Rez contribution to inden: New copper broomstick and Teflon leakage experiments

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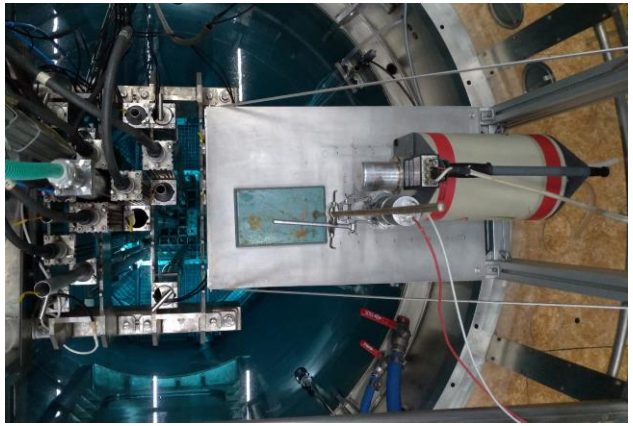
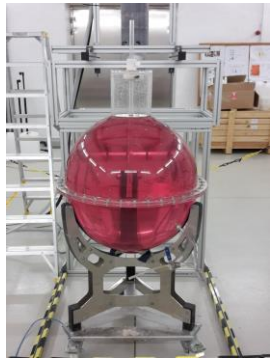
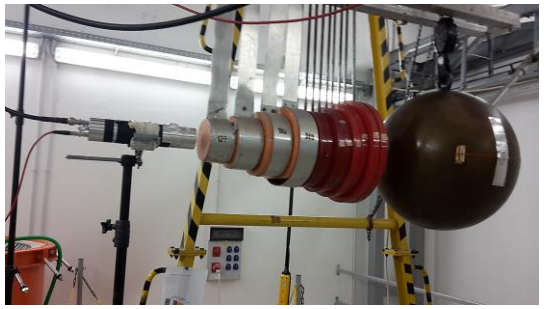
Research infrastructure used by CVR group in experiments







- **4 research reactors LR-0, LVR-15, VR-1 (university, CTU Prague), AKR-2 (TU Dresden)**
- **^{252}Cf neutron sources**
  - Material blocks for neutron leakage measurements:
    - spheres (Fe, Ni … and others)
    - cubes (CF_2, Al, stainless steel, Cu, graphite …)
  - Spherical tank with aqueous solutions for prompt gamma leakage measurements
    - NaCl, $MnSO_4$, $FeSO_4$, …. , planned $CO(NH_2)_2$ (ad blue) , and many others
- **DT generators**
- **Well-described AmBe**
- **XRF analyzers**
- **(and many others)**

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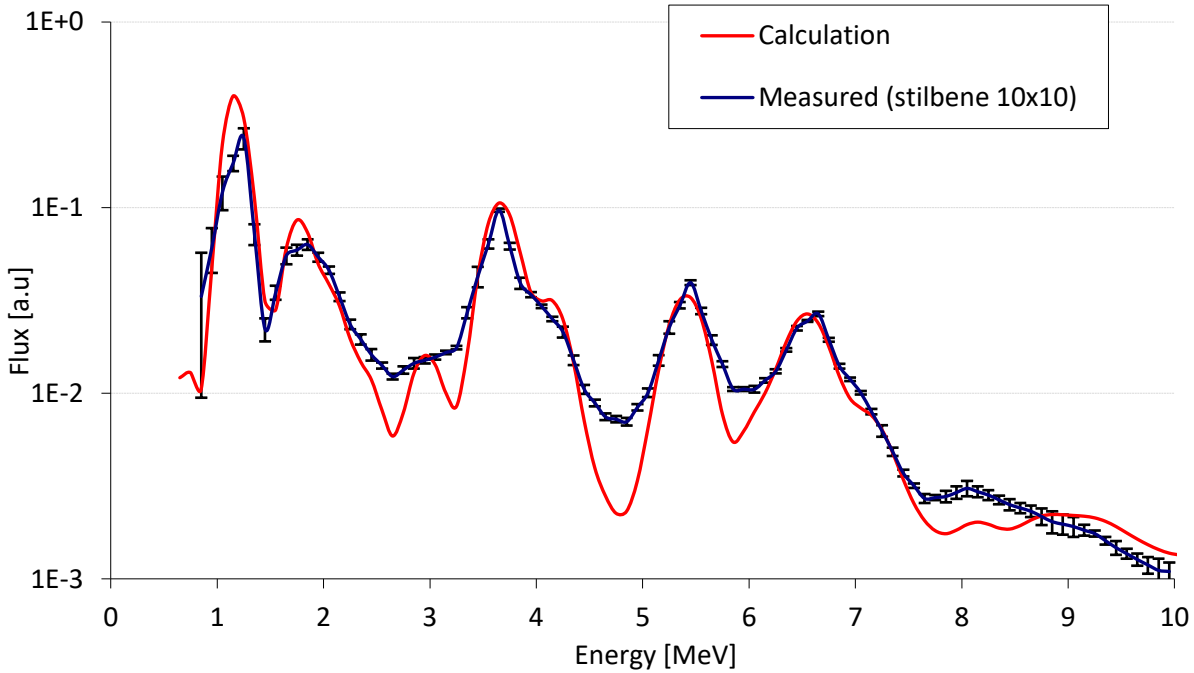
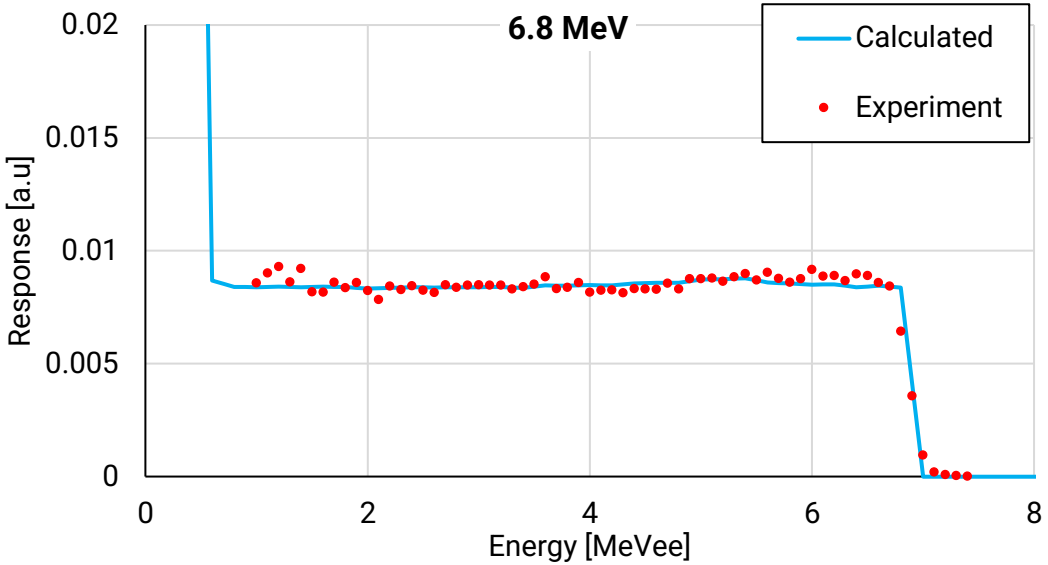
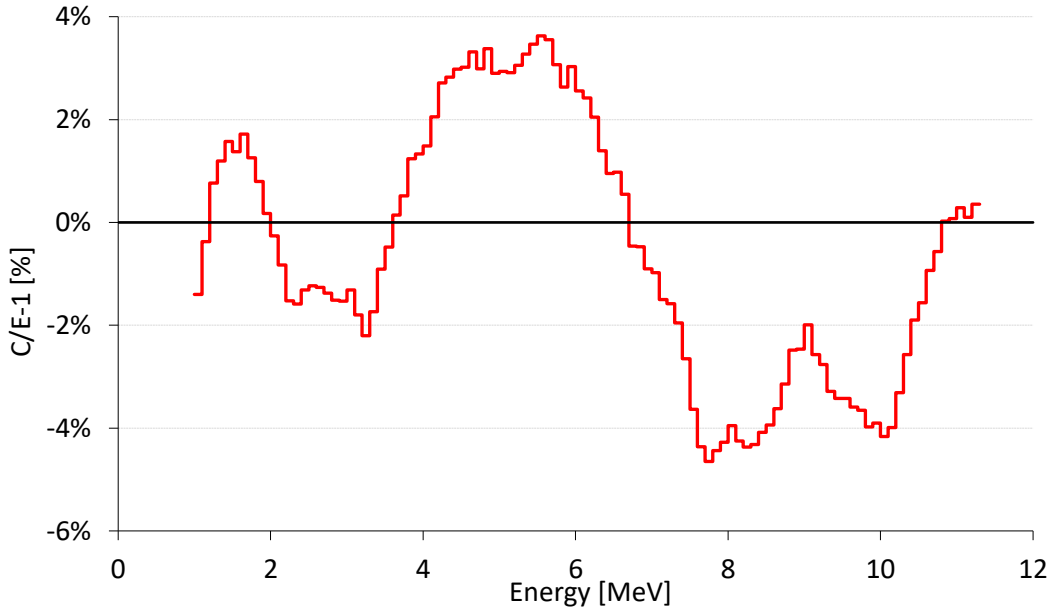
Neutron spectrometry

- Well-characterized spectrometer
- Validation in PTB
- Validation in ^{252}Cf
- Verified in Si filtered spectrum







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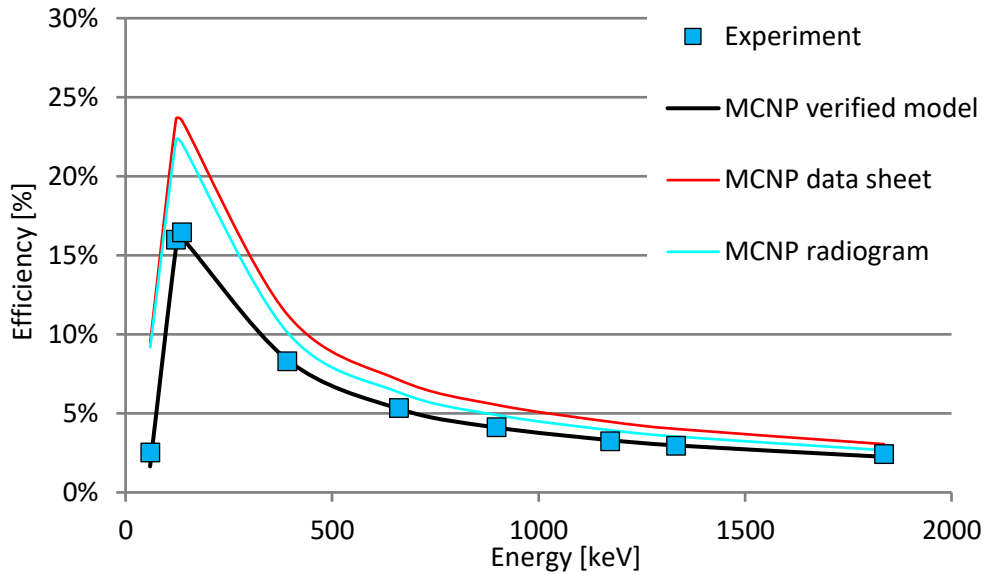
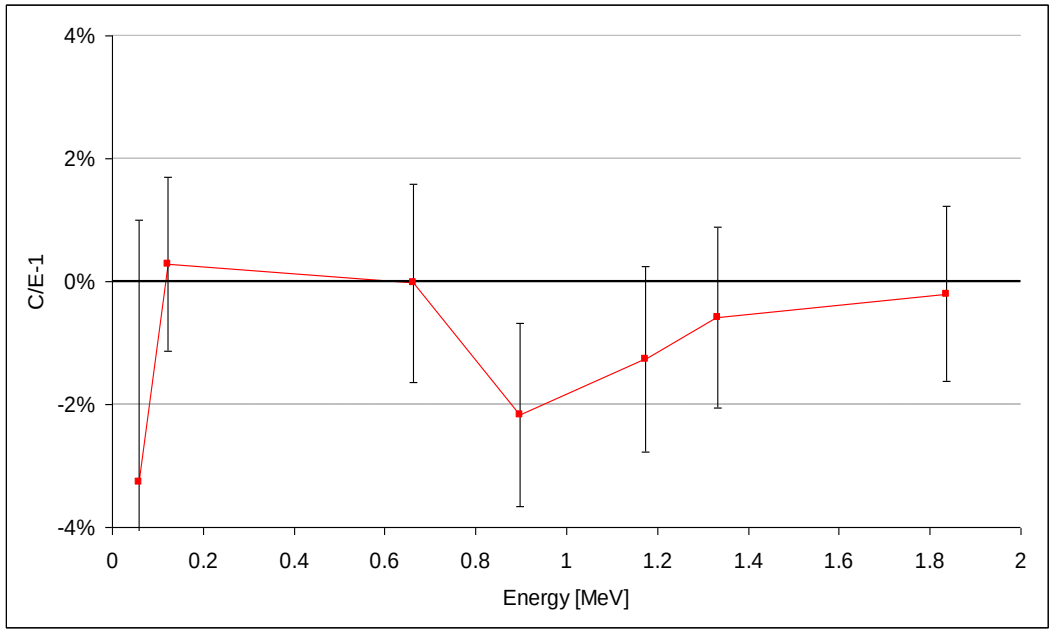
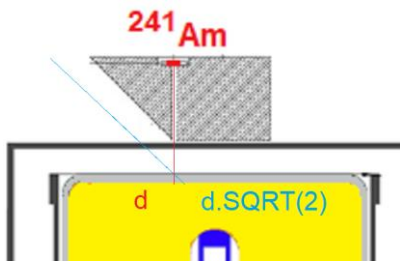
Radulovic et al., IAEA, INDC(NDS)-0746, 2018

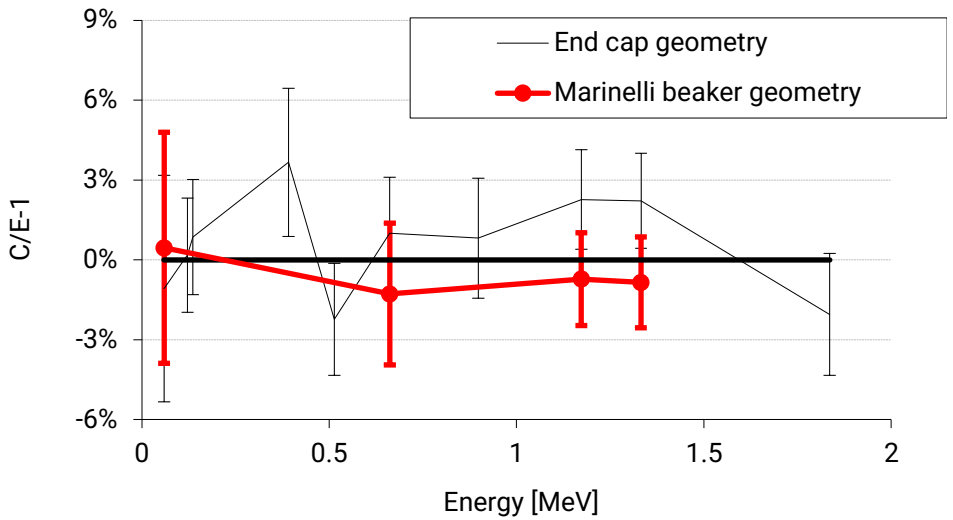
Gamma spectrometry - HPGe

- **Most important is detector sensitivity**
- **Irradiated pins measurement**
  - Mathematical model allows arbitrary axial power density profile
- **Foil measurement**
  - Mathematical model allows even large samples on detector cap
  - Determination of coincidence summing correction
- **Gamma flux measurement**
  - Model allows evaluation of gamma flux (only the









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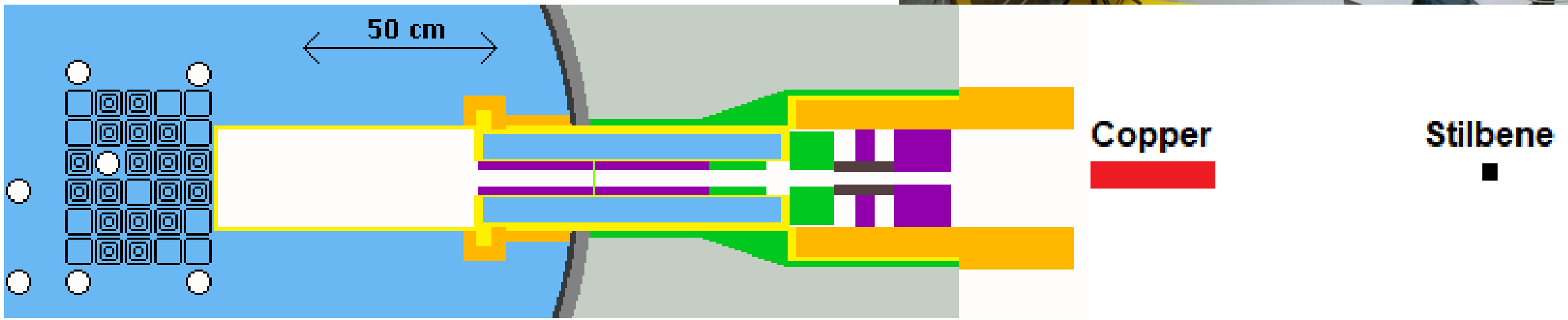
Czakoj et al., Rad. Phys. and Chem. 202 (2023) 110542

Broomstick experiment

- **Integral quantities can usually be measured much more accurately than differential nuclear data,**
  - Useful to use for tuning nuclear data evaluations to improve integral performance.
- **Our experiment – measurement of spectra behind various thickness broomstick material**
- **The measured spectra are compared with calculation**
- **The experiment was realized in VR-1 reactor**



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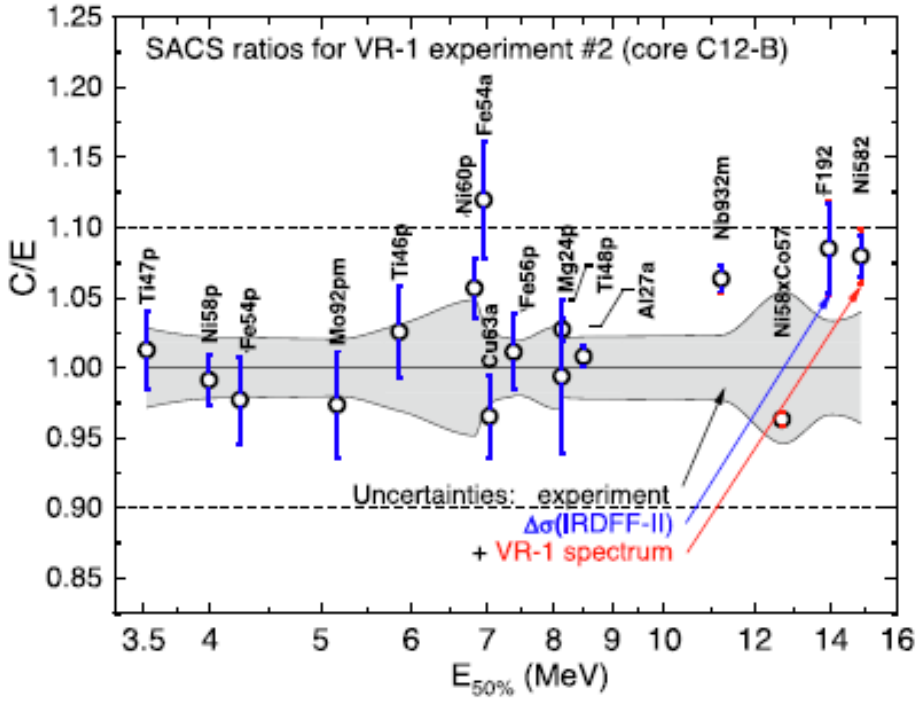
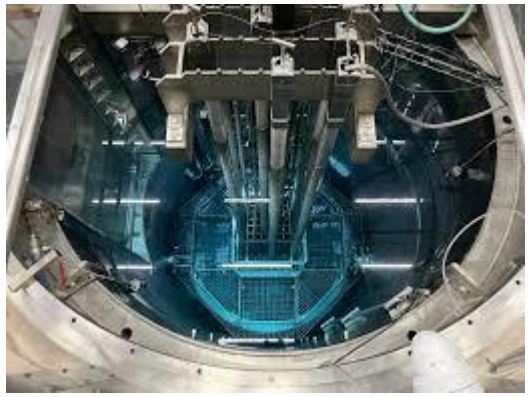
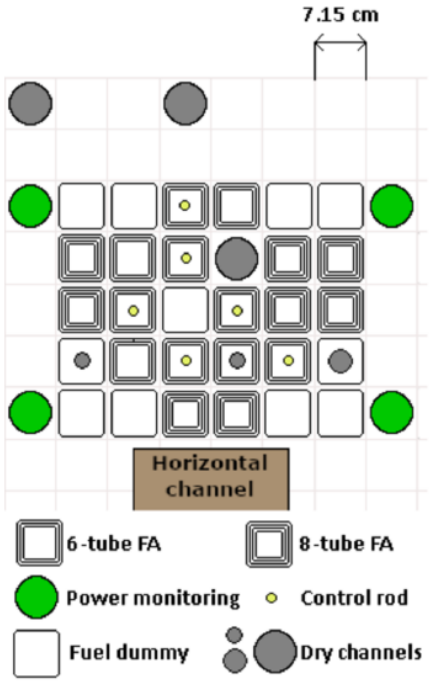
Kostal et al., Broomstick experiment with copper in VR-1 reactor, Annals of Nuclear Energy, Vol. 211, 2025, p. 110993

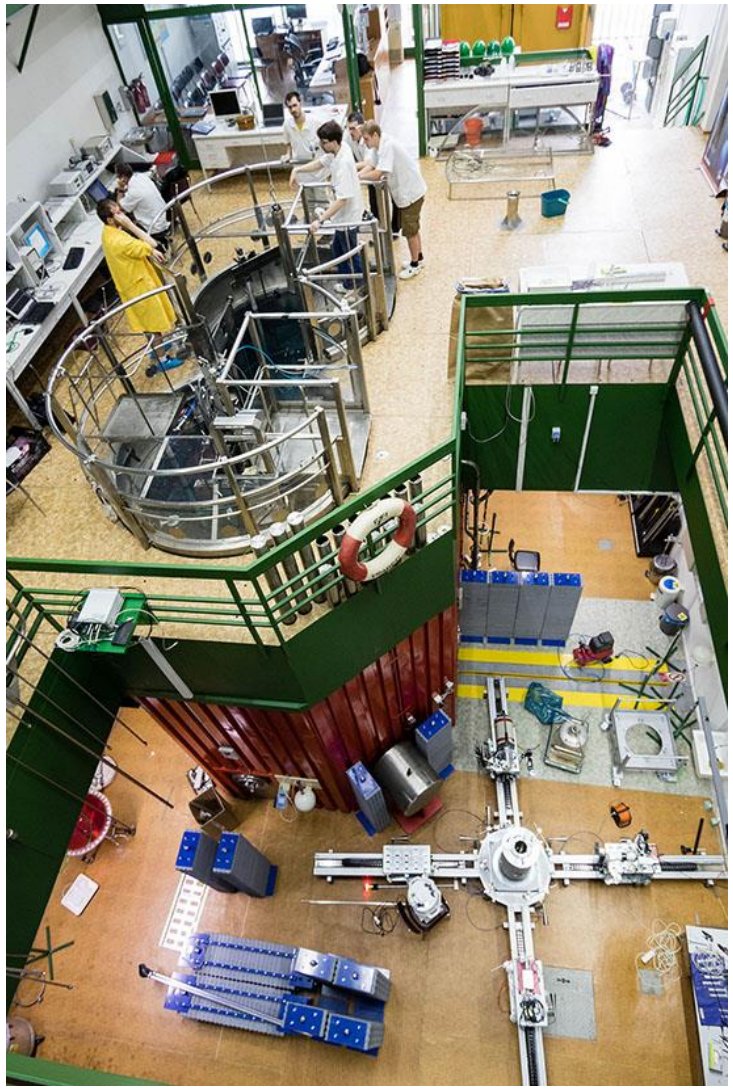
VR-1 reactor

- VR-1 university research reactor operated by CTU Prague
- Characterized neutron spectrum in radial channel
- Source spectrum known (large set of SACS measurements realized)









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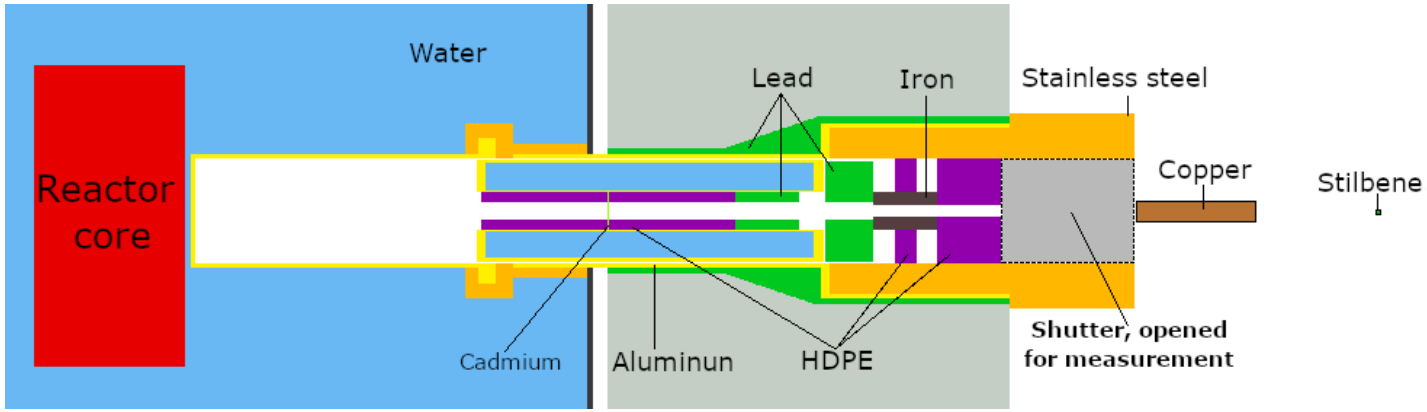
Kostal et al., Characterization of mixed N/G beam of the VR-1 reactor, Annals of Nuclear Energy, 122, (2018), pp. 69-78

Kostal et al., Validation of IRDFF-II library in VR-1 reactor field using thin targets, Annals of Nuclear Energy, 158, (2021), p. 108268

Development of pinhole beam

- Special insertion in VR-1 channel to collimate beam to diameter of 3 cm
- Large Pb block to suppress the gamma background
- Shutter to allow closing the beam without reactor shutdown



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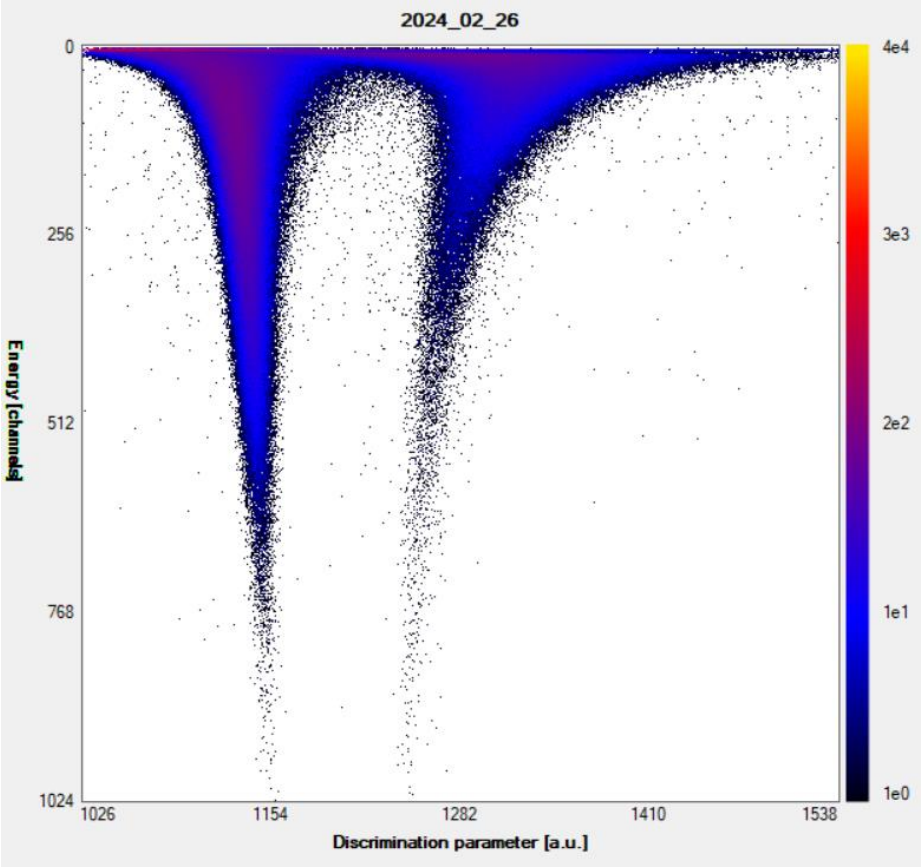
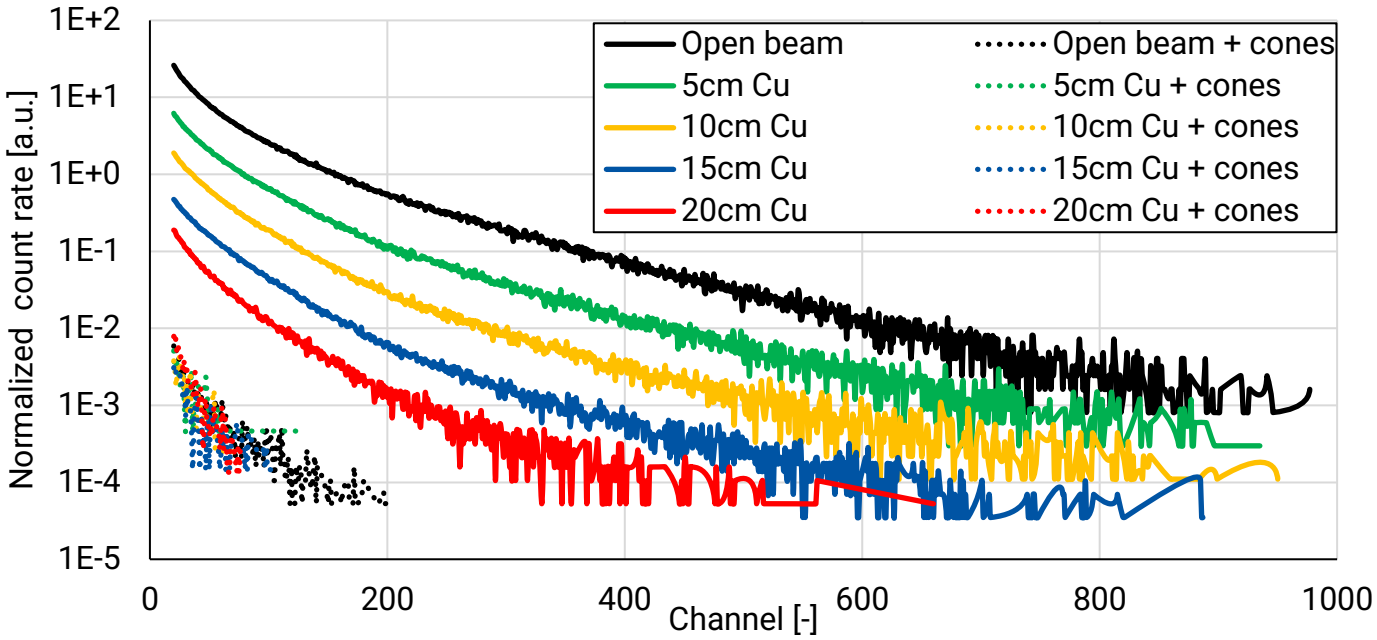
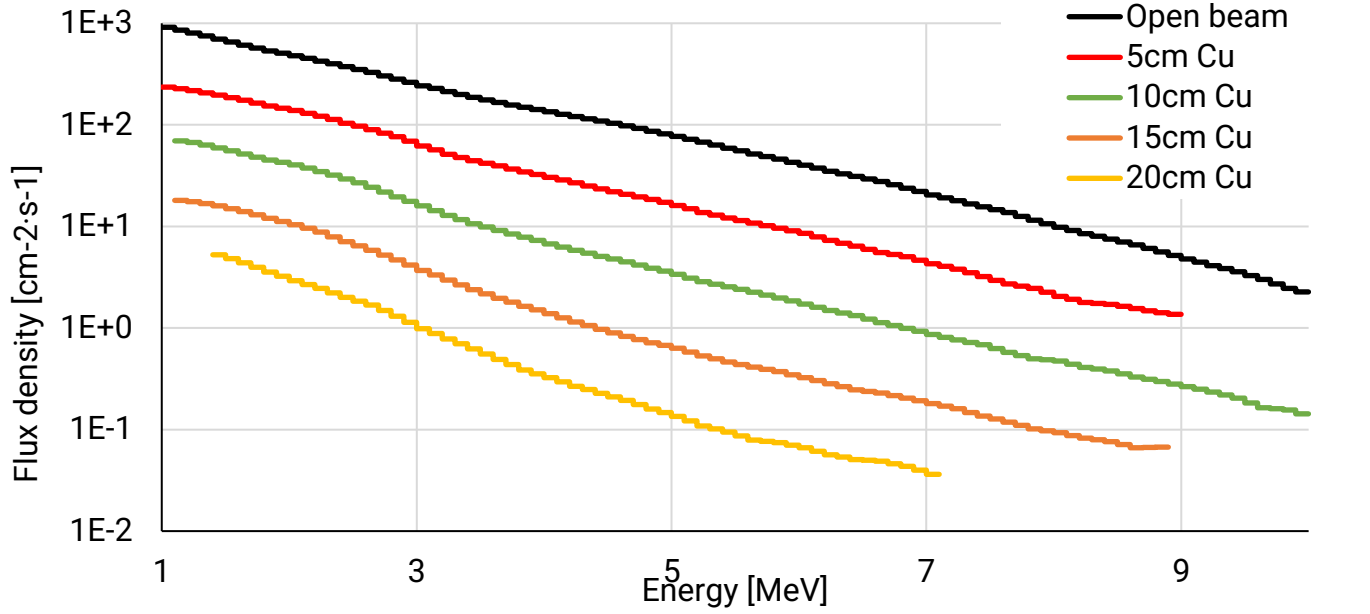
Kostal et al., Broomstick experiment with copper in VR-1 reactor, Annals of Nuclear Energy, Vol. 211, 2025, p. 110993

Spectra measurement

- Stilbene crystal 10 mm × 10 mm
- Good N/G separation
- Calibration using Cs (0.661 MeV) and H capture peak (2.23 MeV)

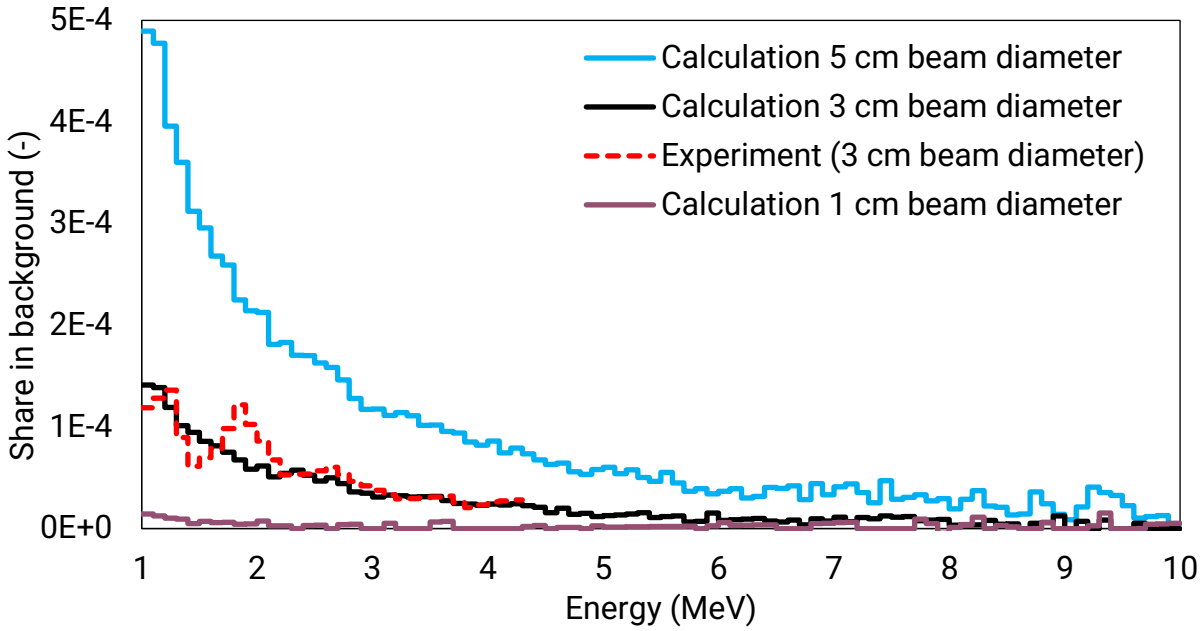


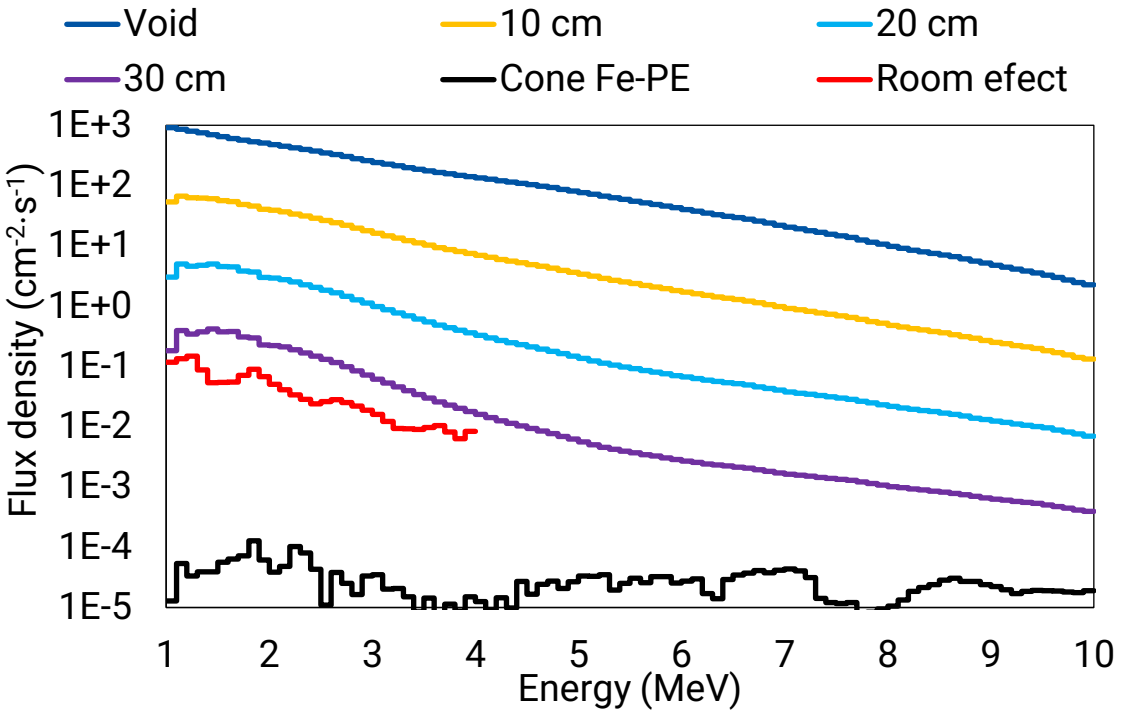




Background determination

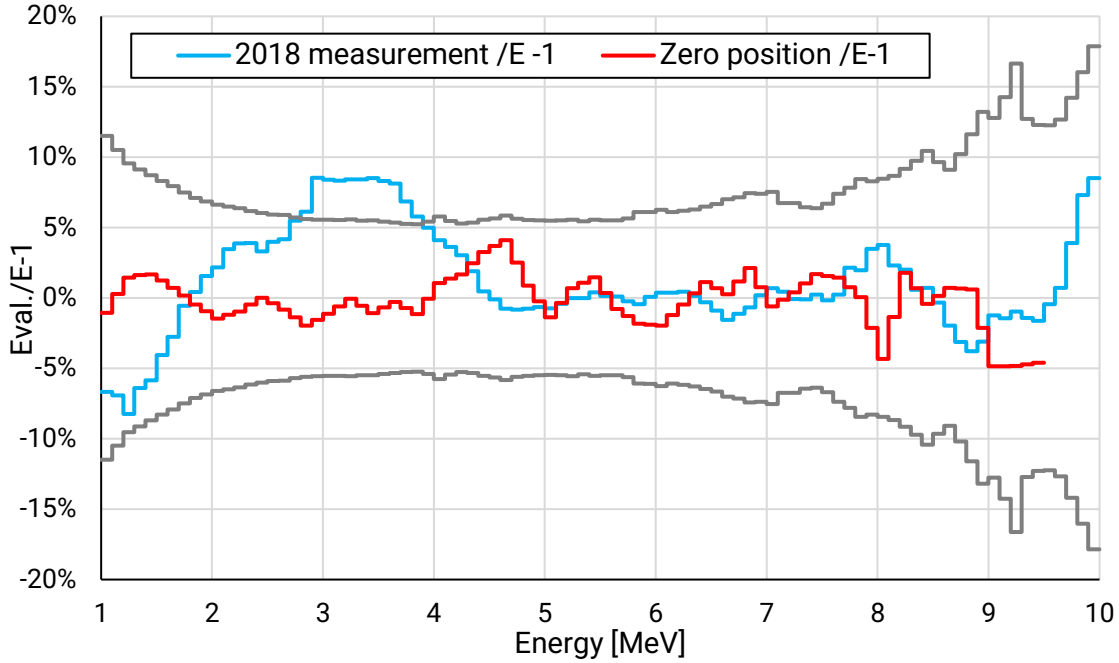
- Room effect determined using shielding cylinder
- Iron + HDPE
- Its magnitude is affected by aperture diameter
- For blocks shorter than 20 cm Cu (attenuation ~ 1000) room effect is negligible

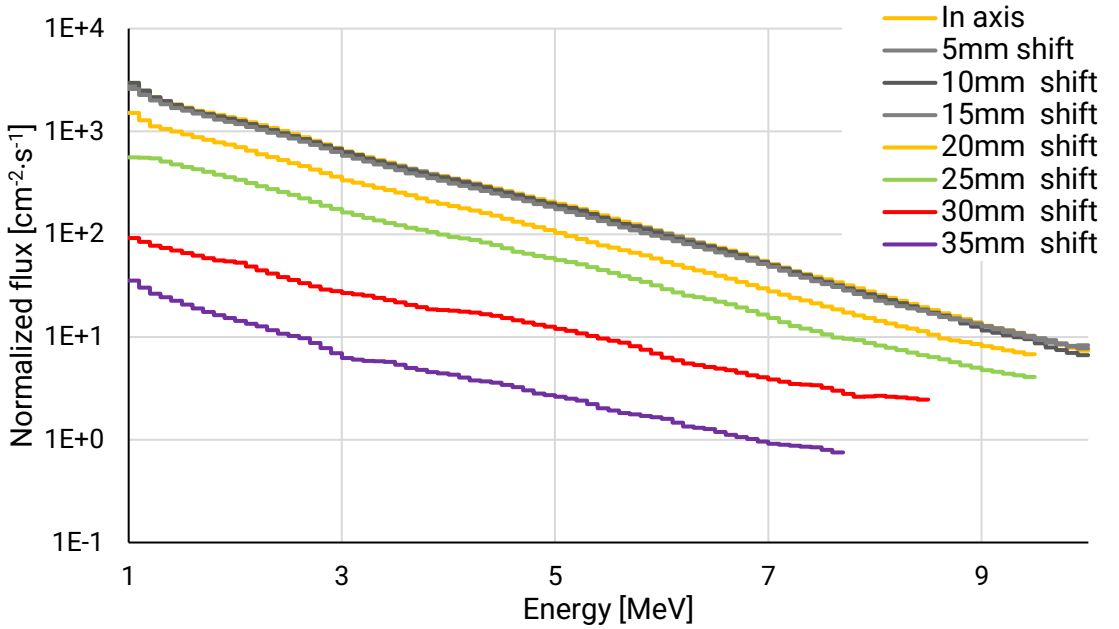




Beam characterization

- The spectrum in beam is similar to spectrum in chanel in previous measurement
- Spectra in output and measuring position are identical
  - Flux decrease (factor 2.612) implies that beam is relatively not divergent
- The beam is sharp (1% when moved by 35 mm corresponds to scatter from probe).





Misalignment [mm]	Rel. flux
0 (In axis)	1.000
5	0.965
10	0.963
15	0.905
20	0.533
25	0.265
30	0.044
35	0.011

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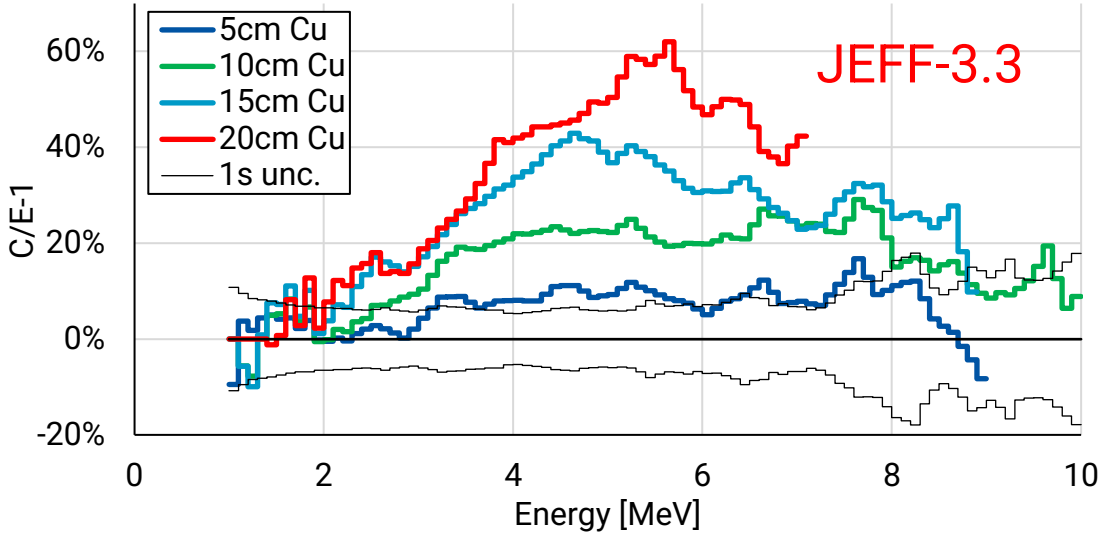
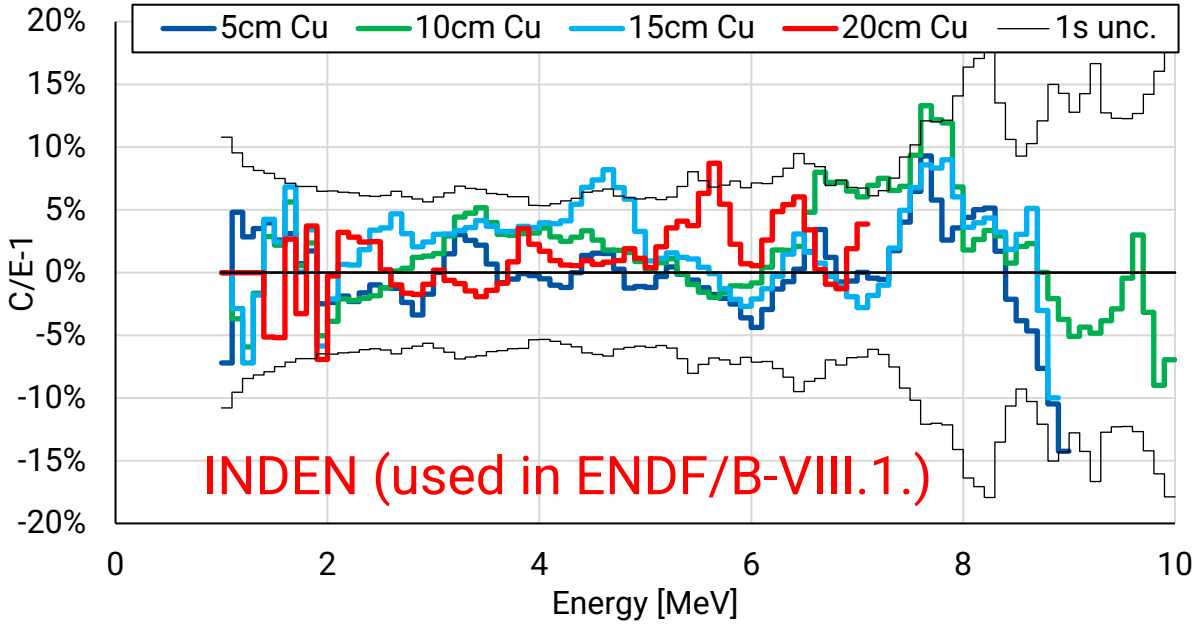
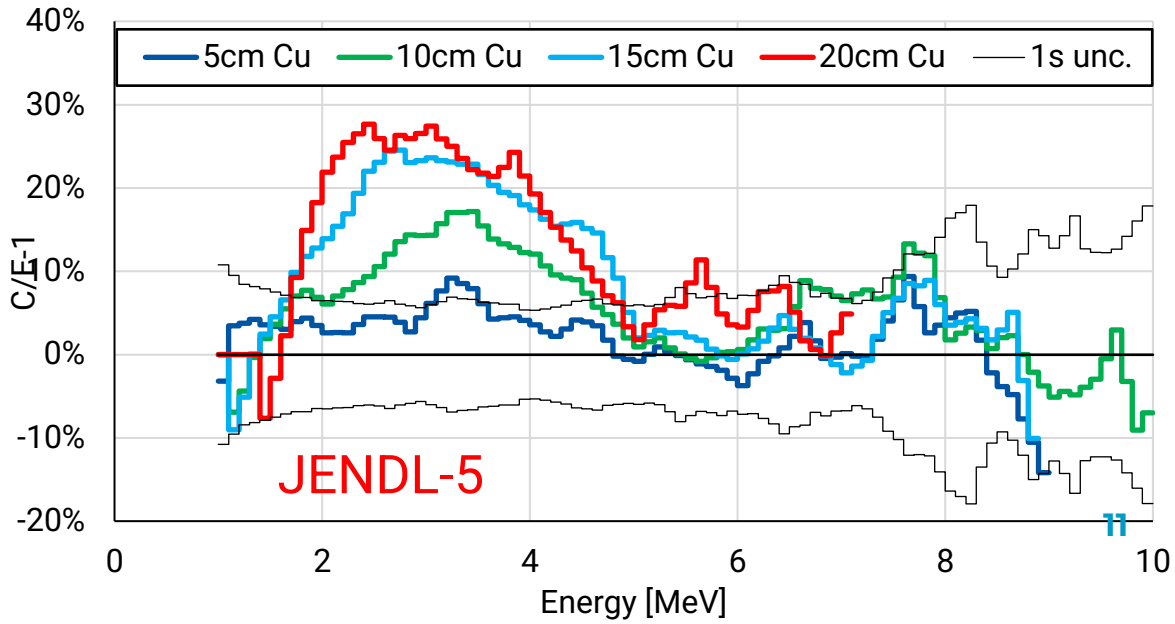
Comparison with various evaluations

- **Low uncertainty experiment (beam transmission)**
  - Simple geometry
  - Good source description
- **Discrepancies from simulation (if any) are on account of cross section evaluation**
  - JEFF-3.3 highly discrepant
  - ENDF/B-VIII.1 GOOD
  - JENDL-5 problematic







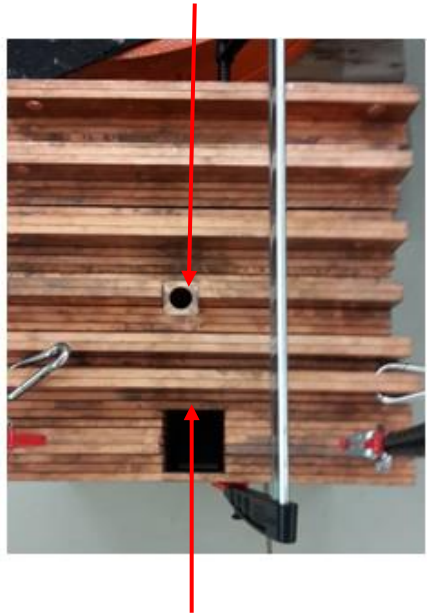
Leakage from copper cube

Copper cube evaluated (>=99.95% Cu)

Support for benchmarks - 2 m above the lab.floor (as usually)

Leakage spectrum (1 - 10 MeV)

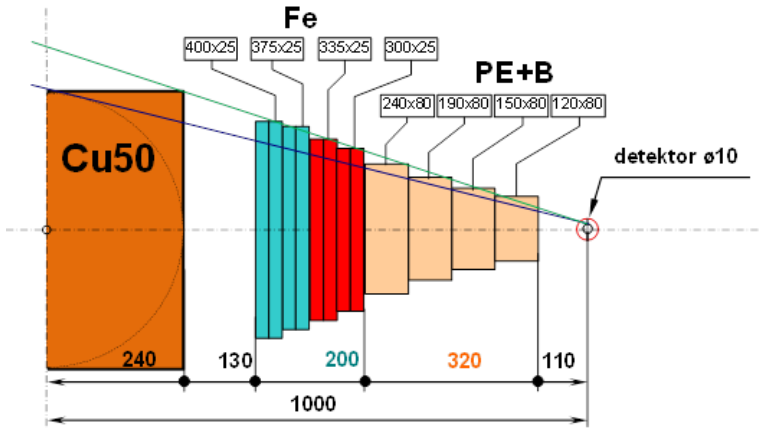
100 cm from center



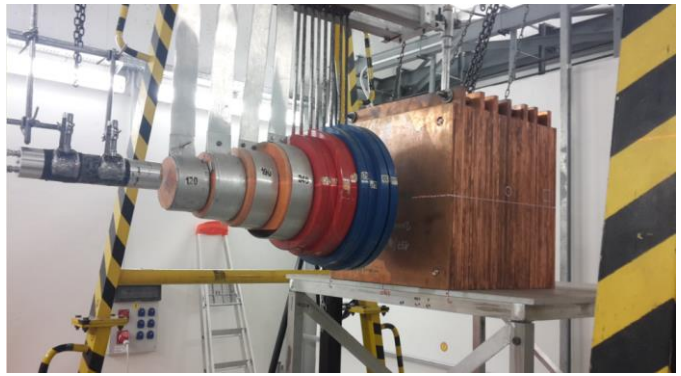
Reaction rates of :

$^{197}Au(n,g)^{198}Au$
$^{58}Ni(n,p)^{58}Co$
$^{93}Nb(n,2n)^{92m}Nb$
$^{55}Mn(n,g)^{56}Mn$

Background spectrum (room effect)

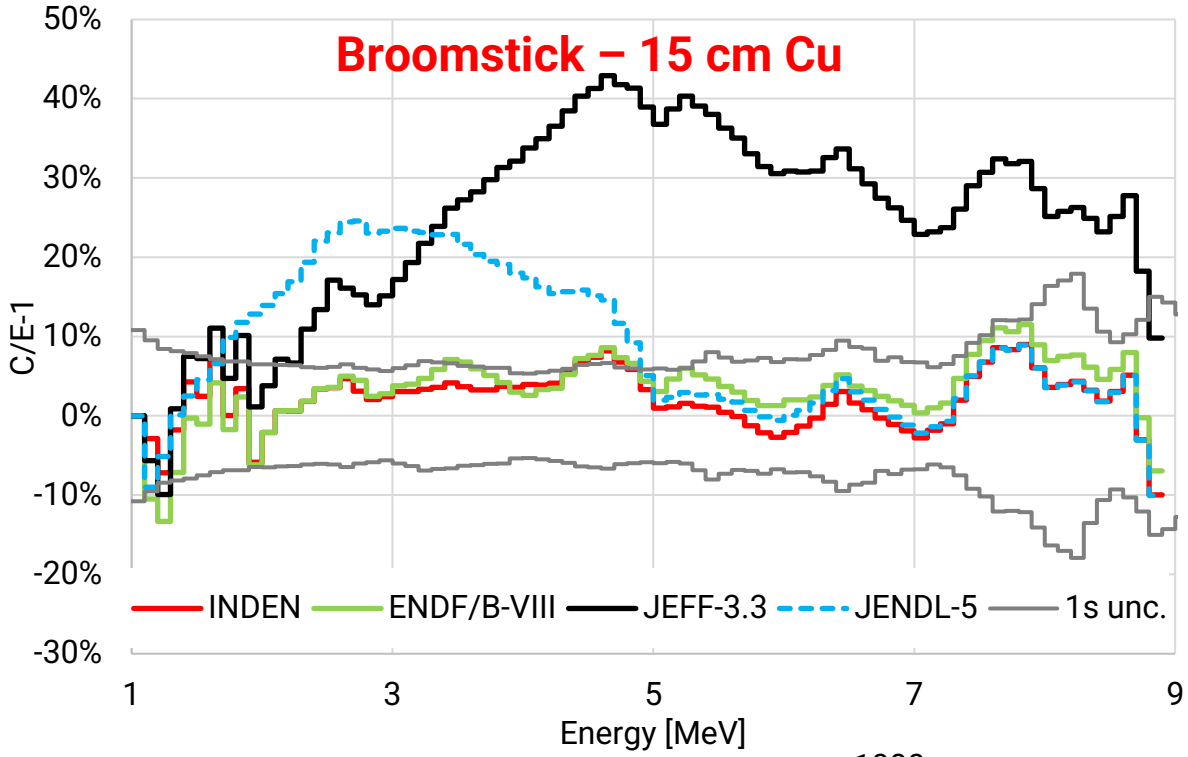


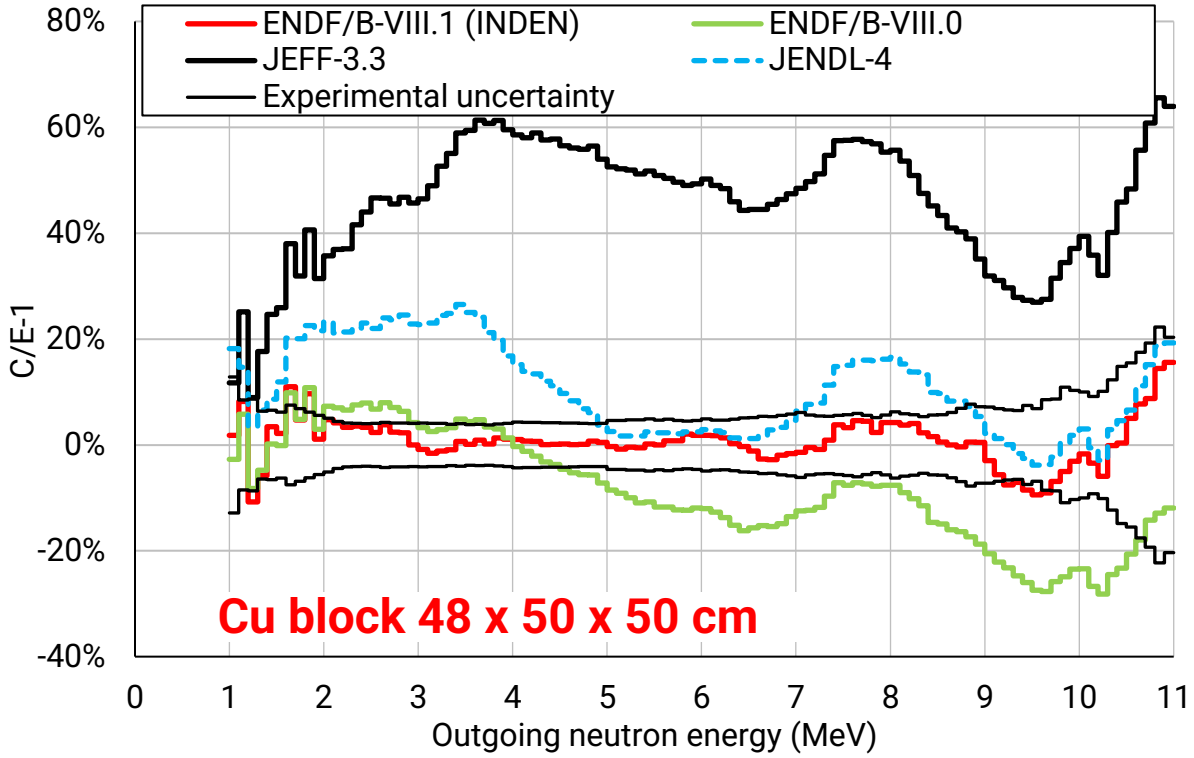
Cone 20cm Fe – 32cm PE



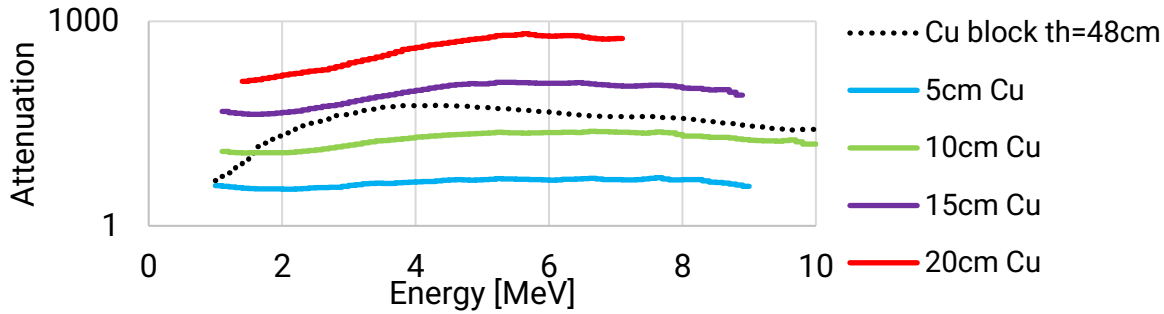
Comparison of broomstick and leakage

- **Obtained results are in good consistence with previously measured neutron leakage from copper block**





In broomstick more effective attenuation



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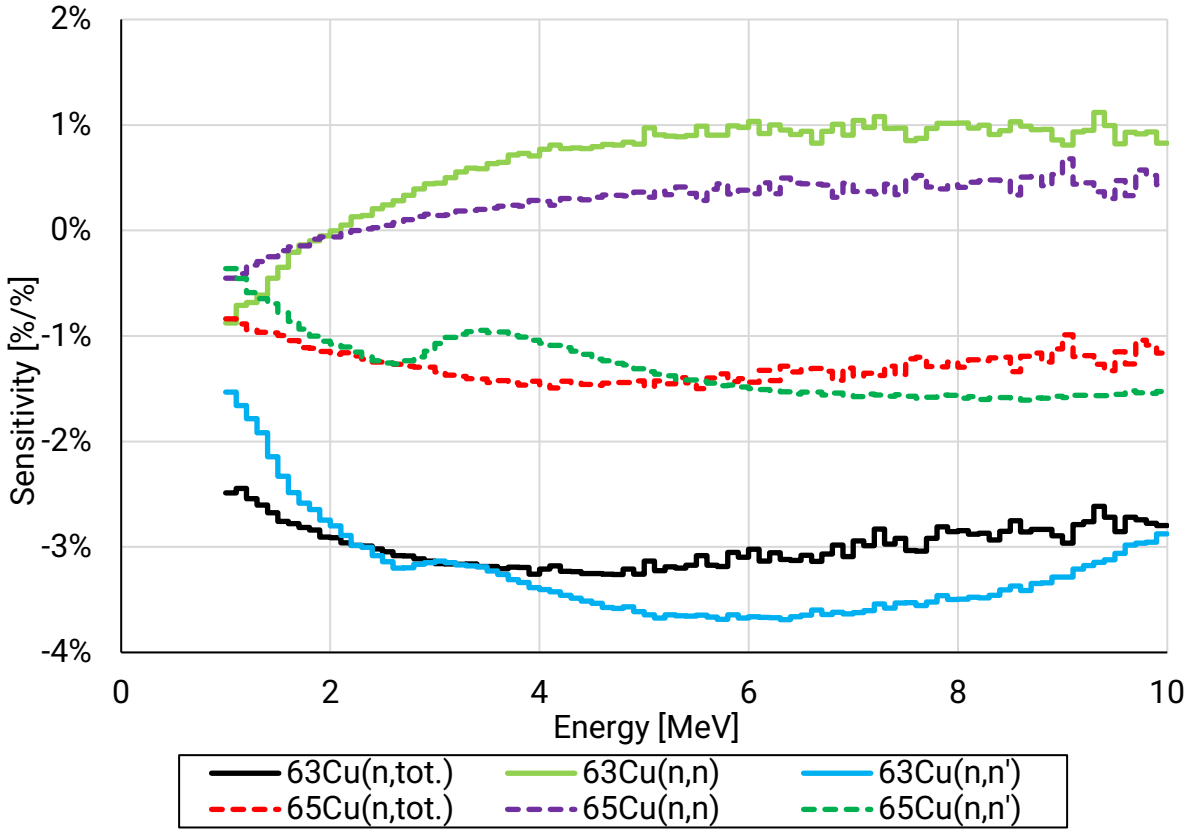
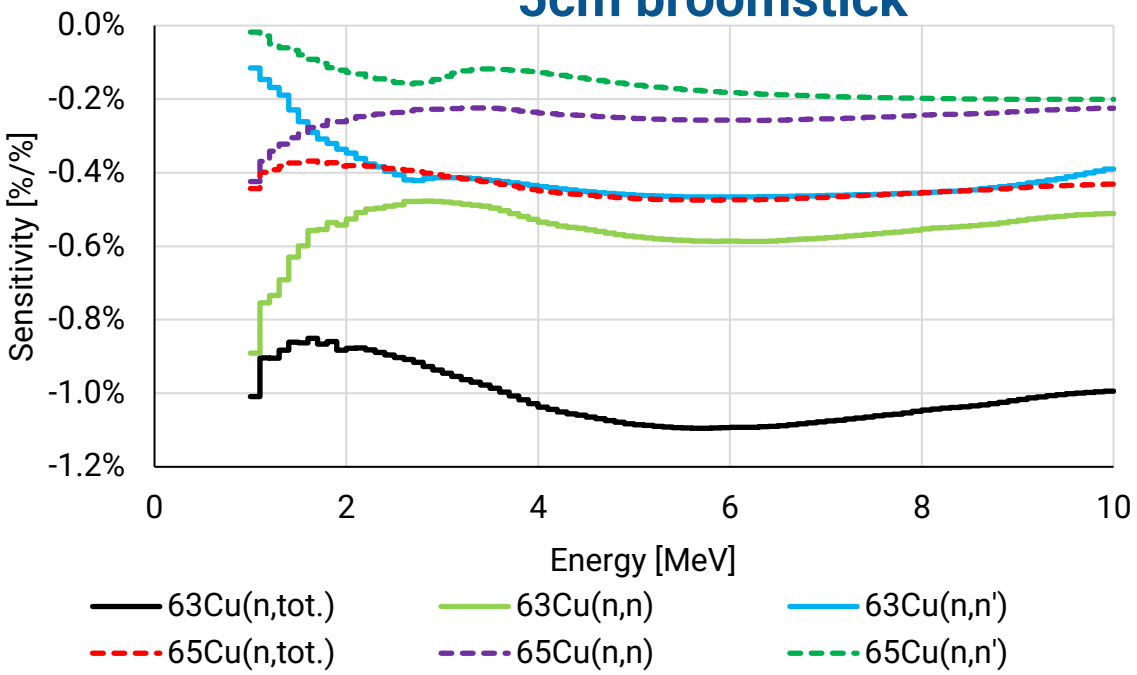
Sensitivities

- **Broomstick is excellent accompanying experiment in cross section validation because sensitivities are different from case of leakage from material block**

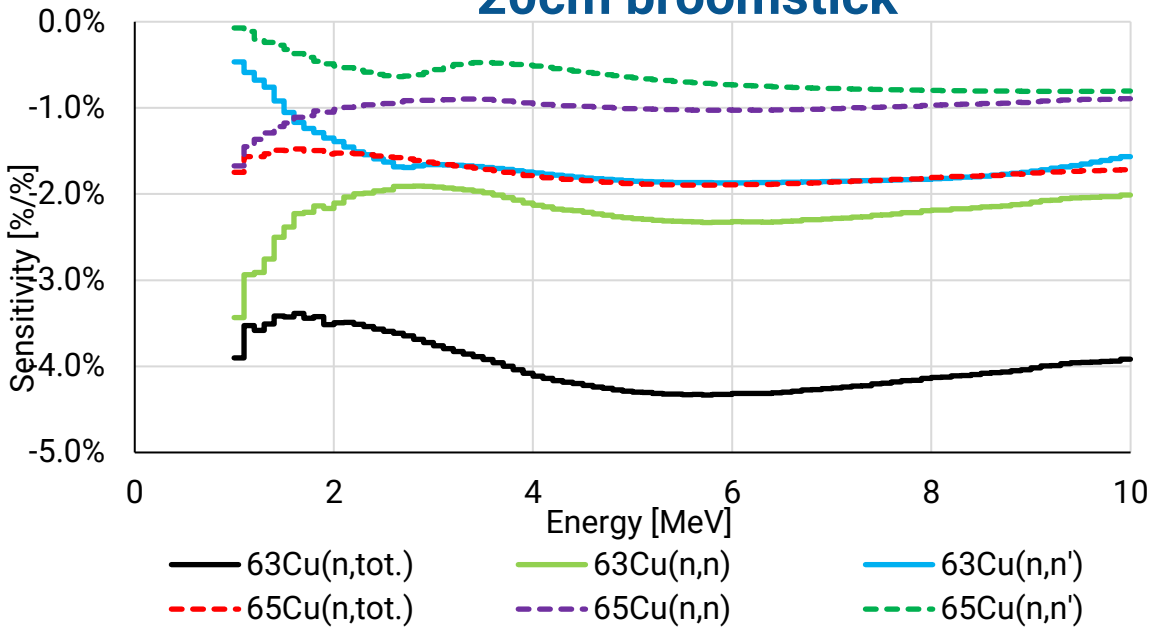
Cu block



5cm broomstick



20cm broomstick

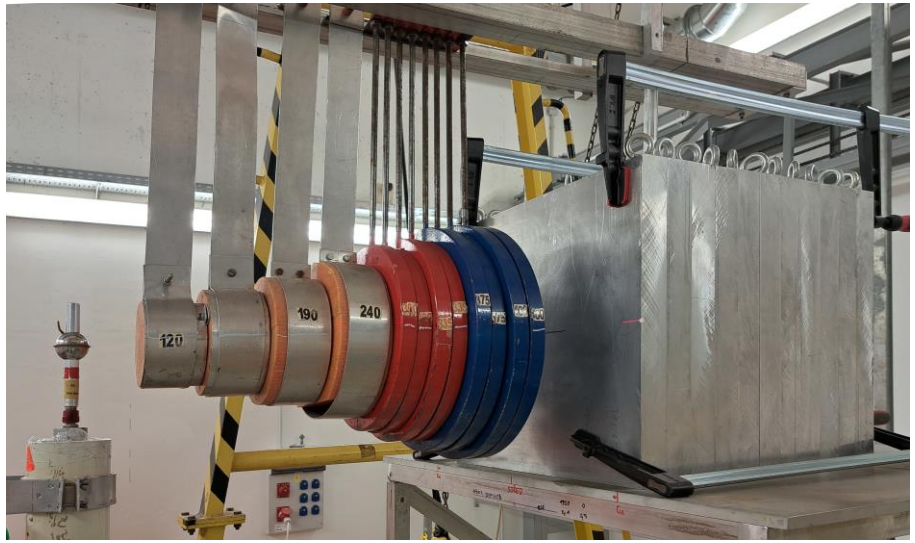


New neutron leakage experiments

PTFE block
60 × 50 × 50 cm

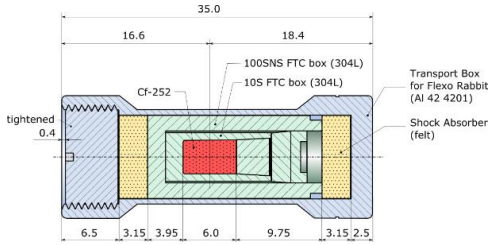
Perchloretylene D=50cm

Aluminium block
55 × 50 × 50 cm



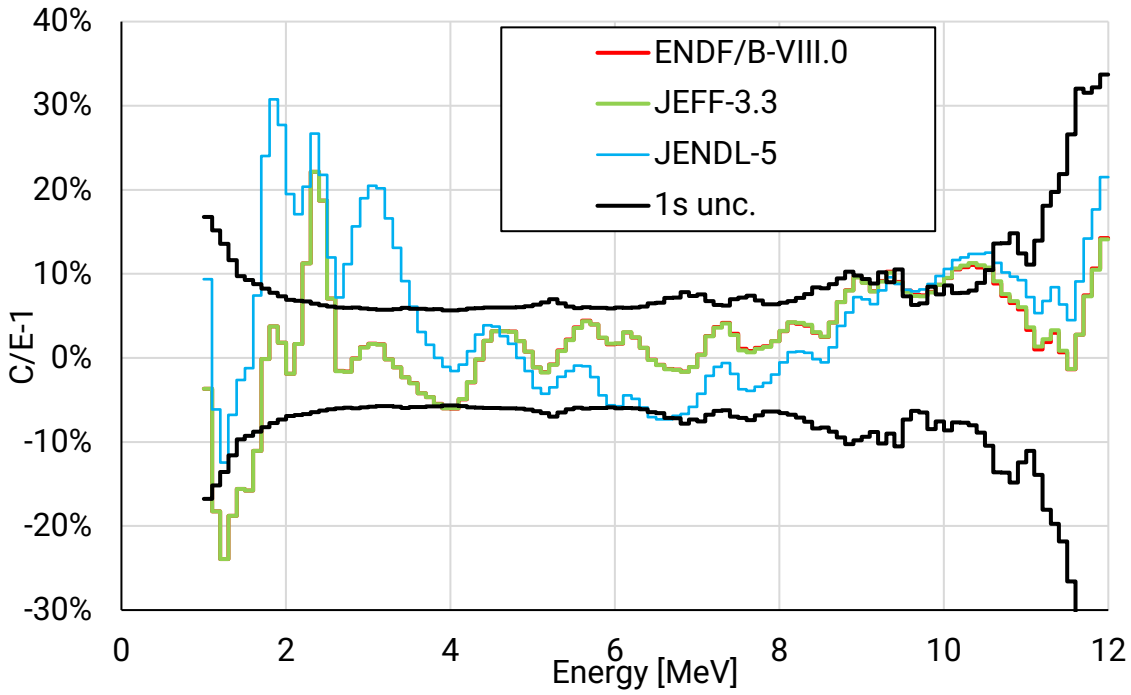
Cones = 32cm PE + 20cm Fe

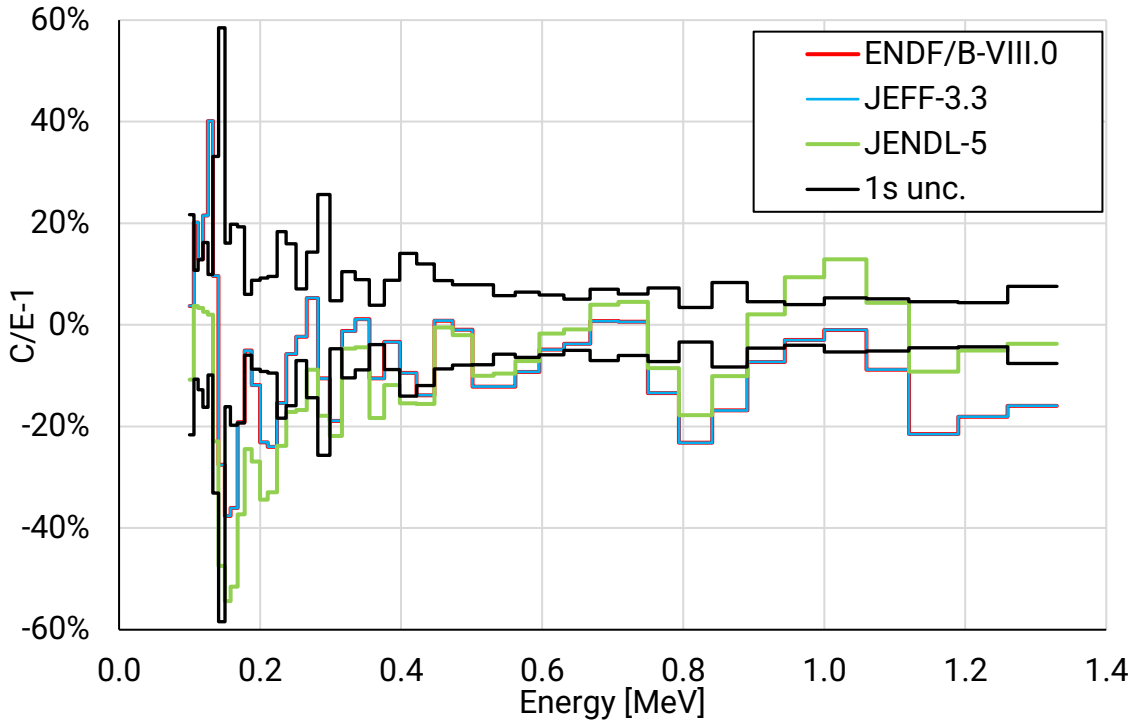
^{252}Cf in well defined cladding



Support for benchmarks - 2 m above the lab.floor (as usually)

Al leakage spectra

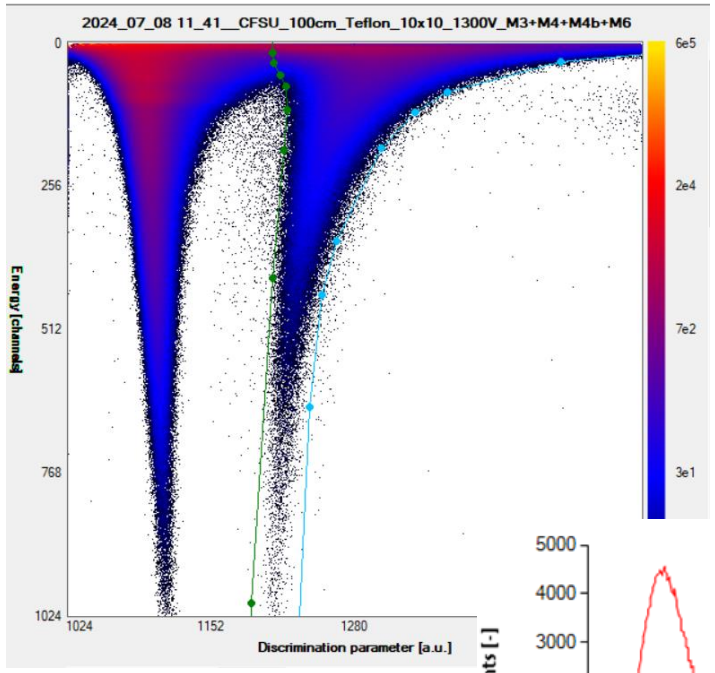


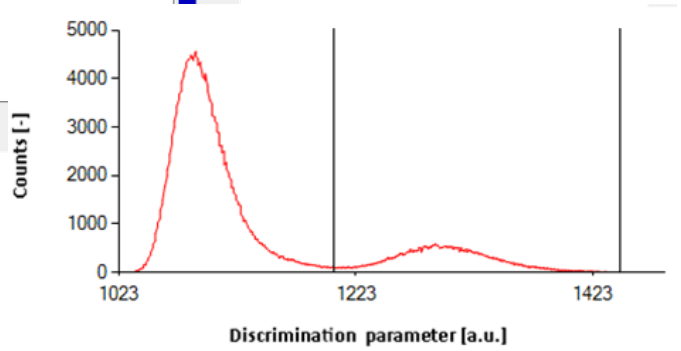


		115In(n,n')				58Ni(n,p)			
Plate position	Al thickness [cm]	ENDF/B-VIII.0 [%]	JEFF-3.3 [%]	JENDL-5 [%]	Unc. [%]	ENDF/B-VIII.0 [%]	JEFF-3.3 [%]	JENDL-5 [%]	Unc. [%]
6	1.18	-2	-2	-2.3	3.9	-9.4	-9.4	-9.6	12.2
7	6.12	-8.7	-8.7	-7.1	2.5	-7.2	-7.2	-6.5	4.3
8	11.06	-12.2	-12.2	-8.2	2.5	-8.7	-8.4	-6.6	2.9
9	16.01	-12.6	-12.6	-6.2	2.8	-11.9	-11.5	-10	2.6
10	20.95	-18.3	-18.3	-10.2	2.8	-8	-8	-2.7	2.4
11	25.91	-16.9	-16.9	-6.8	3.5				

Stilbene measurement of PTFE leakage flux

- Neutron leakage spectra in 1 m
- Stilbene detector 10x10 mm
- Not high gamma background (good PSD discrimination)

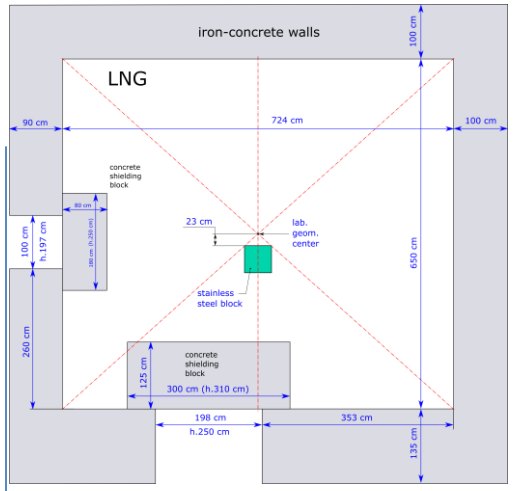




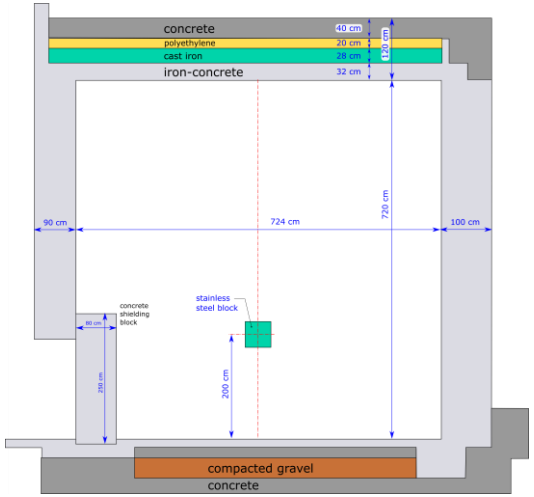
discrimination in 34 channel ~ 0.99 MeV

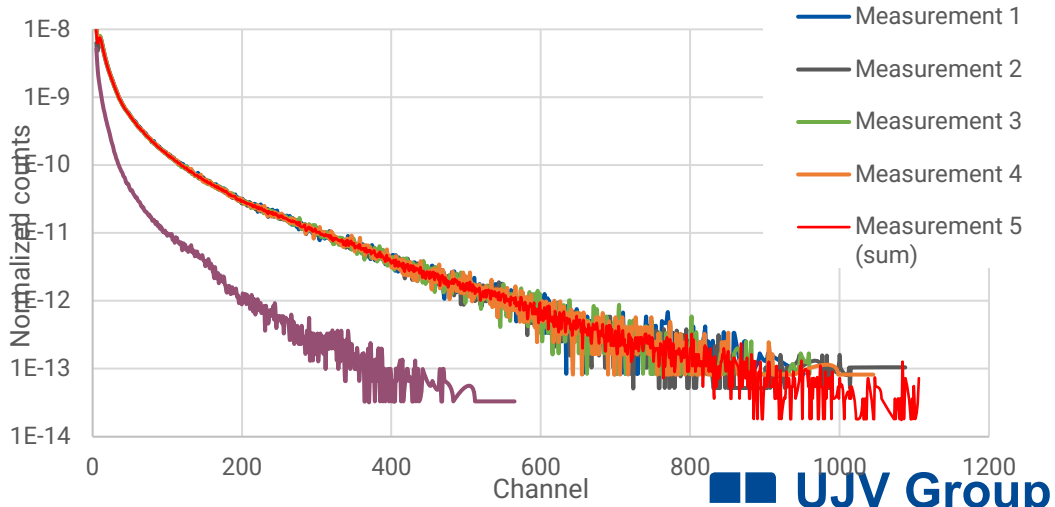
Room effect evaluation

Horizontal view



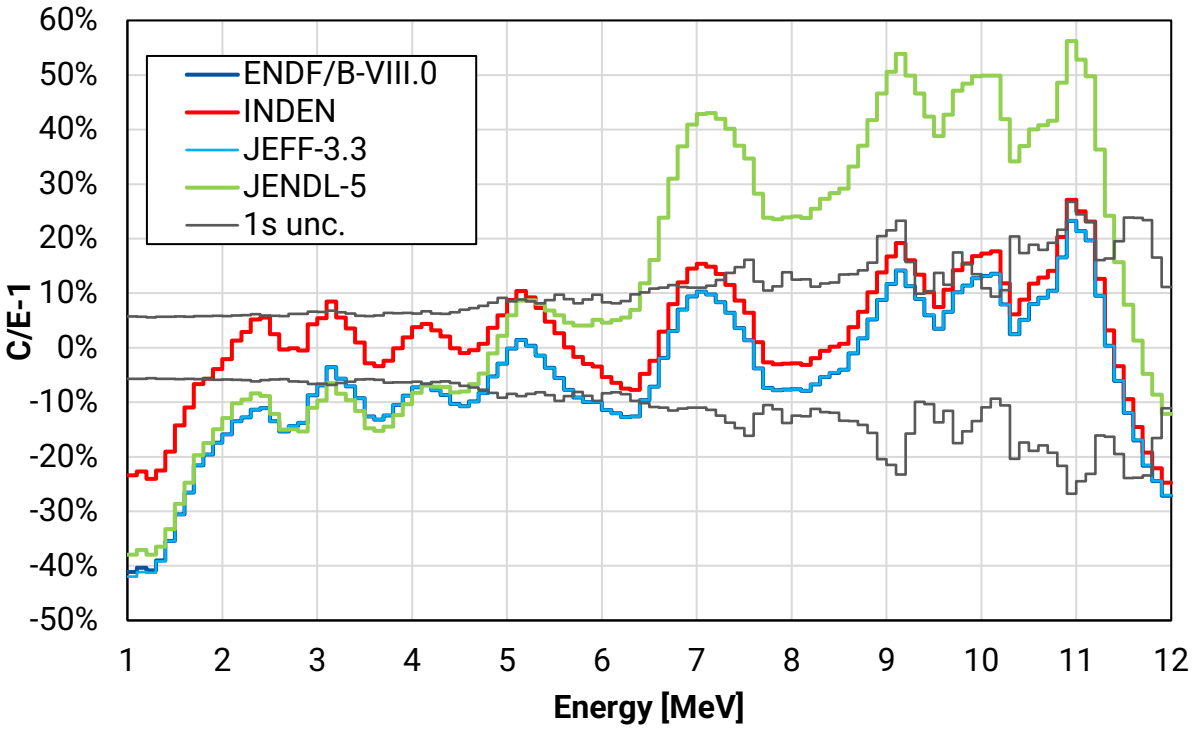
Vertical view

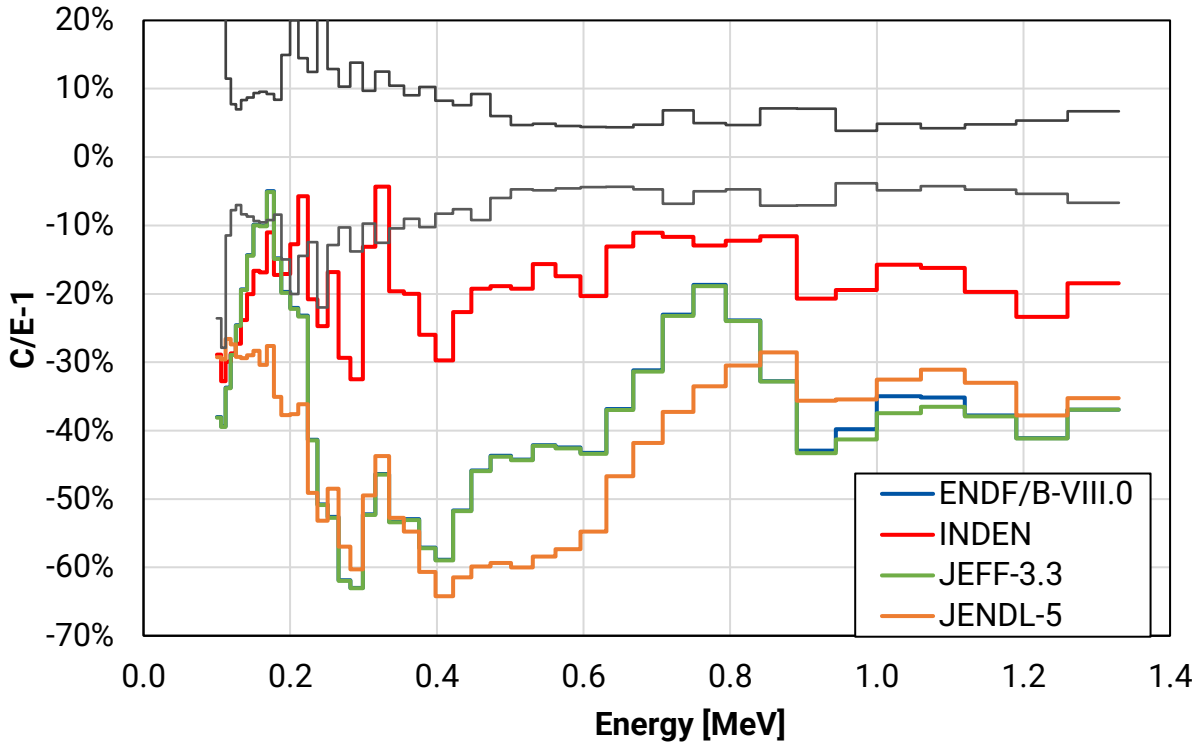




C/E comparison of measured spectra

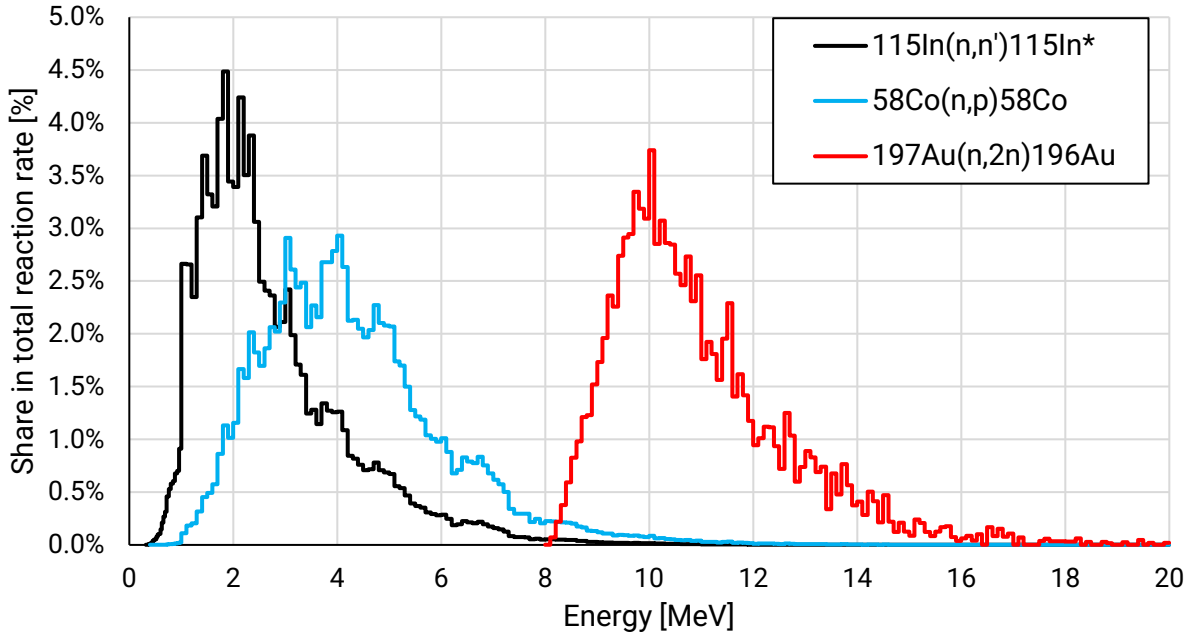
- **Best agreement in case of INDEN (ENDF/B-VIII.1.) however still some discrepancies are notable in region below 2 MeV**





Foil results

- Independent monitors of neutron flux
- Even high flux monitored 5g Au foil, 2 month activation, 5d measurement => NPA ~ 1200 cts



Indium ^{115}In(n,n')

Placement on plate No. back side	C_2F_4 thickness [cm]	ENDF/B-VIII.0	INDEN	JEFF-3.3	JENDL-5	u_r [%]
6	1.40	4.4	2.0	4.4	2.2	3.9
7	6.82	-4.8	-4.8	-4.8	-7.5	3.0
8	12.28	-5.2	-1.8	-5.3	-7.5	3.1
9	17.68	-14.4	-8.1	-14.5	-15.9	4.4
10	23.09	-24.6	-16.3	-24.6	-25.0	7.5
11	28.48	-26.7	-14.7	-26.8	-25.1	5.5

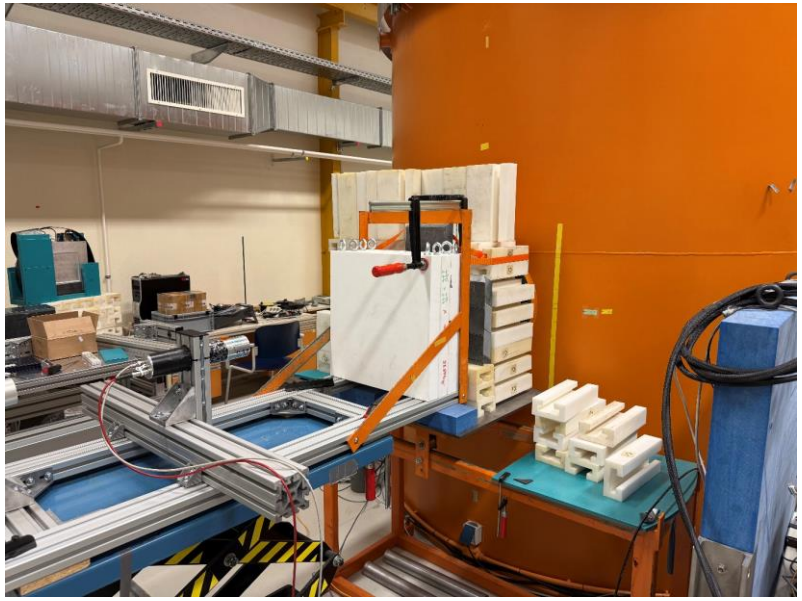
Nickel ^{58}Ni(n,p)

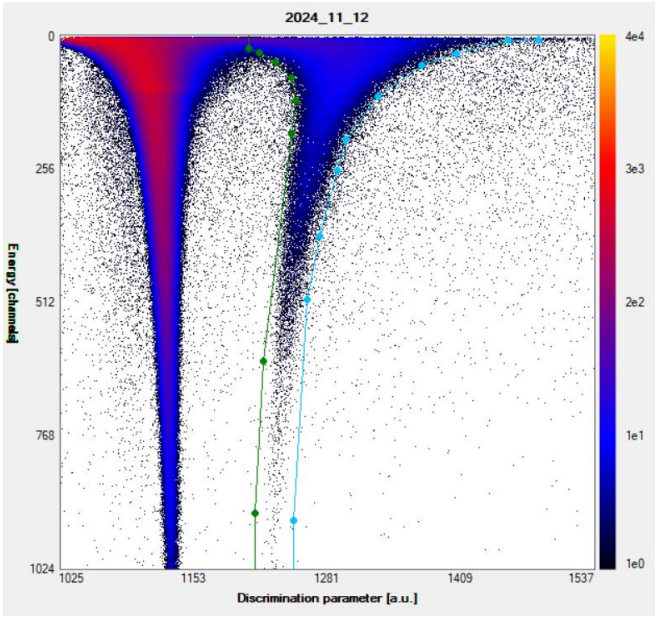
Placement on plate No. back side	C_2F_4 thickness [cm]	ENDF/B-VIII.0	INDEN	JEFF-3.3	JENDL-5	u_r [%]
6	1.40	3.1	2.1	3.1	1.8	9.0
7	6.82	-2.0	-1.7	-2.1	-3.3	3.4
8	12.28	-5.6	-2.9	-5.6	-5.7	2.9
9	17.68	-7.8	-3.0	-7.8	-6.6	3.3
10	23.09	**-12.3**	-5.5	-12.3	-9.6	3.2
11	28.48	-9.8	0.5	-9.8	-4.0	3.5

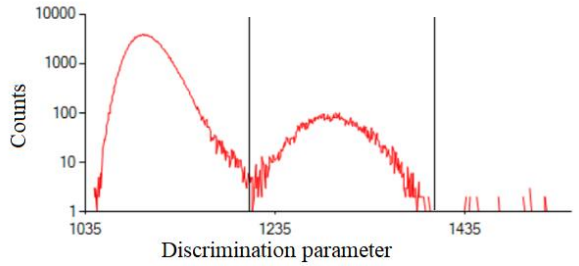
Gold ^{197}Au(n,2n)

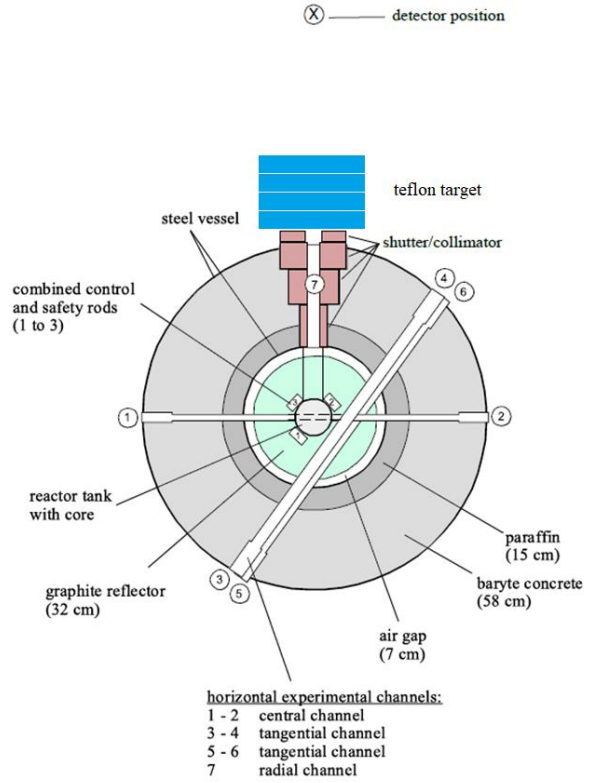
Placement on plate No. back side	C_2F_4 thickness [cm]	ENDF/B-VIII.0	INDEN	JEFF-3.3	JENDL-5	u_r [%]
10	23.09	-3.8	-2.6	-4.4	17.0	17.8

AKR-2 experiment





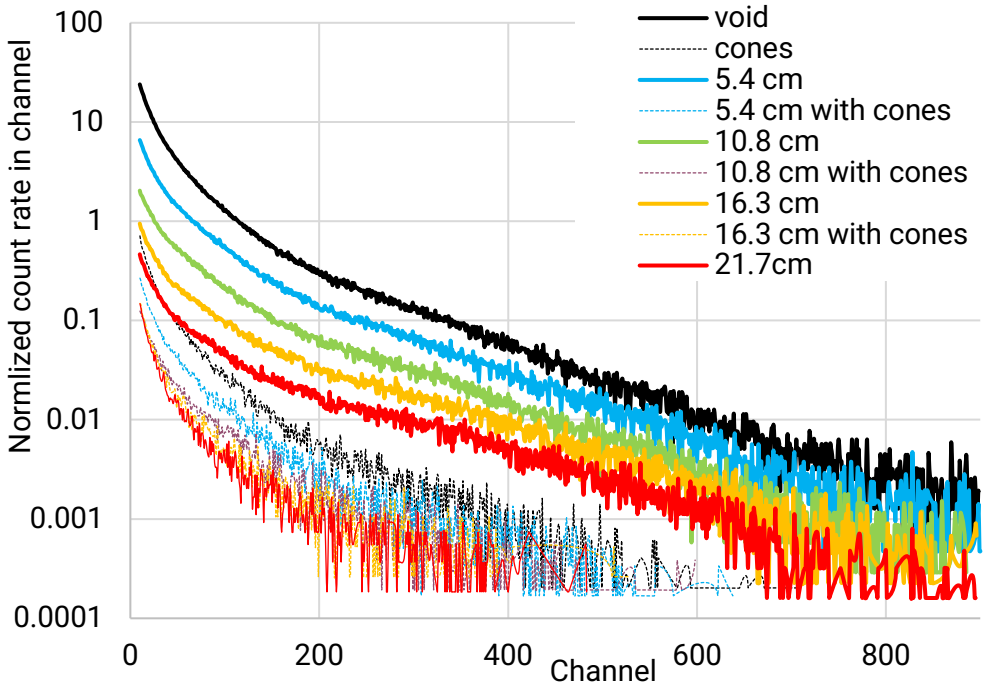


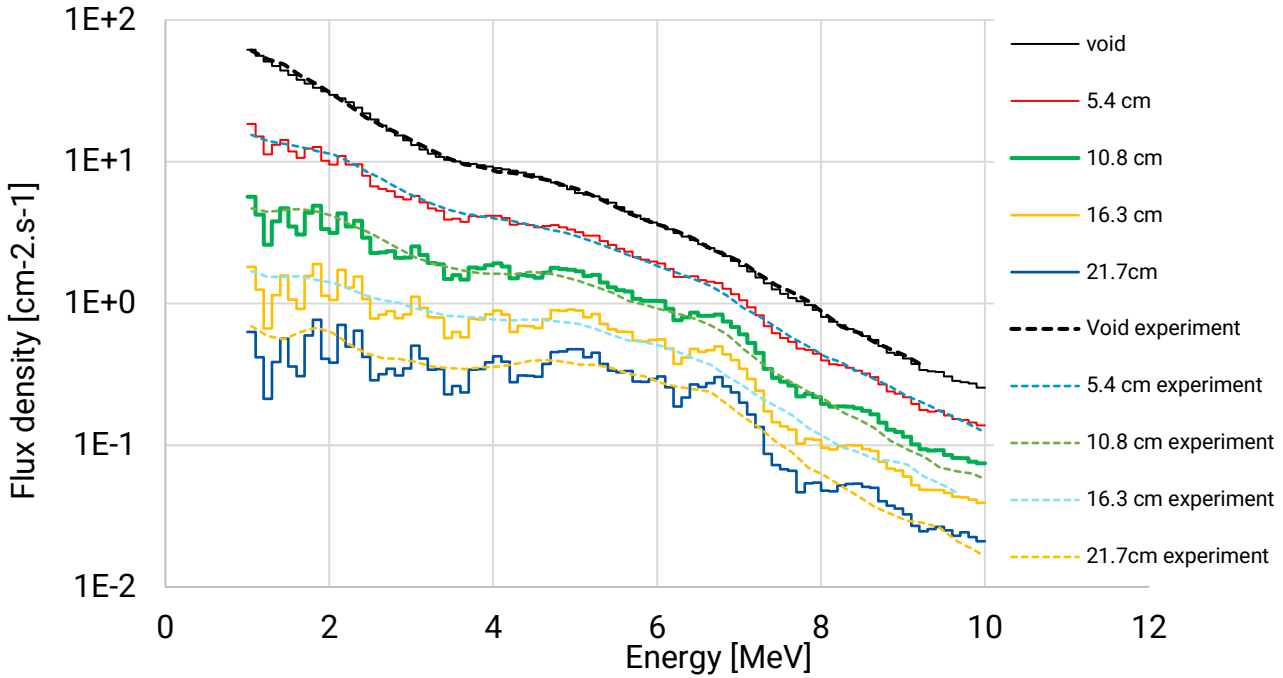


discrimination in 41 channel ~ 1.1 MeV

AKR-2 spectra

- Large beam diameter ~ D=12 cm in this experiment
- Due to geometry (holding table) + beam diameter … notable background ..
- In this large beam diameter also elastic/inelastic play role . . . (but not so high as in leakage experiments)





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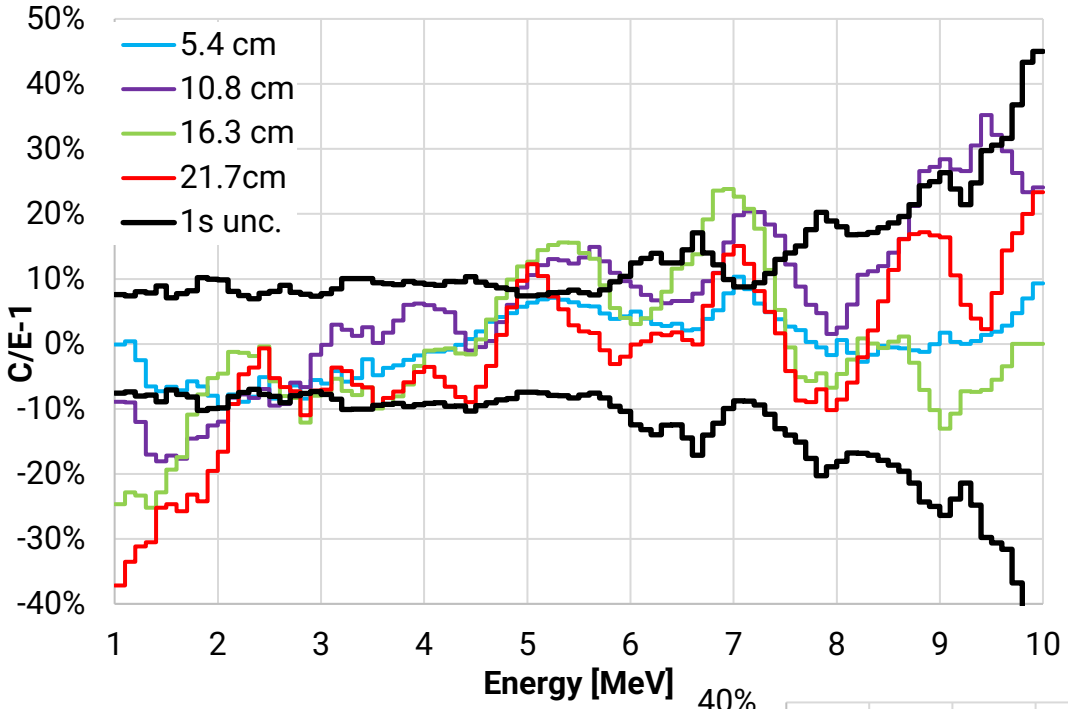
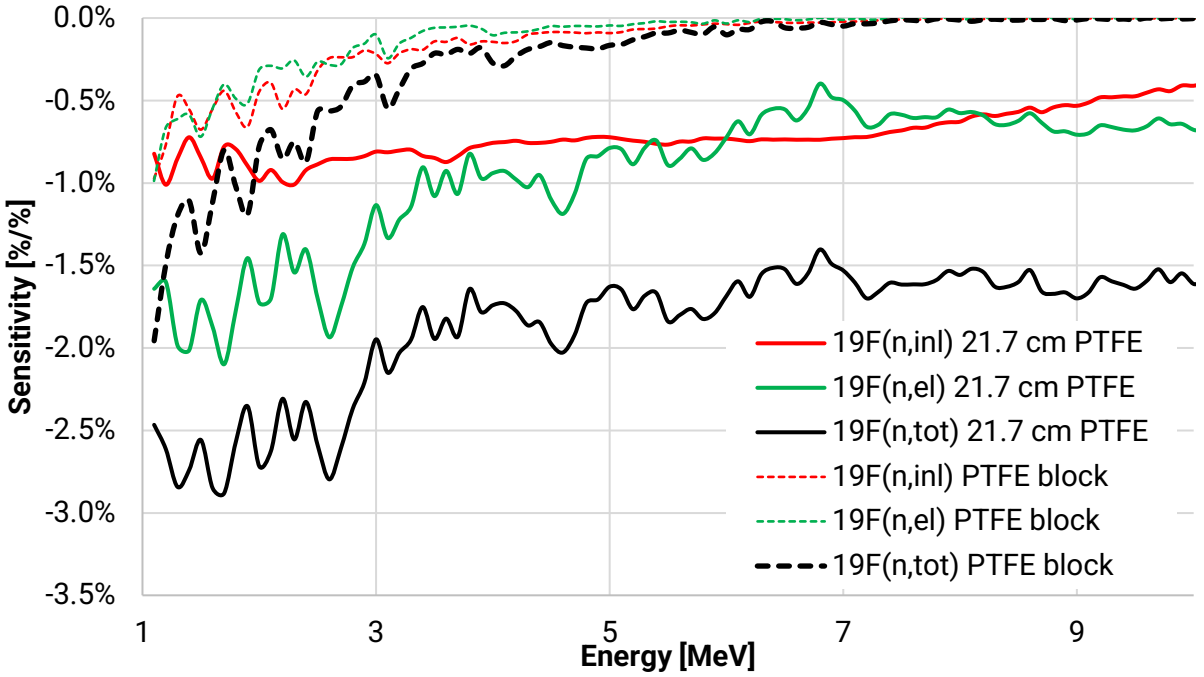
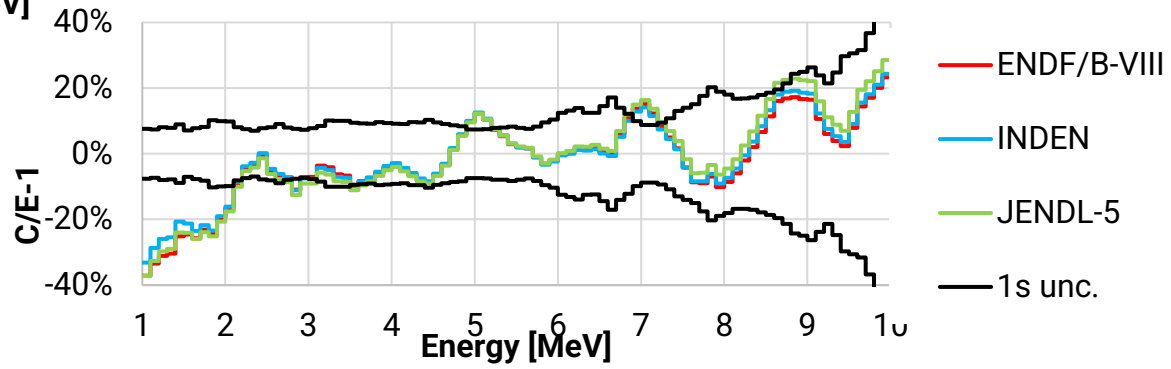
C/E of measured spectra

- Above 2 MeV good agreement below discrepancies similarly as in californium experiment
- Most likely issue in ^{19}F total cross section below 2 MeV







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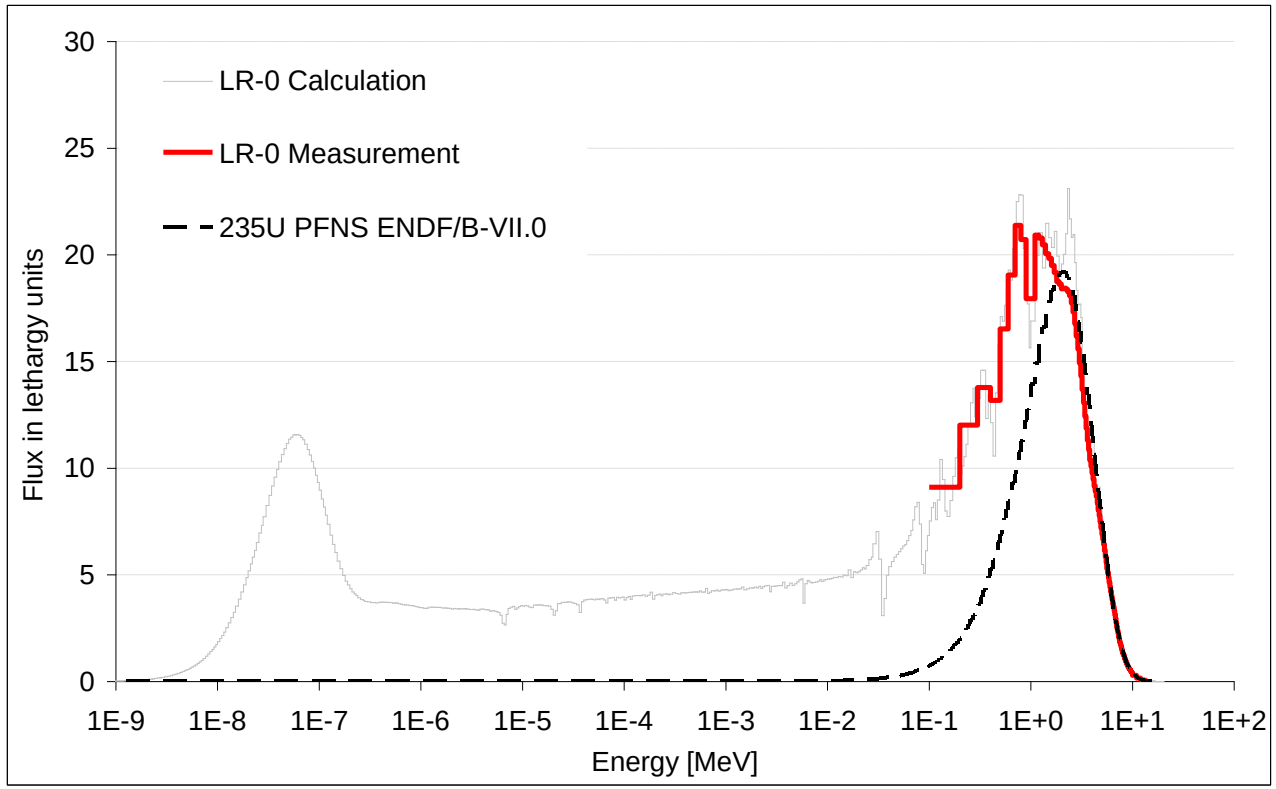
New experiments in Reference Neutron Benchmark Field

- Permanent reproducible neutron field
- Well defined spatial distribution of the neutron field
- Well defined neutron energy spectrum
- Characterized gamma spectrum

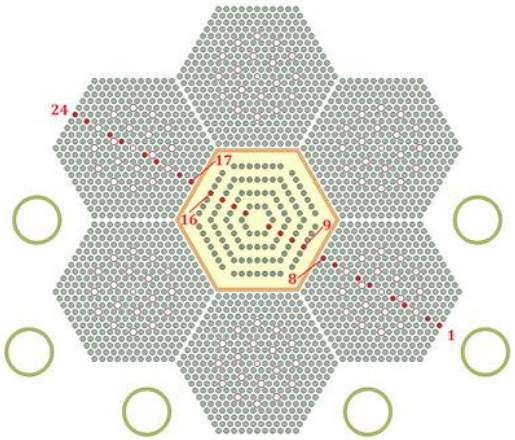


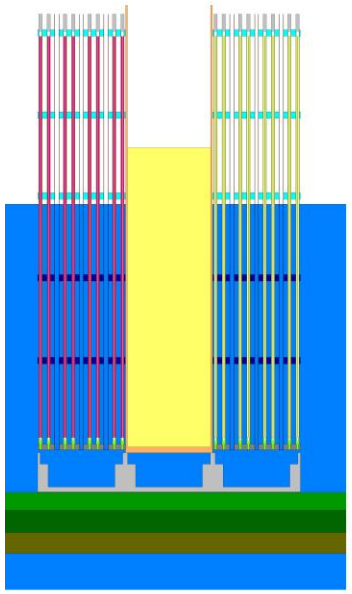
IRDFF-II: A New Neutron Metrology Library

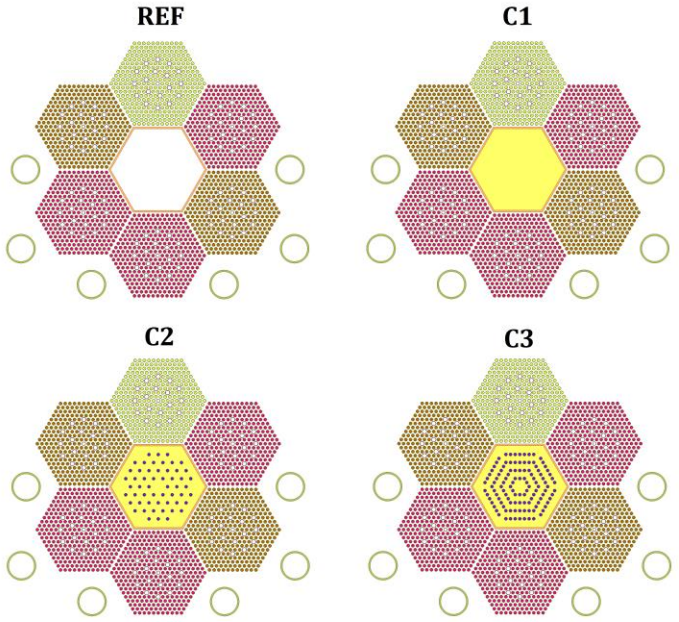
Trkov et al., Nuclear Data Sheets 163 (2020), pp. 1–108

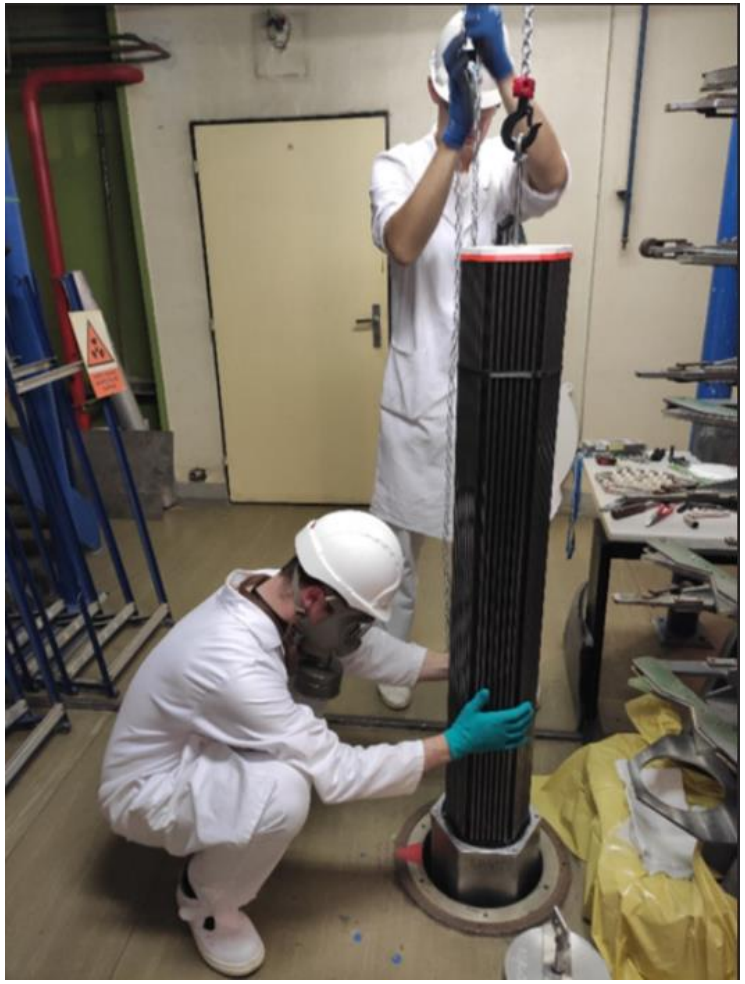
Validation of chlorine cross sections

- **Some molten salt reactor (MSR) concepts propose using molten chlorides**
- **New experiments realized in LR-0 special core in Rez**
  - C_2Cl_4 (C is very well known => discrepancies are on account of Cl)
  - Keff
  - Power density profile









REF – reference LR-0 core without C_2Cl_4,
C1 – case only with C_2Cl_4,
C2 – case with C_2Cl_4 and 54 fuel pins,
C3 – case with C_2Cl_4 and 114 fuel pins

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Criticallity results C2Cl4

- **Critical parameter determined for selected arrangements depending on Cl content**
  - Driven by water
  - Systematic uncertainties ~200pcm
- **Large discrepancies in arrangements with chlorine**
  - Significant underprediction

- **Difference from reference case, core with ENDF/B-VIII.0**

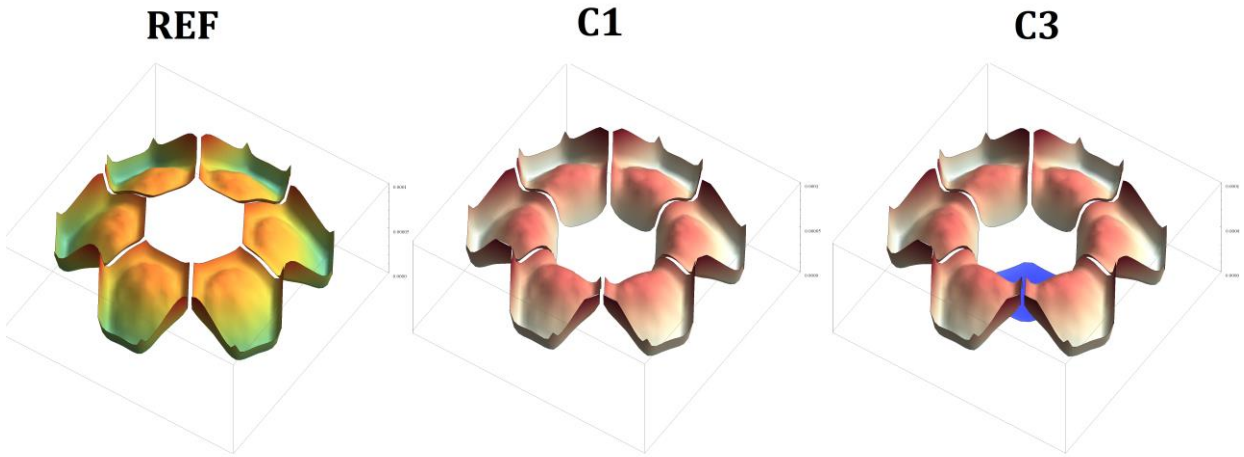
Library	Difference from reference case		
	C1	C2	C3
ENDF/B-VIII.0	-162	-168	-174
ENDF/B-VII.1	-166	-163	-175
JEFF-3.3.	-162	-170	-184
JENDL-5.	**-38**	**-63**	**-90**

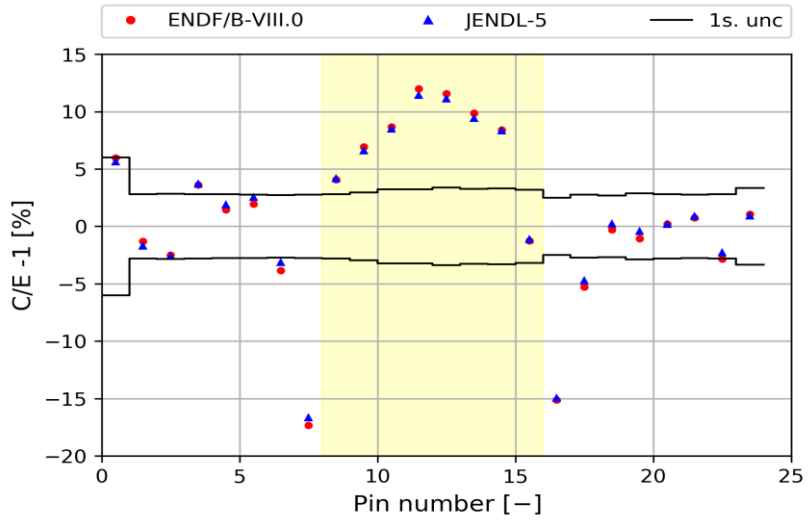
Modification	H_{cr} [mm]	Unc.	dρ/dH [pcm/cm]	Unc.
Reference core	538.75	0.81	285.67	11.64
Case 1	727.24	0.11	125.96	0.82
Case 2	709.84	0.08	130.03	0.68
Case 3	692.95	0.09	146.15	2.40

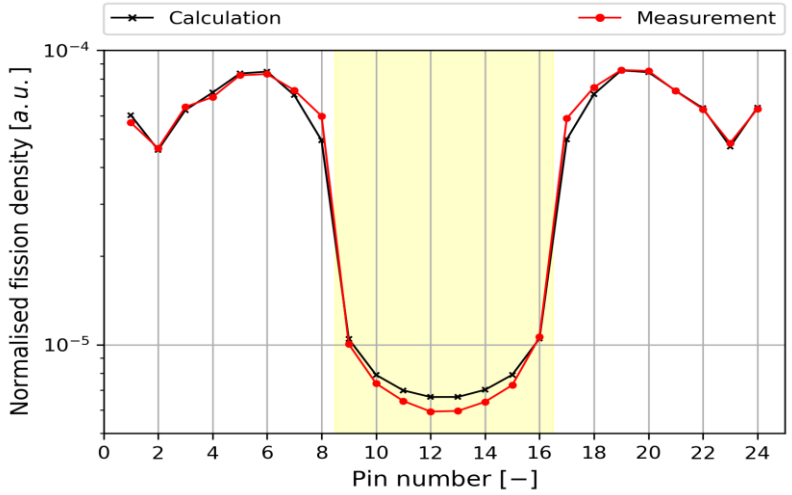
Library	k_{eff} [-] ± 0.00004			
	REF case	C1	C2	C3
ENDF/B-VII.1	0.99990	0.99825	0.99826	0.99816
ENDF/B-VIII.0	0.99953	0.99791	0.99785	0.99779
JEFF-3.3.	1.00174	0.99957	0.99959	0.99961
JENDL-5.	1.00152	1.00067	1.00042	1.00023

Power density profile

- **Simulations are predicting significant effect on power profile**
- **The decrease is really observed**
- **…**
  - Systematic uncertainties ~200 pcm
- **Large discrepancies in arrangements with chlorine**
  - Significant underprediction

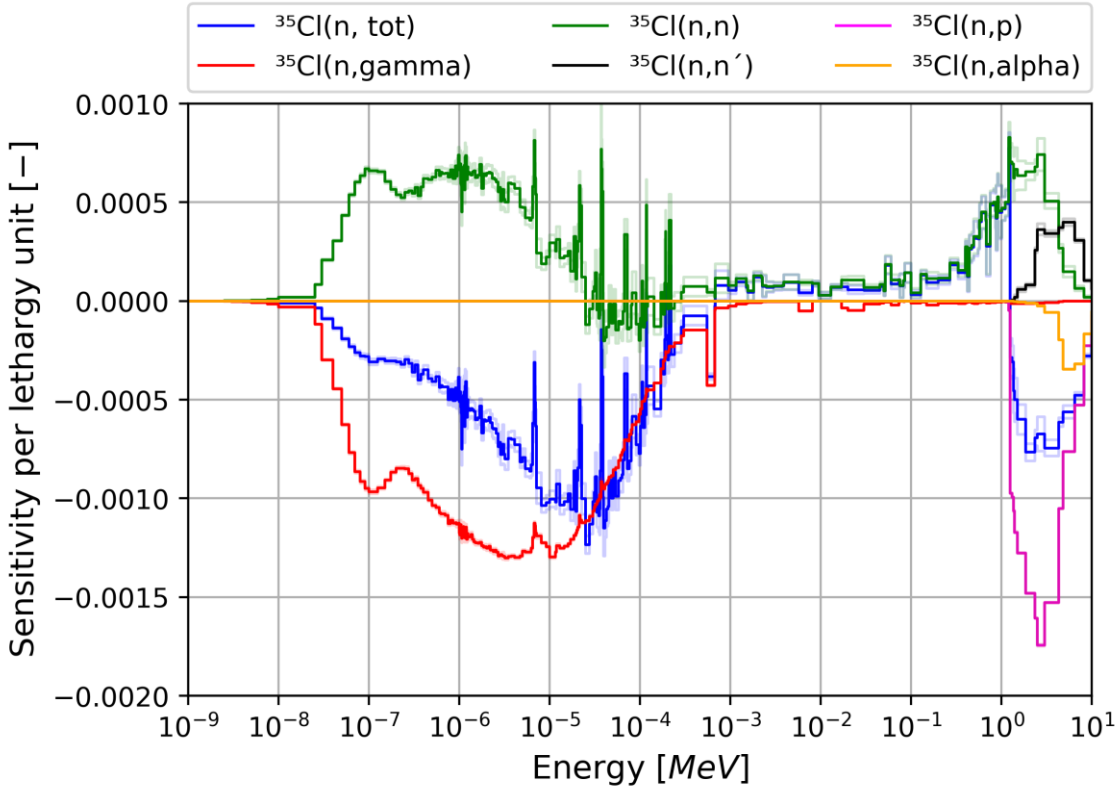






Sensitivity analysis

- This experiment is highly sensitive for $^{35}Cl(n,\gamma)$ in low energy, $^{35}Cl(n,p)$ in high energy

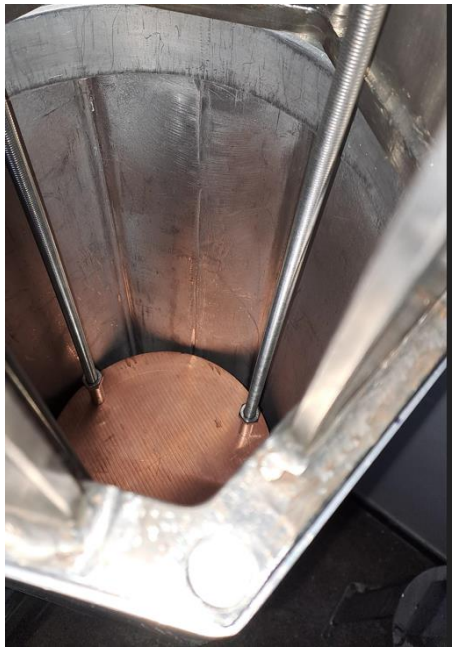


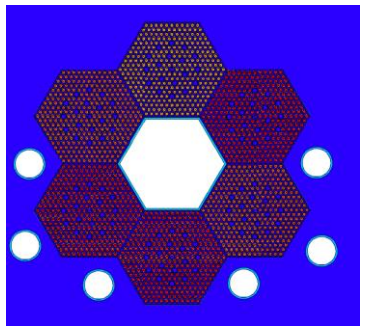
Nuclide	Reaction	Sensitivity [pcm]	Std. Dev. [%]
^{35}Cl	(n,γ)	-915	0.12
^{35}Cl	(n,total)	-560	0.91
^{35}Cl	(n,n)	538	0.92
^{nat}C	(n,total)	240	1.77
^{nat}C	(n,n)	239	1.77
^{35}Cl	(n,p)	-202	0.07
^{37}Cl	(n,total)	75	2.88
^{37}Cl	(n,n)	67	3.18
^{35}Cl	(n,n')	48	1.41
^{35}Cl	(n,α)	-27	0.15
^{37}Cl	(n,n')	13	2.42

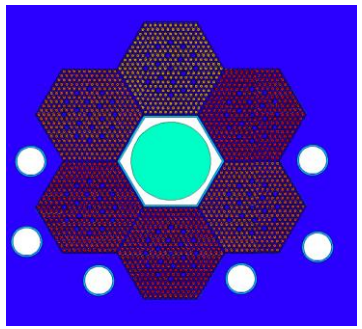
Construction materials in reactivity experiments

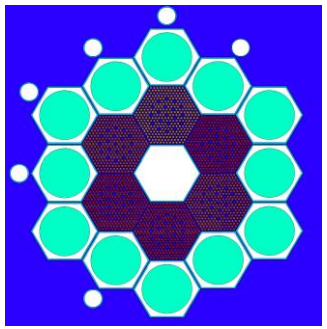
- The effect of inserted block is studied
- In past was tested steel (iron + 1.5% Mn)
- New experiment with copper block

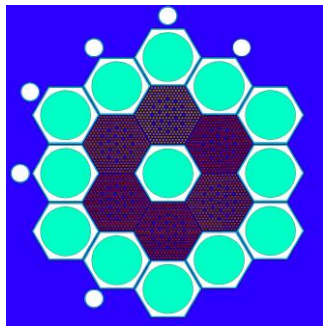
  - Reference core . . . . 541.51 +/- 1.32 mm
  - Copper in center . . . . 611.42 +/- 0.12 mm
  - Iron in center . . . . . 579.01 +/- 0.79 mm
  - Iron around . . . . . 548.09 +/- 0.69 mm
  - Iron around + center . . . . . 598.23 +/- 0.92 mm











	ENDF/B-VIII.0	ENDF/B-VII.1	JEFF-3.3
Reference case	0.99960	0.99989	1.00176
Iron in center	0.99808	0.99843	1.00001
Iron around	0.99651	0.99692	0.99946
Iron around + center	0.99520	0.99538	0.99785

63Cu(n,g)

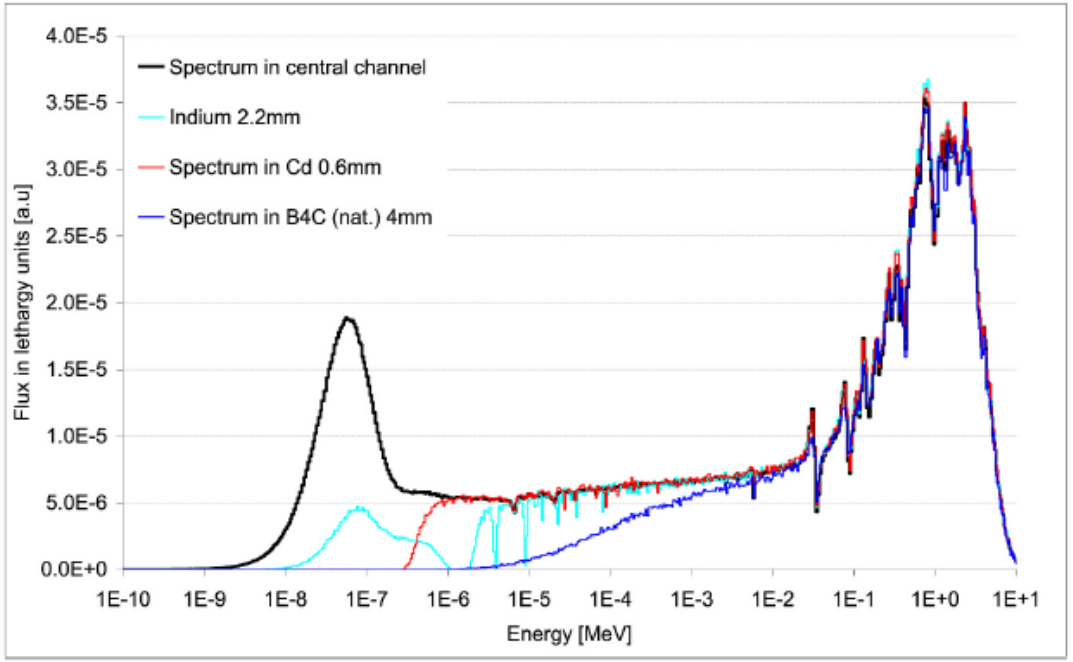
- **Planned measurements with B_4C (^{10}B) filters (JSI collaboration), spring 2025**
- **In 2023 preliminary experiment with natural boron capsule (nearly equivalent to JSI one) ~ 2.364 g/cm^3 instead of JSI 2.36 g/cm^3**

	Poured	Sintered
Density [g/cm^3]	1.197	2.36
Thickness [mm]	7.9	4
55Mn(n,g) [s^{-1}]	3.67E-29	3.75E-29

Table 5
Summary of C/E−1 for $^{63}Cu(n,g)^{64}Cu$ reaction in different neutron fields.

$^{63}Cu(n,g)^{64}Cu$	ENDF/B-VIII.0	JEFF-3.3	JENDL-5	IRDFF-II	Uncertainty
Void	20.2%	23.4%	20.9%	20.2%	4.5%
Cd filter	17.7%	28.1%	19.4%	17.8%	3.8%
B_4C filter	13.4%	26.4%	24.0%	13.9%	3.6%
$^{252}Cf(s.f)$	−2.4%	−2.0%	−1.7%	−3.6%	3.4%

Schulc et al., Appl. Rad. and Isot. 215, (2025), 111586



Kostal et al., Appl. Rad. and Isot. 169 (2021) 109566

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New benchmarking of reference core

During characterization of heterogenous critical assembly, in ch-1 of ICSBEP benchmark, the evaluators define material, geometrical, … etc parameters. In case of fuel cladding use of producer certificate is welcomed. But is it reliable ??

Zr case

- **Producer certificate**
  - Zr 98.97 %
  - Nb 1 %
  - Hf < 0.03 %

XRF analysis

El	m/m%	StdErr
--	--------	-------
Zr	96.84	0.47
Nb	1.63	0.08
Mo	0.80	0.17
Si	0.62	0.26
Cl	0.11	0.026

Mass spectrometry

	mean	unc
Hf	0.04	0.0032
Nb	1.10	0.088
Zr	97.70	7.816

NAA analysis

Hf	449 ppm	50ppm
Ta	2 ppm	0.2ppm
K	18 ppm	1ppm
Nb	1.25%	0.18%

Conclusions

Broomstick experiment realized at the VR-1 and it seems excellent tool for total cross section testing

There is a strong potential of AKR-2 for broomstick – discussion about use of C_2Cl_4 in future experiments is planned

The Cf benchmark experiment for Teflon and Aluminium will be submitted to ICSBEP

The new experiments realized in LR-0 reference field. The new benchmarking is ongoing …

Thank you for attention

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Acknowledgements

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CICRR
Czech International Centre of Research Reactors

XRF detail