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PSI

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Reactor Physics and Thermal-Hydraulics

EPFL

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

PhD Public Defense, Zoom Video-Conference, September 16th 2020

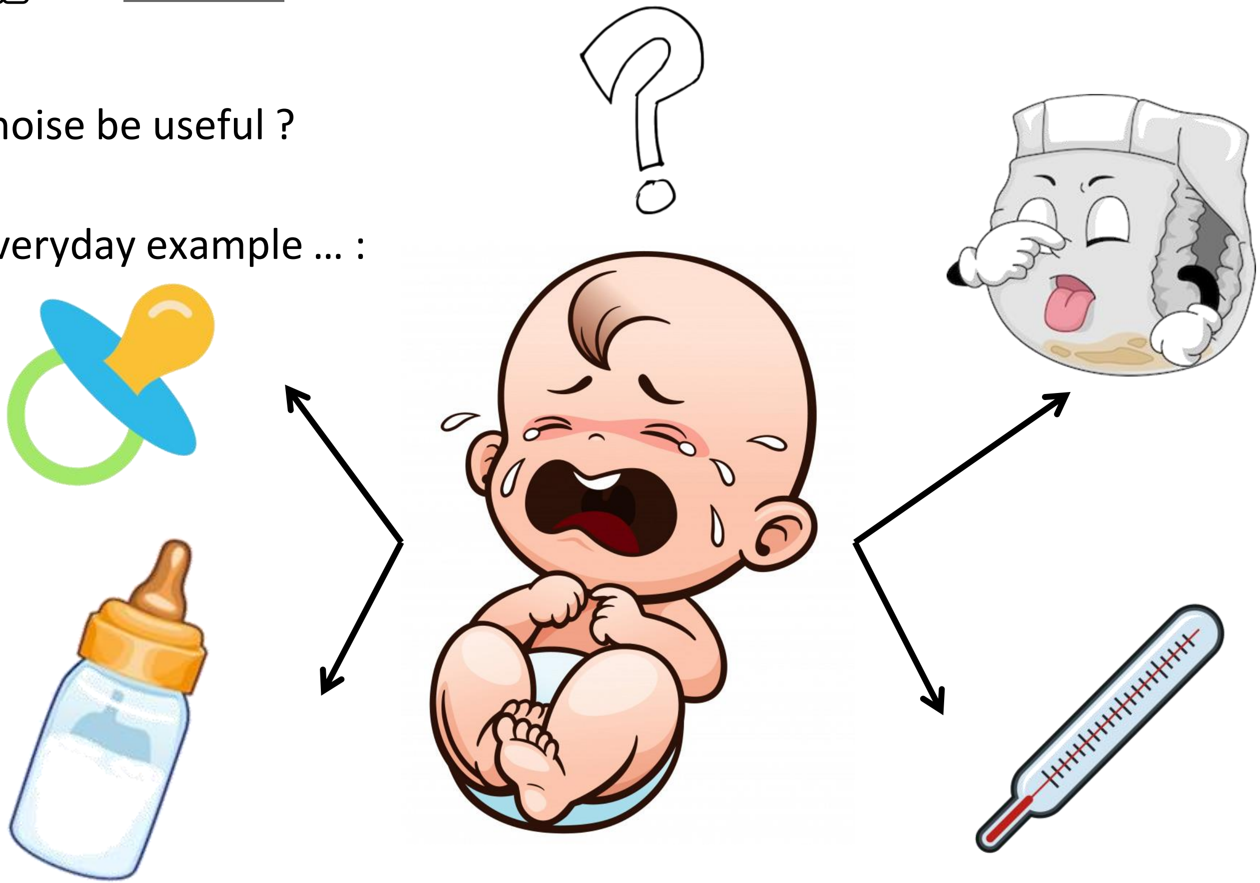
- Noise is everywhere
- It disturbs us
- It deteriorates the useful information of a signal

Does noise always have a negative nature?

Can noise be useful ?

…

An everyday example … :



➢ Extract useful information from noise:

Experience
Perception
Etc.

By analyzing noise coming from a nuclear reactor we can assess the reactor behavior

Noise in Nuclear Reactors

- Extract useful information from noise:

→

\+ Experience
Perception
Etc.

→

By analyzing noise coming from a nuclear reactor we can assess the reactor behavior

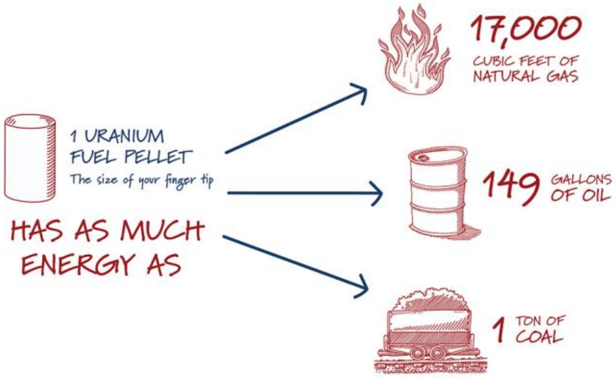
Noise in Nuclear Reactors

➢ **Nuclear reactor:** 24/7 reliable production of CO2-free energy

Nuclear fuel pellet

made of uranium

- *2 cm diameter*
- *1 cm height*
- *10 g weight*



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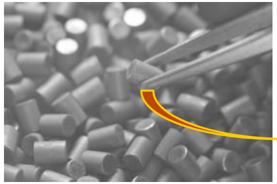
Noise in Nuclear Reactors

➢**Nuclear reactor:** 24/7 reliable production of CO2-free energy



Nuclear fuel pellet

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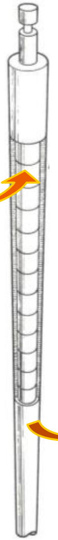
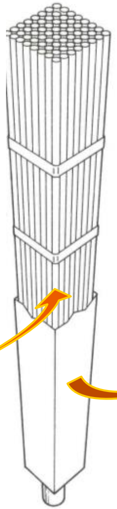


Nuclear fuel rod

containing *300 fuel pellets*

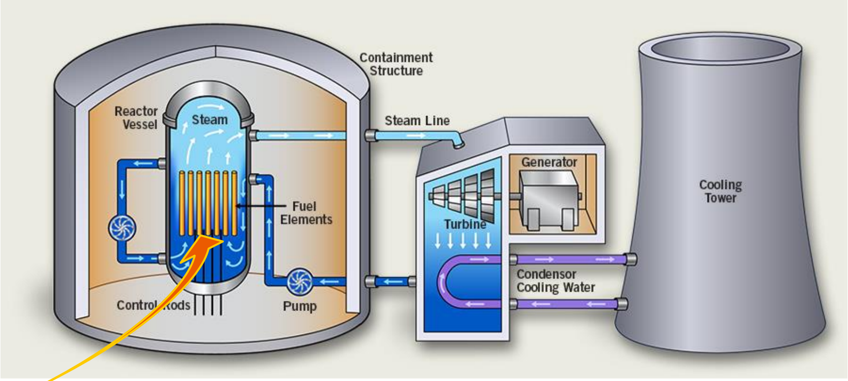
- *~3 m height*
- *~4 kg weight*



Nuclear fuel assembly

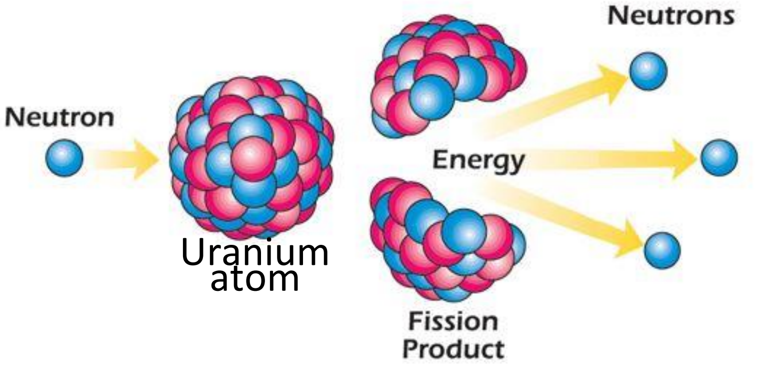
containing *100-300 fuel rods*

- *20 cm across*
- *~4 m height*
- *~600 kg weight*



- Neutrons interact with uranium atoms (nuclear fuel)
- Fission of uranium generates energy/heat
- Heat warms water
- Water turns into steam
- Steam turns a turbine
- Turbine turns a generator
- Electricity is produced

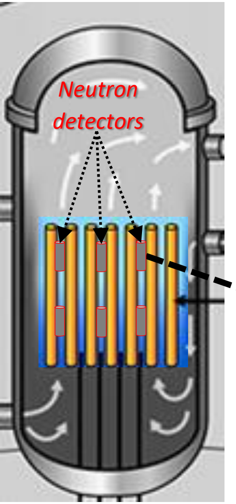
Noise in Nuclear Reactors



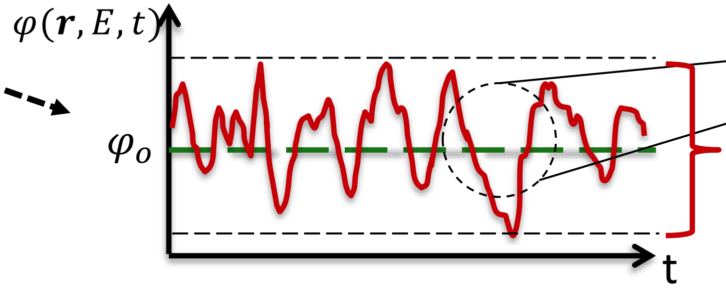
- Energy from fission -> Power of a nuclear reactor
- By controlling the number of available neutrons, the released energy from fission can be controlled

  -> control the reactor power
- The number of available neutrons (per unit volume & time) depends on many parameters:
  - Temperature of nuclear fuel
  - Temperature of water (coolant)
  - Surrounding environment/materials
  - Etc.

Noise in Nuclear Reactors



φ: **neutron flux** *(number of neutrons per unit volume & time)*
has a **fluctuating behavior**



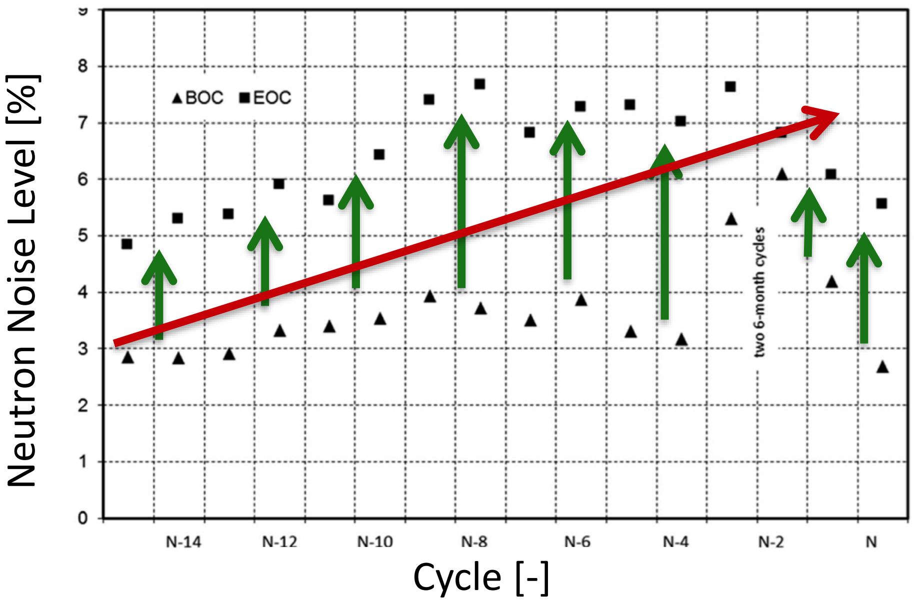
Neutron flux
fluctuations
⇓
Neutron noise

- reactor behavior
- reactor dynamics
- malfunctions‘ detection

$$\frac{1}{v(E)}\frac{\partial}{\partial t}\varphi(\boldsymbol{r},E,t) - \nabla \cdot D(\boldsymbol{r},E,t)\nabla\varphi(\boldsymbol{r},E,t) + \Sigma_t(\boldsymbol{r},E,t)\varphi(\boldsymbol{r},E,t) =$$
$$\int_0^\infty \Sigma_s(\boldsymbol{r},E' \to E,t)\varphi(\boldsymbol{r},E',t)dE'$$
$$+\frac{\chi^p(E)}{4\pi}\int_0^\infty \nu(\boldsymbol{r},E')\Sigma_f(\boldsymbol{r},E',t)\varphi(\boldsymbol{r},E',t)dE' + \sum_{i=1}^{N^d}\frac{\chi^{d,i}(E)}{4\pi}\lambda_i C_i(\boldsymbol{r},t) + Q(\boldsymbol{r},E,t)$$

neutrons gaining rate
=
neutrons loosing rate

PhD Thesis **Motivation**



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

*Cycle: Operational period of 11 months
BOC: Beginning of cycle
EOC: End of cycle

Noise increase trend:

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

Noise characteristics:

✓ *within-the-cycle increase*

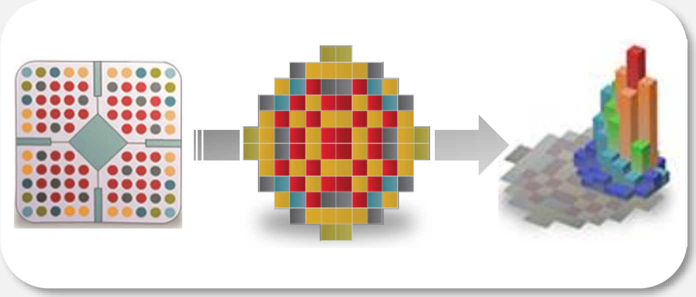
✗ *cycle-to-cycle increase*

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

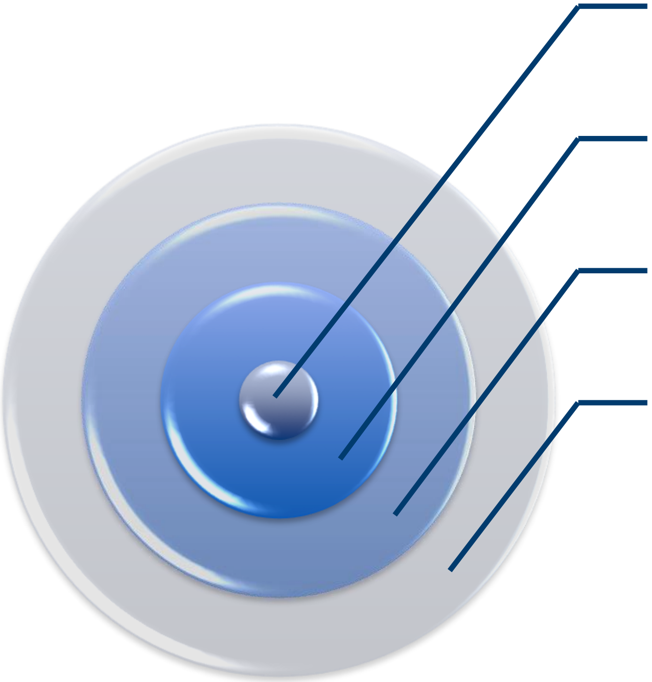


Developing numerical models &
core simulation methods
to reproduce plant measurements

***Explaining** the neutron noise phenomenology in operating reactors*

Thesis Accomplishments

Noise in Nuclear Reactors



- Identification of **noise characteristics** for the Gösgen nuclear power plant **(KKG)**
- In-house **neutron noise modelling** capabilities development
- Reproduction of **KKG noise signatures**
- In-house **connectivity analysis toolbox**; supportive diagnostics tool

Content

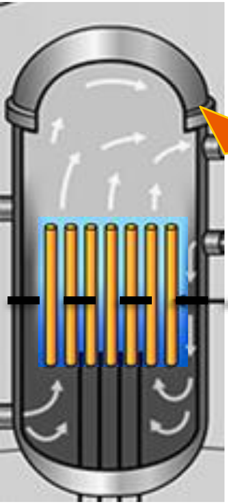
- **Signal analysis of plant data from the Gösgen nuclear power plant (KKG)**

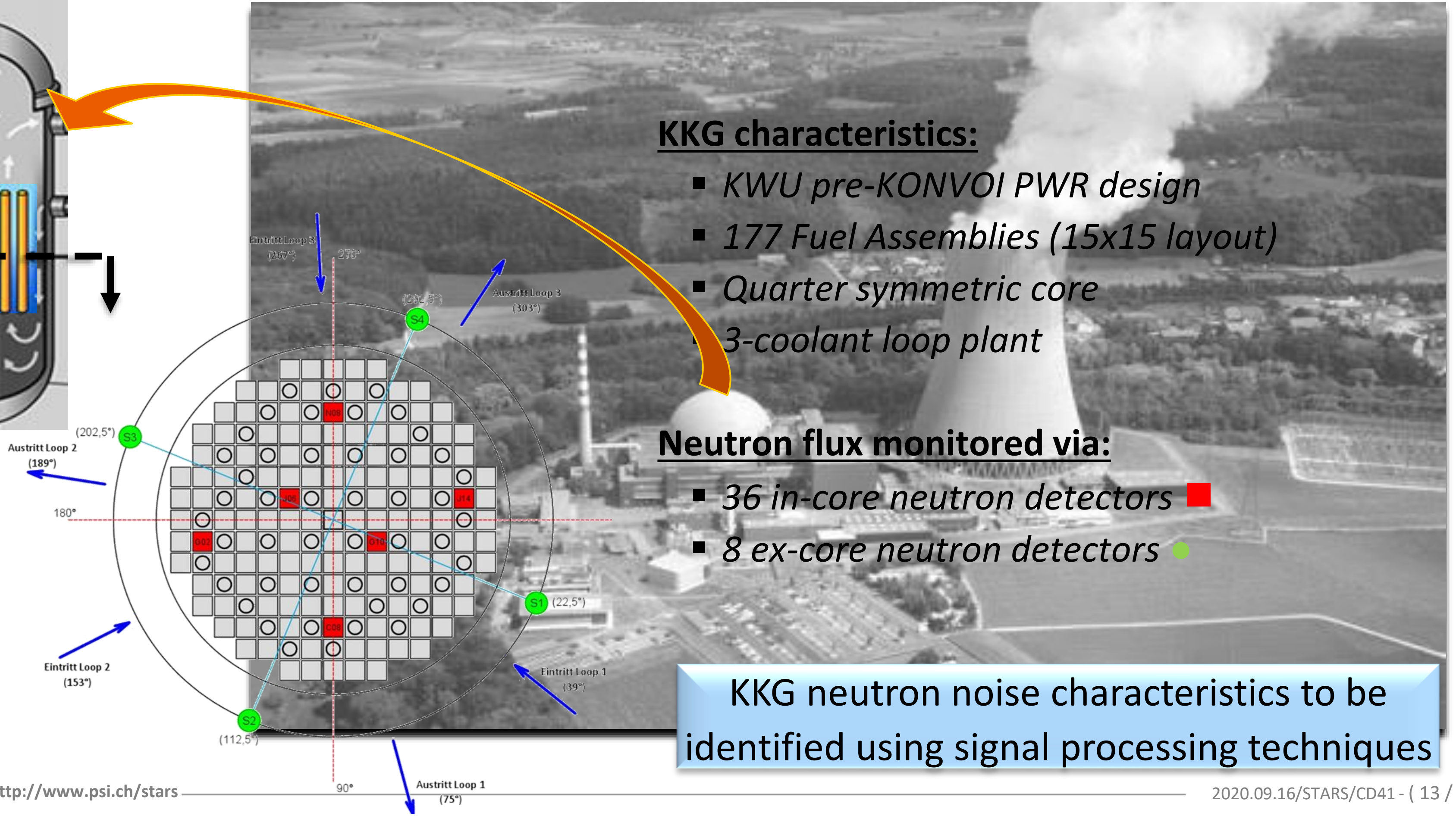
D. Chionis et al., "PWR neutron noise phenomenology: Part II – Qualitative comparison against plant data", Physor '18 (2018)

- **PSI neutron noise modelling methodology**

- **PSI connectivity analysis methodology**

Nuclear Power Plant Gösgen (KKG)





KKG characteristics:

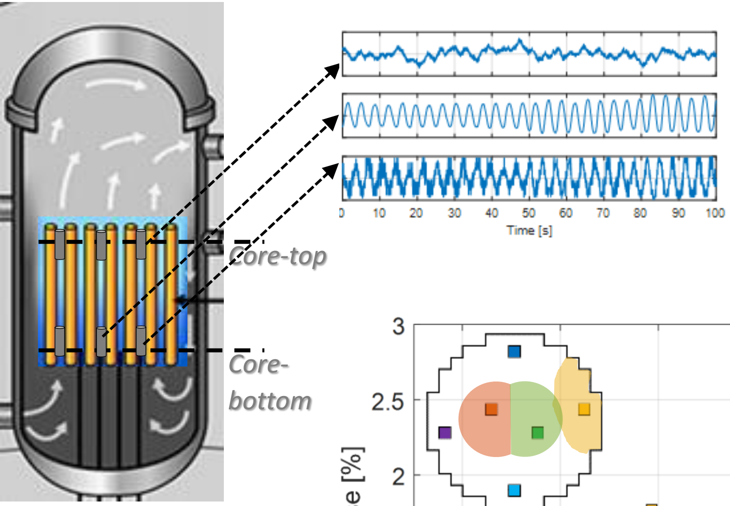
- *KWU pre-KONVOI PWR design*
- *177 Fuel Assemblies (15x15 layout)*
- *Quarter symmetric core*
- *3-coolant loop plant*

Neutron flux monitored via:

- *36 in-core neutron detectors*
- *8 ex-core neutron detectors*

KKG neutron noise characteristics to be identified using signal processing techniques

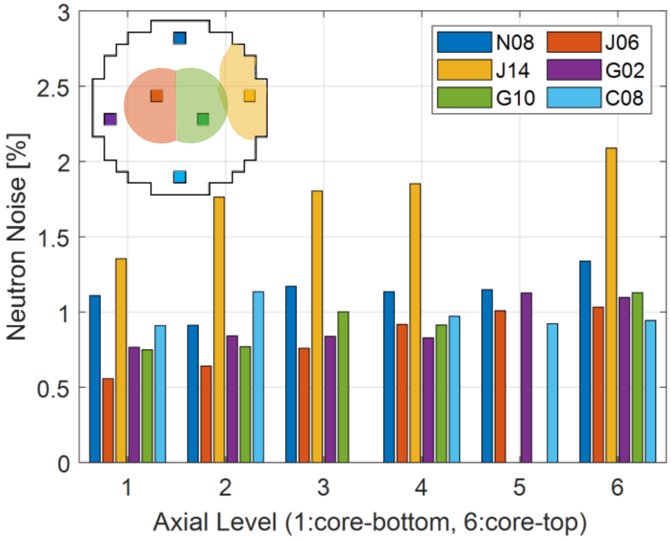
Noise Analysis for KKG *[time domain]*



Neutron Noise

$$CV_i = 100 \cdot \frac{\sigma_i}{\bar{\phi}_i}$$

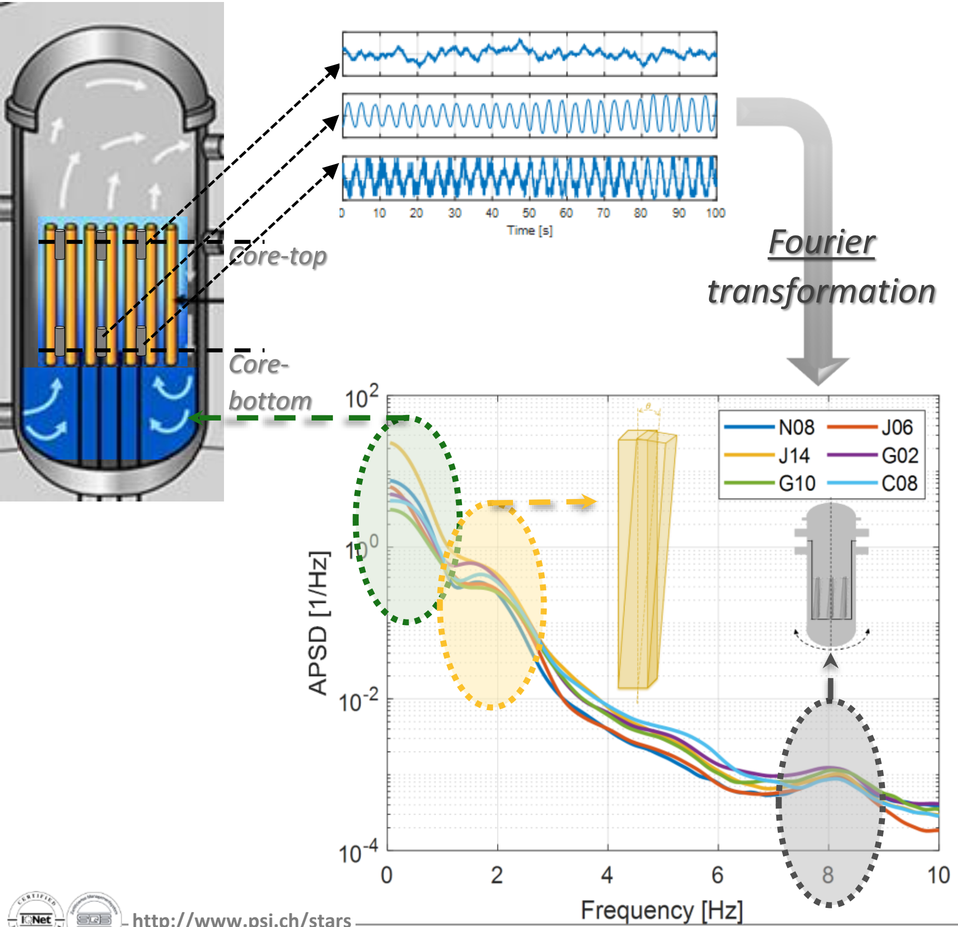
*i: neutron detector



- **core-east** side exhibits **highest noise level**
  ⇒ *unique KKG characteristic*
- **central region** exhibits **lowest noise levels**
- Slight shift of higher noise towards core-bottom as the End of Cycle approaches

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

Noise Analysis for KKG *[freq. domain]*



- *Stronger spectrum at **<1.5Hz***
  ⇒ <u>coolant properties fluctuations</u>
- *Spectral peak at **1.5-2.0Hz***
  ⇒ <u>fuel assemblies vibration</u>
  with an indication of a noise source at the core center
- *Spectral peak at **8.0Hz***
  ⇒ global character of the <u>core barrel pendular movement</u>

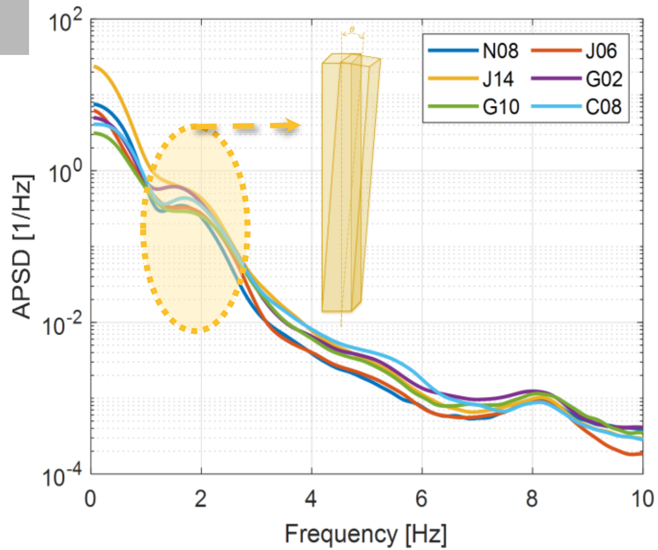
Content

- Signal analysis of plant data from the Gösgen nuclear power plant (KKG)

- **PSI neutron noise modelling methodology**

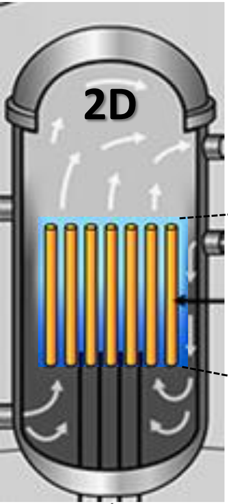
D. Chionis et al., "Development and verification of a methodology for neutron noise response to fuel assembly vibrations", submitted to ANE (2020)
D. Chionis et al., "SIMULATE-3K analyses of neutron noise response to fuel assembly vibrations and thermal-hydraulics parameters fluctuations", M&C'17 (2017)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

Noise Modelling Methodology

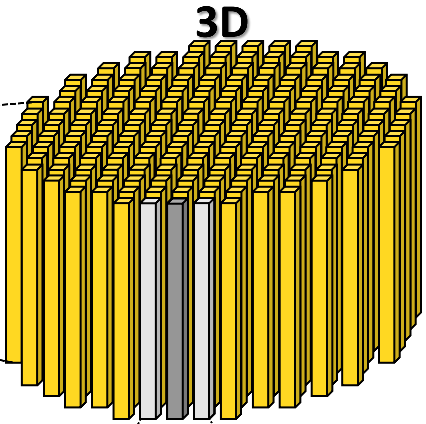


- **Fuel assembly vibration** ⟹ key noise source
  ⟹ key contributor to noise increase
- Use of state-of-the-art simulation codes **CASMO-5/SIMULATE-3/SIMULATE-3K**
- In-house process development for **automatizing**, **extending** and **improving** the fuel assembly vibration modelling
- Systematic investigation
- Reproduction of KKG noise sources

Noise Modelling Methodology

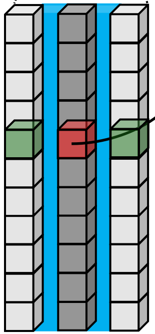


reality



computational modelling using the state-of-the-art codes CASMO-5/SIMULATE-3/SIMULATE-3K

In-house **MATLAB scripts** development allowing all types of fuel vibration



Solution of
time-dependent **neutron diffuse**
in every core **node**

Modelling approximation

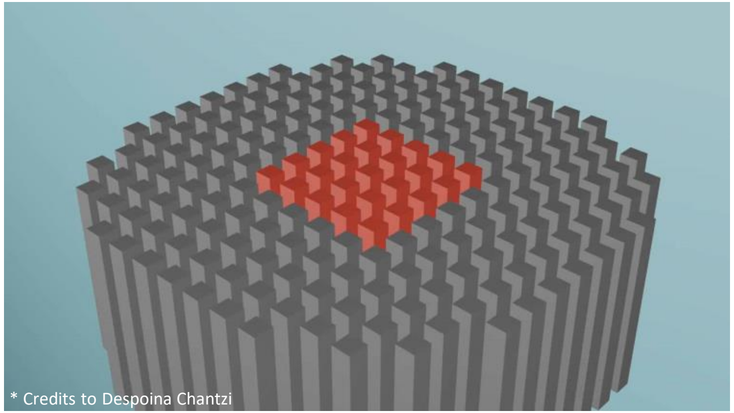
fuel node vibration

$\Longrightarrow$

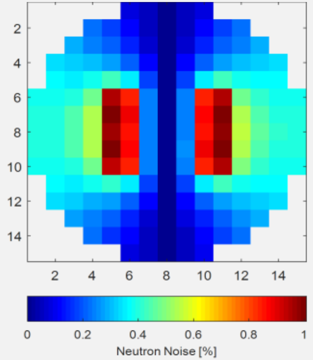
time-dependent modification of **water gaps** between a **node** & its **neighbors**

PSI Noise Modelling Methodology Application

central cluster vibration & coolant properties fluctuation

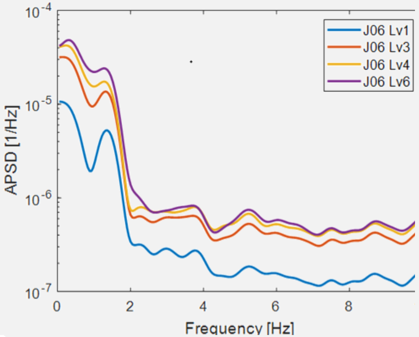


Time domain analysis of simulated nodal responses



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

Frequency domain analysis of simulated detectors responses

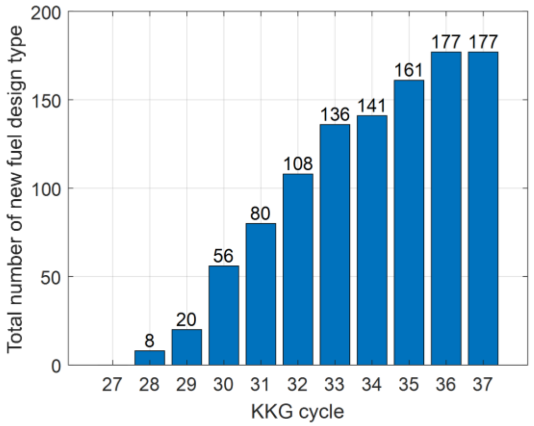


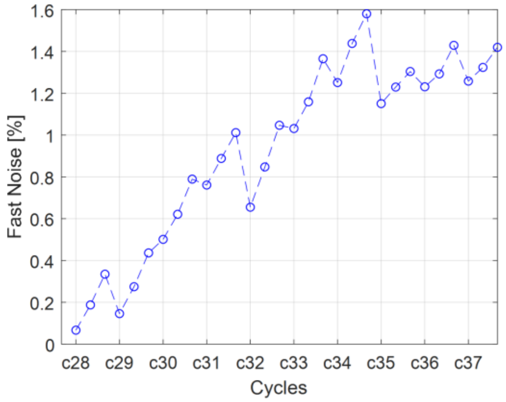
- Spectral phenomenology in low frequencies is driven by inlet coolant temp. fluctuations
- Above 2 Hz, fuel assembly vibration has leading role

PSI Noise Modelling Methodology Application

- 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





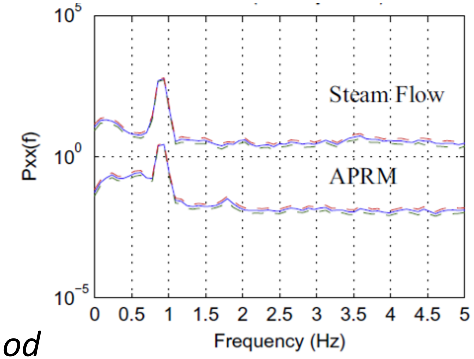
The simulation methodology can successfully capture the studied phenomena

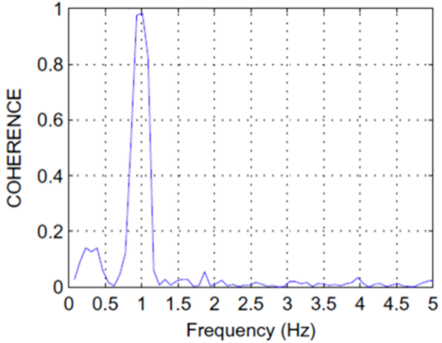
Content

- Signal analysis of plant data from the Gösgen nuclear power plant (KKG)
- PSI neutron noise modelling methodology
- **PSI connectivity analysis methodology**

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



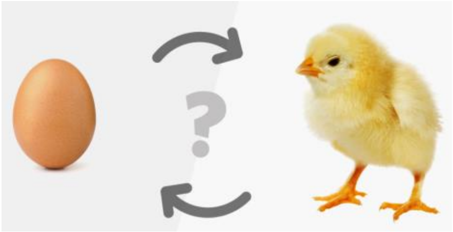


Demeshko M. et al., ANE vol. 75, pp. 645-657 (2015)

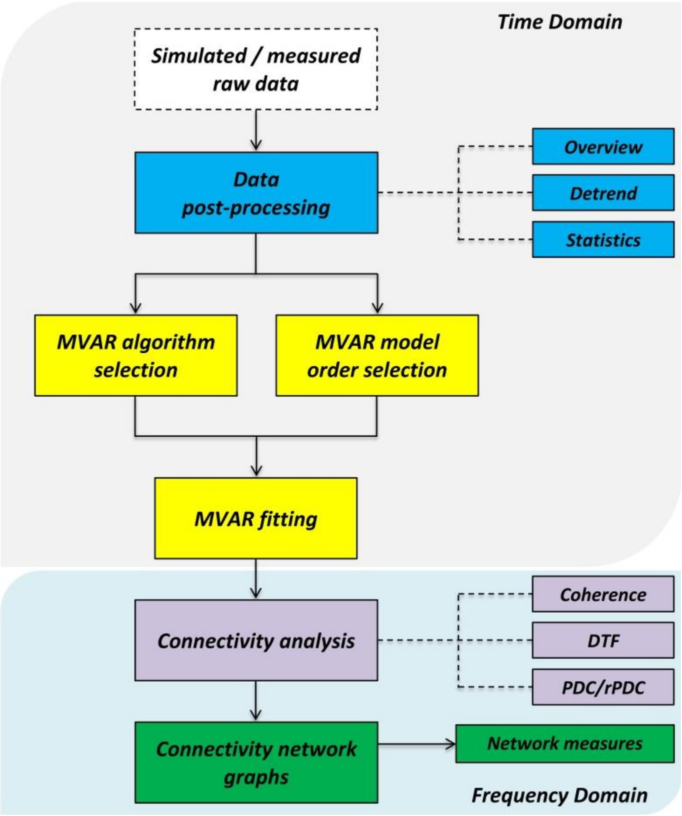
- **Coherence analysis**
  - *commonly utilized method*
  - *easy formulation*
  - *computationally inexpensive method*
  - ***but, can only estimate the correlation level of two signals***

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

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

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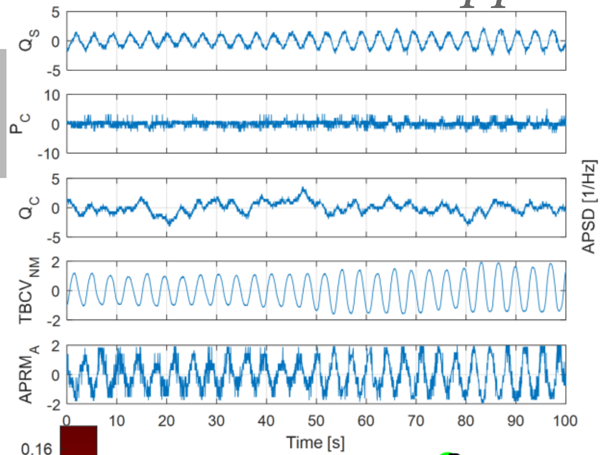
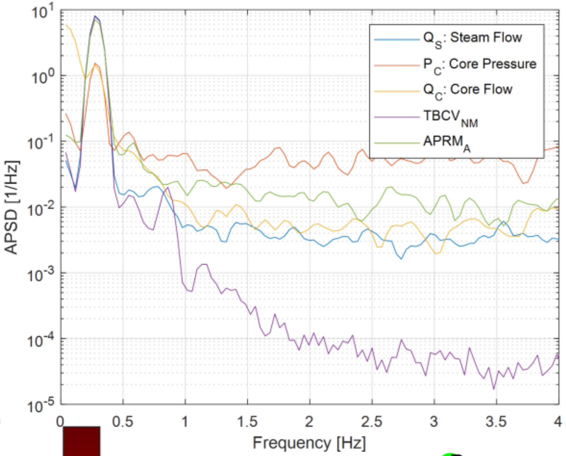
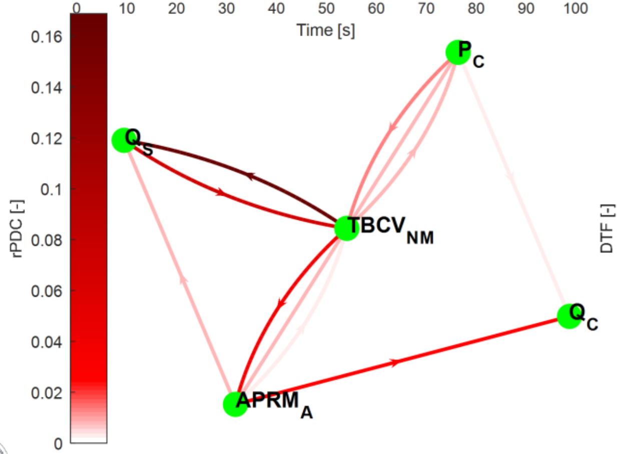
PSI Connectivity Analysis

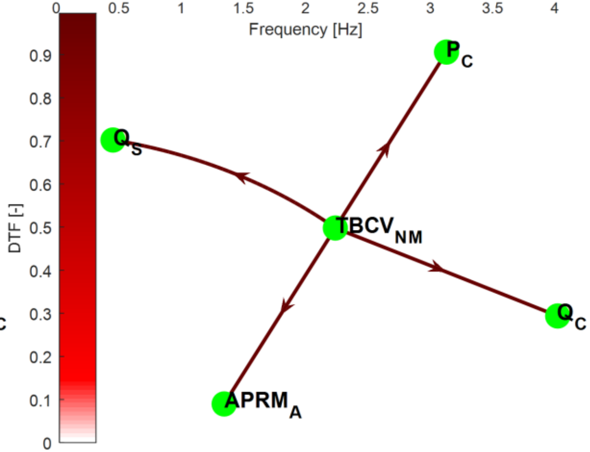
KKL application





- KKL cycle 33 start-up
- Unexpected high decay-ratios at low power / low flow
- Strong spectral content at ~0.3 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

- 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:
  - *Explained a series of measured noise observations*
  - *Few noise characteristics could not be fully identified; research continuation is needed.*

- 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 & benchmark of developed noise simulation tools against reference results.
- Extend the noise modelling to BWR applications.

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Future Work Recommendations

Infoscience

EPFL scientific publications

1 of 3 › » Back to search

Development of Advanced Methodologies for Monitoring and Modelling of Neutron Noise in Modern LWR Cores

Chionis, Dionysios ; Pautz, Andreas ; Dokhane, Abdelhamid

Nuclear reactors are inherently stochastic systems, in which neutronic and thermal-hydraulic parameters fluctuate continuously even during steady-state conditions. In addition, structural components vibrate due to the coolant hydraulic forces. This stochasticity is the cause of the neutron population fluctuating behavior, a phenomenon referred as neutron noise. The neutron noise is monitored over the reactor lifetime, providing valuable knowledge of the core behavior.

Thesis available online (open-access) via ***https://infoscience.epfl.ch*** *from 17.09.2020*

My thanks go to

- H. Dokhane, H. Ferroukhi, A. Pautz (PSI)

<u>*for their close and continuous supervision*</u>

- *Prof. Demazière, Prof. Montalvo, Prof. Prasser, Dr. Cherkaoui*

<u>*For joining the jury committee and their valuable comments*</u>

- *swissnuclear*

<u>*for funding this project*</u>

swissnuclear
Fachgruppe Kernenergie der swisselectric

- L. Belblidia, G. Grandi

<u>*for their technical help and guidance*</u>

Studsvik

- G. Girardin, L. Meyer, R. Meyer, F. Jatuff

<u>*for their support and for providing plant data*</u>

Kernkraftwerk Gösgen

Thank you for your attention!

I would be happy to answer your questions