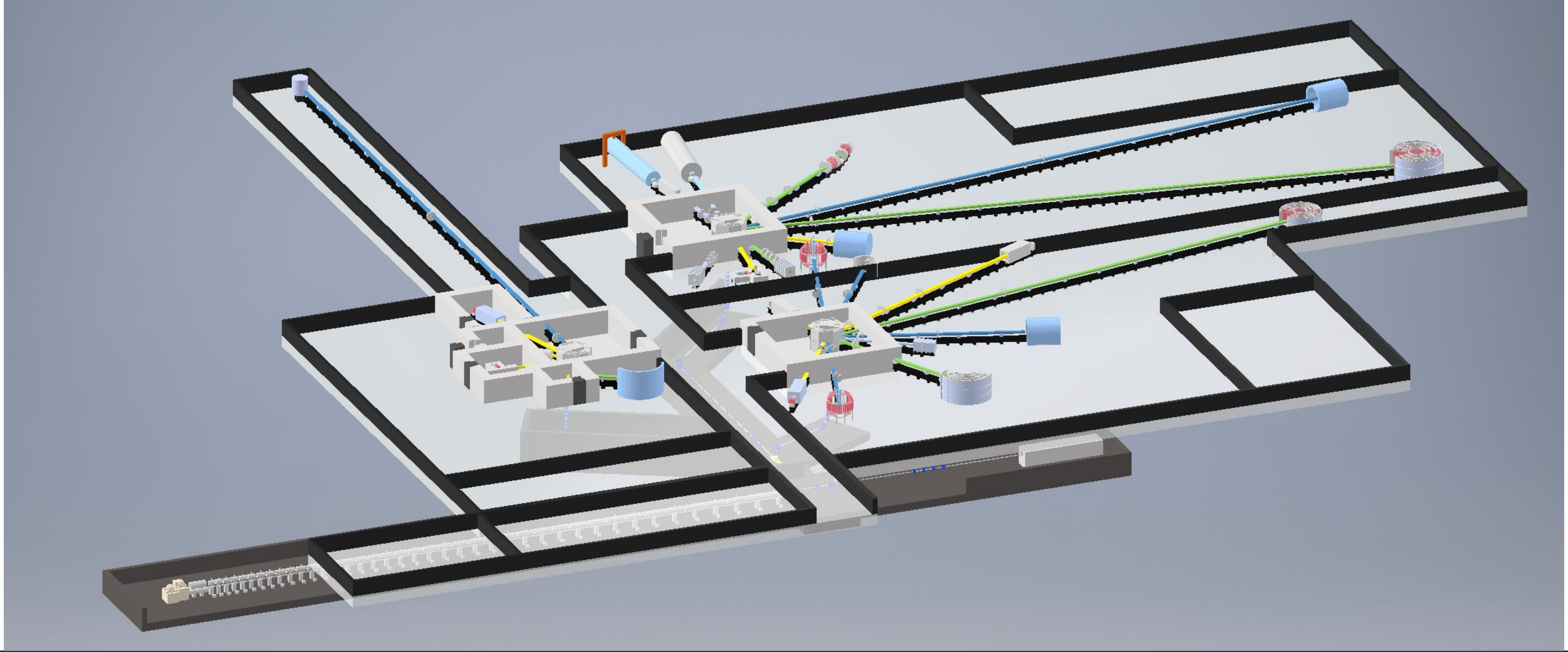

Conceptual Design of the Neutron Imaging Instruments for the HBS

14.02.2024 | M.Eng. Norberto Schmidt (no.schmidt@fz-juelich.de)

Jülich Centre for Neutron Science (JCNS-2/PGI-4) – PhD + PostDoc days

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JÜLICH Forschungszentrum

Summary

1. High Brilliance Neutron Source

2. Neutron Imaging: Introduction and Fundamentals

3. PhD Objectives and Work Schedule

4. Source Simulations
   a. TMR for cold and thermal neutrons
   b. TMR for epithermal and fast neutrons

5. Instruments Design
   a. Proposed Methodology
   b. Validation of the Simulations
   c. Preliminary Design and Simulations

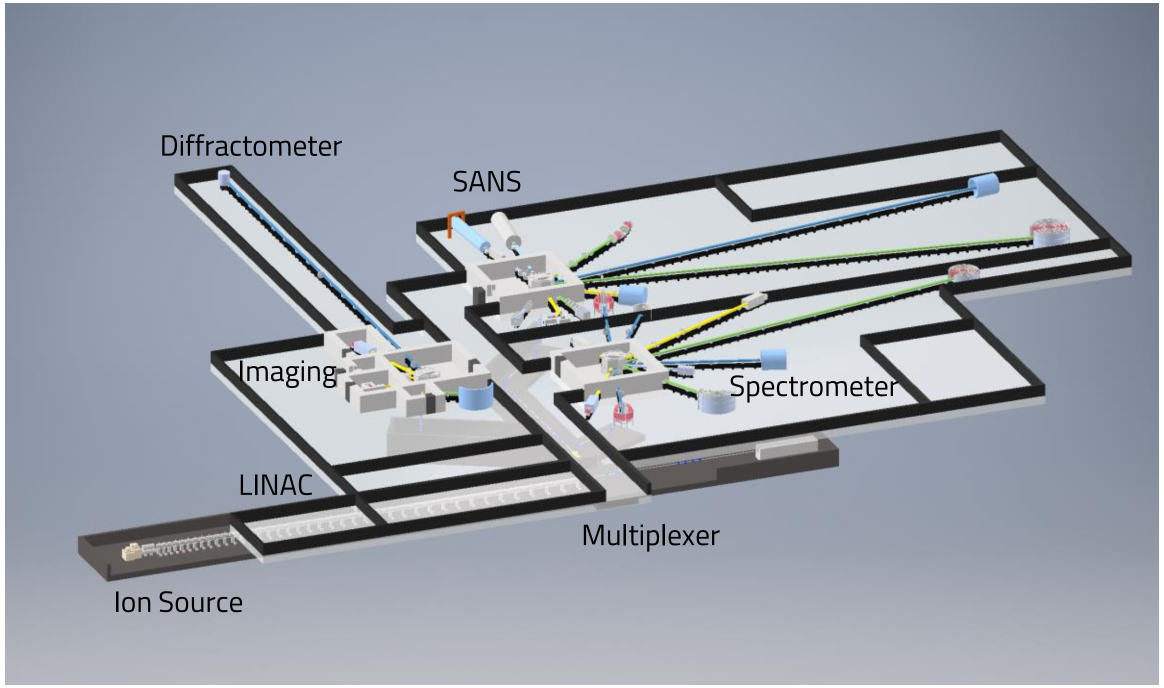
6. Prototype Development
   a. Experimental Setup at the JULIC Platform

7. Future Work

High Brilliance Neutron Source

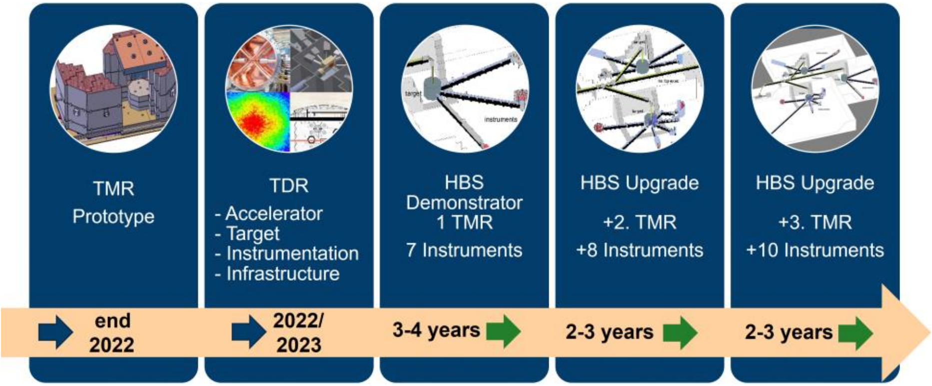
Accelerator:

- Average Power: 100 kW
- Proton Energy: 70 MeV
- Duty Cycle: 1.6 %
- Proton Current: 89.3 mA
- Neutron target: Tantalum



3 Target-Moderator-Reflector (TMR) Stations:

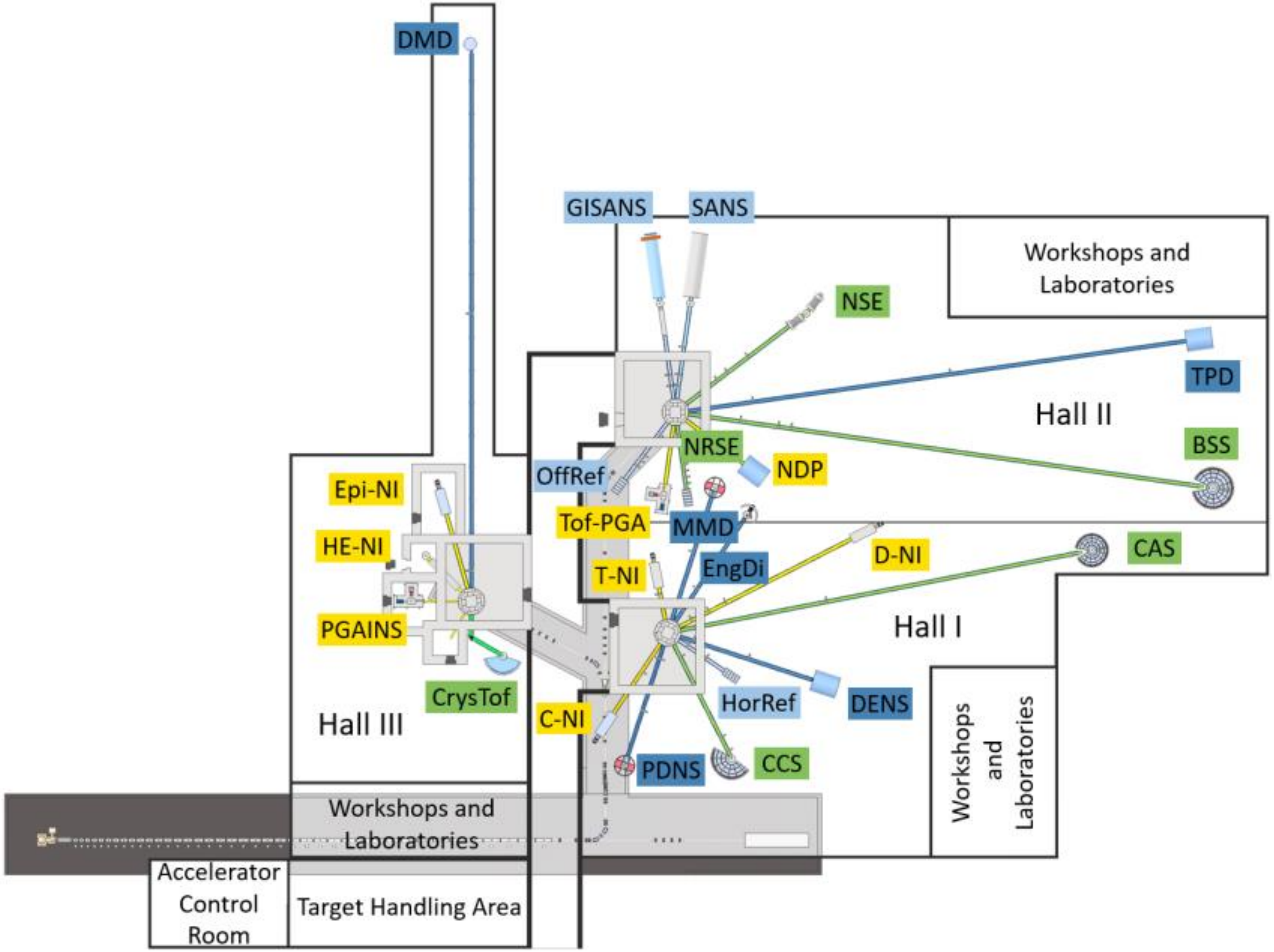
Frequency [Hz]	Period [ms]	Duty cycle [%]	Pulse width [μs]	Purpose
24	41.7	1.60	667	Long pulse, cold neutrons
96	10.4	1.60	167	Medium pulse, thermal neutrons
96	10.4	1.60	167 (down to 1-10)	Short pulse, epithermal neutrons



High Brilliance Neutron Source

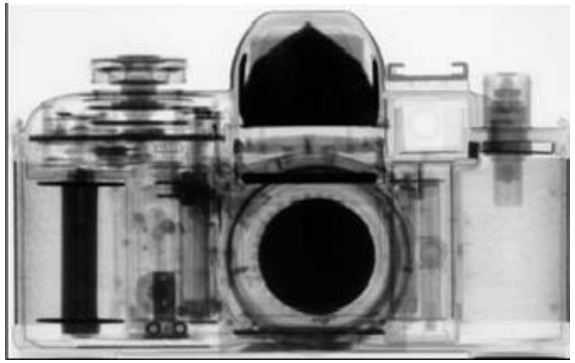
24 Instruments investigated for the Technical Design Report (TDR)

- 6 Diffractometers
- 4 Large Scale Structure Instruments
- 6 Spectrometers
- 8 Analytics Instruments
  - **5 Imaging Instruments**

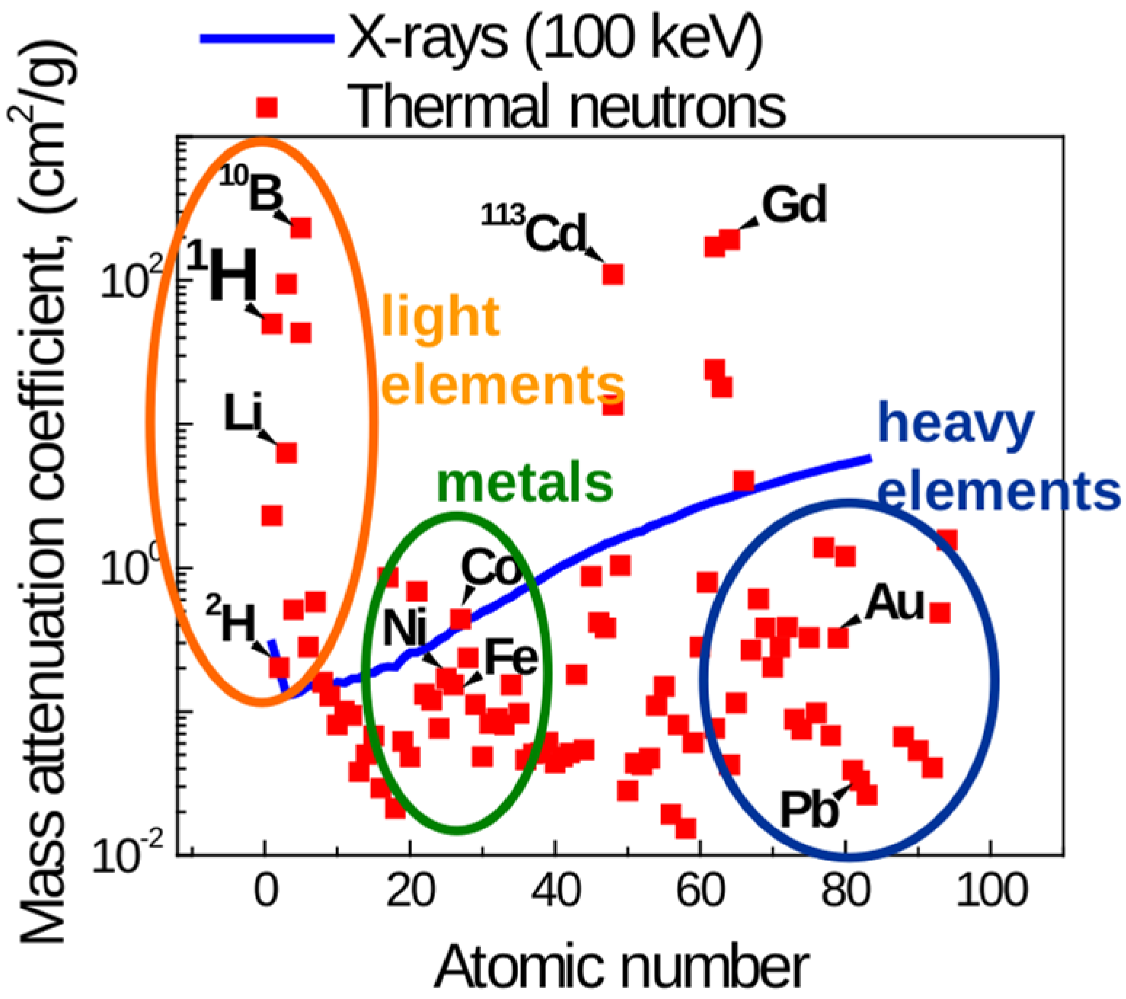


Neutron Imaging: Introduction

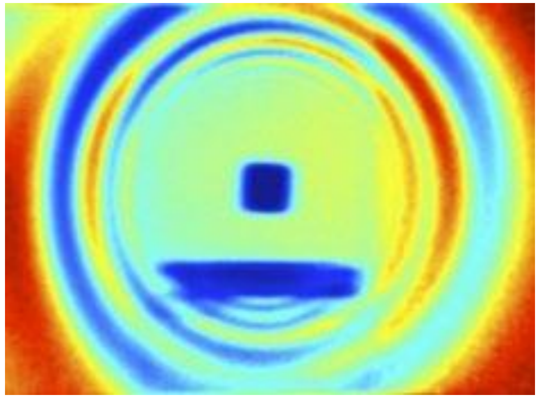
Radiography example [1]



Neutrography example [1]



Mass attenuation coefficient, for X-rays and thermal neutrons, as function of the atomic number [1]

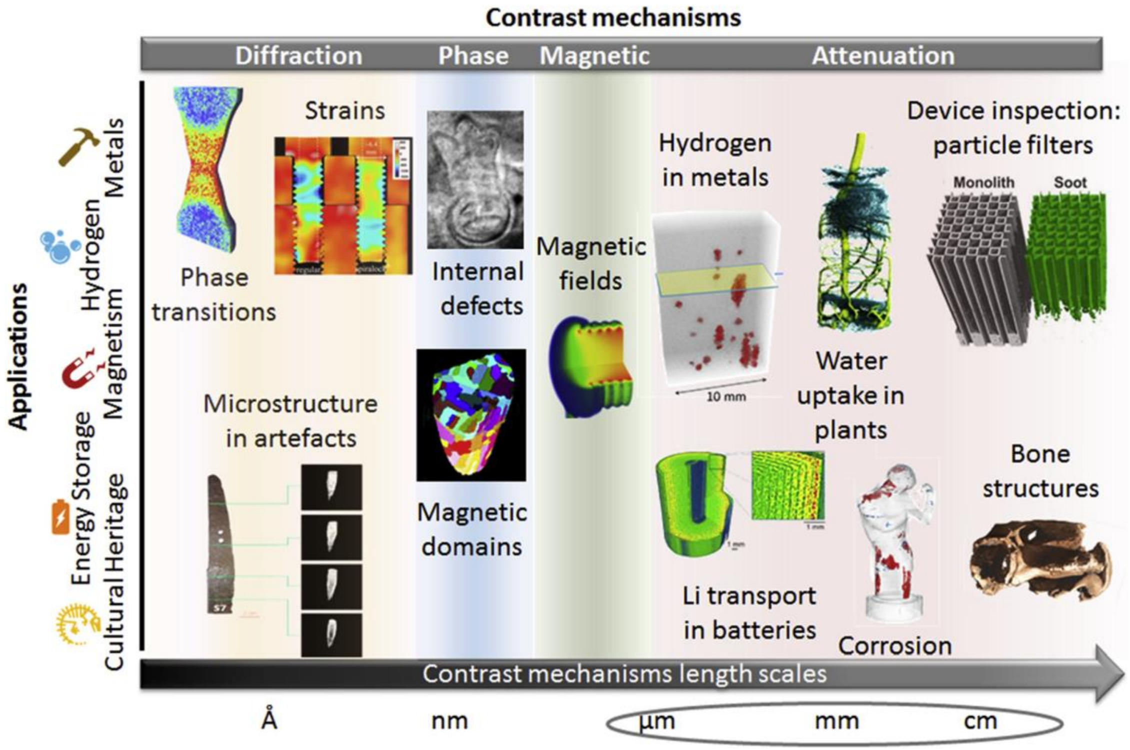


Distribution of magnetic fields [3]

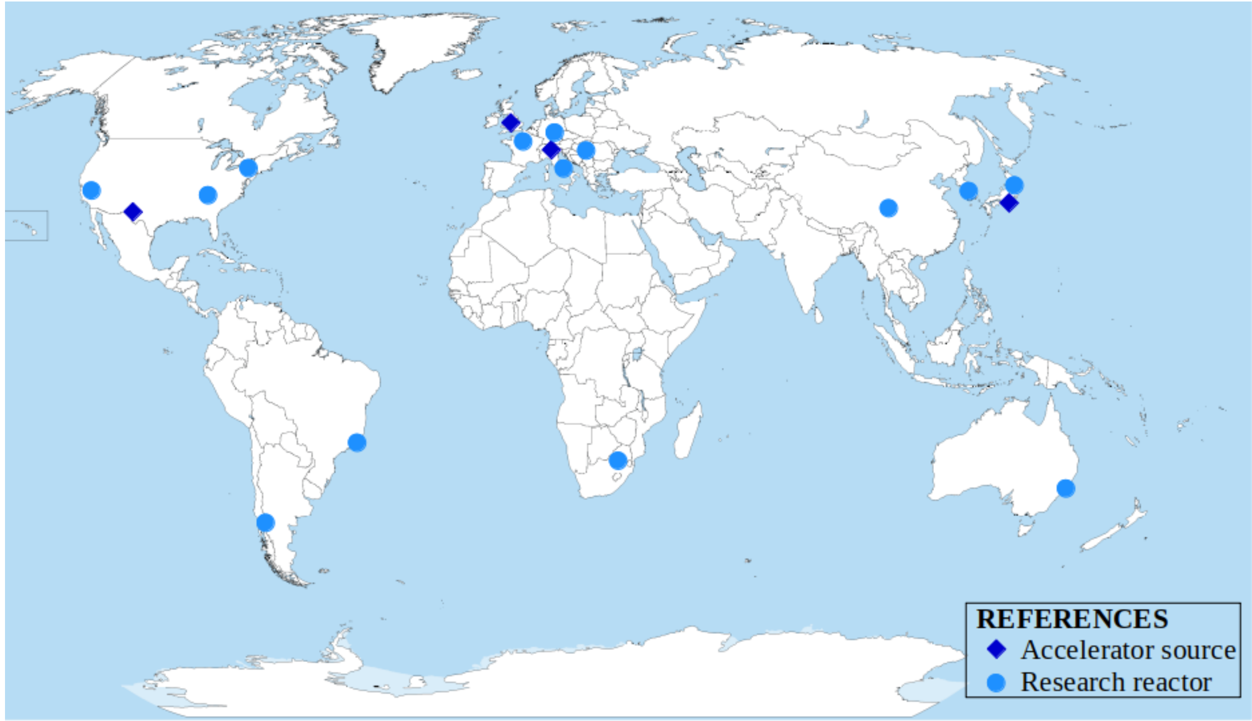
Water uptake in plant’s root [2]

Tomography of a bronze sculpture [3]

Neutron Imaging: Introduction



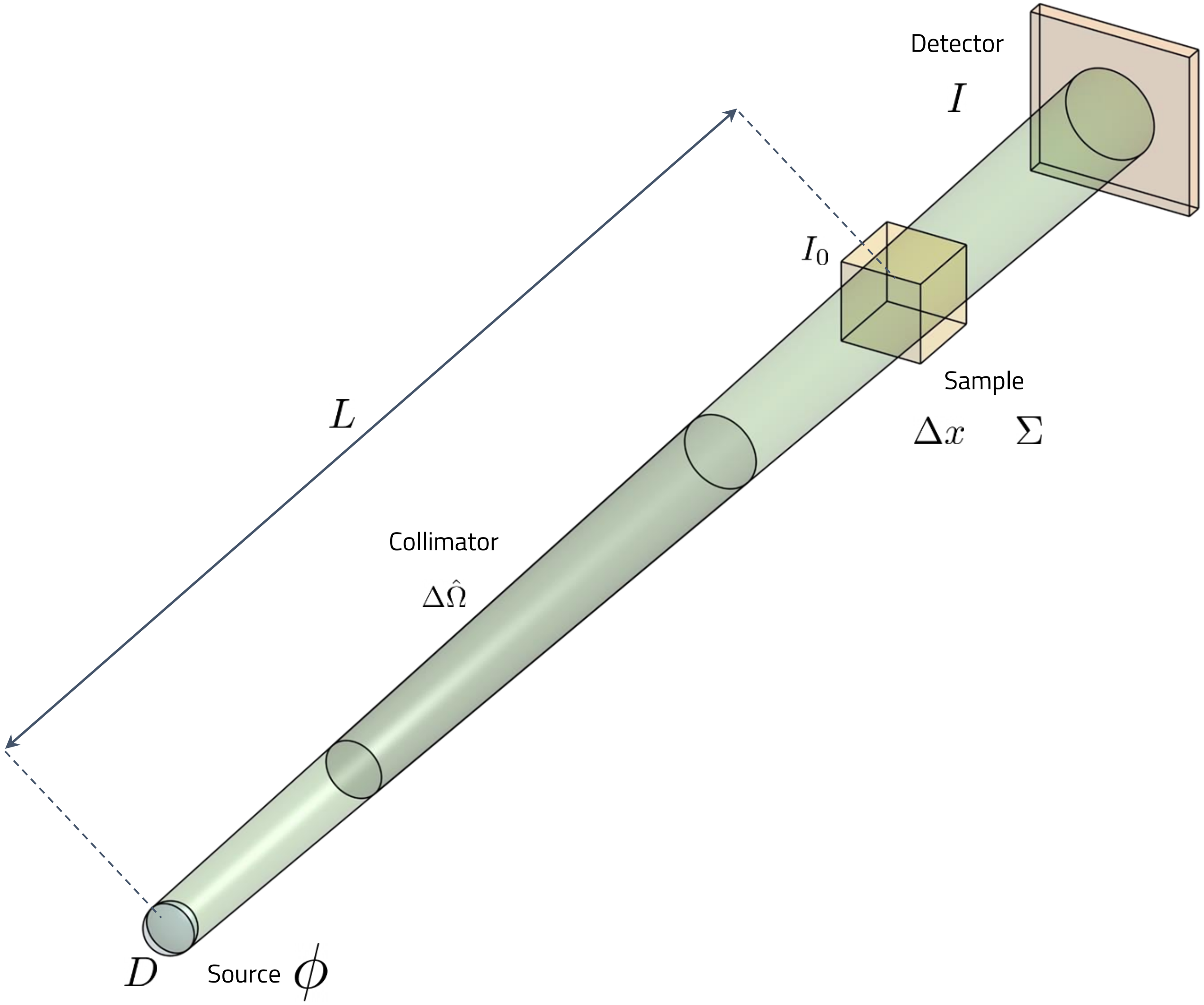
Contrast mechanisms and application fields [2]



Most important neutron imaging facilities under operation around the world by source type, according to [4], [5]

Total: ~50 facilities worldwide

Neutron Imaging: Fundamentals

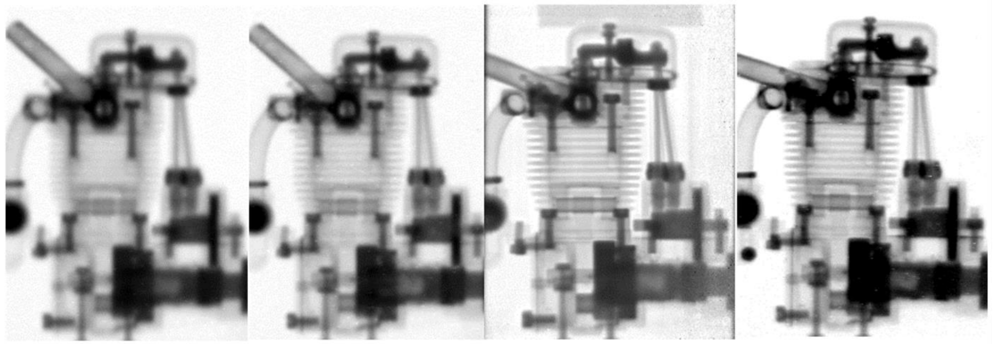


Beer-Lambert's law (neutron attenuation):

$$I = I_0 \cdot e^{-\Sigma \cdot \Delta x}$$

Intensity at the sample:

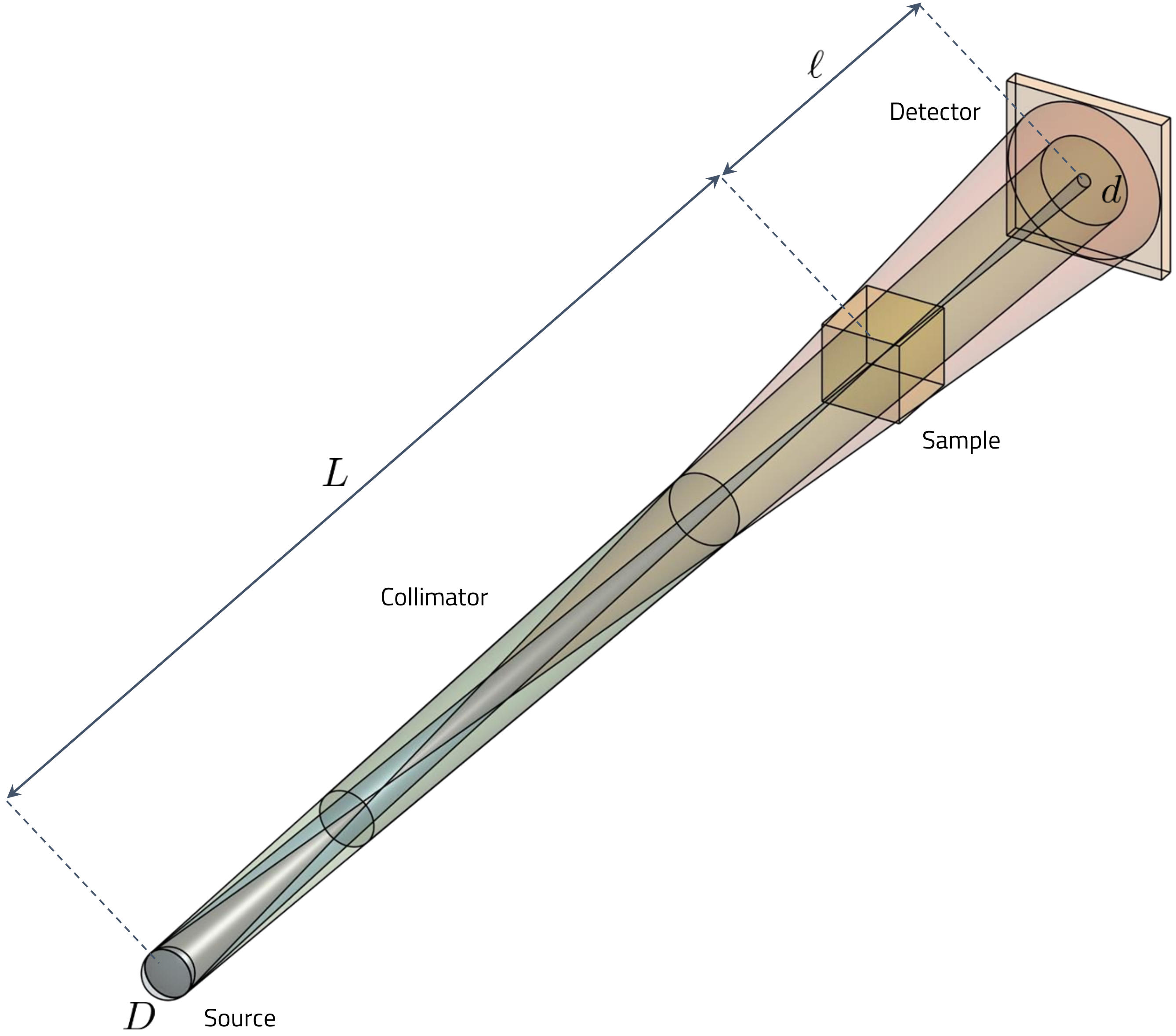
$$I \propto \phi \cdot \frac{\Delta\hat{\Omega}}{4\pi} \approx \frac{\phi}{16} \cdot \left(\frac{D}{L}\right)^2$$



L/D=71 L/D=115 L/D=320 L/D>500.

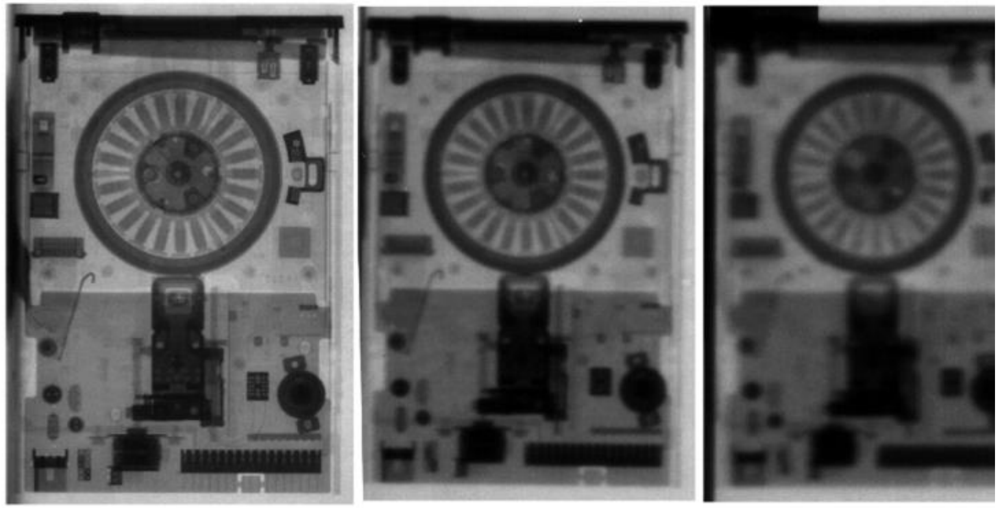
Radiographs of a small motor taken at different beam positions with different L/D ratios. [1]

Neutron Imaging: Fundamentals



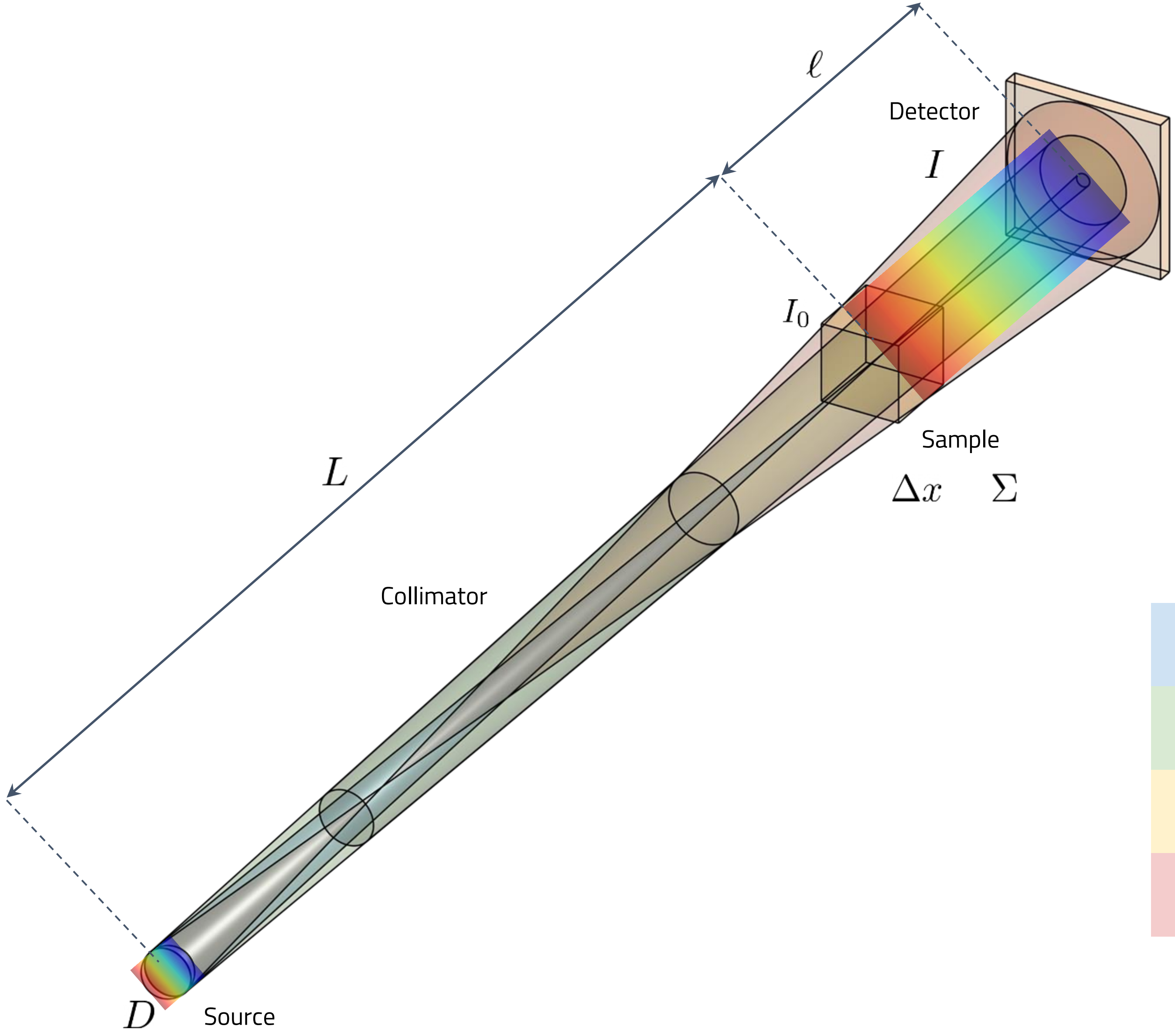
Spatial resolution equation:

$$d = \frac{\ell}{L/D}$$



Radiographs of a floppy drive in different distances from a film detector taken at a cold neutron guide with L/D=71 [1]

Neutron Imaging: Fundamentals



Time-of-flight attenuation for pulsed sources:

$$I(E) = I_0(E) \cdot e^{\Sigma(E) \cdot \Delta x}$$

Correlation between energy, distance and time-of-flight:

$$E \propto \left(\frac{L + \ell}{\mathrm{ToF}} \right)^2$$

	Energy	**Velocity**	**Wavelength**	**ToF (10 m)**
Fast	> 10 keV	> 1.4E6 m/s	< 3 mÅ	< 7 µs
Epithermal	< 10 keV	< 1.4E6 m/s	> 3 mÅ	> 7 µs
Thermal	< 0.5 eV	<1.0E5 m/s	> 0.4 Å	> 1 ms
Cold	< 10 meV	< 1.4E3 m/s	> 2.9 Å	> 7 ms

Energy, velocity and wavelength ranges for moderated neutrons

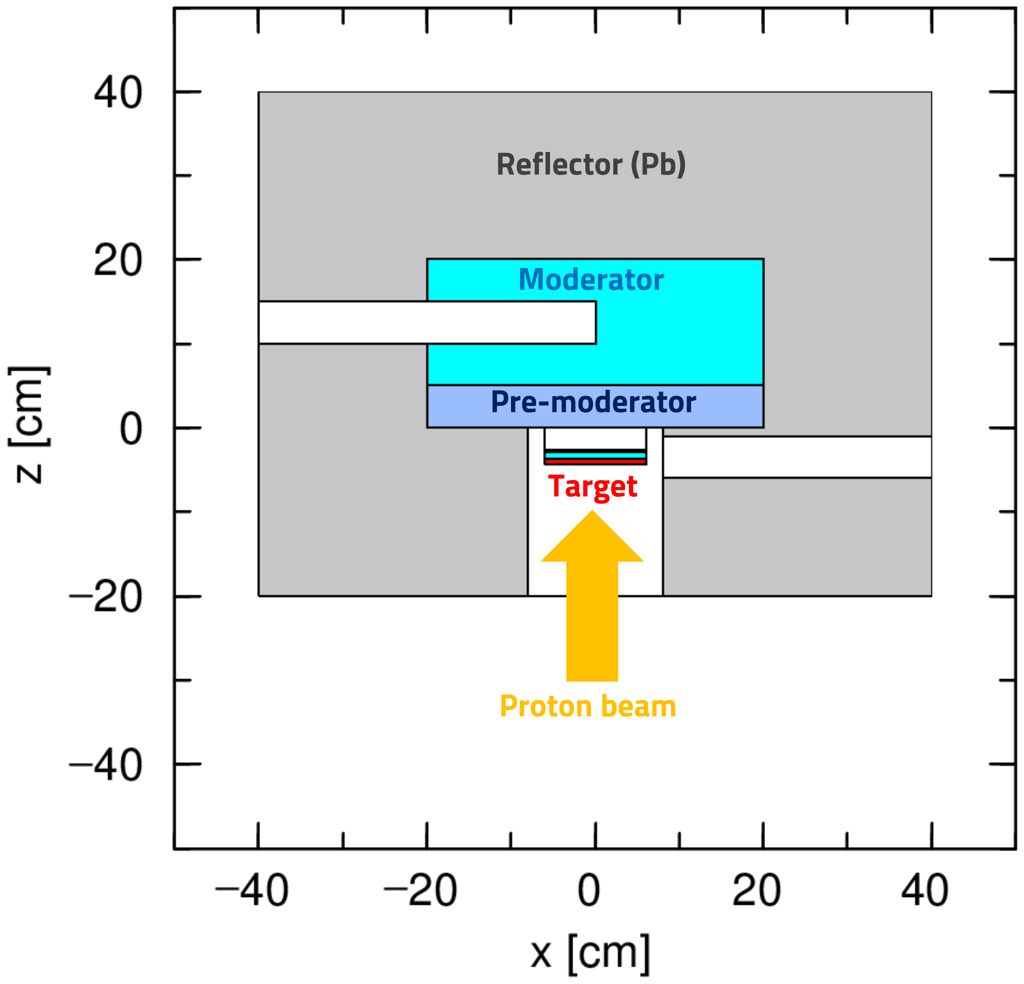
PhD Objectives and Work Schedule

General objective: Design and optimize instruments for time-of-flight cold, thermal and epithermal neutron imaging, within the framework of the High Brilliance Neutron Source (HBS) project at the Jülich Centre for Neutron Science (JCNS)

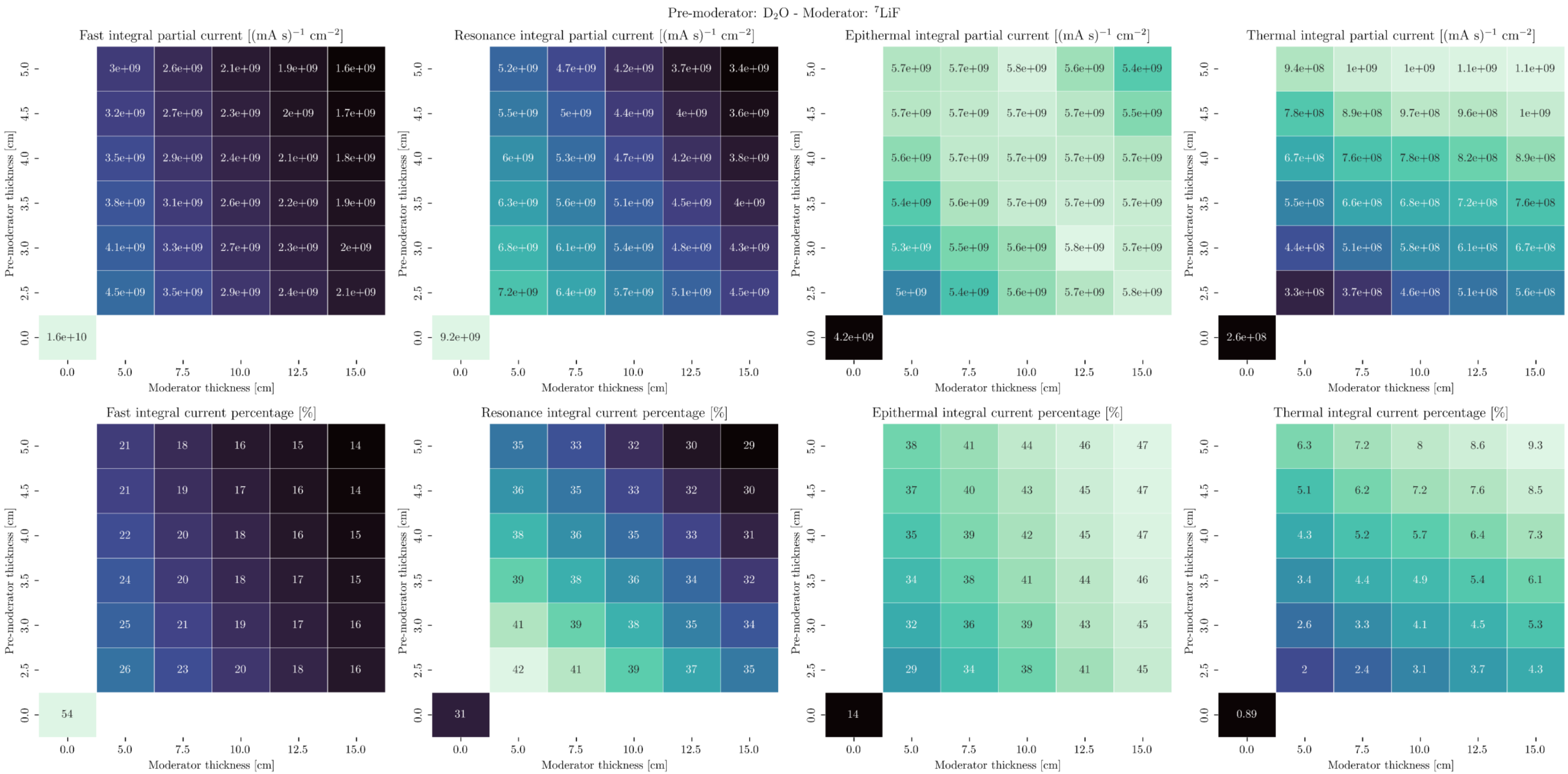
1) Baseline study	2) Source simulations	3) Instruments design	4) Prototype development	5) Prototype testing
NI instruments to be considered: - MLZ (Germany) - BER-II (Germany) - PSI (Switzerland) - ISIS (UK) - J-PARC (Japan) - LANL (USA) - RA-6 (Argentina)	- HBS model simulations with Monte Carlo codes - Validation of the codes - Cold and thermal neutron spectra analysis - Epithermal and fast spectra development	- Instruments simulations with VITESS and McStas - Neutron optics - Cold and thermal instruments - Epithermal and fast instruments	- Collimator development - TMR for epithermal and fast neutrons - Detectors development	- Test of optical components and ToF settings at the JULIC platform - Data analysis of the experiments

Source simulations: TMR for epithermal and fast neutrons

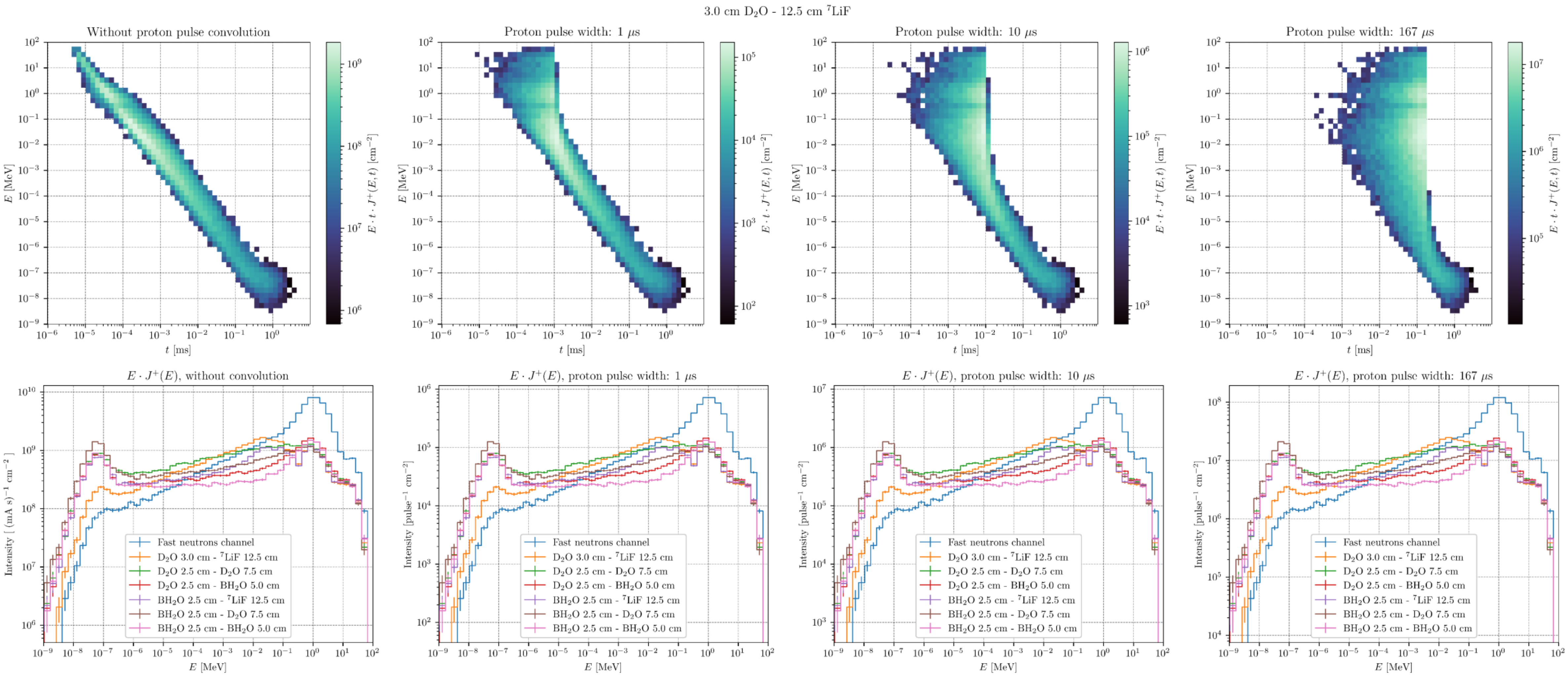
- Pb reflector, cylindrical, 20 cm thickness in all directions
- One fast channel (5 cm diameter) looking directly to the target
- One epithermal channel (5 cm diameter) looking to the moderator
- Pre-moderators: D_2O, H_2O, BH_2O (H_2O + 1% wt. H_3BO_3) (from 2.5 to 5.0 cm, every 0.5 cm)
- Moderators: D_2O, H_2O, BH_2O, Graphite, ^7LiF (from 5.0 to 15.0 cm, every 2.5 cm)
- Tallies: dump-files to save all the particles that cross-out both epithermal and fast channels



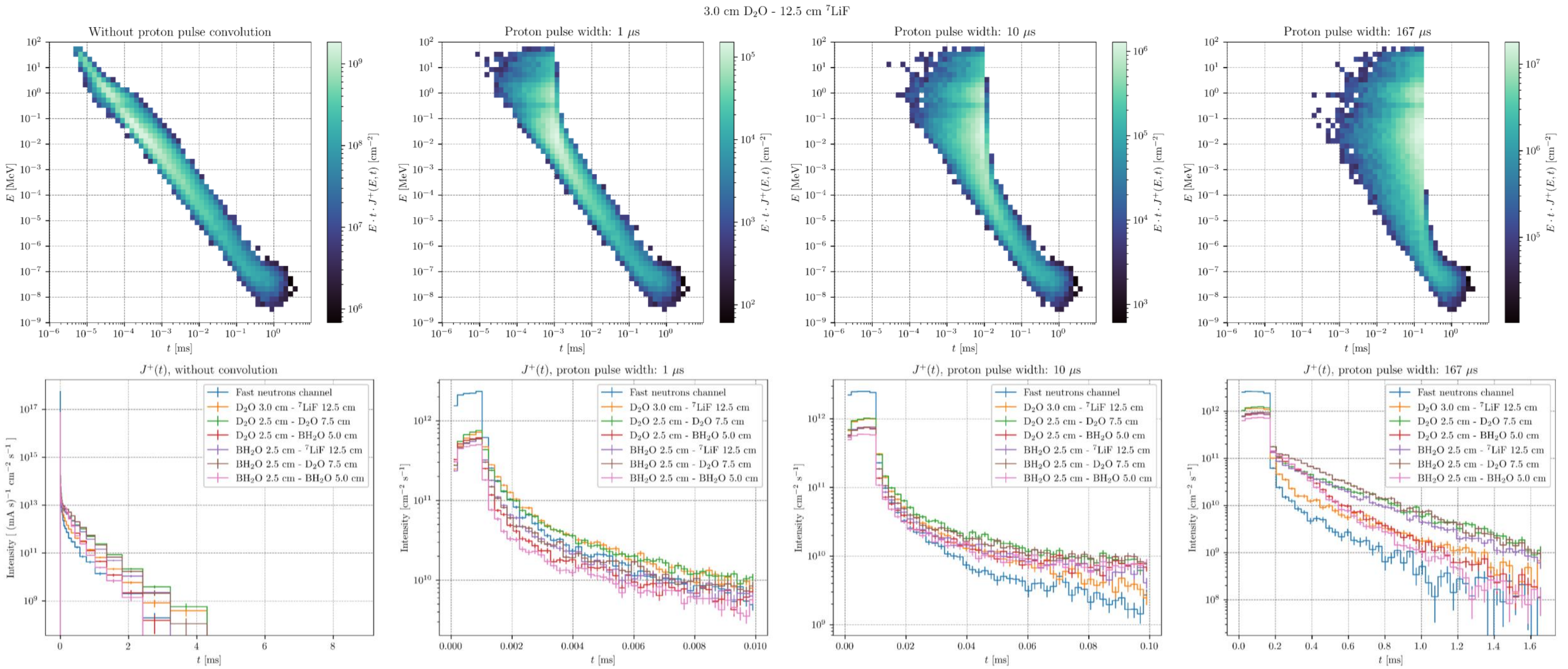
Source simulations: TMR for epithermal and fast neutrons



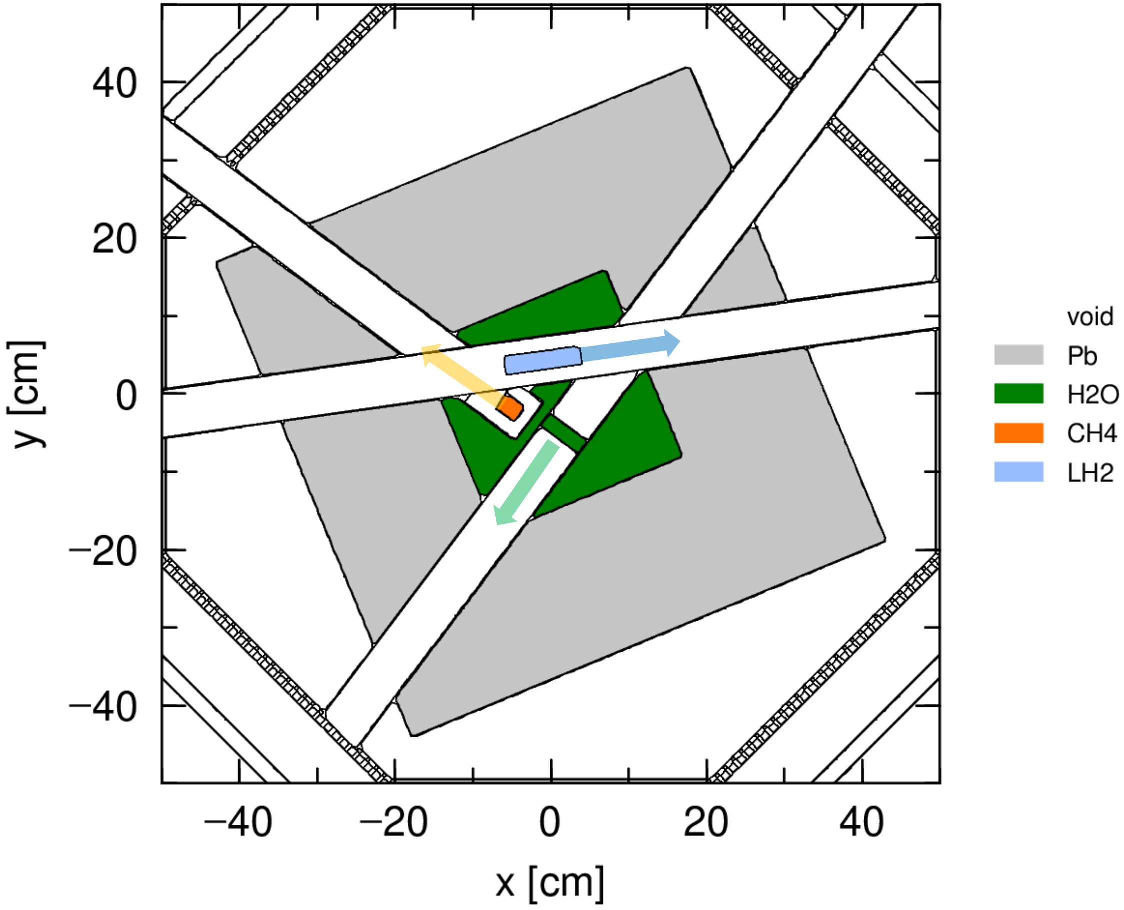
Source simulations: TMR for epithermal and fast neutrons

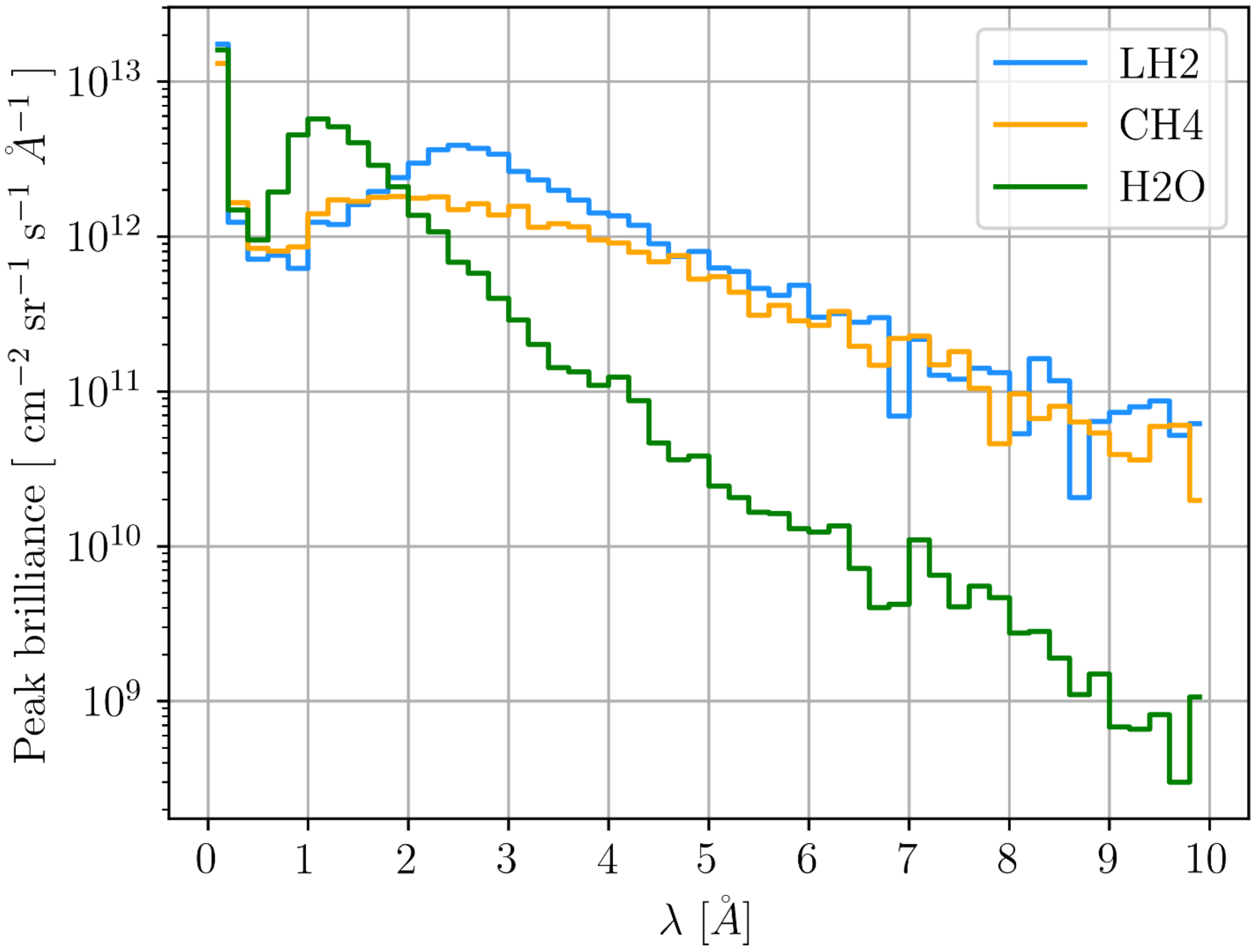


Source simulations: TMR for epithermal and fast neutrons



Source simulations: TMR for cold and thermal neutrons





Instruments Design: Proposed Methodology

TMR Source Simulations → **Virtual Sources Generation** → **Instruments Simulations**

TMR Source Simulations (PHITS – Particle and Heavy Ion Transport code System)

- Cold+Diffractive
- Thermal
- Epithermal
- Fast

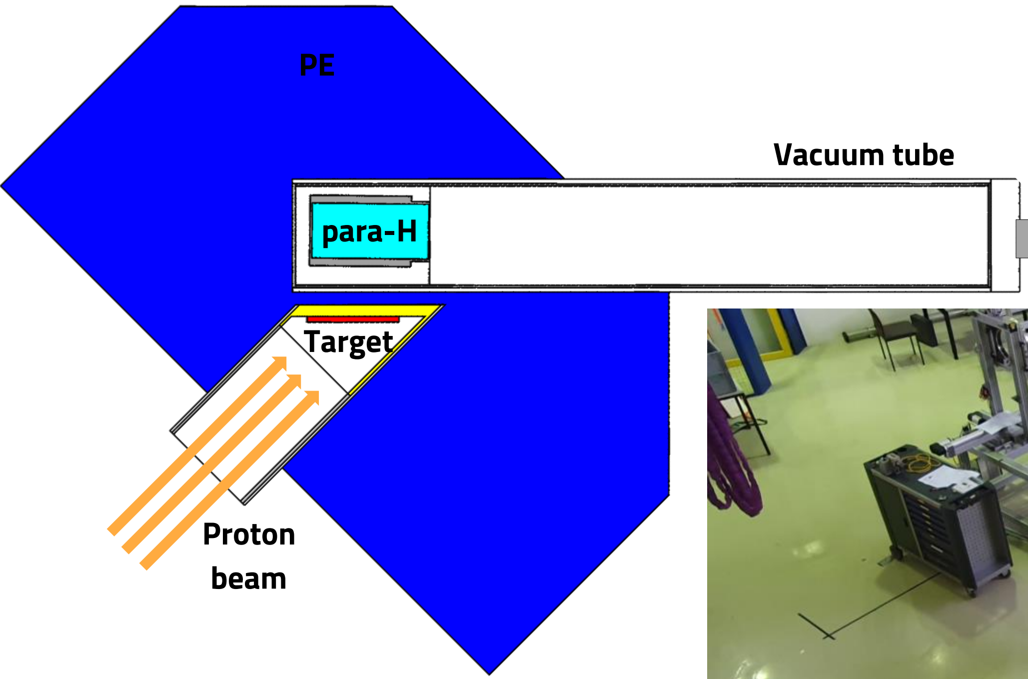
Virtual Sources Generation (KDSource)

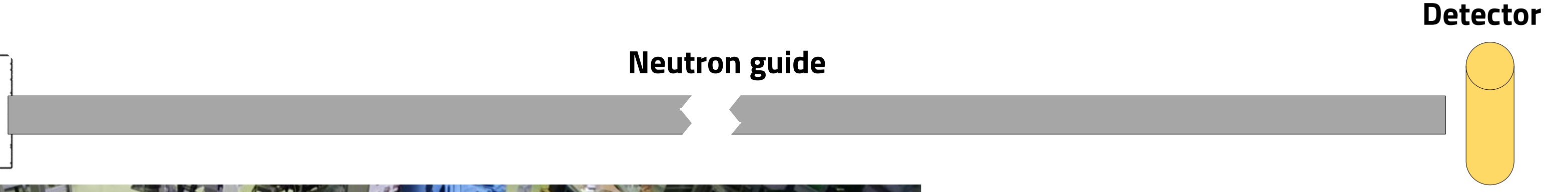
- Machine learning tools
- Resampling from the original sources

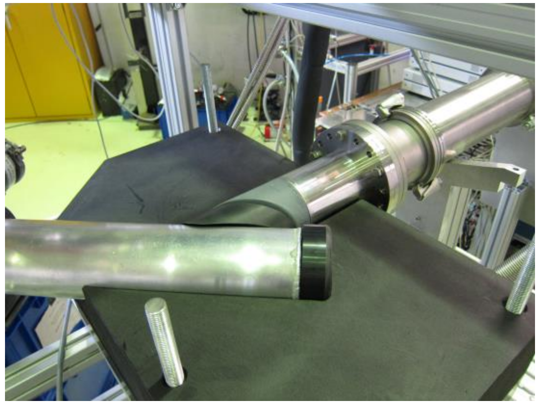
Instruments Simulations (VITESS, McStas)

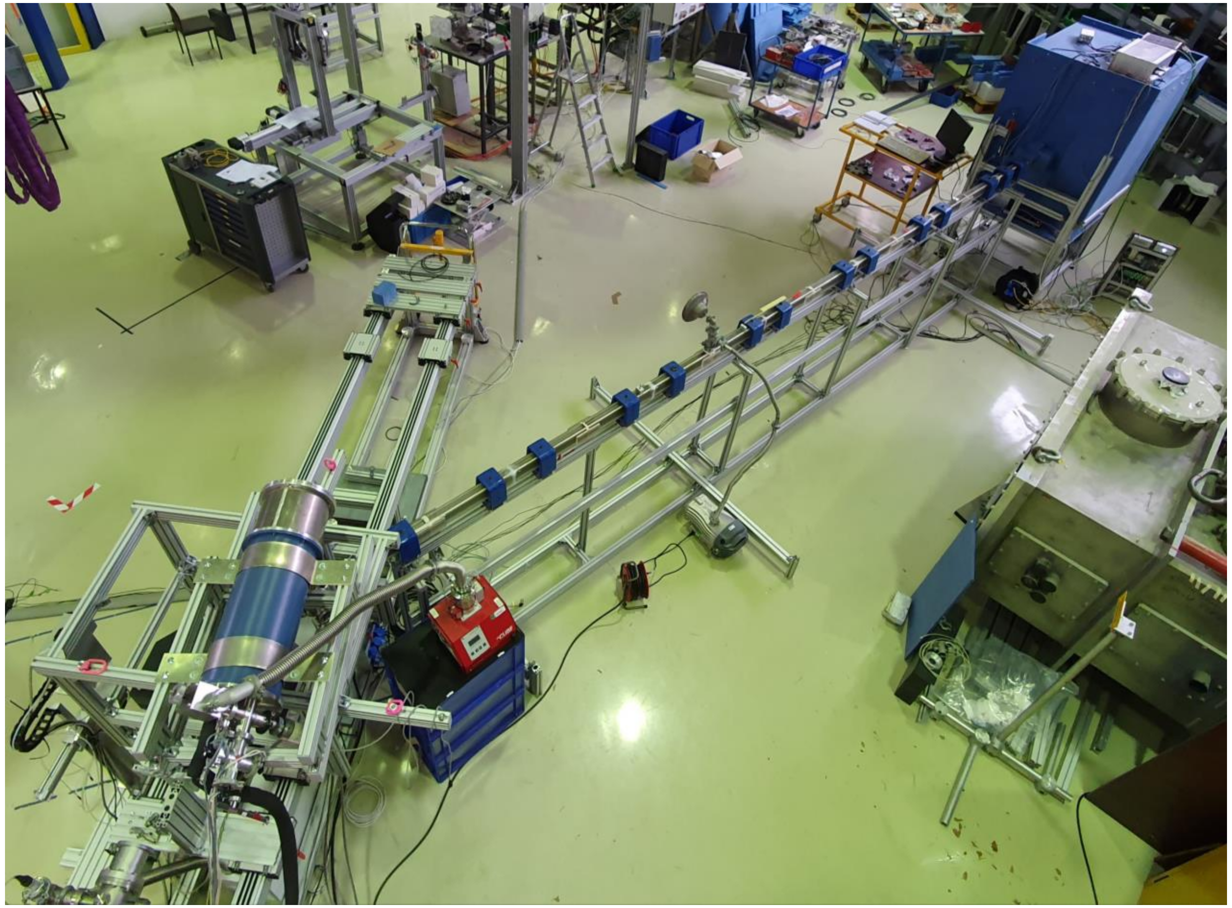
- Flux at the sample
- Field of view (FOV)
- Collimation (L/D)
- Spatial distribution
- TOF distribution
- Frame overlap

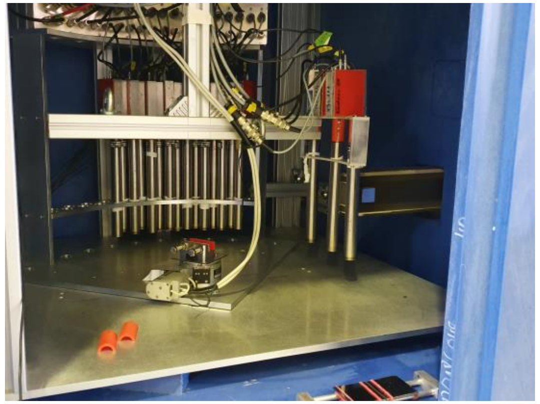
Validation of the simulations: experiments description



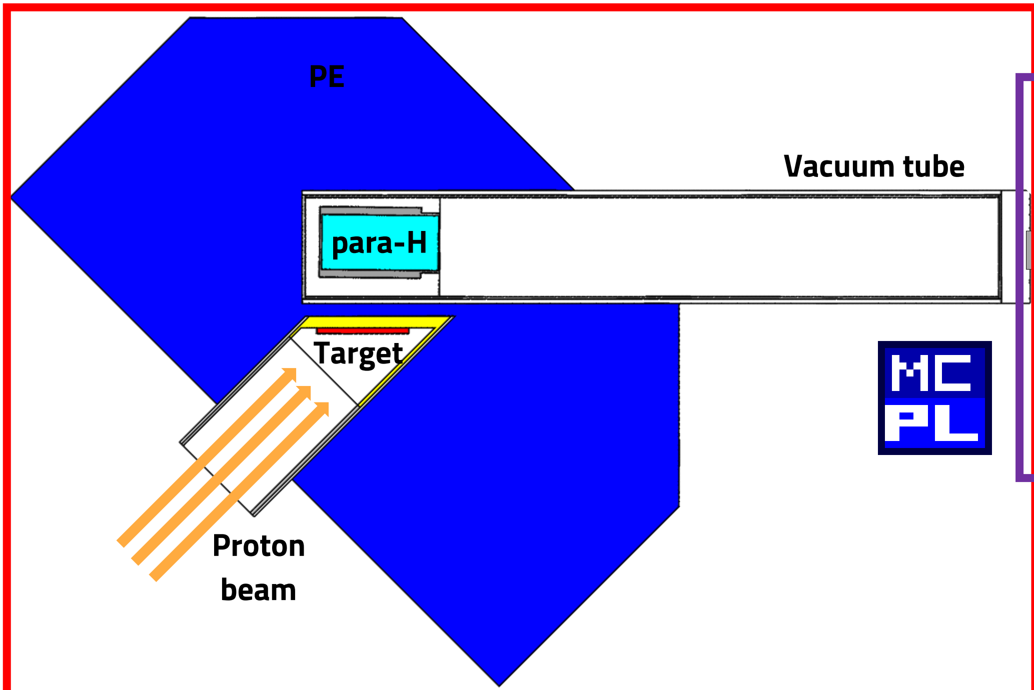




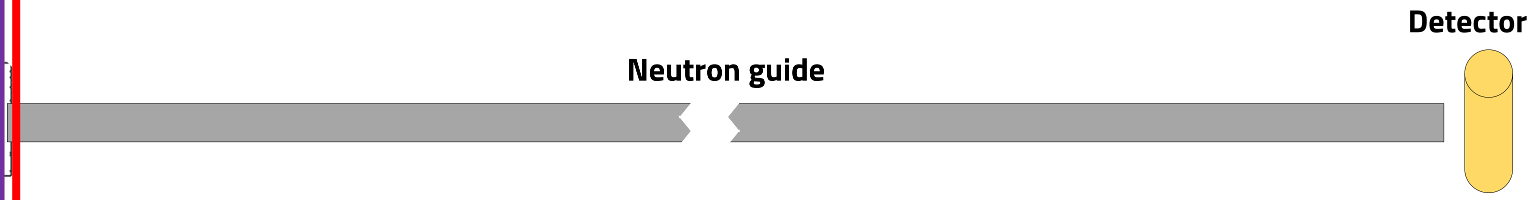




Validation of the simulations: codes used



MCPL



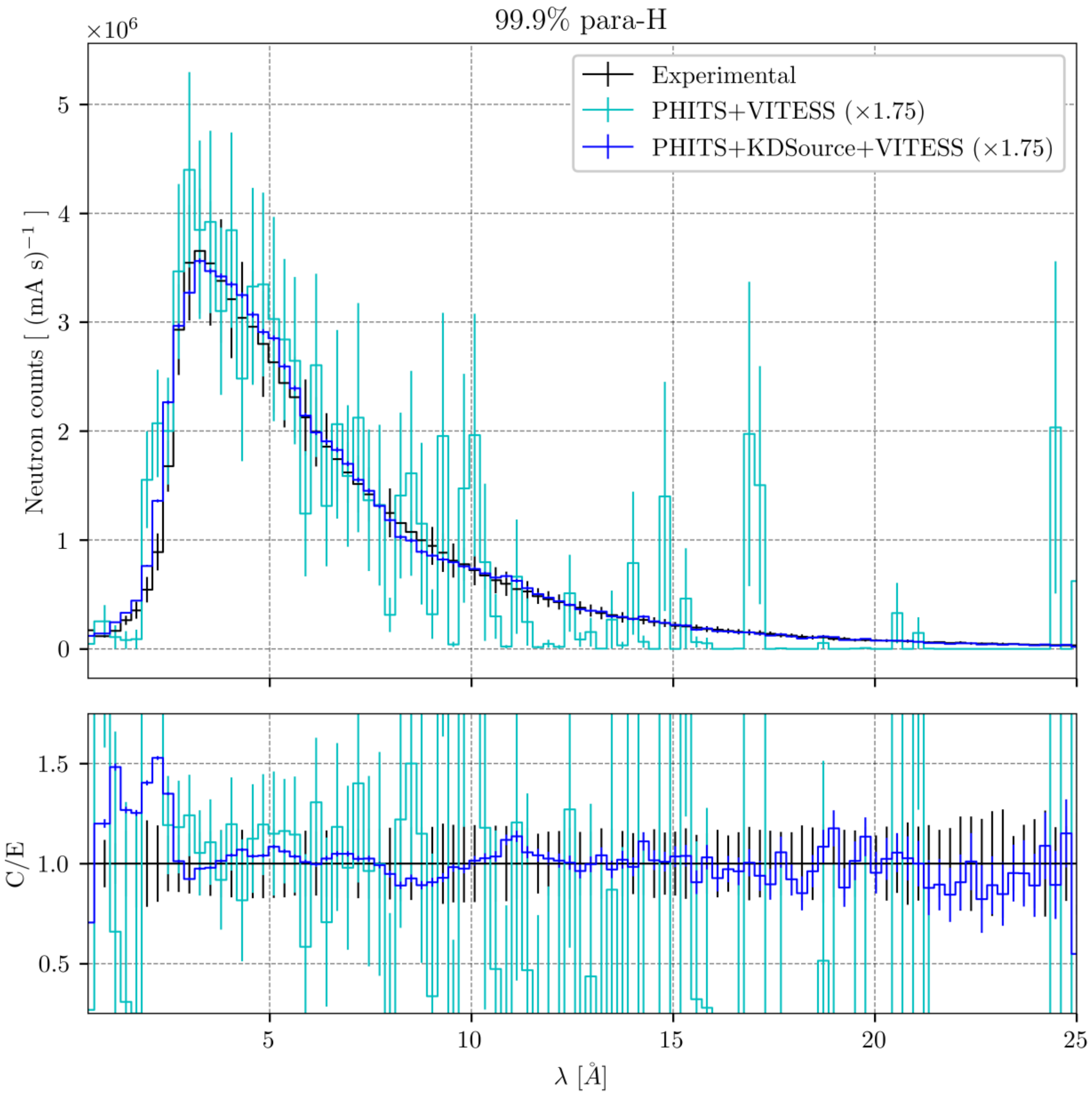
KDSource McStas VITESS

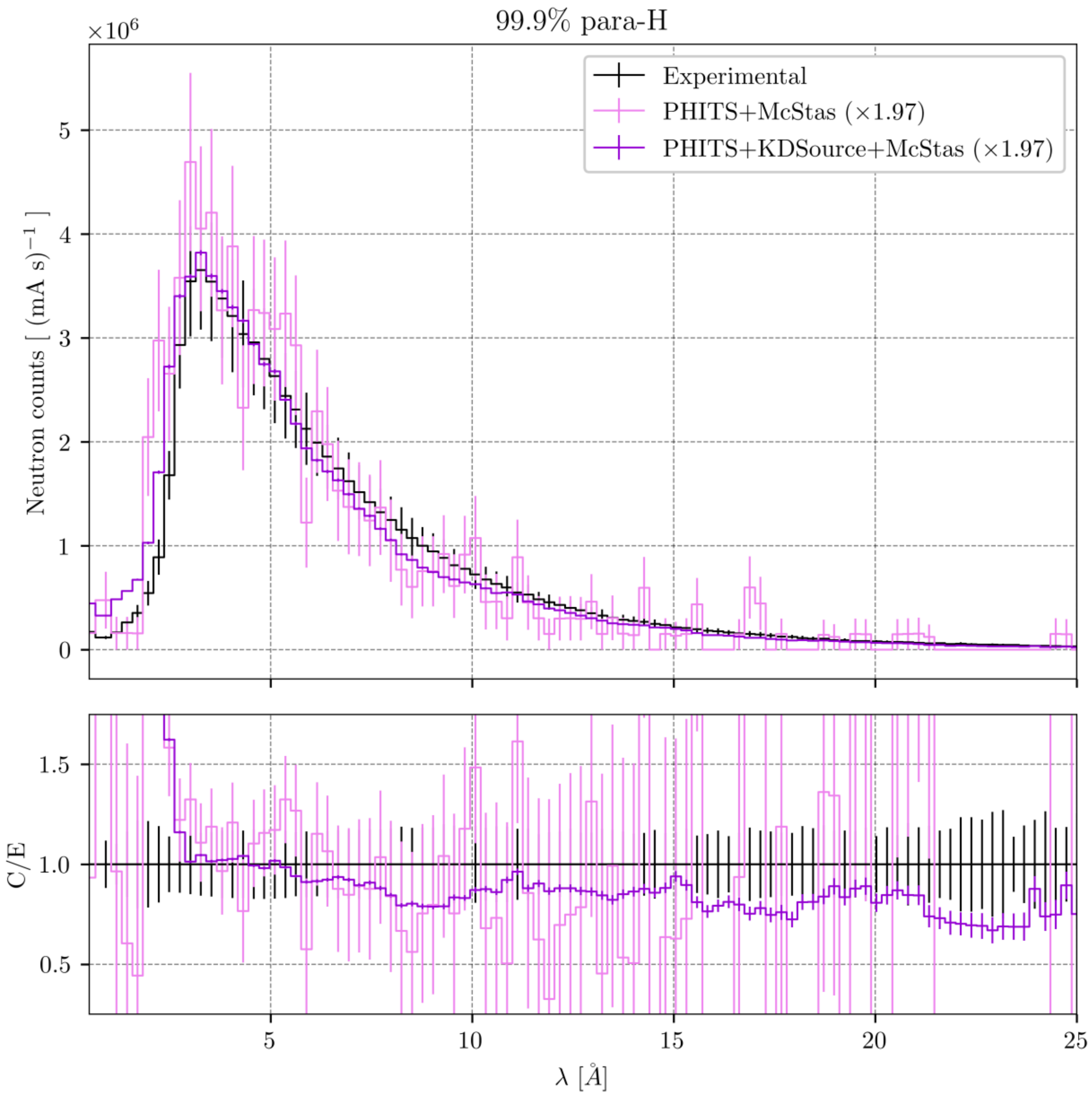
MCNP6 PHITS Particle and Heavy Ion Transport code System

ENDF B-VII.1 JENDL-5

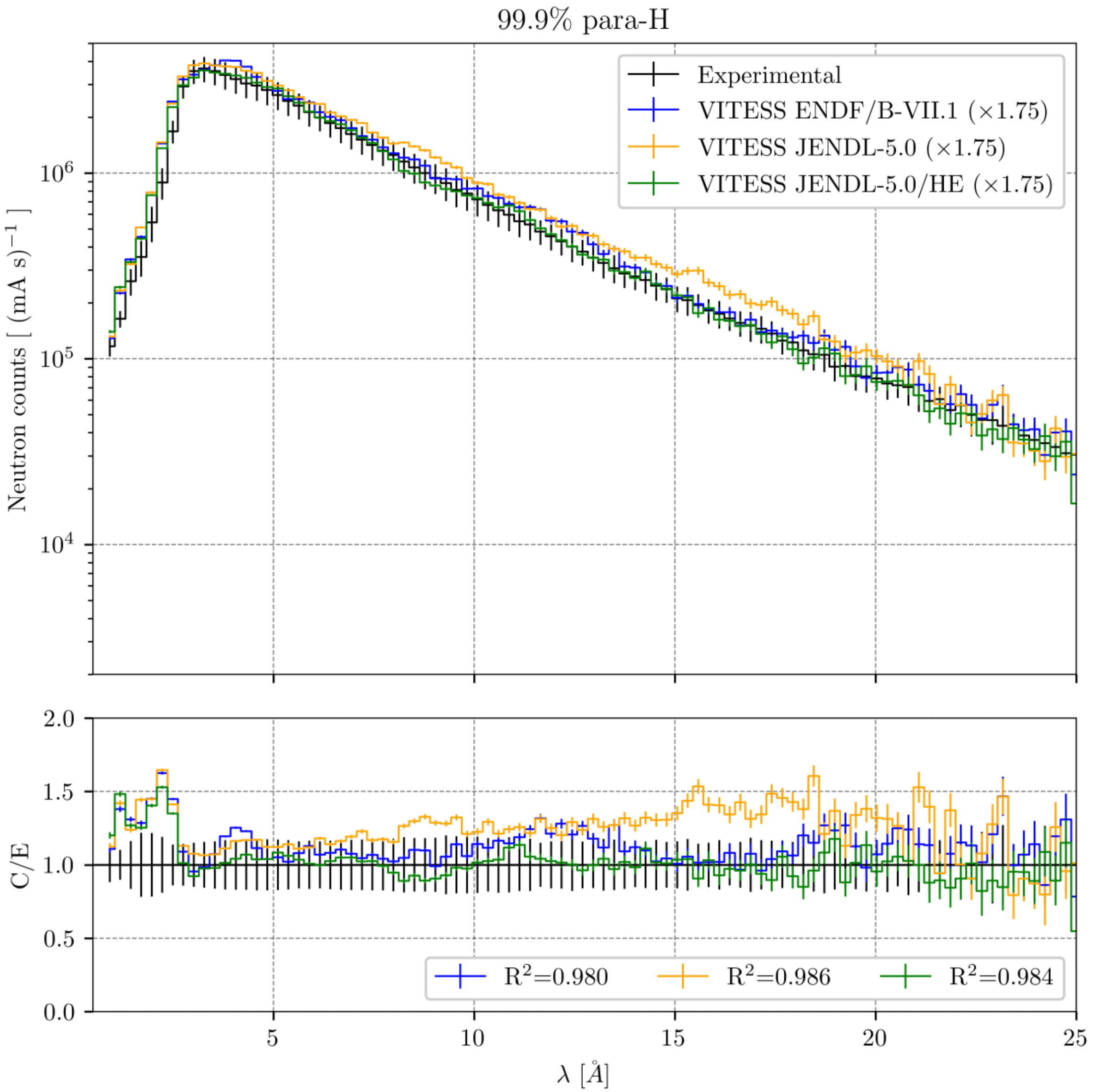
Objective: cross validate the simulations obtained by different Monte Carlo codes and nuclear data cross sections against the experimental time-of-flight measurements.

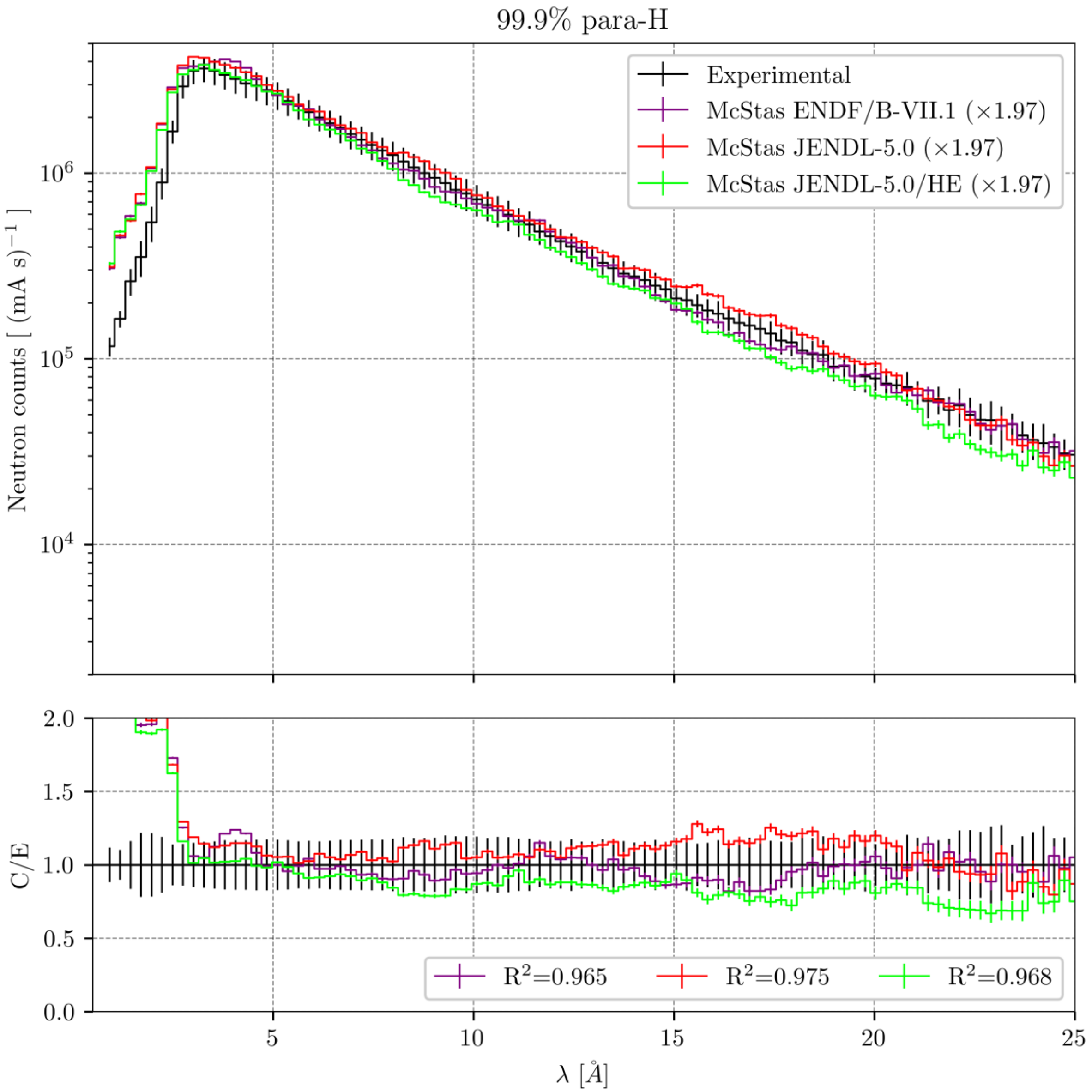
Validation of the simulations: VITESS and McStas using KDSource



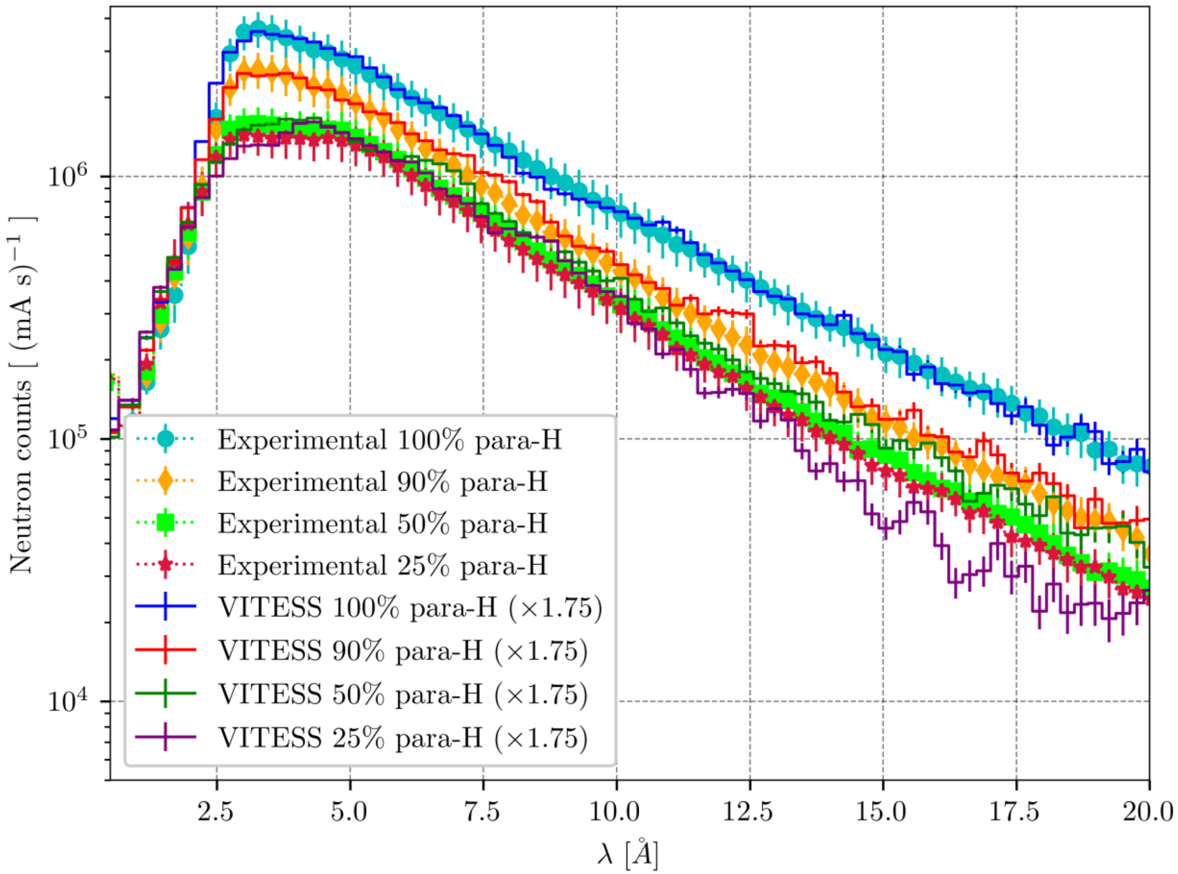


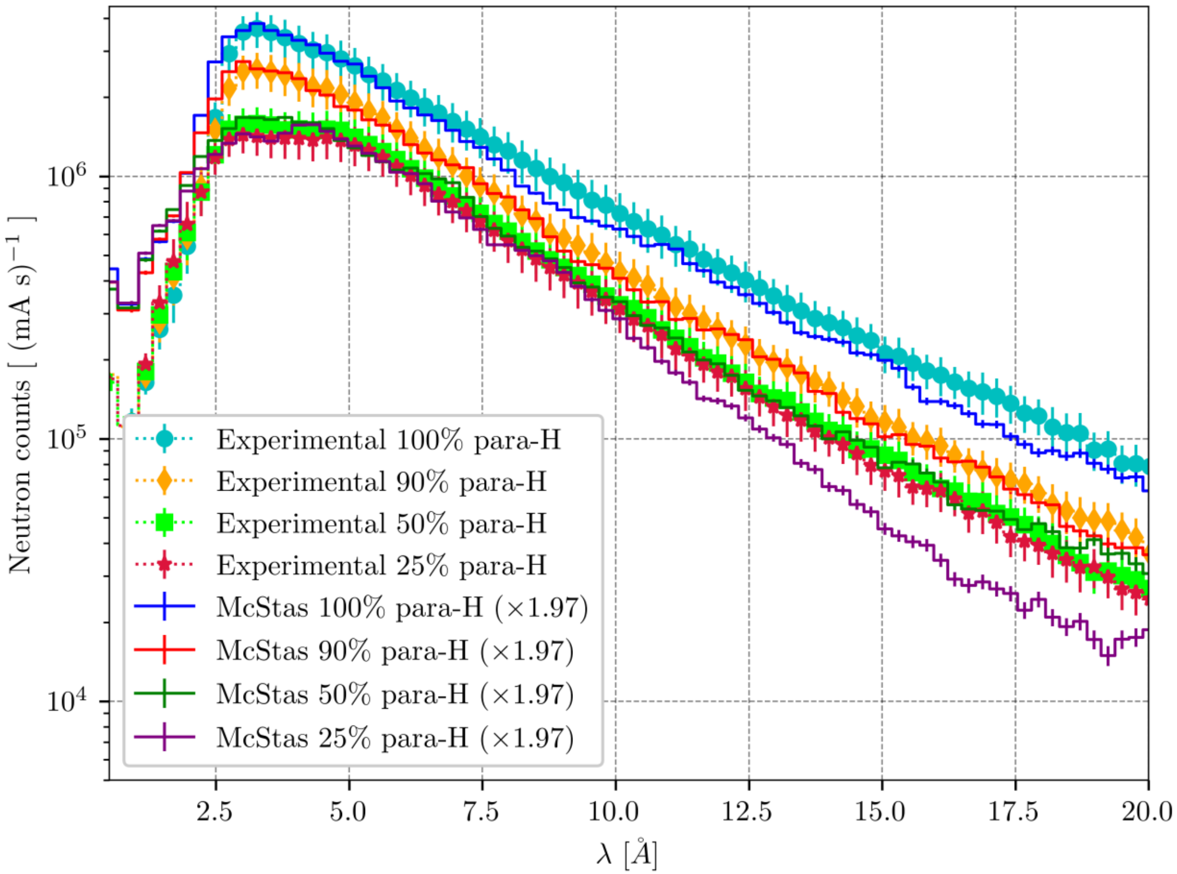
Validation of the simulations: VITESS vs McStas for different libraries





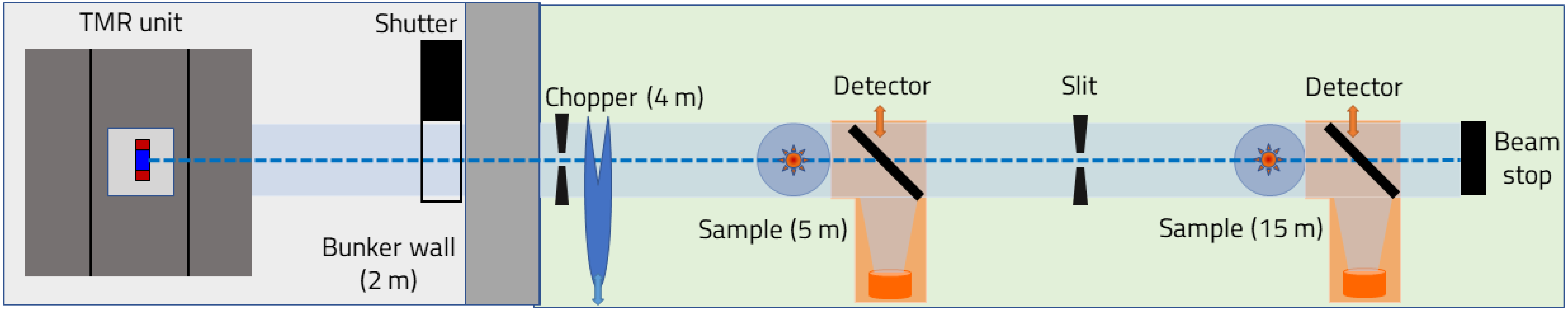
All para-H ratios: Experimental vs VITESS and McStas



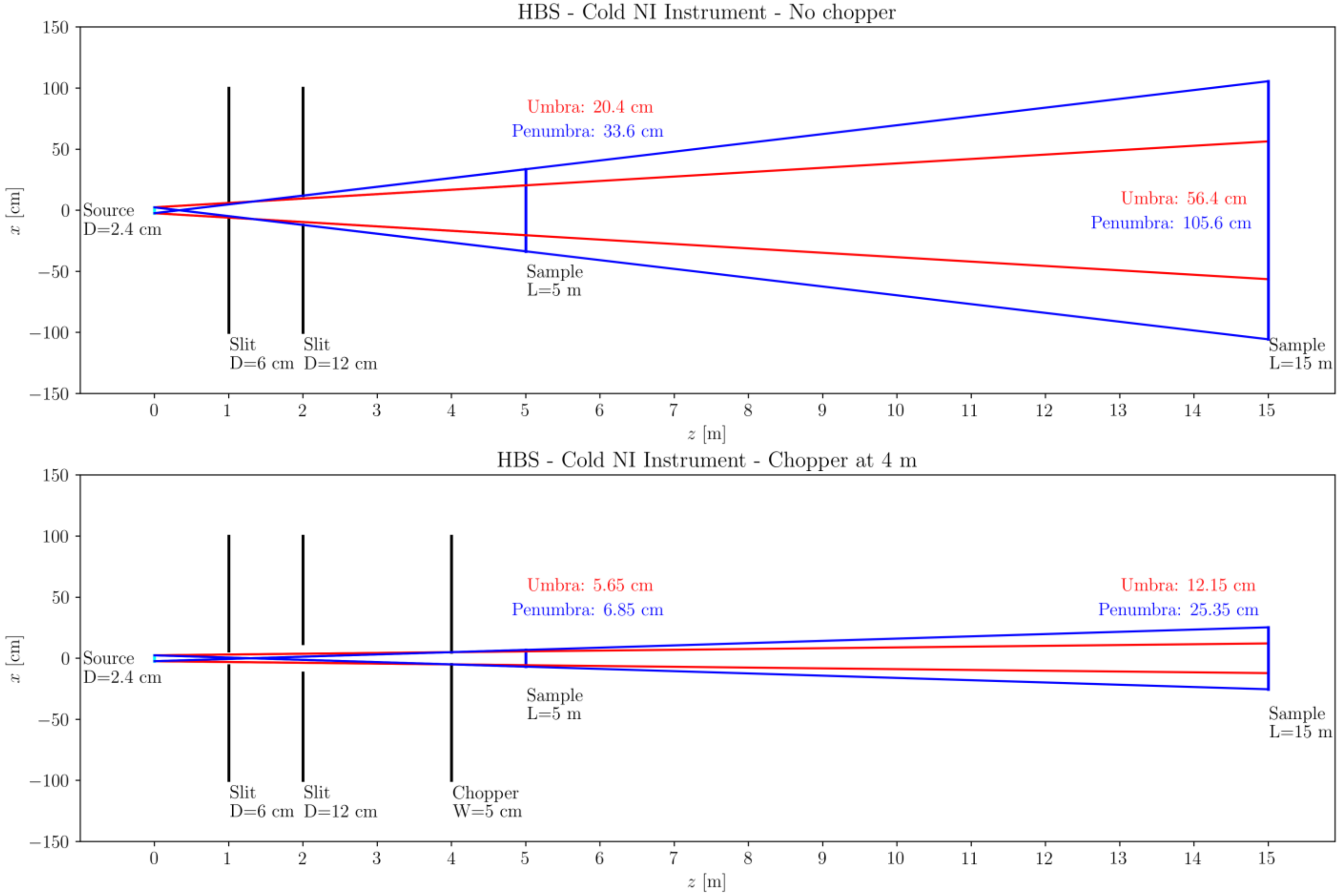


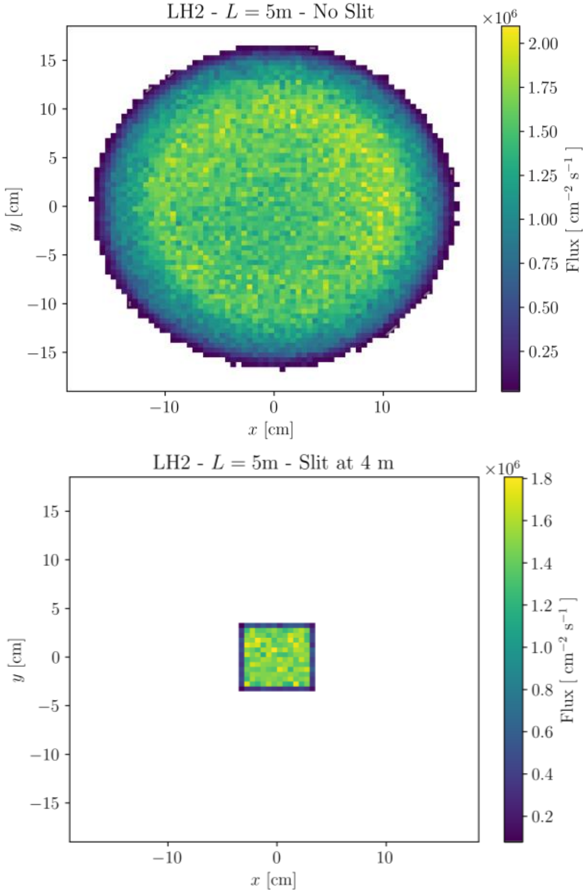
Preliminary Design: Cold Neutron Imaging Instrument

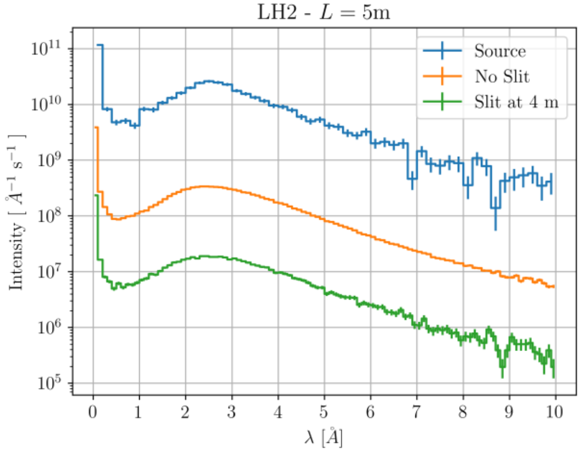
Instrument	Energy range	Wavelength range	Chopper	Guide	Sample positions [m]	Flux at sample [n/(cm² s)]	FOV [cm²]	Collimation L/D	Spatial resolution	Energy/wavelength resolution
Cold (96 Hz)	0-10 meV	>2.9 Å	Yes	No	5 15	$3x10^6$ $3x10^5$	5 x 5 15 x 15	200 625	High	1 - 15 Å / 8 Å, 5% 1 - 15 Å / 3 Å, 1%



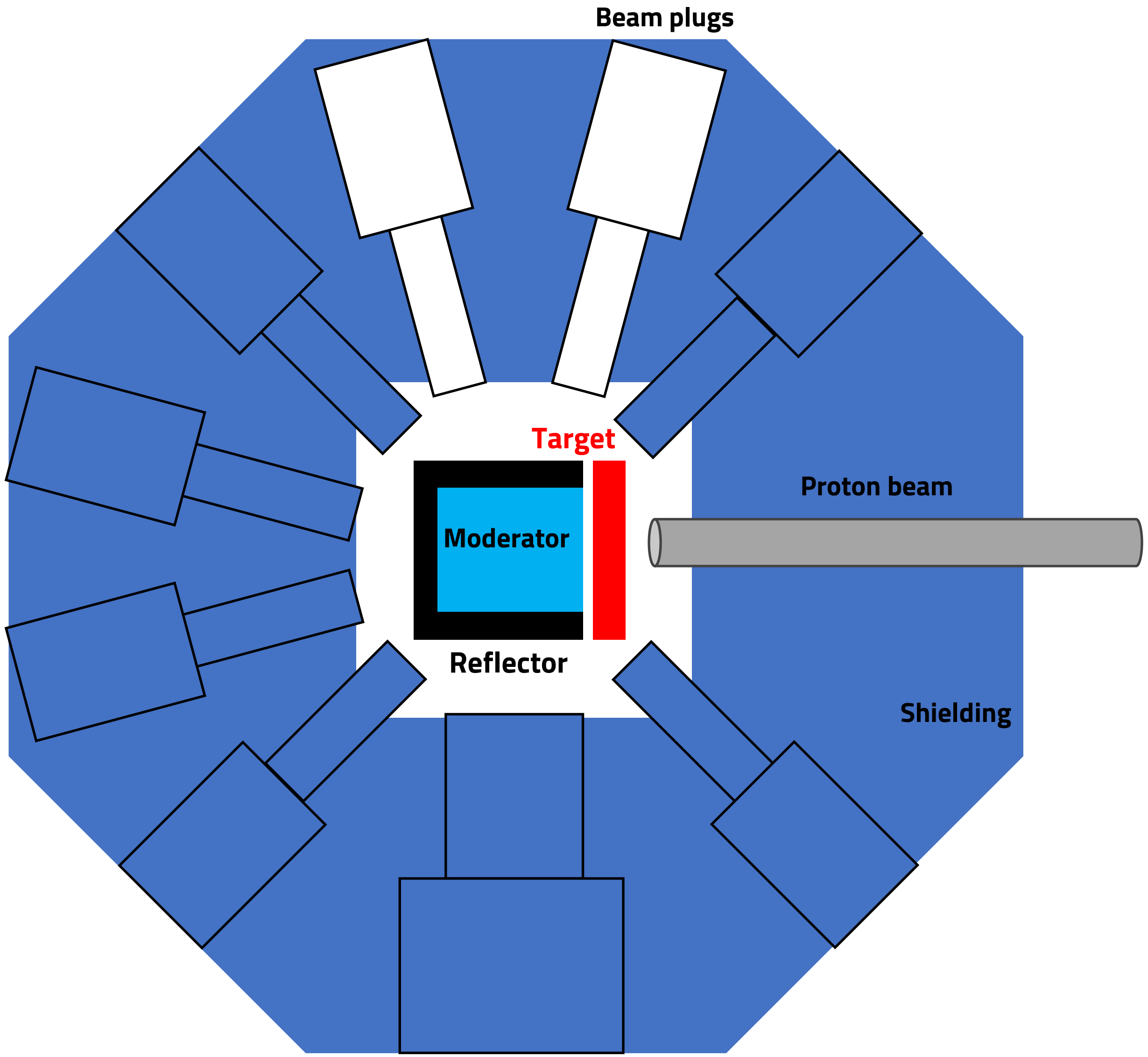
Preliminary Design: Simulations of the Cold Neutron Imaging Instrument





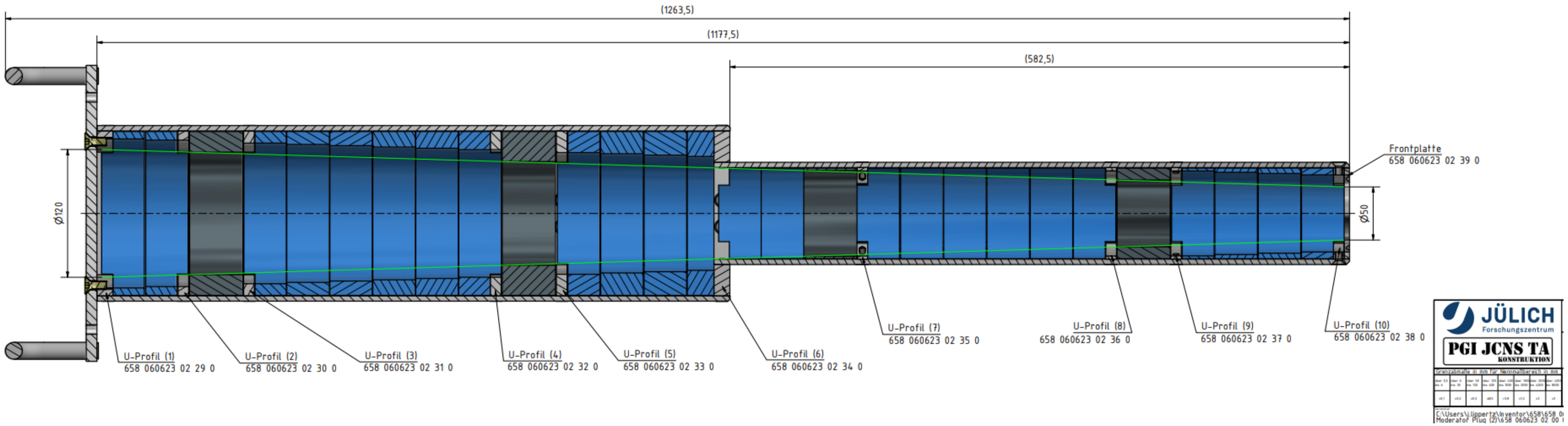


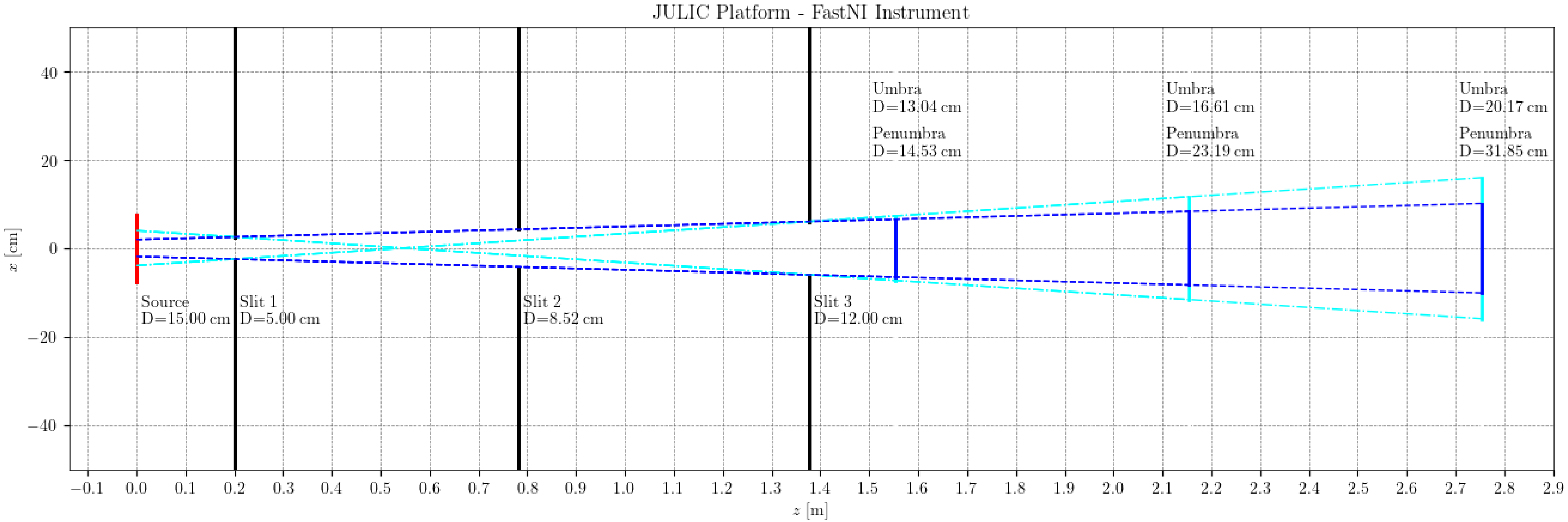
Prototype Development: Experimental Setup at the JULIC Platform



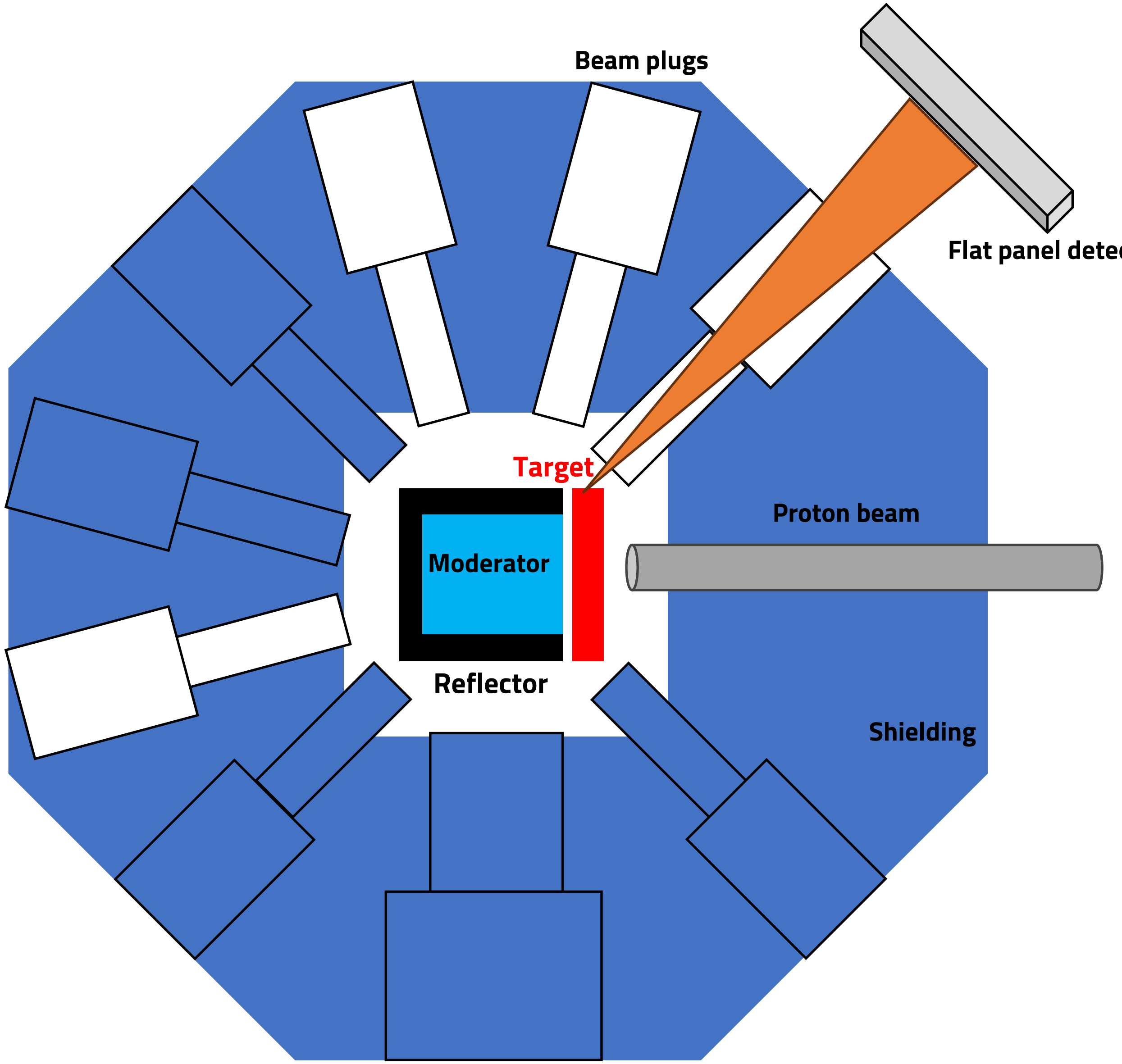
Photography of the JULIC platform.

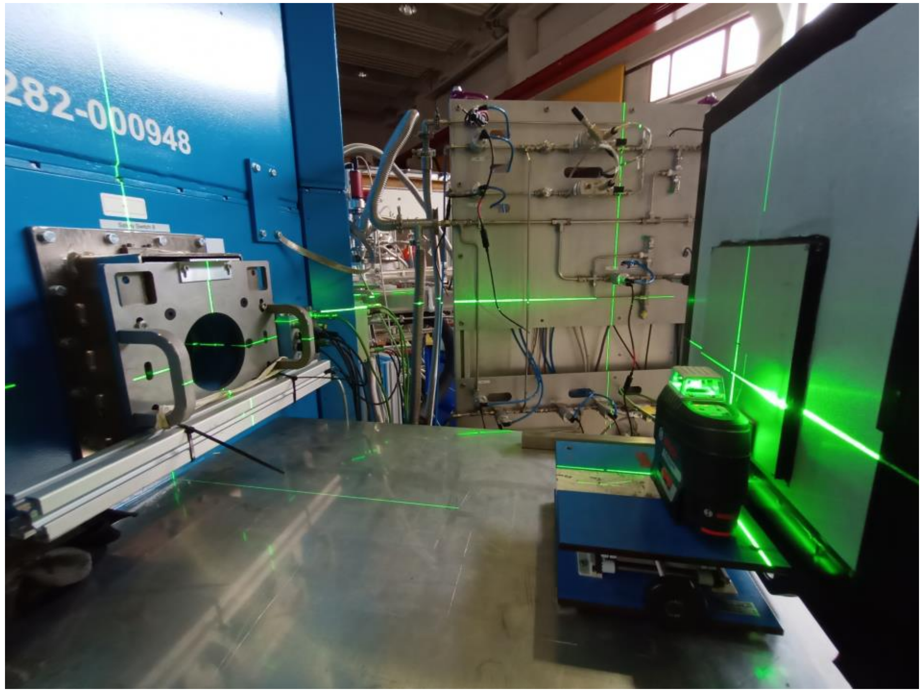
Prototype Development: Experimental Setup at the JULIC Platform





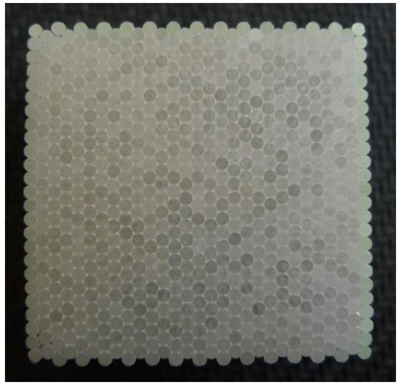
Prototype Development: Experimental Setup at the JULIC Platform





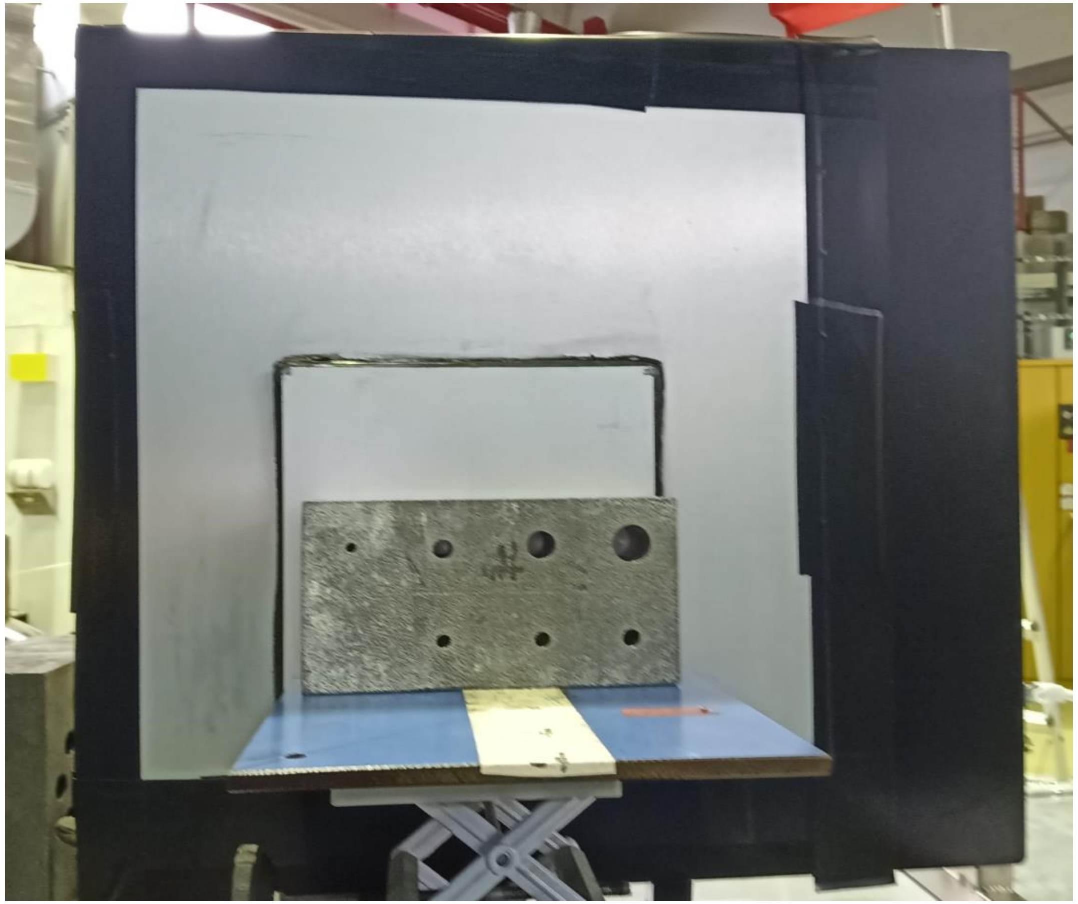
Photography of the Fast Neutron Imaging setup.

Plastic scintillator (40 x 40 cm²)

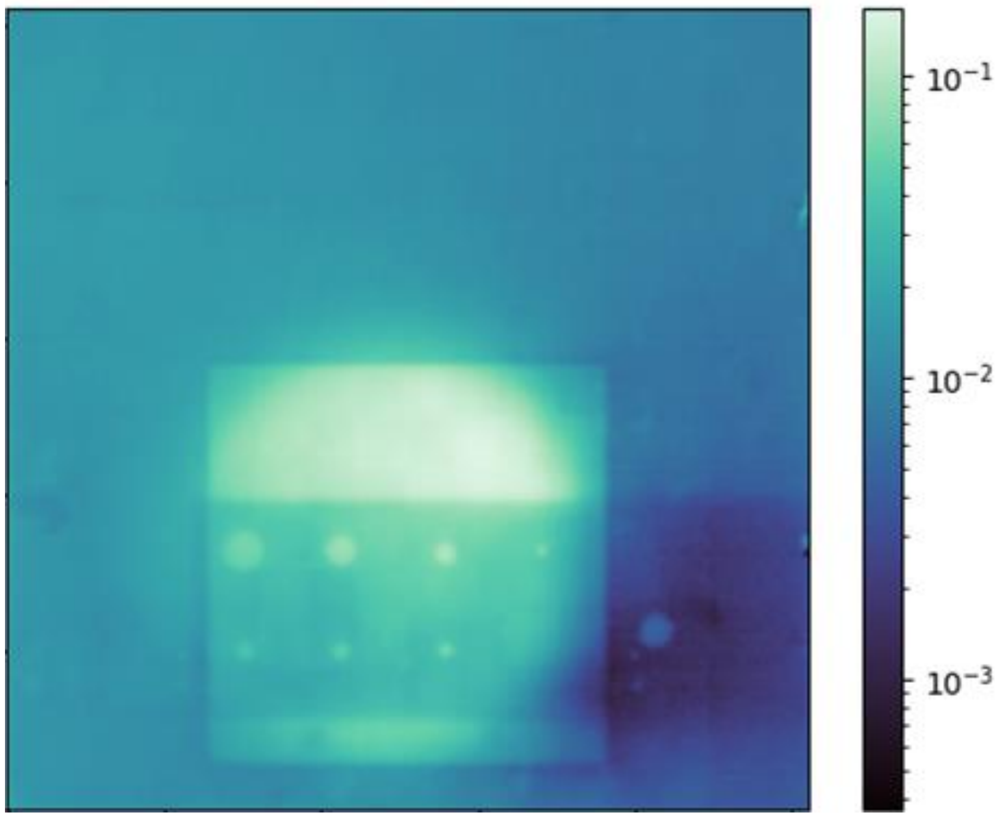


Scintillating fibers (20 x 20 cm²)

Prototype Development: Experimental Setup at the JULIC Platform

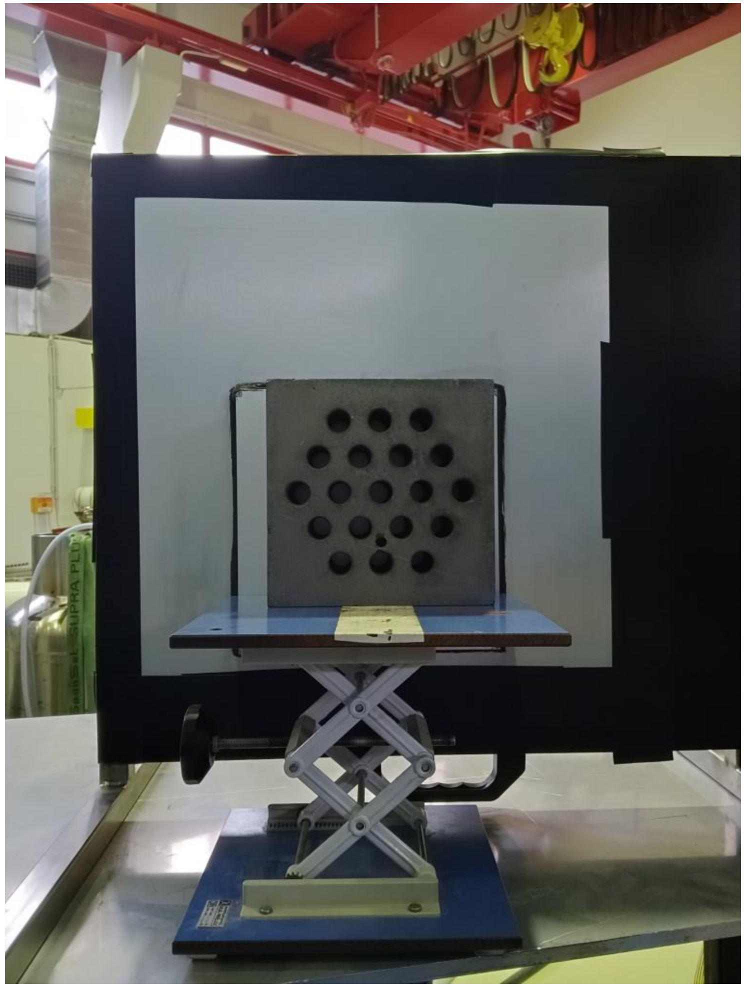


Flat panel detector with a lead brick as a sample.



First image obtained with the lead brick (continuous source)

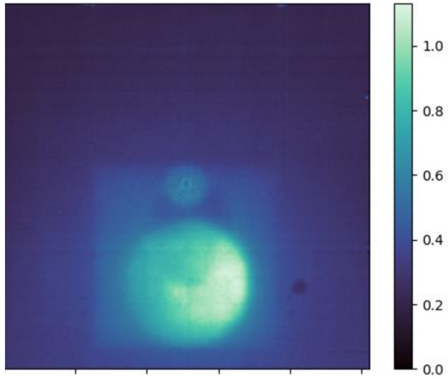
Prototype Development: Experimental Setup at the JULIC Platform



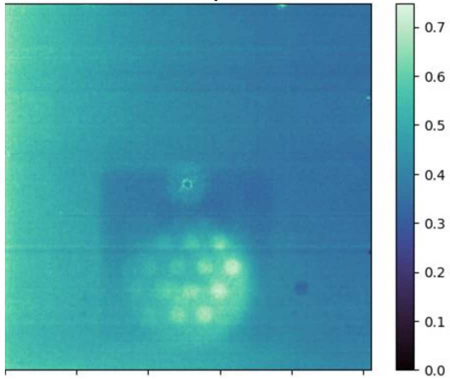
Flat panel detector with a graphite block as a sample.

$$I = I_0 \cdot e^{-\Sigma \cdot \Delta x} \Rightarrow \log\left(\frac{I_{white\ beam} - I_{offset}}{I_{sample} - I_{offset}}\right) = \Sigma \cdot \Delta x$$

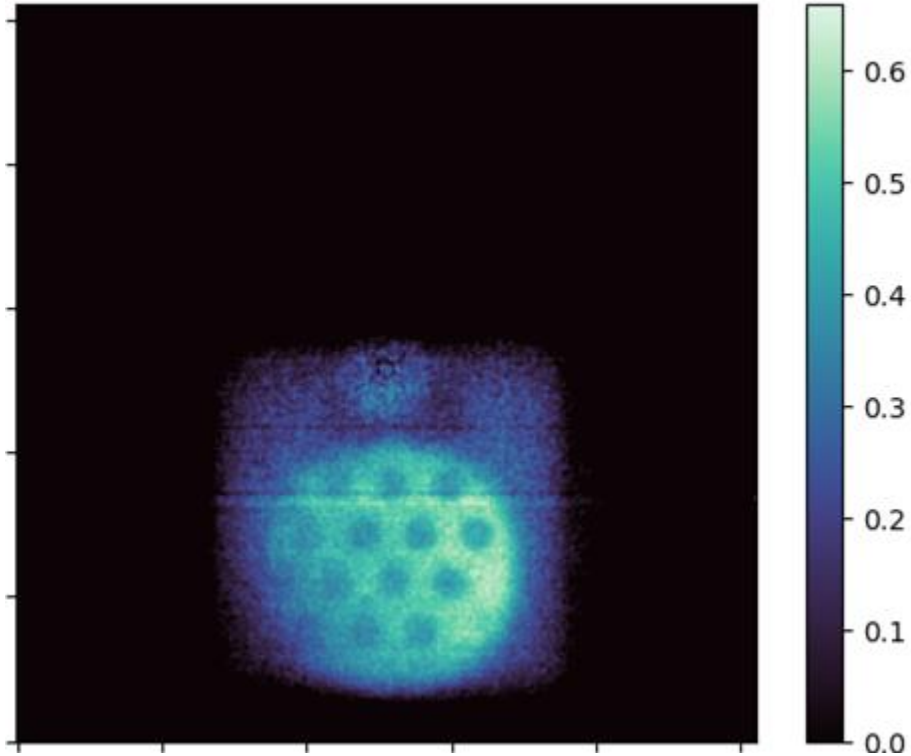
White beam



Sample



Attenuation result



Future Work

General objective: Design and optimize instruments for time-of-flight cold, thermal and epithermal neutron imaging, within the framework of the High Brilliance Neutron Source (HBS) project at the Jülich Centre for Neutron Science (JCNS)

1) Baseline study → 2) Source simulations → 3) Instruments design → 4) Prototype development → 5) Prototype testing

1) Baseline study

NI instruments to be considered:
- MLZ (Germany)
- BER-II (Germany)
- PSI (Switzerland)
- ISIS (UK)
- J-PARC (Japan)
- LANL (USA)
- RA-6 (Argentina)

2) Source simulations

- HBS model simulations with Monte Carlo codes
- Validation of the codes
- Cold and thermal neutron spectra analysis
- Epithermal and fast spectra development

3) Instruments design

- Instruments simulations with VITESS and McStas
- Neutron optics
- Cold and thermal instruments
- Epithermal and fast instruments

4) Prototype development

- Collimator development
- TMR for epithermal and fast neutrons
- Detectors development

5) Prototype testing

- Test of optical components and ToF settings at the JULIC platform
- Data analysis of the experiments

Future Work

1) Optimization of the TMR design for epithermal neutrons

2) Simulation of the cold lines with a neutron guide inside the TMR channel

3) Design of the Neutron Imaging instruments with KDSource, McStas and VITESS

a) Variables to optimize: L/D, homogeneity, flux, frame overlap

b) Instruments to simulate: choppers, neutron guides, pinholes

4) Analyse the experimental data obtained from the last beam-times at the JULIC platform

References

- [1] Kardjilov, N. (2019). Neutron imaging. Oxford School on Neutron Scattering.
- [2] Kardjilov, N., Manke, I., Woracek, R., Hilger, A., & Banhart, J. (2018). Advances in neutron imaging. Materials Today, 21(6), 652-672.
- [3] PSI (2011). Neutron Imaging at the spallation source SINQ: information for potential users and customers. Technical report.
- [4] International Society for Neutron Radiography (2019). Neutron Imaging Facilities Survey. Technical report.
- [5] Lehmann, E. H., Vontobel, P., Frei, G., Kuehne, G., & Kaestner, A. (2011). How to organize a neutron imaging user lab? 13 years of experience at PSI, CH. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 651(1), 1-5.

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- Engineering

IKP-4:
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A. Lehrach
M. Rimmler
R. Similon
- Nuclear physics

INM-5:
B. Neumaier
- Radio isotopes

S. Böhm
J.P. Dabruck
R. Nabbi
- Nuclear simul.

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Ch.Haberstroh
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S. Eisenhut
- AKR-2, liquid H_2

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GSI / HIM
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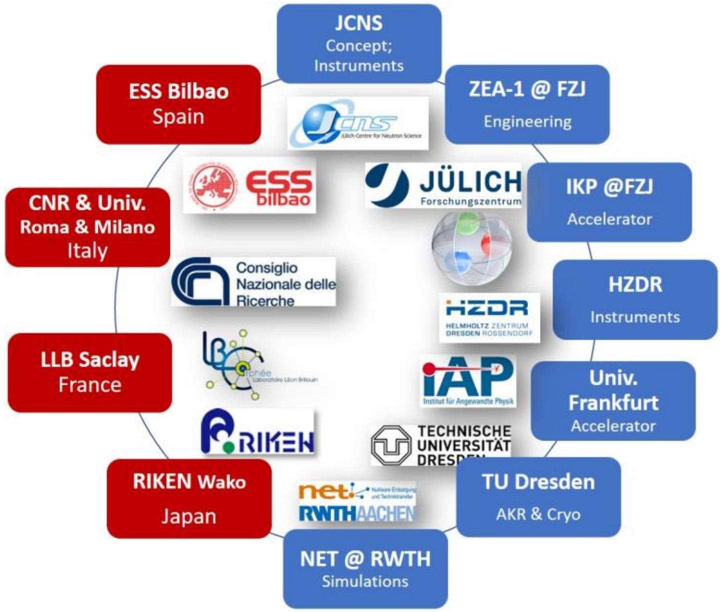
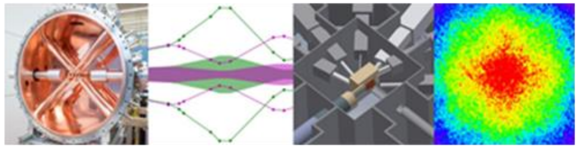
A. Wolfertz
- JULIC Neutron Platform Experiments



HBS Innovationpool Project

Federal Ministry of Education and Research



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