Zero power noise with fission matrices: Simulations vs Measurement in the CROCUS reactor

Max Begue[1], Vincent Lamirand[2], Axel Laureau[3], Thomas Ligonnet[4], Elsa Merle[5], Julien Vukasin[6]

[1] CNRS-LPSC/Orano (max.begue@lpsc.in2p3.fr)
[2] EPFL/PSI
[3] CNRS
[4] EPFL
[5] CNRS-INPG
[6] ORANO

07/07/2026

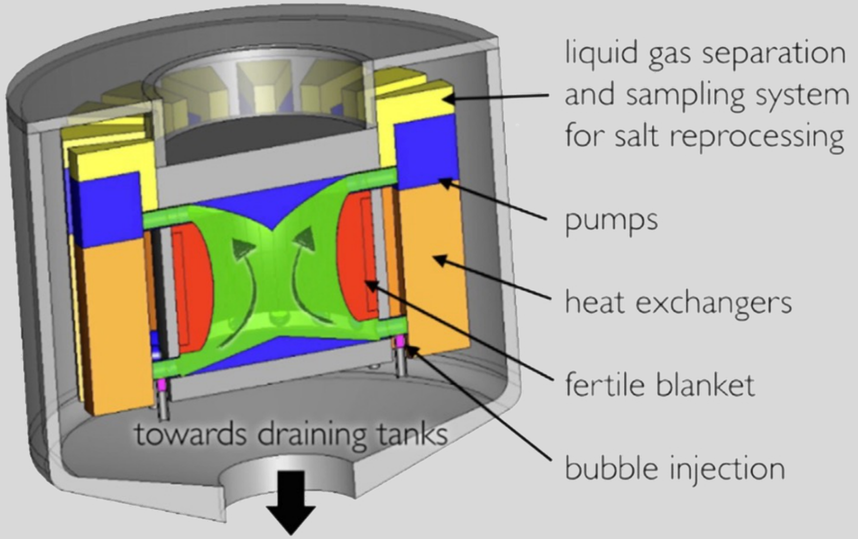
Table of contents :

Part 1:
The Molten Salt Reactors (MSR)

Molten salt fueled reactors

The interesting characteristics of fast MSRs for this study are:

- Fast neutronic spectrum
- No internal structures
- Very turbulent flow inside the core ($\mathrm{Re} \approx 10^6$)



*Scheme of the molten salt fast reactor**

* *Michel Allibert, Sylvie Delpech, Delphine Gerardin, Daniel Heuer, Axel Laureau, Elsa Merle, Chapter 7 - Homogeneous Molten Salt Reactors (MSRs): The Molten Salt Fast Reactor (MSFR) concept Editor(s): Igor L. Pioro, In Woodhead Publishing Series in Energy, Handbook of Generation IV Nuclear Reactors (Second Edition), 2023, Pages 231-257, ISBN 9780128205884*

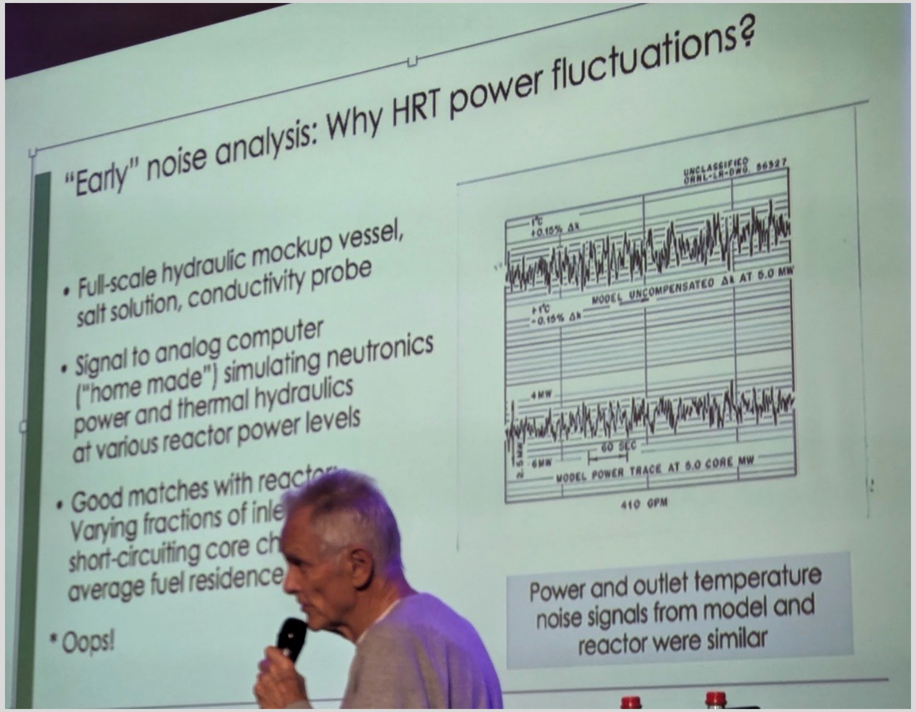
Link with neutron noise

Objective:

- Study the impact of turbulence on neutronic noise:
  → Transport of delayed neutron precursors
  → Local variations of salt properties

Means:

- Use the Transient Fission Matrix (TFM) approach to simulate neutron showers
- The approach is tested on Rossi-$\alpha$and Cohn-α measurement

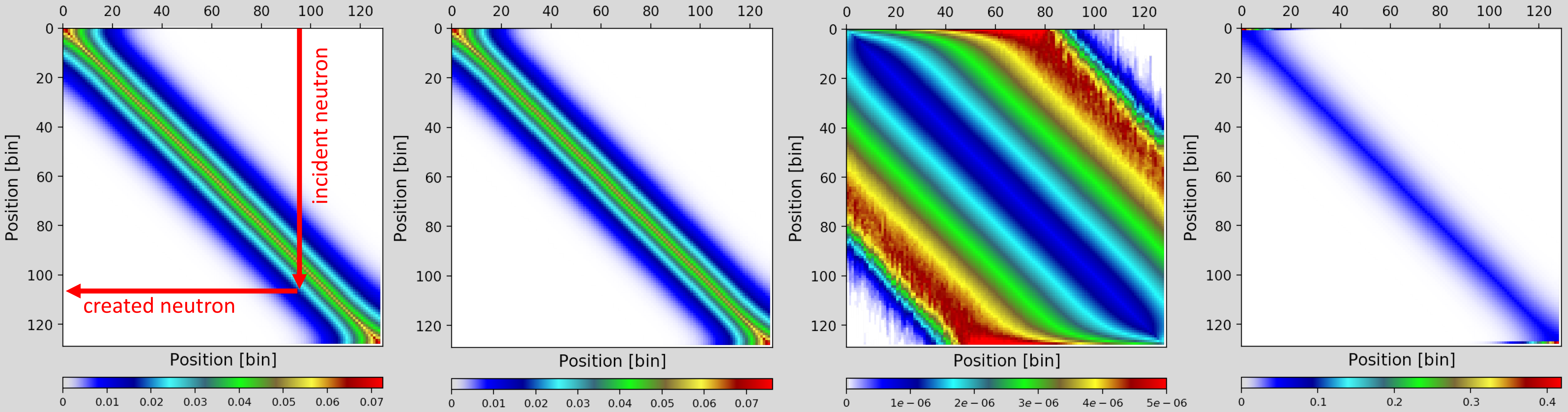


Syd Ball, MSRE operator, presenting measurements on the impact of bubbling on neutron noise in the MSRE (French MSR bootcamp, October 2023).

Part 2:
Quick reminder on fission matrices
(@Axel Laureau's previous talk)

Transient fission matrices

- Matrices are pre-computed with Monte Carlo calculations (with OpenMC code)
- They contain the probability of absorption of one neutron born in bin **j** in all other bins **i**
- There is one matrix per interaction and per neutron type (delayed / prompt) and one for transport time
- The scattering is not resolved and only the fissions and captures are computed
- This model was initially developed for neutronic-thermohydraulics coupling and their application to noise simulation is tested in this work



$\underline{\underline{K}}_{\chi_p \to \nu_p}$ $\underline{\underline{K}}_{\chi_d \to \nu_p}$ $\underline{\underline{T}}_{p \to p}$ $\underline{\underline{A}}_d$

How to get kinetic parameters from matrices

$\underline{\underline{K}}_{tot} = \begin{pmatrix} \underline{\underline{K}}_{pp} & \underline{\underline{K}}_{dp} \\ \underline{\underline{K}}_{pd} & \underline{\underline{K}}_{dd} \end{pmatrix}$ is the complete transport operator:

→ Eigen value is the multiplication coefficient

→ Eigen vector is the steady state neutron distribution

$$\underline{\underline{K}}_{tot}\ \underline{V}_{tot} = k_{eff}\ \underline{V}_{tot} \quad \text{with} \quad \underline{V}_{tot} = (\underline{V}_p, \underline{V}_d)$$

It is also possible to define the importance of neutrons by making the same computation with the transposed operator

$$\underline{\underline{K}}^*_{tot}\ \underline{V}^*_{tot} = k_{eff}\ \underline{V}^*_{tot}$$

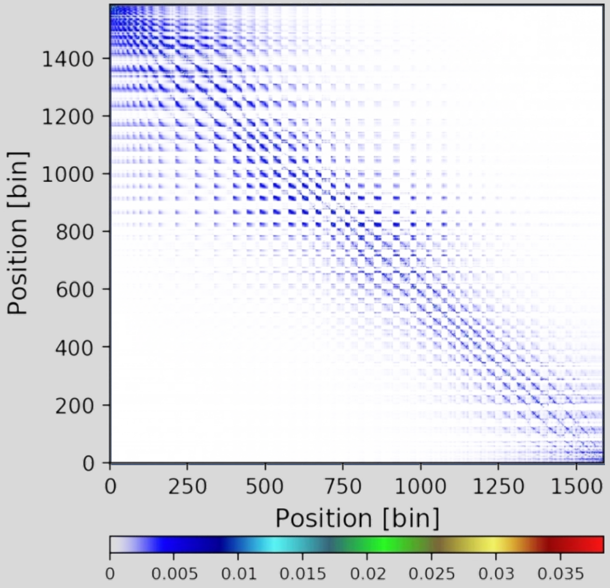
Other kinetic parameters and their effective values (adjoint flux weighted):

Delayed neutron fraction

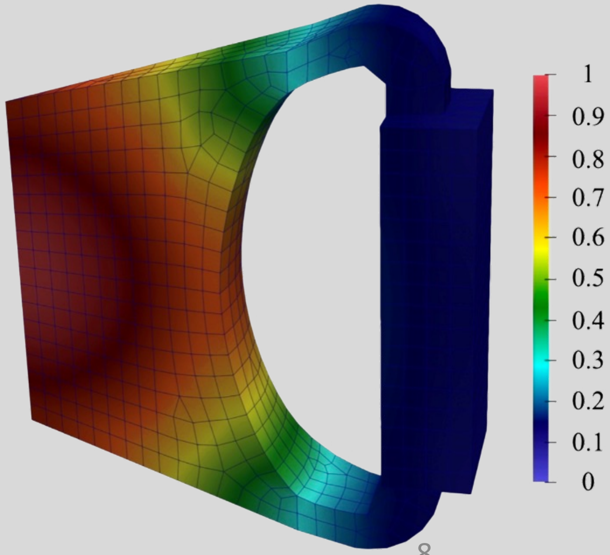
$$\beta_0 = \frac{\Sigma_i (\underline{V}_d)_i}{\Sigma_i (\underline{V}_{tot})_i} \quad \text{and} \quad \beta_{eff} = \frac{\underline{V}^*_d . V_d}{\underline{V}^*_{tot} . V_{tot}}$$

Fission to fission time

$$l = \frac{\Sigma_i \left(\underline{\underline{K}}_{pp}\ \underline{\underline{T}}_{pp}\ \underline{V}_p\right)_i}{\Sigma_i \left(\underline{\underline{K}}_{pp}\ \underline{V}_p\right)_i} \quad \text{and} \quad l_{eff} = \frac{\underline{V}^*_p . \left(\underline{\underline{K}}_{pp}\ \underline{\underline{T}}_{pp} V_p\right)}{\underline{V}^*_p . \left(\underline{\underline{K}}_{pp} V_p\right)}$$



$K_{\chi_p \to \nu_p}$

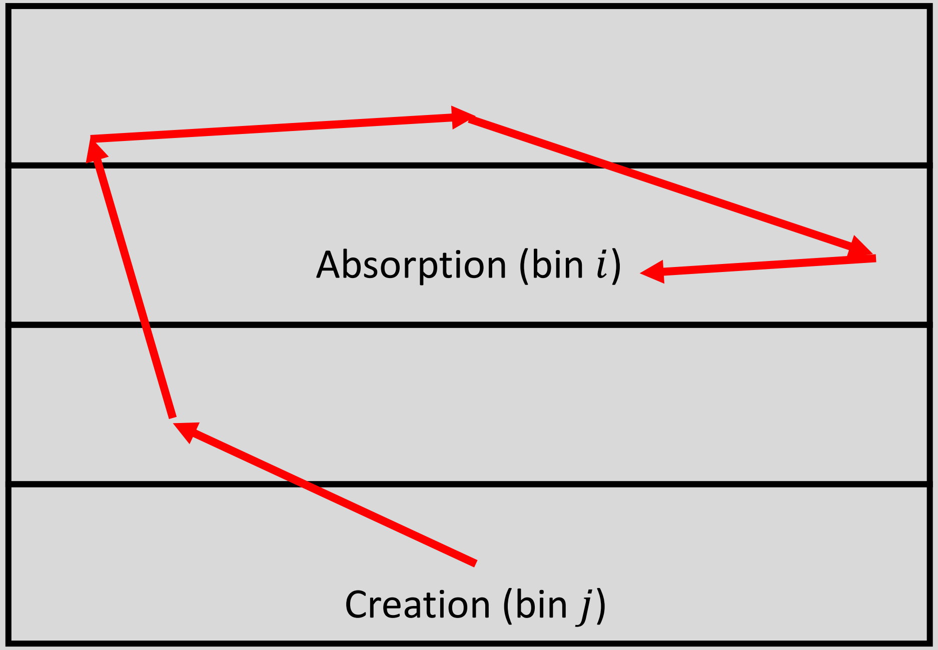


Eigenvector [a.u.]

Transient fission matrices vs Monte Carlo

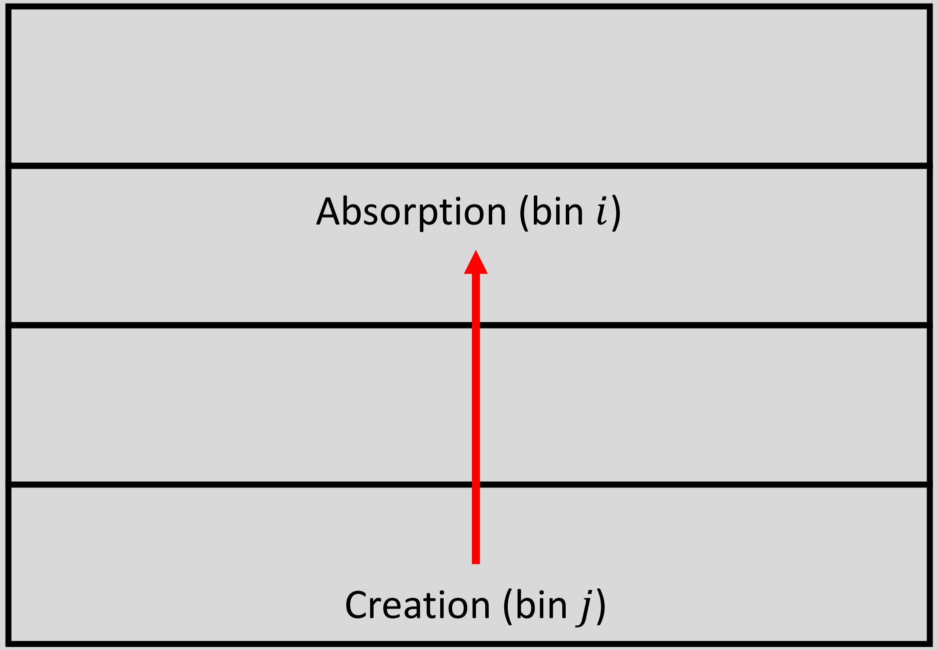
- **TFM** is a **macroscopic approach**, making it fast for producing neutron showers
- Reminder: only **absorptions and fissions**, **once** per neutron

Classic Monte Carlo simulation from j to i



Neutron transport requires multiple samples (distance, reaction…) up to neutron absorption
$\sim 10^4$ neutrons per second

TFM based Monte Carlo Simulation from j to i

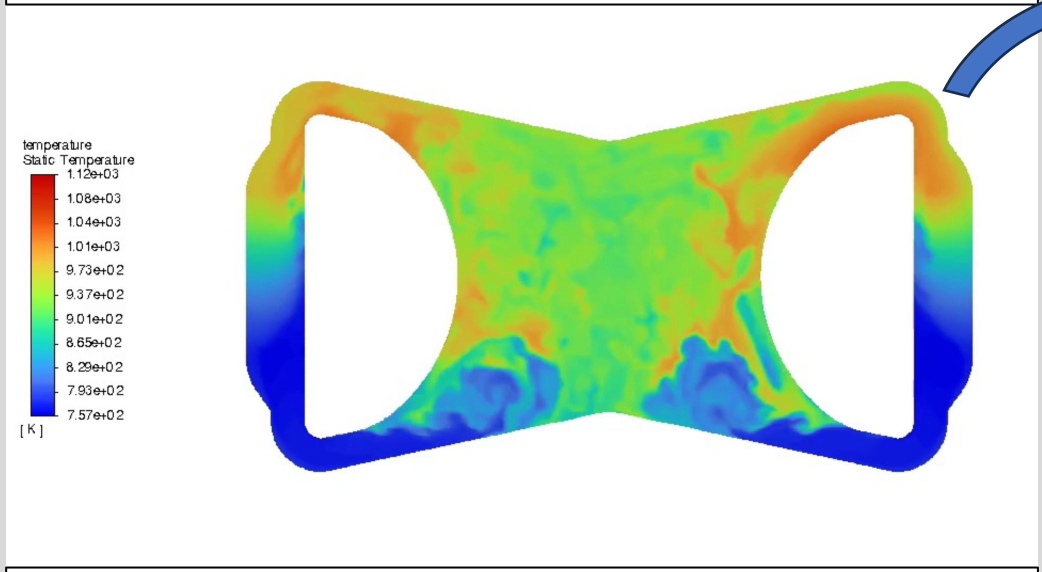


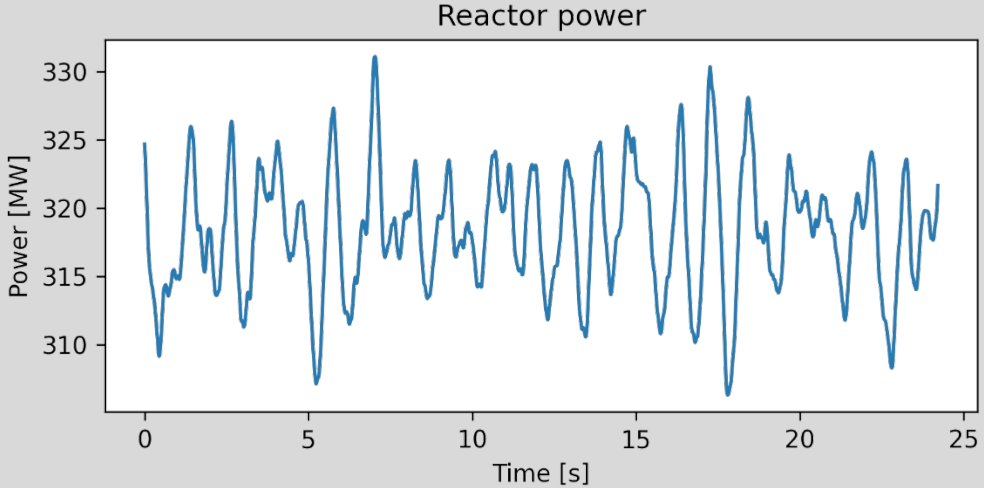
We only sample one destination bin and if a fission or a capture occurs
$\sim 10^7$ neutrons per second

Part 3:
Typical power noise in MSR

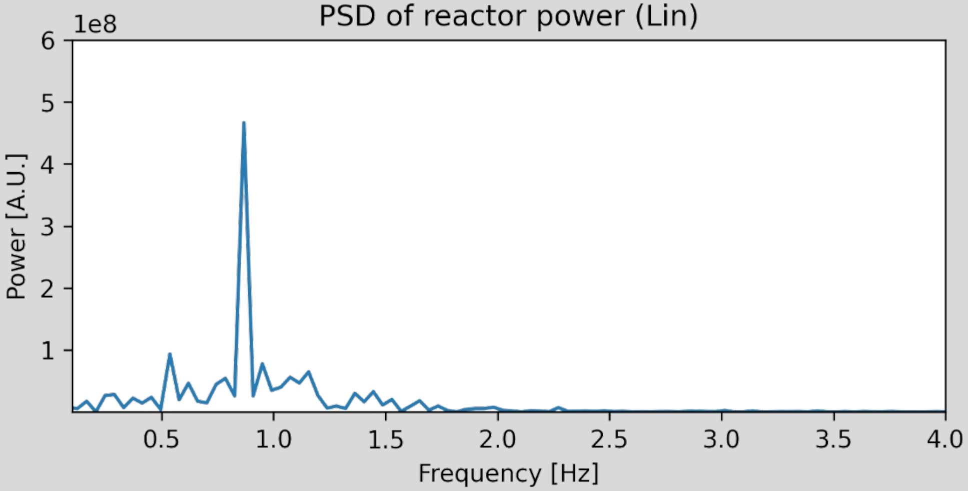
Power noise due to temperature fluctuations

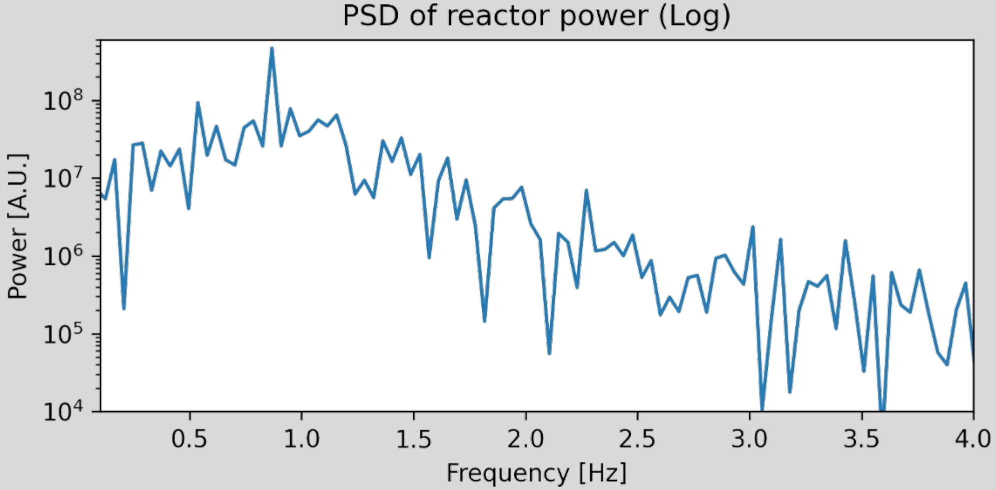
Turbulence ⇒ temperature fluctuations





Temperature fluctuations ⇒ power fluctuations





How to "validate" the code ?

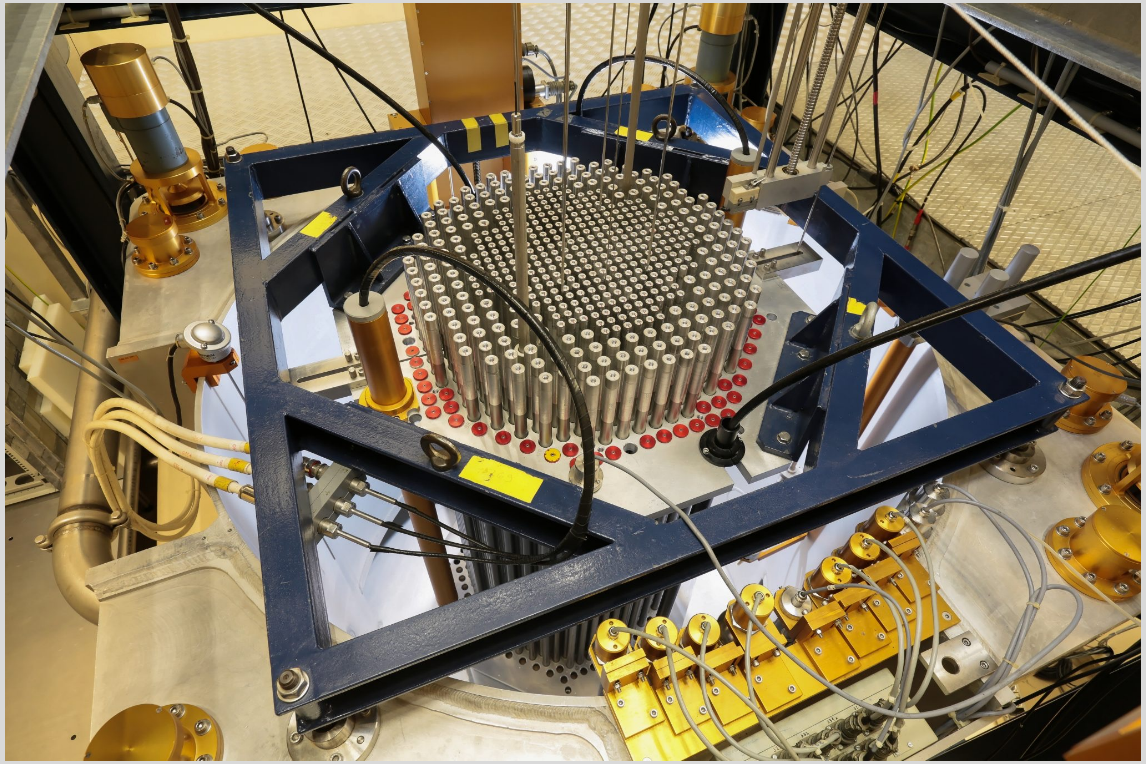
At low power:
Still the movement of the precursors

Need to solve for it !

→ TFM approach with precursor field obtained from coupled simulation

But how to validate the code ?

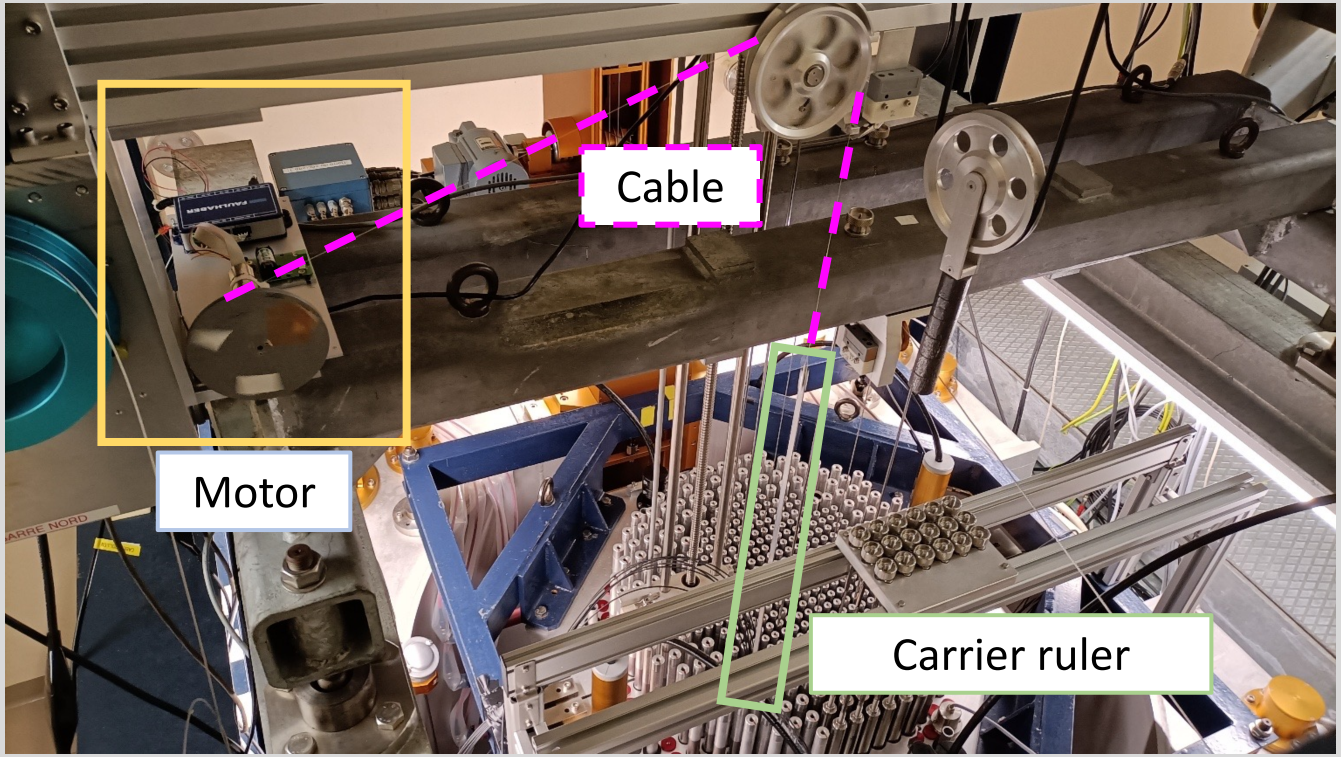
No MSR to compare with simulations:
→ pseudo random reactivity oscillations (mimics turbulence) performed in the CROCUS reactor !

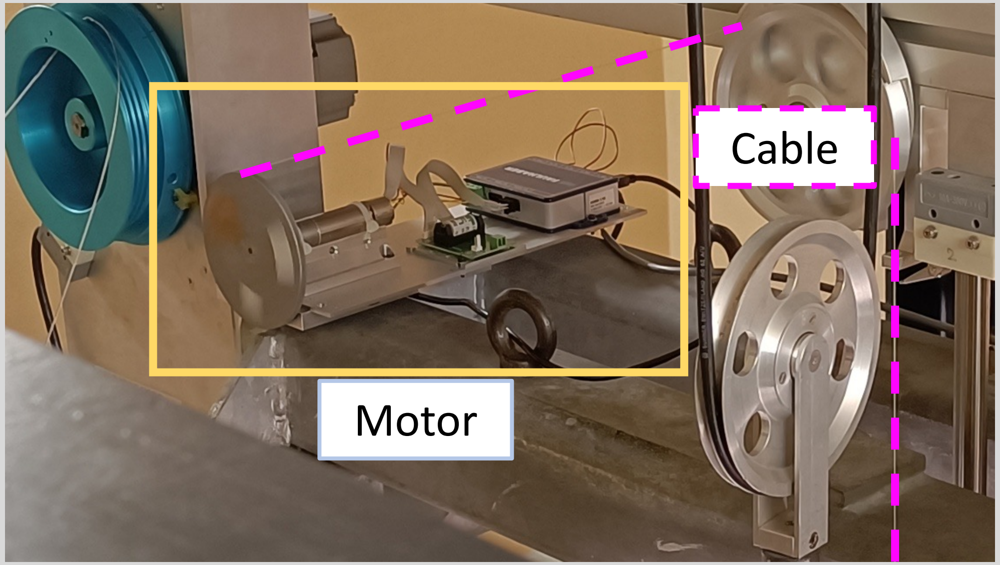


Picture of the CROCUS reactor [@EPFL]

POLLEN oscillator [1]

Oscillation of an absorber in the core
- Sample attached at the end of the ruler (inside a guide tube)
- The motor follows a time series on the height of the sample
- The ruler is attached via a para-aramid (Kevlar) cable





POLLEN oscillator

[1] Ligonnet, T., Weiss, N., Lamirand, V., Laureau, A., & Pautz, A. (2023). POLLEN: A pile-oscillator for the Bloom experimental program. In *EPJ Web of Conferences* (Vol. 288, p. 04018). EDP Sciences.

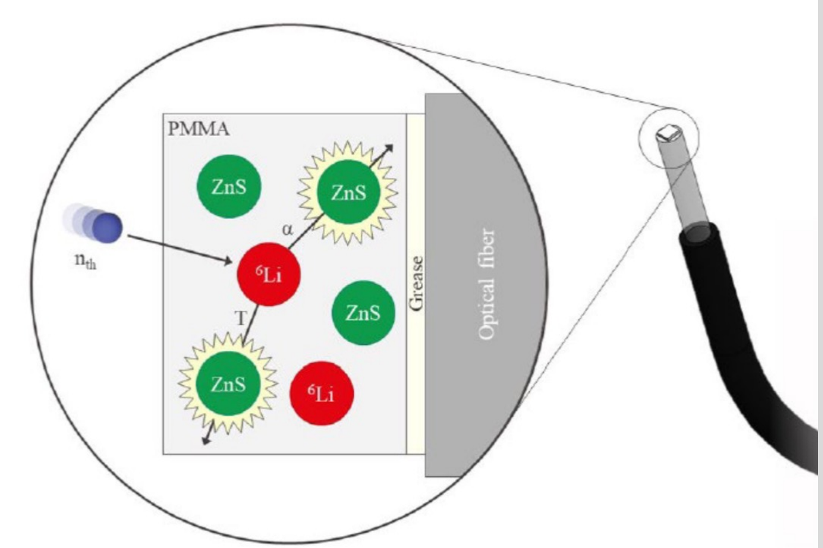
Detectors

4 CFUL:

- Fission chambers with 1 gramme ^{235}U coating operated in current mode
- High resolution

SAFFRON [2]:

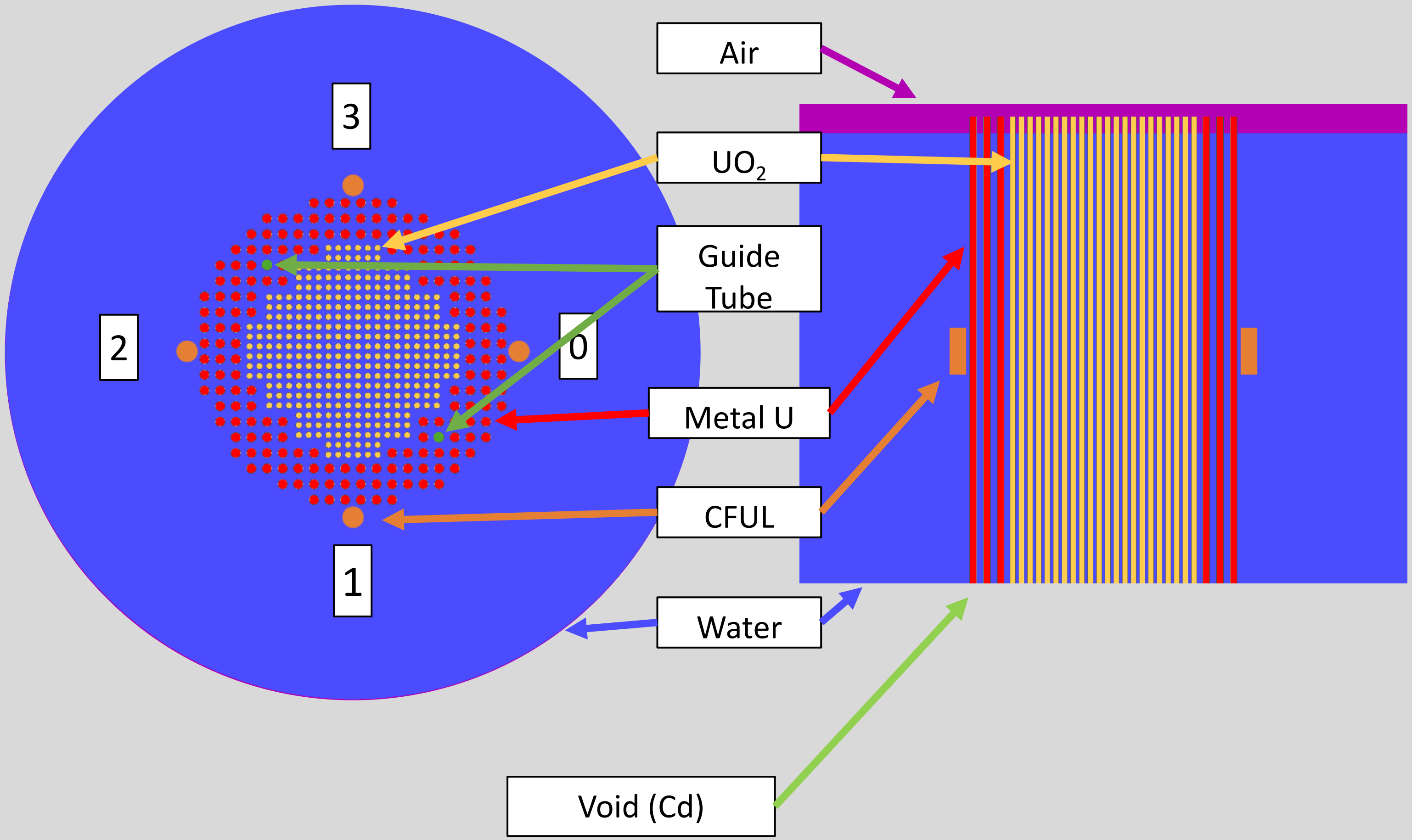
- 160 ZnS(Ag):6LiF scintillators spatially distributed inside the core
- Lower efficiency
- Limits the core power to 1W to prevent pile up effect it the time tagging device



SAFFRON MiMi detector

[2] Vitullo, F., Lamirand, V., Godat, D., & Pautz, A. (2023). Simultaneous inter-calibration of 160 MiMi neutron detectors. *EPJ Web of Conferences*, *288*, 04023. https://doi.org/10.1051/epjconf/202328804023

Simulation setup



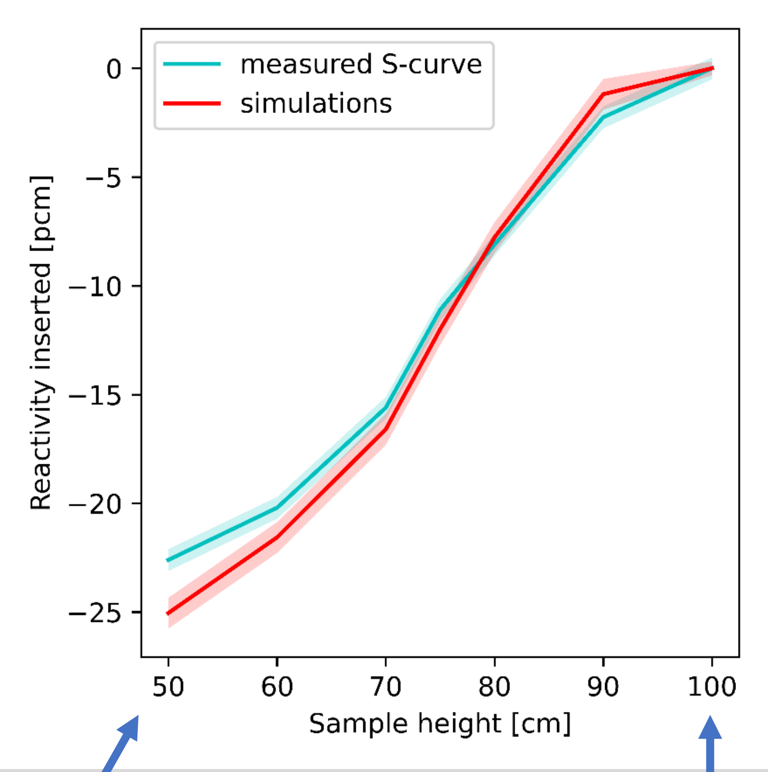
Simplified geometry:

- Bottom of the core cut (cadmium plate)
- Missing instrumentation
- Carrier ruler not solved

Resolved features:

- Dry part of the fuel (variable water level)
- Natural Ta ($\approx{}^{181}$Ta) sample in the guide tube (variable height)

First measurement: S-curve



Sample at the center of the core

Sample out of the core

Measured by:

- Change the sample height
- Adjust the water level to reach criticality (4,18 pcm/cm of water)

Simulated by:

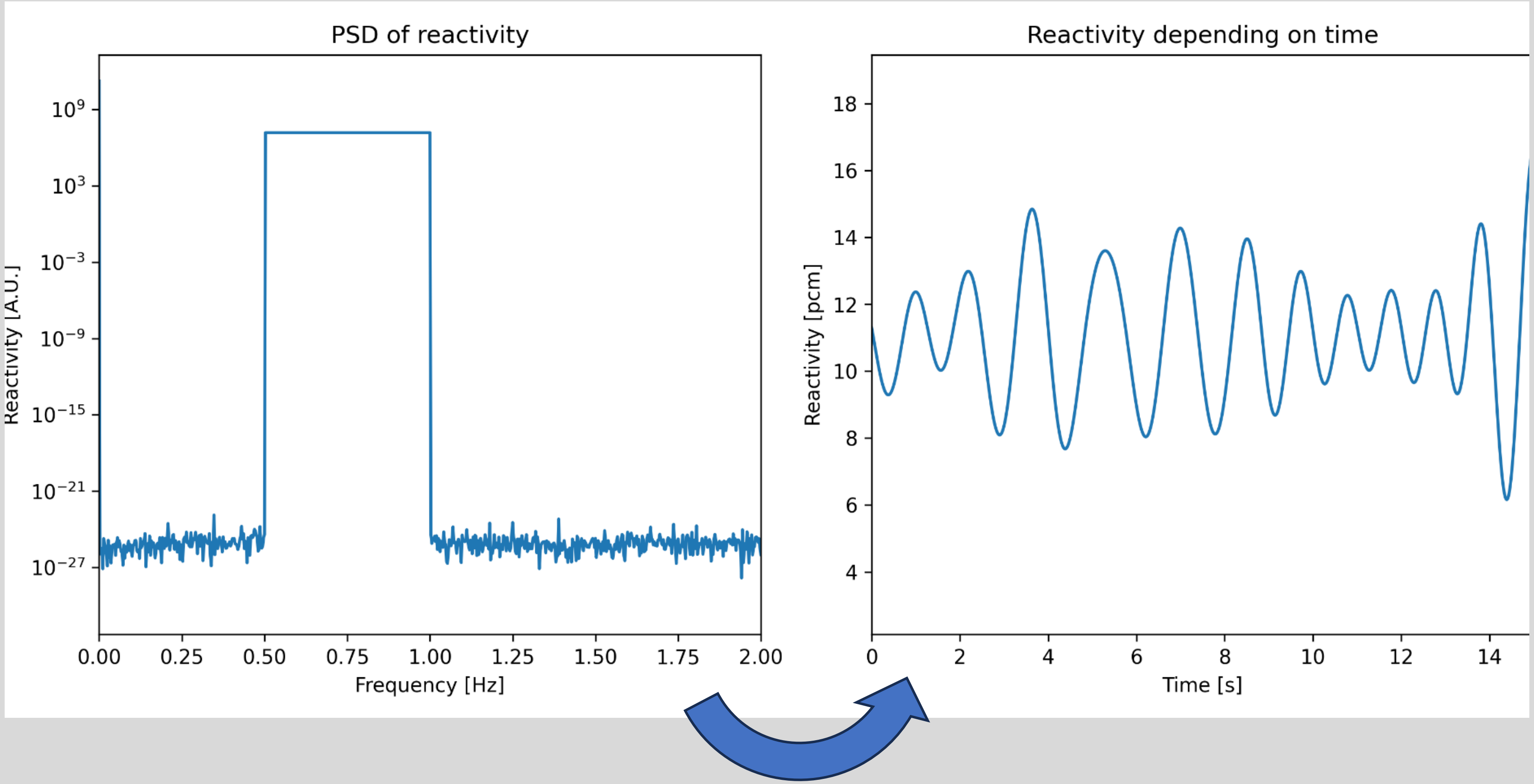
- Changing the sample height
- Reading the k_{eff} value (no water level change)

Good agreement

Measurements could be improved if more time was available

S-curve used for simulations and reactivity time series: measured

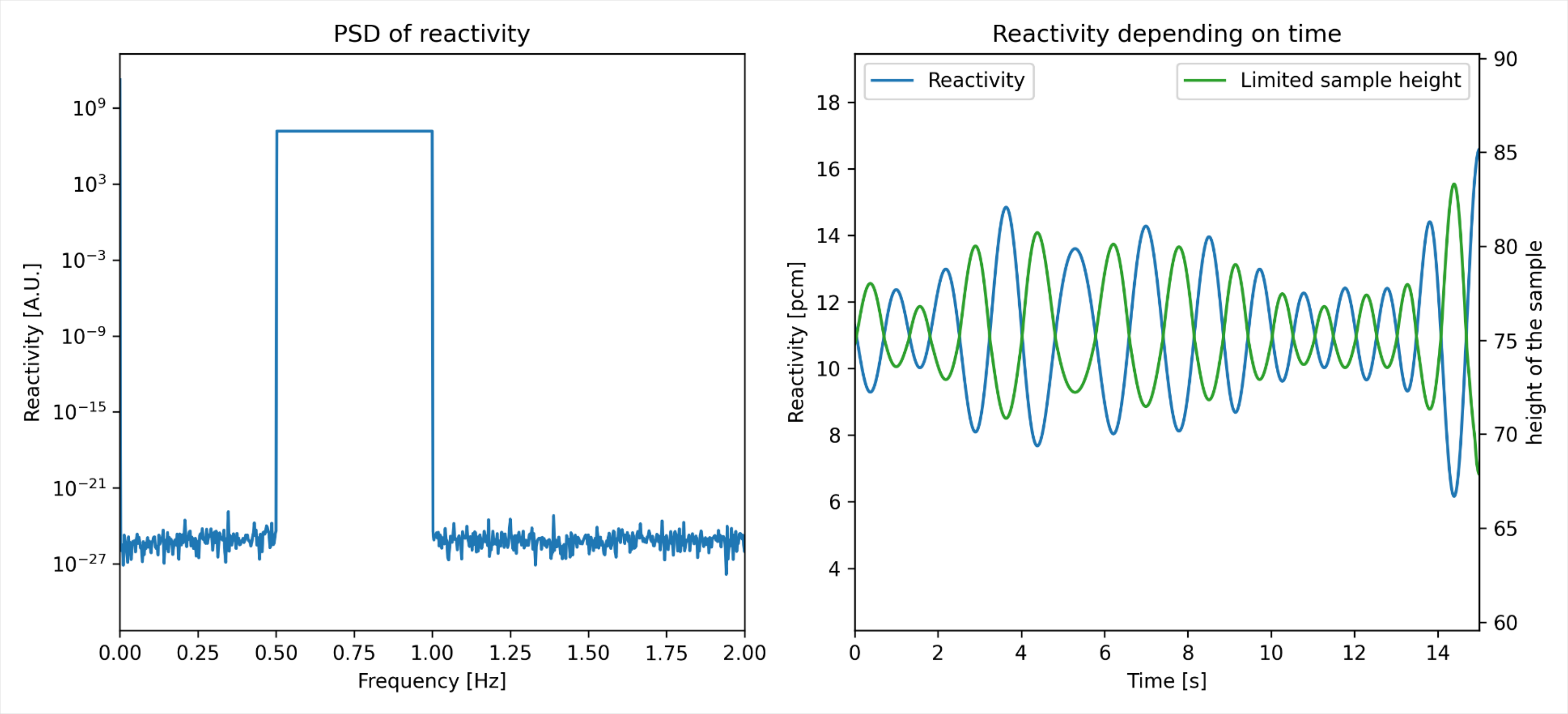
Pseudo-random oscillation generation



- Start with a door-like function in frequency domain
- Door because the spectrum is reactor dependant.
- To ensure generality, the door shape is chosen

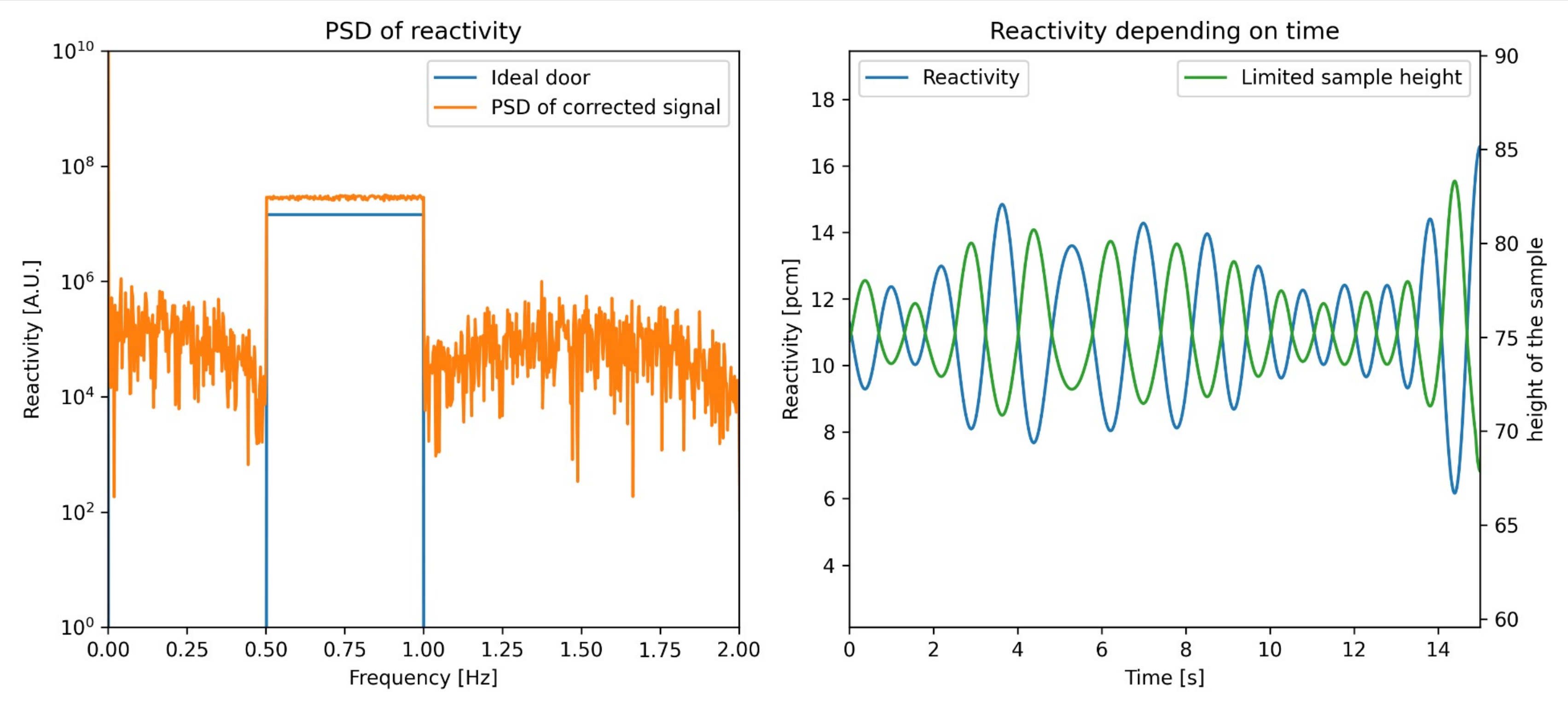
Use inverse Fourier transform to obtain time signal for reactivity

Pseudo-random oscillation generation



Convert the reactivity target into sample height

Pseudo-random oscillation generation



Check that the original FT is conserved :
Dicrepencies appear at the reactivity/height conversion step because of the linear interpolation of the S-curve

List of measurement

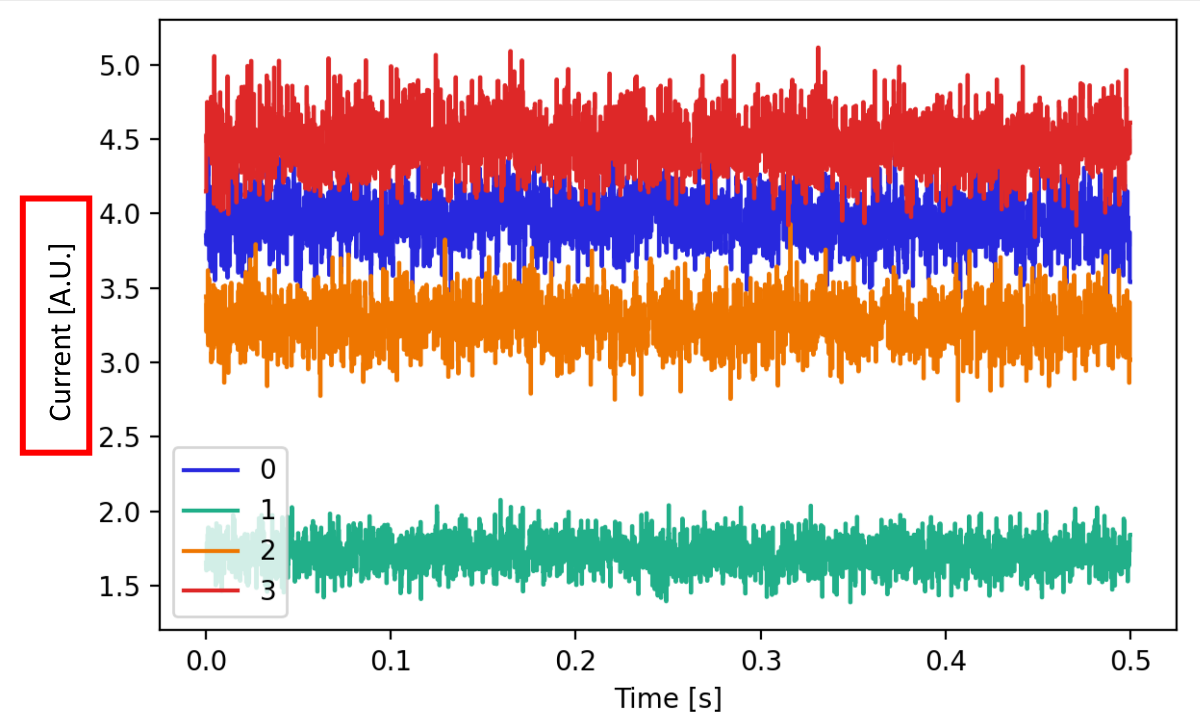
Simulation	Frequency [Hz]	Amplitude [pcm]	Power [W]
Reference	[0.5-1]	2	0.9
Sinusoidal	1	3	0.9
Low power	[0.5-1]	2	0.2
Low frequency	[0.01-0.5]	2	0.9

- The reference and the low power oscillation use the same time series for the reactivity
- The low frequency region was chosen due to constraints on acceleration and speed ($a_{\max} = 0{,}5g$)
- Measurement time is one hour

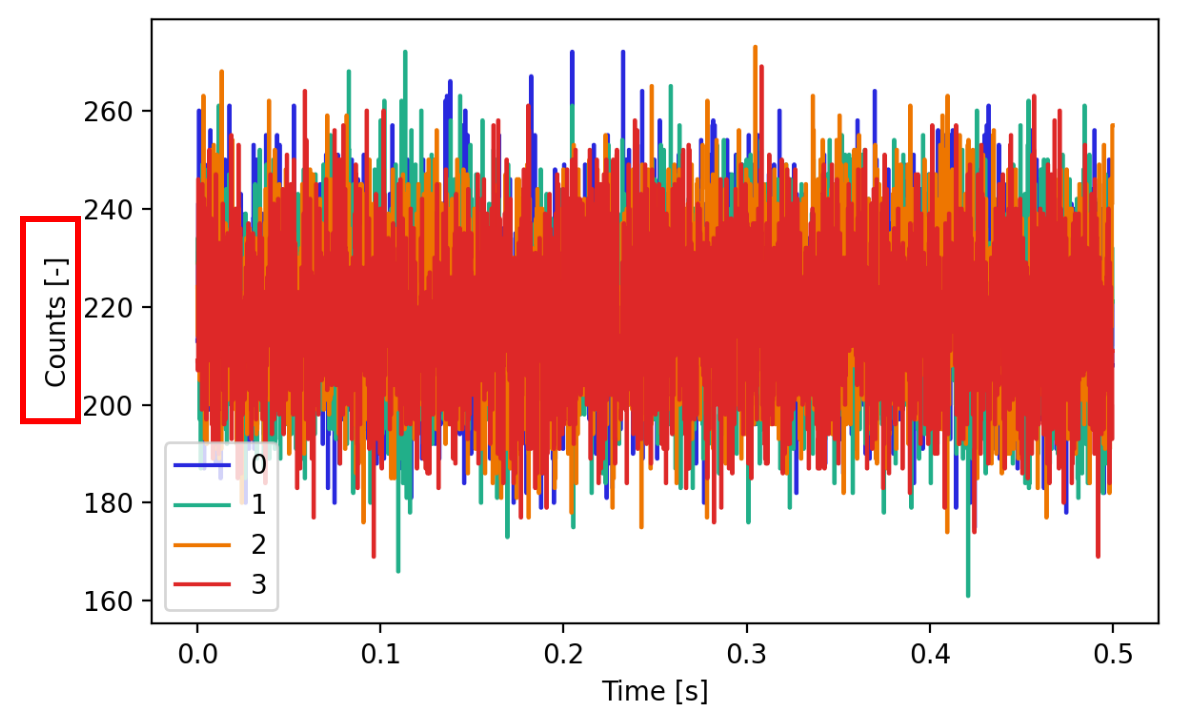
Part 4:
Results and discussion

Reference simulation: count rate

Measurement - CFUL



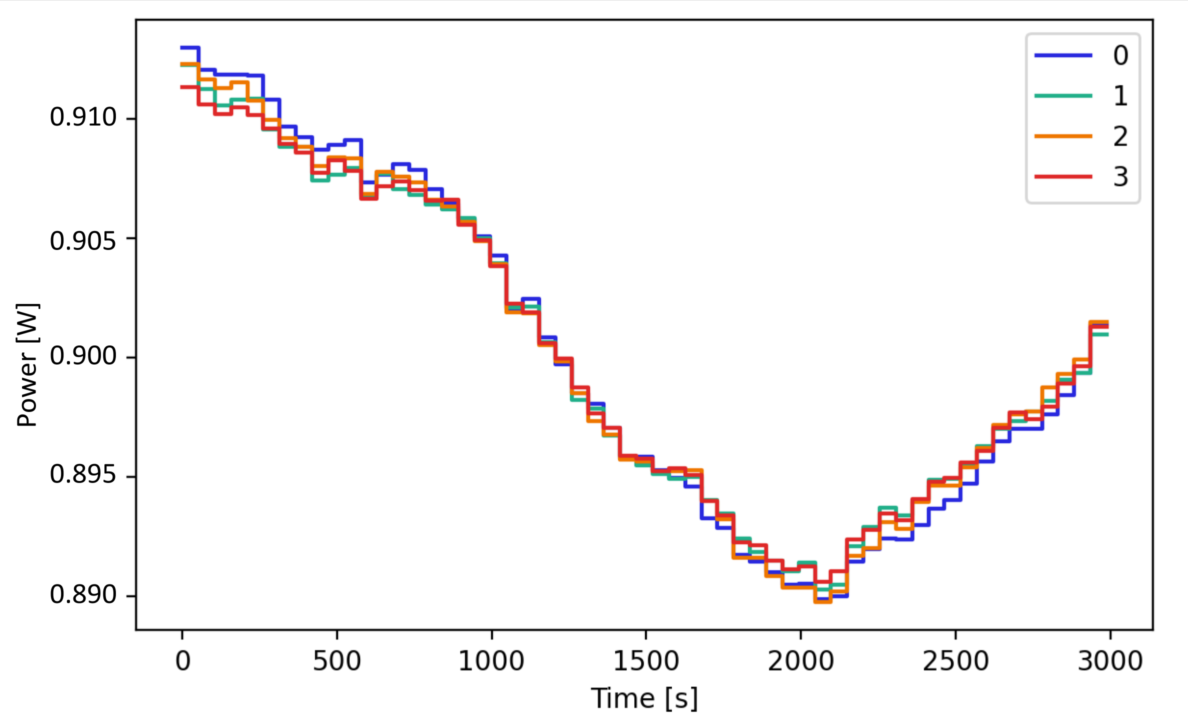
Simulation



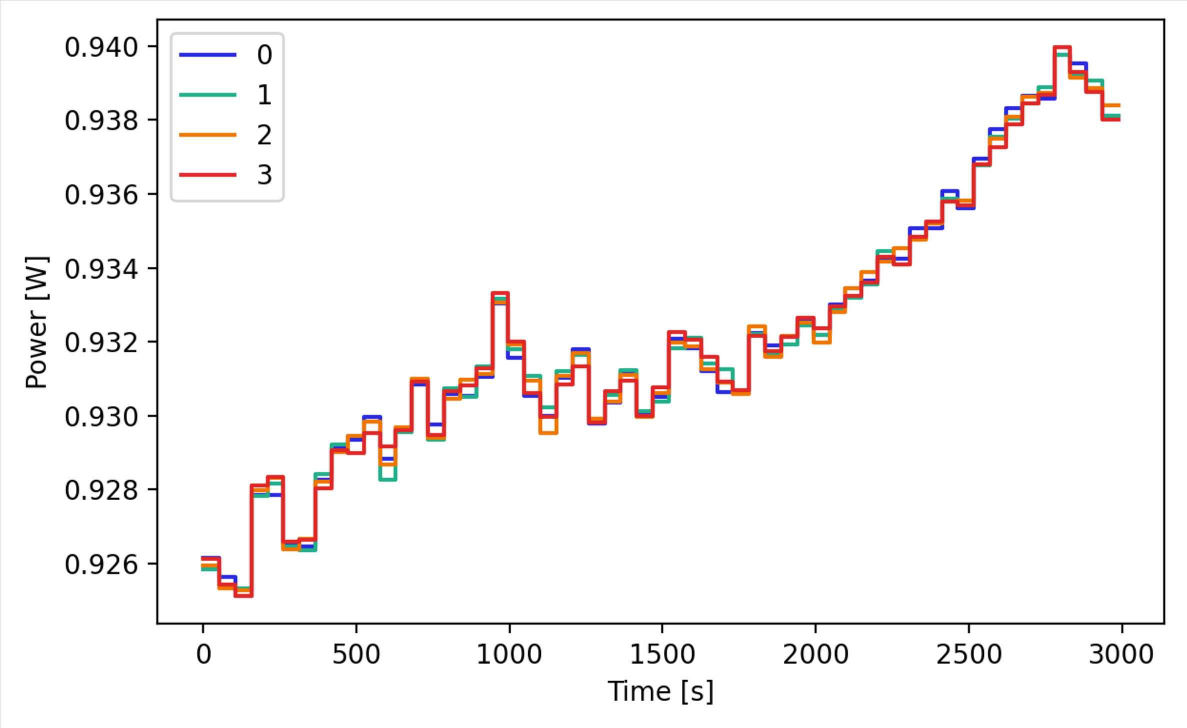
- Dwell time of 0.2 ms (sampling rate of the CFUL for the current)
- CFULs have different efficiencies (not modeled) because of other experiments (like CHAMAN)
- CFULs work in current mode while the simulation uses time tagging (grouped in chunks of 0.2 ms)

Reference simulation: reactor power during transient

Measurement - CFUL



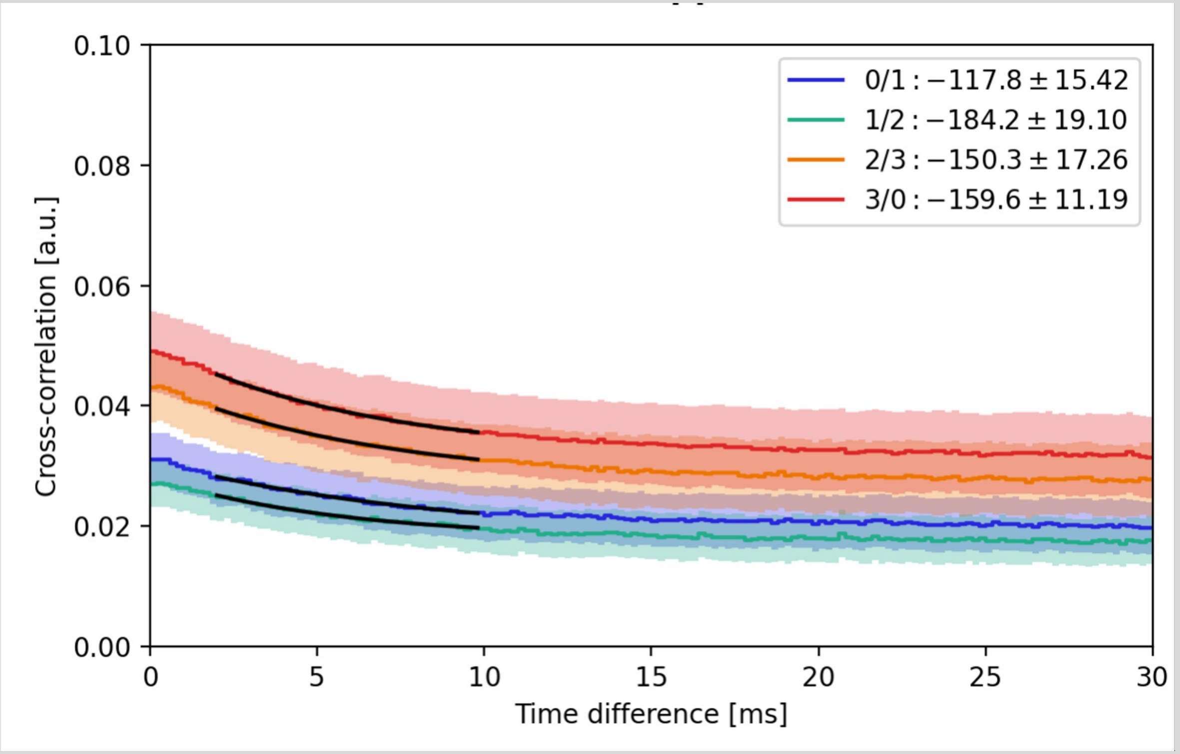
Simulation



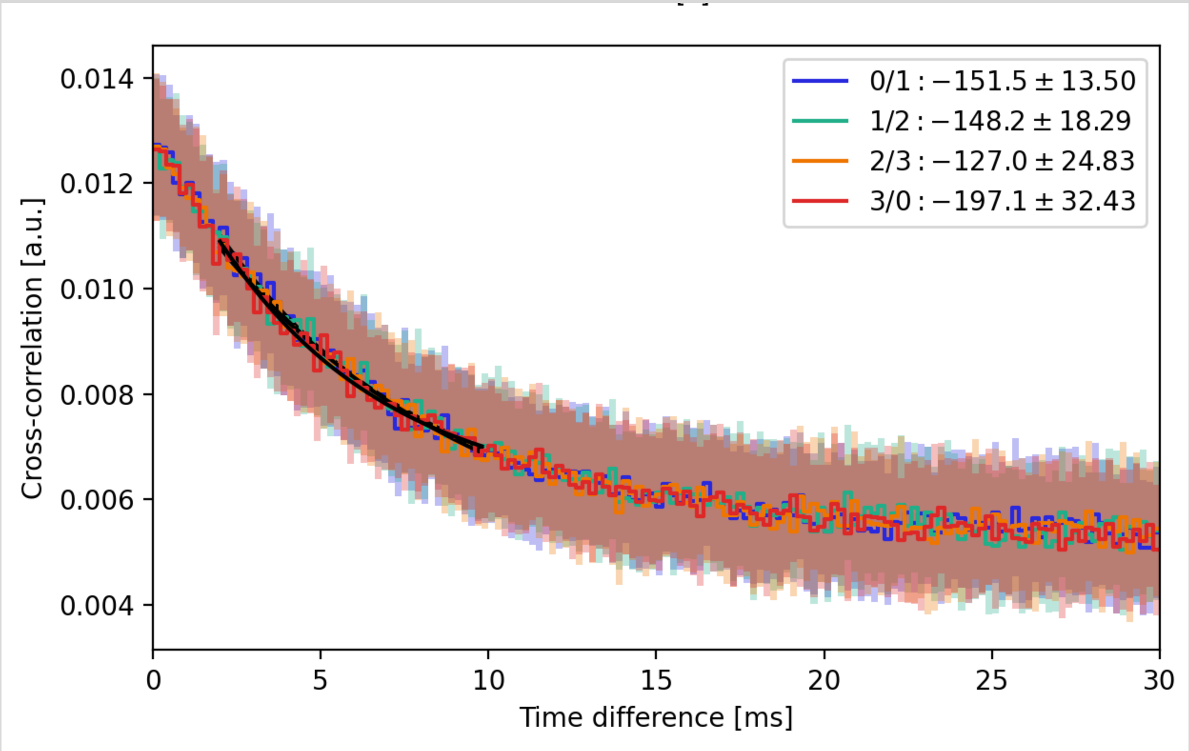
- Water level adjustment during the measurement
- Small increase of the power during the simulation

Reference simulation: Alpha Rossi

Measurement



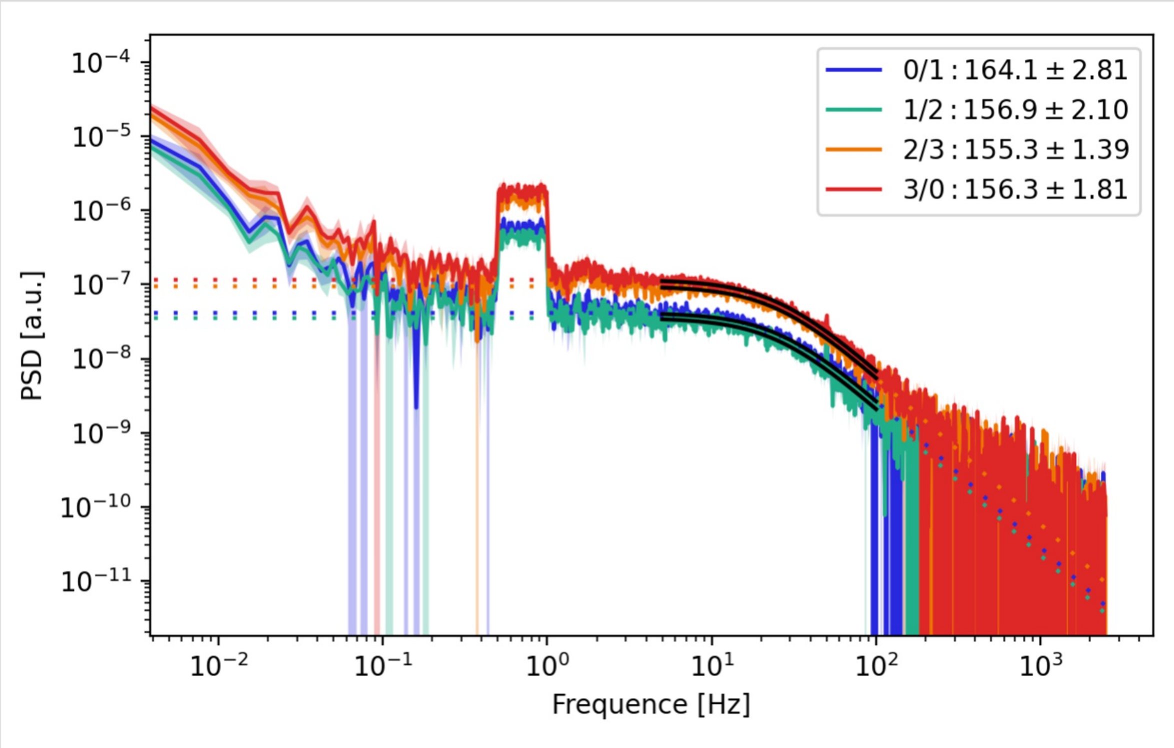
Simulation



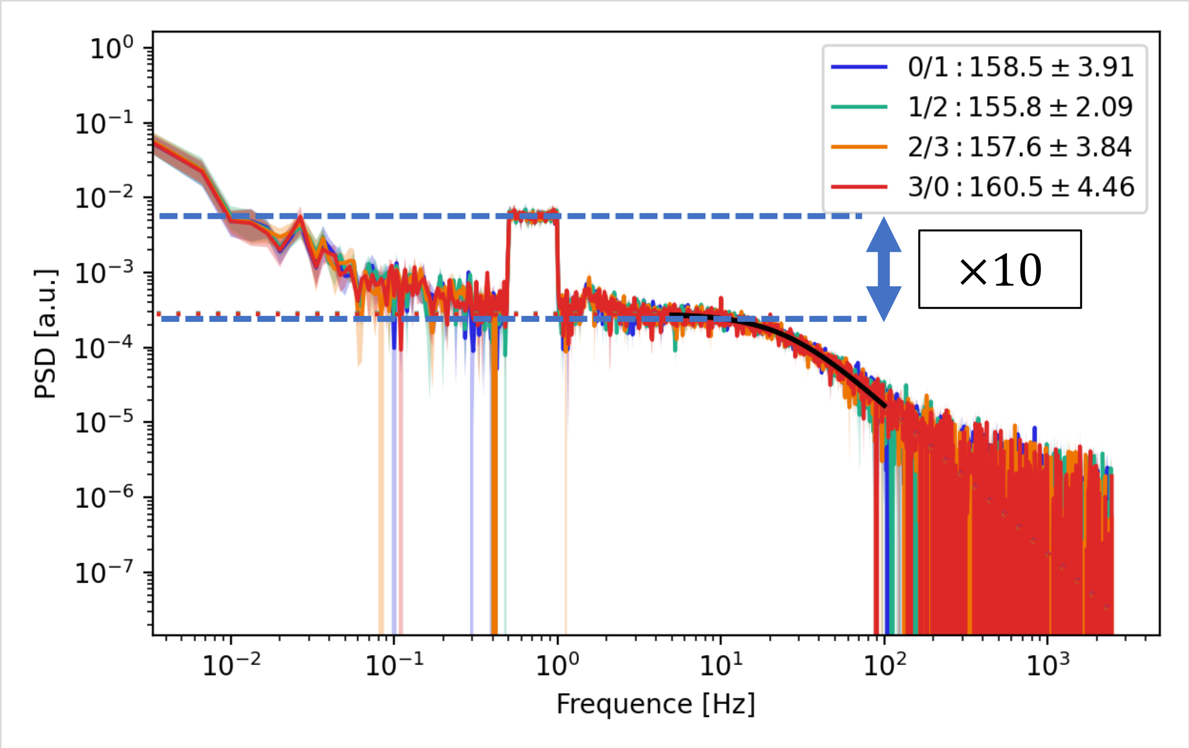
High uncertainty on the CFUL !
Uncertainty evaluated with jackknife technique (need to set all chunk average to 0 to correct the artificially high uncertainty)
$\alpha = 155.9 \pm 0.1\ s^{-1}$ for CROCUS (based on fission matrices effective parameters)

Reference simulation: CPSD

Measurement



Simulation

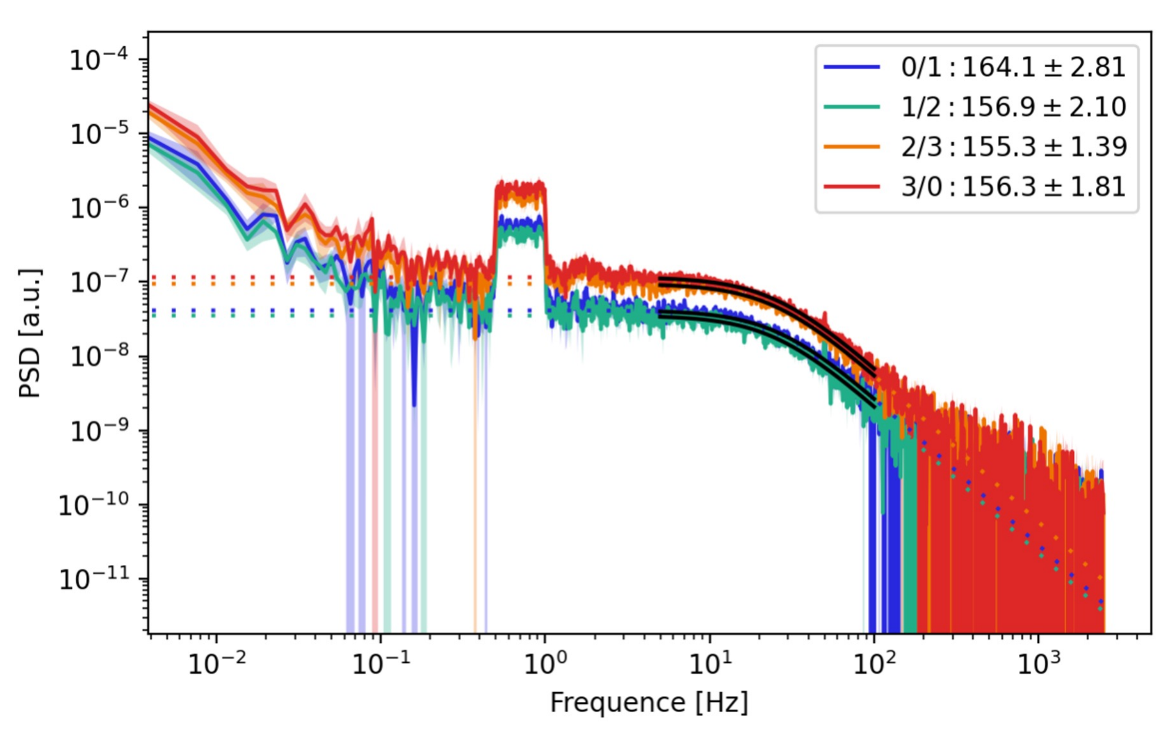


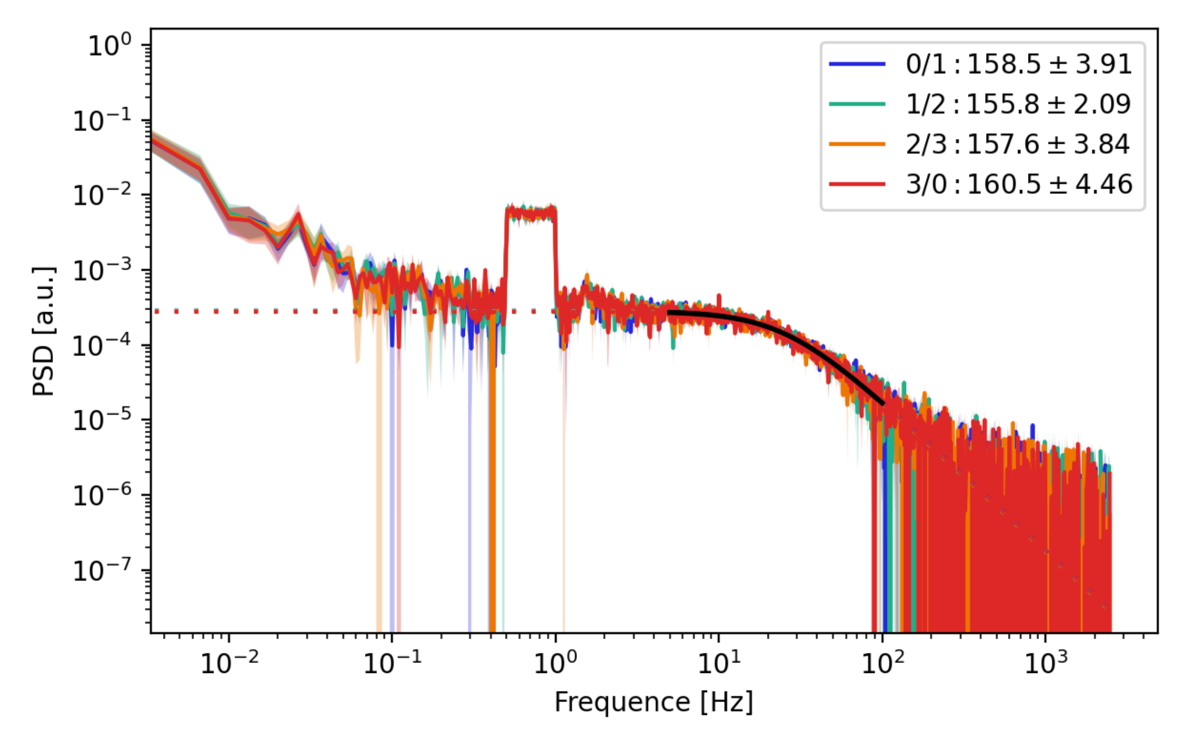
- Qualitatively: good agreement (value of PSD is different because current vs time tagging)
- To compare the simulation and measurement: ratio of door vs plateau because time tagging vs current
  - Measurement ratio: [10.6 – 11.2]
  - Simulations ratio: [9.7 – 10.4]

Reference simulation: CPSD (CFUL)

Measurement CFUL

Simulation





Current

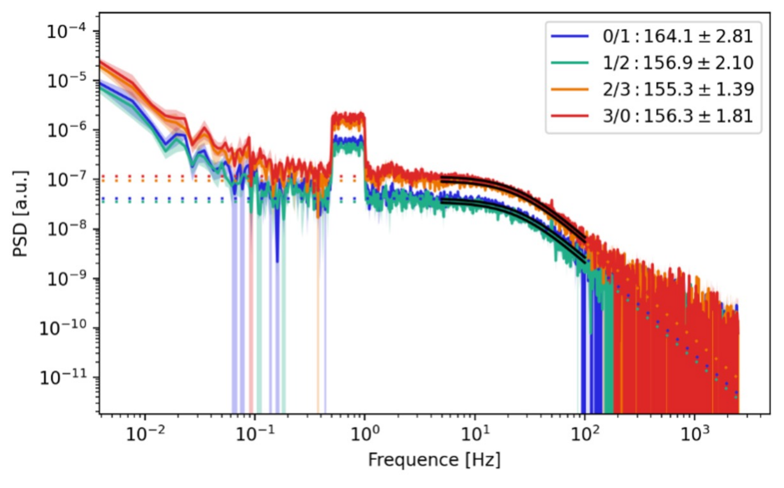
VS

Time tagging

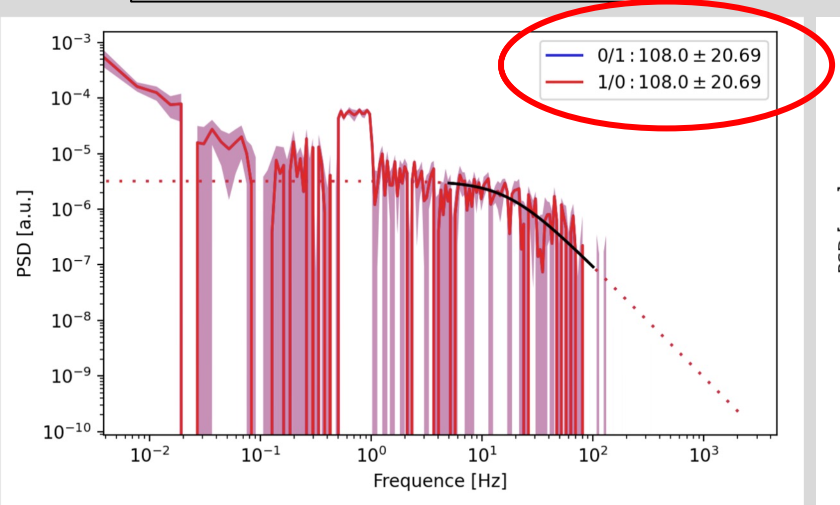
It works… but why ?
There should be an extra factor in the ratio…

Reference simulation: CPSD

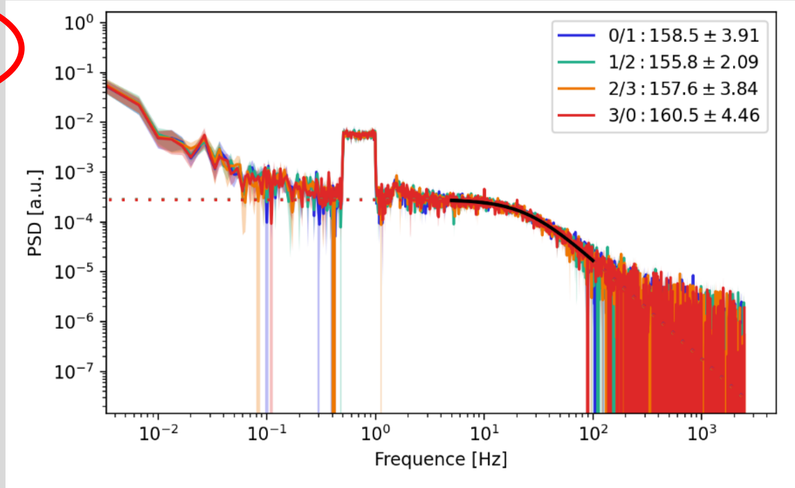
Measurement CFUL



Measurement SAFFRON



Simulation

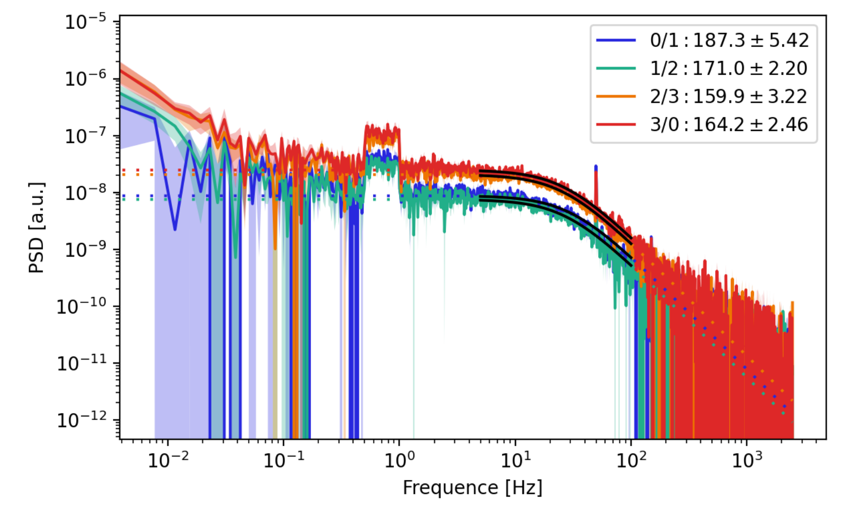


Saffron results were not fully exploited due to lower efficiency and high uncertainties

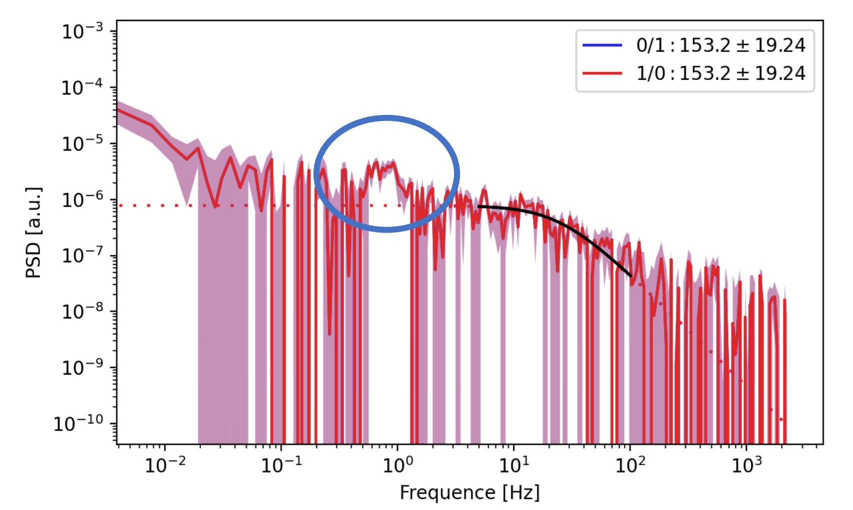
Ratio door/plateau with SAFFRON: ≈ 20

200 mW simulation:

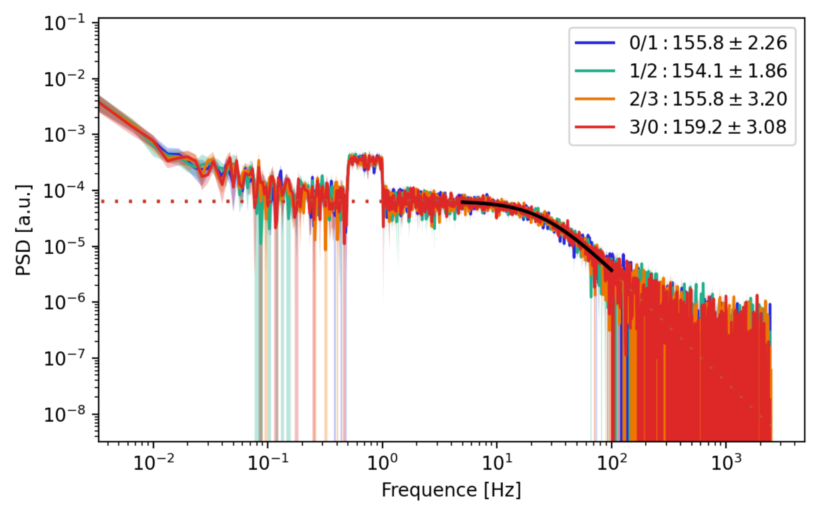
Measurement CFUL



Measurement SAFFRON



Simulation



- Qualitatively: good agreement (value of PSD is different because current vs time tagging)
- Ratio of door vs plateau:
  - Measurement (CFUL): [1.9 – 3.8]
  - Measurement (SAFFRON): [≈ 5]
  - Simulations: [3.12 - 3.17]

Part 5:
Conclusion and prospects

Conclusion…

- MSRs exhibit modulation noise even at zero power

- This noise is distributed on a “wide” frequency range

- To mimic it, pseudo random reactivity oscillations were inserted in CROCUS:
    - Experimentally
    - Numerically with the TFM approach

- The results with the CFUL are clearer than the ones with SAFFRON, but the current mode makes the comparison difficult because the conversion ratio is still unknown

- The CPSDs give similar results (shape and values, even if this point still need investigations)

… and prospects

- The current mode vs time tagging of the simulation must be sorted out

- The next step is to use the code with moving precursors in an MSR to quantify the influence of the movement of the precursors (ongoing)

- The Random TFM approach will be used directly in coupled simulations (neutronics-thermalhydrtaulics) to remove the generation-based time advancement of the traditional TFM approach

Acknowledgements

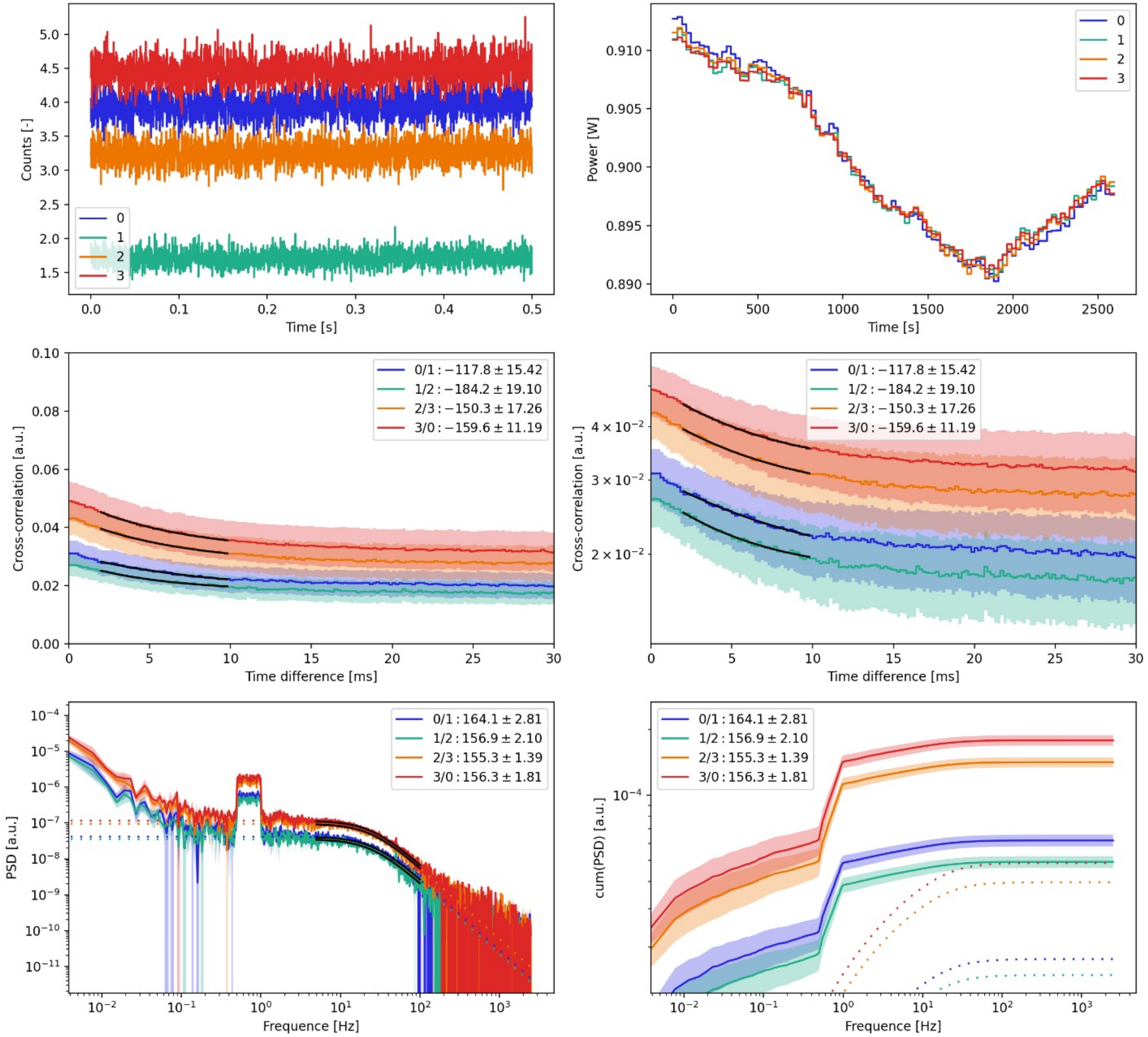
Thank you very much to Vincent Lamirand and Thomas Ligonnet for welcoming us at the EPFL, operating the reactor for 2 days and helping with advices and happiness !!

Any questions ?

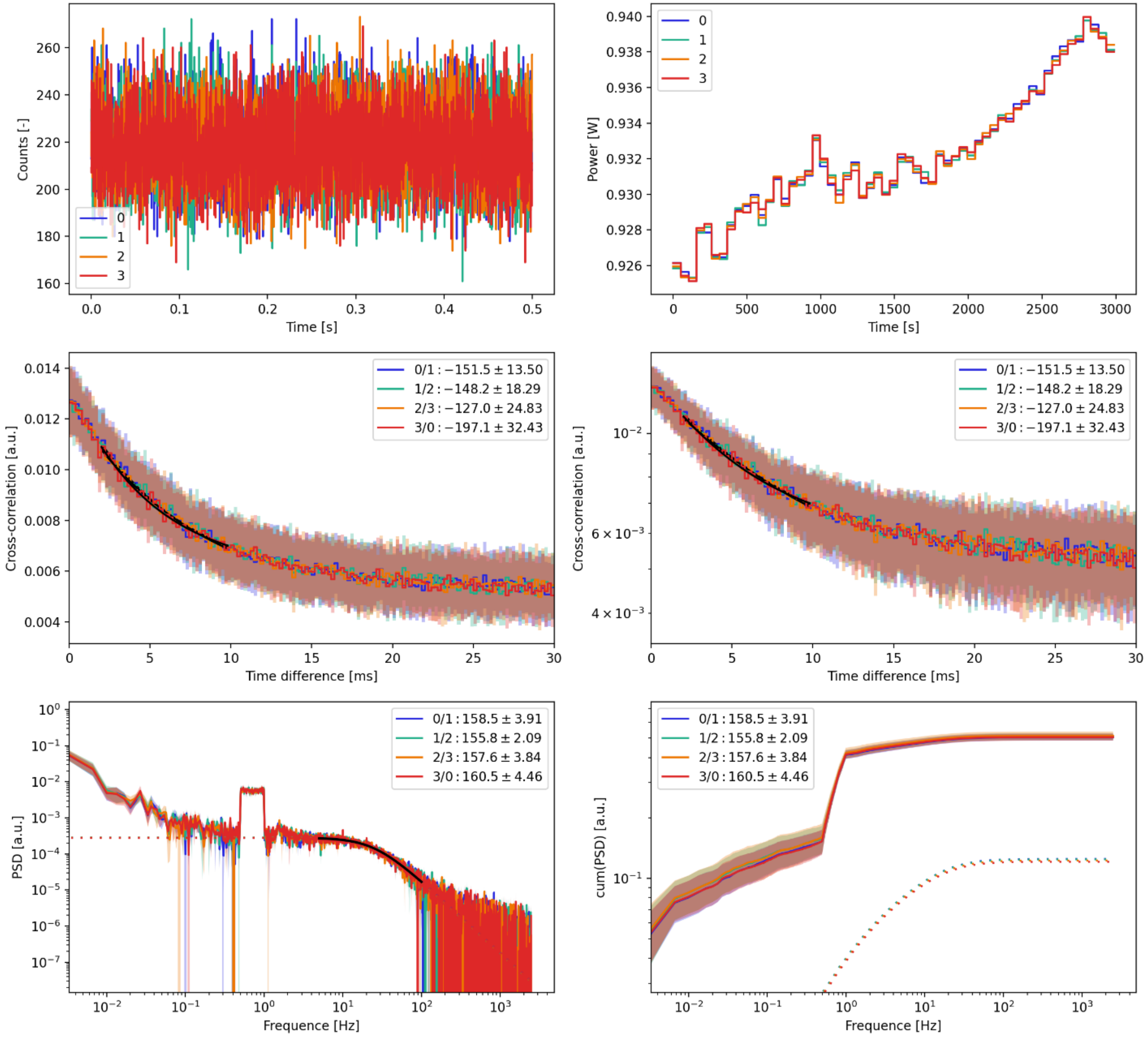
Part 6:
All results: CFUL

Comparisons: reference

measurement



Simulation

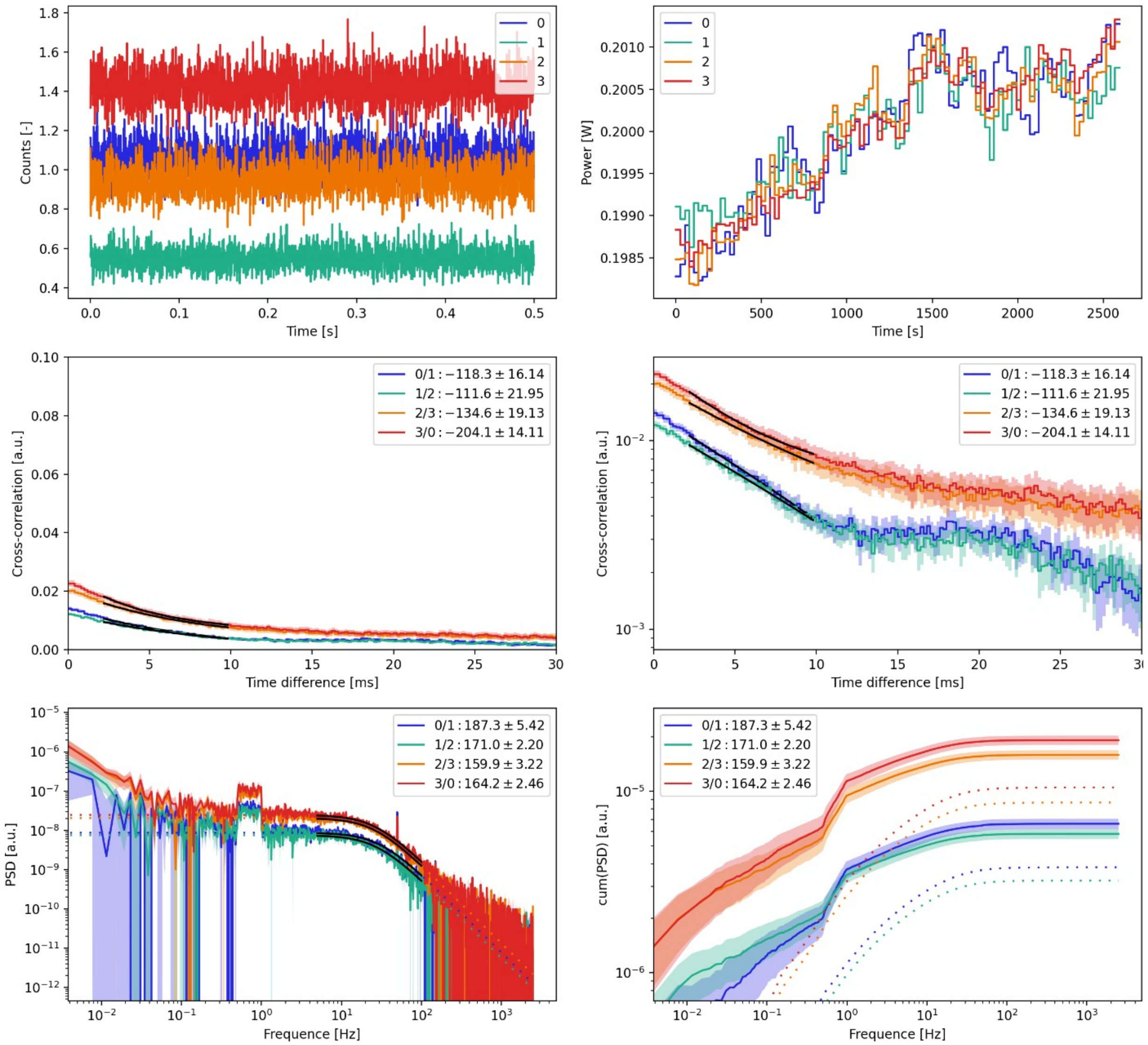


~900 mW, [0.5-1] Hz door, 2 pcm std

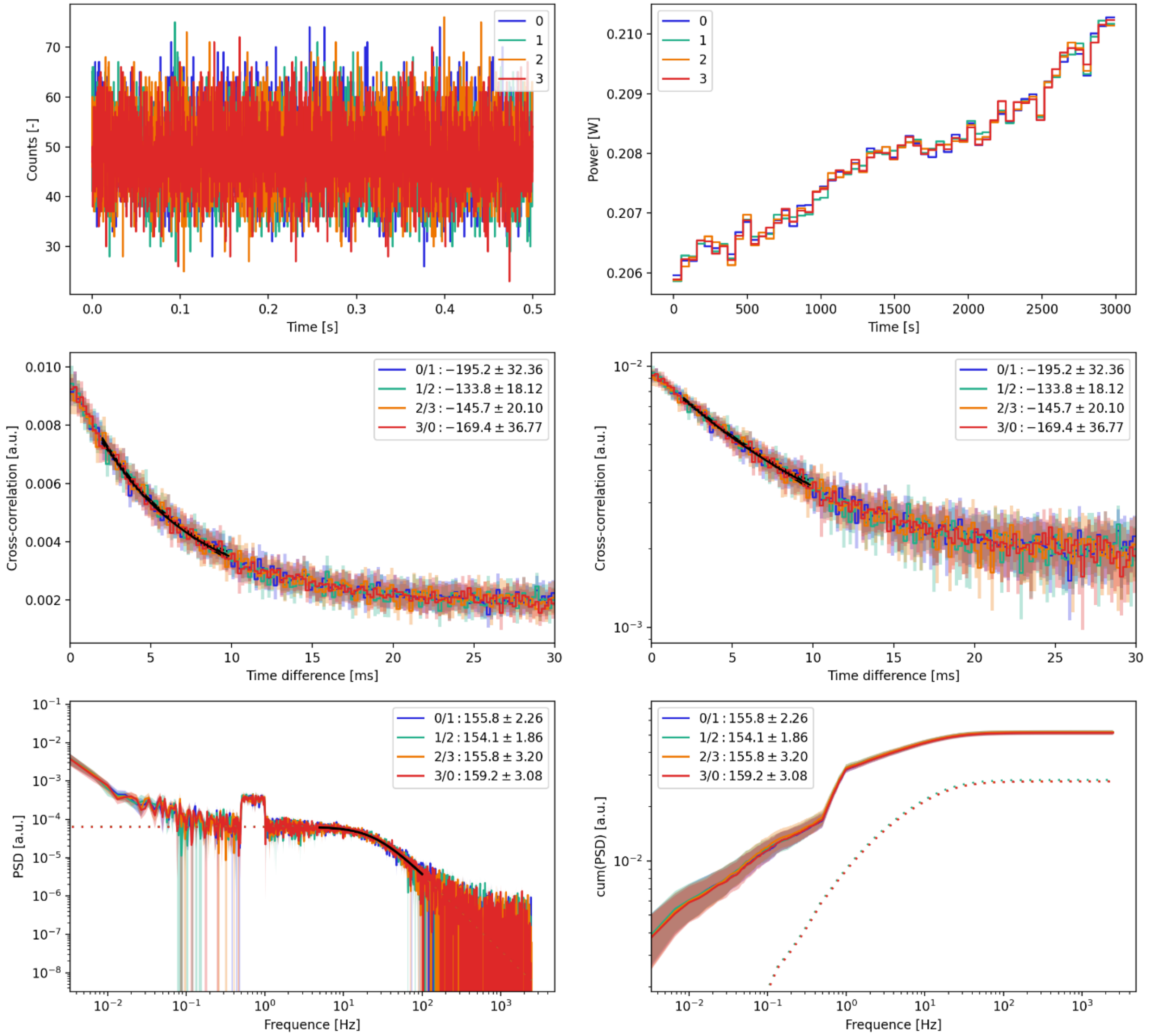
k_sub=0.9999987 beta_eff=736.2pcm 1-kp_inf=736.7pcm beta_eff/lambda_eff=157.4 alpha_rossi=157.5 alpha_rossi_batch=158.1=a in np.log(-a*geneff)=kp_inf

Comparisons: 200 mW

measurement



Simulation

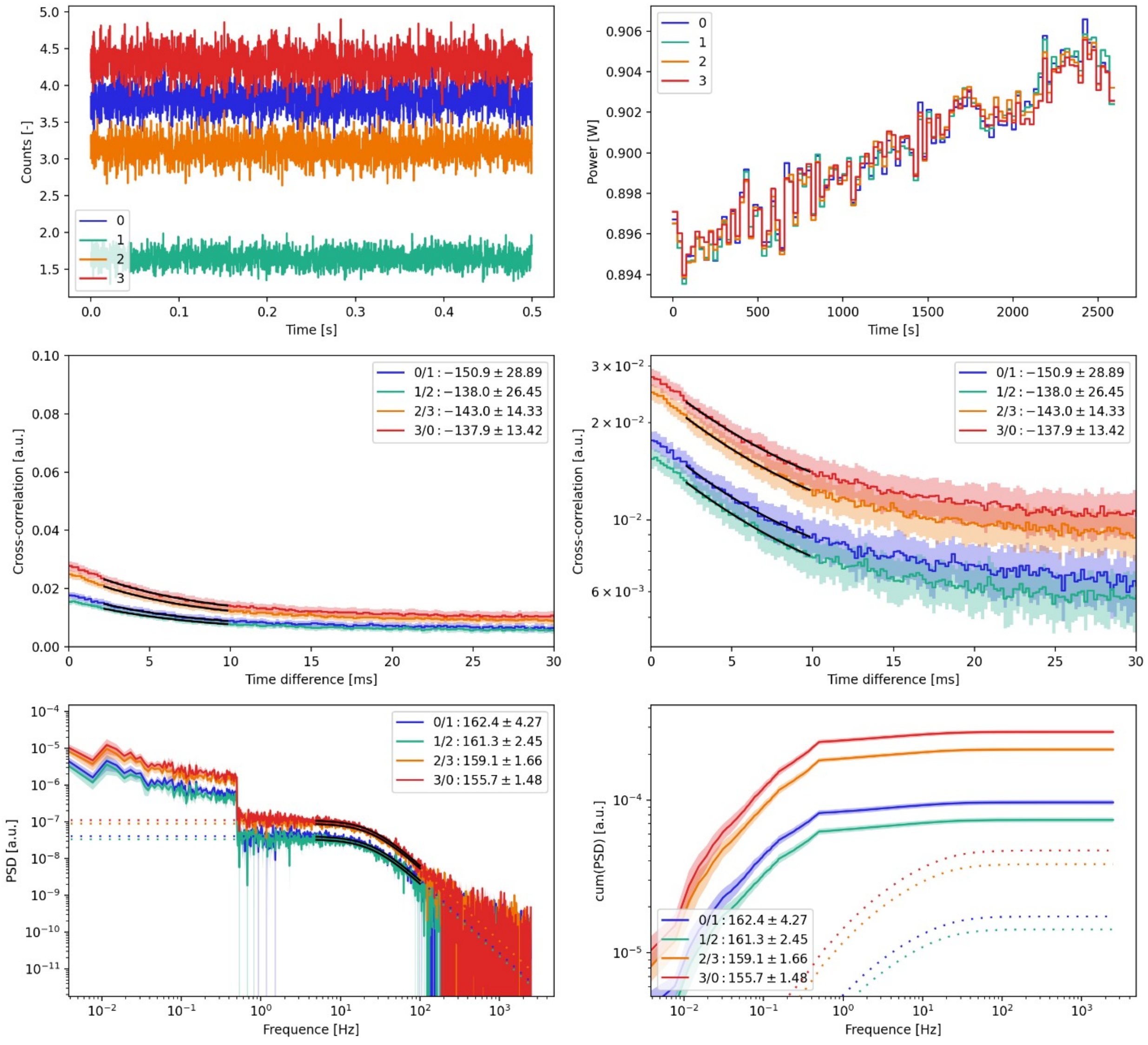


~200 mW, [0.5-1] Hz door, 2 pcm std

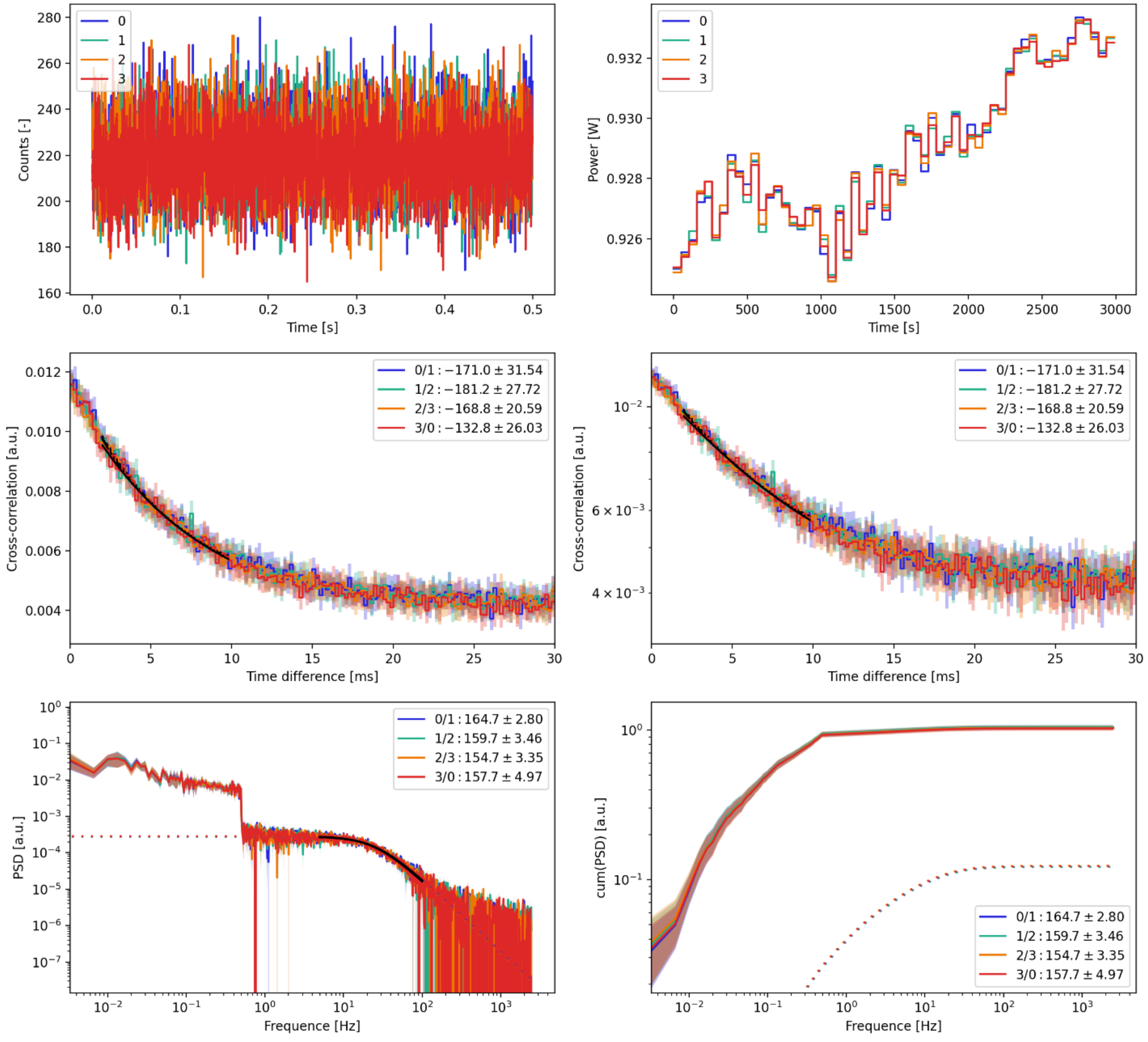
k_sub=0.9999993 beta_eff=736.2pcm 1-kp_inf=736.7pcm beta_eff/lambda_eff=157.4 alpha_rossi=157.5 alpha_rossi_batch=158.0=a in np.log(-a*geneff)=kp_inf

Comparisons: low frequency

measurement



Simulation



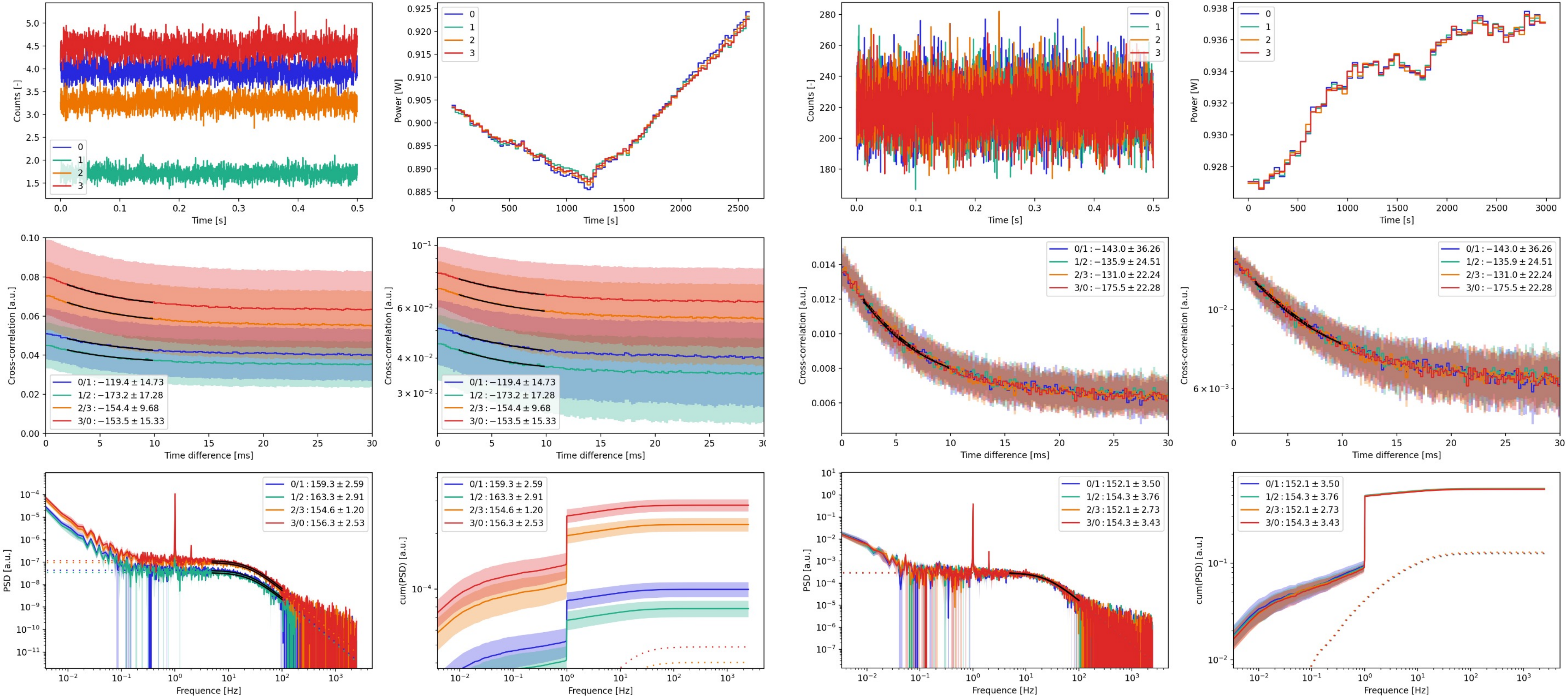
~900 mW, [0.01-0.5] Hz door, 2 pcm std

k_sub=0.9999987 beta_eff=736.2pcm 1-kp_inf=736.7pcm beta_eff/lambda_eff=157.4 alpha_rossi=157.5 alpha_rossi_batch=158.1=a in np.log(-a*geneff)=kp_inf

Comparisons: pure sinus

measurement

Simulation



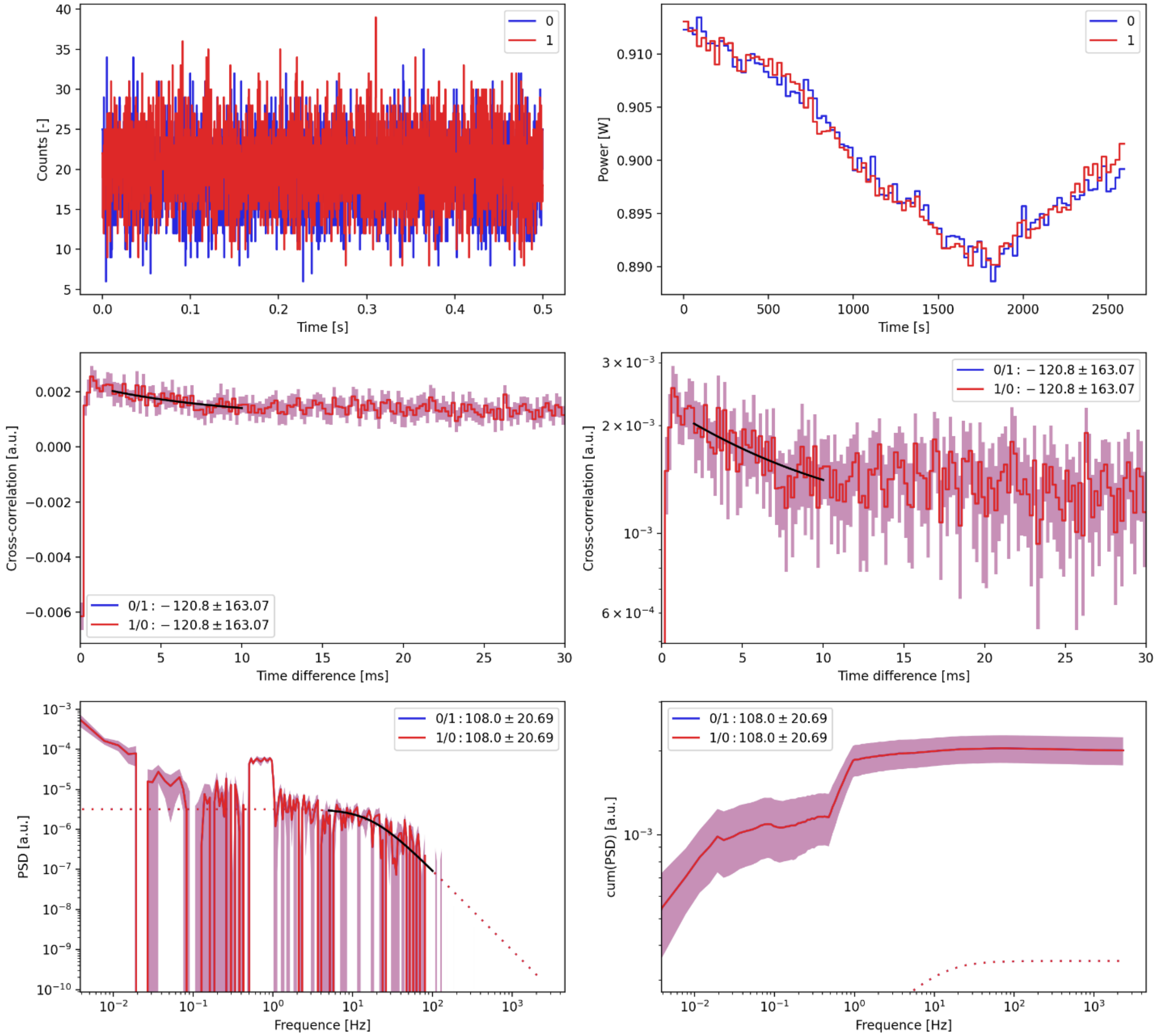
~900 mW, 1 Hz pure sinus, 3 pcm std

k_sub=0.9999999 beta_eff=736.2pcm 1-kp_inf=736.6pcm beta_eff/lambda_eff=157.4 alpha_rossi=157.4 alpha_rossi_batch=158.0=a in np.log(-a*geneff)=kp_inf

Part 6:
All results: SAFFRON

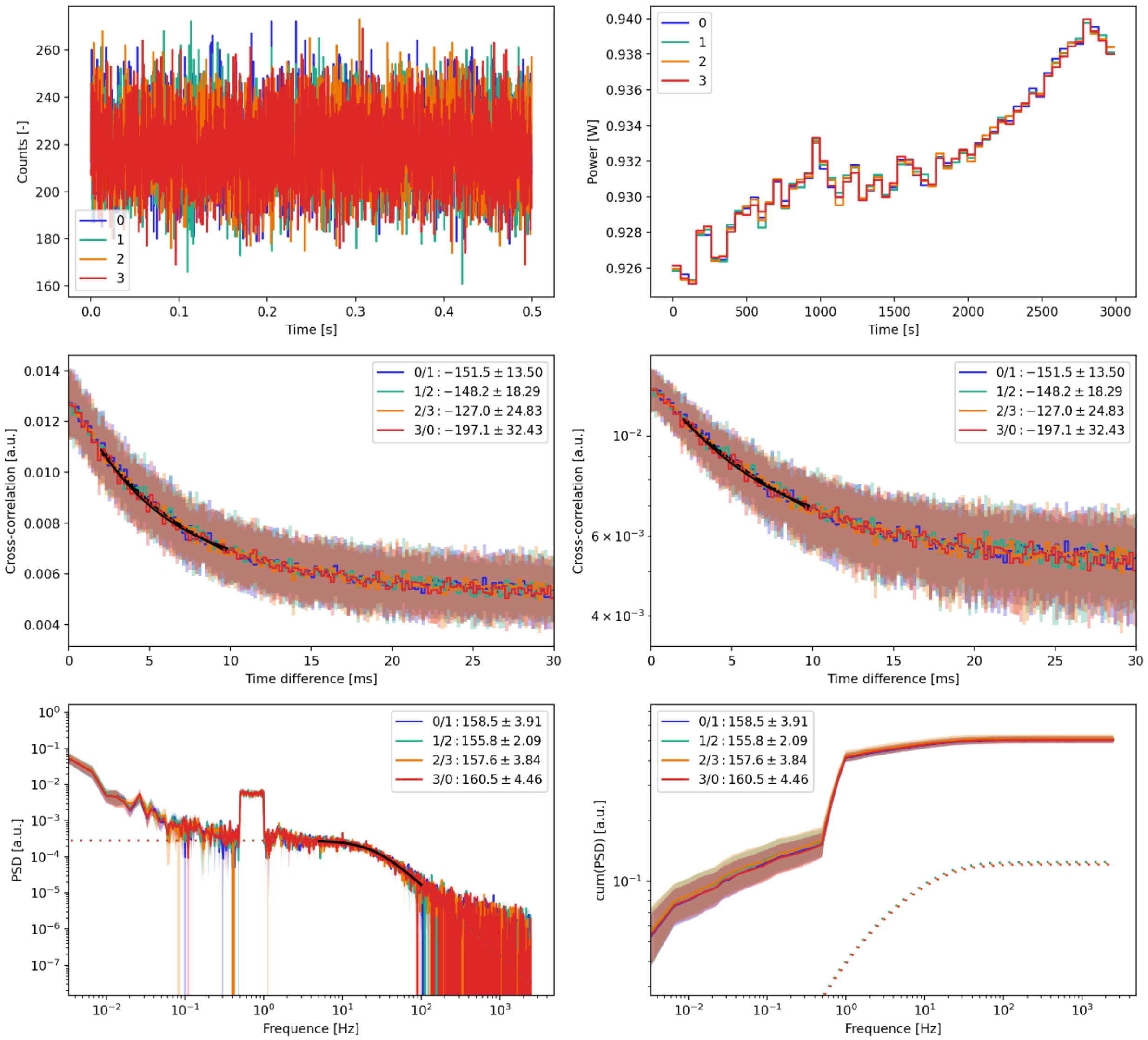
Comparisons: reference

measurement



~900 mW, [0.5-1] Hz door, 2 pcm std

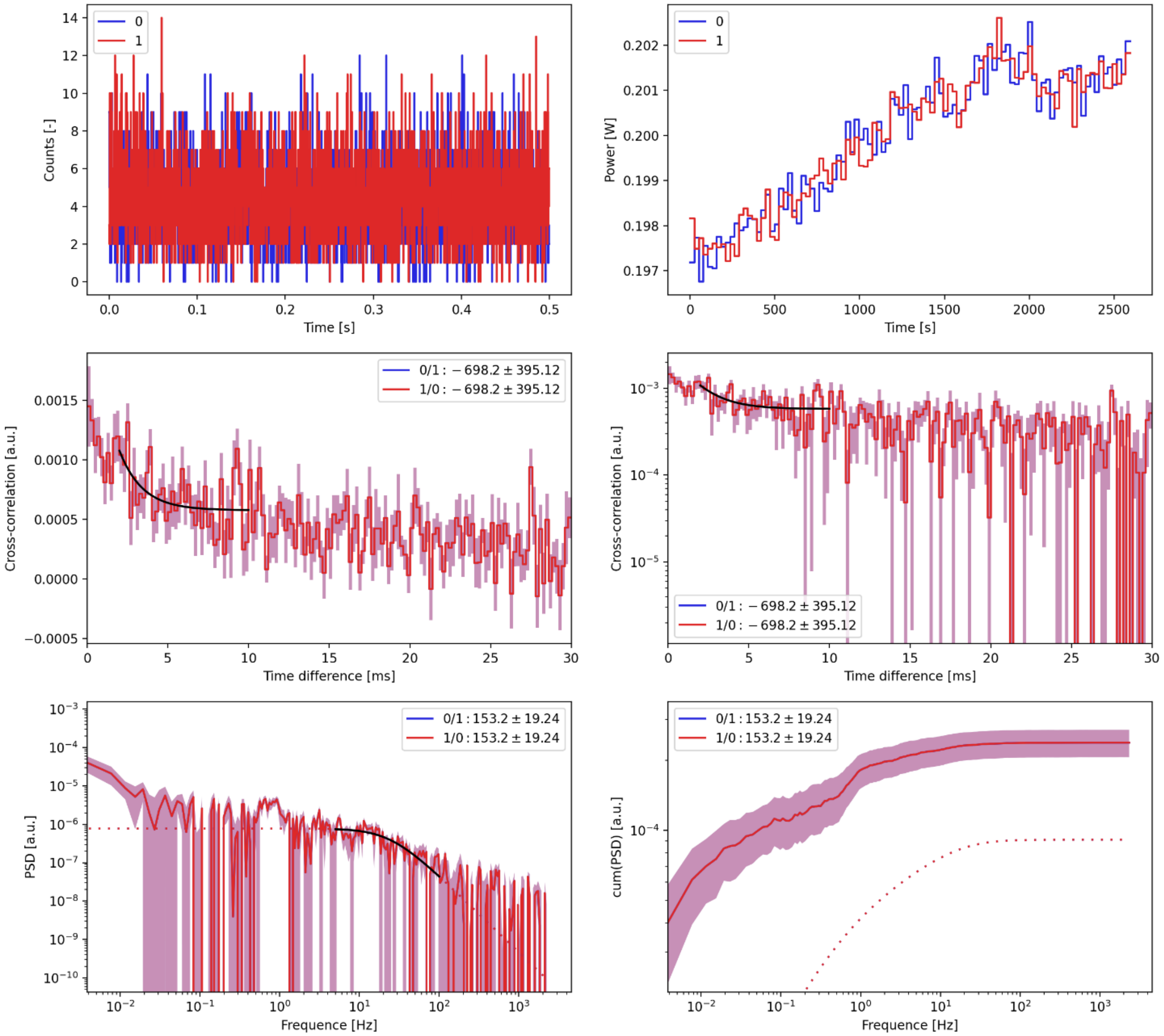
Simulation



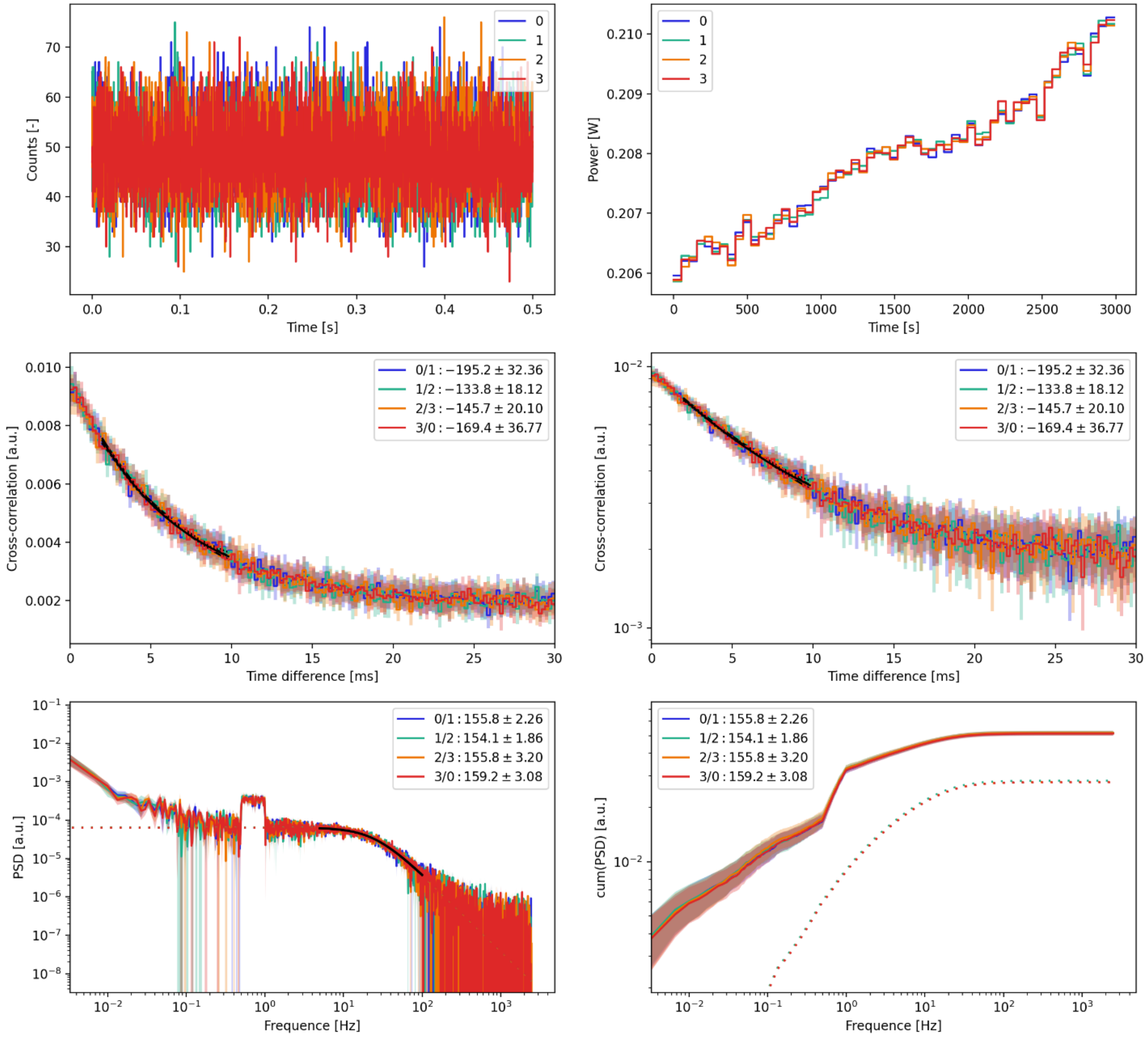
_sub=0.9999987 beta_eff=736.2pcm 1-kp_inf=736.7pcm beta_eff/lambda_eff=157.4 alpha_rossi=157.5 alpha_rossi_batch=158.1=a in np.log(-a*geneff)=kp_inf

Comparisons: 200 mW

measurement



Simulation



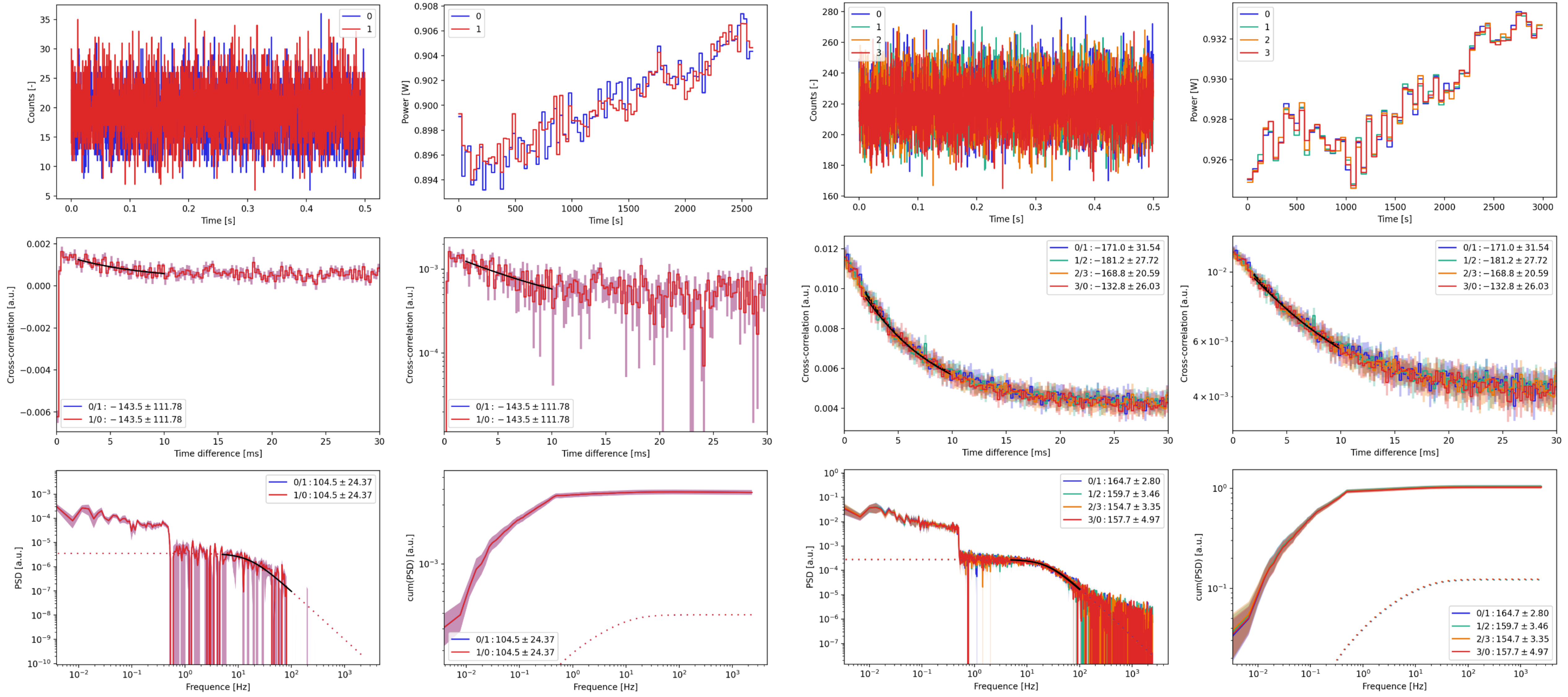
~200 mW, [0.5-1] Hz door, 2 pcm std

_sub=0.9999993 beta_eff=736.2pcm 1-kp_inf=736.7pcm beta_eff/lambda_eff=157.4 alpha_rossi=157.5 alpha_rossi_batch=158.0=a in np.log(-a*geneff)=kp_inf

Comparisons: low frequency

measurement

Simulation



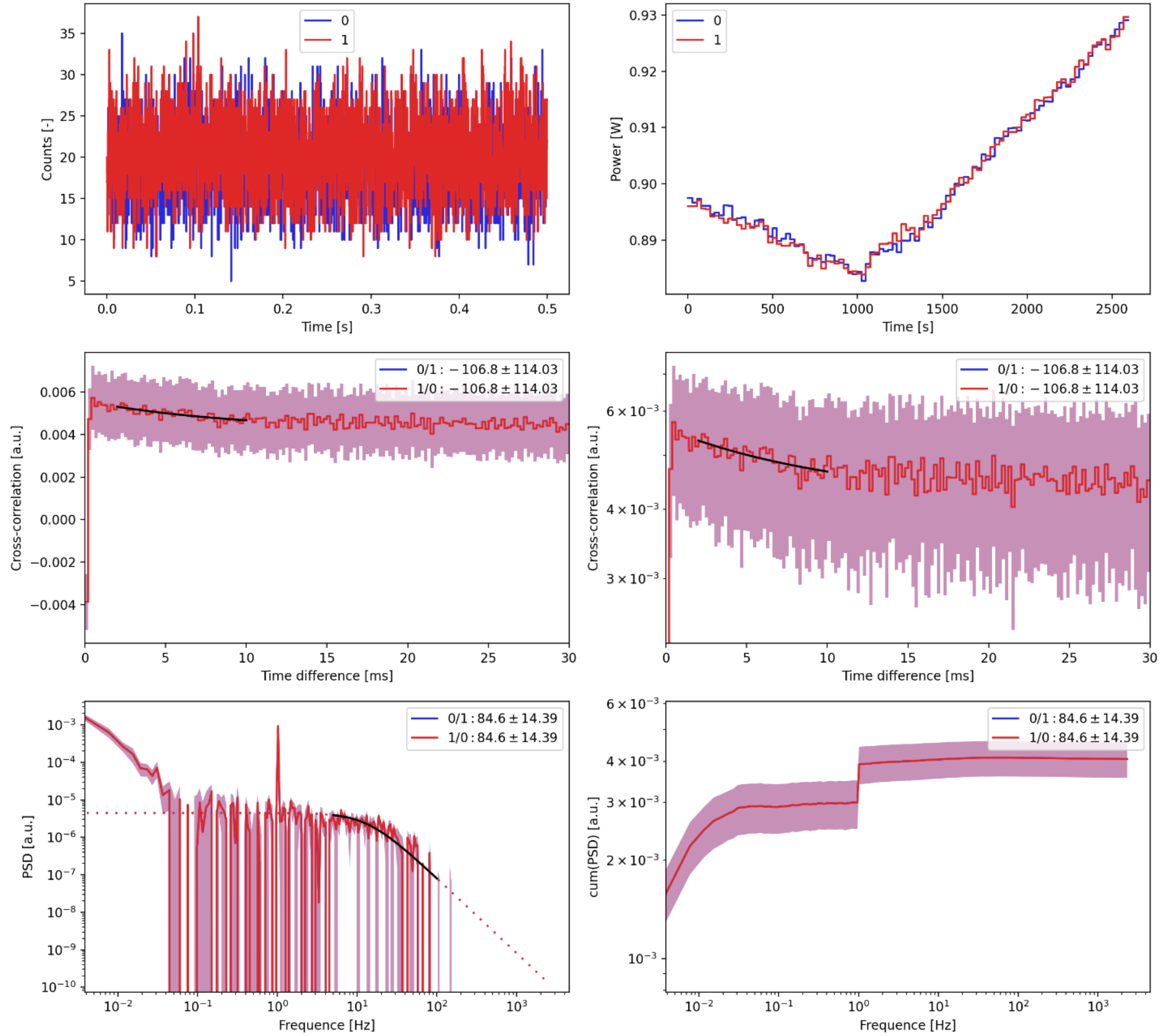
~900 mW, [0.01-0.5] Hz door, 2 pcm std

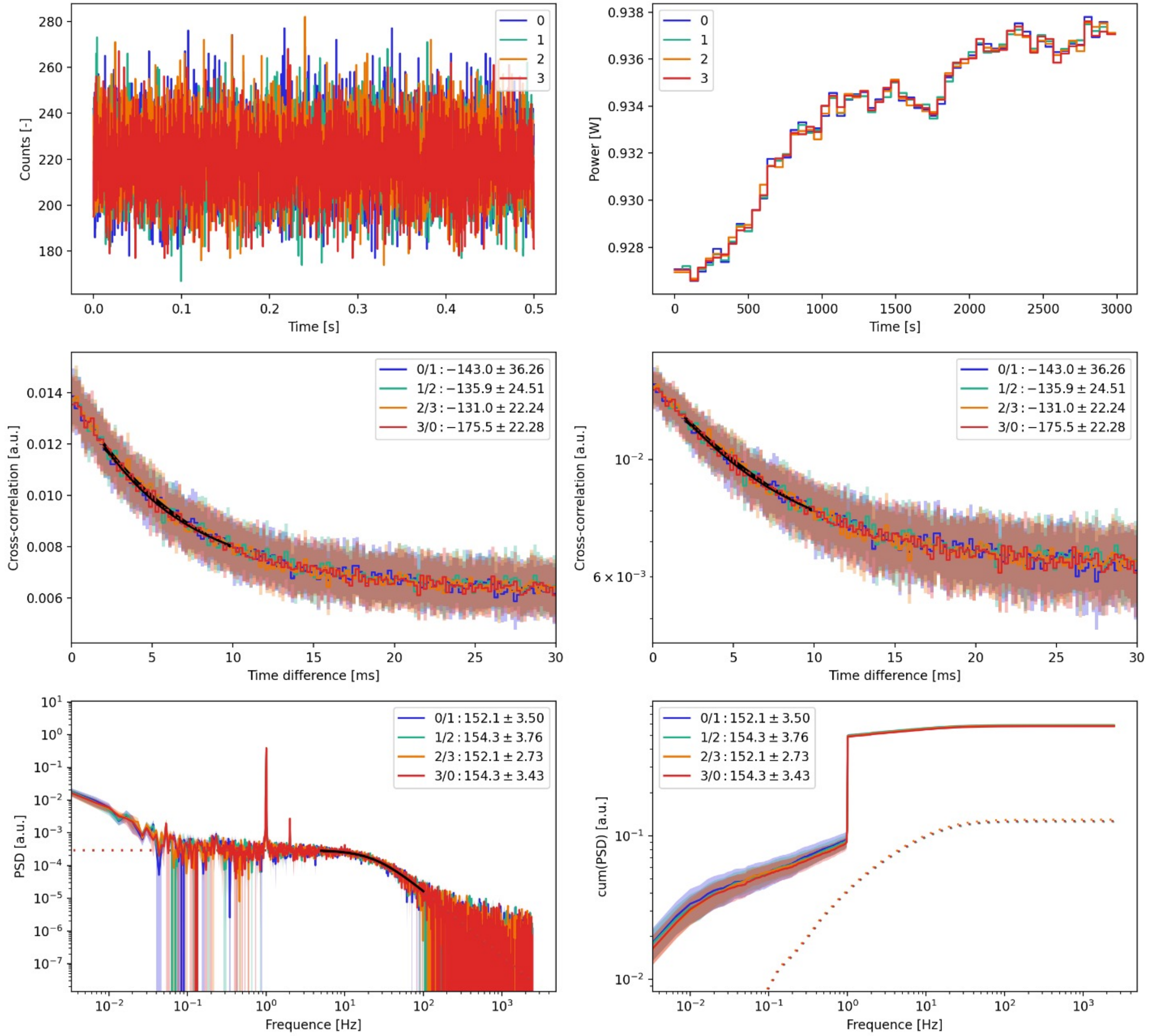
_sub=0.9999987 beta_eff=736.2pcm 1-kp_inf=736.7pcm beta_eff/lambda_eff=157.4 alpha_rossi=157.5 alpha_rossi_batch=158.1=a in np.log(-a*geneff)=kp_inf

Comparisons: pure sinus

measurement

Simulation





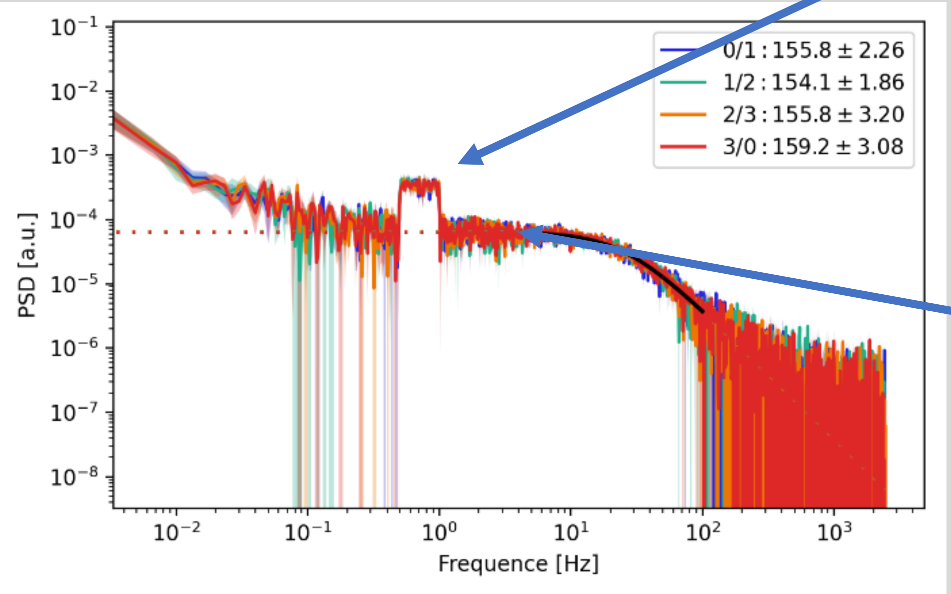
~900 mW, 1 Hz pure sinus, 3 pcm std

_sub=0.9999999 beta_eff=736.2pcm 1-kp_inf=736.6pcm beta_eff/lambda_eff=157.4 alpha_rossi=157.4 alpha_rossi_batch=158.0=a in np.log(-a*geneff)=kp_inf

Commentary on the door/plateau ratio

F: fission rate
I: Current intensity

For counts : Door intensity $\propto F^2$
For current mode : Door intensity $\propto I^2$



For counts : plateau intensity $\propto F$
For current mode : plateau intensity $\propto I$

For counts : $\frac{door}{plateau} \propto F$
For current mode : $\frac{door}{plateau} \propto I$

We expect different ratios for counts and current mode yet observe similar ones experimentally. Why ?