CORTEX
Core monitoring techniques and experimental validation and demonstration

CORTEX WORKSHOP

WP 2: Validation of the modelling tools against experiments in research reactors

in connection with

WP 4: Application and demonstration of the developed modelling tools and signal processing techniques against plant data

Some Aspects of Signal Analysis of WP 2 CROCUS and AKR-2 Experiments in Comparison to WP 4 NPP Goesgen Measurements

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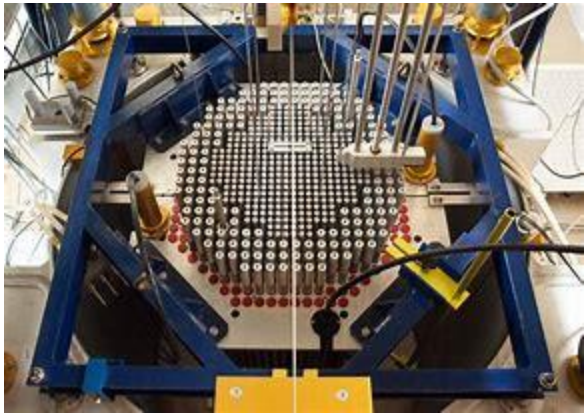
12th – 13th March 2020 at GRS gGmbH in Garching

Part 1

AKR-2 TU Dresden

CROCUS EPFL Lausanne



NPP Goesgen

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CORTEX Objectives

CORTEX is designed to develop innovative techniques for improved reactor safety and aims to address these challenges by developing an innovative core monitoring technique that allows *to detect anomalies in nuclear reactors, such as excessive vibrations of core internals, flow blockage, coolant inlet perturbations, etc. The technique will be mainly based on using the inherent fluctuations in neutron flux recorded by in-core and ex-core instrumentation, from which the anomalies will be differentiated depending on their type, location and characteristics.*

WP 2:
To set up and perform ***neutron noise measurements*** corresponding to a so-called absorber of variable strength as well as to a so-called vibrating absorber and vibrating fuel element. This will allow the validation of the neutronic modelling tools.

WP 4:
Using actual plant data (***neutron noise measurements***), to demonstrate the applicability, usefulness and importance of the proposed and developed methodology to the nuclear industry. The possibility of classifying the detected anomalies depending on their safety impact will be emphasized.

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Neutron Flux Density Fluctuations

1. The neutron flux density noise is caused by the stochastic process of the nuclear fission in the reactor core. The number of fissions and thus the neutron balance in a defined time interval follow a random distribution.

2. According to the random distribution the thermal neutron flux density varies about an average value. This value corresponds to the stationary space-dependent neutron flux density distribution in the reactor core.

3. The fluctuation of the neutron flux density at a local core position is linked to the space-dependent neutron flux density distribution at this position. To compare the amplitudes of neutron flux density fluctuations at different core locations we have to normalize the amplitude values by the corresponding average values of these fluctuations.

4. For the frequencies of the neutron flux density fluctuations values lower than 50 Hz can be observed, according to the Poisson random distribution (low-pass characteristics in frequency domain). The amplitudes of the fluctuations decrease exponentially with higher frequencies.

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Neutron Flux Density Fluctuations (cont.)

5. Due to the feedback processes in power reactors the fluctuations of the coolant temperature influence the fluctuations of the neutron flux density via the Moderator-Temperature-Coefficient of reactivity (MTC) in a wide-band frequency range. This effect does not appear in zero power reactors.

6. In power reactors, the amplitudes of the fluctuations of the neutron flux density (about an average value) will increase during a fuel cycle of the reactor due to the changing of the fission, absorption and capture cross sections with increased core burnup (the MTC will get more negative). The boron concentration of the coolant will decrease in correlation to the burnup to have constant reactivity.

7. Thermal-hydraulic fluctuations and mechanical vibrations of core internals cause modulations of the neutron flux density noise in a small-band or pass-band frequency range. The frequencies of these effects are defined by the reactor design and are determined by the Eigen frequencies of the core internals or by the frequencies of forced vibrations.

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Neutron Flux Density Fluctuations (cont.)

8. For the neutron flux noise signal analysis we have to take into account that the neutron flux signal is composed of a wide-band noise part, which corresponds to the random fission process (**stochastic behavior**) and is influenced by the MTC in power reactors, and of a pass-band fluctuation part (**deterministic behavior**) , which represents the modulation of the neutron flux density noise by thermal-hydraulic fluctuations and mechanical vibrations for certain frequencies.

9. Neutron flux density fluctuations may be influenced by reactivity effects (so-called **global effects**) and space-dependent effects (so-called **local effects**) in the core.
   Reactivity effects cause a changing of the thermal neutron balance in the core and the corresponding changing of the relative amplitudes of the neutron flux density fluctuations is the same at each core position.
   Space-dependent effects cause a changing of the neutron flux distribution at local positions without any reactivity perturbation and the corresponding changing of the relative amplitudes of the neutron flux density fluctuations is different at local core positions.

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Neutron Flux Data Acquisition and Signal Analysis

1. First we have analogous signals from the detectors (Ionization Chambers, SPNDs, Counter Tubes) at a measurement. These signals have a continuous time character as current signals or as series of pulses (in case of a small zero power reactor). By used data acquisition systems we sample these signals and we transform the continuous time signals in discrete time series. The non-trivial task for the sampling is to avoid aliasing effects. This is also valid for generating of artificial noise time series in modelling procedures. (Therefore, see textbooks like “Time Series Analysis” by Box and Jenkins).

2. We can perform the post-processing or analysis of the obtained time series in time domain or in frequency domain. In both cases we have to use suitable statistical procedures according to the noise character of the time series. The Fast Fourier Transform (FFT) is useful to transform the time series into the frequency domain by reducing the noise and single out the frequency peaks of the data series (**harmonic analysis**). In contrast to that the Parameter Modelling like auto-regression procedure (AR) is useful to describe the stochastic character in time domain (**noise analysis**) and not the deterministic content of the data series.

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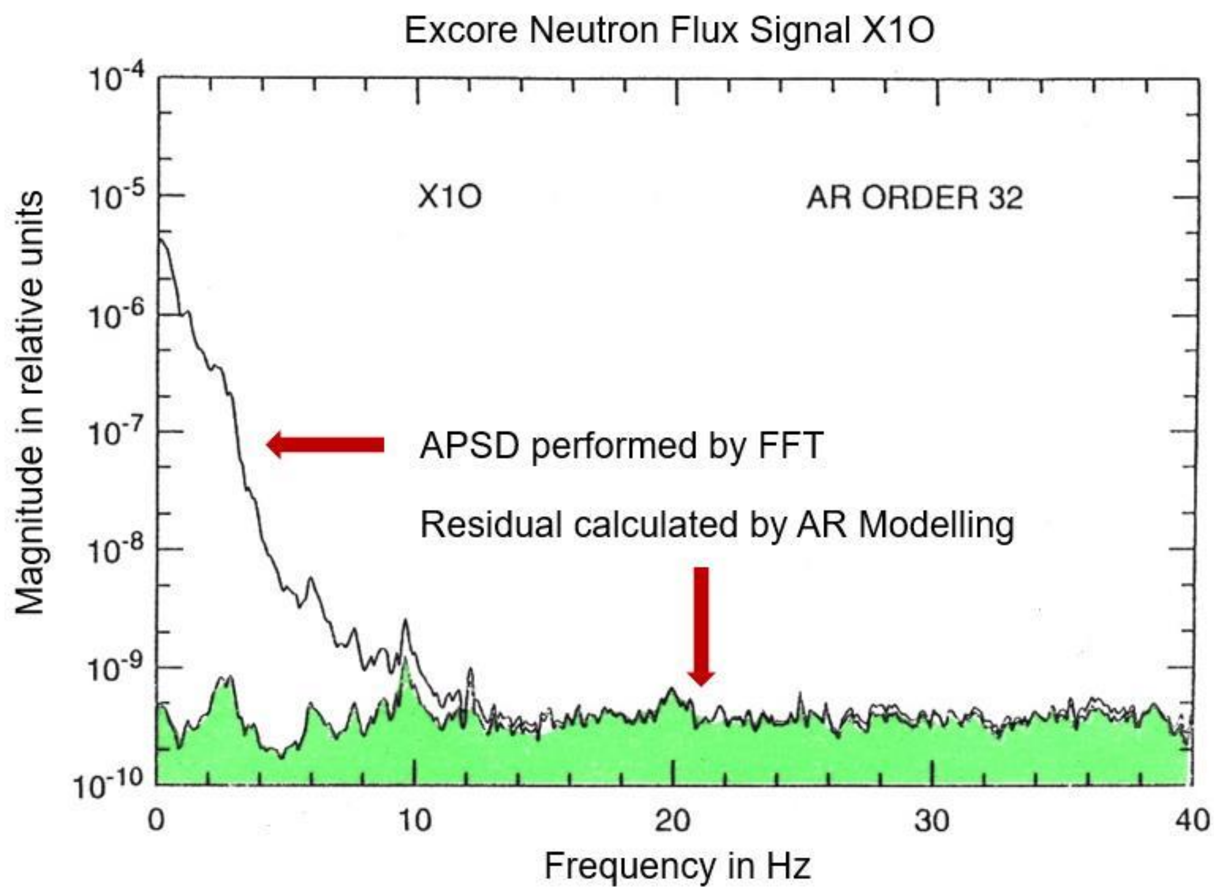
Neutron Flux Data Acquisition and Signal Analysis



Example of AR Modelling

Excore Signal X1O APSD and AR Residual

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Neutron Flux Data Acquisition and Signal Analysis (cont.)

3. Performing the FFT we have to know what block size, what kind of data window and what average number will be successful. Performing the AR we have to know what model order will be the best to optimize the result. (Therefore, see textbooks like "Measurement and Analysis of Random Data" by Bendat and Piersol).
   For the comparison of the results of different institutions of the CORTEX project the **used analysis parameters** are important and should be indicated with the results.

4. In most cases, the analysis results are represented in frequency domain as Power Spectral Densities (PSDs). The magnitude (y-axis) is represented in a logarithmic scale, because the magnitude of the neutron flux density fluctuations varies over many decades. The frequency (x-axis) is represented in a linear scale, because there are equidistant frequency values up to one decade or two decades maximum. This was and is the standard representation of neutron flux noise spectra in world-wide publications on this subject.
   For the comparison of the results of different institutions of the CORTEX project a **standardized format of graphs** will be helpful.

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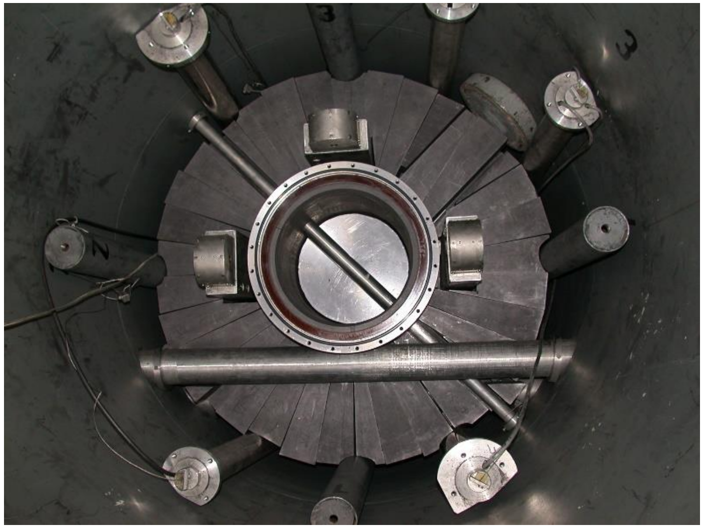
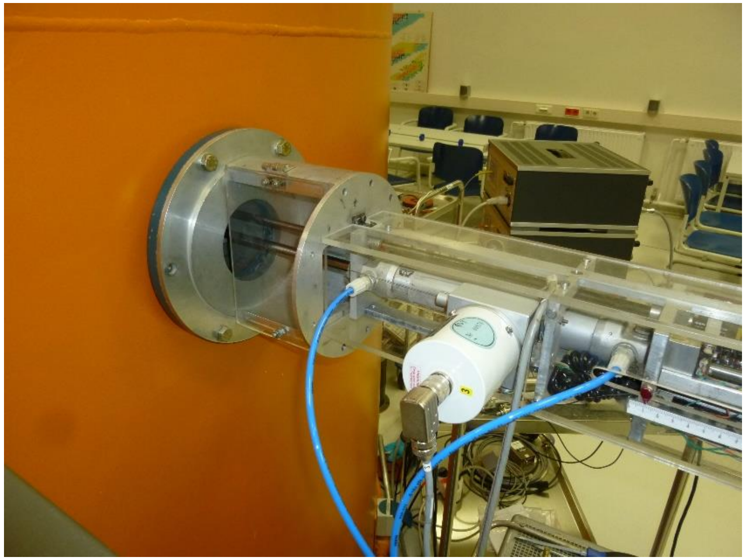
WP 2: AKR-2 Experiments

Moving Absorbers



Pile Oscillator



Rotating Absorber

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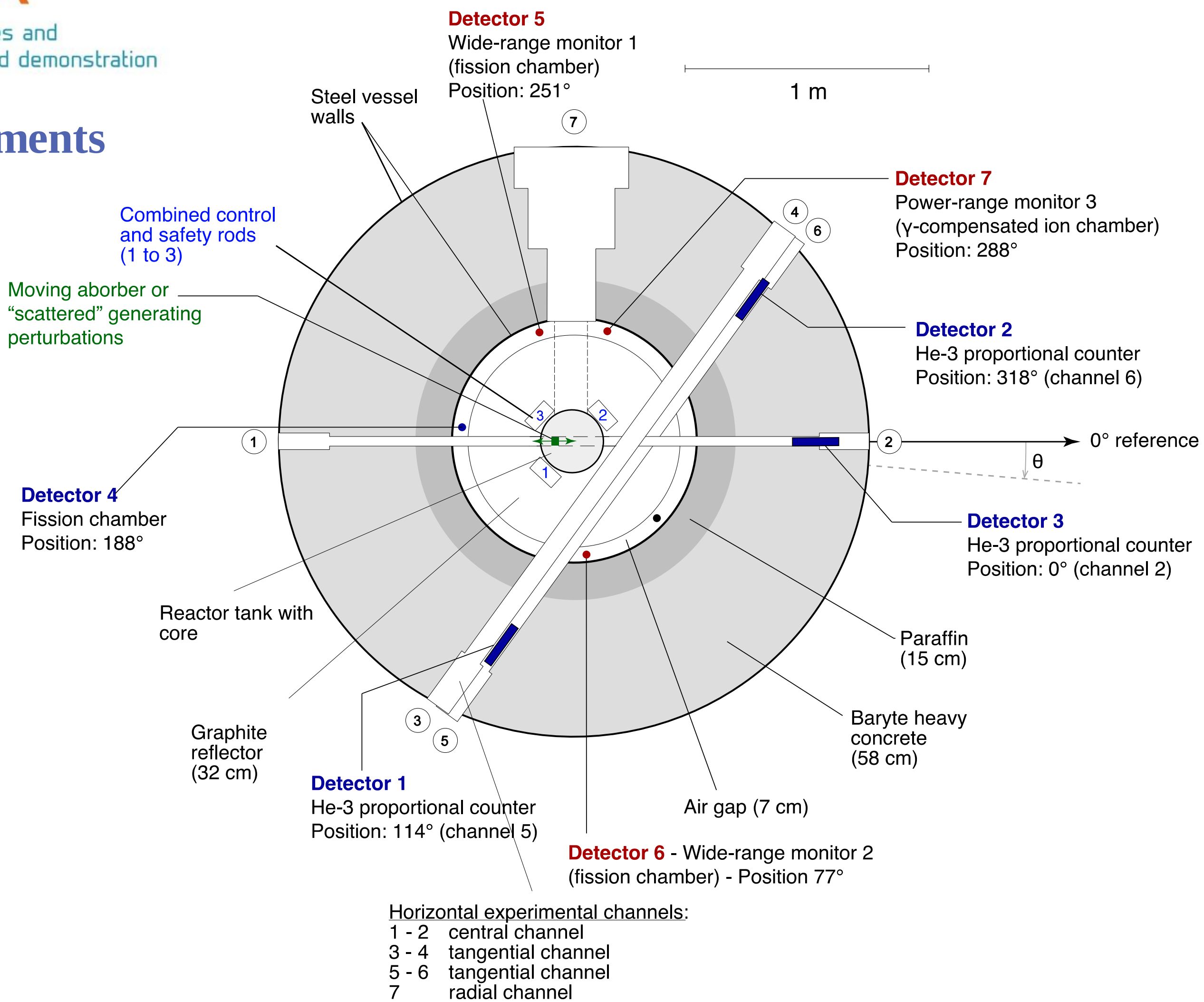
WP 2: AKR-2 Experiments (cont.)

Moving Absorbers

1. Pile Oscillator
2. Rotating Absorber



Positions of Detectors

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WP 2: AKR-2 Experiments (cont.)

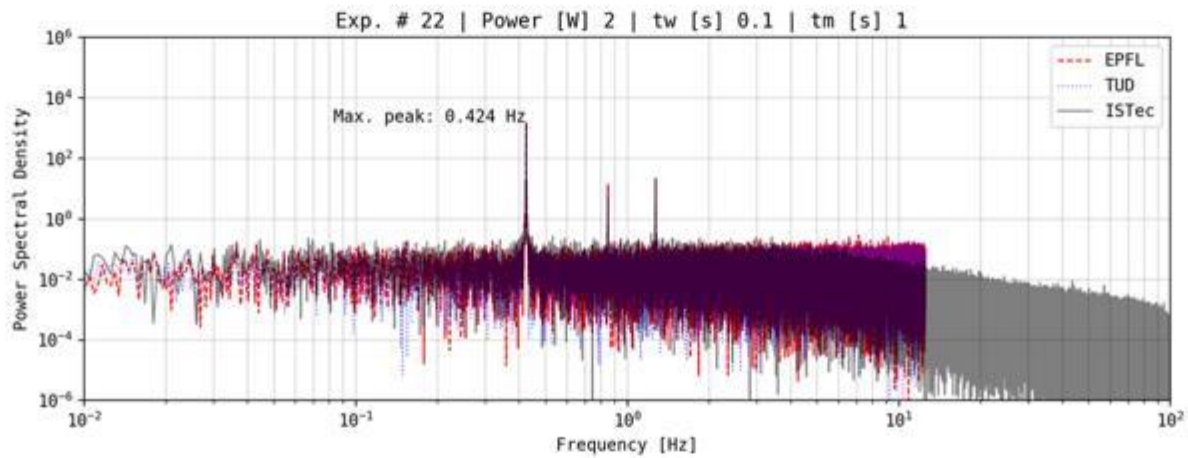
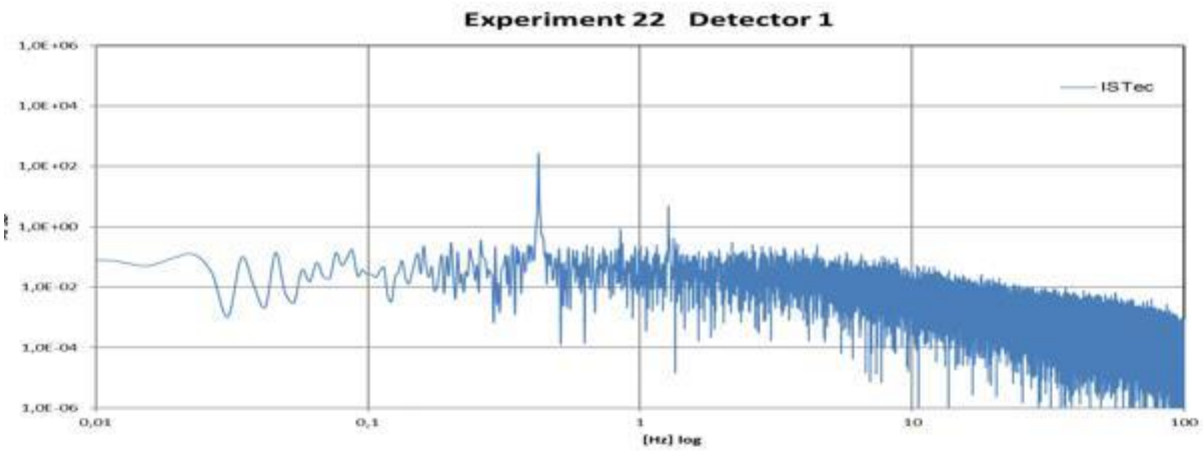


Figure 29 – Power spectral density for pile oscillator exp. 22 - Detector 1
(FFT calculated by EPFL – red graph)



Power spectral density for pile oscillator exp. 22 - Detector 1
(FFT calculated by ISTec – blue graph) x-axis in logarithmic scale
FFT: 65536 samples per block, 1 block, no averaging, Hanning window
Amplitude is not normalized by the DC

Comparison of APSD Estimation and Representation AKR-2 Experiment 22

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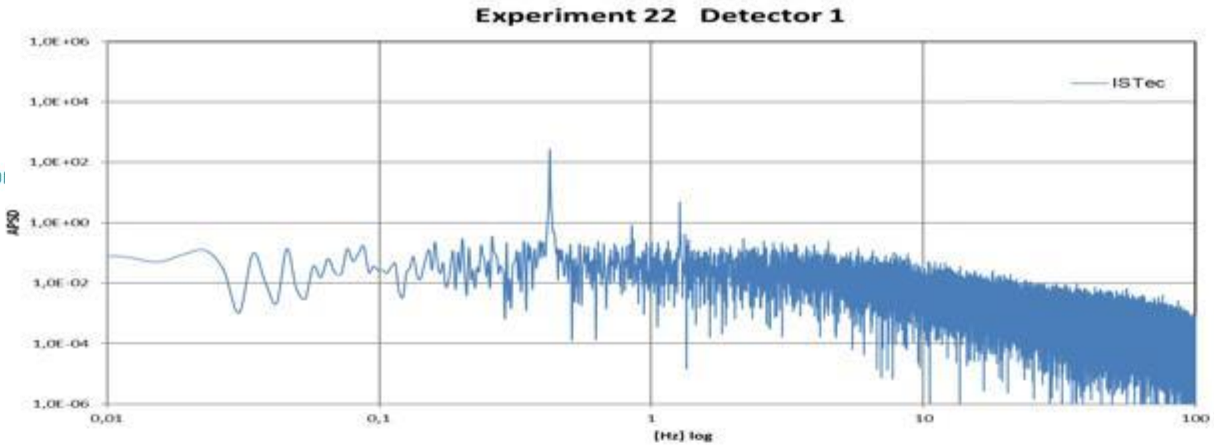
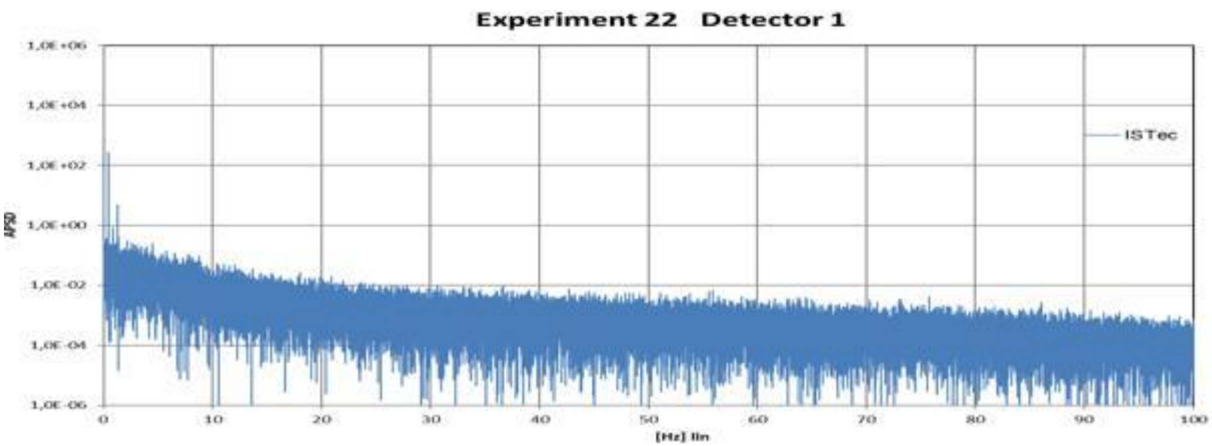
Core monitoring techniques and experimental validation and demo

WP 2: AKR-2 Experiments (cont.)



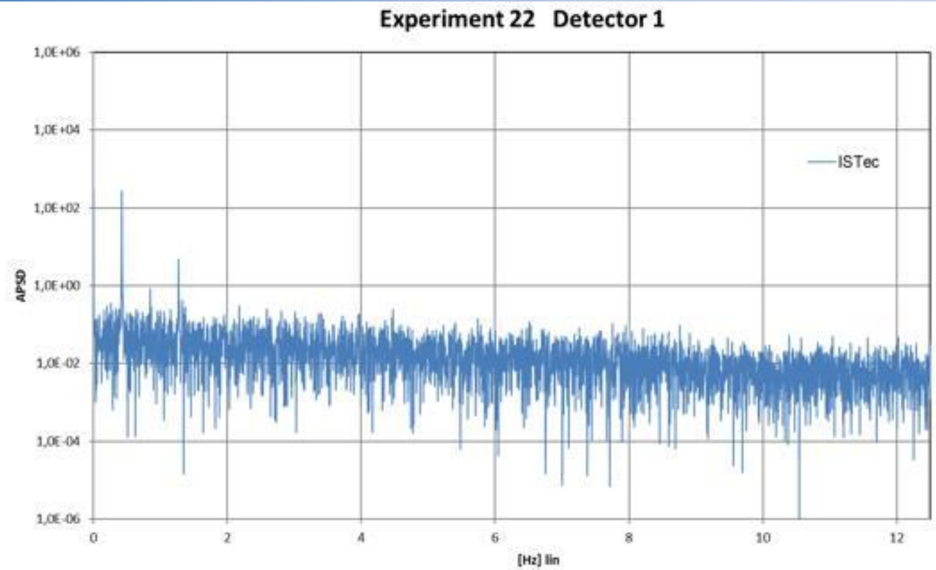
Power spectral density for pile oscillator exp. 22 - Detector 1
(FFT calculated by ISTec – blue graph) x-axis in logarithmic scale
FFT: 65536 samples per block, 1 block, no averaging, Hanning window



Power spectral density for pile oscillator exp. 22 - Detector 1
(FFT calculated by ISTec – blue graph) x-axis in linear scale up to 100 Hz
FFT: 65536 samples per block, 1 block, no averaging, Hanning window

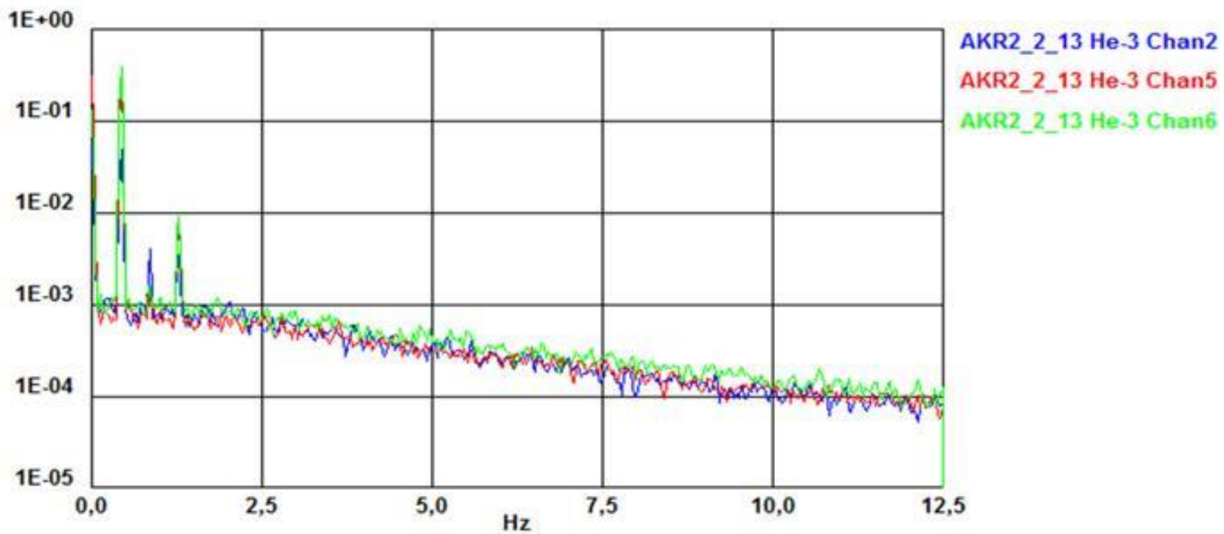
Comparison of APSD Estimation and Representation AKR-2 Experiment 22

WP 2: AKR-2 Experiments (cont.)



Power spectral density for pile oscillator exp. 22 - Detector 1 (AKR2_2_13 He_3 Chan2)
(FFT calculated by ISTec – blue graph) x-axis in linear scale up to 12.5 Hz

FFT: 65536 samples per block, 1 block, no averaging, Hanning window
Amplitude is not normalized by the DC



Comparison of APSD Estimation and Representation AKR-2 Exp. 22

Power spectral density for pile oscillator exp. 22 - Detector 1 (AKR2_2_13 He_3 Chan2)
(FFT calculated by ISTec)

FFT: 8192 samples per block, 52 blocks averaged, Hanning window
PSD result: 4096 frequency points in 125 Hz, resolution 0.031 Hz
Amplitude is normalized by the DC

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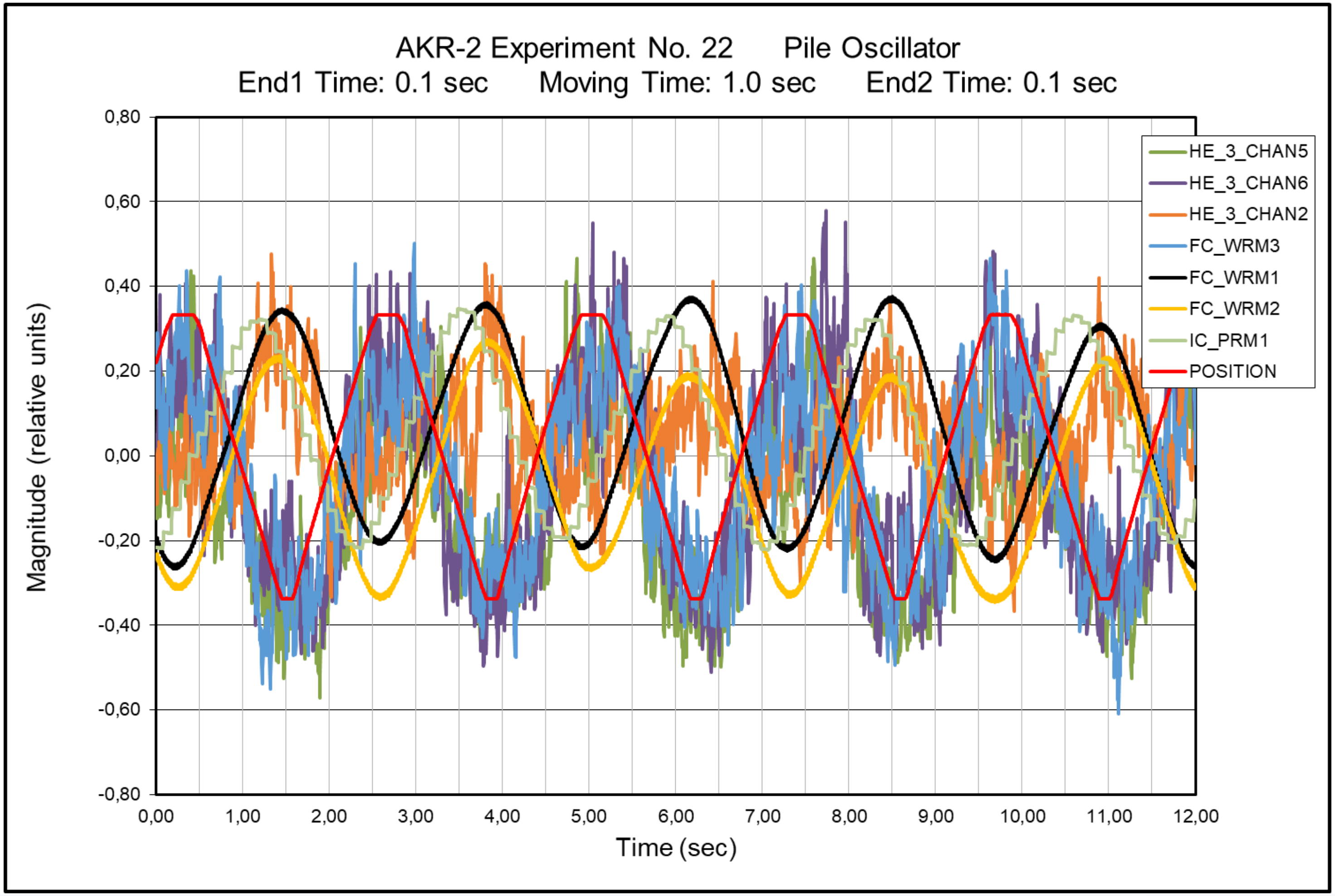
WP 2: AKR-2 Experiments (cont.)



AKR-2 Exp. 22
Pile Oscillator
Digital Time Series

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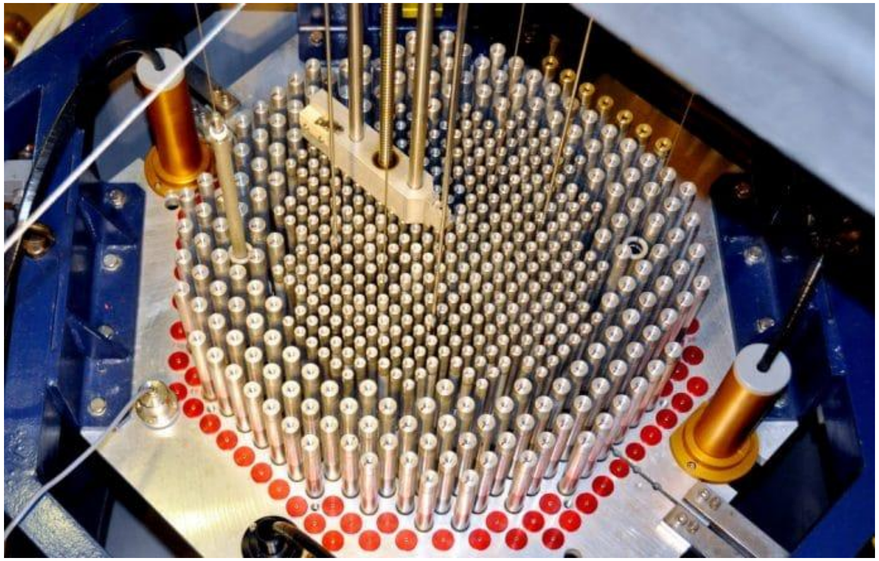
WP 2: CROCUS Experiments



Moving Fuel Element Ensemble COLIBRI

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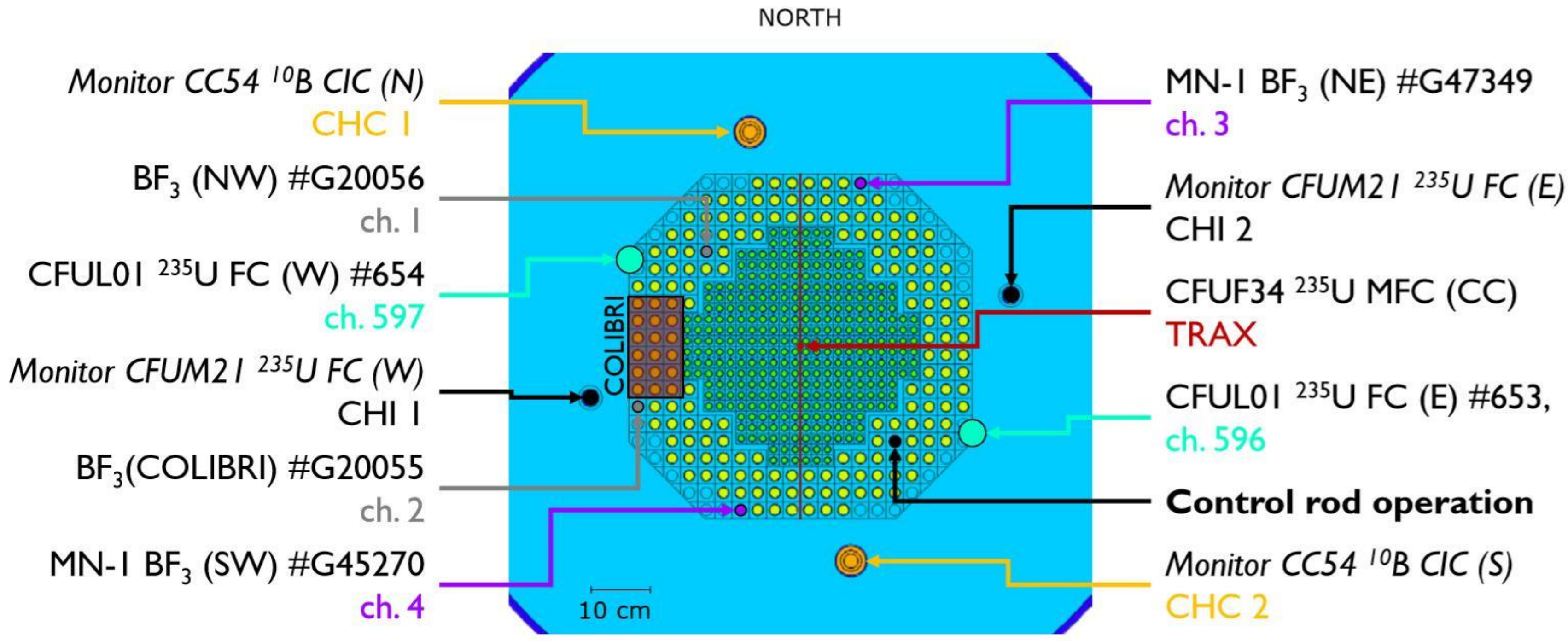
WP 2: CROCUS Experiments (cont.)

Moving Fuel Element Ensemble COLIBRI



Experimental locations and associated detectors

Positions of Detectors

WP 2: CROCUS Experiments (cont.)

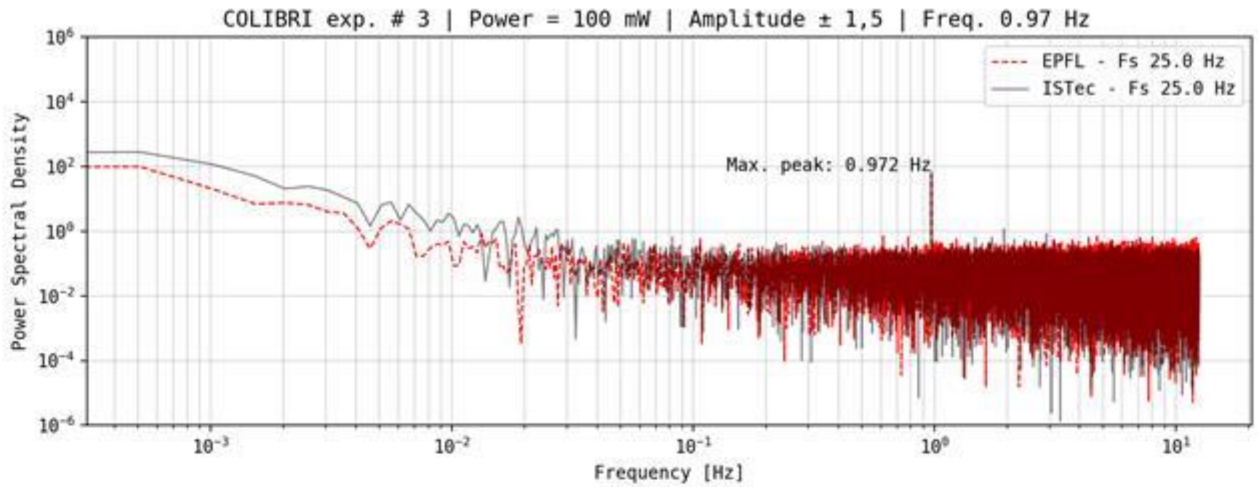
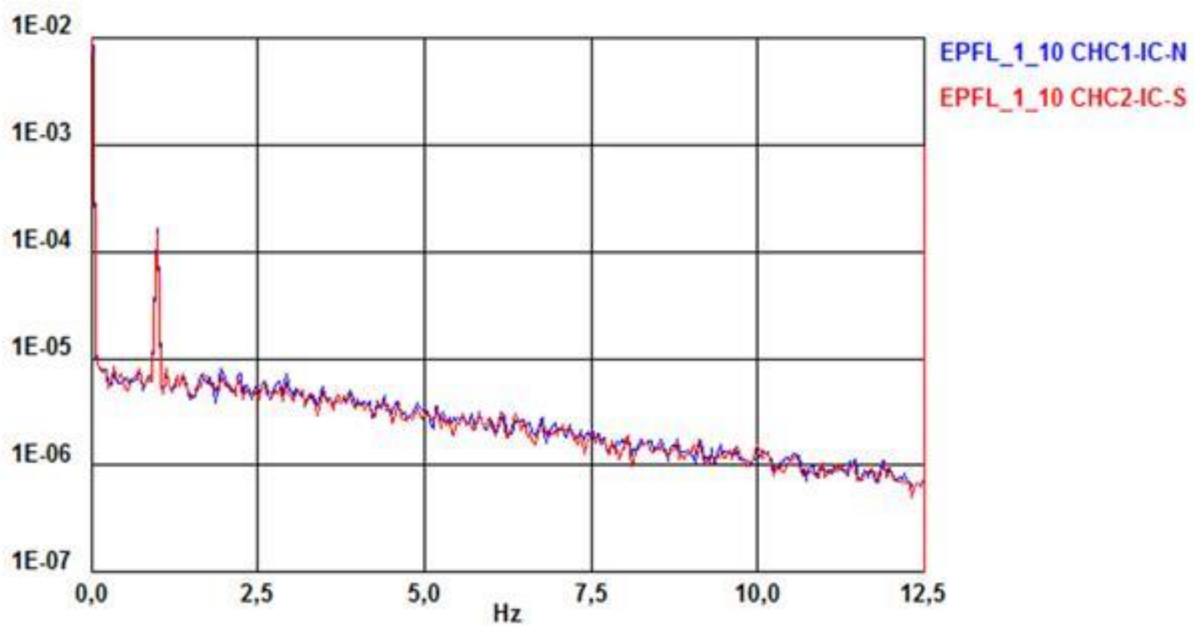


Figure 30 – Power spectral density for COLIBRI exp. 3 - Detector 6 (current mode).
(FFT calculated by EPFL – red graph)



Power spectral density for COLIBRI exp. 3 - Detector 6 (EPFL_1_10 CHC1-IC-N)
(FFT calculated by ISTec)

FFT: 8192 samples per block, 61 blocks averaged, Hanning window
PSD result: 4096 frequency points in 125 Hz, resolution 0.031 Hz
Amplitude normalized by the DC

Comparison of APSD Estimation and Representation CROCUS Experiment 03

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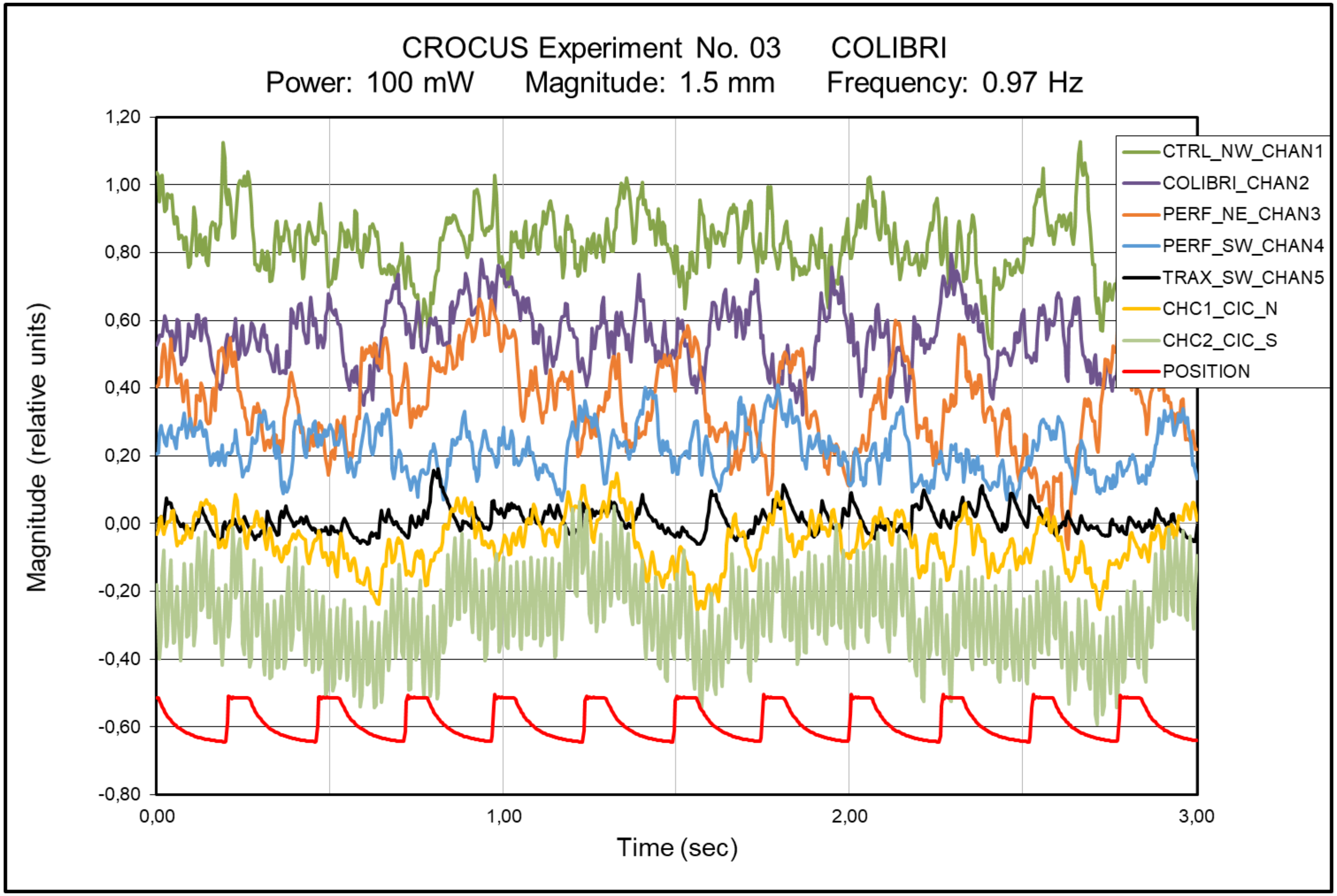
WP 2: CROCUS Experiments (cont.)

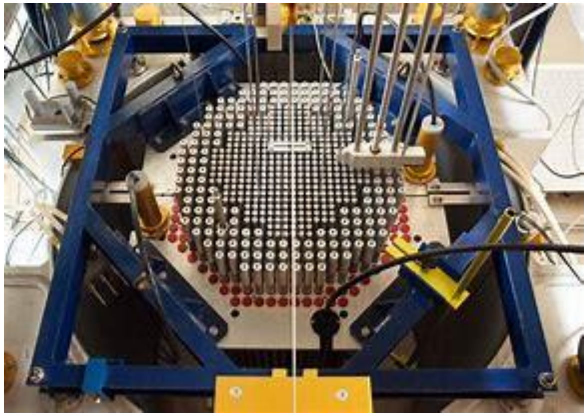


CROCUS Exp. 03
COLIBRI
Digital Time Series

Part 2

AKR-2 TU Dresden

CROCUS EPFL Lausanne



NPP Goesgen

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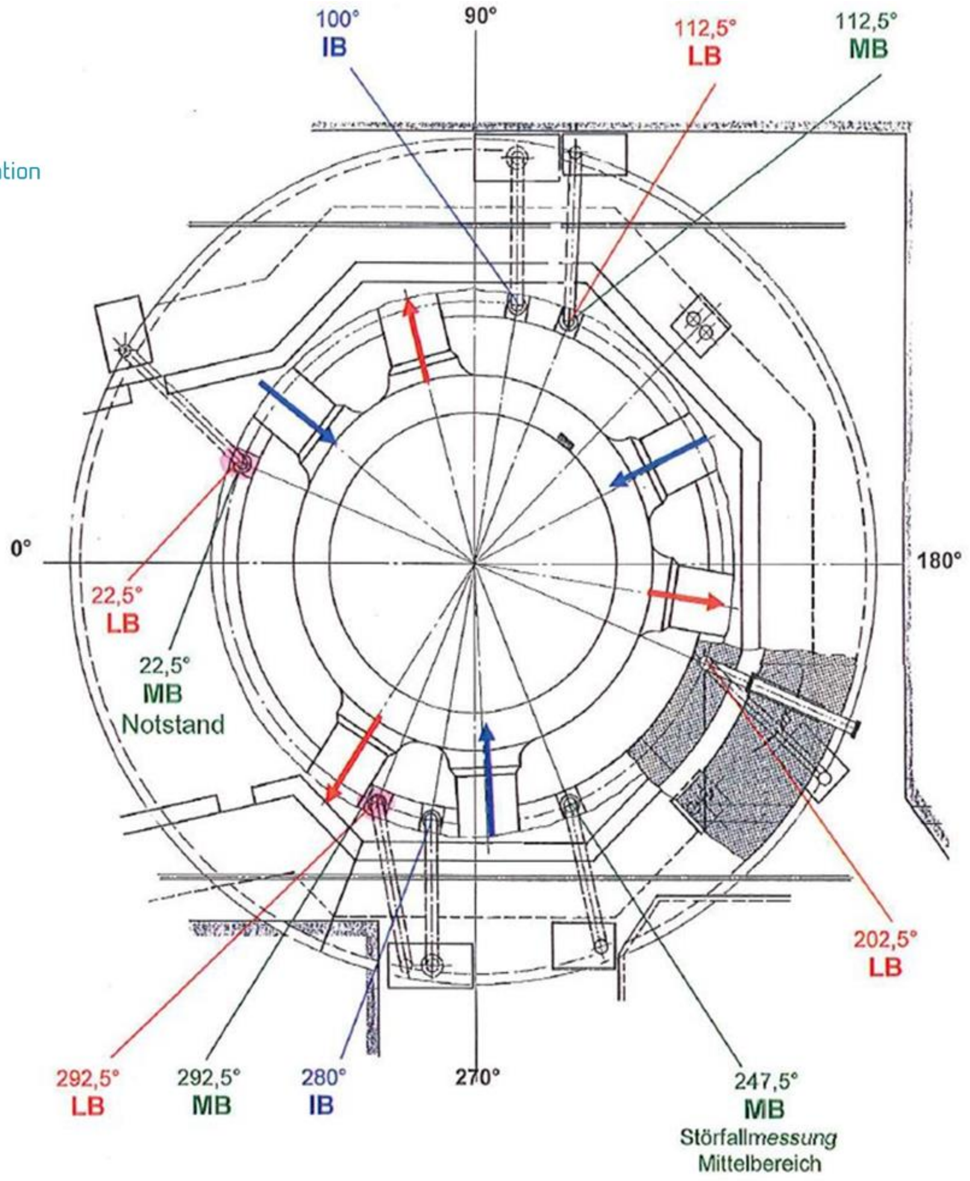
WP 4: NPP Goesgen Measurements

NPP Goesgen

3-Loop-PWR
Pre-convoy KWU Design
3002 MW thermal power

Positions of Excore-Detectors

X-0225-O/U	22,5° LB
X-1125-O/U	112,5° LB
X-2025-O/U	202,5° LB
X-2925-O/U	292,5° LB



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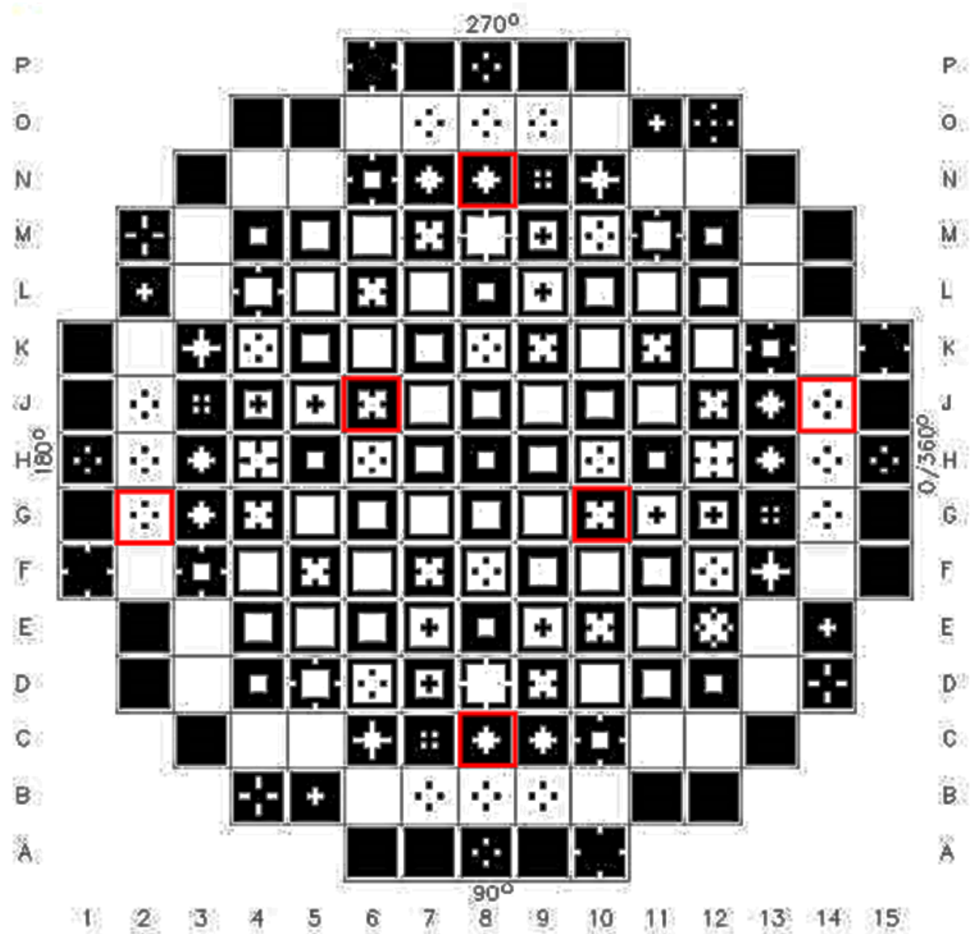
WP 4: NPP Goesgen Measurements (cont.)

NPP Goesgen

Core Cross Section Fuel Elements with different burnup



Positions of Incore-Detectors

L-G02-1/6
L-C08-1/6
L-J06-1/6
L-J14-1/6
L-N08-1/6
L-G10-1/6

WP 4: NPP Goesgen Measurements (cont.)

Excore Signals

EOC 39

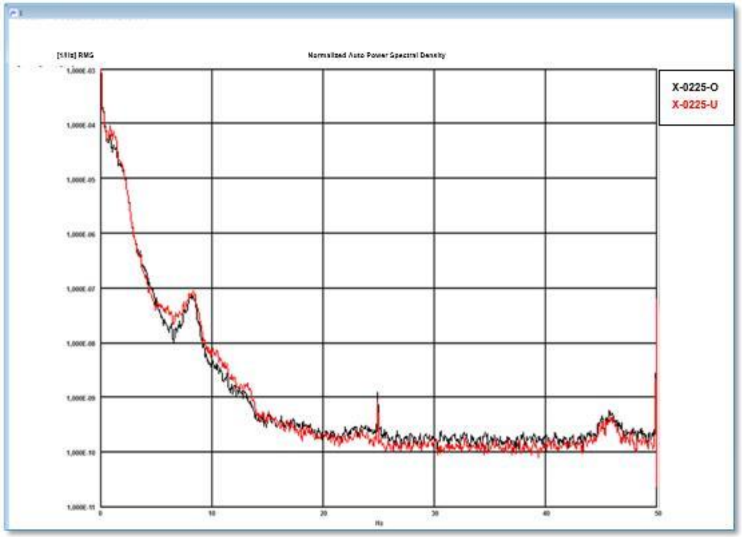


Figure 13: NAPSDs of Ex-Core Signals X-0225-O/U

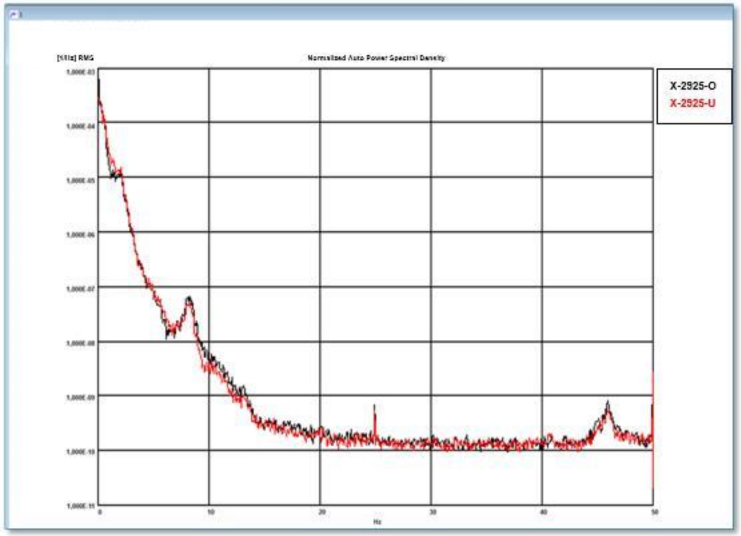


Figure 15: NAPSDs of Ex-Core Signals X-2925-O/U

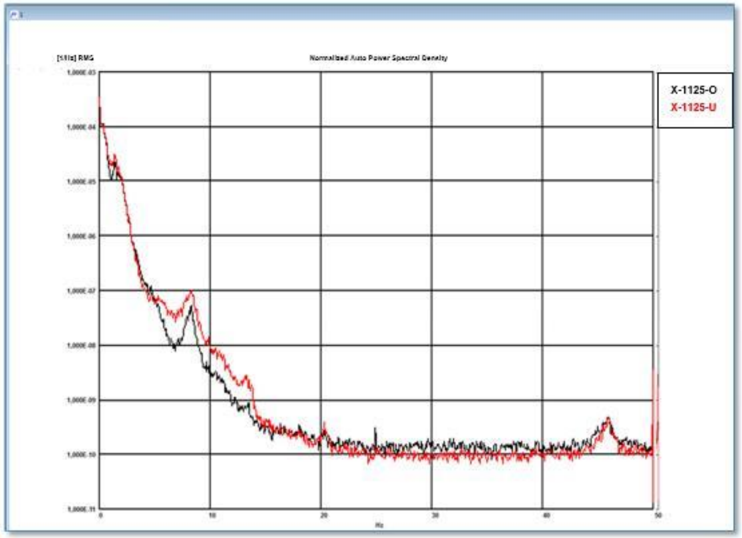


Figure 14: NAPSDs of Ex-Core Signals X-1125-O/U

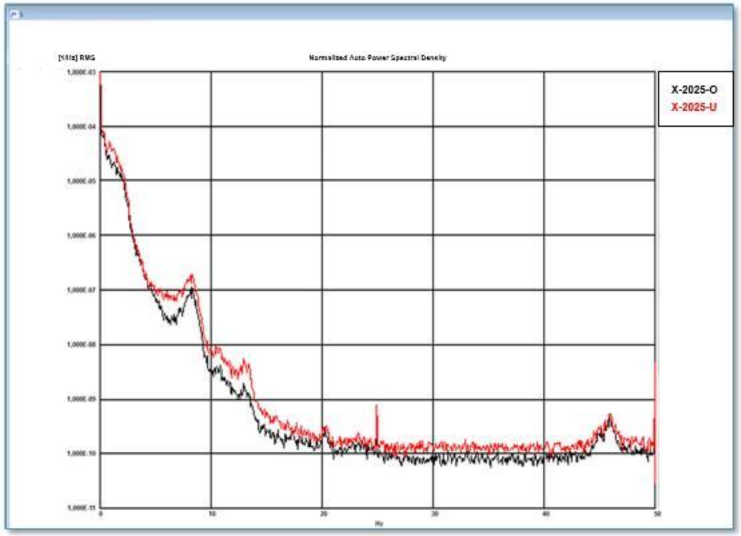


Figure 16: NAPSDs of Ex-Core Signals X-2025-O/U

WP 4: NPP Goesgen Measurements (cont.)

Incore Signals

EOC 39

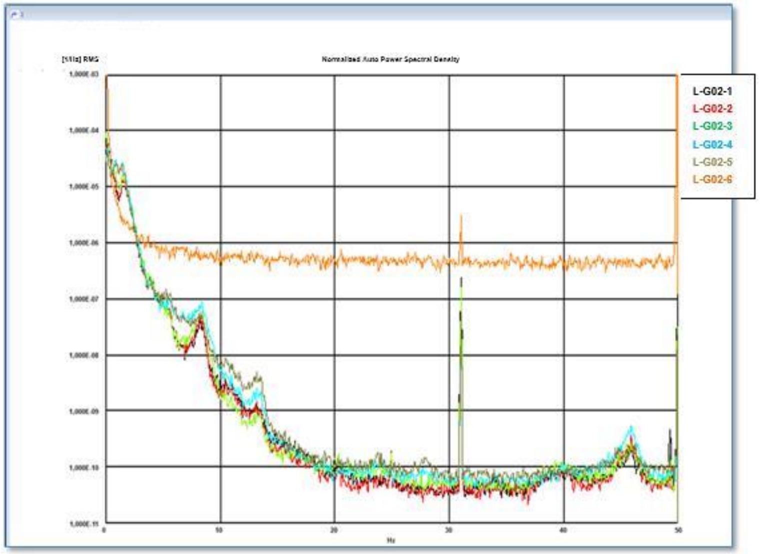


Figure 7: NAPSDs of In-Core Signals of String L-G02-1/6 (EOC 39)

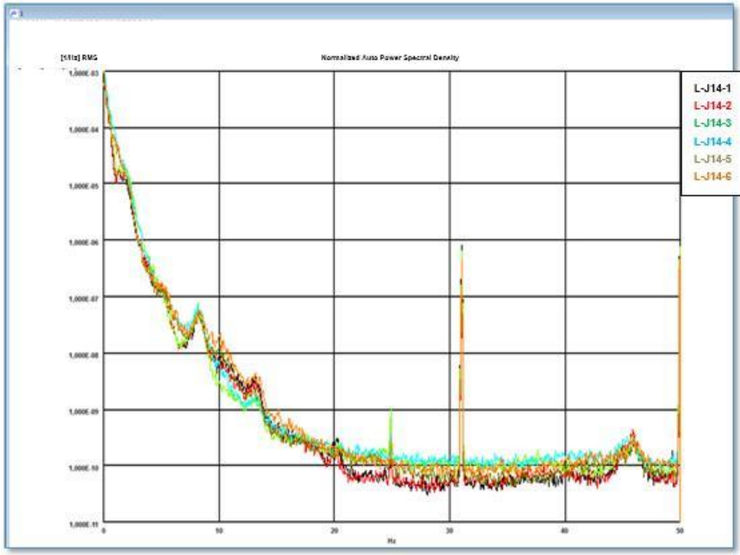


Figure 10: NAPSDs of In-Core Signals of String L-J14-1/6

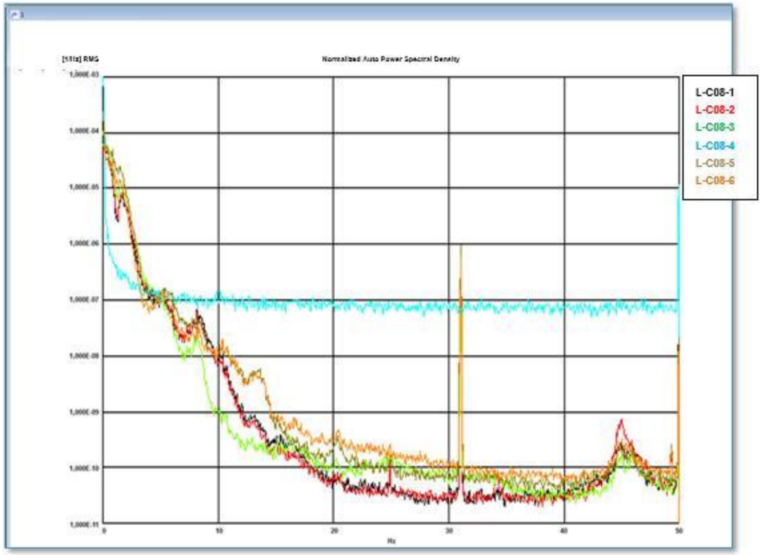


Figure 8: NAPSDs of In-Core Signals of String L-C08-1/6 (EOC 39)

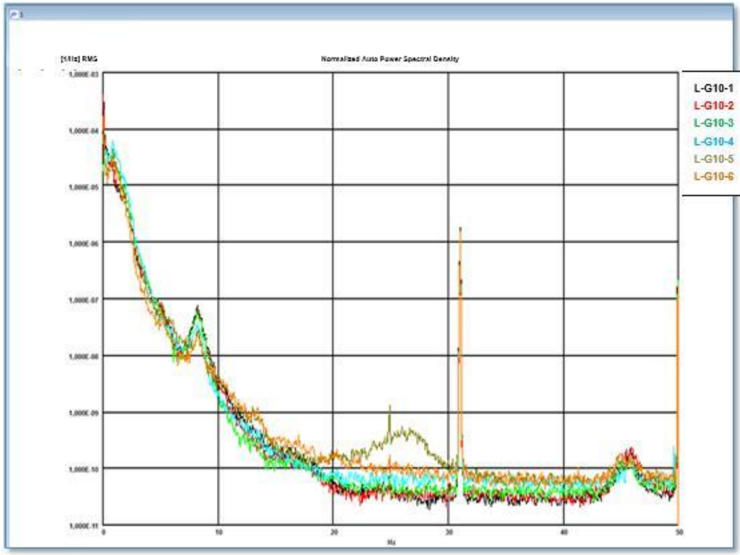


Figure 12: NAPSDs of In-Core Signals of String L-G10-1/6

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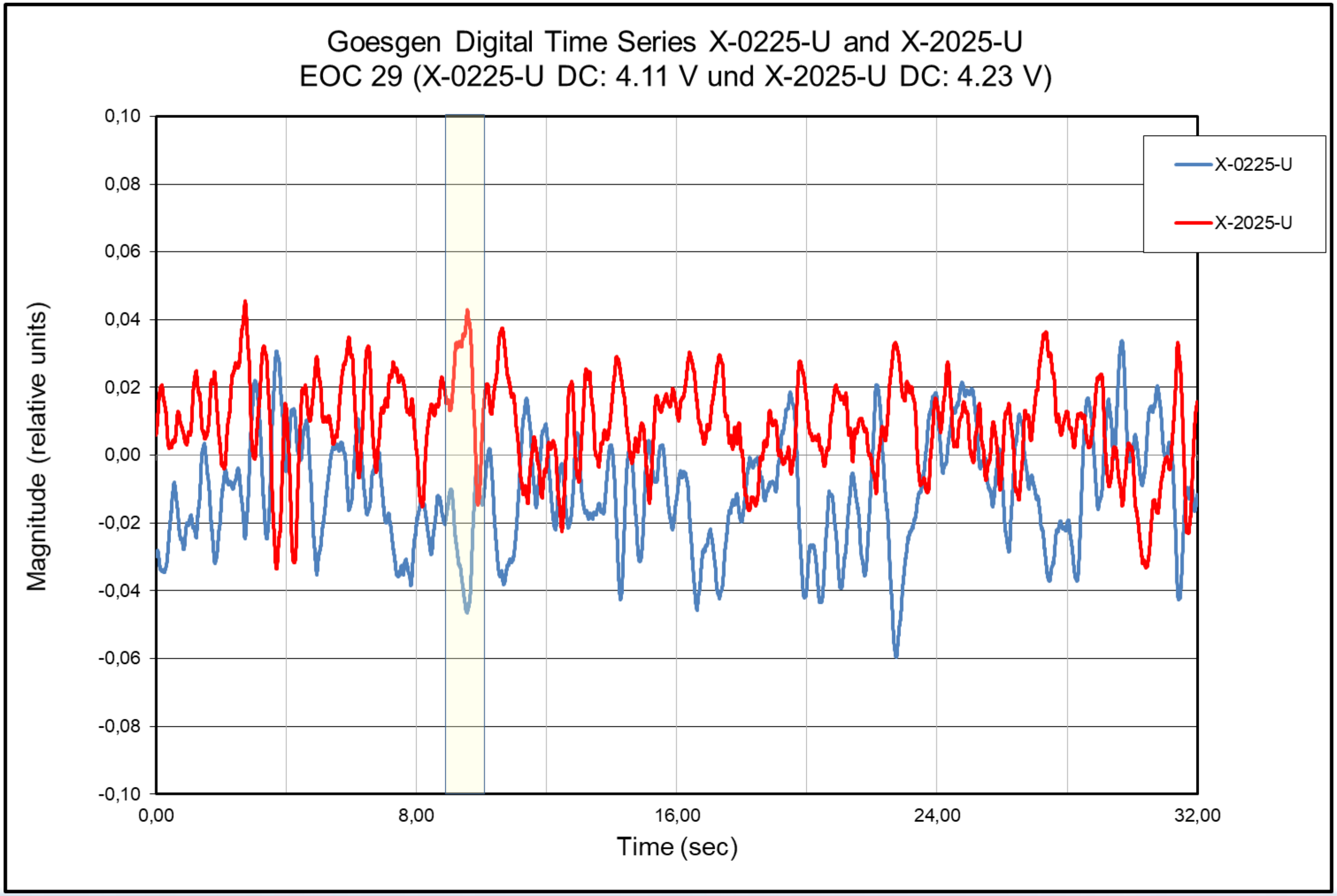
WP 4: NPP Goesgen Measurements (cont.)

Out-of-Phase Oscillations

Excore-Detectors in opposite core Positions (180°)

NPP Goesgen
Signal X-0225-U
Signal X-2025-U
EOC 39



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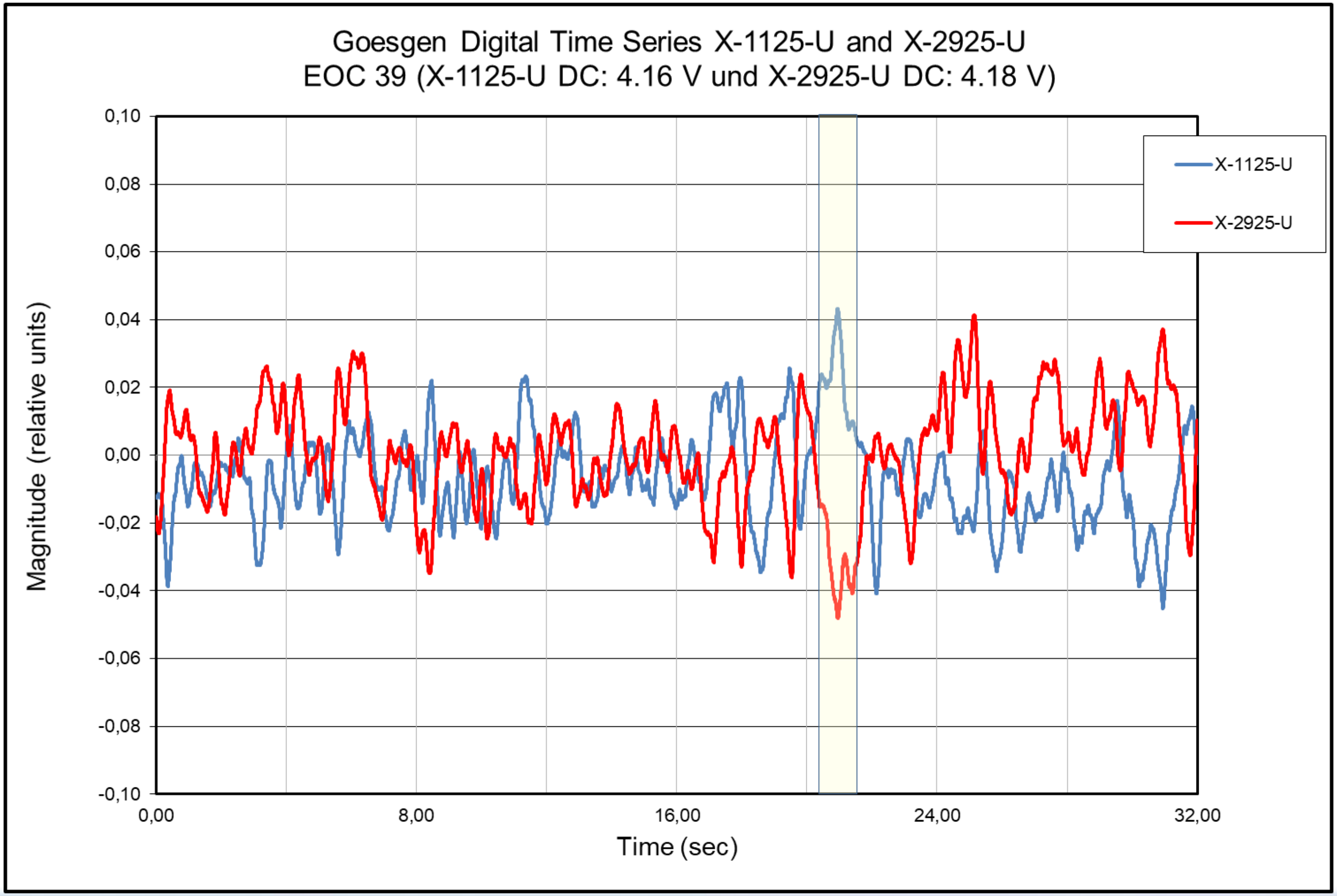
WP 4: NPP Goesgen Measurements (cont.)

Out-of-Phase Oscillations

Excore-Detectors in opposite core Positions (180°)

NPP Goesgen
Signal X-1125-U
Signal X-2925-U
EOC 39



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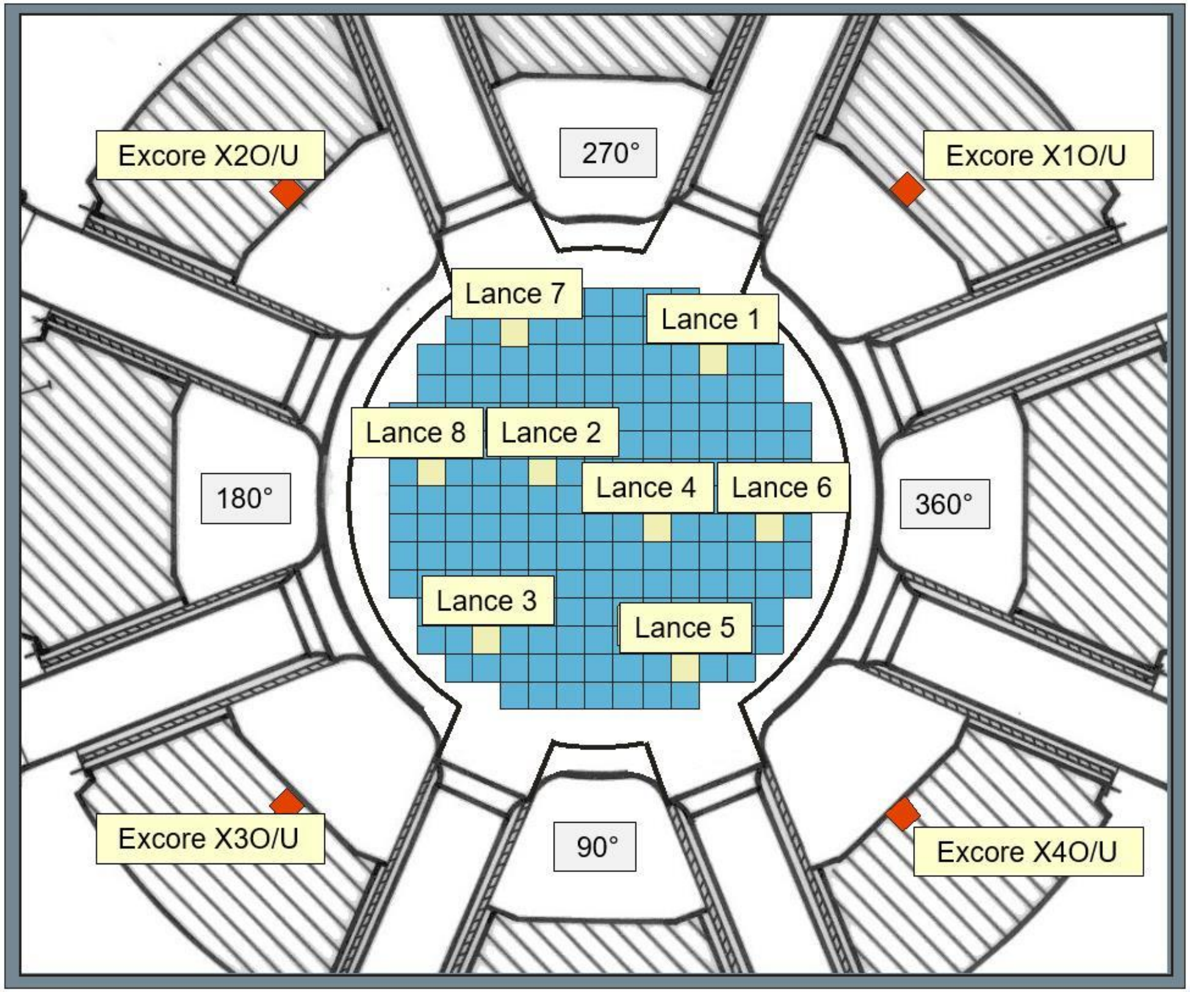
Experiences with German PWRs

4-Loop-PWR KWU

Positions of Detectors

X1O/U:	X-315-O/U
X2O/U:	X-225-O/U
X3O/U:	X-135-O/U
X4O/U:	X-045-O/U
Lance 1:	L-N12-1/6
Lance 2:	L-J06-1/6
Lance 3:	L-C04-1/6
Lance 4:	L-G10-1/6
Lance 5:	L-B11-1/6
Lance 6:	L-G14-1/6
Lance 7:	L-O05-1/6
Lance 8:	L-J02-1/6



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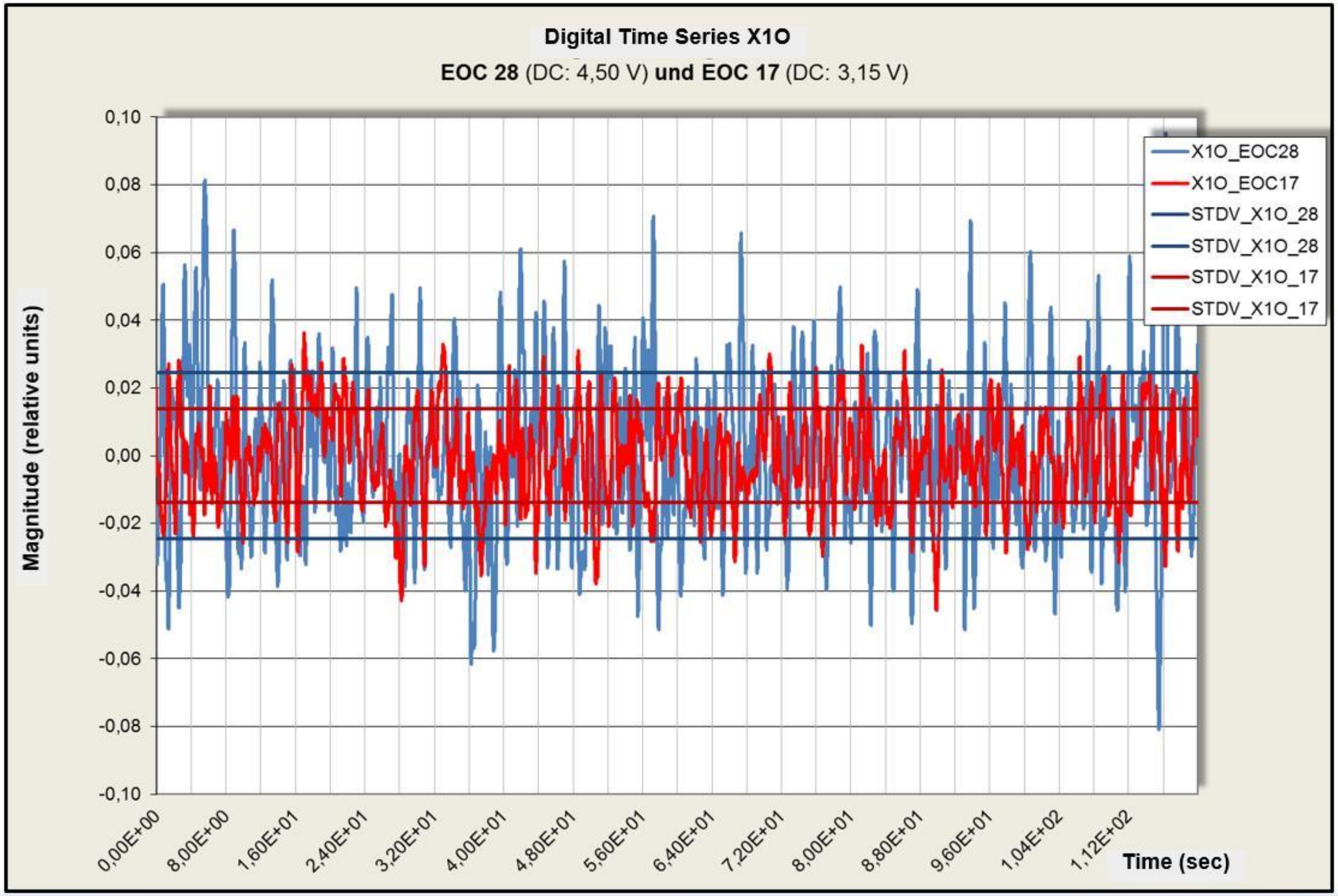
Experiences with German PWRs (cont.)



Increased Neutron Flux Fluctuations

Excore Signal X1O
EOC 28 vs EOC 17

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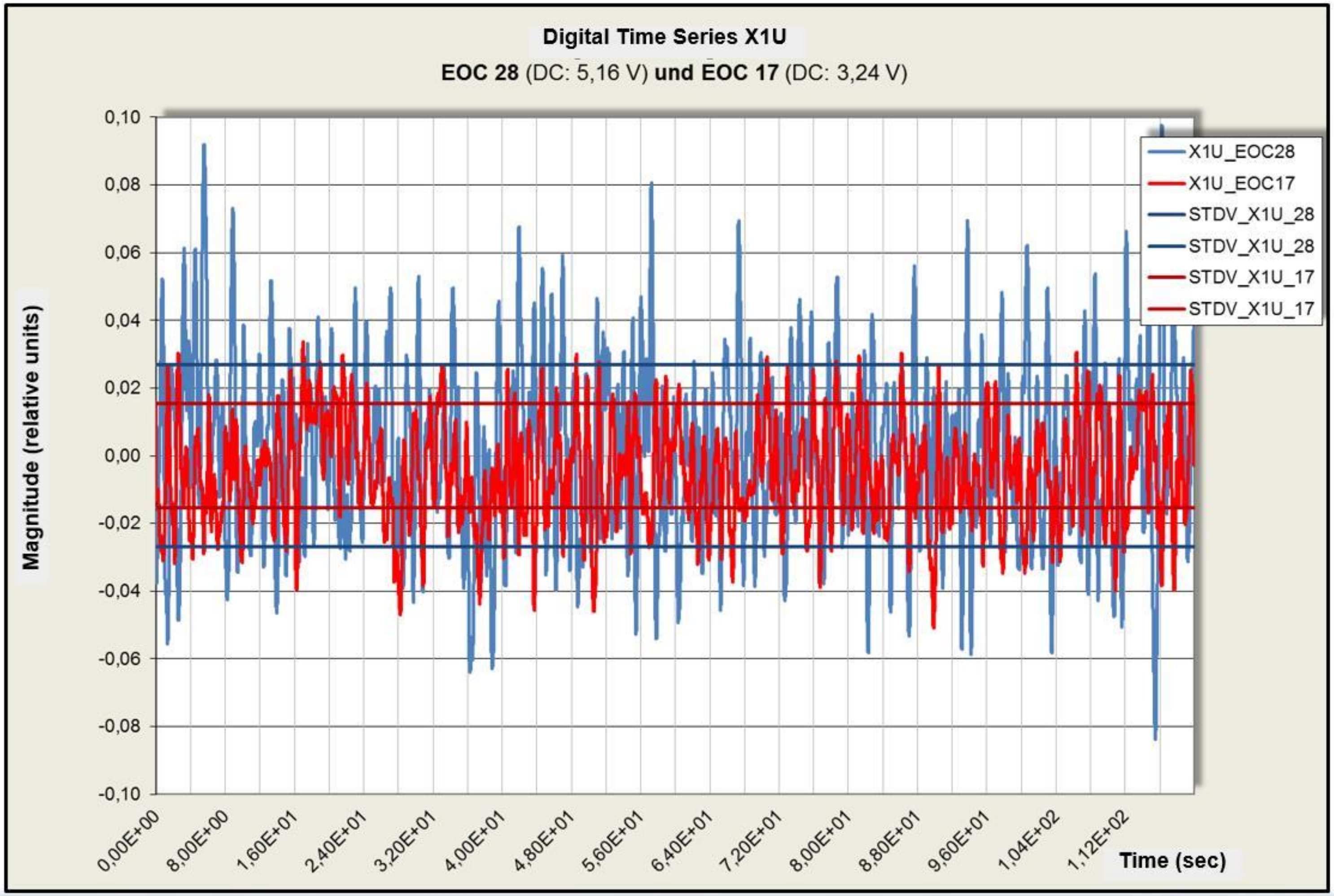
Experiences with German PWRs (cont.)

Increased Neutron Flux Fluctuations



Excore Signal X1U
EOC 28 vs EOC 17

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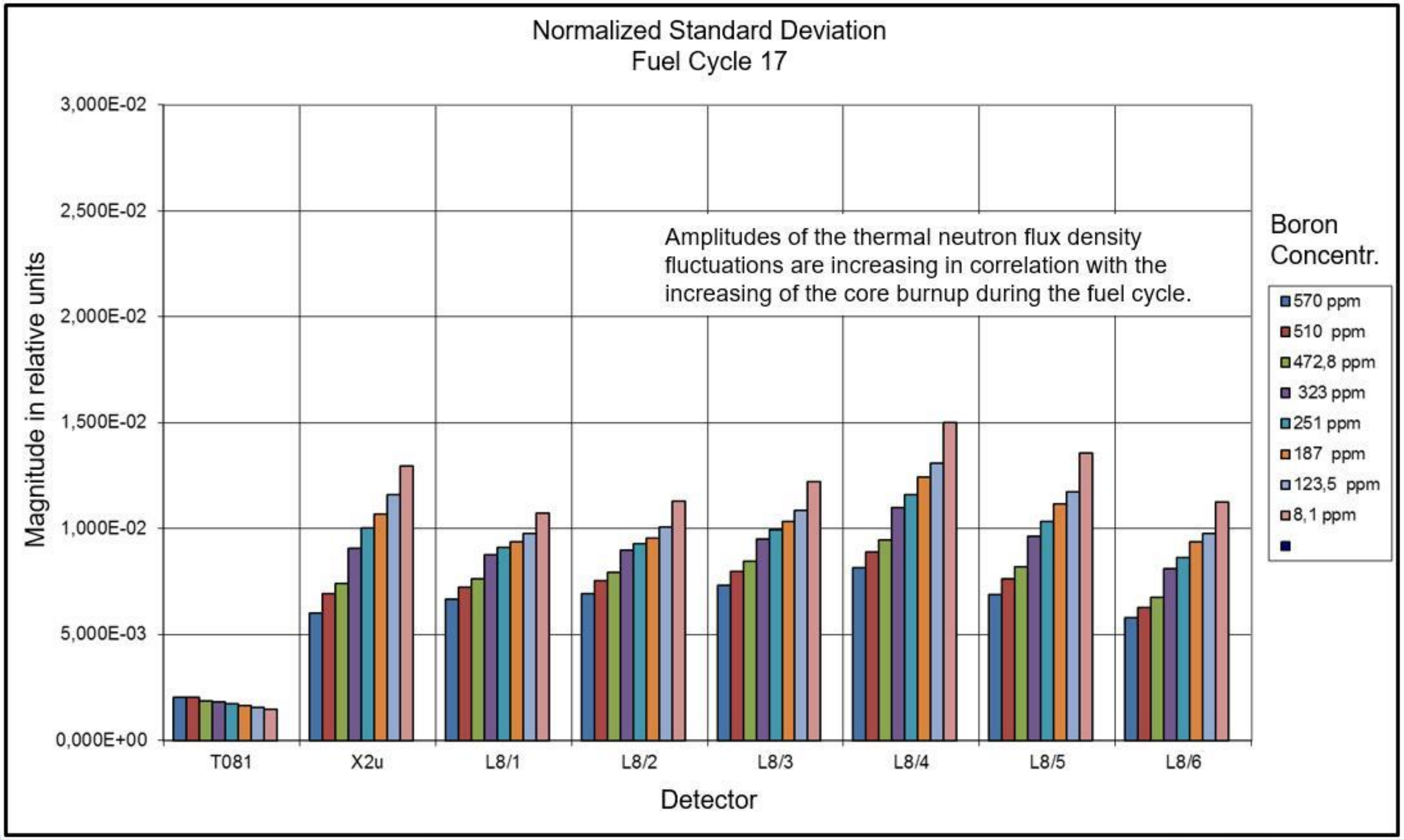
Experiences with German PWRs (cont.)



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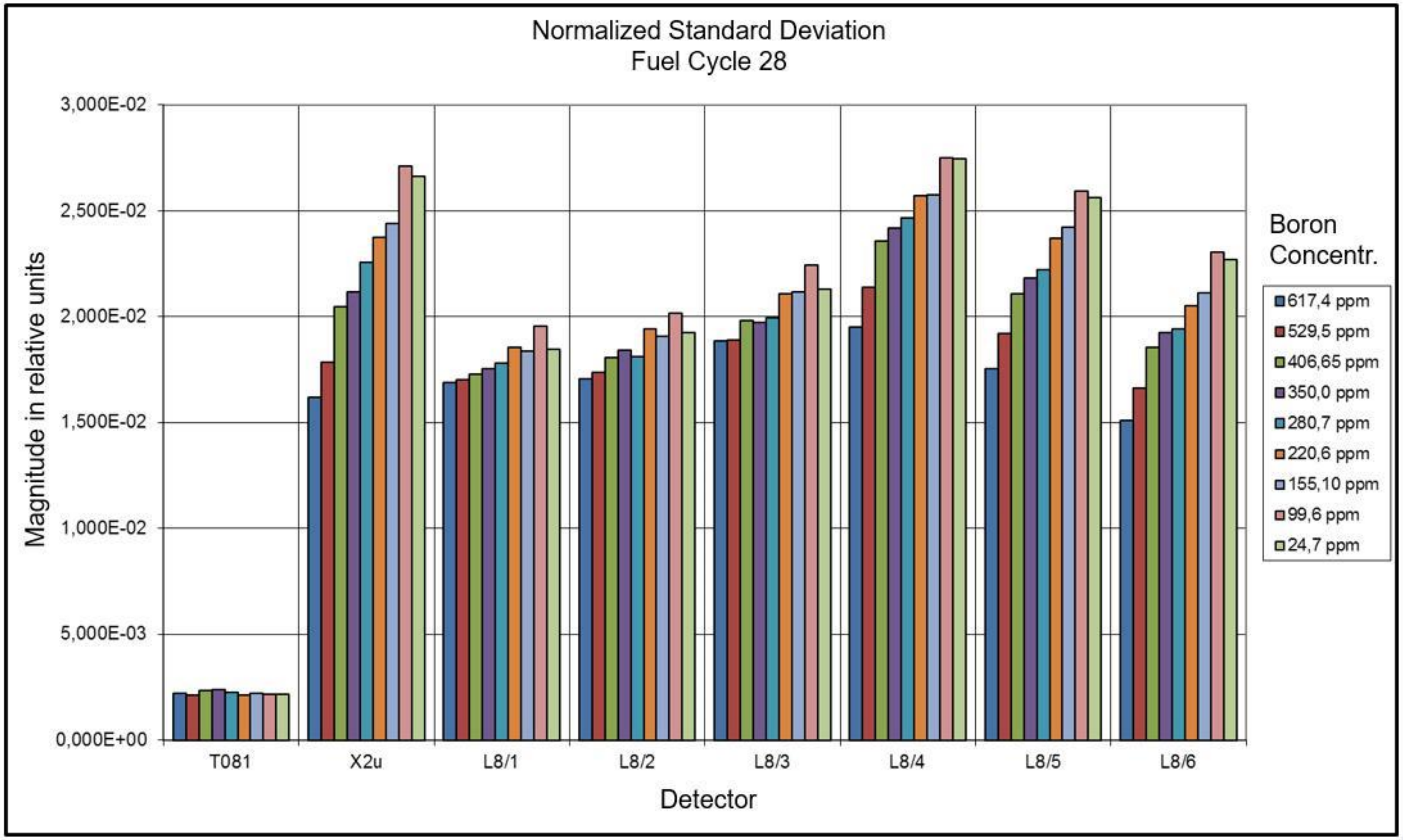
Experiences with German PWRs (cont.)



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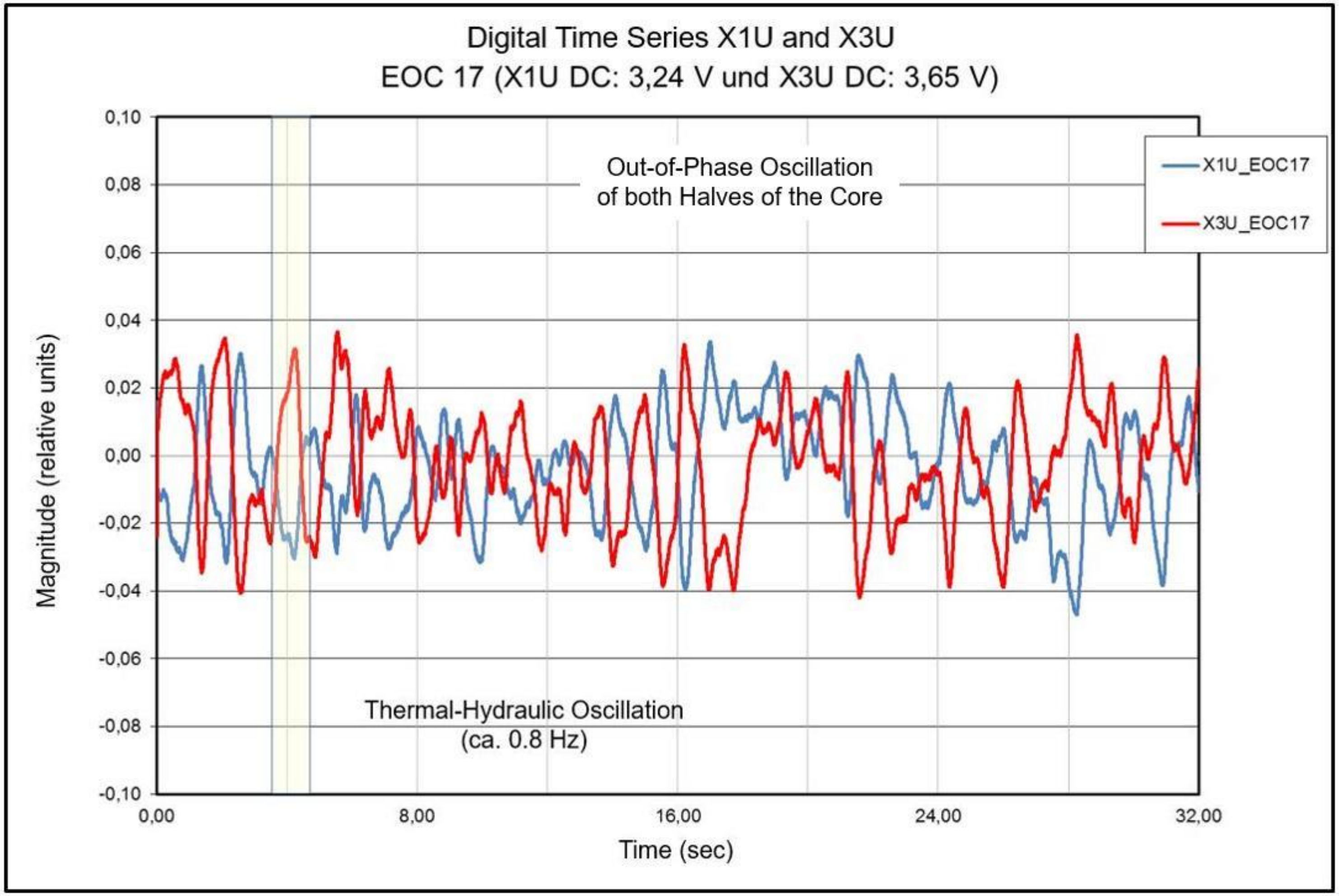
Experiences with German PWRs (cont.)

Out-of-Phase Oscillations

Excore-Detectors in opposite core Positions (180°)

Excore Signal X1U
Excore Signal X3U
EOC 17



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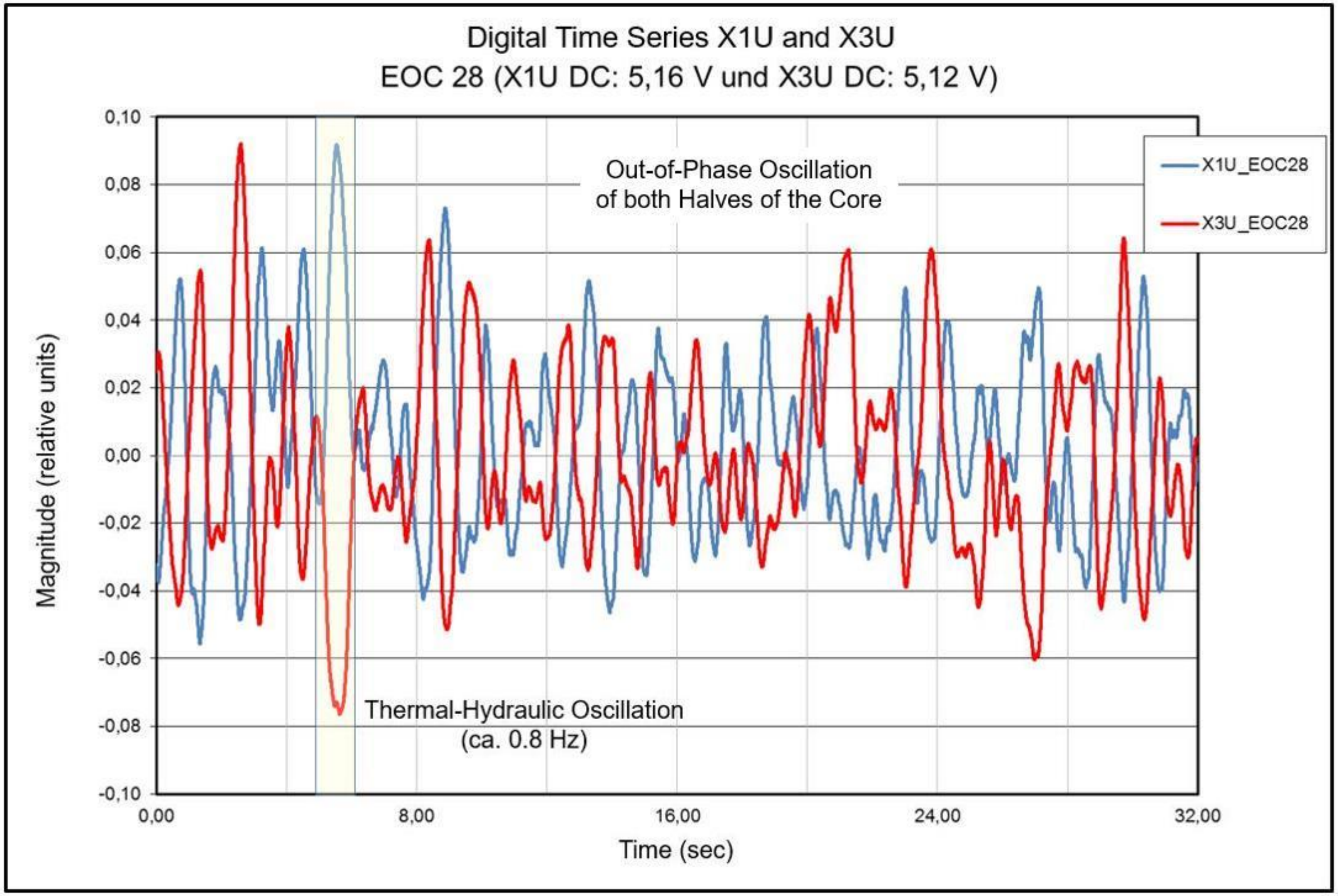
Experiences with German PWRs (cont.)

Out-of-Phase Oscillations

Excore-Detectors in opposite core Positions (180°)

Excore Signal X1U
Excore Signal X3U
EOC 28



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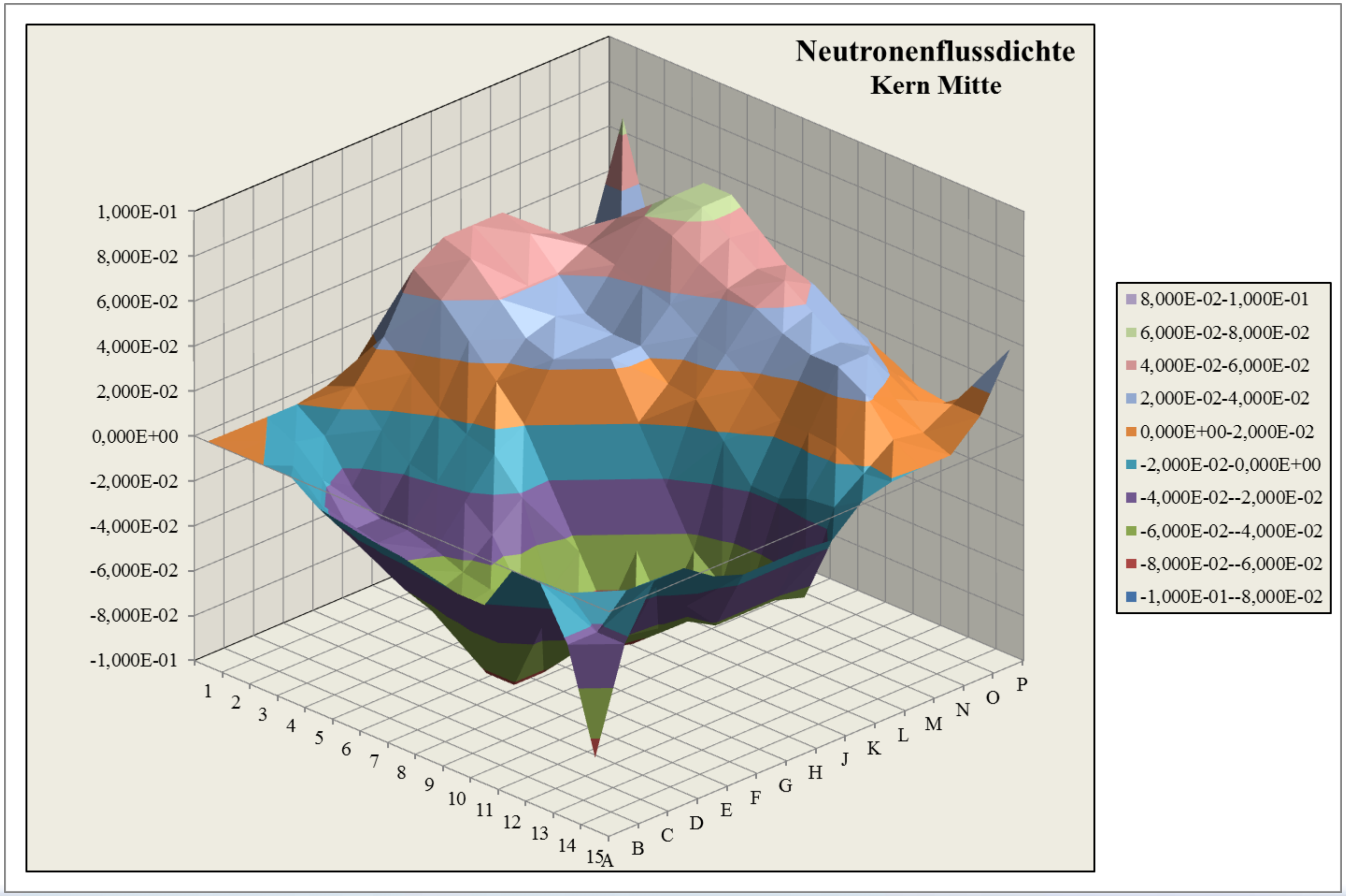
Experiences with German PWRs (cont.)

Interpolation of all samples at same time

of detectors at excore and incore positions

3D Graph 1
Neutron Flux Density
EOC 30



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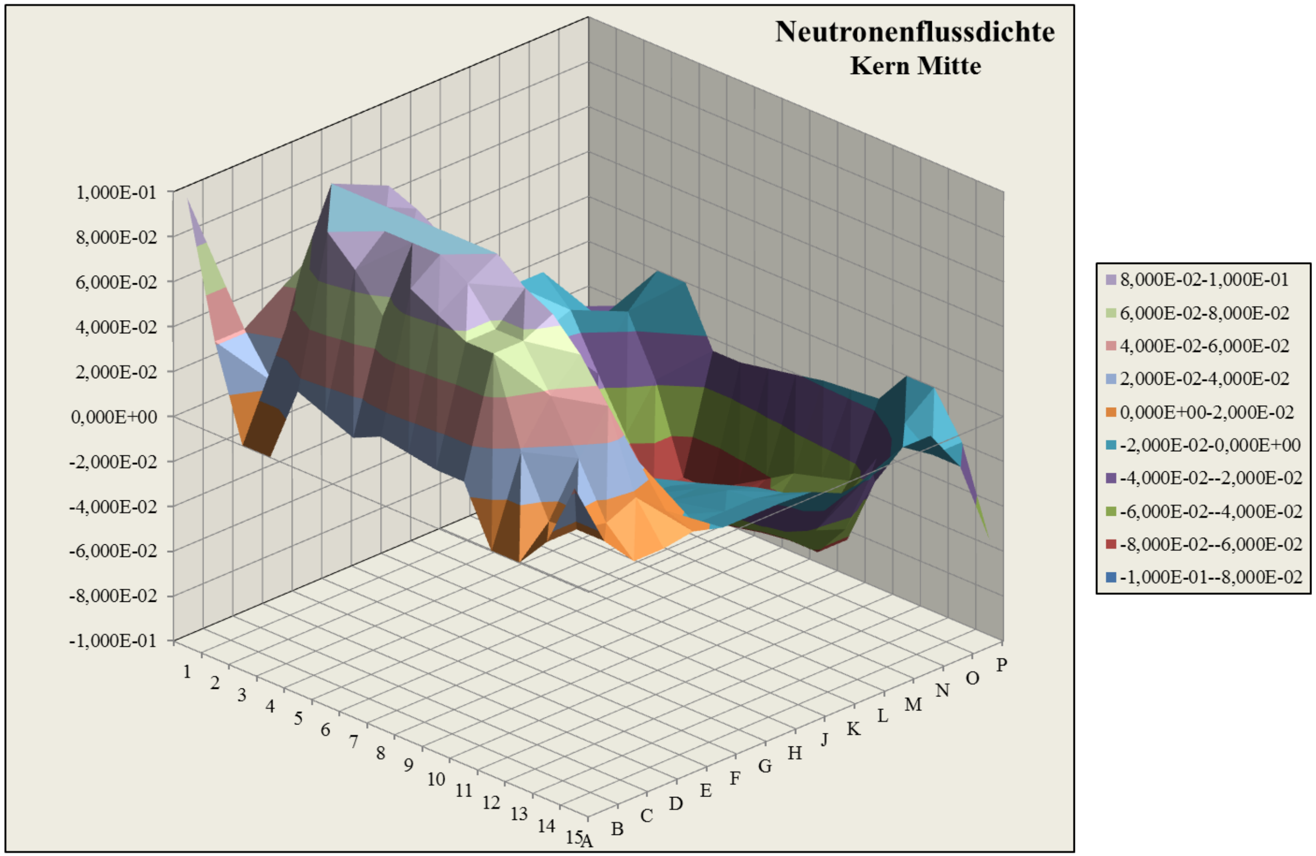
Core monitoring techniques and experimental validation and demonstration

Experiences with German PWRs (cont.)

Interpolation of all samples at same time

of detectors at excore and incore positions



3D Graph 2
Neutron Flux Density
EOC 30

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Core monitoring techniques and experimental validation and demonstration

Experiences with German PWRs (cont.)

1. The cause of the increased neutron flux fluctuations has been identified as an increased oscillation of the water gap width in the cooling channels of the fuel elements due to higher amplitudes of the mechanical oscillation of fuel rods and fuel elements forced by periodically pressure fluctuations of the thermal-hydraulic transportation effect.

2. The changed amplitudes of the mechanical oscillation of fuel rods and fuel elements were made possible by the less stronger mechanical mounting of fuel rods of the used and new developed HTP fuel elements. Changes of the periodically pressure fluctuations of the thermal-hydraulic transportation effect could not be established.

3. The investigated pressure fluctuations in the core with a certain frequency is based on the specific thermal-hydraulic conditions in connection with the geometric design of the reactor vessel and reactor core. Periodically forces in the reactor core stand out from the well-known stochastic Karman vortex street and have not been investigated yet.

CORTEX
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Experiences with German PWRs (cont.)

4. The increasing of the average core burnup in the treated fuel cycles causes in addition to the described pass-band effect further significant increasing of the amplitudes of neutron flux fluctuations as a wide-band effect in frequency domain.

5. The cause-effect-chain has been worked out clearly and in this respect, the results of the investigations represent an innovation concerning the state of the art in science and technology. For the determination of the transfer functions of the proposed cause-effect-chain, further investigations are necessary.

6. For more information see report ISTec-A-3695, Untersuchung veränderter Neutronenflussschwankungen und Brennstab-Beanspruchungen in DWR-Anlagen im Rahmen der Sicherheitsforschung (Investigation of changed neutron flux fluctuations and fuel rod loads in frame of safety research), J. Pohlus, U. Paquée, October 2018.
   The investigation results can be used for the verification of numerical codes on the process behavior in the reactor core and for the development of advanced monitoring procedures for PWRs in power operation as a complement to CORTEX investigations.

THANK YOU!