CORTEX
Core monitoring techniques and experimental validation and demonstration

Modelling the effect of stationary perturbations onto the neutron flux in nuclear reactors

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Prof. Christophe Demazière, Chalmers University of Technology

demaz@chalmers.se

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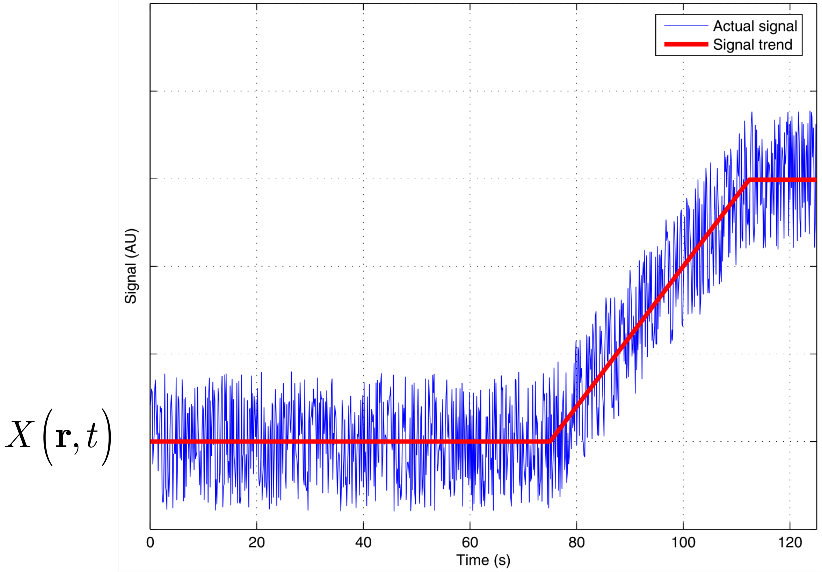
Introduction and background

Introduction and background

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



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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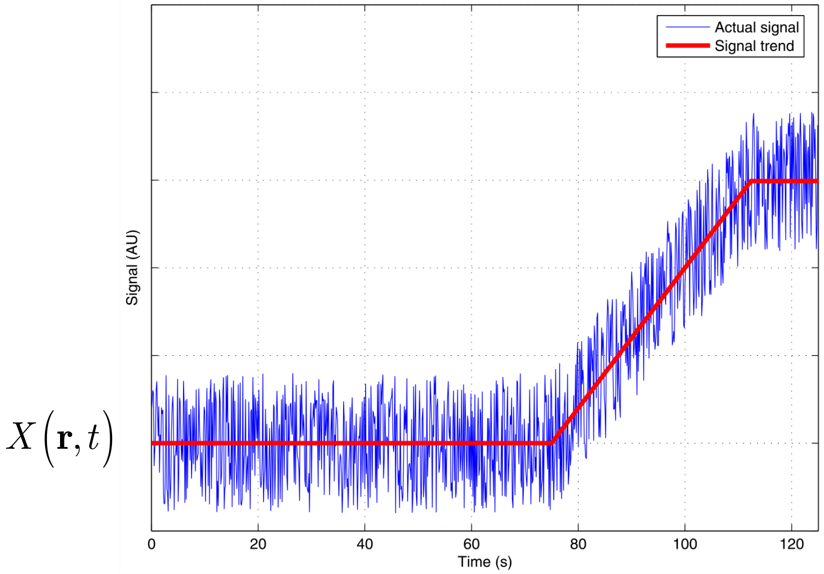

Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

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

actual signal

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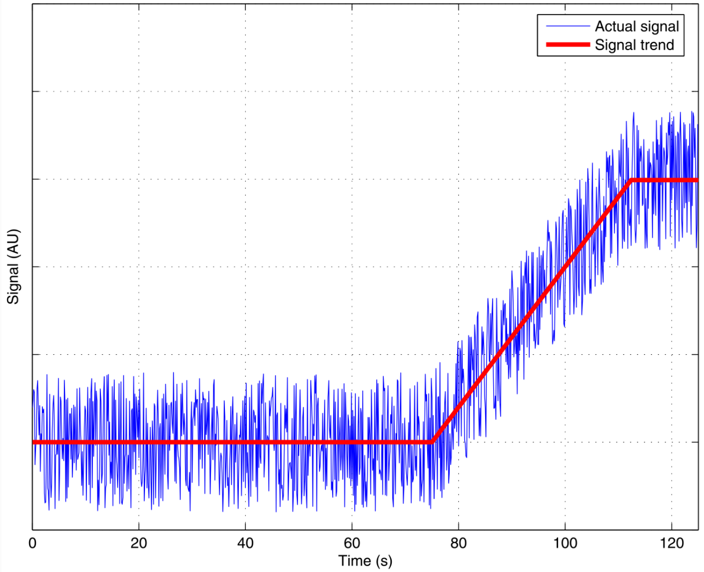

$X(\mathbf{r},t)$

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

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

signal
trend or mean

Introduction and background

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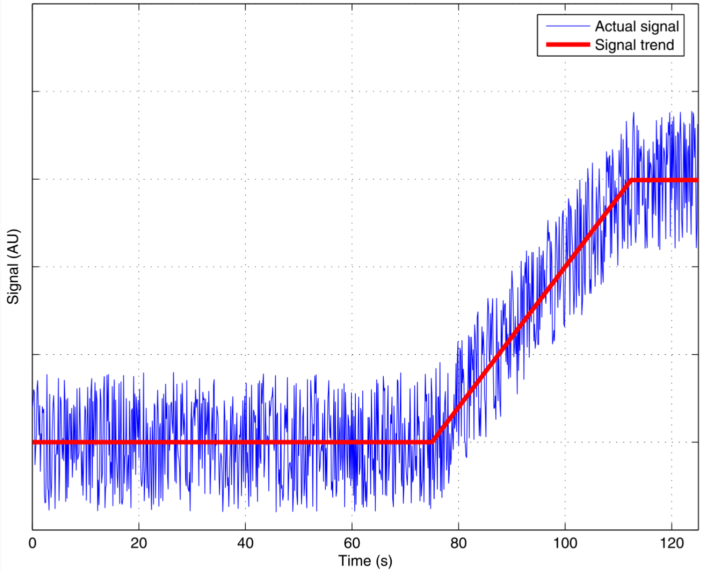
$X(\mathbf{r},t)$



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

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

fluctuations or "noise"

➢ Fluctuations carrying some valuable information about the system dynamics

Introduction and background

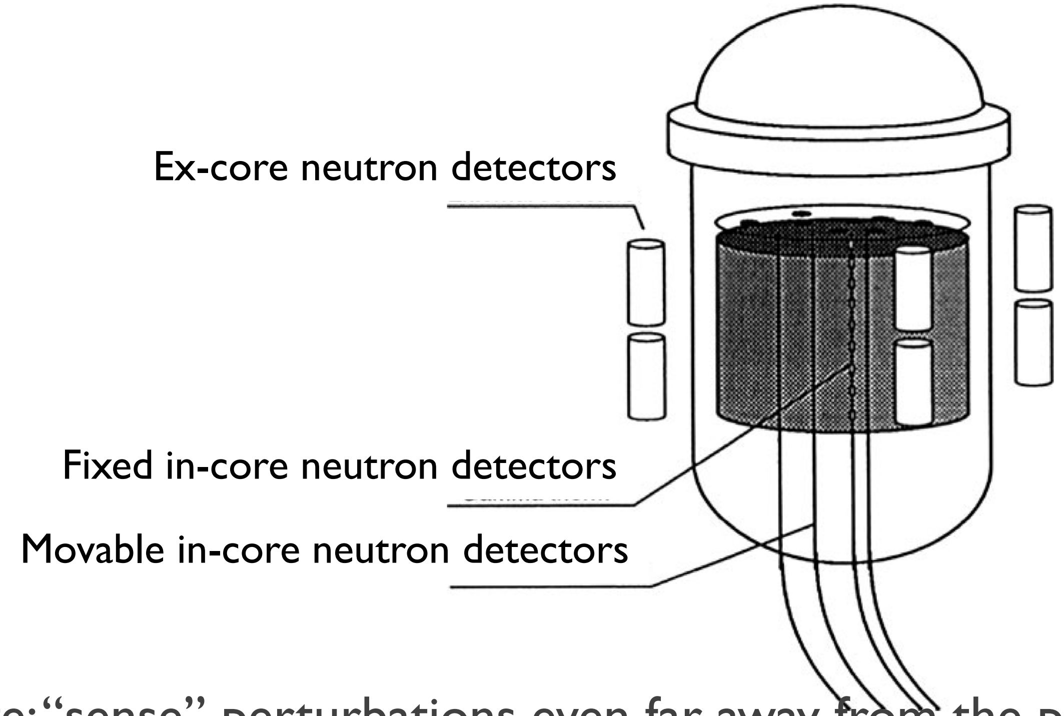
- Fluctuations could be used for "diagnostics", i.e.:
  - Early detection of anomalies
  - Estimation of dynamical system characteristics

… 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 in-core and ex-core:

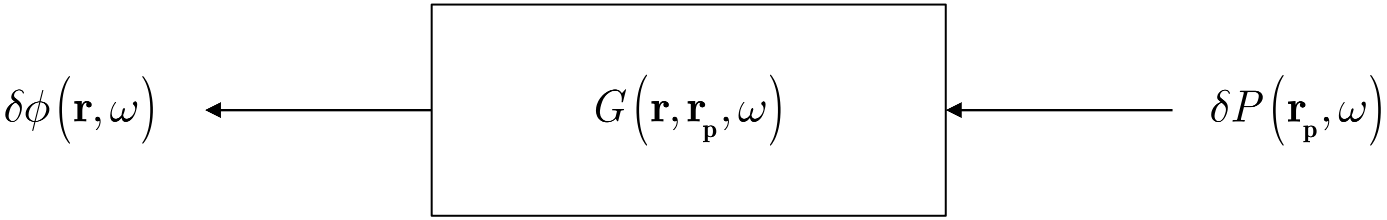


  - ➢ Advantage: "sense" perturbations even far away from the perturbations
  - ➢ Disadvantage: western-type reactors do not always contain many in-core neutron detectors

Introduction and background

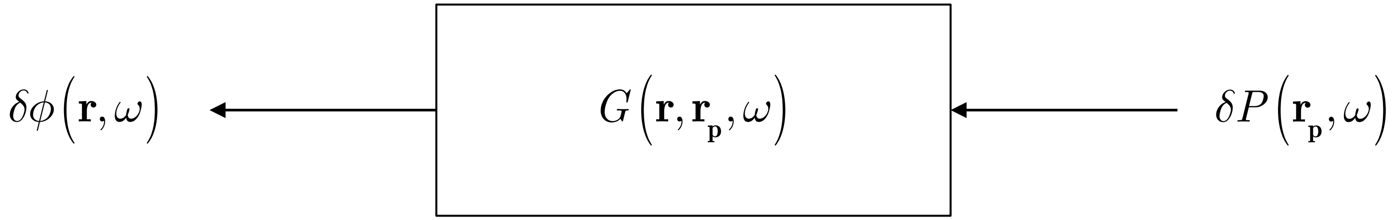
- Neutron noise diagnostics requires establishing relationships between neutron detectors and possible perturbations

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



Introduction and background

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



Introduction and background

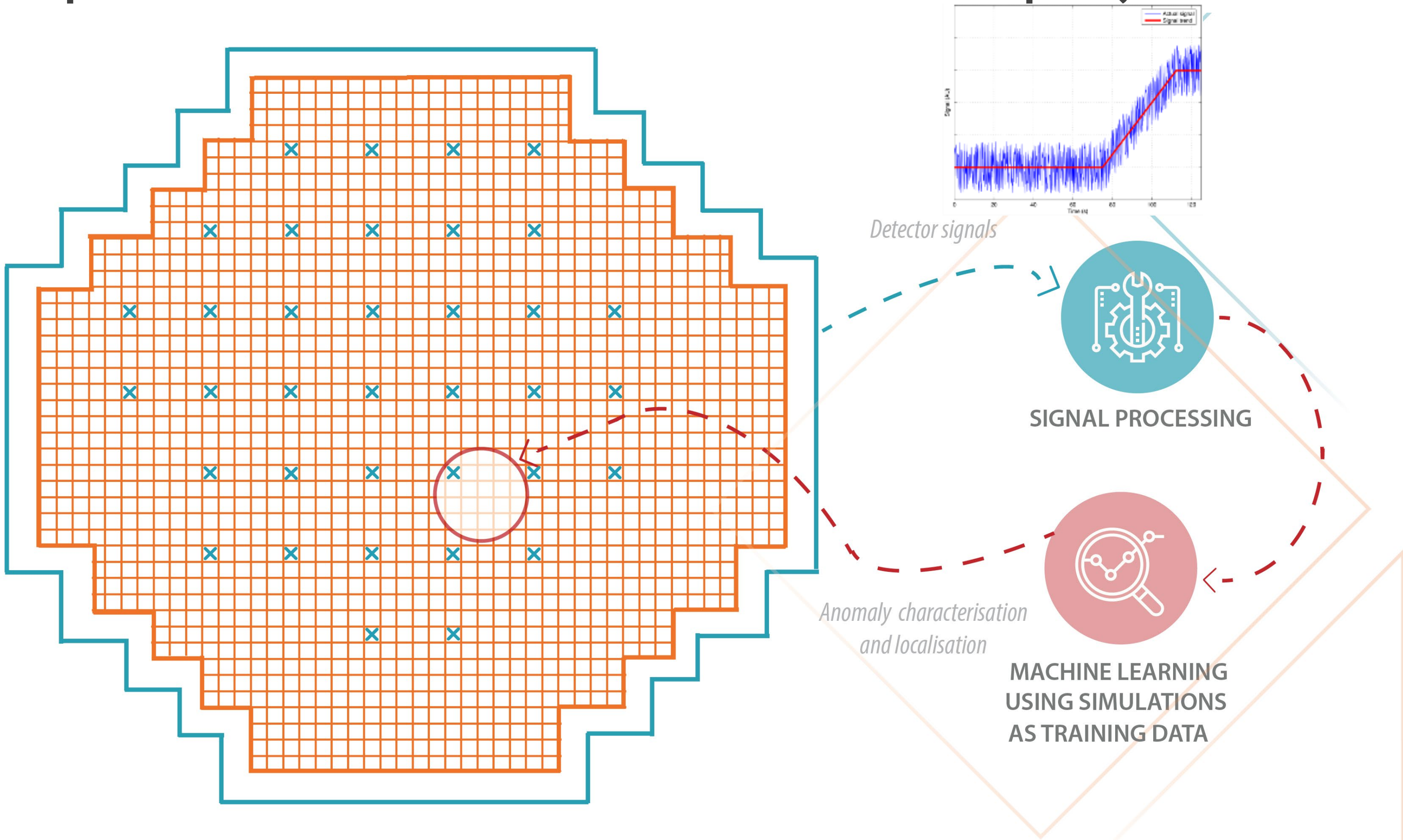
- But noise diagnostics requires the inversion of the reactor transfer function $G(\mathbf{r},\mathbf{r}_\mathbf{p},\omega)$

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

- ➢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

- 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

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)

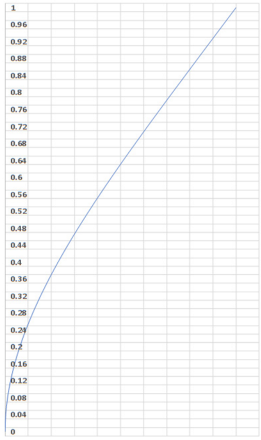
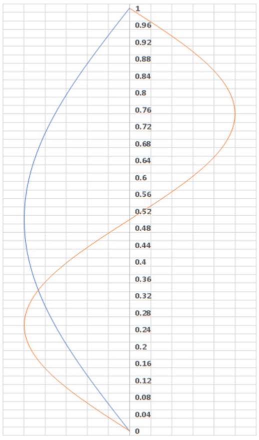
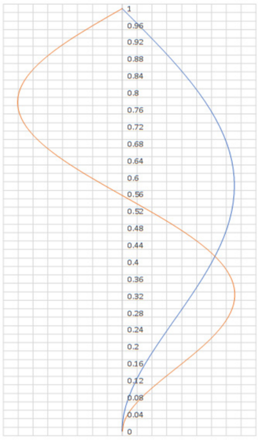
➢ Noise source modelling strongly dependent on the choices made by the user

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

Noise source modelling

Possible axial vibration modes for fuel assemblies:

	Cantilevered beam	Simply supported on both sides	Cantilevered beam and simply supported
Axial shape of the displacement $d(z,t)$ in arbitrary units as a function of the relative core elevation z		 first mode in blue, second mode in orange	 first mode in blue, second mode in orange
Oscillation frequency	Ca. 0.6 – 1.2 Hz	Ca. 0.8 – 4 Hz for the first mode Ca. 5 – 10 Hz for the second mode	Ca. 0.8 – 4 Hz for the first mode Ca. 5 – 10 Hz for the second mode

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):

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

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 analyses

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

- 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

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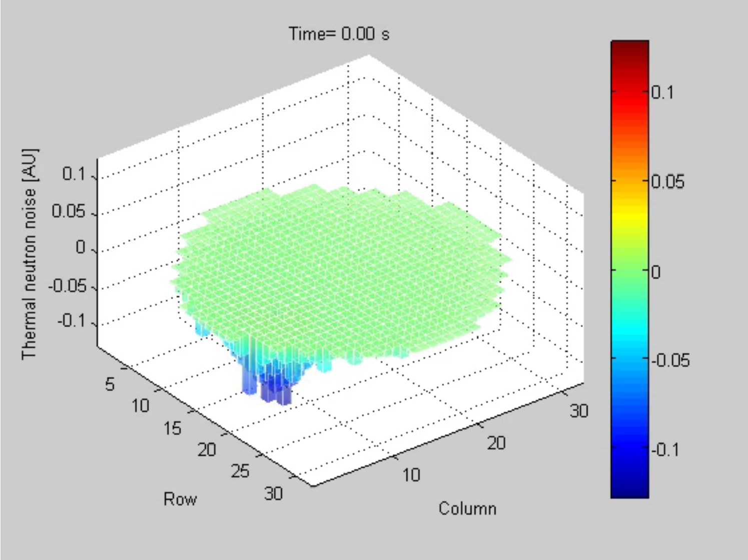
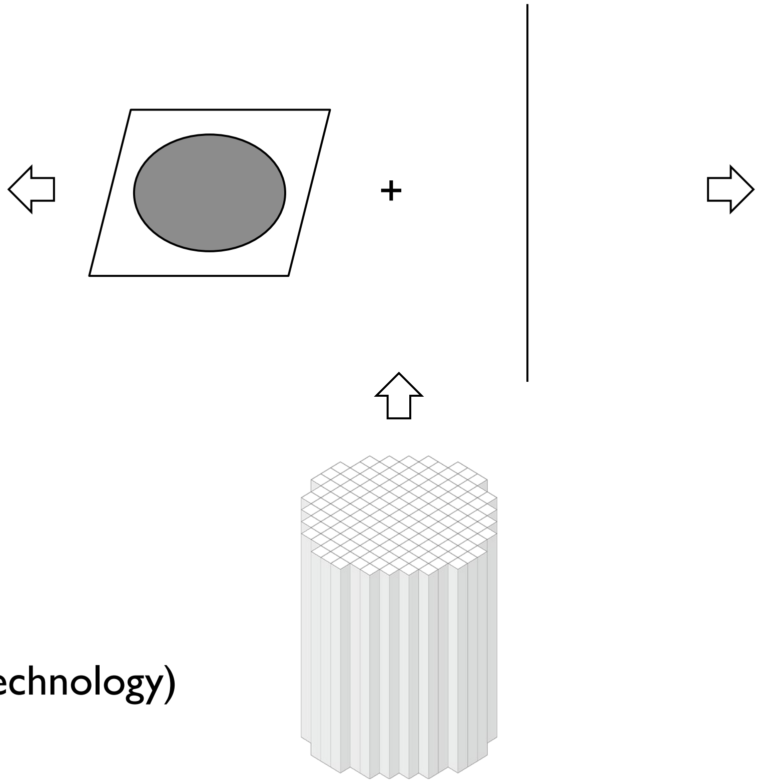
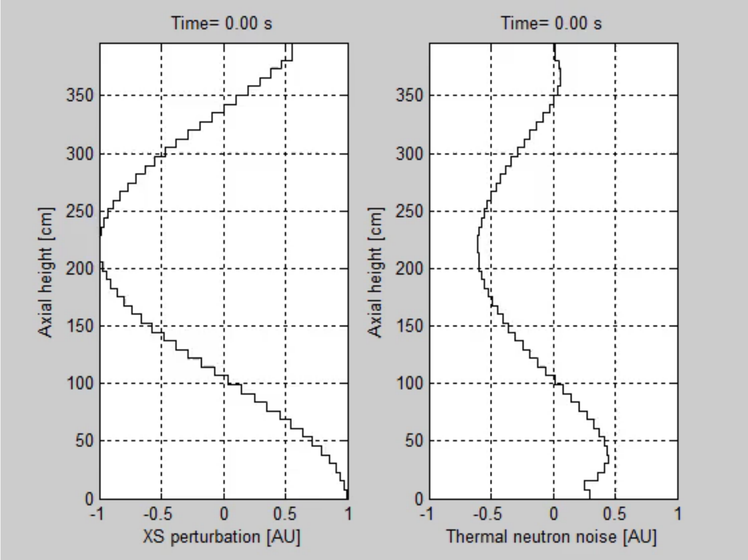
CORE SIM		✓	✓		✓			✓	✓	
CORE SIM+		✓	✓		✓		✓		✓	
Sn-based solver		✓	✓			✓	✓		✓	
Extension of MCNP		✓	✓			✓	✓			✓
Extension of TRIPOLI-4®		✓	✓			✓	✓			✓
Equivalence-based method using MCNP		✓	✓			✓		✓		✓

Modelling of the induced neutron noise

- Example of a travelling perturbation @ 1Hz

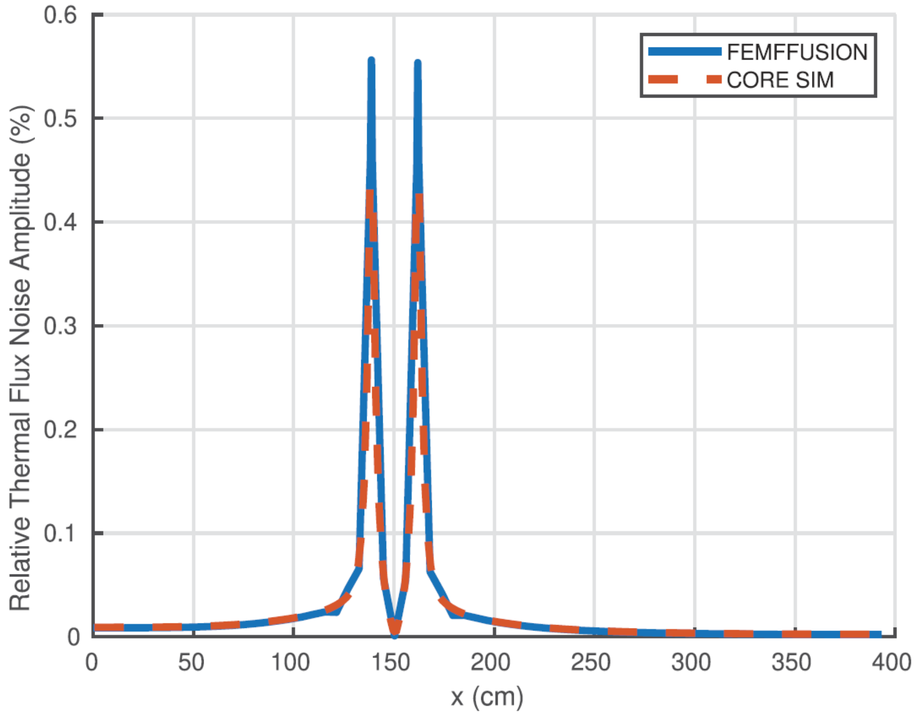


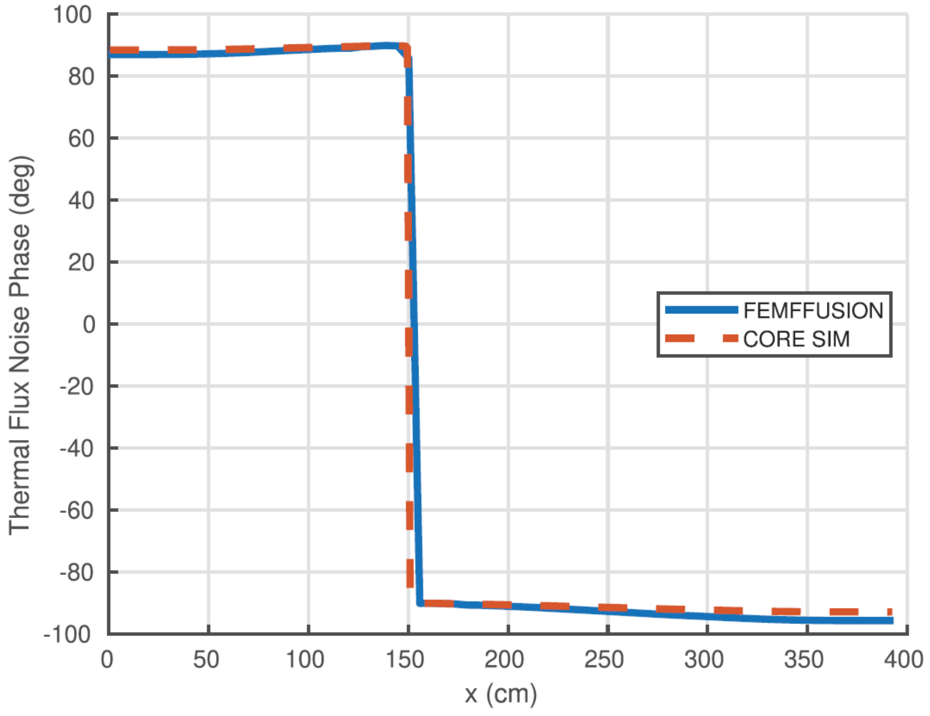




Modelling of the induced neutron noise

- Example of comparisons between frequency- and time-domain approaches:





Conclusions and outlook

Conclusions and outlook

- Modelling the effect of noise sources can be done in many ways:
  - Time-domain/frequency-domain
  - Diffusion/transport
  - Deterministic/probabilistic
  - Fine/coarse spatial mesh

- Taking full advantage of noise analysis requires:
  - A correct modelling of the noise source
  - The estimation of the reactor transfer function
  - Its inversion

Conclusions and outlook

- Extensive verification/validation work (still on-going):
  - By cross-comparisons of the tools in numerical benchmarks
  - Using noise experiments carried out at the AKR-2 and CROCUS reactors

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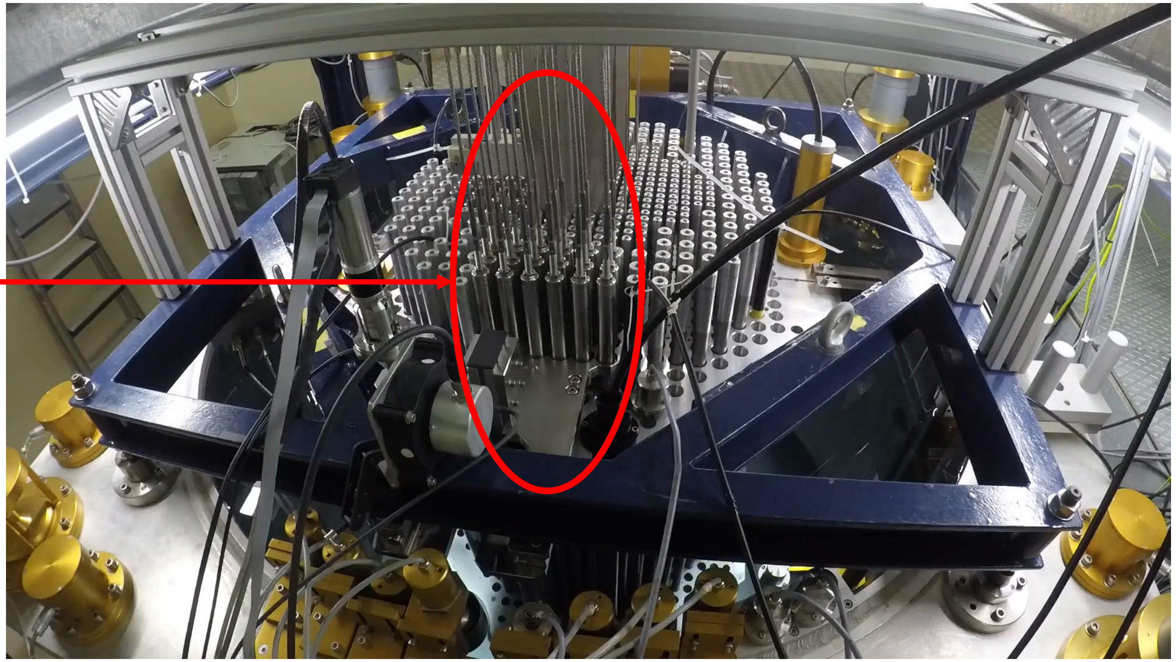
Oscillating fuel rods



COLIBRI experiments
in CROCUS
(© EPFL, Switzerland)

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