CORTEX

Core monitoring techniques and experimental validation and demonstration

Welcome and project overview

Final CORTEX workshop

Online

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Agenda

June 21, 2021 – CORTEX in a nutshell

08:30 – 08.45: Welcome and project overview
(C. Demazière, Chalmers University of Technology, Sweden)

08:45 – 09:00: Theoretical basis of neutron noise and core diagnostics
(C. Demazière, Chalmers University of Technology, Sweden)

09:00 – 11:00: Development, verification and validation of neutron noise-specific modelling tools

09:00 – 09:45: Overview of the modelling tools used or developed in CORTEX and their verification
(P. Vinai, Chalmers University of Technology, Sweden)

09:45 – 10:15: Break

10:15 – 11:00: Overview of the validation exercises undertaken in CORTEX
(M. Hursin, Ecole Polytechnique Fédérale de Lausanne, Switzerland)

11:00 – 11:45: Development of advanced signal analysis and machine learning techniques in support to core diagnostics
(S. Kollias, University of Lincoln, United Kingdom)

11:45 – 12:30: Questions and wrap-up
(C. Demazière, Chalmers University of Technology, Sweden)

Agenda

June 22, 2021 – Neutron noise-based core diagnostics applied to commercial nuclear reactors

08:30 – 08:35: Welcome and introduction
(J. Herb, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany)

08:35 – 09:05: Required instrumentation and data acquisition system
(G. Girardin, Kernkraftwerk Gösge-Daniken AG, Switzerland)

09:05 – 09:15: Required data for modelling the reactor transfer function
(C. Demazière, Chalmers University of Technology, Sweden)

09:15 – 09:45: Necessary signal processing
(C. Montalvo, Universidad Politécnica de Madrid, Spain)

09:45 – 10:15: Break

10:15 – 11:45: Machine learning architectures versus diagnostic tasks
(G. Leontidis, University of Aberdeen, United Kingdom; M. Yu, University of Lincoln, United Kingdom;
G. Alexandridis, Institute of Communication and Computer Systems, Greece)

11:45 – 12:15: Examples of applications on commercial reactors within CORTEX
(J. Herb, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany)

12:15 – 12:45: Questions and wrap-up
(J. Herb, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany;
C. Demazière, Chalmers University of Technology, Sweden)

Practicalities

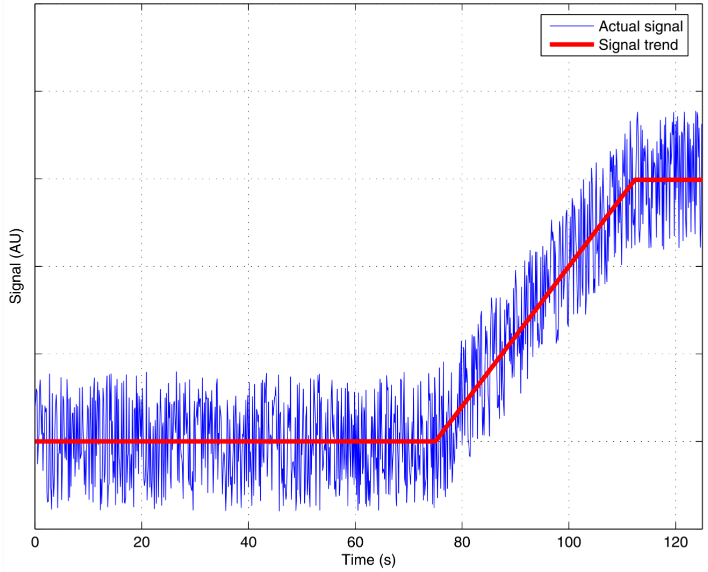
- Turn off your camera and you microphone by default
- In case of question, use "Raise your hand" and turn on your camera and microphone when instructed by the moderator of the meeting
- Meeting will be recorded

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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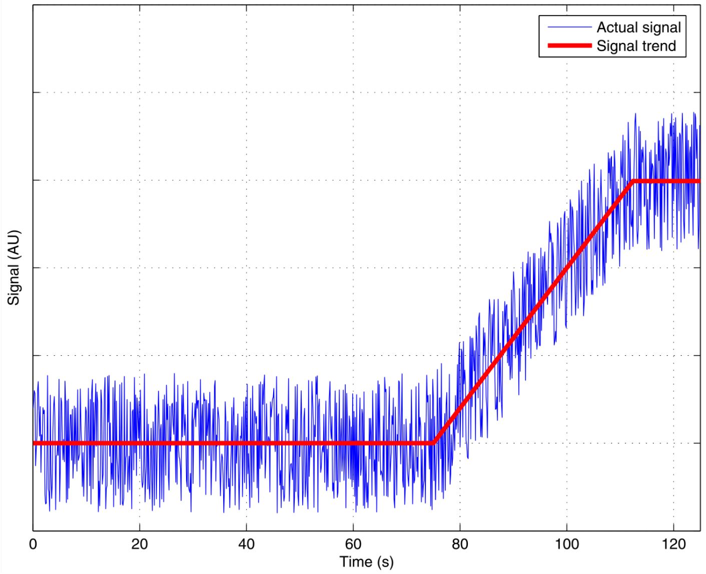

Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

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

actual
signal

Introduction and background

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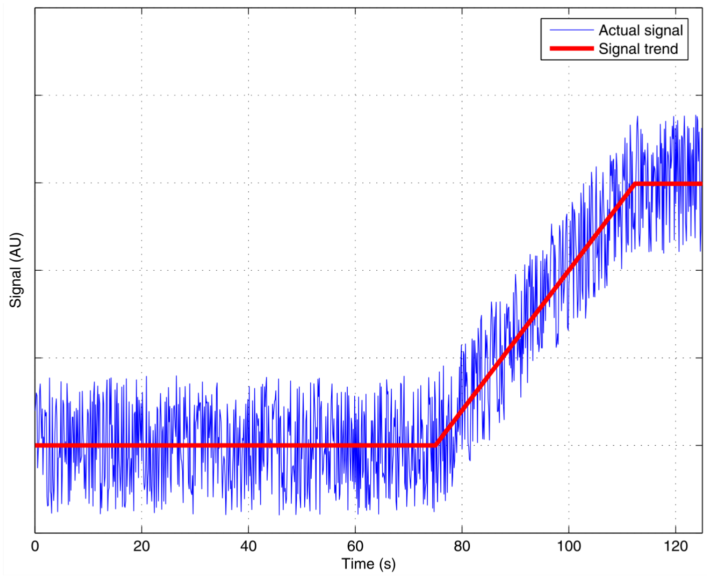
$X(\mathbf{r},t)$



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

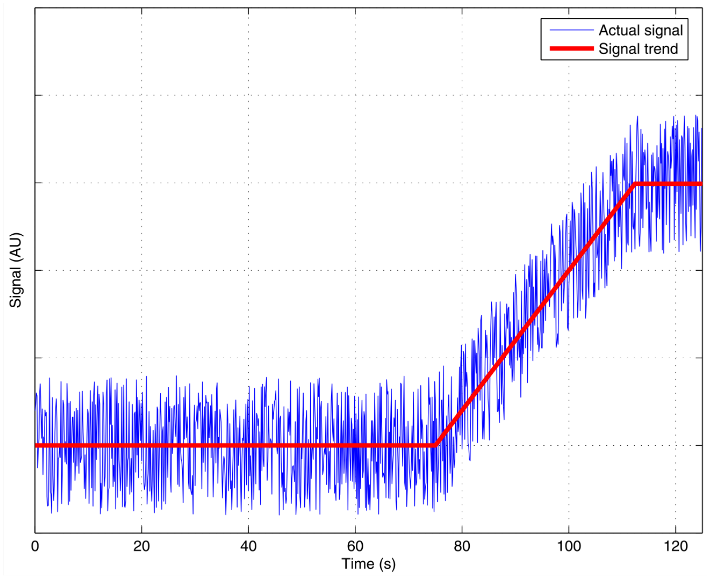
$$X(\mathbf{r},t) = X_0(\mathbf{r},t) + \delta X(\mathbf{r},t)$$

signal
trend or mean

Introduction and background

- 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

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

fluctuations or "noise"

➢ Fluctuations carrying some valuable information about the system dynamics

Introduction and background

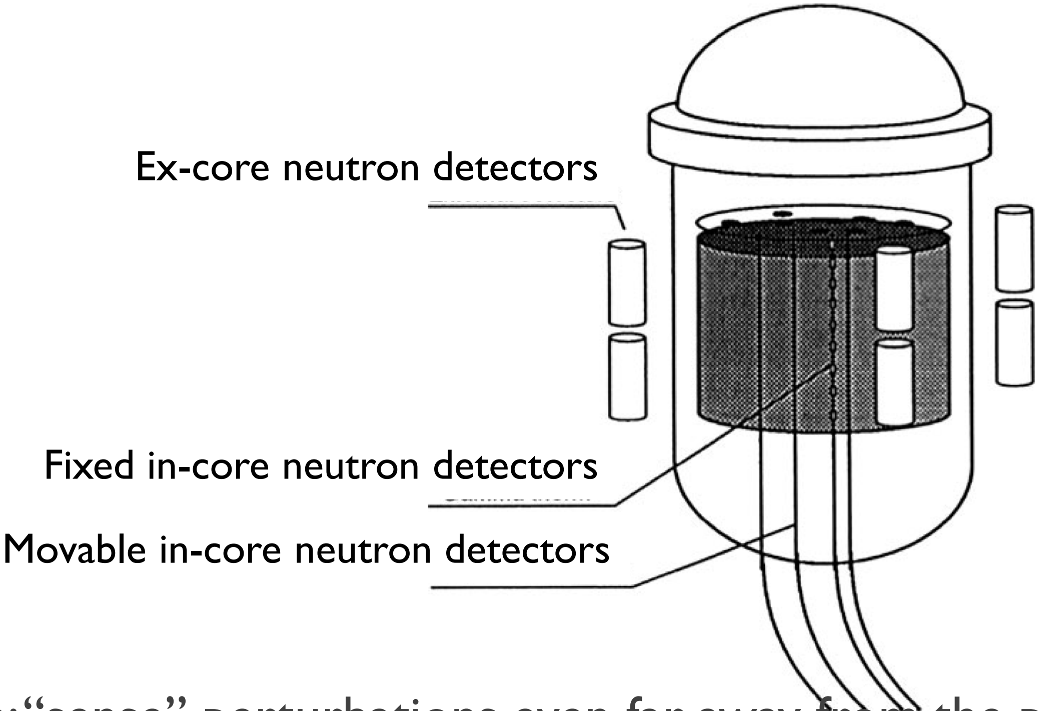
- Fluctuations could be used for "diagnostics", i.e.:
  - Early detection of anomalies
  - Estimation of dynamical system characteristics

… 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" $G\left(\mathbf{r},\mathbf{r}_{\mathbf{p}},\omega\right)$ needs to be determined

$$\delta\phi\left(\mathbf{r},\omega\right) \longleftarrow \boxed{G\left(\mathbf{r},\mathbf{r}_{\mathbf{p}},\omega\right)} \longleftarrow \delta P\left(\mathbf{r}_{\mathbf{p}},\omega\right)$$

Introduction and background

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

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Introduction and background

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

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

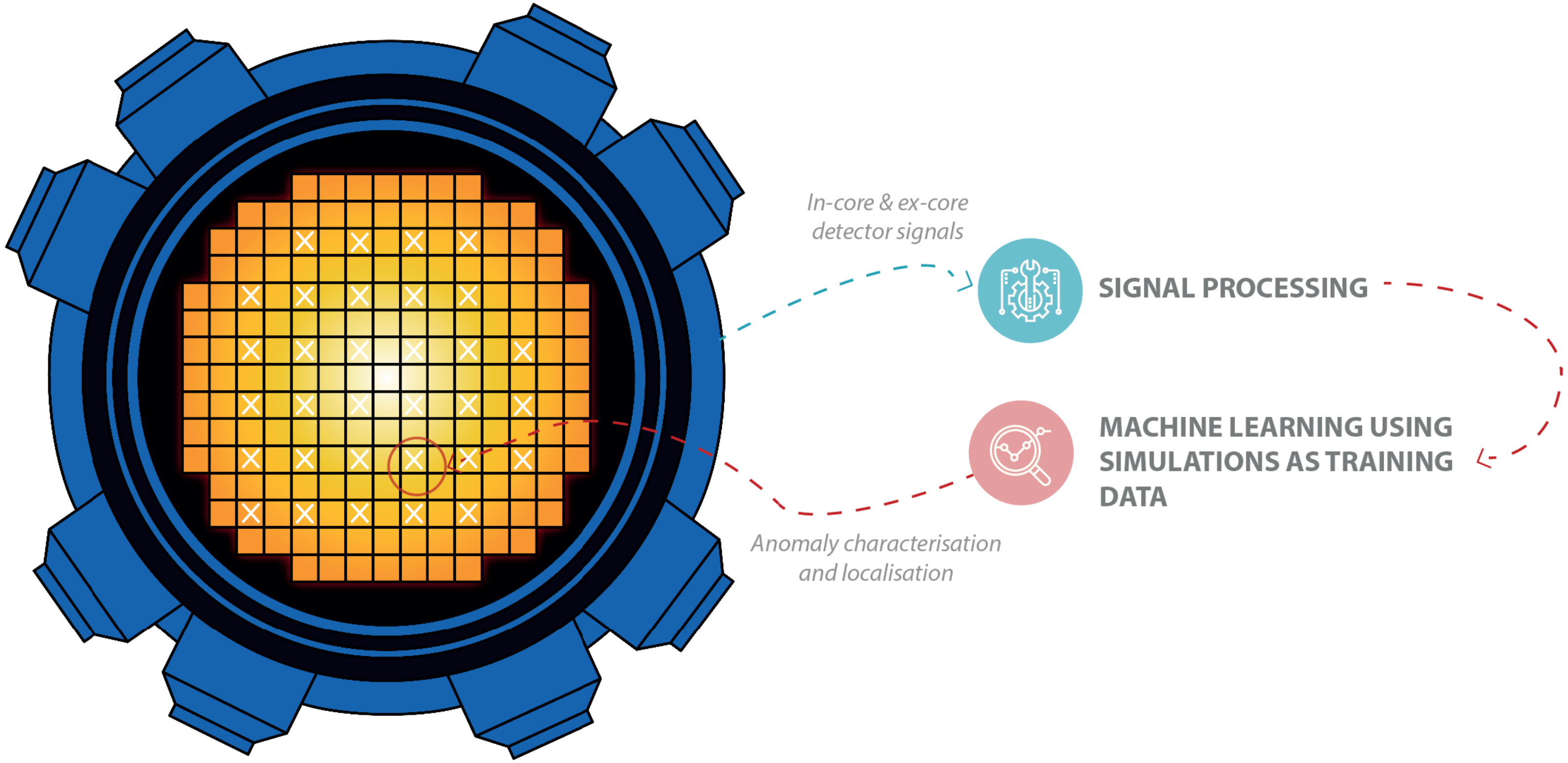
➢ Machine learning could be used for that purpose

➢ 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)

CORTEX project overview

CORTEX project overview

- Overall principle of the Horizon 2020 CORTEX project:



More info at:
cortex-h2020.eu

CORTEX project overview

- Project aims for CORTEX:
  - WP1: **Developing high fidelity tools for simulating stationary fluctuations**
    (leader: P. Vinai, Chalmers University of Technology, Sweden)
  - WP2: **Validating those tools against experiments to be performed at research reactors**
    (leader: M. Hursin, Ecole Polytechnique Fédérale de Lausanne, Switzerland)
  - WP3: **Developing advanced signal processing and machine learning techniques** (to be combined with the simulation tools)
    (leader: S. Kollias, University of Lincoln, United Kingdom)
  - WP4: **Demonstrating the proposed methods for both on-line and off-line core diagnostics and monitoring**
    (leader: J. Herb, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany)
  - WP5: **Disseminating the knowledge gathered from within the project to stakeholders in the nuclear sector**
    (leader: C. Demazière, Chalmers University of Technology, Sweden)

CORTEX project overview

- 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)

CORTEX project overview

- 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)

CORTEX project overview

- Project started on September 1st, 2017 and ends on August 31st, 2021
- More than 70 researchers involved
- 25 deliverables to the European Commission
- 23 presentations made at conferences and workshops
- 5 poster presented at conferences
- 35 peer-reviewed conference papers
- 15 peer-reviewed journal publications
- 8 training courses/hands-on training sessions offered

Theoretical basis of neutron noise and core diagnostics

Theoretical basis of neutron noise and core diagnostics

- Neutron noise dating back from the early days of nuclear power (oscillator experiments in the Clinton Pile at Oak Ridge National Laboratories, USA in late 40ies)
- First applications in commercial reactors:
  - Core-barrel vibrations at the Palisades plant, USA (1975)
  - Estimation of in-core coolant velocity in German BWRs (1979)

Theoretical basis of neutron noise and core diagnostics

- Modelling of the neutron noise can be done using the neutron transport equation (Boltzmann equation):

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

➢ A model to represent the effect of a given perturbation onto the macroscopic cross-section is required

Theoretical basis of neutron noise and core diagnostics

- Modelling of the effect of the cross-section perturbations onto the neutron flux can be done in several ways:
  - Low/high order in angle
  - Low/high order in space
  - Low/high order in energy
  - Time- or frequency-domain
  - Deterministic methods or probabilistic methods (Monte Carlo)

➢ See WP1 presentation titled "Overview of the modelling tools used or developed in CORTEX and their verification"

➢ See WP2 presentation titled "Overview of the validation exercises undertaken in CORTEX"

Theoretical basis of neutron noise and core diagnostics

- For diagnostic purposes, one needs to check that the induced neutron noise is significantly different, depending on the type of perturbation and its location

➢ Examination of the amplitude and phase of the neutron noise usually allows differentiating the type of perturbation

➢ Nevertheless, some more intricate responses can arise in some cases

  ➢ Requires a faithful modelling of the reactor transfer function

➢ For the identification of the location of a perturbation, an appreciable deviation from point-kinetics is required

Theoretical basis of neutron noise and core diagnostics

- Point-kinetic component of the neutron noise:

  Using the factorization:

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

  with

  $P(t)$ amplitude factor

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

  such that

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

Theoretical basis of neutron noise and core diagnostics

- 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: $\delta\psi\left(\mathbf{r},t\right)$

Theoretical basis of neutron noise and core diagnostics

- Point-kinetic component of the neutron noise:

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

$$\delta P\left(\omega\right) = G_0\left(\omega\right)\delta\rho\left(\omega\right)$$

with

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

zero-power reactor transfer function

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

Theoretical basis of neutron noise and core diagnostics

- The ability to localize anomalies from very few detector readings requires a “sufficient” deviation from point-kinetics

➢ See WP3 presentation titled “Development of advanced signal analysis and machine learning techniques in support to core diagnostics”

➢ See WP4 presentations tomorrow “Neutron noise-based core diagnostics applied to commercial nuclear reactors”

Theoretical basis of neutron noise and core diagnostics

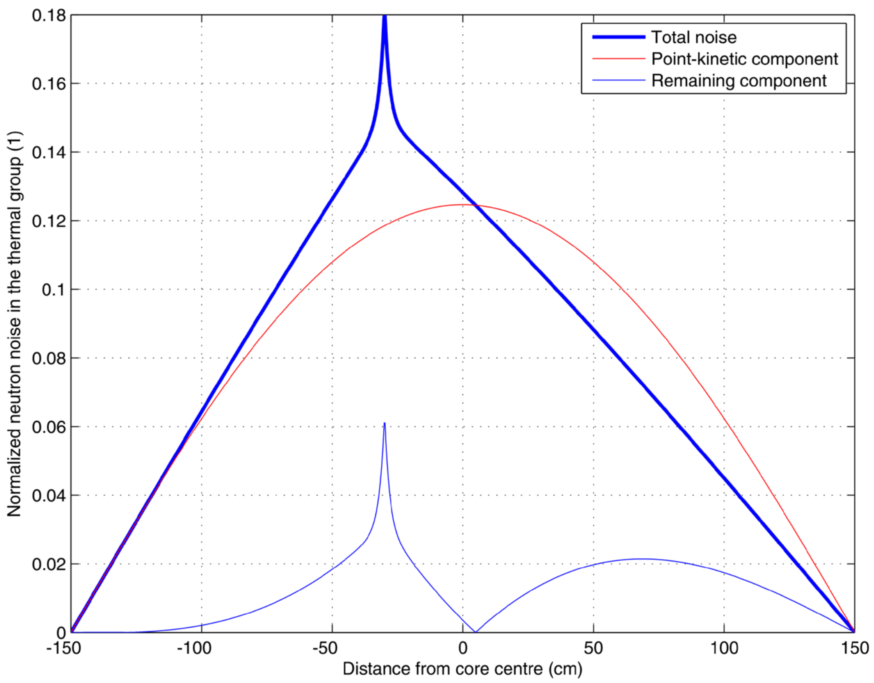


Illustration of the difference between the point-kinetic component and the total induced neutron noise in the frequency domain at 1 Hz, for a perturbation located at -30 cm from the centre of a nuclear core of size 300 cm.

Conclusions

Conclusions

- CORTEX methodology relying on a cross-disciplinary expertise in:
    - Reactor physics, dynamics, and modelling
    - Experimental reactor physics
    - Plant measurements
    - Signal processing and analysis
    - Artificial Intelligence and Machine Learning

➢ Main purpose of the workshop: summarize the main findings and their implications for core monitoring in commercial reactors

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