Cross-section validation for (n,2n) reactions

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Outline

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- Characterization of LR-0 reactor
- Characterization of HPGe detector
- Validation of $^{90}Zr(n,2n)$, $^{55}Mn(n,2n)$ and $^{127}I(n,2n)$ reactions

Motivation

- The measurement of SACS for selected reactions is of high interest because they are used for the practical reactor dosimetry, where these reactions are used to monitor the neutron flux behind reactor vessel and then determine reactor vessel damage.

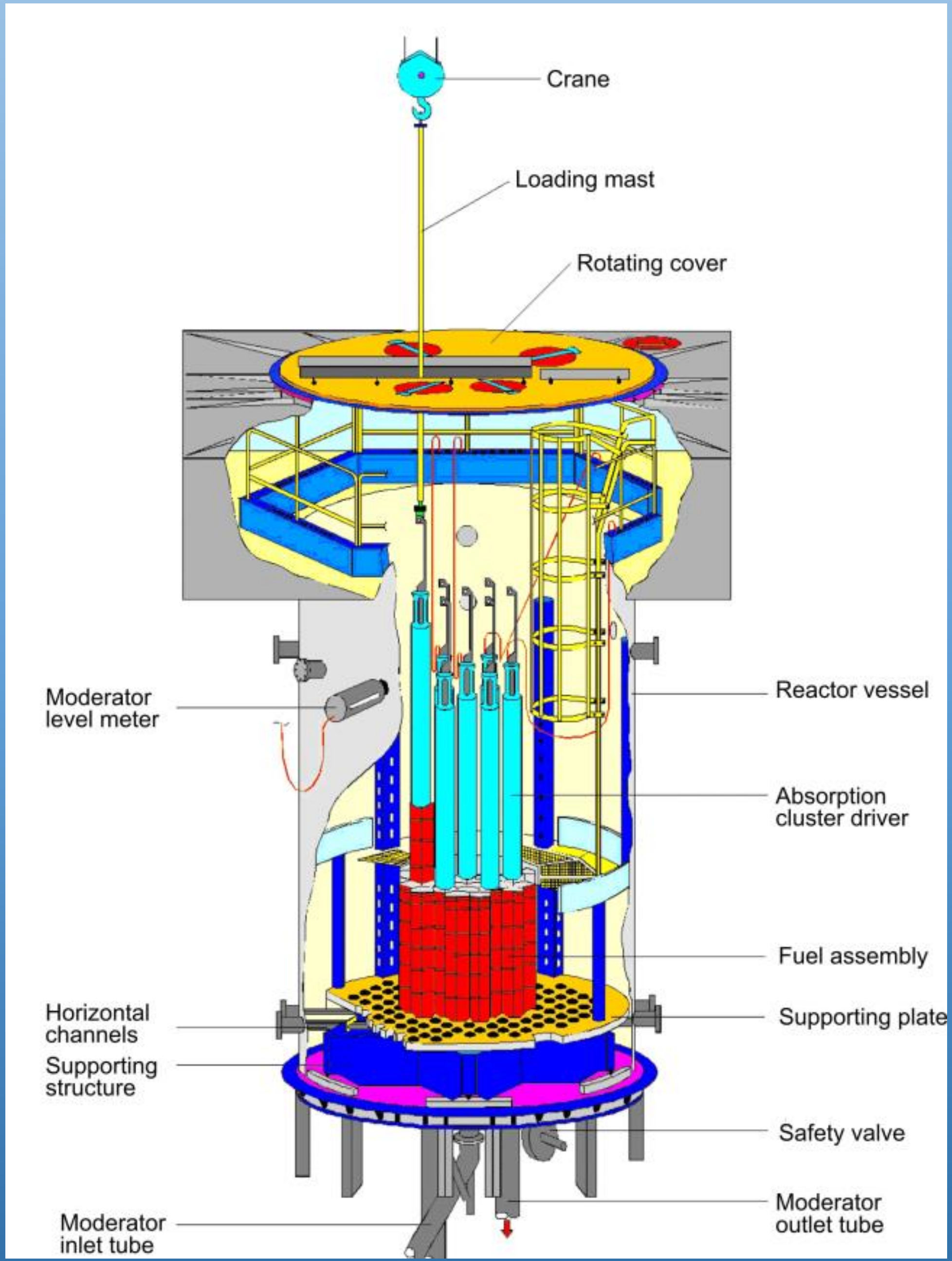
- These verifications are also important for refining neutron fission spectrum of ^{235}U in region of higher neutron energies.

LR-0 reactor

For measuring and validation were chosen LR-0 reactor for its better-described neutron spectrum.

Basic parameters of reactor:

- Water pool type
- Continuous nominal power 1kW
- Fast neutron flux (above 1MeV) $2x10^8$ $cm^{-2}s^{-1}$
- Thermal neutron flux about 10^9 $cm^{-2}s^{-1}$
- Suitable for physics experiments on VVER
- Wide range of fuel enrichment
- Various concentration of H_3BO_3 in moderator

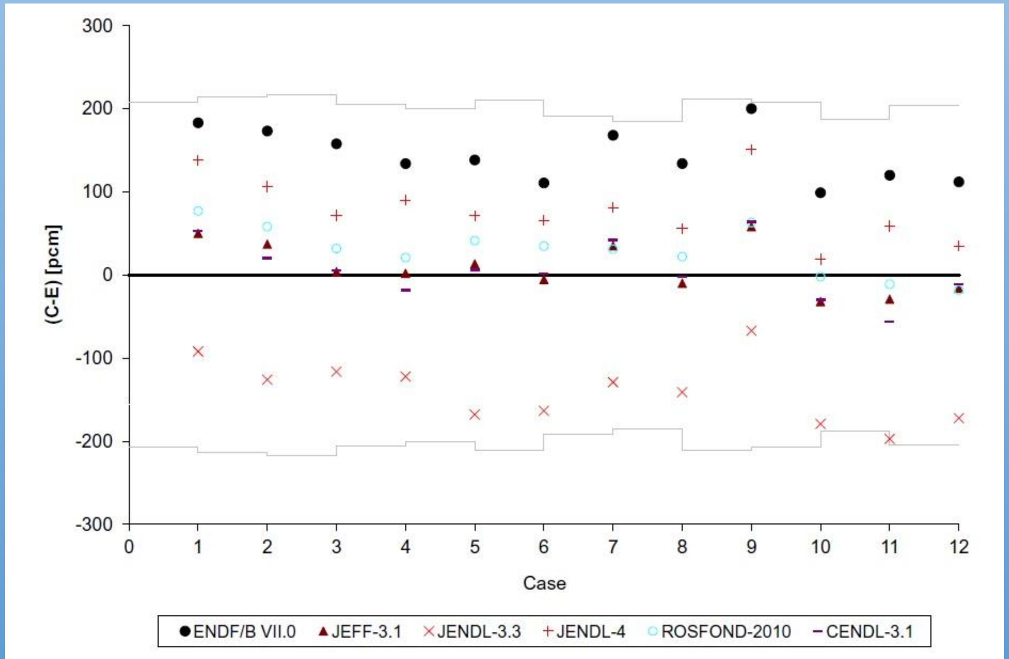


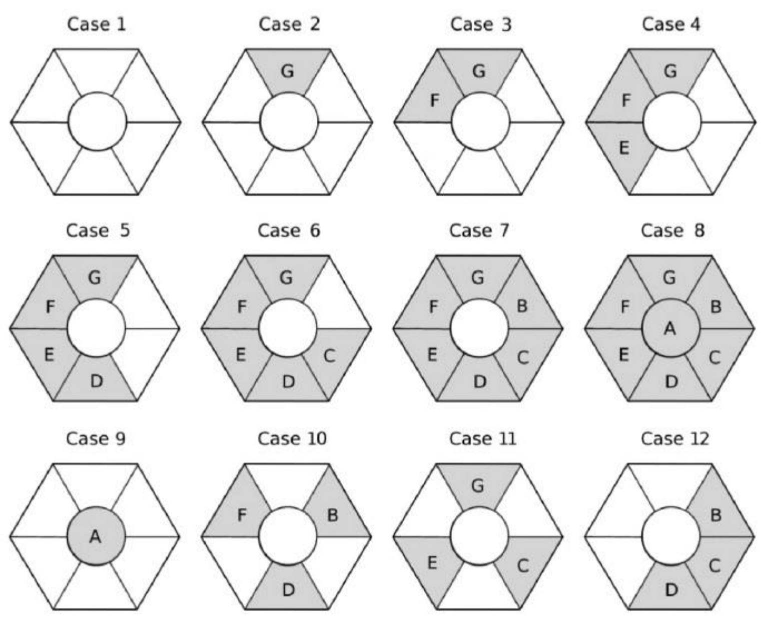
Characterization of reactor spectrum

- Several experiments were performed to compared measured results with the model of reactor core
- Mainly two factors are needed: critical experiment and power profile experiment.
- For greater certainty were performed other experiments: stilbene measuring of fast neutron spectra and spatial distribution experiment.
- It was also shown, that over 6 MeV LR-0 spectrum is undistinguishable from ^{235}U Prompt Fission Neutron Spectra (^{235}U PFNS).

Critical experiment

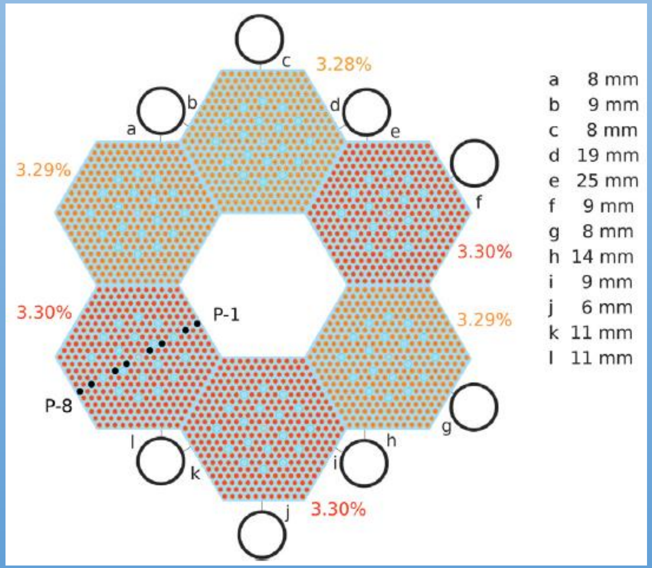
- Critical height H_{cr} of reactor were detected by measuring the number of neutrons in reactor core
- The measured H_{cr} were after compared with calculated H_{cr}
- This experiment were also performed with graphite inside the dry central channel

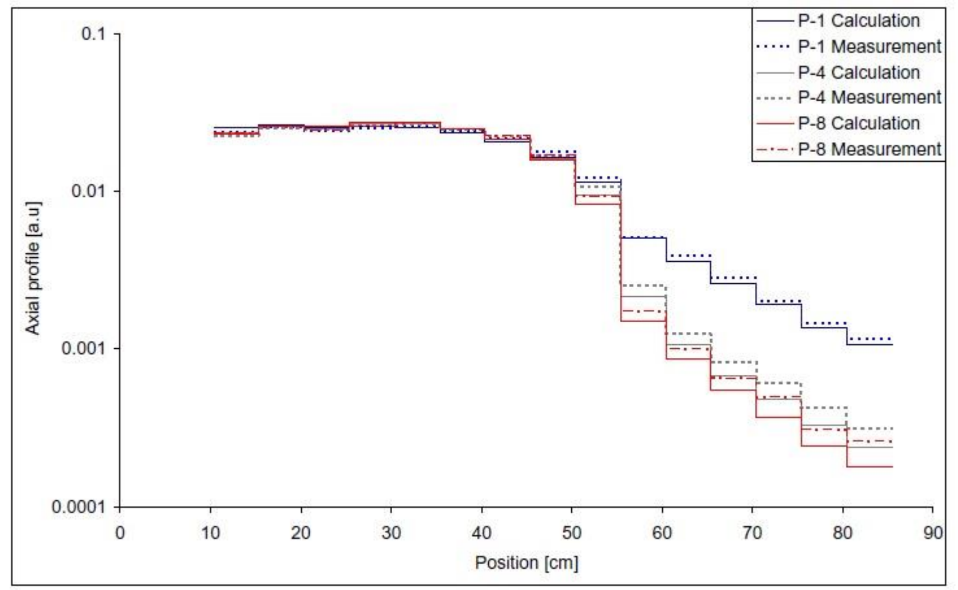


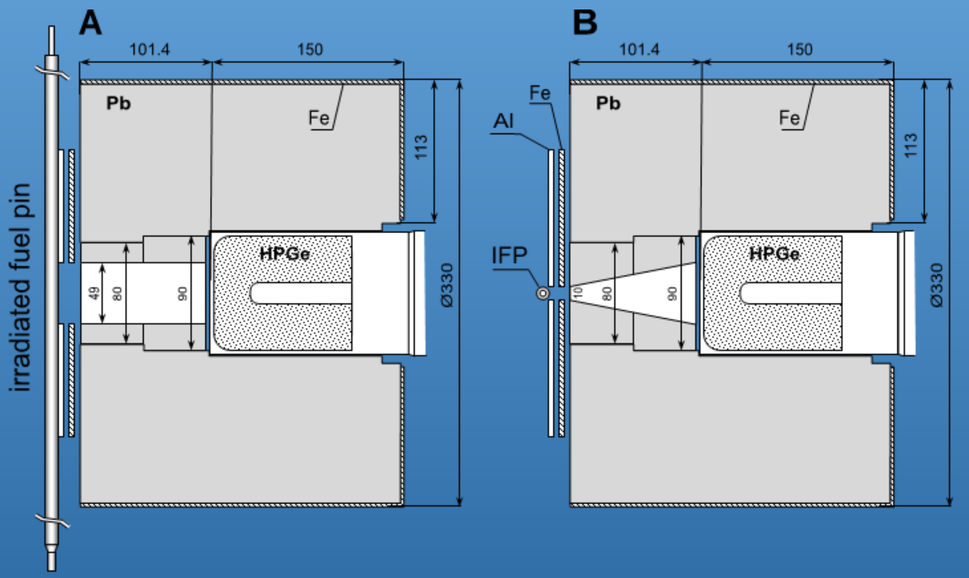


Power profile of LR-0 reactor

- Reactor fuel assembly can be dismantled and each fuel pin can be measured separately
- 8 pins were selected for measurement
- Measurement were compared with MCNP6 calculations

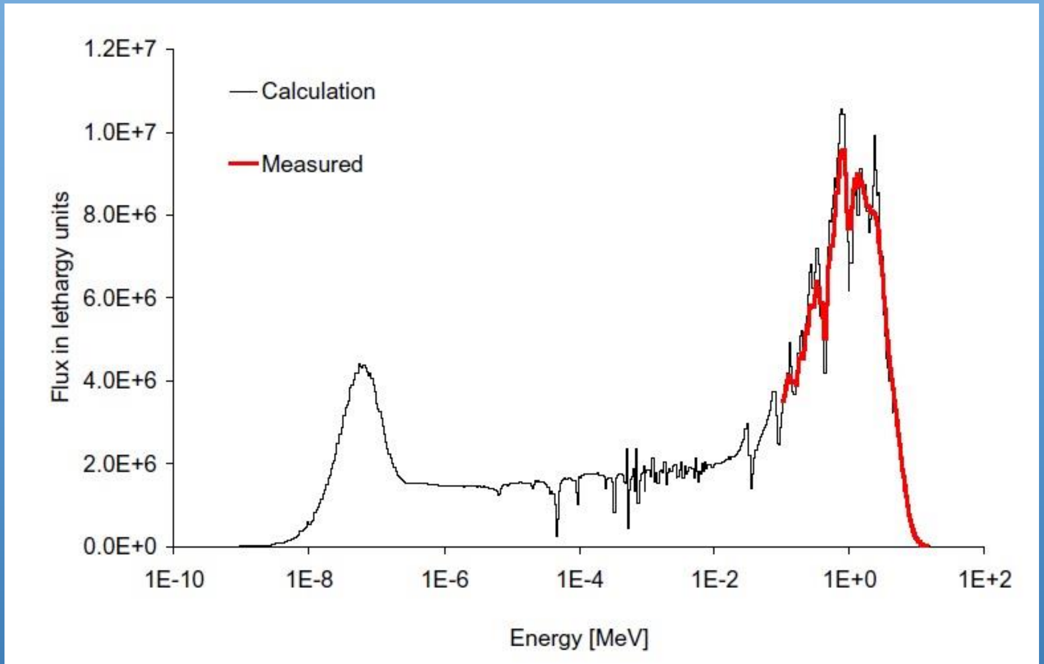




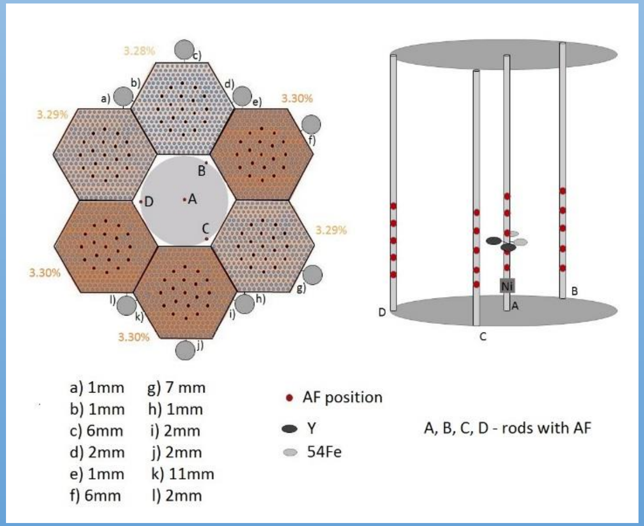


Fast neutron spectra measurement

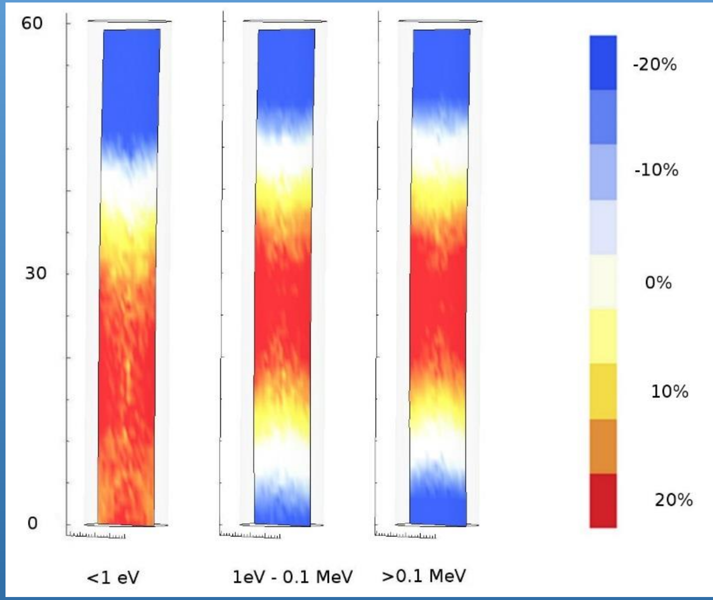
- Scintilation stilbene detector were placed in the middle of core, same place where all samples are irradiated
- Measurement were compared with MCNP6 calculations



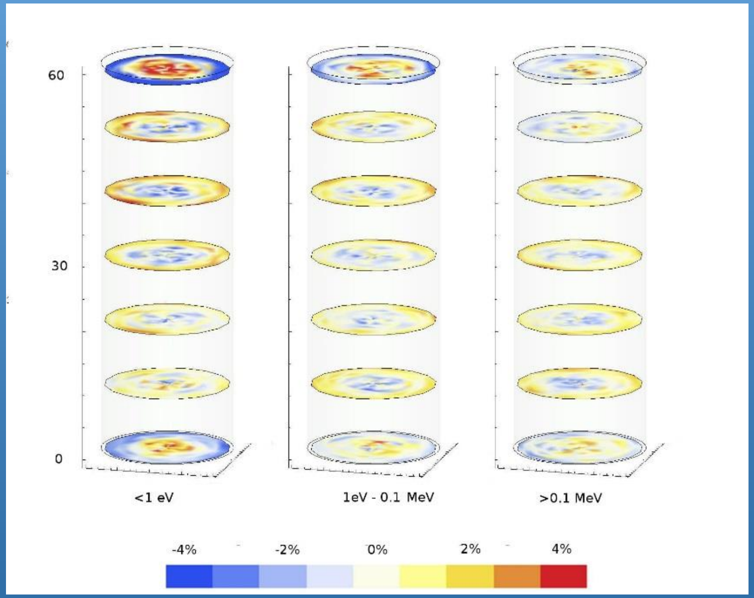
Spatial distribution experiment



- Aluminum holder with activation foils, mainly Au and Ni
- Non-homogeneities are negligible in the part where samples are irradiated
- MCNP6 calculations were compared with activation foils measurement



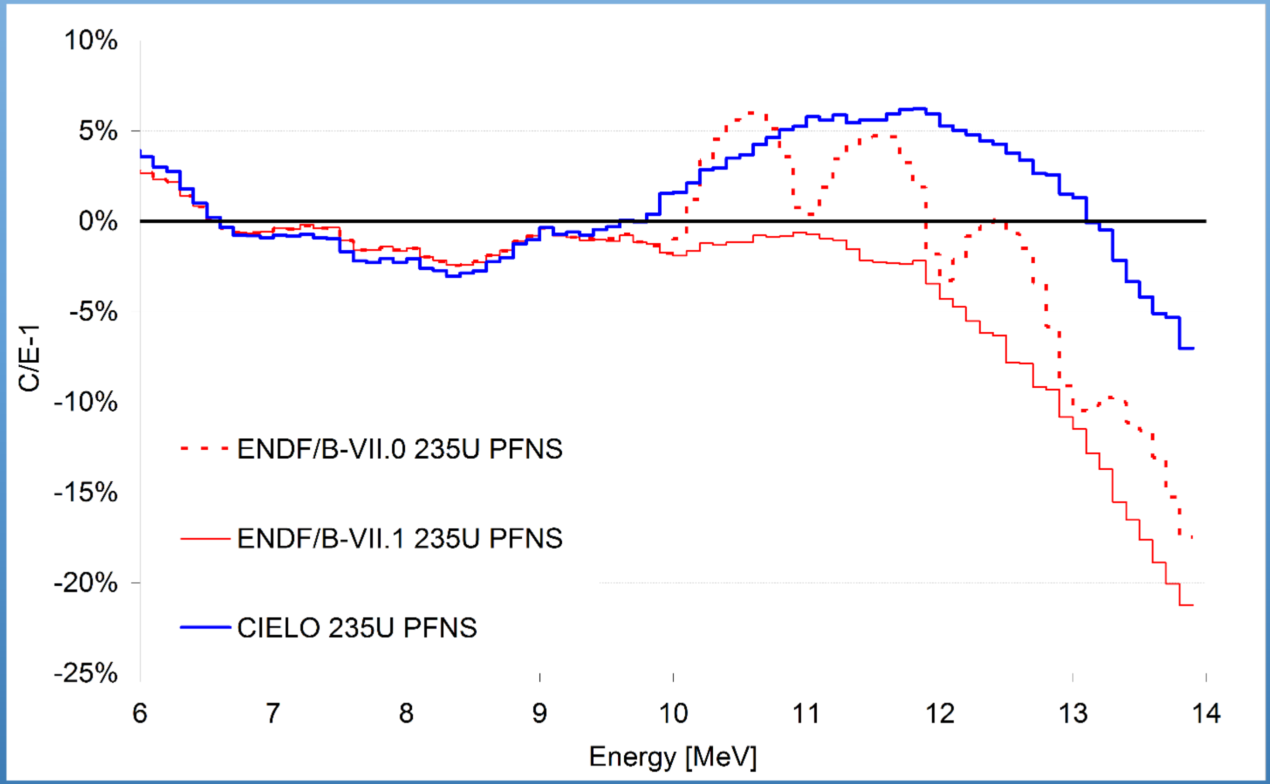
Obr.1: Calculated axial non-homogeneities



Obr.2: Calculated radial non-homogeneities

Prompt fission neutron spectra

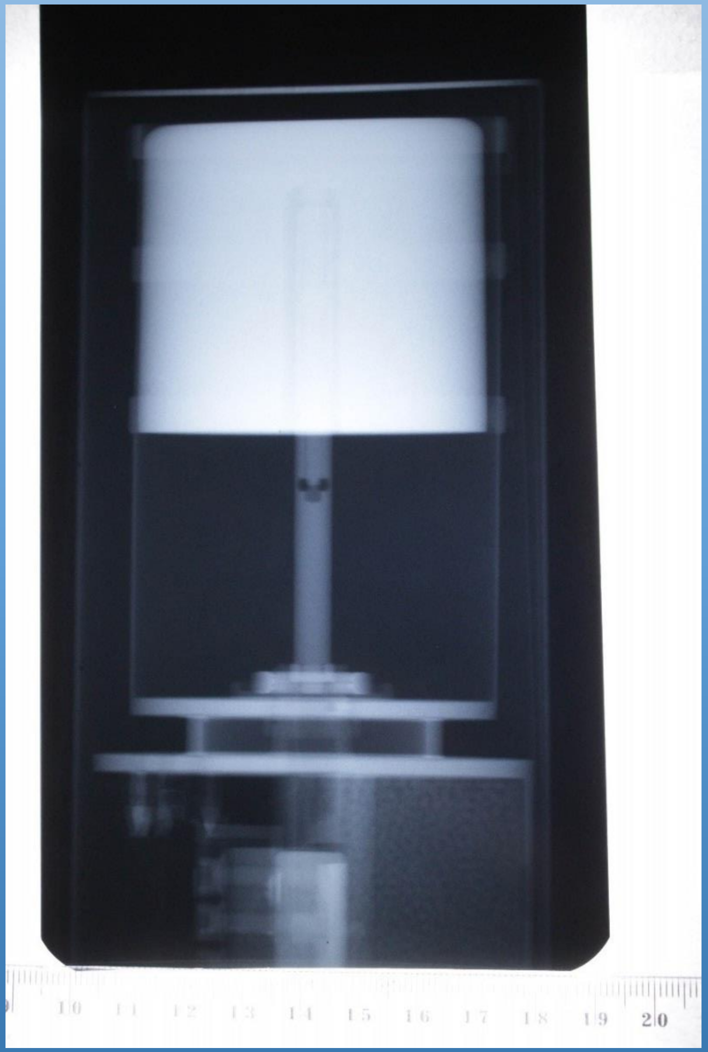
- Comparison of measured LR-0 reactor spectrum with calculated PFNS of ^{235}U from ENDF/B-VII.0, ENDF/B-VII.1 and CIELO nuclear data libraries above 6MeV
- Up to 10MeV the difference is negligible
- Above 10MeV also nuclear data libraries have different data - cross-section measurement also validate this PFNS of ^{235}U
- Experiments shows greater accuracy of CIELO nuclear data library



Characterization of HPGe detector

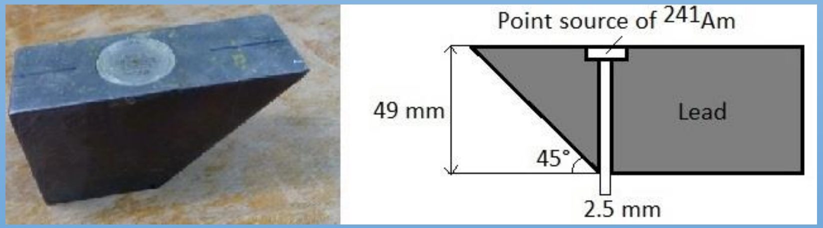
- Detector was irradiated 2 hours in pure ^{137}Cs gamma source in distance 5m at ČMI
- From the resulting radiogram were measured detector parameters
- Due to the divergence of the ^{137}Cs source beam, it was necessary to made a correction

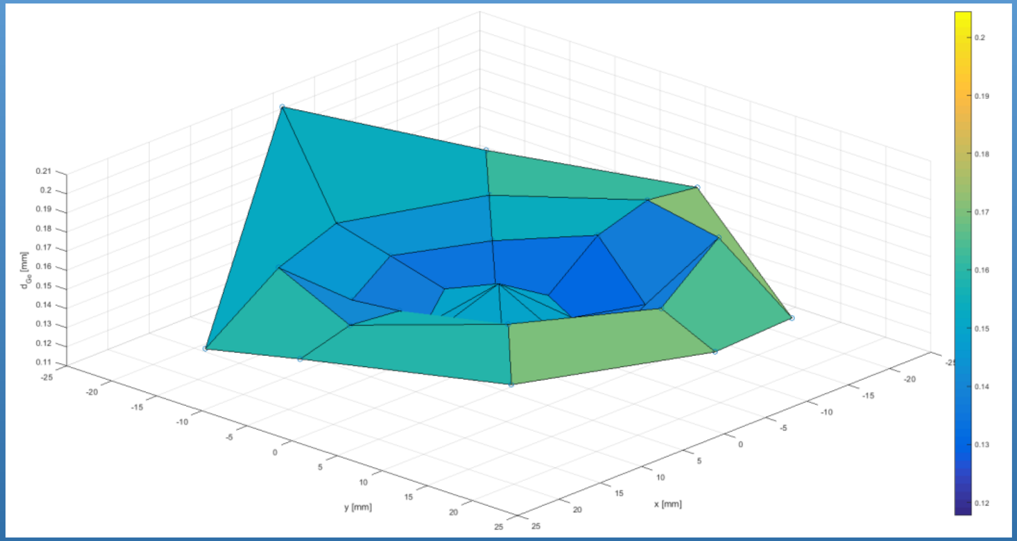
	Measured value [cm]	Uncertainty [cm]
Crystal radius	3.003	0.010
Crystal length	5.525	0.020
Hole radius	0.482	0.011
Hole length	4.420	0.035
Cap thickness (aluminum)	0.143	0.013
Pin radius	0.331	0.024
Pin contact length	0.369	0.026
Gap thickness (vacuum)	0.480	0.018



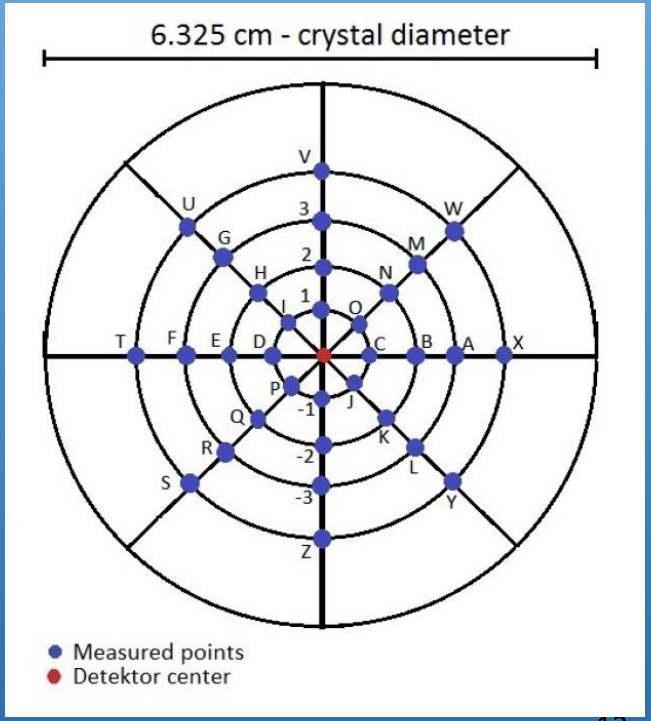
Characterization of HPGe detector

- Obtained parameters were used for insensitive layer thickness measurement
- Designed collimator with ^{241}Am source - 59.54keV
- Measurement at two angles - 90° and 45°





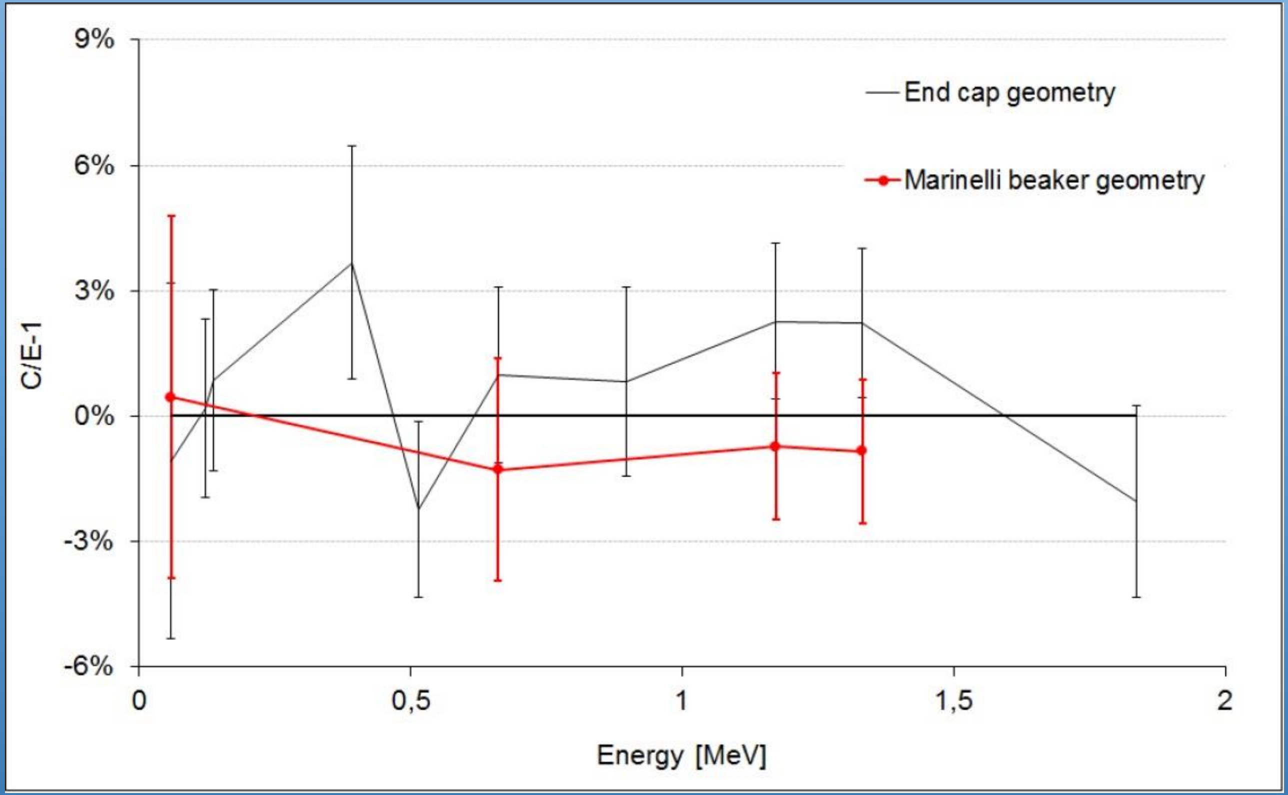
d_{Ge} = 0.158 ± 0.003 cm



Characterization of HPGe detector

- Detector model was verified with the point etalon and Marinelli beaker sources

- Discrepancy between calculation and experiment in relevant gamma energy region is about 1.9% in the point source (identical with foils measurement) and 1% in Marinelli beaker geometry (close to the capsule measurement)



Validation of $^{90}Zr(n,2n)$, $^{55}Mn(n,2n)$ and $^{127}I(n,2n)$ reactions

- Reaction rates *q* were determined by measuring NPA using HPGe detector

$$q = \left(\frac{A_{\mathrm{Sat}}(\overline{\mathrm{P}})}{A(\overline{\mathrm{P}})} \right) C(\mathrm{T}_m) \frac{\lambda}{\varepsilon \eta N} \frac{1}{\left(1 - e^{-\lambda . \mathrm{T}_m}\right)} \frac{1}{e^{-\lambda . \Delta \mathrm{T}}}$$

- Experimental reaction rate of the studied (n,2n) reactions were scaled to unit neutron emission in the core using the scaling factor K derived from the monitoring activation foils.

$$K = \frac{K_{Au} + K_{Ni}}{2}$$

$$K_{Au} = \sum_{i=1}^{N} \frac{q^i_{Au}(1\,nps)_{Calculated}}{q^i_{Au}(\overline{P})_{Measured}}$$

$$K_{Ni} = \sum_{i=1}^{N} \frac{q^i_{Ni}(1\,nps)_{Calculated}}{q^i_{Ni}(\overline{P})_{Measured}}$$

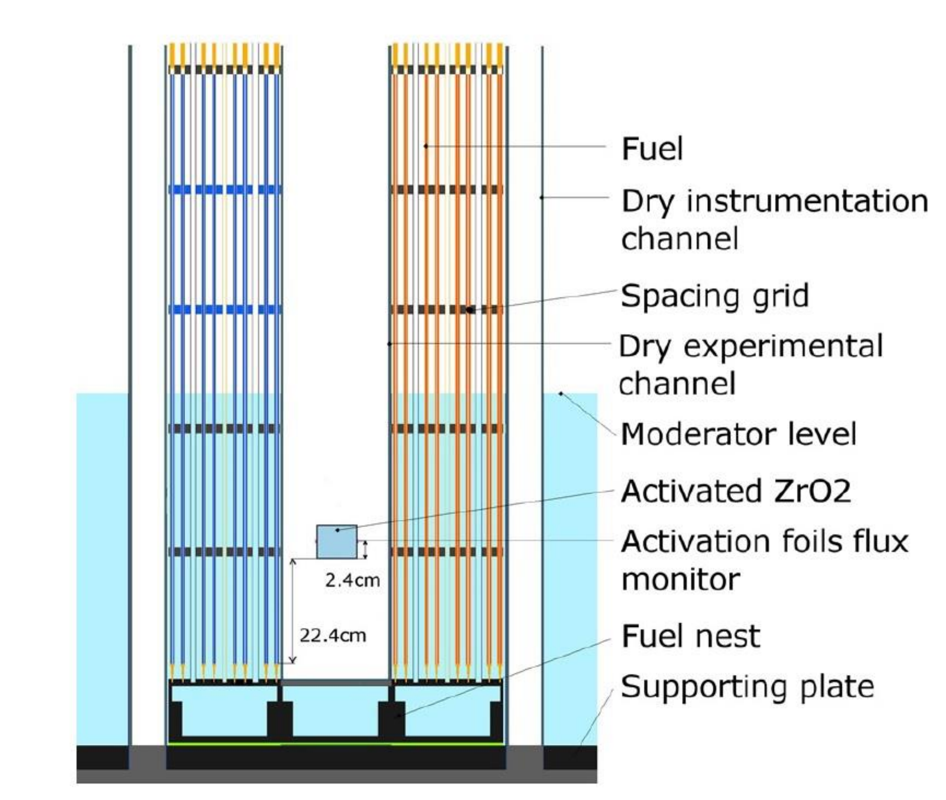
Validation of $^{90}Zr(n,2n)$, $^{55}Mn(n,2n)$ and $^{127}I(n,2n)$ reactions

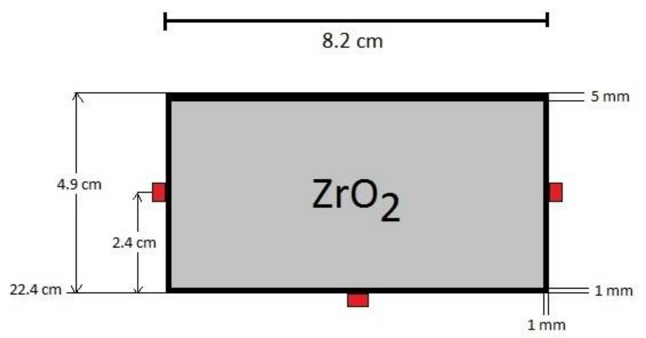
- ^{235}U prompt fission neutron spectra (PFNS) was calculated by ENDF-VII and CIELO nuclear data libraries
- neutron flux Φ is obtained by multiplying calculated relative flux (MCNP6) ϕ_{rel}(1 nps) with the scaling factor K
- For the correctness of the calculations, a well-defined reactor spectrum is needed

$$\overline{\sigma}^{exp.}_{E>10MeV} = \frac{1}{K} \frac{q}{\int\limits_{E>10\,MeV} \varphi(E)\,dE} C$$

$^{90}Zr(n,2n)$ measurement

- ZrO_2 were placed in aluminum can with the same diameter as HPGe detector
- At the surface were placed activation foils of Au and Ni
- Zr and activation foil were measured at HPGe detector
- detector efficiency calibration was calculated by MCNP6 code (well-characterized detector model is needed)





$^{90}Zr(n,2n)$ measurement

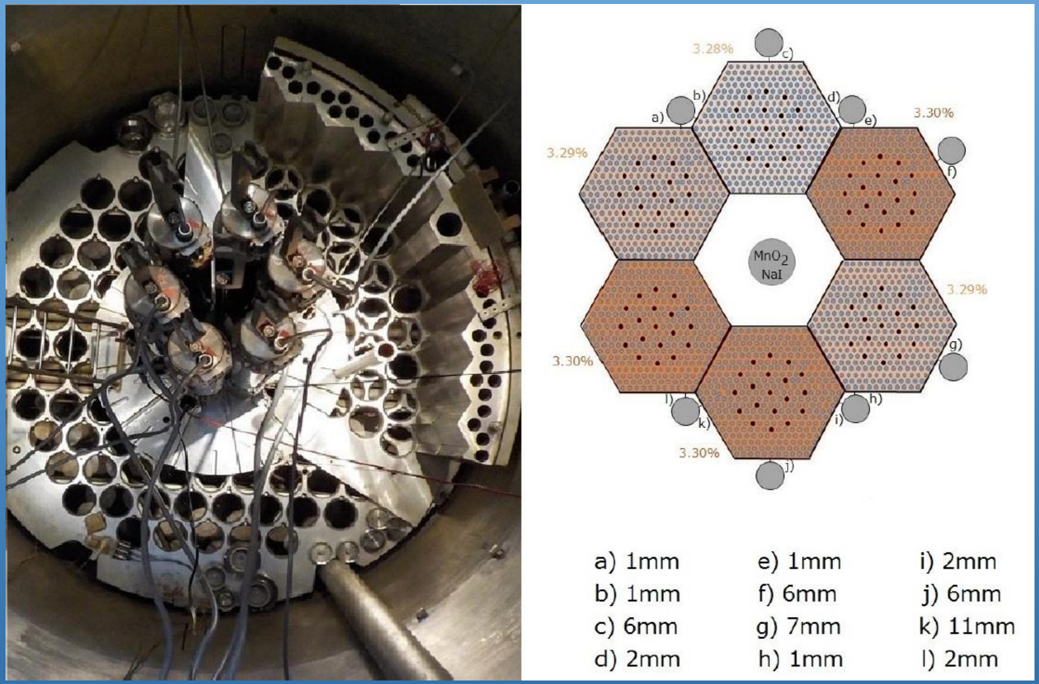
- Calculated and measured spectral average cross-sections were compared for various libraries
- PFNS was calculated by ENDF-VII and CIELO nuclear data libraries

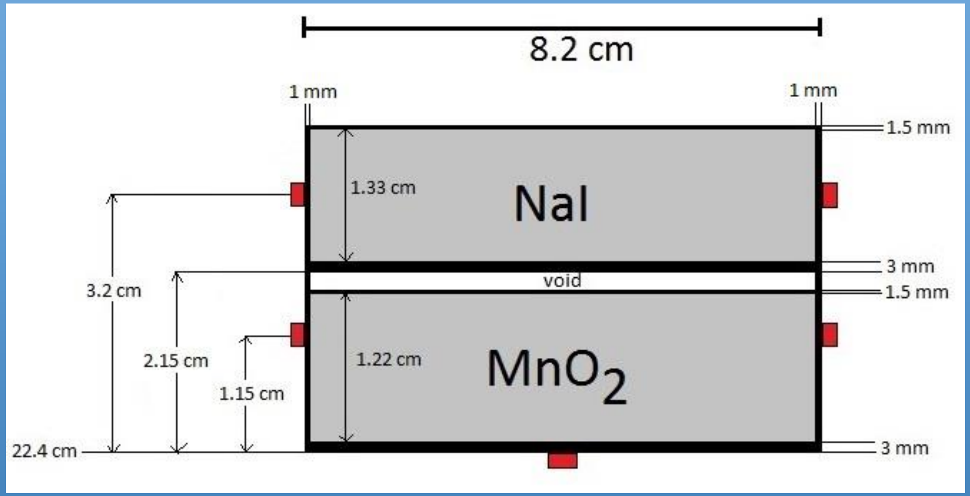
	^{90}Zr(n,2n)
A [Bq]	47.91
q [s^{-1}]	2.40E-21
Neutron emission rate [s^{-1}]	3.82E+11
Correction to spectral shift	0.999
Correction to flux loss	6.2%
SACS in reactor spectra > 10 MeV [mb]	76.8
Cross-section in ^{235}U [mb]	**0.107**
Uncertainty	**3.88%**

	^{90}Zr(n,2n)			
	Calculated q [s^{-1}] (ENDF-VII)	C/E-1	Calculated q [s^{-1}] (CIELO)	C/E-1
ENDF VII.1	5.54E-33	-11.9%	6.24E-33	-0.7%
ENDF VII	5.62E-33	-10.7%	6.32E-33	0.4%
JEFF 3.2	5.85E-33	-7.0%	6.57E-33	4.4%
JEFF 3.1	5.54E-33	-12.0%	6.22E-33	-1.0%
JENDL 3.3	5.85E-33	-7.0%	6.57E-33	4.4%
JENDL 4	5.85E-33	-7.0%	6.57E-33	4.4%
ROSFOND	5.43E-33	-13.7%	6.12E-33	-2.7%
CENDL 3.1	5.85E-33	-7.0%	6.57E-33	4.4%
IRDFF	5.51E-33	-12.4%	6.20E-33	-1.4%
Uncertainty	1.4%	4.13%	1.7%	4.23%

^{55}Mn(n,2n) and ^{127}I(n,2n) measurement

- Same measurement as in the case of Zr
- Each capsule were measured separately at the HPGe detector





$^{55}Mn(n,2n)$ and $^{127}I(n,2n)$ measurement

- PFNS was calculated by ENDF-VII nuclear data library
- Calculated and measured spectral average cross-sections were compared for various libraries

	^{55}Mn(n,2n)	^{127}I(n,2n)
A [Bq]	8.0465	453.8715
q [s^{-1}]	5.13E-21	2.78E-20
Neutron emission rate [s^{-1}]	4.2E+11	
Correction to spectral shift	0.954	0.991
Correction to flux loss	10.3%	6.6%
SACS in reactor spectra > 10 MeV [mb]	163.6019	858.4357
Cross-section in ^{235}U [mb]	**0.2393**	**1.2087**
Uncertainty	**4.21%**	**4.36%**

	^{55}Mn(n,2n)		^{127}I(n,2n)	
	Calculated q [s^{-1}] (ENDF-VII)	C/E-1	Calculated q [s^{-1}] (ENDF-VII)	C/E-1
ENDF VII.1	5.13E-21	0.1%	2.73E-20	-2.0%
ENDF VII	4.93E-21	-3.9%	2.73E-20	-2.0%
JEFF 3.2	5.48E-21	6.8%	2.97E-20	6.6%
JEFF 3.1	5.13E-21	0.1%	2.97E-20	6.6%
JENDL 3.3	5.13E-21	0.1%	3.66E-20	31.3%
JENDL 4	5.13E-21	0.1%	3.66E-20	31.3%
ROSFOND	5.13E-21	0.1%	2.73E-20	-2.0%
CENDL 3.1	5.13E-21	0.1%	3.09E-20	11.1%
IRDFF	4.32E-21	-15.8%	2.69E-20	-3.5%
Uncertainty	2.99%	5.2%	1.94%	4.8%