CORTEX

Core monitoring techniques and experimental validation and demonstration

Power reactor noise theory

CORTEX 2nd validation workshop

Online

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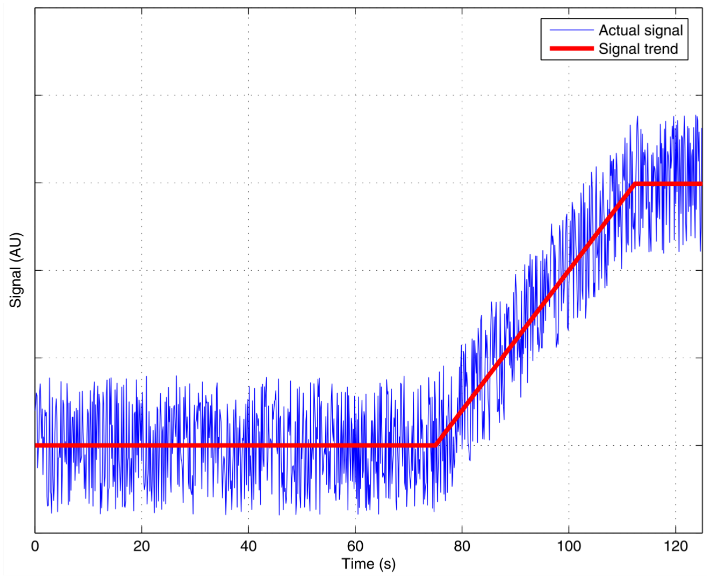
This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754316.

Introduction and background

Introduction and background

- 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

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

Introduction and background

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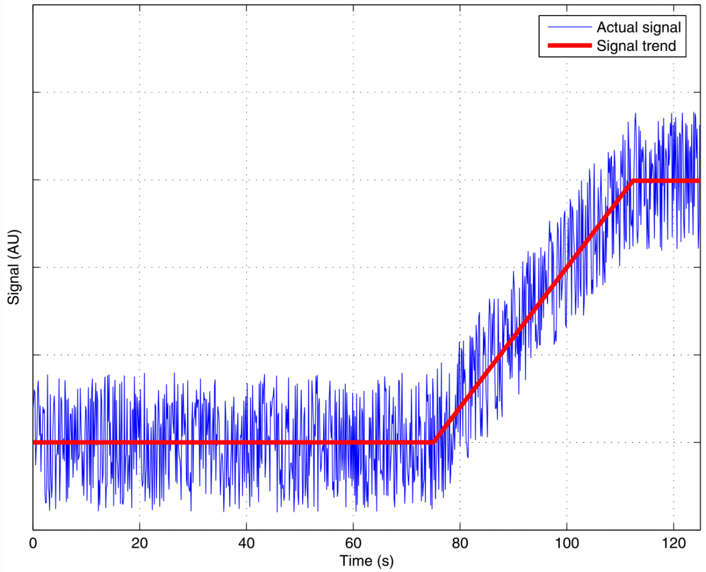

Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

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

actual signal

Introduction and background

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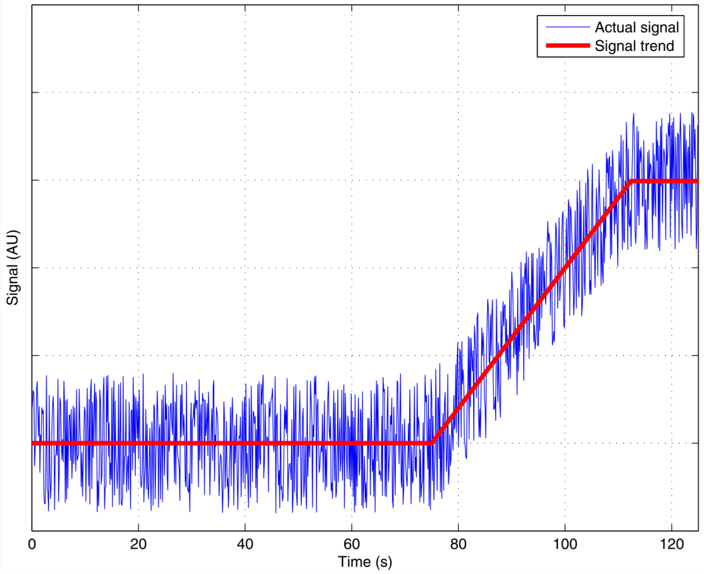

Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

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

signal
trend or mean

Introduction and background

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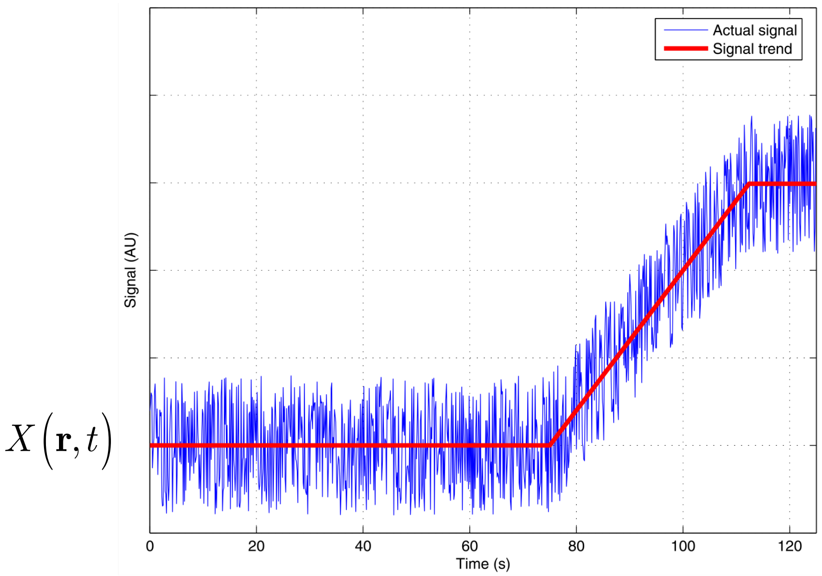


Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

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

fluctuations or "noise"

➢ Fluctuations carrying some valuable information about the system dynamics

Introduction and background

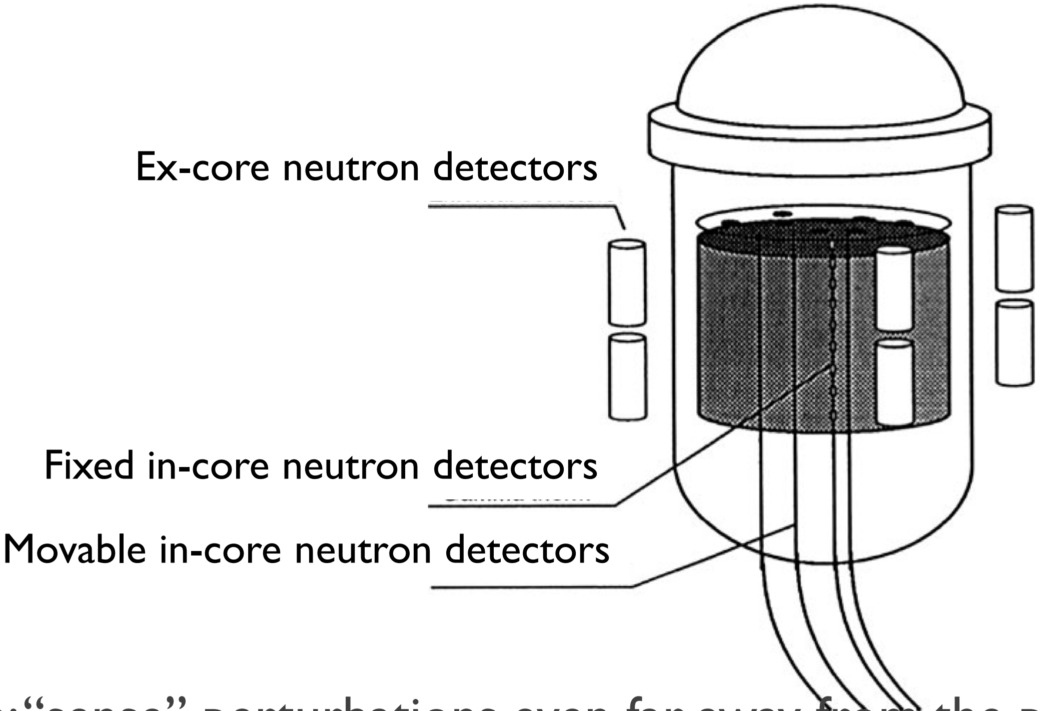
- Fluctuations could be used for “diagnostics”, i.e.:
  - Early detection of anomalies
  - Estimation of dynamical system characteristics

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

➢ Fluctuations in the neutron density in nuclear reactors can be used for core diagnostics and monitoring

Introduction and background

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

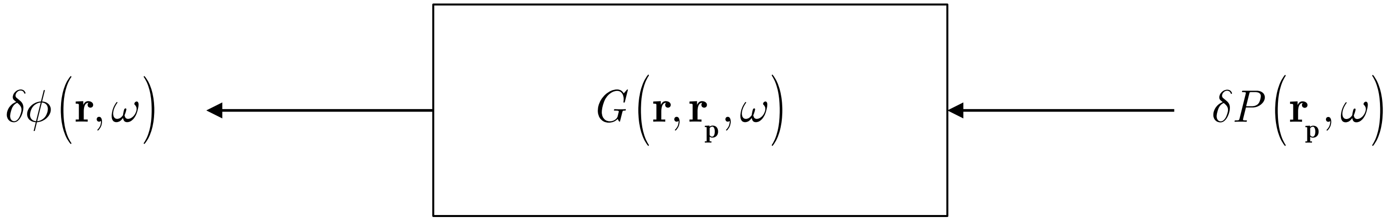


> ➢ Advantage: "sense" perturbations even far away from the perturbations
> ➢ Disadvantage: western-type reactors do not always contain many in-core neutron detectors

Introduction and background

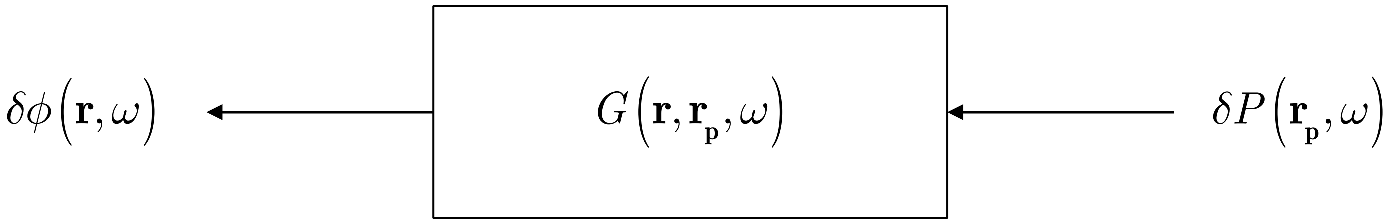
- Neutron noise diagnostics requires establishing relationships between neutron detectors and possible perturbations

➢ The "reactor transfer function" $G(\mathbf{r}, \mathbf{r_p}, \omega)$ needs to be determined



Introduction and background

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



Introduction and background

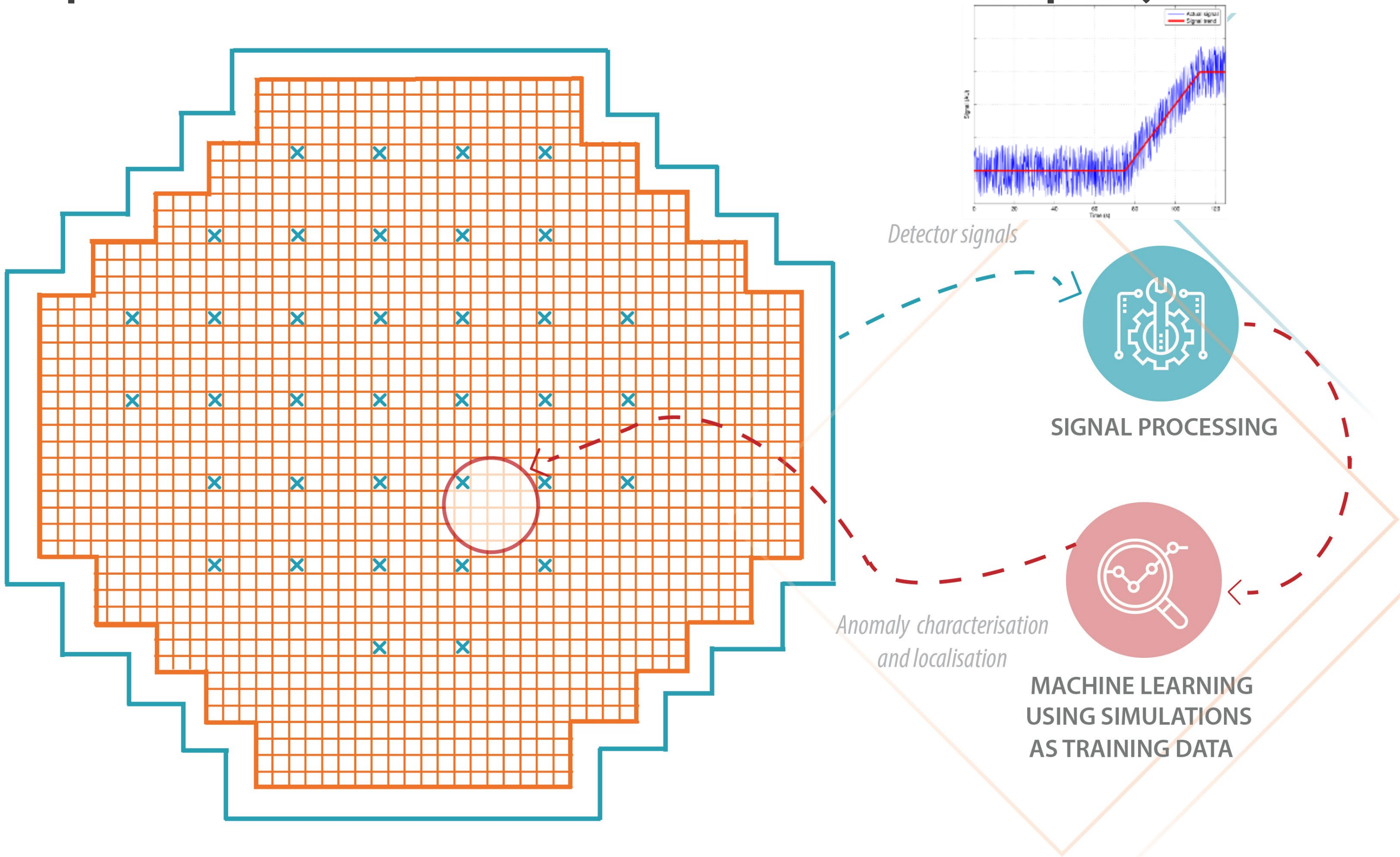
- But noise diagnostics requires the inversion of the reactor transfer function $G\left(\mathbf{r},\mathbf{r}_\mathbf{p},\omega\right)$

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

- ➢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)

Introduction and background

- Overall principle of the Horizon 2020 CORTEX project:



More info at:
cortex-h2020.eu

Introduction and background

- Project aims for CORTEX:
  - WP1: Developing high fidelity tools for simulating stationary fluctuations
  - WP2: Validating those tools against experiments to be performed at research reactors
  - WP3: Developing advanced signal processing and machine learning techniques (to be combined with the simulation tools)
  - WP4: Demonstrating the proposed methods for both on-line and off-line core diagnostics and monitoring
  - WP5: Disseminating the knowledge gathered from within the project to stakeholders in the nuclear sector

Introduction and background

- CORTEX project participants:
  - Project led and coordinated by Chalmers University of Technology
  - 18 European organizations involved in the project:
    - CEA and LGI Consulting (France)
    - Centre for Energy Research, Hungarian Academy of Sciences – MTA EK (Hungary)
    - EPFL, KKG, PSI (Switzerland)
    - GRS, ISTec, TIS, PEL, TU Dresden and TU Munich (Germany)
    - Institute of Communication & Computer Systems - National Technical University of Athens (Greece)
    - UJV (Czech Republic)
    - University of Lincoln (UK)
    - UPM and UPV (Spain)

Introduction and background

- CORTEX project participants:
  - 2 non-European organizations formally involved in the project:
    - KURRI (Japan)
    - AMS Corp (USA)

  - 7 additional organizations involved in the Advisory End-User Group:
    - IRSN (France)
    - KKG (Switzerland)
    - PEL (Germany)
    - Ringhals (Sweden)
    - Tractebel (Belgium)
    - CNAT (Spain)
    - Framatome GmbH (Germany)
    - Westinghouse Electric Sweden AB (Sweden)
    - NRG (the Netherlands)

Introduction and background

- Modelling of the neutron noise includes two basic steps:
  - Modelling of the noise source in terms of macroscopic cross-section perturbations
  - Modelling of the neutron noise induced by fluctuations of the macroscopic cross-section perturbations

- Presentation focusing on:
  - Noise source modelling
  - Induced neutron noise modelling
  - Some theoretical remarks on power reactor noise

Noise source modelling

Noise source modelling

- Perturbations can be defined:
  - In the time-domain, more or less as they are, with limitations/approximations due to the mesh used.
  - In the frequency-domain, after typically a first-order approximation of the perturbation, subsequently followed by a Fourier transform + limitations/approximations due to the mesh used.

➢ Modelling possibly supplemented by other modelling tools (e.g. fluid-structure modelling tool)

➢ Noise source modelling strongly dependent on the choices made by the user

Noise source modelling

- Different scenarios investigated in CORTEX:
  - “Absorber of variable strength”: localized perturbation of which its amplitude varies in time at a fixed position
  - “Vibrating absorber”: lateral movement of a weak absorber
  - Axially-travelling perturbations
  - Inlet flow rate perturbations
  - Core barrel vibrations: several types of vibrations possible
  - Fuel assembly vibrations: several possible modes of vibrations

Modelling of the induced neutron noise

Modelling of the induced neutron noise

- Once the noise source is modelled, need to estimate the response of the neutron flux to the applied perturbation

➢ Could be done using the neutron transport equation (Boltzmann equation):

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

Modelling of the induced neutron noise

- Different approaches possible:
  - Time-domain modelling

    Advantages:

    - Existing time-domain codes could be used
    - Non-linear effects inherently accounted for
    - Thermal-hydraulic feedback automatically taken into account

    Disadvantages:

    - Lengthy calculations
    - Challenging to get a highly accurate solution for the noise
    - Codes originally not developed for that purpose
    - Lack of verification and validation for noise analysis

Modelling of the induced neutron noise

- Different approaches possible:
  - Frequency-domain modelling

    Time-domain equations transformed into frequency-domain equations according to the following procedure:

    - Splitting between mean values and fluctuations
    - Linear theory used because of the smallness of the fluctuations
    - Fourier-transform of the balance equations for the dynamical part only

Modelling of the induced neutron noise

- Different approaches possible:
  - Frequency-domain modelling

    Advantages:
    - Codes specifically developed for noise analysis, thus usually fully verified (validated?)
    - Highly accurate noise solution
    - Usually high flexibility in the modelling
    - Very fast calculations

    Disadvantages:
    - No commercial code available
    - Possible linear effects disregarded
    - Thermal-hydraulic feedback generally not taken into account (but could be)

Modelling of the induced neutron noise

- Beyond using the time- or frequency-domain, the modelling can be done in many ways:
  - Diffusion/transport
  - Deterministic/probabilistic
  - Fine/coarse spatial mesh

Modelling of the induced neutron noise

- Codes used in CORTEX:

Code name	Domain		Non-linear terms		Angular resolution		Spatial resolution		Approach	
	Time	Frequency	Not modelled	Modelled	Diffusion	Transport	Fine-mesh	Coarse-mesh	Deterministic	Probabilistic
SIMULATE-3K	✓			✓	✓			✓	✓	
DYN3D	✓			✓		✓		✓	✓	
QUABBOX/ CUBBOX	✓			✓	✓			✓	✓	
PARCS	✓			✓	✓	(✓)		✓	✓	
FEMFUSSION	✓	✓	✓	✓	✓		✓		✓	
APOLLO3®	✓			✓		✓	✓		✓	

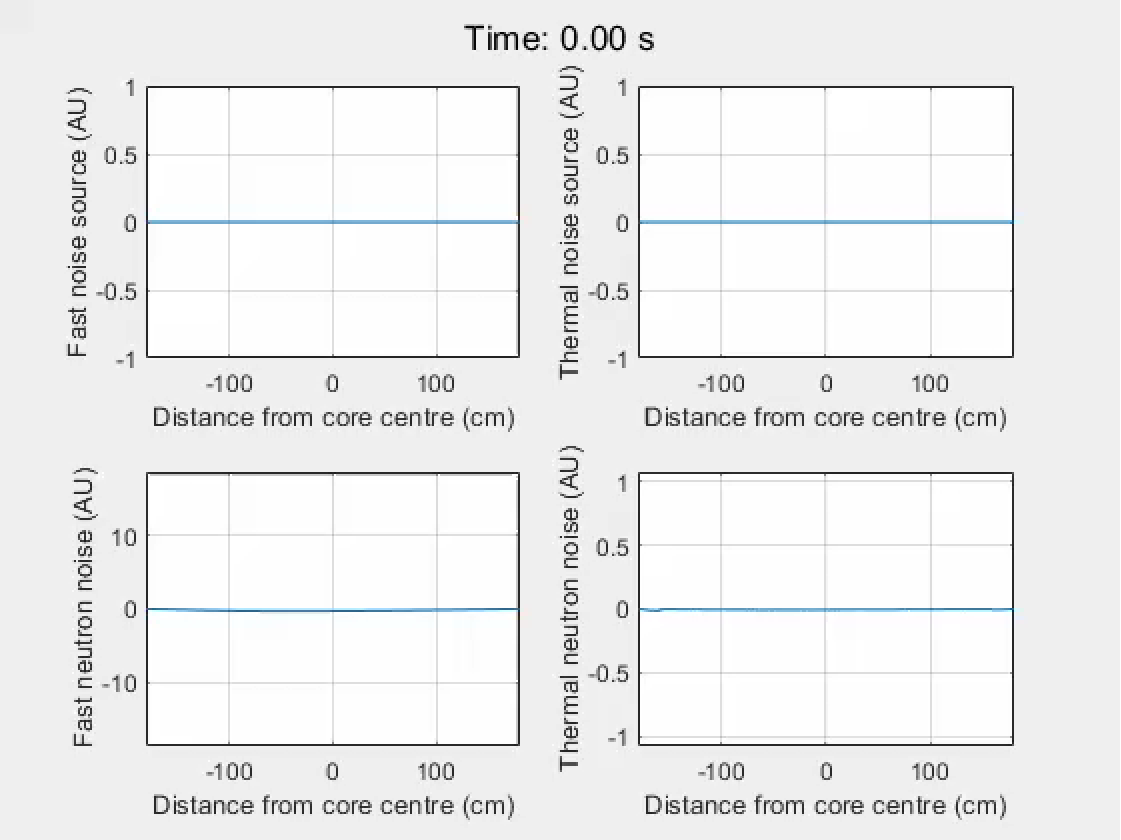
Modelling of the induced neutron noise

- Codes used in CORTEX:

Code name	Domain		Non-linear terms		Angular resolution		Spatial resolution		Approach	
	Time	Frequency	Not modelled	Modelled	Diffusion	Transport	Fine-mesh	Coarse-mesh	Deterministic	Probabilistic
CORE SIM		✓	✓		✓			✓	✓	
CORE SIM+		✓	✓		✓		✓		✓	
Sn-based solver		✓	✓			✓	✓		✓	
Extension of MCNP		✓	✓			✓	✓			✓
Extension of TRIPOLI-4®		✓	✓			✓	✓			✓
Equivalence-based method using MCNP		✓	✓			✓		✓		✓

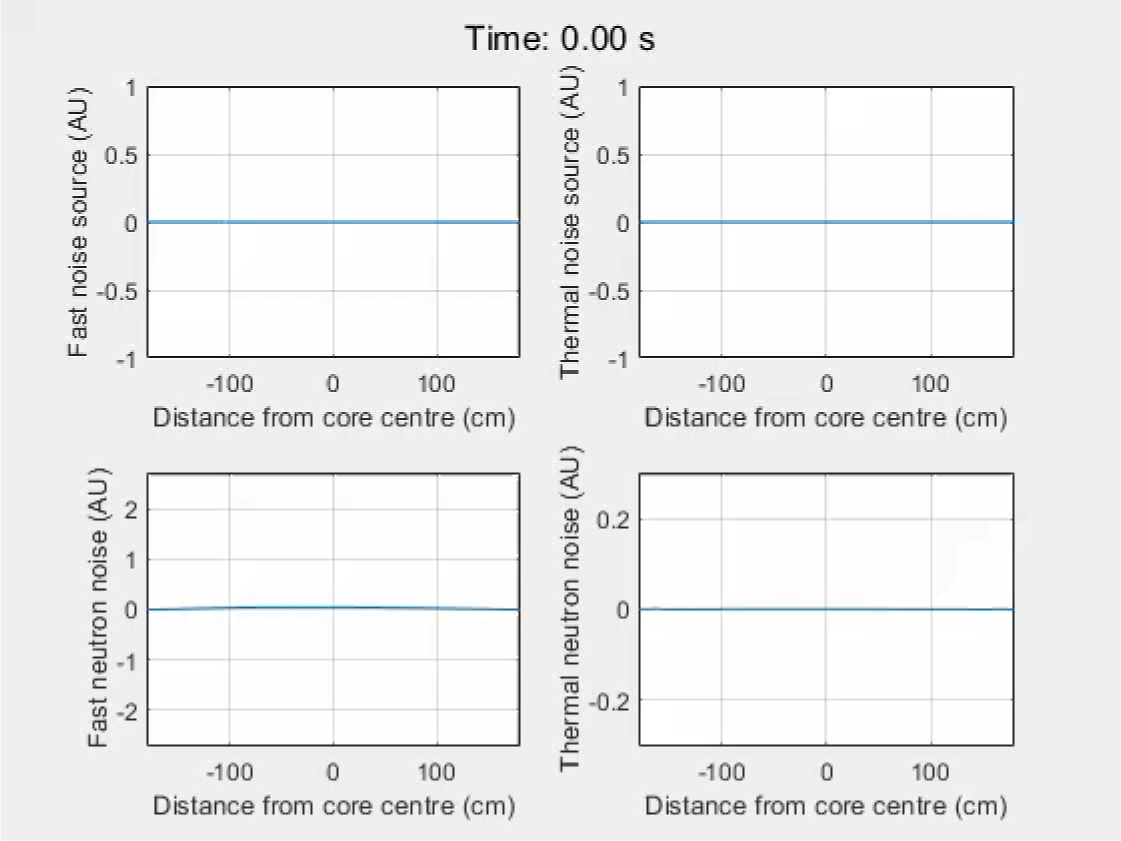
Modelling of the induced neutron noise

- Example of an absorber of variable strength at 1 Hz in a 1-D heterogeneous reactor model:



Modelling of the induced neutron noise

- Example of a vibrating fuel assembly at 1 Hz in a 1-D heterogeneous reactor model:



Some theoretical remarks on power reactor noise

Some theoretical remarks on power reactor noise

- What is the point-kinetic component of the neutron noise?

  Using the factorization:

$$\phi\left(\mathbf{r},t\right) = P\left(t\right)\cdot\psi\left(\mathbf{r},t\right)$$

with

$P\left(t\right)$ amplitude factor

$\psi\left(\mathbf{r},t\right)$ shape function

such that

$$\frac{\partial}{\partial t}\int\phi_0\left(\mathbf{r}\right)\psi\left(\mathbf{r},t\right)d^3\mathbf{r} = 0$$

Some theoretical remarks on power reactor noise

- What is the point-kinetic component of the neutron noise?

  One obtains in first order:

$$\delta\phi\left(\mathbf{r},t\right) = \delta P\left(t\right)\phi_0\left(\mathbf{r}\right) + \delta\psi\left(\mathbf{r},t\right)$$

  where one assumed:

$$P_0 = 1$$
$$\psi\left(\mathbf{r},t=0\right) = \phi_0\left(\mathbf{r}\right)$$

  - Point-kinetic response: $\delta P\left(t\right)\phi_0\left(\mathbf{r}\right)$
  - "Space-dependent" response: $\delta\psi\left(\mathbf{r},t\right)$

Some theoretical remarks on power reactor noise

- What is the point-kinetic component of the neutron noise?

  The fluctuations of the amplitude factor are further given, in the frequency domain, as:

$$\delta P(\omega) = G_0(\omega)\,\delta\rho(\omega)$$

with

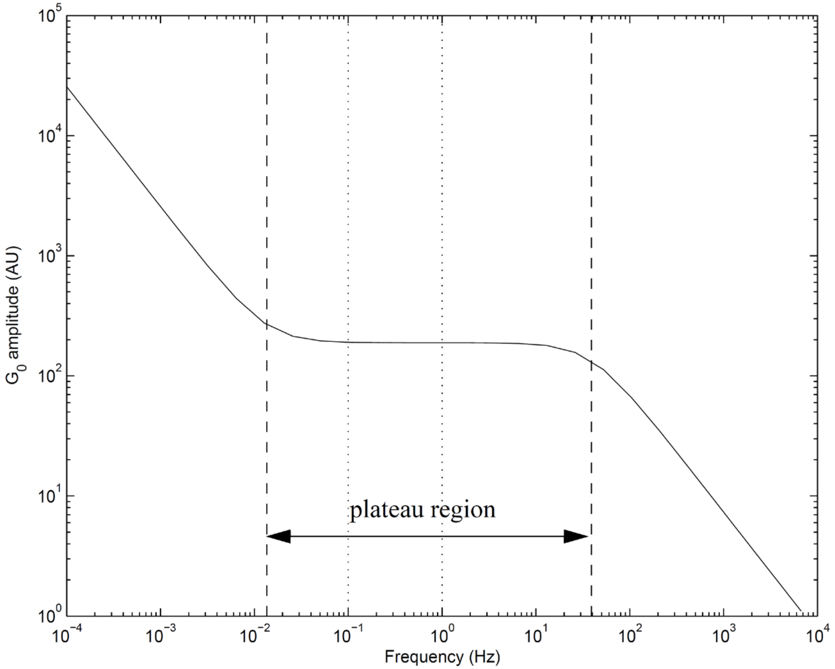
$$G_0(\omega) = \frac{1}{i\omega\left(\Lambda_0 + \dfrac{\beta}{i\omega + \lambda}\right)}$$

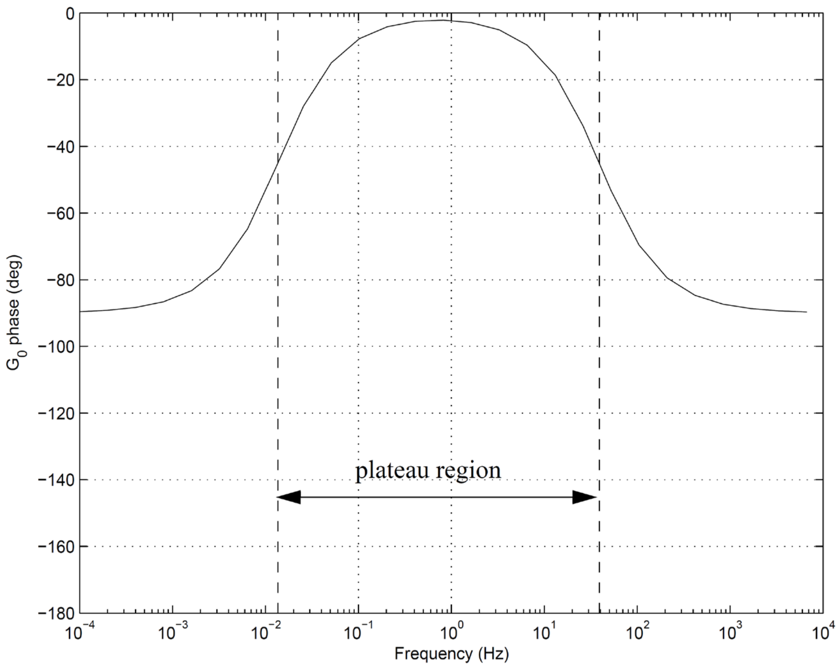
zero-power reactor transfer function

(better name: *point-kinetic* zero-power reactor transfer function)

Some theoretical remarks on power reactor noise

- What is the point-kinetic component of the neutron noise?





Amplitude and phase of the zero-power reactor transfer function

Some theoretical remarks on power reactor noise

- What is the point-kinetic component of the neutron noise?

  Remark:

  Even at zero power (i.e. without feedback), the reactor response deviates from point-kinetics in the most general case

Some theoretical remarks on power reactor noise

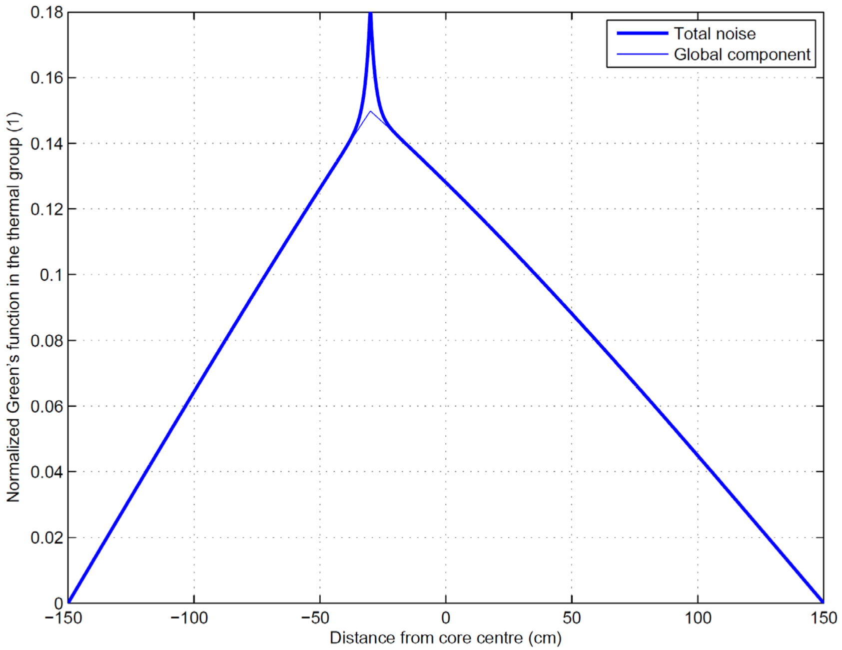
- What are the local and global components of the reactor noise?

  In more than or equal to two energy groups, the space-dependence of the induced neutron noise shows two relaxation lengths:

  - A short relaxation length: the *local* component
  - A long relaxation length: the *global* component

Some theoretical remarks on power reactor noise

- What are the local and global components of the reactor noise?



Example of the space-dependence of the amplitude of the thermal component of the Green's function in two-group diffusion theory (at 5 Hz)

Some theoretical remarks on power reactor noise

- What are the local and global components of the reactor noise?

Remarks:

- The local component does not exist in one-group theory!
- The global component should not be mistaken with the point-kinetic component!

Some theoretical remarks on power reactor noise

- What are the local and global components of the reactor noise?

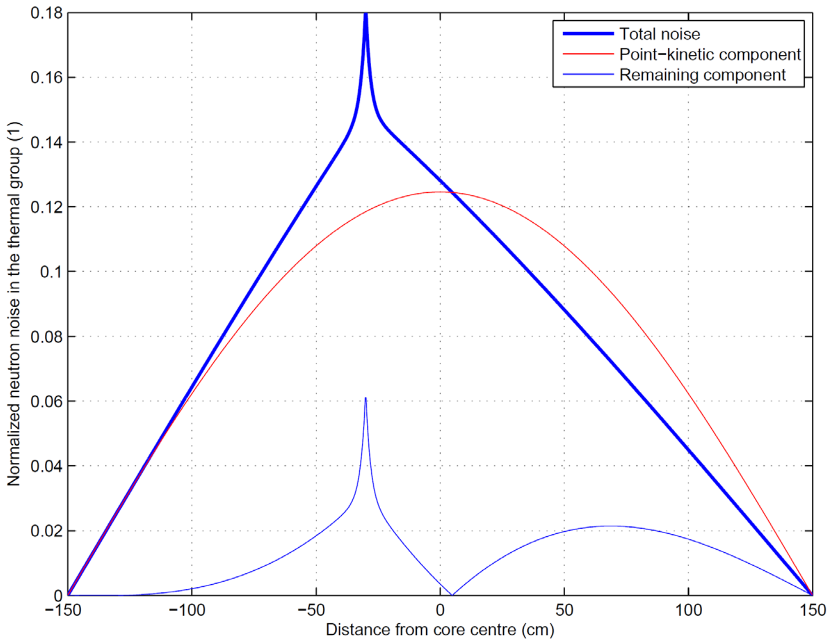


Illustration of the difference between the global component and the point-kinetic component (at 1 Hz)

Some theoretical remarks on power reactor noise

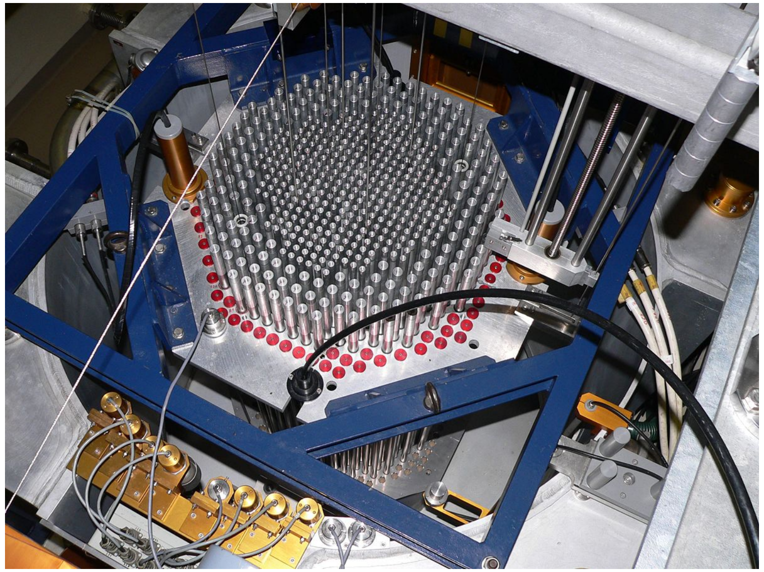
- Go to www.menti.com

Conclusions

Conclusions

- Need to verify and validate the modelling tools for noise analysis

➢ Purpose of this workshop:
Illustration of the validation exercises undertaken in CORTEX using the CROCUS reactor and the AKR-2 reactor



CROCUS reactor @EPFL, Switzerland

AKR-2 reactor @TU Dresden, Germany

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