Tailored additively manufactured shielding structures for neutron beamlines

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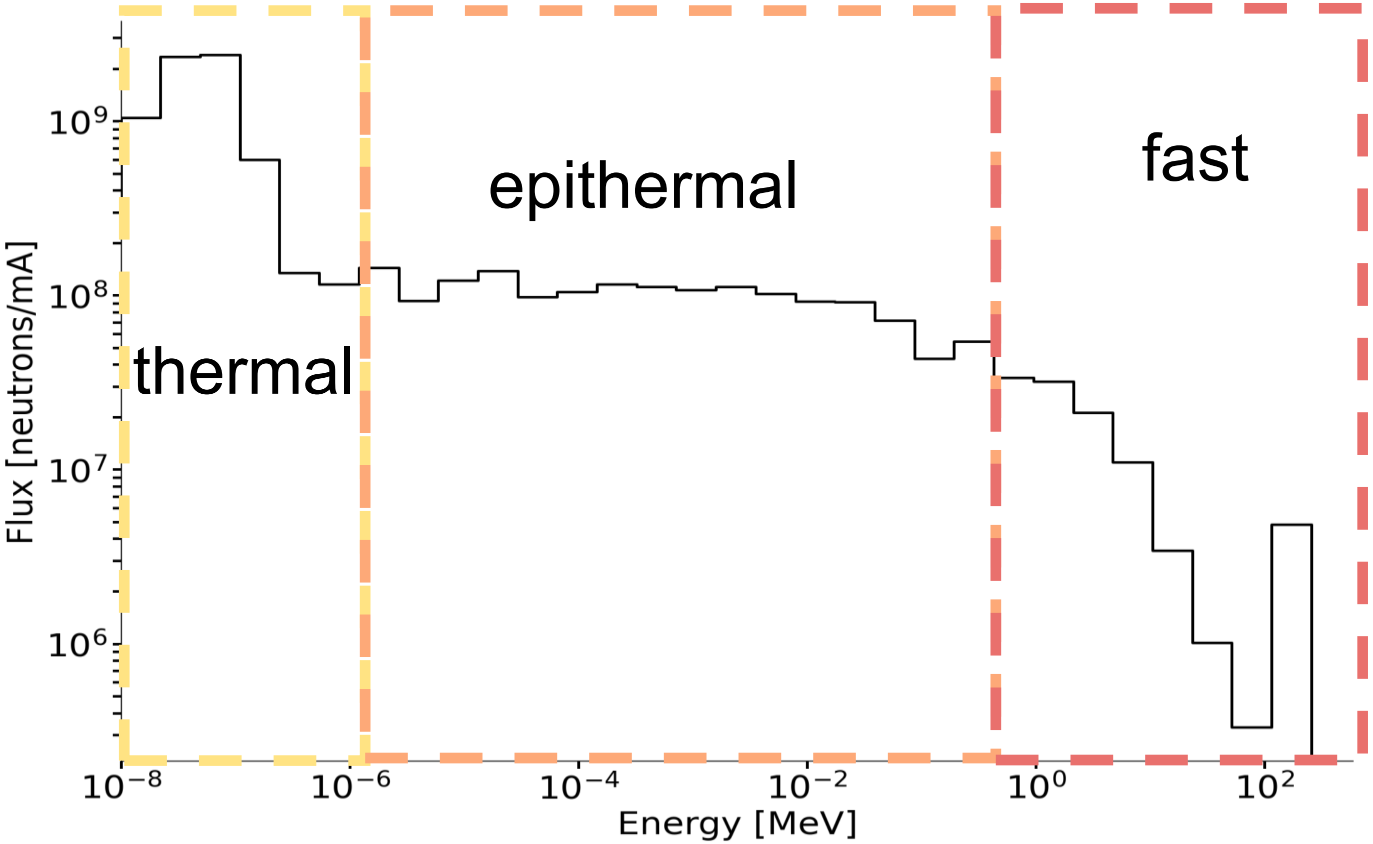
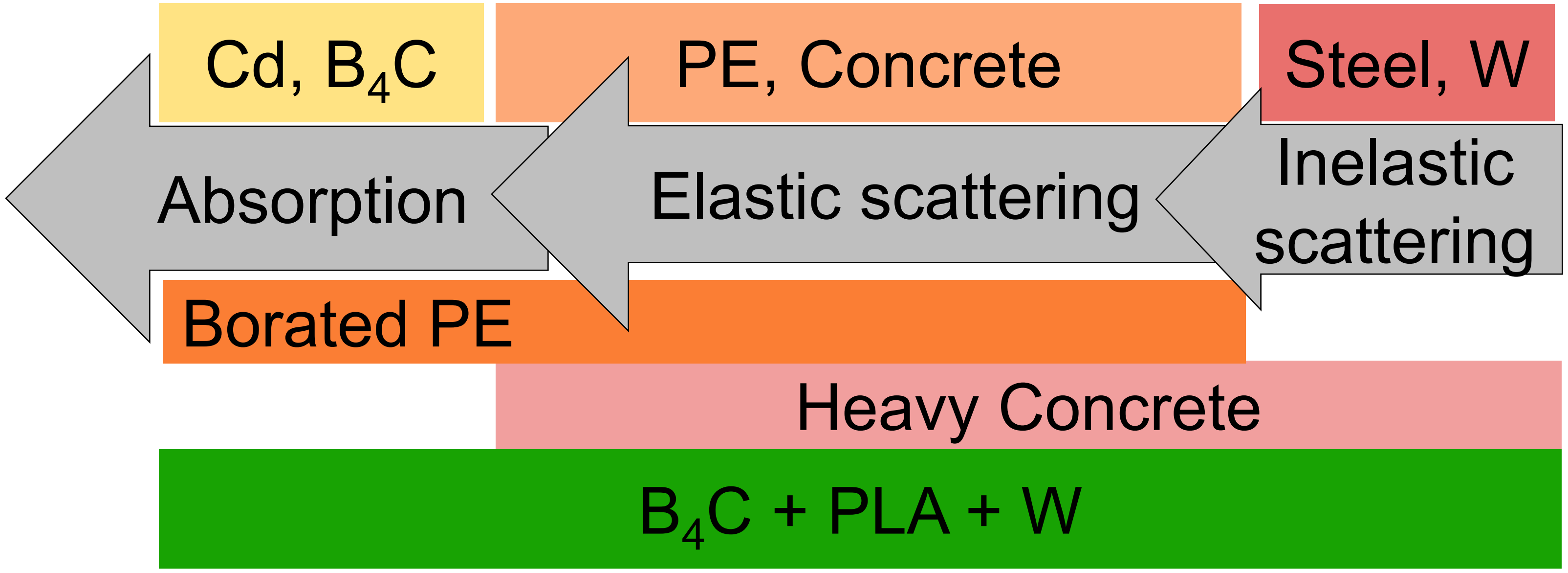
Motivation

- Spallation neutron sources produce neutrons ranging from thermal energies up to several hundred MeV
- Higher energy neutrons cause background and limit signal-to-noise
- No single material can attenuate the full range of neutron energies

- **Goal:**
  - **develop absorber-loaded filaments**
  - **print beamline-specific shielding structures**





Cd, B_4C

PE, Concrete

Steel, W

Absorption

Elastic scattering

Inelastic scattering

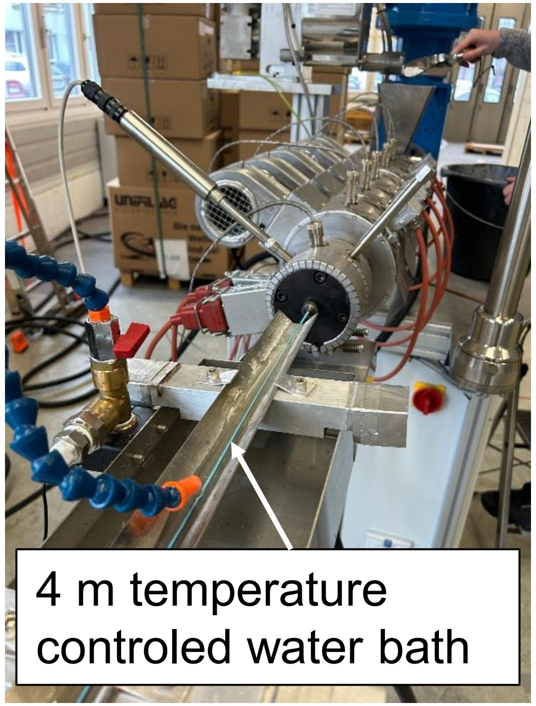
Borated PE

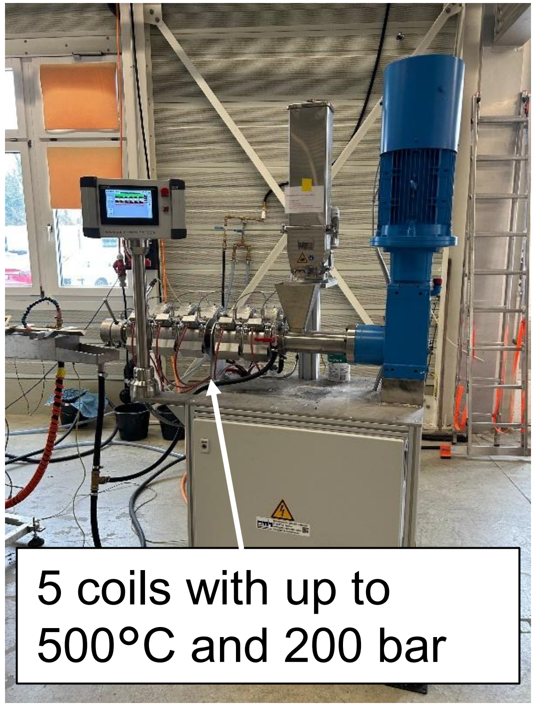
Heavy Concrete

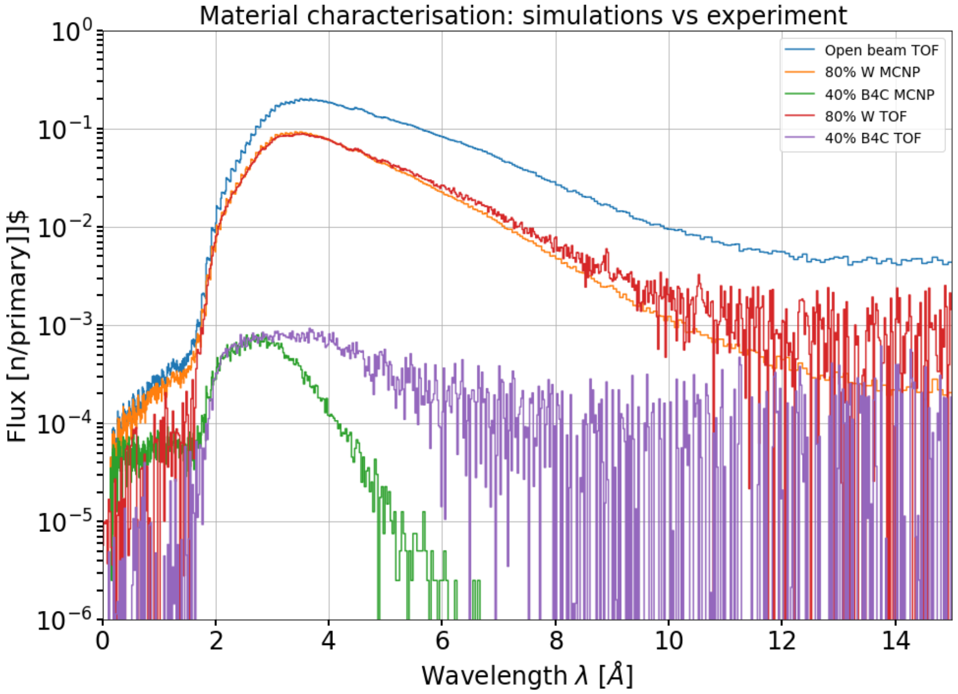
B_4C + PLA + W

Additive manufacturing

- Dry mixing of W and/or B_4C granulate with PLA powder
- Extrusion of feedstock for additive manufacturing in a custom extruder
- Fused Deposition Modeling printing
- Simulation of material in MCNP
- Experimental validation at cold beamlines BOA & SANS-LLB

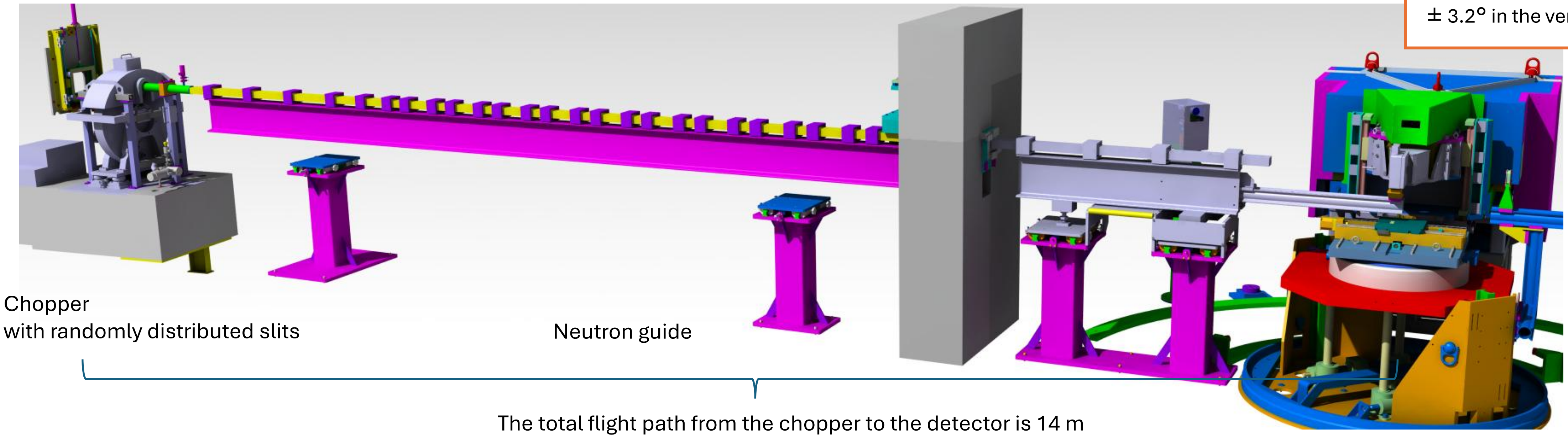

4 m temperature controled water bath


5 coils with up to 500°C and 200 bar



POLDI: Pulse OverLap Diffractometer

POLDI is a neutron Time-Of-Flight (TOF) diffractometer, designed to function as a strain scanner for the investigation of residual stress in engineering materials and components.



single ^{3}He detector
(400 wires)

± 15° in the horizontal plane
± 3.2° in the vertical plane

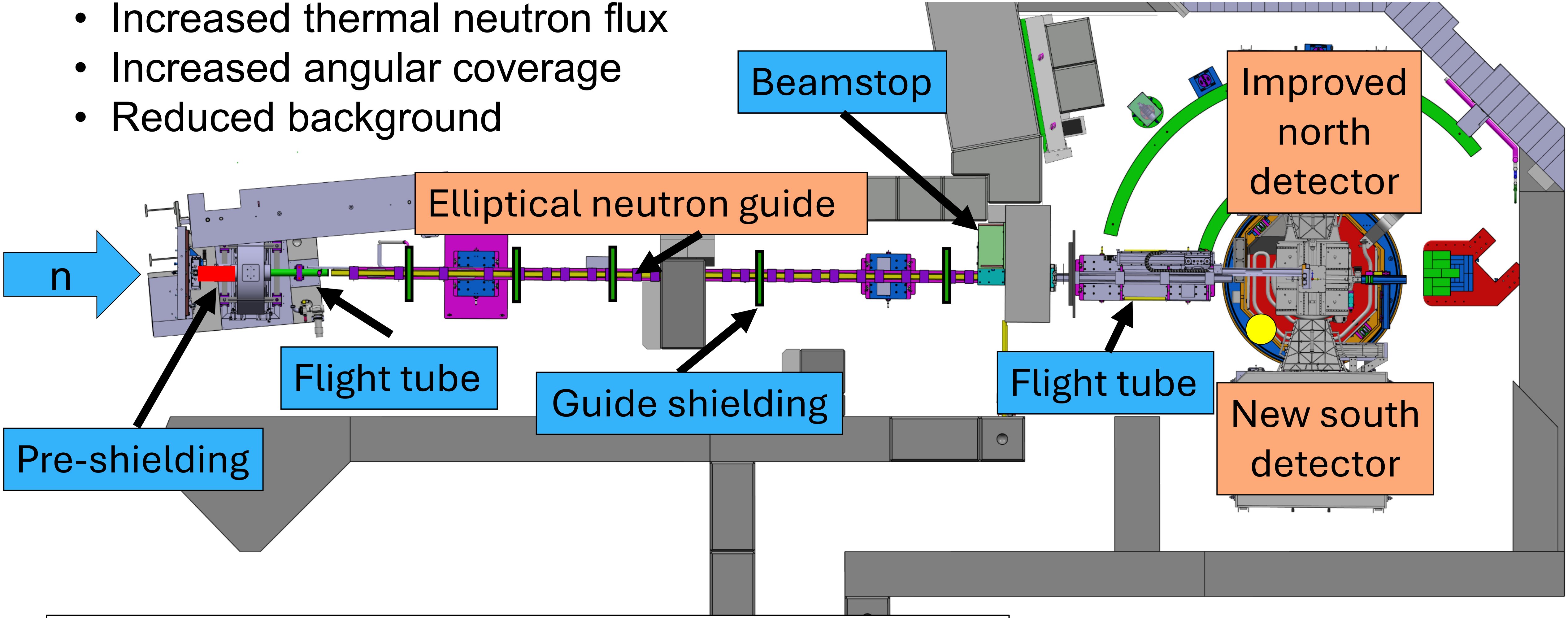
Chopper
with randomly distributed slits

Neutron guide

The total flight path from the chopper to the detector is 14 m
(chopper-to-sample: 12 m, sample-to-detector: 2 m)

Elements of POLDI Upgrade

- Increased thermal neutron flux
- Increased angular coverage
- Reduced background



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Beamstop

Elliptical neutron guide

Improved north detector

Flight tube

Guide shielding

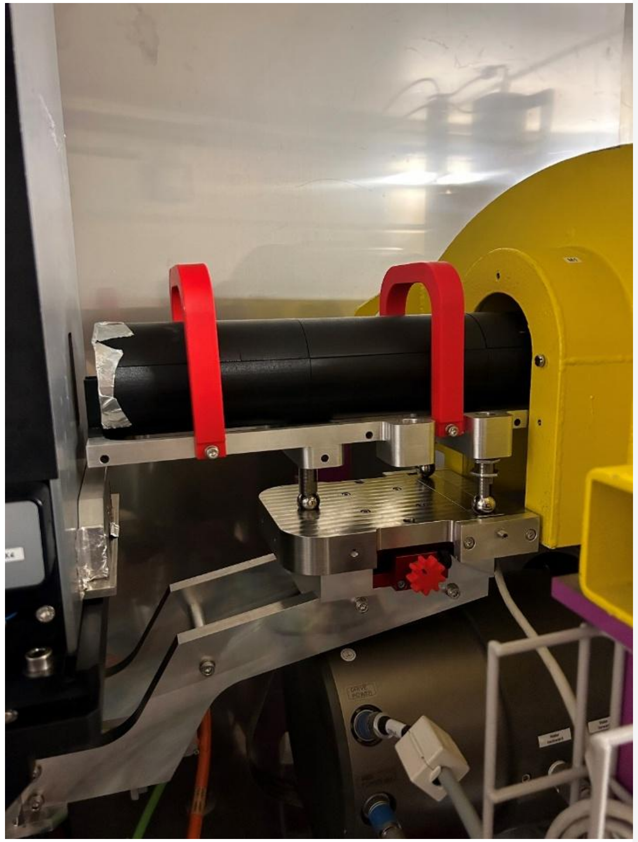
Flight tube

Pre-shielding

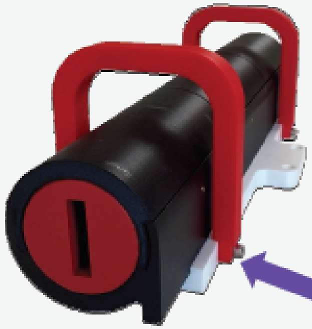
New south detector

Additive manufacturing used for most components!

Pre-shielding and flight tube



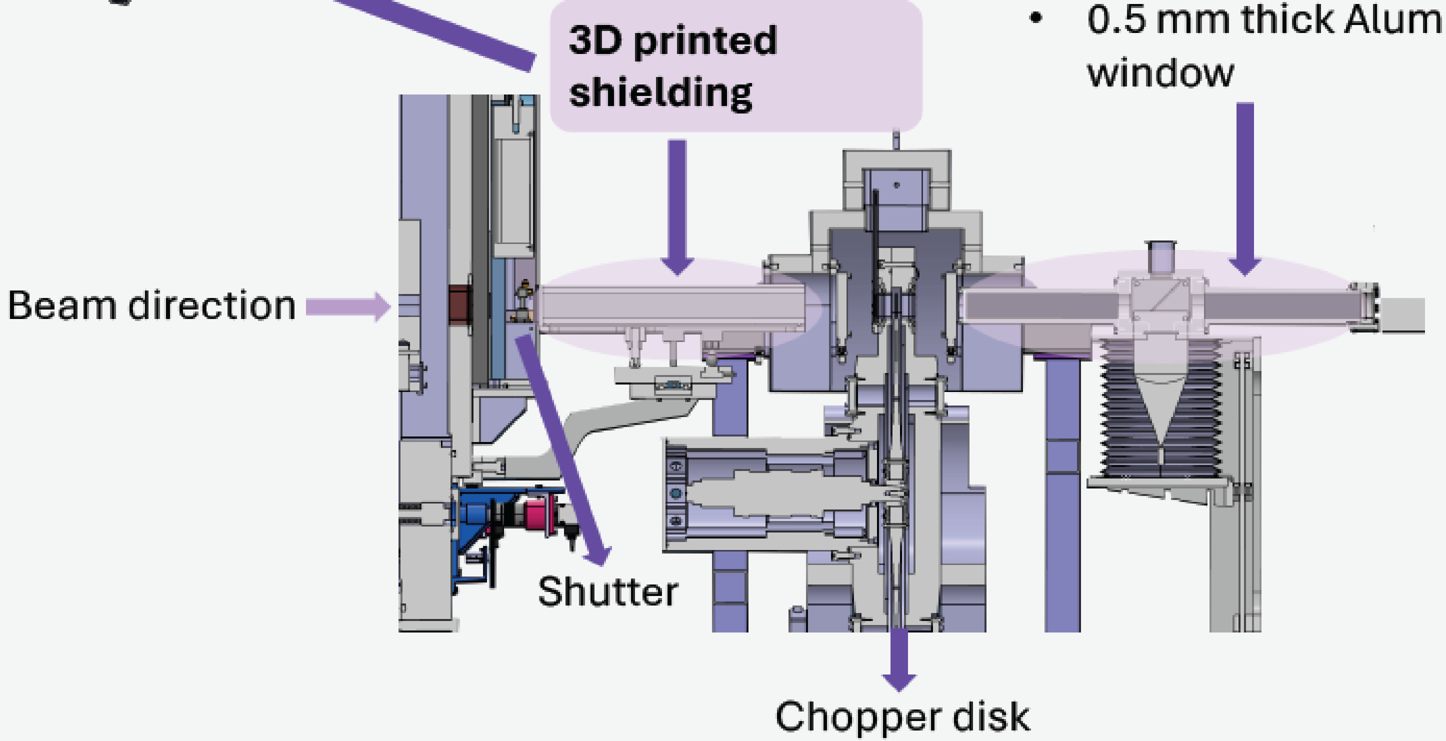
POLDI upgrade setup



- Outer: 70%W + 5%B_4C + 15%PLA
- Middle: 40%B_4C + 60%PLA
- Insert: 70%W + 5%B_4C + 15%PLA

3D printed vacumizable Flight Tube

- Prototype with BN succesfully tested at BOA
- Vacuum-capable down to 10^{-2} mbar
- 0.5 mm thick Aluminium neutron window



3D printed shielding

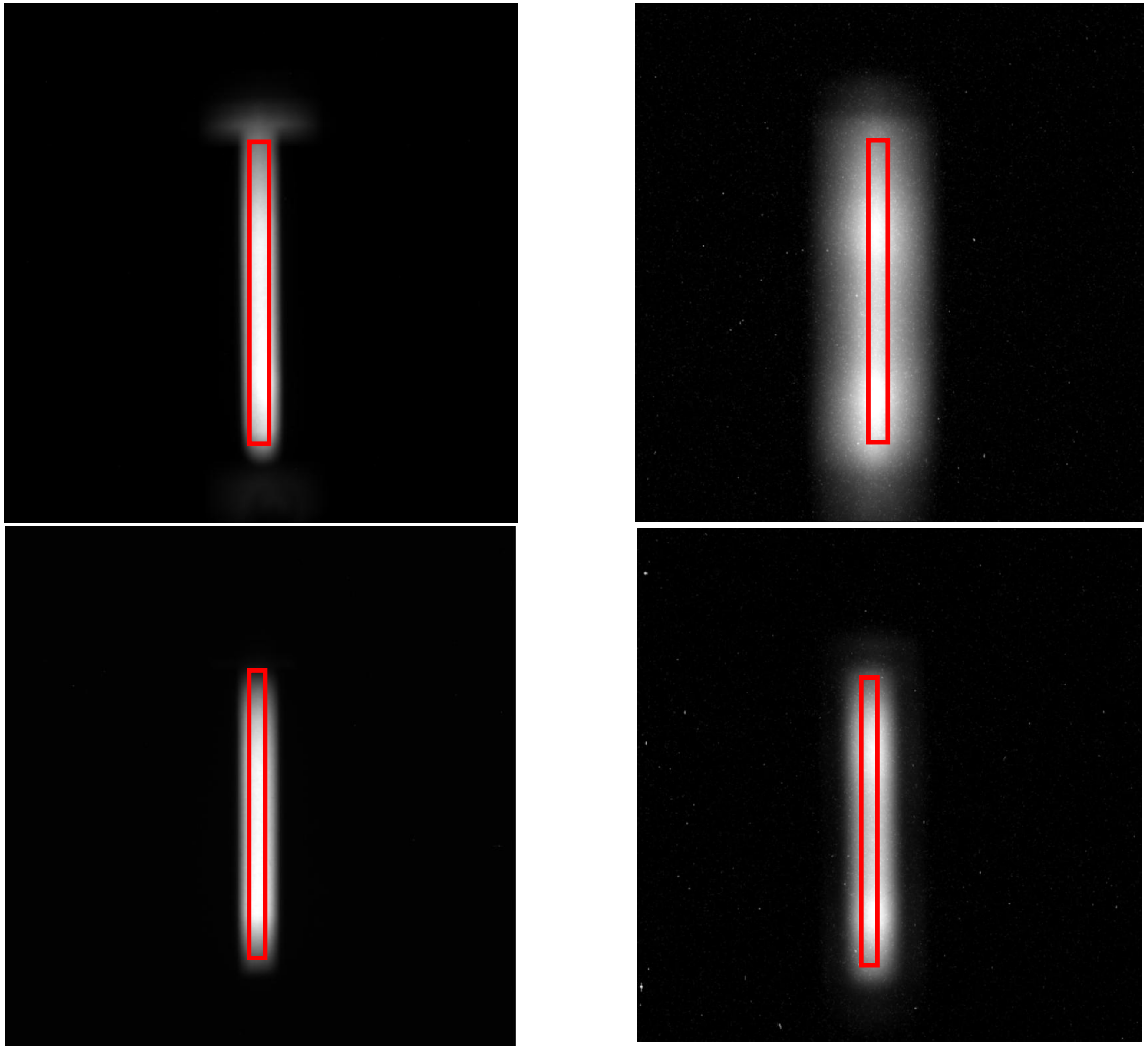
Neutron imaging behind chopper

Thermal neutrons

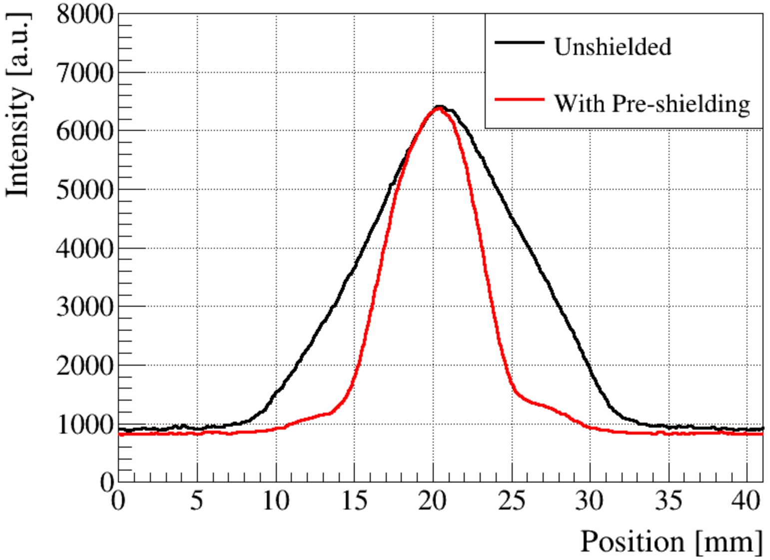
Fast neutrons

Unshielded

With pre-shielding



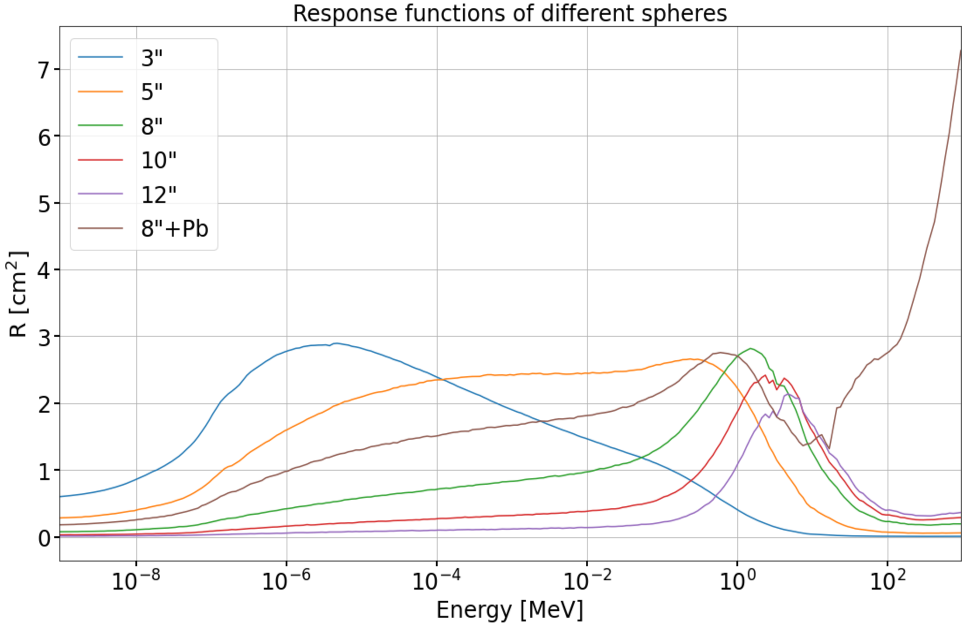
Fast neutrons



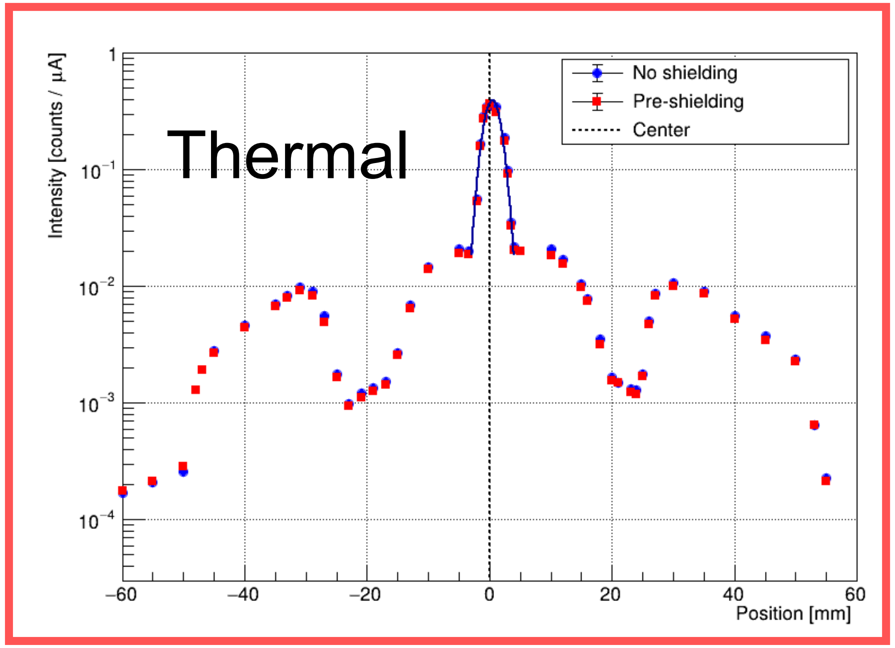
Bonner Sphere Spectrometer (BSS)

- He3 proportionality counter surrounded by moderating spheres
- Increased sphere size leads to increased peak response energy
  - 10 PE spheres detect neutrons up to 20 MeV
  - 4 spheres built in-house with additional Cu/Pb layer detect neutrons up to 2 GeV

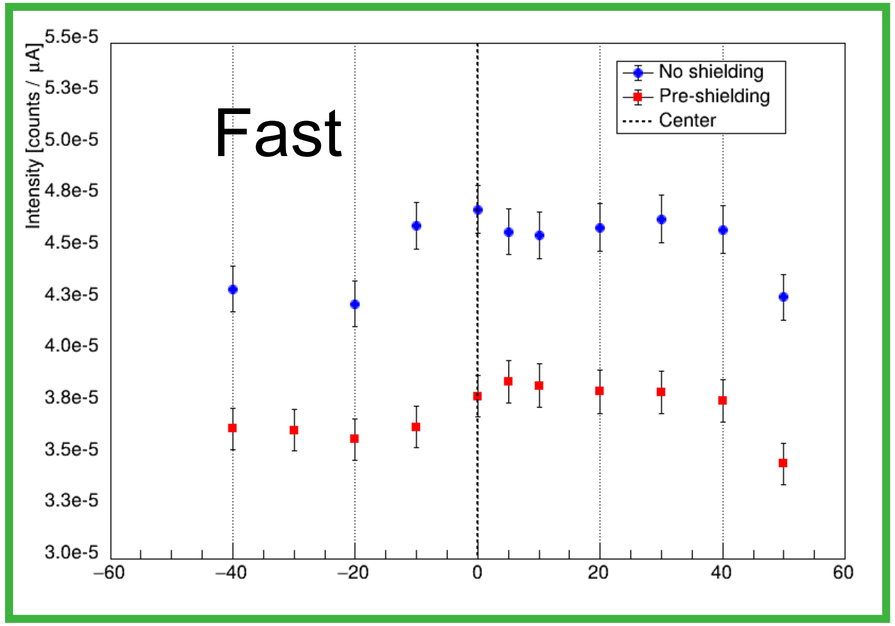
- Measurements with different spheres in homogeneous neutron fields can be used to unfold neutron spectra
- Response functions have been validated in quasi-homogeneous reference field



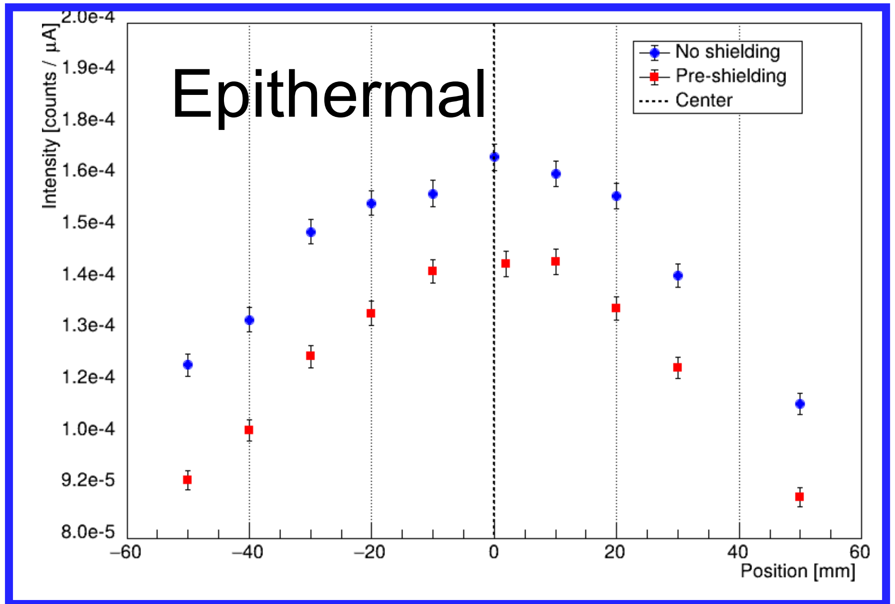
Neutron background at sample table



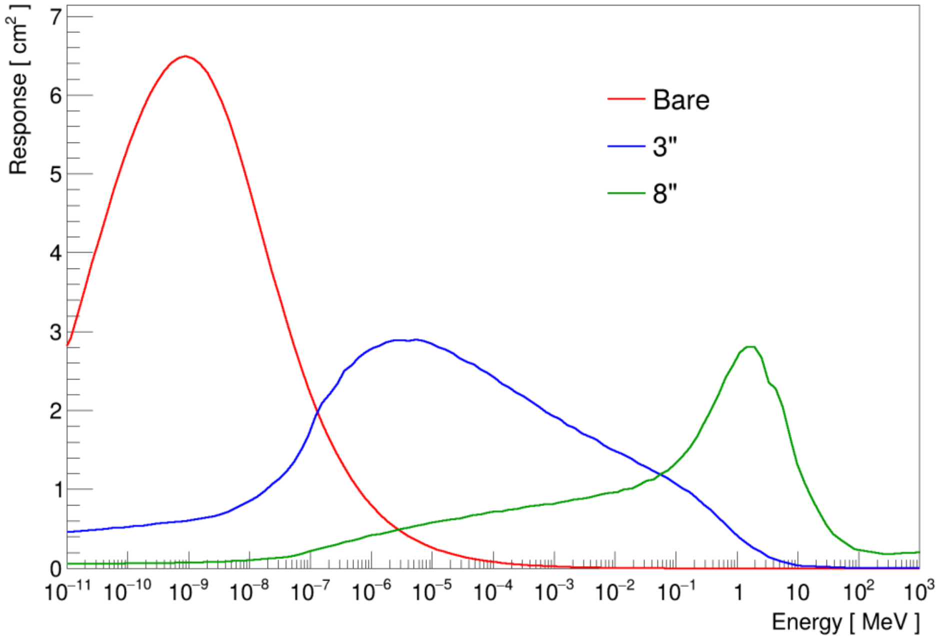
Unaffected



-20%

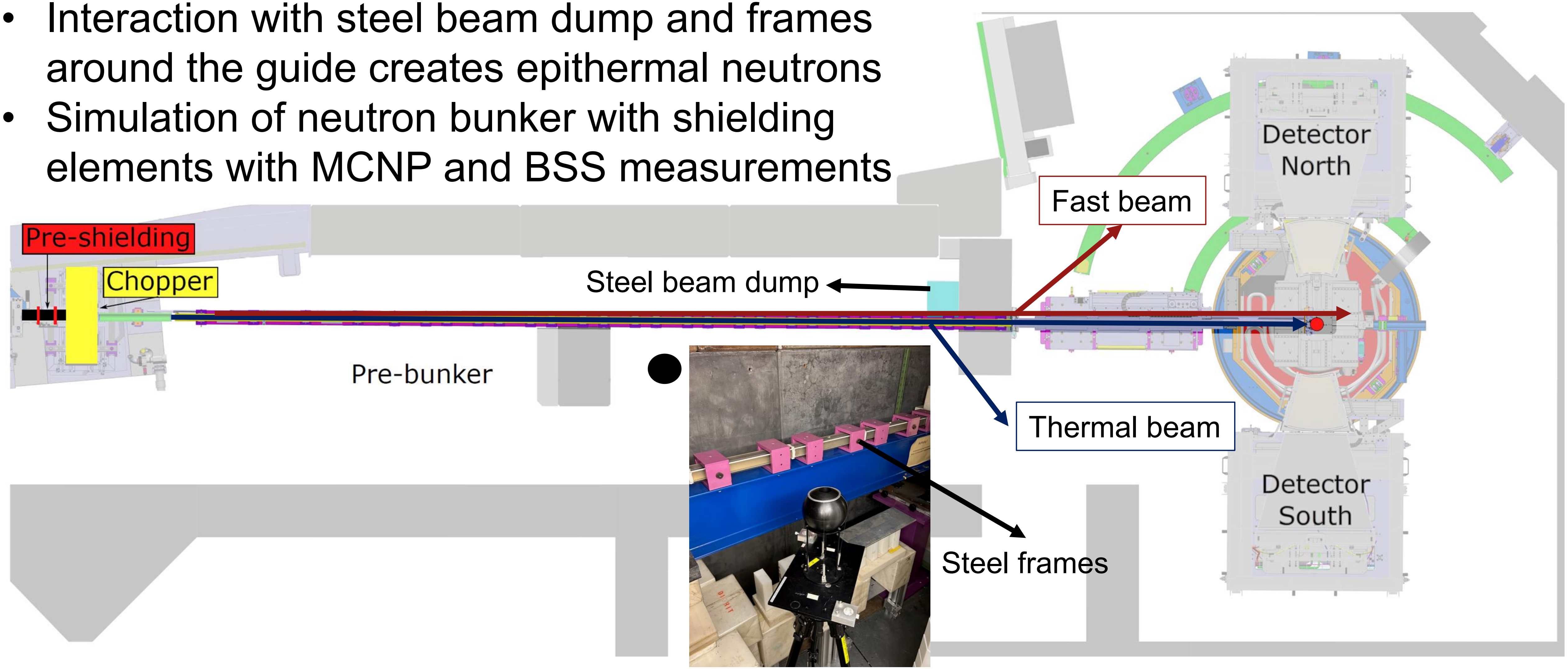


-20%



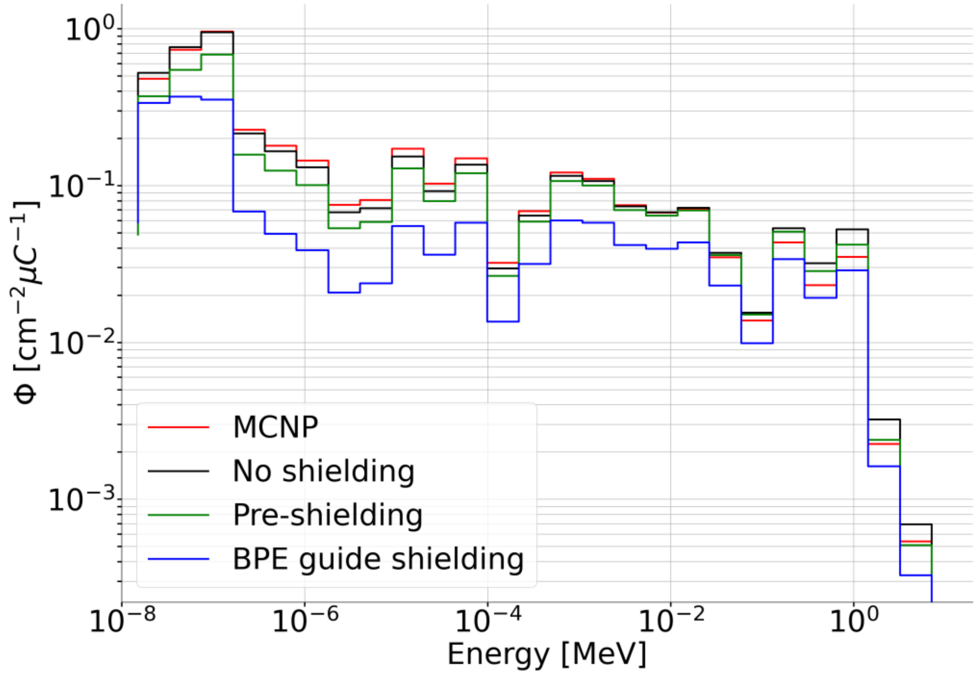
Neutron background at POLDI

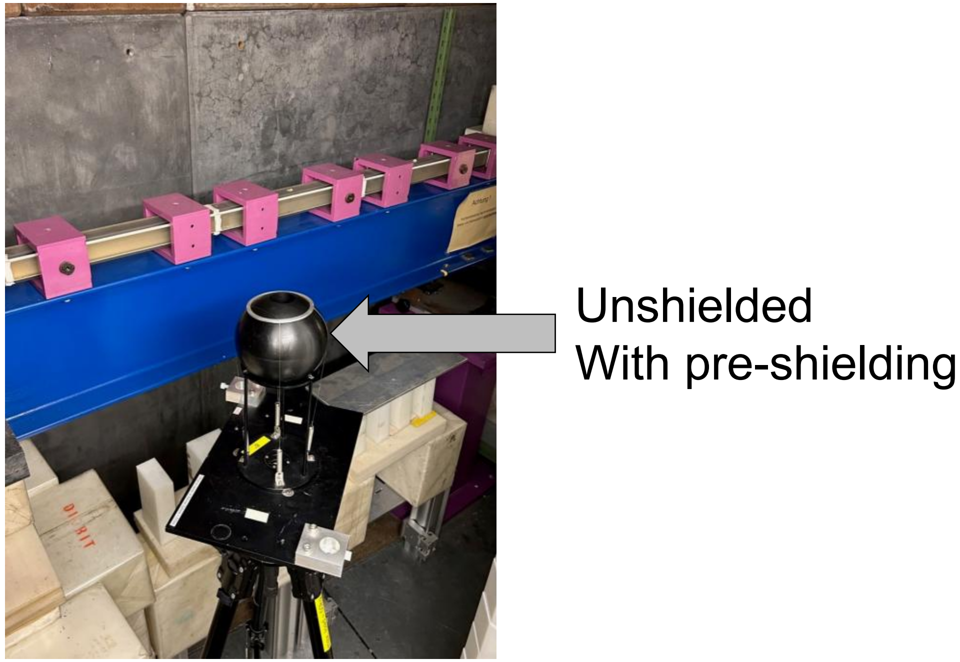
- Fast neutron beam going straight while neutron guide bends thermal neutrons
- Interaction with steel beam dump and frames around the guide creates epithermal neutrons
- Simulation of neutron bunker with shielding elements with MCNP and BSS measurements

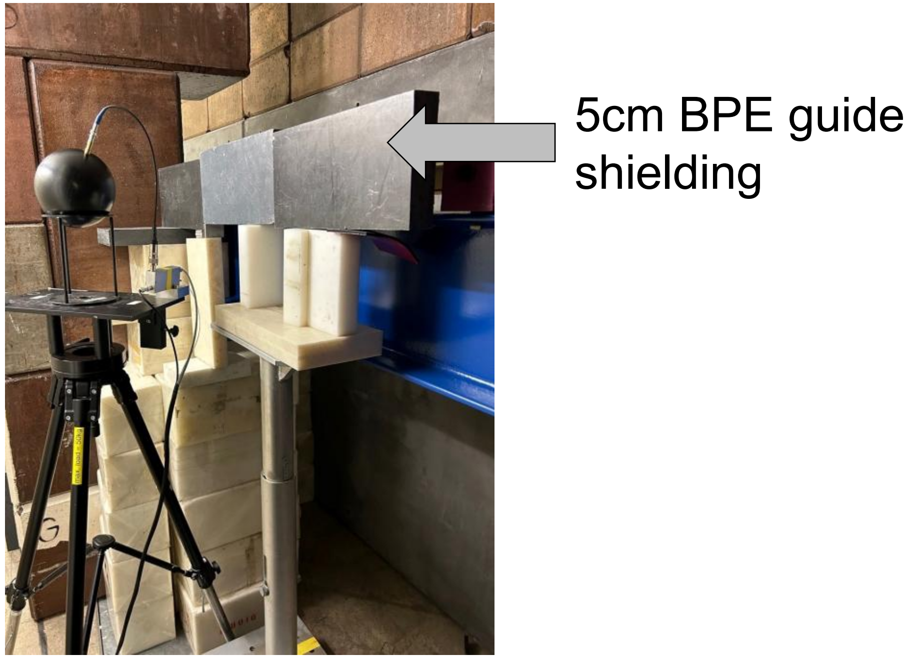


Neutron background at POLDI

- Neutron background next to the guide is mostly thermal and epithermal
- Pre-shielding reduces thermal (-25%) and epithermal (-10%)
- Shielding the guide instead with 5cm of BPE reduces thermal (-60%) and epithermal (-50%) more significantly







Conclusions and outlook

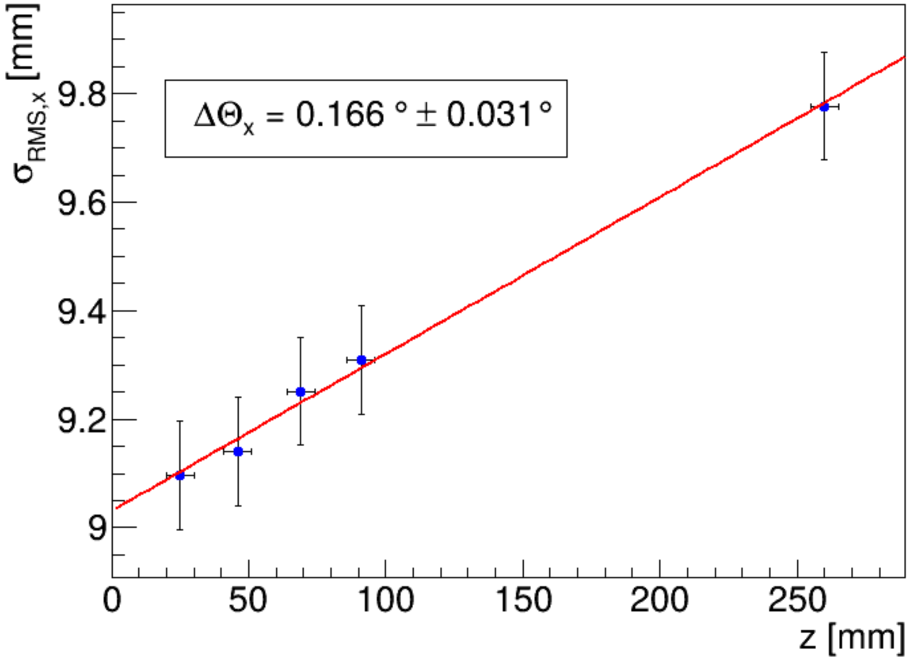
- Absorber loaded filaments were produced, characterized and printed for shielding applications
- Epithermal and fast neutron flux is reduced by around 20% at the sample position with pre-shielding while thermal neutron flux is unaffected
- BSS measurements were performed with and without pre-shielding to validate MCNP simulations

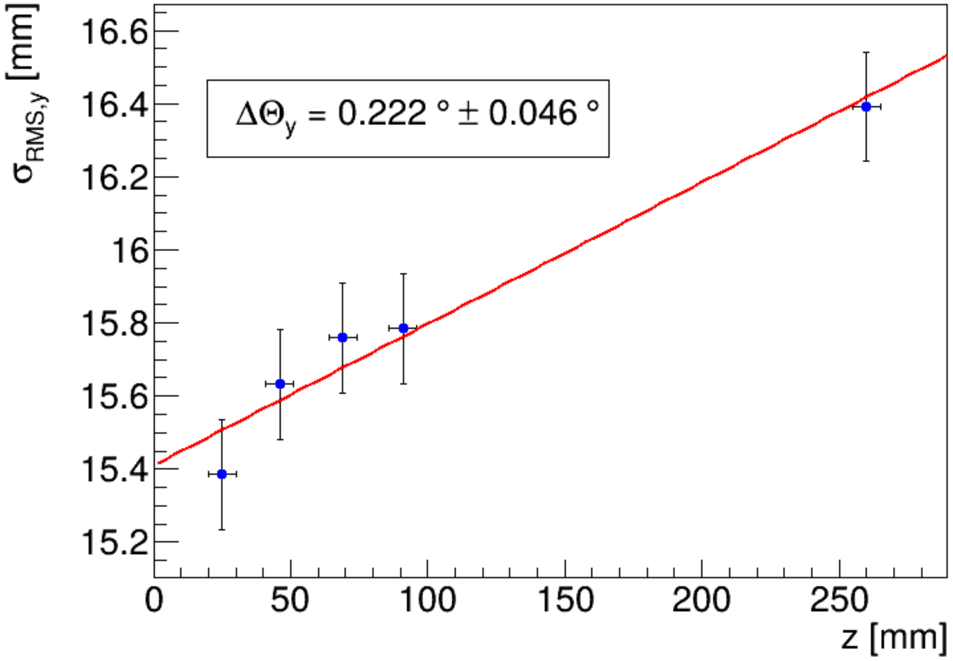
- Sources of background were identified and shielding solutions will be designed:
- Steel guide frames → Aluminum guide frames + guide shielding
- Steel beamstop → W+PLA+B_4C beamstop surrounded by B_4C as neutron trap

- **Application to other beamlines at SINQ and other spallation sources!**

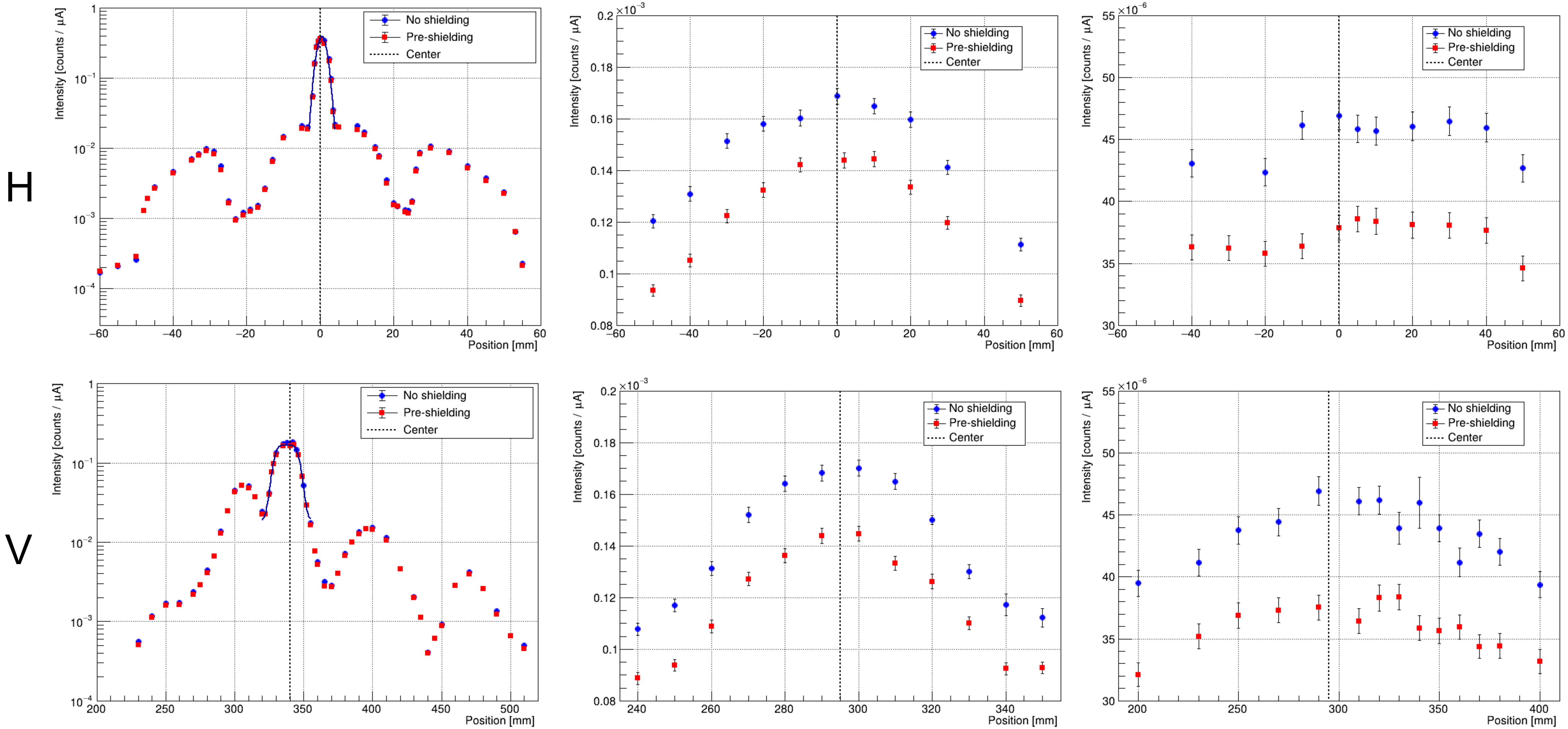
Thank you for your attention!

- Divergence measured with neutron scintillator
- Matches divergence calculated with geometry of channel upstream of the chopper
- Fast beam at beamstop roughly 65mm w x 130mm h





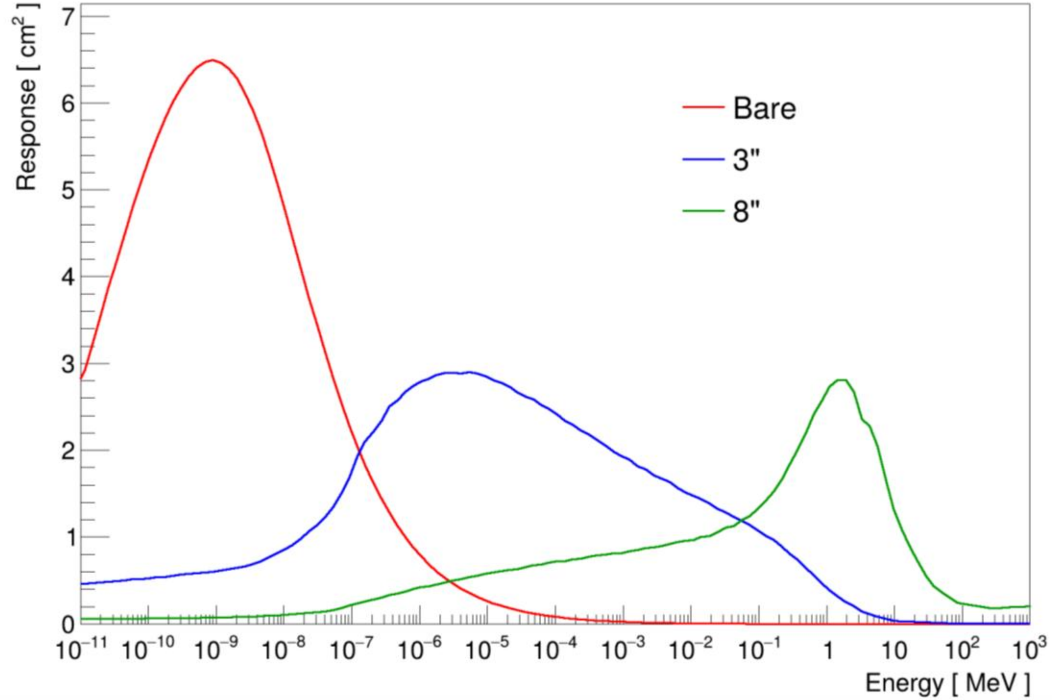
Thermal Epithermal Fast



Background at sample table

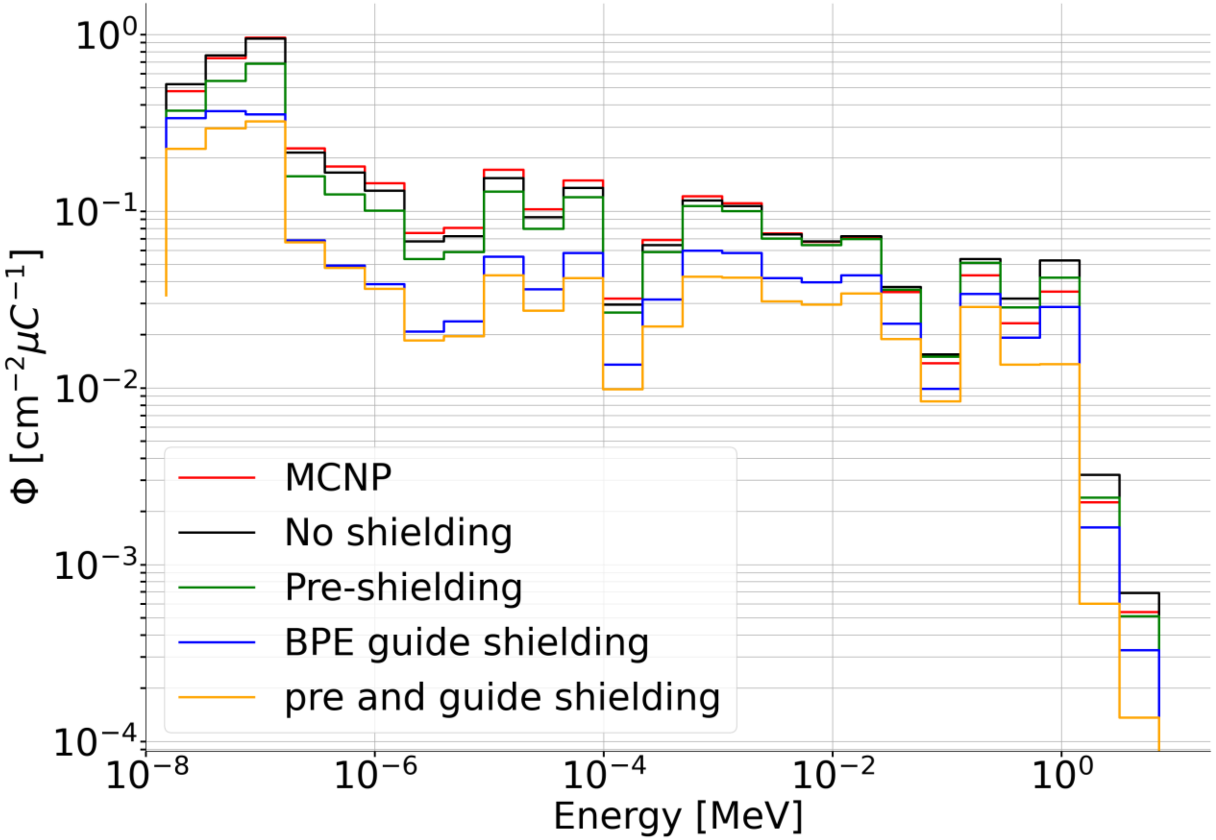
- Bare with 1 mm collimator (thermal)
- 3 inch with Cd (epithermal)
- 8 inch with Cd (fast)

1mm B4C aperture

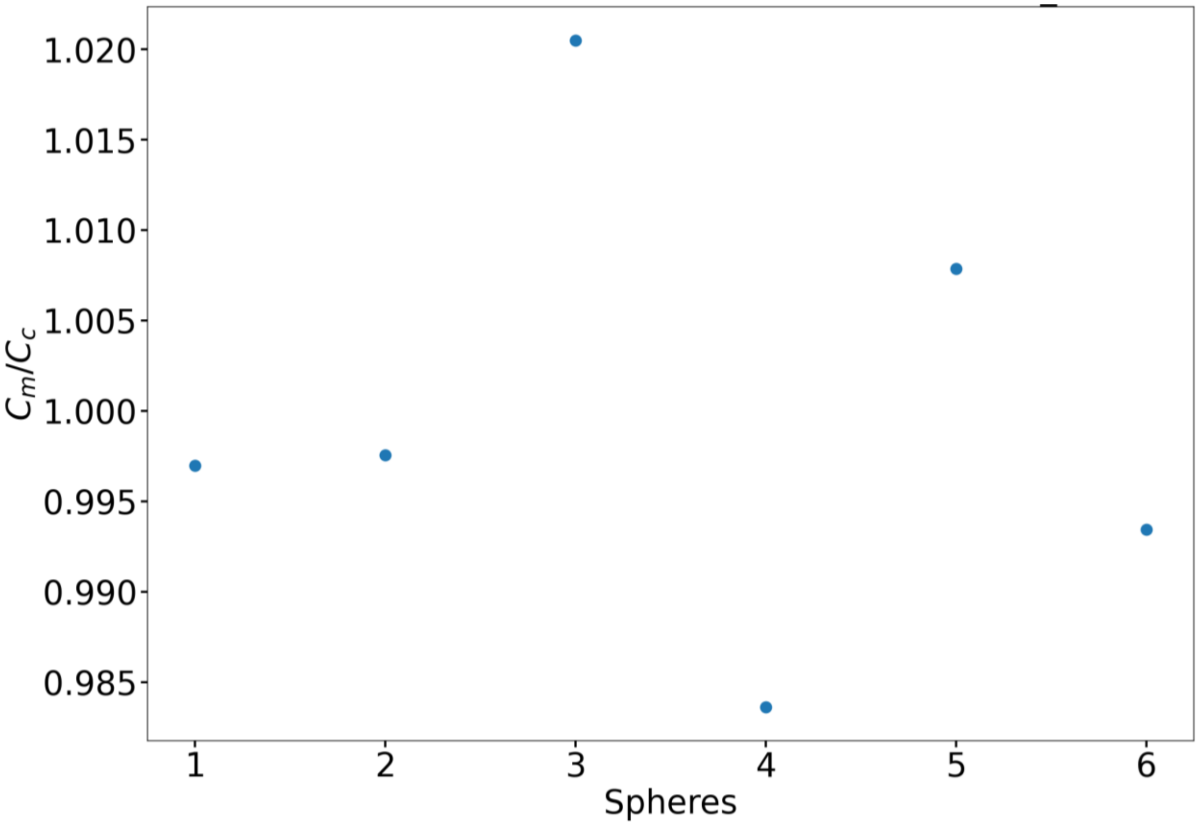


Neutron background at POLDI

Spectra with all shielding configurations



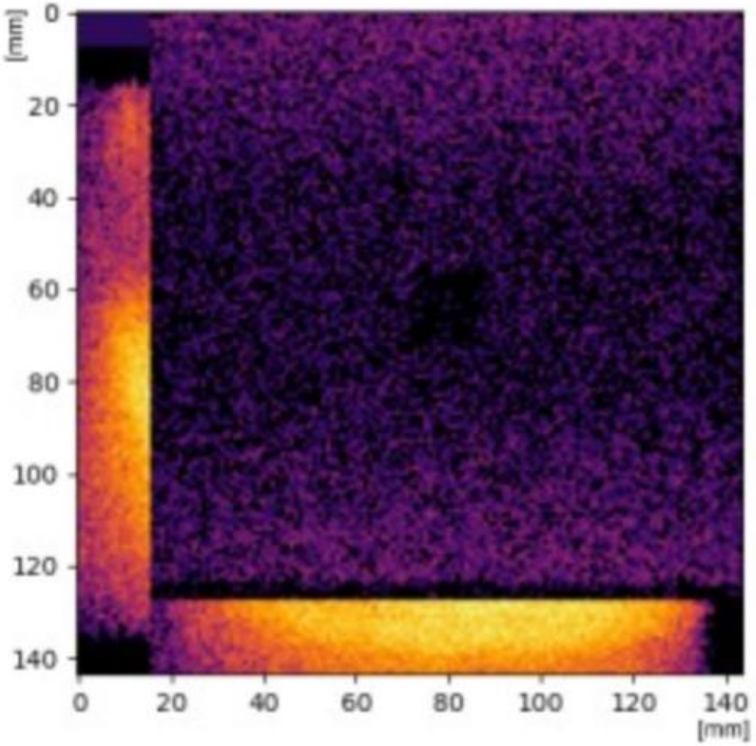
Ratio measured / calculated



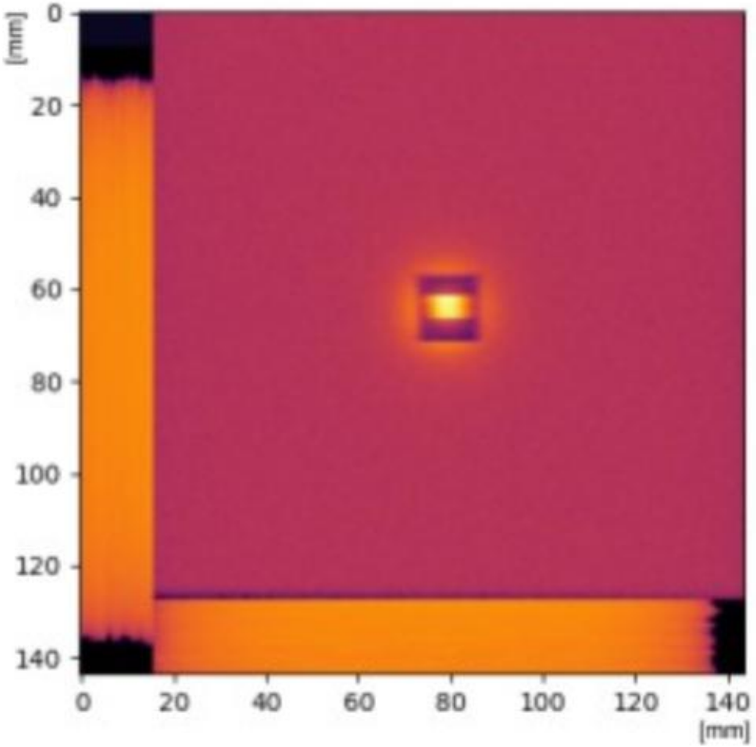
SANS @ SANS-LLB Beamline

Measurement at 5A

40%B4C + 60%PLA

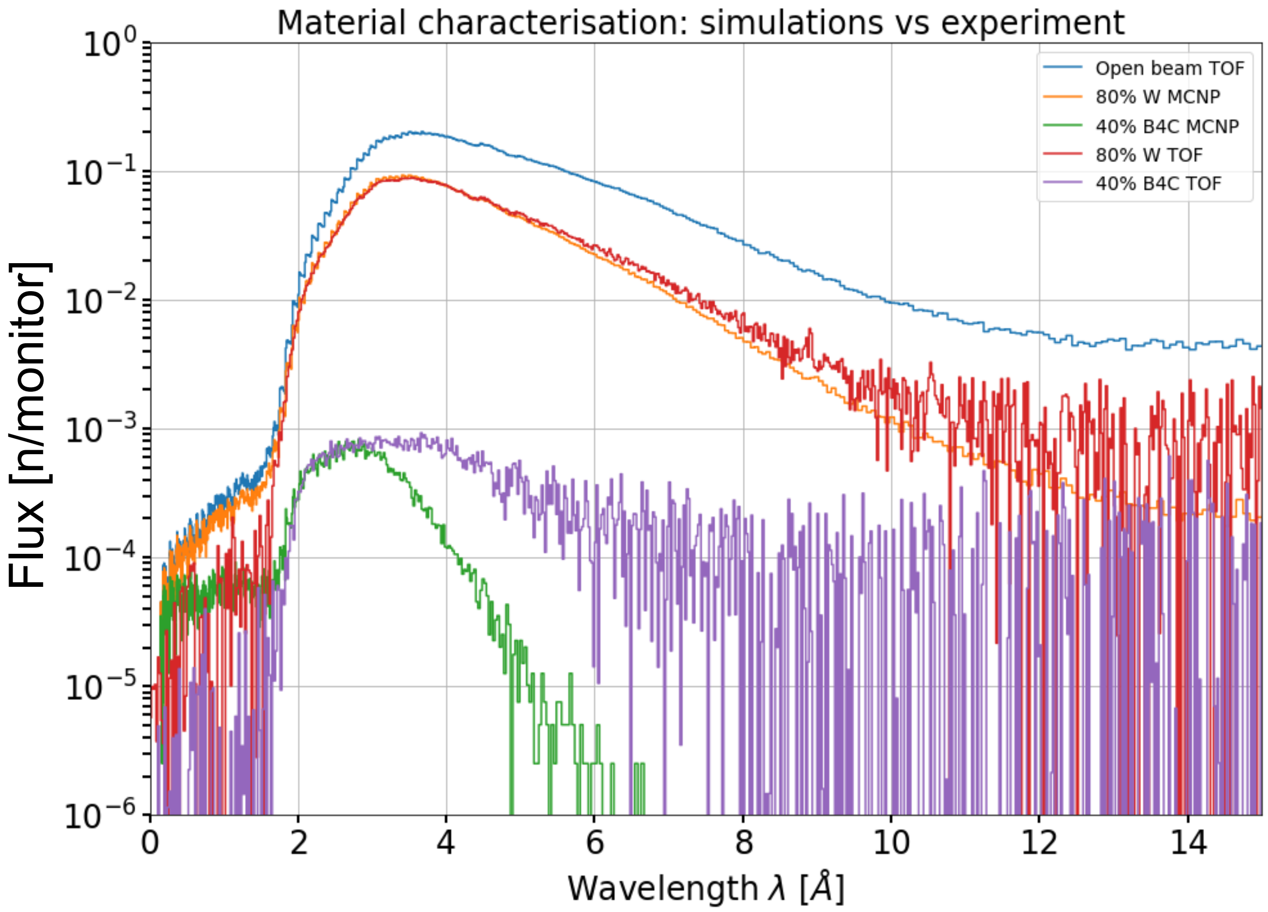


80%W + 5%B4C + 15%PLA



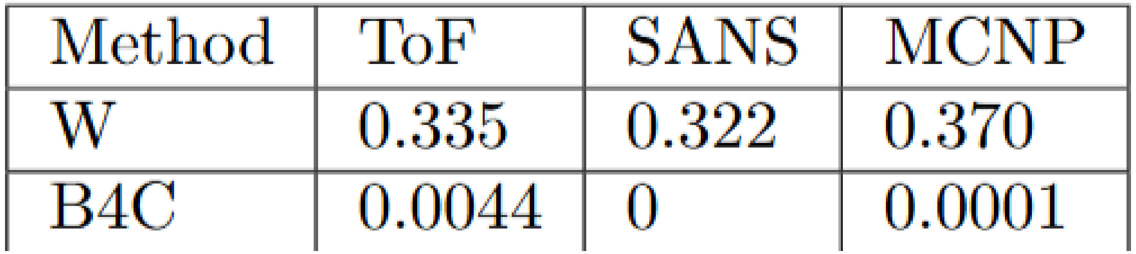
Time-of-Flight at BOA

Calibration with Be Bragg edge @ 4A
Normalization of simulation to measured spectrum



Transmission at BOA and SANS

Transmission at 5 A

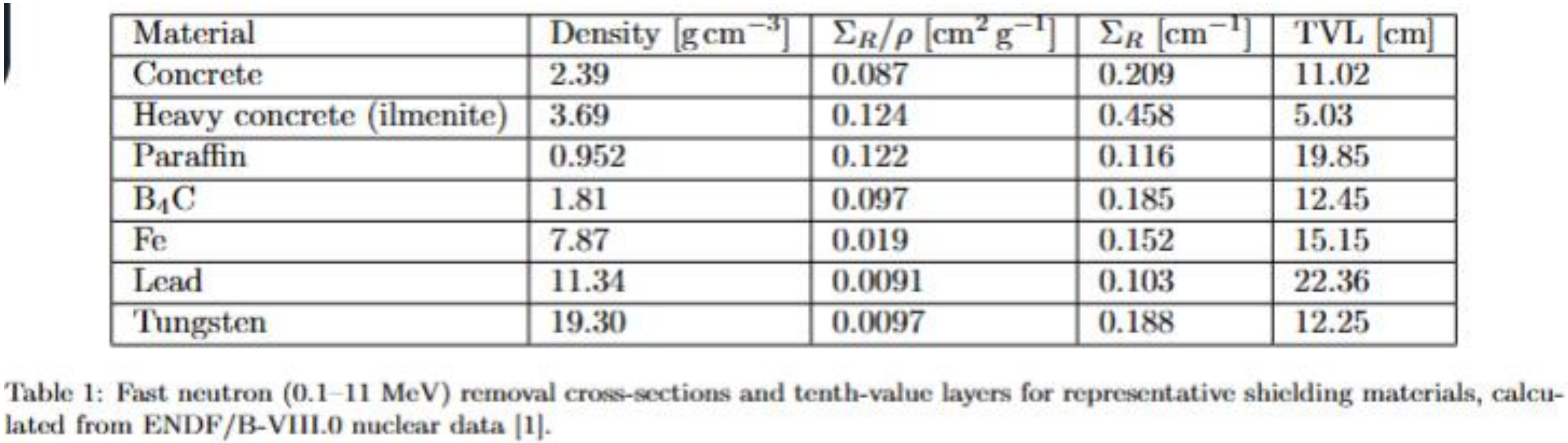


Method	ToF	SANS	MCNP
W	0.335	0.322	0.370
B4C	0.0044	0	0.0001

Moderation capabilities of different materials

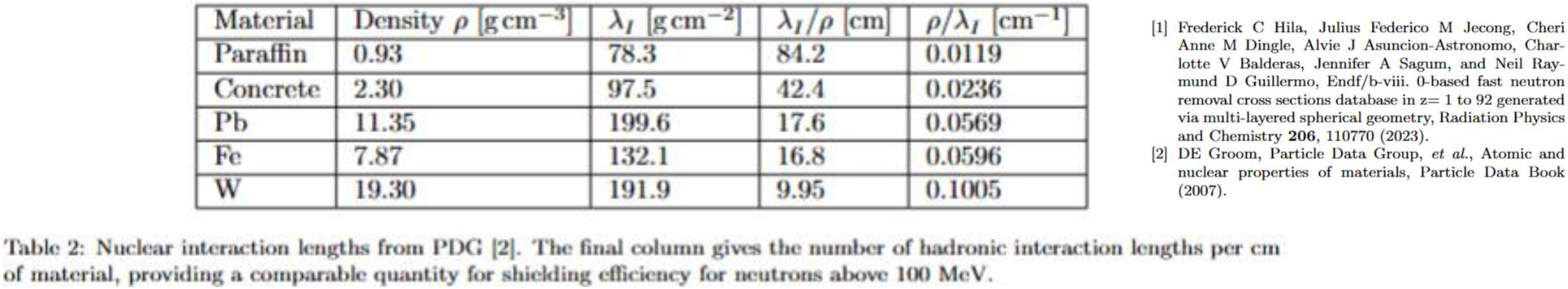
	H_2O	Be	D_2O	C	Fe	Pb
α	-	0.64	-	0.72	0.93	0.98
ξ	0.93	0.21	0.51	0.16	0.04	0.01
Σ_s (1/cm)	1.50	0.87	0.37	0.38	0.96	0.37
Collisions to 1 eV	16	69	28	91	414	1450
Time to 1 eV (μs)	1.5	8.5	9.7	25	43	390

Macroscopic cross sections



Material	Density [$\mathrm{g\,cm^{-3}}$]	Σ_R/ρ [$\mathrm{cm^2\,g^{-1}}$]	Σ_R [$\mathrm{cm^{-1}}$]	TVL [cm]
Concrete	2.39	0.087	0.209	11.02
Heavy concrete (ilmenite)	3.69	0.124	0.458	5.03
Paraffin	0.952	0.122	0.116	19.85
B_4C	1.81	0.097	0.185	12.45
Fe	7.87	0.019	0.152	15.15
Lead	11.34	0.0091	0.103	22.36
Tungsten	19.30	0.0097	0.188	12.25

Table 1: Fast neutron (0.1–11 MeV) removal cross-sections and tenth-value layers for representative shielding materials, calculated from ENDF/B-VIII.0 nuclear data [1].



Material	Density ρ [$\mathrm{g\,cm^{-3}}$]	λ_I [$\mathrm{g\,cm^{-2}}$]	λ_I/ρ [cm]	ρ/λ_I [$\mathrm{cm^{-1}}$]
Paraffin	0.93	78.3	84.2	0.0119
Concrete	2.30	97.5	42.4	0.0236
Pb	11.35	199.6	17.6	0.0569
Fe	7.87	132.1	16.8	0.0596
W	19.30	191.9	9.95	0.1005

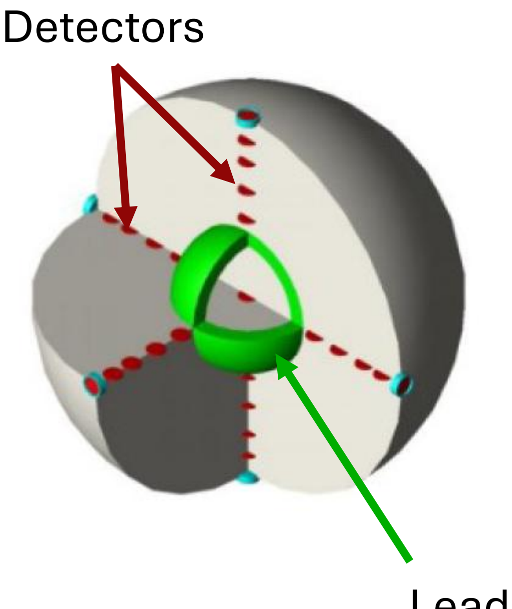
Table 2: Nuclear interaction lengths from PDG [2]. The final column gives the number of hadronic interaction lengths per cm of material, providing a comparable quantity for shielding efficiency for neutrons above 100 MeV.

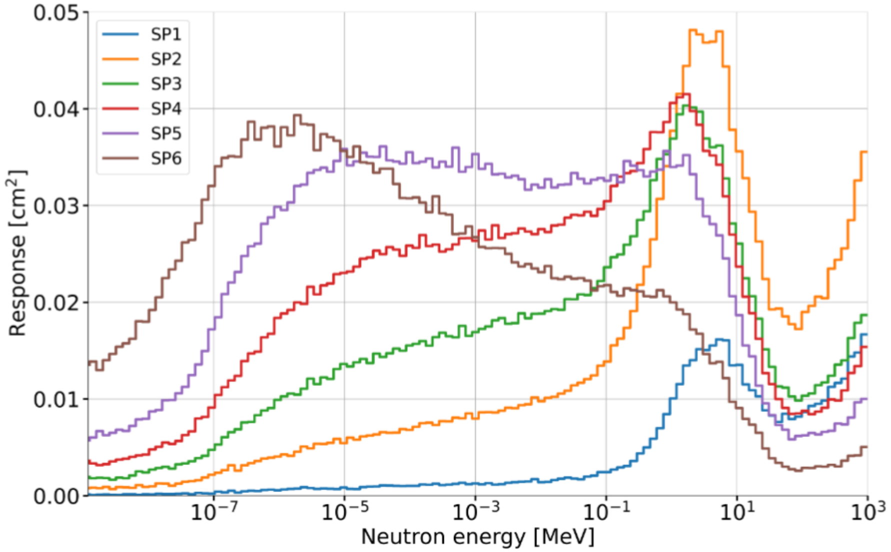
[1] Frederick C Hila, Julius Federico M Jecong, Cheri Anne M Dingle, Alvie J Asuncion-Astronomo, Charlotte V Balderas, Jennifer A Sagum, and Neil Raymund D Guillermo, Endf/b-viii. 0-based fast neutron removal cross sections database in z= 1 to 92 generated via multi-layered spherical geometry, Radiation Physics and Chemistry **206**, 110770 (2023).

[2] DE Groom, Particle Data Group, *et al.*, Atomic and nuclear properties of materials, Particle Data Book (2007).

Single-Sphere-Spectrometer SP2

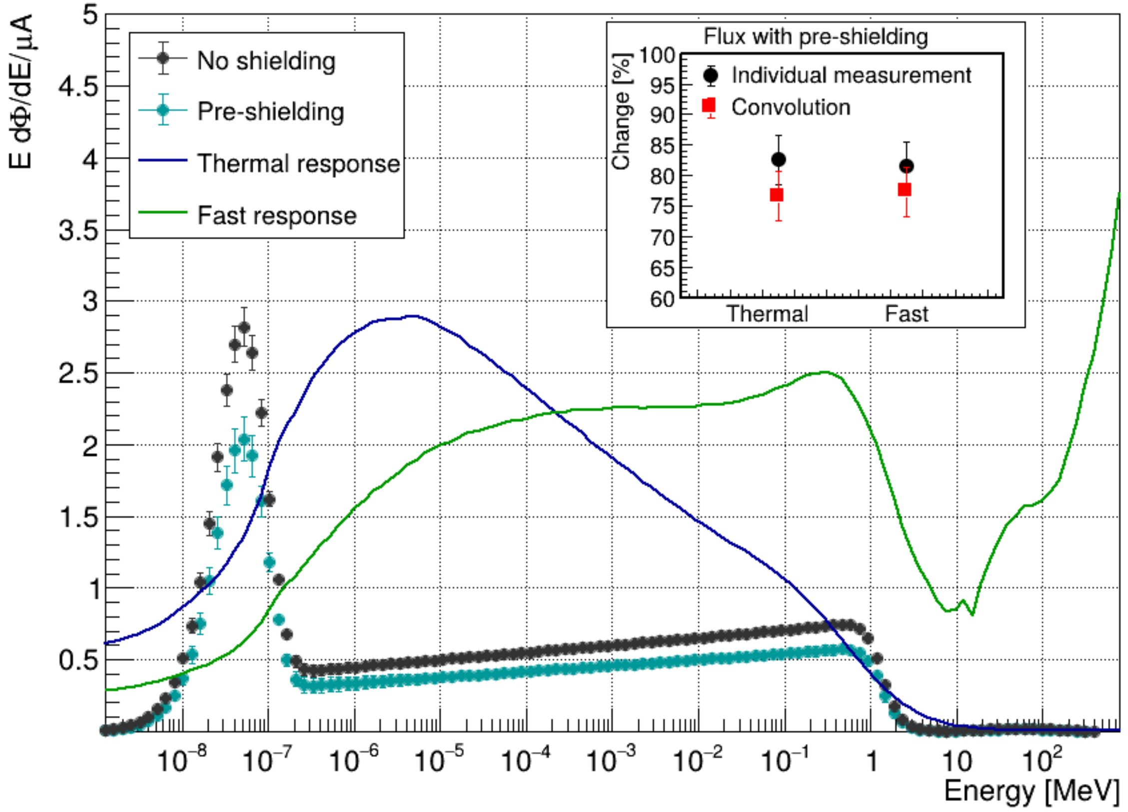
- 32 Si-diodes detect tritium and alpha particles emitted from $6Li$ through thermal neutrons.
- Detection occurs at varying depths in the moderator material, allowing for the detection of neutron from thermal up to few GeV.
- Enables neutron spectrometry across a broad energy range, from thermal to GeV, in homogeneous fields.



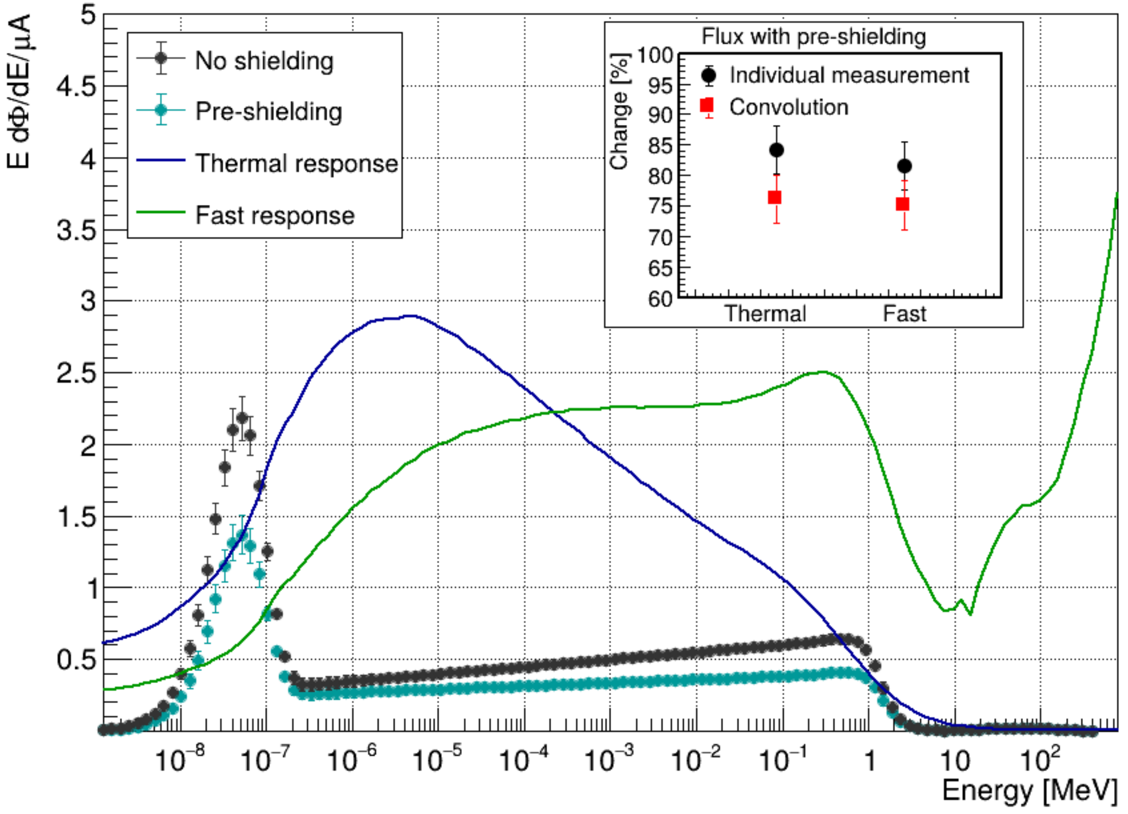


Sample room background

- Background measured on both sides of the guide
- SP2 + 2 Bonner spheres to validate spectra



North position



South position