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Experimental Development of Transfer Functions from Mechanical Vibrations to Neutron Flux in the ZED-2 Zero-Power Heavy Water Reactor

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About Canadian Nuclear Laboratories (CNL)

What is CNL?

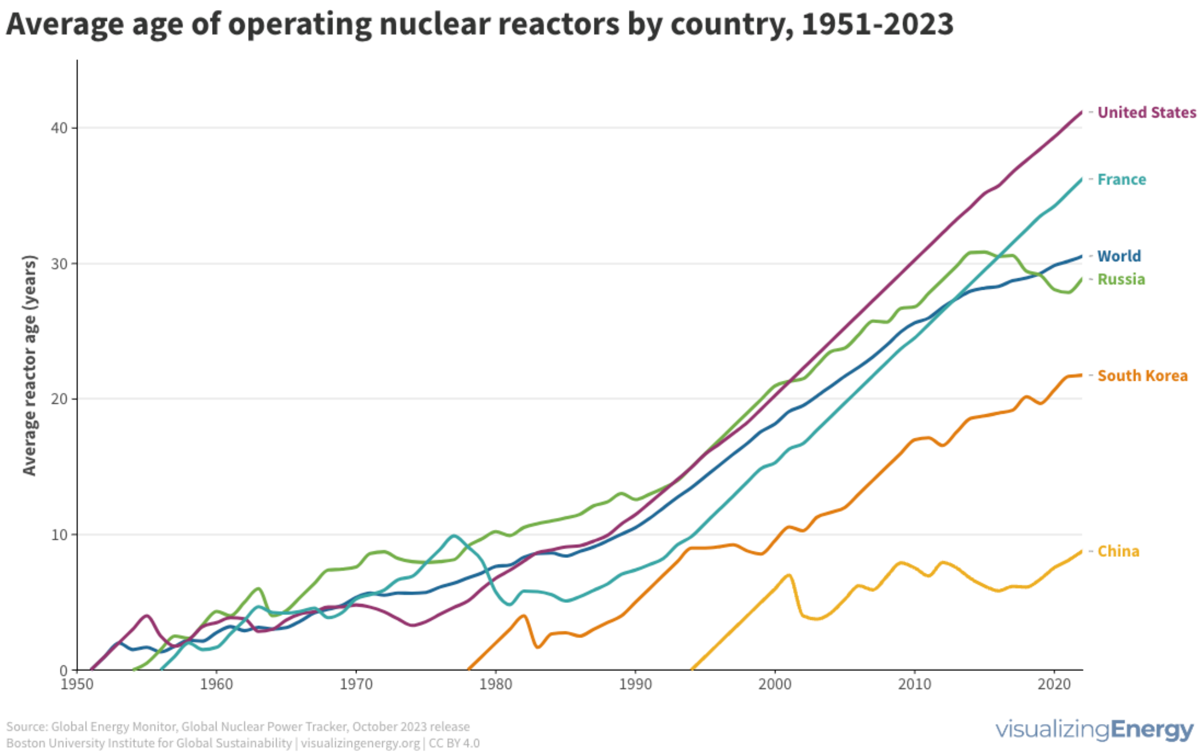
- CNL is Canada's national nuclear laboratory
- Main campus is Chalk River Laboratories which houses the facilities that supported the development of the CANDU reactors
- Ongoing mission is to conduct applied nuclear research for the domestic and international nuclear industry
- Longstanding involvement in neutron noise analysis, in collaboration with CANDU utilities

SECTION 1

Overview

Overall Objectives

- Novel and advanced vibration monitoring techniques from existing station information is needed to support an aging fleet of reactors
- Determining vibration magnitude is crucial to define action limits for operators



SECTION 2

Review of Existing Work

Review of Existing Work – Station ICFD Data

- Analysis of CANDU station data revealed statistical signatures related to vibration of fuel channels and other reactor internals as well as degradation of the dynamic response of neutron instrumentation
- ICFD (In-core flux detector) tube vibrations, introduced by moderator flow, caused strong peaks in the APSD (auto power spectral density) and coherence functions with zero phase difference at the fundamental frequency of the tube vibration
- Fuel channel vibration could be detected along groups of ICFDs aligned along the same group of horizontal channels, with localization of fuel channel possible by phase difference between pairs
- Changes in APSD peak magnitude, frequency shift and peak width indicated change in vibration magnitude, mechanical/support conditions or increasing impact
- Changes in reactor condition could be tracked, but action limits were not well defined

References:

O. Glöckler, M.V. Tulett, Application of reactor noise analysis in the CANDU reactors of Ontario hydro, Progress in Nuclear Energy, Volume 29, Issues 3–4, 1995, Pages 171-191, ISSN 0149-1970, https://doi.org/10.1016/0149-1970(95)00006-6

O. Glöckler, Reactor Noise Measurements In The Safety And Regulating Systems Of Candu Stations, 8th Symposium On Nuclear Reactor Surveillance And Diagnostics, Göteborg, Sweden, May 27-31, 2002

Review of Existing Work - FEA of Vessel Internals and Validation

- Mode shapes of PWR reactor internals and fuel assemblies characterized with FEA and validated by neutron noise analysis with good agreement
- In-core and ex-core signals used to identify fuel bundle natural frequencies by comparing phase
- Model could be used to simulate axial preload degradation
- Action limits based on APSDs still to be defined

References:

Jinho Park, Jeong Han Lee, Tae-Ryong Kim, Jong-Beom Park, Sang Kwon Lee, In-Soo Koo, Identification of reactor internals' vibration modes of a Korean standard PWR using structural modeling and neutron noise analysis, Progress in Nuclear Energy, Volume 43, Issues 1–4, 2003

Review of Existing Work – Neutron Noise for Structural Health Monitoring

- Based on station operating experience of unexpected degradation, finite element analysis (FEA) was performed on core barrel model and coupled with neutron noise analysis to diagnose the degradation
- Machine learning methods developed to assess fault signatures in reactor vessel internals based on historical data and FEA
- Predictions based on model and neutron noise analysis were validated during subsequent outage, showing promise for proactive structural health monitoring

References:

Banyay, GA, Palamara, MJ, & Smith, SD. "Coupling of Neutron Noise and Dynamic Finite Element Analyses to Perform Remote Condition Monitoring for Reactor Vessel Internals." *Proceedings of the . Volume 3: Fluid Structure Interaction; High Pressure Technology*. Virtual, Online. July 13–15, 2021. V003T04A006. ASME. https://doi.org/10.1115/PVP2021-62201

Review of Existing Work - CORTEX

- Horizon 2020 project funded by European Commission for neutron noise analysis of power reactors
- Strategic Objectives:
  - Develop high fidelity simulation tools,
  - Experimental validation of simulation tools
  - Advanced signal processing and machine learning techniques combined with transfer function modelling
  - Combine all tools in a set that can be directly used to analyze plant data
- Experimental campaigns in AKR-2 (TU Dresden) and CROCUS (École Polytechnique Fédérale de Lausanne) oscillated fixed and variable absorber and fuel pins

References:

C. Demazière, A. Rouchon, A. Zoia, Understanding the neutron noise induced by fuel assembly vibrations in linear theory, Annals of Nuclear Energy, Volume 175, 2022, 109169, ISSN 306-4549, https://doi.org/10.1016/j.anucene.2022.109169.

Lamirand, Vincent, et al. Experimental report of the 3rd campaign at AKR-2 and CROCUS. Horizon 2020 Programme, 2021.

SECTION 3

Current Objectives

Objectives of Ongoing Work

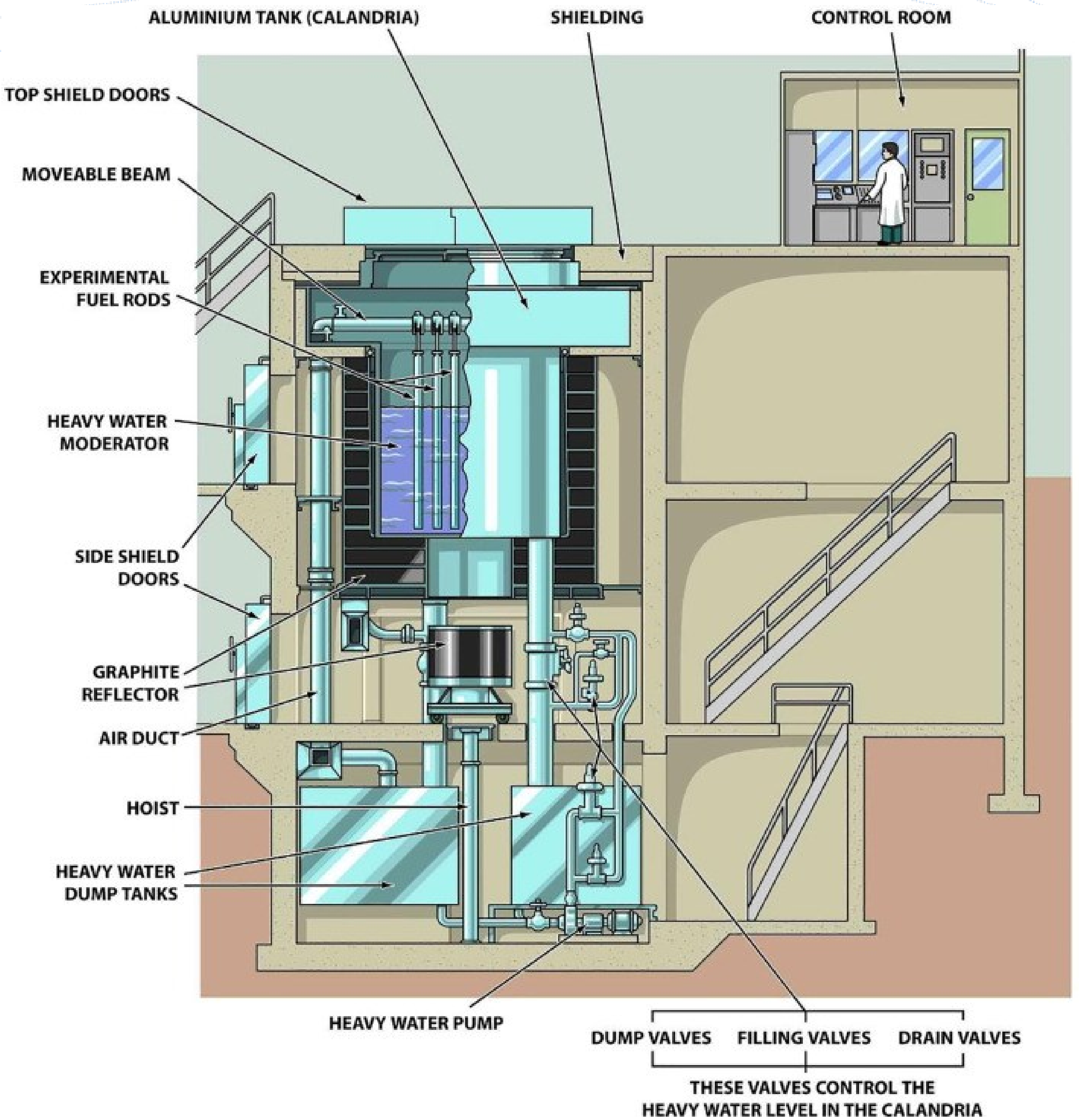
- Establish transfer functions for the neutron response of an easily characterizable vibrating structure
- Assess the effect of different neutron absorption cross sections (absorber vs transparent)
- Assess the effect of flux profile and spatial effects
- Extend transfer function to simple flexible structure with known mode shape

SECTION 4

ZED-2

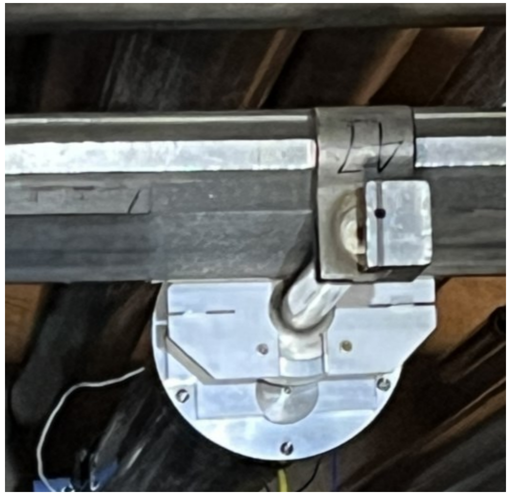
The ZED-2 Reactor

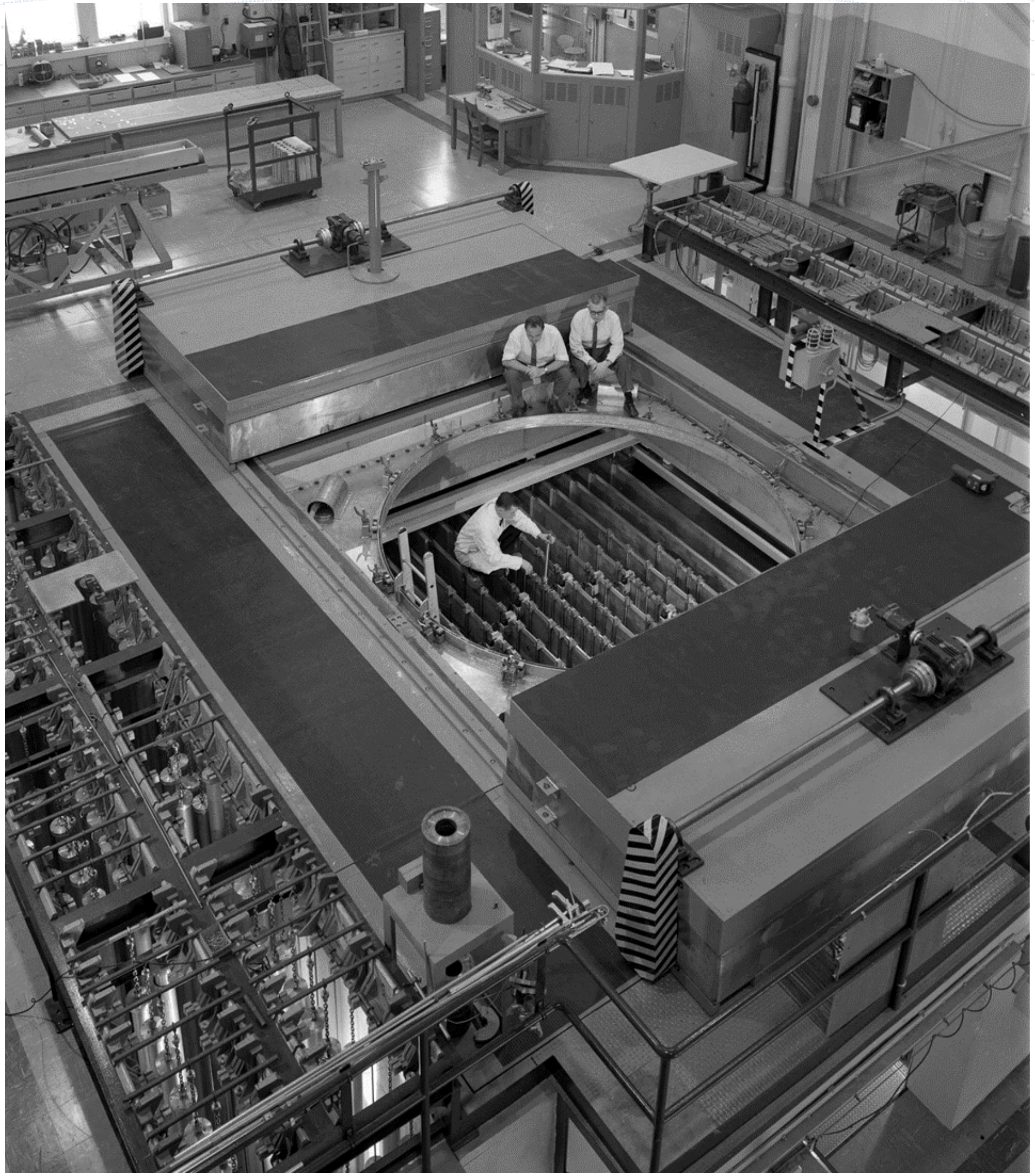
- Zero-power, heavy water moderated tank type reactor
- Up to ~200 W thermal power, peak neutron flux of 1×10^9 n/cm^2 s thermal, 5×10^8 n/cm^2 s fast
- Criticality achieved by pumping heavy water (99.8 to 97.5 weight% D_2O) into calandria
- Built to support development of NPD and CANDU reactors, first critical in 1960
- Has been used to confirm reactor physics designs of all of Canada's power reactors



Reconfigurable Core

- Fuel channels suspended by hooks along movable steel beams, can be configured in virtually any pitch and grid
- Fuel channels can be filled with a variety of fuels, and can be filled from the full core to a single bundle
- In-core ion chambers (IC) can be added to fuel channels





View of core from above, circa 1960s

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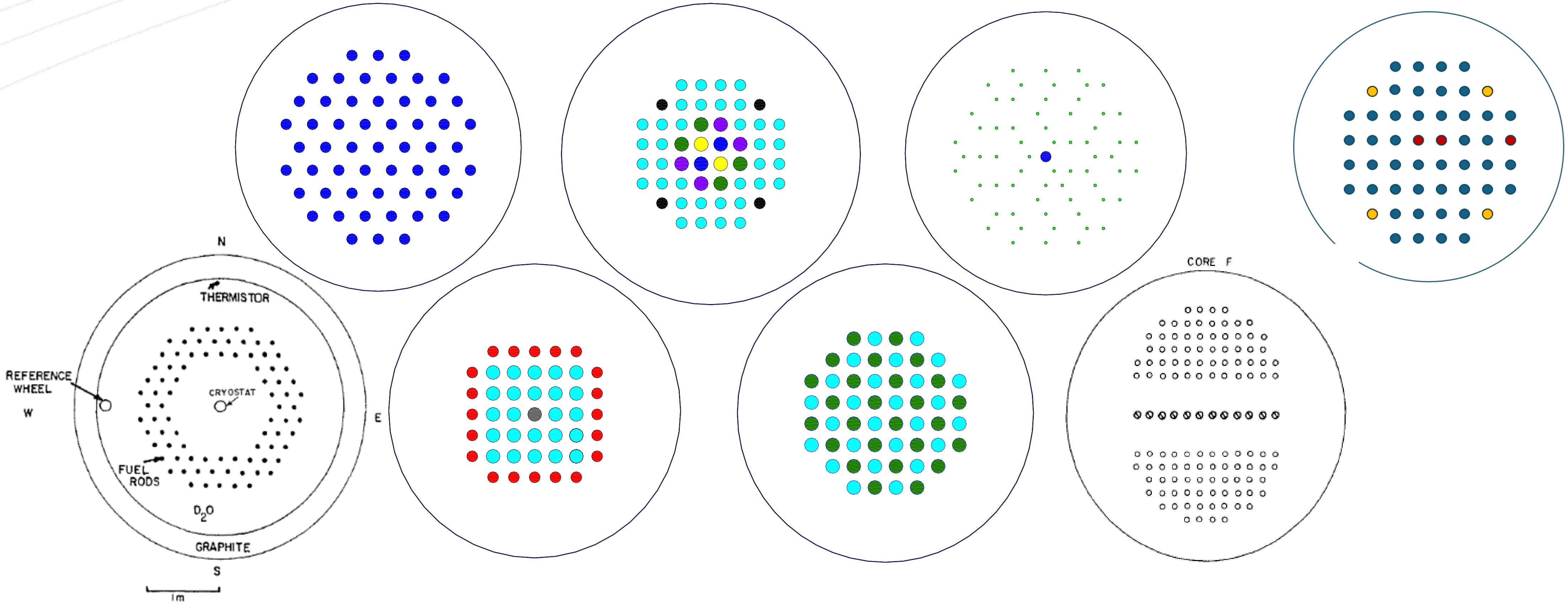
Reconfigurable Core, Fuel And Instrumentation Arrangements



Examples of core maps from historical experiments

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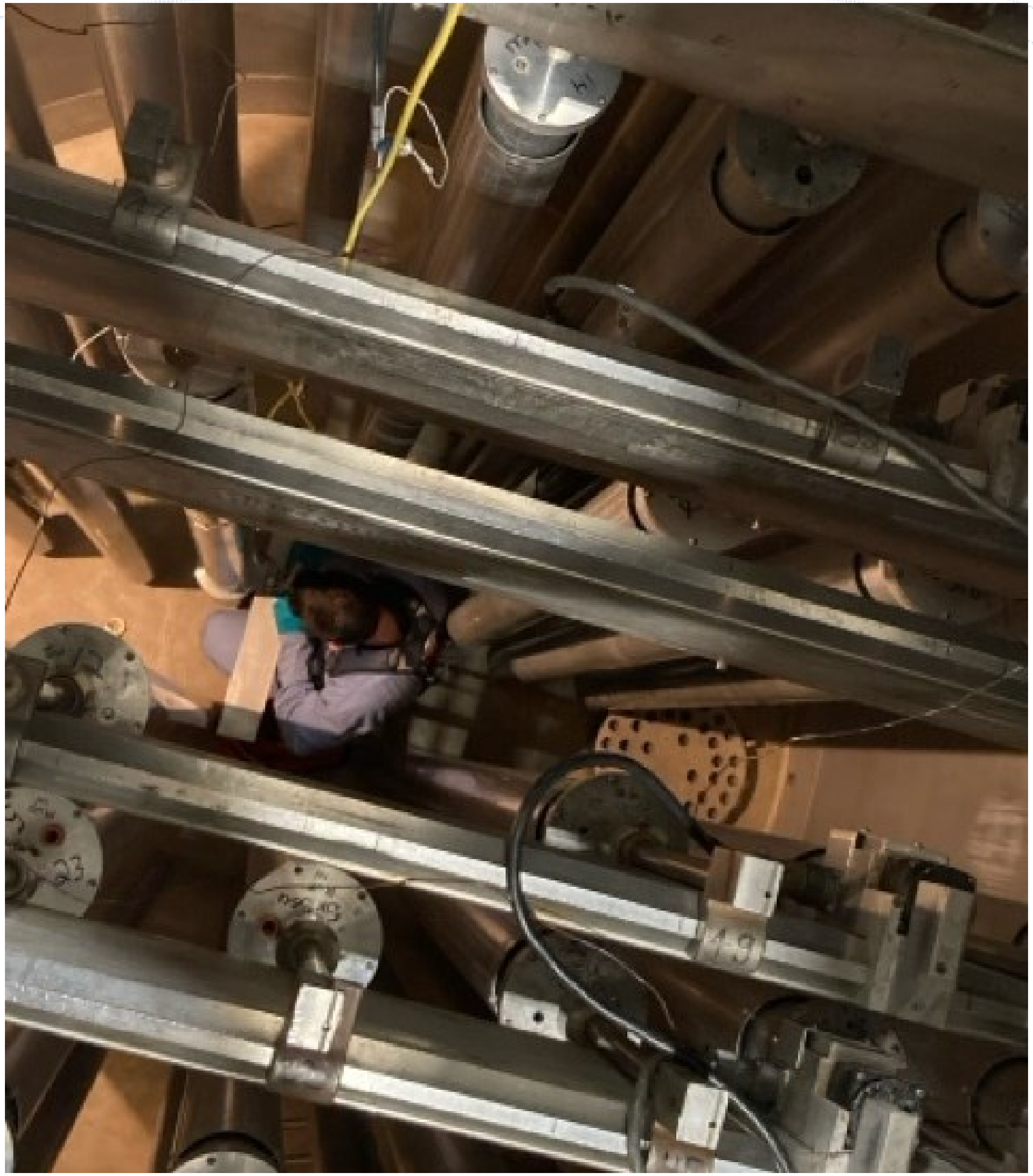
Advantages and Limitations

- Open tank design with reconfigurable core allows flexibility in experimental design
- Low power and no fuel burnup allows flexibility in installing equipment directly on fuel channels, even in-vessel
- Fixed temporary absorber limited to $<\beta_{eff}$, typically 6.5 mk. Experimental apparatus and in-core detectors share this limit
- Manual control of power by moderator level is challenging for extended periods



SECTION 5

Experimental Design

Technical Requirements and Constraints

- Simple and characterizable mechanical system; flat plate oscillating horizontally
- Sizing of absorber and associated in-core ICs based on neutronics modelling and fixed absorber limit of reactor
- Safety analysis required to ensure vibrating plate will not excite fuel channel in a way that would excite neighbouring fuel channels through fluid coupling in moderator

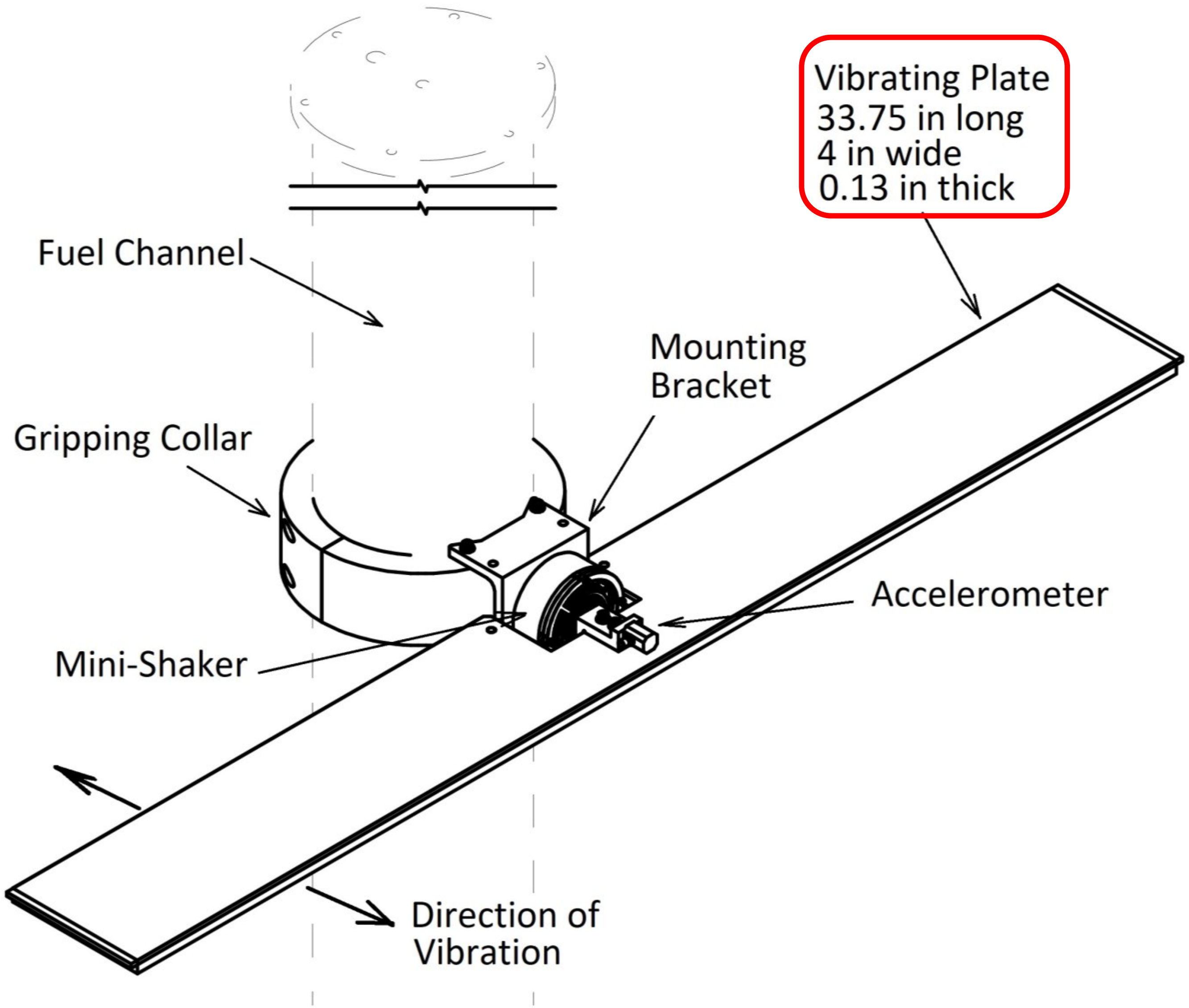
Absorber Selection

- An analysis of reactivity worth of various absorbers was performed using Monte Carlo N-Particle (MCNP) 6.2 with the E70CRL nuclear data library
- 1/8" thick 304 Stainless plate, 33.75" x 4" (3.2 x 857 x 102mm) was selected due to large mass while remaining under the 6.5mk worth limit
- Aluminum plate with comparable mass, identical length and width was selected as the neutron transparent plate

Description	keff	u_mcnp	Plate thickness (in)	reactivity worth (mk)	Plate mass (g)
Base Model (no absorber)	0.99823	0.00012	0	0.0	0
Cd, 2.5 thou thick	0.98272	0.00012	0.0025	-15.8	48
Cd, 5 thou thick	0.98113	0.00012	0.005	-17.5	96
Cd, 10 thou thick	0.98072	0.00011	0.01	-17.9	191
Cd, 10 thou thick, only one lattice pitch long	0.99113	0.00013	0.01	-7.2	191
Cd, 30 thou thick	0.98053	0.00012	0.03	-18.1	640
Cd, 20 thou thick	0.98066	0.00012	0.02	-17.9	471
Stainless 304 1/16 inch thick	0.99512	0.00012	0.0625	-3.1	1101
Stainless 304 1/4 inch thick	0.98976	0.00012	0.25	-8.6	4402
Stainless 304 1/8 inch thick	0.99289	0.00011	0.125	-5.4	2201

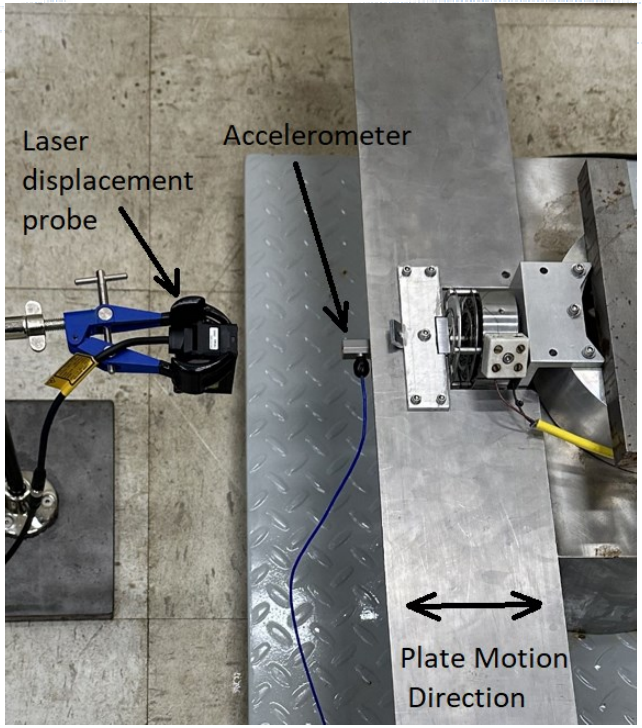
Vibrating Plate and Electrodynamic Shaker Design

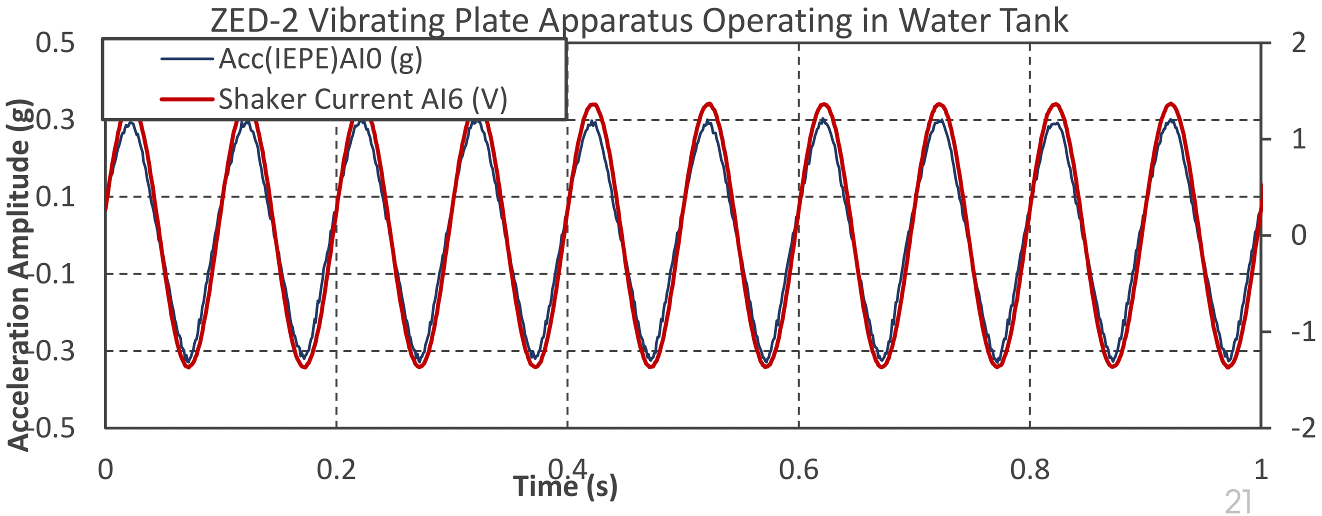
- Plate and apparatus will be in direct contact with moderator
- Electrodynamic shaker provides sinusoidal excitation to plate horizontally
- Radiation-hardened accelerometer provides feedback on absorber position relative to fuel channel
- Additional accelerometers on neighbouring fuel channels



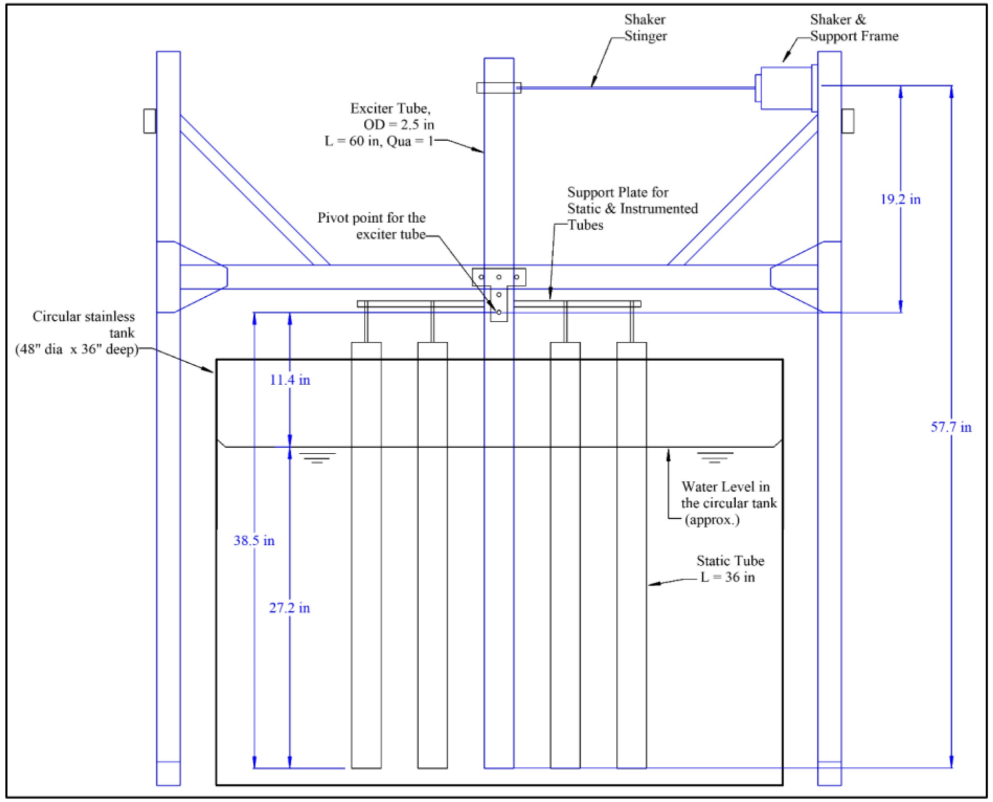
Frequency Considerations

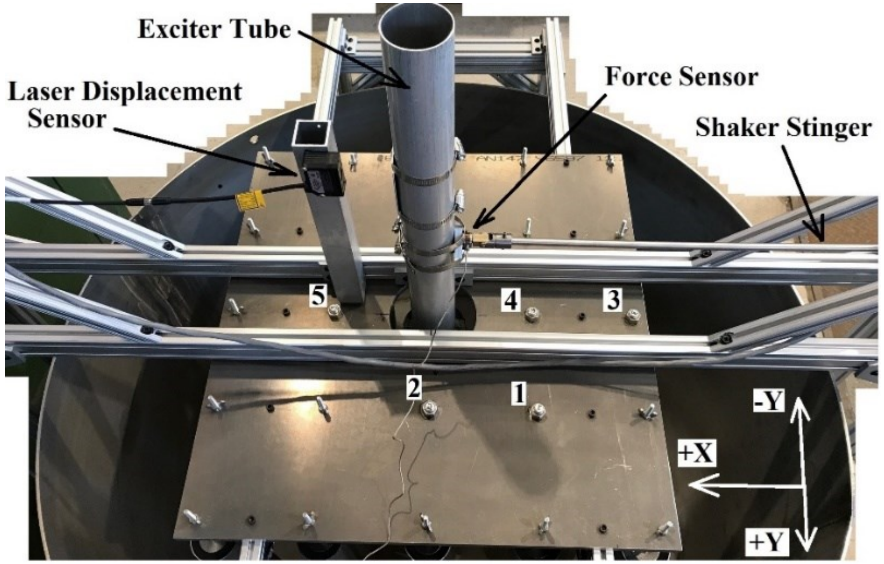
- Frequencies below 2 Hz should be avoided, as they may influence reactor operation
- Important to avoid swaying frequencies of fuel channels, approximately 0.3 Hz
- Resonant frequencies of vibrating plate apparatus to be avoided, 12-14 Hz
- Experimental analysis required to determine fluid coupling between excited channel and neighbouring channels





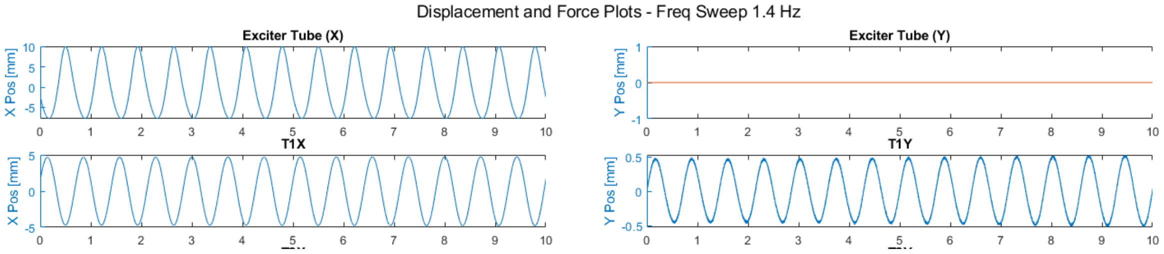
Safety Analysis - Fluid coupling



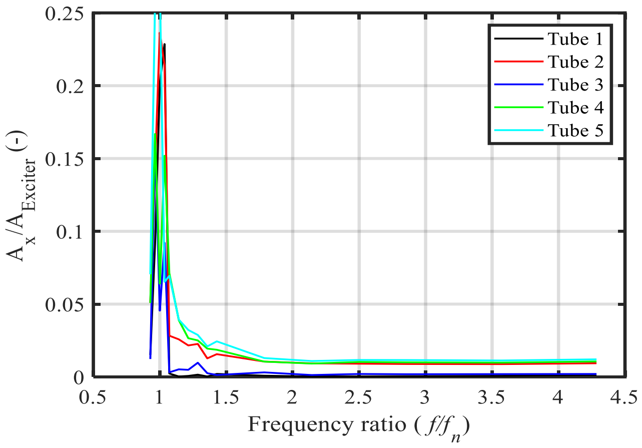


Safety Analysis - Fluid coupling

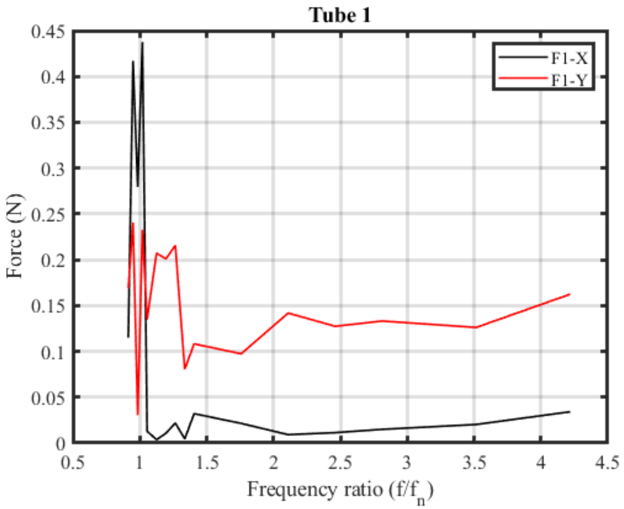
Tip Displacement, $f_n = \mathbf{1.4Hz}$



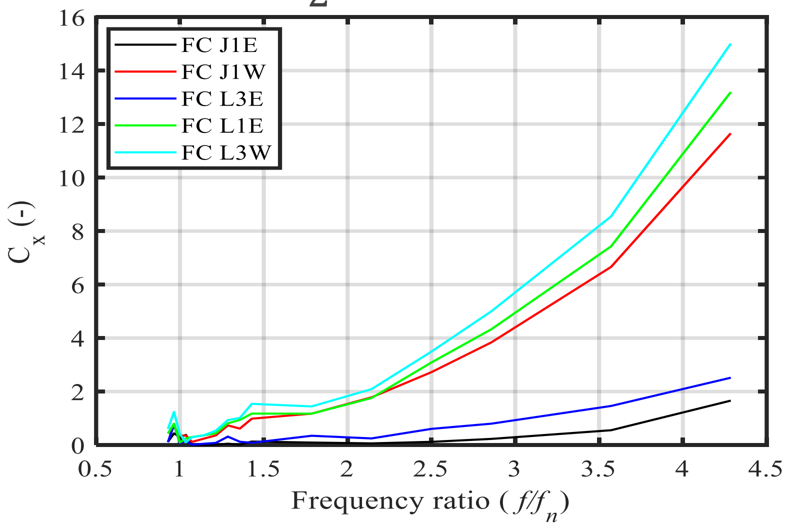
Normalized Amplitude Ratio, Static Tube to Excited Tube, X



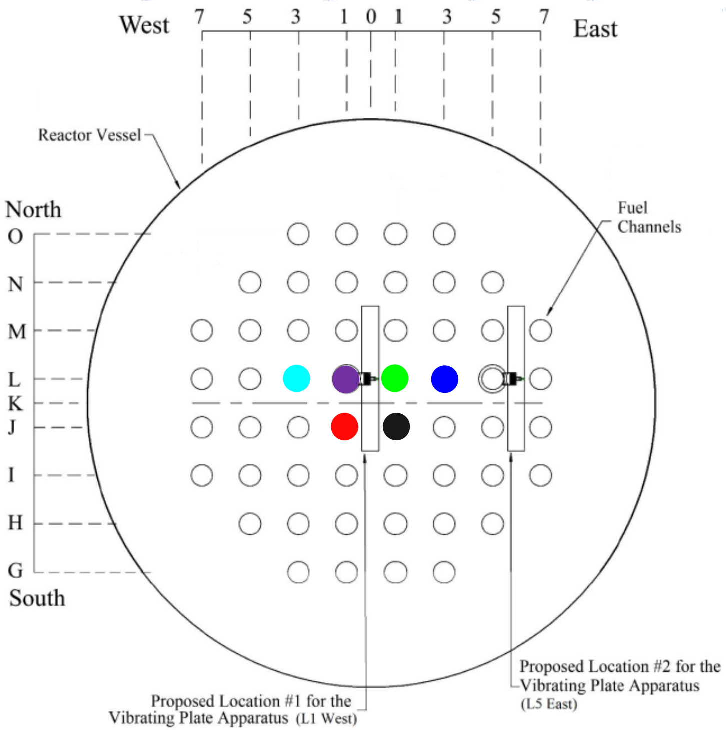
$$M_{Total}\ddot{X} + (2\zeta\omega_{water}M_{Tube})\dot{X} + kX = F_X(t)$$



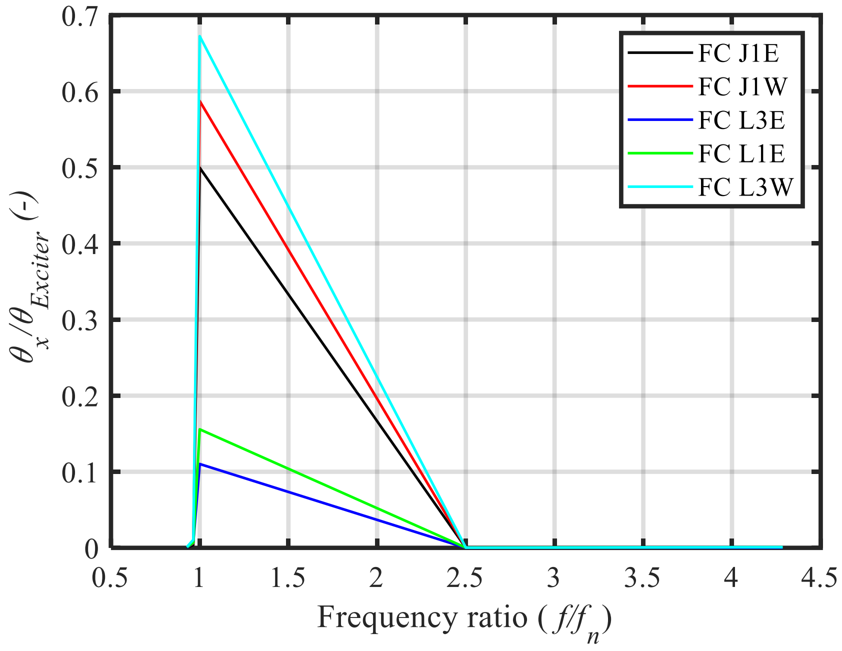
$$C_x = \frac{F_x}{\frac{1}{2}\rho(DL)(\omega L_{exc})^2}$$

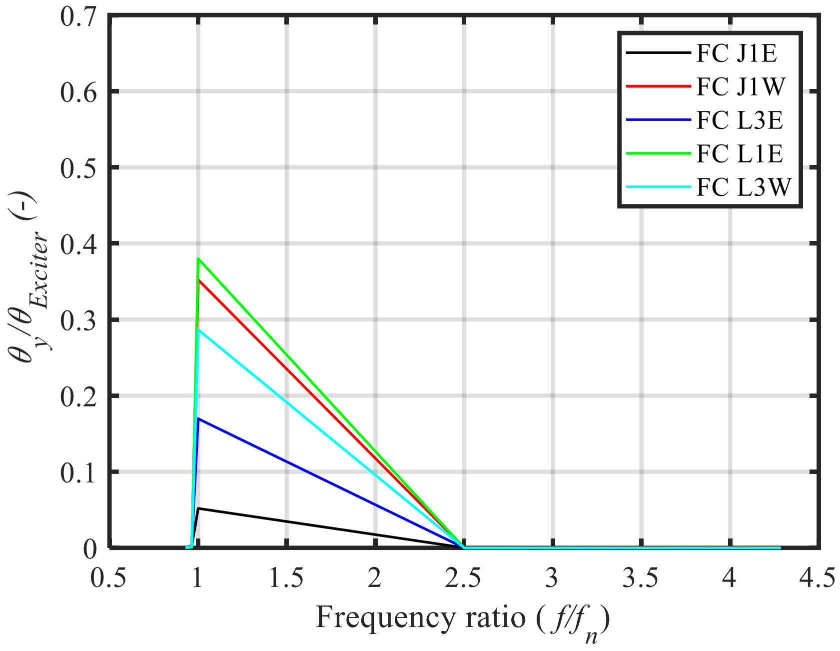


Fuel Channel Response from Safety Analysis



● Excited channel

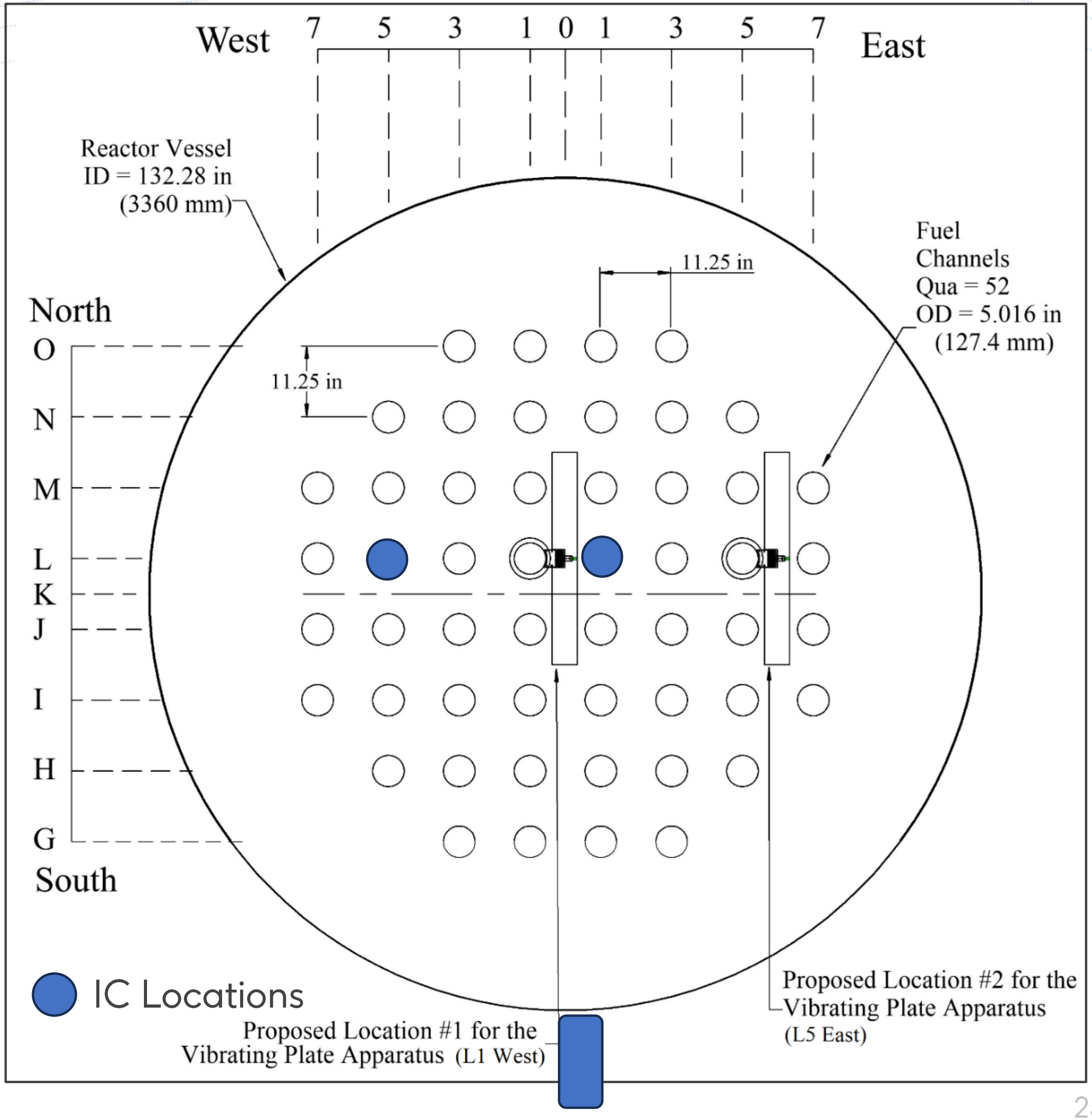




- Cross coupling forces scaled to full sized channels
- Modal analysis of fuel channel found $f_n = 0.3\ Hz$
- Fluid coupling not expected at or above minimum allowable frequency of 2 Hz (frequency ratio > 6.7)

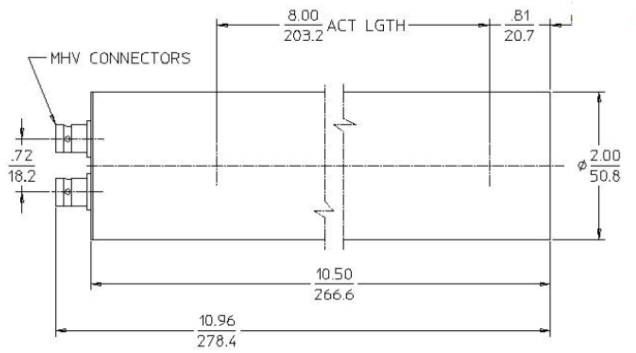
Core Map and Location

- Two channels selected to install apparatus: L1 West, L5 East
- Core configured in square grid, 11.25" (286mm) pitch

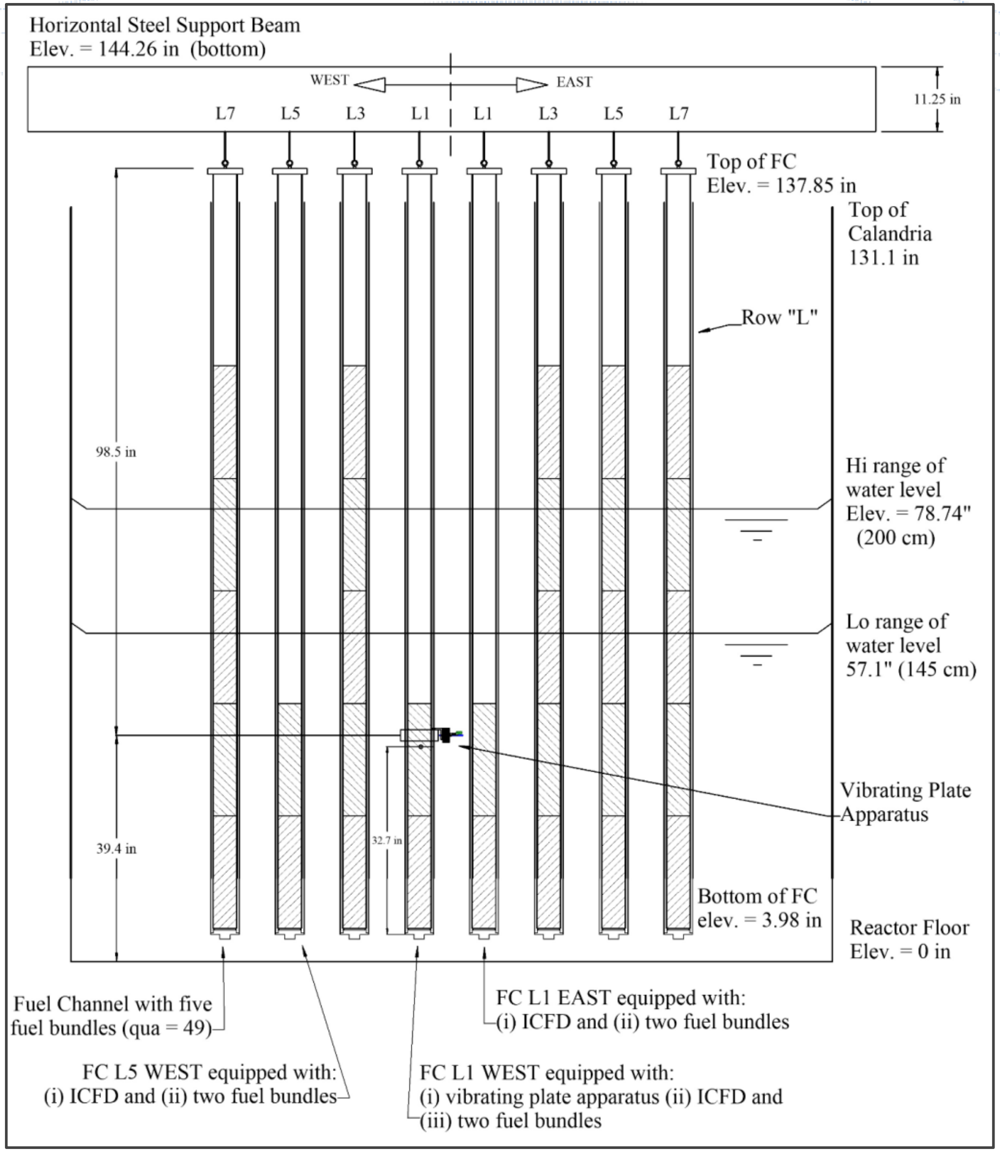


Fuel Assemblies, Detectors

- 49/52 channels fully fueled
- 2 channels partially fuelled with B-10 neutron ionization chamber installed inside channel above bundles
- Channel with vibrating plate apparatus partially fuelled



Ion Chamber Dimensions



SECTION 6

Experimental Conditions

Simplified Test Matrix

L1 West Location

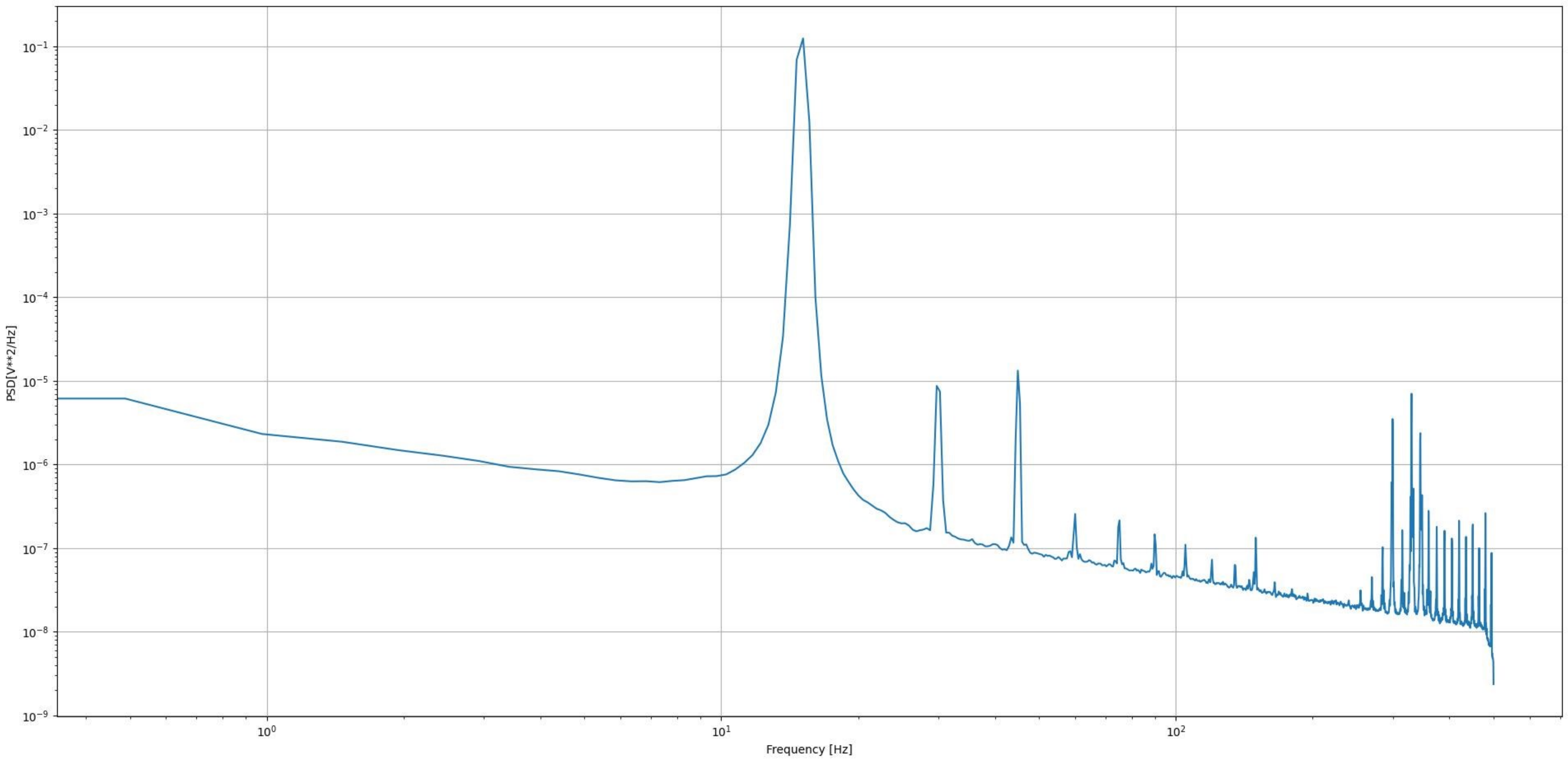
Test Series	Configuration	Key Objectives	Status
1a	No Apparatus, Radial IC only	Record baseline neutron data	Completed
1b	Apparatus installed, no absorber plate, ex-core IC only	Confirm predicted reactivity worth of apparatus, confirm shaker functionality	Completed
1c	Apparatus installed, 316SS plate, ex-core IC only	Confirm predicted reactivity worth of apparatus with absorber, confirm no fluid coupling	Completed
1d	Apparatus installed, 316SS plate, ex-core IC and two in-core IC	Examine frequency effects in the range of 6-17 Hz, examine amplitude effects in the range of 0.2 – 0.8 mm zero-to-peak	Planned
1e	Apparatus installed, aluminum plate, ex-core IC and two in-core IC	Repeat conditions of 1d with neutron transparent vibrating plate	Planned

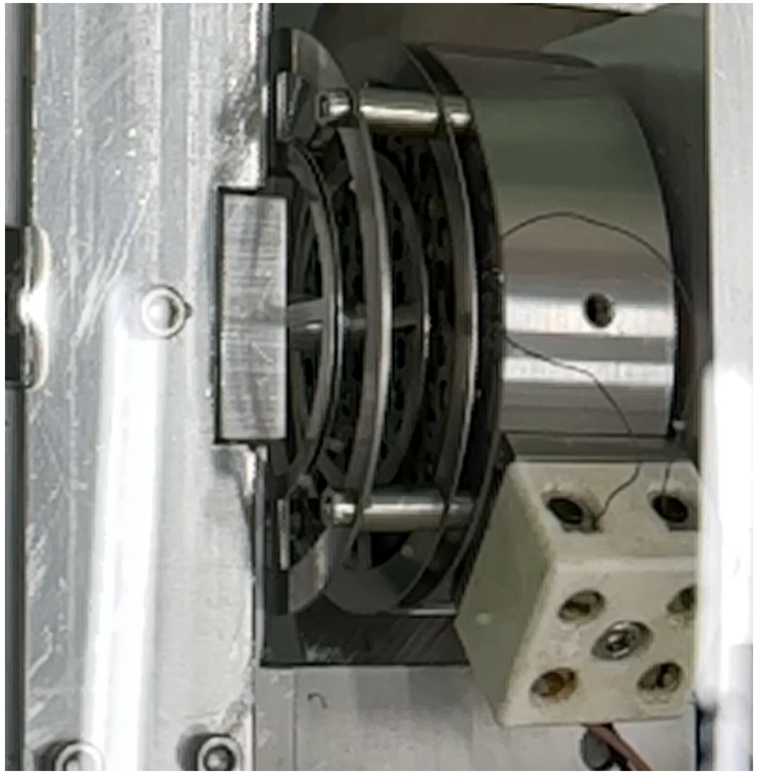
SECTION 6

Preliminary Results

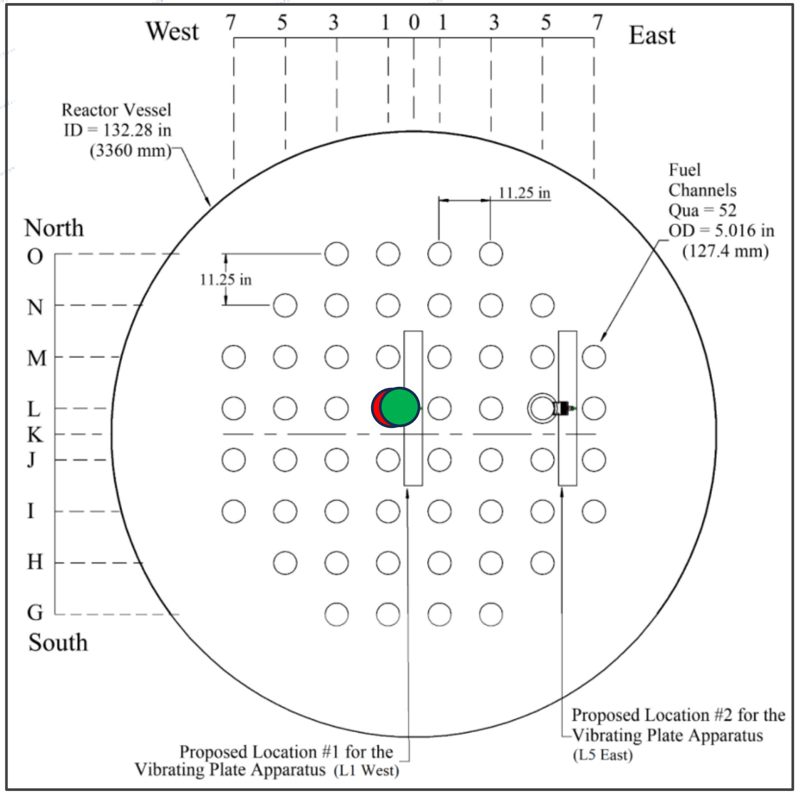
Preliminary Results – Mechanical Validation

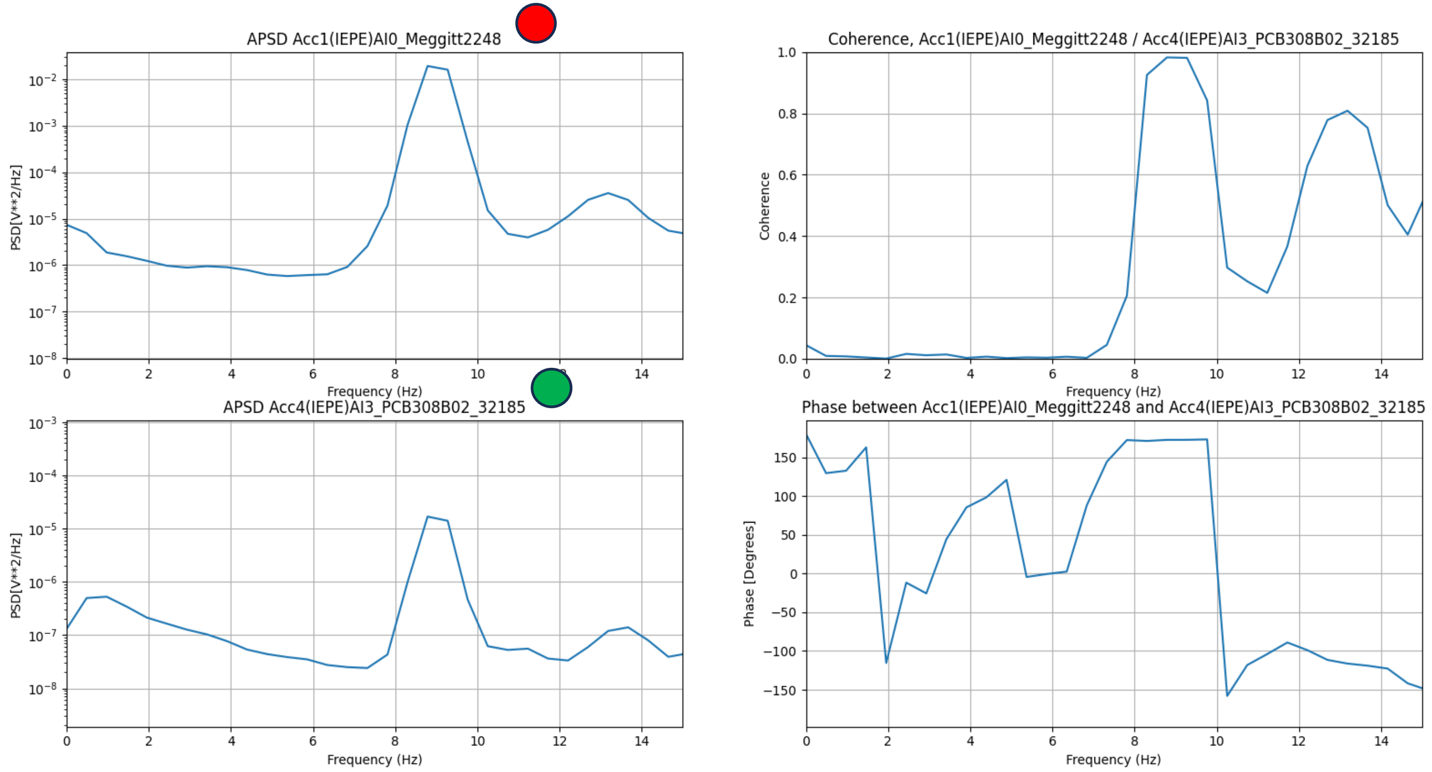
PSD, Accelerometer, 15 Hz, 1 mm Peak-Peak





Preliminary Results Fluid Coupling Validation - Test 1c

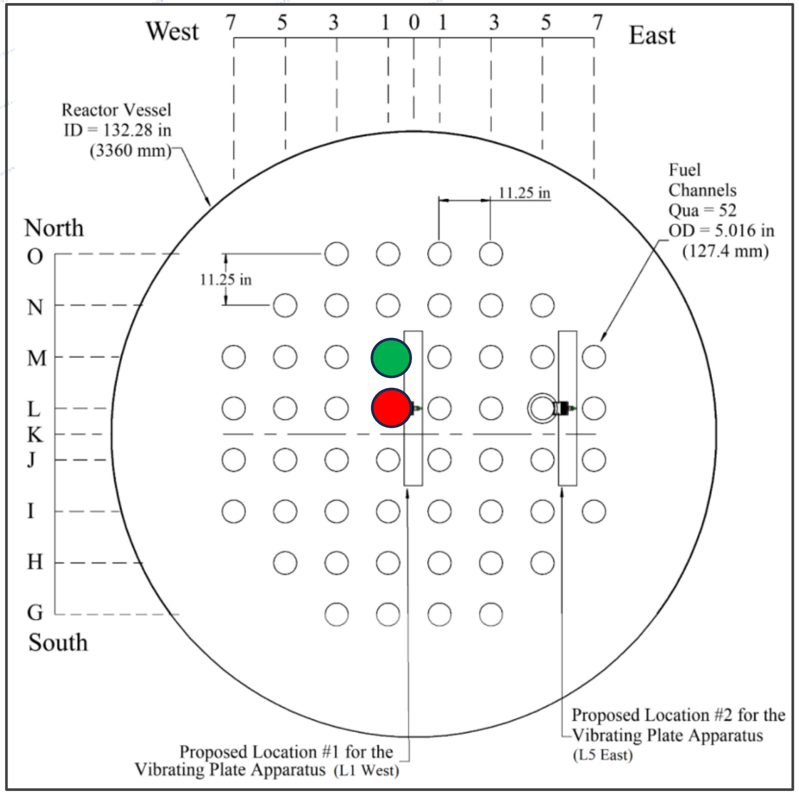




- Plate accelerometer
- Fuel channel accelerometer

Vibration on shaker fuel channel as expected, no coupling to neighbouring channels found

Preliminary Results Fluid Coupling Validation - Test 1c



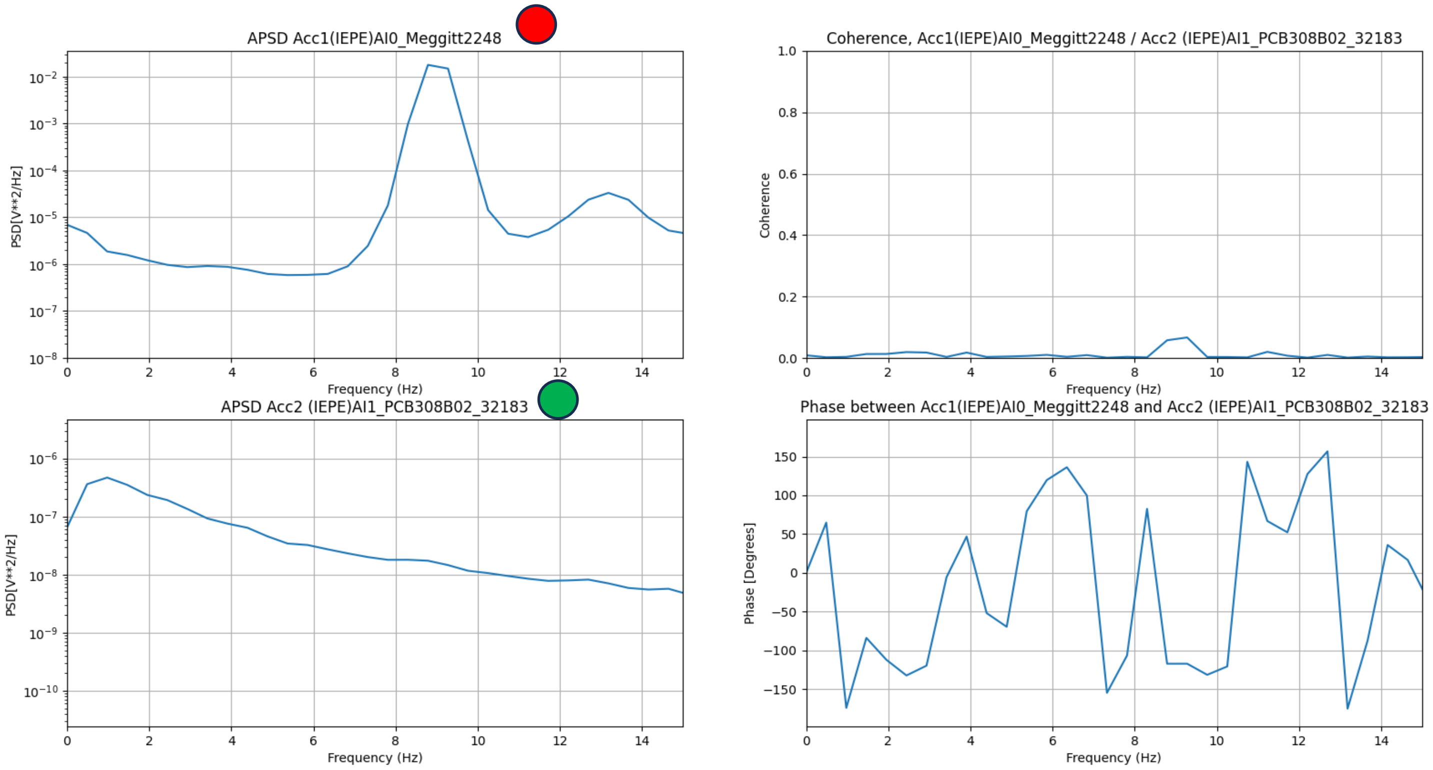
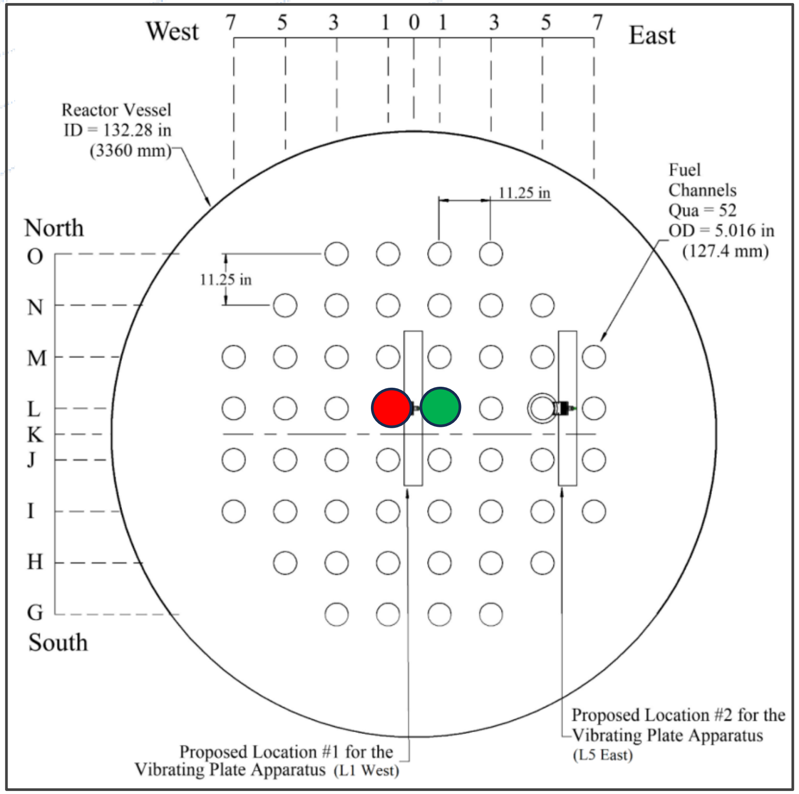


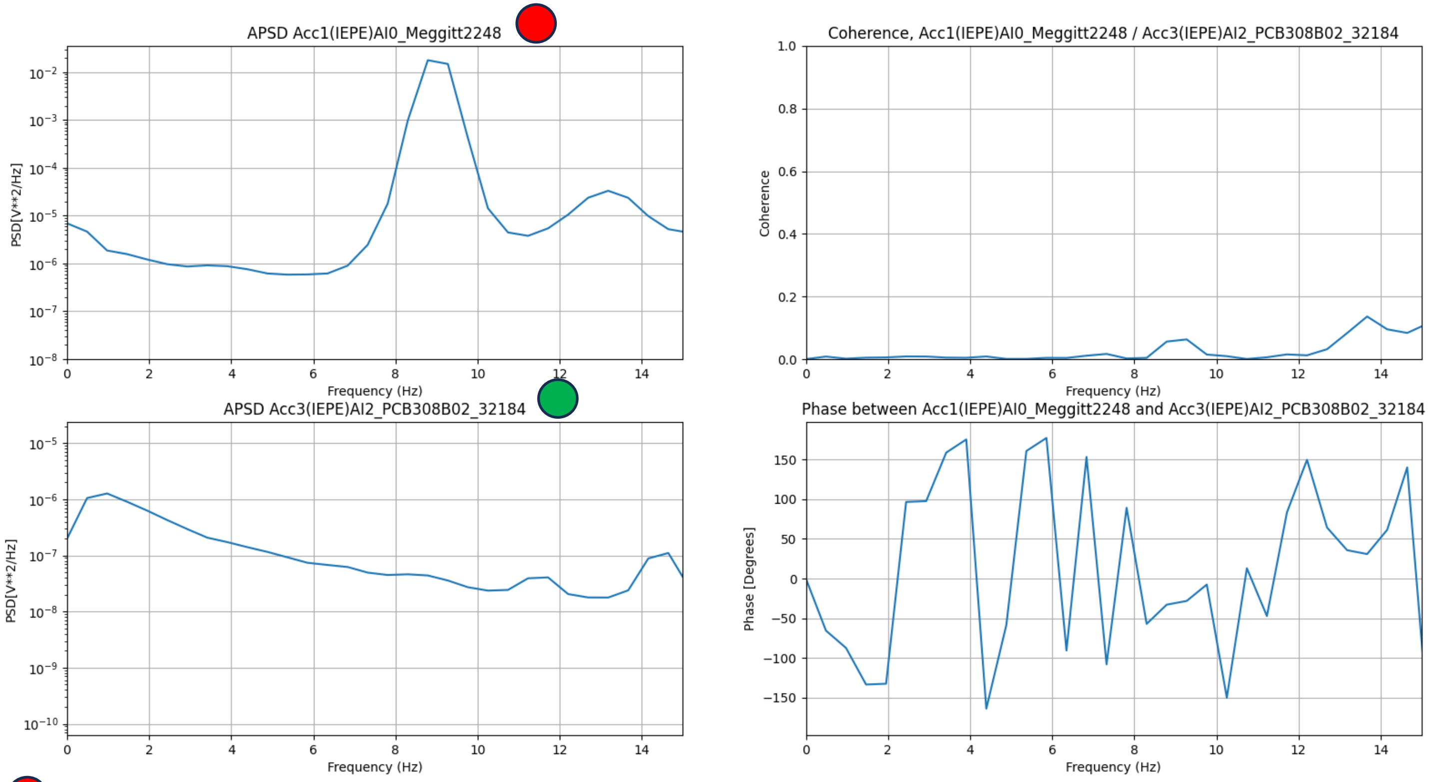
Plate accelerometer

Fuel channel accelerometer

Vibration on shaker fuel channel as expected, no coupling to neighbouring channels found

Preliminary Results Fluid Coupling Validation - Test 1c



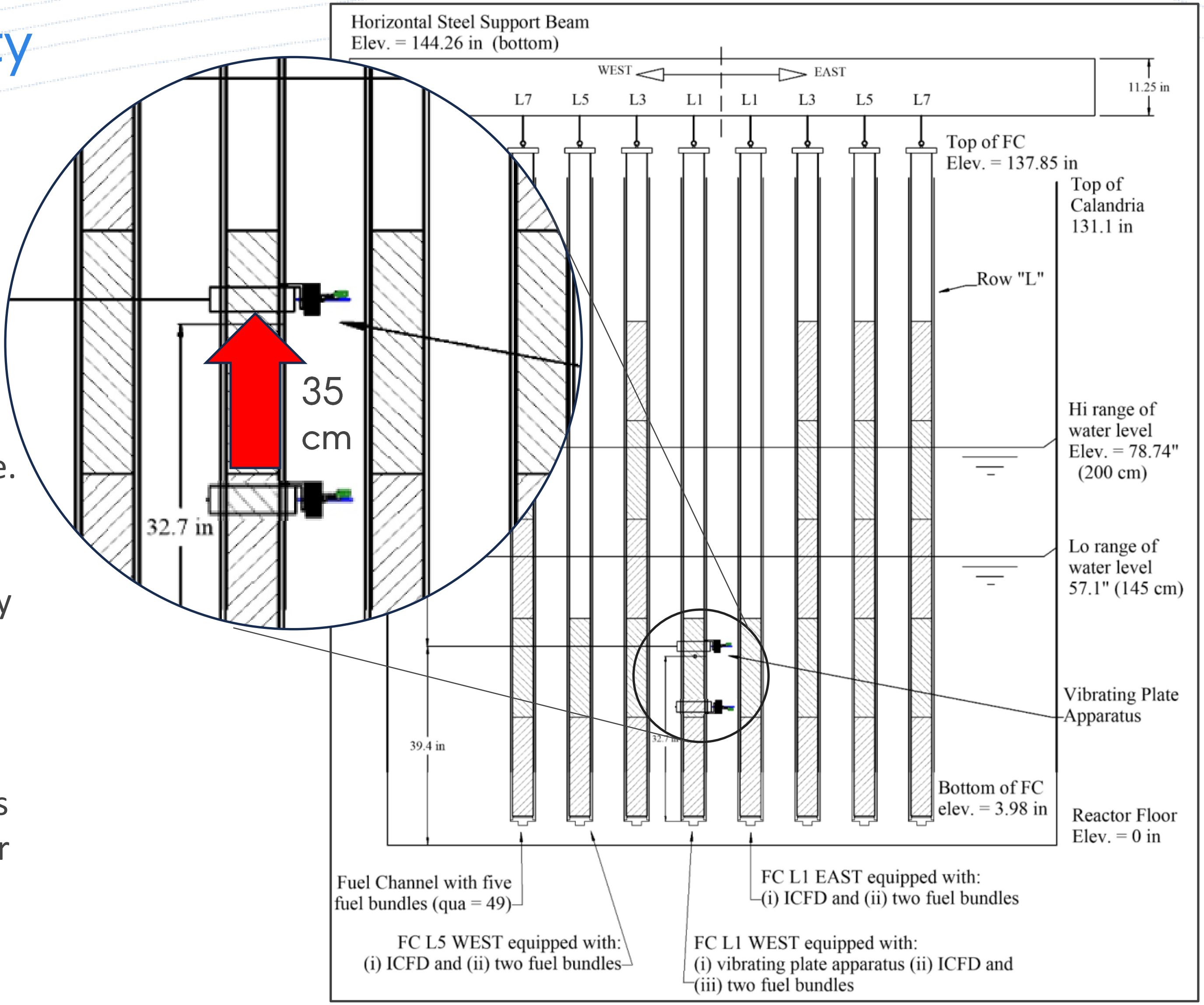


- Plate accelerometer (red)
- Fuel channel accelerometer (green)

Vibration on shaker fuel channel as expected, no coupling to neighbouring channels found

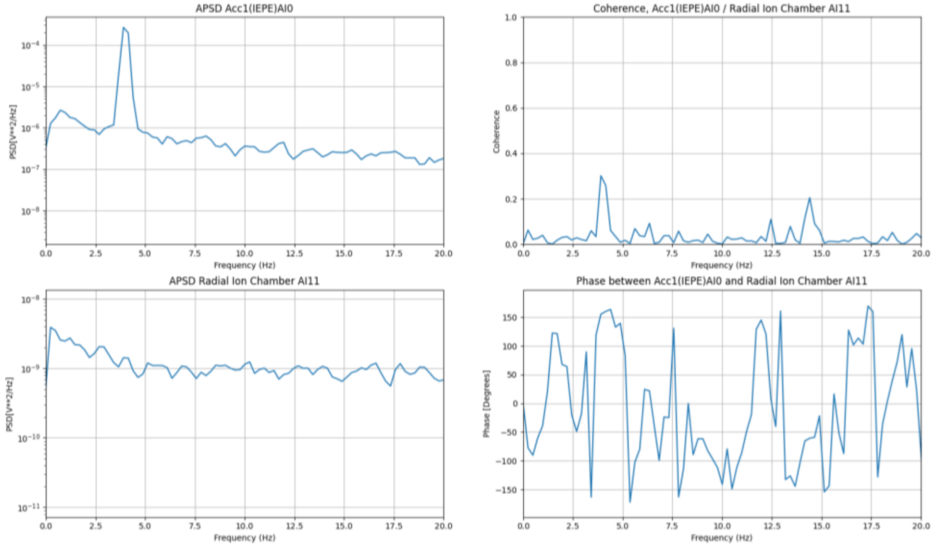
Preliminary Results – Reactivity Worth Test 1b, 1c

- Reactivity worth was measured directly during test 1b and compared to simulations
- Initially apparatus installed at height corresponding to peak flux
- Actual reactivity worth of the collar and shaker was found to be ~0.5mk higher than the predicted value. Based on the measured results, and predicted worth of the plate, the entire assembly would exceed the maximum temporary absorber reactivity worth limit. Therefore, the total worth of the assembly needed to be reduced
- To maintain the largest possible absorber, the apparatus was moved upward by 13.8” (35cm). This was favoured over reducing the size of the absorber
- Corrected worth of apparatus with absorber was measured in experiment 1c and in agreement with the updated prediction

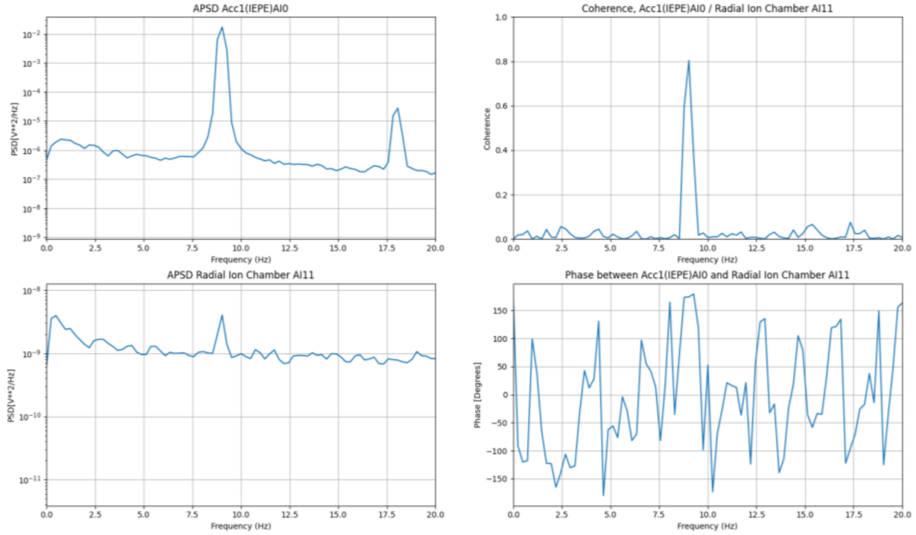


Preliminary Results Ex-Core IC, Test 1b

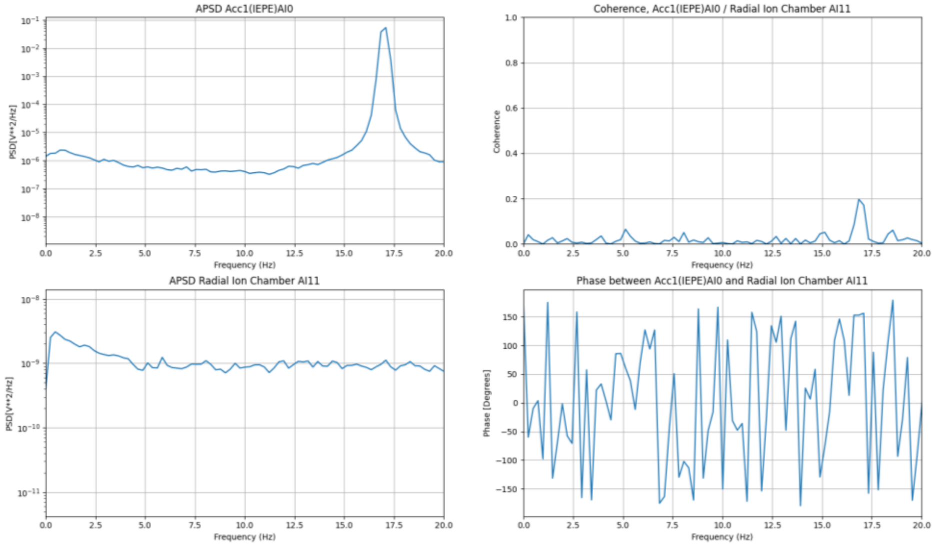
4Hz Oscillation



9Hz Oscillation



17Hz Oscillation



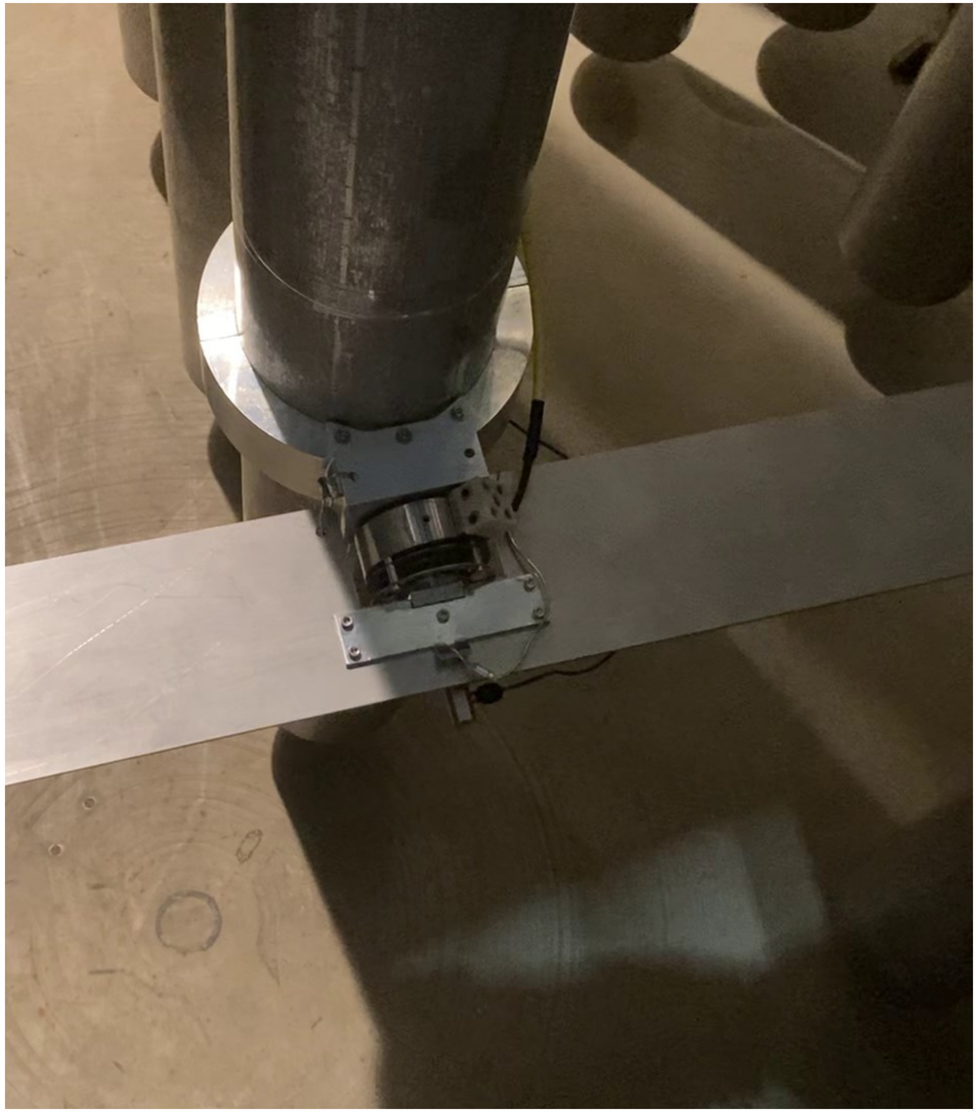
Based on apparatus vibration without additional absorber, coherence peaks are noted at fundamental frequencies

SECTION 7

Summary and Path Forward

Summary and Path Forward

- To Date:
  - Experimental design and fabrication completed
  - Safety case validated
  - Functional testing complete
  - Test matrix determined for two locations, absorber and transparent plate
- Path Forward:
  - Complete test matrix with rigid plates
  - Conduct test campaign with flexible oscillator with known mode shape
  - Oscillate full scale fuel bundle
  - Use findings to support validation of neutron noise simulation tools



Thanks for Listening!
Questions?

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