EUROfusion

Design of Gas Electron Multiplier detector as a compact neutron spectrometer to fusion devices

ICFDT7, Frascati | 21 – 23 October 2024

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- **Motivation:**

Neutrons emitted from a deuterium/tritium fusion plasma are the main signature of the nuclear fusion process and some important plasma parameters. Different measurement methods can be used:

- Time resolved neutron yield monitor
- Activation system
- Neutron profile camera
- Neutron spectrometer

Introduction

❑ Motivation:

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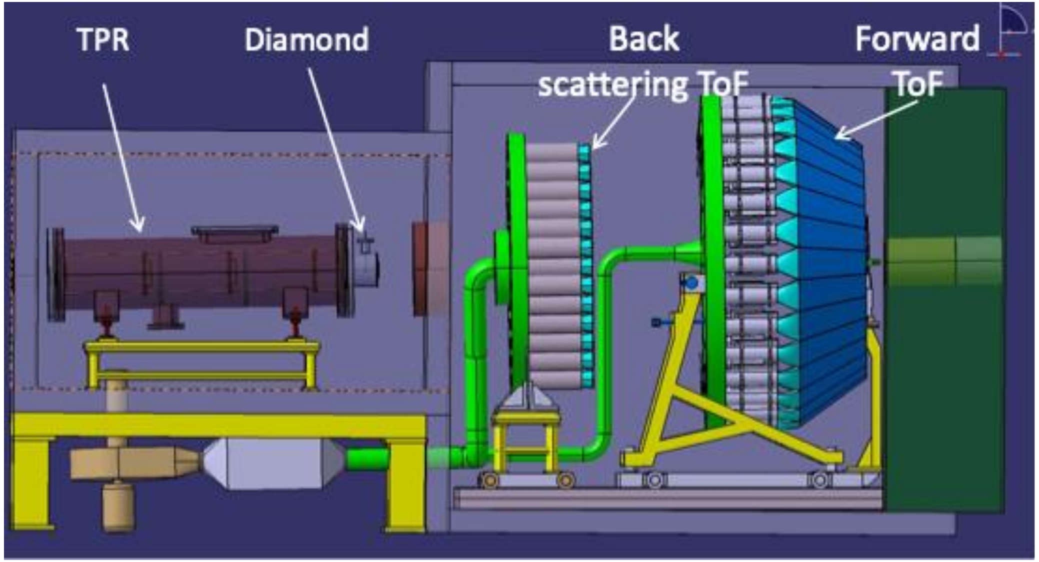
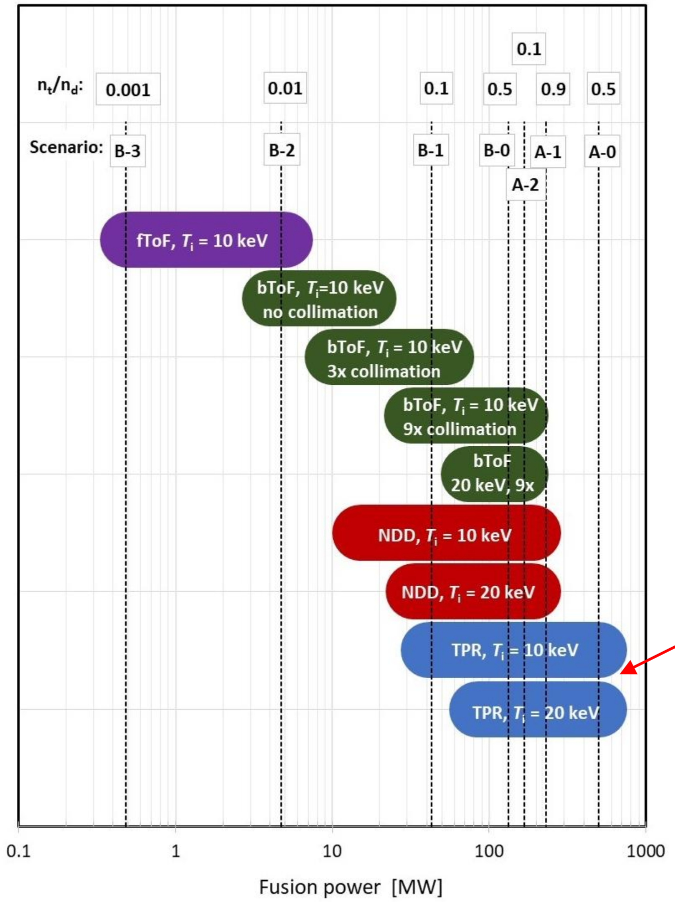
❑ Function of High-Resolution Neutron Spectrometer (HRNS) for the ITER tokamak:

- Primary: Prediction of fuel ion ratio n_T/n_D with uncertainty of less than 20% for a measurement time window of 100 ms
- Supplementary: fuel ion temperature measurement with uncertainty less than 10% for a measurement time window of 100 ms

To fulfill the requirement on n_T/n_D for a fusion power range of 0.5 to 500 MW, four different neutron spectrometers are proposed. The set of neutron spectrometers suggested for the HRNS system are as follows:

- **Thin Proton Recoil (TPR)**
- **Neutron Diamond Detectors**
- **Back-scattering Time-of-Flight (bToF)**
- **Forward Time-of-Flight (fToF)**





[M. Scholz et al. (2019) Nucl. Fusion 59 065001]

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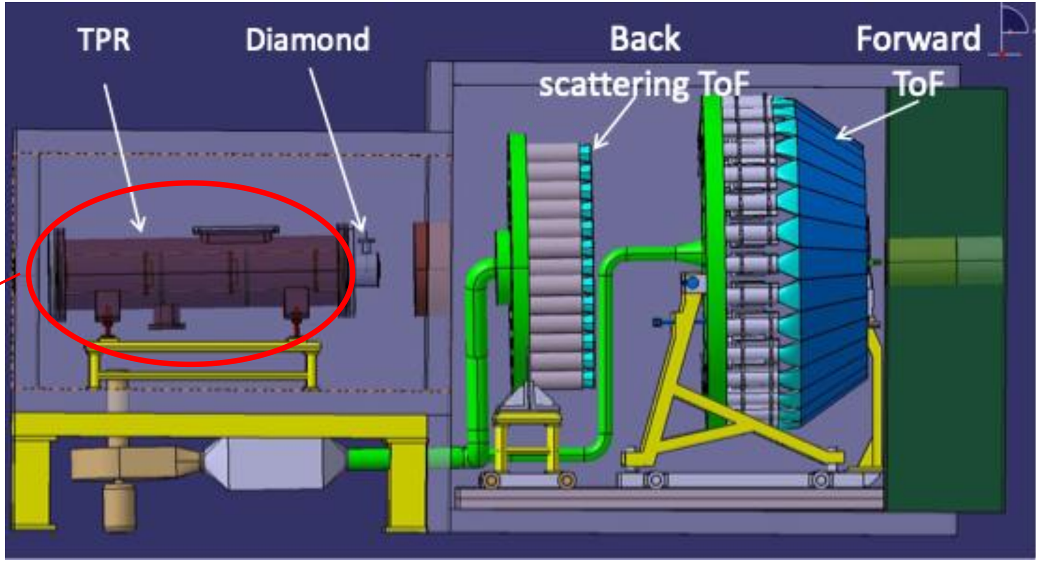
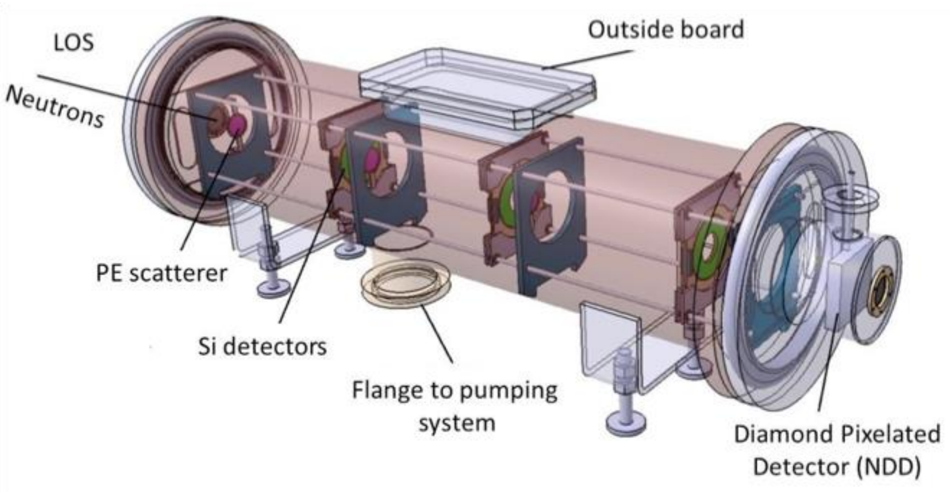


Thin-foil Proton Recoil (TPR)

- **TPR spectrometer of ITER** equipped with annular silicon (Si) detectors.
- Polyethylene (PE) foils used as neutron-proton convertor.
- Three PE-Si detection systems placed along the LOS, under vacuum.



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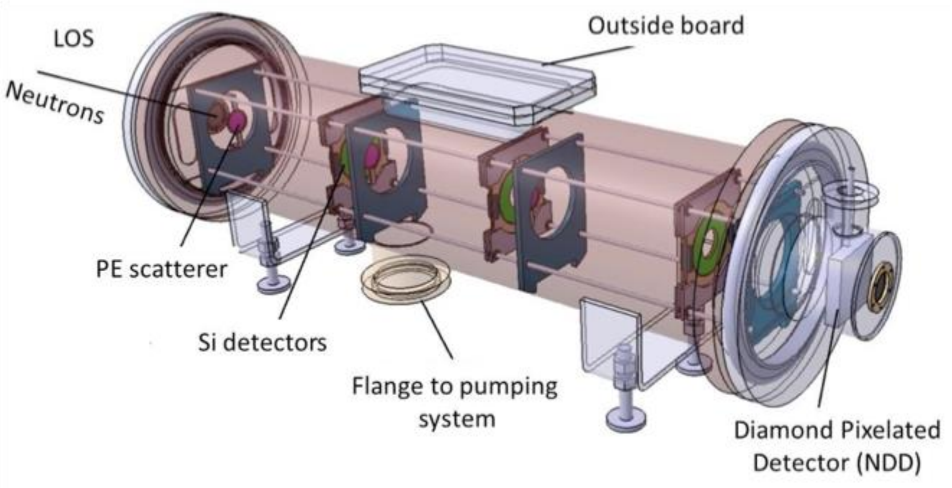
Recoil protons are directed toward the Si detector behind the PE foil, where it generates a signal (pulse height) proportional to its energy.



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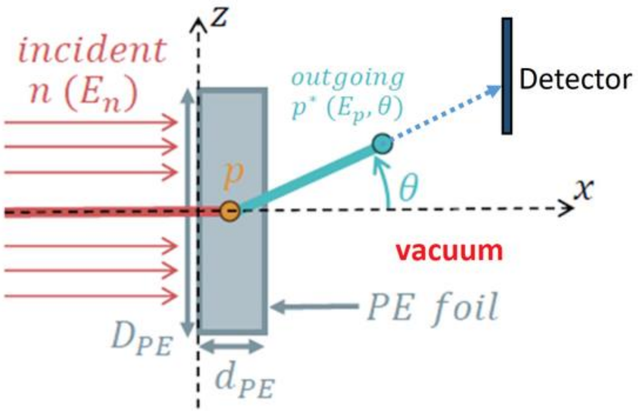
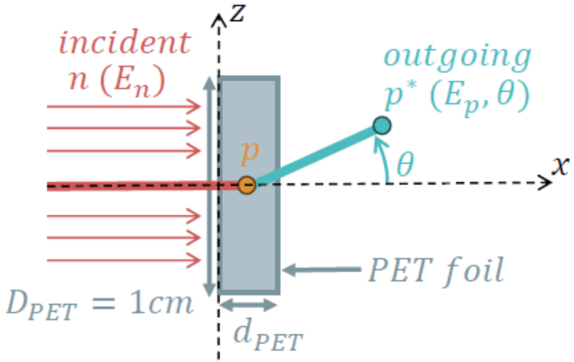


$$E_n = \frac{E_p}{\cos^2 \theta}$$

Basic idea of compact NS-GEM detector: estimate energies of protons from TPR by measuring their specific energy losses dE/dx and record proton tracks in the GEM active volume, to then reconstruct the energy spectrum of incident neutrons.

Thin-foil Proton Recoil (TPR)



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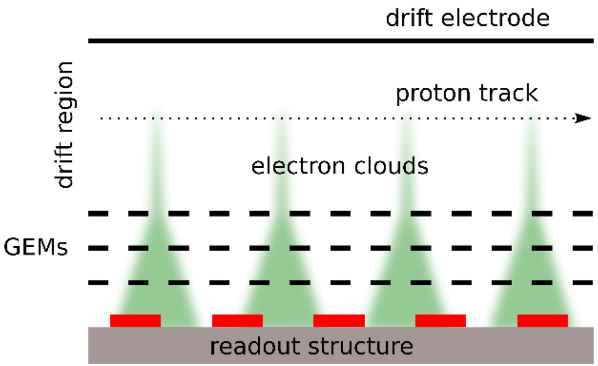
Gas Electron Multiplier (GEM)



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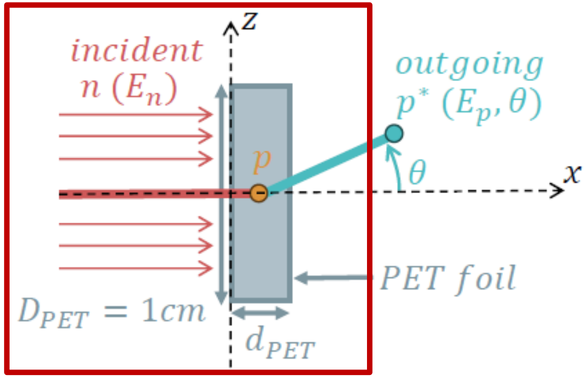

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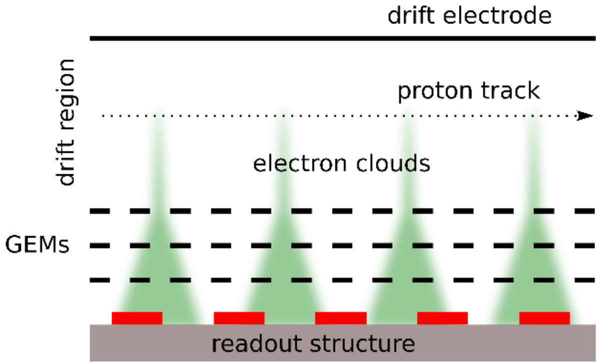

Detection idea:

- Neutron collimation
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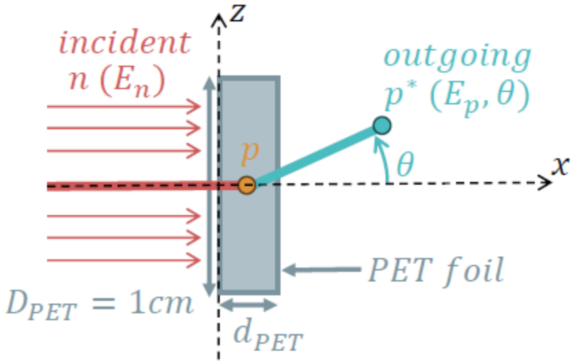

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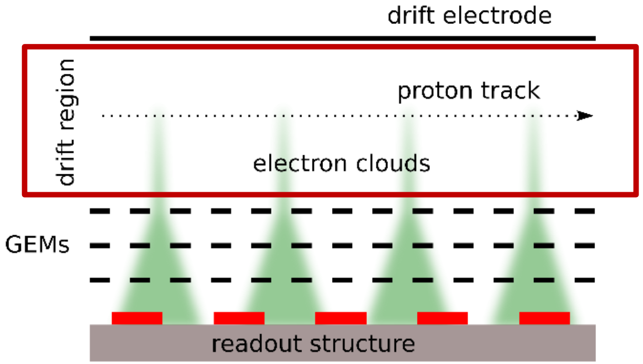

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- Reconstruction of whole proton track for recoil angle and energy loss measurement

Neutron Spectrometer based on GEM (NS-GEM)

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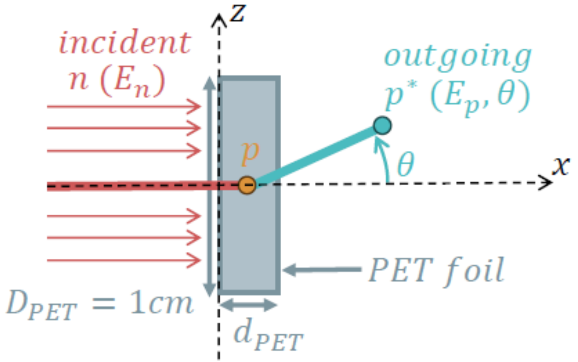

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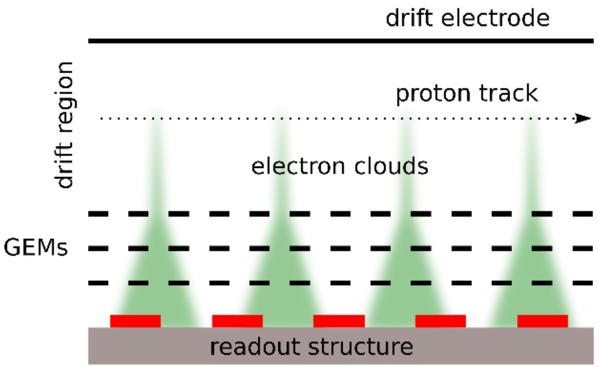

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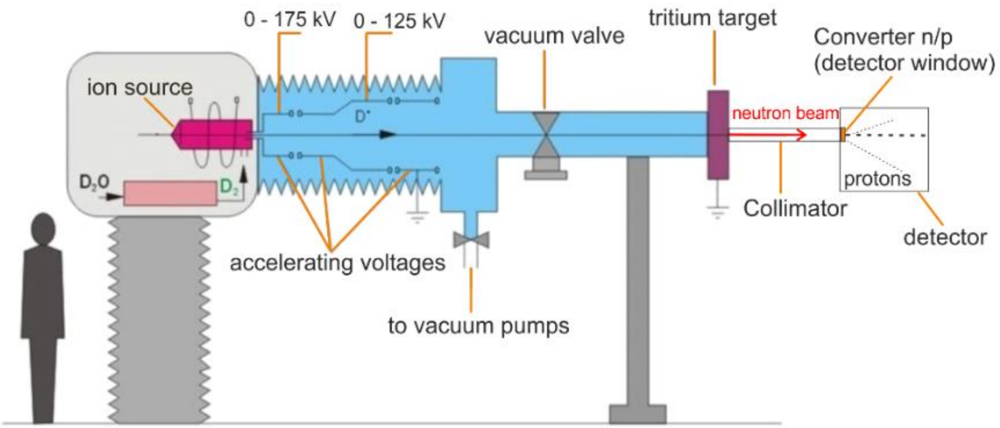
- Proton passing through the GEM drift region
- Reconstruction of whole proton track for recoil angle and energy loss measurement
- Reconstruction of initial proton energy E_p from *dE/dx* (energy loss) calibration curve
- Calculation of neutron energy based proton energy E_p and scattering angle θ

NS-GEM experiments at IGN-14 (IFJ PAN, Krakow)



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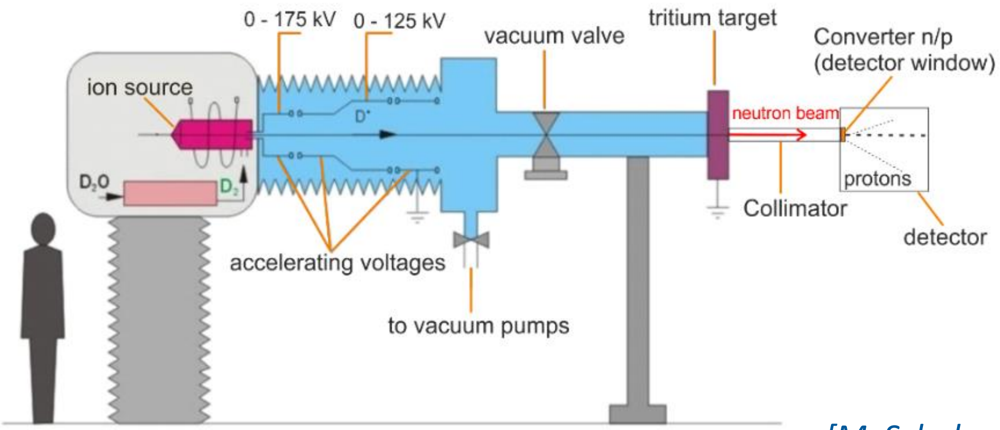

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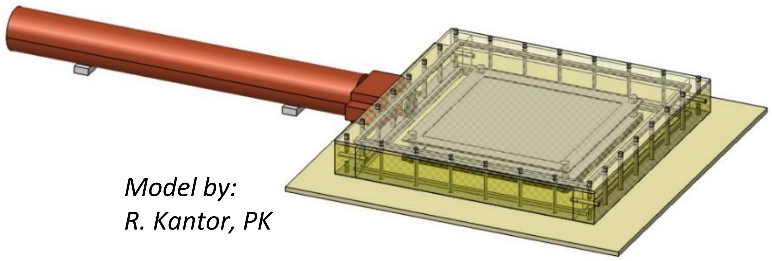

Model by:
R. Kantor, PK

[M. Scholz et al, JINST 2023]

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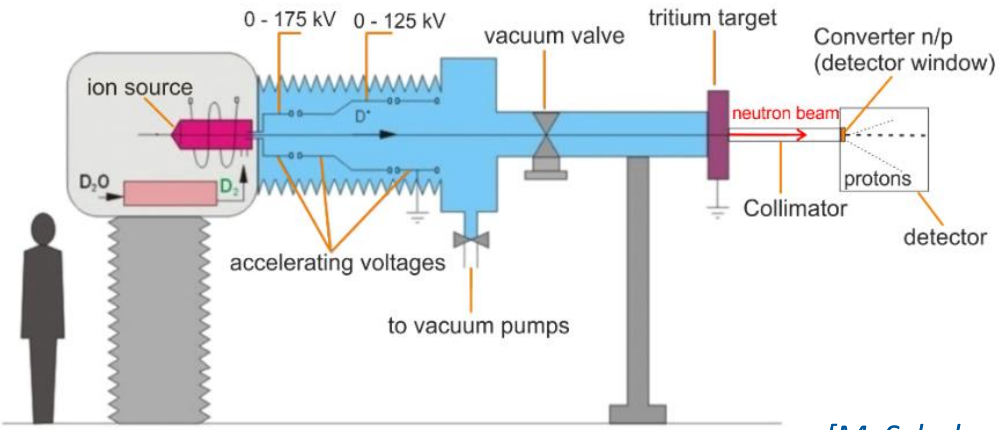

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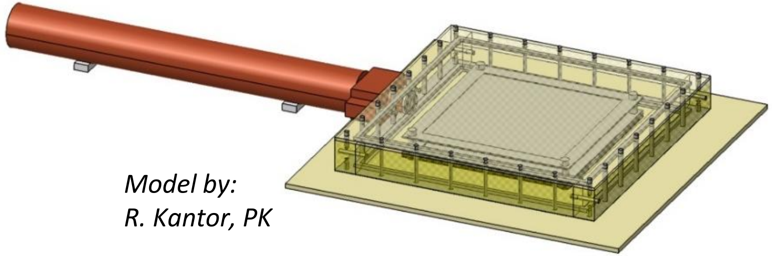

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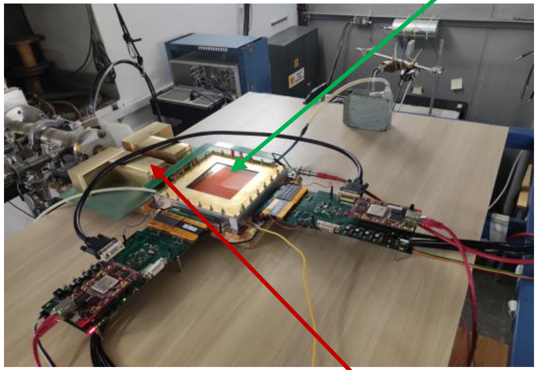
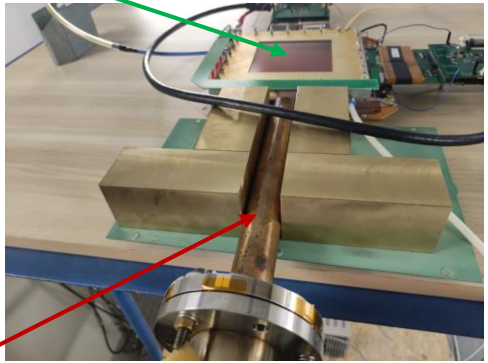
GEM detector

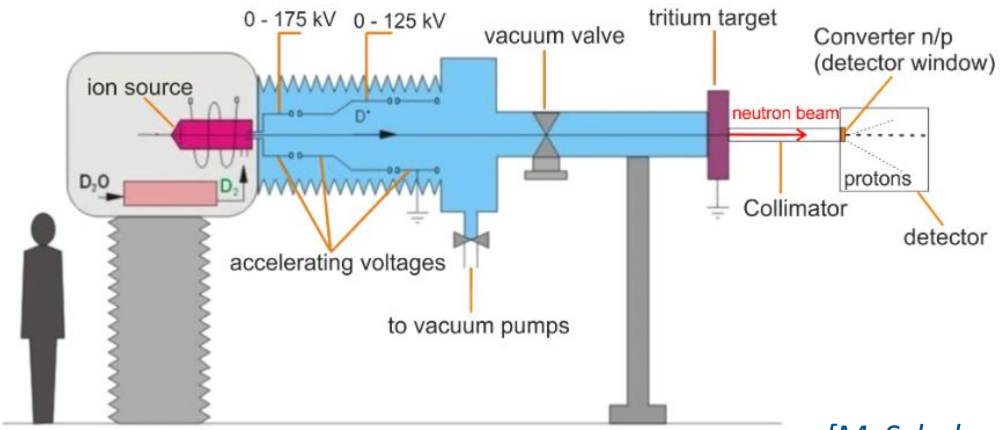




Collimator

Neutron source

NS-GEM experiments at IGN-14 (IFJ PAN, Krakow)



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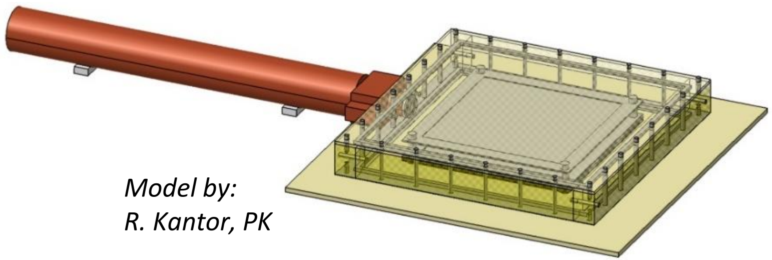

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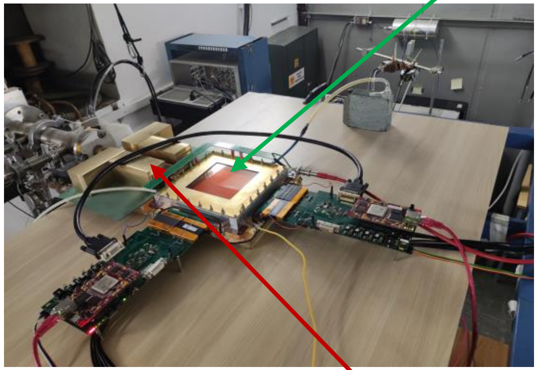

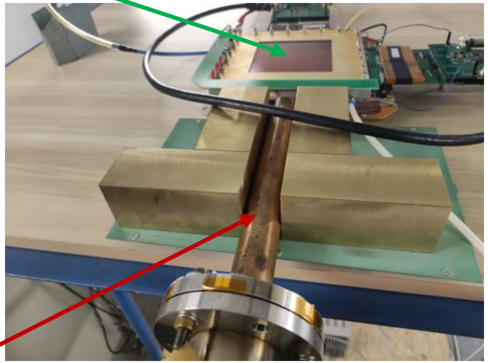

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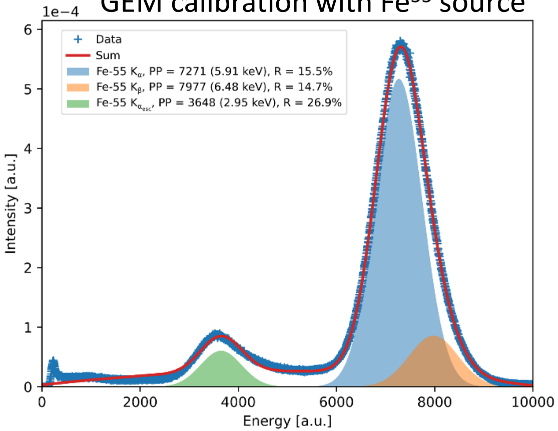
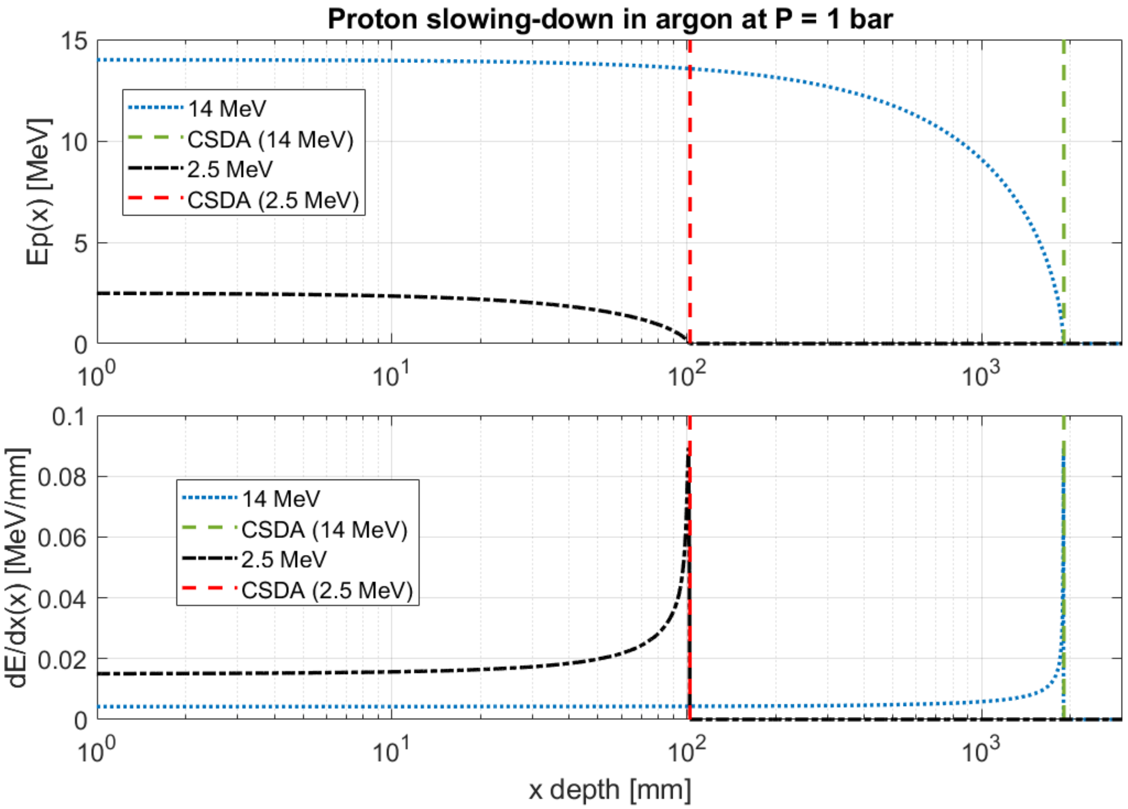
Neutron source

GEM calibration with Fe^{55} source



Proton Bragg curve & measurement strategy

- "Compact" 10 × 10 cm NS-GEM detector: high-energy protons (14 MeV) cannot be fully slowed-down in the GEM.



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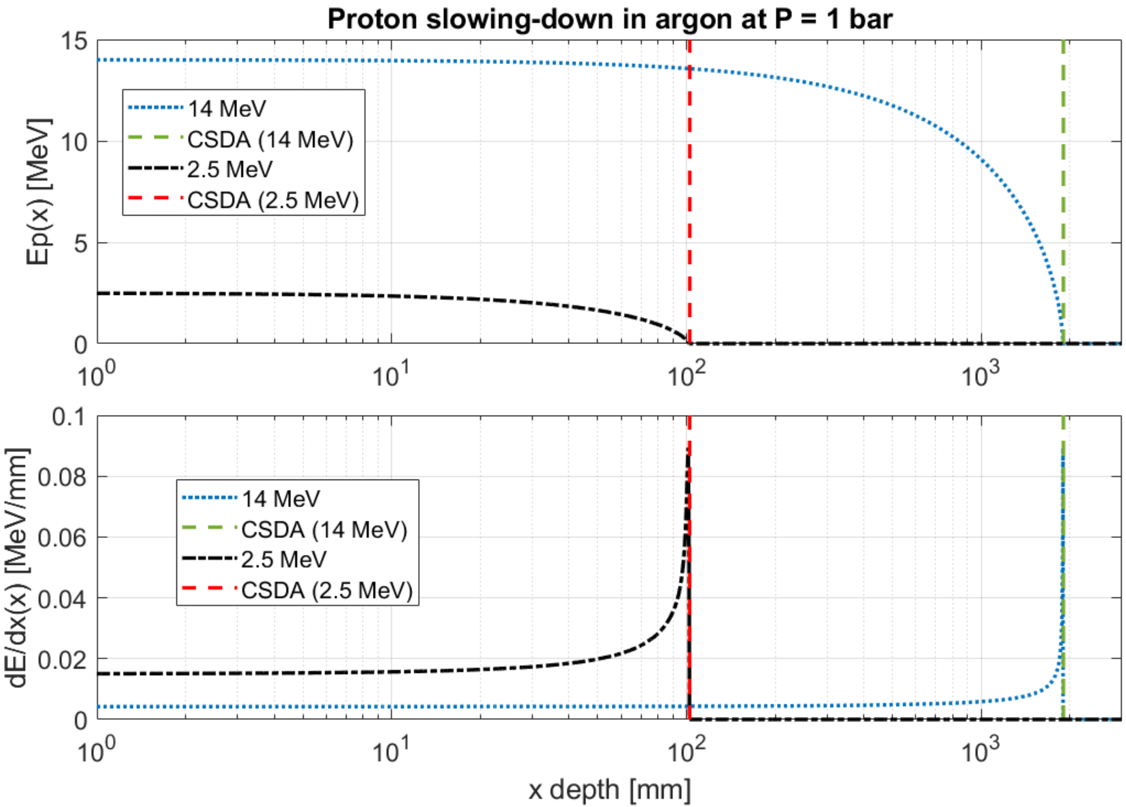
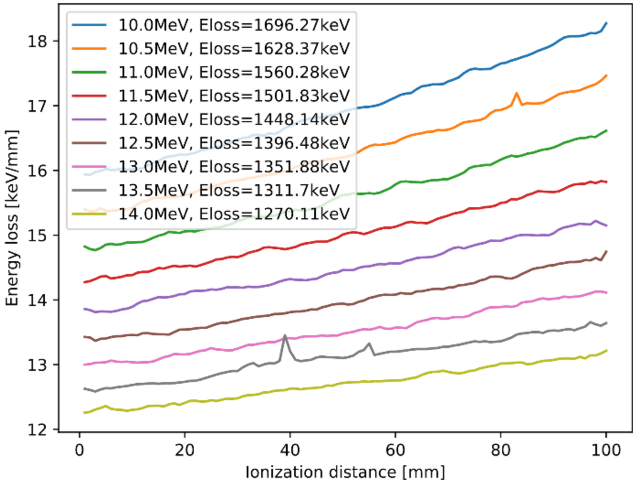


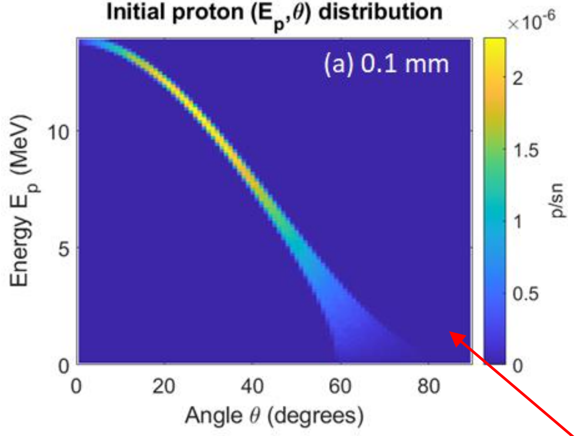


dE/dx approach

Partial absorption before the Bragg peak

Polyethylene (PE) foil - neutron→proton conversion

- Conversion rate and proton energy-angle distribution exiting the polyethylene (PE) foil:



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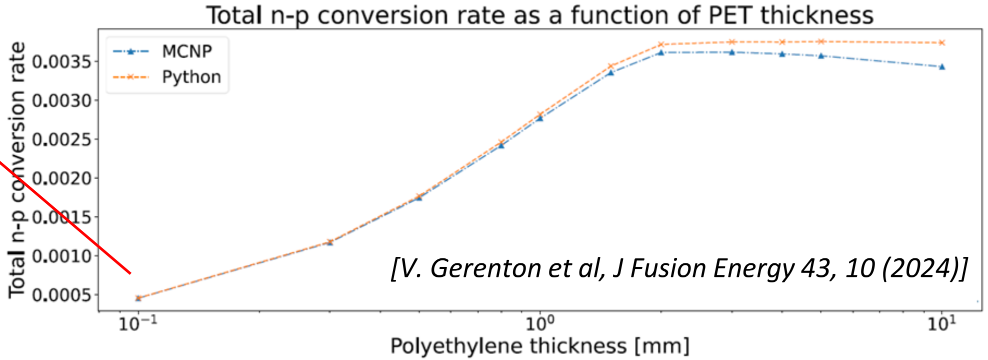

[V. Gerenton et al, J Fusion Energy 43, 10 (2024)]

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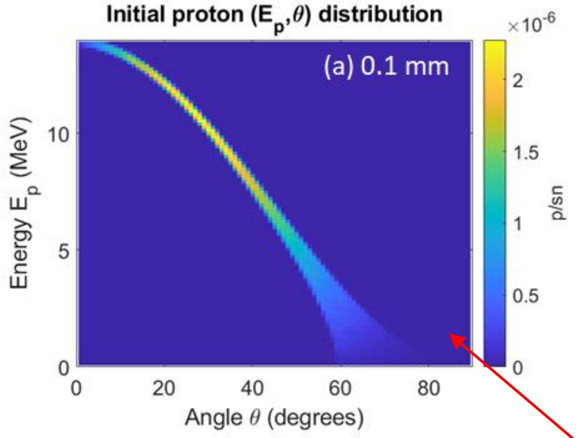

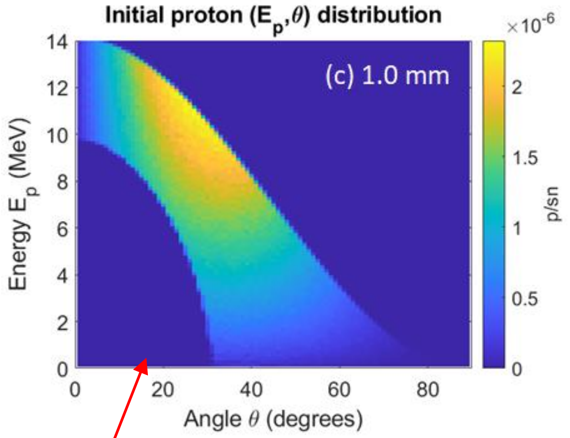

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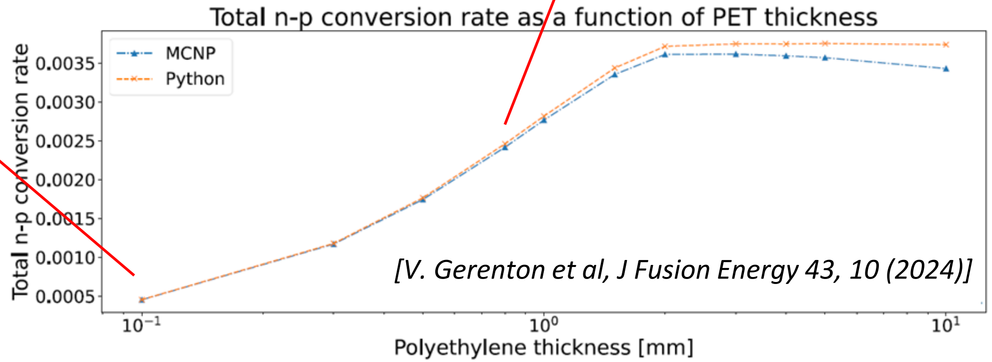

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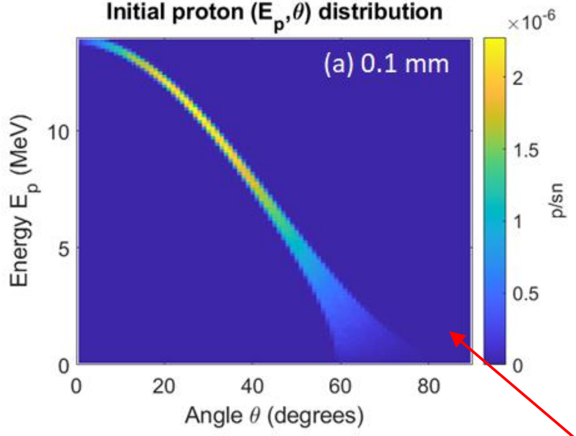

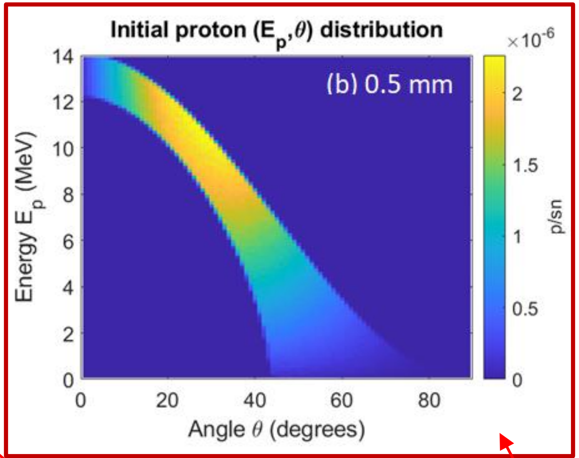

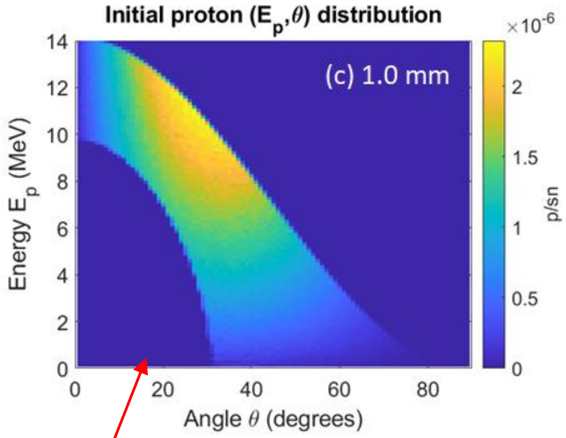

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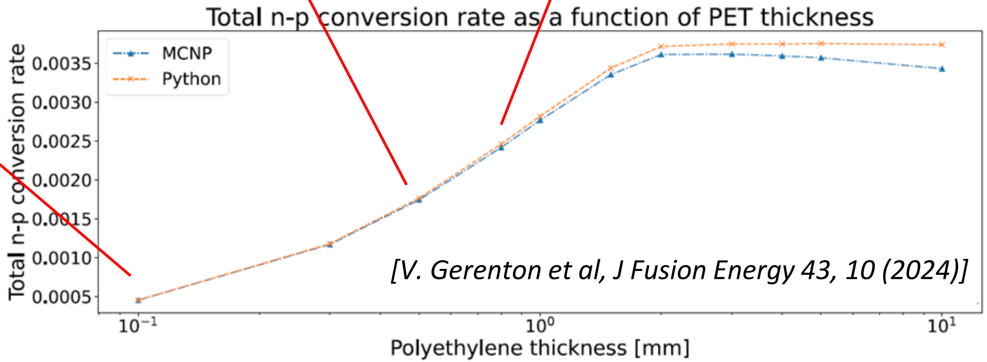
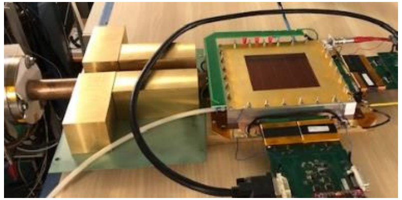
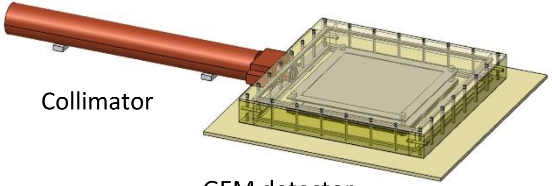
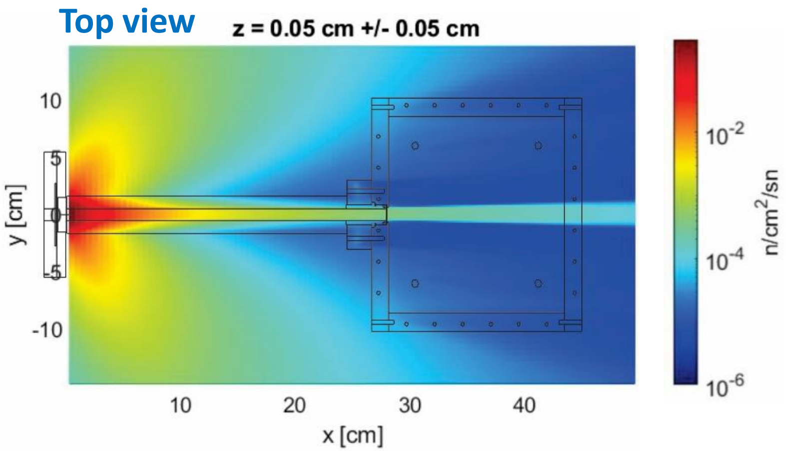


[V. Gerenton et al, J Fusion Energy 43, 10 (2024)]

- Neutron transport in the NS-GEM detector at the IGN-14 generator(**MCNP**):



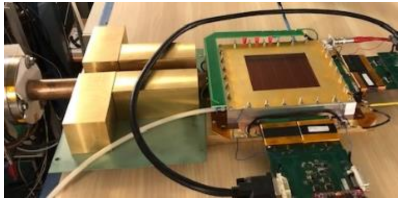


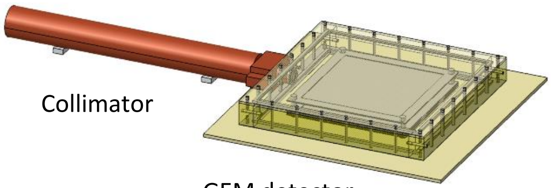


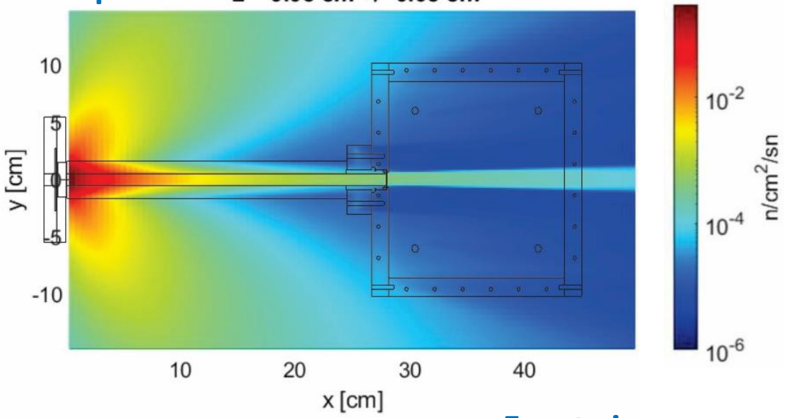
MCNP 6.2
MeshTally: 2 mm x 2 mm x 1 mm

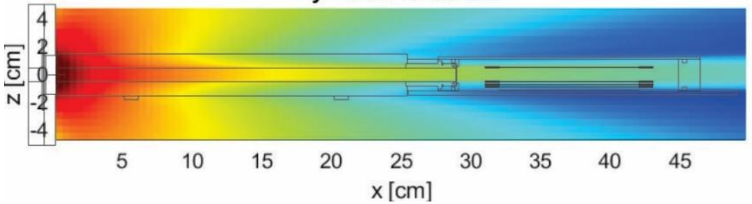
Neutron transport in the NS-GEM prototype (MCNP)

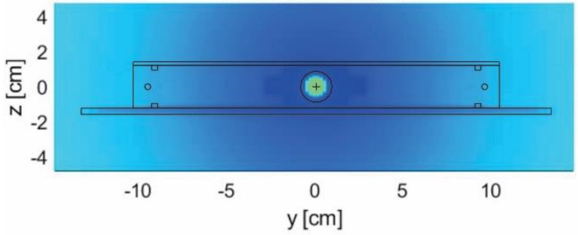
- Neutron transport in the NS-GEM detector at the IGN-14 generator(**MCNP**):











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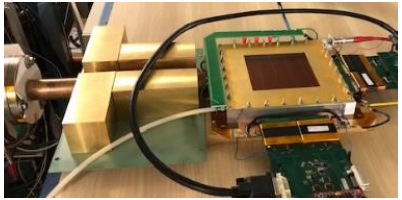
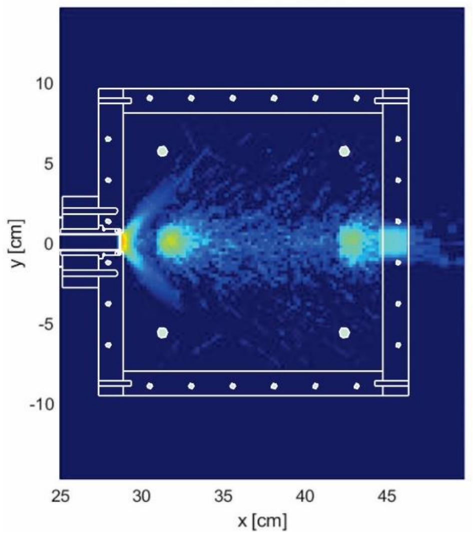
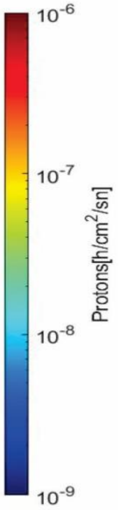
Proton distribution in the NS-GEM prototype (MCNP)



- Protons in the NS-GEM detector at the IGN-14 exterimental stand:

0 MeV – 3 MeV





Protons from the n/p converter only

θ ~(60 – 90) deg

$$E_n = \frac{E_p}{cos^2\theta}$$

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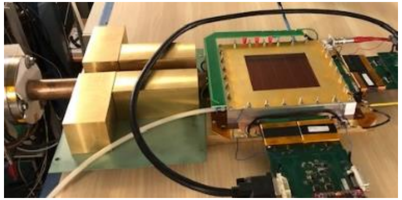

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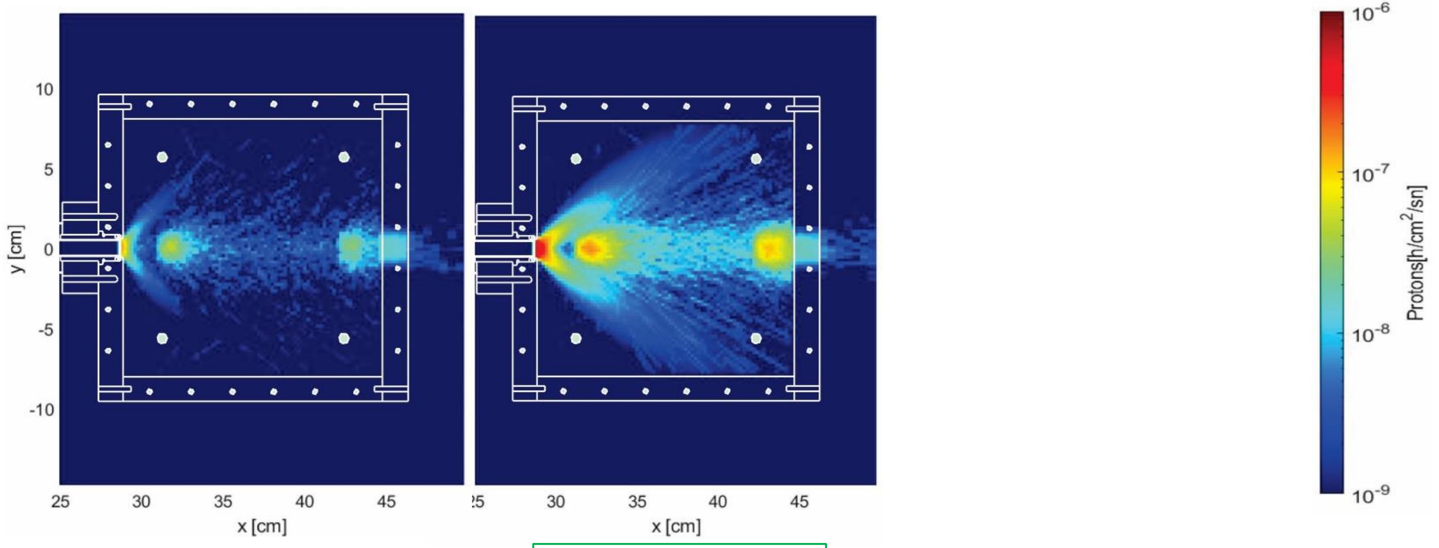
0 MeV – 3 MeV

3 MeV – 10 MeV



θ ~(60 – 90) deg

θ ~(30 – 60) deg

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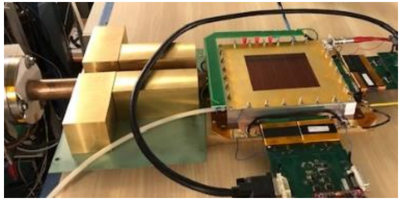
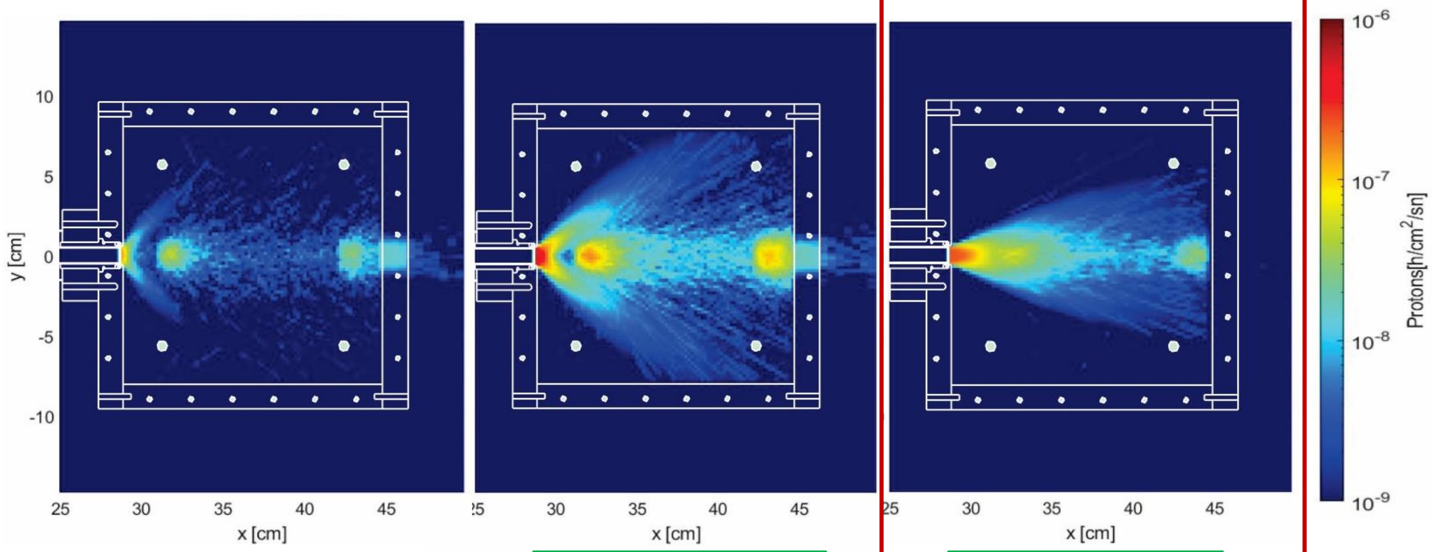


- Protons in the NS-GEM detector at the IGN-14 exterimental stand:

0 MeV – 3 MeV | 3 MeV – 10 MeV | 10 MeV – 14 MeV



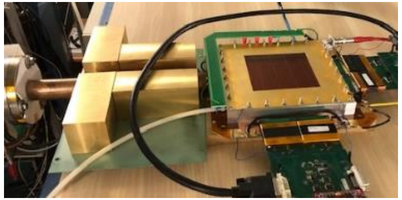
θ ~(60 – 90) deg | θ ~(30 – 60) deg | θ ~(0 – 30) deg

Protons from the n/p converter only

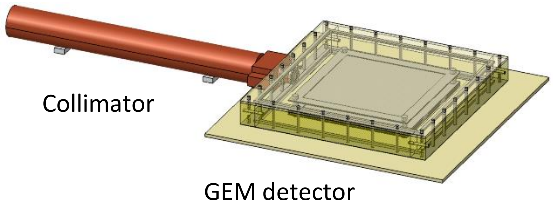
$$E_n = \frac{E_p}{cos^2\theta}$$

MCNP 6.2
MeshTally: 2 mm x 2 mm x 1 mm

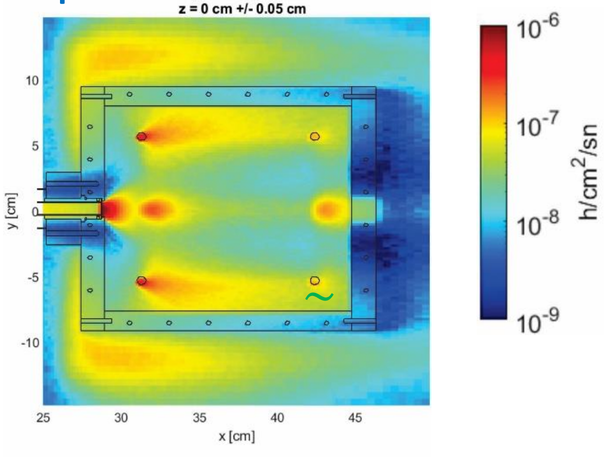
Proton distribution in the NS-GEM prototype (MCNP)



- Protons in the NS-GEM detector at the IGN-14 exterimental stand:



Top view

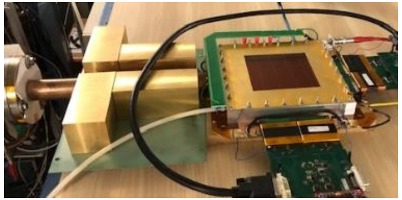


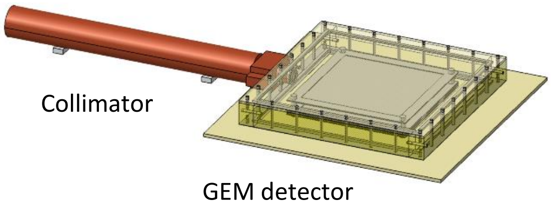
Protons from the
n/p converter
&
construction elements

MCNP 6.2
MeshTally: 2 mm x 2 mm x 1 mm

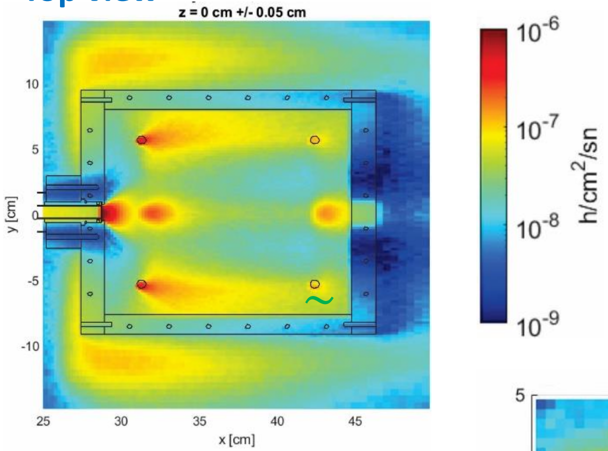
Proton distribution in the NS-GEM prototype (MCNP)

- Protons in the NS-GEM detector at the IGN-14 exterimental stand:

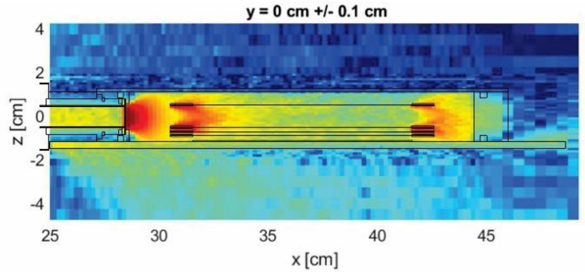




Top view

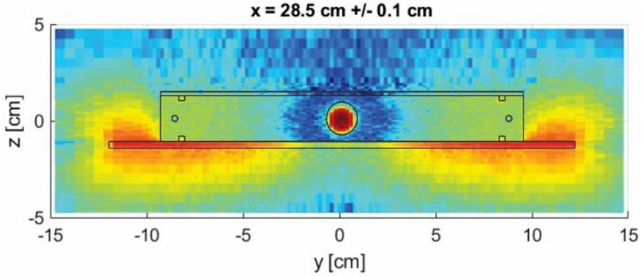


Side view



Protons from the n/p converter & construction elements

Front view



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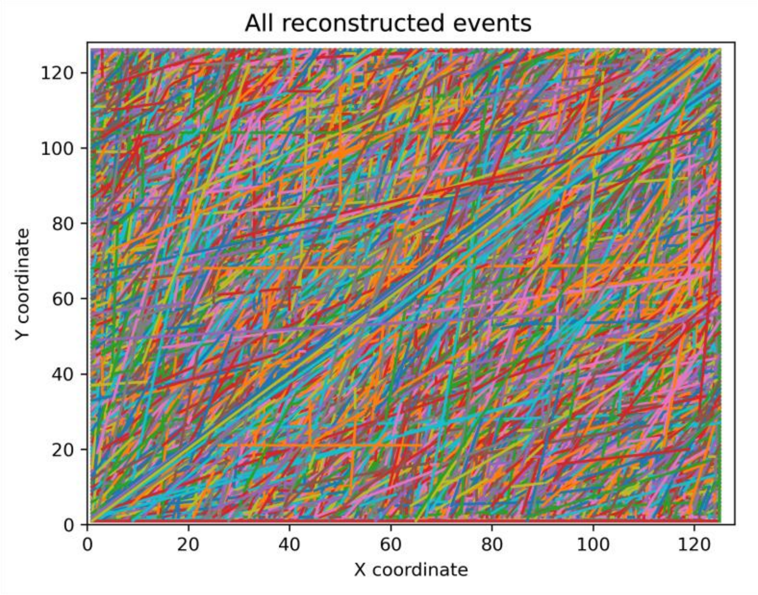
MeshTally: 2 mm x 2 mm x 1 mm

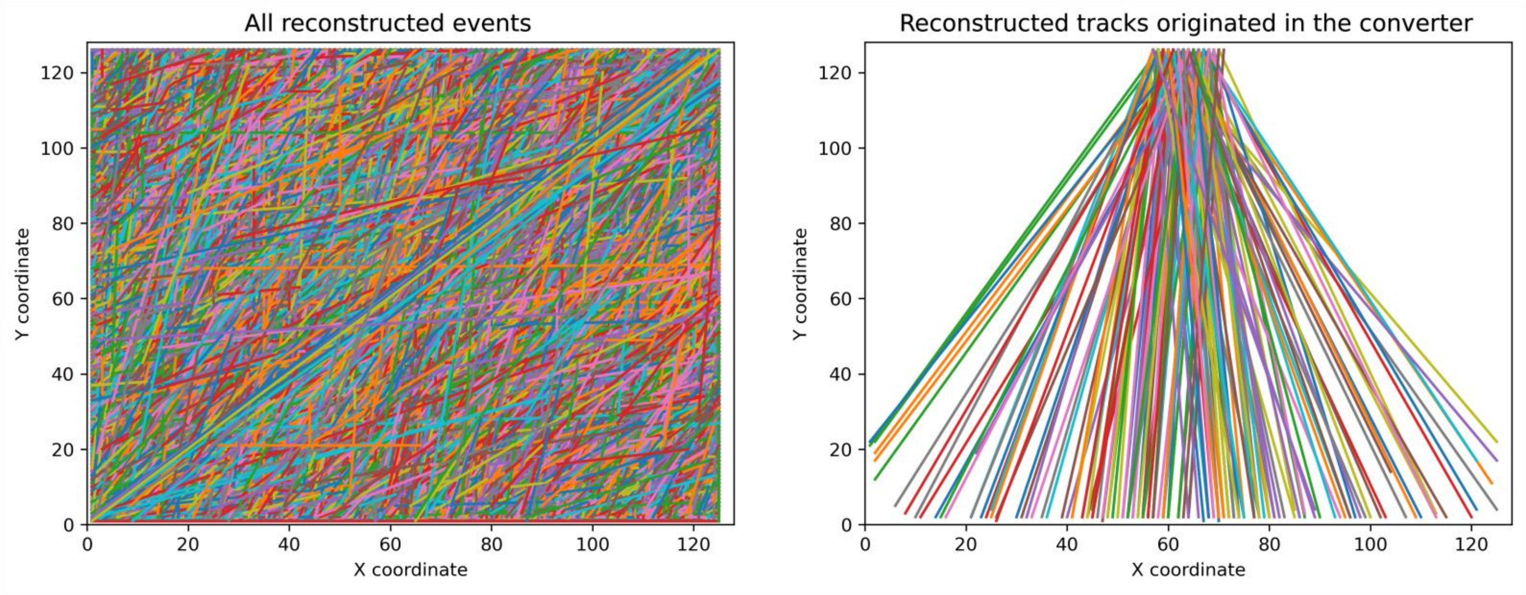
Reconstruction of proton tracks

- Proton measurements and analysis of the test results of the NS-GEM demonstrator

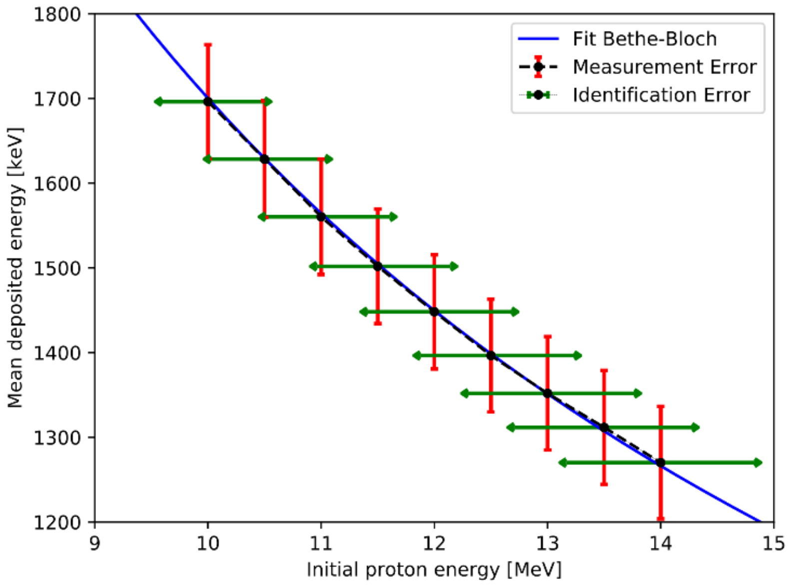


Reconstruction of proton tracks

- Proton measurements and analysis of the test results of the NS-GEM demonstrator
- Filtering algorithm developed for the selection of meaningful proton tracks

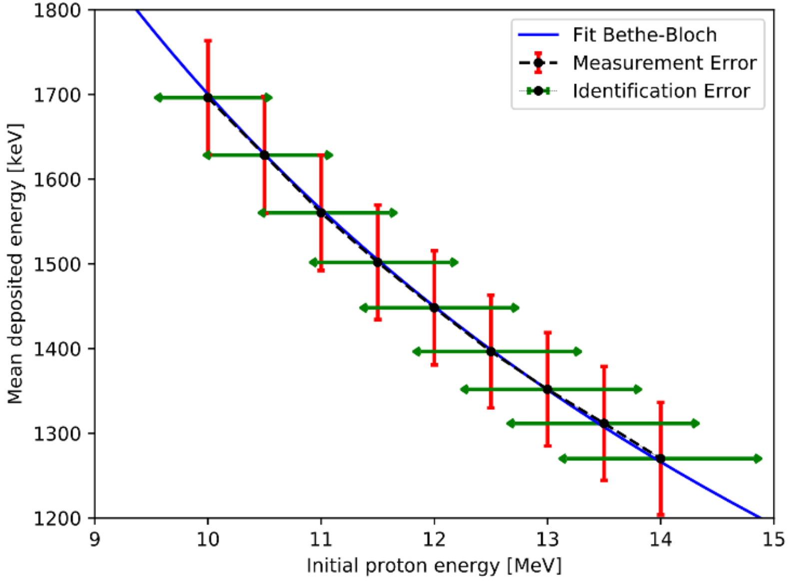


- Calibration curve determined with Geant4 used to estimate initial proton energy.



Reconstruction of neutron spectrum

- Calibration curve determined with Geant4 used to estimate initial proton energy.
- Neutron energy recovered using estimated proton energy and scattering angle.



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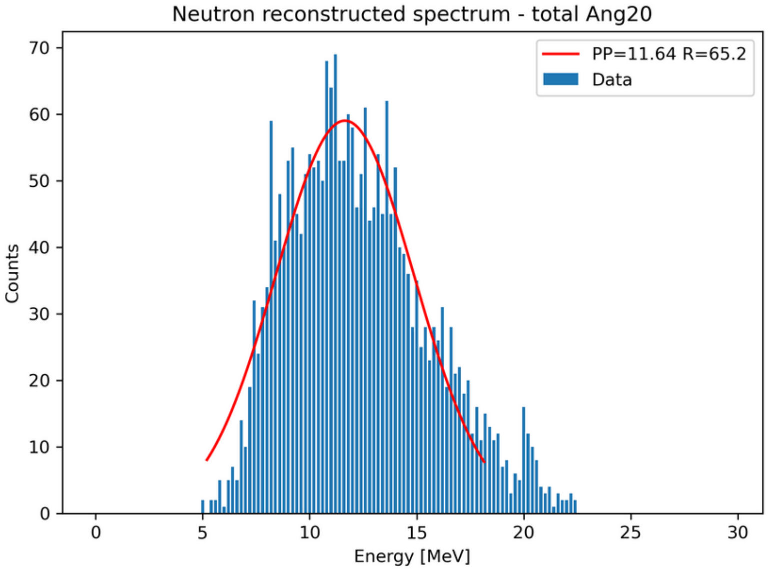
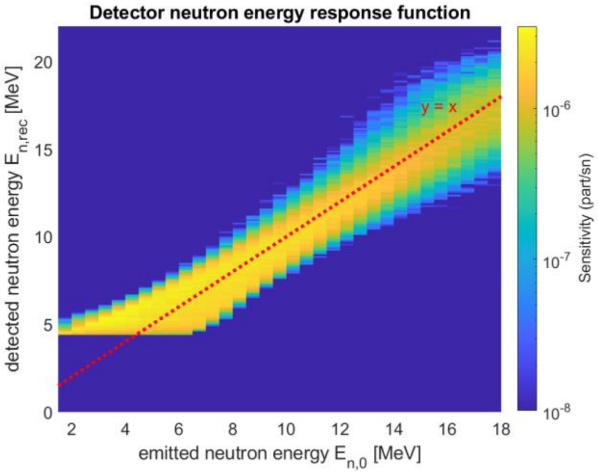


Issue of energy reconstruction (energy shift) – likely related to readout electronics (crosstalk between the readout planes), but it needs to be studied further

NS-GEM energy response function

- Impact of PE foil thickness and gas length on detector response function (for **1 bar $ArCO_2$ pressure**):

0.5 mm, 10 cm gas depth
(+PE-GEM gap 3 cm)



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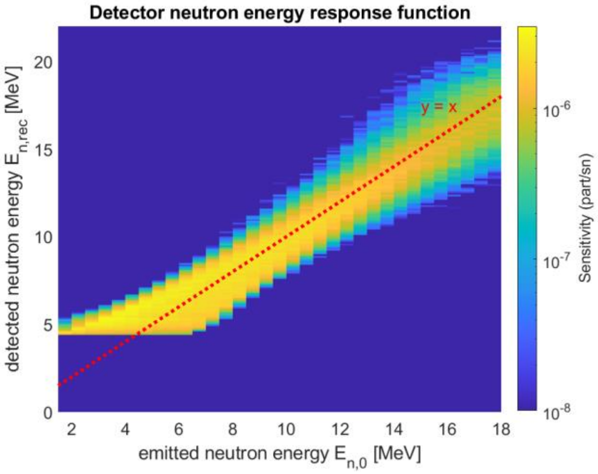
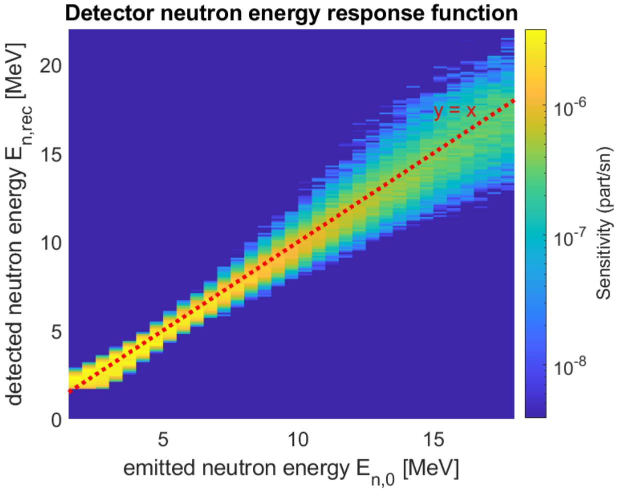


0.1 mm, 10 cm gas depth
(+reduced gap 0.1 cm)



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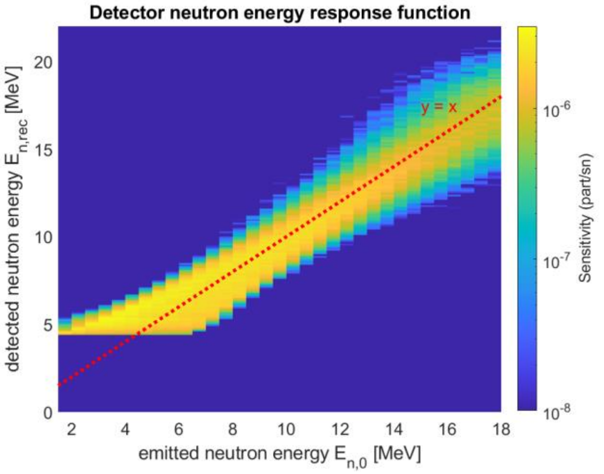

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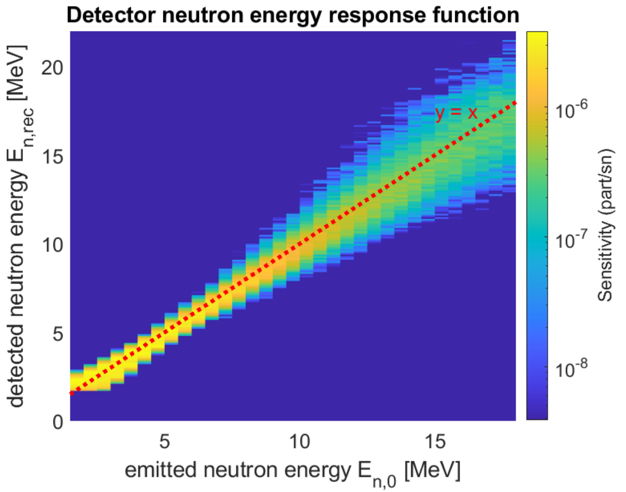
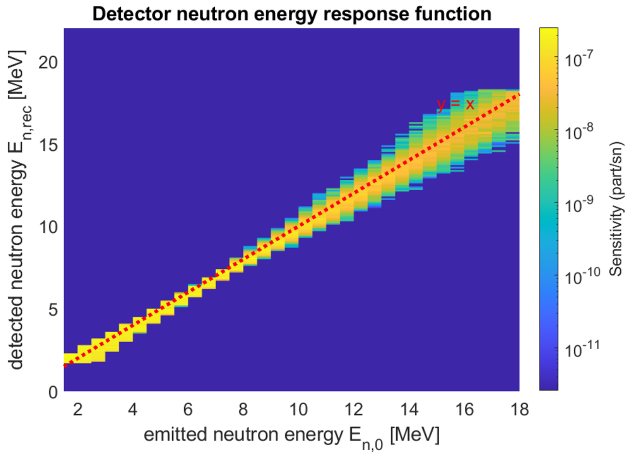
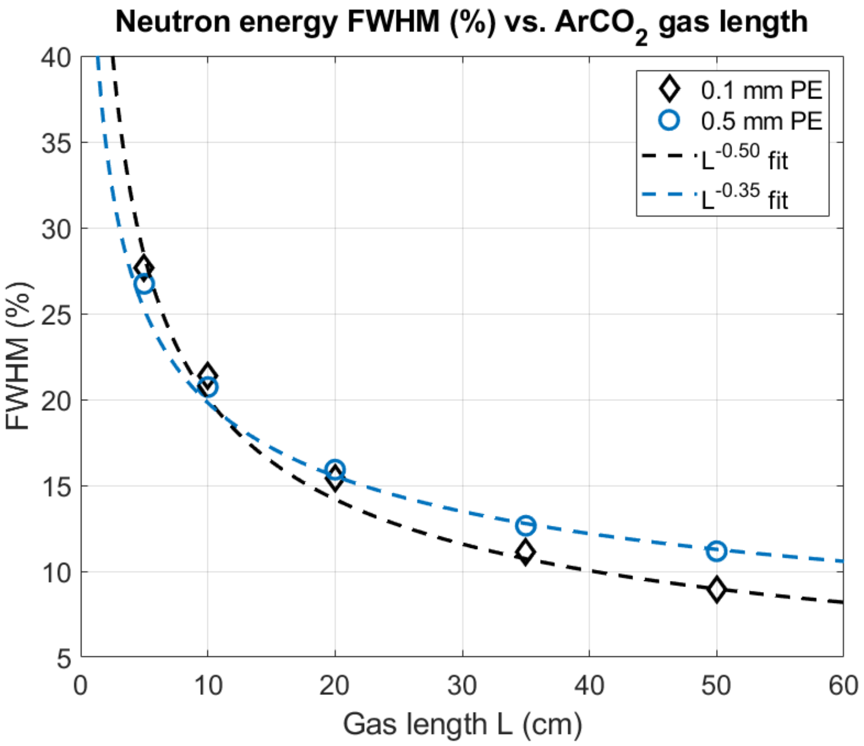


0.1 mm, 50 cm gas depth
(+reduced gap 0.1 cm)



→ Energy resolution can be increased at the cost of efficiency (decreased count rate)

- **Expected neutron energy resolution FWHM** as a function of the $ArCO_2$ (70-30, 1 bar) gas length for incident 14 MeV neutrons:

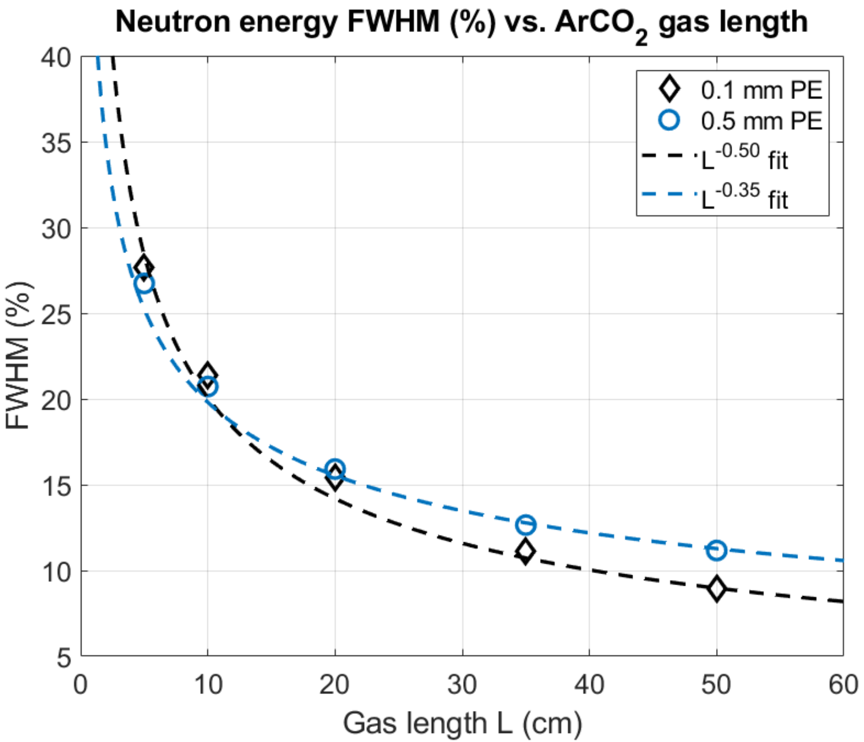


[A. Jardin et al, Phys. Plasmas 31 (2024) 082514]

Perspectives: NS-GEM energy resolution

- Expected neutron energy resolution FWHM as a function of the $ArCO_2$ (70-30, 1 bar) gas length for incident 14 MeV neutrons:

- Solutions to get to the required resolution: minimize proton scattering and/or get closer to the Bragg peak
- ✓ Thinner PE foil, down to 0.1 mm or lower
- ✓ Extend depth of gas mixture ≳ 50 cm (larger detector)
- ✓ Work at higher gas pressure > 1 bar



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- We are open to collaboration on this topic: marek.scholz@ifj.edu.pl , axel.jardin@ifj.edu.pl

Further reading:

1. M. Scholz et al, *Conceptual design of the high resolution neutron spectrometer for ITER*, 2019 Nucl. Fusion 59 065001. https://doi.org/10.1088/1741-4326/ab0dc1
2. M. Scholz, U. Wiącek, K. Drozdowicz, A. Jardin, U. Woźnicka, A. Kurowski, A. Kulińska, W. Dąbrowski, B. Łach and D. Mazon, *Concept of a compact high-resolution neutron spectrometer based on GEM detector for fusion plasmas*, Journal of Instrumentation, Vol.18, 2023, C05001. https://doi.org/10.1088/1748-0221/18/05/C05001
3. A. Jardin, J. Bielecki, W. Dąbrowski, K. Drozdowicz, D. Dworak, V. Gerenton, D. Guibert, R. Kantor, K. Król, A. Kulińska, A. Kurowski, B. Łach, D. Mazon, Y. Savoye-Peysson, M. Scholz, J. Walkowiak, U. Wiącek, U. Woźnicka, WEST team; *Energy-resolved x-ray and neutron diagnostics in tokamaks: Prospect for plasma parameters determination*. Phys. Plasmas 31 (8): 082514 (2024). https://doi.org/10.1063/5.0213721
4. V. Gerenton, A. Jardin, U. Wiącek, K. Drozdowicz, A. Kulinska, A. Kurowski, M. Scholz, U. Woźnicka, W. Dąbrowski, B. Łach & D. Mazon, *AI-supported Modelling of a Simple TPR System for Fusion Neutron Measurement*. J Fusion Energ 43, 10 (2024). https://doi.org/10.1007/s10894-024-00403-0