbergstrasse 80, 4056 Basel, Switzerland*

Ultranarrow, electric-dipole forbidden transitions between rovibrational states in molecules and molecular ions with expected natural linewidths on the Hz level present intriguing opportunities for the development of highly precise mid-infrared frequency standards and for the exploration of fundamental physical problems such as possible time variations of fundamental constants [1]. The molecular nitrogen ion N_2^+ has been proposed as an attractive system for precision molecular spectroscopy because, as an apolar diatomic ion, it features small systematic shifts and transitions with low sensitivity to magnetic fields in its electronic ground state [2,3]. However, the experimental detection of pure rovibrational transitions in systems like N_2^+ [4] and their precision spectroscopy is challenging on several levels. Besides the weak line strengths, which require highly sensitive detection methods, the positions of the lines are usually known only with substantial uncertainties based on spectroscopic constants determined through indirect methods. Moreover, theoretical predictions of the line strengths are also affected by significant uncertainties.

Here, we report the first observation of electric-quadrupole rovibrational transitions in single molecular ions using a highly sensitive quantum-logic detection protocol [5]. We studied individual hyperfine-Zeeman components of the $|v=1, N=2\rangle \leftarrow |v=0, N=0\rangle$ rovibrational transition in the $X^2\Sigma_g^+$ electronic ground state of single N_2^+ ions confined in a radiofrequency ion trap with a co-trapped Ca^+ ion used for sympathetic laser cooling and quantum-logic state detection. The transitions were directly driven by rapid adiabatic passage using a frequency-chirped laser pulse from a mid-infrared quantum cascade laser. This approach enabled the effective, fully reversible transfer of the rovibrational populations even without precise knowledge of the transition frequencies and at the same time allowed the recycling of the same single molecule in sequential spectroscopic experiments. Thus, line positions could be detected with a 2 MHz uncertainty limited by the frequency sweep of the laser pulse. The present approach represents a powerful methodology for coherently manipulating single molecules on ultranarrow spectroscopic transitions for precision measurements and quantum technologies applications. It can readily be adapted for other diatomic and polyatomic species, provided suitable laser sources for excitation and quantum-logic detection of transitions are available.

[1] Safronova, M.S., Budker, D., DeMille, D., Kimball, D.F.J., Derevianko, A. and Clark, C.W. *Rev. Mod. Phys.* **90**, 025008 (2018).
[2] Kajita, M. *Phys. Rev. A*, **92**, 043423 (2015).
[3] Najafian, K., Meir, Z., and Willitsch S. *Phys. Chem. Chem. Phys.*, **22**, 23083 (2020).
[4] Germann, M., Tong, X., and Willitsch S. *Nat. Phys.*, **10**, 820 (2014).
[5] Sinhal, M., Meir, Z., Najafian, K., Hegi, G., and Willitsch S. *Science*, **367**, 1213 (2020).

Structural transitions and stochastic dynamics of Coulomb clusters in a 3D Paul trap

A. Ayyadevara,[1] A. Prakash,[1] S. Dutta,[1] A. Paramekanti,[2] and S. A. Rangwala[1]

[1]*Raman Research Institute, Bengaluru, India*

[2]*University of Toronto, ON, Canada*

We present structural transitions observed in clusters formed by a few laser-cooled atomic ions confined in a three dimensional (3D) end-cap type trap [1]. Numerical analysis of the clusters' vibrational modes reveals distinct lattice dynamics at specific transition points. Real-time imaging enables us to capture distinct dynamics: mode softening of a 3D cluster at a symmetry-breaking continuous transition, stochastic switching between distinct configurations at a discontinuous transition, and hysteresis across a spinodal point, where metastable minima vanish. Remarkably, we find a unique triple point-like feature where a symmetry-breaking transition and a symmetry-changing transition occur simultaneously [2].

In addition, we identify a few clusters with two symmetry-equivalent configurations. In real time, the ions reorient as the entire cluster switches between the two potential energy minima. To understand the transition pathway and the switch rate, we apply methods from quantum chemistry [3] and reaction rate theory [4]. The theoretical predictions agree well with stochastic-dynamics simulations and experimental observations, pointing towards a thermal-activation process due to the photon bath used for Doppler-cooling of the cluster. Our experiments and analysis of tuneable Coulomb clusters show how symmetries, energy landscapes, and dynamical pathways govern transitions in finite-sized systems.

[1] C. Schrama, E. Peik, W. Smith, and H. Walther, Optics Communications 101, 32 (1993).
[2] Ayyadevara, A. Prakash, S. Dutta, A. Paramekanti, and S. A. Rangwala, arXiv:2505.16378.
[3] G. Henkelman and H. Jónsson, J. Chem. Phys. 113, 9978 - 9985 (2000).
[4] H. Kramers, Physica 7, 284 (1940).

A non-neutral plasma simulator based on laser-cooled trapped ions

C. Klein,[1] M. Collombon[1], M. Baldovin[2], G. Hagel,[1] M. Housin,[1]

R. Dubessy,[1] **C. Champenois[1]**

[1]*Aix-Marseille University and CNRS, PIIM, Marseille, France*

[2] *Institute for Complex Systems CNR, Rome, Italy*

We propose a joint experimental and theoretical approach to measure the self-diffusion in a laser-cooled trapped ion cloud where part of the ions are shelved in a long-lived dark state. The role of the self-diffusion coefficient in the spatial organization of the ions is deciphered, following from the good agreement between the experimental observations and the theoretical predictions. This comparison furthermore allows to deduce the temperature of the sample. Protocols to measure the self-diffusion coefficient are discussed, in regard with the control that can be reached on the relevant time scales through the dressing of the atomic levels by laser fields.

In this work, laser-cooled clouds of atomic ions stored in a radio-frequency trap are practical realizations of a finite-size One Component Plasma (OCP) in the strongly coupled regime.

The OCP is a reference model in the study of strongly coupled Coulomb systems and by tuning the density and temperature of the sample, different regimes can be explored from gas to liquid and crystals. Standard kinetic theories fail to describe transport plasma properties under conditions of strong Coulomb coupling because they neglect effects of spatial and temporal correlations induced by nonbinary collisions. This fundamental problem needs to be solved to accurately model the transport properties, and equations of state of dense laboratory and astrophysical plasmas. This is the problem we want to solve [1] by analyzing the competition between the radiation pressure force and the self-diffusion in a laser-cooled cloud of ions where part of them are shelved in a long-lived metastable state.

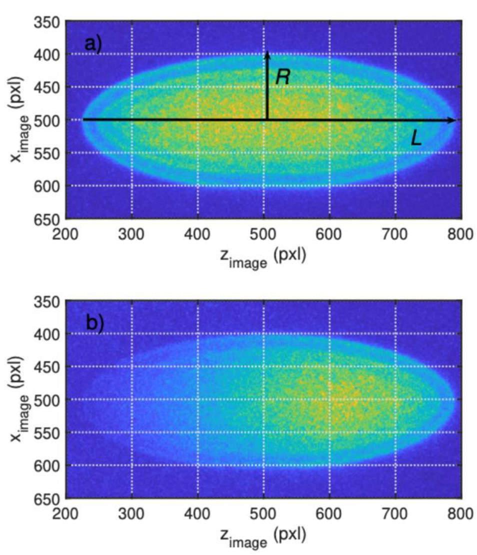


Figure 7: (a): picture of the fluorescence of a trapped ion cloud made of 1240 +/- 50 Ca^+ ions. (b) : same cloud with an extra laser admitted, propagating toward z>0 on the picture, this laser is shelving part of the ions in a metastable dark state.

[1] Self-diffusion in a strongly coupled non-neutral plasma, M. Baldovin *et. al Phys. Rev. A* **109**, 043116 (2024)

Derivation and demonstration of four- and six-photon stimulated Raman transitions

G. J. Gregory,[1] A. Quinn,[1] S. Brudney,[1] E. R. Ritchie,[1] D. J. Wineland,[1] D. T. C. Allcock,[1] and **J. O'Reilly[1]**

[1]*University of Oregon, Oregon, USA*

We experimentally demonstrate transitions between electronic angular momentum states with a difference in magnetic quantum number $\Delta m_J \geq 3$ via resonant four- and six-photon stimulated Raman transitions. Derivation of the corresponding Rabi frequencies, which are verified experimentally, follows the standard treatment of two-photon transitions including the adiabatic elimination of intermediate states. We show super-linear scaling of the Rabi frequency with drive beam intensity and characterize intermediate state population both theoretically and experimentally. Finally, we discuss pathways to increase the presented multi-photon transition fidelities, providing a tool for efficient, high-fidelity qu*d*it control.

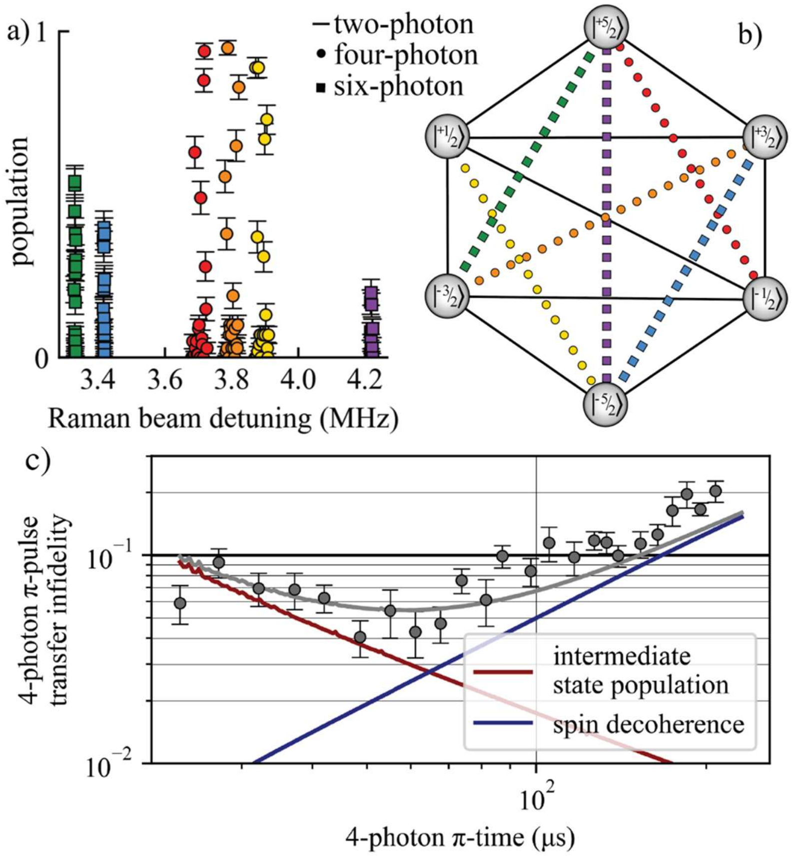


Figure 8: (a) Rabi spectroscopy of transitions within $D_{5/2}$ with $\Delta m_J \geq 3$ as driven by four (circles) and six (squares) photon processes. (b) Diagram illustrating full unitary connectivity in the $D_{5/2}$ manifold enabled by four- and six-photon transitions. (c) Measured four-photon π-pulse transfer infidelity between $m_J = +5/2$ and $m_J = -1/2$ at different Raman beam powers. The blue line is infidelity due to spin decoherence and the red line is infidelity due to intermediate state population, both based on full numeric simulations.

Frequency metrology with antimatter

J. Nauta[1] on behalf of the ALPHA collaboration

[1] *CERN, Geneva, Switzerland*

According to the fundamental symmetries that underpin the Standard Model, both matter and antimatter should have been produced in equal quantities at the Big Bang. The absence of antimatter in our Universe as we observe it today, strongly motivates direct matter-antimatter comparisons, where any observed difference would lead to new physics. The Antihydrogen Laser Physics Apparatus (ALPHA) collaboration at CERN produces and traps antihydrogen atoms by combining antiproton and positron plasmas, which are then used for precise studies. Recent progress includes the accumulation of thousands of atoms, direct laser cooling of the antihydrogen sample [1] and the first observation of the motion of antihydrogen in a gravitational field [2].

Laser spectroscopy of antihydrogen has already resulted in a test of CPT symmetry to a relative precision of 2×10^{-12} [3]. In hydrogen however, the same spectral feature, the 1S-2S transition, has been determined up to a precision of 4×10^{-15} [4]. To enable matter-antimatter comparisons at that level and beyond, we have implemented a Cs fountain clock in collaboration with NPL [5]. The fountain provides a local realization of the SI second and is used to steer an active hydrogen maser in the same laboratory. In addition to comparing the frequency of the maser with our fountain, we also cross-check against national metrology labs via satellite frequency transfers. A frequency comb and a stabilized fiber link, as well as two ultra-low expansion cavities, then allow for accurate determination of the laser frequency that is used to interrogate the antihydrogen sample.

Recently, we have observed a novel transition in the hydrogen spectrum: the 2S4P resonance. Accurate determination of the center frequency of this transition via excited state laser spectroscopy will allow us to access fundamental quantities such as the antiproton charge radius.

I will present recent progress and the current status towards a more precise measurement of the 1S2S transition, as well as the latest results of the 2S4P transition in antihydrogen. I will also outline novel experimental techniques to further reduce the linewidth of the observed resonances, boosting the accuracy of searches for symmetry breaking between matter and antimatter.

[1] C. J. Baker et al., *Nature* ***592***, 35 (2021).
[2] E. Anderson et al., *Nature* **716**, 621 (2023).
[3] M. B. Ahmadi et al., *Nature* **557**, 71 (2018).
[4] C. G. Parthey, A Matveev, J. Alnis, B. Bernhardt, A. Beyer, R. Holzwarth, A. Maistrou, R. Pohl, K. Predehl, T. Udem, T. Wilken, N. Kolachevsky, M. Abgrall, D. Rovera, C. Salomon, P. Laurent, and T. W. Hänsch, *Phys. Rev. Lett.* **107**, 20 (2011).
[5] R. J. Hendricks, F. Ozimek, K. Szymaniec, B. Nagórny, P. Dunst, J. Nawrocki, S. Beattie, B. Jian, and K. Gibble, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **66**, 624 (2019).

Trapped heavy, highly charged ions - recent results at the HITRAP deceleration facility

N. Stallkamp,[1,2] Z. Andelkovic,[2] S. Fedotova[2], W. Geithner[2], F. Herfurth[2], N.Kehl[3], J. Ködel[3], D. Neidherr[2], W. Nörtershäuser[3,4], S. Rausch[3,4], S. Trotsenko[2], G. Vorobjev[2], D. Zisis[3]

[1]*Goethe University, Frankfurt am Main, Germany*

[2]*GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany*

[3]*Technical University of Darmstadt, Darmstadt, Germany*

[4]*Helmholtz Akademie Hessen für FAIR HFHF, TUD, Darmstadt, Germany*

The HITRAP facility, at the GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt, is designed to decelerate and cool heavy, highly charged ions (HCI) created by the GSI accelerator complex [1]. The system consists of a two-stage linear decelerator, followed by a cryogenic Penning trap for subsequent ion cooling. The deceleration stages reduce the ion energy from 4 MeV/u to 500 keV/u and to 6 keV/u respectively, before forwarding a slow, but hot ion bunch towards the cooling trap. The trap is operated in a so-called nested configuration, in which the electrons, created by an external photoelectron source, are stored simultaneously with the HCI and serve as a cold thermal bath. After cooling, the ions can be transported via a low-energy transfer beamline towards various attached experiments [2]. For commissioning of the trap as well as a source of light HCI for attached experiments, a dedicated small ion source (Dresden EBIT) is attached to the beamline [3].

So far, deceleration of heavy HCI has been regularly set up down to 6 keV/u. The subsequent electron cooling process is under development with promising results. The first indications of electron cooling of locally produced HCI in a Penning trap could be achieved, a major milestone towards heavy HCI at eV energies.

Recently, the first user-experiment could be successfully carried-out, in which a decelerated $^{197}Au^{79+}$ beam was delivered for a material research experiment. The status and results of the facility as well as future aspects will be presented.

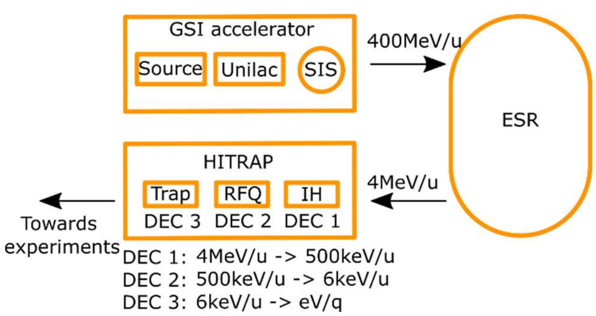


Figure 9: Schematic of the HITRAP facility in the frame of the GSI accelerator (left). Picture of the decelerator beamline (right).

[1] F. Herfurth et al., Phys. Scr., 014065 (2015)
[2] Z. Andelkovic et al., Nucl. Instr. Methods Phys. Res. Sec. A vol. 795 2015 055 (2015)
[3] A. Sokolov et al., JINST 5 C11001 (2010)

Towards simulation of topological superconductors with a Penning trap

J. Y. Z. Jee,[1] J.H. Pham,[1] G. Cafe,[1] N. Makadia,[1] M. J. Biercuk[1] and R. N. Wolf[1]

[1]*University of Sydney, New South Wales, Australia*

The p+ip superconductor is an unconventional superconductor in which Cooper pairs form with angular momentum in two dimensions. These chiral systems exhibit protected dynamical phases that hold potential for topological quantum computing [1]. In this work, we present preliminary results in generating the initial Bardeen-Cooper-Schrieffer (BCS) phase of a p+ip superconductor using a Penning trap, which naturally confines over a hundred ion qubits in a two-dimensional ion Coulomb crystal. The ions' spin states encode the presence or absence of a Cooper pair while the ion positions take the role of the momentum of the Andersen pseudospins. We initialize the radially symmetric BCS spin configuration by leveraging the natural rotation of the crystal. To achieve this, we generate a radially dependent AC Stark shift across the crystal plane by precisely controlling the tilt angle of a spin-dependent force with respect to the crystal plane [2]. Finally, with individual spin-state readout [3], we perform a full tomographic reconstruction of the individual spins of all the ions to confirm the state initialization protocol.

[1] A. Shankar et al, PRX Quantum **3,** 040324 (2022).
[2] J. H. Pham et al, Adv. Quantum Technol **7**, 2400086 (2024).
[3] R. N. Wolf et al, Rhys. Rev. Applied **21,** 054067 (2024).

Trapped ions as a platform for a quantum repeater and quantum communication over an urban fiber link

Christian Haen,[1] Max Bergerhoff,[1] Omar Elshehy,[1] Elena Arenskötter,[1] Stephan Kucera,[1,2] Jonas Meiers,[1] Tobias Bauer,[1] Christoph Becher,[1] Jürgen Eschner[1]

[1]*Universität des Saarlandes, Saarbrücken, Germany*

[2]*Luxembourg Institute of Science and Technology (LIST), Belveaux, Luxembourg*

A possible route towards quantum communication over existing telecom fiber infrastructure is using single ions as quantum memories and single photons as quantum information carriers. This faces challenges such as exponential transmission loss and environment-induced drifts that decohere polarization-encoded quantum information. Losses may be overcome by deploying quantum repeaters that asynchronously entangle the quantum memories, while polarization infidelities may be mitigated by active polarization compensation or time-bin encoding.

We report on the characterization of the 14 km long Saarbrücken fiber link, see Fig. 1, for quantum communication experiments, and the implementation of a polarization drift compensation, reaching >99% process fidelity. We demonstrate entanglement distribution as well as atom-to-photon quantum state teleportation with ~84% average fidelity over the fiber link. The realized quantum communication protocols employ a $^{40}Ca^{+}$ single-ion quantum memory, heralded absorption of one photon from an entangled, ion-resonant photon pair source, and quantum frequency conversion [1].

We also demonstrate, in a laboratory experiment, an asynchronous entanglement-based quantum repeater cell [2] with two $^{40}Ca^{+}$ ions in the same Paul trap. We swap atom-photon entanglement to photon-photon entanglement with ~76% average fidelity by applying a Mølmer–Sørensen quantum gate on the ions. Additionally, we show progress towards a quantum repeater segment using a photonic Bell state measurement, as well as first steps towards interfacing the trapped-ion and color-center quantum memory platforms.

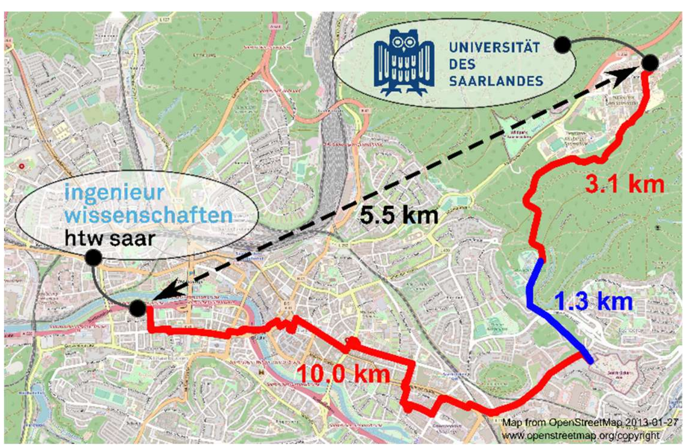


Figure 10: Map of Saarbrücken fiber link

[1] S. Kucera et al., npj Quantum Inf. **10**, 88 (2024)
[2] M. Bergerhoff et al., Phys. Rev. A **110**, 032603 (2024)

Distributed Quantum Computing between Two Ion-Trap Nodes in a Quantum Network

D. Main, P. Drmota, D. P. Nadlinger, E. M. Ainley, A. Agrawal, B. C. Nichol, R. Srinivas, **G. Araneda** and D. M. Lucas

University of Oxford, UK

No quantum computing platform has yet established a clear path to the scalability required for achieving practical quantum advantage, meaning the ability to outperform classical systems in solving useful problems. In classical computing, scalability is achieved through clusters of interconnected processors, which act as individual nodes and communicate through a shared network to execute tasks collaboratively. A similar architectural approach is emerging as a promising direction for quantum computing. In this presentation, I will describe our recent experimental results toward building such quantum clusters. In particular, we have used a photonic network to generate remote entanglement between two quantum processors based on trapped ions, located several meters apart. This entanglement enables the deterministic execution of distributed quantum computing protocols, including quantum gate teleportation and, for the first time, a distributed implementation of Grover's search algorithm across two quantum nodes [1]. I will also present our latest results on multi-partite multi-species entanglement shared across multiple nodes and involving different atomic species, advancing the prospects for scalable and modular quantum networks.

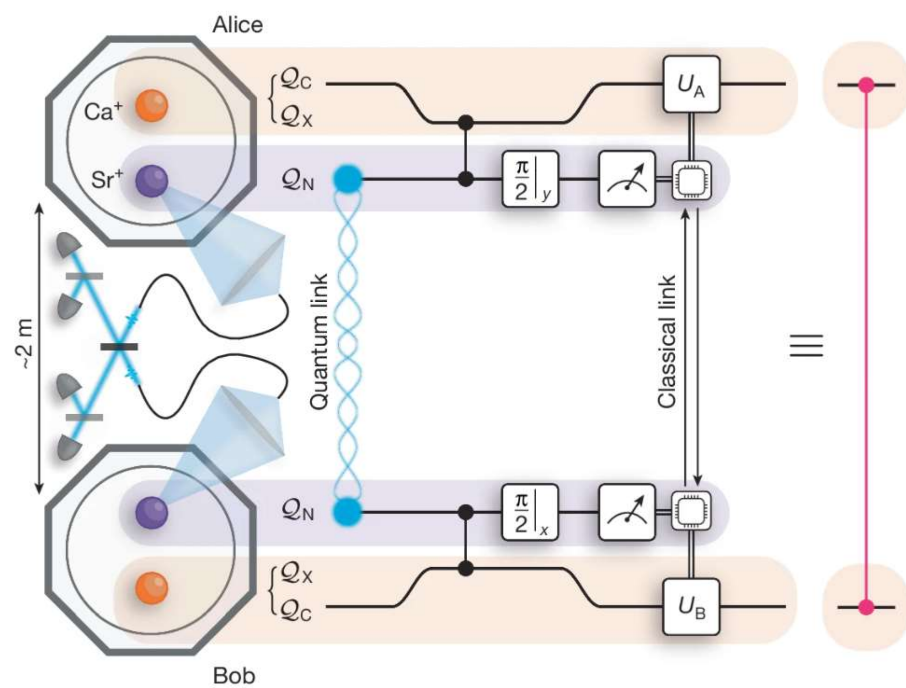


Figure 11: Circuit used for the deterministic teleportation of a CZ gate between two remote trapped-ion quantum computers

[1] Nature **638**, 383–388 (2025)

Doubly-driven trapped ion coupled to a nanomechanical oscillator

M. Weegen,[1] **A.G. Poindron,[1]** M. Poggio,[2,3] and S. Willitsch[1]

[1]*Department of Chemistry, University of Basel, Basel, Switzerland*

[2]*Department of Physics, University of Basel, Basel, Switzerland*

[3]*Swiss Nanoscience Institute, University of Basel, Basel, Switzerland*

Hybrid traps are versatile platforms that provide excellent control of the interaction between diverse atomic and molecular systems [1,2,3,4]. In parallel, nano- and micromechanical systems have also established themselves as highly precise instruments [5,6]. Their integration in particle traps and optical cavities [7,8,9] has facilitated new kinds of interactions between small- and large-scale systems, in turn providing new insights on their dynamics and interactions [10,11,12]. We recently reported the coupling of $^{40}Ca^{+}$ ions with an oscillating charged Ag_2Ga nanowire [8] (Fig. 1a), which is the first step towards the creation of more sophisticated ion–nanowire couplings inducing coherent states of motion or the reciprocal probing and control of each subsystem [12]. Here the coupling was studied in the context of Duffing equation, where the anharmonicity of the potential is represented by a quartic term and the laser-cooling by both a linear and a cubic velocity term. We have determined both related quantities by measuring the amplitude hysteresis under a frequency sweep of the oscillator (Fig. 1b). A scenario involving two driving forces has been explored, during which the amplitude of the oscillator as a function of the relative phase between the driving forces has been observed (Fig. 1c).

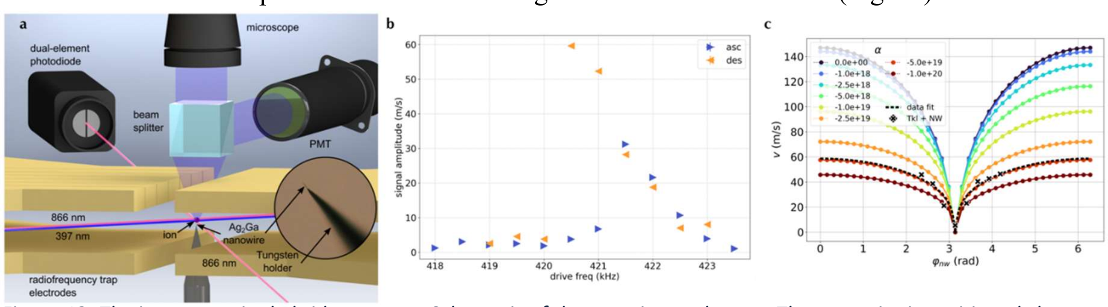


Figure 12: The ion–nanowire hybrid system. a. Schematic of the experimental setup. The nanowire is positioned close to the trapped ions in a miniaturised trap made of four wafers separated by 400 µm. b. Velocity amplitude measured as a function of single-drive frequency for ascending (blue) and descending (orange) order. c. Oscillator maximum velocity vs. relative phase between the two driving forces of same amplitude (φ_{tkl} = 0). Coloured points are the numerical solutions of the model for different anharmonicity constants α. Coloured lines are analytical fits. Black crosses are experimental results, black dashed line is the analytical fit of the data, yielding an anharmonicity constant of α = -4.78 10^{19}.

[1] B. M. Mihalcea *et al.*, *Physics Reports* **1016** (2023).
[2] M. Sinhal and S. Willitsch (2023). Molecular-Ion Quantum Technologies. *In* Photonic Quantum Technologies.
[3] M. Tomza *et al.*, *Rev. Mod. Phys.* **91** (2019).
[4] A. Härter and J. Hecker Denschlag, *Contemporary Physics* **55** (2014).
[5] M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, *Rev. Mod. Phys.* **86** (2014).
[6] R. Desgarceaux *et al.*, *Nano lett.* **20** (2020).
[7] A. Jöckel *et al.*, *Nature nanotechnology* **10** (2015).
[8] M. Weegen, M. Poggio and S. Willitsch, *Phys. Rev. Lett.* **133** (2024).
[9] E. Bonvin, *et al.*, *Phys. Rev. Research* **6** (2024).
[10] D. Hunger *et al.*, *Comptes Rendus Physique* **12** (2011).
[11] C. Gonzalez-Ballestero *et al.*, *Science* **374** (2021).
[12] P. N. Fountas, M. Poggio and S. Willitsch, *New J. Phys.* **21** (2019)

Towards Ramsey-Comb spectroscopy of singly-ionized helium

A.E. Díaz, [1] A. Martínez de Velasco, [1] E.L. Gründeman, [1] V. Barbé,[1] L.S. Dreissen,[1]
R. Taïeb[2], and K.S.E. Eikema[1]

[1]*LaserLaB, Vrije Universiteit, Amsterdam, the Netherlands.*

[2]*Sorbonne Université, Paris, France.*

The 1S–2S transition of hydrogen-like systems is a benchmark for testing fundamental physics. We focus our efforts on singly ionized helium (He^+), which enables improved determination of the alpha particle charge radius and provides a test of higher-order QED terms [1].

We recently reported the first successful laser excitation of the 1S-2S transition in an atomic helium beam in a manner that will enable precision spectroscopy. This was achieved by combining an ultrafast amplified pulse from a frequency comb laser at 790 nm with its 25th harmonic at 32 nm, produced by high-harmonic generation in an argon jet [2].

For precision spectroscopy of the transition at the 50 kHz level or better, we are working now towards implementing Ramsey-Comb Spectroscopy (RCS) with a He^+ ion confined in a Paul trap. This method requires tight control of the ion's motion to enable interaction with two laser pulses separated by up to several microseconds in a synchronized manner. The He^+ ion will be trapped together with a beryllium ion (Be^+), which serves both as a cooling agent and as a readout ion. Fast loading techniques for both He^+ and Be^+ are being developed to optimize the speed of the data taking.

We are currently implementing the ion trapping and laser system hardware. To detect 1S-2S He^+ excitation we intend to focus on destructive double-ionization and we report on the progress of these targets.

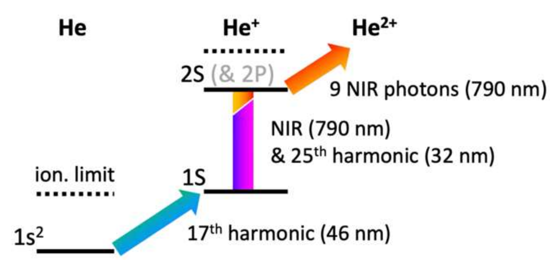


Figure 13. Level scheme of the He^+ 1S-2S experiment [2].

[1] J. Krauth et al., PoS (FFK2019) **49** (2019).
[2] E.L. Gründeman et al., Commun. Phys. **7**, 414 (2024).

Poster 3

Testbeds for quantum technology at PTB

A. P. Kulosa[1], M. Hesse[1], J. Mattil[1], R. Singh[1], F. Salahshoori[1], C. Grimpe[1], G. Du[1], J. E. Jordan[1], C. Flasch[1,2], C. Rössler[2], N. Spethmann[1] and T. E. Mehlstäubler[1,3]

[1] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, DE-38116 Braunschweig*
[2] *Infineon Technologies Austria AG, Siemensstraße 2, AT-9500 Villach*
[3] *Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, DE-30167 Hannover*

Ion traps have evolved into a mature technological device, serving as an enabling technology for state-of-the-art quantum sensors [1], optical atomic clocks [2], and quantum computers [3]. Miniaturised chip-size ion traps [4] or 3D ion traps [5] can be fabricated using semiconductor and micro-electro-mechanical system (MEMS) fabrication processes. Facing this degree of miniaturisation, the integration of micro-optics [6] or nano-photonics for laser cooling and clock interrogation [7] as well as ion state detection via single-photon avalanche detectors (SPAD) [8] is a promising solution for a novel generation of compact and scalable optical clocks or quantum computers. Laser light required for ion cooling, state detection, repumping and quantum manipulation typically spans from the UV to the IR regime. The realisation of low-loss and high-quality laser light delivery to the ions via nano-photonics still remains to be a major technological challenge and requires careful characterisation of the photonic components.

We give an overview on the different test beds for quantum technology at PTB, which have been set up in a collaboration between the "Quantum Clocks and Complex Systems (QuaCCS)" group [9] and the Quantum Technology Competence Center (QTZ) [10]. The user facility "Ion Traps" was established for a standardised characterisation of ion traps from academia and industry and provides the complete hard- and software required for trapping of Yb^+ ions. A steel vacuum chamber supporting macroscopic 3D ion traps is already in full operation, while a compact titanium chamber for the integration of microfabricated (surface) ion traps is currently under construction.

In addition, we have established a photonics test lab providing testing capabilities ranging from UV to IR laser wavelengths, such as optical laser beam tomography (e.g. output characterisation of grating couplers) and imaging of photonic layers of ion trap chips. In the frame of the "Qu-Test" project, we currently characterise photonic integrated chips as a use case from industry in close collaboration with Infineon Technologies Austria AG. In parallel, a joint use case on ion trap characterisation led to a European initiative on standardised characterisation methods as a "New Work Item Proposal" submitted to CEN/CENELEC's Joint Technical Committee 22 (JTC22).

[1] J. Yoo et al., *Nano Convergence* **12**, 12 (2025)
[2] S. M. Brewer et al., *Phys. Rev. Lett.* **131**, 059901 (2023)
[3] C. D. Bruzewicz et al., *Appl. Rev. Phys.* **6**, 021314 (2019)
[4] Z.D. Romasko et al., *Nature Review Physics* **2**, 285-299 (2020)
[5] S. Auchter et al., *Quantum Sci. Technol.* **7**, 035015 (2022)
[6] X. Fernandez-Gonzalvo & M. Keller, *Scientific Reports* **13**, 523 (2023)
[7] N. Chauhan et al., *arXiv:2402.16742* (2024)
[8] J. Kwon et al., *Nature Comm.* **15**, 3709 (2024)
[9] https://www.quantummetrology.de/quaccs/home/
[10] https://www.qtz.ptb.de

Towards a direct high-precision measurement of the nuclear magnetic moment of $^{3}He^{2+}$ with 1ppb accuracy.

<u>Ankush Kaushik[1]</u>, Annabelle Kaiser[1], Marius Müller[1], Stefan Dickopf[1], Stefan Ulmer[2,3], Andreas Mooser[1] and Klaus Blaum[1]

[1]Max-Planck-Institut für Kernphysik, Heidelberg, Germany

[2]RIKEN, Wako, Japan

[3]HHU Düsseldorf Germany

Absolute magnetometry with ^{3}He and its application in fundamental and applied science has gained significant attention in recent years [1]. From muon g-2 measurement to medical diagnostics, material characterisation and geophysical exploration, magnetometry plays a vital role. The accuracy of magnetometry with the current standard water NMR probes is limited due to its complex molecular structure and significant systematic effects. Overcoming these limitations, ^{3}He promises enhanced accuracy and precise calibration over a broad spectrum of magnetic fields. However, establishing ^{3}He as an NMR standard requires a precise value for its nuclear magnetic moment. So, we aim to perform a direct parts-per-billion measurement of the nuclear magnetic moment of $^{3}He^{2+}$ in a Penning trap, improving on our previously achieved most precise value using the magnetic moment of $^{3}He^{1+}$ and a theoretical value for diamagnetic shielding. To this end, spin flips of a single nucleon, indicated by miniature frequency changes, need to be detected over background frequency fluctuations. Since the latter fluctuations are directly proportional to the motional energy, preparing a particle at micro eV energies is essential [2]. To address these constraints, we modified our Penning trap and introduced two new traps that enable fast and efficient preparation of particles at the required energies. As such, these new traps will be crucial for a successful measurement. The design and expected performance of these new traps, along with the result of the $^{3}He^{1+}$ measurement, will be presented.

[1] Mooser et al., J. Phys.: Conf. Ser. 1138 012004 (2018)
[2] Ulmer et al., Physical Review Letters, 106(25) 253001 (2011)

Programmable quantum simulator with 2D ion crystals

A. Zhdanov,[1] M. Bock,[1] N. Griesbach,[1] C. F. Roos,[1,2] S. R. Muleady,[4] R. Kaubruegger,[3] A. M. Rey,[3] L. Arceci,[2] P. Zoller[2]

[1]*University of Innsbruck, Innsbruck, Austria*

[2]*IQOQI, Innsbruck, Austria*

[3]*JILA, Boulder, Colorado, USA*

[4]*University of Maryland, College Park, Maryland, USA*

Trapped ions are a great platform for quantum simulation due to their excellent coherence properties, possibility to induce variable range spin-spin interactions, ease of single particle control and readout. Typically, ions are held either in the form of a lattice in a Penning trap or as a linear chain in a Paul trap. The former can trap many more ions, while the latter has the important advantage of having site-resolved control and readout of individual ions' electronic states.

In our project we overcome the limitations of a standard Paul trap and go beyond 1D chains, expanding ion crystals to 2D lattice while keeping individual addressing and readout capabilities. To do so, we have designed and built a monolithic Paul trap, capable of storing 100+ ions in a stationary 2D crystal.

To simulate quantum interaction in the system, state-dependent forces are induced via stimulated Raman transition within the ground state manifold of $40Ca^{+}$ ion. These forces make out-of-plane (drumhead) modes of a 2D crystal act as an entanglement mediator. With this, we implemented Ising, transverse field Ising and XY spin-spin interaction models with variable interaction range.

Moreover, recently we have gained an ability to control each particle state independently, as well as to create an entanglement between any arbitrary pair of particles via tightly focused laser pulses on $40Ca^{+}$ quadrupole transition.

We show that it is possible to combine multiple single particle unitary rotations with a spin-spin interaction model of choice, and to perform two-qubit entangling gates between any pair of ions in a 2-dimensional crystal of ions, thus qualifying our platform as a programmable quantum simulator. This paves the way to explore complex dynamics of entangled states in a lattice of spins.

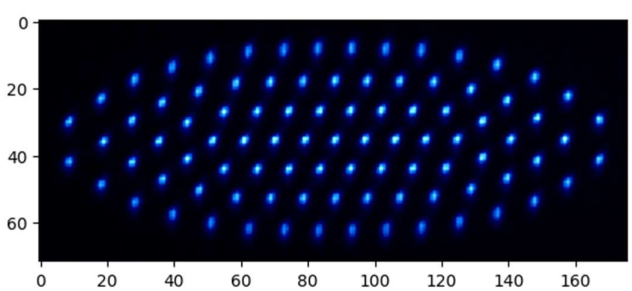


Figure 14: EMCCD Camera shot of a 2D ion crystal in our trap

Poster 6

Commercial optical frequency standard based on a single $^{171}Yb^{+}$ ion

A. Friedenauer,[1] P. Thoumany,[1] S. Jeyalathaa Karthikeyan,[2] B. Lipphardt,[2] N. Huntemann,[2] S. Ritter[1] and J. Stuhler[1]

[1]*TOPTICA Photonics AG, Lochhamer Schlag 19, 82166 Graefelfing, Germany*

[2]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, Braunschweig, Germany*

Spectacular progress in the field of optical frequency standards (OFS) has led to the most precise instruments ever developed [1] and supports the concrete plan for a redefinition of the second [2]. Most of the current OFS are, however, highly specialized laboratory systems with very limited reliability and uptime. For the practical realization of this redefinition, commercially available OFS enabling robust operation and high uptime are crucial.

Several research projects involving both academic and industrial partners have realized demonstrators surpassing the stability of current primary standards by more than order of magnitude, e.g. the opticlock project [3]. Now companies take over and develop OFS focusing on robust and stable long-term operation.

Here, we present a commercial OFS industry prototype contained in two 19” racks building up on expertise obtained with opticlock [3]. The OFS is based on the $^{2}S_{1/2}$ (F=0) – $^{2}D_{3/2}$ (F=2) electric quadrupole transition in a single $^{171}Yb^{+}$ ion at 435.5 nm. Preliminary characterization of the OFS via interleaved operation promises relative frequency instabilities of $< 5 \times 10^{-15}/\mathrm{sqrt}(t)$, where t is the averaging time. The system's systematic uncertainty is currently limited due to the uncertainty in atomic parameters to low 10^{-17}, however, the long-term stability and reproducibility are expected to reach the low 10^{-18} level. We will present an overview of the system design and report on the current status of the metrological characterization of the OFS at PTB.

[1] M. Marshall et al, “High-Stability Single-Ion Clock with 5.5 × 10−19 Systematic Uncertainty”, arXiv (Accessed May 30, 2025)
[2] N. Dimarcq et al., “Roadmap towards the redefinition of the second”, Metrologia **61** (2024) 012001
[3] J. Stuhler et al., “Opticlock: transportable and easy-to-operate optical single-ion clock”, Meas. Sens. **18** (2021) 100264

Towards a network of $^{43}Ca^+$ optical clocks for entanglement-enhanced metrology

A. Agrawal,[1] Beth C. Nichol[1], Ellis M. Ainley[1], Dougal Main[1], Adam R. Martinez[1], Peter Drmota[1], Jacob A. Blackmore[1], David P. Nadlinger[1], Gabriel Araneda[1], David B. Hume[2,3], David M. Lucas[1], Raghavendra Srinivas[1]

[1]*University of Oxford, Oxford, United Kingdom*

[2]*National Institute of Standards and Technology, Boulder, USA*

[3]*Department of Physics, UC Boulder, USA*

Over the past few decades, advancements in optical atomic clocks have enabled measurements of time and frequency with unprecedented stability and systematic uncertainty [1, 2]. Precision frequency comparisons between macroscopically separated clocks have applications in geodesy [3], probing variations in fundamental constants, and in dark matter searches [4]. Frequency comparisons between independent clock systems are limited by the standard quantum limit (SQL). In contrast, a set of N entangled atomic clocks can achieve a $\sqrt{N}$ stability improvement to surpass the SQL and approach the Heisenberg limit – the ultimate precision possible in quantum theory.

We previously demonstrated this enhancement in a network of two $^{88}Sr^+$ clocks [5] on the 674 nm $5S_{1/2} \leftrightarrow 4D_{5/2}$ quadrupole transition using Ramsey spectroscopy, whose stability was mainly limited by the short probe duration of 20 ms due to magnetic field fluctuations. We are now setting up the next generation of the experiment wherein we map the remote Sr-Sr entanglement onto two $^{43}Ca^+$ ions. The 729 nm $^{43}Ca^+$ $|4S_{1/2}\ F{=}4,\ mF{=}4\rangle \leftrightarrow |3D_{5/2}\ F{=}4,\ mF{=}3\rangle$ optical clock transition is field-insensitive at 4.96 G, enabling probe durations at the excited state lifetime limit of ~1 s (comparable to the start-of-the-art clocks [1]) and thus improve our stability.

We will present progress towards these clock experiments, including the setup of a 729 nm laser system locked to a high finesse cavity, as well as fibre noise cancellation on a 20 m fibre. We will further present some theoretical work on practically scaling up entanglement-enhanced differential spectroscopy measurements to larger networks of clocks.

[1] S. M. Brewer et al., *Phys. Rev. Lett*. **123**, 33201 (2019).
[2] E. Oelker et al., *Nature Photonics* **13**, 714–719 (2019).
[3] T. E. Mehlstäubler et al., *Reports on Progress in Physics 81*, 064401 (2018).
[4] M. S. Safronova et al., *Rev. Mod. Phys.* **90**, 025008 (2018).
[5] B. C. Nichol et al., *Nature* **609**, 689–694 (2022).

Towards a scalable ion trap architecture - Trapping 2D arrays of Calcium ions in a surface penning trap

J. Flannery[1], **B. E. Asenbeck[1],** N. Schwegler[1], P. Hrmo[1,2], S. Jain[2], T. Sägesser1[2], P. Filippov[1], K. Hanke[1], R. Moyard[2], M. Marti[1], D. Kienzler[1], J. Home[1]

[1]*Institute for Quantum Electronics, ETH Zurich, Otto-Stern-Weg 1, 8093 Zurich, Switzerland*
[2]*ZuriQ, Zurich*

Trapped-ion quantum computing remains a leading platform for small-scale quantum information processing, thanks to its excellent isolation in ultra-high vacuum and high-gate fidelities. However, scaling these systems presents significant challenges. A promising approach involves replacing conventional radio-frequency (RF) Paul traps with microfabricated Penning traps, which use only static electric and magnetic fields for confinement [1,2]. This architecture removes the need for RF fields, thereby eliminating micromotion as well as RF power dissipation due to currents in the ion trap chip. Penning traps also allow arbitrary three-dimensional transport of ions, offering a level of control that is not possible with Paul traps [1]. In the framework of the quantum charge-coupled device (QCCD) architecture, this flexibility allows for scalable ion transport without the need for junctions [3]. As a next step towards scalability in this architecture, we here present recent progress towards trapping calcium ions (Ca^+) in such a surface-electrode Penning trap. Calcium provides more accessible laser wavelengths and a richer atomic level structure, which expands experimental possibilities and improves compatibility with commercial laser systems. Our work focuses on confining an array of ions in individually controlled two-dimensional arrays of potential wells. This configuration supports parallel control and interaction across sites, providing a foundation for scalable quantum logic operations.

[1] Jain, S., Sägesser, T., Hrmo, P. et al. Penning micro-trap for quantum computing. Nature 627, 510–514 (2024). https://doi.org/10.1038/s41586-024-07111-x
[2] Jain, S., Alonso, J., Grau, M. and Home, J.P. Scalable Arrays of Micro-Penning Traps for Quantum Computing and Simulation. Phys. Rev. X 10, 031027 (2020). https://doi.org/10.1103/PhysRevX.10.031027
[3] Delaney, R. D., Sletten, L. R., Cich, M. J. et al. Scalable Multispecies Ion Transport in a Grid-Based Surface-Electrode Trap. Phys. Rev. X 14, 041028 (2024). https://doi.org/10.1103/PhysRevX.14.041028

The ARTEMIS experiment: Towards high-precision g-factor measurements on highly charged ions

B. Reich,[1,2] A. Krishnan,[1,3] P. Baus,[3] G. Birkl,[3] W. Quint[1] and M. Vogel[1]

[1]*GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany*

[2]*University of Heidelberg, Heidelberg, Germany*

[3]*Technical University of Darmstadt, Darmstadt, Germany*

The ARTEMIS experiment[1] located at the HITRAP facility at GSI in Darmstadt, Germany, aims to measure the magnetic moments of bound electrons in heavy, highly charged ions (HCI) at the 10^{-9} level of accuracy by performing laser-microwave double-resonance spectroscopy.

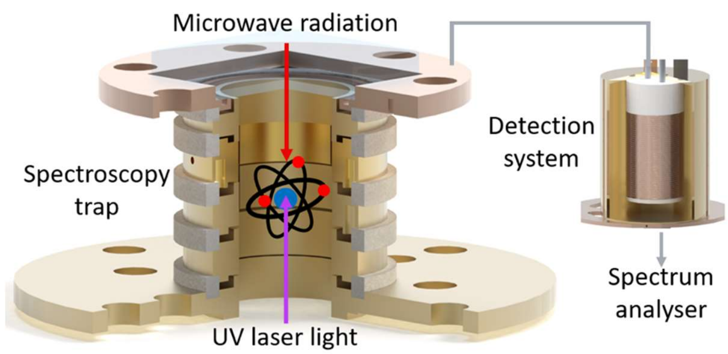


Figure 15: Schematic picture of the laser-microwave double-resonance spectroscopy at the ARTEMIS experiment

The goal is testing QED in extreme fields including the study of higher-order Zeeman effects[2]. The heart of ARTEMIS is a Penning trap stack inside a 7T superconducting magnet. It consists of two connected Penning traps: a creation trap and a spectroscopy trap. The former is a mechanically compensated trap with open endcaps and equipped with a field emission point for in-trap creation of HCI. The latter is of a dedicated half-open design[3] and electrically compensated. First commissioning has demonstrated successful in-trap ion production, storage, selection and cooling[4,5]. To test and develop the experimental setup and methods, a test ion is required which has a fine-structure splitting in the laser-accessible domain as well as a suitable ionisation potential for the in-trap creation. Therefore, $^{40}Ar^{13+}$ was chosen while $^{209}Bi^{82+}$ will be taken for the future beamtime. For access to these heavy few-electron ions, ARTEMIS is connected to the HITRAP facility[6] via a beamline that features dedicated ion optics, non-destructive ion detectors, and will accommodate a cryogenic fast-opening valve[7] keeping the extreme vacuum of the trap stable while allowing access for ions and laser light. This beamline is currently being upgraded towards efficient and well-controlled ion injection. We present the status and design updates of this beamline and the experiment itself.

[1] W. Quint et al., *Phys. Rev. A* **78,** 032517 (2008)
[2] D. Lindenfels et al., *Phys. Rev. A* **87,** 023412 (2013)
[3] D. Lindenfels et al., *Hyp. Int.* **227,** 197-207 (2014)
[4] Kanika et al., *J. Phys. B* **56,** 175001 (2023)
[5] M.S. Ebrahimi et al., *Phys. Rev. A* **98,** 023423 (2018)
[6] F. Herfurth et al., *Phys. Scr.,* 014065 (2015)
[7] J. Klimes et al., *Rev. Sci. Instr.* **94,** 113202 (2023)

Engineering tunable anharmonic potentials with light-atom interaction for chemical dynamics simulations

C. McGarry[1,2], T. Chalermpusitarak[1,2], K. Schwennicke[3], F. Scuccimarra[1,2], C. Valahu[1,2], P. Nagpal[1,2], V. Matsos[1,2], M. Millican[1,2], I. Kassal[3,2,4], T. R. Tan[1,2,4]

[1]*School of Physics, University of Sydney, NSW 2006, Australia*

[2]*ARC Centre of Excellence for Engineered Quantum Systems, University of Sydney, Australia*

[3]*School of Chemistry, University of Sydney, NSW 2006, Australia*

[4]*Sydney Nano Institute, University of Sydney, NSW 2006, Australia*

Trapped-ion platforms have emerged as a powerful architecture for simulating quantum dynamics in chemical systems. They have enabled studies of time-resolved vibrational spectroscopy [1], geometric phase effects at conical intersections [2, 3], and classically intractable open-system dynamics [4]. However, existing implementations have been limited to harmonic oscillator models, failing to encapsulate the anharmonicity present in molecular potentials.

Here, we investigate implementing anharmonic dynamics in a trapped-ion system using all-optical quantum control. Specifically, we develop a flexible control scheme that leverages state-dependent forces and qubit rotations to engineer tunable anharmonic dynamics. As an example, we engineer a tunable double-well potential of the form $V(x) = \delta x^2 + \epsilon \cos(\eta x)$. This allows access to rich, nonlinear motional dynamics, most notably quantum tunneling between the two wells. These results establish a new pathway for simulating chemically relevant potentials in a controllable quantum platform.

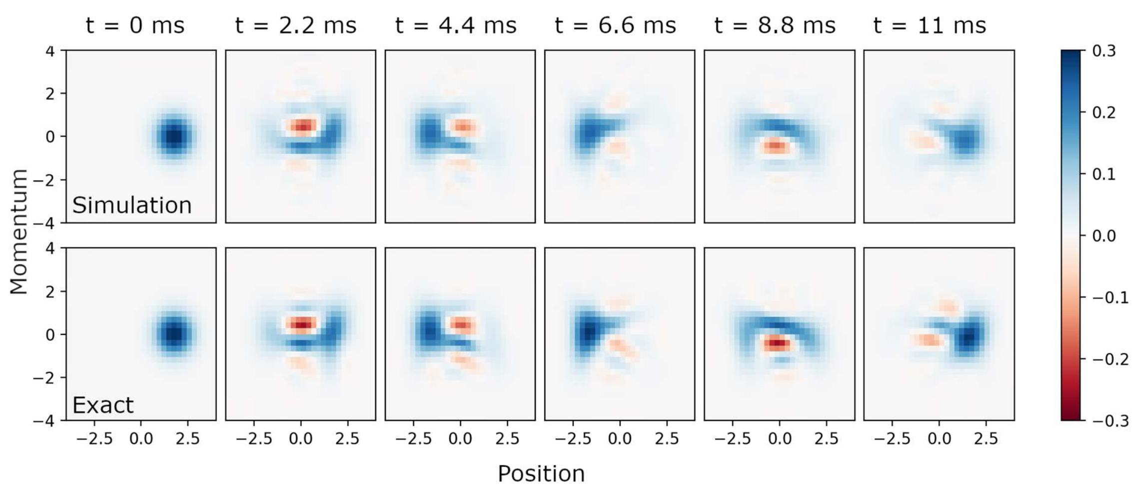


Figure 1: Evolution of the Wigner function through time of an engineered double well potential. Top row: simulation of the state evolution under the anharmonicity quantum control scheme. Bottom row: exact numerical solution to the time-dependent Schrödinger equation for the evolution in the target trapping potential.

[1] MacDonnell et al., *Chem. Sci.*, **14**, 9439 (2023)
[2] Valahu et al. *Nature Chemistry* **15**, 1503–1508 (2023)
[3] Whitlow et al. *Nature Chemistry* **15**, 1509–1514 (2023)
[4] Navickas et al. *J. Am. Chem. Soc.* (2025)]

Isomerization and bistability in two-dimensional Coulomb crystals

N. Mizukami,[1,2] G. Gatta,[1,3] L. Duca,[1,2] and **C. Sias**[1,2]

[1]*LENS, Sesto Fiorentino, Italy*

[2]*INRIM, Torino, Italy*

[3]*University of Florence, Florence, Italy*

Isomerization is a ubiquitous phenomenon in few-body systems such as molecules and nuclei. While passing from one configuration to another, particles undergoing isomerization may enter regimes of bistability, in which two metastable configurations can co-exist. In our work, we investigate isomerization and metastability by using two-dimensional Coulomb crystals, in which the shape of the confining potential plays the role of the electronic orbitals in molecules.

By tuning the aspect ratio of the trapping potential in a system of six Ba+ ions, we identify a bistable regime in which the ions arrange into either a hexagonal, benzene-like isomer or a pentagonal configuration with one ion at the center the trap. Using a Monte Carlo simulation, we compute the energies of the different isomers and reveal a double-well structure, where the relative depth of each well can be tuned using a DC field.

Experimentally, we identify the isomer formed by the ions by monitoring the photons scattered from the center of the trap. With this observable, we extract the probability of being in each isomer state as a function of the trap aspect ratio. The experimental data are in excellent agreement with the simulation, enabling us to extract the temperature of the ions (see Fig.1). Furthermore, by quenching the trap aspect ratio, we populate a highly excited isomer and witness its relaxation dynamics with sub-millisecond resolution. As predicted by the simulation, we observe that the relaxation time decreases as the energy gap between the isomers increases.

Our study demonstrates a versatile platform for modeling isomerization processes, and for exploring second-order phase transitions and quantum superpositions of crystalline configurations.

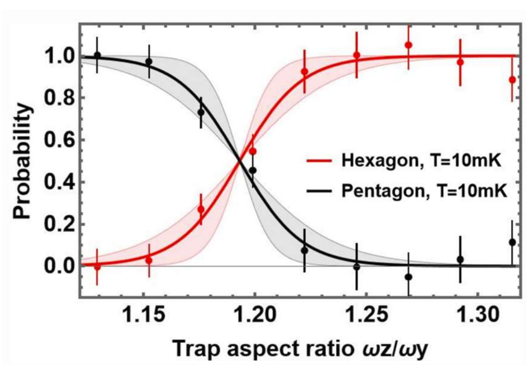


Figure 16: Probability for a 6-ion, 2-dimensional Coulomb crystal of being in a hexagon or pentagon configuration as a function of the trap aspect ratio. The red and black lines are the results of a MonteCarlo simulation with only the temperature as a free parameter. The shaded areas correspond to a change of 5mK from the best fitting temperature.

[1] L. Duca et al. *Phys. Rev. Lett.* **131,** 083602 (2023).
[2] P. Haenggi, P. Talkner, and M. Borkovec, Rev. Mod. Phys. 62, 251 (1990).
[3] N. Mizukami et al., in preparation.

Fidelity bounds for spin-dependent kicks with pulsed lasers

C. Sagaseta,[1] H. Liu,[2] V.D. Vaidya,[2] C.R. Viteri,[2] J.J. García-Ripoll,[3] and E. Torrontegui[1]

[1] *Departamento de física, Universidad Carlos III de Madrid, Leganés (Madrid), Spain*

[2] *IonQ, Inc., College Park, MD, USA*

[3] *Instituto de Física Fundamental IFF-CSIC, Madrid, Spain*

A spin-dependent kick (SDK), a spin flip accompanied by a momentum transfer with signs depending on the spin state, can be realized with fast Raman pulses on hyperfine qubits. This allows for faster-than-trap-period entangling gates with qubits of long coherence time for practical quantum computation. In this work, we follow a semiclassical approach to characterize the control parameters that optimize the fidelity of single-ion SDKs for different number of pulses. Numerical simulations of the dynamics for those optimal operation points provide bounds of the minimum infidelity that can be achieved with fast pulsed protocols. This work lays the foundation for sub-microsecond trapped ion quantum computing.

Fabrication and Automated Characterisation of Optical Cavity Mirrors for Quantum Networking

C.E.J. Challoner, T. Hinde, S. Saner, P. Drmota, T.H. Doherty, and J.F. Goodwin

Department of Physics, University of Oxford, Clarendon Laboratory,

Parks Road, Oxford OX1 3PU, United Kingdom

To achieve high rates in photonically connected trapped ion quantum networks [1], the Purcell enhancement offered by optical cavities can be used to achieve near-unit photon collection efficiency [2]. Here, we address the challenges of fabricating and characterizing cavity mirror substrates with ultralow roughness (Å level) necessary to achieve high-cooperativity microcavities interfacing with single trapped ions. We use focused ion beam (FIB) milling to produce features with state-of-the-art surface roughness for this size and scale [3,4]. To rapidly characterize these mirrors and to enable further iterative improvements of the fabrication methods employed, we have developed a hexapod-based automated mode matching routine.

Using this system, we can establish near-perfect mode matching of optical cavities of varying sizes in the space of ~minutes, and perform spectroscopic analysis, vastly accelerating the characterisation of large arrays of microcavities. These developments will enable us to demonstrate a repeatable and scalable route to the fabrication of high finesse, ultralow roughness microcavity mirrors, suitable for integration into ion trap network nodes.

[1] L.J. Stephenson, et al., *Phys. Rev. Lett.* **124**, 110501 (2020).
[2] J. Schupp, *PRX Quantum* **2**, 020331 (2021).
[3] P. Maier, *Opt. Express* **33**, 19205-19219 (2025).
[4] A.A.P. Trichet et al., *Opt. Express* **13** 17205-17216 (2015).

Poster 14

Monolithic Integration of Apodized Grating Couplers for Trapped-Ion Photonic Control

<u>Chiyoon Kim,</u>[1,2] Jaewoo Kim,[3] Uihwan Jeong,[1,2] Kwangyeul Choi,[1,2] Suhan Kim,[1,2] Seungun Kim,[3] Youngmin Kim,[3] Donghwan Ahn,[3] Changsoon Kim,[4] and Taehyun Kim[1,2,5]

[1]*Dept. of Computer Science & Engineering, Seoul National University, Seoul, South Korea*

[2]*Automation and System Research Institute, NextQuantum, Inter university Semiconductor Research Center, Seoul National University*

[3]*Kookmin University, Seoul, South Korea*

[4]*Department of Intelligence and Information, Seoul National University, Seoul, South Korea*

[5]*Institute of Computer Technology, Institute of Applied Physics, Seoul National University*

Integrated photonics has emerged as a pivotal solution for enhancing the scalability and stability of trapped-ion quantum computing systems [1]. In such platforms, integrated photonics typically involves the monolithic integration of waveguides for routing laser light, grating couplers for diffracting this guided light into free space to precisely target the ions, and beam splitters to enable versatile on-chip functionality [2,3].

In this study, we report the fabrication of photonic components for a trapped-ion system using electron beam lithography (EBL). Employing two distinct types of EBL resist, we achieved fabrication with resolution below 40 nm, enabling the definition of forward- and backward-diffracting apodized grating couplers. These components were designed to couple light at a simulated ion height of 100 μm with a horizontal offset of 150 μm. Our simulation results predict a Gaussian beam diffraction profile and efficient mode conversion enabled by the apodized gratings. We are also designing inverse-tapered waveguides and edge-coupling interfaces to integrate with fiber arrays, ensuring low-loss coupling from external laser sources [1,2].

This research aligns with the broader objective of realizing scalable and modular trapped-ion architectures, where integrated photonics is expected to play a critical role in enhancing scalability and improving system stability.

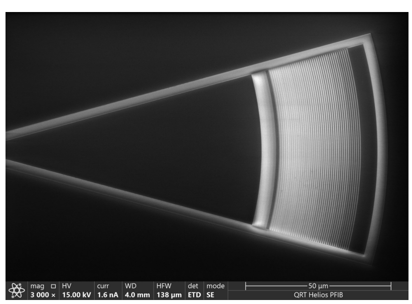


Figure 17: SEM image of apodized grating coupler for trapped-ion light delivery.

[1] Mehta, K. K., Zhang, C., Malinowski, M., Nguyen, T.-L., Stadler, M., & Home, J. P. (2020). Integrated optical multi-ion quantum logic. *Nature*, 586(7829), 533–537.
[2] Niffenegger, R. J., Stuart, J., Sorace-Agaskar, C., Kharas, D., Bramhavar, S., Bruzewicz, C. D., Loh, W., Maxson, R. T., McConnell, R., Reens, D., West, G. N., Sage, J. M., & Chiaverini, J. (2020). Integrated multi-wavelength control of an ion qubit. Nature, 586(7829), 538–542.
[3] Kwon, J., Setzer, W. J., Gehl, M., Karl, N., Van Der Wall, J., Law, R., Blain, M. G., Stick, D., & McGuinness, H. J. "Multi-site integrated optical addressing of trapped ions." Nature Communications 15.3709 (2024).

Enabling technologies for ion trap-based quantum computers

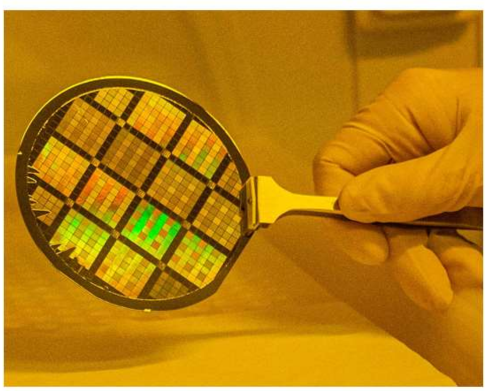
M. Braun[1], **C. Glasenapp[1]**, D. Zillmann[1], F. Niekiel[1], J. Buchheim[2]

[1]*German aerospace center (QT-IMN), Hamburg, Germany*

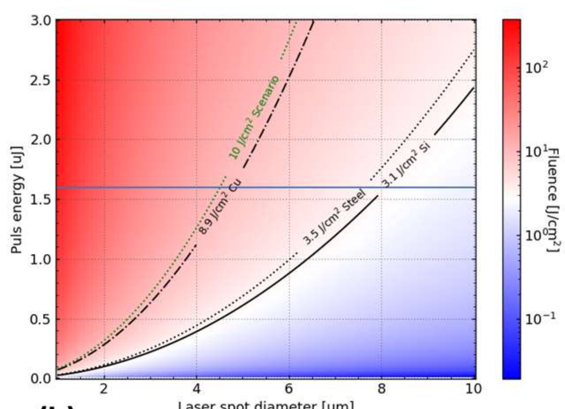
[2]*German aerospace center (QT-IMN), Ulm, Germany*

The institute of Quantum Technology at the German Aerospace center is closely collaborating with companies involved in Germany's quantum computing initiative, to develop enabling technologies for ion-trap-based quantum computers. Within this conference contribution we report about the current state of those developments and about their integration into ion traps. Three key components are therein included: Firstly, we grow and structure micro-scale magnetic SmCo structures on a chip and magnetize them with a custom-built magnetization tool. Secondly, we develop SiN based, as well as directly written optical waveguides, that can be used as interposer technologies and integrated into trapping chips. We characterize the optical waveguides in terms of their optical losses as well as their damage threshold behavior with an in-house testing setup. Lastly, we are working on a miniaturized atom source that enables the light-induced backside loading of atoms into the ion trap. Laser ablation and optical heating are explored as release mechanism and characterized through the determination of the atom release threshold. Therefor a vacuum setup, including a high precision and ultrafast mass spectrometer, is used.

Moreover, our institute operates a state-of-the-art cleanroom facility that is tailored to the production of surface ion-traps. The cleanroom is operated as a user facility to be used by industry partners and research centers.



(a)



(b)

Figure 18: (a) micromagnetic SmCo structures. (b) Ablation threshold for different materials plotted together with the damage threshold of PECVD grown SiN waveguides at a pulse duration of 10 ns and a repetition rate of 100 kHz [1].

[1] Lanxuan Zhang et al., *Opt. Express* **29**, 29755-29765 (2021).

Progress Towards Mixed-Species, Laser-Free Quantum Logic Operations in a Surface Electrode Ion Trap

C. M. Bowers,[1,2] J. J. Barta,[1,2] D. Palani,[2,3] D. Leibfried,[2] and D. H. Slichter [2]

[1]*University of Colorado Boulder, USA*

[2]*NIST, USA*

[3]*University of Colorado Denver, USA*

The mixed-species data/helper architecture in trapped ion quantum processors enables sympathetic cooling and quantum-logic-based state preparation and readout of the data ions, thus eliminating light resonant with data species transitions which can cause errors on spectator qubits. This should help maintain high fidelities and low crosstalk in scaled systems. Implementing both data qubit control and data/helper quantum logic operations using oscillating magnetic fields and gradients provides the additional benefit of replacing all the data species lasers with stable, inexpensive electronic sources that can drive operations on many qubits simultaneously. Moreover, using these fields to perform high fidelity, motionally insensitive entangling gates could substantially decrease the time required for cooling prior to gate operations and thus increase the duty cycle for computation.

We present progress towards motional mode coupling and sympathetic cooling for a $^{25}Mg^{+}$ data ion using a co-trapped $^{40}Ca^{+}$ helper ion in a surface electrode trap. We successfully demonstrate mode-coupling in a mixed-species crystal—a critical first step in performing indirect state-preparation and readout of Mg^{+} using magnetic-gradient-based quantum logic operations—by utilizing the hybridized motional mode as a quantum bus. Additionally, we present progress towards a motionally insensitive entangling gate on a two-ion Ca^{+} crystal, which can be extended to a mixed-species crystal in future work.

Poster 17

Quantum-enhanced multi-parameter sensing in a single mode

C. H. Valahu,[1] M. P. Stafford,[2] Z. Huang,[3] V. G. Matsos,[1] M. J. Millican,[1] T. Chalermpusitarak,[1] N. C. Menicucci,[4] J. Combes,[5] B. Q. Baragiola,[4] T. R. Tan[1]

[1]*University of Sydney, Australia,* [2]*University of Bristol, United Kingdom,* [3]*University of Macquarie, Australia,* [4]*RMIT University, Australia,* [5]*University of Melbourne, Australia*

Measuring incompatible parameters suffers from fundamental limits, exemplified by Heisenberg's uncertainty principle which bounds the uncertainties of position and momentum. Here, we demonstrate single-mode measurements of two incompatible parameters by instead measuring their modular counterpart [1]. We reduce the uncertainties of modular position and momentum below the standard quantum limit (SQL) by using grid states prepared in the mechanical motion of a $^{171}Yb^{+}$ trapped ion. We further demonstrate a phase estimation algorithm with Bayesian inference to estimate small displacements with a combined variance below the SQL. Finally, we investigate simultaneously estimating number and phase which are the polar counterparts of position and momentum. This is performed by preparing a novel quantum resource---number-phase states---and we demonstrate a metrological gain over their SQL.

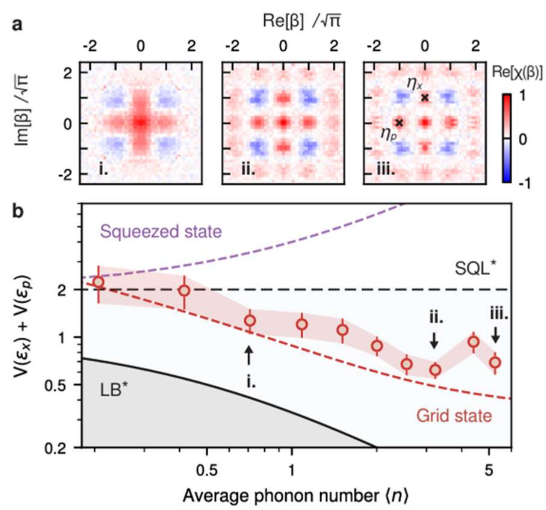


Figure 1: Grid states are used to reduce the simultaneous uncertainty of modular position and momentum for multi-parameter displacement sensing. As we prepare grid states of increasing energy (a), the multi-parameter variance decreases (b), and we demonstrate a gain over the simultaneous standard quantum limit (SQL*). Figure taken from [1].

[1] C. H. Valahu et al., *arXiv:*2412.04865 (2024)

Poster 18

Towards a new hybrid atom-ion system

Claudia Galantini[1], Luc Verwaal[1], Edgar Vredenbregt[1], Rianne S. Lous[1]

[1]*Eindhoven Hendrik Casimir Institute and Department of Applied Physics and Science Education, Eindhoven University of Technology*

Hybrid ion-atom systems combine the well-controllable platforms of trapped ions and ultracold quantum gases and link them together by the intermediate-range ion-atom interaction. These quantum systems offer opportunities for buffer gas cooling, quantum simulation of many-body systems, as well as state-to-state quantum chemistry [1]. To fully benefit from the combination, it is essential to understand, characterize, and control the interactions between the atoms and ions. At TU/e, a new experimental setup is being built to go beyond alkali hybrid atom-ion systems and exploit the novel combination of a trapped ion – Yb+ - with dipolar atoms - Dy. This mixture offers new opportunities and here we present the progress made on developing it.

[1] Lous and Gerritsma, *AAMOP* **71**, 65-133 (2022).

A silicon-based ion trap chip protected from semiconductor charging

D. Chung,[1] K. Choi[1], W. Lee[1], C. Kim[1], H. Shon[1], J. Park[1], and T. Kim[1]

[1]*Dept. of Computer Science and Engineering, Seoul National University*

In this work, we report on a significant progress achieved in a silicon-based microfabricated ion trap chip, specifically regarding the suppression of semiconductor charging. While silicon substrates serve as a versatile platform for scalable ion trap fabrication, photoinduced charging resulting from the strong absorption of light, especially at exposed etched surfaces, poses a severe challenge for the precise control of ions. Based on a quantitative model for semiconductor charging [1], we have fabricated an ion trap chip with all exposed silicon surfaces coated in gold, and have successfully demonstrated mitigation of the detrimental phenomenon [2]. We present fabrication methods to minimize absorption and scattering of light from the etched silicon substrate and experimentally verify that semiconductor charging in the improved chip is suppressed to negligible levels, basically being undetectable in regular experiments. This leads to enhanced control over the vibrational states of the trapped ion, enabling sideband cooling and entangling gate operations previously unattainable in the un-protected chip.

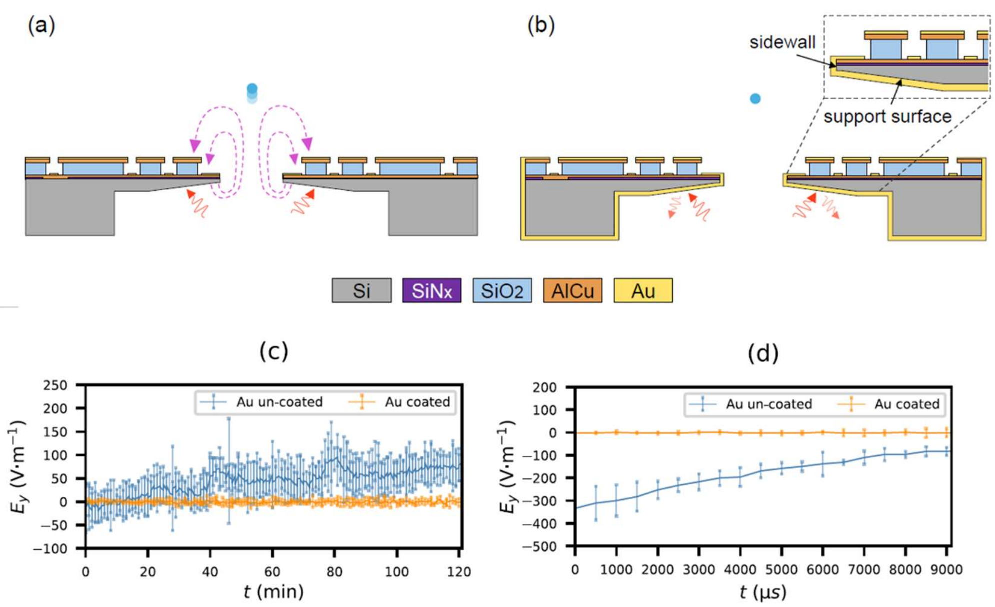


Figure 1. Figures captured from reference [2]. Schematic cross-sectional view of the silicon-based ion trap chip (a) without and (b) with gold coating. Comparison of photoinduced stray fields originating from silicon, shown (c) over an extended period, (d) shortly after switching on the laser.

[1] W. Lee, D. Chung et al., *Phys. Rev. A.* **109,** 043106 (2024).
[2] D. Chung, K. Choi et al., *Quantum Sci. Technol..* **10,** 035014 (2025).

Scalable trapped-ion quantum computing via optical tweezer-based control

D. Schwerdt,[1] L. Peleg,[1] Y. Shapira,[1,2] N. Priel,[2] Y. Florshaim,[2] A. Gross,[2] A. Zalic,[2] G. Afek,[2] G. Dekel,[1] L. Rajagopal,[1] O. Matoki,[1] N. Akerman,[1] A.B. Kish,[2] A. Stern,[1] and R. Ozeri[1,2]

[1]*Weizmann Institute of Science, Rehovot, Israel*
[2]*Quantum Art, Nes Tziyona, Israel*

We present several theoretical and experimental developments on the application of optical tweezers to trapped ion systems, an exciting and rapidly-growing area of interest in the trapped ion community. The first work [1] proposes a scalable architecture for quantum computing, based on large registers of trapped-ion qubits together with dynamically operated optical potentials. Our proposed architecture circumvents the two most prominent challenges in working with large ion-crystals – prohibitively high heating rates and spectral crowding of the ions' motional modes. It does so by effectively segmenting an arbitrarily large trapped-ion crystal into several independent segments of a manageable size. Connectivity across the full trapped-ion crystal is enabled by rapidly reconfiguring the optical potentials. The optical potentials also enable mid-circuit measurements of the confined ions, followed by classical feedback. An overview of the architecture is illustrated schematically in Figure 1.

In the second work [2], we propose an entanglement protocol where ions illuminated by optical tweezers serve as control qubits. We experimentally demonstrate this proposal with a controlled Mølmer–Sørensen operation on a three-ion crystal, analogous to the canonical Toffoli gate. Furthermore, we discuss how our protocol generalizes to a broad class of unitary operations and larger qubit systems, enabling a single-pulse implementation of *n*-controlled unitaries.

Finally, we report a set of precision measurements relevant to the integration of optical tweezers with trapped ions. Using Ramsey spectroscopy on a superposition of motional states, we characterize the optical trapping potential with high accuracy. We also observe the emergence of a polarization gradient across a tightly focused optical tweezer, resulting from deviations beyond the paraxial approximation. This effect, previously highlighted in theoretical work (e.g. Mazzanti et al., *Phys. Rev. Research* 2023), may play an important role in future experiments involving tightly focused beams in trapped ion platforms.

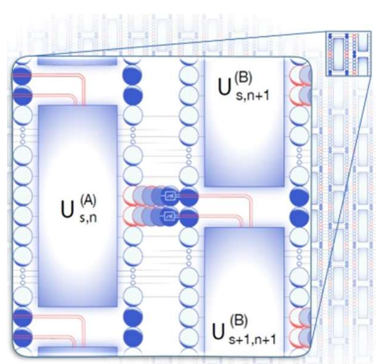


Figure 19: Schematic of a large-scale quantum circuit within our proposed architecture. It illustrates a segmented ion crystal, parallel multi-qubit gates, optical potential reconfiguration, and mid-circuit measurements.

[1] D. Schwerdt, L. Peleg, Y. Shapira, N. Priel, Y. Florshaim, A. Gross, A. Zalic, G. Afek, N. Akerman, A. Stern, A. B. Kish, and R. Ozeri, *Scalable architecture for trapped-ion quantum computing using rf traps and dynamic optical potentials*, Phys. Rev. X 14, 041017 (2024).

[2] D. Schwerdt, L. Peleg, G. Dekel, L. Rajagopal, O. Matoki, A. Gross, Y. Shapira, N. Akerman, and R. Ozeri, *Optical tweezer-controlled entanglement gates with trapped ion qubits*, In preparation (2025)

Hard magnetic microstructures for microfabricated ion trap-based quantum computers

D. Zillmann[1], M. Braun[1], C. Glasenapp[1] F. Niekiel[1], J. Buchheim[2]

[1]*German aerospace center (QT-IMN), Hamburg, Germany*

[2]*German aerospace center (QT-IMN), Ulm, Germany*

The institute of quantum technologies of German Aerospace Center (DLR) closely collaborates with companies being a part of DLR's quantum computing initiative (QC-I), which establishes an ecosystem for quantum computing in Germany. In respect of the initiative, we develop enabling technologies and microtechnological manufacturing processes for ion-trap-based quantum computers. This conference contribution particularly sheds light on the fabrication and integration of Sm-Co permanent magnetic microstructures in surface ion traps.

In order to utilize hard magnetic structures on ion trap chips, SmCo must exhibit the corresponding crystalline phases before being structured using microfabrication methods. We consider two approaches for structuring SmCo layers: (1) Substrate structuring prior deposition and (2) layer structuring after deposition (Fig. 1a). Subsequently, locally specific magnetizations of the microstructures are imperative to provide adequate field properties in the regions of interest. As a consequence, we develop a tool, which allows in-plane and out-of-plane magnetizations, respectively. At tool's heart, two writing heads generate the corresponding magnetizing fields providing maximal inductions of 1.5 Tesla and minimal writing areas of 0.04 mm² (Fig. 1b). Their mounting to a positioning system allows camera-assisted navigation on substrate and automated magnetizations on microscale.

The foundation of our activities is a state-of-the-art cleanroom facility at DLR QC-I's innovation center in Hamburg (IZHH), which is tailored for the fabrication of surface ion traps. It is operated by our institute, which hosts DLR QC-I's second innovation center in Ulm (IZUL). Currently, the cleanroom at IZHH is a user facility for industries only, but it will also welcome research groups in future.

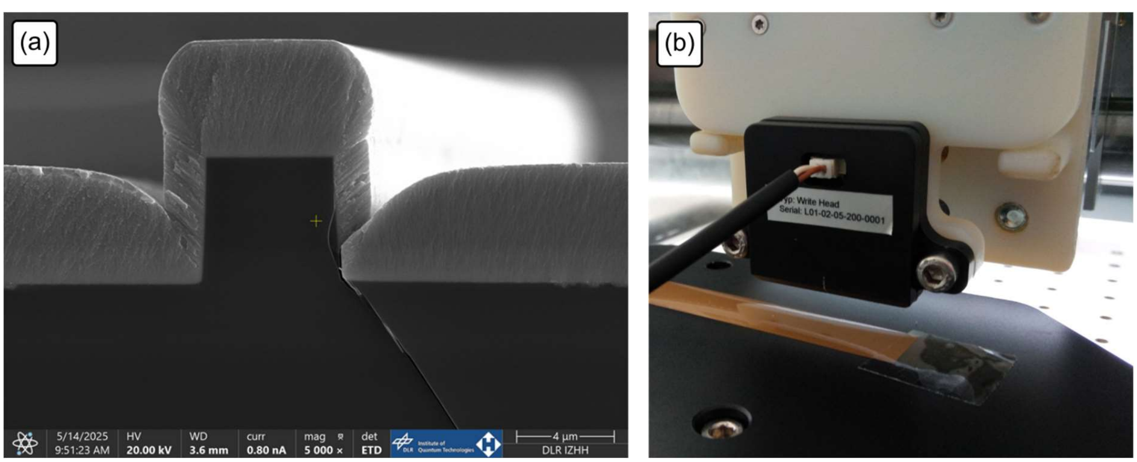


Fig. 20: (a) Hard magnetic layer on pre-structured Si wafer and (b) magnetic writing head.

PTB's Al^+ clock and its frequency ratios with Yb^+ and Sr

D. Drapier[1], M. A. Ali[1], F. Dawel[1], V. Barbé[1], K. Dietze[1], B. Benny[1], L. Pelzer[1], J. Klose[1], K. Stahl[1], E. Benkler[1], S. Dörscher[1], C. Lisdat[1], M. Filzinger[1], M. Steinel[1], N. Huntemann[1] and P. O. Schmidt[1,2]

[1]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*

[2]*Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany*

Optical atomic clocks based on quantum-logic spectroscopy of $^{27}Al^+$ are among the most stable and accurate ion-based clocks, reaching fractional frequency uncertainties as low as 5.5×10^{-19} [1]. This outstanding precision enables, for example, to measure gravitational redshift on the centimeter scale, with significant implications for geodesy, but also, to improve measurements of clock frequency ratios in the search for new physics. This makes $^{27}Al^+$ based clocks a candidate for a future redefinition of the SI second.

We present the latest results of our $^{27}Al^+$ clock, using a co-trapped $^{40}Ca^+$ ion for cooling and quantum logic spectroscopy. We employ electromagnetically induced transparency cooling during the interrogation to reduce the effect of motional heating and to keep the second order Doppler shift small. This introduces an additional ac-Stark shift of the cooling lasers of $(8.6 \pm 2.0) \times 10^{-18}$ [2], limiting our systematic fractional frequency uncertainty to 2.9×10^{-18} [3]. We have demonstrated the clock performance in a measurement campaign together with the ^{87}Sr lattice clock Sr3 [4] and the octupole transition of the $^{171}Yb^+$ ion clock Yb1 [5] at PTB. With fractional uncertainties well below 10^{-17}, the obtained frequency ratios are among the most accurate measured to date.

To further enhance clock performance, we now focus on increasing the aluminum ion lifetime, currently limited to a few hours by chemical reactions with background gas forming AlH^+. Reloading Al^+ ions can take several hours, resulting in significant dead time. To mitigate this, we have implemented a resonance-enhanced multiphoton dissociation scheme using a new 360 nm laser addressing the first exited electronic state of the molecule combined with the existing 267 nm light used for quantum logic spectroscopy to reach the dissociation threshold. The first dissociation events were observed within minutes after activating the lasers. Efforts are underway to automate the detection and dissociation process in the clock locking loop.

[1] Marshall, Mason C., *et al*. "High-Stability Single-Ion Clock with 5.5×10^{-19} Systematic Uncertainty." *arXiv preprint arXiv:2504.13071* (2025).
[2] Dawel *et al*., "A high-stability optical clock based on a continuously ground-state cooled Al^+ ion without compromising its accuracy", in preparation
[3] Dawel *et al*., in preparation
[4] R. Schwarz, (2022). *A cryogenic Strontium lattice clock*. [Doctoral thesis, Leibniz University Hannover] DOI: 10.15488/11929
[5] C. Sanner *et al*., Nature 567, 204 (2019)

Generation of nonlinear motional interactions in trapped ions

D.J. Webb, I.R. Øvergaard, K. Shinbrough, S. Saner, O. Băzăvan, R. Srinivas, C.J. Ballance

University of Oxford, Oxford, United Kingdom

A trapped ion forms a hybrid system composed of an electronic spin and bosonic motional modes. Much work has focussed on experimentally realising a universal gate set for discrete variable quantum computation based on the ion spin. However, recently, there has been a growing interest in utilising the Bosonic degree of freedom for quantum computation, due to the large accessible Hilbert space. Bosons offer a natural encoding for some problems, leading to fewer required physical resources. Here, we describe experimental work on route to demonstrating a universal gate set for continuous variable quantum computation, consisting of linear and nonlinear motional interactions, and interactions coupling multiple oscillators.

Our approach to generating the required nonlinear motional interactions is through spin-motion couplings. Using two spin-dependent forces, which are linear in the bosonic mode but conditioned on non-commuting spin operators, we generate effective nonlinear interactions [1]. The strength of this method lies in its favourable scaling compared to conventional techniques driving higher order motional sidebands [2]. To maintain the non-commuting relationship between the spin-components, we actively stabilize the optical phase of the driving fields. As such, we are able to demonstrate n^{th}-order squeezing interactions: squeezing, trisqueezing, and the first experimental realisation of quadsqueezing [3].

By utilising a method that is dependent on spin, we can also prepare arbitrary motional superposition states via mid-circuit measurement of the spin state and post selection [4]. These states are nonclassical, non-Gaussian and can be used for either sensing or as a resource in continuous variable quantum computation.

We briefly outline a new experimental apparatus with the intent of scaling this method to multiple ions, and control over many motional modes. Scaling to multiple motional modes opens up the possibility for demonstrating quantum algorithms [5] and resource-efficient fundamental simulations [6], however at the cost of increased experimental control complexity.

[1] Sutherland, R. T. & Srinivas, R. *Phys. Rev. A* **104**, 032609 (2021).
[2] Meekhof, D. M., et al., *Phys. Rev. Lett.* **76**, 1796–1799 (1996).
[3] Băzăvan, O., et al., *Preprint at* arxiv:2403.05471 (2024).
[4] Saner, S., et al. *Preprint at* arxiv:2409.03482 (2024).
[5] Brenner, L., et al. *Preprint at* arxiv:2412.13164 (2024).
[6] Varona, S., et al. *Preprint at* arxiv:2411.05092 (2024).

Micromotion compensation using dark and bright ion species

Orr Barnea[1], **Dror Einav**[1], Jonas Drotleff[1], Idan Hochner[1] and Ziv Meir[1]

[1]*Weizmann Institute of Science, Rehovot, Israel*

Stray electric fields induce excess micromotion in ion traps, limiting experimental performance. We present two new micromotion-compensation techniques [1] that only require ion imaging, and thus can be readily implemented in most ion-trapping experiments. The first utilizes a dark ion in a multi-specie bright-dark-bright linear ion crystal. Stray electric fields in the trap's radial plane deform the crystal due to the different masses of the dark and bright ions (see Figure). Tuning the trap frequency close to the crystal's transition to the zig-zag configuration enhances the crystal deformation, turning the crystal into a sensitive sensor for stray fields. The second technique is a modified ion-displacement compensation method using a single bright ion. Our modification allows us to compensate stray fields on the 2D radial plane from a 1D measurement of the ion position on the camera by controlling the asymmetry of the two radial modes of the trap. With both methods, we show EMM compensation well below 1 V/m of stray-electric-field amplitude.

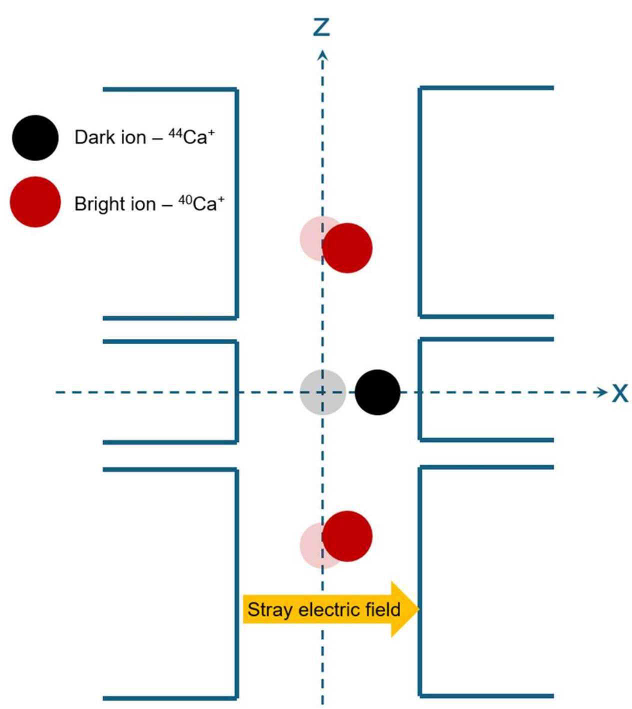


Figure: ***Micromotion compensation using a multi-specie bright-dark-bright ion crystal. In the absence of stray electric fields, the ions form a linear crystal along the trap's axial axis (faded circles).*** *Radial stray electric fields displace the ions proportional to their masses, leading to axial deformation of the linear crystal (solid circles).*

[1] Barnea, O., Einav, D., Drotleff, J., Hochner, I., & Meir, Z. (2025). Micromotion compensation using dark and bright ions. *arXiv preprint arXiv:2503.12417*.

Quantum Networking and Error Detection with Trapped $^{88}Sr^{+}$ and $^{43}Ca^{+}$ Ions

E. M. Ainley, D. Main, A. Agrawal, A. R. Martinez, J. A. Blackmore, P. Drmota, D. P. Nadlinger, R. Srinivas, G. Araneda, D. M. Lucas

University of Oxford, United Kingdom

By interfering photons from two network nodes separated by 2 m, we create remote entanglement between two $^{88}Sr^{+}$ ions with 97 % fidelity at a rate of ~10 s^{-1}. This remote entanglement enabled demonstrations of device-independent quantum key distribution [1] and a network of entangled optical atomic clocks [2]

Additionally, the integration of robust quantum memory qubits in $^{43}Ca^{+}$ [3] has enabled demonstrations of distributed quantum computing [4] and deterministic and verifiable blind quantum computing through adaptive polarisation measurements [5].

Here, we demonstrate error detection using mid-circuit parity measurements on spatially separated $^{43}Ca^{+}$ memory qubits via the $^{88}Sr^{+}$ entanglement link. We also extend the network link to 200 m. We further show remote entanglement storage for up to 10 s, and a variety of remotely entangled states that we create between the modules.

[1] D.P.Nadlinger et al., *Nature* **607**, 682-686 (2022)
[2] B.C.Nichol et al., *Nature* **609**, 689-694 (2022)
[3] P.Drmota et al., *Phys. Rev. Lett*. **130**, 090803 (2023)
[4] D.Main et al., *Nature* **638**, 383-388 (2025)
[5] P.Drmota et al., *Phys. Rev. Lett.* **132**}, 150604 (2024)

Same-species sympathetic cooling of $^{43}Ca^+$ ions

E. Vandrey,[1] M. Smith,[1] M. Gely[1] and D. Lucas[1]

[1]*University of Oxford, Oxford, United Kingdom*

While running algorithms composed of long sequences of gates on trapped-ion quantum computers, it is essential to cool the ions' motional modes in order to minimize errors caused by motional heating. This can be achieved by sympathetically cooling the logic ion with an ion of a different species, such that the laser beams required for cooling one ion do not affect the information stored in the other. However, this approach significantly increases the hardware complexity, and the difference in mass between the ion species leads to a sub-optimal cooling efficiency.

Using microwave-driven sideband cooling in combination with a narrow-linewidth quadrupole laser at 729 nm, we implement sympathetic cooling with two ions of the same species. Due to the large hyperfine splitting of the $^{43}Ca^+$ ground-state manifold at 28.8 T, the information stored in the logic ion is preserved during the cooling process. In addition to reducing hardware complexity and increasing cooling efficiency, same-species sympathetic cooling offers the benefit that between cooling cycles, the coolant ions could be repurposed as ancilla qubits for error correction schemes.

The IDEAL trap- A 3D diamond ion trap with integrated optics

E.G. Jansson,[1] J.E. Jordan,[1] and T.E. Mehlstäubler,[1,2,3]

[1] *Physikalisch- Technische Bundesanstalt (PTB), Braunschweig, Germany*

[2] *Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany*

[3] *Laboratorium für Nano- und Quantenengineering, Leibniz Universität Hannover, Hannover, Germany*

I will present the IDEAL trap, a 3D chip ion trap made from CVD diamond with integrated optics (see Figure 1). The trap design is based on the 3D chip traps of PTB [1, 2] and was the result of the *IDEAL* research project with industry and academic partners [3]. The trap was produced using high precision laser cutting. For the assembly of the trap, precise self-alignment structures in the chips were used that ensured alignment tolerances of ±4 µm. The precise alignment is important for minimizing micro-motion [4]. With integrated fiberized GRIN-lenses for laser cooling and ion control, the size of the experimental setup can be reduced. Free space and fiberized detection lenses enable simultaneous read-out of ions in different trap segments. To ensure the grounding of the integrated lenses, a combined indium tin oxide + antireflective coating with a high optical transmission of 80% and low scattering of 0.012±0.002% was developed [5]. The trap will be used for the realization of a multi ensemble clock and to test dead-time free optical atomic readout with Yb^+ ions.

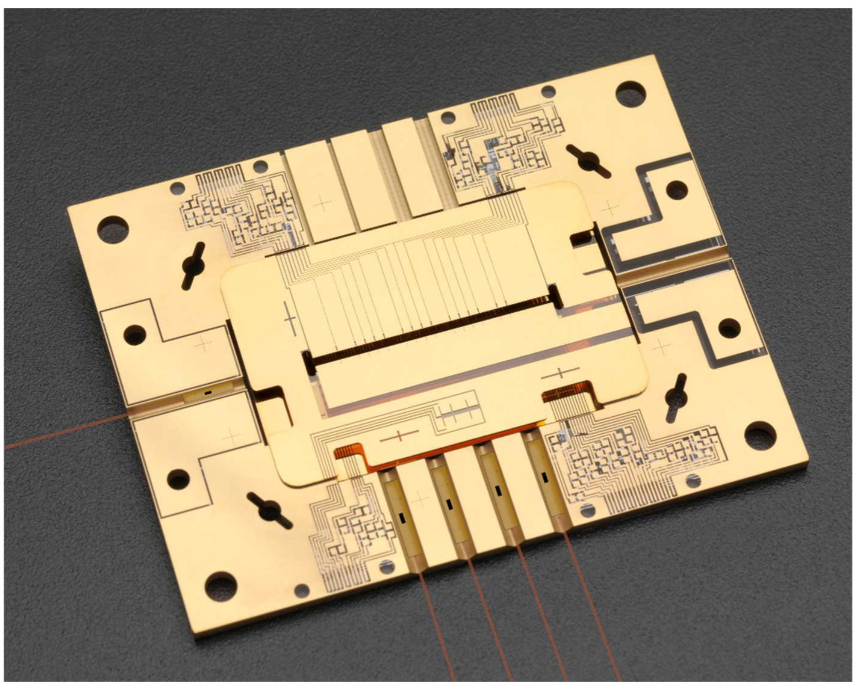


Figure 21: The IDEAL trap and carrier board. The fiberized lenses for laser cooling and ion control can optionally be mounted in the provided v-grooves and the detection optics are mounted on the back side of the trap shown here.

[1] J. Keller et al., Phys. Rev. A, **99**, 013405 (2019).
[2] T. Nordmann et al., Rev. Sci. Instr., **91**, 111301 (2020).
[3] https://integrierte-diamant-ionenfallen.nanofabrication.de/
[4] N. Herschbach et al., Appl Phys B **107**, 891–906 (2012)
[5] E. Jansson, et al., Appl. Opt. **64**, 1715-1722 (2025)

Technical requirements for combining an optical cavity with a linear ion trap for an efficient inter-module interface

E. Kassa,[1] S. Gao,[1] S. Teh,[1] D. van Dinter,[2] S. Oya,[1] and H. Takahashi[1]

[1]*EQuIP, Okinawa Institute of Science and Technology, Japan*

[2]*QMS, Okinawa Institute of Science and Technology, Japan*

We address the challenge of integrating miniature optical cavities into linear ion traps to facilitate scalable quantum computing architectures. While prior implementations have successfully incorporated fiber-based Fabry-Perot cavities into three-dimensional Paul traps for single ions [1,2], extending this integration to linear traps accommodating multiple ions has remained problematic. We propose that electrically conductive shielding of cavity fibers can significantly mitigate adverse effects such as stray charges and motional heating caused by dielectric materials [3]. However, a compatibility issue arises between these conductive shields and conventional radio-frequency (RF) drives used in ion traps. To resolve this, a dual RF drive system with opposing phases is introduced, ensuring stable ion confinement in the presence of conductive shielding. Furthermore, we analytically examine the role of electrode symmetry, revealing that two-dimensional surface traps lack the necessary geometrical symmetry for effective integration of shielded miniature optical cavities. Based on these insights, we propose essential design components and strategies for successfully integrating miniature optical cavities into linear ion traps, advancing the development of modular quantum systems.

[1] M. Steiner, H. Meyer, C. Deutsch, J. Reichel, and M. Koehl, *Phys. Rev. Lett.*, **110**, 043003 (2013).
[2] H. Takahashi, E. Kassa, C. Christoforou and M. Keller, *Phys. Rev. Lett.*, **124**, 013602 (2020).
[3] E. Kassa, S. Gao, S. The, D. van Dinter and H. Takahashi, *Phys. Rev. App.*, **23**, 024038 (2025).

Towards precision XUV frequency comb spectroscopy of the 1S-2S transition in He+

F. Egli,[1] J. Moreno,[1] J. Weitenberg,[2] T. W. Hänsch,[1,3] Th. Udem,[1,3] and A. Ozawa[1,4]

[1]*Max Planck Institute of Quantum Optics, Garching, Germany*

[2]*Fraunhofer ILT, Aachen, Germany*

[3]*Ludwig-Maximilians-Universität, Munich, Germany*

[4]*Yokohama National University, Yokohama City, Japan*

The energy levels of hydrogen-like atoms and ions are accurately described by bound-state quantum electrodynamics (QED). The frequency of the narrow 1S-2S transition of atomic hydrogen has been measured with a relative uncertainty of less than 10^{-14}. In combination with other spectroscopic measurements of hydrogen and hydrogen-like atoms, the Rydberg constant and the proton charge radius can be determined. The comparison of the physical constants obtained from different combinations of measurements serves as a consistency check for the theory [1]. For QED tests, it is also interesting to measure hydrogen-like systems other than hydrogen, which are more sensitive to different terms of the theory. The measurement of the Lamb shift in muonic hydrogen, for instance, gave rise to the proton radius puzzle [2].

Another interesting spectroscopic target is the hydrogen-like He^+ ion. Ideal conditions for high-precision measurements can be achieved, since the He^+ ions can be held nearly motionless in the field-free environment of a Paul trap. Interesting higher-order QED corrections scale with large exponents of the nuclear charge, making this measurement much more sensitive to these corrections compared to hydrogen.

In this talk, we describe our progress towards precision spectroscopy of the 1S-2S two-photon transition in He^+ [3]. The transition can be directly excited by an extreme-ultraviolet frequency comb at 60.8 nm generated by a high-power infrared frequency comb using high-harmonic generation (HHG). The spectroscopic target is a small number of He^+ ions trapped in a linear Paul trap and sympathetically cooled by co-trapped Be^+ ions. After successful excitation to the 2S state, a significant fraction of the He^+ ions will be further ionized to He^{2+} and remain in the Paul trap. Sensitive mass spectrometry using secular excitation will reveal the number of trapped He^{2+} ions and will serve as a single-event sensitive spectroscopy signal. To enable Doppler-free spectroscopy, the frequency comb is split into counterpropagating double pulses that are overlapped at the ion position. In this talk, I will discuss methods to test and optimize the pulse overlap. These include the driving of a two-photon transition in Be^+ and a direct AC Stark shift measurement method on the Be^+ ground-state hyperfine levels.

[1] T. Udem, Nature Phys 14, 632 (2018)
[2] R. Pohl et al., Nature 466, 213 (2010)
[3] J. Moreno et al. Eur. Phys. J. D 77, 67 (2023)

Experimental Quantum Simulation of Chemical Dynamics

T. Navickas,[1,2] R. J. MacDonell,[2,3,4] C. H. Valahu,[1,2,5] V. C. Olaya-Agudelo,[2,3] **F. Scuccimarra,[1,2]** M. J. Millican,[1,2] V. G. Matsos,[1,2] H. L. Nourse,[3] A. D. Rao,[1,2] M. J. Biercuk,[1,2] C. Hempel,[1,2,6] I. Kassal,[3,2,5] T. R. Tan[1,2,5]

[1]*School of Physics, University of Sydney, NSW 2006, Australia*

[2]*ARC Centre of Excellence for Engineered Quantum Systems, University of Sydney, NSW 2006, Australia*

[3]*School of Chemistry, University of Sydney, NSW 2006, Australia*

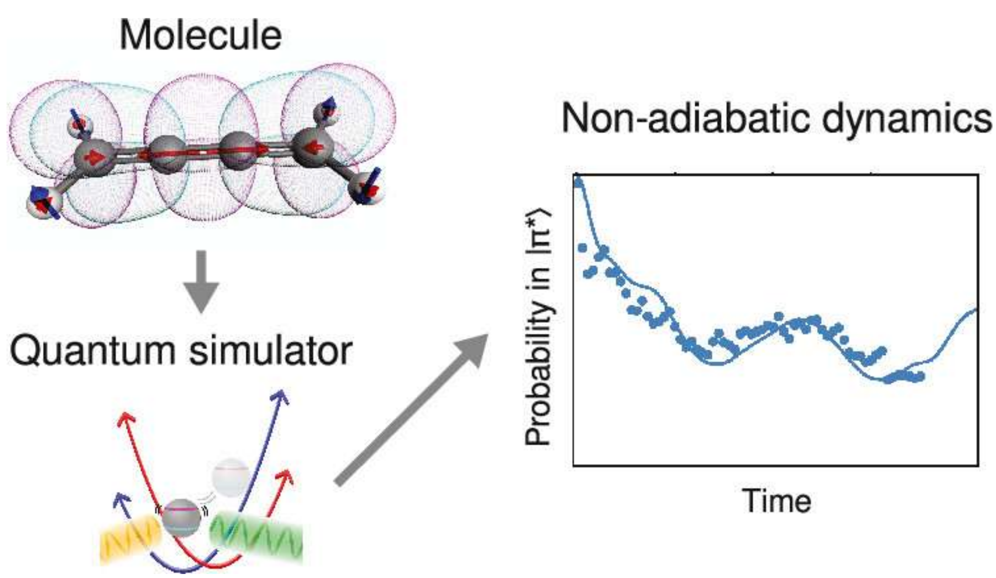
[4]*Departments of Chemistry and Physics, Dalhousie University, Halifax, NS B3H 4R2, Canada*

[5]*University of Sydney Nano Institute, University of Sydney, NSW 2006, Australia*

[6]*ETH Zurich-PSI Quantum Computing Hub, Laboratory for Nano and Quantum Technologies (LNQ), Paul Scherrer Institut, 5232 Villigen, Switzerland*

Simulating chemical dynamics is one of the toughest challenges in quantum chemistry. Digital quantum computing offers a more efficient way to perform these simulations compared to classical computers. However, current algorithms require hundreds of logical qubits and very high-fidelity operations, far beyond the reach of current quantum devices.

In this work we present the first quantum simulations of chemical dynamics, achieved with the *mixed-qudit-boson* (MQB) approach: a resource-efficient scheme that leverages both the electronic and vibrational degrees of freedom of trapped ions. We simulate the ultra-fast vibrational-electronic (vibronic) dynamics of chemical processes – which are particularly difficult to study as they break the Born-Oppenheimer approximation – for three different molecules, showcasing the versatility of our approach. Additionally, we extend our work to the simulation of *open* quantum systems, where the dynamics of our target molecule are now influenced by environmental interactions.



Cryogenic Apparatus for Dual-Isotope Trapped-Ion Crystal Experiments

G.J. Giuli,[1] L.I. Huber[1], J. Flannery[1], R. Matt[1], M. Stadler[1], R. Oswald[1], F. Schmid[1], D. Kienzler[1], D.P.L.A. Craik[1], and J. Home[1]

[1]*Institute for Quantum Electronics, ETH Zurich, Zurich, Switzerland*

We present a cryogenic experimental apparatus for trapped-ion experiments on dual-isotope long crystals of calcium. Dual isotope operation makes this system ideal for quantum error correction protocols, as isotope shifts provide spectral separation between data and ancilla qubits. In addition, this setup has been used to probe beyond-standard-model effects by measuring isotope shifts via correlation spectroscopy [1].

The experimental setup features passive Mu-metal shielding and active trapping potential stabilization for extended coherence times in both the motional and spin degrees of freedoms. Ions can be individually addressed with an optical fiber array whose output is focused and aligned with the ion crystal [2]. Future revisions of the addressing system will feature a 3D laser-written waveguide array for improved crosstalk suppression [3]. Parallel ion state detection is performed with a low-latency EMCCD imaging system integrated with a custom FPGA-based control system.

[1] A. Wilzewski, et al, *arXiv preprint arXiv:2412.10277* (2024).
[2] J. Flannery, et al, *Quantum Science and Technology* 10.1 (2024): 015012.
[3] F. Timpu, et al." *European Conference and Exhibition on Optical Communication*, 2022.

Coupling light from an airplane to a single ion

H. Dang,[1,2] S. Luff,[1,2] M. Fischer,[1] S.H. Huang,[1,2] T. Dirmeier,[1,2] M. Sondermann,[1,2] C. Marquardt[1,2] and G. Leuchs[1,2]

[1]*Max Planck Institute for the Science of Light, Erlangen, Germany*

[2]*Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Department of Physics, Erlangen, Germany*

Trapped ions are promising candidates for establishing long-distance quantum networks. Their ability to reliably retain quantum information as quantum memories makes them ideal building blocks to create such networks [1]. However, the operation of a quantum network necessitates the exchange of information stored in the quantum memories over long distances. An aerial link between ground stations is thus considered as a means to effectively transfer information. As a first step towards establishing long-distance communication, 935 nm photons originating from a coherent source on an airplane have been successfully coupled to a single $^{174}Yb^{+}$ ion trapped in a parabolic mirror on the ground. The parabolic mirror focuses the infrared light from the airborne source onto the ion from nearly full solid angle, increasing the efficiency of coupling photons to the ion [2]. A stylus-like Paul trap is used to trap the ion at the focus of the deep parabolic mirror.

During the flight experiment, only a laser at 370 nm is used to continuously drive the ion on the $^2S_{1/2}$ – $^2P_{1/2}$ Doppler cooling transition. The resulting 370 nm fluorescence light emitted by the ion is monitored throughout the experiment with single photon detectors. Without a repump laser at 935 nm however, the population will accumulate in the meta-stable $^2D_{3/2}$ state, leading to a decrease in the observed fluorescence count rate. As soon as 935 nm photons from the airplane are then successfully coupled to the ion, the observed count rate increases since the ion is repumped back to the $^2S_{1/2}$ state.

This flight experiment is part of the larger German QuNET initiative and aims to develop the technology needed to interface light from a moving source with a single trapped ion. By having the source on an airplane, the impact of losses on the coupling efficiency due to atmospheric absorption, disturbances, weather and Doppler-shift caused by the motion of the airplane, among others, can be studied. A second flight experiment is planned with a Whispering Gallery Mode Resonator (WGMR) onboard the airplane operating as a single photon source to couple single 935 nm photons to the ion.

[1] N. Sangouard et al., *Rev. Mod. Phys.* **83,** 33 (2011).
[2] R. Maiwald et al., *Phys. Rev. A.* **86,** 043431 (2012).

Poster 33

Optimizing high-fidelity spin-dependent kicks in pulsed and CW regimes

<u>H. Liu[1]</u>, V. D. Vaidya,[1] A. Poudel,[1] C. R. Viteri[1]

[1] *IonQ, Inc.*

We propose high-fidelity single-qubit spin-dependent kicks (SDKs) using either mode-locked (pulsed) or continuous wave (CW) lasers via amplitude and frequency modulations. In both cases, we demonstrate optimized SDKs with infidelity approaching the spontaneous emission limit. This study lays the foundation for the realization of ultrafast two-qubit gates via SDKs in various experimental implementations.

Poster 34

Progress on the two-qubit quantum processor at PTB

H.Mendpara,[1,2] M.Duwe,[1,2] A. Onkes,[1,2] C. Ospelkaus,[1,2]

[1]*Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover*

[2]*PTB, Bundesallee 100, 38116 Braunschweig*

A universal quantum gate-set can be realized by the combination of single-qubit rotations and one entangling two-qubit operation. We realize such a universal gate-set using the microwave near-field approach [1, 3]. We trap $^{9}Be^{+}$ ions in a surface-electrode trap at room temperature and perform the quantum logic operations with embedded conductors. The individual qubits are addressed via micromotion sidebands [2] and the entangling gate is performed via a Mølmer-Sørensen type interaction [4]. In this work, we report on recent experimental upgrades and developments aimed at benchmarking errors in quantum processes. This will provide us with more insights into the fidelity and reliability of gate errors within a computational context. Additionally, we discuss the establishment of a cloud interface for the quantum processor, which enhances accessibility and promotes collaborative efforts with our theory colleagues.

[1] N. Pulido-Mateo *et al.*, Physical Review Research 6, **2** (2024)
[2] U. Warring *et al.*, Phys. Rev. Lett. **17**, 173002 (2013)
[3] C. Ospelkaus *et al.*, Nature 471 **7337** (2011)
[4] M. Duwe *et al.*, Quantum Sci. Technol. **7**, 045005 (2022)

Integrated Photonics Ion Trap for Background Free Detection and Light Shift Gates

H.Hirzler,[1] G.J. Beck,[1] S.Cavallini,[1] A.Ferk,[1] J.P. Home,[1]

[1] *Institute for Quantum Electronics, ETH Zürich, Zürich, Switzerland*

Integrated photonics light-delivery for surface-electrode ion traps presents a promising approach for scaling up trapped-ion quantum computing and offers an exciting playground to explore light-matter interaction. Diffraction limited beams from integrated emitters enable the creation of micron-scale spot sized laser beams and excellent beam-pointing stability with respect to the ion position. With high-intensity light delivery to the ions we aim to drive the 732nm quadrupole transition in our calcium ion, facilitating a background-free two-photon detection scheme. Our chip also includes regions for generating 532nm standing waves, supporting high-fidelity two-qubit gate operations. Our material stack - containing both SiN and AlO waveguides - allows us to use all relevant calcium ion frequencies reaching from 375nm to 866nm.

Experiments with trapped molecular nitrogen ions

I. Hochner,[1] **T. Shahaf,[1]** D. Einav,[1] O. Barnea,[1] E. Kipiatkov,[1] T. Levin,[1] and Z. Meir[1]

[1] *Weizmann Institute of Science, Rehovot, Israel*

Molecules have a unique energy structure that includes rotations, vibrations, and different isomers. This makes molecules appealing candidates for metrology, precision measurement, and quantum computing. Diatomic homonuclear molecules such as N_2^+, with their relatively simple structure and long-lived states, provide direct experimental access to fundamental questions in molecular physics and quantum control. However, these advantages also have drawbacks: most molecules cannot be detected using fluorescence, and they cannot be optically pumped or cooled. In the last decade, quantum-logic techniques were developed and implemented in molecular ions to resolve these issues.

We have built an ion trap connected to a molecular beam source capable of co-trapping atomic and molecular ions in the Lamb-Dicke regime (see Figure 1). With this setup, we plan to perform coherent quantum control of molecular transitions in diatomic homonuclear molecules, specifically, coupling two different nuclear-spin isomers of the molecule, a molecular property that has been scarcely studied [1].

Our first experiment focuses on the molecule N_2^+, trapping, cooling, and preparing it at a specific initial state. Here, we present the key methods we plan to implement in our experiment. These include ground-state cooling of N_2^+ using quantum-logic protocols, initial state preparation using resonance-enhanced multi-photon ionization, and state detection using state-dependent optical forces. We show our progress in characterizing the trapping time and the chemical stability of N_2^+ in our trap.

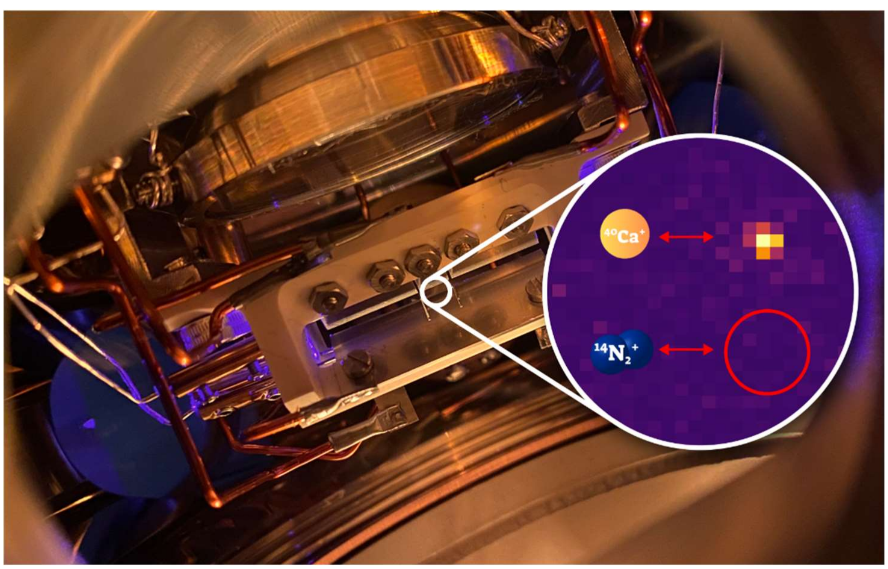


Figure 22: In the inset, a bright Calcium ion co-trapped with a dark molecular Nitrogen ion ($^{14}N_2^+$).

[1] T. Levin, Meir Z., *Phys. Rev. Research* **7**, 013274 (2025).

Enabling high-fidelity, fast entangling gates in multi-ion chains

I.R. Øvergaard, D.J. Webb, K. Shinbrough, S. Saner, O. Băzăvan, R. Srinivas, C.J. Ballance

University of Oxford, Oxford, United Kingdom

Scalable quantum computation on the trapped-ion platform requires the development of faster two-qubit gates to improve resilience to experimental drifts, and, crucially, to allow deeper circuits to run within the system's coherence time.

Conventional geometric phase gates, operating in the regime where the gate duration far exceeds the motional mode period, are limited in achievable fidelity by decoherence. In parallel, errors caused by off-resonant coherent interactions, which grow with increasing laser intensity and ion-register size, impose limits on the achievable gate speed. Fortunately, since these limits are set by coherent effects, they can be surpassed by improving experimental control. Previous work has shown that using amplitude-shaped pulses and a structured optical intensity profile, which mitigate errors due to multi-mode participation and off-resonant coupling, respectively, enables entangling gate durations on the timescale of the motional mode period (typically 0.1–1 μs) [1, 2].

Here we present a new, purpose-built experiment designed to realize fast, high-fidelity entangling gates in intermediate-scale ion crystals by combining high-intensity light with optimised amplitude shaping and structured intensity profile techniques. The system uses $^{40}Ca^{+}$ ions confined in a 3D segmented trap [3], which allows control over the geometry of many-ion chains while maintaining a low heating rate. To enable any-to-any two-qubit operations, the setup incorporates single-ion addressing via a high-power, narrow-linewidth 729 nm laser steered with crossed acousto-optic deflectors. Building on our previous work, where we demonstrated an actively stabilized optical standing wave with phase stability of order $\lambda/100$ [2], the new system integrates individually addressed, phase-stable standing waves delivered via a pair of high numerical-aperture objectives. With the new capabilities afforded by this setup, we aim to push the limits of gate speed and fidelity in intermediate-scale crystals, advancing the scalability and practicality of trapped-ion quantum computation.

[1] Schäfer, V. M., et al., *Nature,* **555**, 75 (2018).
[2] Saner, S., Băzăvan, O., et al., *Phys. Rev. Lett.* **131**, 220601 (2023).
[3] Wilpers, G., et al., *Nat. Nanotechnol.* **7**, 572 (2012).

Novel Microfabrication Approaches for Developing Scalable Ion Trap Systems and Monolithic 3D Traps on Glass and Sapphire Substrates

J. Stupp,[1] N. D. Stahr,[1] F. Giebel,[2] E. Iseke,[1,2] N. Krishnakumar,[1,2] M. Billah,[1] K. Thronberens,[2] M. Wehrheim,[2] C. Ospelkaus,[1,2]

[1]*Leibniz University Hannover, Hannover, Germany*

[2]*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

The high potential of using quantum technology is increasingly pivotal in advancing ion trap systems. In particular, the continued development of such systems is crucial for their future use in quantum computers and in specialized experimental setups, where quantum logic spectroscopy is a key component. As these ion trap systems evolve, they face requirements for scalability, high precision in fabrication, and the integration of photonic structures. This evolution necessitates the development of novel and enhanced fabrication techniques. In this context, certain materials have emerged as promising candidates for ion trap substrates. Among them, glass and sapphire substrates stand out, especially when processed by new fabrication methods such as selective laser-induced etching (SLE) [1]. We demonstrate how these substrates can be effectively structured and metallized using cutting-edge manufacturing processes, enabling the creation of 3D (micro)structures like through-substrate vias (TSVs). This capability is crucial for realizing scalable quantum computers based on multilayer planar surface ion traps [2] and the fabrication of monolithic 3D traps. The flexibility and precision offered by these materials and techniques facilitate the development of advanced ion trap architectures, laying the groundwork for more robust quantum systems. Additionally, the possibility of fabricating these substrates with integrated photonic elements enables new functionalities, paving the way for scalable, high-performance quantum systems and advances toward breakthroughs in quantum computing [3].

Figure 23: 3D ion trap blank made from a piece of fused silica using SLE.

[1] Butkutė, A. et al., *Micromachines*, 14, 7 (2023).
[2] Bautista-Salvador, A. et al., *New J. Phys.* 21 043011 (2019).
[3] Niffenegger, R.J et al., *Nature* 586, 538–542 (2020

Characterizing and cancelling periodic motional dephasing from mains-induced noise in a trapped ion

J. You,[1,2] J. Kang,[1,2] K. Kim,[1,2] W. Choi,[1,2] and T. Kim[1,2,3]

[1]*Dept. of Computer Science & Engineering, Seoul National University, Seoul, South Korea*

[2]*Automation and Systems Research Institute, NextQuantum, Seoul National University*

[3]*Institute of Computer Technology, Institute of Applied Physics, Seoul National University*

Motional decoherence in trapped ions is often described by Gaussian noise models and Lindblad-type master equations; however, such approaches become insufficient when structured, slow noise sources are present. A representative example is the 60 Hz (or 50 Hz) mains-induced noise, which generates narrow-band, sinusoidal fluctuations. While the impact of mains noise on qubit coherence has been widely studied [1], its effect on the motional mode has remained largely unexplored.

We investigate the influence of this periodic noise on the motional mode of a trapped ion using blue-sideband Ramsey spectroscopy, supplemented by echo-type and CPMG dynamical decoupling sequences. The measured coherence exhibits Bessel-function-like decay with revivals near 1/60 s, in agreement with theoretical predictions for sinusoidal dephasing [2]. The extracted motional frequency fluctuation at a secular frequency near 1 MHz is 40–60 Hz. Additionally, we implement passive noise cancellation by adjusting the phase offset of the CPMG sequences based on fits to the observed oscillations, enabling partial compensation of the known periodic modulation.

Beyond passive techniques, we realize active noise cancellation by injecting a 60 Hz feedforward correction into the PI controller stabilizing the trap RF amplitude. This effectively suppresses the periodic modulation, leading to a significant recovery of motional coherence.

These results demonstrate complementary passive and active strategies for mitigating periodic environmental noise in trapped-ion systems. The methods developed may offer a general approach for identifying and compensating periodic noise sources affecting motional modes in precision quantum experiments.

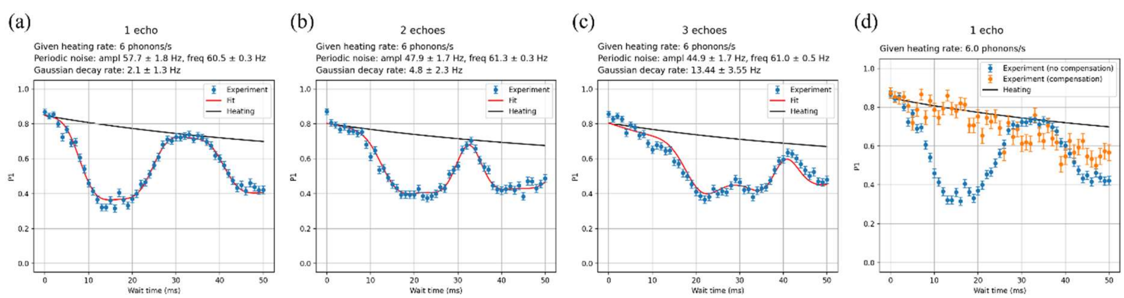


Figure 24: (a)–(c) Characterization of mains-induced noise using blue-sideband CPMG sequences with 1, 2, and 3 echoes. (d) Demonstration of active noise cancellation using feedforward compensation of the trap RF amplitude.

[1] H. Hu et al., *Appl. Phys. B* **129,** 163 (2023).
[2] C. Flühmann, PhD thesis, ETH Zurich (2019).

Status of the BASE Hannover Penning trap experiment

J. Schaper,[1] N. Poljakov,[1] J.A. Coenders,[1] J.M. Cornejo,[1] S. Ulmer,[3,4] and C. Ospelkaus[1,2]

[1]*Leibniz University Hannover, Germany*

[2]*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

[3]*Heinrich-Heine-University, Düsseldorf, Germany*

[4]*Ulmer Fundamental Symmetries Laboratory, RIKEN, Japan*

Multi-Penning trap experiments are an excellent tool for CPT symmetry tests in the context of the search for physics beyond the standard model. The BASE collaboration contributes to these tests by measuring the charge-to-mass ratios and *g*-factor ratios of protons and antiprotons in a cryogenic Penning trap [1-3]. BASE Hannover is developing new measurement schemes based on sympathetic cooling and quantum logic spectroscopy to further reduce measurement time and the statistical uncertainty, using $^{9}Be^{+}$ both as cooling and logic ion [4].

This contribution will focus on our time-varying waveform transport scheme, allowing the shuttling of a single $^{9}Be^{+}$ ion in the ms-regime using low-pass filter predistortion [5]. Also, the latest status of the BASE Hannover experiment will be presented. This includes upgrades on the laser systems and a new Penning trap stack, featuring a microfabricated Penning trap for proton-beryllium coupling, which has been simulated in a double-well potential.

Figure 25: Picture of the BASE Hannover Penning trap at 4K inside the superconducting magnet. In the middle is the aspheric lens for imaging of the $^{9}Be^{+}$ fluorescence signal.

[1] Schneider et al., *Science* **358**, 1081 (2017)
[2] Smorra et al., *Nature* **550**, 371 (2017)
[3] M.J. Borchert et al., *Nature* **601**, 53 (2022)
[4] Cornejo et al., *Phys. Rev. Research* **6**, 033233 (2024)
[5] von Boehn et al., *Commun. Phys.* **8** 107 (2025)

High-precision mass measurements on highly charged ions with the PENTATRAP Penning-trap experiment

J.H. Nägele,[1] J. Franke,[1] P. Filianin,[1] S. Eliseev,[1] and K. Blaum,[1]

[1]*Max Planck Institute for Nuclear Physics, Heidelberg, Germany*

The PENTATRAP experiment at the Max Planck Institute for Nuclear Physics in Heidelberg is a high-precision Penning-trap mass spectrometer that utilizes a cryogenic environment, a stable magnet, and an image current detection system to determine mass ratios of stable and long-lived highly charged ions with relative uncertainties in the low 10^{-12} regime [1]. The data acquired by this state-of-the-art apparatus contributes to different fields of fundamental physics, e.g., fifth force search, neutrino physics, and highly charged ion clocks. In this contribution I will present recent measurements on long lived electronic states [2], Q values of neutrino physics [3], and isotope shifts [4] followed by future perspectives of PENTATRAP.

[1] J. Repp et al., *Appl Phys B* **107**, 983 (2012).
[2] R.X. Schüssler et al., *Nature* **581,** 42 (2020).
[3] C. Schweiger et al, *Nat. Phys.* **20**, 921 (2024).
[4] M. Door et al, *PRL* **134**, 063002 (2025).

Microwave gate zones for modular surface-electrode ion traps

J. Bätge[1], M. Billah[1], R. Munoz[1], F. Ungerechts[1], A. Hoffmann[1,2], G. Zarantonello[1,3] and C.Ospelkaus[1,4]

[1] *Institut für Quantenoptik, Leibniz Universität Hannover, Germany*

[2] *Institut für Hochfrequenztechnik und Funksysteme, Leibniz Universität Hannover, Germany*

[3] *QUDORA Technologies GmbH, Braunschweig, Germany*

[4] *Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

Surface-electrode ion traps are a promising platform for scalable quantum computers. In the Quantum CCD architecture, transport of ions between registers allows to limit the number of ions that has to be kept in a single potential well at any given time and to implement specialized registers for storage, cooling, detection and gate operations. Here we discuss the design of registers for quantum gate operations based on chip-integrated microwave conductors [1]. We discuss these designs in the context of a demonstrator chip design based on an X junction to route the ions between storage registers, a detection register and a gate operation register.

The design of the chip-integrated microwave conductor geometry in the gate operation register is critical to achieve the desired microwave near-field for quantum gates. To implement a modular architecture, registers should be self-contained and the influence of the surrounding chip layout should be controlled. We discuss challenges in achieving modular designs and present design results of gate registers for different ion species to be implemented in the demonstrator chip design.

[1] C. Ospelkaus et al., PRL 101, 090502 (2008)

Correlated readout of a GKP logical Bell state in a single trapped ion with finite energy corrections

Jeremy Metzner[1], Moritz Fontboté-Schmidt[1], Florence Berterottiere[1], Stephan Welte[2], Daniel Kienzler[1], Jonathan Home[1]

[1] *Institute for Quantum Electronics, ETH Zürich*

[2] *Physikalisches Institut and Center for Integrated Quantum Science and Technology, University of Stuttgart*

Bosonic codes such as the Gottesman-Kitaev-Preskill (GKP) code [1, 2] provide an alternative approach for quantum error correction by encoding information in the continuous degrees of freedom of an oscillator. Recent experimental progress in this area include the ability to error correct GKP states [3, 4, 5] and perform logical two qubit gates using an intermediary unencoded spin qubit [6]. I will present work in which we couple GKP states in two different modes directly via a beam-splitter interaction, which when combined with squeezing and anti-squeezing operations can be used to implement an encoded 2-qubit gate [7]. We have demonstrated the use of the beamsplitter to generate entangled GKP qubits in a two mode Bell state by inputting two qunaught states, which show the periodic features of GKP qubits but cannot encode logical information. We demonstrate readout of the correlated characteristic function using measurement techniques designed for finite energy GKP states, showing clear signatures of entanglement between the modes. These techniques can not only form the basis for error-corrected gates, but also for realizing novel quantum transduction protocols [8].

[1] D. Gottesman, A. Kitaev, and J. Preskill, *Phys. Rev. A.* **64**, 012310 (2001)
[2] C. Flühmann, T.L. Nguyen, M. Marinelli et. al., *Nature* **566,** 513-517 (2019)
[3] P. Campagne-Ibarcq et. al., *Nature* **584**, 368 (2020).
[4] V.V. Sivak, A. Eickbusch, B. Royer, et al., *Nature* **616**, 50–55 (2023).
[5] B. de Neeve, TL. Nguyen, T. Behrle, *et al. Nat. Phys.* **18,** 296-300 (2022)
[6] V. G. Matsos, C. H. Valahu, et. al., arXiv:2409.05455 [quant-ph] (2024).
[7] I. Rojkov, P. M. Röggla, M. Wagener, et al. *Phys. Rev. Lett.* **133**, 100601 (2024)
[8] W. Zhaoyou, J. Liang, *Phys. Rev. X* **15,** 021003 (2025)

Multimode bosonic state tomography with single-shot joint parity measurement of a trapped ion

H. Jeon,†[1,2] **J. Kang,[1,2]** W. Choi,[1,2] K. Kim,[1,2] J. You,[1,2] and T. Kim[1,2,3,4,5,6]

[1]Dept. of Computer Science & Engineering,[2]Automation and Systems Research Institute,[3]Inter-university Semiconductor Research Center,[4]Institute of Computer Technology, [5]Institute of Applied Physics,[6]NextQuantum, Seoul National University, Seoul, South Korea

†Current address: Duke University, Durham, USA

We demonstrate multimode bosonic state tomography in a trapped-ion system by implementing a spin-dependent beam splitter interaction [1] that enables single-shot measurement of joint parity across multiple motional modes. This interaction coherently exchanges phonons between modes and encodes joint parity information in the relative phase of the spin state, allowing joint parity to be read out via spin-state detection. Using this capability, we directly measure Wigner function tomograms of two-mode Fock states and entangled coherent states (ECS) [2], revealing clear signatures of nonclassicality. From the measured tomograms, we reconstruct the density matrix of the ECS and estimate its fidelity relative to the ideal target state.

Furthermore, we verify the entanglement of the generated ECS by predicting a violation of the Clauser–Horne–Shimony–Holt inequality [3] through numerical simulations that incorporate experimental imperfections, confirming the presence of genuine quantum correlations between motional modes. Notably, the joint parity measurement is non-destructive when the spin is projected onto the dark state. We demonstrate that this property enables recovery of a two-mode Fock state after motional heating via a heralded joint parity measurement.

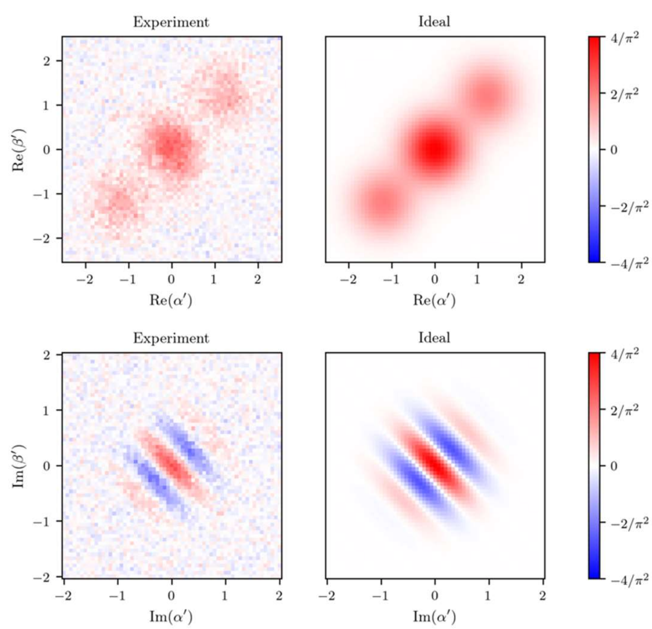


Figure 26: Measured Wigner function $W(\alpha', \beta')$ tomograms of an even ECS $|\alpha\rangle|\beta\rangle + |-\alpha\rangle|-\beta\rangle$ (unnormalized), with $\alpha = \beta = 1.2$. "Experiment" and "Ideal" columns represent the experimental and theoretical data, respectively.

[1] C. -H. Nguyen et al., arXiv:2103.10219 [quant-ph].
[2] H. Jeon et al., *Sci. Rep.* **14,** 6847 (2024).
[3] J. F. Clauser et al., *Phys. Rev. Lett.* **23,** 880 (1969).

Cooling of Trapped Ion Chains: A Quantum-Classical Approach

J. Pedregosa Gutierrez, E. Paez, I. Khait

[1]*IonQ Inc*

Trapped ions are a leading platform for quantum information processing [1], where precise control over ion temperatures is essential for achieving high-fidelity operations. We investigate sympathetic cooling of linear chains of barium ions motivated by realistic experimental implementations. Our novel approach combines quantum (MCWF [2]) and classical (molecular dynamics [3]) methods to analyze ion chain dynamics and optimize cooling duration as well as other available degrees of freedom (for example, laser parameters and qubit and coolant ion placements). This provides key insights into the interplay of cooling and heating processes, allowing us to achieve the necessary reductions in the final temperature to facilitate high-quality quantum information processing. These results pave the way for improved scalability and performance of trapped-ion quantum computers.

[1] J.S Chen et al, Quantum 8, 1516 (2024).
[2] K. Molmer, Y. Castin and J. Dalibard J. Opt Soc. Am. B, vol10, 1993
[3] J. Pedregosa Gutierrez and J. Dempsey, arXiv:2106.11143m 2021

Poster 46

Quantum Mpemba effect in a trapped-ion quantum simulator

Experiment: **<u>Johannes Franke</u>,[1,2]** Florian Kranzl,[1,2] Rainer Blatt,[1,2] Christian F. Roos,[1,2] and Manoj K. Joshi[1,2]

Theory: Lata Kh. Joshi,[1,3,4] Aniket Rath,[5] Filiberto Ares,[3] Sara Murciano,[6] Peter Zoller,[1,4] Benoît Vermersch,[1,4,5] and Pasquale Calabrese[3,7]

[1]*IQOQI, Innsbruck, Austria*

[2]*University of Innsbruck, Institute for Experimental Physics, Innsbruck, Austria*

[3]*SISSA and INFN, Trieste, Italy*

[4]*University of Innsbruck, Institute for Theoretical Physics, Innsbruck, Austria*

[5]*Univiversit´e Grenoble Alpes, Grenoble, France*

[6]*Walter Burke Institute for Theoretical Physics, Pasadena, USA*

[7]*ICTP, Trieste, Italy*

Non-equilibrium dynamics in many-body quantum systems give rise to a range of fascinating behaviors. A recent theoretical prediction—known as the *quantum Mpemba effect*—reveals a counterintuitive feature: a ferromagnet initially prepared farther from a symmetric state can restore its symmetry more rapidly after undergoing time evolution with an entangling interaction than one prepared closer to it. In this presentation, we report the first experimental observation of this effect using a trapped-ion quantum simulator. Symmetry breaking and restoration are quantified via entanglement asymmetry, accessed through randomized measurements and analyzed using the classical shadows technique. Furthermore, comparison between the experimentally evolved state and the theoretically predicted thermal symmetric state provides direct evidence of subsystem thermalization. These results open new avenues for exploring anomalous relaxation dynamics in quantum systems [1].

[1] L. K. Josh et al., *Phys. Rev. Lett*. **133**, 010402 (2024).

Trapped thorium-229 ions in the 1+, 2+ and 3+ charge state

J. Tiedau,[1] G. A. Zitzer,[1] V. Lal,[1] S. S. Maurya,[1] N. Irwin,[1] M. V. Okhapkin,[1] and E. Peik[1]

[1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

A thorium-229 nuclear clock offers many advantages in terms of stability, accuracy and sensitivity to new physics [1]. A milestone in this development were the recent direct laser excitation experiments of Th-229 nuclei in solid state hosts [2-5]. Complementary to the solid-state approach, trapped ions promise lower stability but an increase in accuracy making it an interesting candidate as a primary time standard as well as highly sensitive sensor for physics beyond the standard model.

We will present our latest results on the direct laser excitation of Th-229 ions in the 1+ and 2+ charge state. Via laser ablation we are able to load about 10^6 Th^{1+} ions in a Paul trap. Photoionization is then applied to convert up to 1% of this cloud to the 2+ charge state. The advantages and disadvantages for direct laser excitation of these two species will be discussed and compared.

In addition, we report on a U-233 recoil ion source for the generation of Th-229(m) ions in the 3+ charge state. Our latest measurements on the hyperfine structure [6,7] improve the knowledge of the A and B hyperfine parameters by a factor of three. These findings are important for the understanding of higher order nuclear moments and the understanding of nuclear models.

[1] E. Peik, Chr. Tamm., Euro. Phys. Lett. **61**, 181 (2003)
[2] J. Tiedau, et al., Phys. Rev. Lett. **132**, 182501 (2024)
[3] R. Elwell, et al., Phys. Rev. Lett. **133**, 013201 (2024)
[4] C. Zhang, et al., Nature **633**, 63 (2024)
[5] C. Zhang, et al., Nature **636**, 603 (2024)
[6] G. Zitzer et al., *Phys. Rev. A.* **109,** 033116 (2024).
[7] G. Zitzer et al., *Phys. Rev. A.* **111,** L050802 (2025).

Precision isotope shift measurements with entangled Ba^+ ions for the search of beyond the standard model physics

J. Helgert,[1] A. Lohde,[1] L.S. Dreissen[1]

[1] *LaserLaB, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands*

Precision quantum sensors have become a powerful tool for tests of the standard model and searches for new physics [1]. Specifically, a hypothetical boson-mediated fifth force between hadrons and leptons can be probed by accurate isotope-shift measurements through a so-called King plot analysis [2]. Recent measurements in calcium and ytterbium revealed anomalous signals, which provided a benchmark for nuclear theory and competitive bounds on new physics [3, 4]. Singly ionized barium (Ba^+) features five stable bosonic isotopes and two quadrupole transitions with lifetimes on the order of several tens of seconds — a system that is particularly promising for precision isotope shift spectroscopy. However, resolving the natural line width of these transitions is usually strongly hampered by systematic effects and environmental noise. These effects are typically correlated on the scale of the ion-to-ion separation (~10 µm) and can be overcome by probing an ensemble of entangled ions in a decoherence-free subspace. By applying this method to a mixture of two different isotopes, the phase evolution of the state is directly proportional to the isotope shift, which can be read out via a parity measurement [5]. By applying these techniques, we expect to reach a lifetime-limited frequency resolution at the 10mHz level, increasing our sensitivity to a fifth force coupling between neutrons and electrons 100-fold compared to any previously reported King plot analysis. Here we present the recent progress for the realization of such a trapped Ba^+ quantum sensor.

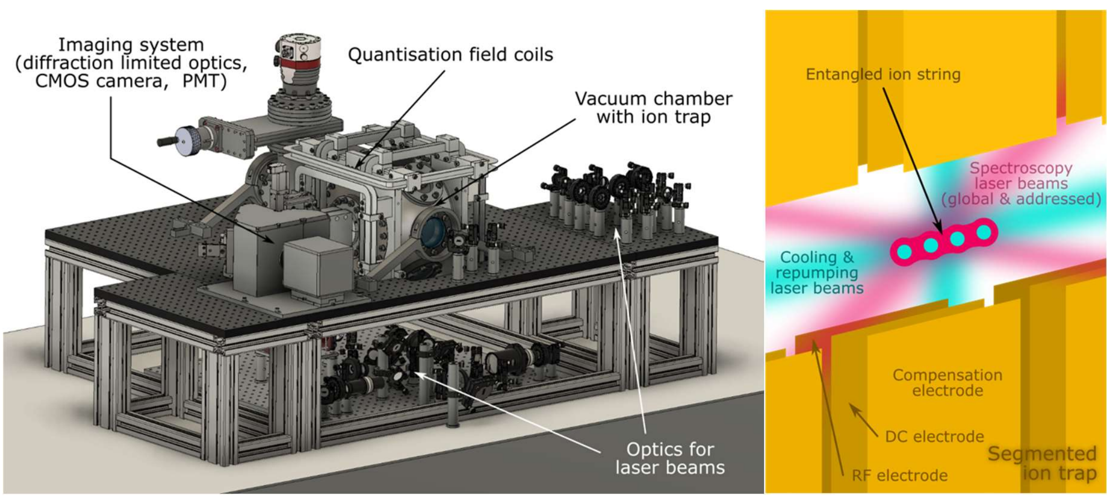


Figure 27: CAD design of the setup and schematic of entangled ions in the trap

[1] M. S. Safranova et al., *Rev. Mod. Phys.* **90,** 025008 (2018).
[2] J. C. Berengut et al., *Phys. Rev. Lett.* **120,** 091801 (2018).
[3] A. Wilzewski et al., *arXiv.* 2412.10277 (2024).
[4] M. Door et al., *Phys. Rev. Lett.* **134,** 063002 (2025).
[5] T. Manovitz et al., *Phys. Rev. Lett.* **123,** 203001 (2019).

Integration of a low finesse optical cavity with a microfabricated surface ion trap

J. Tost, E.L. Wette, N. Taylor, and M. Cetina

Duke University, Durham, NC, USA

We present initial data on a new system in which a long, near-concentric optical cavity is integrated coaxially with a silicon micro-fabricated surface electrode ion trap (Roadrunner, Sandia National Laboratories) [1] with the goal of scaling systems up to more ions for computation and simulation. The system makes use of visible-spectrum HR-coated mirrors to create a low- to medium-finesse optical cavity coupled to a chain of barium ions. We present data on cavity cooperativity and finesse across a range of wavelengths, as well as the characteristics of the new Roadrunner ion trap. This new system will allow us to explore several new schemes, including a fast, coherent, photonic interface between ion chains [2]. This may allow the entanglement of individual spatially separated qubits within one single trap with rates above 10 kHz. Further scaling will be possible by using two-photon networking protocols, demonstrating cavity-enhanced photon collection from ensembles of ions, which could be used to connect multiple, independent, cavity-based modules. Finally, we show the use of the cavity mode to form a blue-detuned optical lattice with 435 nm light to suppress the motion of ions along the axial direction. This may allow individual addressing and controlled spin-spin interactions in chains of up to a hundred ions, with applications to quantum simulation, including that of lattice gauge theories.

[1] M. C. Revelle et al., The Roadrunner Trap (2023).
[2] J. Ramette et al., PRX Quantum, 3, 010344 (2022).

A transportable Al^+/Ca^+ quantum logic optical clock

J. Hinrichs,[1,2] C. Nauk,[1,2] G. Sasidharan,[1,2] V. Galbierz,[1] B. Kraus,[1]
S. Herbers,[1] P. O. Schmidt,[1,2]

[1]*Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany*

[2]*Leibniz University Hannover, Institute of Quantum Optics, 30167 Hannover, Germany*

Optical atomic clocks are precise measurement tools, achieving fractional frequency uncertainties in the order of 10^{-18} and below. To exploit this precision in a wider range, we are building a transportable Al^+ optical clock[2]. Transportable systems enable high-precision frequency ratio measurements on-site at various metrology institutes. These measurements will contribute to one of the requirements of reproducible frequency comparisons for a redefinition of the SI second[3]. Furthermore, transportable clocks are used for relativistic geodesy as they allow height measurements on the cm level over large distances[4].

Our fully rack-integrated clock setup is based on the ${}^1S_0 \rightarrow {}^3P_0$ transition in ${}^{27}Al^+$. A co-trapped ${}^{40}Ca^+$ ion allows sympathetic cooling and state detection through quantum logic spectroscopy.

We present efficient loading of Ca^+ and Al^+, laser cooling, spectroscopy measurements on the Ca^+ ${}^2S_{1/2} \rightarrow {}^2D_{5/2}$ logic transition, and the characterization of our segmented chip-trap. In addition, we present swap rate measurements characterizing our room temperature vacuum chamber and the performance of our mu-metal shield housing the setup.

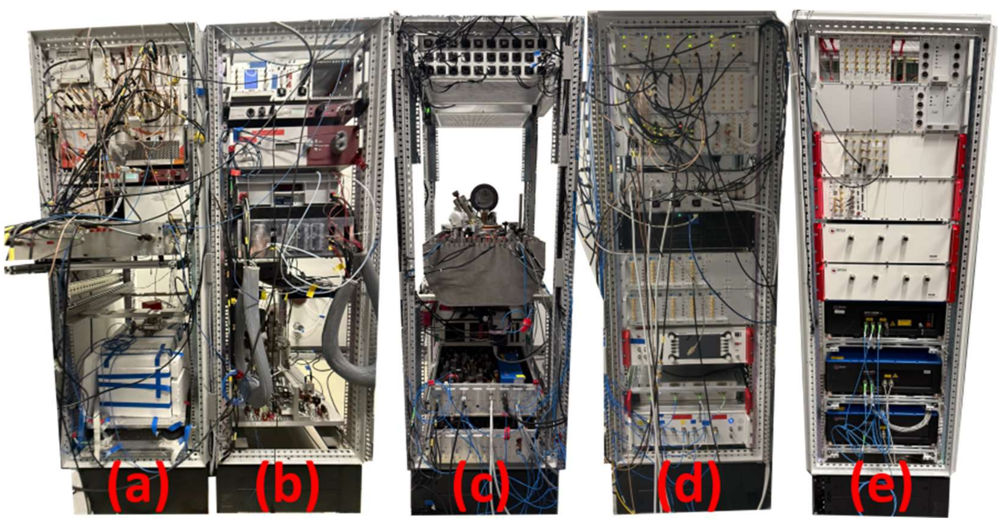


Figure 28: The rack-integrated clock hardware mounted in five 19" racks. From left to right: Al^+ clock laser (a), Al^+ and Ca^+ logic lasers (b), physics package containing the vacuum chamber (c), electronics (d), and a frequency comb (e).

[1] B. Kraus et al., Opt. Lett. 50, 658-661 (2025).
[2] N. Dimarcq et al., Metrologia 61, 012001 (2024).
[3] T. E. Mehlstäubler et al., Rep. Prog. Phys. 81, 064401 (2018)

In situ-tunable spin-spin interaction for 2D ion crystals in a Penning trap

J.H. Pham, J. Y. Z. Jee, M. J. Biercuk, R. N. Wolf

ARC Centre for Engineered Quantum Systems, School of Physics, The University of Sydney

Trapped ions represent a promising candidate for quantum simulation and sensing technologies, providing access to long-lived quantum systems with excellent controllability through optical and microwave fields. Achieving a high ratio of coherent to incoherent interactions is crucial for harnessing their full potential in quantum information processing and precision metrology.

In this contribution, we describe an optomechanical system designed to enhance the coherent spin-motion and spin-spin interactions in two-dimensional ion crystals confined in a Penning trap [1]. This enhancement is achieved by adjusting the opening angle between the laser beams that create a spin-dependent optical dipole force on the ion crystals. The system incorporates actively controlled optical positioners within the limited space of a superconducting magnet bore, enabling precise and reproducible alignment of the beams with respect to the 2D ion crystal.

When combined with electromagnetically induced transparency cooling, the experimental results show a significant increase in coherent-to-incoherent interaction strength. Furthermore, the system exhibits stability of 2×10^{-3} degrees per hour, confirming its suitability for long-duration experiments and emphasising its relevance for future quantum simulations and sensing.

[1] Pham et al., Adv Quantum Technol. 2024, 7, 2400086

Digital predistortion of optical field of a fast and high-fidelity entangling gate for trapped ion qubits

J. Markov,[1] Y. Shapira,[1] N. Akerman,[1] and R. Ozeri[1]

[1]*Weizmann Institute of Science, Rehovot, Israel*

Tapped ion qubits are a leading quantum computing platform. In these systems, entangling gates are performed by driving the normal modes of motion of the ion chain, generating a spin-dependent force that mediates qubit-qubit interactions.

In recent years, there have been many theoretical proposals and experimental demonstrations which have generalized this approach in order to increase the fidelity, robustness, and programmability of the entangling operation. These are all performed by carefully designing the electromagnetic fields which drive the ion chain. However, various components such as amplifiers and modulators, which are used to generate the required field modulations, have inherent non-linear responses, resulting in an inaccurate and low-fidelity implementation of the entangling operations.

We propose a method to mitigate this degradation by using digital pre-distortion of the modulating waveform. Specifically, we measure the temporal and amplitude non-linear response of an acousto-optic modulator used to modulate the optical field driving the ion chain, and use it in a feed-forward correction of the desired waveform.

We measure that the resulting optical field more closely resembles the desired spectrum. Moreover, we use the pre-distorted signal to generate a multi-tone two-qubit entangling gate described in Ref. [1]. We show that our method allows us to utilize all the available optical power in order to drive fast entanglement gates, without incurring fidelity loss due to unwanted non-linear effects. Our method is straightforward to implement, even in complicated waveform modulation, such as Refs. [2,3], which require many driving tones in order to generate multi-qubit robust entanglement gates.

[1] Shapira et al., Phys. Rev. Lett. 121, 180502 (2018).
[2] Shapira et al., Phys. Rev. A 101, 032330 (2020).
[3] Shapira et al., Phys. Rev. Lett. 130, 030602 (2023).

Multi-site surface Penning trap for investigating entangling gates

K. Hanke[1, 2] , T. Sägesser,[3] Y. Cui[2], M. Mazzanti[2], B. Asenbeck[2], M. Simoni[2], S. Jain[3], P. Hrmo[2,3], C. Rössler[1], Y. Colombe[1], D. Kienzler[2], J. Home[2]

[1]*Infineon Technologies Austria AG, Siemensstraße 2, 9500 Villach, Austria*

[2]*Institute for Quantum Electronics, ETH Zurich, Otto-Stern-Weg 1, 8093 Zurich, Switzerland*

[3]*ZuriQ, Zurich, Switzerland*

Implementing high-fidelity entangling gates between trapped ions is a central requirement for a scalable quantum computing architecture. The choice between surface Paul traps and surface Penning traps fundamentally influences the available approaches for achieving the required inter-ion interactions. We investigate this question using a newly installed surface-electrode Penning trap, designed to confine beryllium ions in a 2×2 array of individually controlled trapping sites.

Our approach leverages the unique advantages of Penning trap confinement, which uses only static electric and magnetic fields and enables arbitrary three-dimensional ion transport. Beryllium ions serve as a testbed for these fundamental studies due to their simple level structure and low mass, which provides accessible trap frequencies at a magnetic field strength of 3 T.

Here we present shuttling of individual ions in our new trap over distances above 1 mm. We also discuss how we are working toward simultaneous multi-ion confinement across separate trapping sites. The key next step will be to determine whether entangling interactions are best achieved through ions maintained in individual close-proximity trapping sites or through dynamic protocols that temporarily merge and split trapping sites. These investigations will establish fundamental design principles for implementing scalable quantum logic operations in the Penning QCCD architecture.

A rack mounted laser system for atomic physics experiments

K. Theophilo,[1] S. Thomas,[1] Y. Lekhai,[1] A. Owens ,[1] G. Croft, [1] S. Muralidharan, [1] D. Smith, [1] and C. Deans[1]

[1]*National Quantum Computing Centre, Harwell Campus, Didcot, UK*

Laser trapping, cooling and manipulation of atomic states are the pillars of most atomic physics experiments. Here we propose a reproducible, modular, high performance laser system that can be implemented for a range of different wavelengths. Moreover, it can be adapted to tackle specific needs of a given experiment, like pulse shaping and phase control.

The main modules on this laser system provide distribution, frequency stabilization, frequency scan and amplitude modulation. The system was benchmarked by collecting data from frequency and power stability, overall power delivery and polarization extinction ratio (PER), for wavelengths ranging from 422nm to 1092nm. The avarage power availability is of 25% of the input power, with a stability better than 1%, and a PER of 40dB. The laser linewidth is roughly 300kHz.

The system is rack mounted, except for the cavities used to stabilize the lasers. Assembling the modules is easy, and in typical operation conditions requires minimal realignment once setup (up to 3months without touching the system).

Two of those laser systems were built and deployed, proceeding to successfully trap strontium atoms.

Figure 29: Rendering of the rack mounted system

Development of strontium ion optical clocks at NRC towards the redefinition of the SI second

K. Kato, C. Marceau, B. Jian, S. Beatie, and P. Dubè

National Research Council Canada, Canada

The performance of optical atomic clocks has improved tremendously over the past few decades. The best optical clocks have reached uncertainties below 10^{-18}, outperforming the best cesium fountain clocks by two orders of magnitude. Optical clocks are becoming increasingly reliable as their technology matures. This warrants the need for a redefinition of the SI second based on an optical transition. The Consultative Committee of Time and Frequency (CCTF) has put together a roadmap towards the redefinition and laid out a list of mandatory criteria for contributing clocks to be included in the consideration for the redefinition [2]. In this presentation, we will discuss our work towards meeting the criteria with our strontium ion optical clocks at the NRC.

The criteria mainly considered here are the following:

I.1) Accuracy budgets of optical frequency standard (OFS): $\Delta\nu/\nu \leq 2 \times 10^{-18}$,

I.2) Validation of OFS accuracy budgets: $\Delta\nu/\nu \leq 5 \times 10^{-18}$,

I.3) Continuity with the definition based on Cs: $\Delta\nu/\nu \leq 3 \times 10^{-16}$.

We have performed an absolute frequency measurement of our existing strontium ion clock (NRC-SrIOC1) against the cesium fountain clock (NRC-FCs2) in November and December 2024 for a total duration of 35 days with a clock uptime of 68%. We coordinated with a few other NMIs (VTT, PTB, NPL, and NICT) to perform clock comparisons through GNSS links. Our measurement campaign comparing with FCs2 resulted in an absolute frequency of SrIOC1 with a fractional uncertainty of 1.0×10^{-16}, well below the continuity criterion I.3). However, criteria I.1) and I.2) are unresolved due to the insufficient accuracy of SrIOC1 (evaluated uncertainty of 1.1×10^{-17}, mainly limited by the BBR shift uncertainty), and we have no means to compare our clocks with remotely located clocks at the level of accuracy stated in I.2). In an effort of satisfying criteria I.1) and I.2), we are developing a high-accuracy transportable strontium ion clock to bypass the need for phase-stabilized fiber links and perform the clock comparison directly on site.

A few upgrades have been implemented to the new clock to improve its accuracy. The new ion trap design with high thermal conductivity and low emissivity materials mitigates the BBR shift, and an improved vacuum system results in a longer ion lifetime and a reduced collisional shift uncertainty compared to SrIOC1. The expected uncertainty of the transportable clock is 1.4×10^{-18}, sufficiently accurate to meet the criterion I.1). Two identical systems are being built in parallel to perform an in-house comparison at the 10^{-18} level before launching the transportable system to other NMIs for direct clock comparisons. Collaborating with the University of Toronto, we are also developing a cryogenic ion clock that completely eliminates the BBR shift and the collisional shift. Comparison and agreement with this cryogenic clock will validate the BBR shift evaluation performed on the room-temperature clock systems. Successful rollout of the new transportable clock will allow us to meet the stringent criteria and to contribute to the international effort towards the SI second redefinition.

[1] N Dimarcq et al 2024 Metrologia 61 012001

Post-DRIE Scallop Pattern Removal in Ion-Trap Chip Fabrication

Kwangyeul Choi[1,2,3,4], Seungwoo Yu[1,2,3,4], Chiyoon Kim[1,2,3,4], Suhan Kim[1,2,3,4], Uihwan Jeong[1,2,3,4], Daun Chung[1,2,3], Hosung Shon[1,2,3], Yonghwan Cha[1,2,3], Taehyun Kim[*,1,2,3,4]

[*]*Corresponding author, taehyun@snu.ac.kr*

[1]*NextQuantum, Seoul, South Korea*

[2]*Department of Computer Science and Engineering, Seoul, South Korea*

[3]*Automation and Systems Research Institute, Seoul, South Korea*

[4]*Inter-university Semiconductor Research Center, Seoul, South Korea*

Semiconductor-based ion-trap chips with loading slots are advantageous for scalable quantum computing, but their performance can be compromised by incomplete metal coverage on etched silicon surfaces, which can generate stray electric fields [1]. In this work, we present a refined fabrication process for ion-trap chips using silicon-on-insulator (SOI) wafers that enables uniform gold (Au) coating even on high-aspect-ratio sidewalls. Two scallop-smoothing methods based on reactive-ion etching were developed and compared to eliminate the scallop patterns generated by deep reactive-ion etching (DRIE). The process is based on a previously reported post-etching method using SF6 plasma [2]. In the previous work [3], the absence of an etch-stop layer resulted in inconsistent silicon thickness around the loading slot across different chips, severely limiting the reproducibility of the smoothing process. By utilizing an SOI wafer, a consistent silicon thickness is maintained, enabling effective optimization of the scallop-smoothing process. The optimized process achieved near-complete removal of scallop patterns, as confirmed by scanning electron microscopy (Fig. 1), enabling full Au coverage via angled evaporation. The effectiveness of the fabrication was validated through the trapping of Yb^+ ions and measurement of the motional heating rate, which was found to be 160–200 quanta/s.

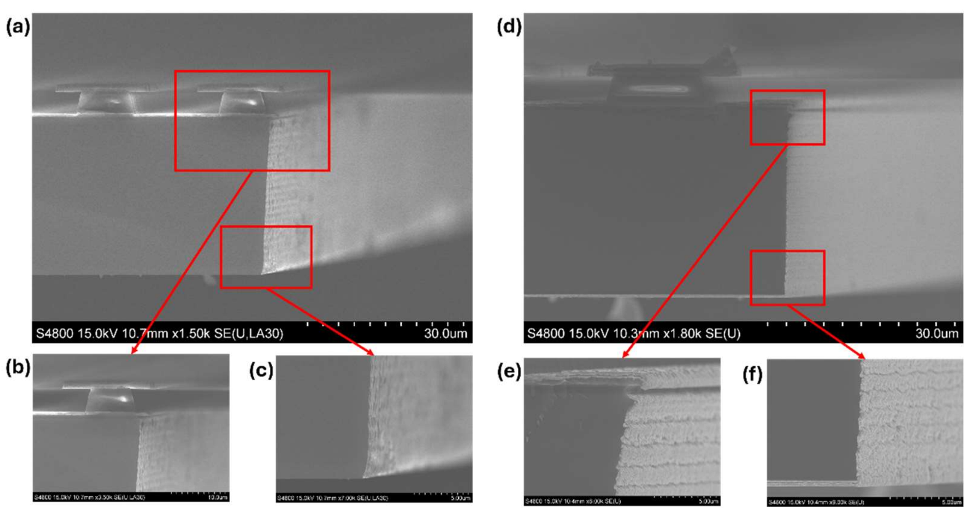


Figure 30: SEM analysis of the slot structure before and after gold deposition, following the scallop smoothing process. (a)–(c) SEM images of the silicon sidewall at the slot structure after applying the scallop smoothing process, showing significant suppression of scallop features. (d)–(f) SEM images of the same structure after gold deposition.

[1] W. Lee et al., *Physical Review A*, **109**, 4, 043106 (2024)
[2] J.S. Park et al., *Micro and Nano Systems Letters*, **8**, 1–8 (2020)
[3] D. Chung et al., *Quantum Science and Technology*, **10**, 3, 035014 (2025)

Development of a Segmented Blade Trap with Laser Ablation Loading of Yb and Ba Ions

K. Kim,[1,2] W. Choi,[1,2] J. Kang,[1,2] J. You,[1,2] and T. Kim[1,2,3]

[1]*Dept. of Computer Science & Engineering, Seoul National University, Seoul, South Korea*

[2]*Automation and Systems Research Institute, NextQuantum, Seoul National University*

[3]*Institute of Computer Technology, Institute of Applied Physics, Seoul National University*

We present the development of a segmented blade trap designed for dual-species ion trapping, targeting quantum computing applications. The segmented electrode architecture provides flexible control over the trapping potential, enabling precise ion manipulation. The electrodes are fabricated from alumina and gold-sputtered to enhance electrical conductivity and surface quality [1]. The trap was assembled with high precision to minimize potential errors and ensure field uniformity. Trap parameters, including stability-q and blade spacing, were optimized through COMSOL simulations to ensure stable confinement [2]. To validate the proper functioning of the segmented trap, we developed a test setup for trapping 174Yb+ ions. We observed ion fluorescence at 369.5 nm and confirmed ion lifetimes exceeding several minutes under Doppler cooling, demonstrating the trap's stability. For ion loading, we implemented a laser ablation technique capable of simultaneously loading ytterbium and barium ions, enhancing both system versatility and efficiency. Instead of using bare barium metal, which readily oxidizes in air, we employed $BaCl_2$ as the target material [3]. We found that $BaCl_2$ maintains sufficient performance even when exposed to high-fluence laser pulses exceeding 5 J/cm^2. Detailed studies of the ablation characteristics were conducted to maximize ion loading rates. We also discuss planned improvements to further enhance system robustness and ion control capabilities.

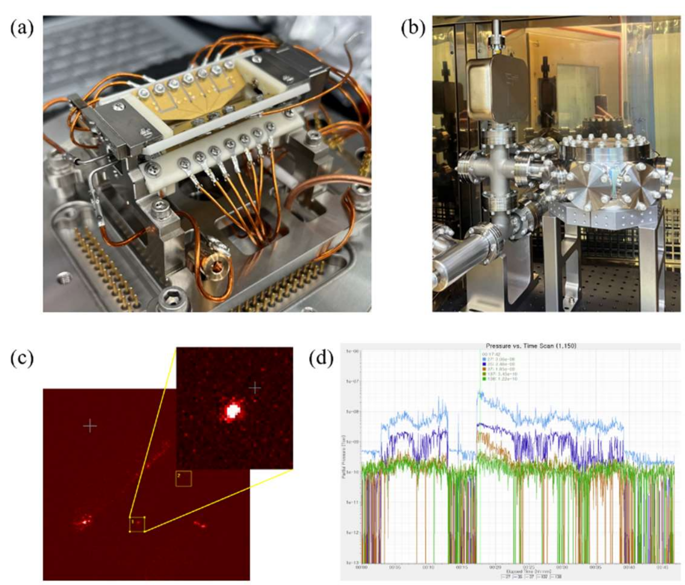


Figure: (a) Segmented blade trap assembly (b) UHV chamber assembly (c) $174Yb^+$ ion fluorescence (d) RGA test of $BaCl_2$ ablation

[1] Hong, J. et al., *Appl. Phys. B* **129**, 16 (2023).
[2] Paul, W., *Rev. Mod. Phys.* **62**, 531 (1990).
[3] Graham, R. D. et al., *AIP Advances* 4, 057124 (2014)

Rack-mounted ion trap with integrated optical cavity

L. Becker,[1] J. Costard,[1] S. Kucera,[1,2], and J. Eschner[1]

[1]*Universität des Saarlandes, Saarbrücken, Germany*

[2]*Luxembourg Institute of Science and Technology, Belveaux, Luxembourg*

Single trapped ions as quantum memories and single photons as quantum information carriers are promising building blocks of quantum networks [1], providing high-fidelity entanglement in controlled single-photon absorption and emission [2]. Ion-photon interfaces are thus well-suited for implementing a quantum repeater that mitigates the propagation loss in direct transmission, and also for connecting quantum processors into a quantum computing network.

We are setting up a multi-segment linear Paul trap for $^{40}Ca^{+}$ ions with an integrated fiber cavity that realizes such an interface with high photon collection and generation efficiency. We are working on two different three-dimensional Paul trap realizations: The ferrule trap design shown in Fig. 1 consists of two laser-machined ceramic ferrules, the other design is a monolithic glass trap fabricated by selective laser etching [3]. Both trap types are metal-coated to create a segmented electrode structure and are equipped with a borehole perpendicular to the trap axis to introduce the sub-mm optical cavity. In a first prototype we integrated a cavity with 220 µm length and 11 000 finesse with a trap of 190 µm electrode separation.

With its compact design, the trap-cavity system including the vacuum chamber, control electronics, ablation and photo-ionization laser, and camera for visual observation will be stored in a single transportable rack. Its implementation will enable quantum repeater protocols [4] over the Saarbrücken fiber link [5].

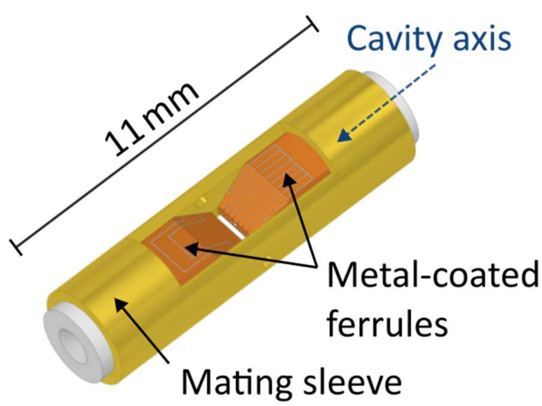


Figure 31: Sketch of the ferrule trap design: The ions are trapped between the two micro-structured and metal-coated ferrules (orange), and the fiber cavity is inserted through their central boreholes.

[1] M. Bock, et al., Nat. Commun. **9**, 1998 (2018).
[2] E. Arenskötter, et al., npj Quantum Inf. **9**, 34 (2023).
[3] https://www.ilt.fraunhofer.de/en/projects-technology-studies/cp_current/cp-iquan.html and https://www.module-qnc.de/en/pilotprojekt-qnc-space-ionenfallen/.
[4] M. Bergerhoff, et al., Phys. Rev. A **110**, 032603 (2024).
[5] S. Kucera, et al., npj Quantum Inf. **10**, 88 (2024).

Towards a nitrogen molecular ion clock for fundamental physics tests

L.J. Blackburn,[1] A.M. Shepherd[1] and M.K. Keller[1]

[1]*University of Sussex, Brighton, United Kingdom*

Many beyond-the-Standard Model theories predict that the fundamental constants may change in time and space. Potential changes in one of those constants, the proton-to-electron mass ratio μ, can be detected by comparing vibrational or rotational transitions in molecules to optical transitions in atoms. In our experiment, a vibrational transition in N_2^+ will be compared to atomic clocks within the QSNET network of quantum sensors [1]. The nitrogen ion will be co-trapped in a linear Paul trap with an auxiliary $^{40}Ca^+$ ion which will be used for ground state cooling and state detection via a quantum logic scheme.

For precision spectroscopy, the nitrogen ion must be prepared in the rovibronic ground state. Resonance-enhanced multiphoton ionisation (REMPI) has been demonstrated to produce nitrogen in this state with a fidelity of >99% [2]. However, simulations show that the high amplitude and inhomogeneous electric fields of the ion trap broaden the ionisation threshold and prevent state-selective loading in many cases. Rapidly switching the trap off during loading may mitigate this to allow state selective loading of the ion trap [3, 4]. In this presentation, I will report on our recent progress on the experiment.

[1] G. Barontini *et al*., EPJ Quantum Technology 9, 12 (2022).
[2] A. Gardner *et al*., Scientific Reports 9, 506 (2019).
[3] L. Blackburn and M. Keller, Scientific Reports 10, 18449 (2020).
[4] L. Blackburn, A. Shepherd and M. Keller, New J. Phys. 27 045001 (2025).

Phase-insensitive sensing with large trapped-ion crystals using spin-dependent squeezing

L.J. Bond,[1,2] C.H. Valahu,[3,4] A. Shankar,[5] T. R. Tan,[3,4] and A. Safavi-Naini[1,2]

[1]*University of Amsterdam, Amsterdam, the Netherlands*

[2]*Qusoft, Amsterdam, the Netherlands*

[3]*University of Sydney, Sydney, Australia*

[3]*ARC Centre of Excellence for Engineered Quantum Systems, Sydney, Australia*

[5]*Indian Institute of Science, Bangalore, India*

Sensing plays a fundamental role in science and technology. Large trapped-ion crystals are particularly well-suited to displacement sensing, due to the sqrt(N) enhancement of the displacement amplitude. We show that spin-dependent bosonic squeezing of N ions can be realized via the first-order sidebands, with a protocol time that scales as 1/sqrt(N). We then show that spin-dependent squeezing can be used for quantum-enhanced phase-insensitive and multi-parameter displacement sensing at the Heisenberg limit. We propose explicit measurement protocols that can be readily implemented in trapped ion platforms. Our work overcomes previous requirements of phase-locking or two-mode squeezing, with applications ranging from fundamental physics to advanced quantum technologies.

Probing new physics with calcium isotope shift measurements using a trapped ion quantum computing platform

L.I. Huber,[1] G.J. Giuli,[1] J. Flannery,[1] R. Matt,[1] M. Stadler, [1] R. Oswald, [1] F. Schmid, [1] D. Kienzler, [1] D.P.L. Aude Craik, [1] and J.P. Home[1]

[1]*ETH Zurich, Zurich, Switzerland*

Precision isotope shift measurements provide the possibility to probe nuclear effects as well as for forces beyond the Standard Model of particle physics. I will describe an improvement in the precision of the isotope shifts of the 729 nm $S_{1/2} \rightarrow D_{5/2}$ transition in the singly charged even calcium isotopes with masses 40, 42, 44, 46, and 48, by a factor of about 100 over previous measurements, using decoherence-free-subspace methods for observing differential shifts at the 50 mHz level. By combining these measurements with results on highly charged ions at PTB Braunschweig and improved mass measurements from MPIK Heidelberg, we obtain a King-plot that reveals a 900σ deviation from linearity [1]. Currently, our ability to use these measurements to rigorously test for beyond-Standard-Model physics is limited by theoretical uncertainty on the nuclear polarization.

I will also present ongoing measurements towards a second set of measurements on the 732 nm $S_{1/2} \rightarrow D_{3/2}$ transition, where we aim for 10 mHz precision. Combination of results on both transitions may allow us to mitigate the nuclear polarization uncertainty and surpass current bounds on a hypothetical beyond-Standard-Model boson that couples the electron to the neutron. Our work takes place in a multi-isotope setup built for quantum computing and demonstrates the use of multi-isotope entanglement and control for precision metrology.

[1] A. Wilzewski, L. I. Huber, M. Door, J. Richter, A. Mariotti et al., arXiv:2412.10277 (2024)

Shell formation and 2D nanofriction in 3D ion Coulomb crystals

L.-A. Rüffert,[1] T. Mehlstäubler,[1,2,3]

[1]*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

[2]*Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany*

[3]*Laboratorium für Nano- und Quantenengineering, Leibniz Universität Hannover, Hannover, Germany*

Friction on the nanoscale governs a wide range of physical and technological phenomena, from energy dissipation in atomic contacts to the performance of nanomechanical devices. As tribological losses contribute significantly to global energy consumption, controlling nanoscale friction is both a fundamental and practical goal. Trapped ion Coulomb crystals offer an ideal platform to study nanofriction under highly controllable conditions, with applications ranging from quantum computing to precision sensing.

These crystals can self-organize into ring- and shell-like structures when confined by a trapping potential. Previously, nanofriction has been studied in 1D and 2D Coulomb crystals by examining the relative motion between adjacent ion chains or rings. Aubry-type transitions from pinning to sliding have been demonstrated experimentally in adjacent ion chains with a topological defect [1,2]. Additionally, the dependence of rotational friction between ionic rings on the ion number has been observed [3]. In all these experiments, the dynamics can be described by 1D nanofriction with 2 chains interacting.

We extend this approach by Investigation of 2D nanofriction between shell structures in 3D ion crystals and analyzing the rotational dynamics of the outer shell in relative to the inner core, using molecular dynamics simulations. We quantify how the effective energy barrier for shell rotation depends on the crystal structure and identify configurations where even small changes in ion number lead to drastic variations in friction. By applying external torques and monitoring the outer shells angular velocity, we map out frictional regimes, including pinned states, stick-slip motion, and smooth sliding.

Our results highlight the strong sensitivity of inter-shell friction to the crystal configuration and open new avenues for tailoring frictional properties in synthetic nanostructures.

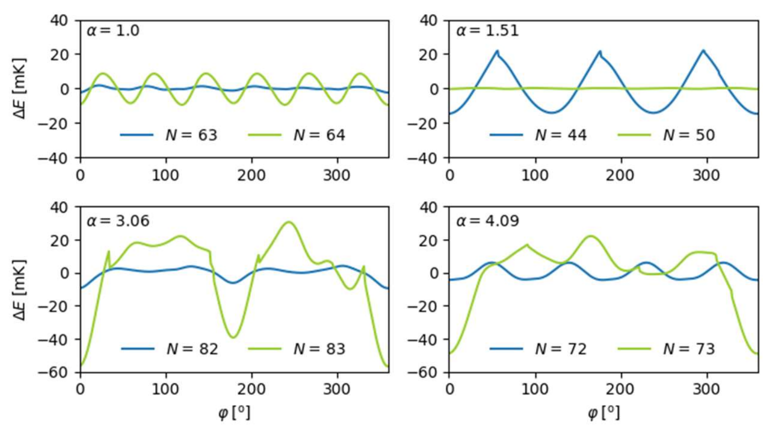


Figure 32: Difference in total potential energy and its mean as a function of the outer shell rotation angle φ

[1] *J. Kiethe et al., Nat Commun 8, 15364 (2017)*
[2] *J. Kiethe et al., New J. Phys. 20, 123017 (2018)*
[3] *L. Duca et al., Phys. Rev. Lett. 131, 083602 (2023)*

Cryogenic setup for experiments with molecular ions

Mai Faibish[1], **Noga Saban**[1], Jacques Piennar[1], and Ziv Meir[1]
[1] *Weizmann Institute of Science, Rehovot, Israel*

Molecular ions offer unique opportunities for quantum-information processing and precision measurements owing to their complex internal structure and long-lived states. We present a cryogenic setup, incorporated with a compact molecular-beam source, designed for quantum control of molecular ions. Using quantum-logic techniques, the molecular ions are to be sympathetically cooled and coherently manipulated via co-trapped atomic ions. A cryogenic environment supports extreme-high vacuum conditions and strongly suppresses blackbody radiation, enabling long interrogation times and compatibility with complex and polar molecules. A key component of our setup is a monolithic design of a Paul trap fabricated by selective laser-induced etching of fused silica. The trap design provides low axial RF penetration and supports deterministic loading of specific ion species [1], making it ideally suited for experiments with complex molecules such as dark-matter searches via correlation-spectroscopy of I_2^+ and Ca^+ [2].

[1] M. J. Zawierucha, T. Rehmert, J. Keller, T. E. Mehlstäubler, P. O. Schmidt, F. Wolf, *Phys. Rev. A* **110**, 013107 (2024).
[2] E. Madge, G. Perez, Z. Meir, Phys. Rev. D 110, 015008 (2024).

An optical atomic clock based on Ni^{12+}

M. Wehrheim,[1] L. J. Spieß,[1] S. Chen,[1] A. Wilzewski,[1] J. R. Crespo López-Urrutia,[1,2] and P. O. Schmidt[1,3]

[1]*Phyisikalisch-Technische Bundesanstalt, Braunschweig, Germany*

[2]*Max-Planck Institut für Kernphysik, Heidelberg, Germany*

[3]*Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany*

Highly charged ion (HCI) optical clocks offer reduced sensitivity to systematic shifts due to the strong binding of the remaining electrons. Furthermore, they feature enhanced QED and relativistic effects allowing for tests of theory and searching for physics beyond the standard model. Our experimental setup is optimized for the production and co-trapping of individual HCI with Be^+ for sympathetic cooling and quantum logic readout. In the past, this approach allowed us to measure frequencies of optical transitions in HCI with uncertainties in the low 10^{-16} range limited by the statistical uncertainty resulting from the ion´s excited state lifetime of ~10 ms [1].

In this work, we present progress towards an HCI clock based on Ni^{12+}, with expected systematic uncertainty at the low 10^{-18} level and reduced instability due to its excited state lifetime of 20 seconds, enabling longer interrogation times. We report on the measurement techniques to identify this forbidden transition [2,3] as well as the first high precision spectroscopy. This paves the way for a new generation of high accuracy optical clocks.

[1] King, S.A., Spieß, L.J., Micke, P. *et al.* An optical atomic clock based on a highly charged ion. *Nature* **611**, 43–47 (2022)
[2] Chen, S., Spieß, L.J. *et al.* Identification of highly forbidden optical transitions in highly charged ions. *Phys Rev Applied* **22**, 054059 (2024)
[3] Cheung, C. *et al.* Finding the ultra-narrow $^3P_2 \rightarrow {}^3P_0$ electric quadrupole transition in Ni^{12+} ion for an optical clock, arXiv:2502.05386

An ion trap quantum processor with integrated ion-photon interface

Maoling Chu, David Kay, Samuel Snowden, Graham Stutter and Matthias Keller

Department of Physics and Astronomy, University of Sussex, Brighton,

BN1 9QH, UK

mc932@sussex.ac.uk

The aim of this project is to build a quantum computing processor with integrated ion-photon interface. It consists of an ion trap with zones for ion loading, QIP and a zone with an integrated optical cavity for enhanced communication. The electrode structure is designed for dual species operation, ion swapping and ion chain splitting. To achieve highly efficient high-fidelity quantum communication between processors, the system is equipped with an integrated cavity, strongly coupling to the trapped ion. To realize this, we designed a chip, which was manufactured using ultrafast laser micromachining (ULM) from a fused silica substrate, and subsequently gold coated. Employing trenches between the electrodes the chip can be metalised without masks. The cavity is formed of fused silica rods instead of optical fibres as has been used previously [1] in order to improve the photon collection efficiency. In previous works, researchers have reported effective photonic entanglement by using high-numerical-aperture lens' to couple two ions' qubits into single-mode optical fibres to attain high rate and fidelity [2]. For our system, we expect significantly higher entanglement rates with high fidelity due to strong coupling operation.

[1] H. Takahashi et al., *Phys. Rev. Lett.*, vol. **124**, p. 013602, (2020).
[2] L. J. Stephenson et al., *Phys. Rev. Lett.*, vol. **124**, p. 110501, (2020).

Coherent control, state preparation and readout of polyatomic molecular ions via quantum logic spectroscopy

Mariano Isaza-Monsalve,[1] Zhenlin Wu,[1] Brandon. J. Furey,[1] Rene Nardi,[1] Tim Duka, [1]Andrea Turci,[1] Miriam Antonia Kautzky, [1] and Philipp Schindler [1]

[1]*University of Innsbruck, Innsbruck, Austria*

Molecular ions offer more degrees of freedom than atomic ions, possibly enabling quantum information mehtods such as quantum error correcting (QEC) schemes that are not available in atomic ions [1]. Full control over molecules at the quantum level can be achieved with quantum logic spectroscopy (QLS). There, co-trapping a molecular ion with an atomic ion facilitates state preparation and readout via the atom. We investigate calcium-based molecules, e.g., CaH^+ or $CaOH^+$, co-trapped with a $^{40}Ca^+$ ion. Coherent control of the rotational state is provided via laser interactions. In particular quantum operations within a rotational manifold can be achieved by stimulated Raman interactions. The goal of our project is to prepare $CaOH^+$ in a well defined rotational state. For this, we perform QLS assisted optical pumping for state preparation, followed by non-demolition measurements of signature transitions that allow us to uniquely determine the rotational state [2]. Our simulations show that the population can get trapped in a Zeeman sub-level during optical pumping when using the usual two-beam Raman interactions. To solve this, we suggest to utilize a third Raman beam to prevent population trapping and subsequently to perform succesful measurement based state initialization. We have developed a comprehensive simulation and Bayesian estimation suite that can be used to select the optimum measurement setting in real time.

[1] Furey, B. J., Wu, Z., Isaza-Monsalve, M., Walser, S., Mattivi, E., Nardi, R., & Schindler, P. (2024). Strategies for implementing quantum error correction in molecular rotation. *Quantum*, *8*, 1578.
[2] Chou, C. W., Collopy, A. L., Kurz, C., Lin, Y., Harding, M. E., Plessow, P. N., ... & Leibrandt, D. R. (2020). Frequency-comb spectroscopy on pure quantum states of a single molecular ion. *Science*, *367*(6485), 1458-1461.

Poster 67

Probing electronic state-dependent conformational changes in a trapped Rydberg ion crystal

M. Mallweger,[1] N. Kuk,[1] V. Shankar,[1] R. Thomm,[1] H. Parke,[1] I. Straka,[1] W. Li,[2] I. Lesanovksy,[2,3] and M. Hennrich[1]

[1]*Stockholm University, Stockholm, Sweden*

[2]*Centre of Mathematics and Theoretical Physics, University Nottingham, United Kingdom*

[2]*Institut für Theoretische Physik, University Tübingen, Germany*

Trapped ions excited to Rydberg states harness two advantages: a well-defined confinement through the charge of the ion and extreme scaling of physical properties with the principal quantum number. While for the ions' ground state the polarizability is negligible, it increases as $\propto n^7$ for Rydberg ions, leading to a change in radial confinement during Rydberg excitation. For a three-ion crystal, this change can be sufficient to induce a conformational change from a linear configuration in the lower-lying electronic states to a zigzag configuration in the Rydberg state. This process creates a strong coupling between electronic and vibrational degrees of freedom. Rydberg excitation thus enables a novel method for studying molecular phenomena with a system of ions in the well-isolated environment of a Paul trap. We present the first experimental realization of such an electronic state-dependent conformational change and spectroscopically investigate the phenomena. We furthermore show that we can tune the conformational change by controlling the ion's polarizability through dressing of two different Rydberg manifolds.

Studies on electron-ion interactions in ion traps

M. Piwiński,[1] Ł. Kłosowski

[1]*Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, Grudziadzka 5, 87-100 Toruń, Poland*

The electron collision experiments are significant data sources on the structure of atoms and molecules. Such studies usually involve bombarding the selected target with a beam of electrons and detecting the non-scattered electrons (transmission methods) or scattered electrons (crossed beams technique). Cross-fired or cell experiments are relatively simple for the neutral target. However, the situation becomes more complicated considering the electron impact on ions. It is generally difficult to provide a beam of ions of sufficiently well-defined geometry and density, allowing the detection of scattered electrons with good statistics. These are the main reasons there is only a small amount of experimental data on electron collisions with singly charged ions, even though there are several theoretical datasets, e.g. for calcium ion ionisation [1–4]. Moreover, such data are interesting for observing autoionising processes, which play a significant role in specific energies.

The new version of the cross-section experimental apparatus is presented, where an ion trap was used as a container for target ions. In this case, the target is detected instead of the projectile (electron), which can be achieved using optical methods similar to depletion spectroscopy [5]. Cross-section data are typically presented as a function of electron energy, so precise control of energy and geometry of the monochromatic electron beam is crucial for the quality of the obtained data. Therefore, the system was optimised to reduce electrons' energy spread and increase the accuracy of measurements.

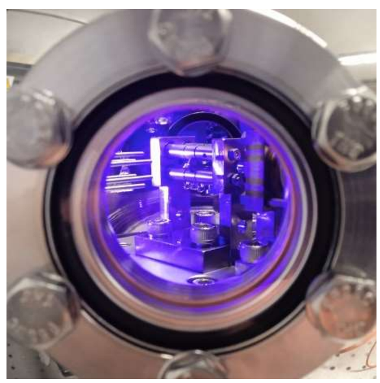


Figure 33: The vacuum chamber containing an ion trap with an integrated monochromatic electron gun.

[1] P.G. Burke, A.E. Kingston, A. Thompson, Electron impact ionisation of Ca^+, *J.Phys. B: At. Mol. Phys.* 16 (13) (1983) L385–L389

[2] D.C. Griffin, M.S. Pindzola, C. Bottcher, Calculations of the contributions of excitation-autoionisation to the electron impact ionisation of Ca^+ and Ba^+ in the distorted-wave approximation, *J.Phys. B: At. Mol. Phys.* 17 (15) (1984) 3183–3191

[3] M.S. Pindzola, C. Bottcher, D.C. Griffin, Indirect processes in the electron impact ionisation of Ca^+ using an LS-term-dependent close-coupling method, *J.Phys. B: At. Mol. Phys.* 20 (14) (1987) 3535–3545.

[4] N.R. Badnell, D.C. Griffin, M.S. Pindzola, Electron impact ionization of Ca^+, *J.Phys. B: At. Mol. Opt. Phys.* 24 (11) (1991) L275

[5] Ł. Kłosowski, M. Piwiński, Experimental method for determination of the integral cross-section for electron impact ionization of ions with optical control of the target's initial quantum state, *J.Electron. Spectrosc. Relat.* Vol. 260, 147239 (2022), p. 1-8

Non-linear Manipulation of a Quantum Oscillator: Herding Multi-Headed Schrödinger Cats

M. Mazzanti,[1] M. Simoni,[1] I. Rojkov,[1] Y. Cui,[1] K. Hanke,[1] W. Adamczyk,[1] A. Ferk,[1] P. Hrmo,[1] S. Jain,[1] T. Sägesser,[1] D. Kienzler,[1] and J.P. Home[1]

[1]*Institute for Quantum Electronics, ETH Zürich, Otto-Stern-Weg 1, 8093 Zürich, Switzerland*

Quantum harmonic oscillators play an important role in quantum technologies, from quantum error correction to precision sensing [1-4]. In particular, non-Gaussian states of oscillators form the basis of bosonic error correction codes, which exploit the infinite-dimensional Hilbert space to redundantly encode quantum information with relatively low hardware overhead [5]. Two main classes of bosonic codes are translation-symmetric and rotation-symmetric codes, represented by the Gottesman-Kitaev-Preskill (GKP) [6] and cat codes [7], respectively. While GKP codes can correct translations, cat codes and their generalizations are better suited for rotations such as those produced by motional frequency dephasing [8].

I will describe our proposal and experimental realization, in a microfabricated Penning trap, of methods for producing and manipulating multi-headed Schrödinger cat manifolds using non-linearities in the light-matter interaction that arise when working outside the Lamb-Dicke regime. We use these to perform Nonlinear Reservoir Engineering [9], utilizing stable points in the non-linear interaction to realize steady-states with two, three, four and five coherent-state components. We then further select suitable high-order sidebands to perform state measurements and purify the resulting states.

To our knowledge, this is the first use of such high-order non-linear processes in a trapped-ion system, providing a new route to rotation-symmetric bosonic codes as well as a toolbox for quantum state engineering and control, with applications in bosonic error correction, quantum computing, and metrology.

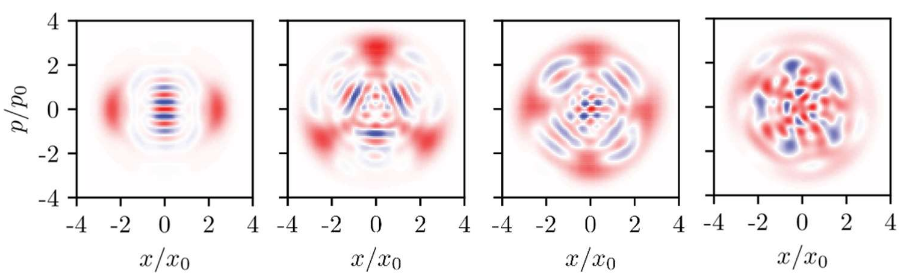


Figure 34: Wigner functions of two-, three-, four- and five-headed cat states.

[1] C. Flühmann et al., *Nature 566, 513–517* (2019).
[2] P. Campagne-Ibarcq et al., *Nature 584, 368–372* (2020).
[3] F. Wolf et al., *Nature Communications, 10, 2929* (2019)
[4] K. A. Gilmore et al., *Science 373,673-678* (2021).
[5] S. Lloyd et al., *Phys. Rev. Lett. 82,* (1999).
[6] D. Gottesman et al., *Phys. Rev. A 64, 012310* (2001).
[7] P.T.Cochrane et al., *Phys. Rev. A 59, 2631* (1999).
[8] K. Noh et al., *Phys. Rev. Lett. 125, 080503* (2020).
[9] I. Rojkov et al., *arXiv:2407.18087* (2024).

ASICs for ion traps

M.F. Brandl,[1] M. Abu Zahra,[1,2] L. Dixius,[1,2] F. Anmasser,[3,4] M. Hartmann,[2] and J. Repp[1]

[1]*Infineon Technologies AG, Neubiberg, Germany*

[2]*Technical University of Munich, Munich, Germany*

[3]*Infineon Technologies Austria AG, Villach, Austria*

[4]*University of Innsbruck, Innsbruck, Austria*

At Infineon, we are working on application specific integrated circuits (ASICs) for ion traps. The main application of these ASICs is to scale up the control to large ion traps for applications like quantum computing or atomic clocks. Often, the ASICs are switching matrices, which enable the control of many DC segments of the ion traps with few input voltages, e.g. DAC channels. From a circuit design perspective, a major problem is charge injection, which causes voltage spikes on the segments whenever a segment is connected to or disconnected from a DAC. Uncompensated, these spikes are so high that they may kick ions out of the ion trap. Therefore, our circuit design focuses on minimal charge injection. For cryogenic operation, another problem arises. Transistors in ICs that can withstand ±10 V or more are typically LDMOS (laterally-diffused metal-oxide semiconductor). At cryogenic temperatures of 50 K or lower, a non-linearity of the on-state resistance starts to appear which increases the differential resistance for low drain-source voltages by multiple orders of magnitude. Therefore, we are analyzing the behavior [1] to develop new types of LDMOS that stay linear at cryogenic operation. With high voltage MOSFETs available at room temperature and at cryogenics, switching matrices with digital control are developed. The first cryogenic version has been tested with ions in the lab in Villach, Austria. In funding projects, we are developing a room temperature switching matrix for the Ospelkaus group in Hannover and a cryogenic switching matrix for the Wunderlich group in Siegen. Furthermore, we are partnering with the Issakov group at TU Braunschweig for cryogenic DACs [2].

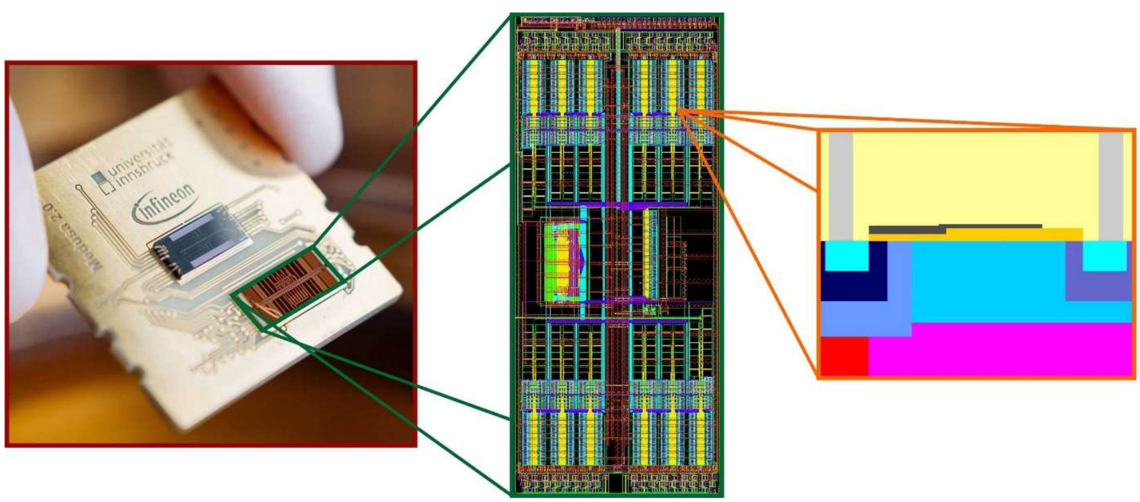


Figure 35: Different layers of electronics for ion traps. Left: QPU level with switching matrix and ion trap, middle: circuit design with GDS of layout, right: single transistor level

[1] M. Abu Zahra et al., *2024 International Semiconductor Conference (CAS)*, pp. 181–184 (2024)
[2] A. Meyer et al., *2024 IEEE European Solid-State Electronics Research Conference (ESSERC)*, pp. 484–487 (2024)

A portable optical atomic clock based on a single $^{40}Ca^{+}$-ion

M. Keller,[1] X. Fernandez-Gonzalvo,[1] T. Bierrum[1]

[1]*University of Sussex, Brighton, UK*

Atomic clocks are ubiquitous in daily life with their applications in navigation and timing, telecom and utility networks, security and defense, and research. The development of new atomic clock systems that are outperforming existing commercial systems is set to improve existing applications as well as enable new ones.

At Sussex we are developing a compact optical atomic clock system based on single trapped calcium ions. The system is designed to be compact and robust to enable its use outside a research lab environment. The system comprises a fibre coupled ion trap, a compact clock laser modules, an all-fibre auxiliary laser system and a compact control electronic system. The ion trap system is a end-cap style trap within a compact vacuum system and a fibre coupled optics assembly. The optics assembly delivers all the required laser light to the ion and collects the ion's fluorescence. The all-fibre coupled design makes is very compact and robust against vibrations and temperature changes. The clock laser system is based on a force-insensitive ULE cavity within in a shielded and temperature controlled vacuum enclosure and a ultra-compact laser modules with integrated feedback electronics. The auxiliary laser system contains all lasers required to photoionise, cool and repump the ion as well as all optical elements to frequency control and switch the lasers as well as generating all laser outputs required for the clock operation. It also contains low noise laser drivers. Finally, the control system provides control over the laser system, the ion trap and clock measurement protocol as well as environmental parameter logging.

We have successfully trapped ions in the compact ion trap using the auxiliary system and control electronics, and the clock laser system is working.

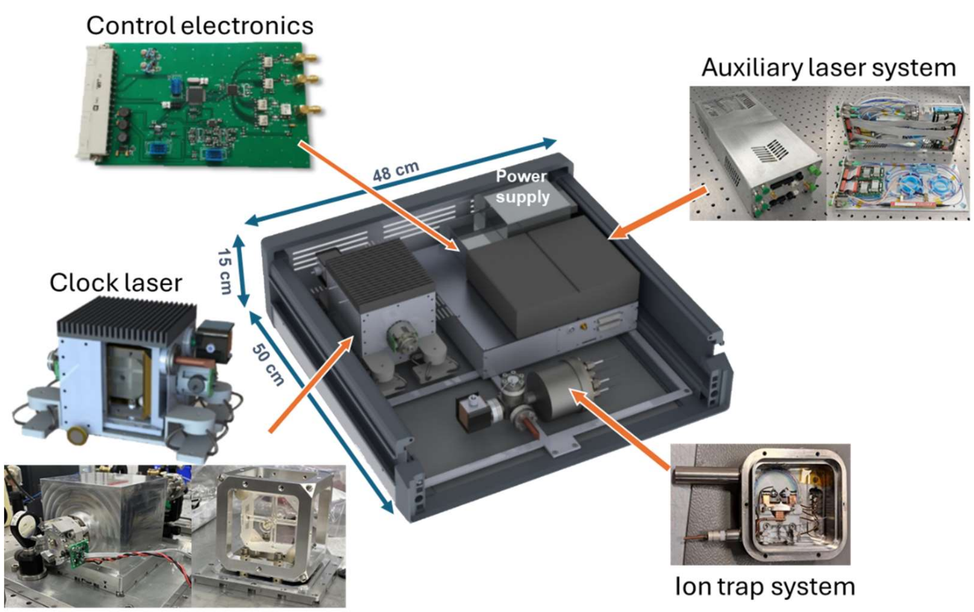


Figure 36: Portable atomic clock system and its sub-systems

Engineering continuous-variable entanglement in mechanical oscillators with optimal control

Maverick J. Millican,[1, 2, 3] Vassili G. Matsos,[1, 2] Christophe H. Valahu,[1, 2, 3]

Tomas Navickas,[1, 2] Liam J. Bond,[4, 5] and Ting Rei Tan[1, 2, 3, †]

† tingrei.tan@sydney.edu.au

[1] *School of Physics, University of Sydney, NSW 2006, Australia*

[2] *ARC Centre of Excellence for Engineered Quantum Systems, University of Sydney*

[3] *Sydney Nano Institute, University of Sydney*

[4] *Institute of Physics, University of Amsterdam, Science Park 904, the Netherlands*

[5] *QuSoft, Science Park 123, 1098 XG Amsterdam, the Netherlands*

We demonstrate an optimal quantum control strategy for the deterministic preparation of entangled harmonic oscillator states in trapped ions. The protocol employs dynamical phase modulation of laser-driven Jaynes-Cummings and anti-Jaynes-Cummings interactions. We prepare Two-Mode Squeezed Vacuum (TMSV) states in the mechanical motions of a trapped ion and characterize the states with phase-space tomography. First, we verify continuous-variable entanglement by measuring an Einstein-Podolsky-Rosen entanglement parameter of 0.0132(7), which is below the threshold of 0.25 for Reid's EPR criterion. Second, we perform a continuous-variable Bell test and find a violation of the Clauser-Horne-Shimony-Holt inequality, measuring 2.26(3), which is above the entanglement threshold of 2. We also demonstrate the flexibility of our method by preparing a non-Gaussian entangled oscillator state–a superposition of TMSV states.

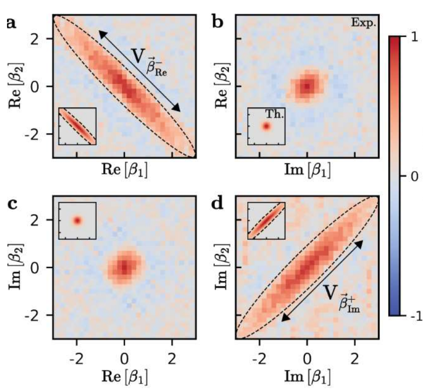


Figure 1. *Experimental characteristic function tomography of a two-mode squeezed vacuum (TMSV) state with target squeezing parameter, $r = 1$. All panels show the real component of the two-mode characteristic function, $Re[\chi(\beta_1, \beta_2)]$. Panels **a.** and **d.** exhibit anticorrelation and correlation, respectively, consistent with two-mode squeezing. Dashed lines plot the Gaussian functions that are fitted to the data, from which the variances $V_{\vec{\beta}^-_{Re}}$ and $V_{\vec{\beta}^+_{Im}}$ are extracted and used to quantify entanglement with Reid's EPR criterion. Panels **b.** and **c.** show negligible correlation, consistent with uncorrelated orthogonal quadratures. Insets show the theoretical target characteristic function obtained from numerical simulations.*

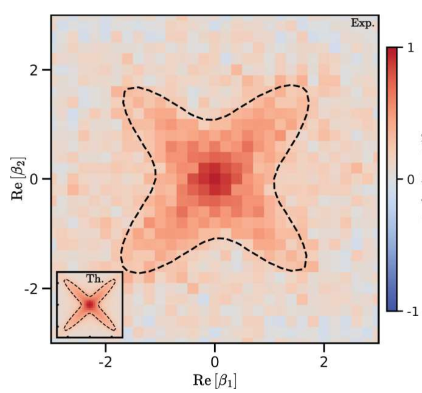


Figure 2. *Joint characteristic function reconstruction of an experimentally prepared superposition of TMSV states. The targeted state is an even superposition of two TMSV states, with squeezing parameter, $r = 1$. The experimentally reconstructed characteristic function, $\mathrm{Re}\,[\chi(\mathrm{Re}[\beta_1], \mathrm{Re}[\beta_2])]$, shows features of the superposition state, with correlation along both axes, $(\beta, \pm\beta)$. The characteristic function is fitted to a distinct sum of two two-dimensional Gaussian functions (dashed lines) to estimate the relative amplitudes and squeezing. Inset shows the theoretical target characteristic function obtained from numerical simulations.*

[1] https://arxiv.org/abs/2505.20844

A multi-ion optical clock with a systematic uncertainty below 1×10^{-18}

M. Filzinger,[1] M. Steinel,[1] J. Jian,[1] D. Bennett,[1] T.E. Mehlstäubler,[1,2] E. Peik,[1] and N. Huntemann[1]

[1]*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

[2]*Leibnitz Universität Hannover, Hannover, Germany*

Optical clocks based on trapped ions can realize unperturbed transition frequencies with fractional systematic uncertainties at and even below the 10^{-18}-level [1]. When interrogating a single ion, quantum projection noise typically makes long averaging times necessary to achieve corresponding low statistical uncertainties. Scaling up to multiple ions promises a reduced measurement time, however controlling frequency shifts across many ions can be challenging. So far, multi-ion clock operation has only been reported with up to four clock ions [2,3].

Here, we present a new optical clock based on the $^2S_{1/2}$ - $^2D_{5/2}$ transition in $^{88}Sr^+$ with a fractional systematic uncertainty below 1×10^{-18}. Despite the transition's strong sensitivity to external fields, we control shift effects not only for a single ion but also for linear ion chains and routinely operate the clock with up to 10 ions.

$^{88}Sr^+$ ions are trapped in a linear, segmented Paul trap based on the design in [4]. The clock transition is split into ten first-order Zeeman sensitive components in a 3 µT external magnetic field. We employ a clock sequence based on the $m_J=\pm1/2\rightarrow m_J=\pm3/2$ and $m_J=\pm1/2\rightarrow m_J=\pm5/2$ Zeeman pairs and construct a clock output that is free of the linear Zeeman shift and, with appropriate weights, tensorial shifts [2]. We use 250 ms and 100 ms long Rabi interrogation of each transition in the respective Zeeman pairs, limited by magnetic field noise.

Chains of ions are homogeneously prepared and interrogated with laser light: For state preparation and readout we use elliptical laser beams, while interrogation of the clock transition is performed with a beam propagating along the ion chain. We obtain ion-resolved information by implementing camera-based state detection into our experimental control sequence. This allows us to investigate and control shift effects that vary along the ion chain, such as those due to a magnetic field gradient and varying electric field gradients from ion-ion Coulomb repulsion.

An optical clock comparison between the new system and an established single-ion clock based on the $^2S_{1/2}$ - $^2F_{7/2}$ transition in $^{171}Yb^+$ yields consistent results between the Sr^+ clock operating with either a single or up to 10 ions. For the frequency ratio, we achieve a statistical uncertainty below 1×10^{-18} and a systematic uncertainty of 3×10^{-18}, limited by that of the Yb^+ clock [5].

[1] M.C. Marshall et al., arXiv:2504.13071 (2025).
[2] M. Steinel et al., Phys. Rev. Lett. **131**, 083002 (2023).
[3] H. N. Hausser et al., Phys. Rev. Lett. **134**, 023201 (2025).
[4] J. Keller et al., Phys. Rev. A **99**, 013405 (2019).
[5] C. Sanner et al., Nature **567**, 7747 (2019).

Cryogenic apparatus for quantum logic spectroscopy of polyatomic molecular ions

M. Popov,[1] P. Paliwal,[1] N. Sunil Kumar,[1] and S. Willitsch[1]

[1]*University of Basel, Basel, Switzerland*

Due to the complexity of their internal energy level structure, controlling molecules' internal states presents a significant challenge. Most molecular ions lack closed optical cycling transitions, which prevents standard state preparation and detection techniques routinely exploited in the atomic community, as well as direct laser cooling techniques. These challenges were recently tackled for some diatomic molecules employing quantum logic spectroscopy techniques (QLS) [1-3]. Unlike diatomic species, polyatomic ones exhibit new properties such as isomerism, chirality, and parity doublet states, which may be utilized in tests of fundamental physical theories [4].

We aim to extend QLS methods to polyatomic molecular ions. Our approach involves the state preparation of molecular ions using a resonant-enhanced multiphoton photoionization technique [5]. The state-prepared molecular ion is trapped and sympathetically cooled inside a crystal of laser-cooled Ca ions. The state of the molecular ion is then detected using a single co-trapped Ca ion by exerting a state-dependent off-resonant optical dipole force on the molecule and reading out the resulting motional excitation of the ion crystal.

Here we discuss the progress in the construction and initial characterization of a cryogenic ion trapping setup, which will be used for trapping and QLS of polyatomic molecular ions, as well as for cold chemistry and collision studies on a state-to-state level.

[1] M. Sinhal et al., *Science* **367**, 1213 (2020).
[2] F. Wolf et al., *Nature* **530**, 457 (2016).
[3] C.-W. Chou et al., *Nature* **545**, 203 (2017).
[4] L. Anderegg et al., *Science* **382**, 665 (2023).
[5] X. Tong et al., *Phys. Rev. Lett.* **105**, 143001 (2010).

High-fidelity quantum logic state detection of single trapped molecular ions

M. Roguski,[1] A. Shlykov,[1] R. Karl,[1] M. Diouf,[1] U. Joshi,[1] Z. Meir[2] and S. Willitsch[1]

[1] *University of Basel, Basel, Switzerland*
[2] *Weizmann Institute of Science, Rehovot, Israel*

Quantum-logic protocols have emerged as an important tool for characterization of trapped atomic and molecular ions with complex energy-level structure. In such schemes, the internal state of the target ion is mapped onto a state of a co-trapped logic ion with accessible transitions, typically via shared motional modes.

Here, we report on quantum-logic state detection of N_2^+ with 99.99% fidelity for as few as nine experimental repetitions - an order-of-magnitude improvement over our previous results [1]. By combining experiments and simulations, we identify the fidelity-limiting role of the population in motional modes not directly involved in the state readout and associate it with Debye-Waller effects. The enhanced detection fidelity reduces the experimental duty cycle and improves sensitivity towards higher molecular states that could be potentially identified under similar experimental conditions.

Our current efforts focus on precision spectroscopy and coherent manipulation of single N_2^+ molecules, which can be used to test fundamental and beyond-standard-model theories, develop THz-range molecular clocks, and investigate state-resolved single-molecule collisions.

[1] Sinhal et al., *Science* **367**, 1213–1218 (2020).

Single-qubit gates with errors at the 10^{-7} level

M.C. Smith,[1] A.D. Leu,[1] K. Miyanishi,[1,2] M.F. Gely,[1] and D.M. Lucas[1]

[1]*Clarendon Laboratory, Department of Physics, University of Oxford*

[2]*Center for Quantum Information and Quantum Biology, Osaka University*

We report the achievement of single-qubit gates with sub-part-per-million error rates, in a trapped-ion $^{43}Ca^{+}$ hyperfine clock qubit [1]. We explore the speed/fidelity trade-off for gate times $4.4 \leq t_g \leq 35$ μs, and benchmark a minimum error per Clifford gate of $1.5(4) \times 10^{-7}$. Calibration errors are suppressed to $< 10^{-8}$, leaving qubit decoherence ($T_2 \approx 70$ s), leakage, and measurement as the dominant error contributions. The ion is held above a microfabricated surface-electrode trap which incorporates a chip-integrated microwave resonator for electronic qubit control; the trap is operated at room temperature without magnetic shielding.

[1] M.C. Smith et al., *arXiv*, 2412.04421 (2025).

Micromotion-enhanced fast gates in experimentally realizable regimes

Phoebe Grosser[1], Zain Mehdi[1], Varun Vaidya[2], Haonan Liu[2], **Monica Gutierrez Galan**[2], Joseph Hope[1], Ricardo Viteri[2]

[1]*The Australian National University*
[2]*IonQ*

A predominant challenge in realizing near-future trapped-ion quantum computers is the implementation of entangling gate operations that enable scalable quantum information processing, while maintaining both high fidelity and speed. Current approaches to trapped-ion entangling gates are based on adiabatic transitions, which scale poorly with the number of ions. A promising alternative is offered by so-called 'fast gates', which utilize carefully-designed impulsive excitations with broadband laser pulses to rapidly entangle qubits. Previous studies significantly constrained fast gate design to reduce the computational complexity of micromotion, and consequently required unrealistic experimental parameters to be realized.

The work presented in this poster removes the limitations of these previous studies and demonstrate that this enhancement allows fast gates in the presence of micromotion to be designed with fidelities above the fault-tolerant threshold required for error-correction (99.9%), with feasible laser repetition rates (100 MHz – 1 GHz), and low pulse numbers (~40). Pulse imperfections are the limiting error that inhibits the experimental realization of fast gates, and here we show a reduction in the number of pulses required through a micromotion enhancement

An optical cavity for two-dimensional crystals of ions

N. Mizukami,[1,2] G. Gatta,[2,3] A. K. Parameswaran,[1,2,4] D. Duca,[1,2] and C. Sias[1,2]

[1] *INRiM, Strada delle Cacce 91, 10135 Torino, Italy*

[2] *LENS, Via Nello Carrara 1, 50019 Sesto Fiorentino FI, Italy*

[3] *Universit`a degli Studi di Firenze, Via G. Sansone 1, 50019 Sesto Fiorentino FI, Italy*

[4] *Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Italy*

Trapped ions are an ideal platform for quantum simulation of mesoscopic systems due to their detection and control at the single particle level. In particular two-dimensional crystals of ions exhibit rotation and structural transition depending on the trap anisotropy. To investigate these features, we have developed a linear Paul trap that can create a two-dimensional pseudo potential. In our previous work, we have observed two-dimensional crystals of ions exhibit orientational melting, in which ions are delocalized only in a rotational degree of freedom due to a thermal fluctuation [1]. To study these features in the quantum regime, excess micromotion originating from the RF field of a Paul trap limits the temperature to which ions can reach. To overcome this obstacle, we are developing an electro-optical trap which uses an optical dipole force instead of an RF field to trap ions [2]. To create an optical dipole force, we have developed a bow-tie cavity which finesse is measured to be more than 10,000 in vacuum. At the center of the cavity, the two crossing beams interfere and create two-dimensional anti-nodes of optical intensity. In addition to trapping ions, the optical cavity can also be used to study cavity QED coupling the whole two-dimensional crystal of ions. At the presentation, the latest results of our research will be shown.

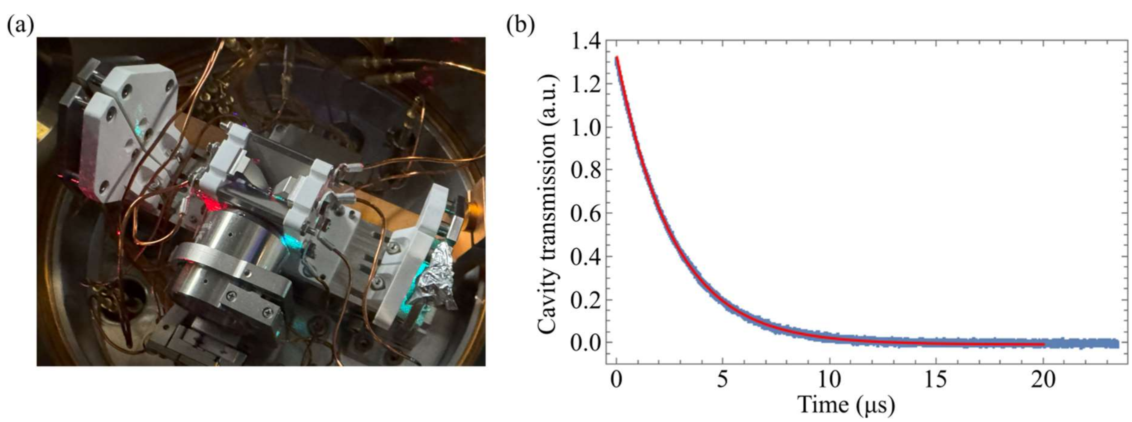


Figure 37: (a) An optical cavity overlapped with a Paul trap. (b) Transmission signal during a ring-down measurement.

[2] L. Duca, N. Mizukami, E. Perego, M. Inguscio, C. Sias, Phys. Rev. Let. 131 083602 (2023).
[3] E. Perego, L. Duca, and C. Sias, Applied Sciences 10 (2020).

Poster 79

Towards a Cryogenic Quantum Processor Based on Rydberg Ions

N. Kuk,[1] M. Mallweger,[1] V.Shankar,[1] S. Schey,[1,2] I. Straka,[1] R. Thomm[1] and M. Hennrich[1]

[1]Stockholm University, Stockholm, Sweden
[2]Infineon Technologies Austria, Villach, Austria

Trapped ions are one of the most successful quantum computing platforms, though not without technological challenges. These include scaling the number of qubits, improving qubit control, and increasing the gate speed. One way to address the latter is to use quantum gates based on Rydberg ions, which can operate in sub-microsecond durations due to their strong dipole-dipole interactions [1].
In our experiment, we are developing a system to confine Rydberg ions using a microfabricated surface trap, in contrast to previous Rydberg ion experiments that utilized macroscopic Paul traps. Furthermore, to mitigate the effects of black-body radiation, which causes the double ionization of Rydberg states with a high principal quantum number, we bring the trap into a cryogenic environment. This setup provides a state-of-the-art experimental platform for Rydberg ion research.
We will present key aspects of the experimental setup, including the mechanical, thermal, and optical designs in order to achieve high numerical aperture laser focusing and imaging at cryogenic temperature. Additionally, we will outline the future directions of the experiment, such as quantifying the influence of black-body radiation on Rydberg ion lifetimes and implementing of novel fast-gate protocols [2].

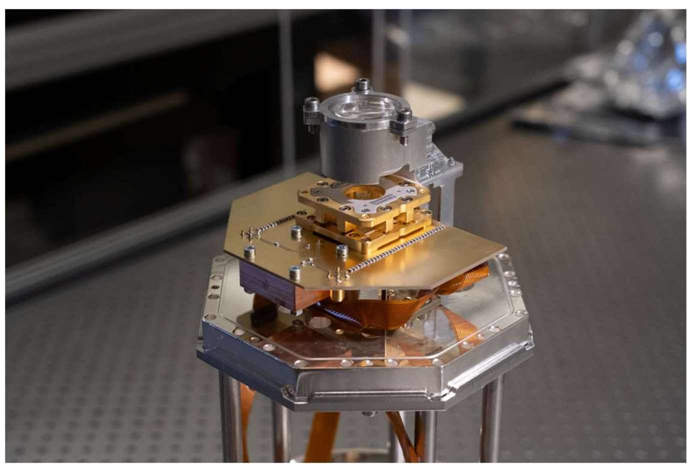


Figure 1: Experimental assembly at an early stage. Photo taken by Simon Schey.

[1] Zhang, C. *et al.* Submicrosecond entangling gate between trapped ions via Rydberg interaction. *Nature* **580**, 345–349 (2020).
[2] Wilkinson, J. *et al.* Two-qubit gate protocols with microwave-dressed Rydberg ions in a linear Paul Trap. *New Journal of Physics*, *27*(6), 064502 (2025).

Poster 80

Optical tweezers for trapped ion quantum simulations

Nella Diepeveen[1], R. X. Schüssler[1], M. Mazzanti[1], C. R. Pereira[1], B. Gerritsen[1], Z.E.D. Ackerman[1], L.P.H. Gallagher[1], A. Safavi-Naini[2], and R. Gerritsma[1]

[1]*Van der Waals-Zeeman Institute,*

Institute of Physics, University of Amsterdam,

Science Park 904, 1098 XH Amsterdam, The Netherlands

[2]*QuSoft, Science Park 123, 1098 XG Amsterdam, The Netherlands*

Quantum simulation provides insight into the dynamics of complicated systems through the use of more controllable ones. We plan to combine 2-dimensional Yb^+ ion crystals in a Paul trap with optical tweezers to create a novel platform for quantum simulations [1, 2]. The hyperfine splitting of the ground state of the ions is used as a qubit, and the interactions between the qubits are mediated by the phonon modes in the ion crystal [3]. Optical tweezers provide an additional trapping potential which changes the phonon mode spectrum of the crystal, expanding the range of accessible Hamiltonians [4, 5]. We present experimental work demonstrating an optimization routine for resonant tweezers using a spatial light modulator (SLM) [6]. We find this offers a fast and robust method for alignment on the ions. We further analyze the beam profile and observe coherent population trapping of the ion states. Lastly, we present our on-going efforts in aligning and optimizing a high power, off-resonant tweezer. This will be used to create a deep trapping potential while minimizing photon scattering for quantum simulation.

[1] J.D. Espinoza, Phys. Rev. A 104, 013302 (2021)
[2] P. Richerme, Phys. Rev. A 94, 032320 (2016).
[3] K. Kim et al, Phys. Rev. Lett. 103, 120502 (2009)
[4] L. Bond, Phys. Rev. A 106, 042612 (2022)
[5] M. Mazzanti et al., Phys. Rev. Lett. 127, 260502 (2021)
[6] M. Mazzanti et al., Phys. Rev. A 110, 043105 (2024)

Poster 81

High-resolution spectroscopy of $^{173}Yb^+$ ions

J. Jiang,[1] A. V. Viatkina,[1,2] S. JK,[1] M. Filzinger,[1] M. Steinel,[1] B. Lipphardt,[1] E. Peik,[1] S.G. Porsev,[3] M.S. Safronova,[3] A. Surzhykov,[1,2] **N. Huntemann[1]**

[1] *Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

[2] *TU Braunschweig, Braunschweig, Germany*

[3] *University of Delaware, Newark, USA*

Trapped Yb^+ ions of different isotopes have been employed in various fields of AMO physics, including atomic clocks [1], quantum simulation and quantum information processing [2], and searches for new physics effects [3]. Compared with other isotopes, $^{173}Yb^+$ is a particularly promising candidate for expanding and improving existing research activities because of its large nuclear spin of I = 5/2, which gives rise to hyperfine mixing, quantum states with high multiplicity, and higher-order nuclear moments.

Optical clocks based on the $^2S_{1/2} \rightarrow {}^2F_{7/2}$ electric octupole transition in $^{171}Yb^+$ (I = 1/2) are among the most accurate clocks today. The weak coupling on this transition results in a yearslong lifetime of the excited state [4] and causes significant light shifts from the probe laser during laser excitation, typically larger than the Rabi frequency. To avoid these shifts in clock operation, specifically tailored interrogation schemes need to be employed.

Theoretical predictions have promised this experimental complexity to be reduced for $^{173}Yb^+$, for which hyperfine interaction should increase the coupling by up to two orders of magnitude [5]. Even though promising, high-precision spectroscopy of $^{173}Yb^+$ has been impeded so far by its more complex atomic structure. We present our approaches to overcome challenges in laser cooling and state preparation of a single $^{173}Yb^+$ ion. We also report on preliminary results from high precision spectroscopy of the 3 lowest-lying states $^2S_{1/2}$, $^2D_{3/2}$ and $^2F_{7/2}$, providing information on their hyperfine structures as well as the frequencies and coupling strengths for the $^2S_{1/2} \rightarrow {}^2D_{3/2}$ and $^2S_{1/2} \rightarrow {}^2F_{7/2}$ transitions. This data is compared with theoretical predictions and can help to improve knowledge on the structure of the Yb^+ nuclei.

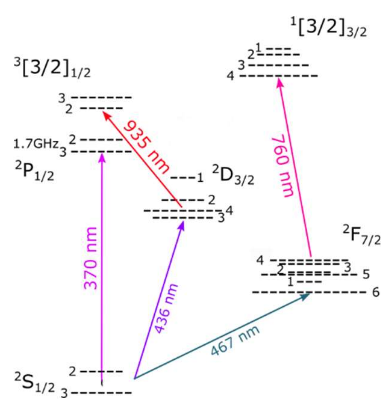


Figure 38: Partial level scheme of $^{173}Yb^+$.

[1] C. Sanner et al., *Nature* **567**, 204 (2019).
[2] S. A. Guo et al., *Nature* **630**, 613 (2024).
[3] M. Filzinger et al., *Phys. Rev. Lett.* **130**, 253001 (2023).
[4] R. Lange et al., *Phys. Rev. Lett.* **127**, 213001 (2021).
[5] V. A. Dzuba et al., *Phys. Rev. A* **93**, 052517 (2016).

Progress for the fused silica surface trap in BAQIS

Pengfei Wang,[1] Xuan fan,[2] Yuan Chai[3], Wenhan Hua,[2] Honghua Fang[3], Hongbo Sun[3] and Kihwan Kim[1,2]

[1]*Beijing Academy of Quantum Information Sciences, Beijing, China.*

[2]*State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics,*

Tsinghua University, Beijing, China.

[3]*State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instrument, Tsinghua University, Beijing, China.*

As one of the leading approaches for scaling up ion trap systems, QCCD (quantum charge-coupled device) performance highly depends on chip fabrication technology. Traditional silicon-based semiconductor manufacturing processes are relatively time-consuming and require extensive, expensive hardware. At BAQIS (Beijing Academy of Quantum Information Sciences), we developed a surface ion trap fabricated from fused silica for QCCD applications. which offers a more cost-effective and simpler fabrication process (laser directly writing - wet chemical etching - gold coating). fused silica also exhibits lower RF signal absorption, and consequently reduces ion heating. Using this new trap design, we successfully trapped both Yb^{+} and Ba^{+} ions and applied the Ba^{+} quadrupole transition at 1762 nm. Characterization of heating rates and other performance metrics is currently underway.

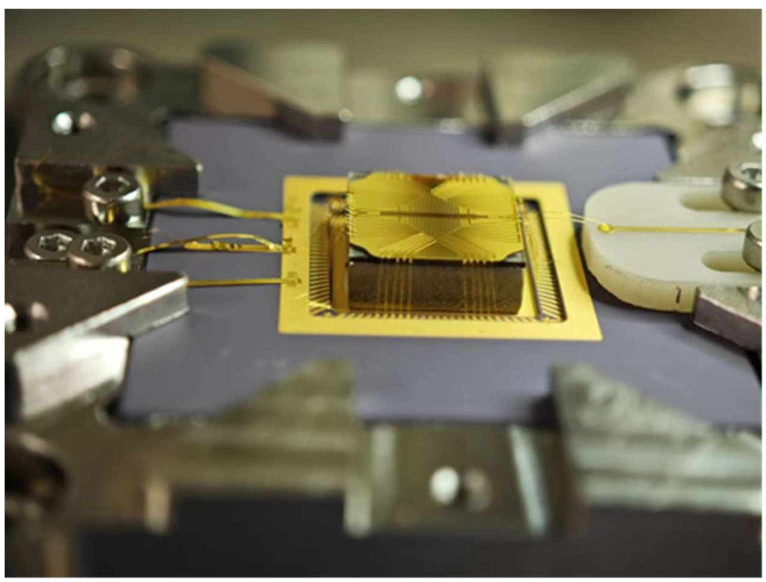


Figure 39: The surface Ion trap made from fused silica.

Nonlocality wins: Experimental Quantum Advantage in the Odd-Cycle Game

P. Drmota,[1] D. Main,[1] E.M. Ainley,[1] A. Agrawal,[1] G. Araneda,[1] D.P. Nadlinger,[1] B.C. Nichol,[1] R. Srinivas,[1] A. Cabello,[2,3] and D.M. Lucas[1]

[1]*Clarendon Laboratory, University of Oxford, UK*

[2]*Departamento de Física Aplicada II, Universidad de Sevilla, Spain*

[3]*Instituto Carlos I de Física Teórica y Computacional, Universidad de Sevilla, Spain*

We report the first experimental demonstration of the odd-cycle game [1], where a quantum strategy provides two cooperating players a winning advantage compared to the best classical strategy. The odd-cycle game has the virtue that it can be explained in everyday terms and that the optimal classical solution is self-evident without formal mathematical proof. Two non-communicating players are tasked to respond to queries about the colour (binary choice) of vertices in an odd cycle (circular graph with an odd number of vertices). They win a round if and only if they respond with identical (different) colours when given identical (adjacent) vertices as inputs. Here, we describe an experiment where the players, separated by ~2m, each own a trapped-ion qubit and share a Bell state. They follow the rules of the game faithfully and without loopholes, and still manage to win the game with a probability ~26 sigma above that allowed by the best classical strategy. We explain the quantum strategy used by the players and quantify the nonlocal content of the entangled resource state that underpins this demonstration of quantum advantage; at 0.54(2), this value represents the largest nonlocal content measured for physically separate devices, free of the detection loophole, ever observed. The same resources that are used for the demonstration of quantum advantage in the odd-cycle game can be utilised for entanglement-assisted orientation in space [2] and for testing the significance of Bell non-locality [3].

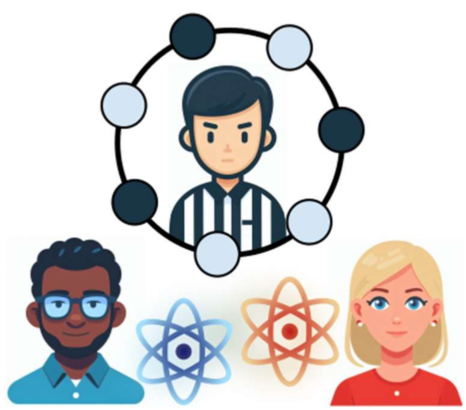


Figure 40 Schematic depiction of a nonlocal quantum game involving a referee (top center) and two players (bottom).

[1] P. Drmota et al., *Phys. Rev. Lett.* **134,** 070201 (2025).
[2] Č.Brukner, et al., *Int. J. Quantum Inf.* **4**, 365-370 (2006).
[3] C.Vieira, R.Ramanathan, and A.Cabello, *Nat. Commun.* **16**, 4390 (2025).

Demonstration of two-dimensional connectivity for a scalable error-corrected ion-trap quantum processor architecture

M. Valentini,[1] M. W. van Mourik,[1] F. Butt,[2, 3] J. Wahl,[1, 4] M. Dietl,[1, 4] M. Pfeifer,[1, 4] F. Anmasser,[1, 4] Y. Colombe,[4] C. Rössler,[4] P. C. Holz,[5] R. Blatt,[1, 5, 6] A. Bermudez,[7] M. Müller,[2,3] T. Monz,[1, 5] and **P. Schindler[1]**

[1]*Institut für Experimentalphysik, Universität Innsbruck, Austria*

[2]*Institute for Theoretical Nanoelectronics, Forschungszentrum Jülich, Germany*

[3]*Institute for Quantum Information, RWTH Aachen University, Germany*

[4]*Infineon Technologies Austria AG, Austria*

[5]*Alpine Quantum Technologies GmbH, Austria*

[6]*Institute for Quantum Optics and Quantum Information, Austria*

[7]*Instituto de Física Teórica UAM-CSIC, Spain*

A major hurdle for building a large-scale quantum computer is to scale up the number of qubits while maintaining connectivity between them. In trapped-ion devices, this connectivity can be provided by physically moving subregisters consisting of a few ions across the processor. The topology of the connectivity is given by the layout of the ion trap where one-dimensional and two-dimensional arrangements are possible. Here, we focus on an architecture based on a rectangular two-dimensional lattice, where each lattice site contains a subregister with a linear string of ions. We refer to this architecture as the Quantum Spring Array (QSA). Subregisters placed in neighboring lattice sites can be coupled by bringing the respective ion strings close to each other while avoiding merging them into a single trapping potential. Control of the separation of subregisters along one axis of the lattice, known as the axial direction, uses quasi-static voltages, while the second axis, the radial, requires control of radio frequency signals. In this work, we investigate key elements of the QSA architecture along both axes: We show that the coupling rate between neighboring lattice sites increases with the number of ions per site and the motion of the coupled system can be resilient to noise, both being key requisites for fast and high-fidelity quantum gate operations. The coherence of the coupling is assessed, and an entangling gate operation of qubits in separate trapping regions along the radial axis is demonstrated. Moreover, we demonstrate control over radio frequency signals to adjust the radial separation between strings, and thus tune their coupling rate.

We further present constructions for the implementation of parallelized, transversal gate operations, and map the 2D lattice architecture to code primitives for fault-tolerant quantum error correction, providing a step towards a quantum processor architecture that is optimized for large-scale fault-tolerant operation.

[1] M. Valentini et al, arXiv:2406.02406

Quantum information processing with qudits in a dual-species trap

<u>P. Nagpal</u>, V. G. Matsos, C. H. Valahu, H. K. Chan, and T. R. Tan

School of Physics, University of Sydney, NSW 2006, Australia

Qudits offer a richer entanglement structure [1] and an increased resilience to noise [2]. Here we build on native interactions in our dual-species trapped-ion system to harness a qudit encoded in lutetium ions. Equipped with error-suppressing pulses through optimized dynamical modulation of optically driven couplings, this is designed to implement universal control for qudit quantum information processing. Additionally, the system can co-trap ytterbium ions, enabling exploration of practical applications such as quantum non-demolition measurements [3], quantum-logic-assisted syndrome readout protocols, and analog quantum simulations for chemistry [4].

[1] T. Kraft et al., Phys. Rev. Lett. 120, 060502 (2018).
[2] D. Cozzolino et al., Adv. Quantum Technol. 2, 1900038 (2019).
[3] D. Hume et al., Phys. Rev. Lett. **99**, 120502 (2007).
[4] R. J. MacDonell et al., ***Chem. Sci.***, 2021,**12**, 9794-9805 (2021).

Poster 86

Characterization of Ion Traps for Industrial Quantum Technology Applications

<u>R.K. Singh,</u>[1,3] M. Hesse,[1] J. Mattil,[1] A. P. Kulosa,[1] U. Hinze[2,3] and T. E. Mehlstäubler [1,3]

[1] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig*

[2] *Laser nanoFab, Steinwartskamp 65, D-30826 Garbsen*

[3] *Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover*

Ion traps continue to serve as a foundational platform for quantum computing [1] and quantum sensing [2], offering exceptional control [3], scalability [4], and long coherence times [5]. As the field progresses toward industrial-scale deployment, standardized and detailed characterization methods are essential to assess performance, stability, and long-term reliability.

At the user facility "Ion traps" of the Quantum Technology Competence Center (QTZ) at Physikalisch-Technische Bundesanstalt (PTB) in Germany, we have developed a fully automated and user-friendly platform for the systematic characterization of ion traps, serving both academic and industrial partners. The entire automation process was successfully implemented using the ARTIQ control system (developed by M-Labs), running on the Sinara hardware enabling nano-second timing accuracy.

This poster presents the results from the characterization of a 3D linear Paul trap developed by the ion trap fabrication team of the QuaCCS (Quantum Clocks and Complex Systems) group at PTB's QUEST Institute serving to benchmark the measurement apparatus. The 50 × 50 mm trap features gold electrodes mounted on a Rogers 4350B PCB substrate [6]. Using the automated platform, we have characterized key trap parameters such as secular frequencies (via cooling laser amplitude modulation), ion micromotion (using the photon-correlation method), and heating rates (through ion thermometry). The characterization results were compiled into an ion trap-specific data sheet, summarizing all key parameters relevant to potential end users. As the next step, we will characterize an industrially fabricated 3D ion trap [7] as part of an industry-focused use case within the framework of the "Qu-Test" project.

[1] C. D. Bruzewicz et al., *Appl. Rev. Phys.* **6**, 021314 (2019)
[2] C. L. Degen et al., *Rev. Mod. Phys.* **89**, 035002 (2017)
[3] C. Monroe et al., *Rev. Mod. Phys*, **93**, 025001 (2021)
[4] K. Wright et al., *Nature Communications* **10**, 5464 (2019)
[5] T. P. Harty et al*., Phys. Rev. Lett.* **113**, 220501 (2014)
[6] E. Jordan et al., *arXiv: 2504.04946* (2025)
[7] https://www.lasernanofab.com

Automation in quantum-logic experiments with cold molecular ions

R. Karl[1], M. Diouf[1], M. Roguski[1], A. Shlykov[1], and S. Willitsch[1]

[1]*University of Basel, Basel, Switzerland*

Modern quantum-logic experiments require frequent sample preparation while coordinating dozens of devices on time scales from hours to nanoseconds. We report a fully automated control framework that realizes this task for quantum-logic spectroscopy on single molecular nitrogen ions [1].

A modular, distributed architecture - built on Python/LabVIEW routines, Sinara/ARTIQ hardware, and TCP/IP message passing - executes the entire experimental cycle without human intervention. Real-time image analysis guides loading of Ca^+ Coulomb crystals, insertion and recognition of a single dark N_2^+ from a pulsed, cold molecular beam [2], adaptive RF-assisted reduction to a two-ion Ca^+–N_2^+ string, and mass confirmation by motional-mode resonance. Synchronized pulse sequences then perform sideband cooling, quantum-logic state detection, and rovibrational or rotational spectroscopy, while on-the-fly data analysis reacts to any emerging spectral feature with higher-resolution interrogation around that frequency.

Unsupervised operation over nights and weekends boosts the duty cycle by a factor >2, produces eight times more molecular ions than manual operation, and quadruples the number of quantum-logic measurements obtainable from each molecular ion before chemical loss.

This automated framework has enabled MHz-resolved identification of dipole-forbidden rovibrational transitions in N_2^+ for which automation was indispensable due to a limited chemical lifetime of about 15 min, a stochastic rovibrational ground state preparation and initially only coarsely known line positions. The same framework offers a transferable blueprint for dual-species ion-trap experiments, especially for quantum-logic based experiments targeting molecular qubits, mid-IR frequency standards, and precision tests of fundamental physics.

[1] M. Sinhal, et al., *Science*, **367**, 1213 (2020).
[2] A. Shlykov, M. Roguski, S. Willitsch, *Adv. Quantum Technol.*, 2300268 (2023).

Towards time-reversing an exponentially rising pulse with a single ground state cooled $^{174}Yb^+$ ion

S. Luff,[1,2] H. Dang, [1,2] M. Fischer, [1] M. Sondermann[1,2] and G. Leuchs[1,2]

[1]*Max Planck Institute for the Science of Light, Erlangen, Germany*
[2]*Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, Germany*

Deterministic excitation of a single ion by a single photon can be realized when the temporal envelope of the photon matches the time-reversed waveform of a spontaneously emitted photon from the same atomic transition [1]. In this work, we implement such a scheme by sending an exponentially rising pulse onto a $^{174}Yb^+$ ion, driving its strong dipole transition (370 nm wavelength, 8.1 ns life time). A similar excitation approach using shaped pulses has been previously demonstrated with neutral atoms [2]. To enhance the photon–ion coupling efficiency, the ion is positioned inside a deep parabolic mirror that covers nearly the full solid angle of the incident light field [3]. This geometry enables near-maximal spatial mode overlap between an incident doughnut-shaped mode and the ion's dipole radiation pattern. Furthermore, the ion is cooled well below the Doppler limit via resolved sideband cooling [4], which minimizes the spatial extent of the ion. We drive the narrow $^2S_{1/2}$ - $^2D_{3/2}$ electric quadrupole transition characterized by a natural linewidth of approximately 3 Hz, using a 436 nm laser that is frequency-stabilized to an optical cavity. In addition, a laser at 935 nm quenches the ion from the $^2D_{3/2}$ state to the $^3D[3/2]_{1/2}$ state, from which it decays back to the $^2S_{1/2}$ ground state. This cooling mechanism ensures that the spatial spread of the ion is smaller than the focal spot size of the parabolic mirror, effectively localizing the ion within the region of maximum intensity of the incident light field and optimizing the coupling efficiency.

[1] Leuchs, G. & Sondermann, M. *Phys. Scr.* **85**, 058101 (2012).
[2] Aljunid, S. A. et al., *Phys. Rev. Lett.* **111**, 103001 (2013).
[3] Maiwald, R. et al., *Phys. Rev. A* **86**, 043431 (2012).
[4] Diedrich, F. et al., *Phys. Rev. Lett.* **62**, 403–406 (1989).

Modular cryogenic ion trap for high-dimensional ^{137}Ba qudit processing

S-. H. Oh,[1] I. Oh,[1] G. Son,[1] B. Park,[1] and J. Kim[1]

[1]*SKKU Advanced Institute of Nanotechnology and Department of Nano Science and Technology, Sungkyunkwan University, Suwon 16419, Korea*

Recent advances in high-dimensional quantum information processing have identified $^{137}Ba^+$ ions as promising candidates for scalable qudit architecture, owing to their long-lived hyperfine states and high-fidelity readout [1]. However, most prior work has relied on rigid, room-temperature ion traps, which inherently limit thermal stability, modularity, and optical access.

We introduce a modular cryogenic ion trap processor uniquely designed for $^{137}Ba^+$ qudit manipulation. The system leverages a commercial cryostat to maintain ultra-high vacuum at 4.2 K, minimizing motional heating and enabling long ion storage. The trap is positioned just 11 mm from the window, allowing the use of a high-NA (≈0.5) external objective for efficient fluorescence collection and site-resolved addressing which is not commonly implemented in cryogenic platforms. The modular mounting design allows fast trap replacement, facilitating direct comparison of different geometries.

Neutral barium atoms are generated by the pulsed laser ablation of a high-purity Ba metal target. This metal-based source enables more than 5× higher shot stability than conventional $BaCl_2$ targets, with real-time plume monitoring via 660 nm atomic fluorescence [2]. Two-photon ionization at 413 nm demonstrates measurable neutral atom flux and fluorescence, laying the foundation for isotope-selective loading of $^{137}Ba^+$ ions.

This platform uniquely combines cryogenic robustness, modularity, and advanced optical access to enable scalable qudit control with $^{137}Ba^+$, offering a new platform for high-dimensional quantum experiments.

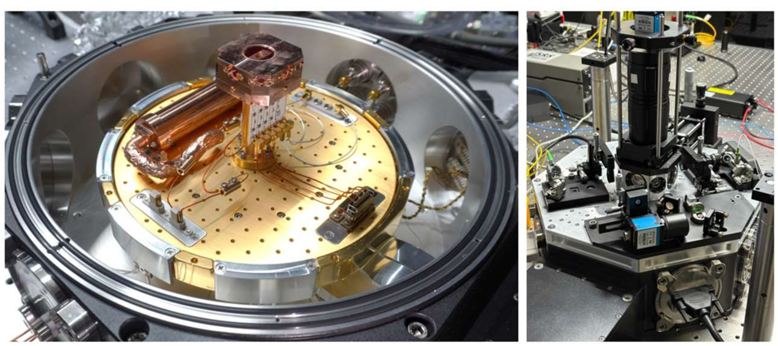


Figure 41: Integrated cryogenic ion trap system based on a FourNine SideKick 100 chamber (left), with external optics for ablation, photoionization, Doppler cooling, repumping, and imaging (right).

[1] P. Low *et al.*, "Control and readout of a 13-level trapped ion qudit." npj Quantum Information 11, 2282 (2025).

[2] J. Choi, E. Lee, D. Yum, K. An, and J. Kim, "Direct measurement of isotope shifts in the barium $6s^2\ ^1S_0$ - $6s5d\ ^3D_1$ transition," Phys. Rev. A 110, 032812 (2024).

SDQC: distributed quantum computing architecture utilizing entangled ion qubit shuttling

Seunghyun Baek[1] , Dongmoon Min[2], Junki Kim[1, 3]

[1]*SKKU Advanced Institute of Nanotechnology (SAINT) & Department of Nano Science and Technology, Sungkyunkwan University, Suwon, 16419, Korea*

[2]*Department of Computer Science and Engineering, Sungkyunkwan University, Suwon, 16410, Korea*

[3]*Department of Nano Engineering, Sungkyunkwan University, Suwon, 16419, Korea*

We propose Shuttling-based distributed Quantum Computing (SDQC) architecture for fault-tolerant scaling quantum computing (QC), which is a hybrid architecture combining the strengths of two existing architectures: Modular Universal Scalable Ion-trap Quantum Computer (MUSIQC) [1] and the Quantum Charge-Coupled Device (QCCD) [2, 3]. MUSIQC is distributed QC utilizing non-local operation (i.e., gate and quantum teleportation) based on remote entanglement generation via ion-photon interface between spatially distinct modules. The photonic interconnection allows arbitrary connectivity topology, overcoming limitation of individual modules (i.e., single ion chain), and provides a scale-independent entanglement distribution rate. On the other hand, QCCD is scalable architecture that relies on physically rearranging the data qubit using shuttling operation. These operations are achieved through dynamic electrical potential shaping to move ions within a trap. Our proposed SDQC is distributed QC architecture using shuttling operation not photonic interconnection, that ensure reliable entanglement distribution rather than photonic interconnection and maintaining a scale-independent time overhead, which is improvement over the time-scaling limitations observed in QCCD.

In this study, we design the architecture structure and its logical operation using quantum error correction optimized with pipelining strategies to maximize parallelism. We also evaluate the architecture's performance in terms of error rate and execution time, comparing it to MUSIQC and QCCD.

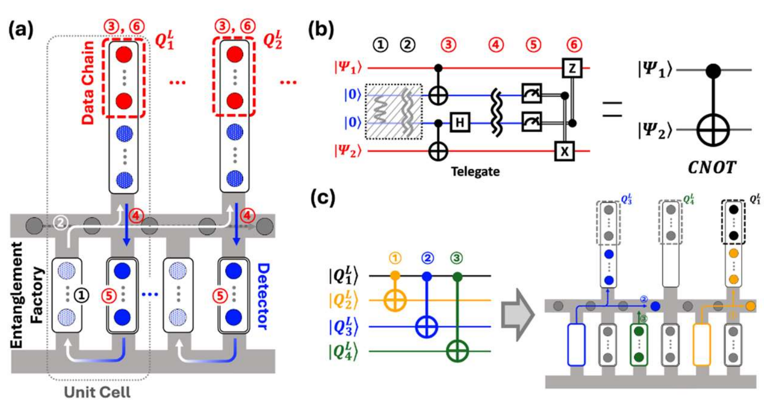


Figure 42: (a) SDQC architecture scheme , (b) MUSIQC, (c) QCCD

[1] Monroe, C et al., *Phys. Rev. A*, **89(2)**, 022317 (2014).
[2] Kielpinski, D et al., *Nature*, **417(6890)**, 709-711 (2002).
[3] Lekitsch, B et al., *Science Advances*, **3(2)**, e1601540 (2017).

Poster 91

Progress Towards Quantum Network Implementation Using $^{171}Yb^{+}$ Ions in Microfabricated Surface-Traps

<u>S.W. Yu,</u>[1,2] K.M. Lee,[1,2] S.M. Park,[1,2] M.W Kim,[1,2] M.J Kim,[1,2] and T.H. Kim[1,2,3]

[1] *Dept. of Computer Science & Engineering, Seoul National University, South Korea*

[2] *Automation and Systems Research Institute, NextQuantum Seoul National University,*

[3] *Institute of Computer Technology, Seoul National University*

The trapped-ion system is a promising platform for the realization of both quantum computing and quantum networking. A key requirement for scalable quantum information processor is to transmit quantum information over long distances, and numerous approaches have been studied [1–3]. In our work, we encoded quantum information onto the frequency of photons and achieved remote entanglement via a Bell-state measurement. Specifically, two $^{171}Yb^{+}$ ions are trapped in spatially separated microfabricated surface traps. A non-deterministic Bell-state measurement is performed using a 50:50 beam splitter. After Bell-state measurement, the quantum state of the two ions can be represented by $\frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$.

The $^{171}Yb^{+}$ ions are frequently chosen for quantum information processing due to its relatively simple energy level structure with hyperfine splitting. However, its optical transition emits photons in the ultraviolet spectral range, posing significant challenges for efficient photon transmission. To address this limitation, we plan to employ a three-stage quantum frequency conversion system to enable the generation of entanglement over kilometer-scale distances, and we have developed the first stage. [4]

Figure 1(a) shows the measured population of both ions after heralded entanglement generation. In the current setup, significant state preparation and measurement (SPAM) errors were observed. Figure 1(b) presents the estimated population considering SPAM errors.

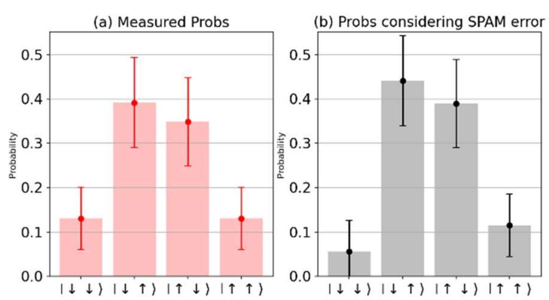


Figure 43: Measured quantum state populations of two remote ions after heralded entanglement generation

[1] Krutyanskiy, V, et al. "Entanglement of trapped-ion qubits separated by 230 meters." Physical Review Letters 130.5 (2023)

[2] O'Reilly, Jameson, et al. "Fast Photon-Mediated Entanglement of Continuously Cooled Trapped Ions for Quantum Networking." Physical Review Letters 133.9 (2024)

[3] Saha, Sagnik, et al. "High-fidelity remote entanglement of trapped atoms mediated by time-bin photons." *Nature Communications* 16.1 (2025): 2533.

[4] Yu, Seungwoo, et al. "Efficient Quantum Frequency Conversion of Ultra-Violet Single Photons from a Trapped Ytterbium Ion." arXiv preprint arXiv:2502.09068 (2025).

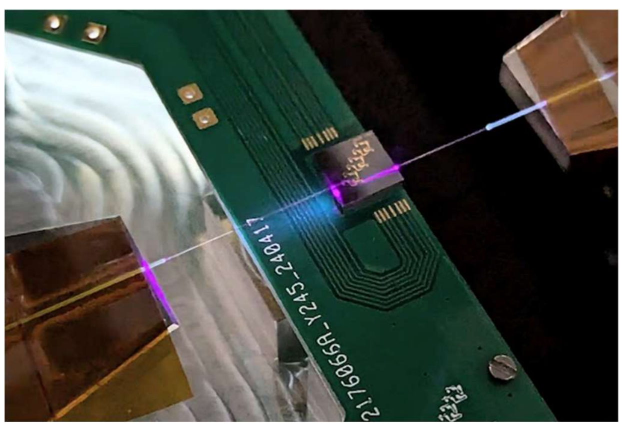
Integrated photonics for self-injection locking of a UV diode laser for trapped ions

S. Cavallini,[1] G.J. Beck,[1] H. Hirzler,[1] and J.P. Home[1]

[1]*Institute for Quantum Electronics, ETH Zürich, Zürich, Switzerland*

Integrated photonics has demonstrated substantial benefits in chip-scale trapped ion systems, including stability, convenience, and scalability [1-3]. As the number of ions increases, controlling a free-space optics setup becomes a complex task, and integrated optics devices present themselves as an available solution to this problem, paving the way for scaling up trapped ions as a quantum information processing platform.

While integrated photonic chips for trapped ions have primarily focused on beam delivery, they also find application in miniaturizing the optics used to prepare the light before the trap. In particular, chip integration is a promising solution for creating compact and portable narrow-line width laser systems [4, 5]. Previous demonstrations of this technology have been limited to visible and infrared wavelengths, but applications in atomic systems, such as cooling transitions in ytterbium and calcium ions at 369 nm and 397 nm motivate development further into the ultraviolet. Our work pursues this goal through the use of an alumina photonic chip for self-injection locking of a UV laser diode. We present ongoing work on the design of a on-chip thermally tunable ring resonator necessary for the self-injection locking scheme and on the characterization of the integrated photonic chips.



[1] K. K. Mehta et al., *Nature Nanotechnology* 11.12 (2016)
[2] K. K. Mehta et al., *Nature* 586, 533–537 (2020)
[3] C. Mordini et al., *Physical Review X* 15.1 (2025): 011040.
[4] W. Loh et al., *Nature Photonics* (2025): 1-7.
[5] N. Chauhan et al., *arXiv preprint arXiv:2402.16742* (2024).

Light shift gate on an optical clock transition

S.M. Decoppet,[1] J.D. Leppard,[1] A. Vazquez-Brennan,[1] W.R. Cutler,[1] and C.J. Ballance[1]

[1] *University of Oxford, Oxford, United Kingdom*

Entanglement operations in trapped-ion quantum computers are mediated through the shared normal modes of motion of the ions in the chain. The two main gate mechanisms used in current systems are the Mølmer-Sørensen (MS) gate [1] and the light-shift (LS) gate [2]. Both methods work by inducing a state dependent geometric phase on the qubit states, but they operate in different bases – the MS gate in the $\sigma_x\sigma_x$ basis and the LS gate in the $\sigma_z\sigma_z$ basis. One notable benefit of working with LS over MS gates is that the $\sigma_z\sigma_z$ entanglement operation commutes with common sources of noise, such as magnetic field or laser phase noise. These induce σ_z errors on the qubit and can therefore be mitigated with dynamical decoupling sequences when using LS gates.[2]

Light-shift gates have been demonstrated with high fidelity in both hyperfine and Zeeman qubits. Implementing this type of gate on clock qubits, however, is technically challenging. Clock qubits benefit from long coherence times, but clock qubits in the ground or metastable levels are not affected by differential light shifts induced by off-resonant coupling to dipole transitions [3]. This limitation can be overcome in two ways. One method is to off-resonantly couple to dipole-forbidden (optical) transitions, which do induce a differential light shift on clock transitions.[4] Another method is to work with optical clock qubits, which *are* affected by off-resonant coupling to dipole transitions.

We present an implementation of an optical transition dipole force gate on an optical clock qubit, following the proposal by Sawyer *et al.* [5] We use $^{137}Ba^{+}$ ions with an optical qubit stored across the ground $S_{1/2}$ and metastable $D_{5/2}$ levels. We drive the LS gate using a pair of counter-propagating beams at 532 nm, which off-resonantly couple to the S-P and D-P transitions. To our knowledge, this is the first implementation of a LS gate on an optical clock transition.

[1] Sørensen et al., *Phys. Rev. Lett.* **82,** 1971 (1999).
[2] Leibfried et al., *Nature* **422,** 412–415 (2003).
[3] Lee et al., *J. Opt. B: Quantum Semiclass. Opt.* **7,** S371 (2005).
[4] Baldwin et al., *Phys. Rev. A* **103,** 012603 (2021).
[5] Sawyer et al., *Phys. Rev. A* **103,** 022427 (2021).

Probing fundamental constants and testing QED theory of molecules through high-precision spectroscopy of molecular hydrogen ions

S. Alighanbari,[1] M.R. Schenkel,[1] M. Bakhshi,[1] V.I. Korobov,[2] J.-Ph. Karr,[3] and S. Schiller[1]

[1]*Institut für Experimentalphysik, HHU Düsseldorf, Düsseldorf, Germany*

[2]*Bogoliubov Laboratory, Joint Institute for Nuclear Research, 141980 Dubna, Russia*

[3]*LKB, Sorbonne Université, CNRS, ENS, Université PSL, Collége de France, Paris, France*

and Université d'Evry-Val d'Essonne, Université Paris-Saclay, 91000 Evry, France

Molecular hydrogen ions (MHIs) are the simplest molecules. They offer unique opportunities to probe fundamental physics: determination of fundamental constants (FCs), searches for physics beyond the Standard Model, and precision tests of CPT invariance [1]. Among the MHIs, the heteronuclear species HD^+ has been the most extensively investigated, yielding highly precise values of rovibrational and rotational transitions. In general, the measured transition frequencies have shown agreement with ab initio theoretical predictions [2]. We have recently extended high-precision spectroscopy of MHIs to the homonuclear H_2^+, which presents experimental challenges due to the absence of electric-dipole transitions. We have overcome this difficulty by successfully measuring an electric-quadrupole transition. This represents the first demonstration of Doppler-free rovibrational laser spectroscopy in H_2^+ [3]. We resolved the spin structure of a first-overtone transition, which enabled the determination of a spin Hamiltonian coefficient with an uncertainty of 150 Hz, improving on values that have remained unchanged for over five decades [4]. From the resolved spin structure we extracted the spin-averaged transition frequency, and by combining with theoretical calculations, we obtained an independent determination of m_p/m_e. It is consistent with the CODATA 2022 value, and has comparable uncertainty [3]. Our experiment lays the foundation for future tests of CPT symmetry via comparisons of rovibrational transitions in H_2^+ and anti-H_2^+ [6,7]. Complementary to this, we are reinvestigating the hyperfine structure of HD^+, where some experimental-theoretical discrepancies appear to exist [5]. Here, we present recent progress in accurately determining the hyperfine structure of HD^+ in the rovibrational ground state and compare with theory.

A long-term perspective in the field is the determination of the set m_p/m_e, m_d/m_e, m_d/m_e, and the triton charge radius with 100-fold reduced uncertainty compared to CODATA 2022 [8]. Using a model calculation, we have shown that this should be possible by measuring a moderately large set of transitions (e.g. 10) on at least 5 of the 6 isotopologues, all with 1-Hz-level experimental uncertainties. New theoretical computations are required, but they do not appear to pose fundamental challenges. In addition, using only data from electronic systems, the proton and deuteron charge radii should become accessible with uncertainties competitive to the results from muonic H/D. This would enable a test of lepton universality.

[1] For an introduction and references, see e.g. S. Schiller, *Contemp. Phys.* **63**, 247 (2022).
[2] S. Alighanbari, et al. *Nat. Phys.* **19**, 1263 (2023) ; I.V Kortunov, et al. Nat. Phys. **17**, 569 (2021);
[3] Alighanbari, et al. *Nature* **581**, 152 (2020); S. Patra, et al. *Science* **369**, 1238 (2025).
[4] S. Alighanbari, et al., *Nature, to appear* (2025).
[5] K.B. Jefferts, *Phys. Rev. Lett.* **23**, 1476 (1969); S.C. Menasian, thesis, U. Washington (1973).
[6] M. Haidar, et al. *Phys. Rev. A* **106**, 042815 (2022).
[7] H.G. Dehmelt, *Phy. Scr.* **T59**, 432 (1995) and E. Myers, *Phys. Rev. A* **98**, 010101(R) (2018).
[8] A.J. Vargas, *Phys. Rev. D* **111**, 015032 (2025) and G.M. Shore, arXiv:2412.09730 (2025).
[9] J.-Ph. Karr, S. Schiller, V.I. Korobov, S. Alighanbari, arXiv:2505.05615 (2025).

Modular Quantum Control Electronics

S. Ulm,[1] V. Daramwar,[1] H. Toth,[1] and A. Schruba[1]

[1] *Akkodis Germany Solutions GmbH, Ulm, Germany*

Today trapped-ion experiments in many cases request the utilization of hundred(s) of trap electrodes and ten(s) of laser beams which have to be operated in a precise and synchronous manner[1] while at the same time the control system might be limited in size and available supplies like in rack-systems[2]. Akkodis is developing the required control electronic system for such tasks. Within the IQUAN project [3] we have designed a modular, scalable electronic system consisting of precision pulse generators and real-time control logic, a DC-AWG for the control of slow, noise-sensitive parameters such as trap electrode voltages, and a RF-AWG optimized for fast quantum gate operations via shaped microwave pulses.

Within the ATIQ project [4] we extend the software to operate within a ARTIQ system and incorporate elements of a ARTIQ system in our system, and provide diagnostic services for the overall system. We present in this contribution the performance measurements of the new RF- and DC-AWG pulse generators like the channel-to-channel synchronization and describe the interfaces for heterogeneous systems and diagnostic services. Designed with scalability, usability, and signal integrity in mind, these generators offer a powerful and future-proof toolset for quantum laboratories and system developers aiming to push the frontier of quantum control.

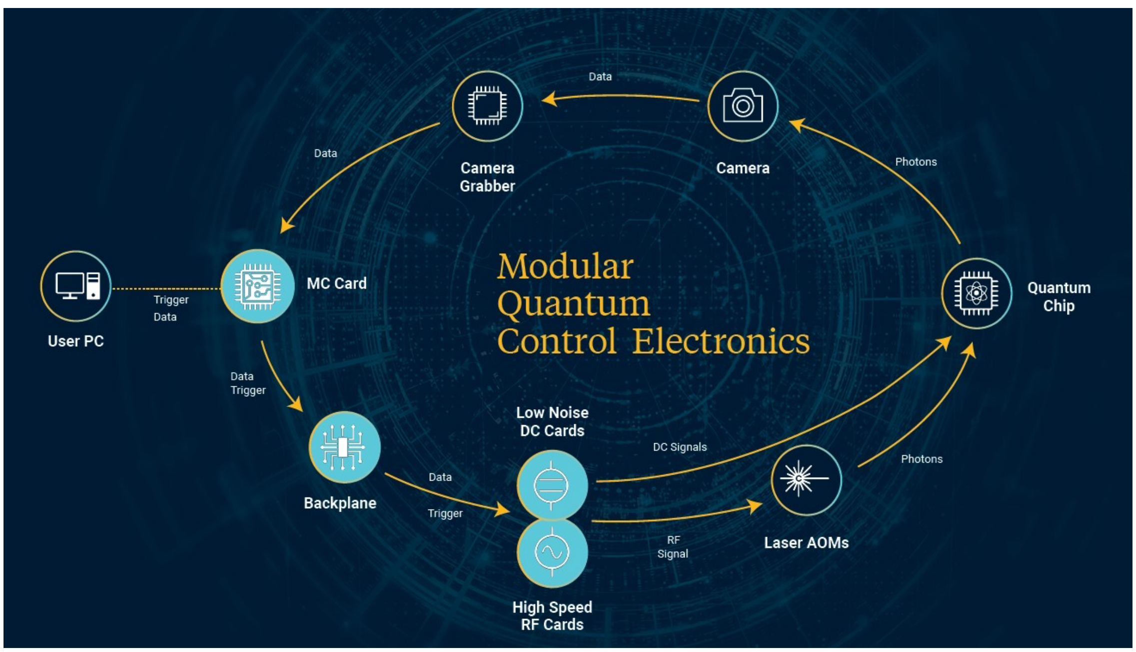


Figure 44: System-Overview.

[1] S.Heußen et al., arXiv:2409.13465 (2024)
[2] I.Pogorelov et al., *PRX Quantum* **2,** 020343 (2021).
[3] https://iquan.physik.uni-mainz.de/
[4] https://www.quantentechnologien.de/forschung/foerderung/quantencomputer-demonstrationsaufbauten/atiq.html

Quantum Simulation of the Generalized Resonant Rabi Model Using a Trapped-Ion Quantum Simulator

S. Lim,[1,2] C. G. Yale[3], C. Im[1], S. M. Clark,[3] and J. Kim[1]

[1]*SKKU Advanced Institute of Nanotechnology and Department of Nano Science and Technology, Sungkyunkwan University, Suwon 16419, Korea,*

[2] *Department of Physics and Astronomy, Seoul National University, Seoul, 08826, Republic of Korea,*

[3]*Sandia National Laboratories, Albuquerque, NM 87123 USA*

The quantum Rabi model (QRM) is the most fundamental theoretical framework for describing quantum light-matter interactions. However, due to the typically weak coupling strength relative to the atomic frequency, the anti–Jaynes-Cummings (anti-JC) term is often neglected. This simplification limits experimental exploration of the full complexity of the model. Recent advances in quantum simulation techniques using trapped ion systems, photonic waveguide platforms, and circuit QED architectures have enabled the study of richer quantum dynamics within the QRM.

In this study, we investigate the generalized resonant Rabi model (GRRM). The GRRM is defined by treating the JC and anti-JC coupling as independent parameters, while setting both the boson frequency and spin frequency to zero. In this regime, parity symmetry $\widehat{\Pi} = e^{i\hat{a}^{\dagger}\hat{a}}\,\hat{\sigma}_z$ divides the Hilbert space into two decoupled parity chains.

We experimentally investigated the zero-energy state of the GRRM using a trapped-ion quantum simulator. The internal states of the ion were used to encode the spin, whereas its quantized motional degrees of freedom served as the bosonic mode. Through adiabatic state preparation by tuning g_2/g_1, we successfully realized the zero-energy state in the GRRM. This zero-energy state, analytically identified as a squeezed-vacuum state, was characterized via measurements of its characteristic function and phonon-number distribution.

These measurements confirmed squeezing in quadrature space. We also revealed that the zero-energy state is composed exclusively of even-numbered Fock states. Moreover, our experimental results show strong agreement with theoretical predictions, incorporating error models that account for realistic experimental imperfections.

Sandia National Laboratories is managed and operated by NTESS, LLC, a subsidiary of Honeywell International, Inc. for the US DOE NNSA under contract DE-NA0003525. This work is funded in part by the US DOE Office of Science ASCR Quantum Testbed Program.

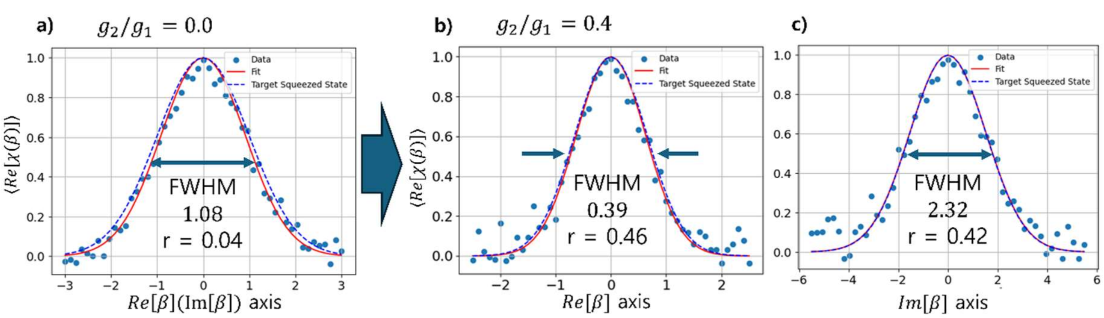


Figure 45 Observed quadrature squeezing in the characteristic function after adiabatic state preparation to g_2/g_1 =0.4. Squeezing along $Re[\beta]$ and expansion along $Im[\beta]$ indicate the realization of the GRRM zero-energy state

Progress towards a cryogenic Sr^+ ion clock

T. Tow,[1] P. Dubé,[2] K. Kato,[2] and A. Vutha[1]

[1]*Department of Physics, University of Toronto, Canada*
[2]*National Research Council of Canada, Ottawa, Canada*

Single-ion clocks offer remarkable fractional frequency accuracy, with errors below 1 part in 10^{18}. The leading contributions to the uncertainty in state-of-the-art Sr^+ clocks, such as the clock operated by the National Research Council of Canada (NRC) [1], are blackbody radiation shifts and collisional shifts from residual background gas. To address these dominant systematic effects, we have built a Sr^+ ion trap for operation at 4 K. We expect cryogenic operation to suppress the blackbody radiation shift by eight orders of magnitude and collisional shifts by at least two orders of magnitude [2,3], which could allow substantial improvements to the performance of single-ion clocks. I will present some of the unique aspects of our cryogenic system, and discuss the thermal and vibrational considerations underlying our design. I will report on our progress in characterizing the performance of this system.

Figure 1: Assembled ion trap

[1] P Dubé et al 2016 *J. Phys.: Conf. Ser.* 723 012018
[2] P. Dubé, K. Kato, S. Smale and A. Vutha. *2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*
[3] Safronova, M. & Kozlov, M. & Clark, C. (2012). *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*. 59. 439-47.

Generalized Single-shot Interferometry based on Quantum Signal Processing

Teerawat Chalermpusitarak[1] and Ting Rei Tan[1,2]

[1]*School of Physics, University of Sydney, New South Wales 2006, Australia*

[2]*ARC Centre of Excellence for Engineered Quantum Systems, University of Sydney, New South Wales 2006, Australia*

Quantum sensing is a primary application of trapped-ion systems. However, most experimental demonstrations have focused on parameter estimation, such as displacement and phase sensing, leaving the general theory beyond parameter estimation unexplored. In this work, we present a generalized interferometric scheme based on bosonic quantum signal processing that can be used to make efficient binary decisions on an arbitrary displacement channel. More specifically, we aim to determine whether the magnitude of the displacement is greater or less than a user-defined threshold by a single-shot readout of the ion's spin state. Our scheme can be considered as a phase-insensitive magnitude sensing protocol, hence, it requires no prior information about the phase of the displacement.

Uncertainty evaluation and comparisons of the VTT MIKES $^{88}Sr^{+}$ optical clock

T. Lindvall,[1] T. Fordell,[1] K. J. Hanhijärvi,[1] M. Doležal,[2] J. Rahm,[3] S. Weyers,[3] Saaswath J. K.,[3] M. Filzinger,[3] M. Steinel,[3] N. Huntemann,[3] and A. E. Wallin[1]

[1] *VTT, National Metrology Institute VTT MIKES, Espoo, Finland*

[2] *Czech Metrology Institute, Prague, Czech Republic*

[3] *Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

The 445 THz $^{88}Sr^{+}$ ion clock transition, a secondary representation of the second, has several advantages: the required laser system is simple, there are efficient schemes for cancelling tensor and micromotion shifts, the quadratic Zeeman shift is extremely small, and the differential static scalar polarizability can be accurately measured. The VTT MIKES $^{88}Sr^{+}$ optical clock is based on an endcap ion trap [1] designed for low rf heating. In 2022, the clock participated in an international comparison [2] within the European metrology project ROCIT [3].

We report on the uncertainty evaluation of the $^{88}Sr^{+}$ clock with a total estimated systematic uncertainty of approximately 1×10^{-18}. The low uncertainty is enabled by a detailed evaluation of the blackbody-radiation temperature, a low vacuum pressure, and by our recent measurement of the differential polarizability. The polarizability measurement utilized the magic rf frequency where the micromotion shifts cancel and reduced the polarizability-related blackbody-radiation uncertainty contribution to 2.2×10^{-19}. The clock self-comparison instability is limited to about $2\times10^{-15}\ \tau^{-1/2}$ by the clock laser, with no added instability due to magnetic-field noise observed for probe times of up to 320 ms.

We also report on two absolute frequency measurements: one against a remote Cs fountain clock at PTB [4], with a total uncertainty of 3.3×10^{-16}, and one against International Atomic Time (TAI). The latter spanned 10 months with monthly optical-clock uptimes of 68–99%, yielding a total uncertainty of 1.1×10^{-16}.

Finally, in 2024, the transportable Opticlock $^{171}Yb^{+}$(E2) clock [5] of PTB visited VTT MIKES for a comparison campaign. With a joint uptime of 90% over a 30-day measurement period, we achieved a statistical uncertainty below 1×10^{-17}. This small statistical uncertainty and the high reproducibility of the transportable standard also allow us to compare the VTT MIKES clock to the PTB laboratory $^{171}Yb^{+}$(E3) and $^{88}Sr^{+}$ clocks.

[1] T. Lindvall et al., *J. Appl. Phys.* **132**, 124401 (2022).
[2] T. Lindvall et al., arXiv:2505.06763 [physics.atom-ph] (2025).
[3] H. Margolis et al., *J. Phys. Conf. Ser.* **2889**, 012022 (2024).
[4] S. Weyers et al., *Metrologia* **55**, 789 (2018).
[5] J. Stuhler et al., Measurement: Sensors **18**, 100264 (2021).

Vibrationally coupled Rydberg atom-ion molecules

Ilango Maran,[1] Liam J. Bond,[2,3] Jeremy T. Young,[2] Arghavan Safavi-Naini,[2,3] and Rene Gerritsma[1,2]

[1]*Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, the Netherlands*

[2]*QuSoft, Science Park 123, the Netherlands*

[3]*Institute for Theoretical Physics, Institute of Physics, University of Amsterdam, Science Park 904, the Netherlands*

Recently, a new type of a long-range molecule consisting of an ion and a Rydberg atom popularly known as Rydberg atom-ion molecules (RAIMs) has been theoretically proposed [1, 2] and experimentally observed in an ultracold cloud of ^{87}Rb atoms [3]. We use a hybrid atom-ion system to create a linear crystal of ions in a Paul trap with RAIMs attached to its either ends to generate ion-mediated Rydberg-Rydberg interactions. We propose a scheme to utilise the common motional modes of a crystal of trapped ions to enhance (facilitation) or suppress (blockade) the probability of forming two RAIMs at the ends of the chain, replacing the typical blockade radius set by the dipole-dipole interaction by the length of the ion crystal. We use detailed Floquet analysis to demonstrate the feasibility of our scheme in the presence of the time dependent rf potential of the Paul trap and identify parameter regimes where the RAIM survives, using an approach based on Landau-Zener-Stuckleberg interferometry which studies the effect of an oscillating field on Landau-Zener (LZ) processes [4], aided by scaling arguments. Lastly, we outline future plans on how these RAIMs could potentially be detected in our hybrid atom-ion experiment [5] without the application of an ion microscope.

[1] M. Deis et al., Atoms 9, 34 (2021).
[2] A. Duspayev et al., Phys. Rev. Research 3, 023114.
[3] N. Zuber et al., Nature 605, 453–456 (2022).
[4] S. Shevchenko, Physics Reports 492, 1 (2010)
[5] H. Hirzler et al., Phys. Rev. A 102, 033109 (2020).

Ion trap loading with a high-efficiency, laser-heated atom source

T. F. Wohlers-Reichel,[1] L. Versini,[1] J. A. Blackmore,[1] P. Drmota,[1] T. H. Doherty,[1] L. J. Stephenson,[1] and J. F. Goodwin[1]

[1] *Clarendon Laboratory, Department of Physics, University of Oxford, Parks Rd., Oxford OX1 3PU, United Kingdom*

The generation of neutral atomic flux for loading ion traps has been demonstrated using a variety of approaches, including electrically- and optically-heated ovens, laser ablated sources, and injection from magneto-optical traps (MOTs). While all these methods have proven capable of successful operation, each suffers from disadvantages, such as the high power dissipated by resistively heated thermal sources [1], the high stream velocity of atoms generated from laser ablation [2], and the significant experimental complexity associated with maintaining a MOT [3].

Here we demonstrate ion trap loading by employing a miniaturised and highly collimated optically-heated atom source. Our source emits a low-velocity, low divergence beam of neutral atoms, which, when combined with a highly efficient thermal design, requires substantially reduced heating powers vs those of traditional thermal sources, greatly reducing power dissipation into the trap system.

We estimate that, due to the efficient design of our source, ~micrograms of source material will be sufficient for continuous operation of the source over decades. Additionally, because of the low flux and collimation of the atomic beam, the oven can be operated continuously, allowing on-demand loading without the risk of undesired effects such as compensation drift, trap electrode shorting or impacts on the background pressure of the vacuum chamber. Combining these features into a compact footprint, we have demonstrated an efficient atomic source, ideal for scalable and reliable ion trap system design.

[1] Ballance T. G et al. Rev. Sci. Instrum. 89, 053102 (2018)
[2] Sheridan, K., Lange, W. & Keller, M. Appl. Phys. B 104, 755–761 (2011).
[3] Sage, J M. and Kerman, A J. and Chiaverini, J, Phys. Rev. A 86, 013417 (2012)

High-fidelity quantum information processing with trapped barium ions via addressed off-resonant interactions

T. Faorlin,[1] L. Panzl,[1] P. Grosser[1], W. Hörmann[1], H. Tian[1], G. Cerchiari,[1,2] R. Blatt,[1,3,4] and T. Monz[1,3]

[1]*Universität Innsbruck, Institut für Experimentalphysik, Innsbruck, Austria*

[2]*Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany*

[3]*Alpine Quantum Technology (AQT), Innsbruck, Austria*

[4]*IQOQI, Innsbruck, Austria*

Within the Hyperion experiment, we aim to push the boundaries of coherent control in trapped-ion systems. Our focus is on improving gate fidelities and minimizing state preparation and readout errors. We pursue this goal using trapped Barium ions. Barium ions, particularly when using the ground state for encoding quantum information, should offer coherence times on the order of minutes, measurement fidelities at the 1e-5 level, and facilitate the use of integrated photonics. This atomic species also provides naturally abundant isotopes with nuclear spin, enabling ground-state encoding between two hyperfine states.

Building on state preparation at the 1e-4 level, state readout at the 1e-5 level, and single-ion addressing cross-talk at the 1e-4 level, I present a novel gate scheme that leverages ground-state qubits with radially addressed Raman interactions using 532 nm light. The entangling gates are mediated through the perpendicular axial motional modes, utilizing the field gradient of the employed laser fields. This novel approach combines the low cross-talk of radial addressing with the improved gate performance enabled by axial-mode-mediated gates.

Poster 103

Large associative ionization cross-section for low lying states of Li

N. Joshi[1] , **Vaibhav Mahendrakar[1]**, M. Niranjan [1,2], Raghuveer Singh Yadav[1], E Krishnakumar[1], A. Pandy[3], R Vexiau[3], O. Dulieu[3] and S. A. Rangwala[1]

[1]*Raman Research Institute, C. V. Raman Avenue, Sadashivanagar, Bengaluru 560080, India*
[2]*Laboratoire Charles Fabry, Institut d'Optique, CNRS, Universit´e Paris-Saclay, 91127 Palaiseau, France*
[3]*Laboratoire Aim´e Cotton, CNRS, Universit´e Paris-Saclay, Orsay, 91400, France*

For a dilute gas of cold lithium atoms in a magneto-optical trap (MOT), (average atomic separation ≈ 10 μm, T ≈ 500μK), the attempt to excite the 2P state atoms to the 3S state, with a very weak resonant laser, results in the formation of ions in large numbers. This is unexpected, as there is no resonant pathway for Li ionization using the different lasers involved in the experiment. The ions are detected, because of our unique hybrid, ion-atom trap experiment [1], where ions and atoms can be co-trapped simultaneously. Due to the long hold times of the ions, concatenated processes are revealed, and the combination of experiments and theory reveal an entire chain of processes.

We experimentally find that the initial ion formed, is the Li_2^+ molecular ion. This is due to associative ionization (AI) of the excited state atoms to a molecular ion state, populating vibrational energy levels of the $X^2\Sigma_g^+$ Li_2^+ state [2], which are lower in energy than the 2P + 3S atomic states. Subsequently, molecular ions decay to the Li^+ atomic ion, via photodissociation as discussed in Jyothi et al for Rb_2^+ [3], and a fast dissociation processes which is not light dependent. A reasonable fraction of Li_2^+ ions created in the low lying vibrational states, survive and can be used for experiments with molecular ions. Numerous novel experimental techniques are used to determine the mechanisms involved, supported by theoretical analysis. The large AI rate of Li_2^+ production suggests a large cross-section for this process. We measure the AI cross-section to be very high ($\approx \pi\,(1000\ a_0)^2$) [4]. This is remarkable, given that the participating atoms [Li(2P) & Li(3S)] are not in high-lying Rydberg states [5].

[1] N. Joshi et al., *arXiv:2411.01209v1 2 Nov 2024*
[2] A.Pandey et al., *Phys Rev A 101,052702 11 May 2020*
[3] S. Jyothi et al., *Phys. Rev. Lett. 117,213002. 18 Nov 2018*
[4] Vaibhav Mahendrakar et al., *in preparation*
[5] Thomas Niederprum et al., *Phys. Rev. Lett. 115,013003. 3 Jul 2015*

Poster 104

Preparation and Control of Bosonic Logical Qubits

V.G. Matsos,[1,2] C.H. Valahu,[1,2] M.J. Millican,[1,2] T. Navickas,[1,2] X.C. Kolesnikow,[1,2] M.J Biercuk,[1,2] and T.R. Tan[1,2]

[1]*University of Sydney, NSW, Australia*

[2]*ARC Centre of Excellence for Engineered Quantum Systems, University of Sydney, NSW, Australia*

We present a robust, high-fidelity, and measurement-free optimal quantum control protocol for preparing and manipulating bosonic logical states encoded in the motional modes of a trapped ion. Our method enables the generation of several bosonic code words relevant to hardware-efficient quantum error correction. Notably, we prepare a Gottesman-Kitaev-Preskill (GKP) code word with a logical fidelity of 0.940(8) and 7.5(2) dB of squeezing, a distance-3 binomial state with an average fidelity of 0.807(7), and a squeezed vacuum state exhibiting 12.91(5) dB of squeezing [1]. Beyond state preparation, we demonstrate that our control techniques enable quantum logic on these bosonic encodings. This includes the first realization of a universal gate set on the GKP code, featuring single-qubit gates with fidelities up to 0.96(2) and, for the first time, a two-qubit entangling gate with a fidelity of 0.73(1). We also directly generate a GKP Bell state from ground-state oscillators in a single step, achieving a logical fidelity of 0.83(3) [2]. Our protocol is fully compatible with standard trapped-ion hardware, establishing optimal control as a powerful tool for advancing hardware-efficient, fault-tolerant quantum computation.

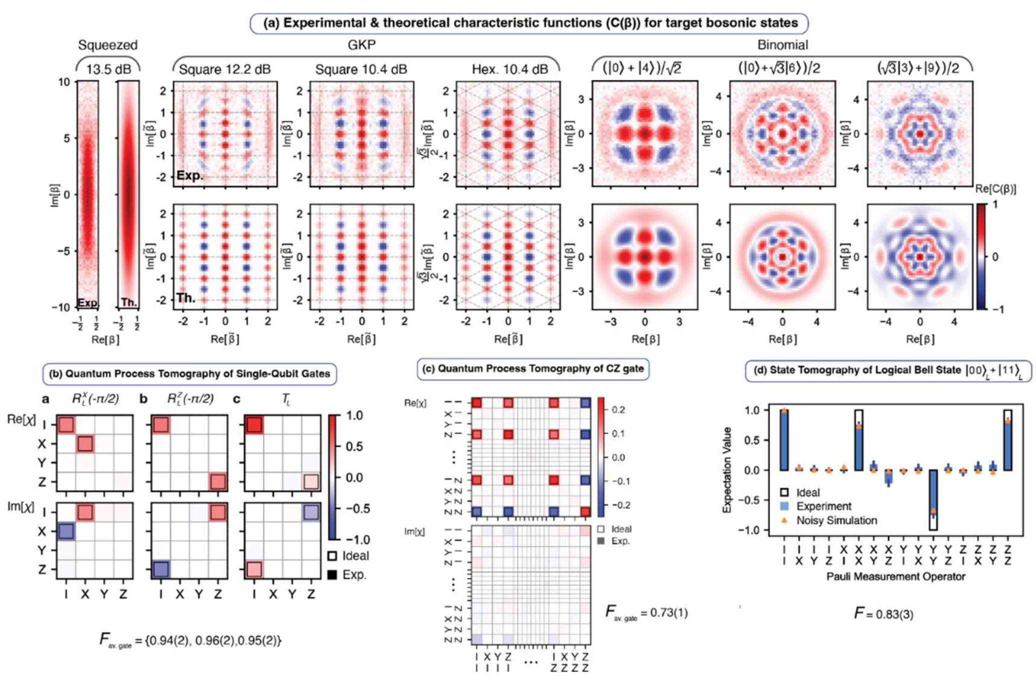


Figure 46: a) Theoretical and experimental characteristic function tomography for various bosonic states considered in in Ref. [1]. b) & c) χ matrices obtained from quantum process tomography of logical single- and two-qubit gates. d) Logical state tomography of a GKP Bell state [2].

[1] V.G. Matsos et al., *Phys. Rev. Lett.* **133,** 050602 (2024).
[2] V.G. Matsos et al., *ArXiv,* 2409.05455

Towards precision spectroscopy of highly charged ions to search for a variation of the fine structure constant

S. Kokh,[1] M. Winkelvoß,[1] F. Mayer,[1] M. Gizewski,[1] M. Schube,[1] A. Sterr,[1] T. Pfeifer,[1] J. C. López-Urrutia,[1] and **V. M. Schäfer[1]**

[1] *Max Planck Institute for Nuclear Physics, Heidelberg, Germany*

Precision spectroscopy of atomic transitions is a promising tool to test our understanding of fundamental physics and search for new physics beyond the standard model. Combining the excellent precision achievable with single trapped ions with the enhanced sensitivities to relativistic effects in highly charged ions (HCIs)[1,2,3] yields an ideal platform to search for a variation of the fine structure constant α - a possibility predicted for example by models for ultralight bosonic dark matter[4]. I will present the TwinTrap experiment, where we plan to perform a direct simultaneous frequency comparison between two complementary highly charged ions - Cf^{15+} and Cf^{17+} - via quantum logic spectroscopy[5]. I will present our progress on the design and construction of the experimental apparatus comprising of two identical cryogenic vacuum systems and an EBIT and ion beamline for delivery of the HCIs.

[1] M. G. Kozlov et al., *Rev. Mod. Phys.* **90**, 045005 (2018)
[2] J. C. Berengut, V. A. Dzuba, and V. V. Flambaum, *Phys. Rev. Lett.* **105**, 1 (2010)
[3] P. Micke et al., *Nature* **578**, 60 (2020)
[4] M. Filzinger et al., *Phys Rev Lett.*;**130**(25) (2023)
[5] P. O. Schmidt et al., *Science* **309**, 749 (2005)

Preparation of Trapped e^- + $^{40}Ca^+$ Platform for Quantum Microwave Detection

V. Kumar[1], N. V. Lausti[1], I. Hudák[1, 2], D. Motyčka[1], A. Jelínek[1], R. Rádek[1], P. Mahmoudi[3], M. Tarana[3], and M. Hejduk[1]

[1]*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*

[2]*Institute of Photonics and Electronics of the CAS, Prague, Czech Republic*

[3]*J. Heyrovský Institute of Physical Chemistry of the CAS, Prague, Czech Republic*

Quantum sensors enable high-precision detection of weak signals, with platforms ranging from superconducting qubits [2] to thermal vapors of alkali atoms [1], ultracold neutral atoms [3], trapped ions [4], and Rydberg atoms [5]. Each offers distinct advantages and technical challenges, such as decoherence from electric field noise in ion traps or laser complexity in Rydberg-based RF sensing [6,7]. We propose a dual-species detection system using a two-frequency Paul trap to simultaneously confine electrons and ions, building on theoretical work [8–10]. Electrons occupy "trap-induced" MHz-spaced energy levels tunable via trap parameters, with their excitation indirectly detected through ion motion.

In our electron-ion experiment (EiTEx) setup, we achieved pressures down to 2.5×10^{-10} mbar using 3D-printed trap and oven components, enabled by vibration-free NEG and ion pumps. Calcium evaporation temporarily degrades the vacuum (~9 min), so ions are preloaded and stored before electron experiments. The AlSi10Mg coaxial trap shows Q > 960 at 2.31 GHz, allowing low-power electron trapping. Blackened surfaces reduced stray light, enabling efficient LED-based fluorescence imaging with ~0.1 s exposure.

As Doppler cooling of $^{40}Ca^+$ ions approaches optimal performance, we are progressing towards the laser-cooled Coulomb crystal teasing via high-frequency GHz control. In this update, we share our latest experimental results on the simultaneous trapping and interaction of electron-ion pairs.

[1] Degen, C. L., et al. *Rev. Mod. Phys.* **89**, 035002 (2017).
[2] Wang, Zhiling, et al. *Nat. Commun.* **13**, 6104 (2022).
[3] Vengalattore, M., et al. *Phys. Rev. Lett.* **98**, 200801 (2007).
[4] Gilmore, A., et al. *Science* **373**, 673–678 (2021).
[5] Fan, H., et al. *J. Phys. B* **48**, 202001 (2015).
[6] Holloway, C. L., et al. *IEEE Trans. Antennas Propag.* **62**, 6169–6182 (2014).
[7] Simons, M. T., et al. *Appl. Phys. Lett.* **108**, 174101 (2016).
[8] Foot, C. J., et al. *Int. J. Mass Spectrom.* **430**, 117–125 (2018).
[9] Trypogeorgos, D., & Foot, C. J. *Phys. Rev. A* **94**, 023609 (2016).
[10] Leefer, N., et al. *Hyperfine Interact.* **238**, 12 (2016).

Poster 107

A single-ion $^{27}Al^{+}$ clock with 5.5×10^{-19} systematic uncertainty

W.J. Arthur-Dworschack,[1,2] D. Rodriguez Castillo,[1,2] M. Marshall,[1] D. Hume,[1]

[1] *Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO, USA*

[2] *Department of Physics, University of Colorado, Boulder, CO, USA*

The $^{1}S_{0}$ –$^{3}P_{0}$ transition in $^{27}Al^{+}$ is a precise and accurate frequency standard due to its narrow linewidth and low sensitivity to environmental perturbations [1]. Quantum logic spectroscopy using a co-trapped $^{25}Mg^{+}$ enables cooling and state readout of the clock ion. The NIST single-ion $^{27}Al^{+}$ clock has demonstrated a systematic uncertainty of $\delta f/f = 5.5 \times 10^{-1}$ and fractional frequency stability of $3.5 \times 10^{-16}/\sqrt{\tau/s}$ [2]. The reduction in uncertainty is due to a redesigned trap and improved vacuum system, as well as better characterization of key systematic shifts. These include new measurements of kinetic energy at the Doppler limit, differential polarizability, and direction-sensitive measurements of the AC magnetic field originating from the ion trap's RF. The improved stability is enabled by an increased Rabi probe duration of the $^{1}S_{0}$ –$^{3}P_{0}$ clock transition.

The NIST $^{27}Al^{+}$ apparatus is tailored for multi-ion operation, which can further improve the stability of the clock. Better control of trap electric fields and the improved vacuum system will enable clock spectroscopy on multiple Al^{+} without sacrificing systematic uncertainty or clock uptime. This poster reports on the NIST ^{27}Al+ clock's new uncertainty budget and progress toward multi-ion operations [3]. Future work with the multi-ion clock will include entangled states of Al^{+}, allowing for measurement stability beyond the standard quantum limit.

[1] Rosenband, T., *et al.* "Observation of the S 0 1→ P 0 3 clock transition in Al+ 27." *Phys. Rev. Lett.* 98.22 (2007): 220801.
[2] Marshall, M., *et al*. "High-Stability Single-Ion Clock with 5.5 x 10^-19 Systematic Uncertainty." arXiv:2504.13071v1, 17 Apr 2025.
[3] Cui, K., *et al.* "Scalable quantum logic spectroscopy." *Phys. Rev. Lett.* 129.19 (2022): 193603.

Filtration and measurement of multimode bosonic states using dispersive shift in trapped ions

W. Choi,[1,2] J. Kang,[1,2] K. Kim,[1,2] J. You,[1,2] and T. Kim[1,2,3]

[1]*Dept. of Computer Science & Engineering, Seoul National University, Seoul, South Korea*

[2]*Automation and Systems Research Institute, NextQuantum, Seoul National University*

[3]*Institute of Computer Technology, Institute of Applied Physics, Seoul National University*

As the number of trapped ions increases, the number of motional modes scales three times faster, rapidly enlarging the dimension of Hilbert space and enabling novel applications in quantum information processing. However, manipulating and measuring multimode bosonic states remains challenging in trapped-ion systems. Here, we present and experimentally demonstrate a multimode phonon-number state measurement and filtering scheme based on the dispersive regime of the Jaynes–Cummings Hamiltonian. This approach leverages the phonon-number-dependent Stark shift—also known as dispersive shift, spin-dependent rotation—to resolve phonon numbers with linear dependence on n, in contrast to the conventional blue sideband method, which resolves phonon numbers with $\sqrt{n}$ scaling. We show that dispersive shift is alternative method to estimate the phonon number population so that it can be used for multimode quantum state tomography. Our scheme requires only a single ancilla qubit to measure multiple phonon modes simultaneously. Furthermore, the dispersive shift acts as a generalized multimode parity operator, enabling phonon-number filtering based on generalized parity. Using this filtering, we generate nonclassical states such as even or odd cat states. We also implement single-shot phonon-number state measurement using repeated application of the filtering process [1]. Figure 1 illustrates the phonon number population before and after filtration. Since the phonon-number-dependent Stark shift is small compared to the Stark shift of the carrier transition, it is susceptible to laser power fluctuations. To address this, we employ a spin-echo technique to dynamically decouple the Stark shift of carrier.

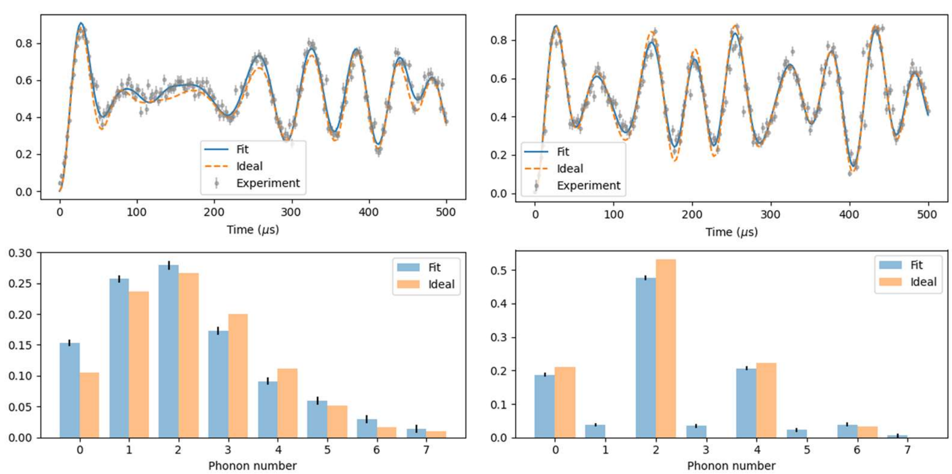


Figure 47. Phonon number state population of coherent state(left) and filtered state(right) with α=1.5. Odd number states are filtered out after filtration.

[1] X. Deng et al., Quantum-enhanced metrology with large Fock states, Nat. Phys. (2024).

Quantum gates with trapped ions and optical tweezers

Z.E.D. Ackerman,[1] L.P.H. Gallagher,[1] M. Mazzanti,[2] R.X. Schüssler,[3] N. Diepeveen,[1] C. Robalo Pereira,[1] A. Safavi-Naini,[4,5] R.J.C. Spreeuw[1] and R. Gerritsma[1]

[1]*Van der Waals – Zeeman Institute, University of Amsterdam, the Netherlands*

[2]*Institut für Quantenelektronik, ETH Zürich, Switzerland*

[3]*GSI Helmholtzzentrum für Schwerionenforschung, Germany*

[4]*QuSoft, The Netherlands*

[5]*Institute for Theoretical Physics, Institute of Physics, University of Amsterdam, The Netherlands*

An ion can experience an off axis, spin-dependent dipole force caused by strong polarization gradients of tightly focused optical tweezers[1]. We present a novel two-qubit quantum gate as an implementation of this effect[2]. This tweezer-driven quantum gate requires only a single beam per ion and promises a fidelity of $F \geq 0.999989$ without the need for ground-state cooling of the ions.

In this poster, I will elaborate on our current experimental setup and our progress in developing a programmable UV hollow-tweezer array, aimed at minimizing photon scattering and AC Stark shift. Our proposed setup integrates an acousto-optical deflector and a spatial light modulator to facilitate precise control over the beam shape while enabling rapid switching between ion pairs for implementing the quantum gates.

[1] R. Spreeuw, *Phys. Rev. Lett.* **125**, 233201 (2020)
[2] M. Mazzanti et al., *Phys. Rev. Research.* **5**, 033036 (2023).

Infrared single photon absorption spectroscopy of a single polyatomic molecular ion

Z. Wu,[1] T.C. Duka,[1] M. Isaza-Monsalve,[1] V. Švarc,[2] M.A. Kautzky,[1] R. Nardi,[1] A Turci,[1] B.J. Furey,[1] and P. Schindler[1]

[1]*University of Innsbruck, Innsbruck, Austria*

[2] *Palacký University, Olomouc, Czech Republic*

Co-trapping molecular ions with auxiliary atomic ions in an ion trap enables molecular spectroscopy at single-molecule level, as experimentally demonstrated on various diatomic species [1-6]. Our research aims to extend this approach to polyatomic molecular ions which feature complex phenomena such as ultrafast intramolecular vibrational energy redistribution. Here, we demonstrate single photon absorption spectroscopy on the O-H stretching mode of CaOH+. Each absorption event transfers single photon recoil onto the shared motion of the molecule and the atom, which can then be readout via the atom. To probe the recoil of infrared photons, an entanglement-assisted readout scheme is introduced [7]. The detection method does not require narrow band lasers and can act as the basis for pump-probe experiment with femtosecond laser pulses on a single trapped polyatomic molecular ion [8]. Furthermore, we also plan to further control and investigate the rovibrational structure of CaOH+ by tailored femtosecond laser pulses [9].

[1] F. Wolf et al., *Nature* **530**, 457–460 (2016).
[2] C.W. Chou et al., *Nature* **545**, 203–207 (2017).
[3] M. Sinhal et al., *Science* **367**, 1213–1218 (2020).
[4] S. Alighanbari et al., *Nature* **581**, 152–158 (2020).
[5] D. Holzapfel et al., *arXiv*:2409.06495 (2024).
[6] L. Qi et al., *arXiv*:2411.07137 (2024).
[7] C. Hempel et al., Nature Photonics **7**, 630–633 (2013).
[8] P. Schindler, *New J. Phys.* **21**, 083025 (2019).
[9] P.R. Stollenwerk et al., *Phys. Rev. Lett.* **125**, 113201 (2020).

Coherent dynamics of a nuclear-spin-isomer superposition

T. Levin,[1] and **Z. Meir[1]**

[1] *Weizmann Institute of Science, Rehovot, Israel*

Preserving quantum coherence becomes increasingly challenging as systems grow in size and complexity. Molecules, with their rich internal structure, offer a unique playground for studying the transition from quantum to classical behavior. Here [1], we present a scheme to coherently couple two distinct nuclear-spin isomers of the same molecule, specifically, the I=0 and I=2 nuclear-spin isomers of the nitrogen molecular ion. Our approach leverages an avoided crossing in the nitrogen-ion spectrum that mixes the two different isomers via an electric-quadrupole hyperfine interaction. We show how to use this avoided crossing to strongly and coherently couple two unmixed nuclear-spin-isomer states, hence creating a nuclear-spin-isomer qubit.

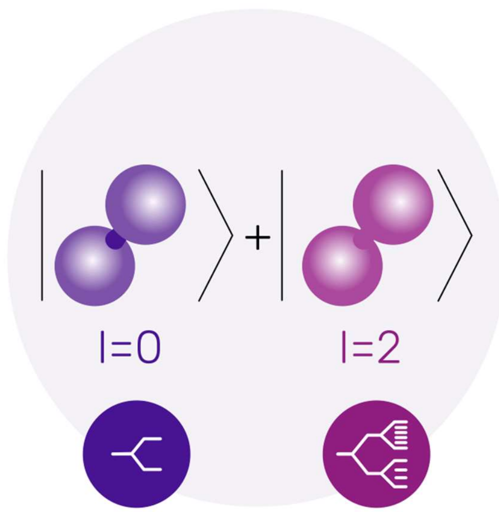


Figure 48: A quantum superposition of two distinct nuclear-spin isomers of the nitrogen molecular ion, N_2^+, where one isomer (I=0) does not have a hyperfine structure, while the other (I=2) does.

[1] T. Levin and Z. Meir, *Phys. Rev. Research* **7,** 013274 (2025).

Poster 112

Observation of Space-Dependent Rotational Doppler Shifts with a Single Ion Probe

Nicolás Adrián Nuñez Barreto[1,2], Muriel Bonetto[1,2], Marcelo Luda[3], Cecilia Cormick[4], Christian Tomás Schmiegelow[1,2]

[1] *Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, Laboratorio de Iones y Átomos Fríos, Pabellón 1, Ciudad Universitaria, 1428 Buenos Aires, Argentina*

[2] *CONICET - Universidad de Buenos Aires, Instituto de Física de Buenos Aires (IFIBA), Pabellón 1, Ciudad Universitaria, 1428 Buenos Aires, Argentina*

[3] *CEILAP, CITEDEF, Buenos Aires, 1603, Argentina*

[4] *Universidad de la República, Facultad de Ingeniería, Instituto de Física, Julio Herrera y Reissig 565, 11300 Montevideo, Uruguay*

We present an experiment investigating the rotational Doppler effect using a single trapped ion excited by two copropagating vortex laser beams. The setup isolates the azimuthal gradients of the fields, eliminating longitudinal and curvature effects. We provide a detailed characterization of the phenomenon by deterministically positioning a single ion across the beams and measuring fluorescence spectra with sharp “dark resonances” whose features depend on the angular velocity of the ion and the difference of optical orbital angular momentum between the two beams. The interpretation of the measurements is supported by numerical simulations and by a simplified analytical model. Our results reveal key properties of the rotational Doppler effect, showing that it increases approaching the center of the beam and that it is independent of the waist of the beam. This offers insights into the feasibility of superkicks or super-Doppler shifts for sensing and manipulating atomic motion transverse to the beams’ propagation direction.

Assessing microwave gate fidelities with trapped ions

H. Keßler,[1] G. Enzian,[1] E. Rowe,[1] F. Köppen,[1] H. Siebeneich,[1] A.-R. Rasul,[1] C. Piltz,[1] T. Gloger,[1] and M. Johanning[1]

[1]*eleQtron GmbH, Siegen, Germany*

In recent years, trapped ions have emerged as a prime candidate for the establishment of noisy intermediate-scale quantum (NISQ) computers. eleQtron builds quantum computers based on trapped $^{171}Yb^{+}$ ions interacting via MAGIC (MAgnetic Gradient Induced Coupling). The magnetic gradient results in a position-depending Zeeman shift of the qubit transition energy and facilitating the use of different microwave frequencies to achieve coherent control of individual ions. Microwave technology is very sophisticated, which makes quantum computers based on that technology promising candidates to overcome the scalability challenge. Nevertheless, it is needed to estimate the error budget of the individual components in the microwave signal chain to identify limits and optimize signal quality. Finally, we use measurements of the lifetime of the prepared quantum state and quantum gate fidelities to verify the estimations.

[1] C. Piltz et al., Nat. Commun. 5, 4679 (2014)

Quantum technologies with trapped electrons

A. Migó I Lluís,[1] **A. Ridley**,[1] **A. Lindner**[1] , R. Willetts[1], R. Álvarez-García[1], J. Pinder[1] and J. Verdú[1]

[1]*University of Sussex, Brighton, UK*

In the Geonium Chip group at the University of Sussex we are developing a novel planar Penning trap technology for trapped electrons [1]. It has applications in both fundamental physics–such as mass spectrometry and the determination of the neutrino mass–and quantum microwave technologies [2] such as radar and microscopy. The trap is fabricated with a printed-circuit-board (PCB) chip, which retains the conventional axial symmetry of the electrostatic trapping potential. Its low parasitic capacitance enables the integration of a differential detection system directly onto the chip, allowing for broadband detection below 1 MHz in specific configurations. Our first prototype of a tuneable planar magnetic field source has demonstrated a homogeneous magnetic field of 0.5 T at 4 K [3]. The next-generation system under development will operate in persistent mode and feature a pioneering flux-pumping technique [4] built on a high-temperature superconducting (HTS) substrate. For this, we have constructed a compact 30 K bench-top cryostat cooled by a Stirling cryocooler. Finally, in order to load the trap, we've achieved currents on the order of 100 nA in high-magnetic fields with a carbon nanotubes field-emission-point source.

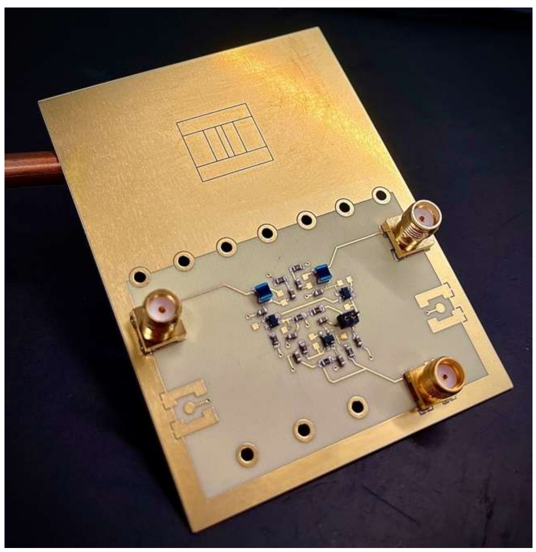


Figure 49: Geonium Chip containing the detection system.

[1] A. Al-Rjoub and J. Verdú, Appl. Phys. B 107, 955 (2012).
[2] A. Cridland et al., Appl. Sci. 6, 23 (2016).
[3] J. Pinder et al., Rev. Sci. Instrum. 91, 103201 (2020)
[4] J.H. Lacy et al., IEEE Trans. Appl. Supercond. 32, 4100905 (2022).

A 7-qubit high optical access trapped-ion system for quantum information process

Yi-Long Chen,[1,2,3] Shu-Qian Chen,[1,2,3] Gong-Chu Li, [1,2] Wen-Hao Qi,[4] Wen-Hao Qi,[1,2] Jin-Ming Cui, [1,2,3] Yun-Feng Huang, [1,2,3] Chuan-Feng Li, [1,2,3] Guang-Can Guo[1,2,3]

[1]*CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, China*

[2]*CAS Center For Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China*

[3]*Hefei National Laboratory, University of Science and Technology of China, Hefei 230088, China*

[4]*Unitary Quantum Co., Ltd., Hefei, China*

Trapped-ion system has proven to be a leading platform for quantum information processing due to its high-quality qubit properties and programmable quantum operations. Here, we present a 7-qubit system, based on a high-optical-access blade trap. By employing far-detuned Raman lasers and dual-side AOD-based addressing, our system achieves low-crosstalk Raman operations ($\sim10^{-3}$)[1], high-fidelity single-qubit gates (average 99.95%), and fully connected two-qubit gates (average >99%). We also develop an efficient entanglement characterization protocol and successfully estimate mixed states entanglement properties corresponding to approximately 877 partitions from a single set of measurement data. Moreover, combined with the ability to track entanglement structure under different circuit dynamics, our system shows as a powerful tool for investigating many-body quantum phenomena in the future.

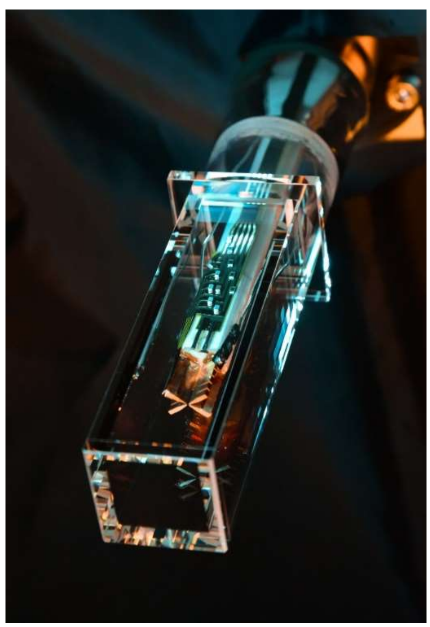


Figure 50: high-optical-access ion trap.

[1] Yi-Long Chen et al., *Phys. Rev. Applied.* **22,** 054003 (2024).

Poster 116

Quantum networks based on ion traps and solid-state quantum memory systems

C.X. Wang,[1,2] Y.C. Li,[1,2] Q.Q. Yao,[1,2] J.M Cui,[1,2] and Y.F Huang[1,2]

[1]*University of Science and Technology of China, Hefei, China*

[2]*Hefei National laboratory, Hefei, China*

We report a quantum network which link the ion trap and solid-state quantum memory. The interface makes use of low-noise and polarization-maintaining quantum frequency conversion to match the photon profiles of the memory. The ion trap and the solid-state quantum memory are located in two separate rooms that are 90 meters apart. We transport the photon from room 1 to room 2, and then store the photon. The ion-photon entanglement between ion trap and memory is in measuring now. Our work shows the feasibility of constructing an integrated large-scale quantum network.

General guidelines:

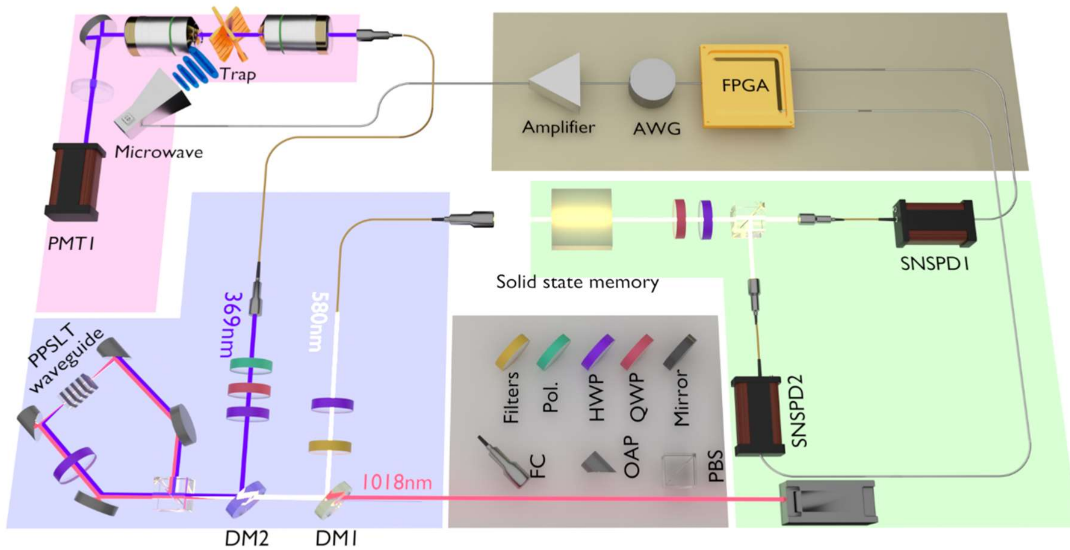


Figure 51: Experiment setup for our quantum network.

Optical tweezer applications in $^{40}Ca^{+}$ trapped ions

P. Leindecker,[1,2] L. Milanovic,[1,2] E. Brucke,[1,2] and C. Hempel[1,2,3,4]

[1]*ETHZ-PSI Quantum Computing Hub*

[2]*Institute for Quantum Electronics, ETH Zürich*

[3]*Quantum Center, ETH Zurich*

[4]*LNQ, Paul Scherrer Institute (PSI)*

Optical tweezers are widely used for trapping neutral atoms, and have also been proposed as a tool for manipulating trapped ions. These tightly focused laser beams create a state-dependent potential, enabling the implementation of both state-dependent motional mode shifts and forces. By employing a deep optical potential at an off-resonant wavelength of 730 nm, we achieve a large differential motional mode shift of up to 34 kHz with minimal scattering-induced decoherence. Using these effects, we demonstrate state-dependent displacement and squeezing of the motional modes of a trapped $^{40}Ca^{+}$ ion. In addition, we experimentally compare Laguerre–Gaussian beam shapes to further minimize AC Stark shifts. Our results establish optical tweezers as a versatile tool for controlling trapped ions, with promising prospects for application in long ion chains for quantum information processing and precision sensing.

Low Loss Photonics for Industrial Ion Trap Chips

Alexander Zesar[1,2], Delia Fugger-Schafhauser[2], Sofia Cano-Castro[2,3], Luca Rieder[2,4], Yves Colombe[2], Max Glantschnig[2,5], Arie McOnie[1,2], Philipp Werhounig[1,2], Silke Auchter[2], Klemens Schüppert[2] and Joachim Krenn[1]

[1]University of Graz, Austria

[2]Infineon Technologies Austria AG

[3]Paul Scherrer Institute, Switzerland

[4]University of Vienna, Austria

[5]Physikalisch Technische Bundesanstalt Braunschweig, Germany

Ion trap quantum processors hosting hundreds of ions require integrated photonics for reliable, precise and high-quality beam placement. This work showcases a CMOS-compatible silicon nitride platform for 200 mm wafer diameter, tailored for integration in complex ion-trap stacks. A best-in-class slab loss of <0.3 dB/cm at 488 nm wavelength [1, 2] as well as an optimized structuring process resulting in < 1 nm line edge roughness enable low optical noise ion-trap operation. On top of that, focusing grating couplers with feature sizes below 100 nm are reliably fabricated via optical lithography. The increase of functionality and complexity being packed into ion-trap chips demand highly uniform and repeatable processes as well as low defect density, provided by an industrial fabrication environment. Lastly, this work discusses a versatile characterization and prototype assembly setup.

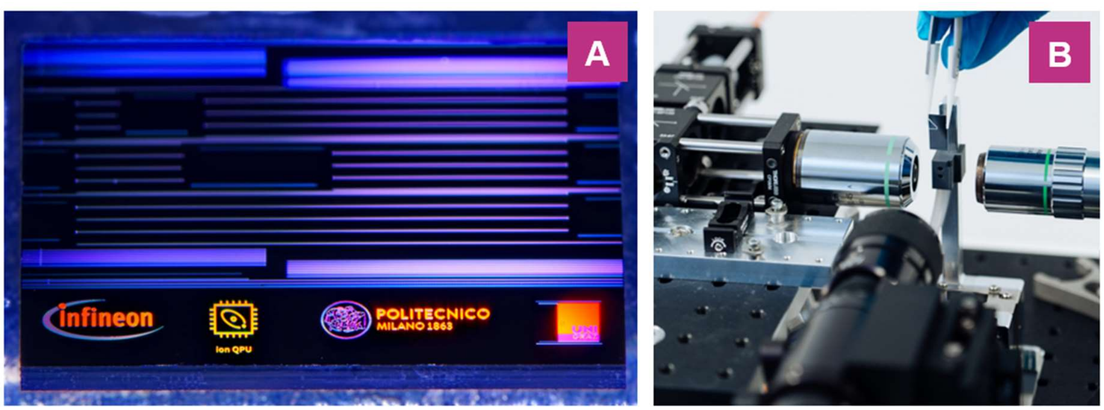


Figure 52. A: Silicon nitride waveguide test vehicle fabricated at Infineon. B: Photonic integrated circuit characterization and prototype assembly setup.

[1] A. Gorin et al., *Opt. Express* **16**, 13509-13516 (2008)
[2] K. Joonhyuk et al., *Nature communications* **15.1** (2024)

Transverse Polarization Gradient Entangling Gates for Trapped-Ion Quantum Computation

Jin-Ming Cui,[1,2,3,4] Yan Chen,[1,2,3] Yi-Fan Zhou, [1,2,3,4] Quan Long, [1,2,3,4] En-Teng An[1,2,3,4], Ran He, [1,2,3] Yun-Feng Huang, [1,2,3,4] Chuan-Feng Li, [1,2,3,4] and Guang-Can Guo[1,2,3]

[1]*Laboratory of Quantum Information, USTC, Hefei 230026, China*

[2]*Anhui Province Key Laboratory of Quantum Network, USTC, Hefei 230026, China*

[3]*CAS Center For Excellence in Quantum Information and Quantum Physics, USTC, Hefei 230026, China*

[4]*Hefei National Laboratory, USTC, Hefei 230088, China*

The construction of entangling gates with individual addressing capability represents a crucial approach for implementing quantum computation in trapped ion crystals. Conventional entangling gate schemes typically rely on laser beam wave vectors to couple the ions' spin and motional degrees of freedom. Here, we experimentally demonstrate an alternative method that employs a polarization gradient field generated by a tightly focused laser beam—an approach theoretically proposed as the Magnus effect for quantum logic gate design [Phys. Rev. Res. 5, 033036 (2023)]. Using this technique, we perform Raman operations on nuclear spin qubits encoded in 171Yb+ ions, generating spin-dependent forces along the axial motional mode in a linear trap. By utilizing an acousto-optic deflector to create arbitrary spot pairs for individual ion addressing in two-ion (four-ion) chains, we achieve Mølmer-Sørensen gates with fidelities exceeding 98.5% (97.2%). Further improvements in numerical aperture (NA) and laser power could reduce gate durations while enhancing fidelity by orders of magnitude. This method is compatible with—and can significantly simplify—optical tweezer architectures, where motional mode engineering enables scalable trapped-ion quantum computation. The technique can be readily extended to two-dimensional ion crystals, representing a key advancement toward large-scale trapped-ion quantum processors.

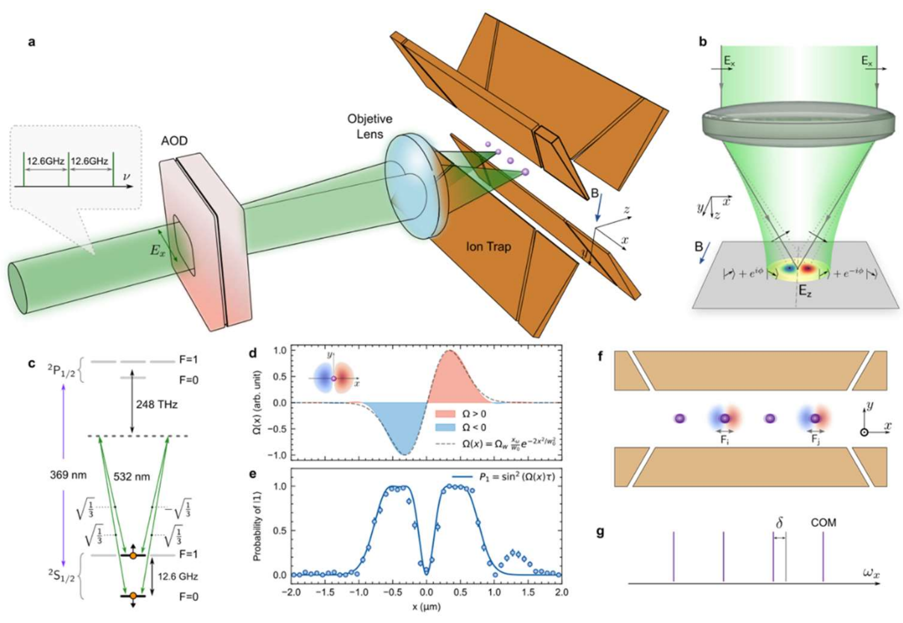


Figure 53

Fast radio frequency-driven entangling gates with trapped ions using back-to-back dynamical decoupling pulses

P. H. Huber[1], M. Nünnerich[1], D. Niroomand[1], and C. Wunderlich[1]

[1]*Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Germany*

Entangling gates are fundamental in quantum information science. Ideally, they operate at high speed in a robust and scalable manner. Here, we report on the generation of Bell states of hyperfine qubits of two ions by applying two resonant radio frequency (RF-) driving fields. The phase of the driving fields vary periodically in discrete values, yielding effectively a sequence of back-to-back dynamical decoupling pulses.

By adjusting the Rabi frequency induced by the driving fields, the effective coupling of the qubits to the ions' motional state is changed, and the entangling gate speed can be varied between ≈ 4 ms and ≈ 300 µs. In currently used micro-structured traps with larger magnetic field gradients, gate speeds on par with laser-driven gates in trapped ions are expected.

The experiments are carried out using two laser cooled $^{171}Yb^{+}$ ions confined in a Paul trap. The ions are exposed to a static magnetic gradient field of 19 T/m that induces an effective qubit-qubit interaction (MAgnetic Gradient Induced Coupling, MAGIC). The hyperfine states $|0\rangle \equiv |^2S_{1/2}, F=0, m_\mathrm{F}=0\rangle$ and $|1\rangle \equiv |^2S_{1/2}, F=1, m_\mathrm{F}=-1\rangle$ serve as qubits.

State-selective preparation and trapping of H_2^+

Daniel Knapp,[1] Daniel Ochoa Franco,[1] Maximilian Beyer[1]

[1]*Vrije Universiteit Amsterdam, Amsterdam, the Netherlands*

Rigorous tests of QED and precise measurements of the proton-to-electron mass ratio are compelling applications for high precision spectroscopy of the dihydrogen cation. We propose to carry out millimeter-wave spectroscopy in the Lamb-Dicke regime on H2+ in a novel radiofrequency wire trap. State-selected ions originate in a mass-analyzed threshold ionization using an excitation to a Rydberg series converging to the desired ro-vibrational ionization threshold at a high repetition rate. This technique doesn't rely on fluorescence and can be broadly applied to provide molecular ions with almost arbitrary excitation of the rovibrational degrees-of-freedom. The Rydberg excitation can proceed from the ground state using vacuum-ultraviolet light, or alternatively, take place from a metastable state prepared using a discharge. Ions are extracted out of a supersonic beam and axially injected into the trap. Electronic transitions are detected in a destructive fashion by monitoring the mass spectrum obtained from selectively photodissociated fragments.

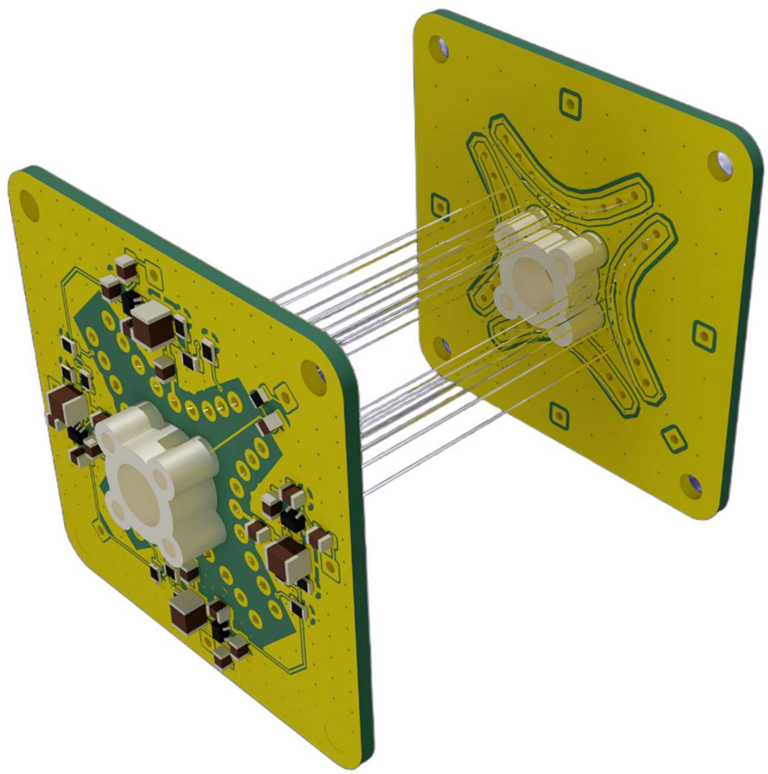


Figure 54: The proposed wire linear Paul trap: macroscopic to ease ion injection, and transparent to ~100GHz millimeter waves that will be used for precision spectroscopy.

Fast Transverse Mode Gate with Trapped Ions

H. Tu,[1] C. Luan,[1] Z. Yin,[1] M. Zou,[1] R. Kamram,[2] and K. Kim[1,2]

[1] *Tsinghua University, Beijing, China*

[2] *Beijing Academy of Quantum Information Sciences, Beijing, China*

Fast two-qubit entangling gates are crucial for executing deep quantum circuits within the coherence time of trapped-ion qubits. Transverse motional modes of provide better spectral control and remain well-behaved as the number of ions increases, making them advantageous for scalable gate operations. Here, we demonstrate light-shift-based phase gates mediated by transverse modes in a system of two trapped $^{171}Yb^{+}$ ions. Entangling gates with durations of 6.45μs, 13.9μs, and 17.60μs are realized, achieving Bell-state fidelities of 87.35%, 93.63%, and 96.27%, respectively. These results highlight the viability of transverse-mode-based gates for fast, robust entangling operations, enabling deeper quantum circuits with enhanced spectral control and stability.

Towards quantum logic spectroscopy of highly charged heavy ions for novel optical clocks

L. Kau,[1,2,4] N. Homburg,[1,2,4] Hiroshi Hayakawa,[1,2,4] Zoran Andelkovic,[1] Thomas Stöhlker,[1,2,3,4] and P. Micke[1,2,3,4]

[1]*GSI Helmholtz Center for Heavy Ion Reasearch, Darmstadt, Germany*

[2]*Helmholtz Institute Jena, Jena, Germany*

[3]*Abbe Center of Photonics, Jena, Germany*

[4]*Friedrich Schiller University Jena, Jena, Germany*

Highly charged heavy ions, particularly hydrogen- or lithium-like species, are exceptional probes for fundamental physics. With extreme internal electromagnetic fields and forbidden hyperfine-structure transitions in the optical regime (e.g. 1019.7 nm in $^{207}Pb^{81+}$ [1]), they are highly sensitive to physics beyond the Standard Model [2 - 4]. Additionally, systematic effects from external perturbations are highly suppressed, and the atomic structure is simple. These ions are therefore excellent systems to test our understanding of nature and to realize novel high-accuracy optical clocks.

While quantum logic spectroscopy (QLS) and an optical clock has been demonstrated with lighter HCIs [5, 6], it remains an open challenge for the heaviest ions in their highest charge states. Currently, for these heavy ions laser spectroscopy in a storage ring sets the state of the art with 10^{-5} uncertainty levels [7, 8]. Setups, which integrate sources for highly charged heavy ions, cryogenic Paul traps, and QLS, are under development and have the potential to improve precision and accuracy by many orders of magnitude. Essentially only limited by the natural linewidth of the clock transition itself, these setups will enable unprecedented tests of fundamental physics and searches for physics beyond the Standard Model.

This contribution reports on our development of a unique and versatile QLS platform for accelerator-produced highly-charged heavy ions downstream the HITRAP decelerator at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt.

[1] Seelig et al., Phys. Rev. Lett. **81** (1998)
[2] S. Schiller et al., Phys. Rev. Lett. **98**, 180801 (2007)
[3] N. S. Oreshkina et al., Phys. Rev. **96**, 030501(R) (2017)
[4] M. G. Kozlov et al., Rev. Mod. Phys. **90**, 045005 (2018)
[5] P. Micke et al., Nature **578**, 60–65 (2020)
[6] S. A. King et al., Nature **611**, 43–47 (2022)
[7] J Ullmann et al., Nat. Commun. **8**, 15484 (2017)
[8] M. Horst et al., Nat. Phys. **8**, 15484 (2025)

Poster 124

Development of fused silica monolithic trap for two-dimensional ion crystal

Lingfeng Ou[1], Erfu Gao[1], Yuan Chai[1], Zhengyang Cai[1], Mu Qiao[1], Honghua Fang[1], Hongbo Sun[1] and Kihwan Kim[1]

[1]*Tsinghua University, Beijing, People's Republic of China.*

Two-dimensional (2D) ion trap platforms are essential for generating highly entangled quantum states and exploring strongly correlated many-body quantum phenomena. In our previous work, we developed a monolithic alumina chip trap capable of stably loading stationary 2D ion crystals [1,2]. However, its performance in scaling up ion numbers and simulating quantum magnetism was primarily constrained by a high anomalous heating rate [2].

To overcome these limitations, we have now developed a novel monolithic trap using femtosecond-laser-assisted selective etching in fused silica. This 3D-printing-based fabrication method significantly enhances structural precision and reduces surface roughness by an order of magnitude. Additionally, the new vacuum system incorporates electric-field shielding structures that effectively suppress ambient electric noise by more than an order of magnitude.

Using this improved platform, we achieved a low heating rate of 70 phonons/s and successfully loaded up to 270 ions in a stable 2D configuration. We believe this fused silica monolithic trap offers a robust foundation for advancing quantum simulations and quantum computations with both one-dimensional ion chains and two-dimensional ion crystals.

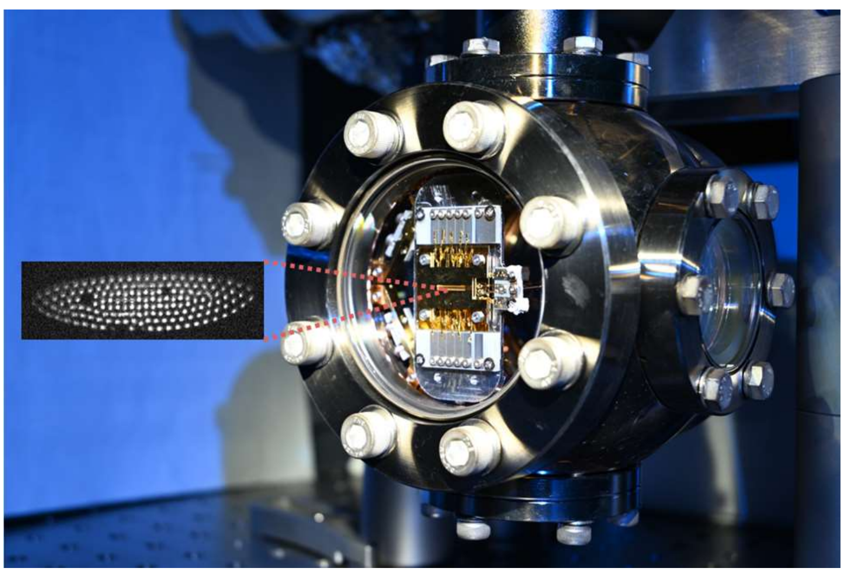


Figure 1: the chip trap in the chamber, insert is the trapped two-dimensional ion crystal.

[1] Wang Ye, et al. ***Adv. Quantum Techn***. 3, 2000068 (2020).
[2] Qiao Mu, et al. ***Nature Physics*** (2024): 1-8.

Micro-structured ion traps with integrated magnets for quantum science

D. Busch[1], B. Bürger[1], I. Boldin[1], P. H. Huber[1], C. Wunderlich[1]

[1]Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Germany

We report on the experimental characterization of a novel micro-structured Paul-trap that includes an integrated microwave electrode for efficient single-qubit manipulations and micro-structured, quasi-2D permanent magnets for creating a magnetic field gradient. This is the basis for scalable laser-free coherent addressing of individual ions and multi-qubit gates via MAgnetic Gradient Induced Coupling (MAGIC). All measurements are carried out using hyperfine qubits of laser cooled $^{171}Yb^{+}$ ions exposed to a static magnetic gradient field of up 45 T/m.

Furthermore, the design of trap chips is reported that feature an advanced arrangement of micro-magnets with optimized field strength, gradient and direction in different trapping zones used for laser cooling and quantum information processing, respectively. The micromagnets are meticulously designed to produce high field gradients while maintaining a low absolute field strength. In the cooling/readout zones, the magnets generate a small homogeneous magnetic field to facilitate efficient Doppler cooling on larger ion crystals. In addition, the magnetic field direction is optimized in each zone to support π- and σ-polarized radio frequency-driven transitions in $^{171}Yb^{+}$ ions for efficient cooling and gate operations, respectively.

Progress on a Deployable Quantum Network Node Based on Trapped $^{40}Ca^+$ Ions Coupled to an Optical Cavity

M. Jia,[1] P. Wintermeyer,[1] B. P. Lanyon,[1] T. E. Northup,[1] J. Schupp[2]

[1]*Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Österreich*

[2]*Alpine Quantum Technologies GmbH, Technikerstraße 17/1, 6020 Innsbruck, Österreich*

Creating a quantum network with long-distance entanglement will enable advances ranging from secure communication and distributed quantum computing to fundamental research in quantum physics. A pivotal component of a quantum network is the end nodes — systems that are capable of preparing, manipulating, and detecting quantum states. Here we present our ongoing work, carried out as part of the Quantum Internet Alliance consortium of the EU's Quantum Flagship: a compact and portable rack-mounted trapped-ion processing node (end node) providing a quantum interface between stationary ions and photons in a quantum network.

The system presented was designed by Alpine Quantum Technologies (AQT), incorporating a compact and refined version of the cavity-integrated ion-trap design originally developed at the University of Innsbruck. In this rack-mounted setup, trapped $^{40}Ca^+$ ions are coupled to the mode of a high-finesse optical cavity. Our first central aim is to demonstrate ion-photon entanglement and then photon-mediated ion-ion entanglement between end nodes, ultimately contributing to a pan-European quantum network.

We have demonstrated stable trapping of crystallised multi-ion strings in the integrated system, along with clear evidence of coupling between the ions and the optical cavity. In preliminary measurements, we have observed that when the cavity is locked, the noise on the lock varies depending on which devices in the rack are on. We are working on strategies to reduce this noise. Furthermore, the current noise is comparable to values reported in Ref. [1] even with all devices on. Additionally, the fully rack-mounted electrical and optical control systems are in place to perform basic quantum control of the trapped ions. Together, these results mark key steps toward a compact ion-cavity interface for quantum network end nodes that are operational under data centre conditions.

Figure 55: Quantum network processing node with rack-mounted ion-trap cavity system.

[1] V. Krutyanskiy, M. Galli, et al., Phys. Rev. Lett. 130, 050803 (2023).

Radio-frequency and laser spectroscopy of the HD^+ molecular ion with high accuracy

J.B.E. Schokking,[1] W.G. Roeterdink,[1] V. Barbé,[1] D.A. Kliukin,[1] K.S.E. Eikema,[1] and J.C.J. Koelemeij[1]

[1]*Vrije Universiteit Amsterdam, Amsterdam, the Netherlands*

Recent two-photon Doppler-free spectroscopy of two hyperfine lines belonging to the v=0→9 overtone transition in the deuterated molecular hydrogen ion (HD^+) revealed a significant (8.5 kHz or 9.1σ) deviation between the observed and the theoretically predicted hyperfine splitting [1,2]. To determine the cause of this deviation we are currently performing radiofrequency (rf) electron spin resonance spectroscopy of the v=0 and v=9 hyperfine structure, employing resonance-enhanced multiphoton dissociation for the detection of rf-driven spin flips with a target uncertainty of 0.1 kHz. The hyperfine shifts may shed light on the origin of the 8.5 kHz deviation. As a consistency check, we also plan on improved measurements (with uncertainty in the Hertz range) of the v=0→9 overtone transition, where we will exploit the national SURF Time&Frequency network service for optical frequency measurements traceable to the SI-second realized at VSL Delft with uncertainty in the 15th decimal place. These measurements could subsequently lead to improved determinations of the proton-electron and deuteron-electron mass ratios, as well as more stringent tests of the quantum electrodynamics of molecular vibrations.

[1] S. Patra et al., *Science* **369,** 1238 (2020).
[2] J.-Ph. Karr and J.C.J. Koelemeij, *Mol. Phys.* **121,** e2216081 (2023).

Observation and Analysis of Phonon Propagation in a Many-ion Array under Harmonic Potential

T. Yuri,[1] Y.-X. Chen,[1] and K. Toyoda[2,1]

[1]*Graduate School of Engineering and Science, The University of Osaka*

[2]*Center for Quantum Information and Quantum Biology, Institute for Open and Transdisciplinary Research Initiatives, The University of Osaka*

In recent years, quantum simulation has emerged as a promising approach for elucidating many-body quantum phenomena that are intractable with classical computational methods [1]. Highly controllable quantum platforms such as superconducting circuits, neutral-atom arrays, and trapped ions have been actively employed for this purpose [2-4]. Among them, the trapped-ion system is particularly attractive because it combines long coherence times [5] with precise, site-resolved control over individual ions.

In quantum simulation using trapped ions, both the internal states (spins) and the vibrational modes (phonons) can be employed as effective simulation resources. The internal state has been widely used in quantum information processing as ideal qubits. On the other hand, vibrational modes possess multiple quantum levels and can also be utilized as effective computational resources in quantum information and quantum simulation [6,7]. However, in large ion arrays, controlling the quantum states of vibrational modes is technically challenging, and experimental studies at the single-phonon level have been limited [8,9]. We experimentally observed the propagation of a single phonon in a 10-ion array (Figure 1) and compared the results with theoretical analysis (Figure 2). We found that the inhomogeneous ion spacing, inherent in harmonic trapping potentials, gives rise to characteristic phonon propagation behavior. In this poster, we report on these results.

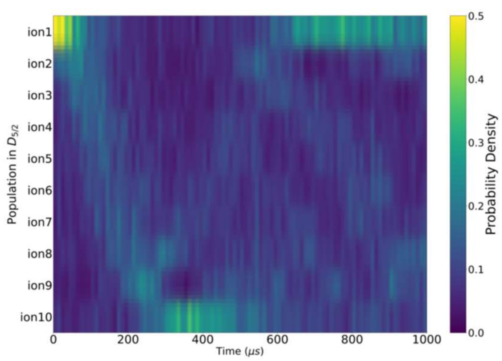


Figure 56: Experimental result showing the propagation propagation of a phonon prepared at site 1.

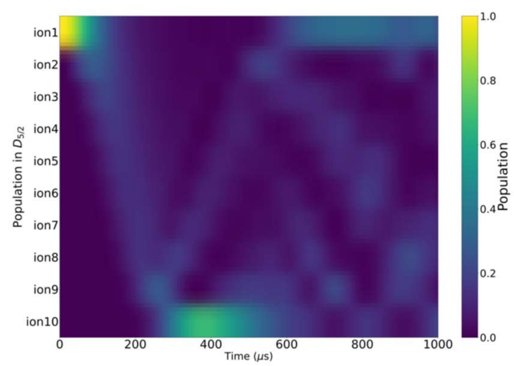


Figure 2: Numerical result showing the of a phonon prepared at site 1.

[1] R. P. Feynman, Int. J. Theor. Phys. 21, 467 (1982).
[2] F. Arute, et al., Nature **574**, 505 (2019).
[3] H. Bernien, et al., Nature **551**, 579 (2017).
[4] R. Islam, et al., Science **340**, 583 (2013).
[5] K. Kim, et al., Science, **331**, 1053 (2023).
[6] C. Flühmann et al., Nature **566**, 513 (2019).
[7] D. Porras and J. I. Cirac, Phys. Rev. Lett. **93**, 263602 (2004).
[8] S. Haze, et al., Phys. Rev. A **85**, 031401 (R) (2012).
[9] M. Tamura, et al., Phys. Rev. Lett. **124**, 200501 (2020).

Efficient characterization and error mitigation of global entangling gates in trapped ion system

Wentao Chen[1], Zhengyang Cai[1], Yuchen Guo[1], Pengfei Wang[1,2], Jialiang Zhang[1], Yingye Huang[1], Guoyu Zou[1], Shuo Yang[1] and Kihwan Kim[1,2]

[1] *Department of Physics, Tsinghua University, 100084, Beijing, China*

[2] *Beijing Academy of Quantum Information Sciences, 100193 Beijing, China*

Quantum error mitigation has been extensively explored to increase the accuracy of the quantum circuits in noisy-intermediate-scale-quantum computation, where quantum error correction requiring additional quantum resources is not adopted. Among various error-mitigation schemes, probabilistic error cancellation has been proposed as a general and systematic protocol that can be applied to numerous hardware platforms and quantum algorithms. In this work, we experimentally demonstrate the quantum process tomography and error mitigation of global entangling gates in a trapped-ion system. Leveraging techniques from tensor-network representations, we simplify the characterization of the noise channel of global entangling gates via quantum process tomography under Pauli-error assumptions, and improve the average measurement population fidelity of global gates under random basis to over 99%. Our work demonstrate a clear pathway of using error mitigation method for large scale quantum systems in the near future.

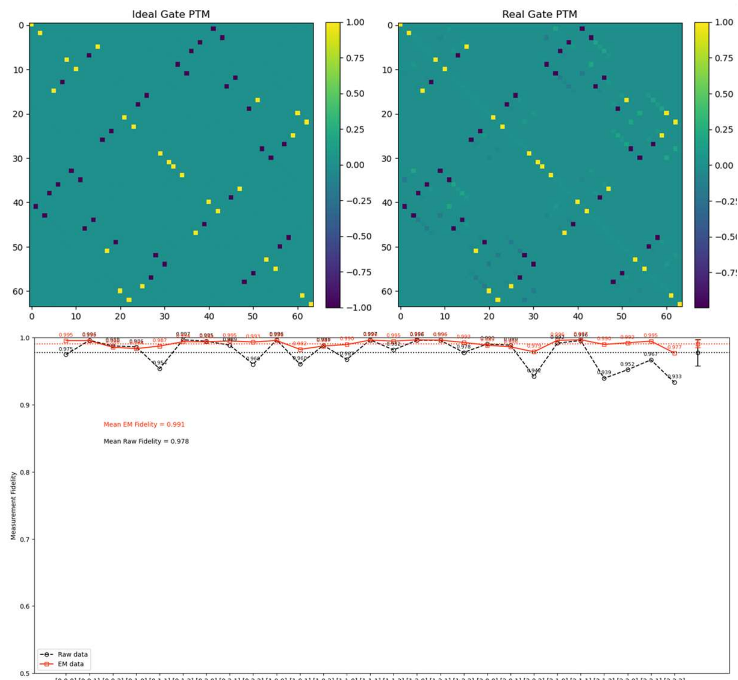


Figure 57: Pauli transfer matrix for a three-qubit global gate and the improvement of measurement state fidelity in different basis.

[1] Chen, Wentao, et al. "Error-mitigated quantum simulation of interacting fermions with trapped ions." npj Quantum Information 9.1 (2023): 122.
[2] Guo, Yuchen, and Shuo Yang. "Quantum error mitigation via matrix product operators." PRX Quantum 3.4 (2022): 040313.

Quantum Computing using NFQC Technology

M. Wahnschaffe,[1] D. Mungpara,[1] G. Zarantonello,[1] and A. Bautista,[1]

[1]*QUDORA Technologies GmbH*

Near-Field Quantum Computing (NFQC) with trapped ions represents a transformative approach to scalable quantum information processing, offering unparalleled control over qubit manipulation through engineered, localized electromagnetic fields. This work presents the comprehensive design and simulation of an NFQC architecture tailored for trapped-ion platforms, utilizing a robust suite of advanced design automation tools, including Python-based workflows and PyAEDT for full-wave electromagnetic analysis. The trap structure integrates a high-frequency RF electrode to provide strong radial confinement, while segmented DC electrodes are strategically placed to enable axial confinement and ion transport.

Integrated microwave conductors are embedded within the trap structure to generate highly localized magnetic fields with strong spatial gradients. These confined magnetic near-fields enable robust single- and multi-qubit gate operations without relying on laser-based control, reducing technical overhead and enhancing scalability. The resulting design supports field gradients exceeding several tens of T/m, enabling strong spin-motion coupling while minimizing decoherence and off-resonant effects. Our simulations demonstrate that precise control over electrode geometry and field distribution enables superior qubit-field interaction with minimized crosstalk and reduced thermal loads.

This co-design approach, combining electromagnetic precision with practical layout constraints, lays the groundwork for scalable, compact, and robust trapped-ion quantum processors. These results position NFQC as a technically robust and scalable platform for realizing next-generation trapped-ion quantum processors.

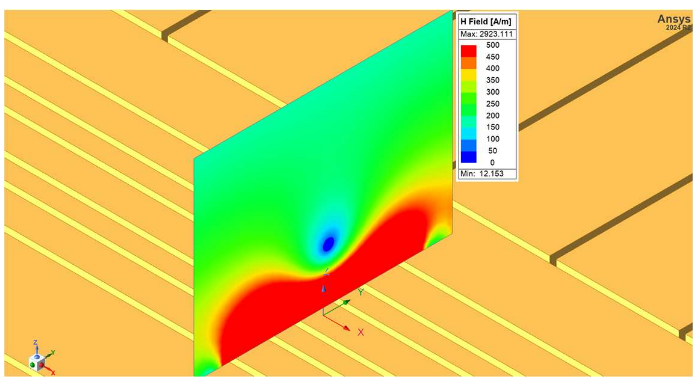


Figure 58: Simulated magnetic field distribution pattern in the radial y-z plane produced by the microwave conductor

[1] QUDORA Technologies GmbH, Commercial quantum computers based on ion trap technology

Poster 131

Development and integration of scalable components for cryogenic trapped-ion quantum computing

C. Torkzaban, [1] T. Pootz,[1] D. Stuhrmann,[1] R. Goyal,[1] S. Agne,[2] J. Parvizinejad, [1] L. Diekmann, [1] L. Kilzer, [1] and C. Ospelkaus[1,2]

[1]*Leibniz Universität Hannover, Hannover, Germany*

[2]*PTB Braunschweig, Braunschweig, Germany*

Two new cryostats for microwave-based trapped-ion quantum computing experiments are now in operation at the Leibniz Universität Hannover as part of the Quantum Valley Lower Saxony (QVLS) and the ATIQ consortium. Our approach to near-field microwave-driven gates is to send microwave current through an S-shaped electrode on the trap surface [1], which drives hyperfine transitions between two energy levels that are to first order magnetic field independent. This approach has been demonstrated successfully with Beryllium ions [2] and is expected to work similarly well for Calcium-43 ions. In order to scale up to larger numbers of qubits, within the QVLS project we have designed and will soon start characterizing a new junction-style trap to enable quantum computing based on the QCCD architecture, and within the ATIQ project we developing integrated waveguides for delivering laser light at multiple zones above a chip. We will present an overview of the cryostat design including the design of the faraday cage and socket-style mount for the junction-style chips and the design for fiber-based laser light delivery to the waveguide chip, provide an overview of our ARTIQ control system, and share an alternative laser-based method for ionizing Beryllium atoms. We will also share some of the lessons learned during the commissioning phase, in particular regarding ablation loading and thermalization challenges.

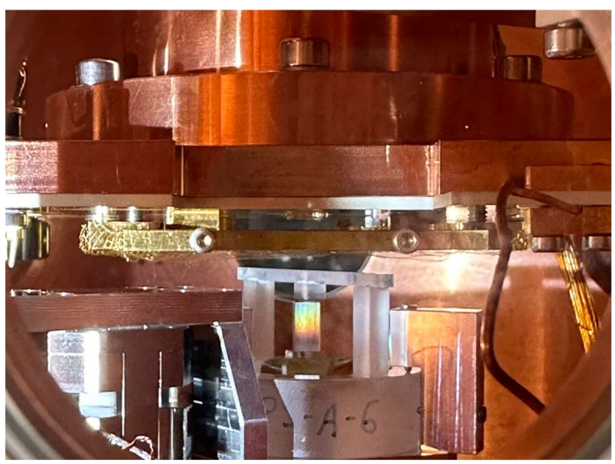


Figure 59: View of the edge of the chip, Faraday cage, and Schwarzschild Objective

[1] Ospelkaus, C., Warring, U., Colombe, Y. *et al.* Microwave quantum logic gates for trapped ions. *Nature* **476**, 181–184 (2011). https://doi.org/10.1038/nature10290
[2] Hahn, H., Zarantonello, G., Schulte, M. *et al.* Integrated $^{9}Be^{+}$ multi-qubit gate device for the ion-trap quantum computer. *npj Quantum Inf* **5**, 70 (2019). https://doi.org/10.1038/s41534-019-0184-5

Laser Spectroscopy of heavy highly charged ions in SpecTrap

R.X. Schüssler[1], A. van Dijk[1,2], M. Vogel[1], V. Hannen[3], G. Birkl[4,5], A. Solders[6], W. Nörtershäuser[4,5], R. C. Thompson[7], and Th. Stöhlker[1,8,9]

[1] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt Germany*

[2] *ELISA Aerospace, Saint Quentin, France*

[3] *Institut für Kernphysik, Universität Münster, Germany*

[4] *Technische Universität Darmstadt, Germany*

[5] *Helmholtz Forschungsakademie Hessen für FAIR, Germany*

[6] *Uppsala Universitet, Sweden*

[7] *Imperial College London, United Kingdom*

[8] *Helmholtz Institute Jena, Germany*

[9] *Institute of Optics and Quantum Electronics, Friedrich Schiller University Jena, Germany*

Heavy highly charged ions (HCI) provide a unique possibility to test fundamental physics in the presence of extreme electromagnetic fields. To this end, the SpecTrap experiment[1] is designed to perform laser spectroscopy of (hyper-)fine structure transitions in hydrogen-like HCIs in a Penning trap. For light atoms, these transitions are usually in the microwave regime, but due to a strong scaling with the atomic number Z, they move to the optical or even UV region for heavy ions. The experiment is therefore situated at GSI Helmholtz Center for Heavy Ion Research. Here, the heavy HCIs are produced in an accelerator facility, collected in the storage ring ESR and decelerated in the HITRAP facility, before being guided to the Penning trap. Within the trap they are cooled down by resistive cooling, with the possibility to introduce sympathetic laser cooling with Mg^+ ions in the future[2].

The experiment is currently being rebuilt. The trap will be situated in a 6T magnet with a warm bore and cooled down to 20K by a cryocooler. It features radial optical access in the central ring electrode for fluorescence collection and axial access for laser excitation.

First measurements will be performed with HCIs from a local EBIT source within HITRAP. Measurements with ions from from the accelerator facility delivered to HITRAP include tests of bound-state QED in the form of hyperfine structure transitions as well as the nuclear transition in thorium by direct nuclear excitation of $^{229}Th^{89+}$ ions.

We will present the current status as well as future plans.

[1] T. Murböck et al., Physical Review A 94, 043410 (2017)
[2] S. Schmidt et al., Journal of Modern Optics 65(5–6), 538–548 (2017)

A Method of Fiber Electrode Fabrication for Ion Trap Systems Integrated with Fiber Fabry-Pérot Cavities

Wei-Bin Chen,[1,2] Ding Fang,[1,2,3] Cheng-Hao Zhang,[1,2] Jin-Min Cui,[1,2,3] Yun-Feng Huang[1,2,3], Chuan-Feng Li[1,2,3] and Guo-Can Guang[1,2]

[1]*CAS Key Laboratory of Quantum Information, USTC, Hefei, China*

[2]*CAS Center For Excellence in Quantum Information and Quantum Physics, USTC, Hefei, China*

[3]*Hefei National Laboratory, University of Science and Technology of China, Hefei 230088, China*

In the ion trap - fiber cavity system, since the Doppler cooling light for most ions is ultraviolet or near - ultraviolet light, and the optical fiber itself is a dielectric, the surface of the fiber will be charged due to the photoelectric effect when irradiated by ultraviolet light. This additional electric field, on the one hand, disrupts the original potential distribution of the ion trap, and on the other hand, significantly increases the ion heating rate, having a fatal impact on ion trapping.

We propose a manufacturing process for fiber electrodes, which can be used to construct a fiber cavity - ion trap system. This system can achieve stable long - term trapping of a single ion in the fiber cavity. Compared with the situation without this process, the ion heating rate is reduced by more than an order of magnitude. This process provides a brand - new idea for the design and construction of the ion trap - fiber cavity system.

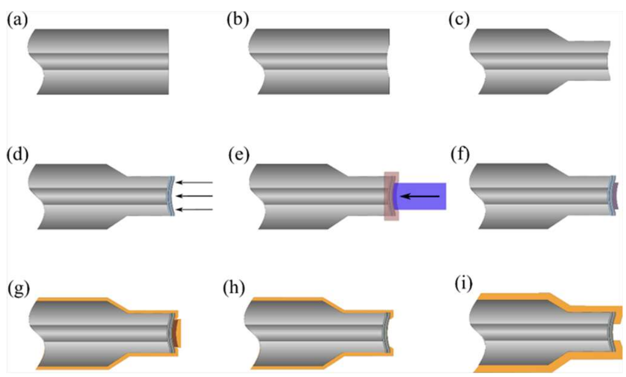


Figure 60: Flow chart for fabricating fiber electrodes.

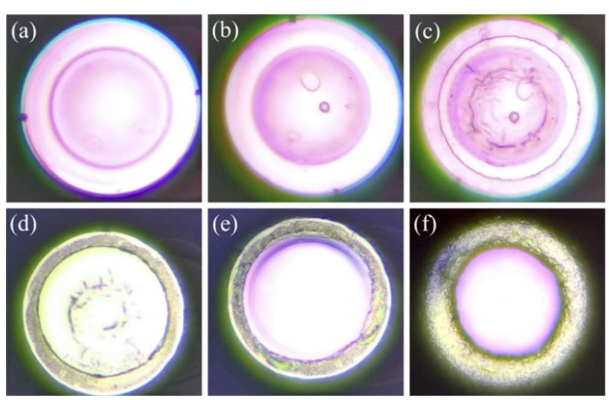


Figure 2: Physical image of the photolithography process.

Poster 134

Flexible ion-photon interfaces for distributed quantum computing

G. Stutter,[1] M. Chu[1] and M.K. Keller[1]

[1]*University of Sussex, Brighton, United Kingdom*

As part of the global effort to scale up ion trap quantum computers, we are working on robust interfaces between trapped ion and photonic qubits. This approach tackles the issue of scalability by combining the advantages of trapped ion qubits with the natural quantum information carrying properties of single photons. A system that connects small-scale ion trap systems in a modular fashion using photonic interconnects would leverage the advantages of both platforms [1,2].

Our high-rate, high-fidelity ion-photon interface consists of a calcium ion, positioned at the centre of a high-finesse optical cavity. This results in a coupling between the ion and the cavity field that allows for coherent control over the emission of single photons.

Building on our previous experience operating in both the strong and weak cavity coupling regimes [3,4], we a constructing a flexible, multi-zone ion-photon interface with the capability of producing ion-photon entanglement, and therefore the ability to act as a processing node in a distributed architecture.

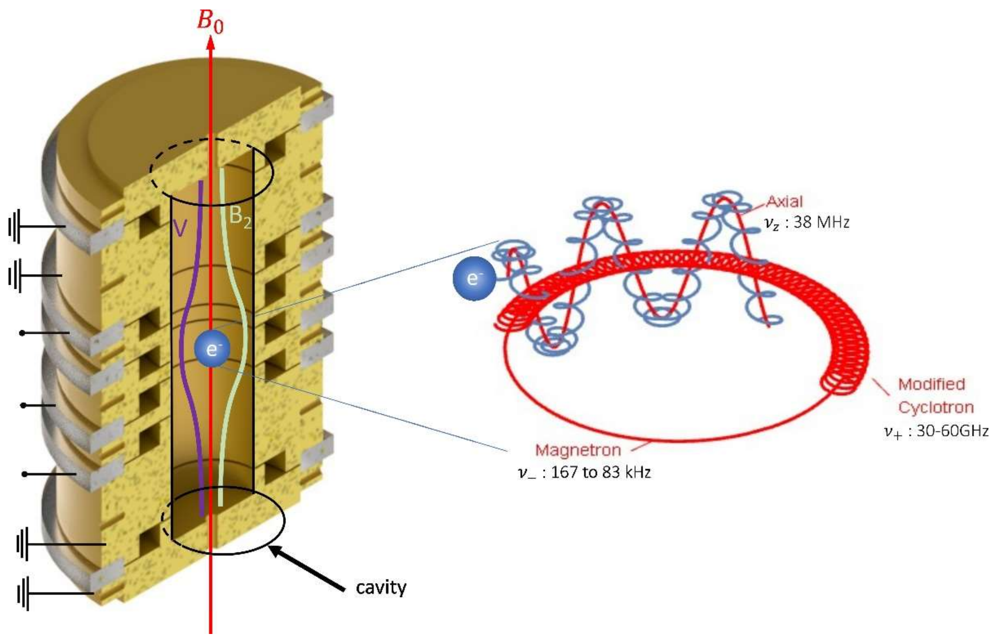
[1] L. J. Stephenson *et al*., Phys. Rev. Lett. 124, 110501 (2020).
[2] V. Krutyanskiy *et al*., Phys. Rev. Lett. 130, 050803 (2023).
[3] H. Takahashi *et al*, Phys. Rev. Lett. 124, 013602 (2020).
[4] T. Ward *et al*, New J. Phys. 24, 123028 (2022).

Developing a Single-Photon Detector Using a Penning Trap

S. Banhatti[1], M. Wojtkowiak[1], H. Zhang[1], J. Shi[1], R. Thompson[1], J. Devlin[1]

[1] *Centre for Cold Matter, Blackett Laboratory, Department of physics, Imperial College London, SW7 2AZ, United Kingdom*

We present early-stage work on the development of a single-photon detector based on an electron confined in a Penning trap. The goal is to utilize the electron as a quantum sensor for detecting individual microwave photons in the 30–60 GHz range. No technology currently exists to efficiently detect single photons in this frequency band. We are developing this new sensor with the long-term aim of searching for the weak microwave signals produced in the decays of a particularly well motivated dark matter particle, the axion.



The experimental setup employs a cryogen-free dilution refrigerator combined with resistive cooling, aiming to achieve ground-state cooling of the cyclotron motion and millikelvin axial temperatures. In our detection scheme, the electron's modified cyclotron frequency is tuned, using the Penning trap magnetic field, to match the expected microwave photon frequency from axion decays. Absorption of a single photon changes the cyclotron quantum number, producing a measurable shift in the axial frequency via a magnetic bottle. We plan to detect this shift using a 'Pulse and Amplify' (PnA) sequence.

We have characterized the cooling power and vibration levels of our dilution refrigerator and found them suitable for operating a photon-counter. Additionally, we have developed custom cryogenic vacuum feedthroughs that support a high density of DC and RF lines into the inner vacuum chamber. Our axial detection system incorporates GaAs switches to allow selective image current detection, axial cooling, and unperturbed axial evolution. We conclude with a brief outlook on the next steps toward a first demonstration of single-photon counting in this system.

Poster 136

Spin squeezing by two-axis twisting on two-dimensional ion crystal

Erfu Gao,[1] Lingfeng Ou,[1] Zhengyang Cai,[1] Mu Qiao,[1,2] and Kihwan Kim [1]

[1]*Department of Physics, Tsinghua University, Beijing, China*

[2]*Université Paris-Saclay, Institut d'Optique Graduate School,*

Two-dimensional (2D) ion crystal is a promising scalable quantum platform for generating highly entangled quantum states and exploring strongly correlated quantum many-body physics phenomena [1]. The ultimate lower bound of uncertainty including spontaneous decay in frequency metrology is asymptotically saturated by squeezed spin states [2]. We generated spin squeezing state on our 2D ion crystal through the programmable spin-spin interactions of trapped ions. We apply two pairs of counter-propagating Raman beams with different detuning on ions and adjust their relative intensity ratio to produce two-axis twisting (TAT) interaction, which is more robust to single-qubit rotation errors than Floquet engineering. We show better squeezing parameter of TAT compared to one axis twisting (OAT) on our platform and demonstrate the unique mean filed dynamics of TAT. We also observe the twin-fock-like state in our system after enough long time TAT interaction. These results will play an important role in promoting the development of quantum precision measurement.

[1] Qiao, M., et al., Nature Physics, 2024. 20(4): p. 623-630.
[2] Ma, J., et al., Physics Reports, 2011. 509(2-3): p. 89-165.

Poster 137

Non-paraxial effects on laser-qubit interactions

L.P.H Gallagher,[1] Z.E.D. Ackerman,[1] M. Mazzanti,[2] R.X. Schüssler,[3] N. Diepeveen,[1] C. Robalo Pereira,[1] A. Safavi-Naini,[4,5] R.J.C. Spreeuw[1] and R. Gerritsma[1]

[1] *Van der Waals – Zeeman Institute, University of Amsterdam, the Netherlands*

[2] *Institut für Quantenelektronik, ETH Zürich, Switzerland*

[3] *GSI Helmholtzzentrum für Schwerionenforschung, Germany*

[4] *QuSoft, The Netherlands*

[5] *Institute for Theoretical Physics, Institute of Physics, University of Amsterdam, The Netherlands*

Optical tweezers offer new opportunities to control and manipulate trapped ions with applications in quantum information processing. We calculate the light potentials induced on trapped ions by an optical tweezer beyond the paraxial approximation. Longitudinal field components in the beam center cause spatially-dependent Rabi frequencies and AC Stark shifts, leading to unexpected qubit-motion coupling [1]. We characterize single- and two-qubit gate infidelities due to this, and provide strategies to minimize adverse effects [2].

We further detail a novel method for driving a quantum logic gate which uses non-paraxial effects to excite the ion chain's vibrational modes [3]. The proposed gate may offer key benefits such as infrastructural simplification – the light only has to be supplied from one direction - and enhanced long-ranged interactions between the ion qubits. Finally, we detail a novel scheme to implement quadratic spin-phonon coupling using optical tweezers on trapped ions. With the addition of Mølmer-Sørenson-type interactions, we show the resulting system can be used to simulate a class of Bose-Hubbard models [4].

[1] R.J.C. Spreeuw. Physical Review Letters 125, 233201 (2020).
[2] Gallagher, L. P. H., et al. arXiv:2502.19345 (2025).
[3] M. Mazzanti et al. Physical Review Research 5 (3), 033036 (2023).
[4] Gallagher, L. P. H., et al. arXiv:2502.04109 (2025).

Industrial microfabrication of ion traps as quantum processors

N. Kandolf,[1] M. Dietl[1,2]

[1]*Infineon Technologies Austria AG, Villach, Austria*

[2]*Universitiy of Innsbruck, Innsbruck, Austria*

Useful trapped-ion quantum processors with 100 or more physical qubits can only be built in sophisticated production environments that offer high levels of process control. Typical product requirements include microscale patterning of electrode and routing layers, and a layer-to-layer alignment accuracy of the order of nanometers. Moreover, each process step must be highly reproducible so as to guarantee identical functionality for each ion trap fabrication.

Based at the Infineon Innovation Fab in Villach, Austria, the Ion Trap Systems (ITS) group is fostering a dynamic ecosystem of world-leading academics and pioneering industry partners.

With full access to one of the most advanced semiconductor manufacturing sites globally, a world-class Failure Analysis department for device analysis and reliability testing, and a state-of-the-art ion trapping lab for in-house trap qualification, ITS drives impactful progress in ion trap manufacturing.

With this poster, we provide an overview of ITS' manufacturing, analysis, and testing capabilities, and showcase our ability to build 2D [1] and 3D [2] multi-metal layer ion traps on both silicon and dielectric [3] substrates. Our ongoing efforts include the integration of photonics structures into our traps to pave the way for optical addressing of individual ions; the development of through-silicon and through-glass vias to enable high-density I/O in next-generation ion traps, and extensive material studies to increase electrical conductivity and reduce thermal load in our ion traps.

[1] Holz et al., Adv. Quantum Technol. **3**, 2000031 (2020)
[2] Auchter et al., Quantum Sci. Technol. 7 035015 (2022)
[3] Dietl et al., Test and characterization of multi-layer ion traps on fused silica [Manuscript in preparation]

A quantum demonstrator with Yb^{+}-Ba^{+} Coulomb crystals and cryogenic control electronics

M. Mohammed,[1] D. Niroomand[1], D. Busch[1], K. Rejaibi[1], E. A. Hackler[1], M. Glantschnig[2], M. Abuzahra[2], M. Hartmann[2], L. Dixius[2], S. Auchter[3], Z. Guo[4], A. Meyer[4], G. Saraswat[5], J. Akram[5], P. H. Huber[1], M. Brandl[2], V. Issakov[2], and C. Wunderlich[1]

[1]*Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Germany*

[2] *Infineon Technologies AG, 85579 Neubiberg, Germany*

[3] *Infineon Technologies Austria AG, A-9500 Villach, Austria*

[4] *Institut für CMOS Design, TU Braunschweig, 38106 Braunschweig, Germany*

[5] *eleQtron GmbH, 57072 Siegen, Germany*

Studying trapped ions in a cryogenic environment can be advantageous, since extreme high vacuum is achieved fast and reliably, enhancing the lifetime of Coulomb crystals, and motional heating of Coulomb crystals is strongly reduced. Therefore, a cryogenic set-up is particularly well suited to characterize multiple generations of micro-structured ion traps for quantum computing. Here, we present the progress of designing, building and operating a cryogenic quantum demonstrator at the University of Siegen in the frame of the German BMFTR project ATIQ. This demonstrator will feature mixed Coulomb crystals of Yb+ and Ba+ ions.

The cryogenic control electronics include cryogenic digital-to-analog converters to control trap voltages and a switching matrix, that is expected to improve the electronic noise profile significantly. The final ATIQ demonstrator will include a trap chip with 3 zones supporting processing of up to 10 ions in each zone.

The demonstrator itself has been fully assembled. Next, we shall bring online the different parts of the system for co-operation. Laser processing units comprising all necessary functions for the mixed crystals have been set up, including modular units for the necessary laser co-alignment. Shuttling of ions in an identical chip installed in a separate non-cryogenic testbed has been demonstrated. Following installation of the ablation loading modules and after bringing the remaining electronics online, we will then proceed to operate the ATIQ demonstrator in full with ions trapped at cryogenic temperatures.

Towards Ion-Photon Entanglement via Fiber Microcavity-Ion Trap Integration

Ding Fang,[1,2,3,4] Wei-Bin Chen,[1,2,3,4] Cheng-Hao Zhang,[1,2,3,4], Jin-Ming Cui,[1,2,3,4]Yun-Feng Huang,[1,2,3,4] Chuan-Feng Li,[1,2,3,4] and Guang-Can Guo[1,2,3,4]

[1]Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, China

[2]Anhui Province Key Laboratory of Quantum Network, University of Science and Technology of China, Hefei 230026, China

[3]CAS Center for Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China

[4]Hefei National Laboratory, University of Science and Technology of China, Hefei 230088, China

We report the development of an ion trap integrated with fiber microcavities. A single $^{138}Ba^{+}$ ion is successfully trapped within the cavity mode, with an estimated cooperativity parameter C of approximately 2. By leveraging the resonant cavity, we demonstrate efficient photon output and observe anti-bunching of spatial photons, validating single-photon emission. Through cavity-based temperature measurements, we confirm that the trapped ion can be Doppler cooled to around 30 phonons. These results collectively establish a robust experimental platform, paving the way for the generation of high-fidelity and high-efficiency ion-photon entanglement.

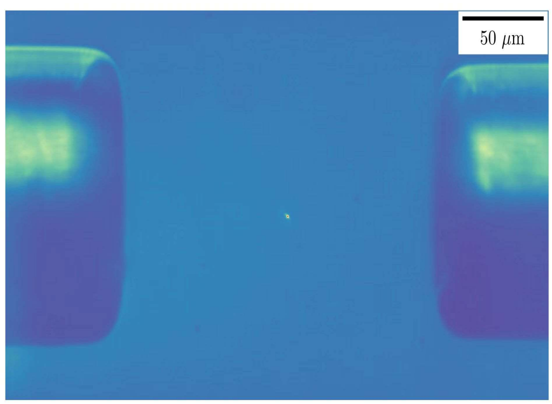


Figure 1: A single ion is trapped between the microcavities formed by two gold-plated optical fibers.

Realising Ion-Photon Entanglement Using An Ion-Cavity system

A. N. Amour[1], I. Ford[1] and M. K. Keller[1]

[1]*University of Sussex, Brighton, United Kingdom*

Combining trapped atomic ions with photons is currently the most promising approach for building distributed quantum computers and large-scale quantum networks. The highest-fidelity single- and two-qubit gates demonstrated to date have been achieved using trapped ions. Trapped ions also allow for high-fidelity state preparation and measurement. Photons, in contrast, are the most reliable carriers of quantum information over long distances. By coupling ions to optical cavities, it is possible to leverage the advantages of both systems, enabling the generation of remote entanglement a prerequisite for quantum networking and distributed quantum computing. Previous research within the group has demonstrated schemes for producing photons with greater indistinguishability and improved robustness against birefringence-induced decoherence, using state selection and time-bin encoding, respectively[1,2]. The aim of this project is to build on this research by producing ion-photon entanglement.

[1] T. Walker et al., Phys. Rev. A, 102, 032616 (2020)
[2] T. Ward and M. Keller, New J. Phys., 24, 123028 (2022)

Poster 142

Direct frequency comparison of multi-ion optical clocks based on Ca^+ and Sr^+

N. Akerman,[1] Y. Sokolik,[1] and R. Ozeri[1]

[1]*Weizmann Institute of science, Rehovot, Israel.*

We report the first direct frequency comparison between multi-ion optical clocks based on the $S_{1/2}$ to $D_{5/2}$ transition in Ca^+ and Sr^+ ions. Using linear chains of 5-10 ions, we demonstrate improved stability by employing dynamic decoupling sequences and interrogation of opposite Zeeman transitions to suppress first-order Zeeman and quadrupole shifts. Excess-micromotion induced shifts are minimized using sideband spectroscopy, with residual inhomogeneity further suppressed by employing a magic radio-frequency (RF) trap frequency. The measured short-term stability is around 2×10^{-15} at one second, where the statistical uncertainty in the frequency ratio reaches 2×10^{-17} after three hours. We estimate (preliminary) a systematic uncertainty of 8×10^{-17} limited by the room temperature black body radiation and a threefold improvement over the currently reported (indirect) frequency ratio [2,3]. Moreover, from the absolute frequency of the Sr^+ transition reported by the PTB [2], we expect to refine the absolute frequency of Ca^+ transition. This work represents the first comparison between two multi-ion clocks, demonstrating their potential for future applications in fundamental physics tests, geodesy, and metrology.

[1] N Akerman and Roee Ozeri, *Phys. Rev. Lett.* **134,** 013201 (2025).
[2] M. Steine et al., *Phys. Rev. Lett.* **131,** 083002 (2023).
[3] H. Zhang et al., *Metrologia* **60**, 035004 (2023)

Poster 143

Cryogenic apparatus design for scalable trapped ion quantum computing experiments

T. Pootz[1], R. Goyal[1], D. Stuhrmann[1], C. Torkzaban[1], C. Ospelkaus[1,2]

[1]*Institute for Quantum optics, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany*
[2]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*

Modern quantum computer architectures demand a high number of qubits and excellent interconnectivity. This poster will present a sophisticated design for state-of-the-art cryogenic trapped ion quantum computing experiments at Leibniz Universität Hannover. The proposed system features surface-electrode ion traps mounted on a universally interchangeable socket. Cryogenic temperatures below 10 K are reached through the vibration-isolated closed-cycle Gifford-McMahon (GM) cooler. The design accommodates access for optical fibers, as well as hundreds of direct current (DC) lines and multiple radio frequency (RF) lines, thus enabling high flexibility for complex trap architectures. The objective is to demonstrate qubit transport through dedicated trap structures, including junctions, storage, detection, and manipulation registers. Using chip-integrated microwave lines, multi-qubit quantum gates will be realised. The design is used for multiple setups and ion species, such as $^{9}Be^{+}$ qubits and $^{40}Ca^{+}$ ions for sympathetic cooling, in addition to $^{43}Ca^{+}$ and $^{88}Sr^{+}$ ions.

A comparison of calcium sources for ion-trap loading via laser ablation

Daisy R.H Smith,[1] Silpa Muralidharan,[1] Roland Hablützel,[2] Georgina Croft,[1] Klara Theophilo,[1] Alexander Owens,[1] Yashna N.D. Lekhai,[1] Scott J. Thomas,[1] and Cameron Deans[1]

[1]*National Quantum Computing Centre, Oxfordshire, OX11 0QX, UK*

[2]*Present address: Nu Quantum Ltd., Cambridge, UK*

Trapped-ion technology is a leading approach for scalable quantum computing. A key element of ion trapping is reliable loading of atomic sources into the trap. While thermal atomic ovens have traditionally been used for this purpose, laser ablation has emerged as a viable alternative in recent years, offering the advantages of faster and more localized loading with lower heat dissipation. Calcium is a well-established ion for qubit applications. Here we examine a range of calcium sources for ablation and provide a comprehensive analysis of each. We consider factors such as ease of use, temperature and yield of the ablation plume, and the lifetime of ablation spots. For each target, we estimate the number of trappable atoms per ablation pulse for a typical surface and 3D ion trap.

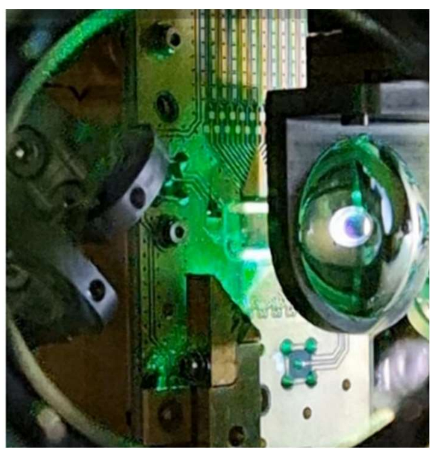


Figure 61: Experimental laser-ablation set-up inside the cryogenic UHV chamber. The targets are mounted to the gold arm seen in the bottom of the image.

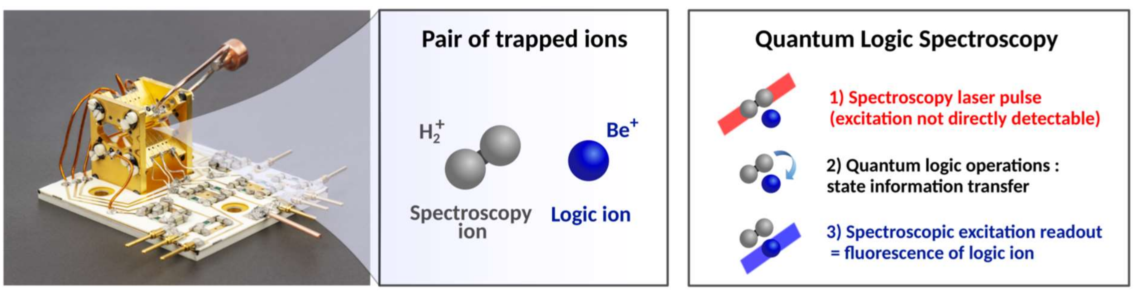
[1] Appl. Phys. B 131, 164 (2025)
[2] https://rdcu.be/eAS2x

Implementing Quantum Logic Spectroscopy on Molecular Hydrogen Ions

V . Barbé ,[1,2] J-Ph. Karr,[1] and L. Hilico[1]

[1]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 place Jussieu, F-75005 Paris, France*
[2]*QUEST Institute for Experimental Quantum Metrology, PTB Braunschweig, 38116 Braunschweig, Germany*

Precision spectroscopy of molecular hydrogen ions (MHIs) has recently been established as a powerful method to measure the proton-to-electron mass ratio [1- 4]. As a result, as of 2022 MHI spectroscopy contributes to the CODATA list of internationally recommended values of the fundamental physical constants. Current MHI techniques are based on rovibrational spectroscopy in large Coulomb crystals and suffer from several limitations, among which the impossibility to achieve single-molecule and single-quantum-state control. I will present prospects to implement Quantum Logic Spectroscopy [5] in H_2^+ for the next generation of MHI experiments at LKB.



Quantum Logic Spectroscopy of molecular hydrogen ions

[1] S. Patra *et al*, Science **369**, 6508 (2020)
[2] S. Alighanbari *et al*, Nature **581**, 152 (2020)
[3] I. V. Kortunov *et al*, Nature **17**, 569 (2021)
[4] S. Alighanbari *et al*, Nat. Phys. **19**, 1263 (2023)
[5] P. O. Schmidt et al, Science **309**, 749 (2005)

Incoherent repumping scheme in the $^{88}Sr^+$ 5-level manifold

V. Martimort[1], S. Guesne[1,4], D Drapier[3], L. Gros-Desormeaux[1], V. Tugaye[1], V. Cambier[1], A. Douillet[2,3], J.-P. Likforman[1], L. Guidoni[1,4]

[1]*Laboratoire Matériaux et Phénomènes Quantiques, Université Paris-Cité, CNRS, F-75013 Paris*
[2]*Université d'Evry-Val-d'Essonne, F-91000 Evry*
[3]*Laboratoire Kastler Brossel, Sorbonne Université, ENS-Université PSL, Collège de France, F-75005 Paris*
[4]*Crystal Quantum Computing SAS, Incubateur Télécom, 9 rue Dareau 75014 Paris*

Laser-cooled trapped ions are atomic systems that usually cannot be described by the simple two-level atom picture. A representative example is the Doppler-cooled $^{88}Sr^+$, where five energy levels and three laser fields - one cooling laser and two repumping lasers- are typically involved in the process.

Figure 62 : The $^{88}Sr^+$ 5-level manifold. a) coherent repumping scheme. b) incoherent repumping scheme.

We performed fluorescence spectroscopy experiments with a single Doppler-cooled $^{88}Sr^+$ ion and developed calculations to simulate these measurments. The aim was to identify optimized repumping laser parameters for efficient cooling. Our model is based on the Optical Bloch Equations within the density matrix formalism and calculates the steady-state populations of cooled $^{88}Sr^+$ in both incoherent and incoherent repumping scheme as described in [1]. The model includes 18 Zeeman sub-levels interacting with 3 laser fields.

We compared experiments and calculations for different values of the laser parameters (intensity, detuning). The results show that fluorescence reaches an optimum for specific ranges of repumping laser intensities and detunings, which are the most favorable for Doppler cooling. We also compared Doppler-cooled $^{88}Sr^+$ ions with the simpler and easier-to-handle case of a two-level atom.

Figure 2 : Scattering rate as a function of the Rabi frequency of the repumping laser @1033nm.

[1] Vincent Tugaye, *Spectroscopie et thermométrie d'ions uniques Sr capturés dans des micropièges surfaciques aspects théoriques et expérimentaux.* PhD thesis, Université Paris-Cité, 2020.

Full Wavelength Integration for a Yb^{+} Optical Clock with Nanophotonics

G. Du,[1] **C. Grimpe**,[1] F. Salahshoori,[1] E. Jordan,[1] G. Beck,[2] K. K. Mehta[3] and T. E. Mehlstäubler[1, 4, 5]

[1]*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*
[2]*Institut für Quantenelektronik, ETH Zürich, Switzerland*
[3]*School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14850, USA*
[4]*Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany*
[5]*Laboratorium für Nano- und Quantenengineering, Hannover, Germany*

Trapped ytterbium (Yb^{+}) ions have been used for precision timekeeping in optical clocks [1], quantum computing [2], and for tests of fundamental physics [3]. They provide a wide range of optical transitions from the ultraviolet to the infrared. However, traditional free-space optics face alignment, stability, and scalability limitations, motivating the exploration of integrated photonics as a compact and robust alternative.

In this work, we present the integration of waveguides and grating couplers to optically address Yb^{+} ions in a surface trap by delivering all the wavelengths required for clock spectroscopy. We systematically investigate the electric field distortion within the surface ion trap caused by the integration of these photonic components using Finite Element Method (FEM) simulations [4]. The targeted transitions include the E2 transitions at 411 nm and 435 nm, and the ultra-narrow E3 transition at 467 nm, along with the wavelengths required for ion loading, state preparation and detection. Notably, the critical 467 nm light for the E3 transition is shaped into a Hermite-Gaussian mode to enhance the E3 transition probability while reducing unwanted light shifts [5]. To cover the wide spectral range, we use aluminium oxide waveguides for ultraviolet and blue light, including 370 nm, 399 nm, 411 nm, and 467 nm. For 760 nm, 935 nm, and 1650 nm, we use silicon nitride waveguides. These materials were chosen for their low loss at these wavelengths. Optical characterization of these waveguides and grating couplers has demonstrated successful coupling of all required beams to the targeted positions, enabling the next phase of testing with trapped ions in vacuum.

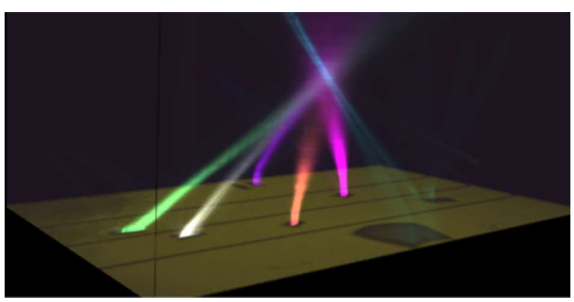


Figure 1: False-colored reconstruction of integrated photonic beam profiles measured using a microscope.

[1] N. Huntemann, et al., Phys. Rev. Lett. **116**, 063001 (2017)
[2] S. Olmschenk, et al. Phys. Rev. A **76**, 052314, (2007)
[3] L. S. Dreissen, et al. Nat Commun **13**, 7314 (2022)
[4] G. Du, et al, arXiv preprint arXiv:2503.20387 (2025)
[5] A. A. Peshkov, et al. ANNALEN DER PHYSIK 535, 2300204 (2024)

Poster 148 / hot topic

Innovative fabrication of gold-filled through substrate vias for scalable ion trap quantum computing

E. Iseke,[1,2] F. Giebel,[1,2] N. Krishnakumar,[1,2] N. Stahr,[1,3] K. Thronberens, [1,2] J. Stupp, [1,3] M. Billah, [2,3] and C. Ospelkaus[1,2,3]

[1] *Leibniz Universität Hannover, Institut für Quantenoptik, Hannover, Germany*

[2] *Physikalisch Technische Bundesanstalt, Quest Institut, Braunschweig, Germany*

[3] *Laboratorium für Nano- und Quantenengineering (LNQE), Hannover, Germany*

To solve real-world problems, quantum computers must be highly scalable. Achieving this scalability is a key challenge for ion trap quantum computers [1]. Traditional wire bonds, while commonly used for electrode connections, introduce limitations, such as blocking optical access and increasing complexity [2]. To overcome these challenges, Through Substrate Vias (TSVs) offer a superior alternative, enabling vertical electrical connections without obstructing critical areas. Classical TSVs use silicon as a substrate and copper as a filling material [3]. Silicon has high RF losses and copper can oxidize and affect stability. We address these issues by using gold-filled TSVs in dielectric substrates like fused silica or sapphire.

Our novel, patent-pending process minimizes processing steps and eliminates complex chemical additives or pulsed electroplating, ensuring high stability and reproducibility. The holes in the substrates are formed using the process of Selective laser-induced etching (SLE). SLE is a two-step process comprising laser modification and wet etching. This method allows a precise via shaping, including a cavity with an additional chamfer that optimizes subsequent metal deposition.

A thin titanium adhesion layer and a gold seed layer are deposited before electroplating. Then electroplating with a simple DC current is performed. The chamfer promotes current crowding, leading to an initial sealing of the cavity and void-free bottom-up filling. This results in highly reliable, defect-free gold-filled TSVs, as shown in Figure 1.

By integrating our gold-filled TSVs, ion trap architectures can transition away from wire bond-based connections towards a more scalable and robust interconnect solution. Additionally, these TSVs facilitate the use of interposer chips, replacing traditional filter boards and further enhancing system integration. Our results demonstrate a significant step towards more scalable and reliable quantum computing hardware.

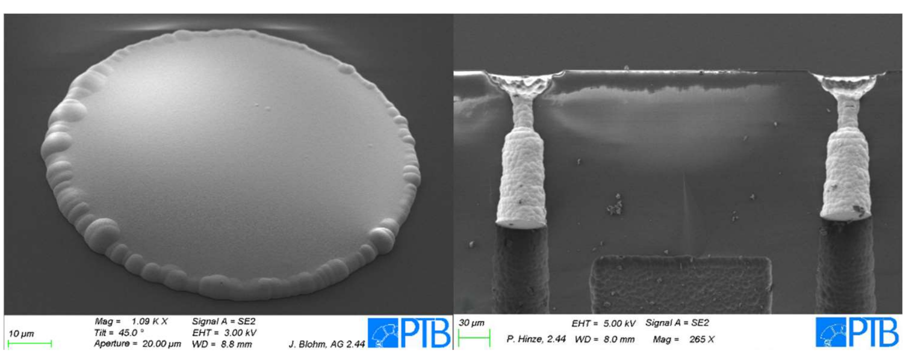


Figure 2 Defect-free gold-filled TSVs in fused silica. Left: Top view of a fully filled TSV. Right: Cross-section of two adjacent TSVs during the filling process.

[1] Bruzewicz et al., *Appl. Phys. Rev.* 6, 021314 (2019).
[2] Guise et al., *J. Appl. Phys*. 117, 174901 (2015)
[3] Wang et al., *Appl. Sci.* 13, 8301 (2023)

A 3-dimensional trapped-ion scanning probe

T. Sägesser,[1,2] S. Jain,[1,2] P. Hrmo,[1,2] A. Ferk,[1] M. Simoni,[1] Y. Cui,[1] C. Mordini,[1,3] D. Kienzler[1] and J. Home[1]

[1]ETH Zürich, Zürich, Switzerland

[2]Present address: ZuriQ AG, Zürich, Switzerland

[3]Present address: Università degli Studi di Padova, Padova, Italy

A wide range of quantum systems suffer from negative effects due to electric fields originating on close-by surfaces [1,2,3]. Among them, trapped ions are exceptionally sensitive to electric fields, which has allowed their use as sensors of noise stemming from surfaces with a diverse set of material compositions and surface treatments [4,5]. However, previous work was restricted in flexibility by the use of radio-frequency traps, limiting spatial positioning to linear translations and calling into question whether the observed results are connected to the radio-frequency fields [6]. Here, we instead use a micro-fabricated Penning trap [7] and demonstrate a single-ion probe which can be freely translated in three dimensions.

We position the ion at distances between 50 µm and 450 µm from a gold surface and above a 200 × 200 μm^2 area and measure static and time-varying electric fields at a grid of locations. From this data, the distribution of unwanted charge on the surface is reconstructed as well as the spatial dependence of the electric-field noise, in particular revealing the scaling behavior with respect to the ion-surface distance. Furthermore, the capability to resolve the fields in 3-d helps to distinguish noise originating on the surface from external contributions. The levels of surface noise observed in our apparatus are consistent with the lowest results obtained in radio-frequency traps to date.

The methods demonstrated here allow similar probing to be carried out on samples with a variety of materials, surface constitutions and geometries, providing a new tool for surface science and for the identification of materials and processes for low-noise performance.

[1] de Graaf et al., *Sci. Adv.* **6**, 5055(2020)
[2] Thiele et al., *Phys. Rev. A* **90,** 013414 (2014)
[3] Kim et al., *Phys. Rev. Let.* **115,** 087602 (2015)
[4] Brownnutt et al., *Rev. Mod. Ph.* **87,** 1419 (2015)
[5] Sedlacek et al., *Phys. Rev. A* **98,** 063430 (2018)
[6] Brown et al., *Nat. Rev. Mat.* **6,** 892–905 (2021)
[7] Jain et al., *Nature* **627,** 510–514 (2024)

Poster 150 / hot topic

Scaling quantum computers to thousands of ions with high fidelity

B. Lekitsch,[1] and J.Hilder[1]

[1]*neQxt GmbH, Erlenbach am Main, Germany*

We're discussing neQxt's approach to scaling trapped ion quantum computers while simultaneously increasing fidelities. To achieve this goal, we combine laser gates making use of individual addressing with ion shuttling and 3D ion traps. We can produce fully three-dimensional shaped trap electrodes on chips, uniformly coat them with metals and then precisely align and join multiple trap chips to make up 3D symmetric ion traps including X-junctions and more complex trap designs.

We make use of far detuned laser gates in combination with small individual addressing beams to achieve very high single and two qubit fidelities. Combined with integrated active waveguide control we attempt to build a quantum processor with more than a thousand ions and to combine multiple processors afterwards.

A universal four-qubit gate set using two trapped ions

A. Vazquez-Brennan,[1] J.D. Leppard[1], S. M. Decoppet[1], A.S. Sotirova,[2], W. R. Cutler[1], F. Pokorny[2], and C.J. Ballance[1,2]

[1] *University of Oxford, Oxford, United Kingdom*

[2]*Oxford Ionics, Oxford, United Kingdom*

Current quantum computing devices face the challenge of making the most efficient use of a small number of individual information carriers (e.g. individual trapped ions, superconducting resonator circuits, photons, etc.). One promising approach is to extend the accessible Hilbert space by using more than two energy levels per information carrier. Such schemes have often made use of qu*d*its to directly compute in base $d > 2$. While these approaches are naturally suited to certain problems, such as simulating quantum chemistry [1] and high-energy physics [2], quantum algorithms have been primarily developed for a binary qubit architecture. This makes a qubit-to-qudit translation step necessary for their implementation on qudit devices. Alternatively, an information carrier with 2^n accessible levels can be used to host n qubits [3-6]. This allows qubit algorithms to be implemented without modification, while requiring fewer information carriers for the same number of qubits in an equivalent two-level processor. Furthermore, existing techniques for qudit operations can be directly used to implement single- and two-qubit gates.

We present a system for manipulating four qubits stored in two trapped $^{137}Ba^+$ ions. Pairs of qubits are encoded within four atomic states distributed across the ground S1/2 and metastable $D_{5/2}$ levels of one ion. We extend the coherence time of the system by choosing states within the hyperfine structure with low relative magnetic field sensitivities. Single- and two-qubit gates on qubits within the same ion are implemented by driving quadrupole transitions between pairs of states using a narrow-linewidth 1762 nm laser. In addition, a pair of 532 nm lasers are used to drive two-ion gates via a light-shift mechanism [7, 8]. This novel gate scheme can be used to implement two-, three- and four-qubit gates, by using additional intra-ion gates that do not require motional coupling. These operations form a universal gate set on this system.

The physical requirements we use are the same as those found in many trapped-ion experiments with single qubits per ion. As such, this approach could be implemented in existing systems to double the number of qubits in a register without increasing the number of ions. This could reduce the complexity associated with controlling many ions, such as crowded motional mode spectra if the ions are stored in a single chain, or large numbers of shuttling operations in QCCD architectures.

[1] MacDonell, R. J. et al., *Chem. Sci.* **12**, 9794 (2021).
[2] Rico, E. et al., Ann. Phys. **393**, 466 (2018).
[3] Saumya, S. et al. (2024), preprint at http://arxiv.org/abs/2406.19332.
[4] Nikolaeva, A. S. et al, *Phys. Rev. A* **109**, 022615 (2024).
[5] Campbell, W. C. and Hudson, E. R. (2022), preprint at http://arxiv.org/abs/2210.15484.
[6] Bian, J. et al (2024), preprint at http://arxiv.org/abs/2407.01196.
[7] Sawyer, B.C. and Brown, K.R., *Phys. Rev. A* **103**, 022427 (2021).
[8] Hrmo, P. et al., *Nat. Commun* **14**, 2242 (2023).

Poster 152 / hot topic

All-to-all fast two-qubit gates for trapped ions

I. Savill-Brown[a], Z. Mehdi[a], P. Grosser[a], S.A. Haine[a], A.K. Ratcliffe[b], V.D. Vaidya[b], H. Liu[b], C.R. Viteri[b], and **J.J. Hope**[a]

[1]Australian National University, Canberra, Australia

[2]IonQ Inc., College Park 20740, USA

The ability to connect arbitrary pairs of qubits has a dramatic effect on the efficiency of quantum circuits. In trapped-ion systems, all-to-all connectivity can be achieved by resolving individual modes of collective motion, but at the cost of reduced fidelity and speed as the length of the ion chain increases. This motivates a range of approaches to scalable operations using shorter ion chains, such as shuttling, photonic interconnects and highly parallel operations. Fast gates, where the ions are subject to maximum possible state-dependent kicks (SDKs) from carefully timed laser pulses, do not require selective addressing of single motional modes. Previous studies have shown that such fast gate schemes are quicker, scale better for longer chains and allow more flexible trap geometry. However, they were only shown to be efficient for nearest-neighbor operations [1].

We present a theoretical study of fast all-to-all entangling gates in trapped-ion quantum processors. We demonstrate that impulsive spin-dependent excitation can be used to perform high-fidelity non-local entangling operations in quasi-uniform long chains. We identify a regime of phonon-mediated entanglement between arbitrary pairs of ions in the chain, where any two pairs of ions in the chain can be entangled at high fidelity in less than two centre-of-mass oscillation periods for chains of up to 30 ions. For longer chains, a subset of distant non-local solutions also exist. We assess the experimental feasibility of the proposed gate schemes, which reveals pulse error requirements that are independent of the length of the ion chain and the distance between the target qubits. Furthermore, we compare the performance of non-local fast gates to equivalent operations composed of sub-microsecond nearest-neighbor gate operations, as well as the achievable performance of spectroscopic protocols employed in existing QCCD and linear-trap architectures. These results suggest entangling gates based on impulsive spin-dependent excitation present new possibilities for large-scale computation in near-term ion-trap devices.

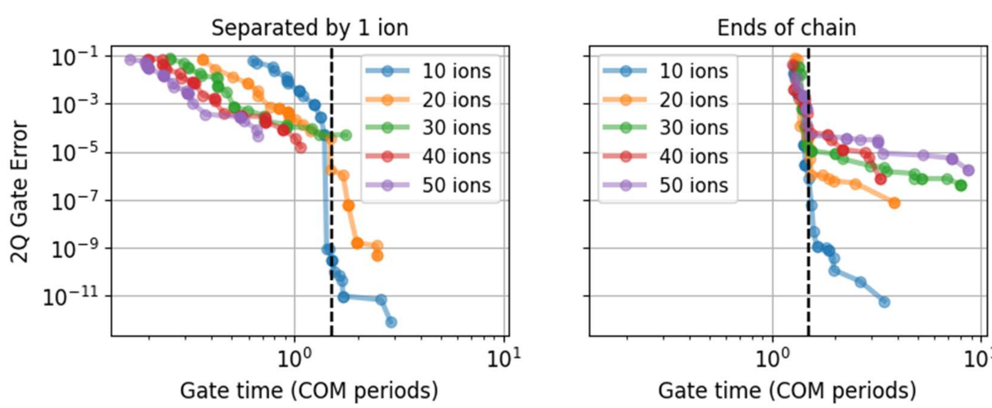


Figure 63: Gate fidelities using a maximum of 200 SDKs, showing feasible gates at minimum and maximum ion separation across long ion chains. Fast gates of two trap periods can be performed between arbitrary pairs of ions up to 30 ions.

[1] Z.Mehdi, A.K.Ratcliffe, and J.J.Hope, Phys. Rev. Research 3, 013026 (2021).

Poster 153 / hot topic

Light shift gates in ion traps with integrated optics

<u>Aditya Kolhatkar,</u>[1] Jack Xing,[1] Hamim Rivy,[1] Vighnesh Natarajan,[1] and Karan K. Mehta[1]

[1] *Cornell University, Ithaca, USA*

Surface traps with integrated optics stand to enable scalable control of trapped ion systems by permitting stable beam delivery and passive phase stability, and providing new opportunities for engineering laser-ion interactions. Previous work on two-qubit entangling operations with integrated photonics demonstrated a Mølmer-Sørensen gate on an optical qubit [1]. In pursuit of high-fidelity gates acting on long-lived ground-state qubits with favorable scaling of required power with gate duration, here we present trap designs for implementing light shift gates [2,3] with $^{40}Ca^{+}$ leveraging integrated optical delivery, for qubits encoded in $4S_{1/2}$ Zeeman sublevels. Spontaneous photon scattering limits gate fidelity in such a scheme, or equivalently, places a lower bound on the Raman detuning and laser power requirement for a target fidelity and gate duration [4]. We present an alternative geometry that yields an order-of-magnitude reduction in power required compared to the conventional two-beam configuration for realistic trap layouts, indicating potential for integrated light delivery to partially alleviate challenges faced with laser-based gates.

We will also present experimental work from our group on fast ground state cooling [5] with integrated photonics, towards realization of these gate schemes.

[1] Mehta, K.K., et al. Integrated optical multi-ion quantum logic. Nature 586, 533–537 (2020)
[2] Leibfried, Dietrich, et al. Experimental demonstration of a robust, high-fidelity geometric two ion-qubit phase gate. Nature 422.6930 (2003): 412-415
[3] Ballance, Christopher J., et al. High-fidelity quantum logic gates using trapped-ion hyperfine qubits. Physical review letters 117.6 (2016): 060504
[4] Ozeri, Roee, et al. Errors in trapped-ion quantum gates due to spontaneous photon scattering. Physical Review A—Atomic, Molecular, and Optical Physics 75.4 (2007): 042329
[5] Z. Xing, K.K. Mehta. "Trapped-ion laser cooling in structured light fields." arXiv:2411.08844 (2024)

Observation of a Doppler free two-photon transition in sympathetically cooled state selected H_2^+ ions

L. Hilico,[1,2] M. Leuliet,[1] D. Aboul Hosen, [1] A.O. Parada Flores, [1] B. Argence,[1] M. Panet, [1] H. Demattos Nogueira, [1] M. Salman, [1] J.-Ph. Karr[1,2]

[1]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL,*

Collège de France, 4 place Jussieu, F-75005 Paris, France

[2]*Université Evry Paris-Saclay, boulevard François Mitterrand, F-91000 Evry, France*

Hydrogen molecular ions have long been identified as promising species for high precision fundamental constant determination [1] since they are calculable systems [2] and are amenable to high precision measurements. Since 2022, HD^+ spectroscopy is included in the CODATA fundamental constant adjustment [3,4,5,6].

We report on the first observation of the (v=0,L=2)←(v=1,L=2) Doppler-free two-photon transition in H_2^+ at 9.166 µm. We present the experimental setup focusing on the sympathetically cooled state selected molecular ions source [7] and the spectroscopy laser frequency control with respect to the *Système International* of units using a frequency comb referenced to the REFIMEVE ultrastable signal [8].

We also discuss the future impact of H_2^+ spectroscopy on the determination of fundamental constants and search for new physics beyond the standard model [9,10].

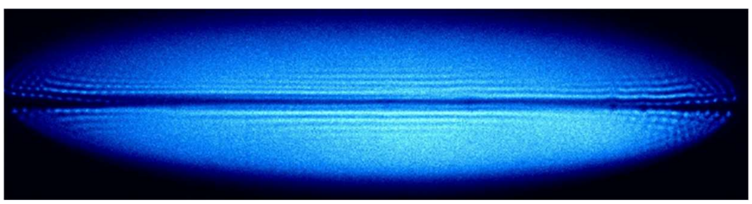


Figure 64: Be^+ coulomb crystal containing state selected H_2^+ ions.

[1] W.H. Wing et al., *Phys. Rev. Lett*. 36, 1488 (1976).
[2] V.I. Korobov et al., *Phys. Rev. Lett*. 118, 233001 (2017).
[3] S. Patra et al., *Science* **369**, 1238 (2020).
[4] S. Alighanbari et al., *Nature* 581, 7807 (2020).
[5] I.V. Kortunov et al., *Nature Physics* 17, 569 (2021).
[6] S. Alighanbari et al, *Nature Physics* 19, 9 (2023).
[7] J. Schmidt et al., *Phys. Rev. Appl*. **14**, 024053 (2020).
[8] https://www.refimeve.fr/index.php/en/
[9] C. Delaunay et al., *Phys. Rev. Lett.* **130**, 121801 (2023).
[10] S. Schiller, *Phys. Rev. A* **109**, 042825 (2024).

Poster 155 / hot topic

Quantum-logic spectroscopy of forbidden rovibrational transitions in single molecular ions

A. Shlykov,[1] M.L. Diouf,[1] R. Karl,[1] M. Roguski,[1] and S. Willitsch[1]

[1]*Department of Chemistry, University of Basel, Klingelbergstrasse 80, 4056 Basel, Switzerland*

Ultranarrow, electric-dipole forbidden transitions between rovibrational states in molecules and molecular ions with expected natural linewidths on the Hz level present intriguing opportunities for the development of highly precise mid-infrared frequency standards and for the exploration of fundamental physical problems such as possible time variations of fundamental constants [1]. The molecular nitrogen ion N_2^+ has been proposed as an attractive system for precision molecular spectroscopy because, as an apolar diatomic ion, it features small systematic shifts and transitions with low sensitivity to magnetic fields in its electronic ground state [2,3]. However, the experimental detection of pure rovibrational transitions in systems like N_2^+ [4] and their precision spectroscopy is challenging on several levels. Besides the weak line strengths, which require highly sensitive detection methods, the positions of the lines are usually known only with substantial uncertainties based on spectroscopic constants determined through indirect methods. Moreover, theoretical predictions of the line strengths are also affected by significant uncertainties.

Here, we report the first observation of electric-quadrupole rovibrational transitions in single molecular ions using a highly sensitive quantum-logic detection protocol [5]. We studied individual hyperfine-Zeeman components of the $|v=1, N=2\rangle \leftarrow |v=0, N=0\rangle$ rovibrational transition in the $X^2\Sigma_g^+$ electronic ground state of single N_2^+ ions confined in a radiofrequency ion trap with a co-trapped Ca^+ ion used for sympathetic laser cooling and quantum-logic state detection. The transitions were directly driven by rapid adiabatic passage using a frequency-chirped laser pulse from a mid-infrared quantum cascade laser. This approach enabled the effective, fully reversible transfer of the rovibrational populations even without precise knowledge of the transition frequencies and at the same time allowed the recycling of the same single molecule in sequential spectroscopic experiments. Thus, line positions could be detected with a 2 MHz uncertainty limited by the frequency sweep of the laser pulse. The present approach represents a powerful methodology for coherently manipulating single molecules on ultranarrow spectroscopic transitions for precision measurements and quantum technologies applications. It can readily be adapted for other diatomic and polyatomic species, provided suitable laser sources for excitation and quantum-logic detection of transitions are available.

[1] Safronova, M.S., Budker, D., DeMille, D., Kimball, D.F.J., Derevianko, A. and Clark, C.W. *Rev. Mod. Phys.* **90**, 025008 (2018).
[2] Kajita, M. *Phys. Rev. A*, **92**, 043423 (2015).
[3] Najafian, K., Meir, Z., and Willitsch S. *Phys. Chem. Chem. Phys.*, **22**, 23083 (2020).
[4] Germann, M., Tong, X., and Willitsch S. *Nat. Phys.*, **10**, 820 (2014).
[5] Sinhal, M., Meir, Z., Najafian, K., Hegi, G., and Willitsch S. *Science*, **367**, 1213 (2020).

Structural transitions and stochastic dynamics of Coulomb clusters in a 3D Paul trap

A. Ayyadevara,[1] A. Prakash,[1] S. Dutta,[1] A. Paramekanti,[2] and S. A. Rangwala[1]

[1]*Raman Research Institute, Bengaluru, India*

[2]*University of Toronto, ON, Canada*

We present structural transitions observed in clusters formed by a few laser-cooled atomic ions confined in a three dimensional (3D) end-cap type trap [1]. Numerical analysis of the clusters' vibrational modes reveals distinct lattice dynamics at specific transition points. Real-time imaging enables us to capture distinct dynamics: mode softening of a 3D cluster at a symmetry-breaking continuous transition, stochastic switching between distinct configurations at a discontinuous transition, and hysteresis across a spinodal point, where metastable minima vanish. Remarkably, we find a unique triple point-like feature where a symmetry-breaking transition and a symmetry-changing transition occur simultaneously [2].

In addition, we identify a few clusters with two symmetry-equivalent configurations. In real time, the ions reorient as the entire cluster switches between the two potential energy minima. To understand the transition pathway and the switch rate, we apply methods from quantum chemistry [3] and reaction rate theory [4]. The theoretical predictions agree well with stochastic-dynamics simulations and experimental observations, pointing towards a thermal-activation process due to the photon bath used for Doppler-cooling of the cluster. Our experiments and analysis of tuneable Coulomb clusters show how symmetries, energy landscapes, and dynamical pathways govern transitions in finite-sized systems.

[1] C. Schrama, E. Peik, W. Smith, and H. Walther, Optics Communications 101, 32 (1993).
[2] Ayyadevara, A. Prakash, S. Dutta, A. Paramekanti, and S. A. Rangwala, arXiv:2505.16378.
[3] G. Henkelman and H. Jónsson, J. Chem. Phys. 113, 9978 - 9985 (2000).
[4] H. Kramers, Physica 7, 284 (1940).

A non-neutral plasma simulator based on laser-cooled trapped ions

C. Klein,[1] M. Collombon[1], M. Baldovin[2], G. Hagel,[1] M. Housin,[1]
R. Dubessy,[1] **C. Champenois[1]**
[1]*Aix-Marseille University and CNRS, PIIM, Marseille, France*
[2] *Institute for Complex Systems CNR, Rome, Italy*

We propose a joint experimental and theoretical approach to measure the self-diffusion in a laser-cooled trapped ion cloud where part of the ions are shelved in a long-lived dark state. The role of the self-diffusion coefficient in the spatial organization of the ions is deciphered, following from the good agreement between the experimental observations and the theoretical predictions. This comparison furthermore allows to deduce the temperature of the sample. Protocols to measure the self-diffusion coefficient are discussed, in regard with the control that can be reached on the relevant time scales through the dressing of the atomic levels by laser fields.

In this work, laser-cooled clouds of atomic ions stored in a radio-frequency trap are practical realizations of a finite-size One Component Plasma (OCP) in the strongly coupled regime.

The OCP is a reference model in the study of strongly coupled Coulomb systems and by tuning the density and temperature of the sample, different regimes can be explored from gas to liquid and crystals. Standard kinetic theories fail to describe transport plasma properties under conditions of strong Coulomb coupling because they neglect effects of spatial and temporal correlations induced by nonbinary collisions. This fundamental problem needs to be solved to accurately model the transport properties, and equations of state of dense laboratory and astrophysical plasmas. This is the problem we want to solve [1] by analyzing the competition between the radiation pressure force and the self-diffusion in a laser-cooled cloud of ions where part of them are shelved in a long-lived metastable state.

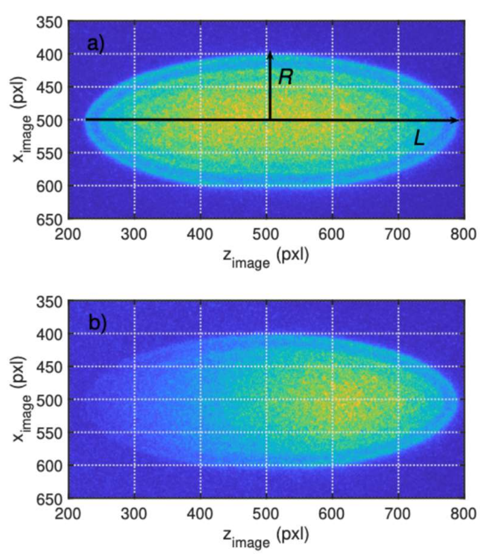


Figure 65: (a): picture of the fluorescence of a trapped ion cloud made of 1240 +/- 50 Ca^+ ions. (b) : same cloud with an extra laser admitted, propagating toward z>0 on the picture, this laser is shelving part of the ions in a metastable dark state.

Poster 158 / hot topic

[1] Self-diffusion in a strongly coupled non-neutral plasma, M. Baldovin *et. al Phys. Rev. A* **109**, 043116 (2024)

Derivation and demonstration of four- and six-photon stimulated Raman transitions

G. J. Gregory,[1] A. Quinn,[1] S. Brudney,[1] E. R. Ritchie,[1] D. J. Wineland,[1] D. T. C. Allcock,[1] and **J. O'Reilly**[1]

[1] *University of Oregon, Oregon, USA*

We experimentally demonstrate transitions between electronic angular momentum states with a difference in magnetic quantum number $\Delta m_J \geq 3$ via resonant four- and six-photon stimulated Raman transitions. Derivation of the corresponding Rabi frequencies, which are verified experimentally, follows the standard treatment of two-photon transitions including the adiabatic elimination of intermediate states. We show super-linear scaling of the Rabi frequency with drive beam intensity and characterize intermediate state population both theoretically and experimentally. Finally, we discuss pathways to increase the presented multi-photon transition fidelities, providing a tool for efficient, high-fidelity qu*d*it control.

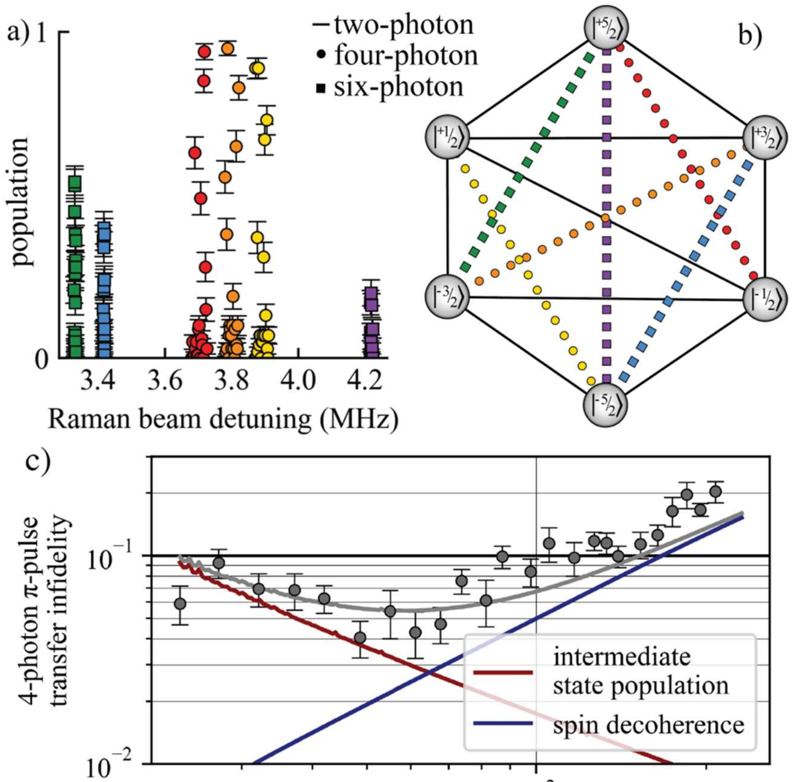


Figure 66: (a) Rabi spectroscopy of transitions within $D_{5/2}$ with $\Delta m_J \geq 3$ as driven by four (circles) and six (squares) photon processes. (b) Diagram illustrating full unitary connectivity in the $D_{5/2}$ manifold enabled by four- and six-photon transitions. (c) Measured four-photon π-pulse transfer infidelity between $m_J = +5/2$ and $m_J = -1/2$ at different Raman beam powers. The blue line is infidelity due to spin decoherence and the red line is infidelity due to intermediate state population, both based on full numeric simulations.

Frequency metrology with antimatter

J. Nauta[1] on behalf of the ALPHA collaboration

[1]*CERN, Geneva, Switzerland*

According to the fundamental symmetries that underpin the Standard Model, both matter and antimatter should have been produced in equal quantities at the Big Bang. The absence of antimatter in our Universe as we observe it today, strongly motivates direct matter-antimatter comparisons, where any observed difference would lead to new physics. The Antihydrogen Laser Physics Apparatus (ALPHA) collaboration at CERN produces and traps antihydrogen atoms by combining antiproton and positron plasmas, which are then used for precise studies. Recent progress includes the accumulation of thousands of atoms, direct laser cooling of the antihydrogen sample [1] and the first observation of the motion of antihydrogen in a gravitational field [2].

Laser spectroscopy of antihydrogen has already resulted in a test of CPT symmetry to a relative precision of 2×10^{-12} [3]. In hydrogen however, the same spectral feature, the 1S-2S transition, has been determined up to a precision of 4×10^{-15} [4]. To enable matter-antimatter comparisons at that level and beyond, we have implemented a Cs fountain clock in collaboration with NPL [5]. The fountain provides a local realization of the SI second and is used to steer an active hydrogen maser in the same laboratory. In addition to comparing the frequency of the maser with our fountain, we also cross-check against national metrology labs via satellite frequency transfers. A frequency comb and a stabilized fiber link, as well as two ultra-low expansion cavities, then allow for accurate determination of the laser frequency that is used to interrogate the antihydrogen sample.

Recently, we have observed a novel transition in the hydrogen spectrum: the 2S4P resonance. Accurate determination of the center frequency of this transition via excited state laser spectroscopy will allow us to access fundamental quantities such as the antiproton charge radius.

I will present recent progress and the current status towards a more precise measurement of the 1S2S transition, as well as the latest results of the 2S4P transition in antihydrogen. I will also outline novel experimental techniques to further reduce the linewidth of the observed resonances, boosting the accuracy of searches for symmetry breaking between matter and antimatter.

[1] C. J. Baker et al., *Nature* ***592***, 35 (2021).
[2] E. Anderson et al., *Nature* **716**, 621 (2023).
[3] M. B. Ahmadi et al., *Nature* **557**, 71 (2018).
[4] C. G. Parthey, A Matveev, J. Alnis, B. Bernhardt, A. Beyer, R. Holzwarth, A. Maistrou, R. Pohl, K. Predehl, T. Udem, T. Wilken, N. Kolachevsky, M. Abgrall, D. Rovera, C. Salomon, P. Laurent, and T. W. Hänsch, *Phys. Rev. Lett.* **107**, 20 (2011).
[5] R. J. Hendricks, F. Ozimek, K. Szymaniec, B. Nagórny, P. Dunst, J. Nawrocki, S. Beattie, B. Jian, and K. Gibble, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **66**, 624 (2019).

Poster 160 / hot topic

Trapped heavy, highly charged ions - recent results at the HITRAP deceleration facility

N. Stallkamp,[1,2] Z. Andelkovic,[2] S. Fedotova[2], W. Geithner[2], F. Herfurth[2], N.Kehl[3], J. Ködel[3], D. Neidherr[2], W. Nörtershäuser[3,4], S. Rausch[3,4], S. Trotsenko[2], G. Vorobjev[2], D. Zisis[3]

[1]*Goethe University, Frankfurt am Main, Germany*

[2]*GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany*

[3]*Technical University of Darmstadt, Darmstadt, Germany*

[4]*Helmholtz Akademie Hessen für FAIR HFHF, TUD, Darmstadt, Germany*

The HITRAP facility, at the GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt, is designed to decelerate and cool heavy, highly charged ions (HCI) created by the GSI accelerator complex [1]. The system consists of a two-stage linear decelerator, followed by a cryogenic Penning trap for subsequent ion cooling. The deceleration stages reduce the ion energy from 4 MeV/u to 500 keV/u and to 6 keV/u respectively, before forwarding a slow, but hot ion bunch towards the cooling trap. The trap is operated in a so-called nested configuration, in which the electrons, created by an external photoelectron source, are stored simultaneously with the HCI and serve as a cold thermal bath. After cooling, the ions can be transported via a low-energy transfer beamline towards various attached experiments [2]. For commissioning of the trap as well as a source of light HCI for attached experiments, a dedicated small ion source (Dresden EBIT) is attached to the beamline [3].

So far, deceleration of heavy HCI has been regularly set up down to 6 keV/u. The subsequent electron cooling process is under development with promising results. The first indications of electron cooling of locally produced HCI in a Penning trap could be achieved, a major milestone towards heavy HCI at eV energies.

Recently, the first user-experiment could be successfully carried-out, in which a decelerated $^{197}Au^{79+}$ beam was delivered for a material research experiment. The status and results of the facility as well as future aspects will be presented.

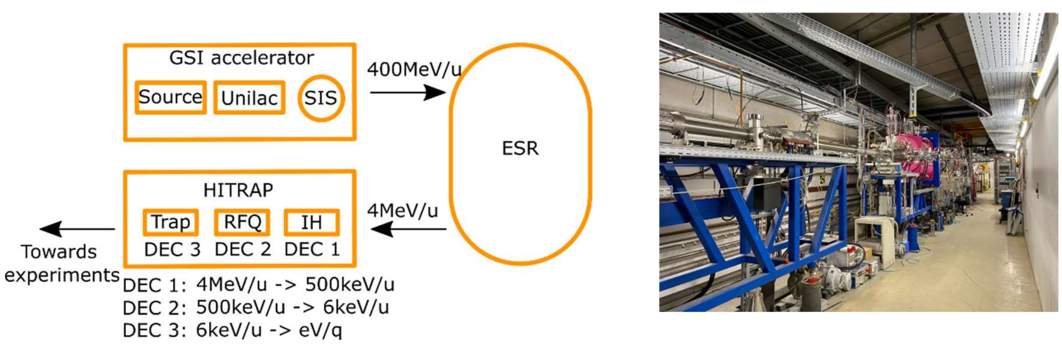


Figure 67: Schematic of the HITRAP facility in the frame of the GSI accelerator (left). Picture of the decelerator beamline (right).

[1] F. Herfurth et al., Phys. Scr., 014065 (2015)
[2] Z. Andelkovic et al., Nucl. Instr. Methods Phys. Res. Sec. A vol. 795 2015 055 (2015)
[3] A. Sokolov et al., JINST 5 C11001 (2010)

Poster 161 / hot topic

Towards simulation of topological superconductors with a Penning trap

J. Y. Z. Jee,[1] J.H. Pham,[1] G. Cafe,[1] N. Makadia,[1] M. J. Biercuk[1] and R. N. Wolf[1]

[1]*University of Sydney, New South Wales, Australia*

The p+ip superconductor is an unconventional superconductor in which Cooper pairs form with angular momentum in two dimensions. These chiral systems exhibit protected dynamical phases that hold potential for topological quantum computing [1]. In this work, we present preliminary results in generating the initial Bardeen-Cooper-Schrieffer (BCS) phase of a p+ip superconductor using a Penning trap, which naturally confines over a hundred ion qubits in a two-dimensional ion Coulomb crystal. The ions' spin states encode the presence or absence of a Cooper pair while the ion positions take the role of the momentum of the Andersen pseudospins. We initialize the radially symmetric BCS spin configuration by leveraging the natural rotation of the crystal. To achieve this, we generate a radially dependent AC Stark shift across the crystal plane by precisely controlling the tilt angle of a spin-dependent force with respect to the crystal plane [2]. Finally, with individual spin-state readout [3], we perform a full tomographic reconstruction of the individual spins of all the ions to confirm the state initialization protocol.

[1] A. Shankar et al, PRX Quantum **3,** 040324 (2022).
[2] J. H. Pham et al, Adv. Quantum Technol **7**, 2400086 (2024).
[3] R. N. Wolf et al, Rhys. Rev. Applied **21,** 054067 (2024).

Poster 162 / hot topic

Trapped ions as a platform for a quantum repeater and quantum communication over an urban fiber link

Christian Haen,[1] Max Bergerhoff,[1] Omar Elshehy,[1] Elena Arenskötter,[1] Stephan Kucera,[1,2] Jonas Meiers,[1] Tobias Bauer,[1] Christoph Becher,[1] Jürgen Eschner[1]

[1]*Universität des Saarlandes, Saarbrücken, Germany*

[2]*Luxembourg Institute of Science and Technology (LIST), Belveaux, Luxembourg*

A possible route towards quantum communication over existing telecom fiber infrastructure is using single ions as quantum memories and single photons as quantum information carriers. This faces challenges such as exponential transmission loss and environment-induced drifts that decohere polarization-encoded quantum information. Losses may be overcome by deploying quantum repeaters that asynchronously entangle the quantum memories, while polarization infidelities may be mitigated by active polarization compensation or time-bin encoding.

We report on the characterization of the 14 km long Saarbrücken fiber link, see Fig. 1, for quantum communication experiments, and the implementation of a polarization drift compensation, reaching >99% process fidelity. We demonstrate entanglement distribution as well as atom-to-photon quantum state teleportation with ~84% average fidelity over the fiber link. The realized quantum communication protocols employ a $^{40}Ca^{+}$ single-ion quantum memory, heralded absorption of one photon from an entangled, ion-resonant photon pair source, and quantum frequency conversion [1].

We also demonstrate, in a laboratory experiment, an asynchronous entanglement-based quantum repeater cell [2] with two $^{40}Ca^{+}$ ions in the same Paul trap. We swap atom-photon entanglement to photon-photon entanglement with ~76% average fidelity by applying a Mølmer–Sørensen quantum gate on the ions. Additionally, we show progress towards a quantum repeater segment using a photonic Bell state measurement, as well as first steps towards interfacing the trapped-ion and color-center quantum memory platforms.

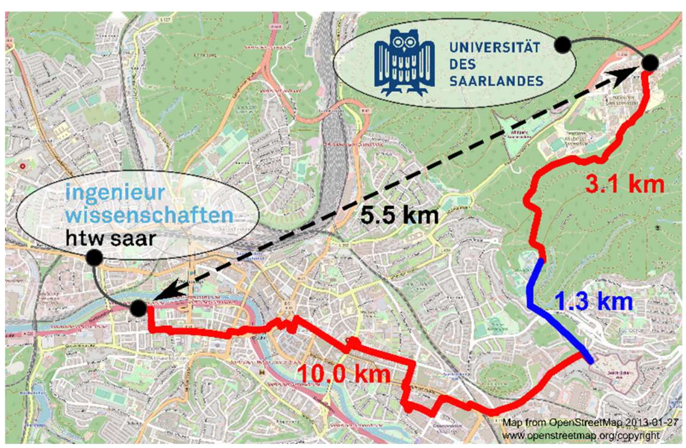


Figure 68: Map of Saarbrücken fiber link

[1] S. Kucera et al., npj Quantum Inf. **10**, 88 (2024)
[2] M. Bergerhoff et al., Phys. Rev. A **110**, 032603 (2024)

Poster 163 / hot topic

Distributed Quantum Computing between Two Ion-Trap Nodes in a Quantum Network

D. Main, P. Drmota, D. P. Nadlinger, E. M. Ainley, A. Agrawal, B. C. Nichol, R. Srinivas, **G. Araneda** and D. M. Lucas

University of Oxford, UK

No quantum computing platform has yet established a clear path to the scalability required for achieving practical quantum advantage, meaning the ability to outperform classical systems in solving useful problems. In classical computing, scalability is achieved through clusters of interconnected processors, which act as individual nodes and communicate through a shared network to execute tasks collaboratively. A similar architectural approach is emerging as a promising direction for quantum computing. In this presentation, I will describe our recent experimental results toward building such quantum clusters. In particular, we have used a photonic network to generate remote entanglement between two quantum processors based on trapped ions, located several meters apart. This entanglement enables the deterministic execution of distributed quantum computing protocols, including quantum gate teleportation and, for the first time, a distributed implementation of Grover's search algorithm across two quantum nodes [1]. I will also present our latest results on multi-partite multi-species entanglement shared across multiple nodes and involving different atomic species, advancing the prospects for scalable and modular quantum networks.

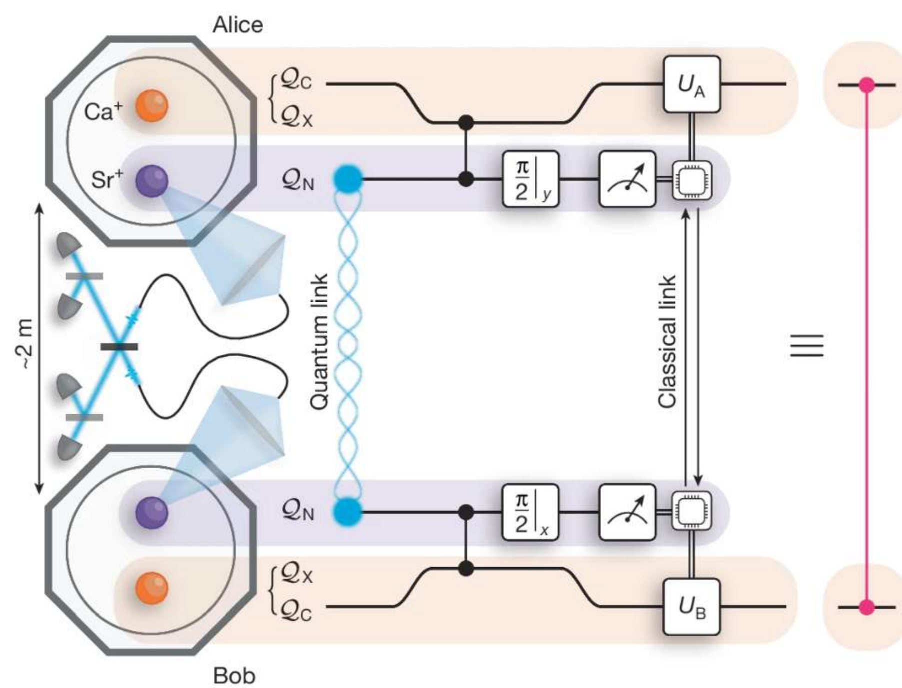


Figure 69: Circuit used for the deterministic teleportation of a CZ gate between two remote trapped-ion quantum computers

[1] Nature **638**, 383–388 (2025)