Simulating reactor noise with vibrations using the random ray method

Paul Cosgrove

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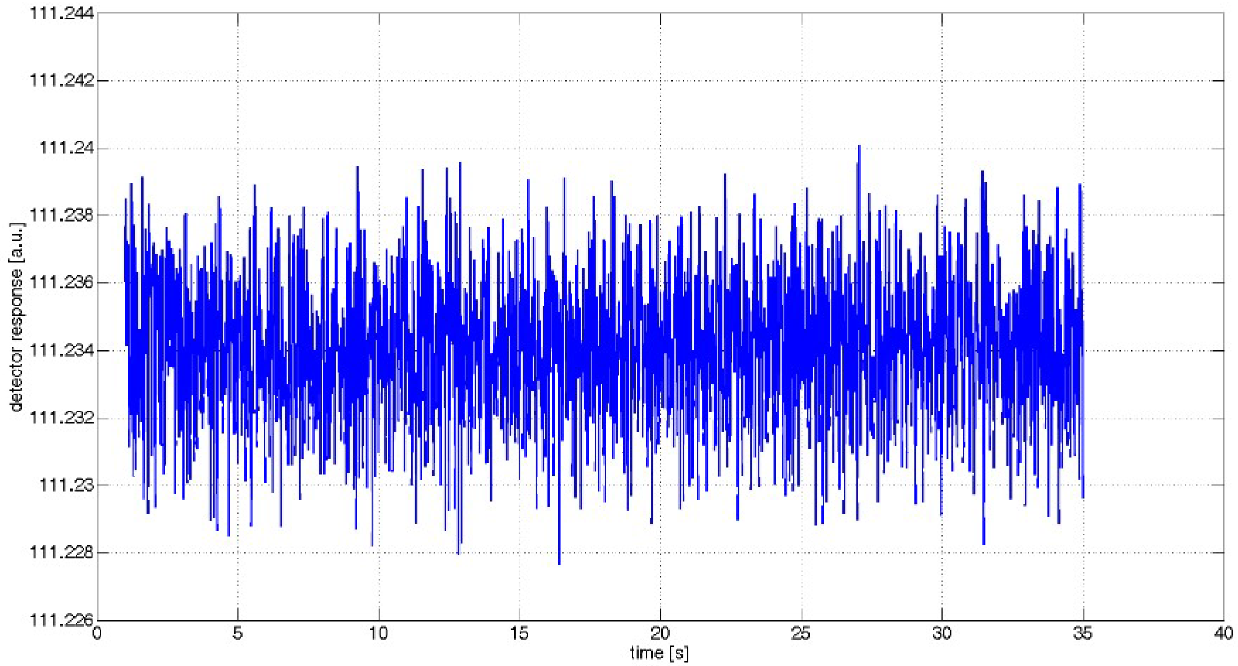
What is reactor neutron noise?

$$\left[\frac{1}{v^g}\frac{\partial}{\partial t} + \mathbf{\Omega}\cdot\nabla + \Sigma_{\mathrm{t}}^{g}\right]\psi^g = \mathbf{\Sigma}\phi$$



$_{\mathrm{t}}\psi^{g}$

CORTEX project website [cortex-h2020.eu].

Solving noise problems

- Can apply deterministic and MC
- Can do a frequency domain noise solve or Fourier transform a dynamic solution

Several significant challenges for frequency domain

1. MC suffers higher variance (complex particle weights)
2. Deterministic can suffer a high memory burden

$$\phi \sim \mathcal{O}(N_{\mathrm{groups}} \times N_{\mathrm{mesh}})$$

Fixed source

$$\left[\mathbf{\Omega} \cdot \nabla + \Sigma_{\mathrm{t}}^{g} + \frac{i\omega}{v^{g}}\right] \delta\psi^{g} = \mathbf{\Sigma}\delta\phi + \boxed{\delta\mathbf{\Sigma}\phi - \delta\Sigma_{\mathrm{t}}\psi^{g}}$$

$$\psi \sim \mathcal{O}(N_{\mathrm{groups}} \times N_{\mathrm{mesh}} \times N_{\mathrm{angles}})$$

X tracks per angle per mesh (for MoC)

3. Convergence is extremely slow

Recent developments

$$\left[\mathbf{\Omega}\cdot\nabla+\Sigma_{\mathrm{t}}^{g}+\frac{i\omega}{v^{g}}\right]\delta\psi^{g}=\mathbf{\Sigma}\delta\phi+\delta\mathbf{\Sigma}\phi-\delta\Sigma_{\mathrm{t}}\psi^{g}$$

Expensive due to this term

$$\left[\mathbf{\Omega}\cdot\nabla+\Sigma_{\mathrm{t}}^{g}+\frac{i\omega}{v^{g}}\right]\delta\psi^{g}+\delta\Sigma_{\mathrm{t}}\psi^{g}=\mathbf{\Sigma}\delta\phi+\delta\mathbf{\Sigma}\phi$$

$$\left[\mathbf{\Omega}\cdot\nabla+\Sigma_{\mathrm{t}}^{g}\right]\psi^{g}=\mathbf{\Sigma}\phi$$

Solve simultaneously during a sweep

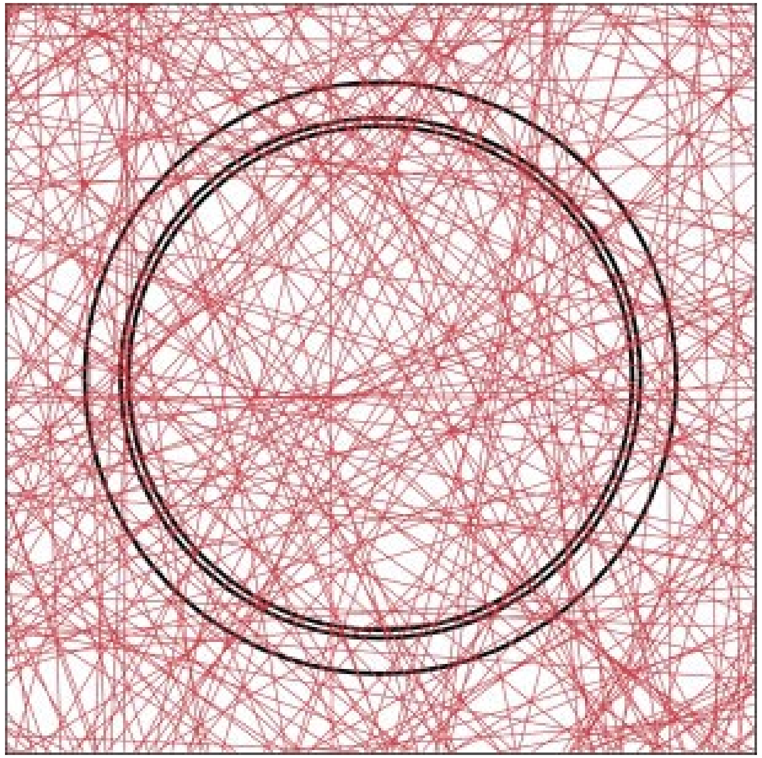
Cosgrove et al. (2024). "A memory-efficient neutron noise algorithm for reactor physics", Annals of Nuclear Energy.

Recent developments

- Frequency-domain noise solvers did not previously include MoC
- Implemented new algorithm in SCONE's random ray MoC solver

Pro: Transport sweeps are very fast

Con: Convergence is stochastic, complicated to determine – noise entropy predicts convergence too early

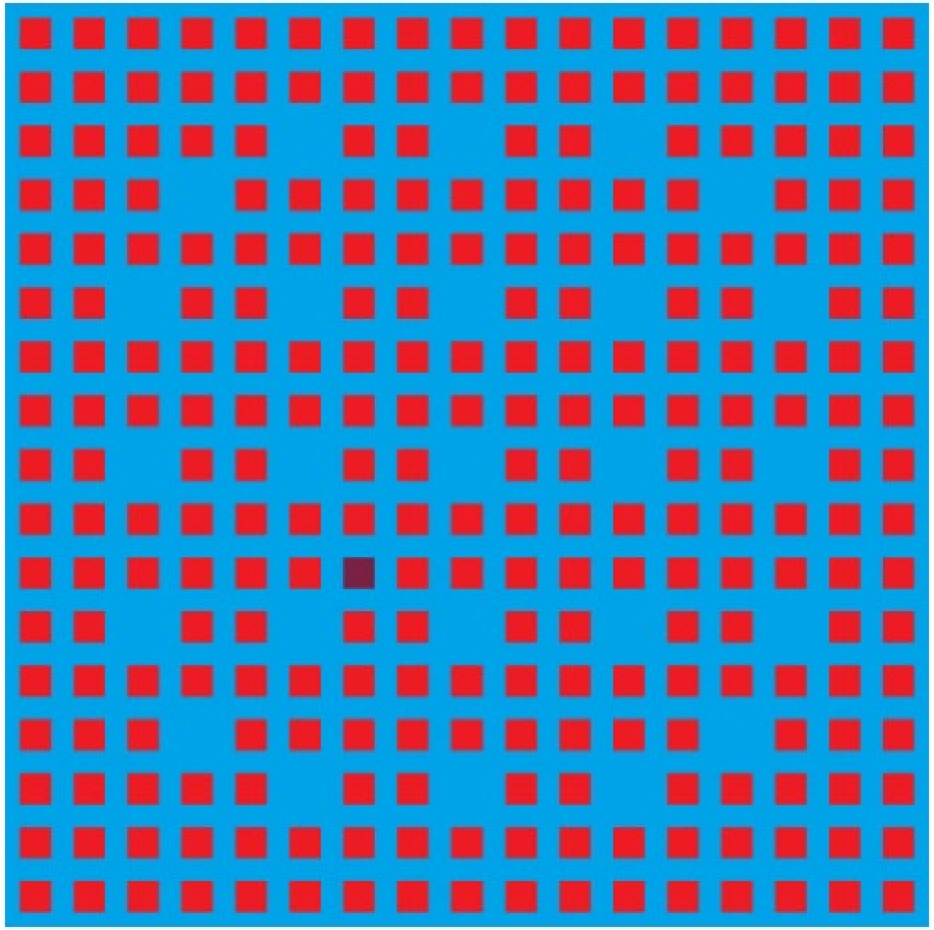


Tramm et al. (2017). "The random ray method for neutral particle transport", Journal of Computational Physics.

UOX Noise Benchmark

- Problem used by several codes:
  - 17 X 17 Square pins with surrounding water blade
  - 2D with reflective boundary conditions
  - 2 group with given cross sections
  - One pin is ‘noisy’
- For example, exercise 2:

$$\delta\Sigma_{c,g}(x_p, y_p, t) = A_{c,g} \sin(2\pi f t + \varphi)$$



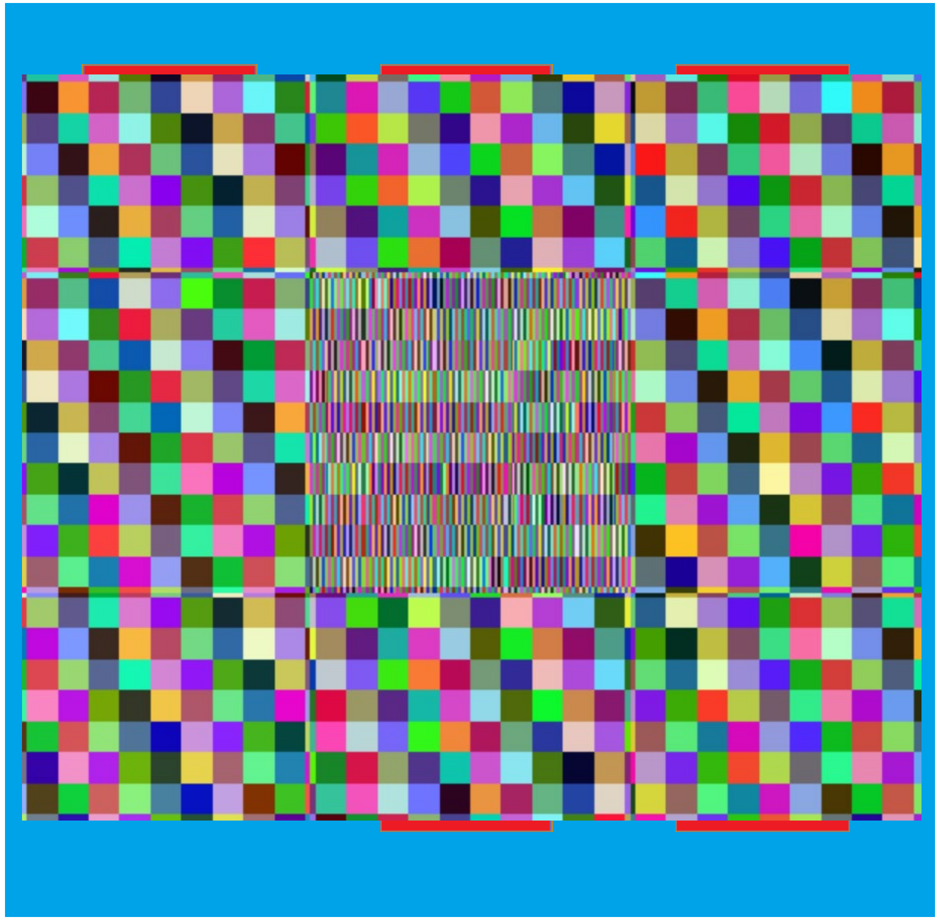
Vinai et al. (2021). “Comparison of neutron noise solvers based on numerical benchmarks in a 2-D simplified UOX fuel assembly”, Proc. M&C.

Exercise 3: Vibration

- The noisy pin vibrates from left-to-right with amplitude of 0.2cm, frequency 1Hz
- Handled with the ϵ/d approximation

$$\delta\Sigma_a(x,E,\omega) = \begin{cases} -i\frac{\pi}{2}\Delta\Sigma_a(E)\delta(\omega-\omega_0), & \text{with } x_0-\varepsilon \le x \le x_0+\varepsilon \\ 0, & \text{otherwise} \end{cases}$$

- Has been challenging for other codes to resolve
- Simulated the problem using SCONE's noise solver (fixing the bugs from before…)

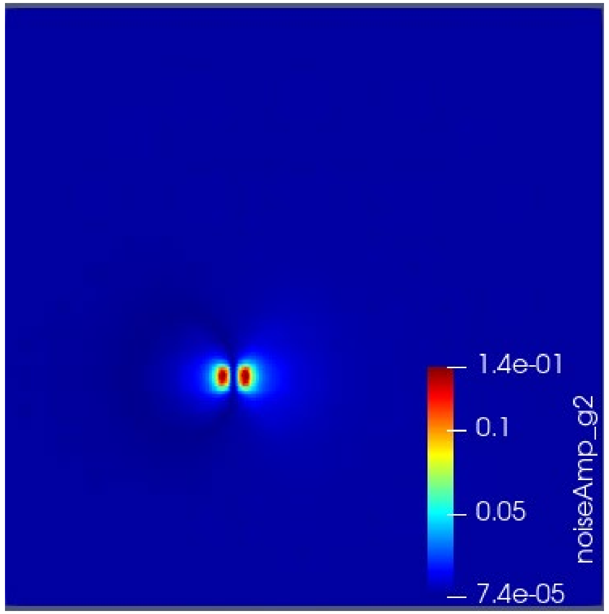


Vinai et al. (2023). "On the simulation of neutron noise induced by vibrations of fuel pins in a fuel assembly", Annals of Nuclear Energy.

Simulation setup

- Runs performed using 2000 rays per iteration, dead length of 100cm, active length of 200cm, 200 active iterations, inactive iterations terminated by measuring fluctuations in an integral phase variable
- Required 5.2k inactive iterations (no convergence acceleration) or 6m15s on an Intel Gold with 3.1GHz
- Notably fewer inactive cycles required than for variable strength absorber problem ~30k

Results – Amplitude Group 2



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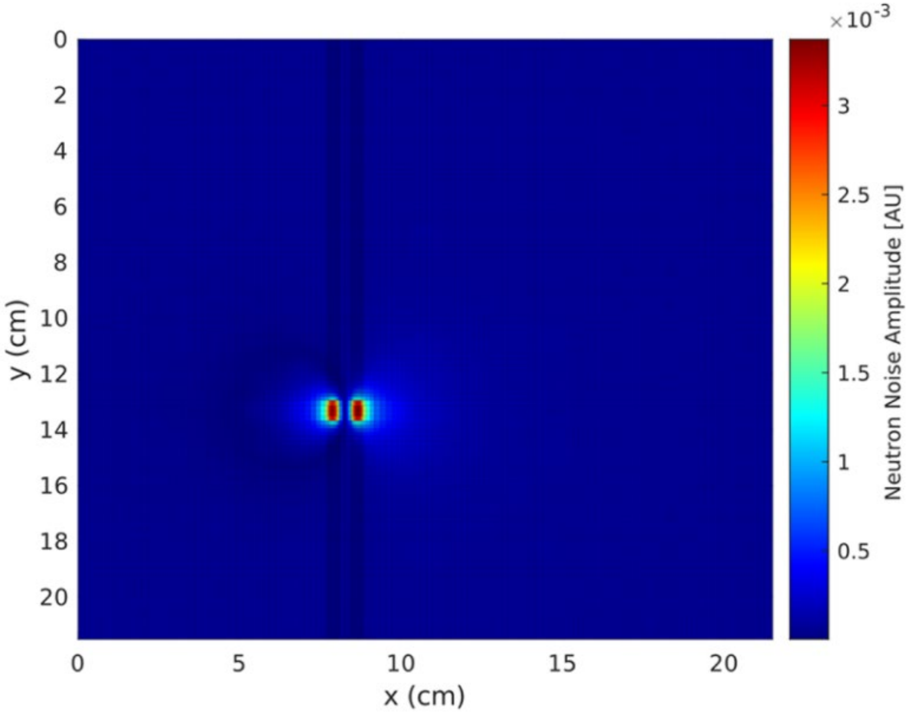
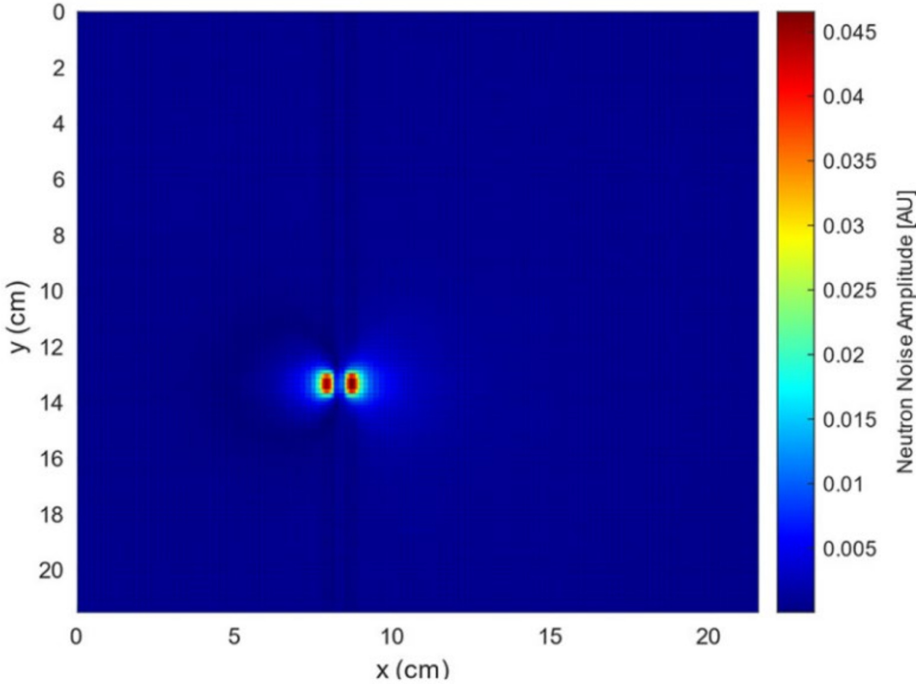
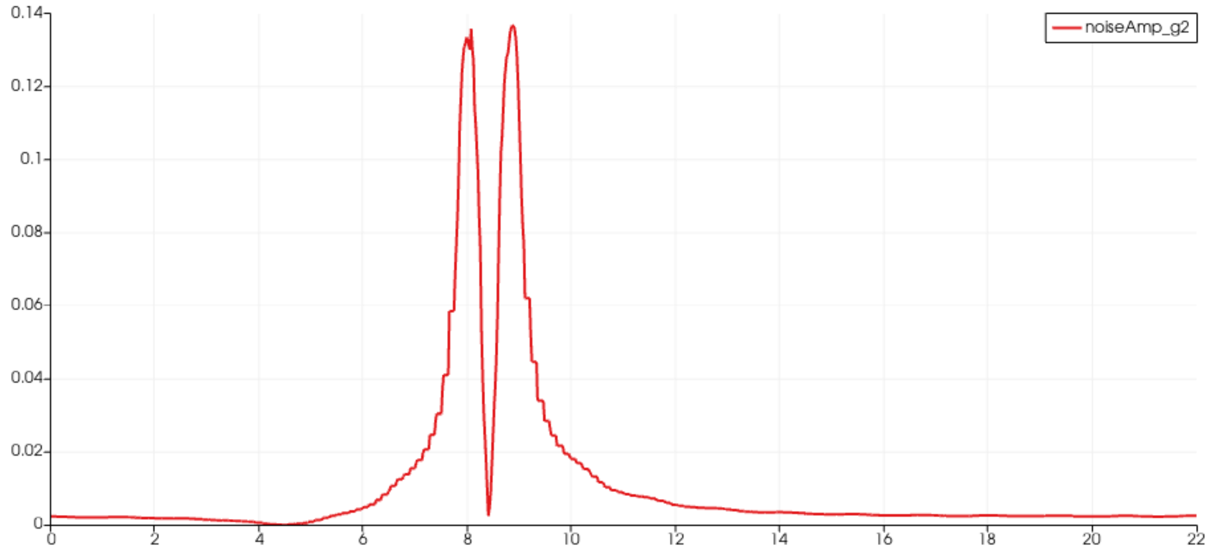


APOLLO3



NOISE-SN

Results – Amplitude Group 2



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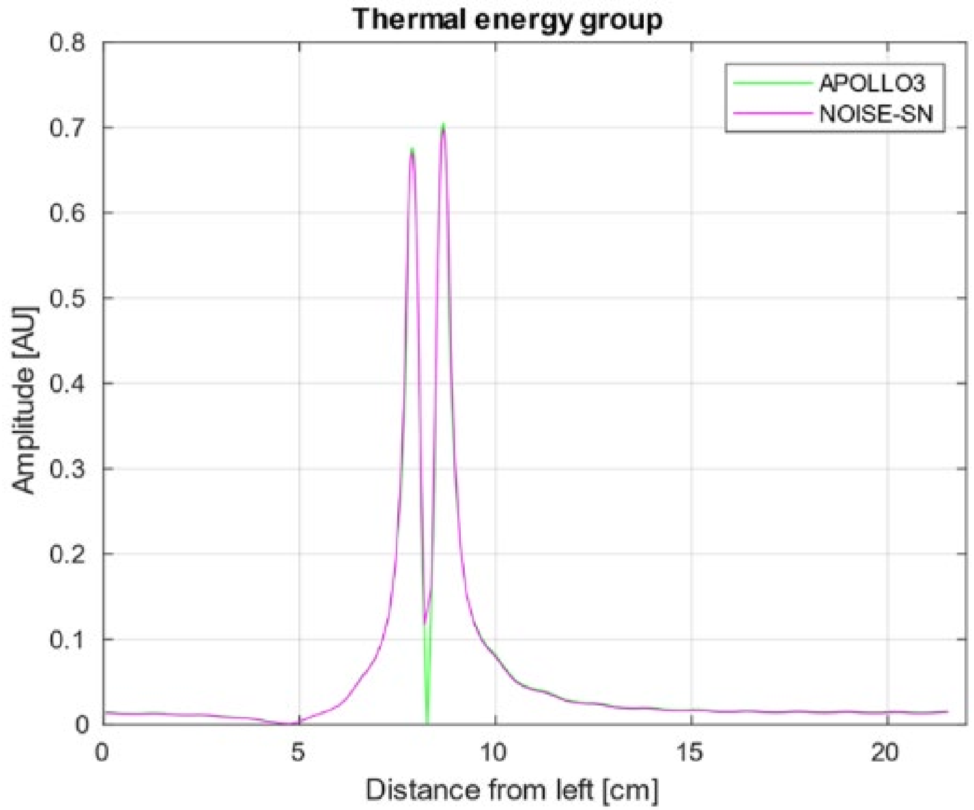
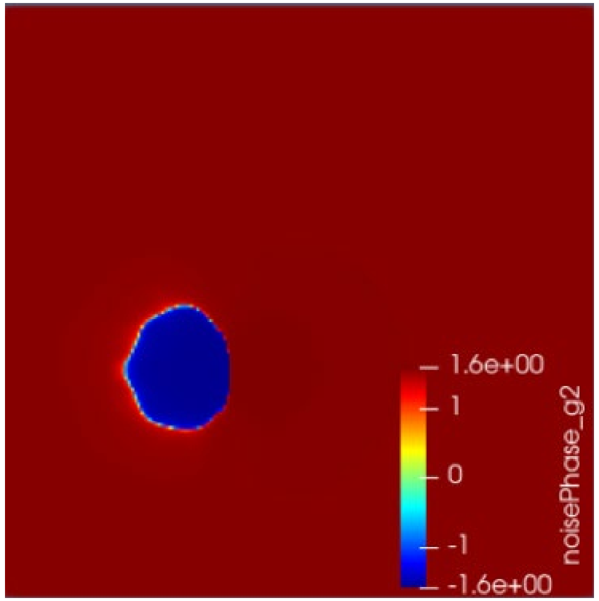


Results – Phase Group 2



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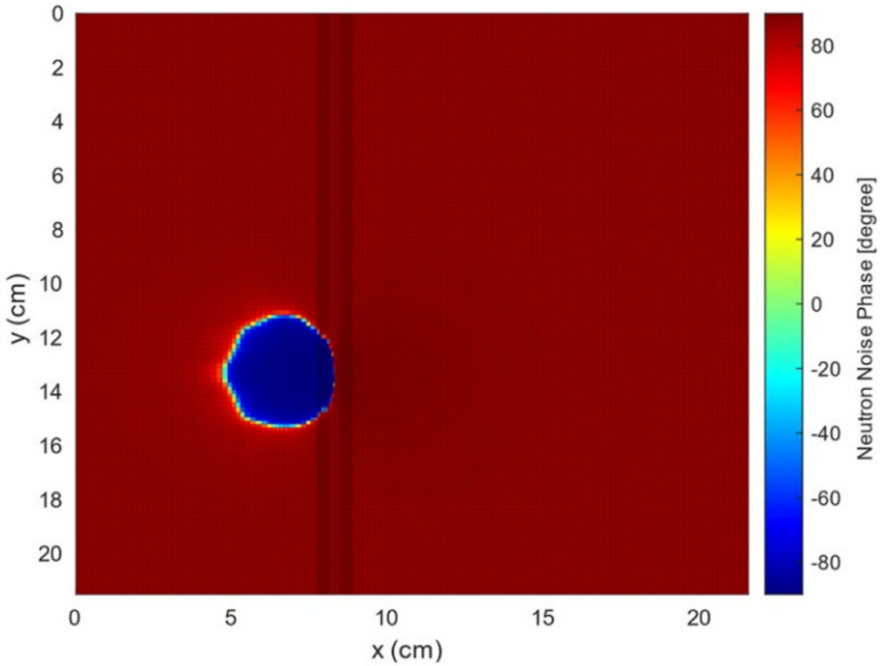

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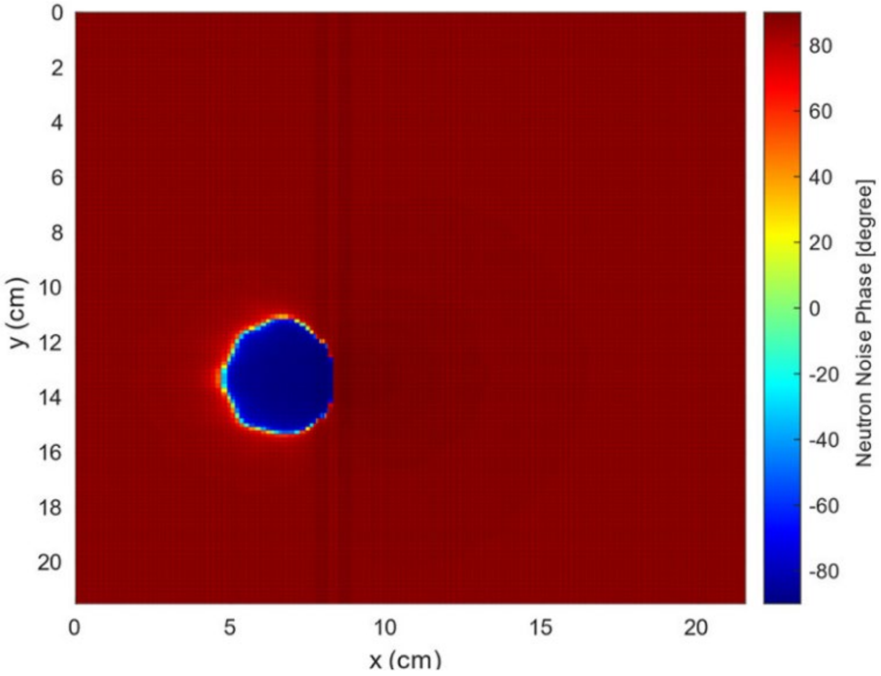

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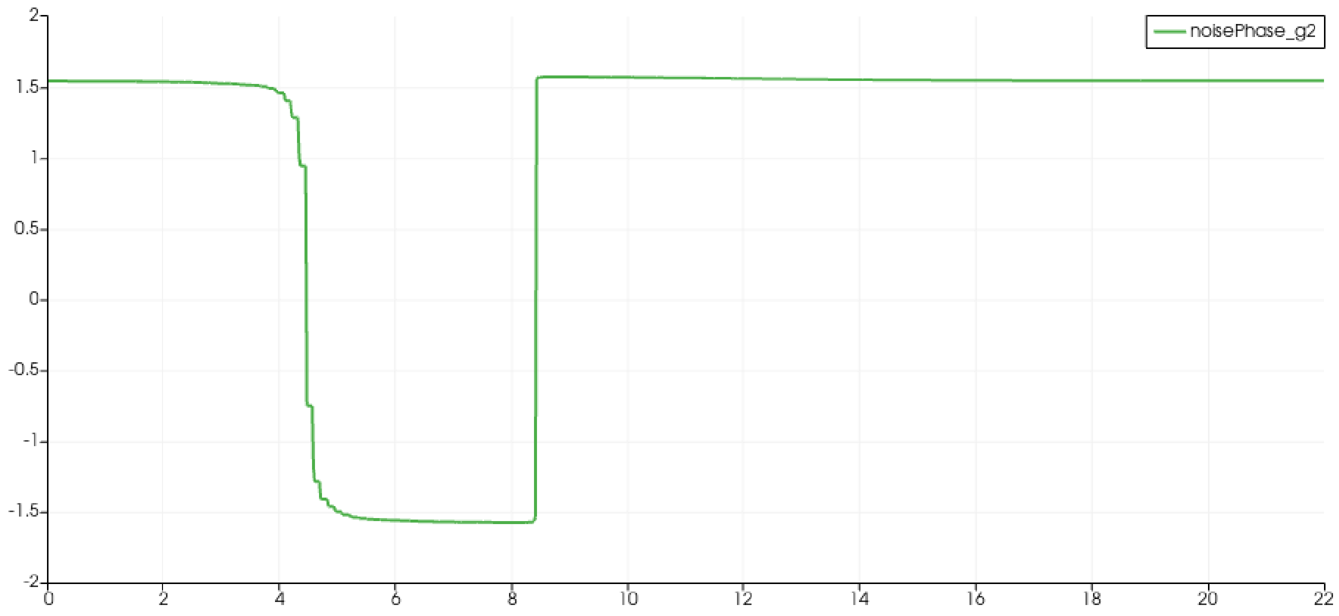

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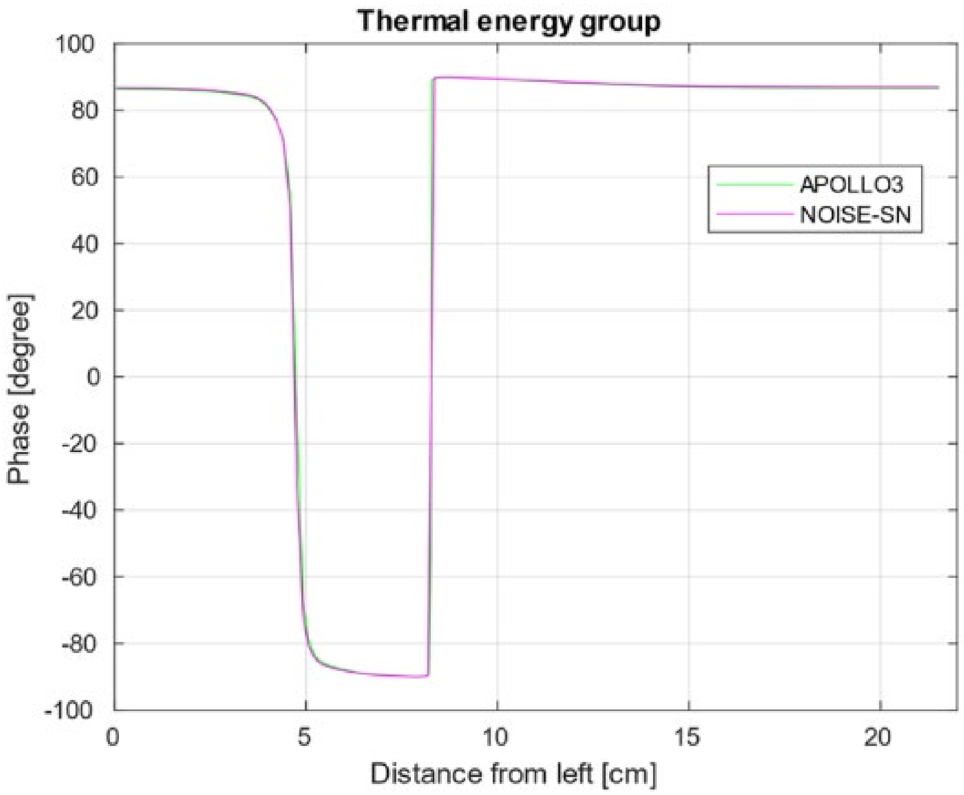
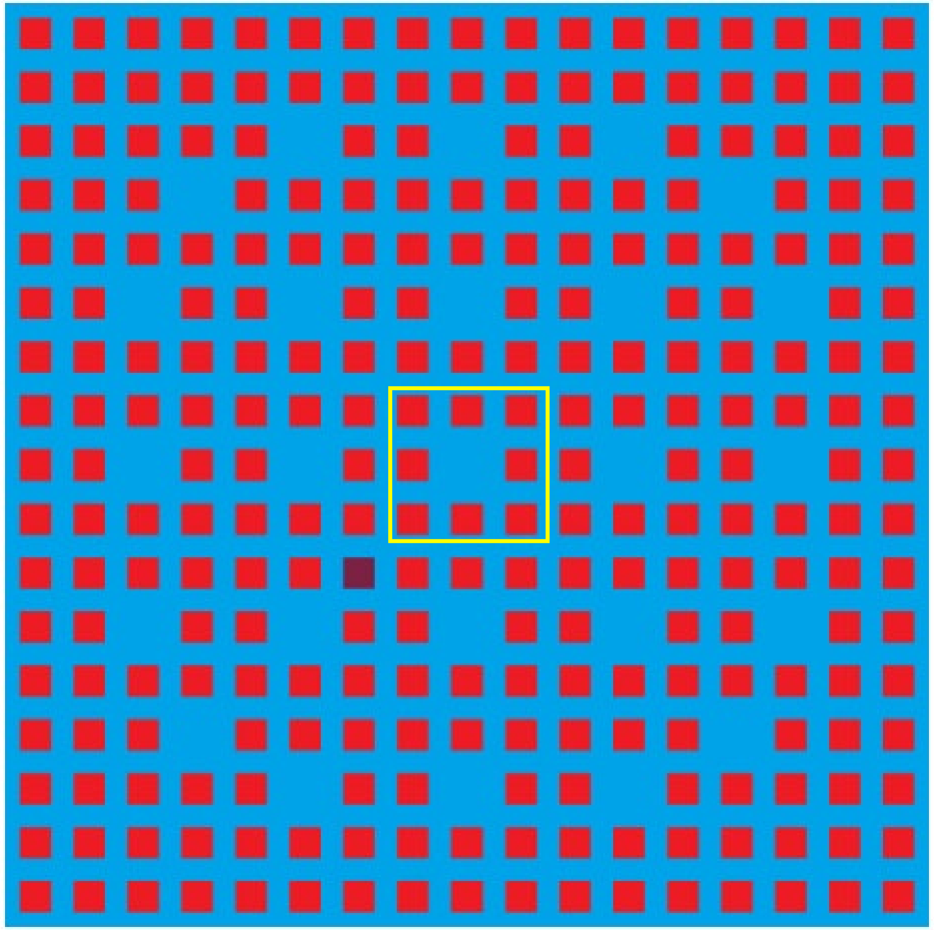


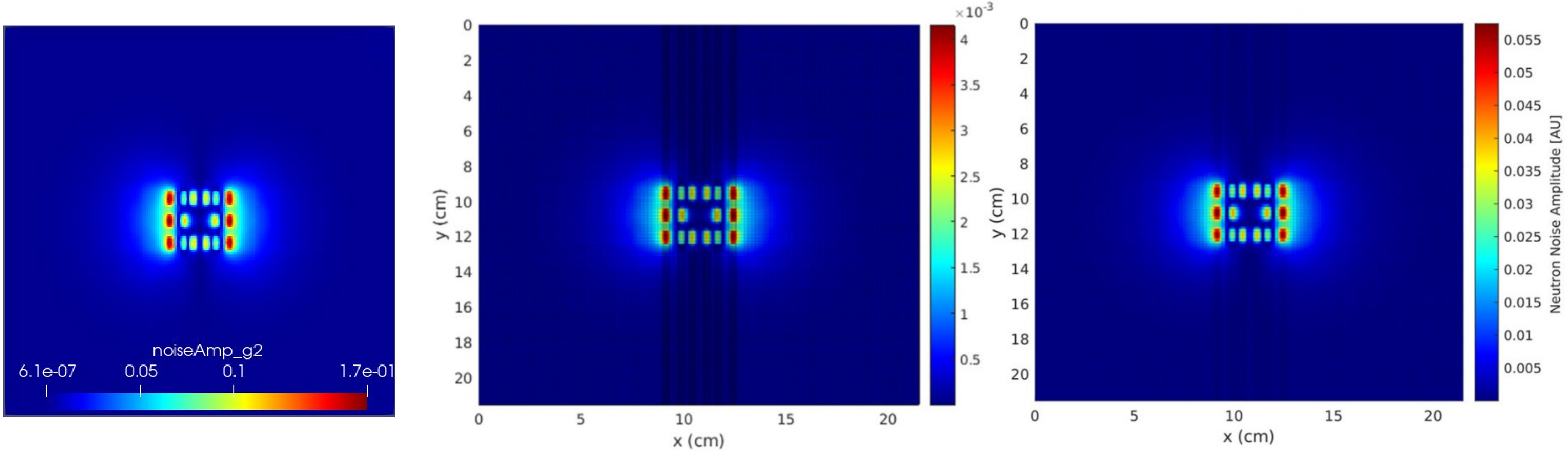
UOX Noise Benchmark – alternative problem

- The benchmark also contains a second vibration case
- Central 8 pins vibrating left-to-right with the same amplitude and frequency as before
- Seemingly not so easy…



Vinai et al. (2021). “Comparison of neutron noise solvers based on numerical benchmarks in a 2-D simplified UOX fuel assembly”, Proc. M&C.

Results – Amplitude Group 2



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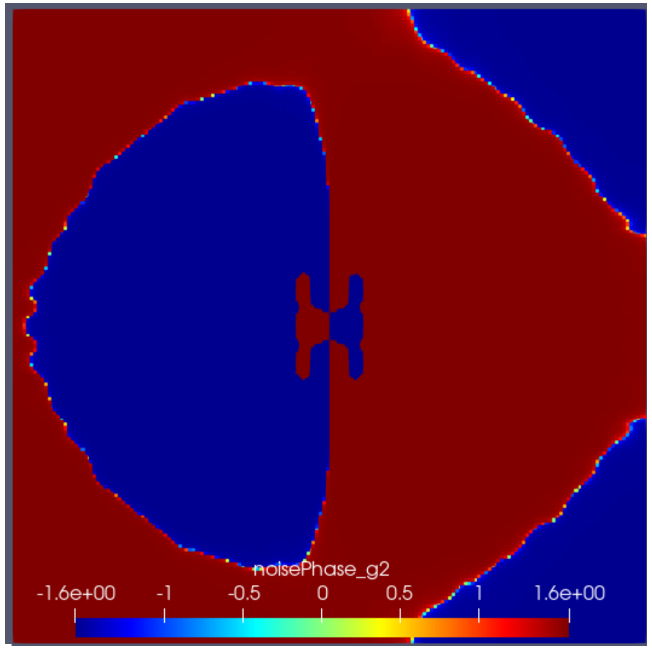
Results – Phase Group 2



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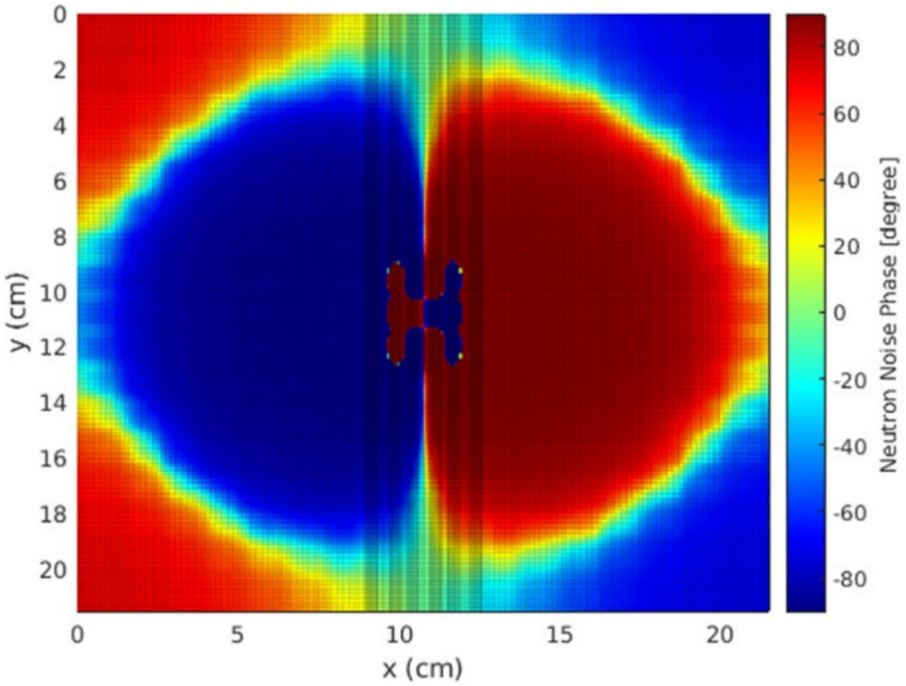

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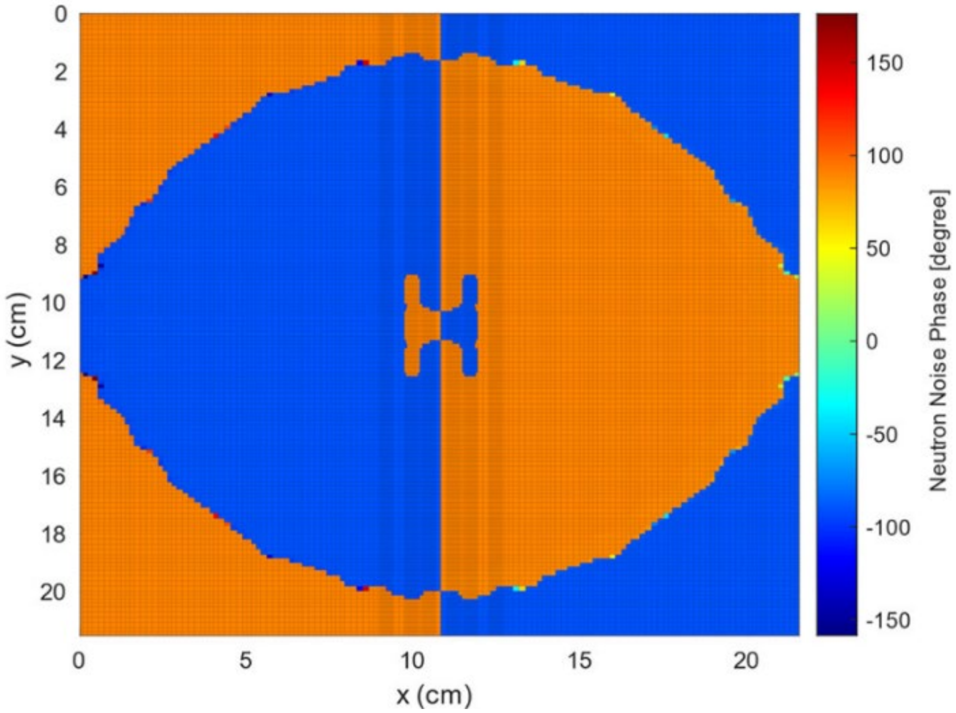

NOISE-SN

Conclusions

- Vibrations can be handled with the new noise algorithm
- Still some anomalous results where the method struggles to converge – probably driven by random’s ray stochastic noise, phase discontinuities, and high spectral radius

Thanks for listening!

IMORN-32 in Cambridge