CORTEX

Core monitoring techniques and experimental validation and demonstration

Anomaly detection in operating nuclear reactors – Overview of the recent advances of the CORTEX project

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Introduction

- Ageing fleet of reactors and more frequent operational problems to be expected
- Recent problems observed in pre-KONVOI PWRs in Germany, Switzerland and Spain

➢ Of value to:

  - Monitor the instantaneous state of the reactor during operation
  - Detect possible anomalies early on
  - Pinpoint the reasons of the anomalies

Overview of CORTEX

- CORTEX project proposal submitted to the Euratom 2016-2017 work program (CORe monitoring Techniques and EXperimental validation and demonstration)

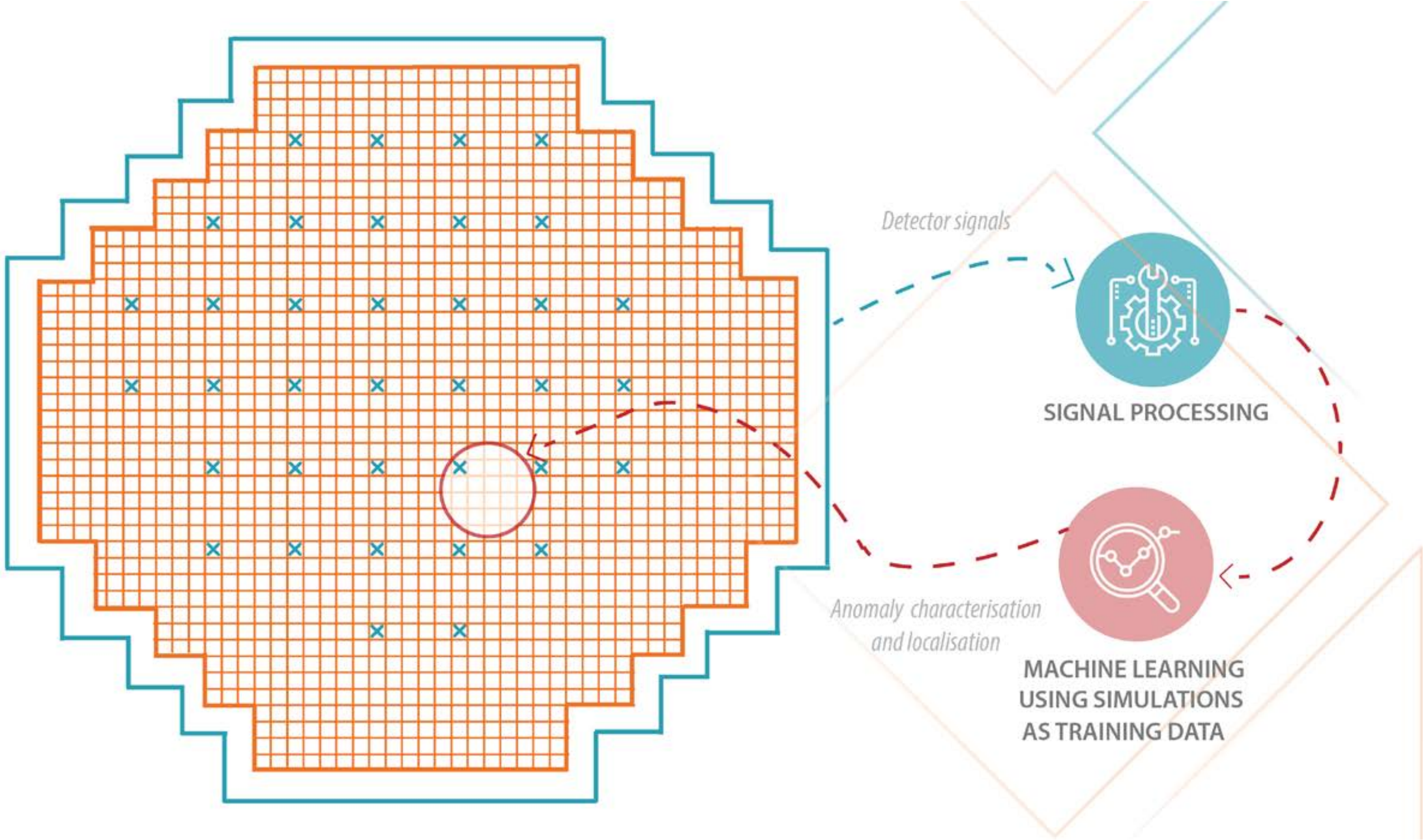
- CORTEX obtained the NUGENIA label in August 2016

- CORTEX project approved for funding by the European Commission in February 2017

- CORTEX project started on September 1st, 2017

Overview of CORTEX

- Project concept:

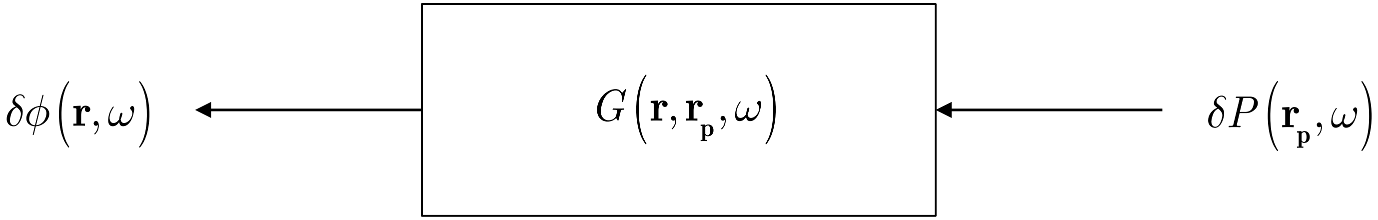


Overview of CORTEX

- Signal analysis techniques of help…

  but insufficient for backtracking the nature and spatial distribution of possible anomalies

➢ Need to be able to invert the reactor transfer function $G\left(\mathbf{r},\mathbf{r_p},\omega\right)$



Overview of CORTEX

- Signal analysis techniques of help…

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➢Need to be able to invert the reactor transfer function $G\left(\mathbf{r},\mathbf{r_p},\omega\right)$

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

Description of CORTEX

- Project technical aims:
  - 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

Description of 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)

Description of 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)

WP1: Development of modelling capabilities for reactor noise analysis

Objectives:

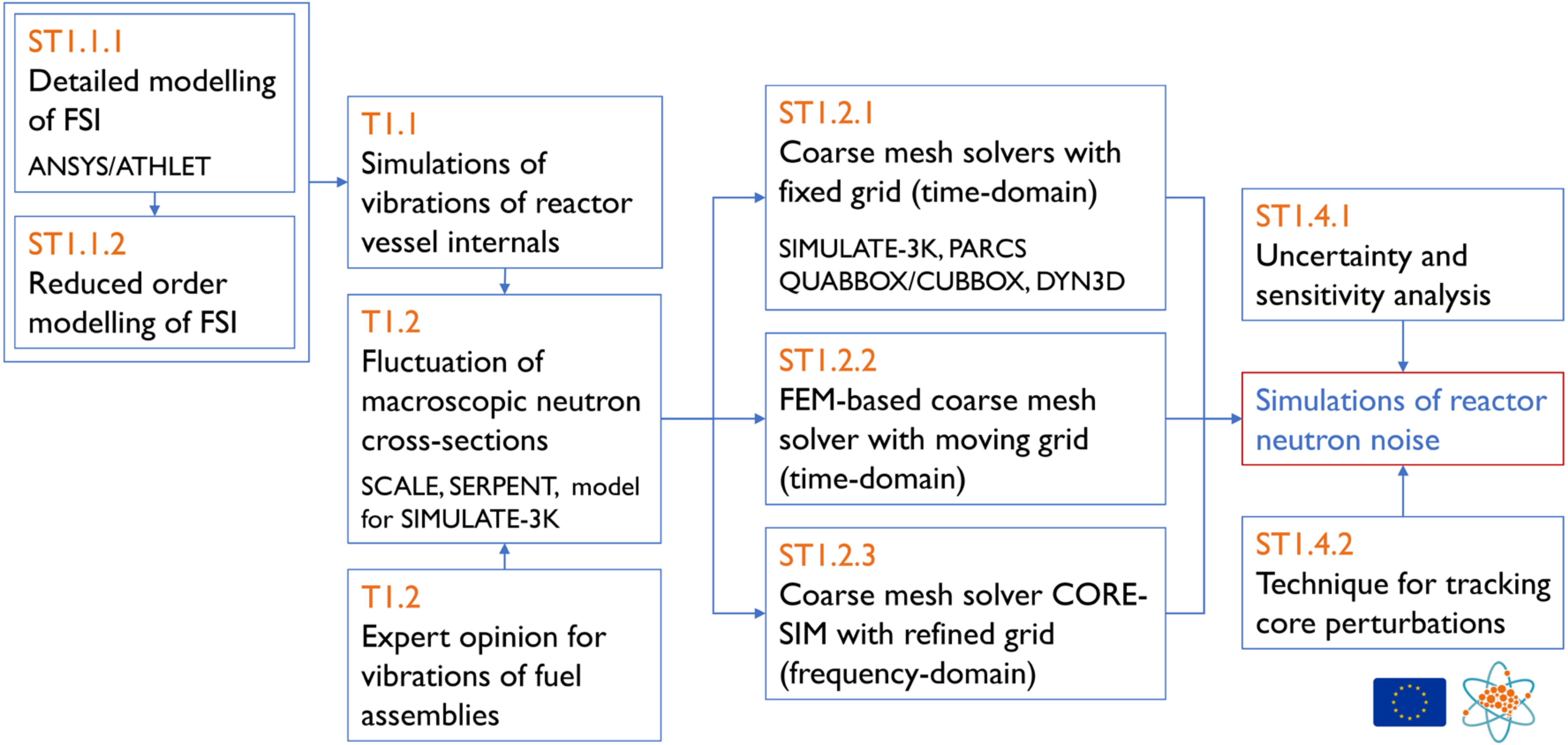
- To develop modelling capabilities allowing the determination, for any reactor core, of the fluctuations in neutron flux resulting from known perturbations applied to the system
- To express such perturbations as either fluctuations of macroscopic cross-sections based on expert opinion, or in more physical terms, such as vibrations of components (FSI)
- To evaluate the uncertainties associated to the estimation of the reactor transfer function and to perform sensitivity analysis in reactor dynamic calculations

WP1: Development of modelling capabilities for reactor noise analysis

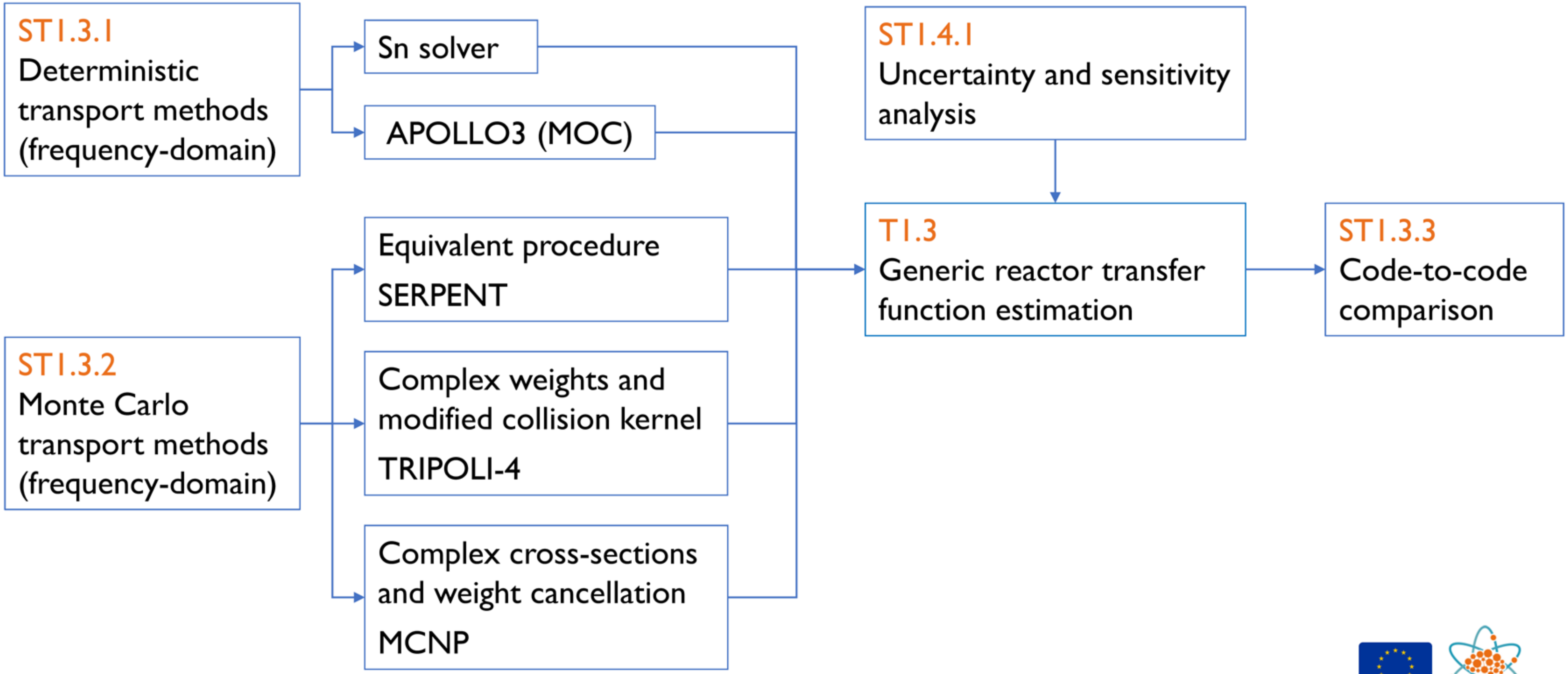
Several complementary approaches:

- Use of existing codes or codes specifically developed for noise analysis
- Codes working in either the time- or in the frequency-domain
- Use of coarse mesh or fine mesh approaches
- Codes based either on deterministic or probabilistic methods

WP1: Development of modelling capabilities for reactor noise analysis

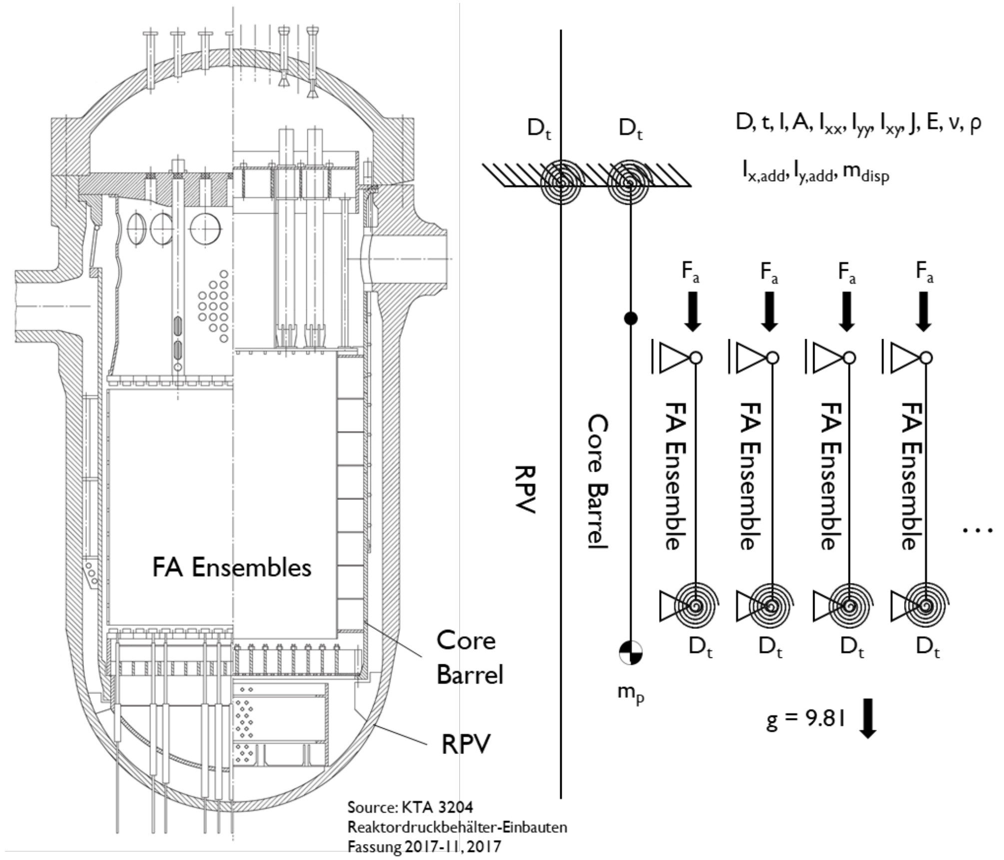


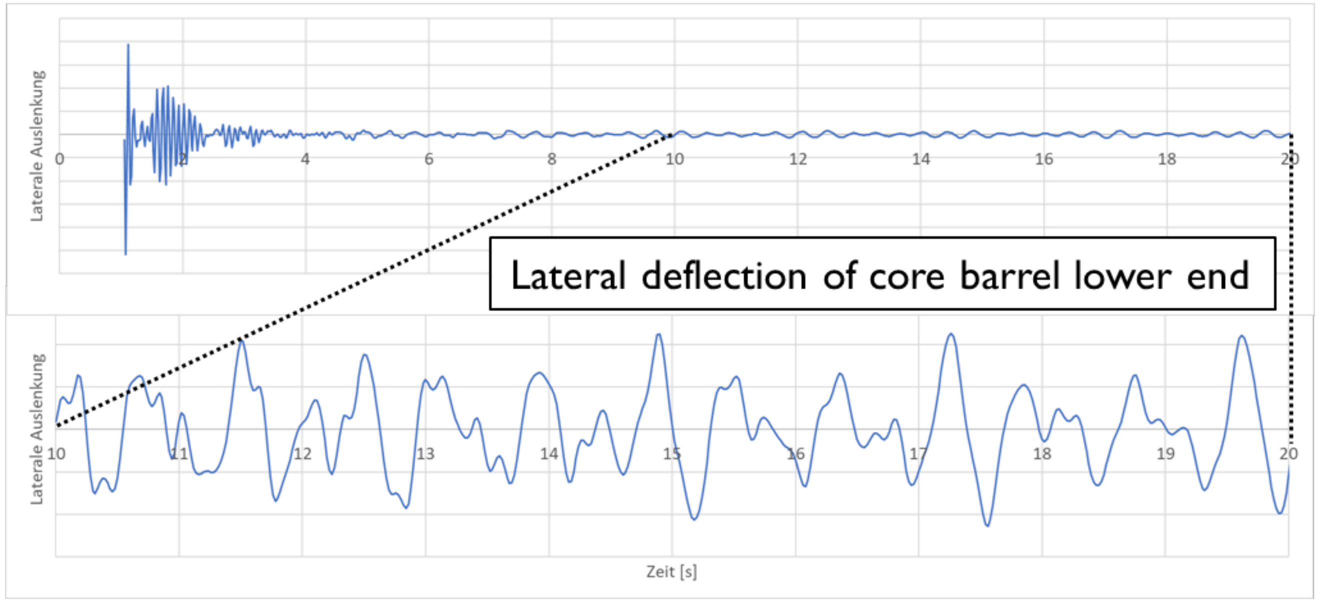
WP1: Development of modelling capabilities for reactor noise analysis



WP1: Development of modelling capabilities for reactor noise analysis

Modelling of FSI (courtesy of GRS) for an arbitrary test deflection:





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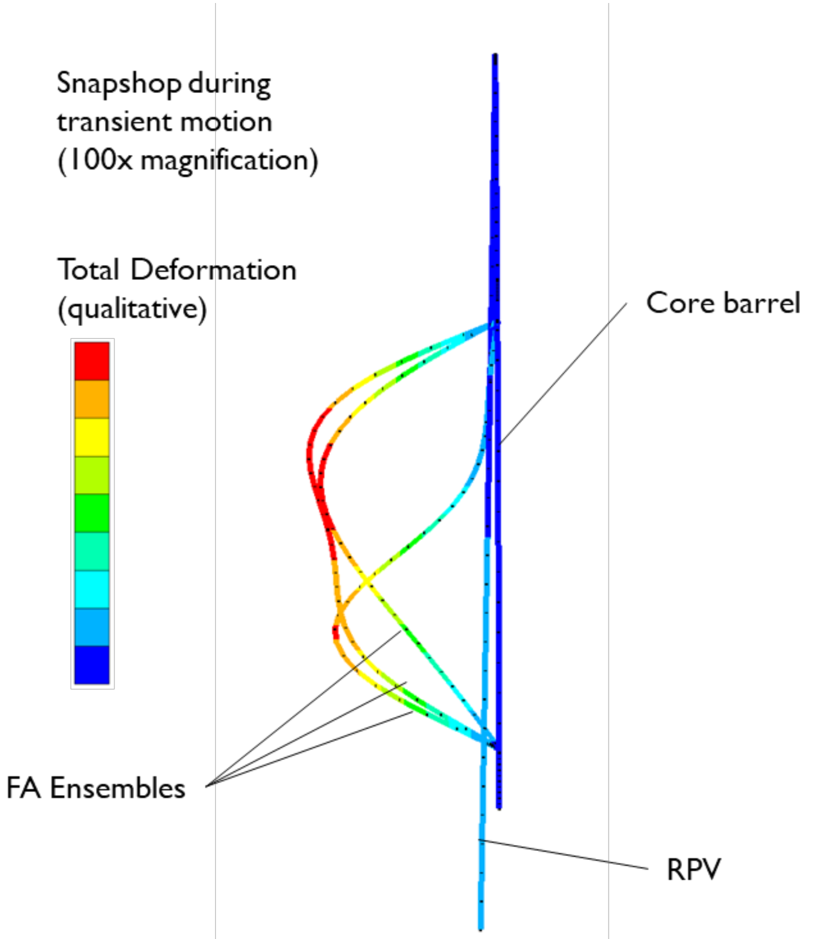
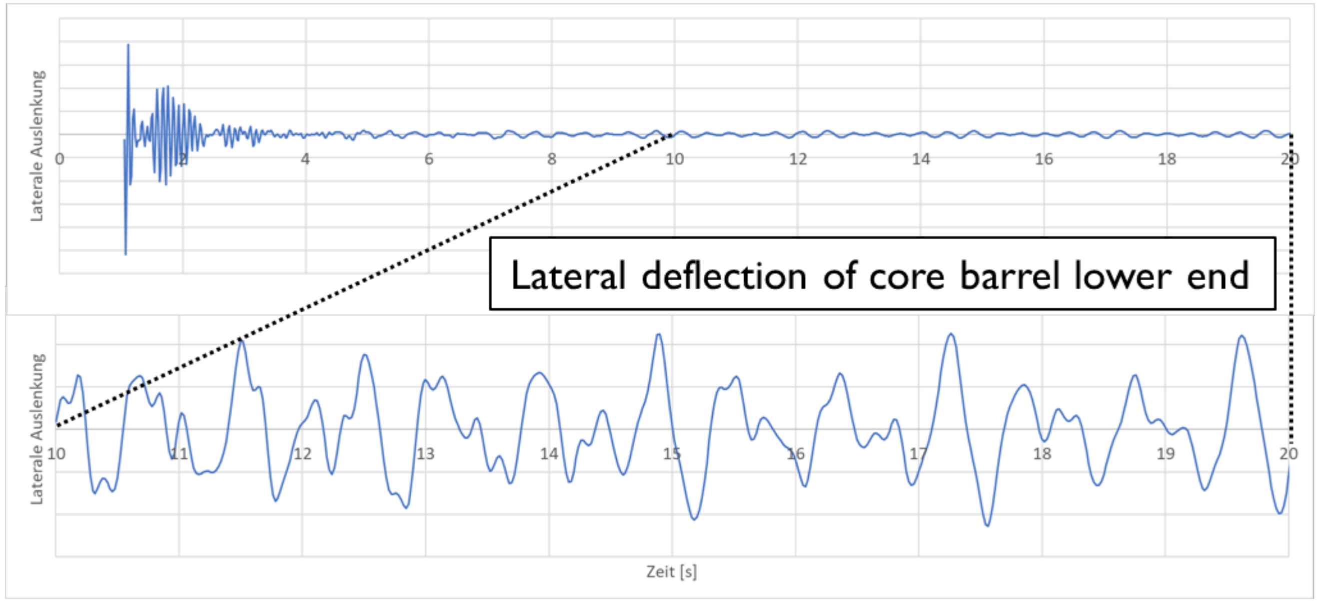
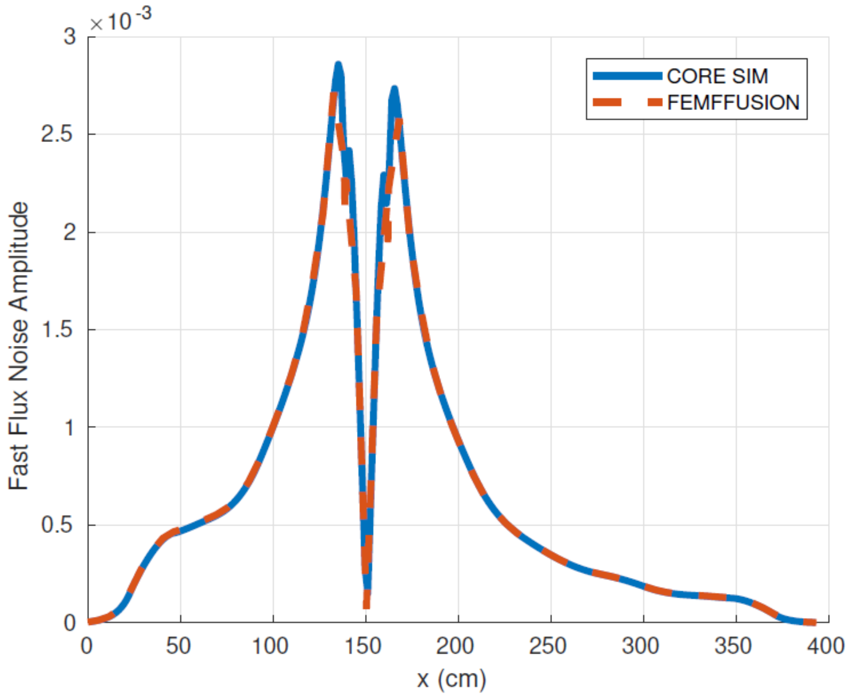


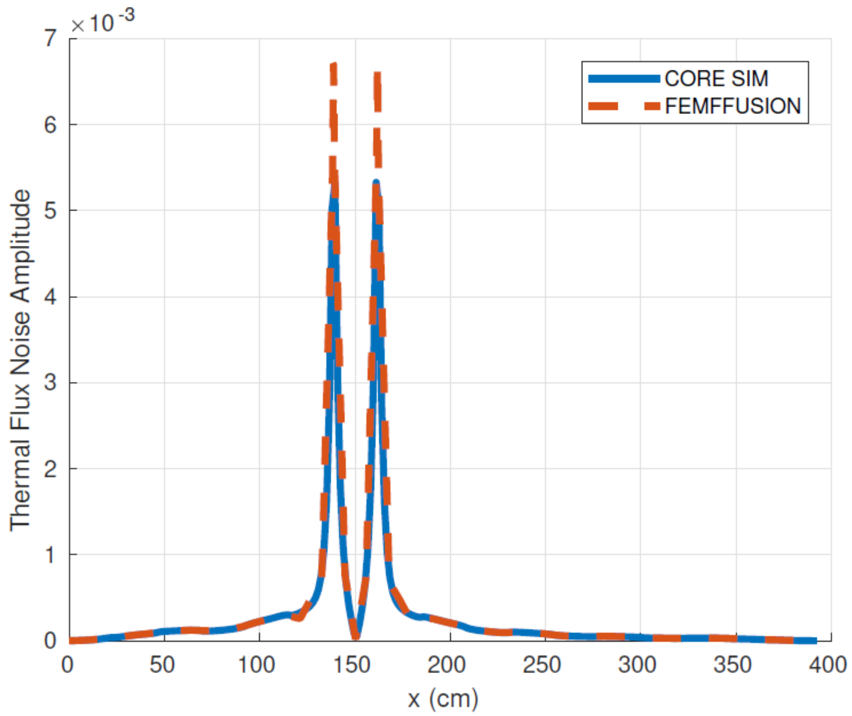


WP1: Development of modelling capabilities for reactor noise analysis

Modelling of fuel assembly vibrations (courtesy of UPV):

- FEMFFUSION = time-domain code based on FEM
- CORE SIM = frequency-domain code based on FVM





WP2: Validation of the modelling tools against experiments in research reactors

Objectives:

- Validation of the modelling tools produced in WP1 against experimental measurements: localized absorber of variable strength + moving absorber

- Development of new detectors

WP2: Validation of the modelling tools against experiments in research reactors

Use of the AKR-2 (TU Dresden) and CROCUS (EPFL) research reactors for reactor transfer function validation

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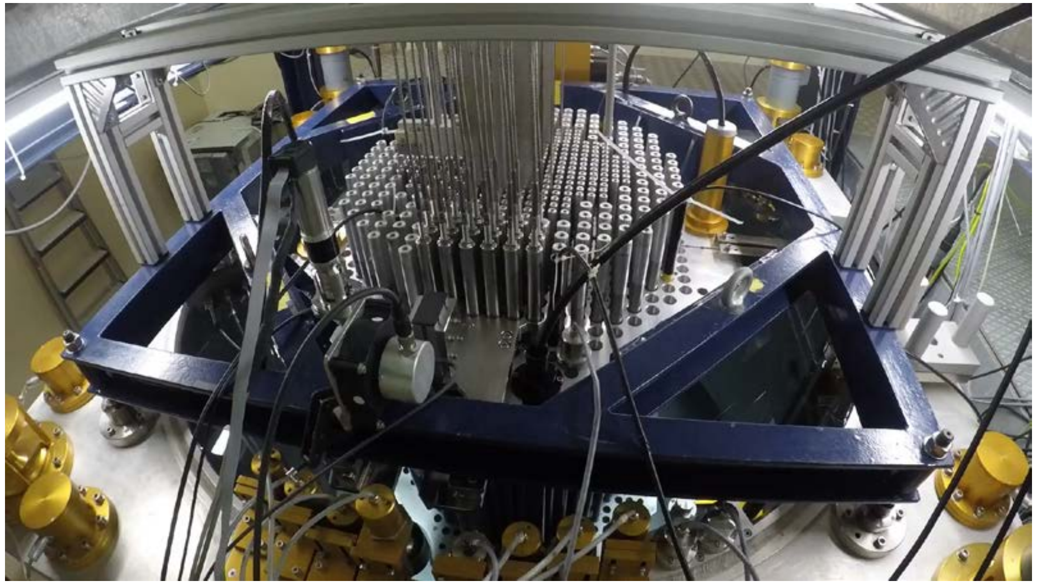


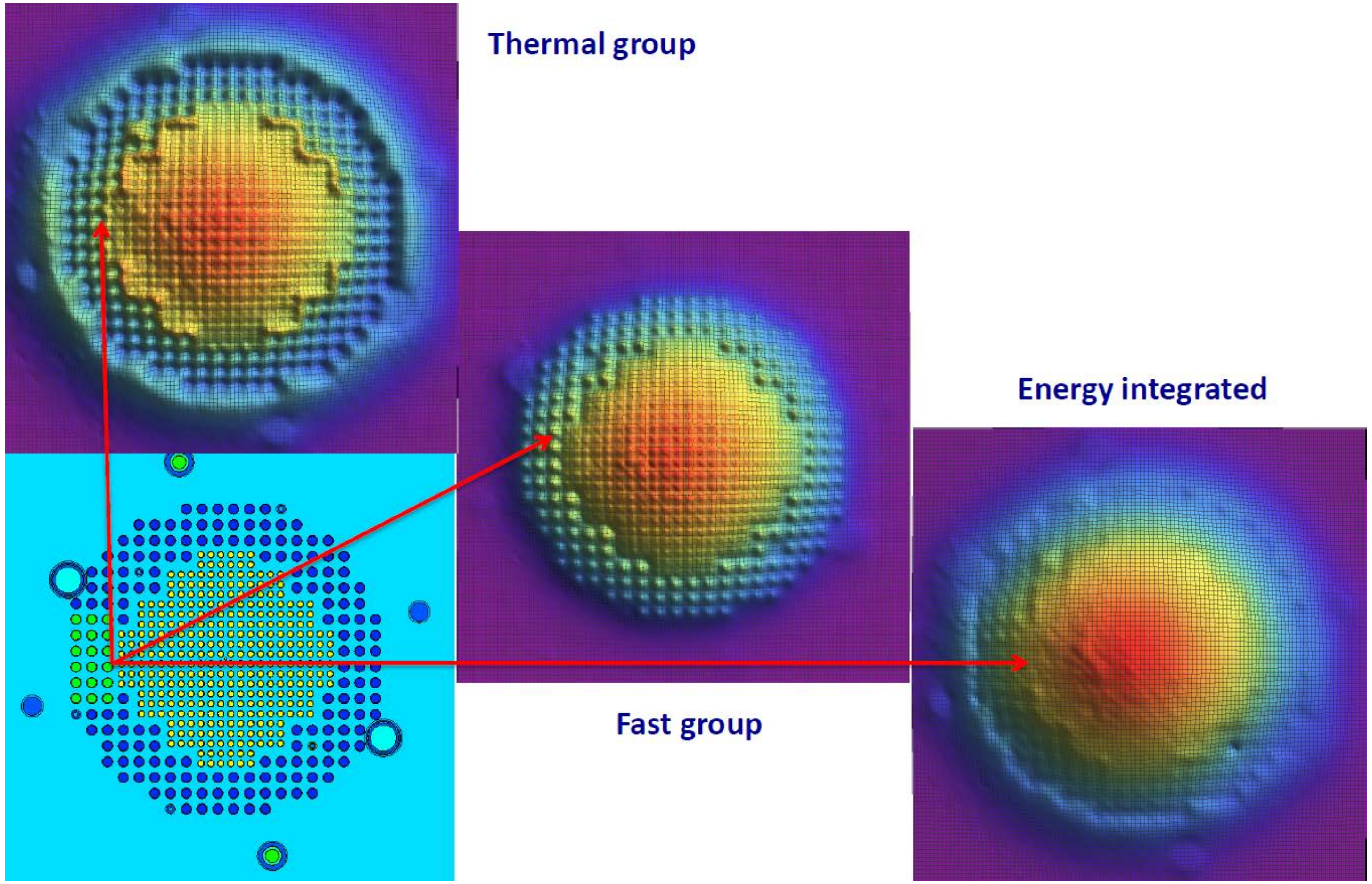
COLIBRI experiments in the CROCUS reactor @EPFL, Switzerland

AKR-2 reactor @TU Dresden, Germany

- Successful qualification of the acquisition systems at AKR-2 and CROCUS

WP2: Validation of the modelling tools against experiments in research reactors

- On-going comparisons between simulations and measurements



Amplitude of the neutron noise estimated by TRIPOLI-4® for the COLIBRI experiments (courtesy of CEA)

WP3: Development of advanced signal processing and machine learning methodologies for analysis of plant data

Objectives:

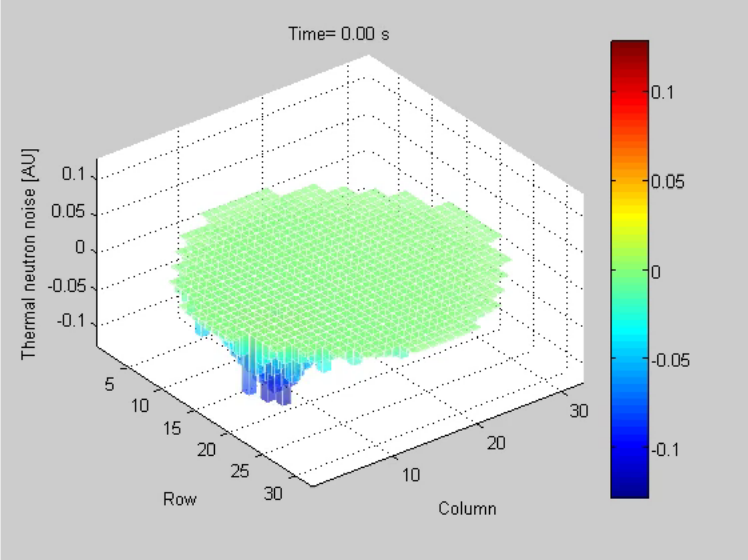
- ➢Detection of abnormal fluctuations and their classification
- ➢Inversion of the reactor transfer function
- ➢Handling of the scarcity of in-core instrumentation
- ➢Handling of intermittences

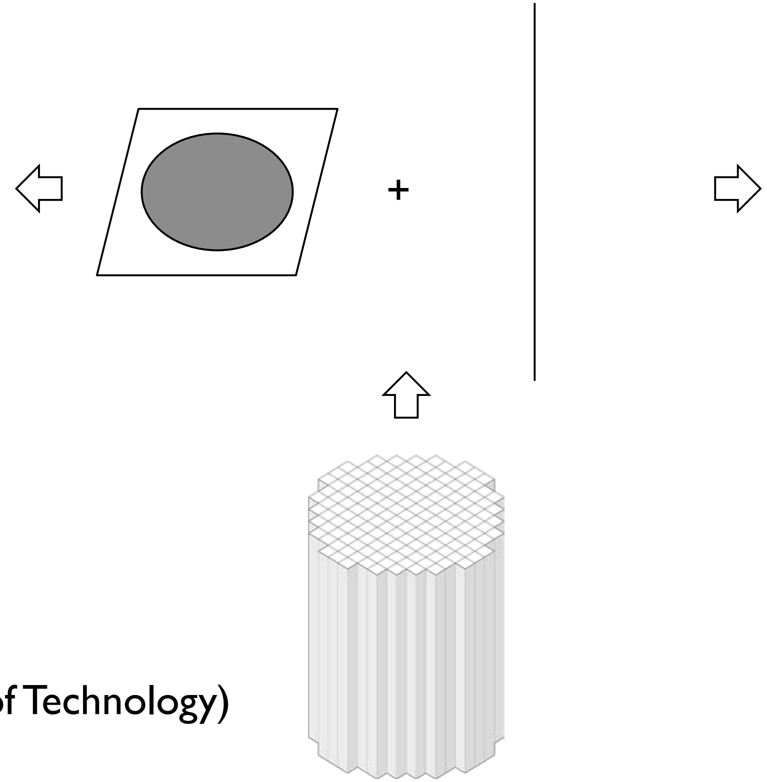
WP3: Development of advanced signal processing and machine learning methodologies for analysis of plant data

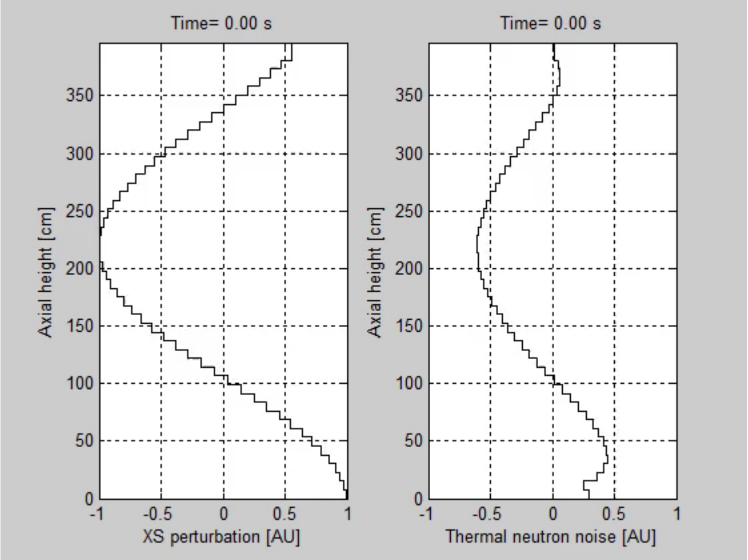
- Use of machine learning for anomaly detection, classification and localization
- Training data sets provided by:
  - Frequency-domain based simulations:
    - Absorber of variable strength
    - Inlet perturbations
    - Fuel assembly vibrations
    - Core barrel vibrations
    - Control rod vibrations
  - Time-domain based simulations:
    - Inlet perturbations
    - Fuel assembly vibrations

WP3: Development of advanced signal processing and machine learning methodologies for analysis of plant data

Example of a travelling perturbation @ 1Hz

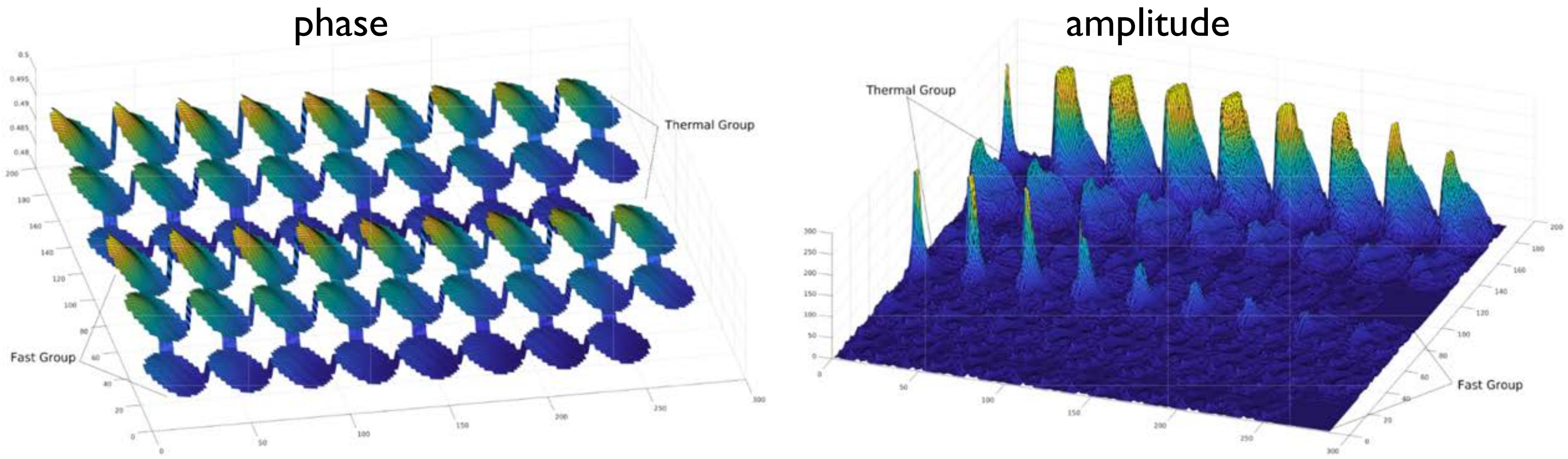






WP3: Development of advanced signal processing and machine learning methodologies for analysis of plant data

- First machine learning tests:
  - Absorber of variable strength
  - 3-D induced neutron noise unrolled as 2-D images:

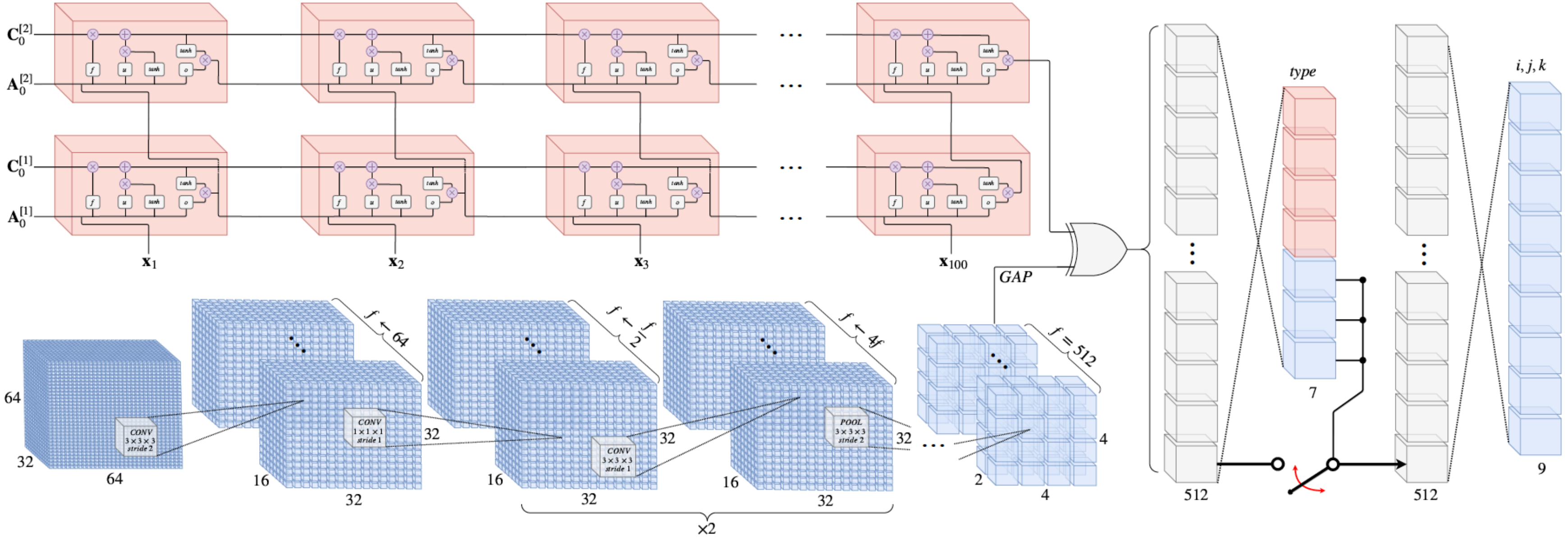


Courtesy of University of Lincoln

➢Use of a Deep Convolution Neural-Network (Inception V3 CNN) leading to excellent unfolding

WP3: Development of advanced signal processing and machine learning methodologies for analysis of plant data

- Subsequent machine learning tests using a unified framework for time- and frequency-domain simulations:
  - Long-Short Term Memory network for classification in the time-domain
  - 3-D Convolution Neural Network for classification and localization in the frequency-domain



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WP3: Development of advanced signal processing and machine learning methodologies for analysis of plant data

- Subsequent machine learning tests using a unified framework for time- and frequency-domain simulations:

3D CNN Perturbation Classification & Localisation				
Sensors (%)	Train/Valid/ Test (%)	Classification Accuracy (%)	(i, j, k) Regression	
			MAE	MSE
20	60/15/25	**99.75±0.09**	**0.2528±0.03**	**0.1347±0.02**
20	25/15/60	99.12±0.17	0.4221±0.05	0.4152±0.07
20	15/25/60	98.62±0.22	0.5886±0.05	0.8174±0.12
5	60/15/25	99.32±0.18	0.326±0.05	0.2086±0.04
5	25/15/60	98.34±0.22	0.4818±0.05	0.6044±0.08
5	15/25/60	97.27±0.54	0.689±0.1	1.0749±0.25
20*	60/15/25	99.82±0.05	0.5602±0.04	1.6036±0.15
20*	25/15/60	99.56±0.07	0.8942±0.04	3.5739±0.16
20*	15/25/60	99.44±0.08	0.9635±0.06	4.2814±0.19
5*	60/15/25	99.47±0.03	0.8809±0.04	3.4424±0.16
5*	25/15/60	98.33±0.24	0.5001±0.04	0.6381±0.08
5*	15/25/60	**97.15±0.15**	**1.9528±0.11**	**11.902±0.66**

Courtesy of University of Lincoln

WP4: Application and demonstration of the developed modelling tools and signal processing techniques against plant data

Objectives:

- ➢Demonstration of the applicability and usefulness of the tools on many reactors (PWRs and VVERs)
- ➢Detection of abnormal fluctuations, understanding of their origin and classification according to their safety impact
- ➢Recommendations about in-core/out-of-core instrumentation

WP4: Application and demonstration of the developed modelling tools and signal processing techniques against plant data

- Data from many reactors being gathered and analysed:
  - A Swiss 3-loop PWR (5 new measurements performed specifically for CORTEX)
  - A German 4-loop PWR
  - A Hungarian VVER-440/213
  - A Czech VVER-1000/320

  +

  An American 3-loop PWR
  Two American 4-loop PWRs

Conclusions

- CORTEX project progressing as planned
- First results very promising (simulations and machine learning tests)
- CORTEX gathering a cross-disciplinary team of experts for developing core monitoring techniques for industrial applications

Conclusions

- Follow the project on LinkedIn and at http://cortex-h2020.eu/

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