CORTEX

Core monitoring techniques and experimental validation and demonstration

Required instrumentation and data acquisition system

Final CORTEX workshop

Online

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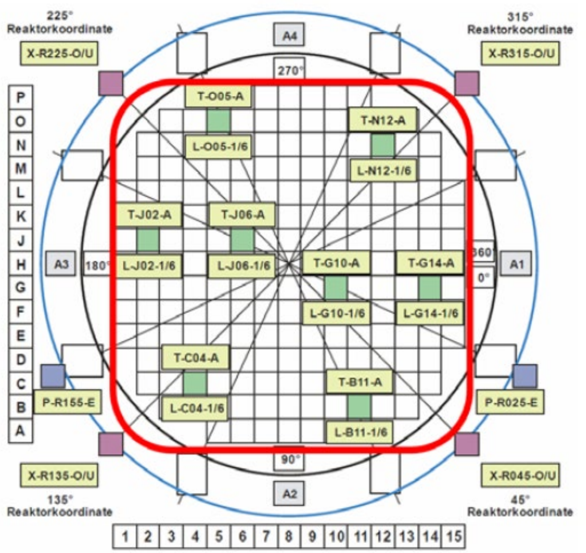
Outline

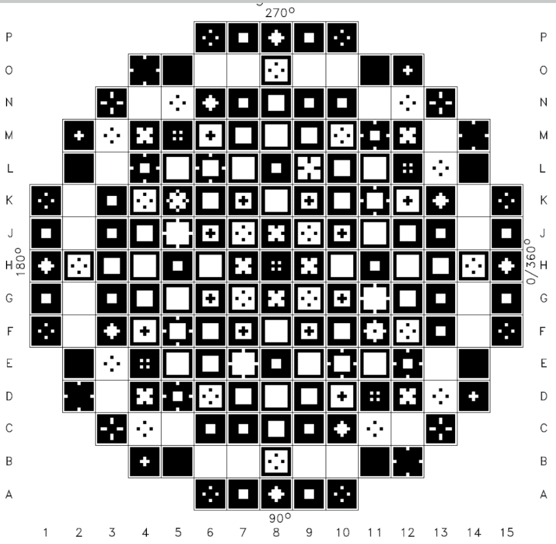
- PWR/VVER cores and instrumentation
- PWR/VVER neutron noise characteristics in commercial reactors
- Neutron noise measurement campaigns / Acquisition systems / Signal analysis
- Recommendations for future work / Conclusion

PWR Cores and Instrumentation

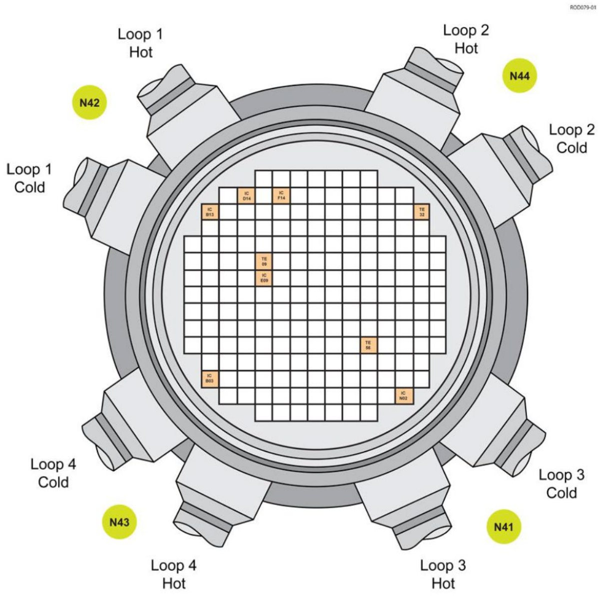
Palette of Cores (PWR, VVER)

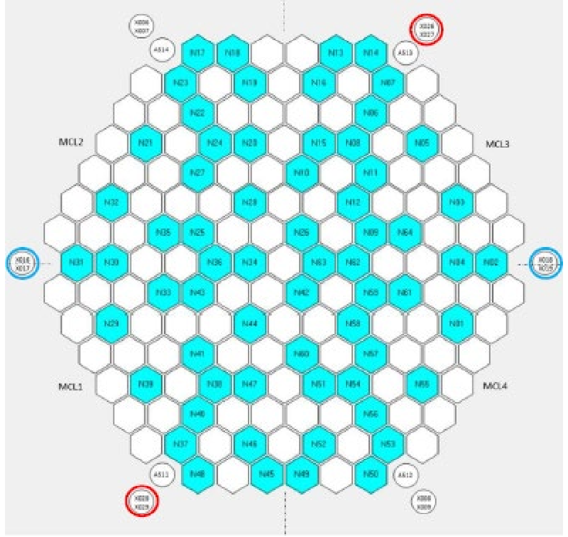
- Available data to the Consortium for code validation purposes
  - German pre-KONVOI 4-loop
  - Swiss pre-KONVOI 3-loop, specific new high measurement campaigns
  - American 3-loop PWR
  - American 4-loop PWR (1) Westinghouse design
  - American 4-loop PWR (2) Westinghouse design
  - VVER 440/213
  - VVER 1000



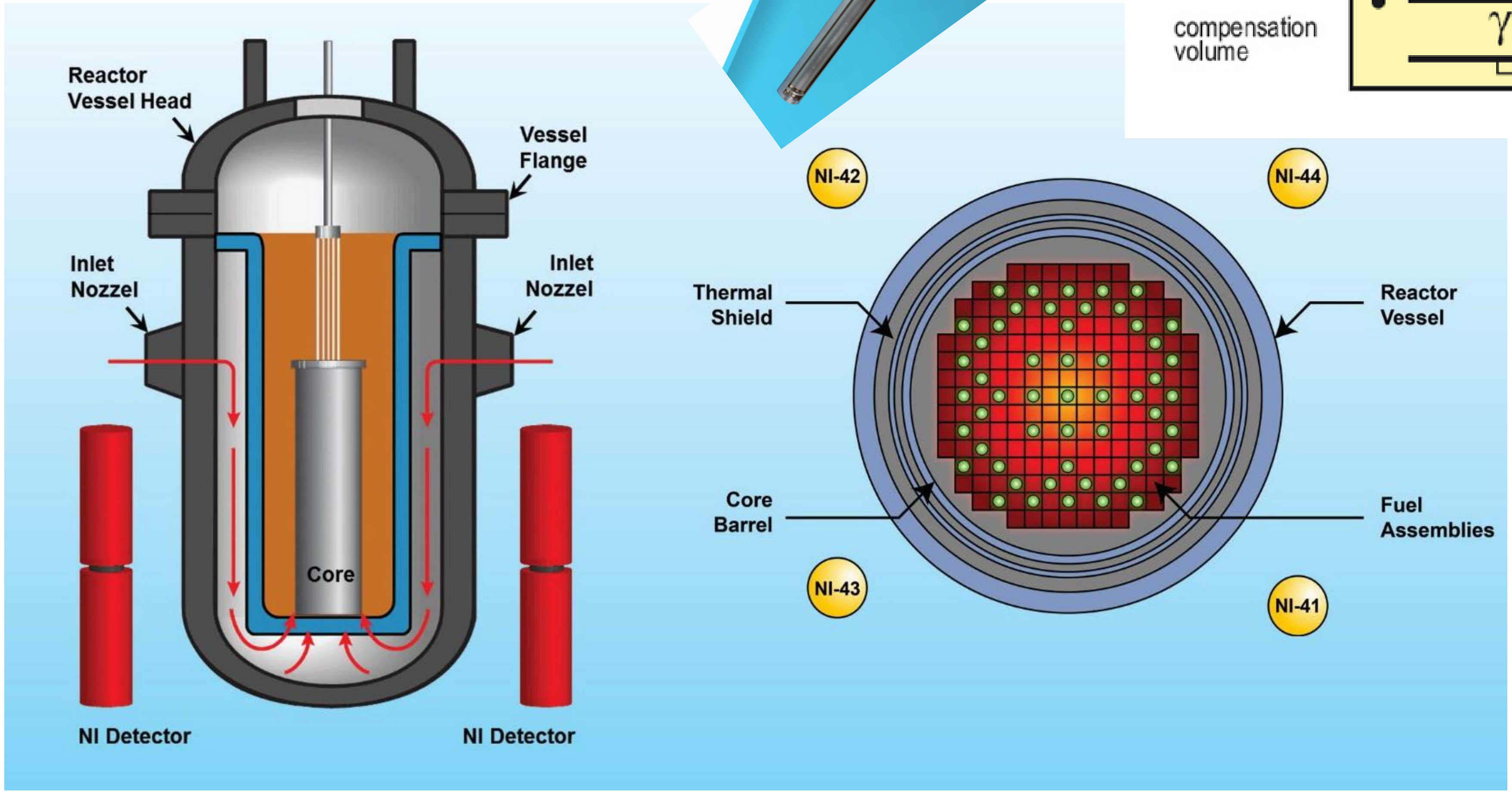


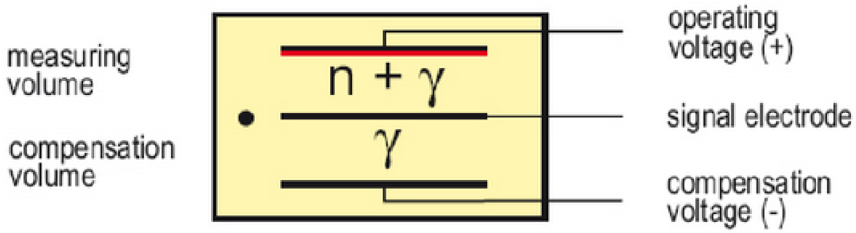
PWR 4-1 In-Core Map





3-loop / 4-loop location of Excore instrumentation





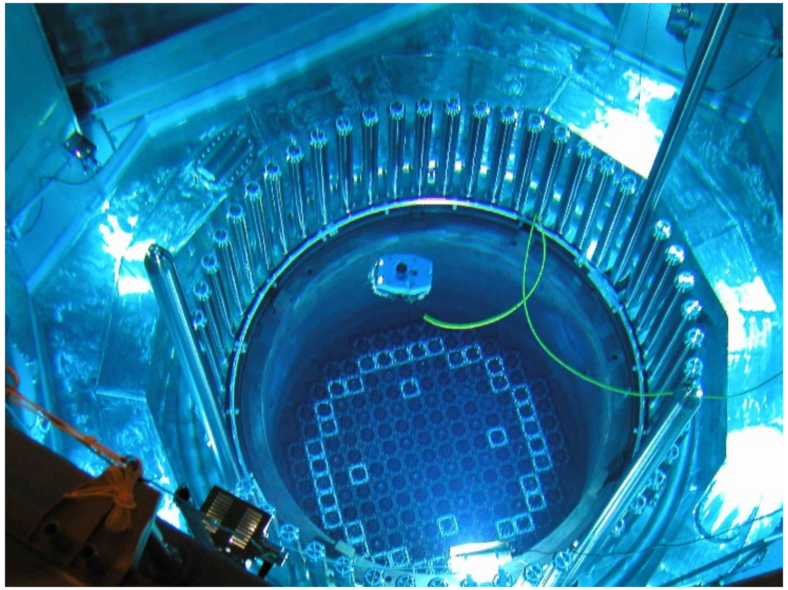
KKG Core: Overview

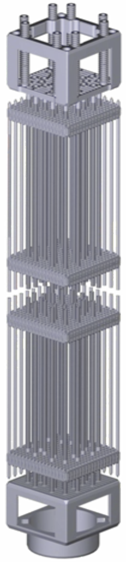
PWR, Siemens / KWU Design

- Single reactor with 1060 MWe (3002 MWth)
- Commissioned in 1979
- 3 loops plant

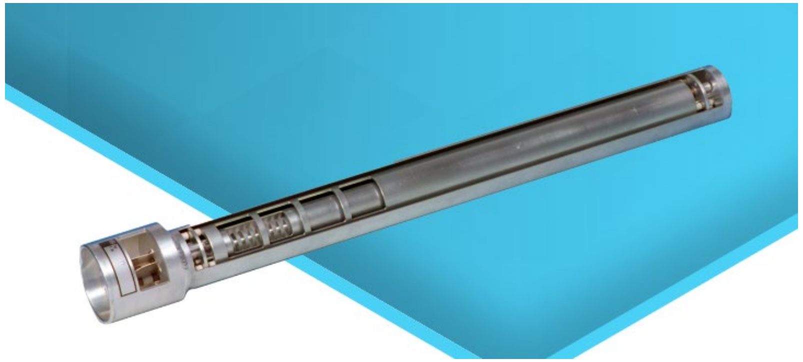
Fuel Key Features

- UO_2 4.95% (U and REP)
- 15X15 FA Design AREVA
- 177 FA in the core
- 205 Fuel Pins per Assembly
- 20 structural tubes per Assembly
- 5-zone core
- Low leakage loading pattern
- Max LHGR 525 W/cm
- Max FA-Burnup 70 MWd/kgHM



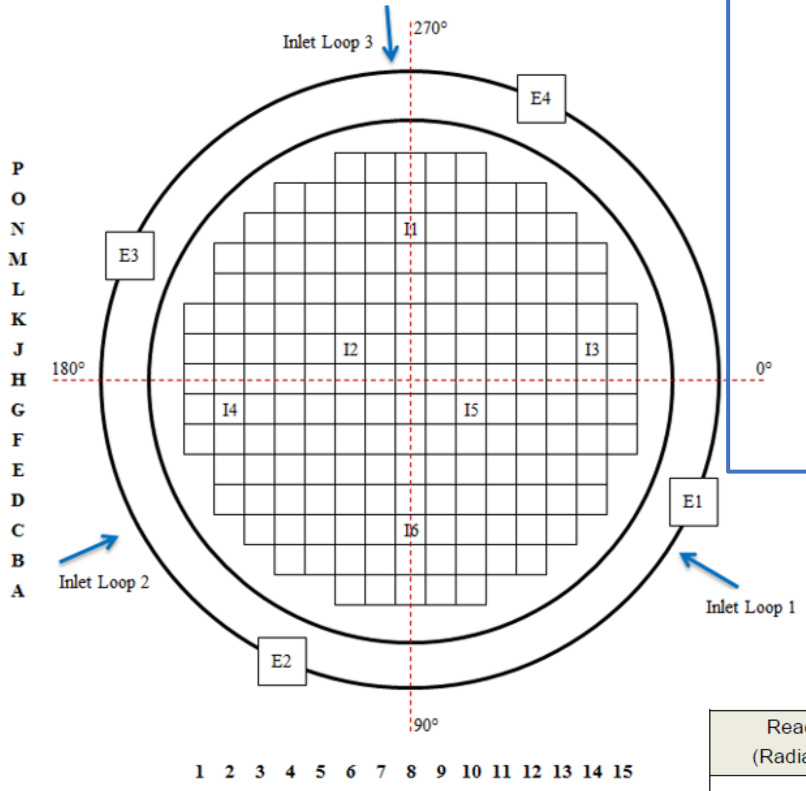


SPND and ionization chambers for neutron viz. noise detection

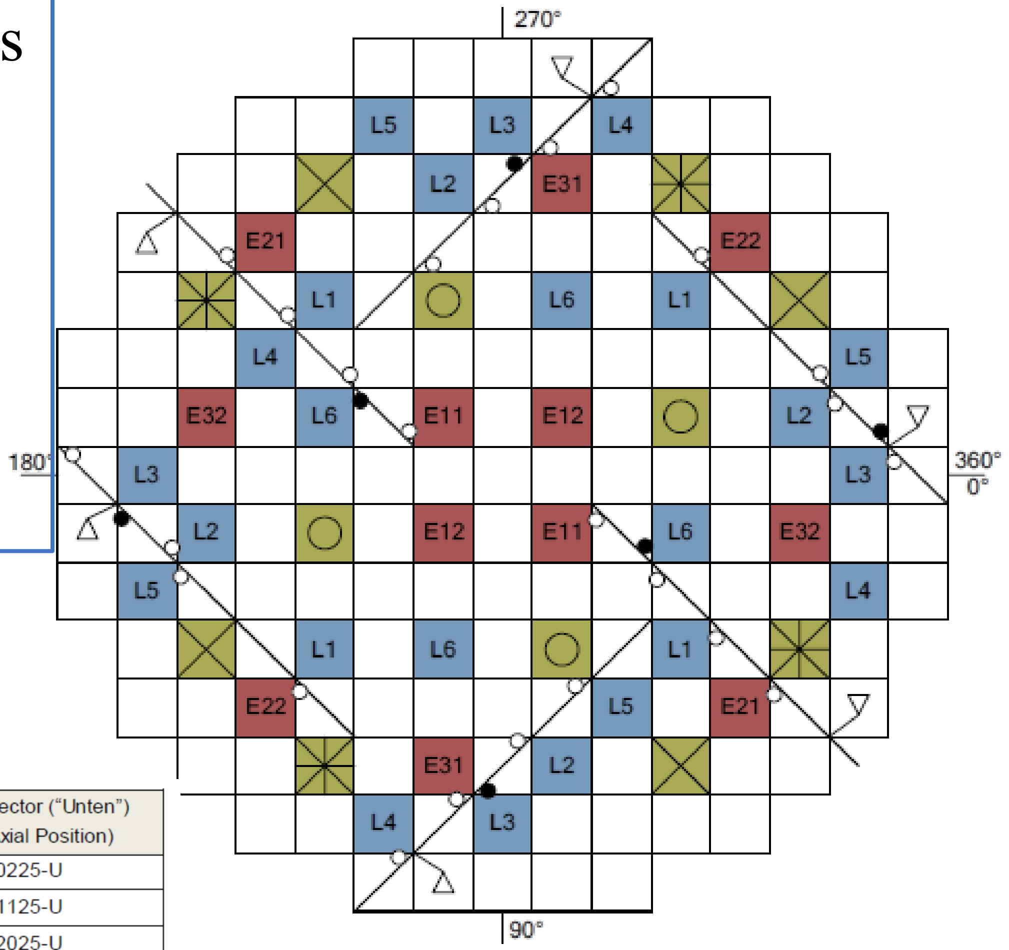


- The neutron sensitivity of these ionization chambers is achieved by the coating of one electrode with enriched boron-10.
- Thermal neutrons react with the isotope boron-10 emitting alpha particles, which produces ionization in the gas within the detector.
- Incore detector is in guide thimble tube placed, diameter of a few mm possible.

Cross-section 3-loop PWR
Location of instrumentation



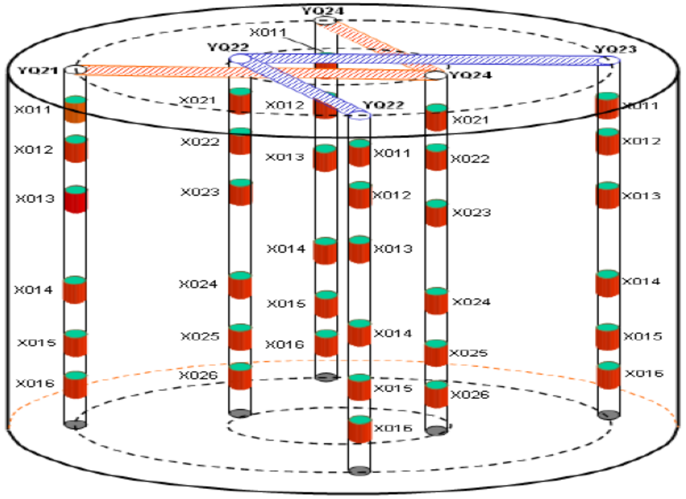
- 8 Ionization chambers
- 6x6 SPND
- 6 Thermocouples
- 1 acquisition system
- Sampling at 250 Hz
- Excores: 3.5 m from center



Reactor Coordinate (Radial Angle Position)	Upper Detector ("Oben") (Upper Axial Position)	Lower Detector ("Unten") (Lower Axial Position)
22,5°	X-0225-O	X-0225-U
112,5°	X-1125-O	X-1125-U
202,5°	X-2025-O	X-2025-U
292,5°	X-2925-O	X-2925-U

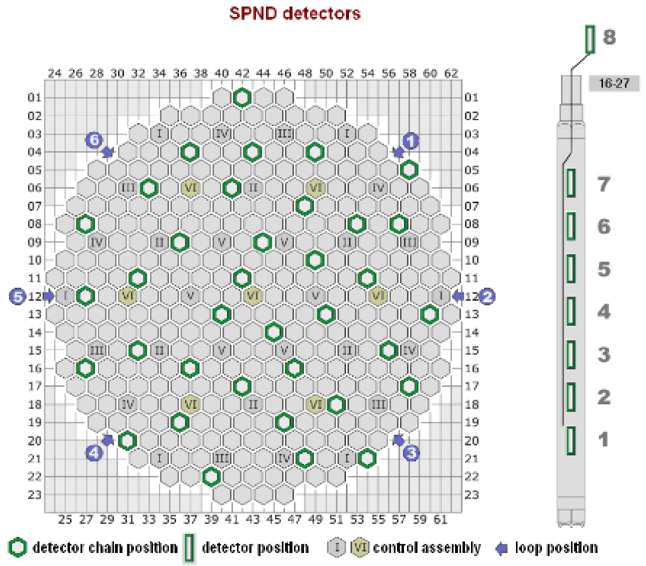
Incore instrumentation SPNDs
KWU,VVER

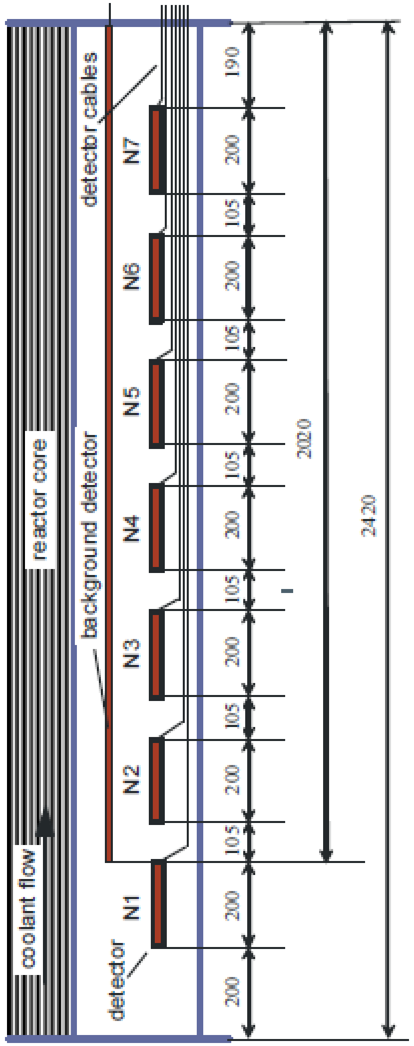
- 3-loop / 4-loop (Pre)-Convoi
- SPND instrumentation
- Cover the whole core region
- Coaxial long cables specially used for simultaneously measurements
- Accelerometers on loop and PRV, not measured at KKG within CORTEX



VVER-440/213

- 210 fuel assembly outlet thermocouples are installed
- 36 assemblies are measured with SPND

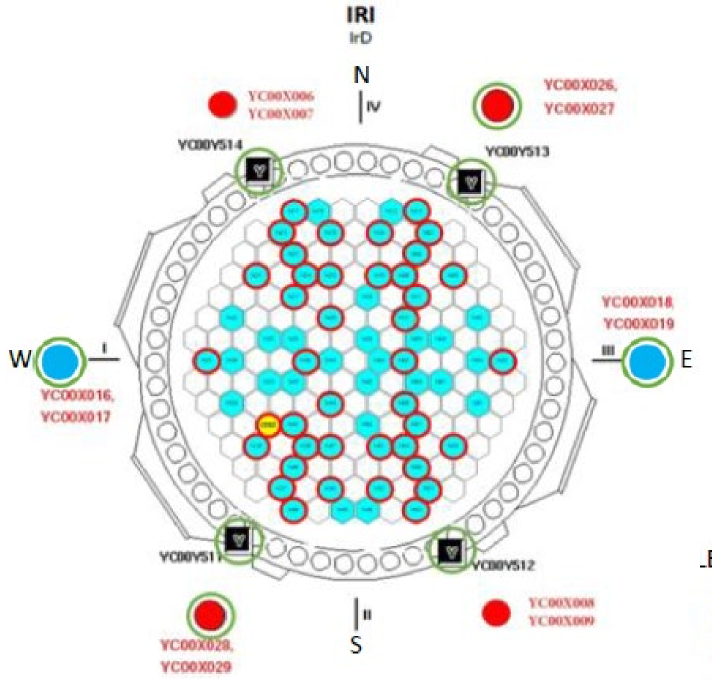


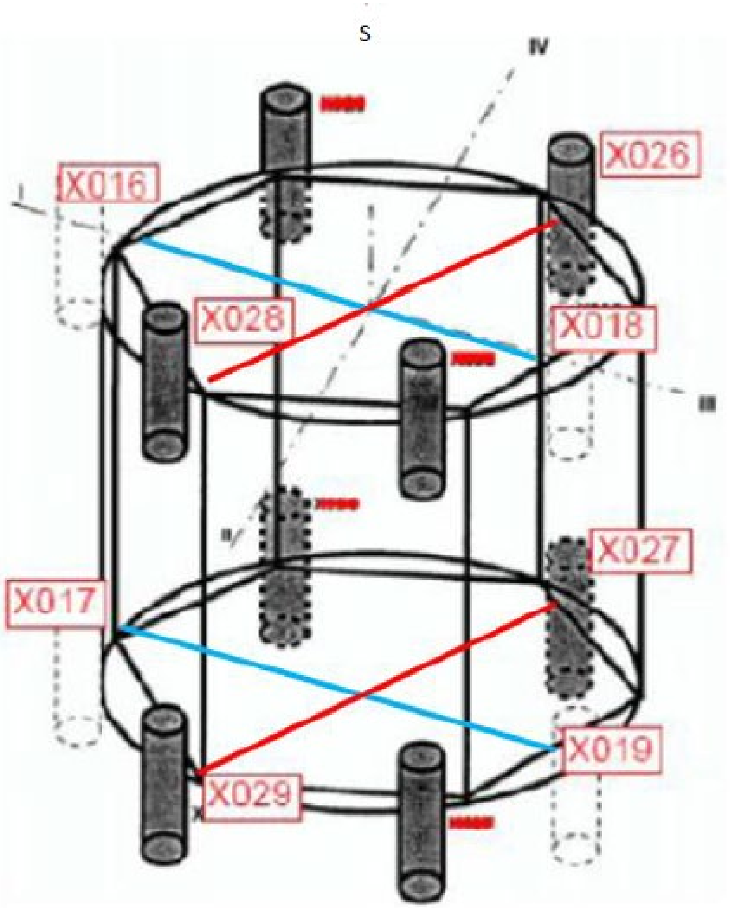


Excore instrumentation Ionization chambers

KWU,VVER

- Ionization chambers
- Cover the whole core region





VVER-1000 Excore Instrumentation

LEGEND

Nijk ... SPND in fuel assembly string Nij and level k
X016-19 ... ionization chambers in W-E plane01 in blue
X026-29 ... ionization chambers in SW-NE plane02 in red
A511-514 ... reactor cover accelerometers

I,II,III,IV ... reactor axis
W,S,E,N ...
MCL1-4 ... main circulation pumps

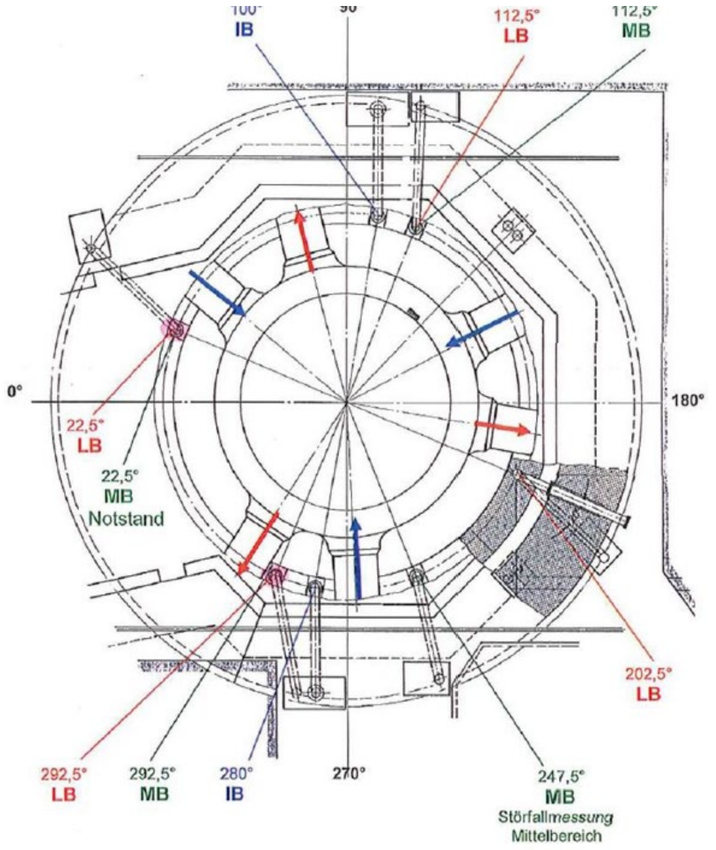
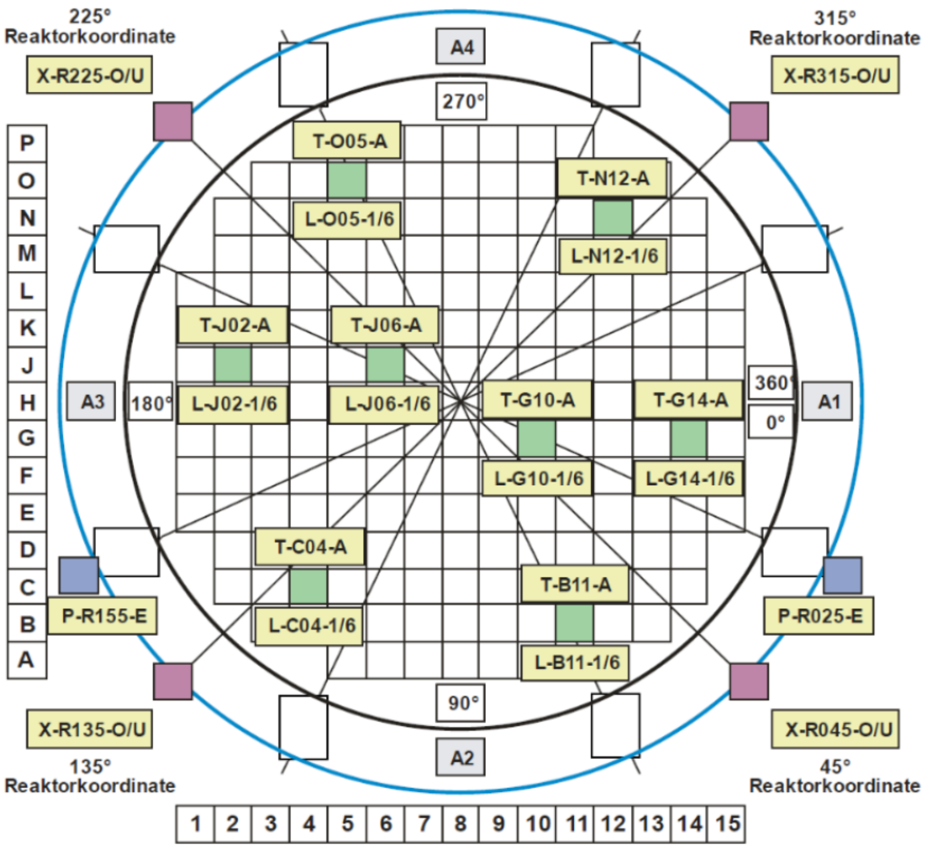
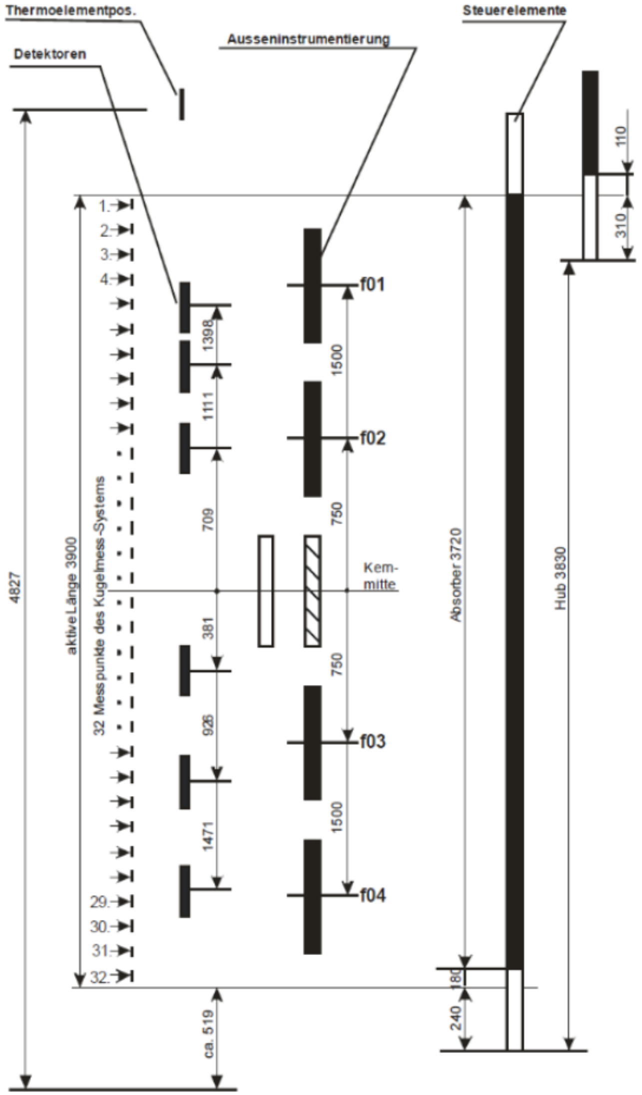


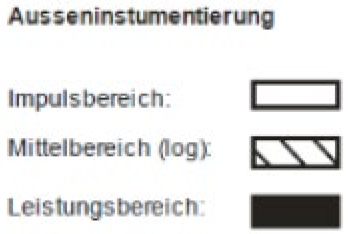
Figure 2: Positions of Ex-Core Detectors

KWU 3-loop Excore Instrumentation

4-loop KWU instrumentation





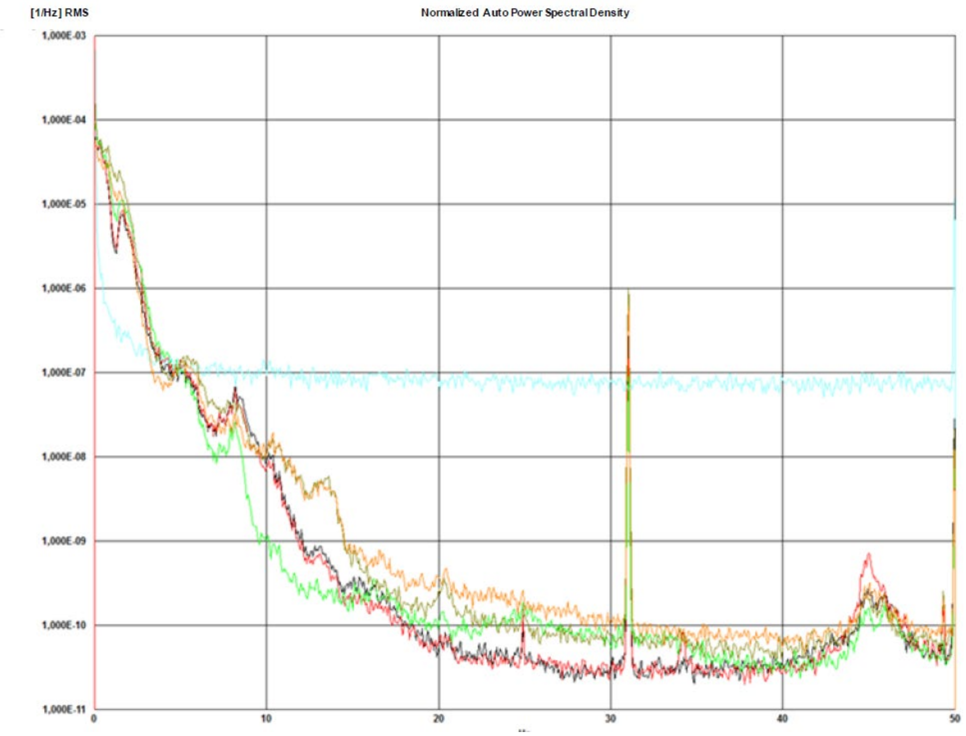


Noise characteristics

Noise measurement in commercial power reactors

- Neutron noise is not(hing) new, but got higher attention since 2010's
- Neutron noise has increased – cycle to cycle – in several PWRs, reason still unclear
- Neutron noise is increasing during cycle with the reduction of the MTC (usually about -70 pcm/K at EOC). The cause is well understood.
- Utilities record periodically neutron noise for follow-up analysis and comparison purposes (e.g. Trillo, Temelin, KWUs, AMS, …)
- New measurements of neutron noise with specific acquisition system were performed in 2018/2019,
  - @KKG during full power operation during cycle 39 (MOC, EOC) and cycle 40 (BOC,MOC,EOC)
- Large available database of data at different burnup of 3-loop / 4-loop PWRs / VVERs
- Signal of interest resp. measured:
  - Excore and Incore
  - FA outlet T
  - Flow rate
  - Accelerometers
  - Plant data from plant information system (usually at reduced sampling rate typically 2 Hz)

Noise Signals in PWR



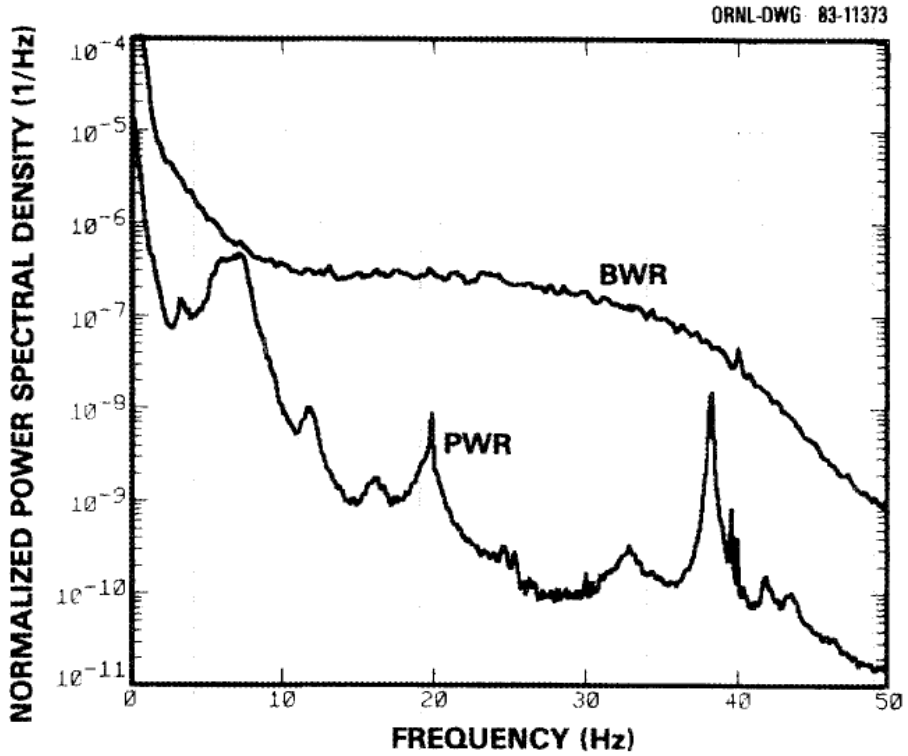
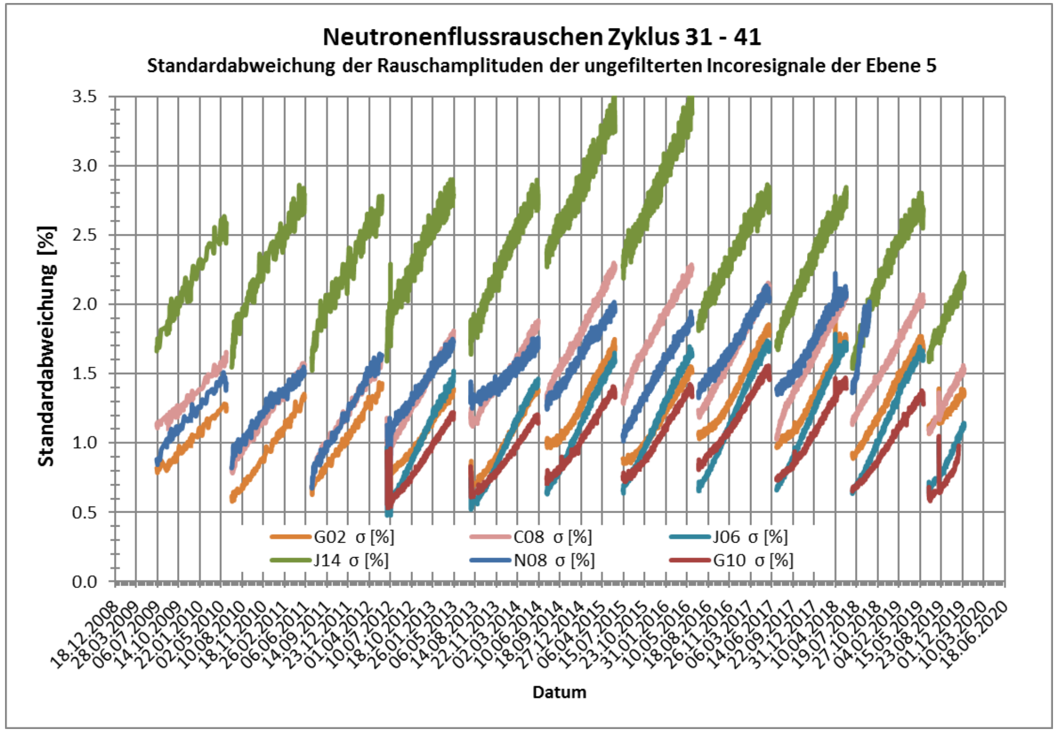
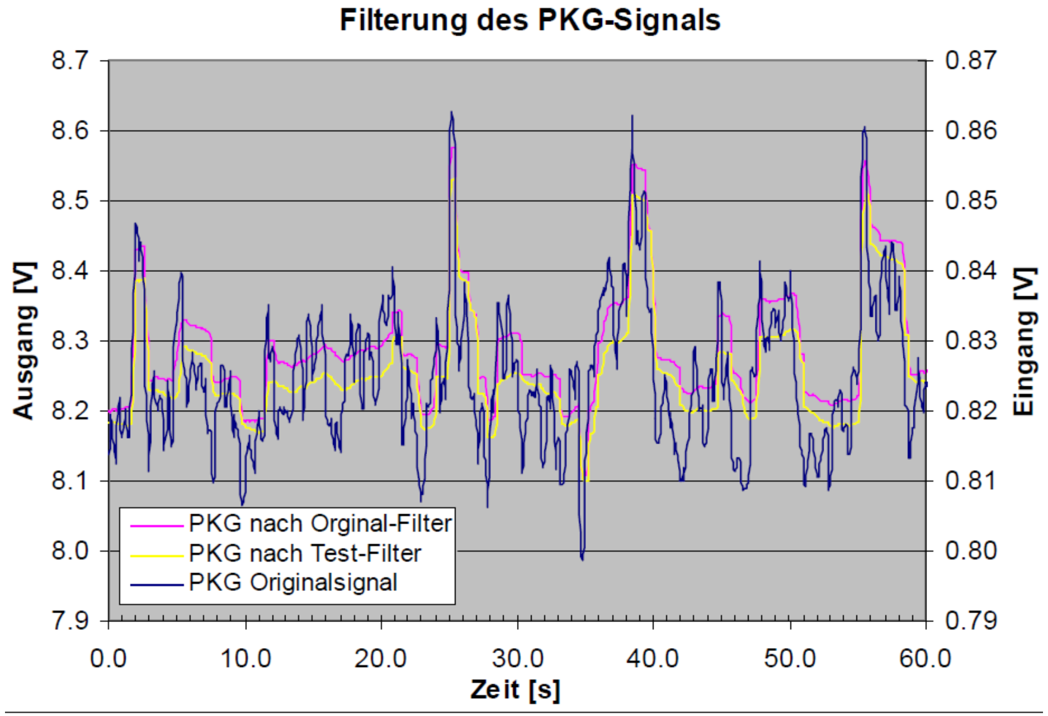


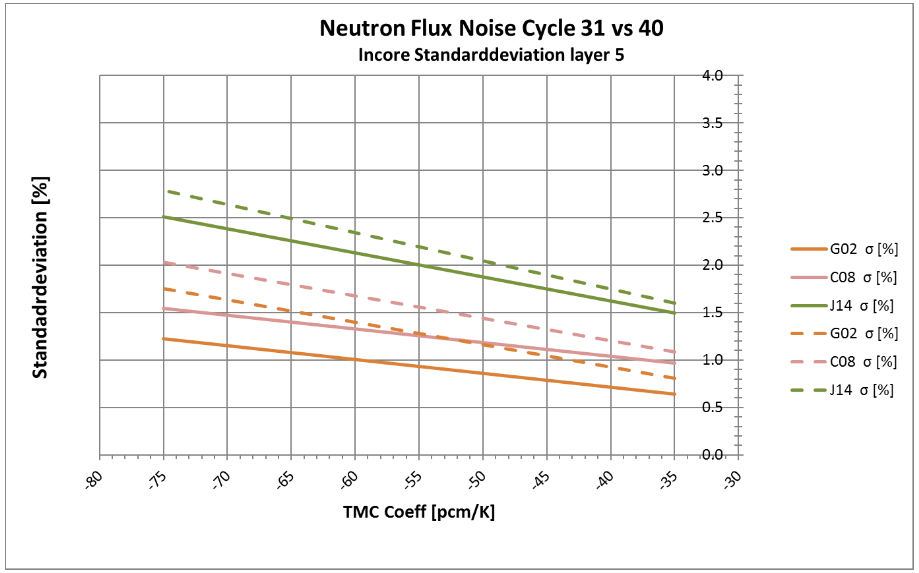
Fig. 4. Comparison of BWR and PWR neutron noise spectra when normalized to the square of the dc signal level.

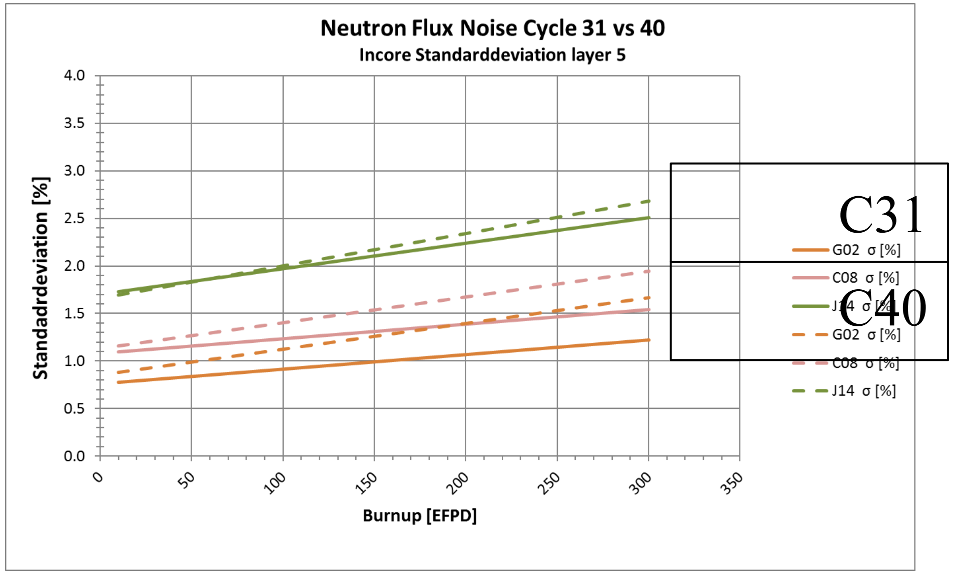
Power Signals: Main characteristics

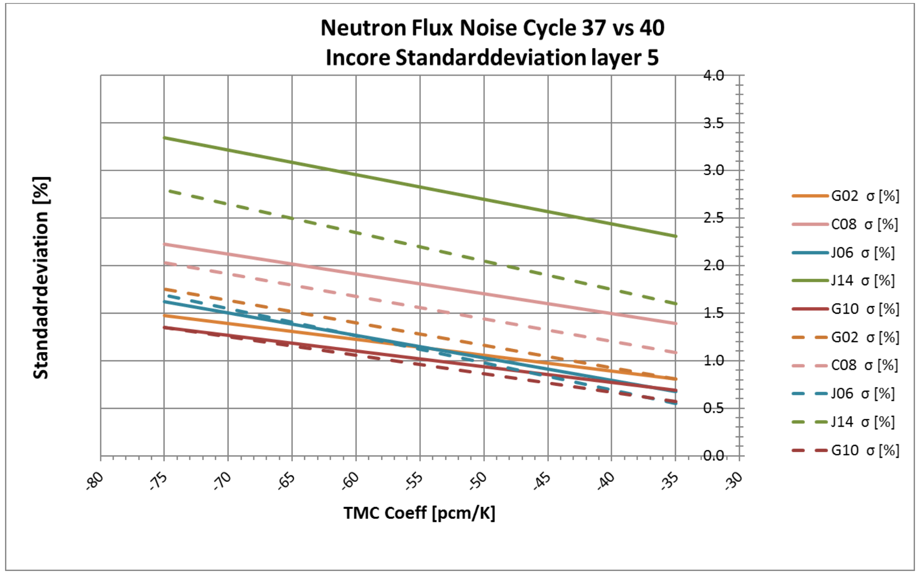


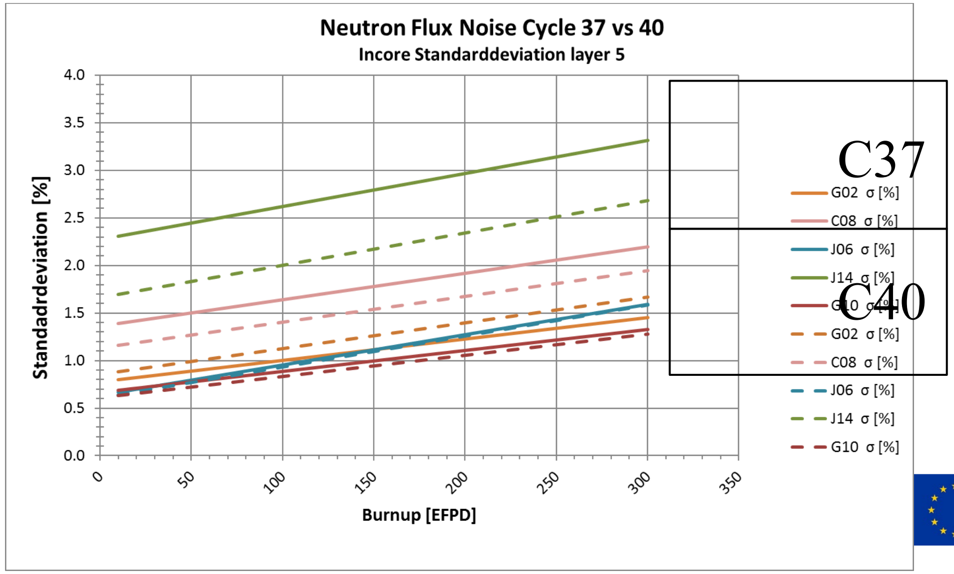


In cycle evolution during cycle 40 3-Loop
Linear trend with MTC resp. Boron concentration observed



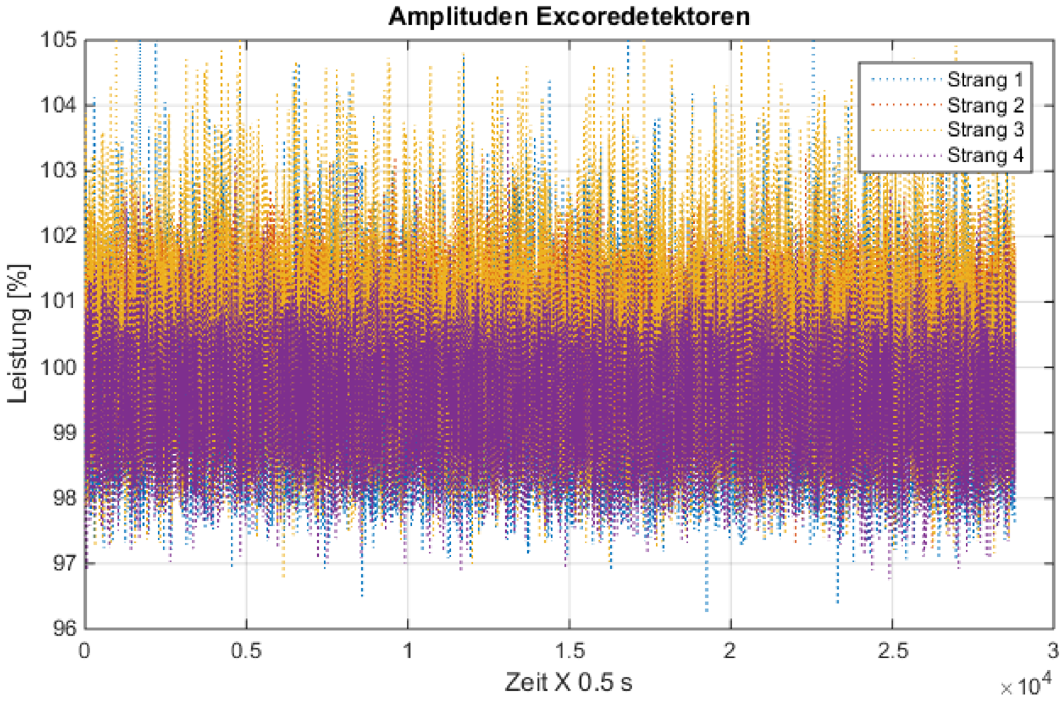




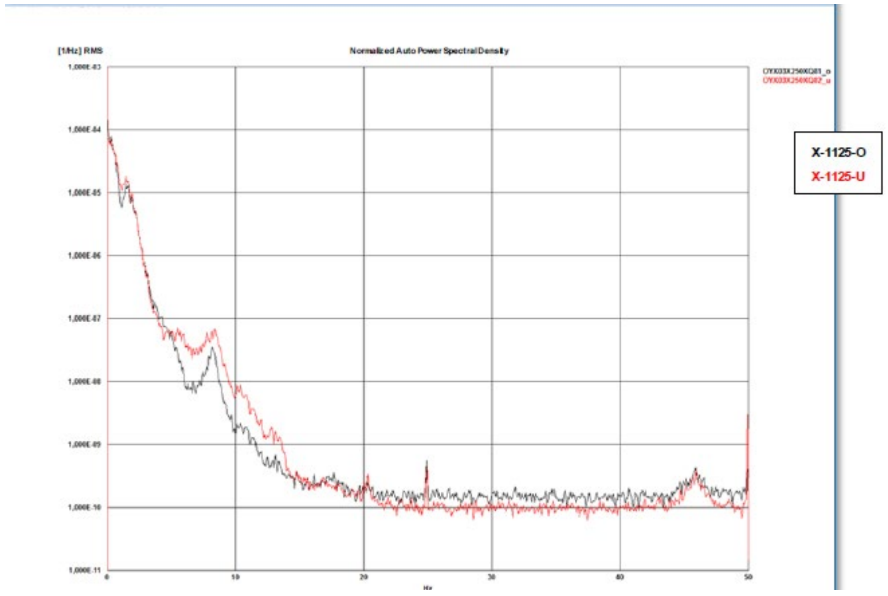


Fluctuations of excore detectors

Time domain



Frequency domain



Measurement Campaigns

Neutron noise measurement campaign (example of Swiss 3-loop)

- Measurement 2 hr. acquisition time at **250 Hz, 50 channels** with the developed ISTec Instrumentation (see later)
- Measurements at full-power, no RCCA or T adjustment during the measurements
- The first measurement was complicated due to concern due to the BNC cables between the cabinets of train 1 to train 4 in case of fire.
- 5 measurements. Last measurement at EOC 40 in May 2019
- Measurement campaigns are well established.

Data Acquisition -I

- Neutron flux and Temp. measured with industrial high quality measuring system SIGMA of ISTec
- The system consists of isolation amplifiers, with an optical connection to avoid any feedback to the plant signals,
- low-pass-filters, to avoid aliasing effects, signal compensation units (to compensate the DC-part), and high precision signal amplifiers and the ADC-unit
- To get a high resolution in the analogue to digital conversion, the signals have been **compensated for the DC-part and amplified for the AC-part.**
- Signals have been digitized by a 12-Bit-ADC (20 Volt range) with a sampling frequency of **250 Hz per signal.**
- The Cut-Off-Frequency of the used low-pass Antialiasing-Filters was fixed to 100 Hz

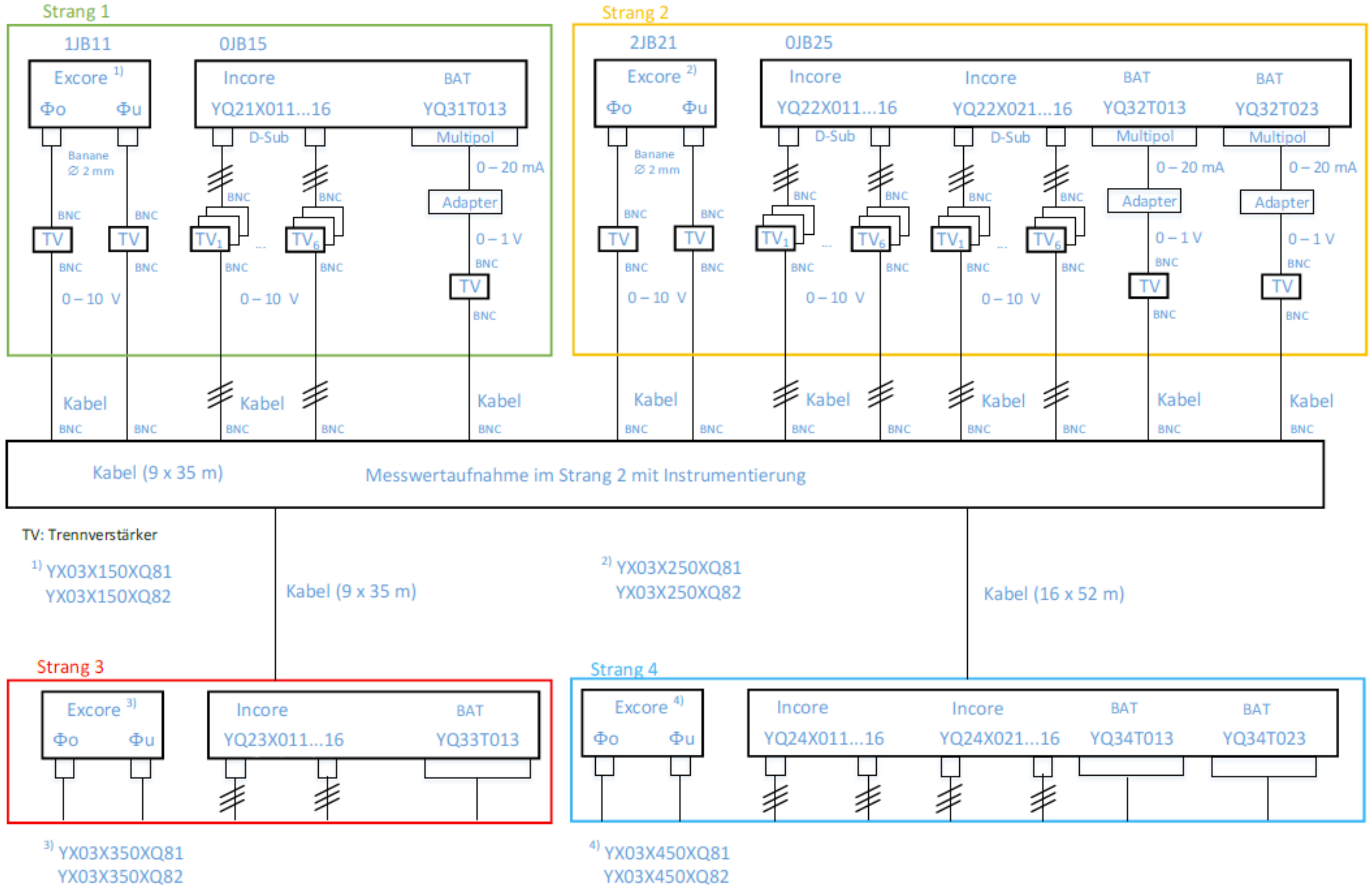
Data Acquisition -II

- Four safety channels at Gösgen NPP contain the electrical cabinets to the neutron flux signals
- it was necessary to connect the detector ports of different plant rooms to a central measuring place.
- A total of ~800 m coax cable with inner shielding was prior to measurements installed
- The plant information system was used to record simultaneously the main plant data, as RCCA position, core power and temperatures.

Instrumentation developed and used by ISTec

Cable connections between four redundant trains

Strang 1 – 22.5°	Strang 2 – 112.5°		Strang 3 – 292.5°	Strang 4 – 202.5°	
0YX03X961	0YX03X962		0YX03X963	0YX03X964	
OYX03X150XQ81 O	OYX03X250XQ81 O		OYX03X350XQ81 O	OYX03X450XQ81 O	
OYX03X150XQ82 U	OYX03X250XQ82 U		OYX03X350XQ82 U	OYX03X450XQ82 U	
LVD:	LVD:		LVD:	LVD:	
G02:	C08:	J06:	J14:	N08:	G10:
0YQ21X011 0YQ21X012 0YQ21X013 0YQ21X014 0YQ21X015 0YQ21X016	0YQ22X011 0YQ22X012 0YQ22X013 0YQ22X014 0YQ22X015 0YQ22X016	0YQ22X021 0YQ22X022 0YQ22X023 0YQ22X024 0YQ22X025 0YQ22X026	0YQ23X011 0YQ23X012 0YQ23X013 0YQ23X014 0YQ23X015 0YQ23X016	0YQ24X011 0YQ24X012 0YQ24X013 0YQ24X014 0YQ24X015 0YQ24X016	0YQ24X021 0YQ24X022 0YQ24X023 0YQ24X024 0YQ24X025 0YQ24X026
BAT:	BAT:	BAT:	BAT:	BAT:	BAT:
0YQ31T013	0YQ32T013	0YQ32T023	0YQ33T013	0YQ34T013	0YQ34T023



Neutron noise measurements KKG

- Cover two typical – almost in equilibrium – cycles (4.95w% 235-U and 5 radial burnup regions)
- From BOC to EOC to cover a large MTC range
- 5 times two hours during cycle 39 and 40
- Comparable loading schemes and MTC (MOC, EOC)

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
MTC [ppm/K]	-60.1	-69.7	-38.0	-56.3	-72.2

Organizational aspects of a measurement campaign in a commercial reactor

- Each of the five measurements was long in advanced prepared (~two months) and necessitate ad-hoc internal authorization documents
- The measurements were performed as "reactor test" without power modification,
- Authorization to access the safety areal by car had to be granted for the acquisition material ("full trunk of a car").
- Pre-job briefing with the operation team prior the installation of the cables into the four cabinets
- Specific procedure was defined in case of emergency and/or signal perturbation in the safety cabinets
- Contact with the operation to avoid temperature and RCCA position move prior and during the 2-hr measurement.
- Adjustment of signal amplifiers on each measured channel. Identification of the non operating channels (not every SPND is operating).
- The measurements are realized at the late afternoon / evening to avoid conflicts with other test programs at the plant.

Signal analysis

Overview of signal analysis

- The signals were all analyzed from ISTec and then transformed from a binary format to ASCII-format prior dissemination in the consortium
- From the measurement of a duration of 120 minutes, a period of 50 minutes has been selected. In total 50 signals (36 in-core signals, 8 ex-core signals and 6 core-exit temperature signals) have been recorded.
- **Normalized Auto Power Spectral Density (NAPSD)** of every signal has been calculated for a time interval of 14.20 minutes.
- Due to the discrete time series of neutron flux and temperature signals the so-called discrete **Fast Fourier Transform (FFT)** has been applied with 4096 samples per block; (52 x 4096 x 0.004 sec = 851.968 sec).
- The NAPSDs have been determined in the frequency range from 0 Hz up to **the Nyquist frequency of 125 Hz** with a frequency resolution of 0.061 Hz (250 Hz / 4096).
- The diagrams represent the spectra in the range up to 50 Hz.
- To compare the spectral amplitude of the neutron flux fluctuations of several positions in the core, the normalized auto spectral density (NAPSD) of the signals have to be calculated and evaluated.
- For this purpose, the measured time series have to be divided by the signal mean values.

Recommendations

Recommendations on instrumentations / future measurement campaigns

- Extend the measurement to «non-core» signals in specific plants
- But also vibrations of fuel elements and/or other internals of the core, mass flow rates in the core channels, and temperatures at the inlet of the core.
- Additional instrumentation for measurement of e.g. coolant velocity would be valuable, but technically challenging in this environment
- Discrimination between different root cause of neutron noise
- Neutron noise measurement in newly commissioned plant(s) (EPR, AP-1000, …) would be interesting
- Consider other possible source than lateral FA vibration, T resp. inlet flow fluctuations as origin of the noise (“out of the box thinking”).

Conclusions

Conclusions

- Using the existing incore / excore instrumentation, neutron noise were recorded in different reactors and data made available to the consortium (data are confidential). The signal analysis (NPSAD, FFT) is well established.
- Measurement campaigns can be made in the plant typically once or twice within a cycle depending on plant operation, operation at constant (full)-power might be difficult to plan long in advance
- Large database for code validation is for (further) analysis available
- Analysis of the provided data is still challenging
- Extension to other core resp. plant signal in some reactors would be valuable since the root-cause has not yet been fully identified

Thank you

„A useful neutron is a neutron with the right energy at the right time at the right place“

Gary Russell, Los Alamos