PAUL SCHERRER INSTITUT

PSI

Laboratory for Reactor Physics and Thermal-Hydraulics

EPFL

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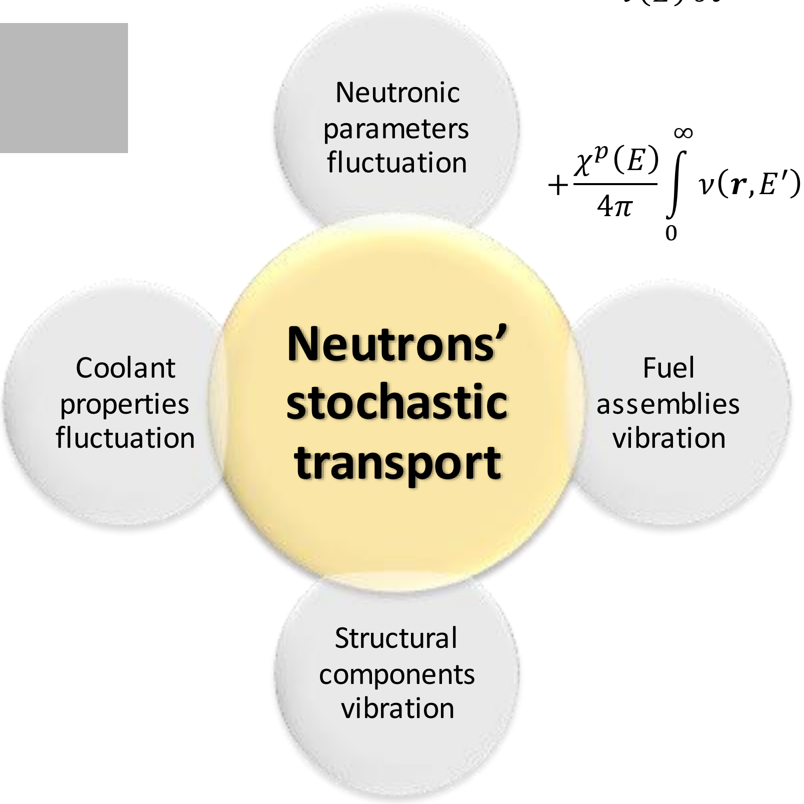
Development of Advanced Methodologies for Monitoring & Modelling of Neutron Noise in Modern LWRs

PhD Oral Exam, Zoom Video-Conference, May 27th 2020

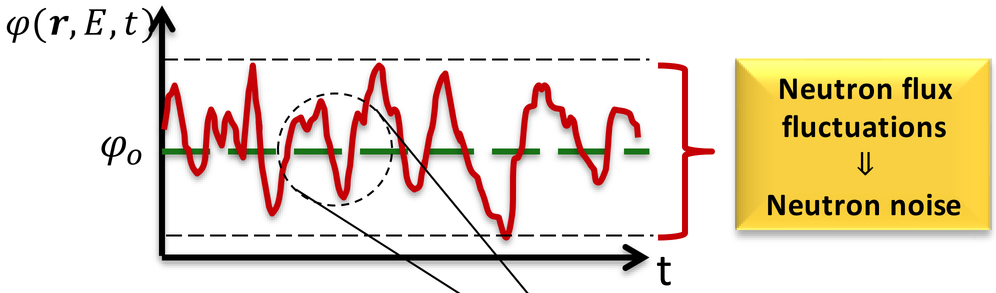
Neutron Noise (NN)

$$\frac{1}{v(E)}\frac{\partial}{\partial t}\varphi(\boldsymbol{r},E,t) - \nabla\cdot D(\boldsymbol{r},E,t)\nabla\varphi(\boldsymbol{r},E,t) + \Sigma_t(\boldsymbol{r},E,t)\varphi(\boldsymbol{r},E,t) = \int_0^\infty \Sigma_s(\boldsymbol{r},E'\rightarrow E,t)\varphi(\boldsymbol{r},E',t)\,dE'$$

$$+\frac{\chi^p(E)}{4\pi}\int_0^\infty \nu(\boldsymbol{r},E')\Sigma_f(\boldsymbol{r},E',t)\,\varphi(\boldsymbol{r},E',t)\,dE' + \sum_{i=1}^{N^d}\frac{\chi^{d,i}(E)}{4\pi}\lambda_i C_i(\boldsymbol{r},t) + Q(\boldsymbol{r},E,t)$$

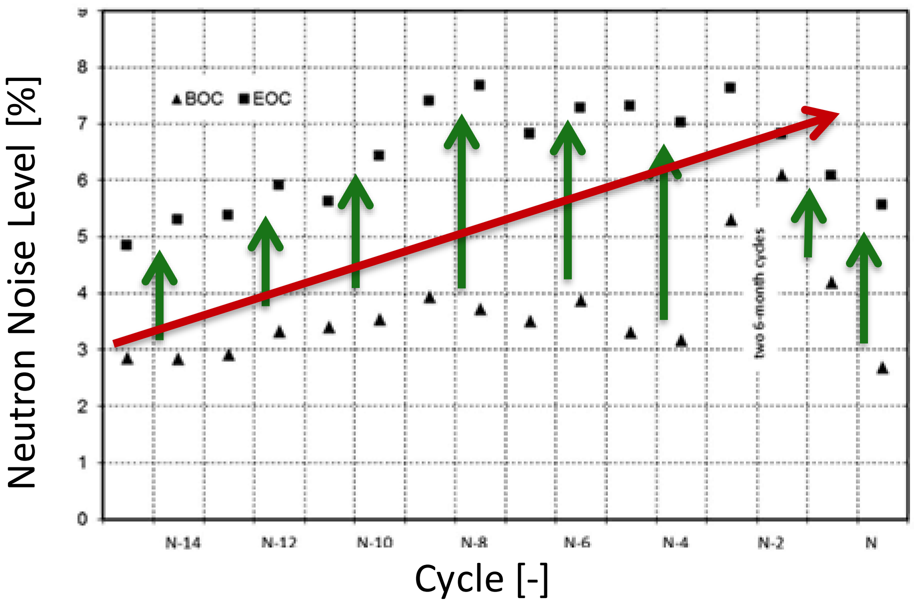


Space/energy/time-dependent scalar neutron flux φ



- reactor behavior
- reactor dynamics
- signature characteristics
- malfunctions' detection

Motivation



M. Seidl et al., PNE vol. 85, pp. 668-675 (2015)

Neutron noise increase trend:

- *observed in several European NPPs*
- *operational burden for the utilities*

Noise characteristics:

✓ *within-the-cycle increase*

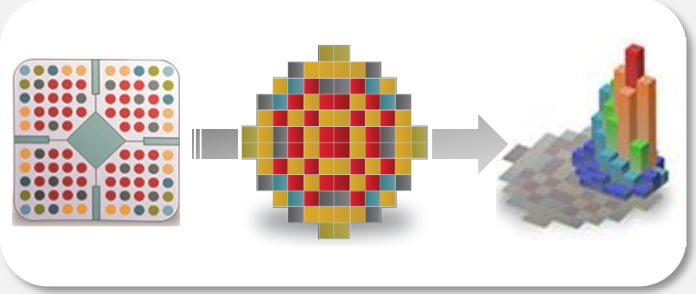
✗ *cycle-to-cycle increase*

Need for better & deeper understanding of neutron noise phenomena

PhD Thesis - Overview

Study neutron noise phenomena and examine the stochastic behavior of a nuclear reactor with a dual approach

Improving
signal analysis
techniques



Developing numerical models &
core simulation methods
to reproduce plant measurements

Explaining *the neutron noise phenomenology in operating reactors*

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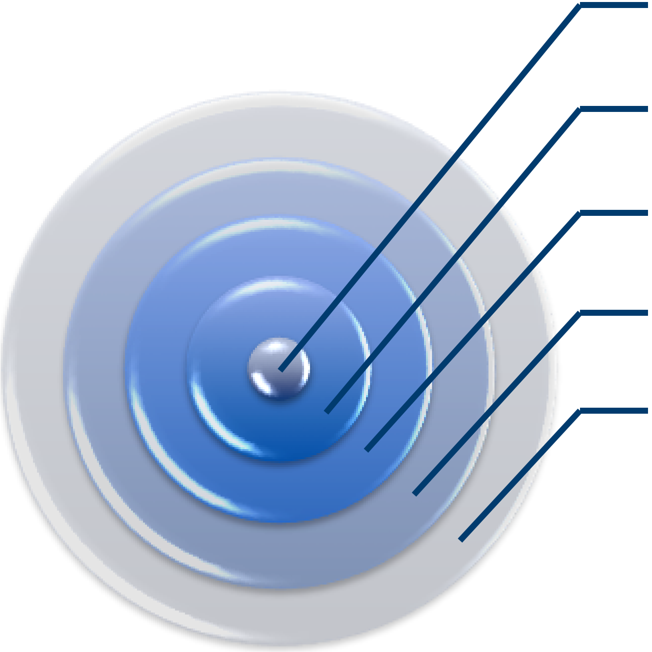
Thesis Accomplishments



- Identification of **KKG noise characteristics**
- In-house **neutron noise modelling** capabilities development
- Reproduction of **KKG noise signatures**
- Neutron noise simulated **data platform** (CORTEX project)
- In-house **connectivity analysis toolbox**; supportive diagnostics tool

Content

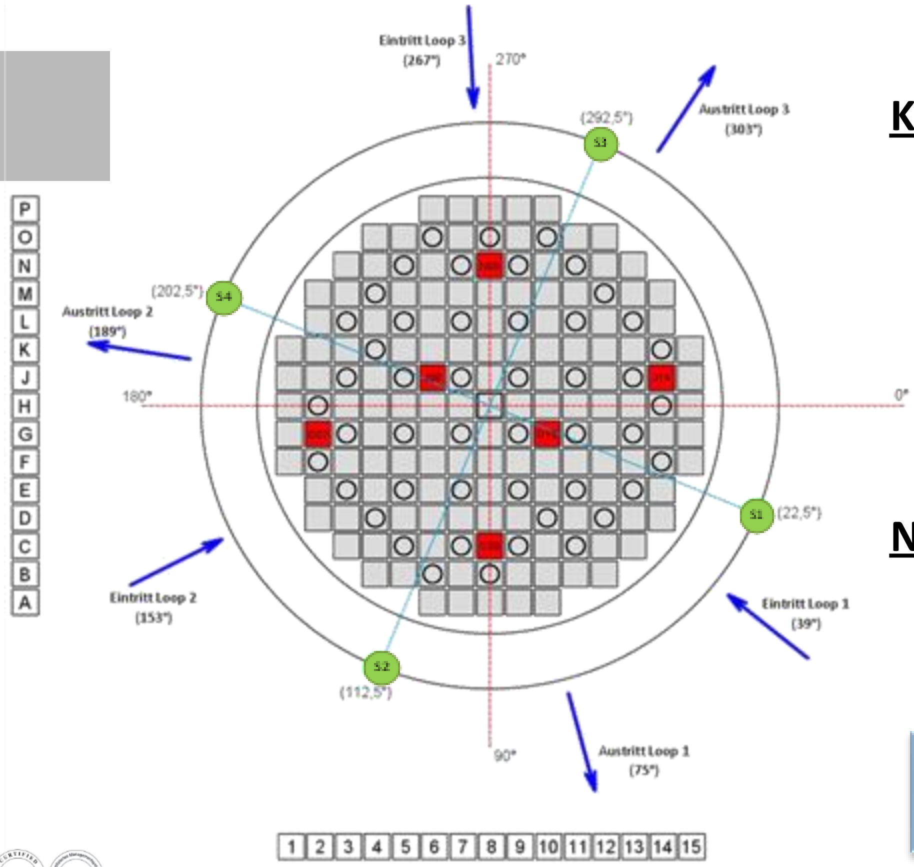
- **Signal analysis of KKG plant data**
  - *KKG description & plant signals' post-processing*
  - *KKG noise phenomenology*

D. Chionis et al., "PWR neutron noise phenomenology: Part II – Qualitative comparison against plant data", Physor '18 (2018)

- **PSI neutron noise modelling methodology**
  - *Simulation procedure*
  - *Fuel assembly vibration modelling*
  - *Inlet coolant properties fluctuation modelling*
  - *Main simulated noise observations*
  - *Explanation of KKG measured noise phenomenology*

- **PSI connectivity analysis methodology**
  - *Causality concept & utilized method*
  - *Application on KKL plant data*

KKG description



KKG characteristics:

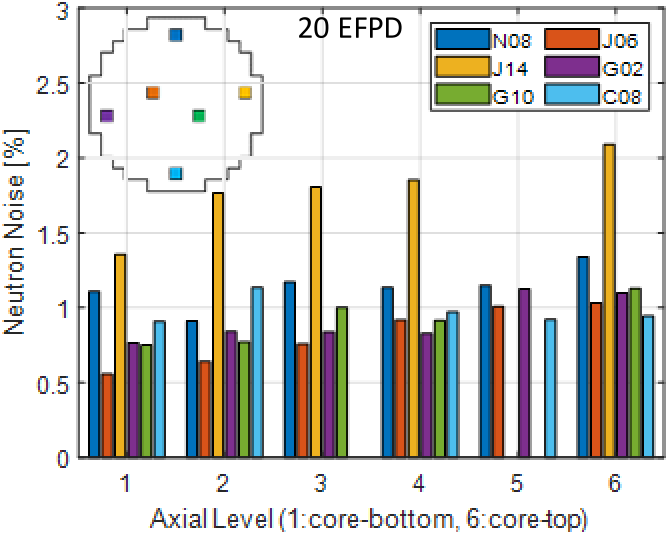
- *KWU pre-KONVOI PWR design*
- *177 Fuel Assemblies (15x15 layout)*
- *Quarter symmetric core*
- *3-coolant loop plant*
- *non-quarter symmetric control rods pattern*

Neutron flux monitored via:

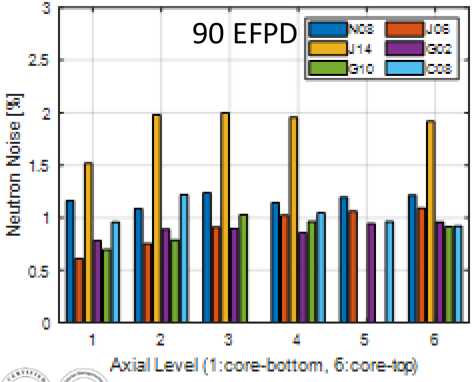
- *36 in-core neutron detectors* □ □ *(SPNDs)*
- *8 ex-core neutron detectors* ● *(ionization chambers)*

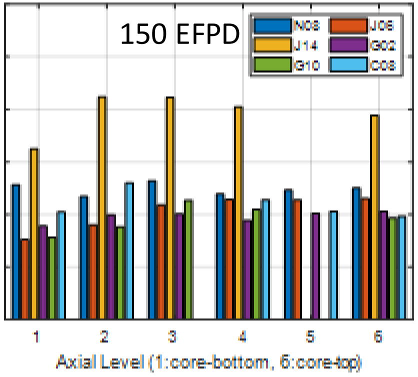
KKG neutron noise characteristics to be identified using signal processing techniques

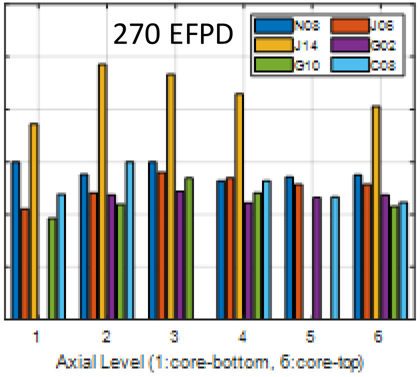
KKG: Neutron Noise Distribution



- J14 exhibits highest NN
  ⇒ *unique KKG characteristic*
- **G10** and **J06** exhibit lowest NN levels
- Slight shift of higher NN towards core-bottom as burnup increases







KKG NN behavior is rather spatial inhomogeneous in both axial & radial directions

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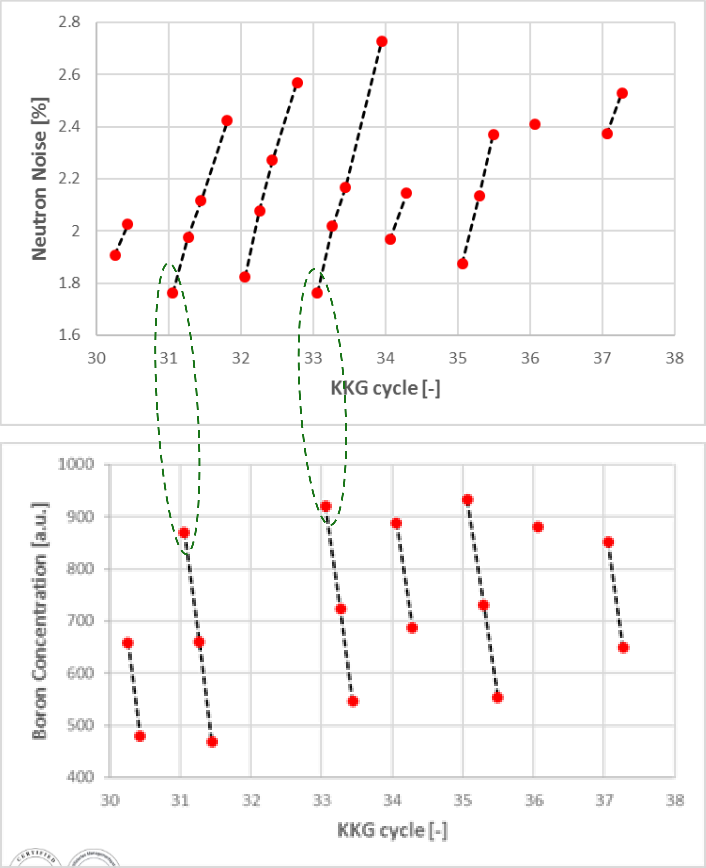
KKG: Neutron Noise Evolution



<u>Within-the-cycle NN trend:</u>

- Clear NN increase within the cycles 31- 33 due to the decrease of Moderator Temperature Coefficient.

<u>Cycle-to-cycle NN trend:</u>

- More pronounced NN increase at the EOC

  EOC31 < EOC32 < EOC33

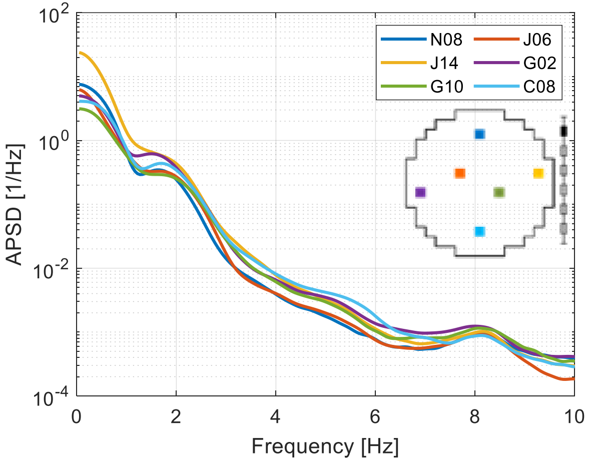
- Not a clear increasing NN trend at BOC

  BOC30 > BOC31 < BOC32 < BOC33

➢ Inversed proportionality between NN and boron concentration evolution.

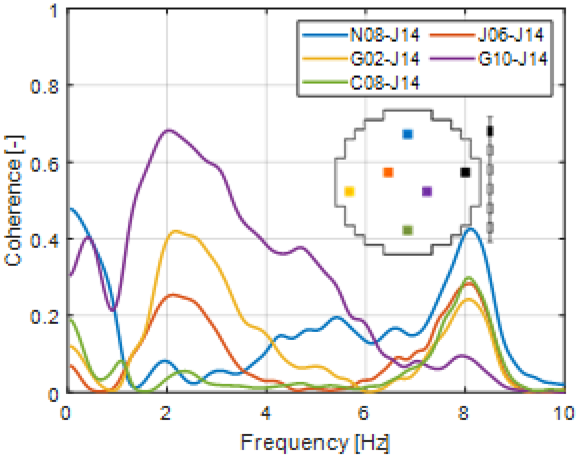
➢ Importance of operating conditions on NN evolution.

KKG: NN Radial Spectral Phenomenology



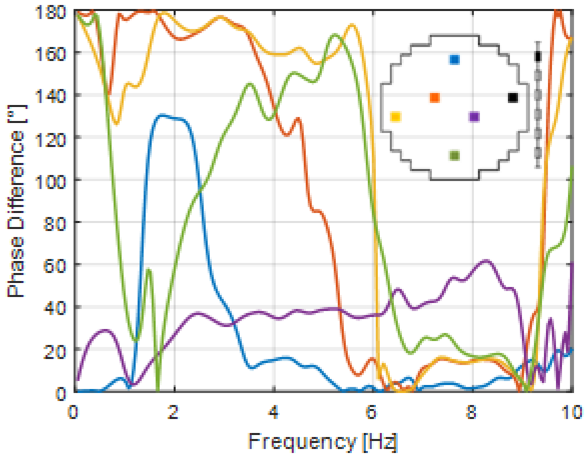
Noise Radial Spectrum

- *Stronger at <5Hz*
- *Spectral peak at 1.5-2Hz; fuel vibration*
- *Spectral peak at 8Hz; core barrel pendular movement*



Radial Coherence

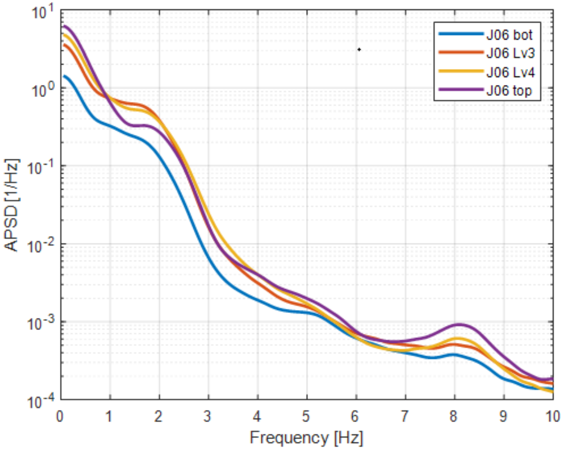
- *Azimuthally neighboring detectors are more coherent at 1.5-2Hz*
- *Detectors are equally strongly coherent at 8Hz*

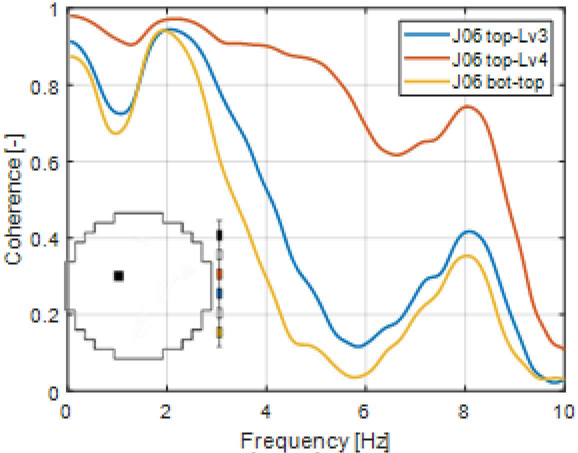


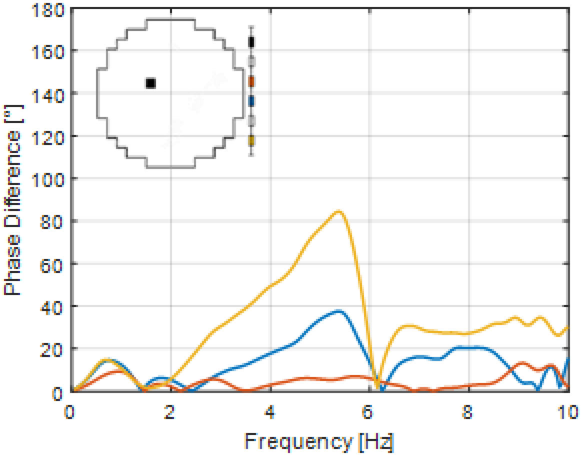
Radial Phase Difference

- *Indication of a vibrating central cluster at 1.5-2Hz in the x-y direction*
- *All detectors at 8Hz are in-phase*

KKG: NN Axial Spectral Phenomenology







Noise Axial Spectrum

- *Stronger at <5Hz*
- *Spectral peak at 1.5-2Hz; fuel vibration*
- *Spectral peak at 8Hz; core barrel pendular movement*

Axial Coherence

- *Stronger coherence btw. axially closest detectors*
- *Inlet coolant temp. transit time relates to dip at 1Hz*
- *Strong coherence at 8Hz*

Axial Phase Difference

- *Relative in-phase behavior btw. detectors located at the same instrumentation string*

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D. Chionis et al., "Development and verification of a methodology for neutron noise response to fuel assembly vibrations", submitted to ANE (2020)
D. Chionis et al., "SIMULATE-3K analyses of neutron noise response to fuel assembly vibrations and thermal-hydraulics parameters fluctuations", M&C'17 (2017)
D. Chionis et al., "PWR neutron noise phenomenology: Part I – Simulation of stochastic phenomena with SIMULATE-3K", Physor '18 (2018)

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PSI Neutron Noise Modelling Methodology

CASMO-5 → **CMS-LINK5** → **SIMULATE-3** → **SIMULATE-3K** → **MATLAB**

CASMO-5
- Cross-sections generation

CMS-LINK5
- Nuclear data library preparation

SIMULATE-3
- Steady-state nodal solver
- Restart files preparation

SIMULATE-3K
- Transient nodal solver
- Noise source modelling

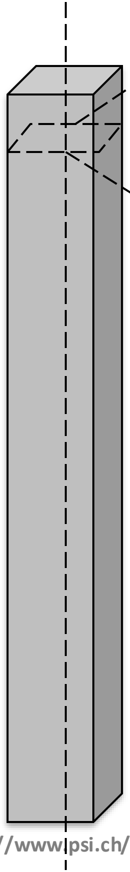
MATLAB
- Results post-processing
- NN phenomenology

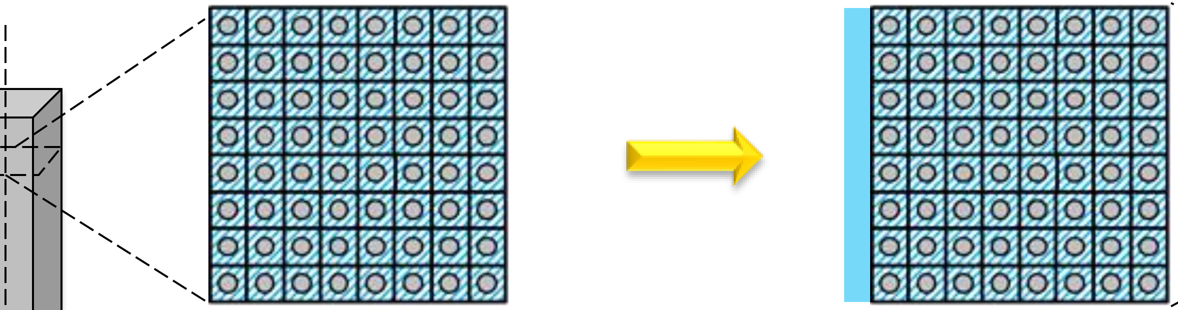
Main emphasis is given on the **fuel assembly vibration modelling**

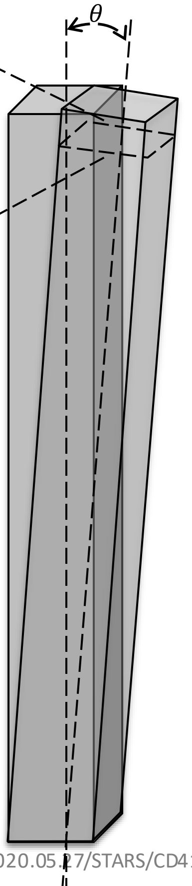
In-house **MATLAB scripts** for extending the SIMULATE-3K NN modelling capabilities

Fuel Vibration Modelling

Lattice Level







- CASMO-5 estimates the two-group homogenized cross-sections

$$\Sigma_{x,G} = \frac{\sum_{g=1}^{G} \Sigma_{x,g} \phi_g V}{\sum_{g=1}^{G} \phi_g V}$$

- Fuel lattice lateral displacement is mimicked by increasing the lattice water width size ⇒ *CASMO-5 Delta gap model (DGA)*

- Computationally efficient approach; no need of dynamic mesh modification

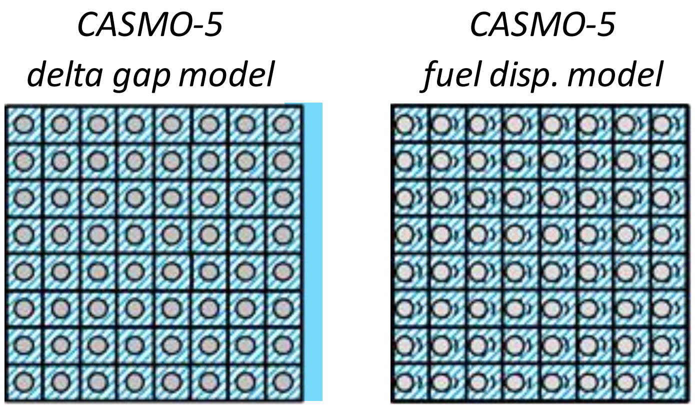
Fuel Vibration Modelling

Lattice Level Verification

- CASMO-5 delta gap model seems am approximate modelling approach
- In reality, the fuel pins are laterally displaced from their reference positions
- CASMO-5 **delta gap model** vs.
  CASMO-5 **fuel displacement model**

  $\Rightarrow$

  up to *0.3% difference in cross-sections*
  with 1.1% difference wrt. to unperturbed lattice
- CASMO-5 delta gap model behaves *quantitative similarly* with reference Serpent-2 results

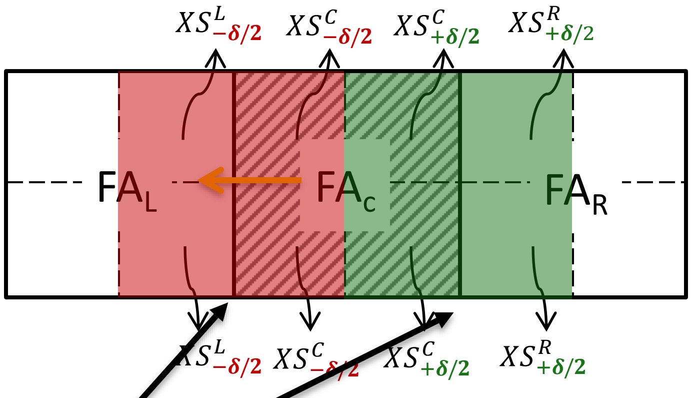


SIMULATE-3K can read data only from DGA model for simulating fuel assemblies vibration

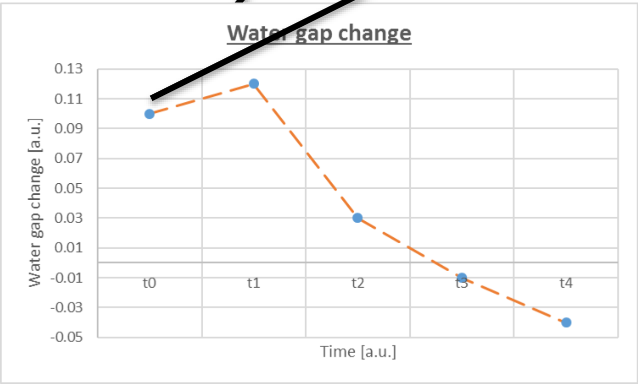
CASMO-5 generates **sufficiently accurate nuclear data** for 3D fuel assembly vibration simulation

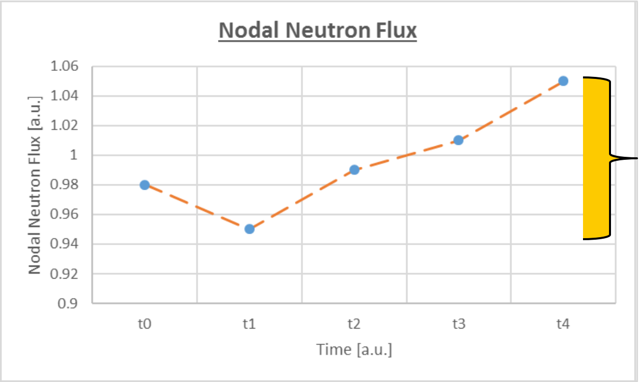
Fuel Vibration Modelling

SIMULATE-3K Nodal Level



- at t_0, FA_C moves towards FA_L
- water gap btw. FA_C and FA_L decreases by δ_0
- water gap btw. FA_C and FA_R **must** increase by δ_0
- water gap change ⇒ Cross-sections change
- neutron flux is modified based on the new set of XSs
- process is repeated for $t=t_1, t_2, \ldots, t_N$, based on user-defined water gap widths

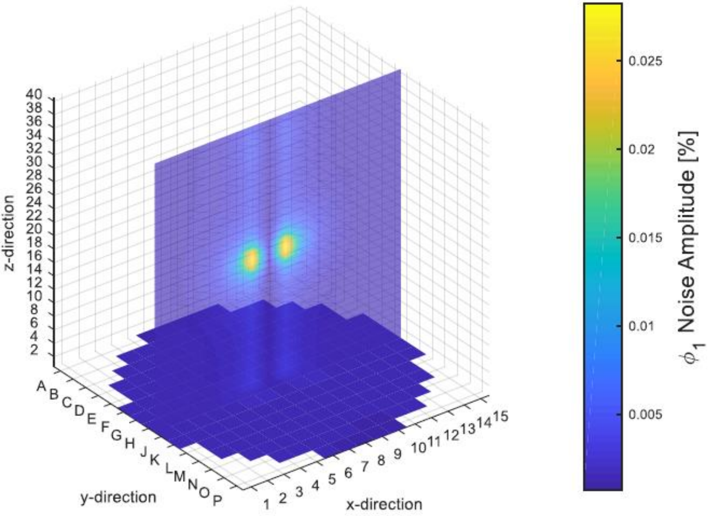


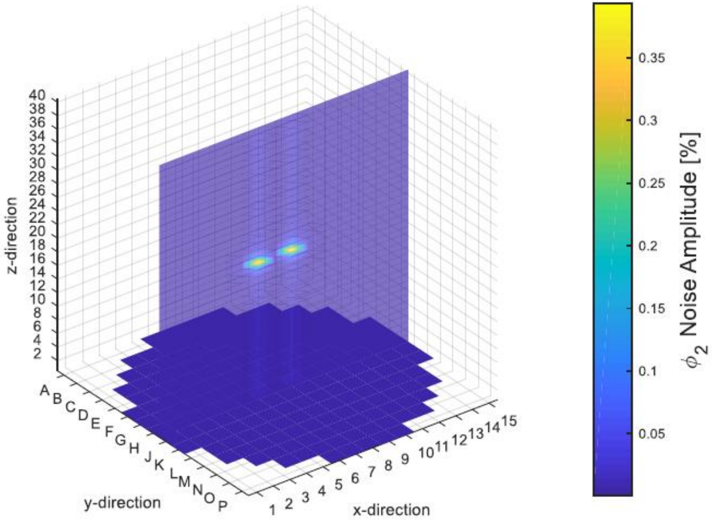


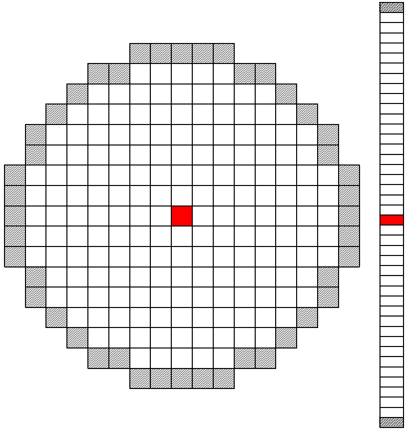
Neutron Noise

$$CV_G = 100 \cdot \frac{\sigma_{\phi_G^{i,j,z}}}{\bar{\phi}_G^{i,j,z}}$$

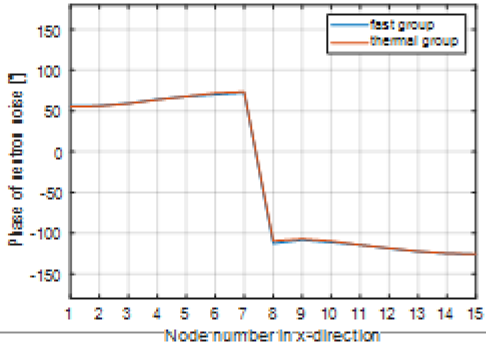
Fuel Assembly Vibration
SIMULATE-3K Nodal Level







- Zero noise level at vibrating node
- Maximum noise at neighboring nodes
- Fast noise more dispersed than thermal noise
- Thermal noise level higher than fast noise level
- Out-of-phase behavior between two core-halves

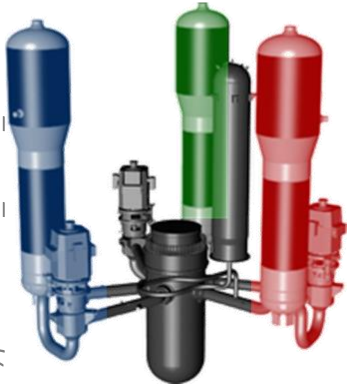


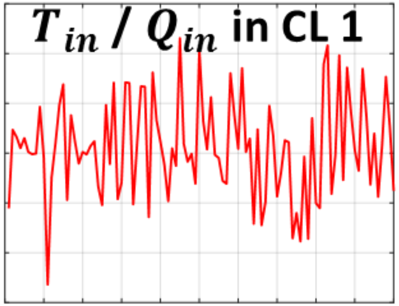
SIMULATE-3K can capture the **key features** of fuel assembly vibration

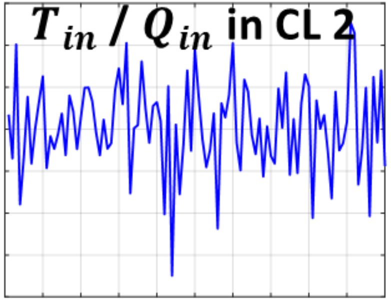
Inlet Coolant Properties Fluctuation

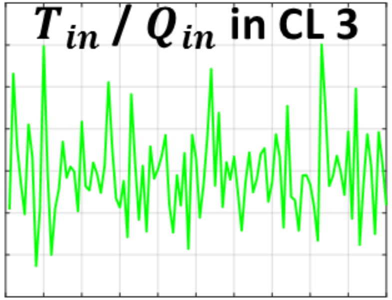
- The inlet coolant properties (temperature & flow) have a key role in neutron noise phenomenology.
- They have a continuous fluctuating behavior.
- SIMULATE-3K allows these noise sources modelling.
- It is assumed that perturbations taking place in a coolant loop (CL) affect inlet conditions at the closest core locations.

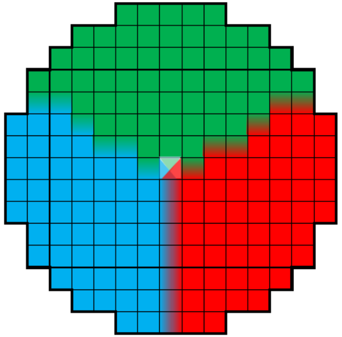
https://en.Wikipedia.org/wiki/pressurized_water_reactor







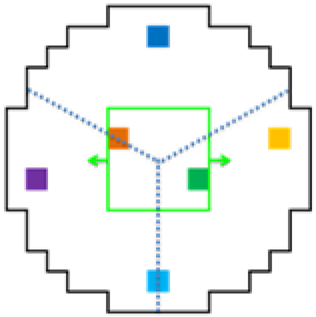




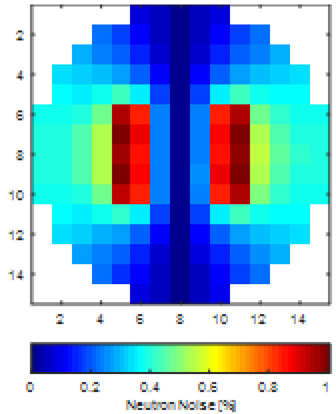
PSI NN Modelling

Key Simulated Observations 1/4

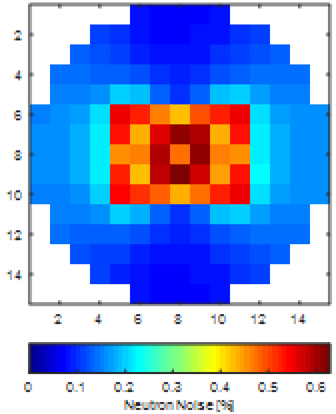
Central 5x5 cluster vibration

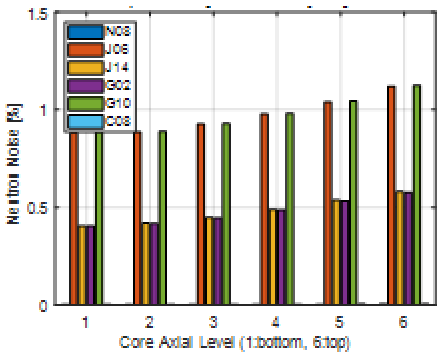


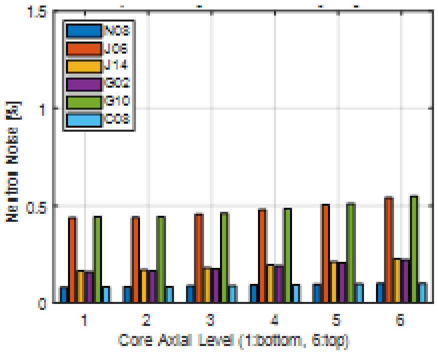
Synchronized vibration



Unsynchronized vibration







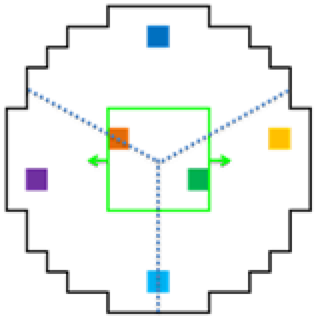
- Synchronized vibration results to two peaking noise areas
- Unsynchronized vibration explains high local noise areas

- Higher noise levels in synchronized vibration
- Tendency of higher noise levels at core-top

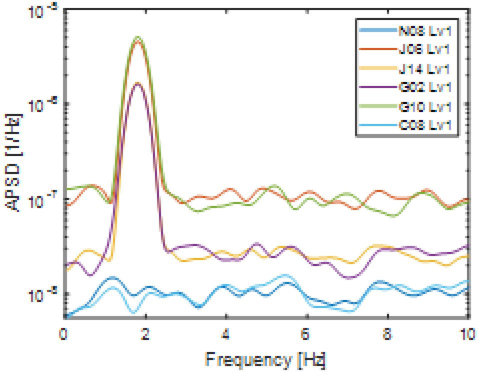
PSI NN Modelling

Key Simulated Observations 2/4

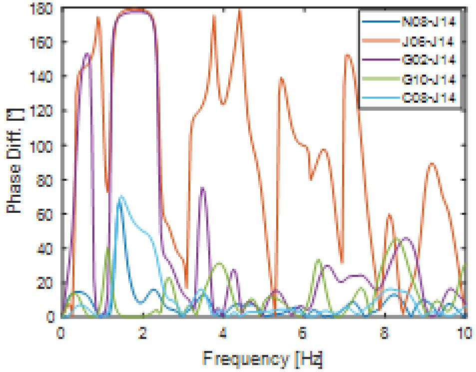
Central 5x5 cluster vibration



1.8 Hz vibration - APSD

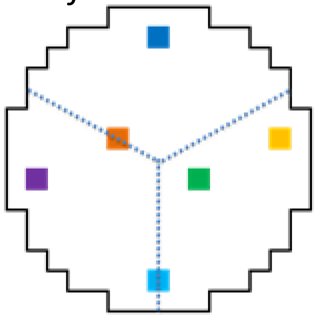


1.8 Hz vibration – Phase

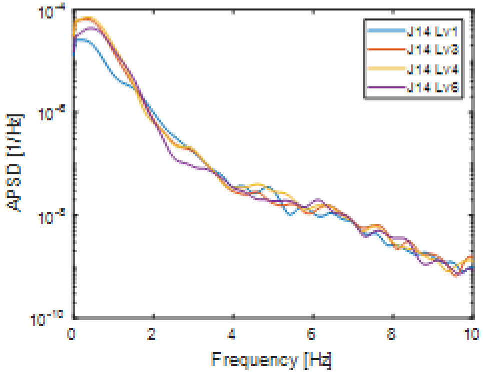


- Sine-wise fuel vibration results to colored spectrum
- Out-of-phase behavior between the two core-halves

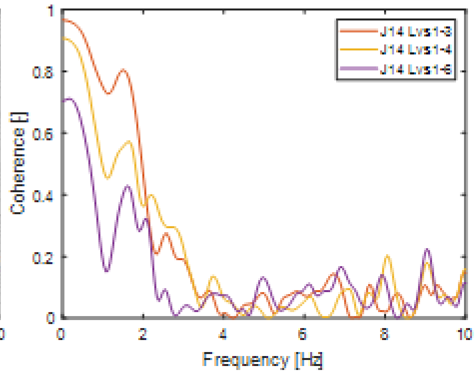
Inlet coolant temp. fluctuation



Noise Spectrum



Noise Coherence

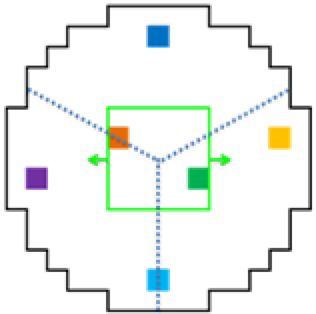


- White fluctuation results to colored spectrum
- Fluctuation transport time characterized by sink frequency of 1 Hz

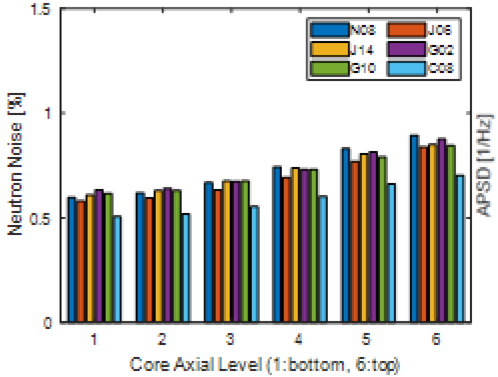
PSI NN Modelling

Key Simulated Observations 3/4

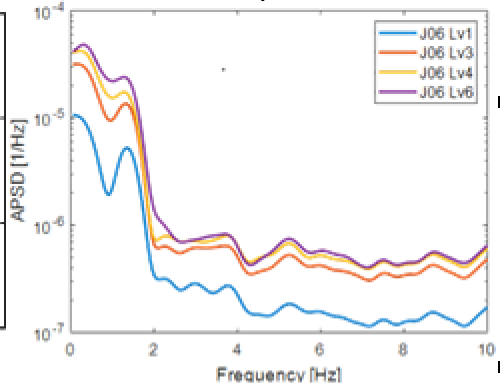
Central 5x5 cluster vibration
+
Inlet coolant temp. & flow fluctuations



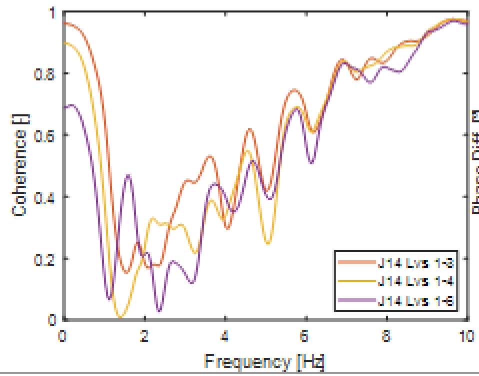
Noise Distribution



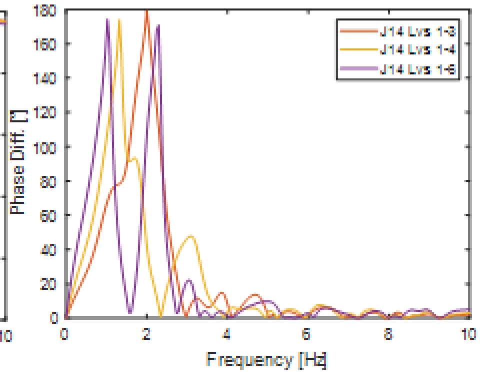
Noise Spectrum



Axial Coherence



Axial Phase Diff.

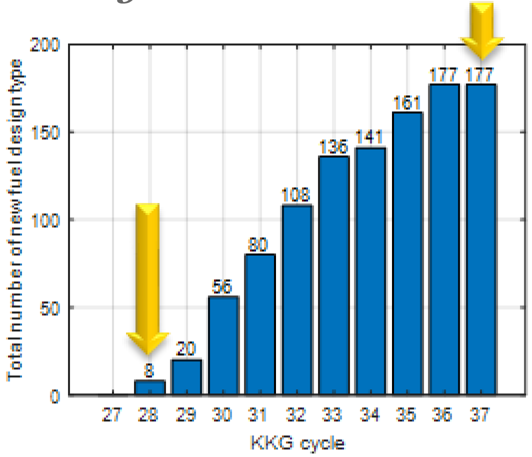


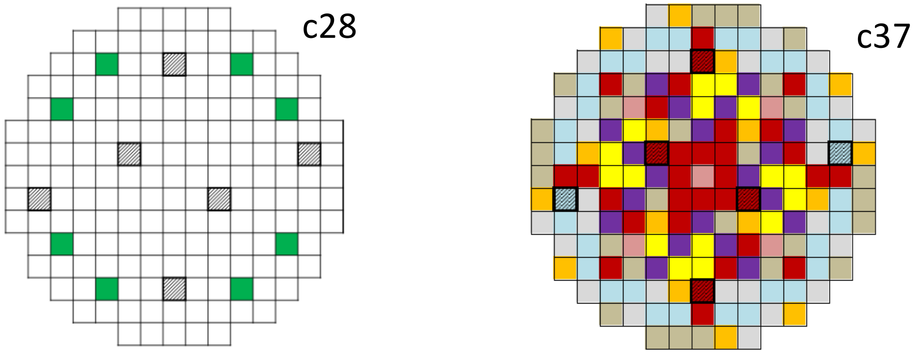
- Result of noise sources combination is driven by the source with the strongest effect
- Spectral phenomenology in low frequencies is driven by inlet coolant temp. fluctuations
- Above 2 Hz, fuel assembly vibration has leading role

PSI NN Modelling

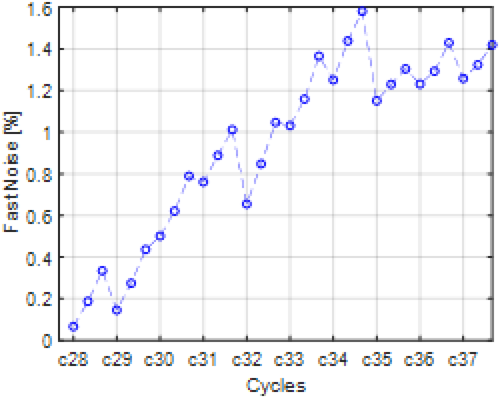
Key Simulated Observations 4/4

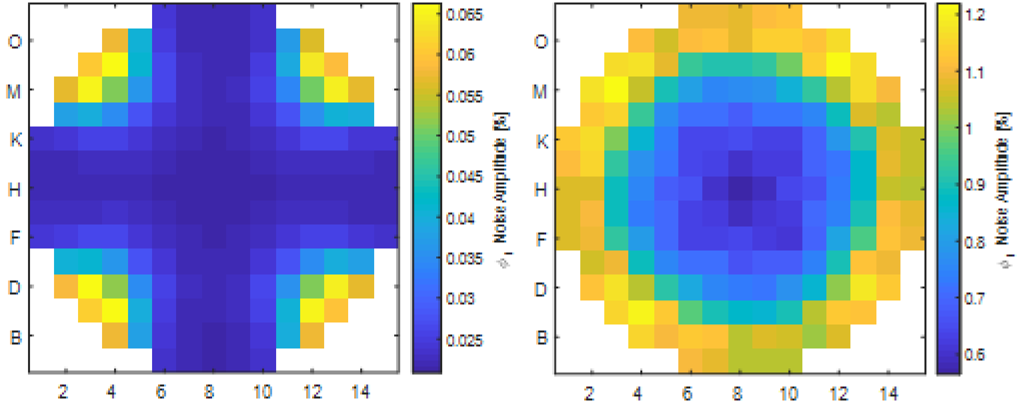
- Gradual loading of new fuel design in KKG, susceptible to lateral vibration, during the last decade.





- Spacers' stress relaxation is assumed to be reduced due to irradiation damage.





Content

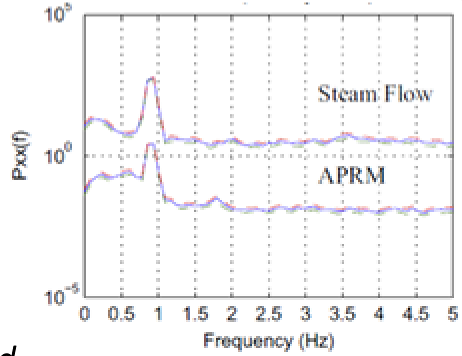
- **Signal analysis of KKG plant data**
  – *KKG description & plant signals' post-processing*
  – *KKG noise phenomenology*

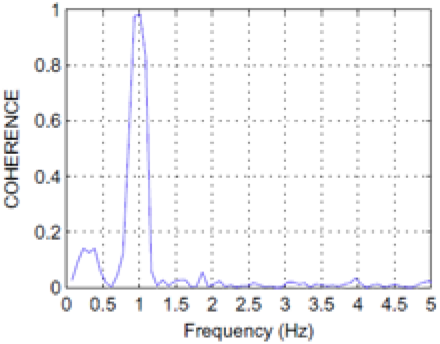
- **PSI neutron noise modelling methodology**
  – *Simulation procedure*
  – *Fuel assembly vibration modelling*
  – *Inlet coolant properties fluctuation modelling*
  – *Main simulated noise observations*
  – *Explanation of KKG measured noise phenomenology*

- **PSI connectivity analysis methodology**
  – *Causality concept & utilized method*
  – *Application on KKL plant data*

D. Chionis et al., "Application of causality analysis on nuclear reactor systems" CHAOS vol. 29, issue 4 (2019)

A need for advanced signal processing tools





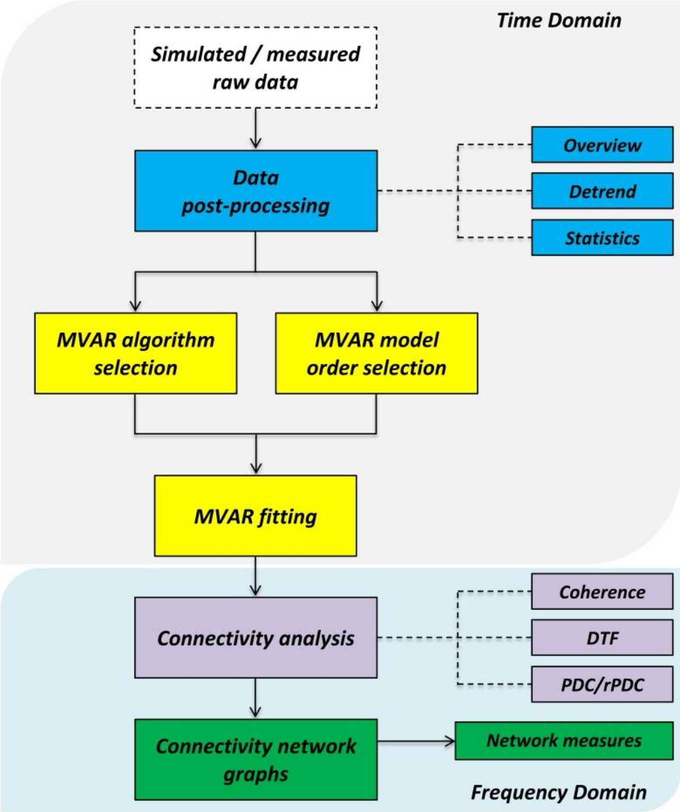
Demeshko M. et al., ANE vol. 75, pp. 645-657 (2015)

- **Coherence analysis**
  - *commonly utilized method*
  - *easy formulation*
  - *computationally inexpensive method*
  - ***but, can only estimate the correlation level of two signals***

In abnormal events, there is a need for identifying the root-cause.

- **Causality analysis**
  - *originates from the neuroscience field*
  - *treats the entire system at once*
  - *identifies cause-and-effect signals' relationships*
  - *identifies information flow paths*
  - ***indicates root-cause of a perturbation***

PSI Connectivity Analysis Methodology



- Simultaneously recorded signals:

$$\boldsymbol{y}(t) = [y_1(t), y_2(t), \dots, y_m(t)]^T$$

- Fitted in a Multivariate Autoregressive Model:

$$\boldsymbol{y}(t) = \sum_{k=1}^{p} \boldsymbol{\alpha}(k)\boldsymbol{y}(t-k) + \boldsymbol{\varepsilon}(\mathrm{t})$$

- Renormalized Partial Directed Coherence

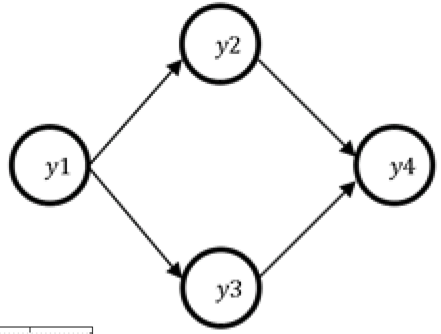
$$rPDC_{ij}(f) = \boldsymbol{Z}_{ij}(f)' \cdot \boldsymbol{V}_{ij}^{-1}(f) \cdot \boldsymbol{Z}_{ij}(f)$$

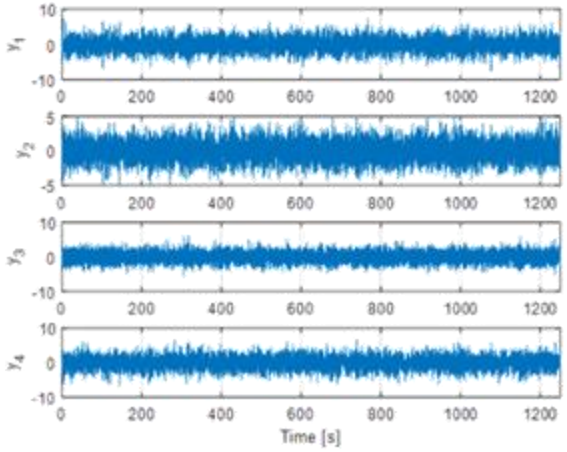
- Directed Transfer Function

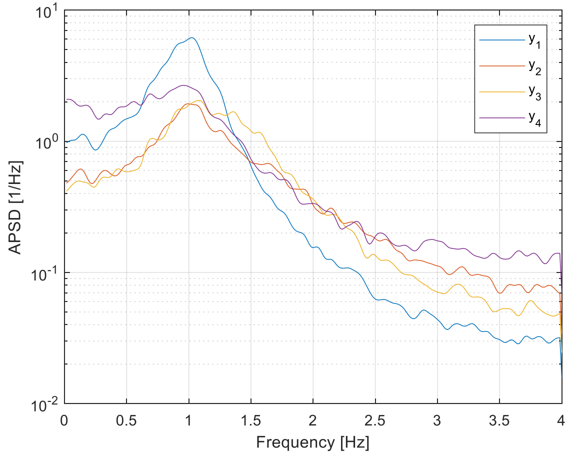
$$DTF_{ij}(f) = \frac{|\boldsymbol{H}_{ij}(f)|}{\sqrt{\sum_{q=1}^{m} |\boldsymbol{H}_{qj}(f)|^2}}$$

PSI Connectivity Analysis
Simplified Example

$$y_1(t) = 1.2y_1(t-1) - 0.7y_1(t-2) + \varepsilon_1(t)$$
$$y_2(t) = 0.5y_2(t-1) - 0.3y_2(t-2) - 0.3y_1(t-1) + \varepsilon_2(t)$$
$$y_3(t) = 0.7y_3(t-1) - 0.5y_3(t-2) - 0.2y_1(t-1) + \varepsilon_3(t)$$
$$y_4(t) = 0.5y_4(t-1) + 0.5y_2(t-1) + 0.4y_3(t-1) + \varepsilon_4(t)$$







PSI Connectivity Analysis
Simplified Example

$$y_1(t) = 1.2y_1(t-1) - 0.7y_1(t-2) + \varepsilon_1(t)$$
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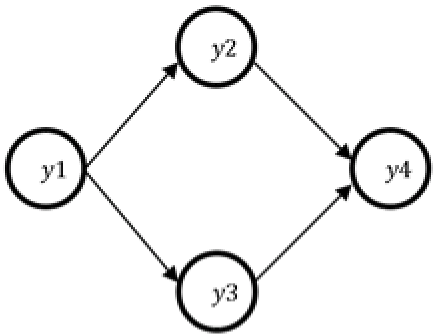
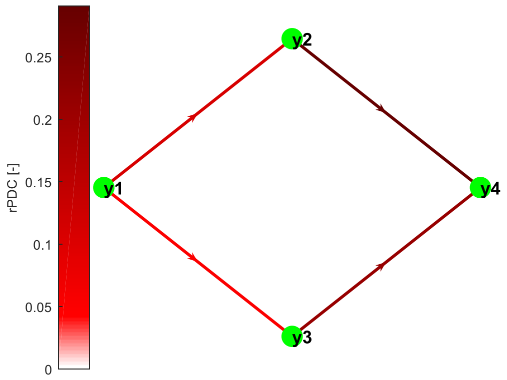
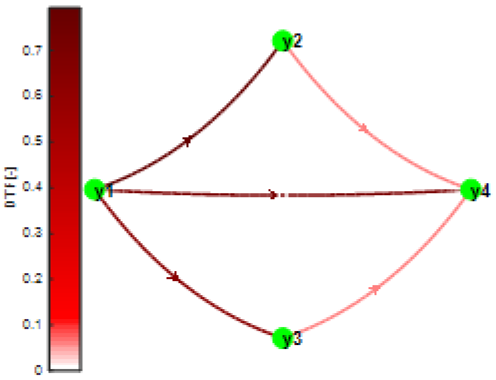
$$y_3(t) = 0.7y_3(t-1) - 0.5y_3(t-2) - 0.2y_1(t-1) + \varepsilon_3(t)$$
$$y_4(t) = 0.5y_4(t-1) + 0.5y_2(t-1) + 0.4y_3(t-1) + \varepsilon_4(t)$$



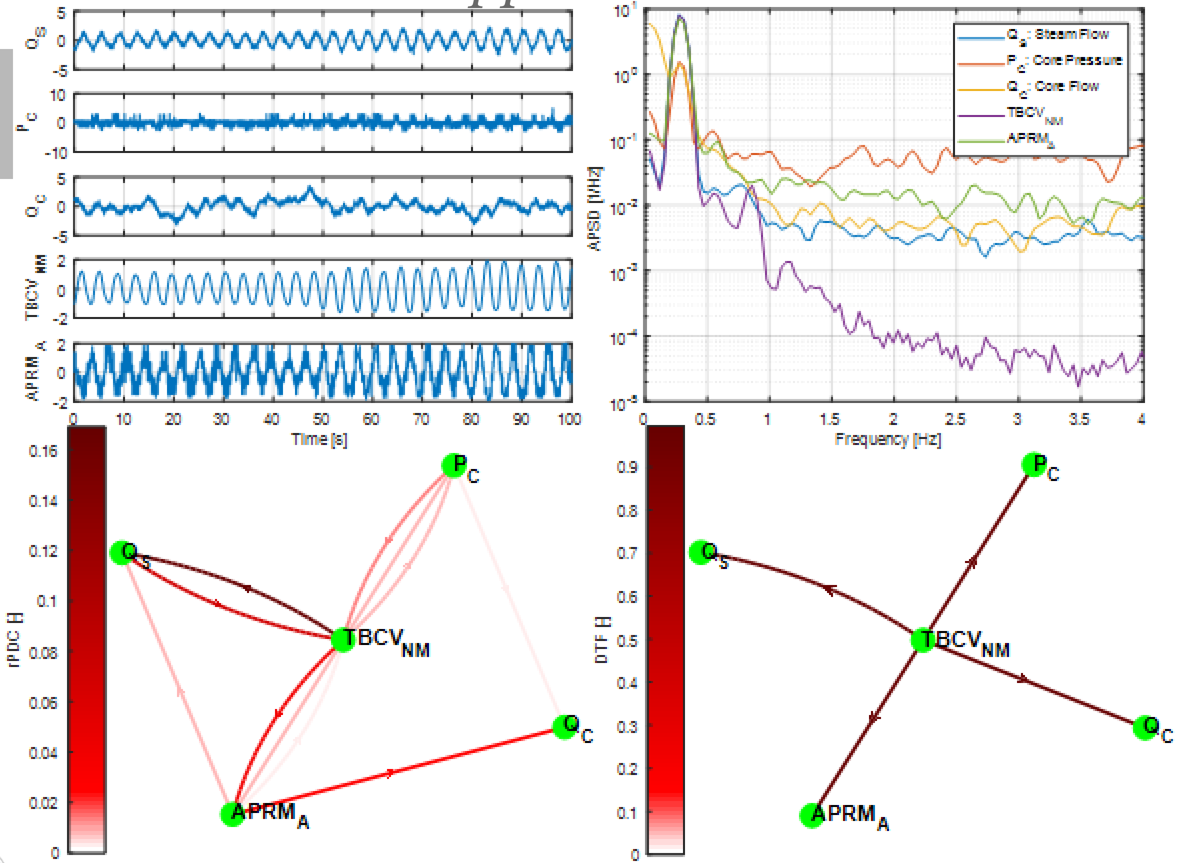




- rPDC *estimates* ***direct interactions***
- DTF *estimates* ***signals reachability property***

PSI Connectivity Analysis

KKL application



- KKL cycle 33 start-up
- Unexpected high decay-ratios at low power / low flow
- Strong spectral content at 0.27 Hz

- Central role of turbine bypass valves (TBCVs)
- Core pressure is adjusted based on the TBCVs opening position
- System response is respectively affected

Thesis Conclusions - *1/2*

- KKG neutron noise characteristics have been identified using the PSI signal processing methodology.

- The KKG neutron noise phenomenology has been reproduced using a newly developed modelling methodology.

- A comparison between KKG measured and simulated results indicate:
  - *The noise strong spectrum at low frequencies corresponds to inlet coolant fluctuations.*
  - *The spectral peak at 1.8-2 Hz is related to fuel assembly vibrations, which explain the out-of-phase relationship between the two core-halves.*
  - *The neutron noise increase trend can be explained by the new fuel design introduced in KKG, susceptible in lateral vibration.*
  - *Few noise characteristics could not be fully explained; research continuation is needed.*

Thesis Conclusions - *2/2*

- The PSI neutron noise modelling methodology has been systematically studied and qualified for modelling the relevant phenomena.

- A platform for generating neutron noise simulated data has been developed in the framework of CORTEX project.

- An in-house connectivity analysis methodology has been developed and successfully applied on both simulated and measured datasets. The newly developed methodology serves as a supportive diagnostic tool.

Future Work Recommendations

- Improvement of plant data acquisition systems
  (e.g. measurement periodicity, sampling frequency, signals variety, etc.).
- Further invest on advanced signal processing techniques by implementing deep-learning methods in the PSI methods.
- Verification SIMULATE-3K fuel vibration model against point-kinetic analytical expression and CORE-SIM reference results.
- Benchmark SIMULATE-3K neutron noise modelling against DYN-3D, PARCS, etc.
- Model the core barrel pendular movement with SIMULATE-3K.
- Extend the fuel vibration model to BWR applications.

PAUL SCHERRER INSTITUT PSI

Wir schaffen Wissen – heute für morgen

Thank you for your attention!

I would be happy to answer your questions