CORTEX

Core monitoring techniques and experimental validation and demonstration

Examples of applications on commercial reactors within CORTEX

Final CORTEX workshop

Online

Joachim Herb – Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH

joachim.herb@grs.de

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Motivation and background

Motiviation

- Broad range of techniques developed in CORTEX to assess neutron flux oscillations
  - Signal processing
  - Machine learning
- Show examples of applications
- This presentation gives overview, for details see the deliverables of CORTEX and the publications: https://cortex-h2020.eu/resources/

Objectives of CORTEX project

Strategic objective 1

- … is to develop simulation tools that shall be specifically dedicated to the modelling of the effect of stationary fluctuations in **power reactors** with a high level of fidelity

Strategic objective 4

- … reactor transfer function estimation and the advanced signal analysis techniques need to be combined into a set of tools that can be directly used for **analysing plant data** and **performing core diagnostics**

Applications for power reactors

- Collect existing and new **measurements**
- **Signal processing**
- **Simulations**
- **Applying machine learning methods**

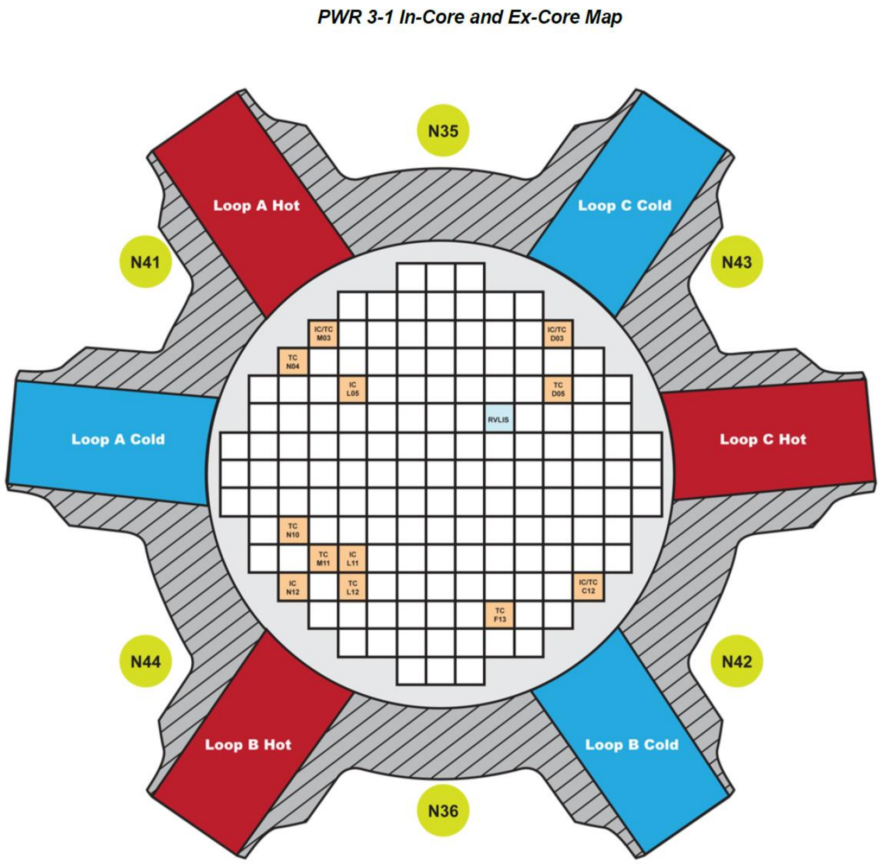
Measurements

Commercial reactors in CORTEX

Data received/additional measurements

- One American **3-loop PWR** and two **4-loop PWR** (provided by AMS)
- Swiss **3-loop pre-Konvoi** (provided by KKG/ISTec/TIS)
- German **4-loop pre-Konvoi** (provided by PEL/ISTec)
- Hungarian **VVER 440** (provided by EK)
- Czech **VVER 1000** (provided by UJV)

American PWR (3-loop)

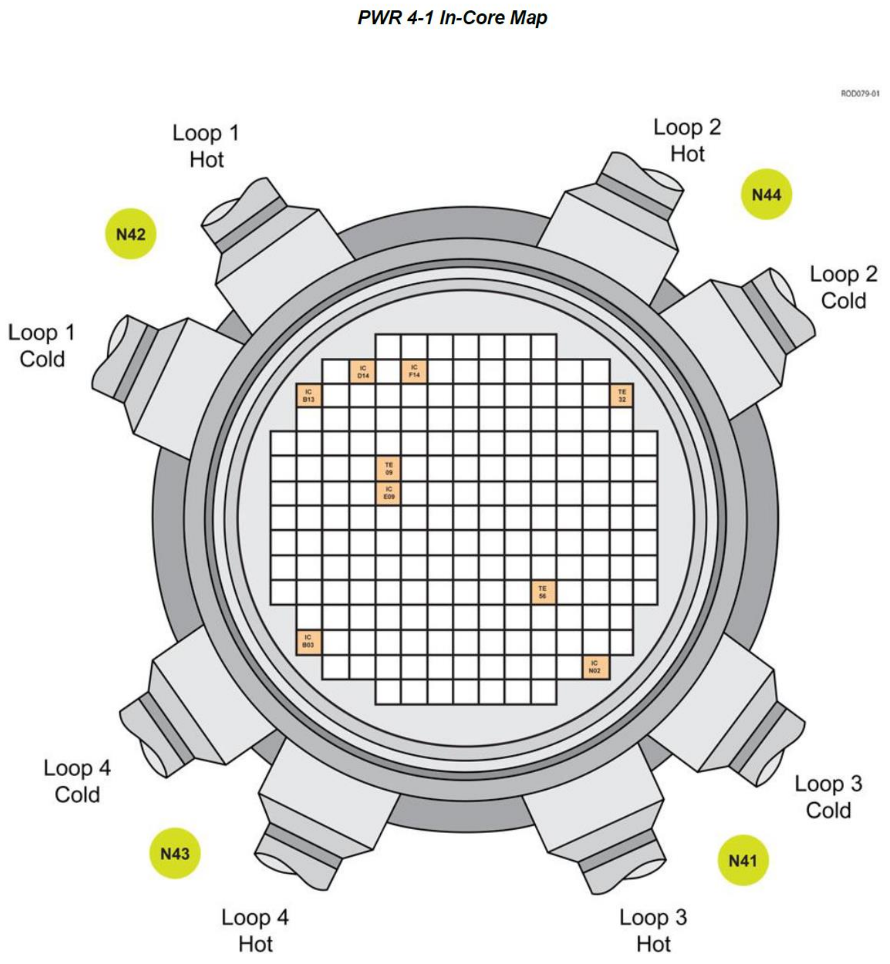


Measurements at 48 %, 55 %, 100 % power

Sampling frequencies: 30 Hz, 250 Hz, 300 Hz

Ex-, in-core flux, process signals, Δp, T secondary side values

1st American PWR (4-loop)

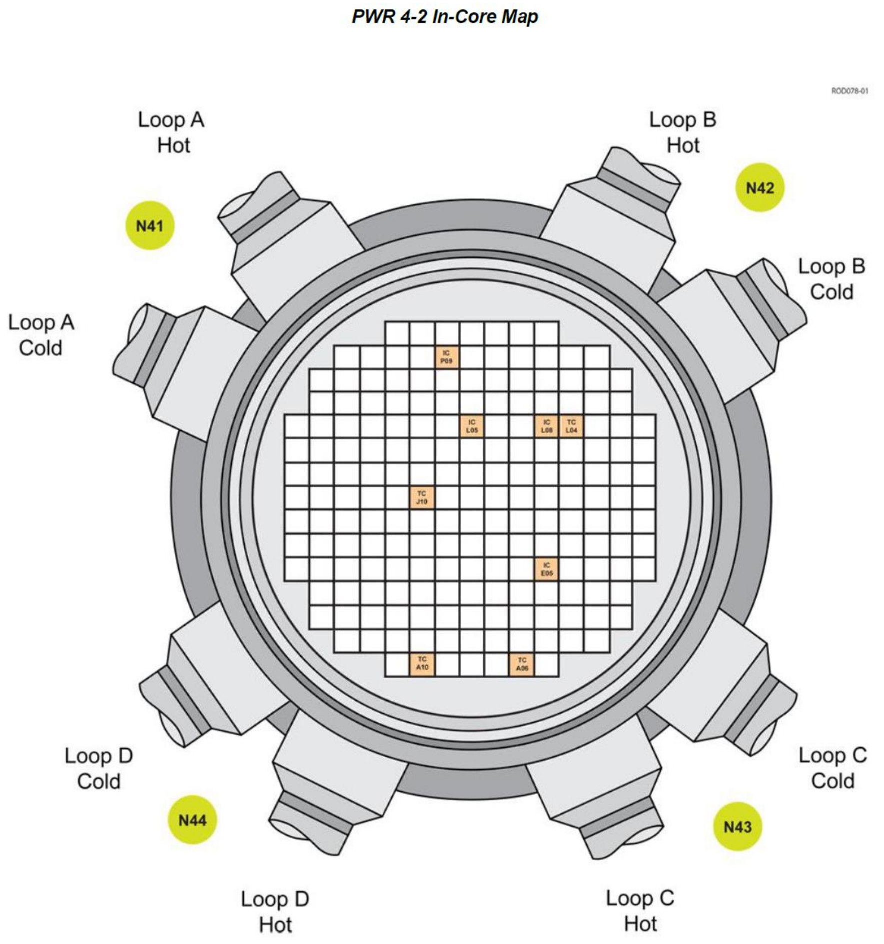


Measurements at 100 % power

Sampling frequency: 200 Hz

Ex-, in-core flux, process signals, Δp, T secondary side values

2nd American PWR (4-loop)



Measurements at 100 % power

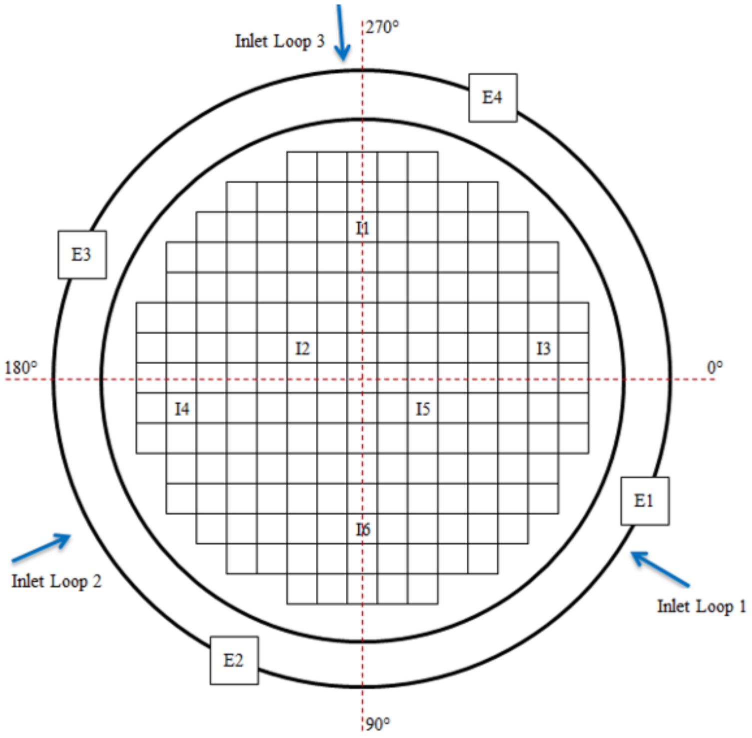
Sampling frequency: 60 Hz

Ex-, in-core flux, process signals, Δp, T secondary side values

American PWRs

- Signal processing techniques were applied
- No simulations/training of machine learning tools possible due to missing core data

Swiss 3-loop pre-Konvoi



Measurements at 100 % power

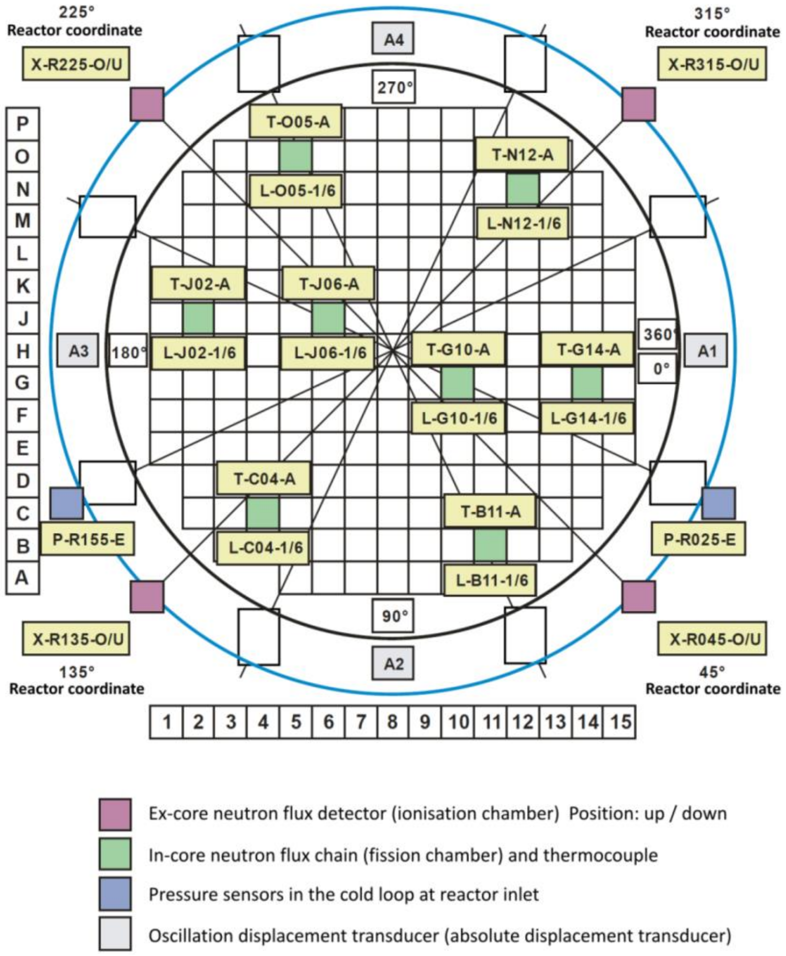
Sampling frequency: 250 Hz

Ex-, in-core flux, T

Table 2 Core conditions for the measurement campaigns

Date	2018-02-07	2018-05-15	2018-07-10	2018-12-11	2019-05-X
Cycle	MOC 39	EOC 39	BOC 40	MOC 40	EOC 40
EFPD (days)	223	320	16	171	325
Boron concentration [ppm]	303	34	911	442	4
Core BU during the measurement [MWd/kgHM]	40	44	32	38.3	44.4

German 4-loop pre-Konvoi



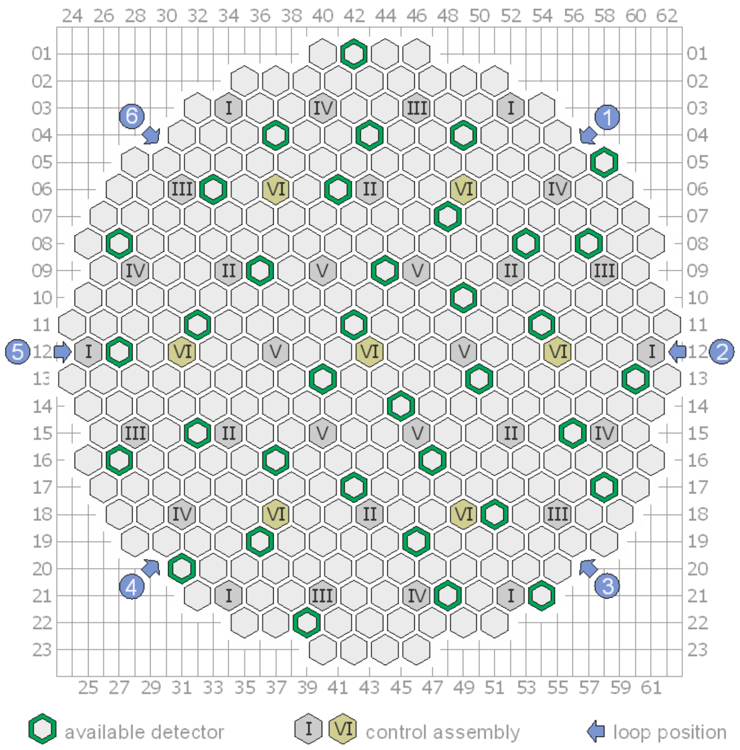
Measurements at 100 % power

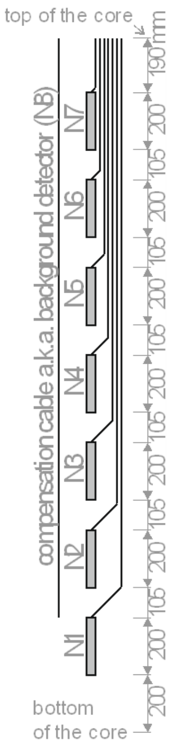
Sampling frequency: 250 Hz

Ex-, in-core flux, T

3 different reactor cycles

Hungarian 6-loop VVER 440





Measurements at 100 % power

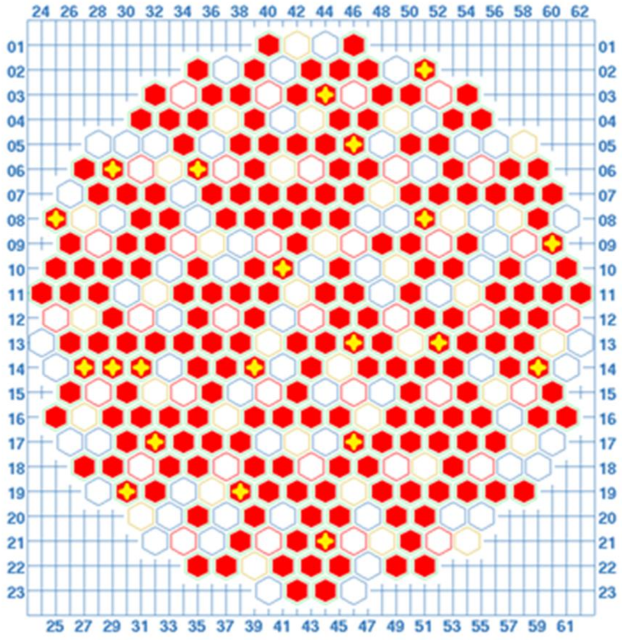
Sampling frequency: 100 Hz

In-core flux (252 signals), T (31 signals)

BOC, MOC, EOC

Hungarian 6-loop VVER 440

Thermo couples



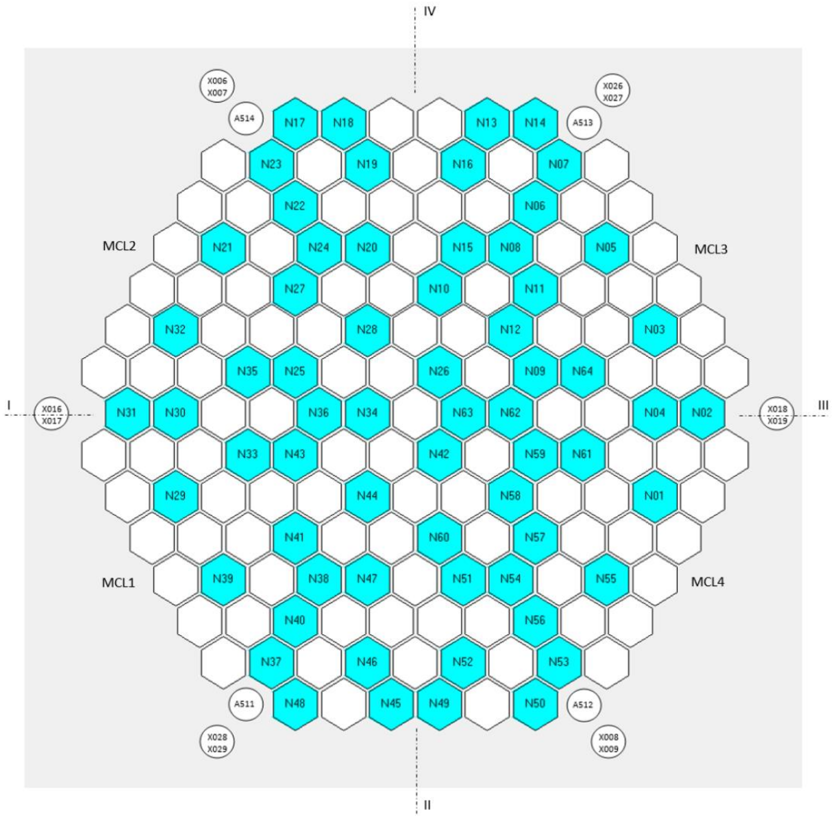
Measurements at 100 % power

Sampling frequency: 100 Hz

In-core flux (252 signals), T (31 signals)

BOC, MOC, EOC

Czech 4-loop VVER 1000



Measurements at 100 % power of BOC physical tests

Ex-core (8), in-core flux(160), RPV acceleration (4)

Sampling frequency: 1000 Hz

12 min records (normalized, offset free noise data)

77 datasets from cycles U1C09 – U1C12

Pre-Konvois, VVERs

- Signal processing techniques were applied
- Steady state core data available

⇒ Simulation could be performed to generate training data for machine learning tools

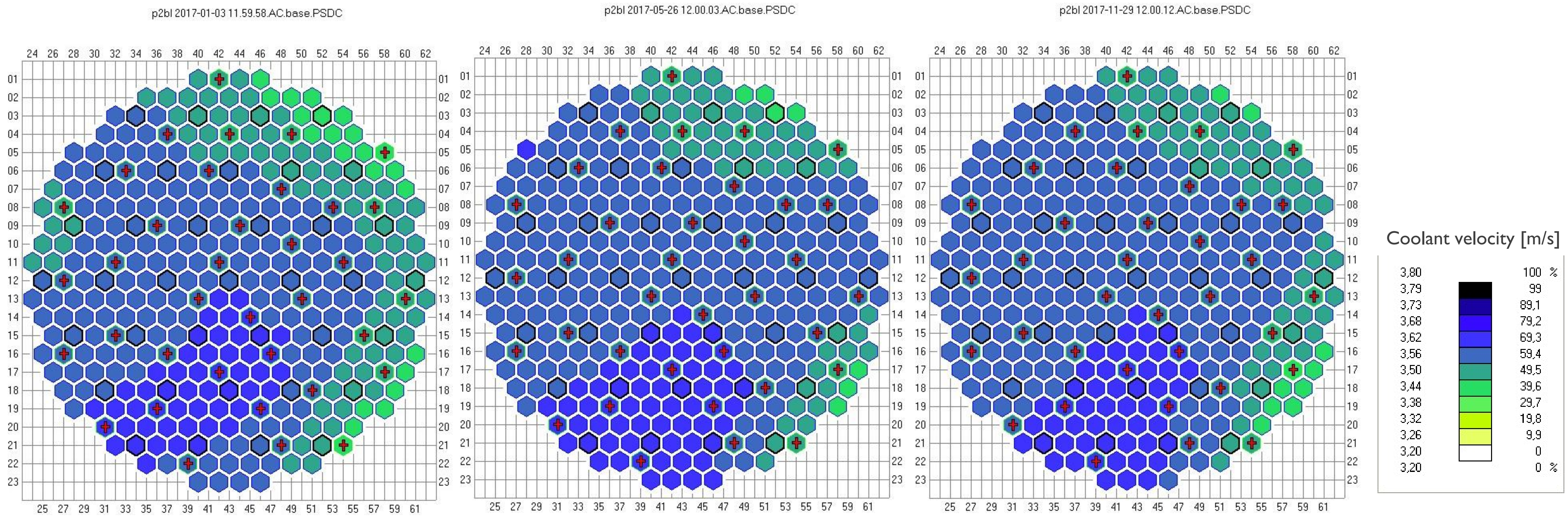
Examples for signal processing

Coolant velocity estimation in VVER 440

By EK

- **Inhomogeneities** of the coolant **passing through the reactor core** induce small fluctuations in the neutron flux in the steady state of the reactor, which
- causes **small transients** in the **in-core neutron detector** signals with a time delay proportional to the distance between the detectors.
- Determination of the time delay: **correlation method** based on FFTs
- For practical reasons impulse response functions are used

Radial distribution of the coolant velocities



Reconstruction of time varying signals

By UJV

- High mutual **correlations**, so each SPND signal can be expressed as a **linear combination** of the SPND signals in the vicinity
- Coefficients can be calculated by the least-squares method
- Can be applied to **identify and/or replace bad data** or for **filling gaps**
- Was used in CORTEX for all reactor types

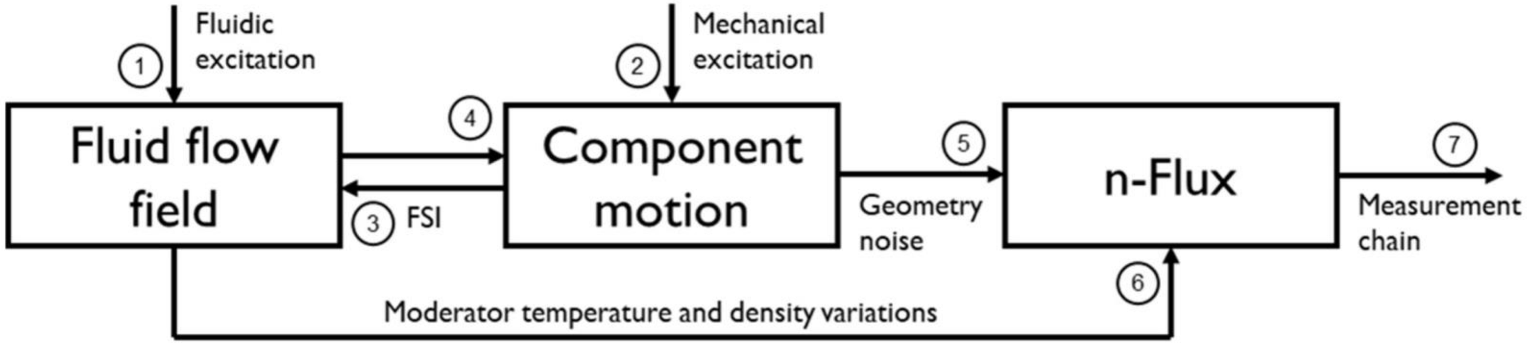
Application to in-core detectors at KKG

Simulations

Simulations of structural mechanics of core internals

By GRS

- **Multi-physics** problem

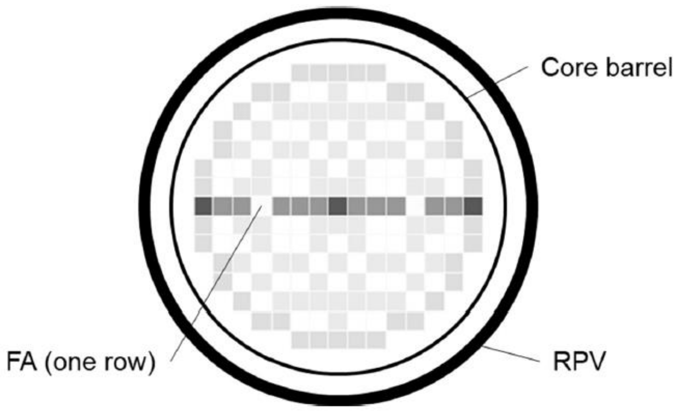


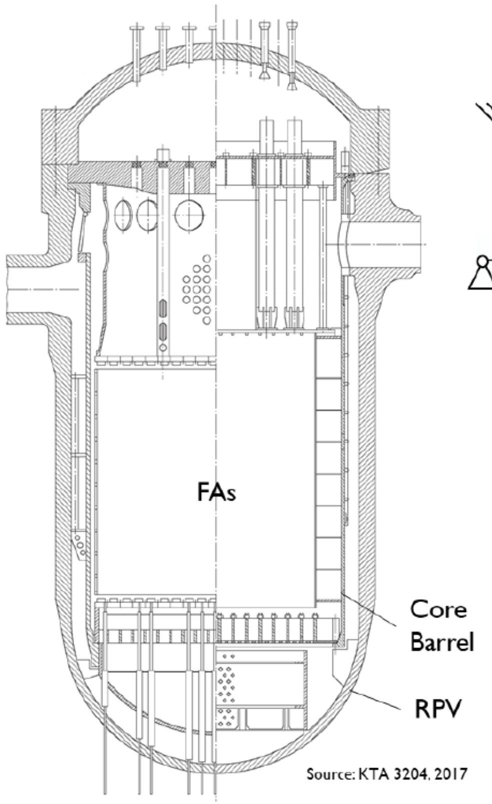
- Mechanical model developed to simulate response of structures to given excitations

- Different mechanical properties for fuel elements

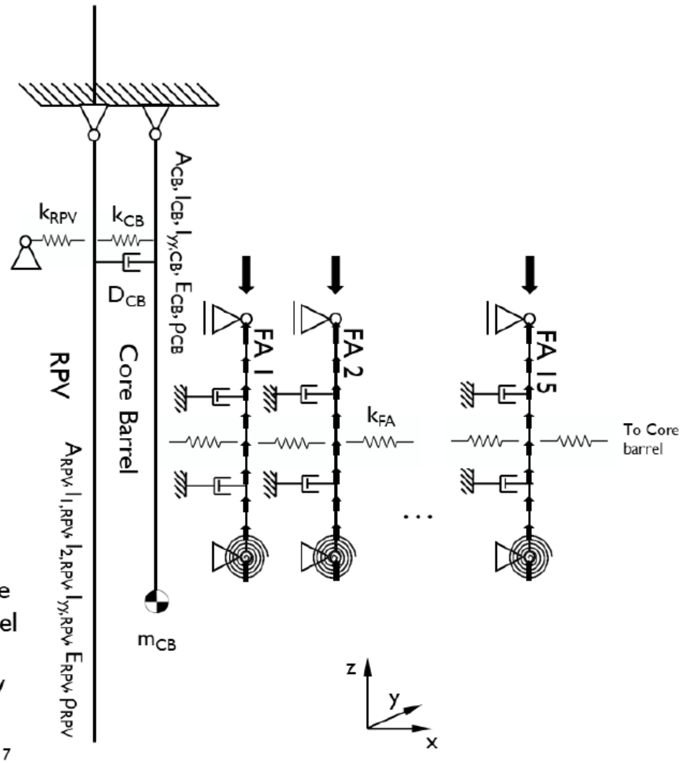
Structural mechanics model

- RPV + core barrel + one row of fuel assemblies
- Damping by fluid
- Fluidic coupling between neighbour fuel elements
- Different lateral stiffness of FA





Source: KTA 3204, 2017



Results

- Example:
  Influence of different simulation parameters

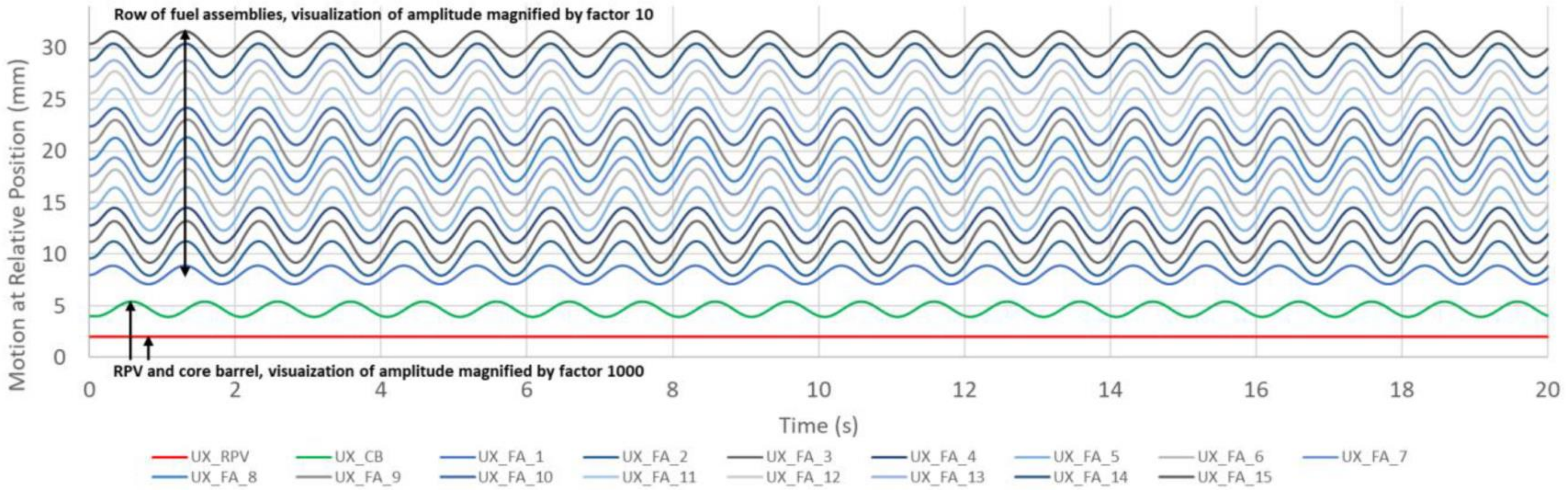


Figure 16: Component oscillation from correlated sinusoidal excitation of all FAs with 200 N amplitude at 1 Hz, damping enabled, fluidic coupling enabled, heterogeneous loading pattern.

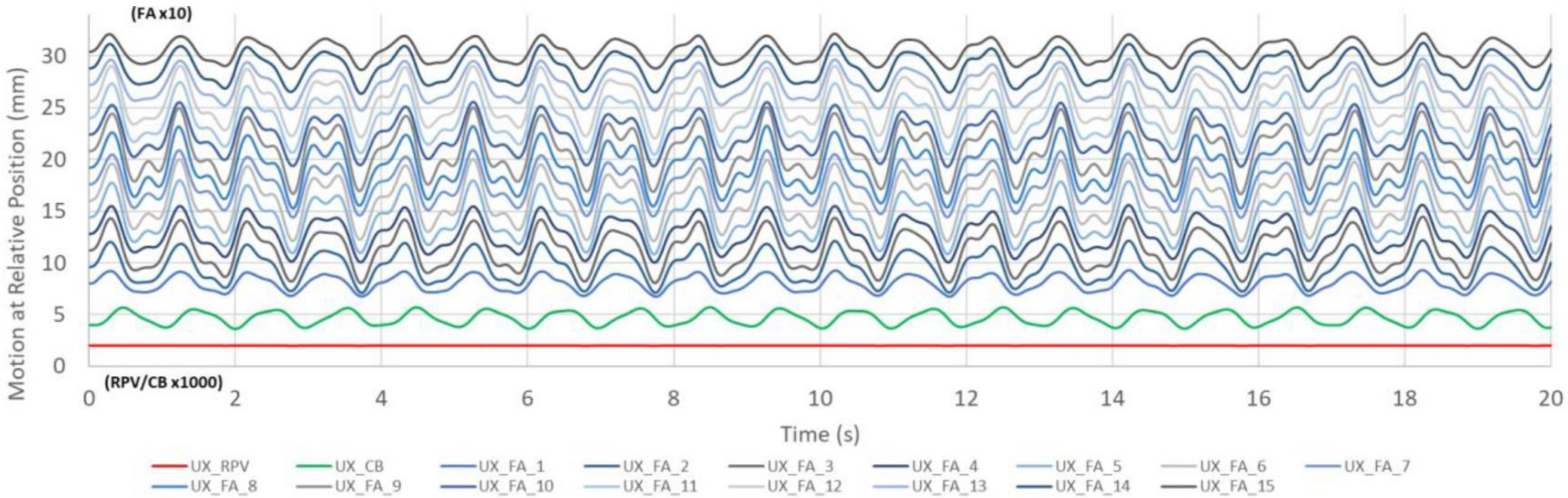
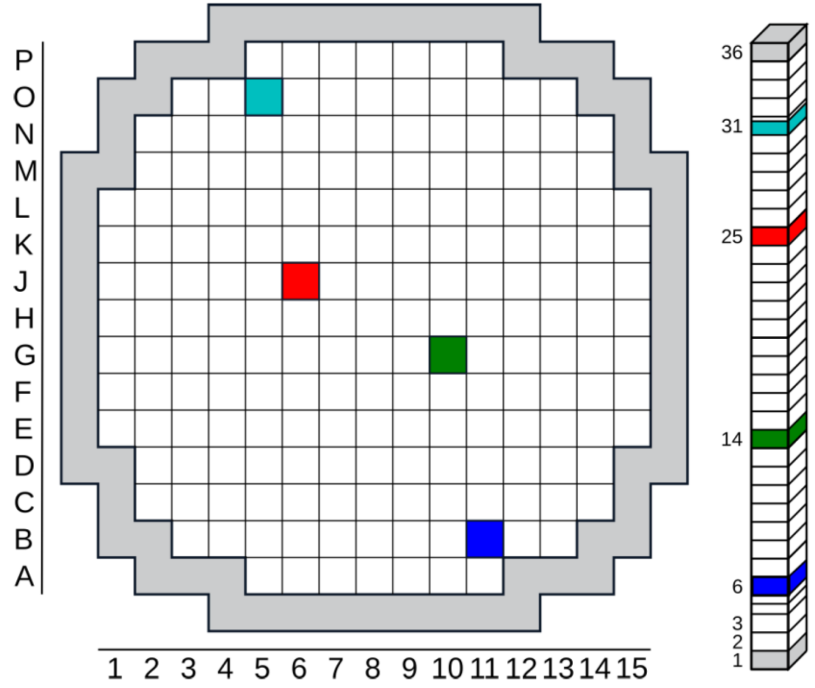


Figure 18: Component oscillation as in Figure 16, but damping disabled.

Noise simulations with an upgraded version of DYN3D

By TU Dresden

- **3D** neutron **diffusion equation** for two energy groups, solved by nodal methods
- **Reduced order model** for **mechanical behaviour** of fuel elements with given **random excitation**



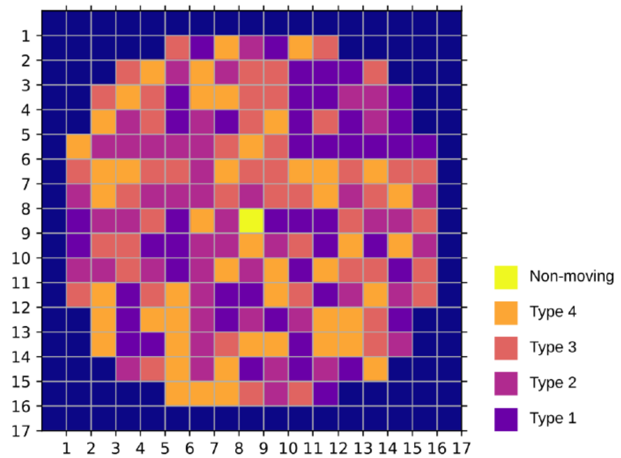
- Enhancement: **Changing nodal cross sections** based on average **fuel assembly pitch** to neighbours
- Different **loading patterns** (burnup, lateral stiffness)

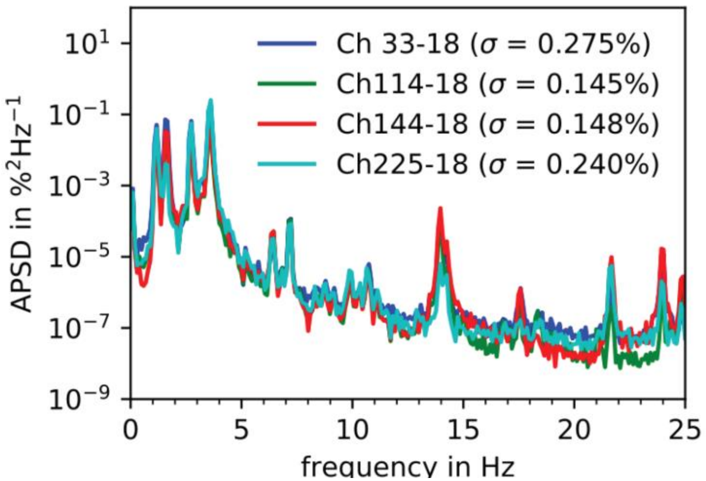
Results

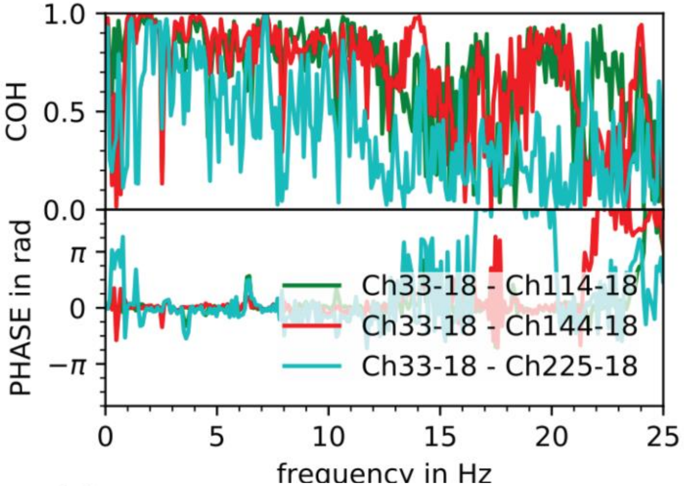
Loading pattern

Coherence/Phase

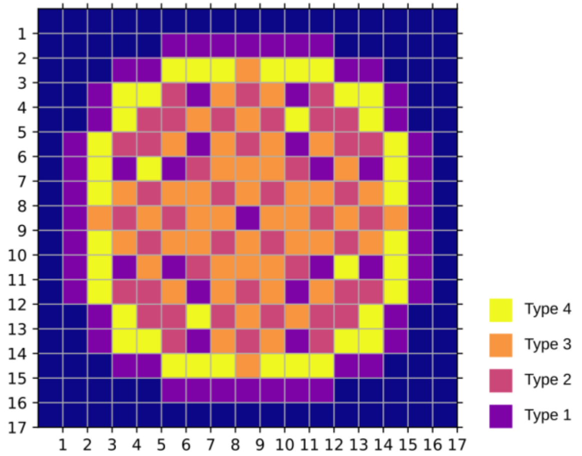
Random pattern

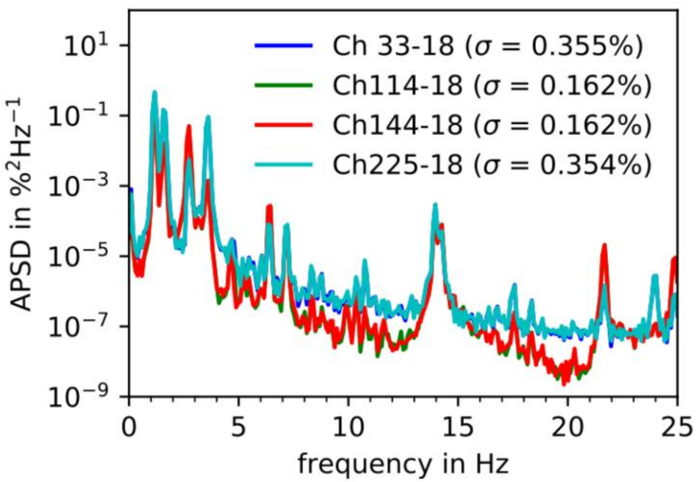


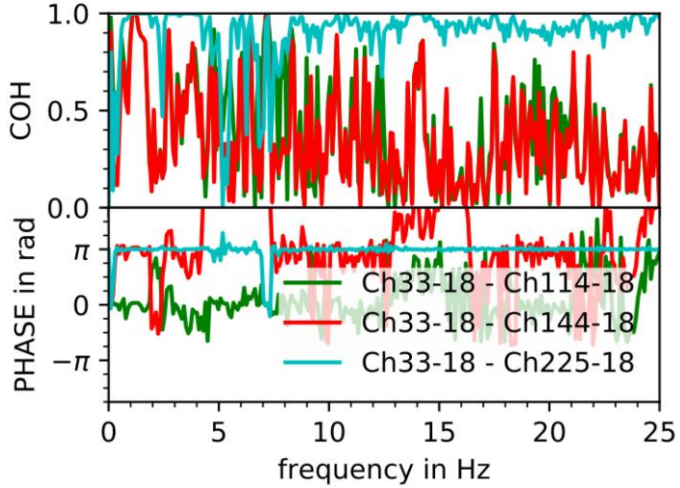




Loading pattern of German PWR





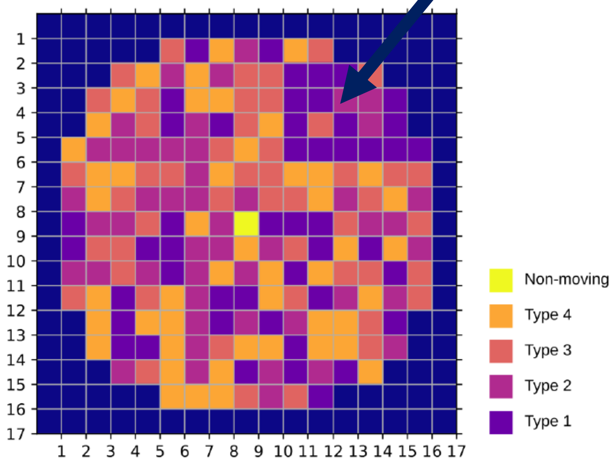


Results

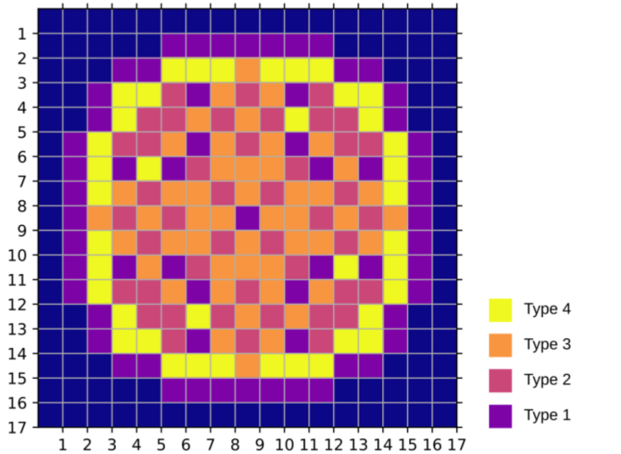
different FA stiffnesses

Loading pattern

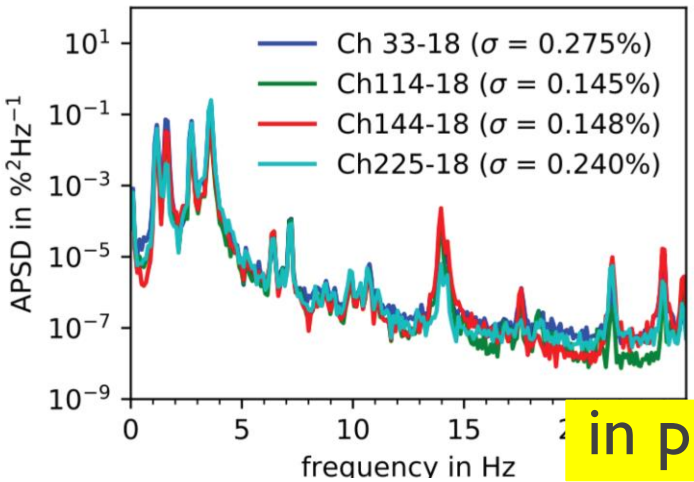
Random pattern

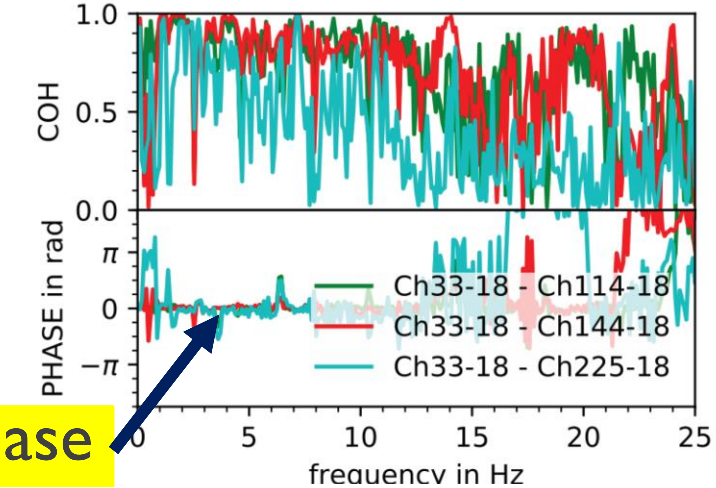


Loading pattern of German PWR

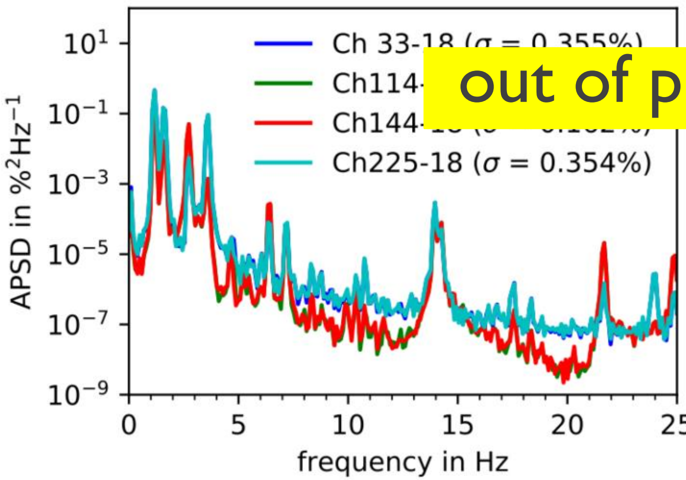


Coherence/Phase

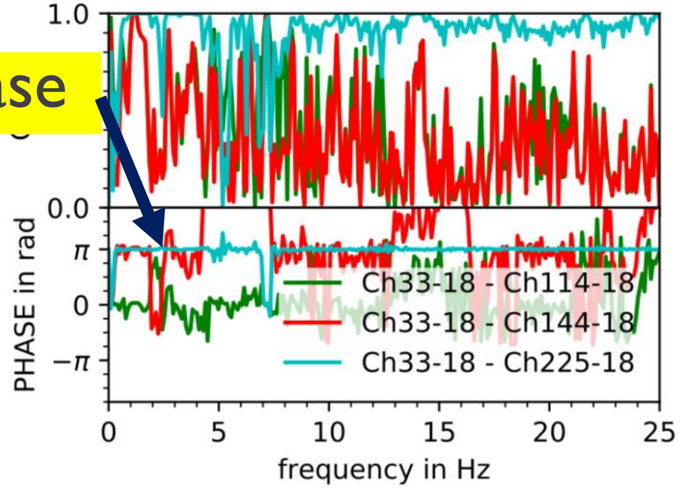




in phase



out of phase



Machine learning methods

Generate training data

By Chalmers, PSI, UPV

- Different reactors: pre-Konvois, VVERs
- Different reactor steady-state conditions (cycles, burn up)
- Different domains: time/frequency

⇒ Different codes: CORE SIM+, SIMULATE-3K, FEMFFUSION

- Different (combinations of) perturbations to be identified

Perturbations simulated

Both pre-Konvois, different cycles/burnups, frequency domain CORE SIM+

Generic "absorber of variable strength" (0.1 - 25 Hz)
Axially travelling perturbations at the velocity of the coolant flow (in core) (0.1 - 25 Hz)
Fuel assembly vibrations (cantilevered beam mode: 0.6 - 1.2 Hz)
Fuel assembly vibrations (simply supported on both sides: first mode 0.8 – 4 Hz, and second mode 5 - 10 Hz)
Fuel assembly vibrations (cantilevered beam and simply supported: first mode 0.8 - 4 Hz, and second mode 5 - 10 Hz)
Control rod vibrations (0.1 - 20 Hz)
Core barrel vibrations (beam or pendular mode) (7 - 13 Hz)

Perturbations simulated

3-loop pre-Konvoi, different cycles/burnups, time domain SIMULATE3K

Vibration of one FA in cantilevered mode (1.2 Hz, 1 mm)
Vibration of one FA in C-shape mode (1.2 Hz, 1 mm)
Random fluctuation in inlet temperature (white noise, 1 K)
Random fluctuation in inlet flow (white noise, 2%)
Simplistic lateral vibration of central 5x5 FA cluster + random TH fluctuations (1.2 Hz, 1 mm, 1 K, 2%)
Cantilevered mode vibration of central 5x5 FA cluster + random TH fluctuations (1.2 Hz, 1 mm, 1 K, 2%)

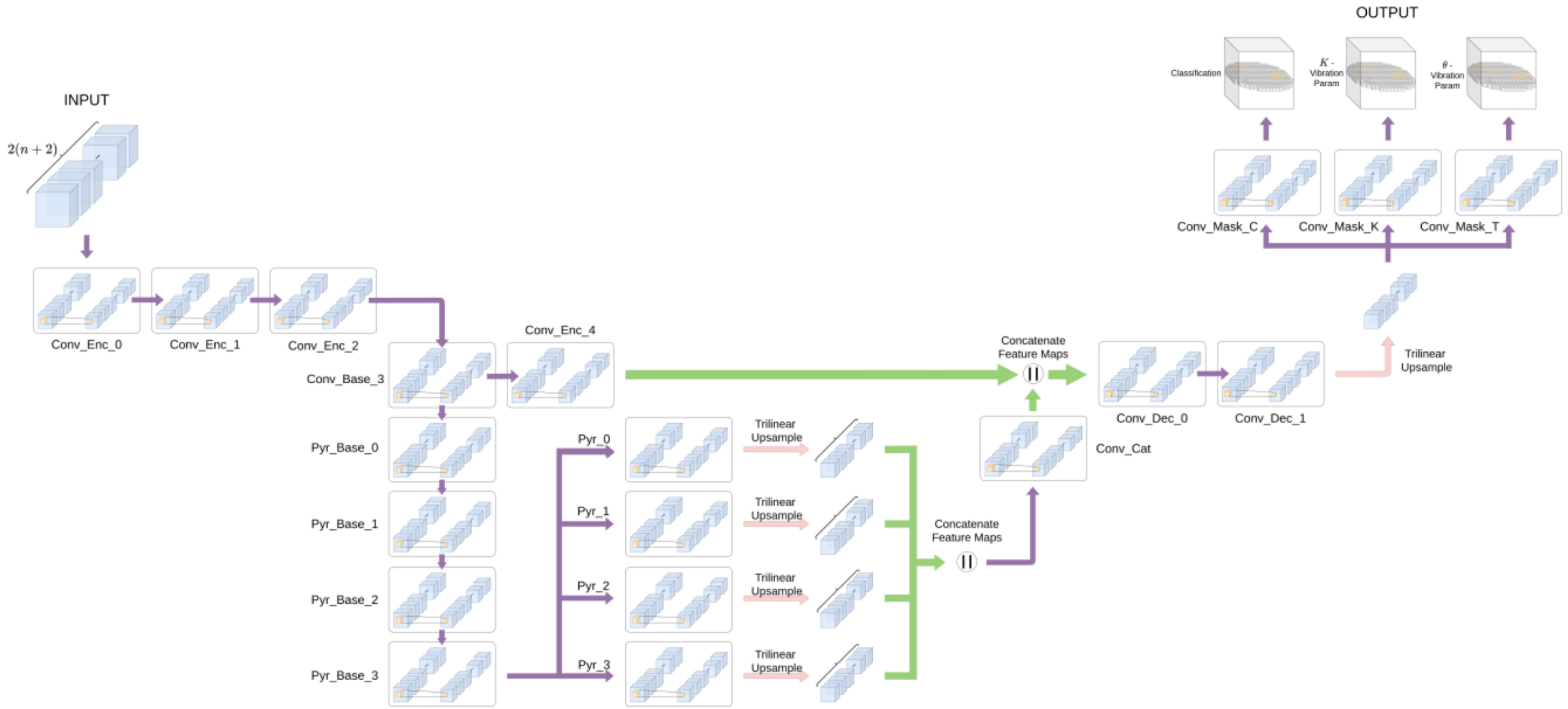
Perturbations simulated

Both VVERs, one cycles/burnup, frequency domain
FEMFFUSION

generic absorber of variable strength (different horizontal and vertical positions of noise source, 0.1 Hz, 1 Hz, 10 Hz, 10%)
axially travelling perturbation (in different core channels, 0.1 Hz, 1 Hz, 10 Hz, v = 1 m/s, 100 %)

Anomaly prediction and analysis of plant measurements

By UoL, ICCS-NTUA

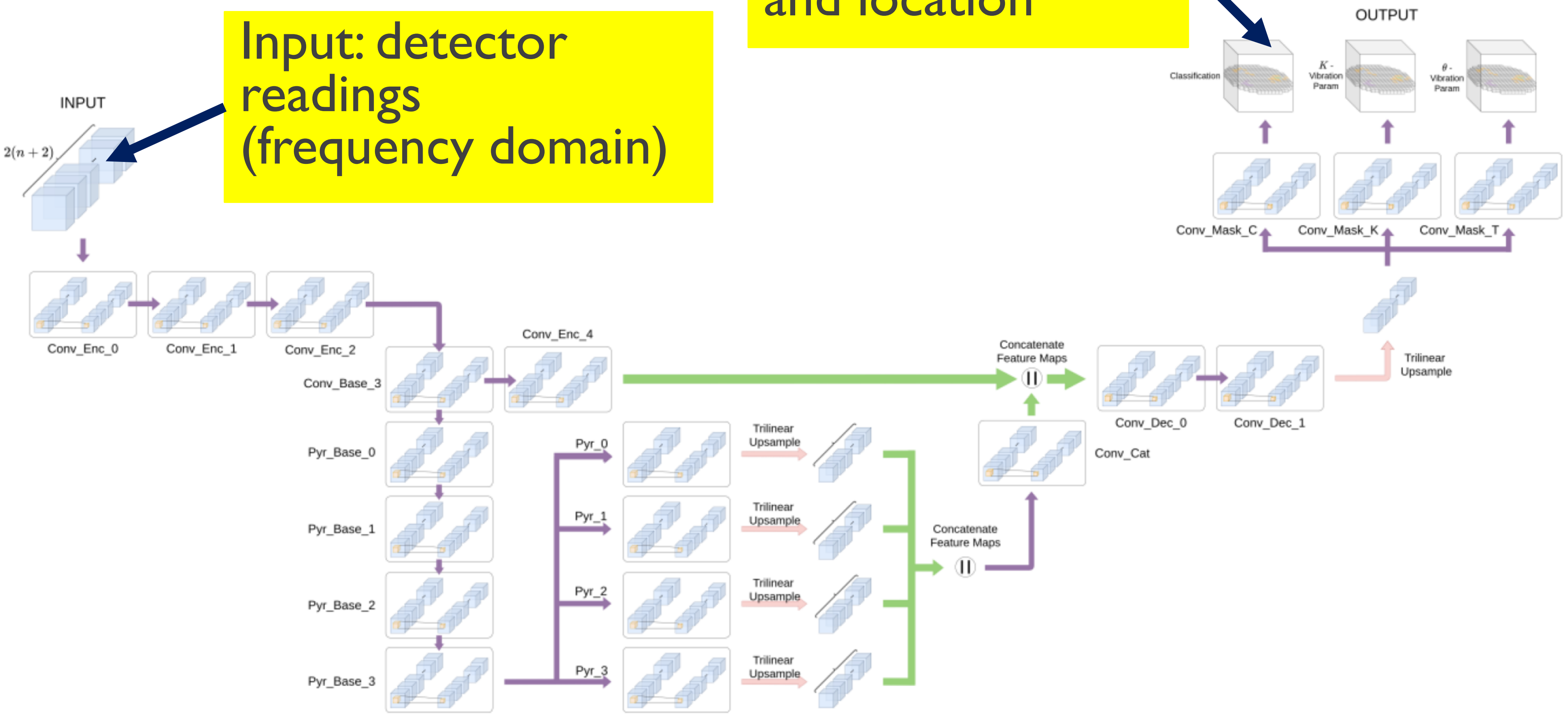


Anomaly prediction and analysis of plant measurements

By UoL, ICCS-NTUA

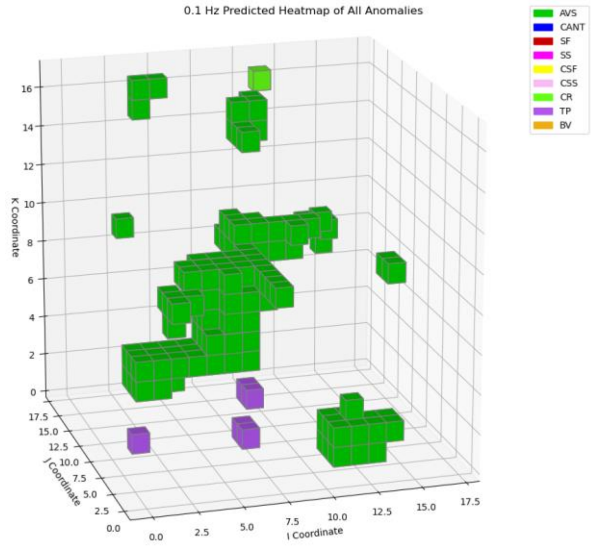
Output: perturbation type and location

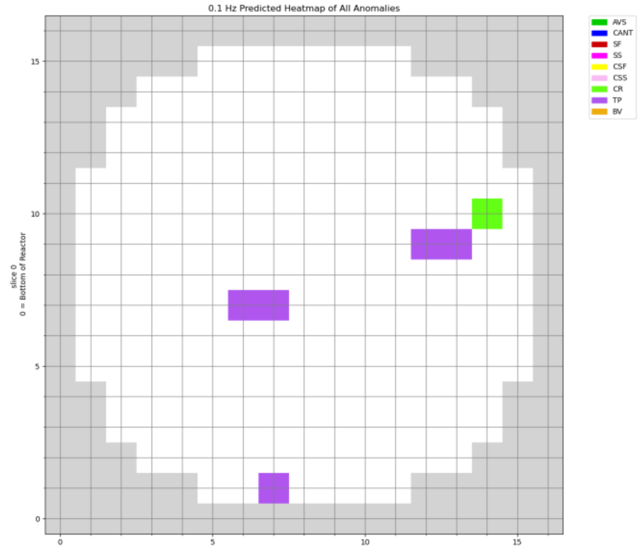
Input: detector readings (frequency domain)



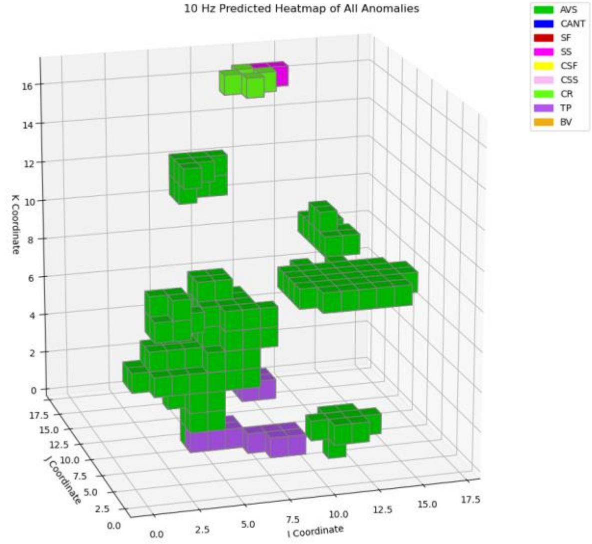
Results for 4-loop pre-Konvoi

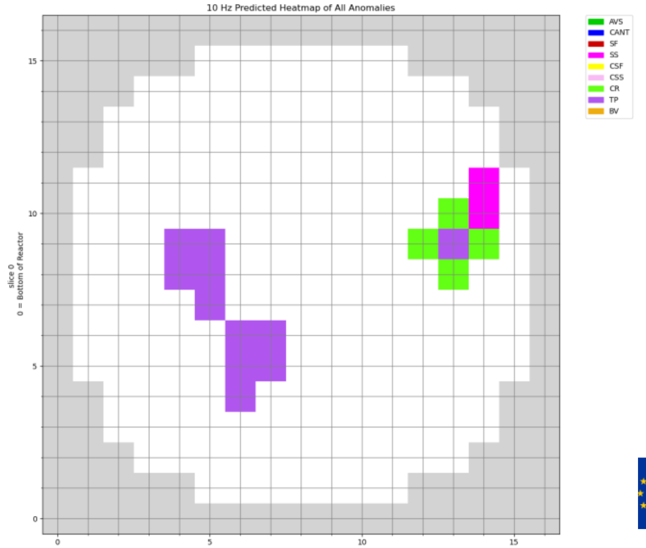
f = 0.1 Hz





f = 10 Hz





Results for 4-loop pre-Konvoi

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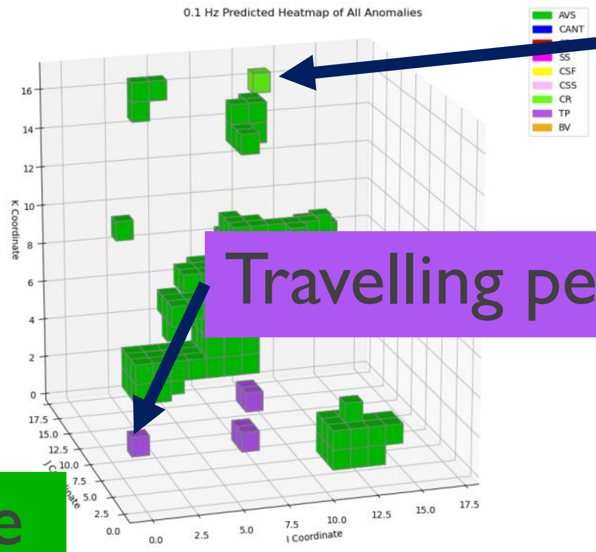
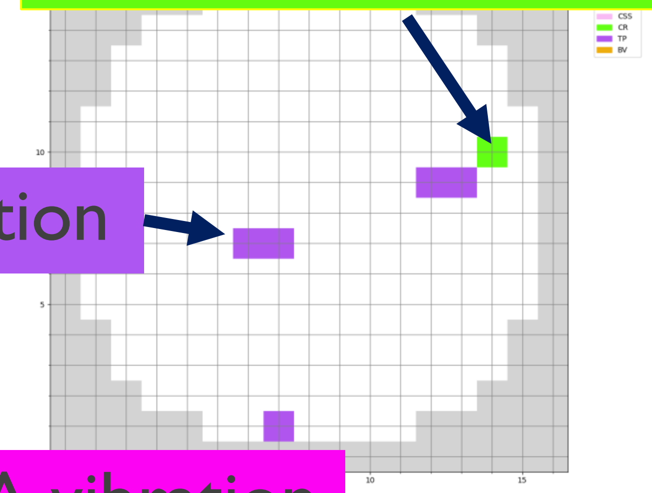




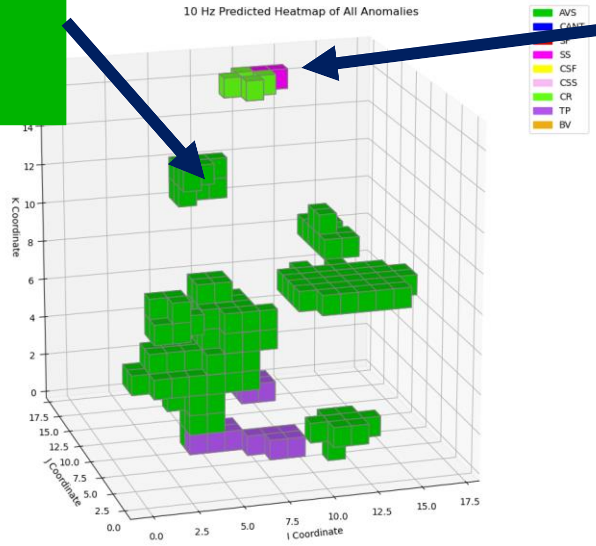
Control rod oscillations

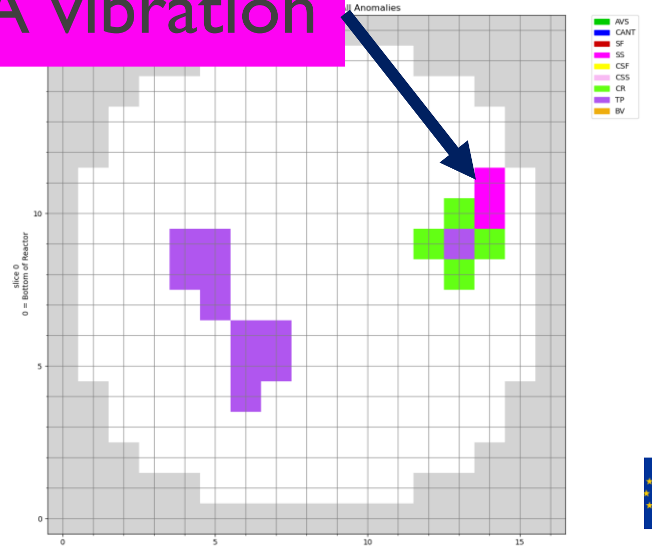
Travelling perturbation

Absorber of variable strength

FA vibration

f = 10 Hz





Conclusions

Conclusions

- **Successful interdisciplinary work:**
  multi-physics: physicists, engineers / computer scientists
- Broad range of **enhanced** and **newly developed tools** applied to **different power reactors**
- The **more data** (simulations and measurements), the **better**
- Need to **democratise** usage of tools