"Listening" to neutron noise – or how to diagnose nuclear reactor systems using the inherent fluctuations in neutron density

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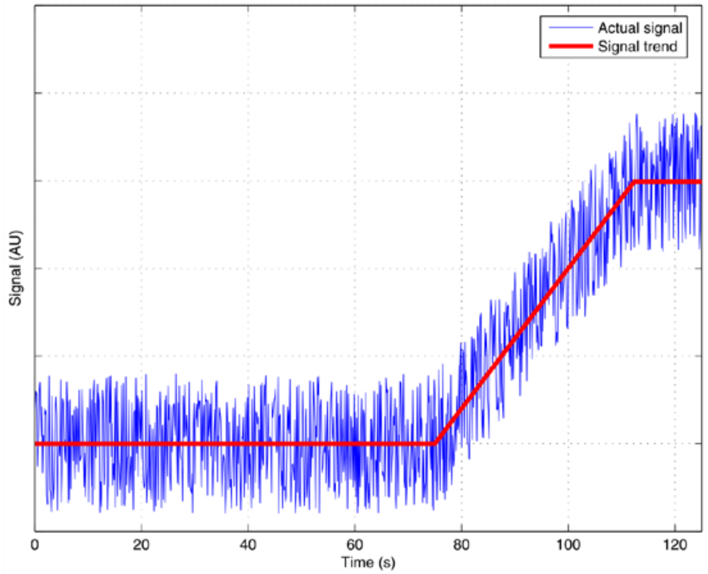
DREAM

Task Force on Deterministic REActor Modelling
at Chalmers University of Technology

Introduction

- Fluctuations always existing in dynamical systems even at steady state-conditions:

$X(\mathbf{r},t)$



Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

$$X(\mathbf{r},t) = X_0(\mathbf{r},t) + \delta X(\mathbf{r},t)$$

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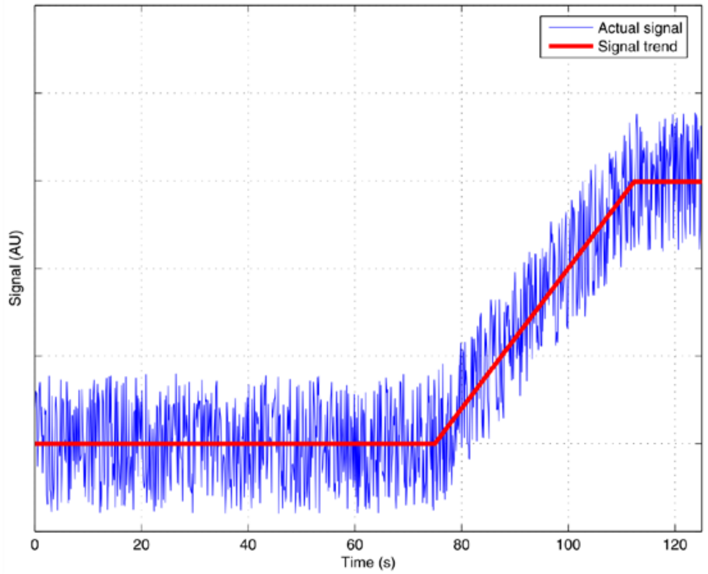

Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

$$X(\mathbf{r},t) = X_0(\mathbf{r},t) + \delta X(\mathbf{r},t)$$

actual signal

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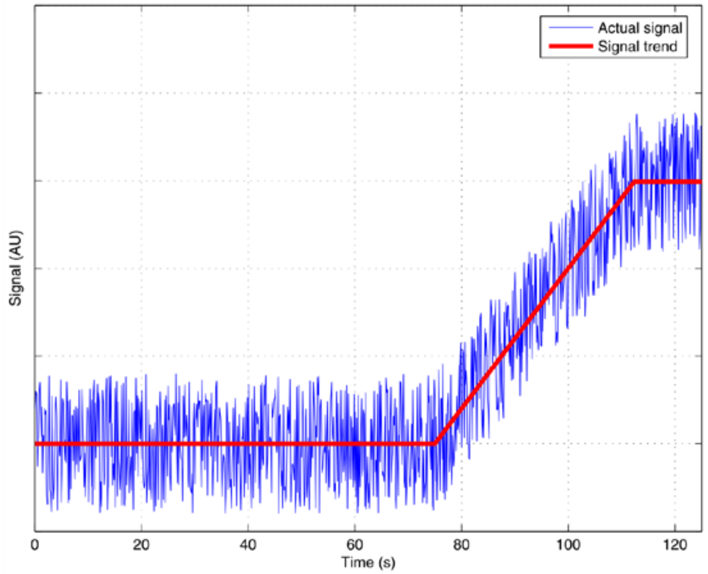

Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

$$X(\mathbf{r},t) = X_0(\mathbf{r},t) + \delta X(\mathbf{r},t)$$

signal trend or mean

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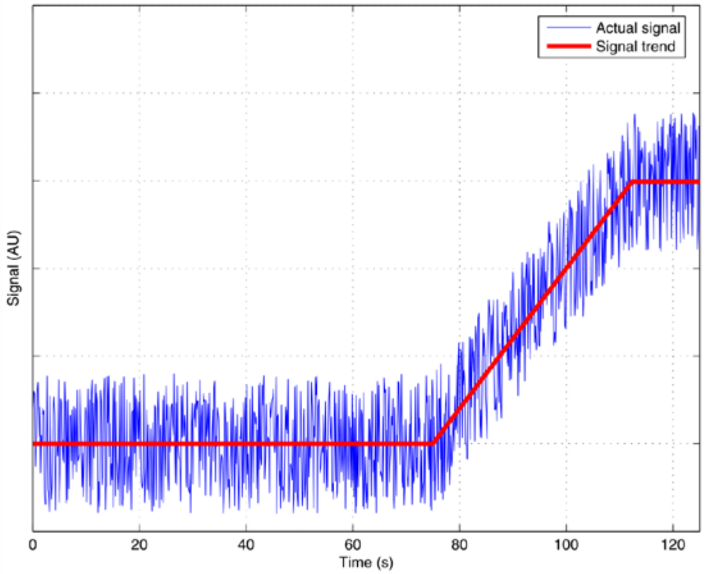


Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

$$X(\mathbf{r},t) = X_0(\mathbf{r},t) + \delta X(\mathbf{r},t)$$

fluctuations or “noise”

➢ Fluctuations carrying some valuable information about the system dynamics

Introduction

- Fluctuations could be used for “diagnostics”, i.e.:
  - Early detection of anomalies
  - Estimation of dynamical system characteristics

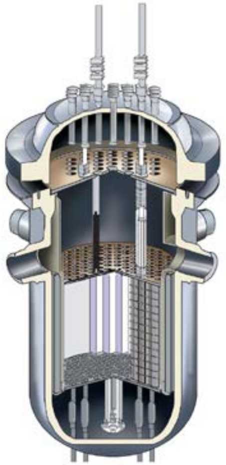
… even if the system is operating at steady-state conditions

➢ Example of nuclear reactors

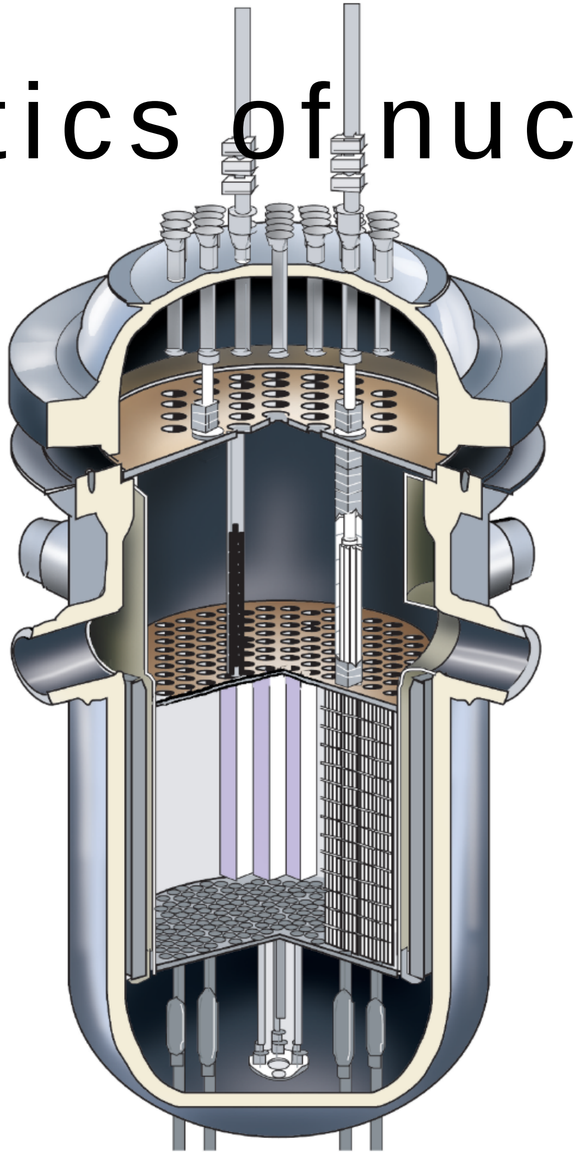
Characteristics of nuclear reactors

- Nuclear reactors = large and complex systems

Characteristics of nuclear reactors



Characteristics of nuclear reactors



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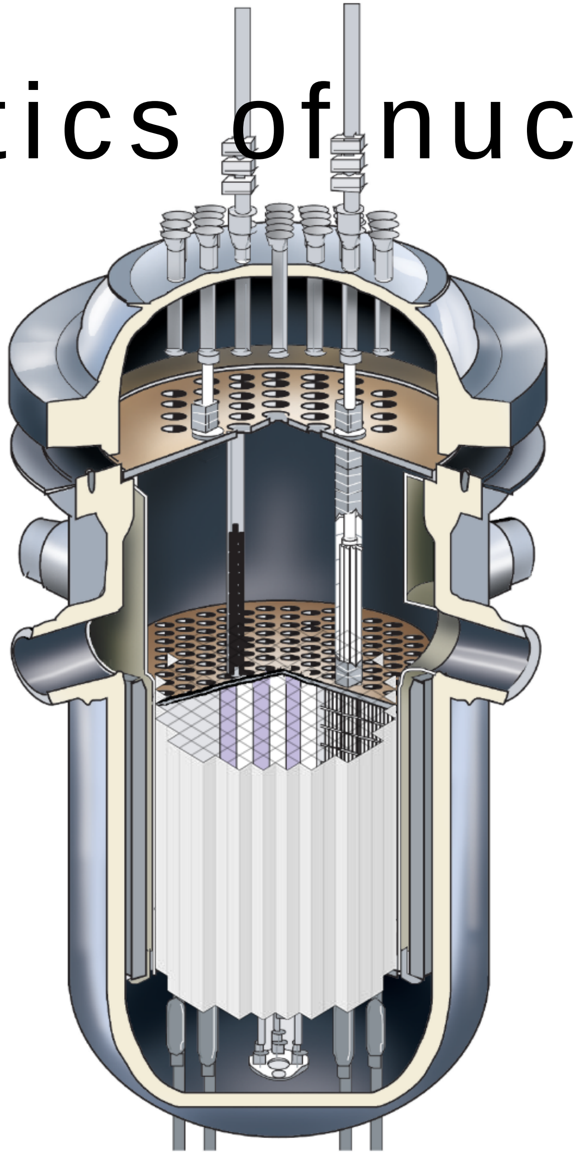
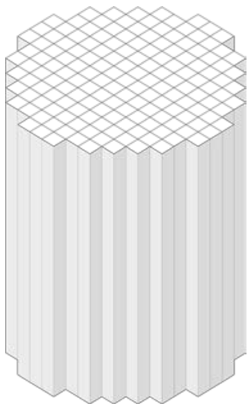
Characteristics of nuclear reactors

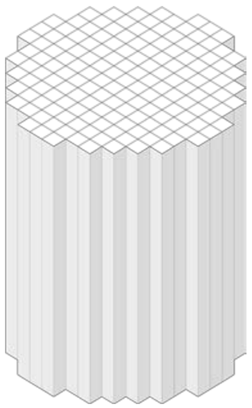


Characteristics of nuclear reactors



reactor core

Characteristics of nuclear reactors



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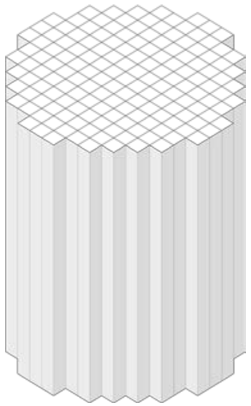

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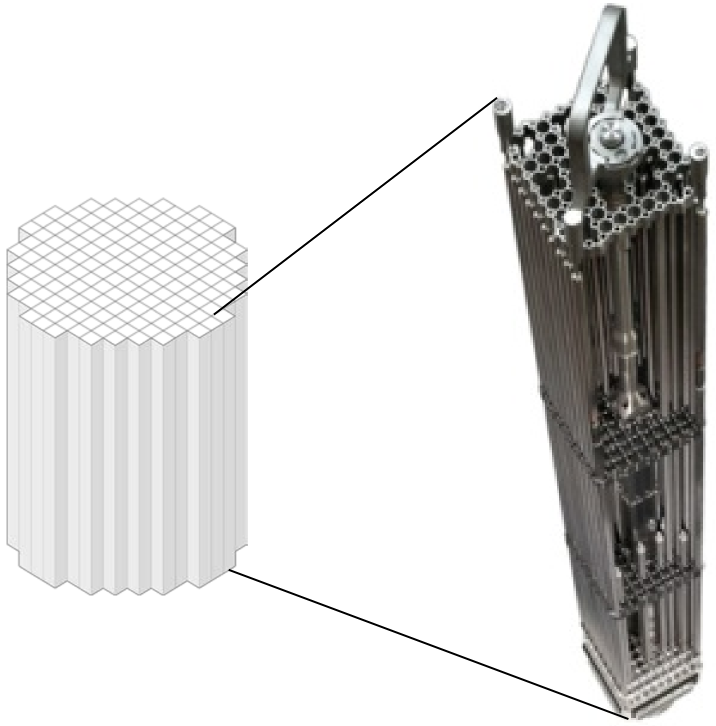
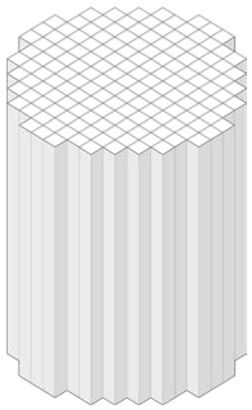
Characteristics of nuclear reactors



Characteristics of nuclear reactors



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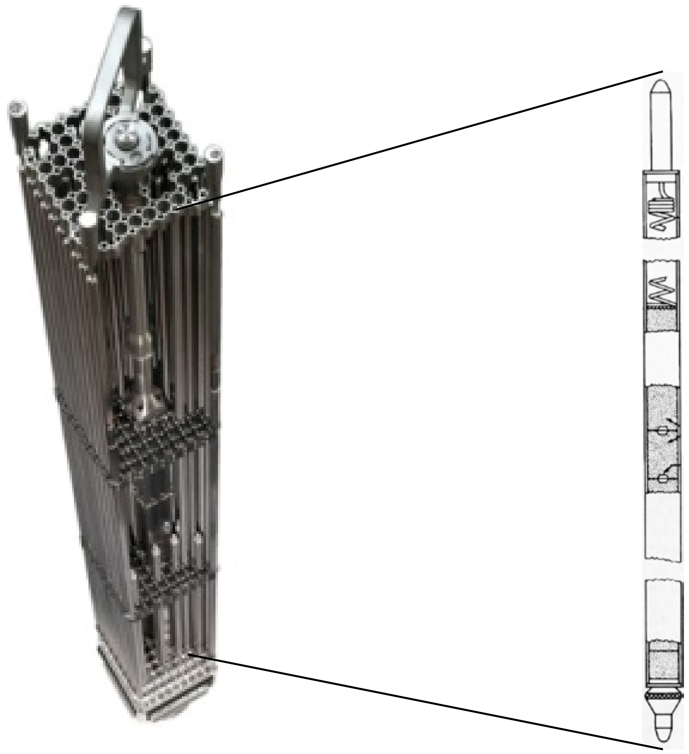

fuel assembly

fuel pin

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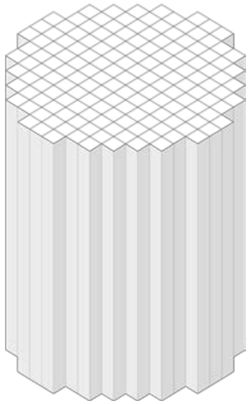
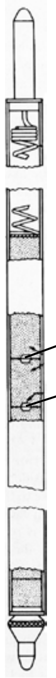
Characteristics of nuclear reactors

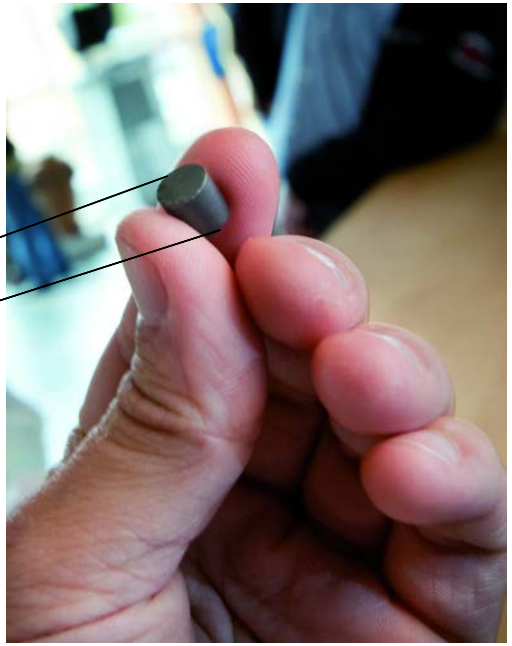


reactor core

fuel assembly



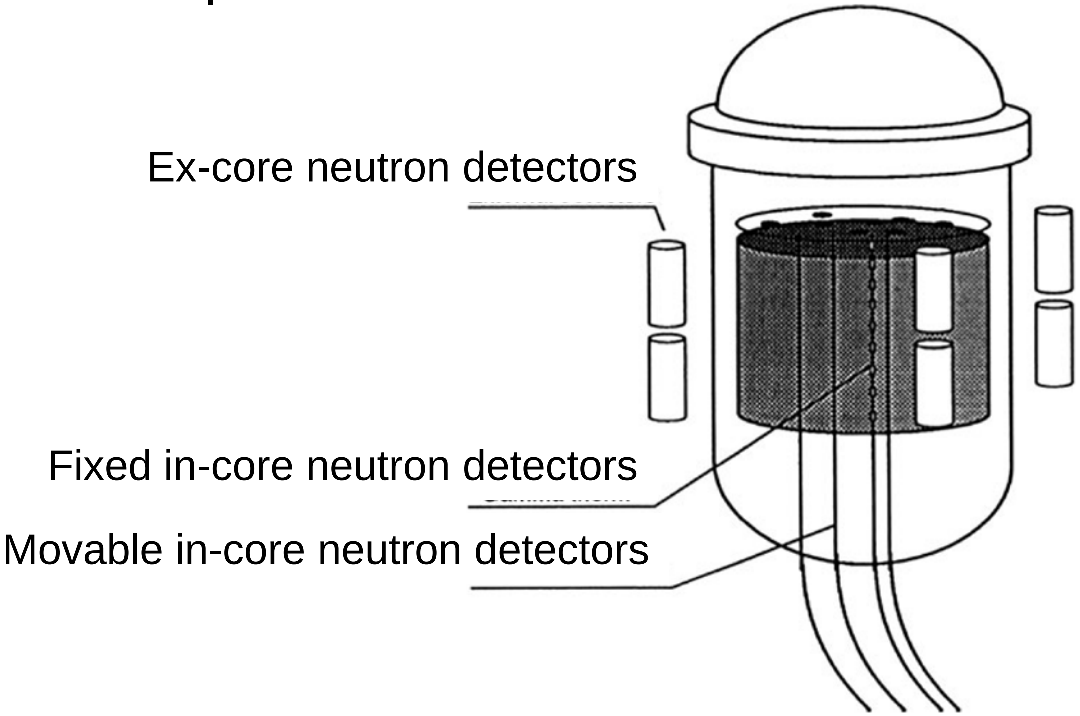
fuel pin



fuel pellet

Characteristics of nuclear reactors

- Neutron detectors present both in-core and ex-core:



- Advantage: “sense” perturbations even far away from the perturbations
- Disadvantage: western-type reactors do not always contain many in-core neutron detectors

Noise diagnostics in nuclear reactors

- Neutron noise diagnostics requires establishing relationships between neutron detectors and possible perturbations

- Could be done using the neutron transport equation (Boltzmann equation) or some simpler forms of it:

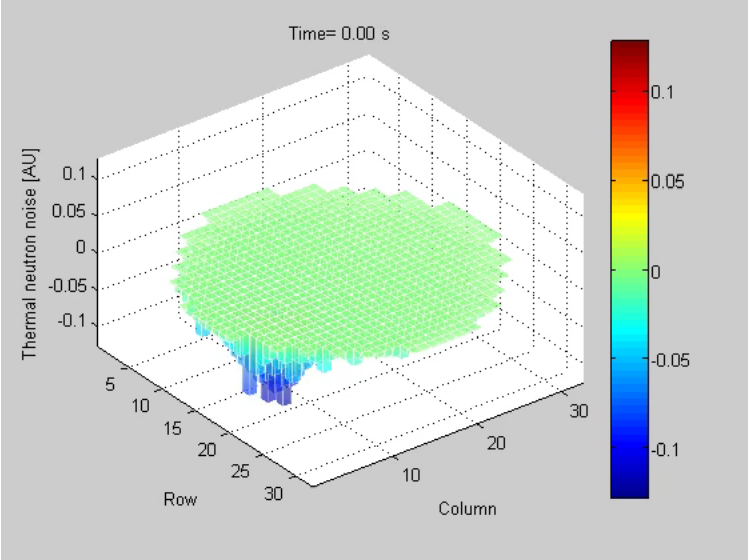
$$\frac{1}{v(E)}\frac{\partial}{\partial t}\psi(\mathbf{r},\boldsymbol{\Omega},E,t)$$
$$= -\boldsymbol{\Omega}\cdot\boldsymbol{\nabla}\psi(\mathbf{r},\boldsymbol{\Omega},E,t) - \Sigma_t(\mathbf{r},E,t)\psi(\mathbf{r},\boldsymbol{\Omega},E,t)$$
$$+\int_{(4\pi)}\int_0^{\infty}\Sigma_s(\mathbf{r},\boldsymbol{\Omega}'\rightarrow\boldsymbol{\Omega},E'\rightarrow E,t)\psi(\mathbf{r},\boldsymbol{\Omega}',E',t)d^2\boldsymbol{\Omega}'dE'$$
$$+\frac{1}{4\pi}\int_{-\infty}^{t}\int_0^{\infty}\nu(E')\Sigma_f(\mathbf{r},E',t')\phi(\mathbf{r},E',t')\left[(1-\beta)\chi^p(E)\delta(t-t')+\sum_{i=1}^{N_d}\chi_i^d(E)\lambda_i\beta_i e^{-\lambda_i(t-t')}\right]dt'dE'$$

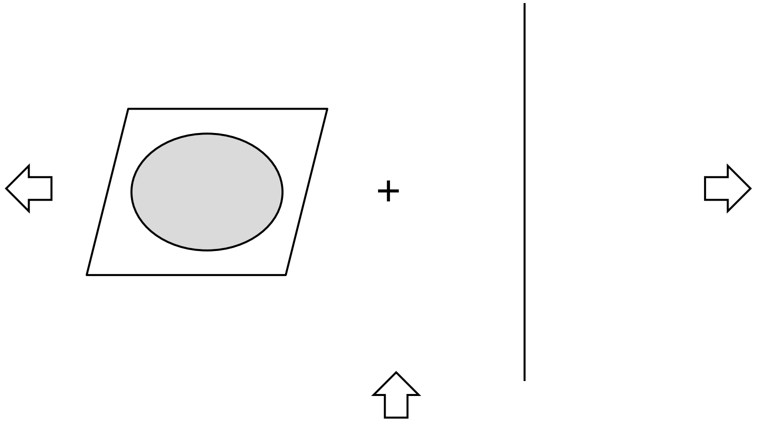
Noise diagnostics in nuclear reactors

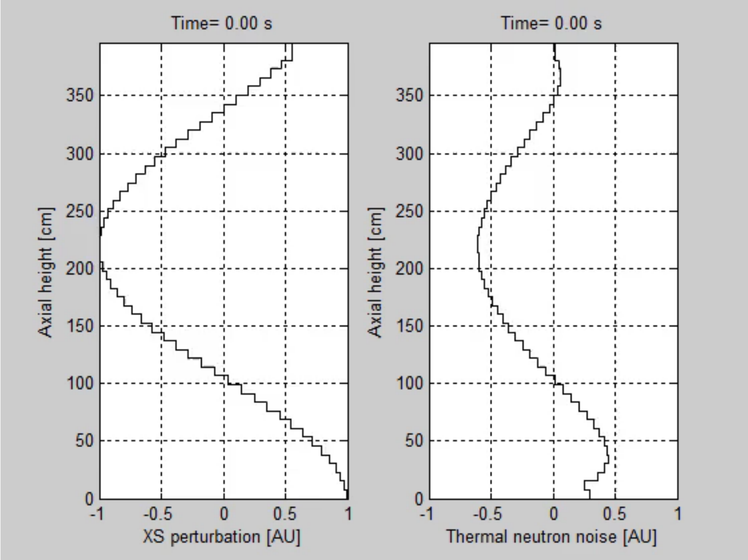
- Calculations to solve the system of equations for noise applications can be performed:
  - In the time- or frequency-domain
  - In linear or non-linear theory
  - Using diffusion or transport theory
  - Using deterministic or probabilistic (Monte Carlo) approaches
  - Using a coarse mesh or fine mesh representation of the phase space

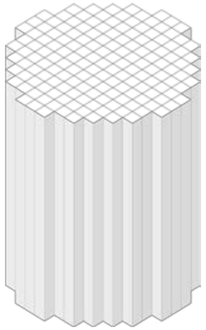
Noise diagnostics in nuclear reactors

- Example of a travelling perturbation @ 1Hz



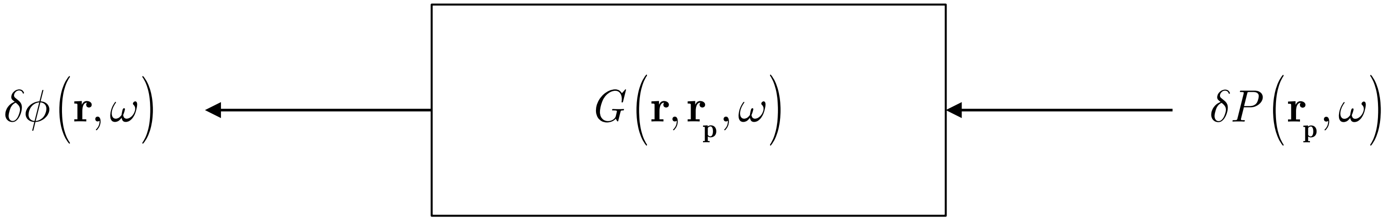






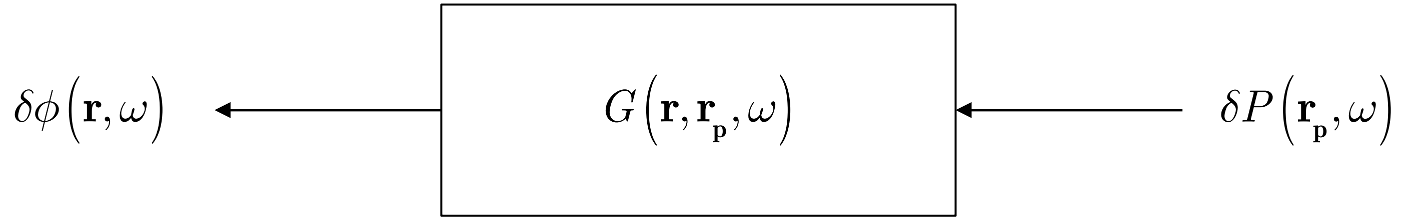
Noise diagnostics in nuclear reactors

- Calculations equivalent to estimating the reactor transfer function $G(\mathbf{r}, \mathbf{r_p}, \omega)$



Noise diagnostics in nuclear reactors

- But noise diagnostics requires the inversion of the reactor transfer function $G(\mathbf{r}, \mathbf{r_p}, \omega)$



Noise diagnostics in nuclear reactors

- But noise diagnostics requires the inversion of the reactor transfer function $G\left(\mathbf{r},\mathbf{r}_{\mathrm{p}},\omega\right)$

$$\delta\phi\left(\mathbf{r},\omega\right) \longrightarrow \boxed{\left[G\left(\mathbf{r},\mathbf{r}_{\mathrm{p}},\omega\right)\right]^{-1}} \longrightarrow \delta P\left(\mathbf{r}_{\mathrm{p}},\omega\right)$$

- Machine learning could be used for that purpose
- Unfolding possible even if very few detectors available, due to the spatial correlations existing between a localized perturbation and its effect throughout the nuclear core
- EU-funded project CORTEX

Noise diagnostics in nuclear reactors

- **CORTEX**: CORe monitoring Techniques and Experimental validation and demonstration – EU funding.

CORTEX
Core monitoring techniques and experimental validation and demonstration

  - Chalmers coordinating the project
  - 20 partners (18 from EU + 1 from Japan + 1 from USA)

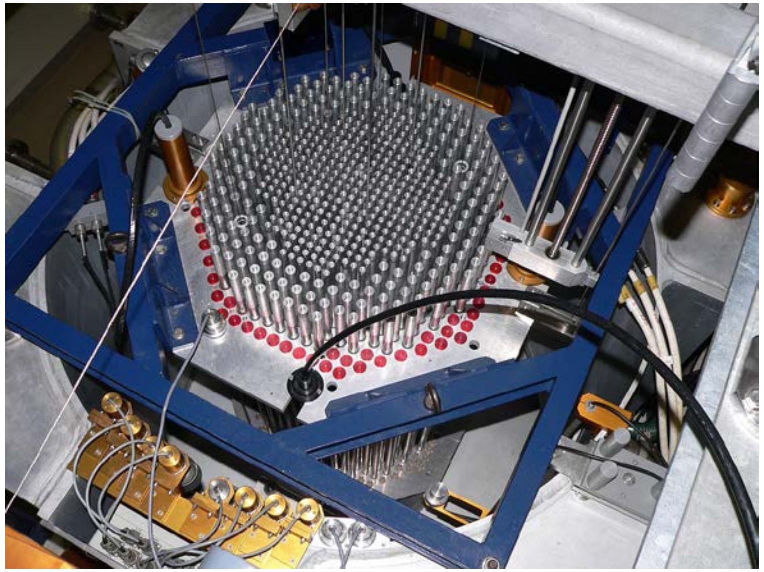
http://cortex-h2020.eu

Follow the project on LinkedIn as well!

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754316.

Noise diagnostics in nuclear reactors

- CORTEX aims:
  - Developing high fidelity tools for simulating stationary fluctuations
  - Validating those tools against experiments to be performed at research reactors



CROCUS reactor @EPFL, Switzerland

AKR-2 reactor @TU Dresden, Germany

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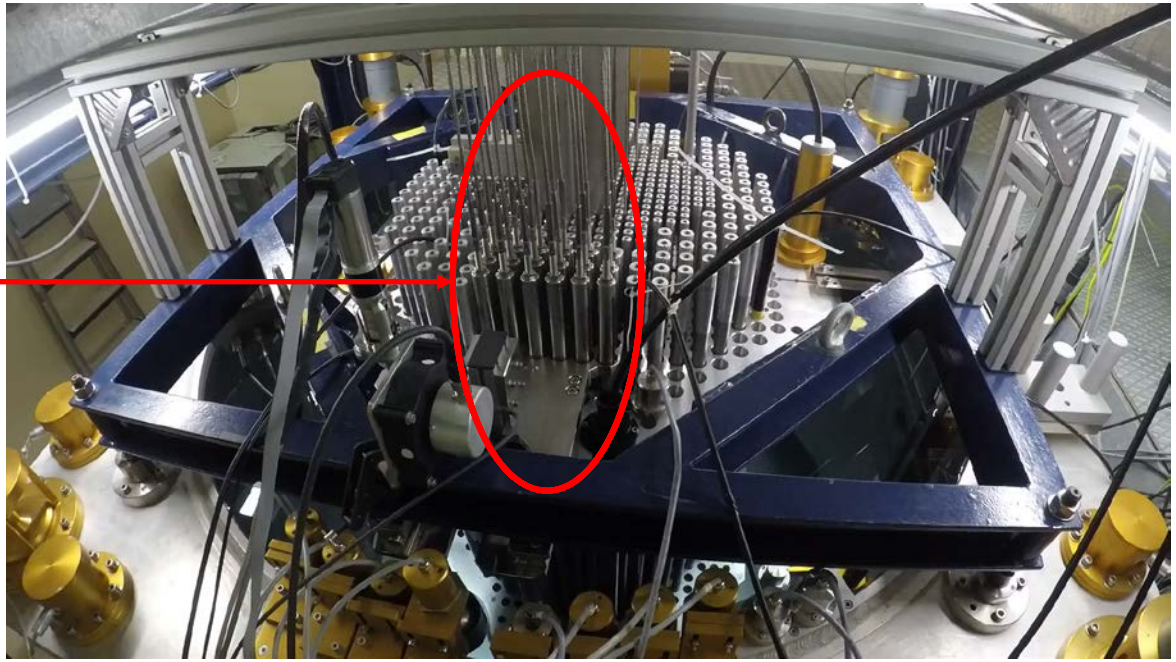
Oscillating fuel rods



COLIBRI experiments
in CROCUS
(© EPFL, Switzerland)

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Noise diagnostics in nuclear reactors

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  - Developing high fidelity tools for simulating stationary fluctuations
  - Validating those tools against experiments to be performed at research reactors
  - Developing advanced signal processing and machine learning techniques (to be combined with the simulation tools)
  - Demonstrating the proposed methods for both on-line and off-line core diagnostics and monitoring

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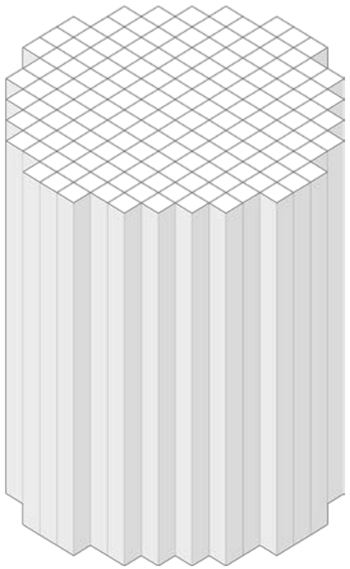
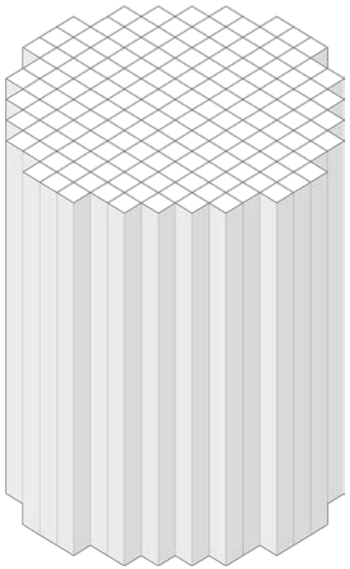
Noise diagnostics in nuclear reactors

- Machine learning able to correctly identify and localize the type of perturbations existing in a nuclear core:

Prediction



Ground truth



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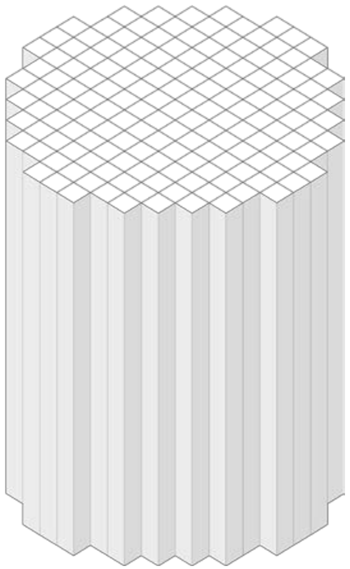

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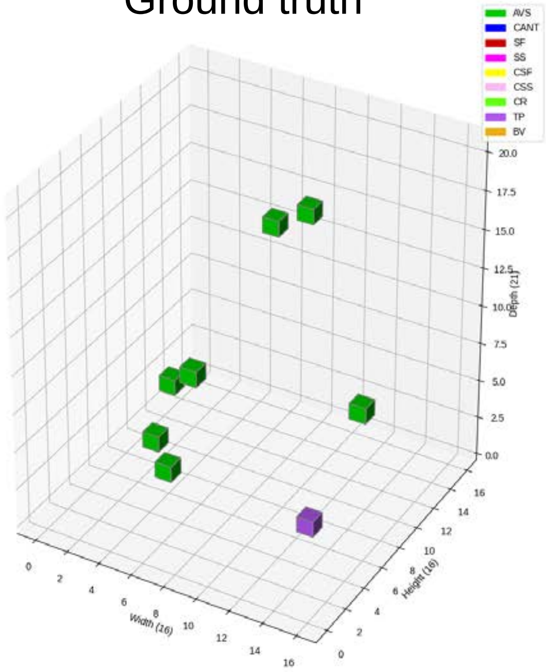

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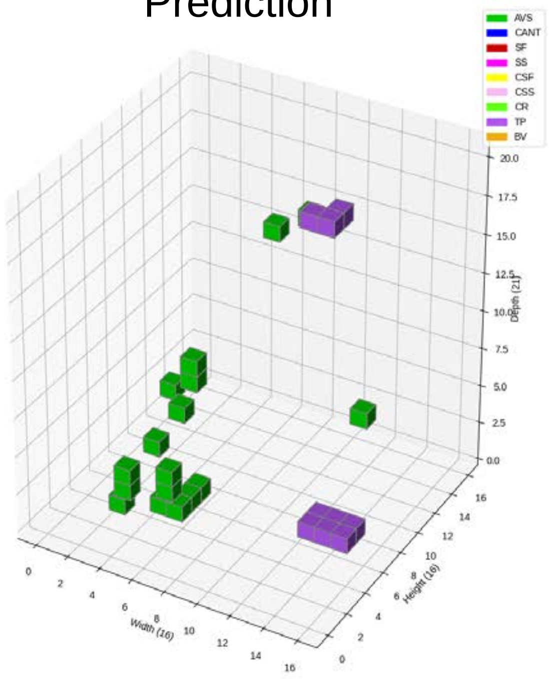

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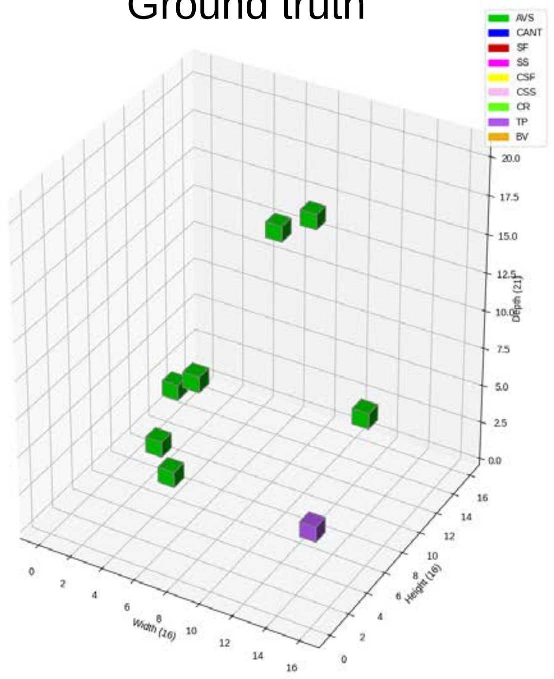

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Conclusions and outlook

- Core diagnostics leading to improved reactor safety

- CORTEX project potentially having a large impact if successful

- Core diagnostics = mix between
  - Basic reactor physics and neutron transport
  - Computational reactor physics
  - Experimental reactor physics
  - Advanced signal analysis
  - Artificial intelligence

… with applications to large industrial installations

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