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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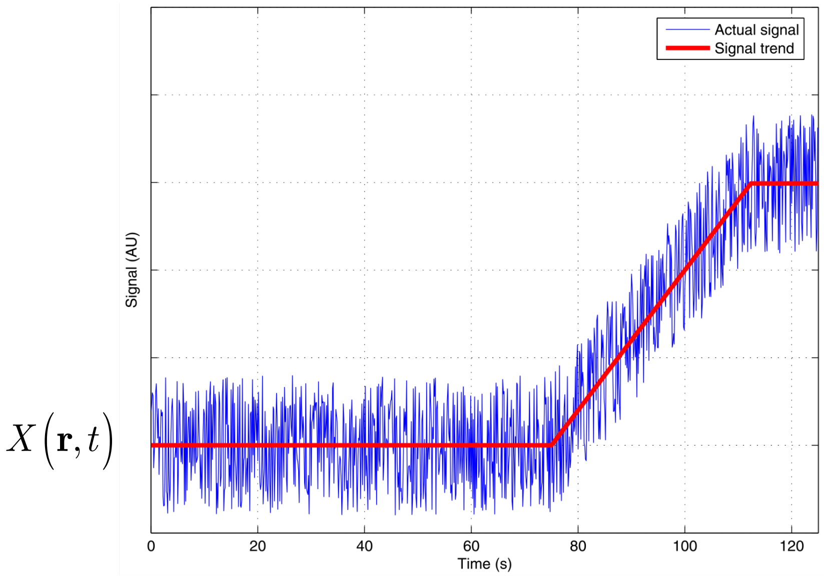
Introduction and background

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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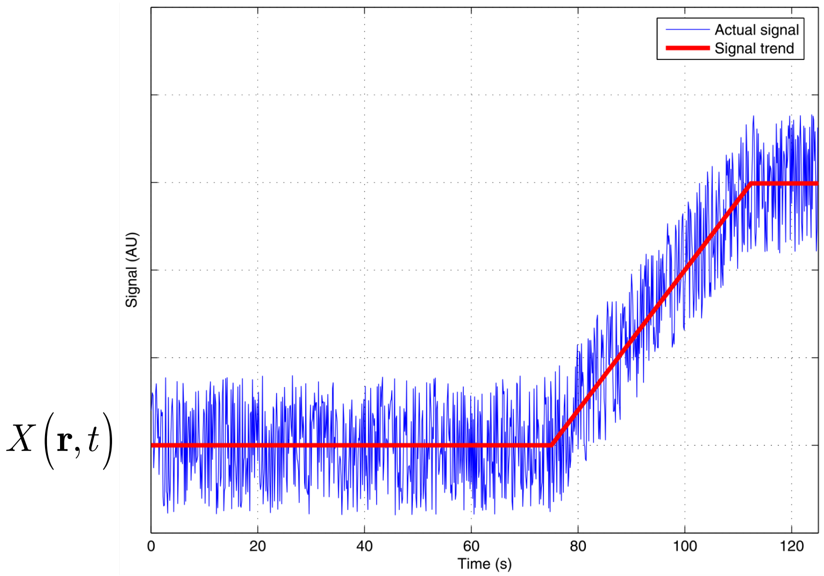

Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

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

actual
signal

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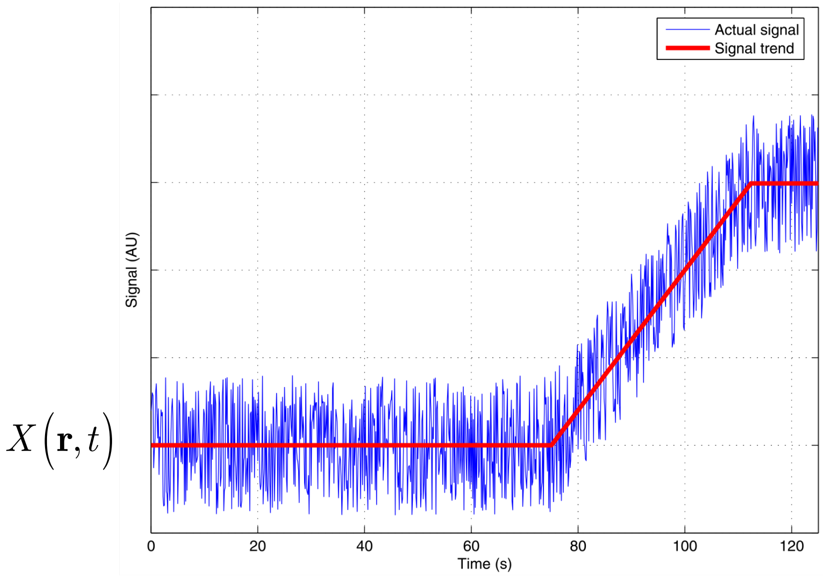

Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

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

signal
trend or mean

Introduction and background

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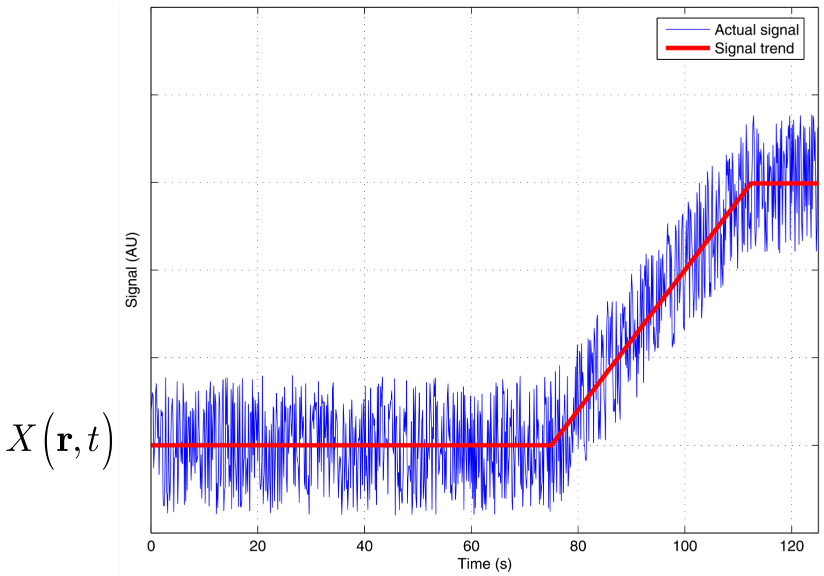


Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

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

fluctuations
or “noise”

➢Fluctuations carrying some valuable information about the system dynamics

Introduction and background

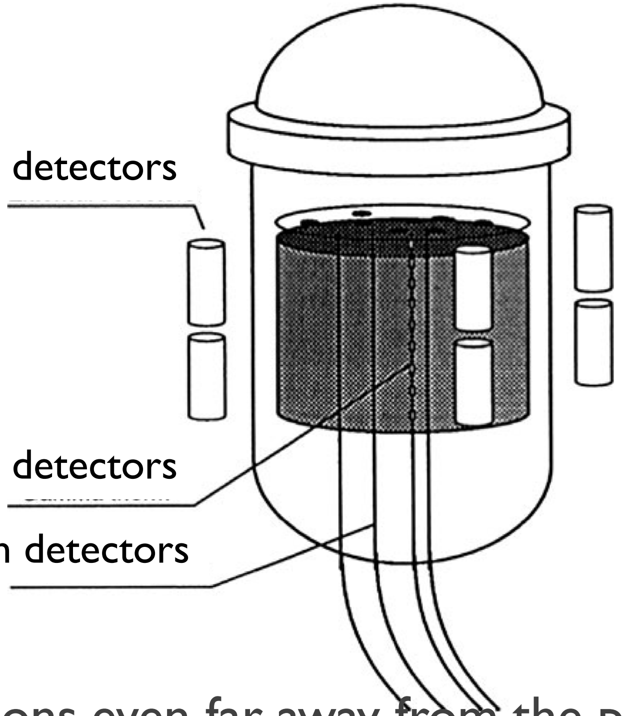
- Fluctuations could be used for “diagnostics”, i.e.:
  - Early detection of anomalies
  - Estimation of dynamical system characteristics

… 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 in-core and ex-core:



Ex-core neutron detectors

Fixed in-core neutron detectors

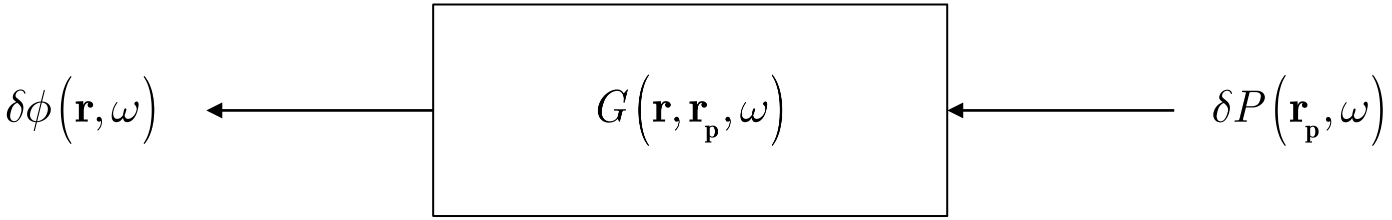
Movable in-core neutron detectors

  - ➢ 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

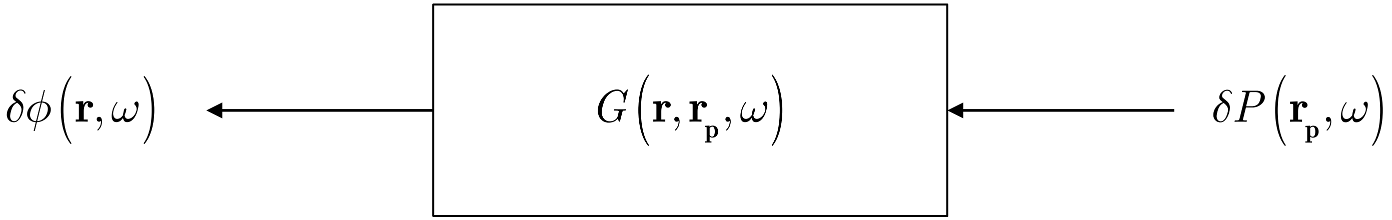
- Neutron noise diagnostics requires establishing relationships between neutron detectors and possible perturbations

➢ 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 $G\left(\mathbf{r},\mathbf{r_p},\omega\right)$



$\delta\phi\left(\mathbf{r},\omega\right)$

$G\left(\mathbf{r},\mathbf{r_p},\omega\right)$

$\delta P\left(\mathbf{r_p},\omega\right)$

Introduction and background

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

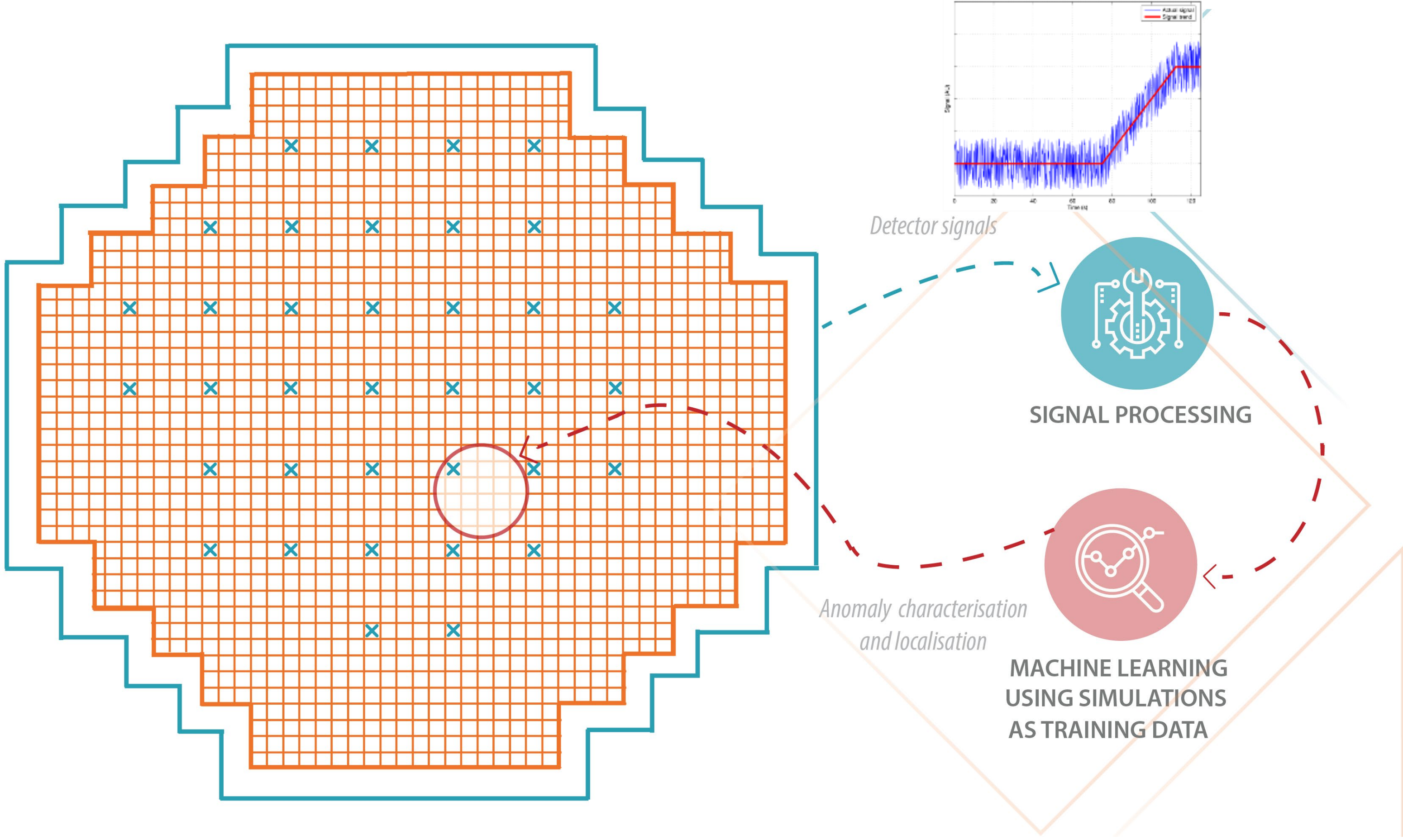
$$\delta\phi\left(\mathbf{r},\omega\right) \longrightarrow \boxed{\left[G\left(\mathbf{r},\mathbf{r}_{\mathbf{p}},\omega\right)\right]^{-1}} \longrightarrow \delta P\left(\mathbf{r}_{\mathbf{p}},\omega\right)$$

➢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:



Detector signals

SIGNAL PROCESSING

Anomaly characterisation and localisation

MACHINE LEARNING USING SIMULATIONS AS TRAINING DATA

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)

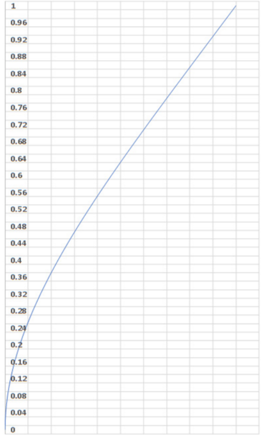
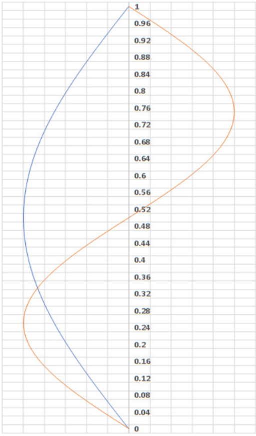
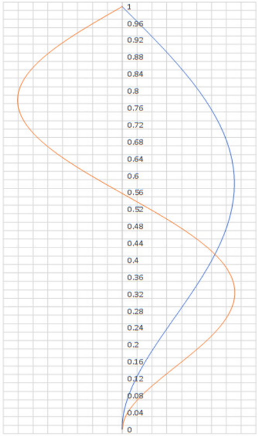
➢Noise source modelling strongly dependent on the choices made by the user

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 $d\left(z,t\right)$ 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):

$$
\begin{aligned}
&\frac{1}{v\left(E\right)}\frac{\partial}{\partial t}\psi\left(\mathbf{r},\mathbf{\Omega},E,t\right)\\
&=-\mathbf{\Omega}\cdot\mathbf{\nabla}\psi\left(\mathbf{r},\mathbf{\Omega},E,t\right)-\Sigma_{t}\left(\mathbf{r},E,t\right)\psi\left(\mathbf{r},\mathbf{\Omega},E,t\right)\\
&+\int_{\left(4\pi\right)}\int_{0}^{\infty}\Sigma_{s}\left(\mathbf{r},\mathbf{\Omega}'\rightarrow\mathbf{\Omega},E'\rightarrow E,t\right)\psi\left(\mathbf{r},\mathbf{\Omega}',E',t\right)d^{2}\mathbf{\Omega}'dE'\\
&+\frac{1}{4\pi}\int_{-\infty}^{t}\int_{0}^{\infty}\nu\left(E'\right)\Sigma_{f}\left(\mathbf{r},E',t'\right)\phi\left(\mathbf{r},E',t'\right)\left[\left(1-\beta\right)\chi^{p}\left(E\right)\delta\left(t-t'\right)+\sum_{i=1}^{N_{d}}\chi_{i}^{d}\left(E\right)\lambda_{i}\beta_{i}e^{-\lambda_{i}\left(t-t'\right)}\right]dt'dE'
\end{aligned}
$$

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

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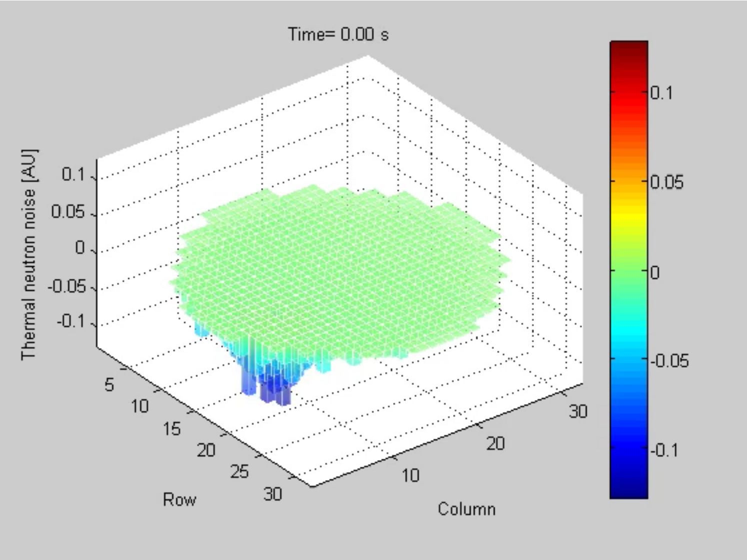
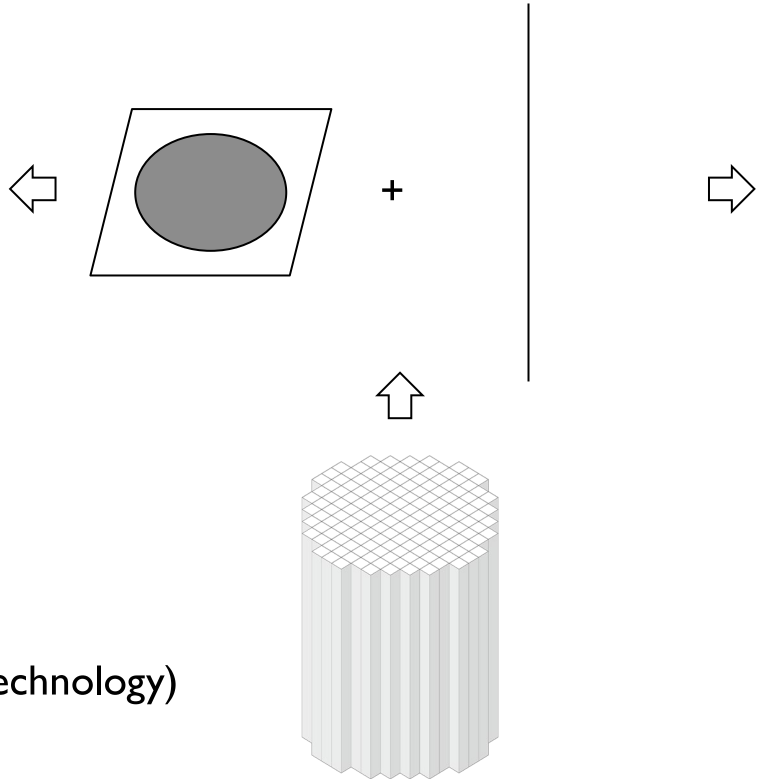
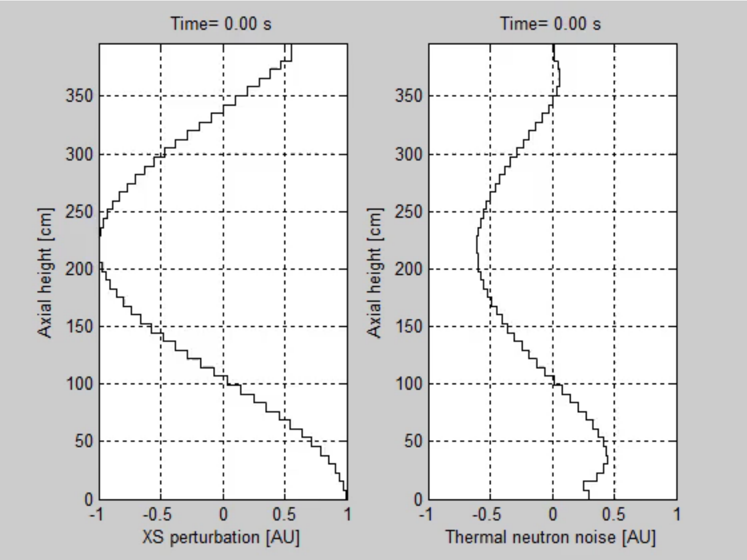
Code name	Domain		Non-linear terms		Angular resolution		Spatial resolution		Approach	
	Time	Frequency	Not modelled	Modelled	Diffusion	Transport	Fine-mesh	Coarse-mesh	Deterministic	Probabilistic
CORE SIM		✓	✓		✓			✓	✓	
CORE SIM+		✓	✓		✓		✓		✓	
Sn-based solver		✓	✓			✓	✓		✓	
Extension of MCNP		✓	✓			✓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

Modelling of the induced neutron noise

- Example of a travelling perturbation @ 1Hz

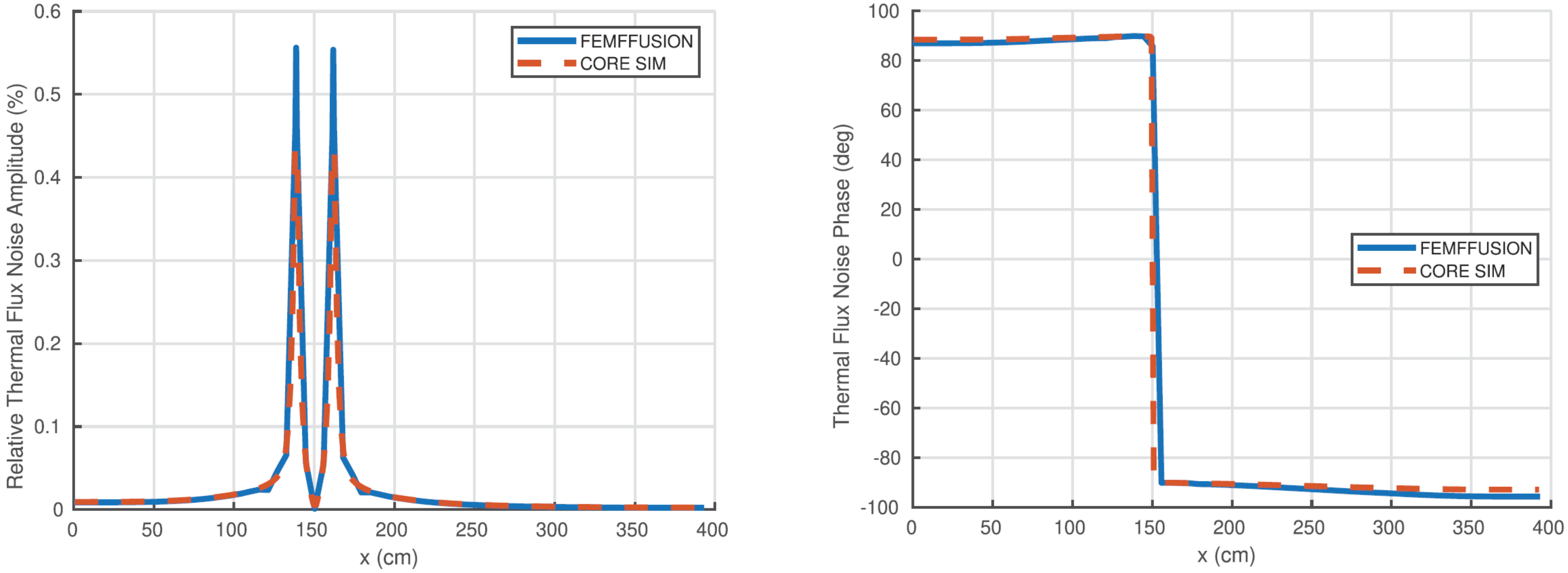






Modelling of the induced neutron noise

- 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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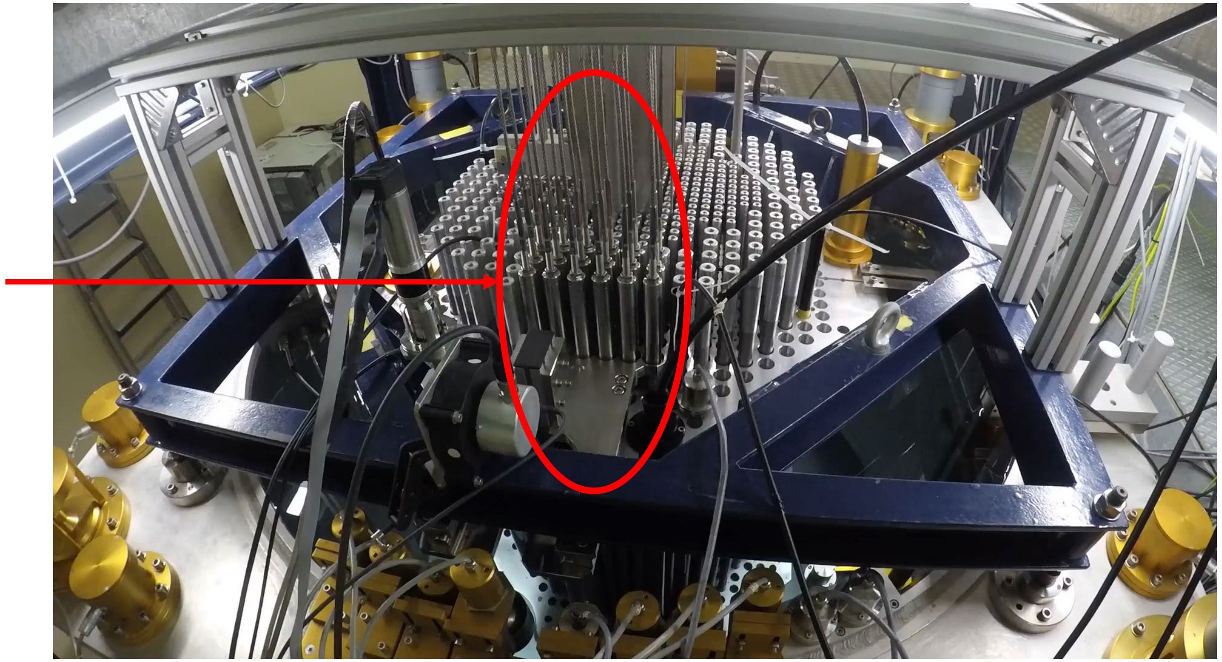

COLIBRI experiments
in CROCUS
(© EPFL, Switzerland)

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