Development of GEM detector as a compact neutron spectrometer for fusion plasmas NS-GEM

Task Specification (TS) 2023

ENR-TEC.01.IPPLM-T001 - D001

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IPPLM-1: Development of GEM detector as a compact neutron spectrometer for fusion plasmas (NS-GEM)

05.02.2024

Task Specifcation 2023:

NS-GEM demonstrator - properties and measurement possibilities

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.
2. NS-GEM demonstrator: Modernization of the design and testing of the NS-GEM demonstrator.
3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

Milestones:

Experimental set-up at NG-14 MeV

Construction of a dedicated experimental set-up at the IFJ PAN neutron generator.

Responsible: K. Drozdowicz, A. Kurowski, M. Turzanski (IFJ PAN)

15.3.2023

DONE

Tests of SN-GEM on neutron sources

Neutron test measurements.

Responsible: W. Dabrowski (AGH), A. Kurowski (IFJ PAN)

30.9.2023

DONE

Milestones:

Assessment of SN-GEM measurement capabilities, Part 1
Analysis of the test results of the SN-GEM demonstrator.
Responsible: W.Dabrowski (AGH)
31.10.2023
DONE
Design review meeting Presentations of the realization of 2023 Milestones
Reviewer: D. Mazon (CEA)
Validation: M. Scholz (IFJ PAN)
Responsible: U. Woznicka (IFJ PAN)
22.11.2023 postpone to 6.12.2023

Task Specifcation:

NS-GEM demonstrator - properties and measurement possibilities

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

[T1] A. Jardin; Theory and modelling: NS-GEM synthetic diagnostic. Modelling of Thin-foil Proton Recoil system toward a NS-GEM synthetic diagnostic. Technical Report, 2023, https://wiki.eurofusion.org/images/b/b0/Report_NS-GEM_2023-12_AJ_synthetic_diagnostic_v5.pdf.

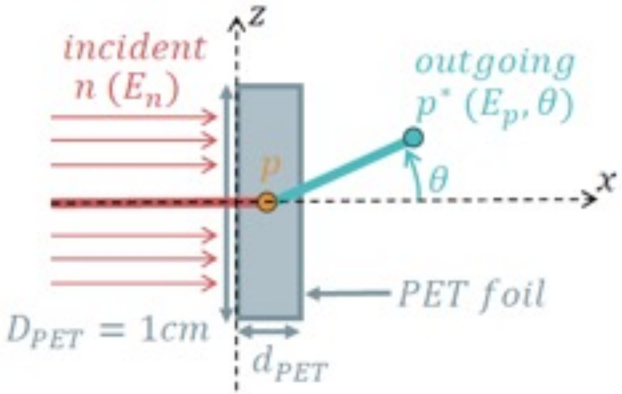
[T2] W. Dąbrowski, B. Łach, A. Korba, P. Wiącek; Assessment of measurement capabilities of the NS-GEM detector: modelling and test results. Technical Report, 2023, https://wiki.eurofusion.org/images/b/ba/2023_Technical_Report_NS-GEM_Demonstrator.pdf

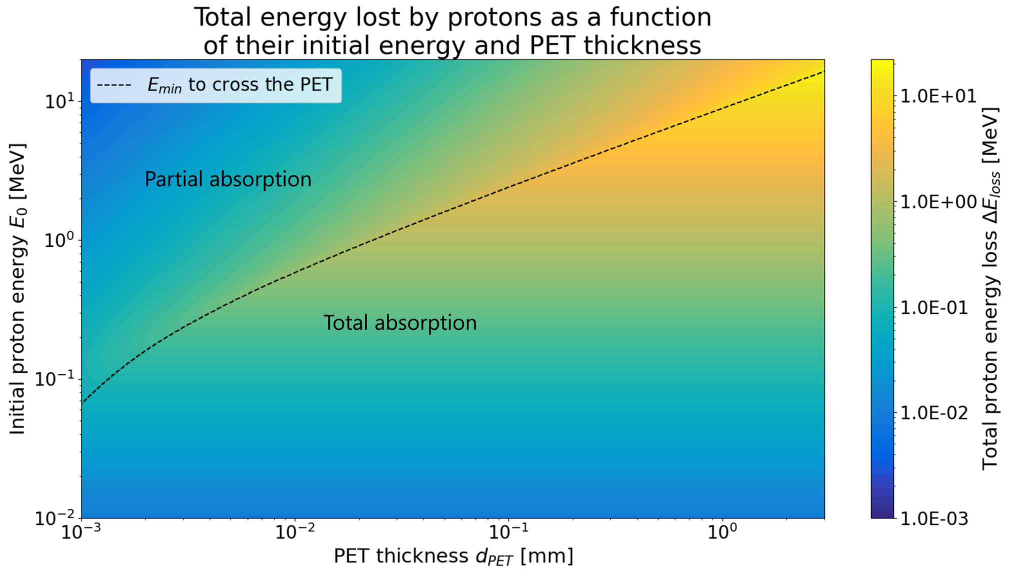
1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

These works focusd on building step-by-step the response function of a compact NS-GEM using the dE/dx method to record tracks of protons from a polyethylene (PET) converter and reconstruct the neutron spectrum.

This task has decomposed in four main parts:

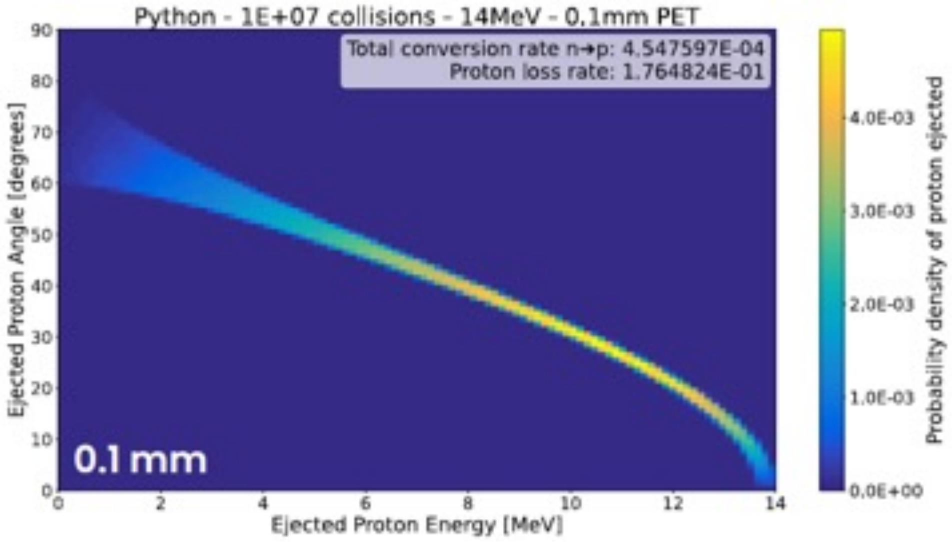
1. Modelling of neutron-proton conversion in PET,
2. Protons energy absorption and track in the GEM gas mixture,
3. Neutron energy spectrum reconstruction,
4. Resulting NS-GEM energy response function.

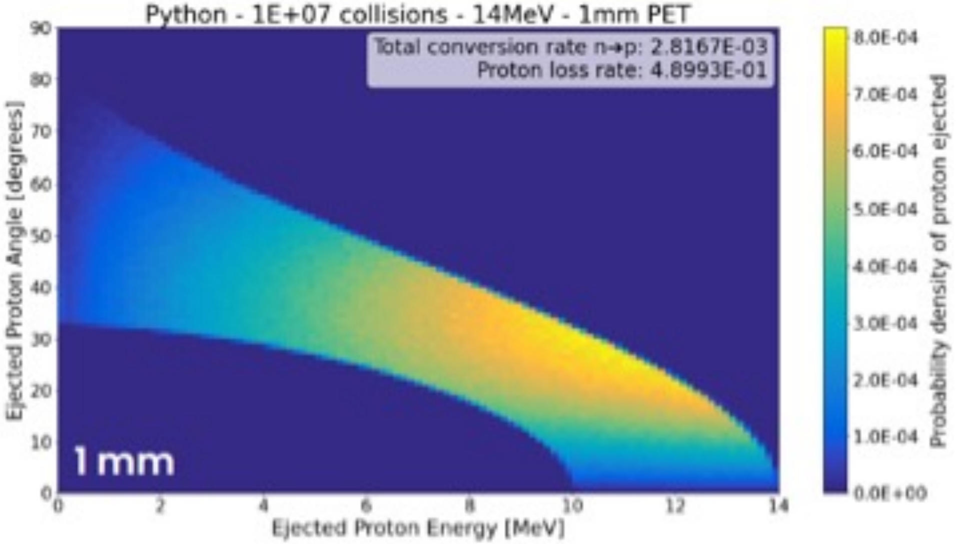




Absorption matrix of proton energy $\Delta E_{loss} = f(E_0, d_{PET})$ in PET

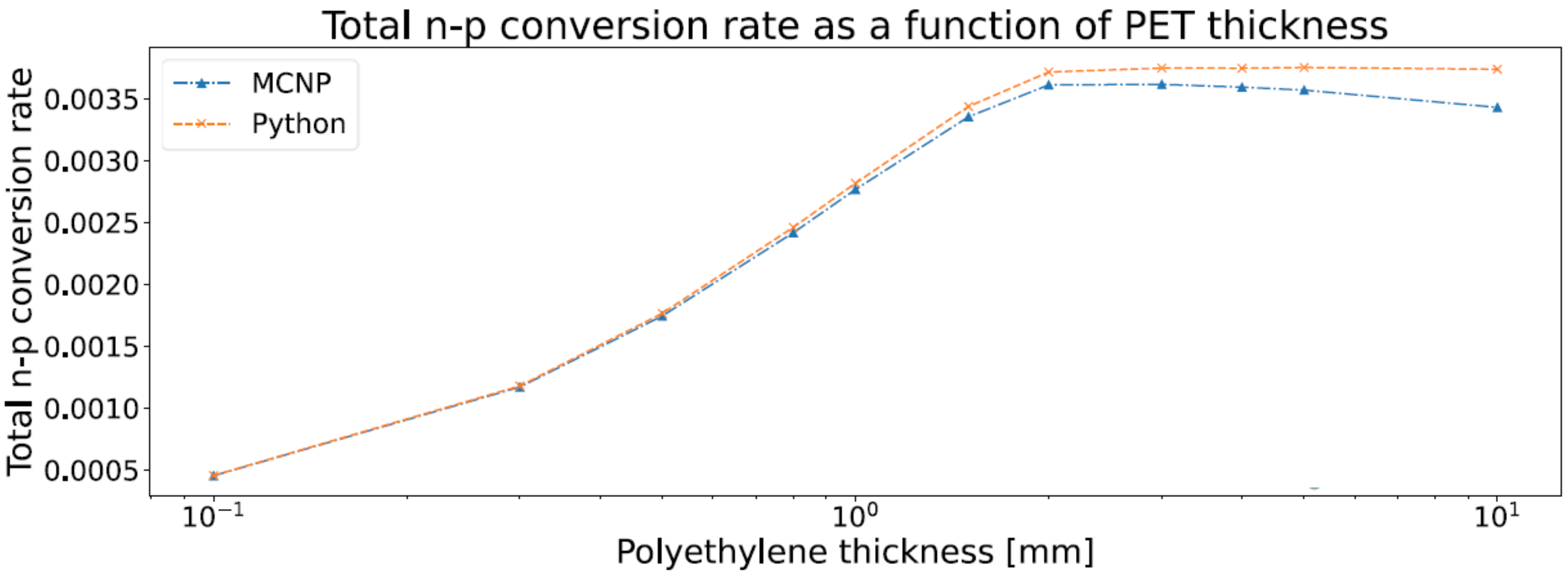
1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.





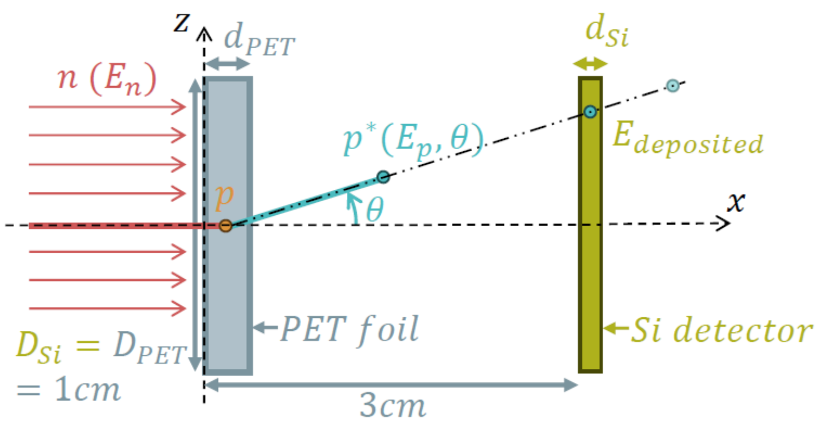
As an example, such distribution obtained with this simplified model for 14 MeV neutrons and PET thicknesses of 0.1 mm and 1.0 mm are presented in above fig.

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

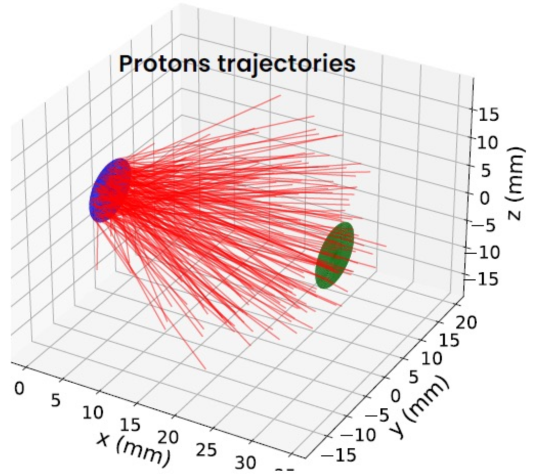


Benchmark of the obtained total n-p conversion rate against MCNP, as a function of the PET thickness. The maximum possible conversion rate is $3.77 \cdot 10^{-3}$.

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.



Parametrization of proton trajectories, including a Si detector placed 3 cm behind the PET foil



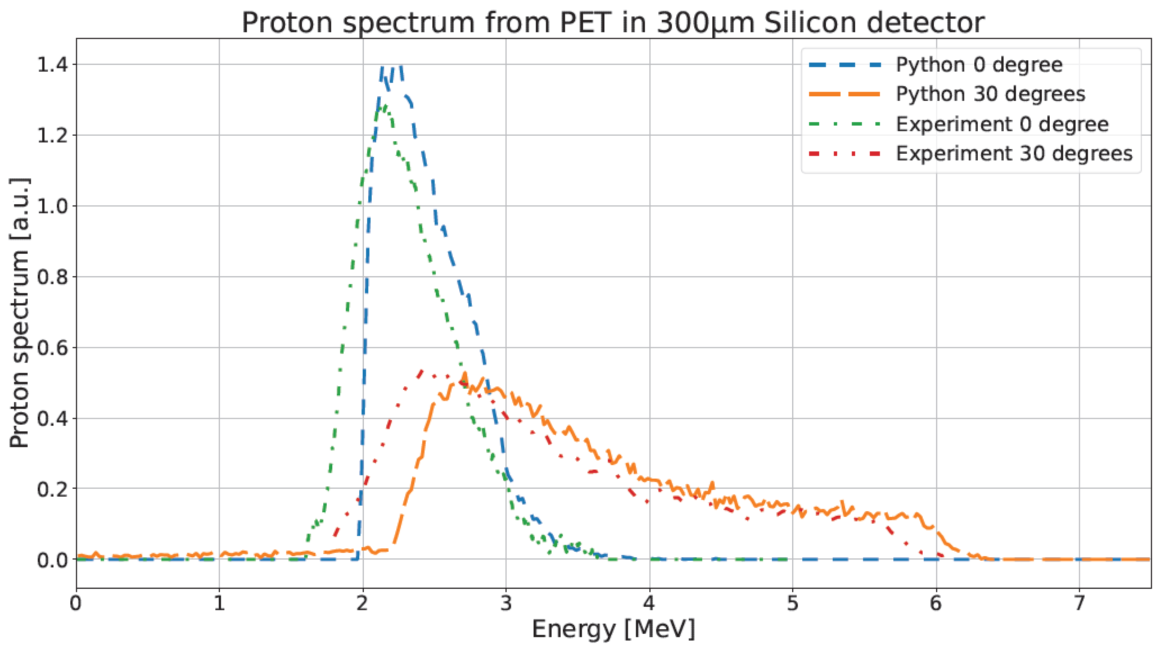
3D view of proton trajectories generated from the PET foil toward the Si detector

To obtain the energy spectrum of the protons reaching the detector, a similar procedure is followed as for building the PET absorption matrix.

- Proton stopping power in silicon is obtained from the NIST database.
- The proton Bragg curve is reconstructed and the absorption matrix in silicon is calculated.

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

Experimental validation on IGN-14 with a 300um silicon detector

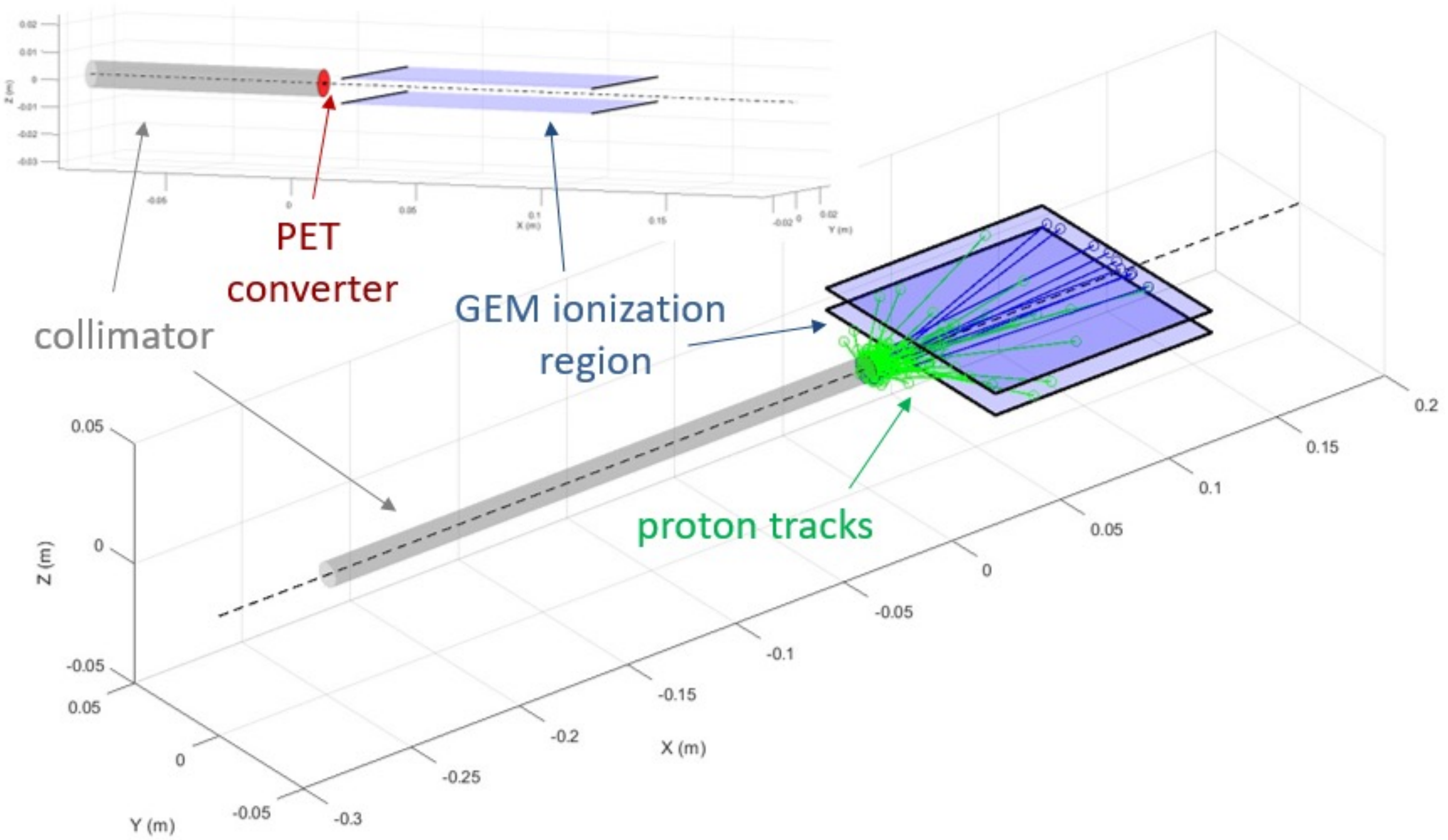


Proton energy spectra obtained with a 300 µm Si detector placed 3 cm after the PET foil

A good agreement is observed between the simulations and the experiment, both in terms of shape of the spectrum and peak location, for the two angles investigated

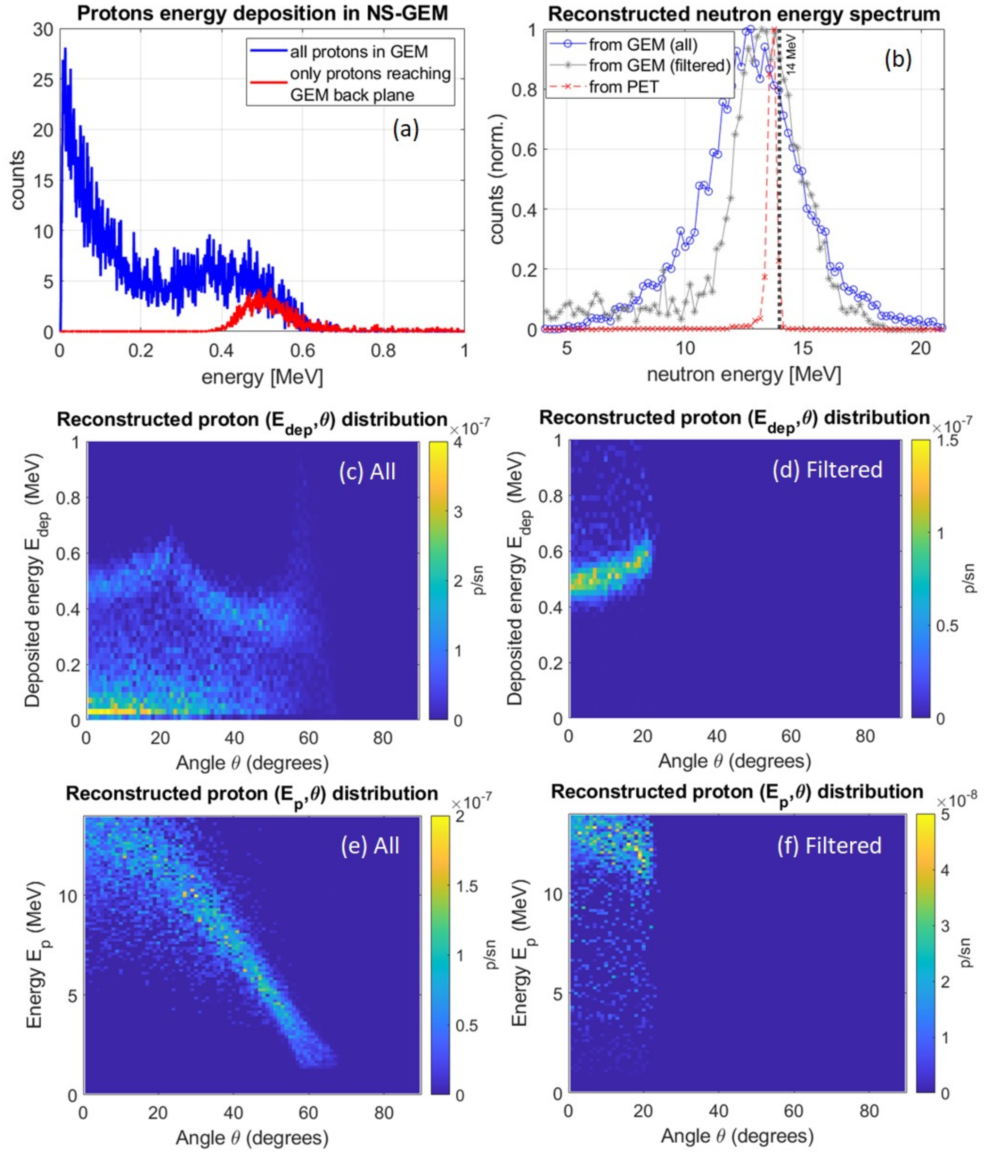
1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

Neutron energy spectrum reconstruction



3D view of the NS-GEM model used in matlab simulations, with the collimator in grey, the PET converter in red, the two GEM planes defining the gas ionization region in blue, and several proton tracks in blue (reaching the GEM back plane) and green (stopped before reaching it)

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.



Neutron energy spectrum reconstruction

Results for a 0.5 mm thick PET.

(a) proton energy deposition in the GEM, for all protons reaching the GEM (in blue) and for “filtered” protons, i.e. reaching the GEM back plane (in red).

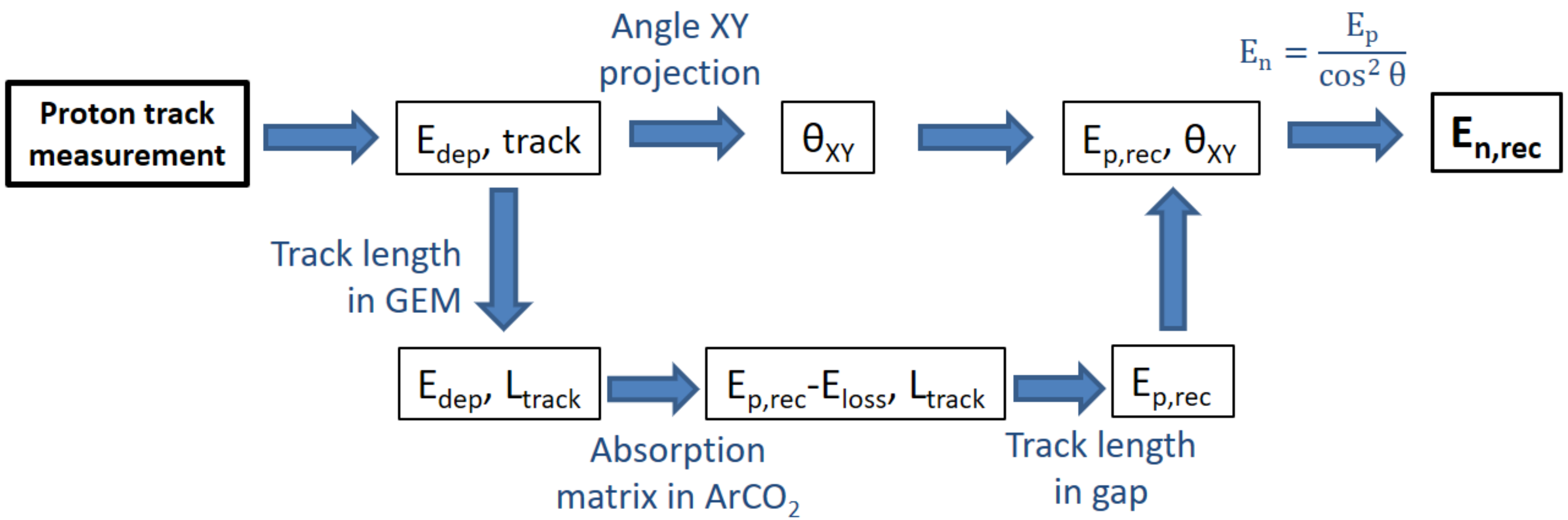
(b) Associated reconstructed neutron spectrum. The red curve (from PET) assumes a perfect knowledge of the proton energy distribution at the exit of the PET converter.

(c, d) Reconstructed distribution of protons deposited energy and angle, for all protons and filtered ones respectively.

(e, f) Reconstructed distribution of protons initial energy and angle, for all protons and filtered ones respectively

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

NS-GEM energy response function



Methodology to reconstruct the incident neutron energy $E_{n,rec}$ based on the measured proton tracks in the NS-GEM prototype, where

(E_{dep}, θ) denote the proton deposited energy and track angle,

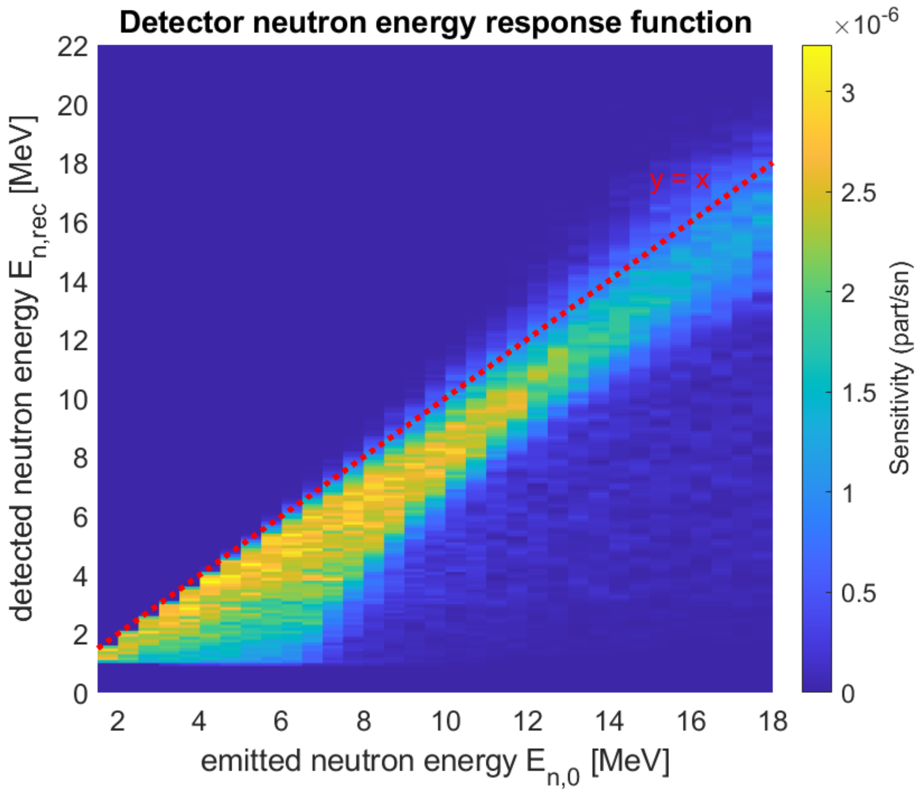
L_{track} its track length in the GEM,

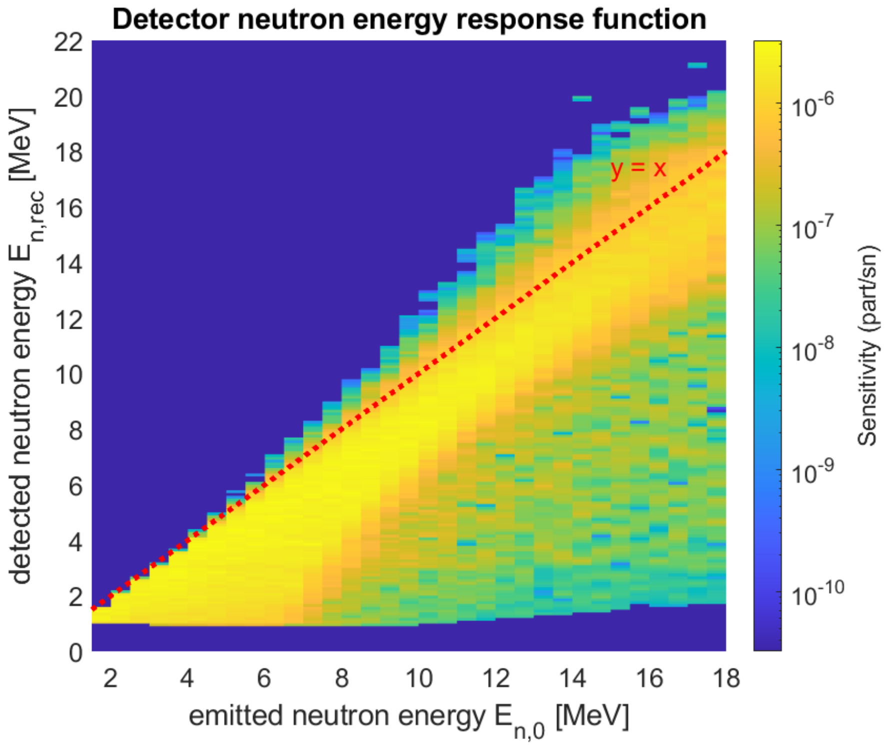
E_{loss} its energy loss in the 2 cm gap,

($E_{p,rec}$, θ_{XY}) the reconstructed proton energy and track angle.

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

NS-GEM energy response function

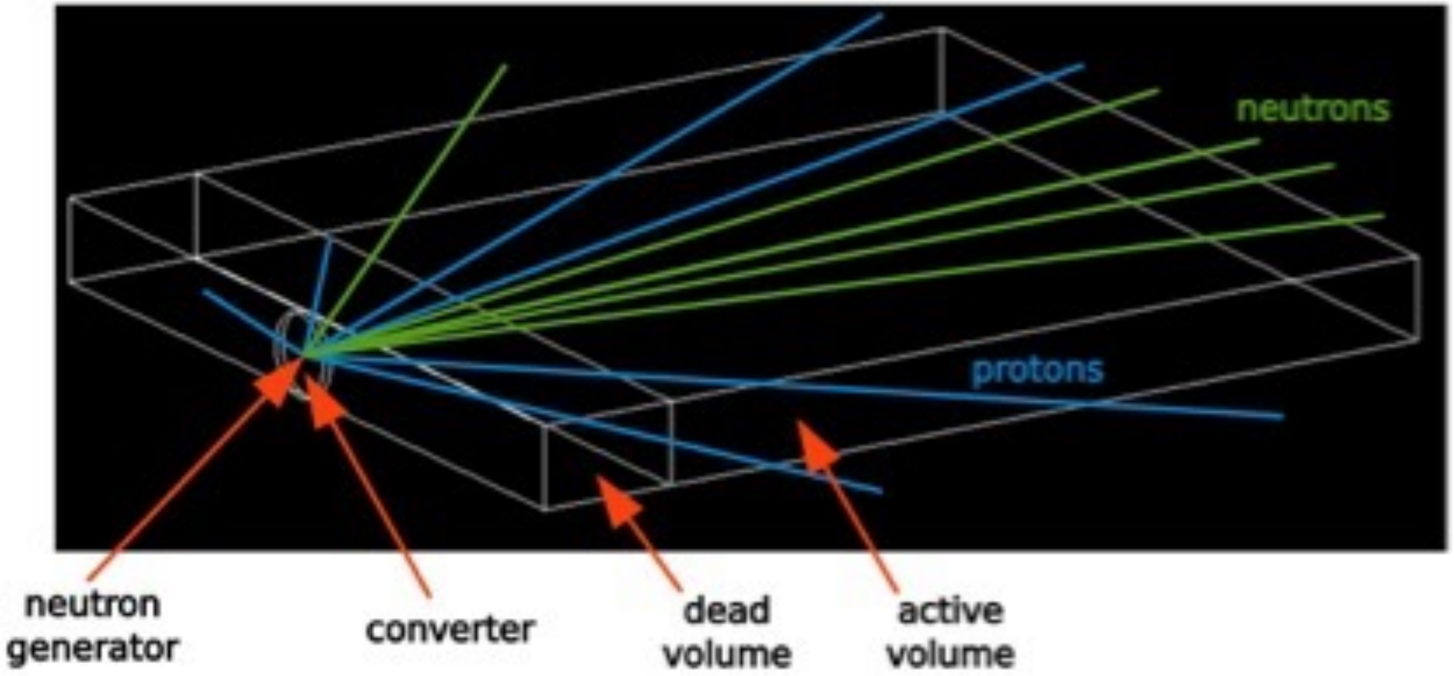




The theoretical energy response function of the NS-GEM prototype is determined, for the 0.5 mm PET (thickness used experimentally), by repeating the procedure for several neutron incident energies from 1.5 MeV up to 18 MeV, by steps of 0.5 MeV. The resulting matrix is presented both in linear and logarithmic scale.

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

Modelling of the NS-GEM response using GEANT4



A sketch of the detector model created in the GEANT4 software and used for the performed simulations. The developed model consists of: 10 mm diameter circular converter with variable thickness, neutron generator placed in the centre of the converter and two separate cuboid-shaped active ($100 \times 100 \times 10$ mm^3) and dead ($17 \times 100 \times 10$ mm^3) detector volumes.

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

Modelling of the NS-GEM response using GEANT4

Estimation of the efficiency of proton generation for various converter thicknesses.

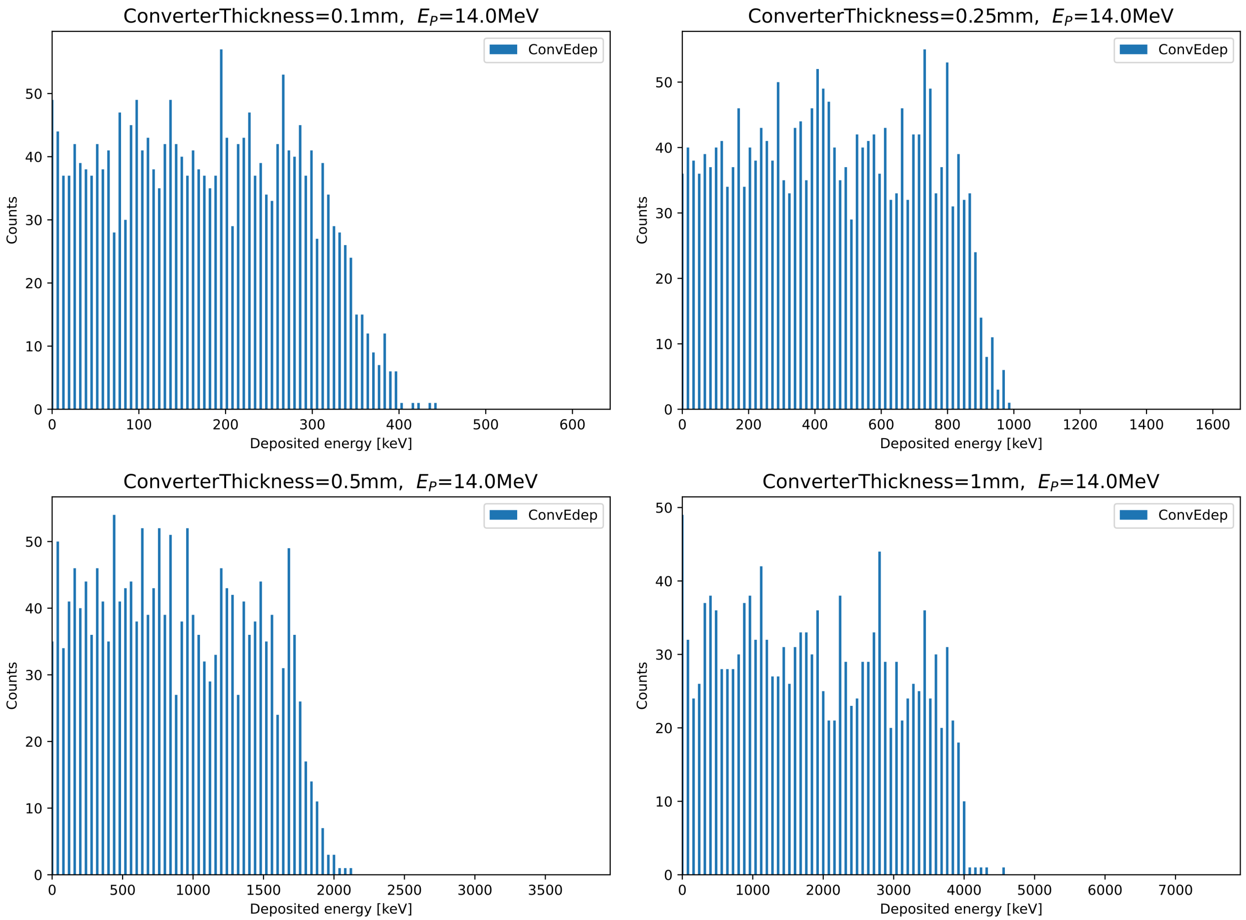
Converter Thickness [mm]	Number of protons generated in the converter per 1 neutron from source		Neutrons approaching converter per 1 second*	Protons measured in 1 hour (estimation)
	All protons ($0^0 < \theta < 90^0$)	Useful protons ($0^0 < \theta < 35^0$)		
0.1	$5.6 \cdot 10^{-4}$	$1.9 \cdot 10^{-5}$	3230	221
0.25	$1.4 \cdot 10^{-3}$	$4.7 \cdot 10^{-5}$	3230	547
0.5	$2.8 \cdot 10^{-3}$	$9.4 \cdot 10^{-5}$	3230	1093
1	$5.6 \cdot 10^{-3}$	$1.8 \cdot 10^{-4}$	3230	2093

*based on the measurements with diamond detector in the experimental hall

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

Modelling of the NS-GEM response using GEANT4

Simulated proton energy loss distributions for 14 MeV and four different thicknesses of the converter.

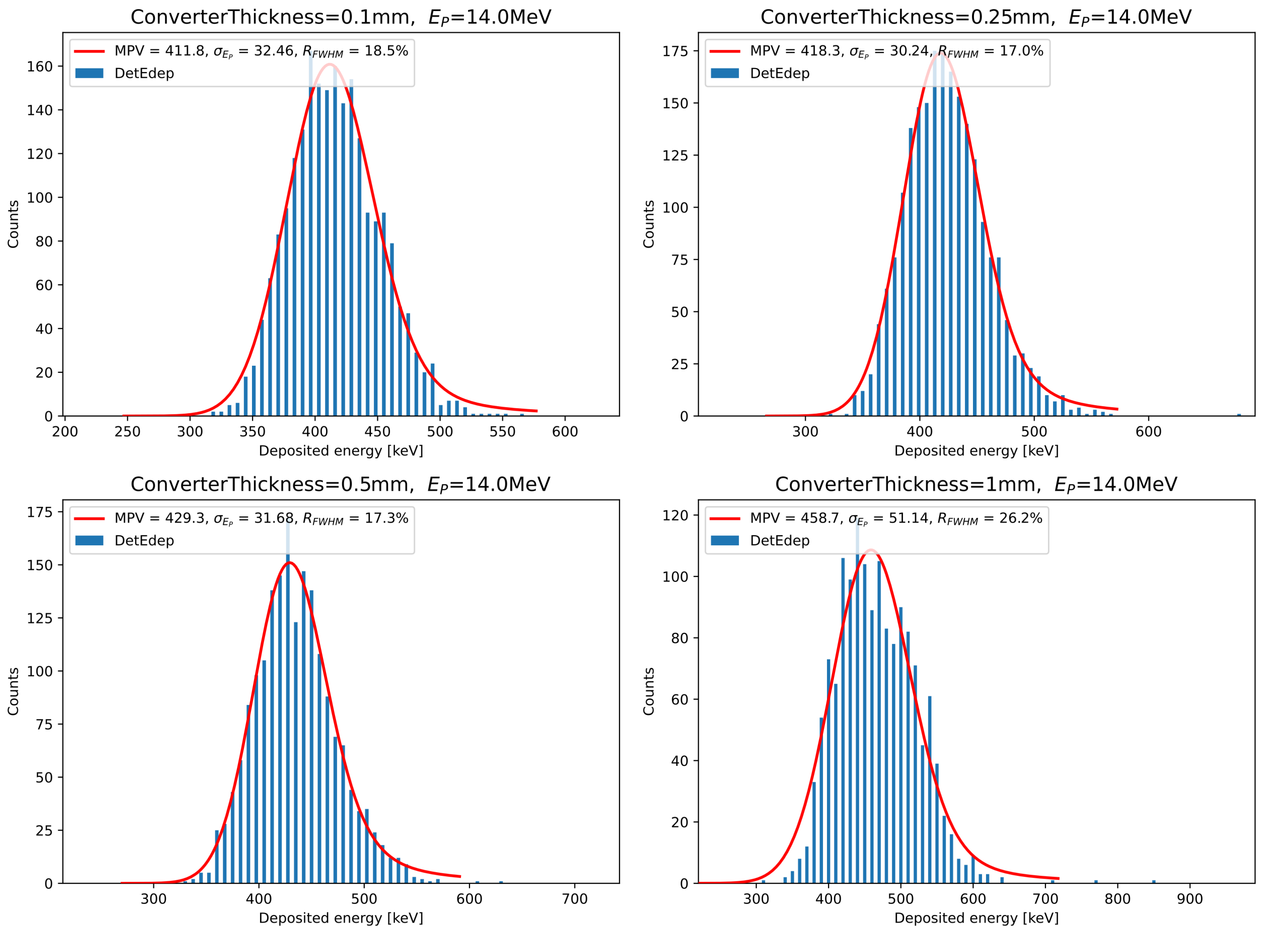


As can be seen from the results, for a given initial proton energy, the thicker converter the wider range of possible energy losses in the converter.

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

Modelling of the NS-GEM response using GEANT4

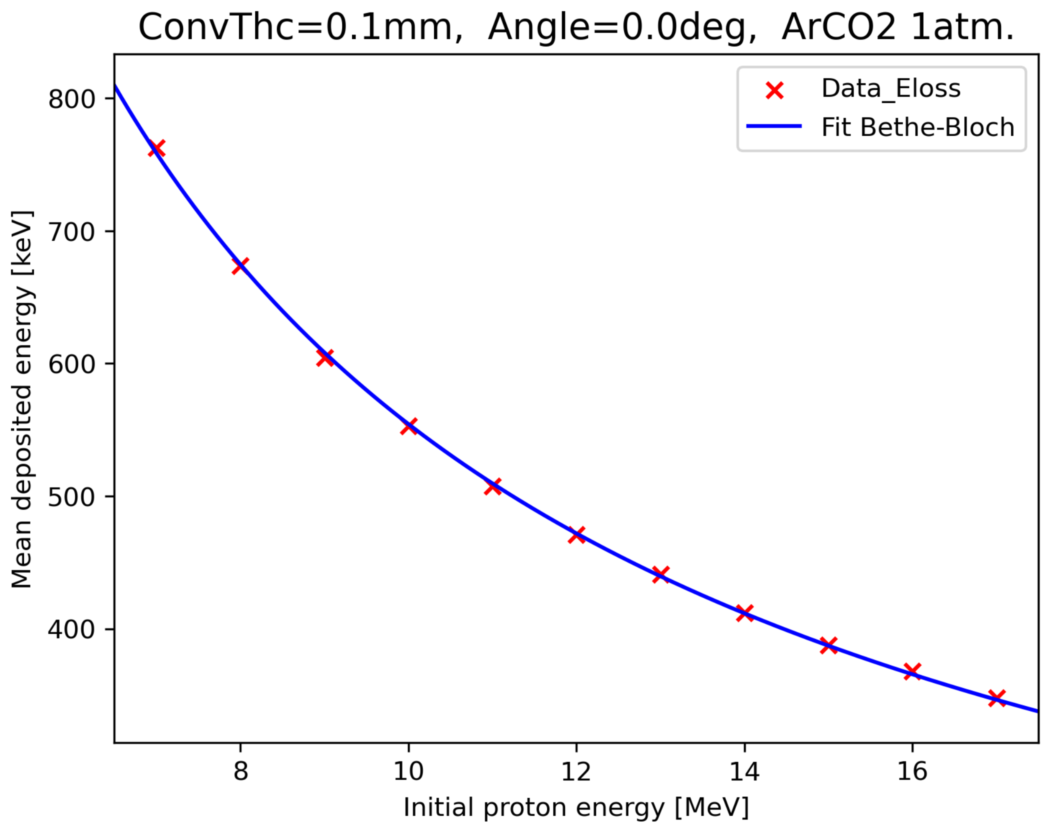
Energy loss distributions in the active detector volume for 14 MeV protons and for different thicknesses of the converter.



In case of 1 mm converter, and especially for 10 MeV protons, the distribution of energy losses is very wide and such a thick converter is definitely not suitable for our detector concept.

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

Modelling of the NS-GEM response using GEANT4

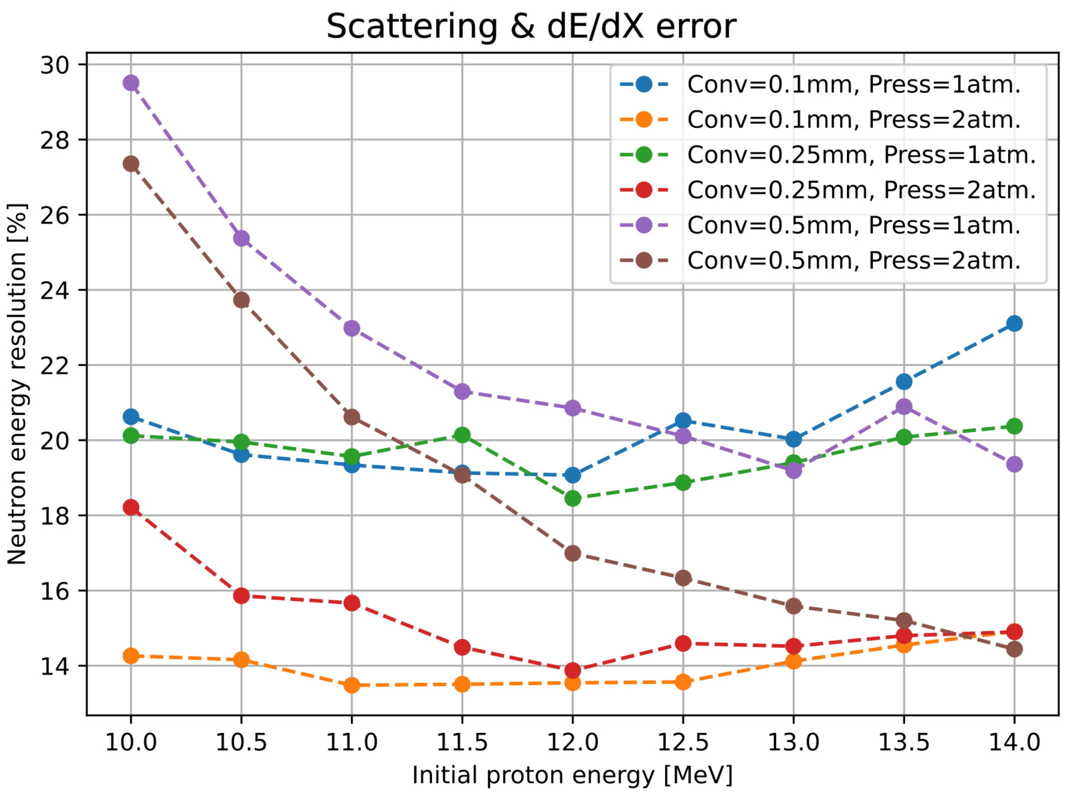


dE/dx calibration curve generated for 0.1 mm converter, scattering angle 0 deg, protons detected at 0 deg, and ArCO2 70/30 gas mixture at 1 atm. pressure

In order to reconstruct the neutron spectra, taking into account both scattering and specific energy losses dE/dx, corresponding calibration curves have been generated.

1. Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.

Modelling of the NS-GEM response using GEANT4



Summary of energy resolution of reconstructed neutron energy taking into account both scattering and specific energy losses dE/dx for three different thicknesses of the converter and ArCO2 70/30 gas mixture at two different pressures.

No significant differences in neutron energy resolution for 0.1 and 0.25 mm converter can be observed. Obtained values are at the level of 20% and 14% for gas mixture at 1 and 2 atm, respectively.

Task Specifcation:

NS-GEM demonstrator - properties and measurement possibilities.

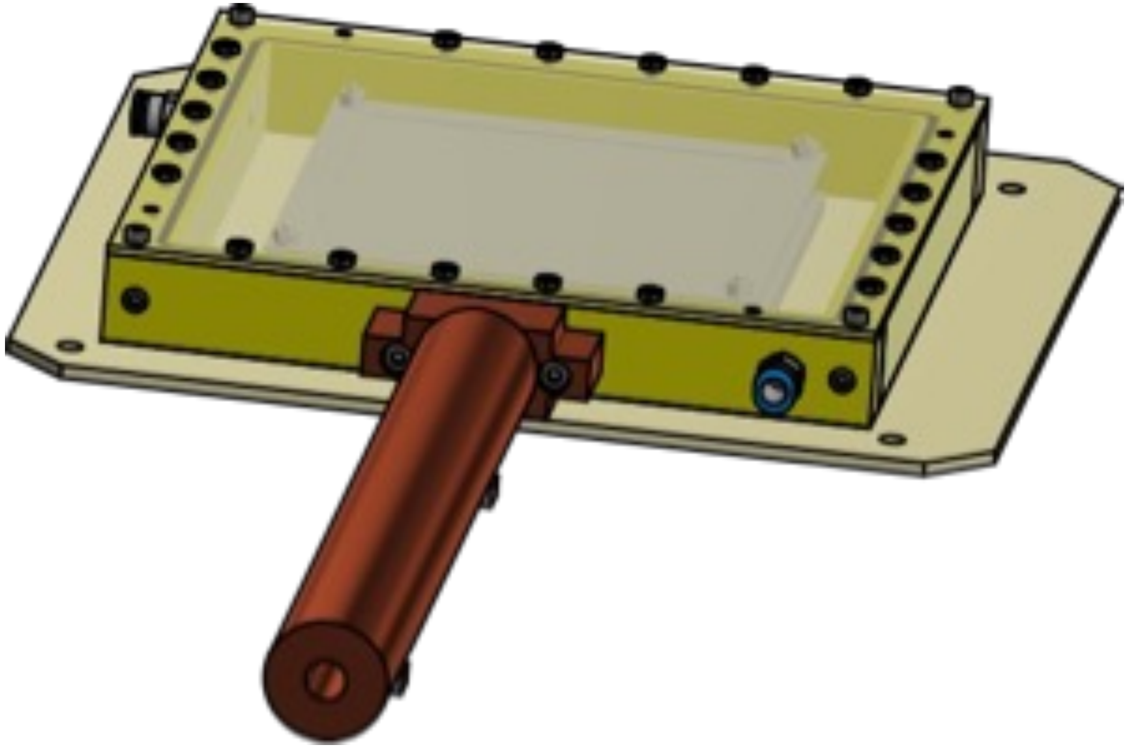
2. NS-GEM demonstrator: Modernization of the design and testing of the NS-GEM demonstrator.

[T2] W. Dąbrowski, B. Łach, A. Korba, P. Wiącek; Assessment of measurement capabilities of the NS-GEM detector: modelling and test results. Technical Report, 2023, https://wiki.eurofusion.org/images/b/ba/2023_Technical_Report_NS-GEM_Demonstrator.pdf

[T3] K. Drozdowicz, W. Janik, A. Kulińska, A. Kurowski, M. Turzański, U. Wiącek; Development of the experimental stand at the IGN-14 neutron generator. Technical Report, 2023, https://wiki.euro-fusion.org/images/1/1e/2023-Tech-Note-Exper.Stand-v2.pdf

2. NS-GEM demonstrator: Modernization of the design and testing of the NS-GEM demonstrator.

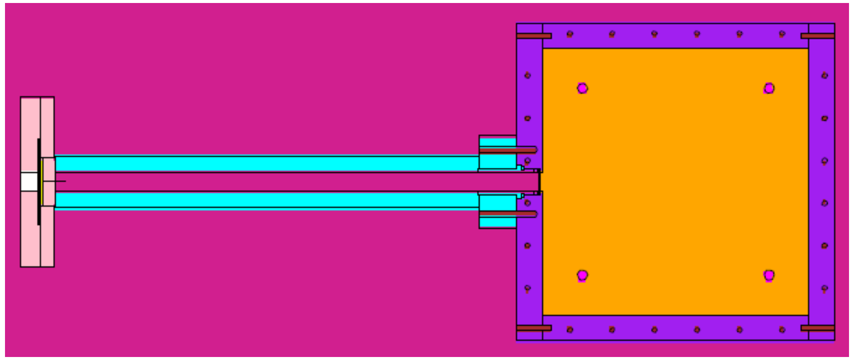
Mechanical construction of the NS-GEM detector



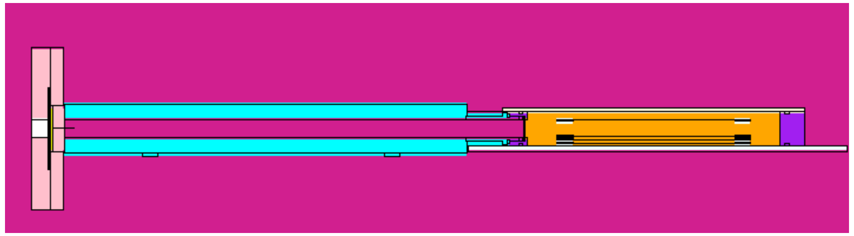
Sketch of mechanical construction of the NS-GEM detector connected with collimator.

As proposed in the initial phase of this project our demonstrator detector is based on a standard 3-stage GEM detector, however, with the thickness of drift region enlarged up to 10 mm compared to the standard thickness of 3 mm. This modification required designing and manufacturing of a new detector frame and proper modification of the voltage divider to ensure the same level of the electric field in the drift region as in the standard design.

2. NS-GEM demonstrator: Modernization of the design and testing of the NS-GEM demonstrator.



Top view

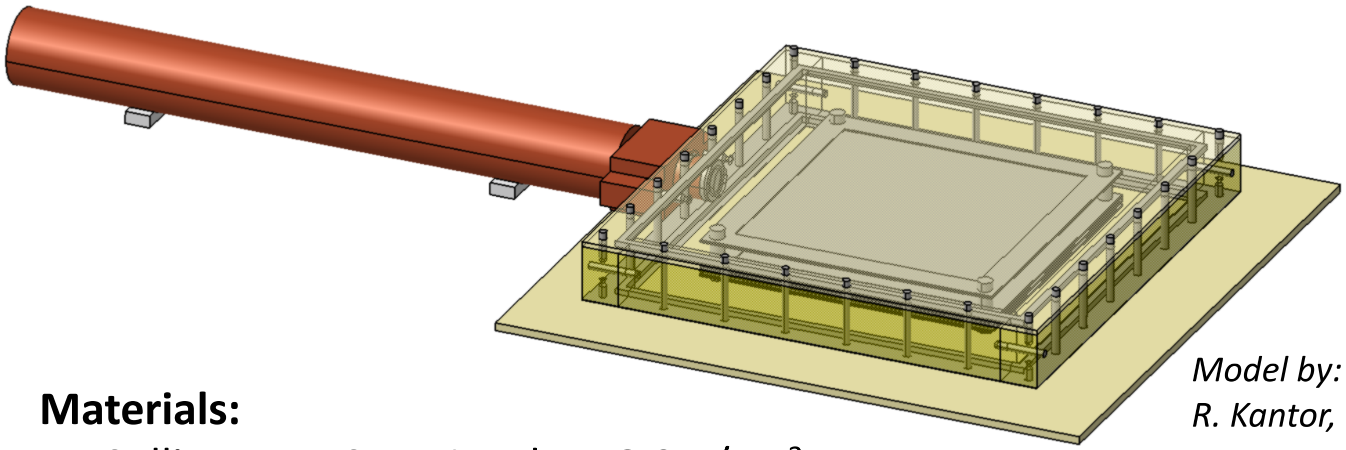


Side view

Collimator length: ~25 cm

Converter d = 0.5 mm

Mechanical construction of the NS-GEM detector



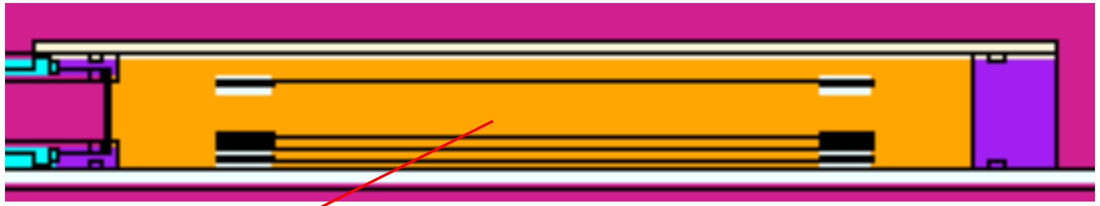
Model by: R. Kantor, PK

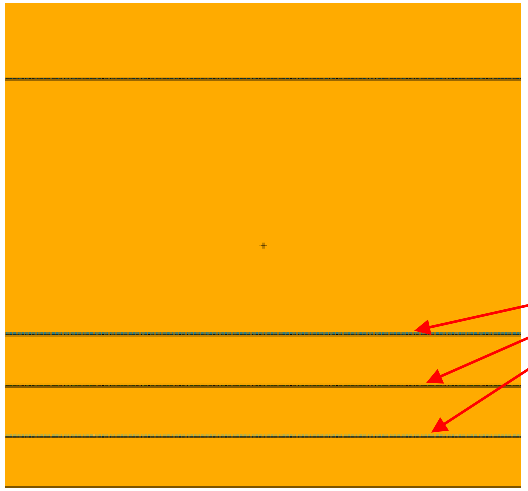
Materials:

- Collimator - Cu M1E; rho= 8.9 g/cm^3
- Gas mixture - Ar + CO_2 (80/20); rho=0.001669 g/cm^3
- Screws - Stainless Steel 304; rho =7.9 g/cm^3
- Detector frame - Alloy PA9 (7075); rho = 2.81 g/cm^3
- Cover plate – Aluminum 1050A; rho = 2.7 g/cm^3
- Kapton; rho = 1.42 g/cm^3
- FR4; rho = 1.85 g/cm^3
- Nylon PA6; rho = 1.084 g/cm^3
- Gasket - Viton FKM; rho = 2 g/cm^3

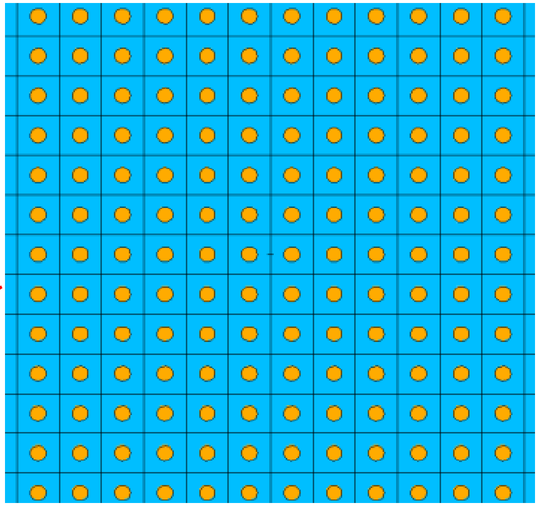
2. NS-GEM demonstrator: Modernization of the design and testing of the NS-GEM demonstrator.

MCNP model of GEM detector



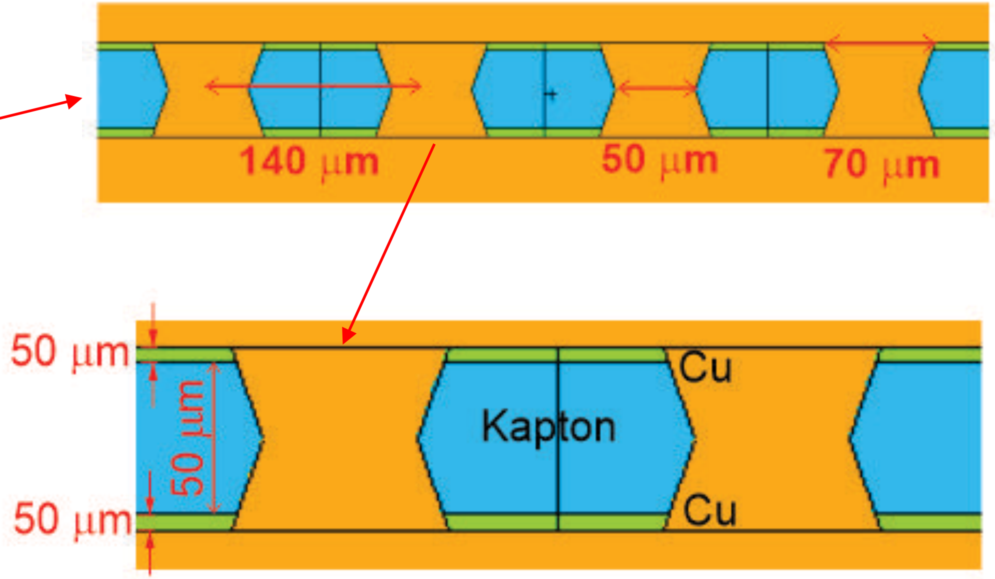


Active area of the detector
(side view)



Kapton foil (top view)

Dimension: 10 cm x 10 cm
~5.1 x 10^5 holes

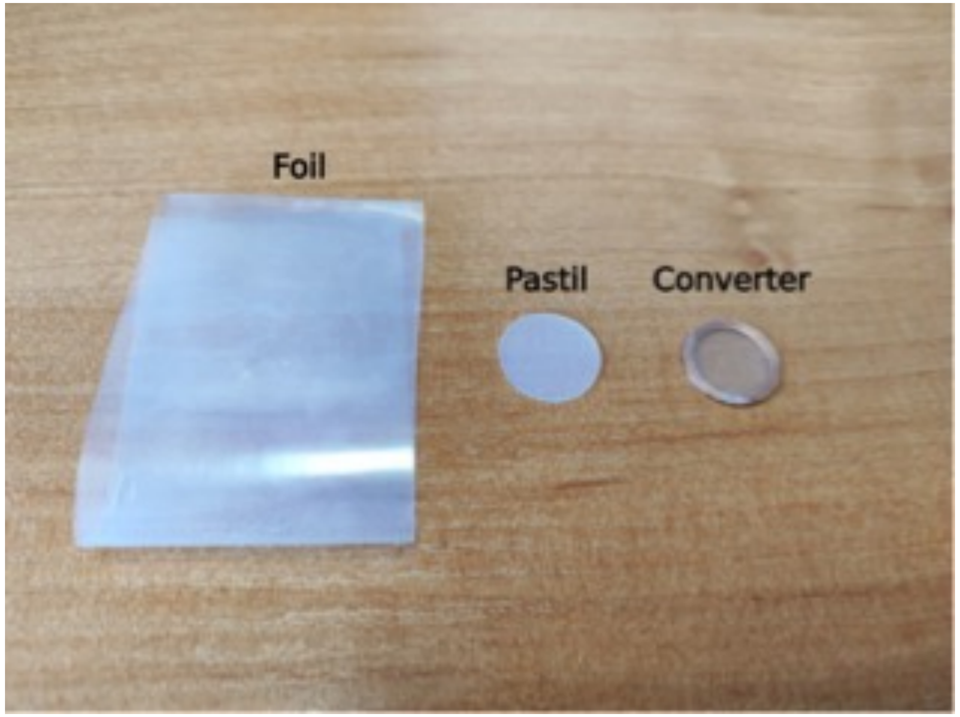


Kapton foil (side view)

2. NS-GEM demonstrator: Modernization of the design and testing of the NS-GEM demonstrator.

The polyethylene materials – XRF measurements

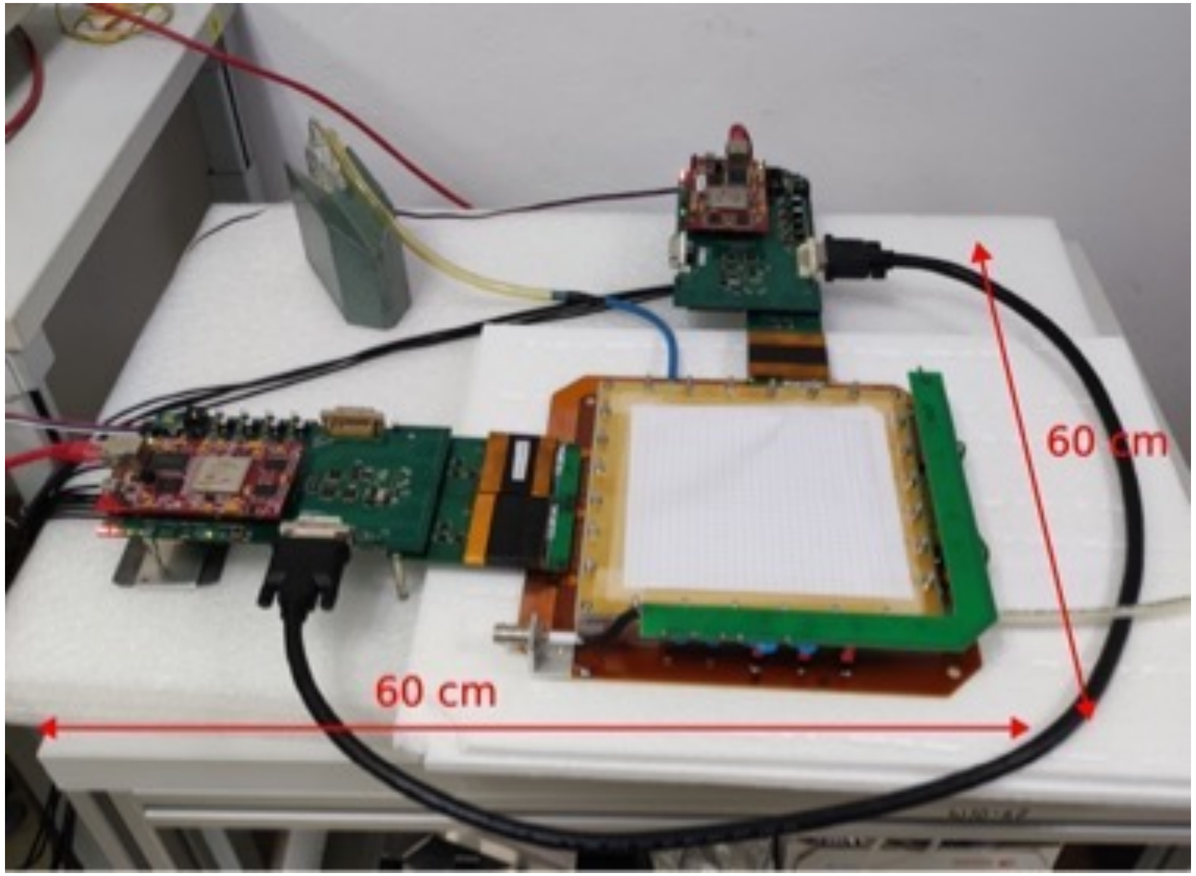
One of the tasks realised before the neutron measurements was investigation of the elemental composition of polyethylene materials, in particular verification of its purity.



Based on fluorescence spectra, in all three investigated polyethylene materials calcium (Ca), iron (Fe), copper (Cu), and zinc (Zn) has been detected, however amounts of detected contaminants are very low.

2. NS-GEM demonstrator: Modernization of the design and testing of the NS-GEM demonstrator.

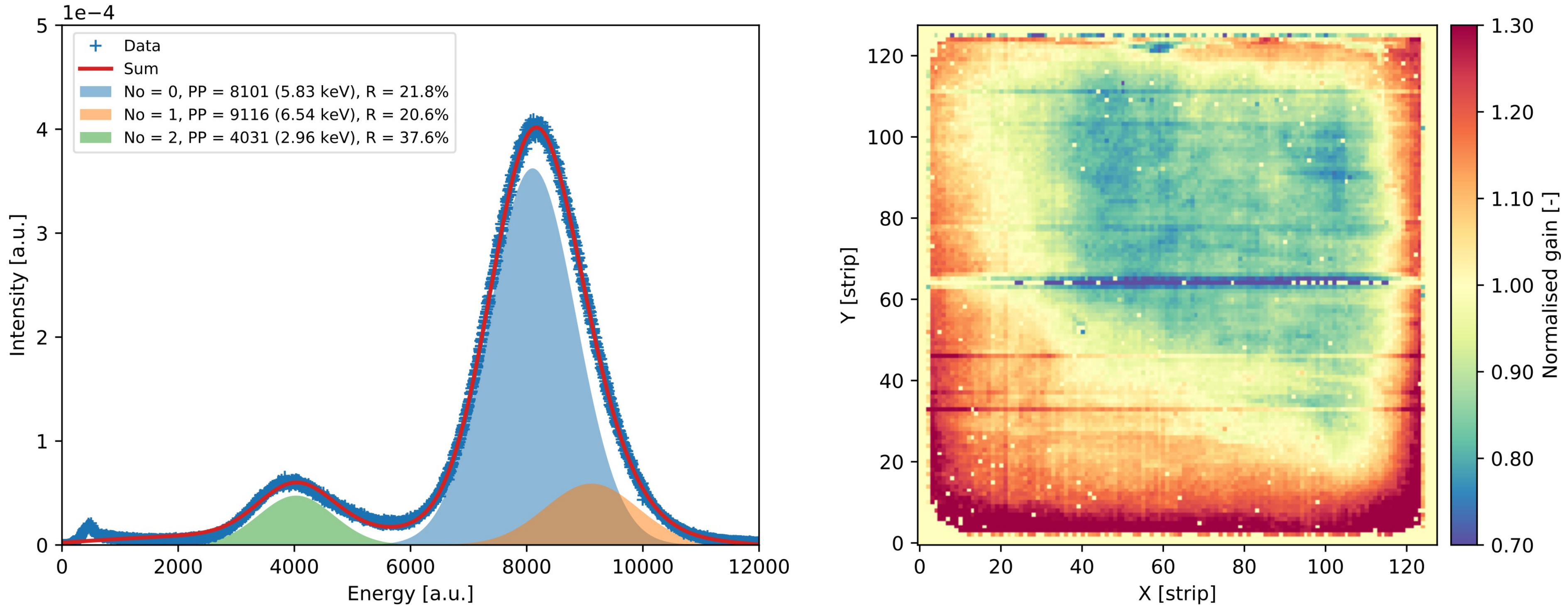
Proton measurements and analysis of the test results of the NS-GEM demonstrator



The assembled NS-GEM detector has been first tested extensively using X-ray ^{55}Fe radioactive source following our standard test and calibration procedures.

2. NS-GEM demonstrator: Modernization of the design and testing of the NS-GEM demonstrator.

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



Performed tests confirmed stable operation of the detector and its performance as expected. The obtained energy spectrum and gas gain factor distribution map are shown in Figure (left and right respectively). The energy resolution is around 22% FWHM for the 5.9 keV line.

Task Specfcation:

NS-GEM demonstrator - properties and measurement possibilities

3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

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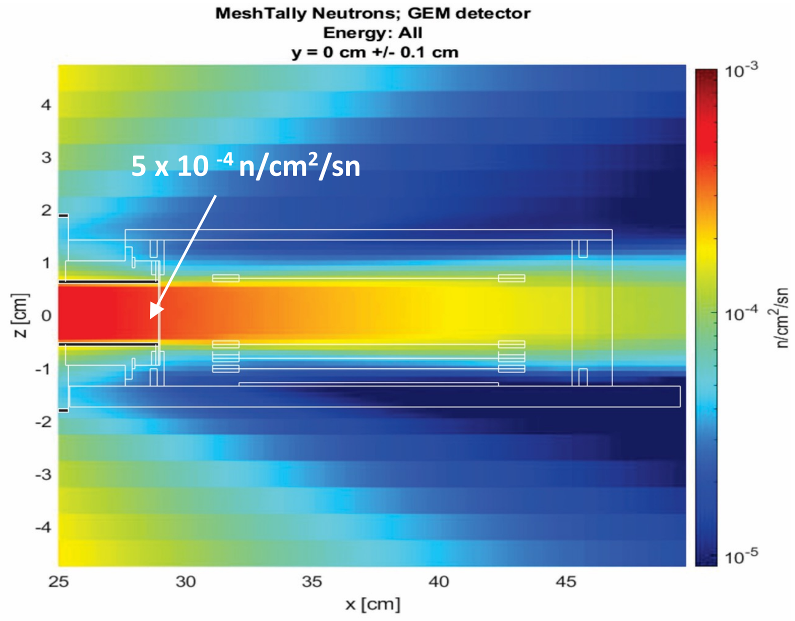
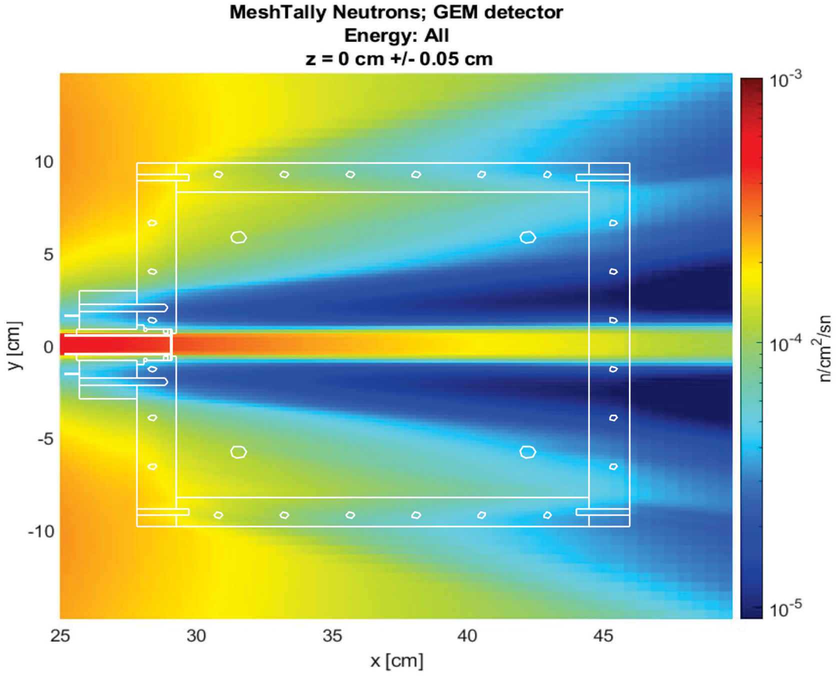
3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

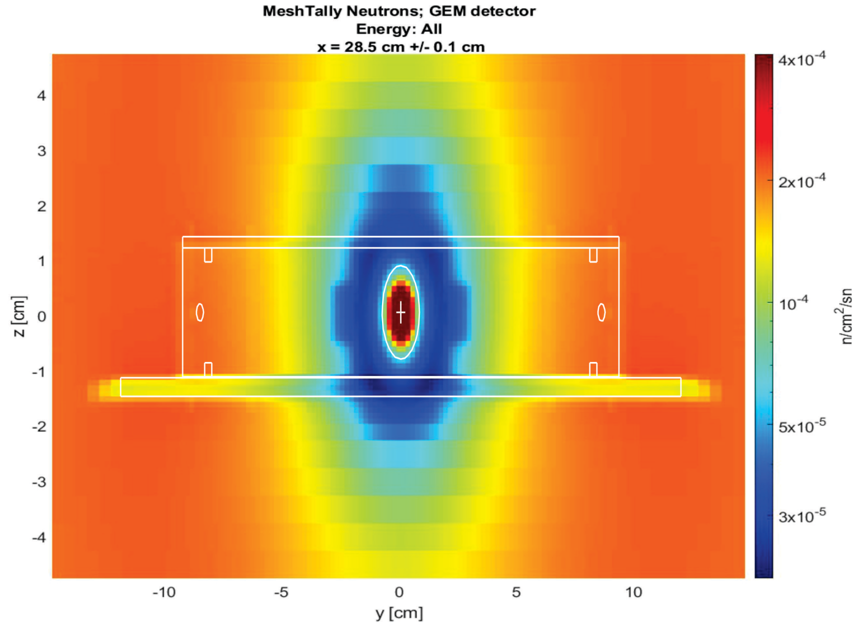
Neutrons from IGN-14



Side view



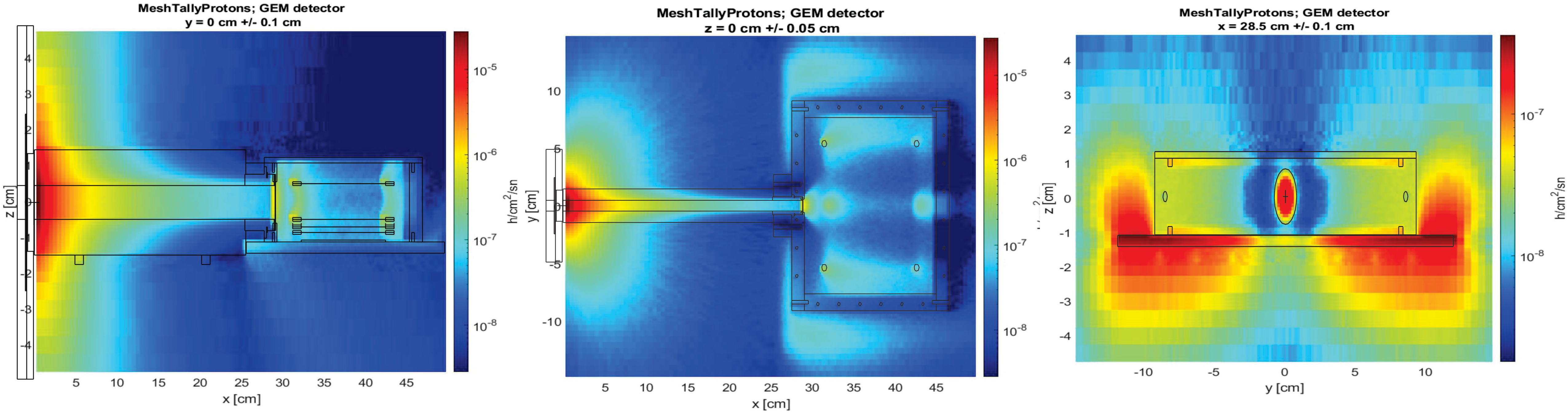
Top view



Front view
(on the converter level)

3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

Protons in GEM detector



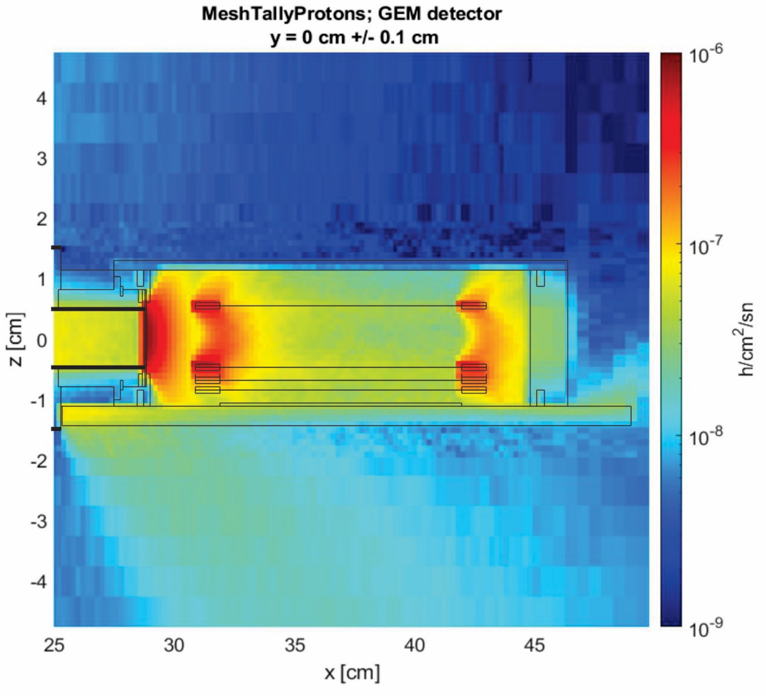
Side view

Top view

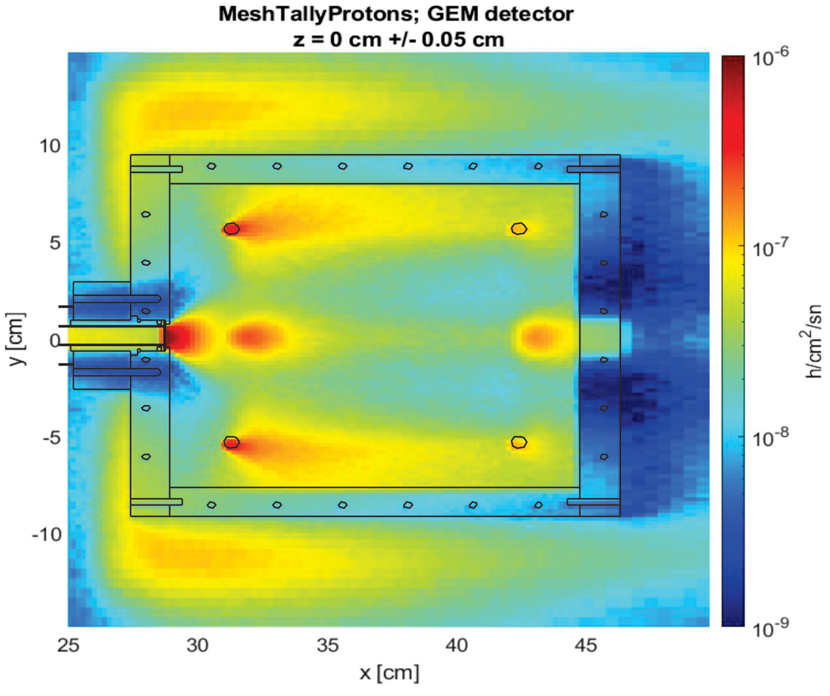
Front view
(on the converter level)

3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

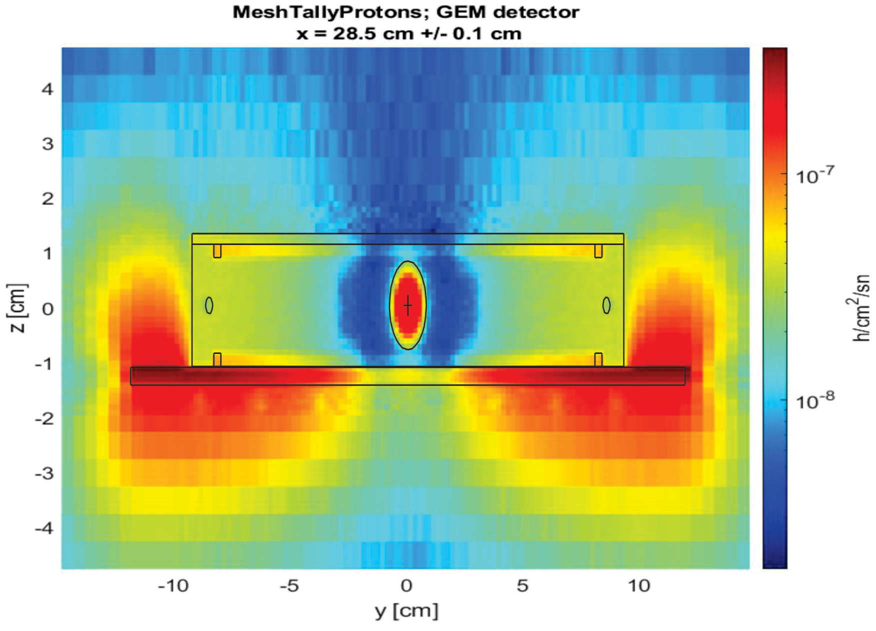
Protons in GEM detector



Side view



Top view



Front view
(on the converter level)

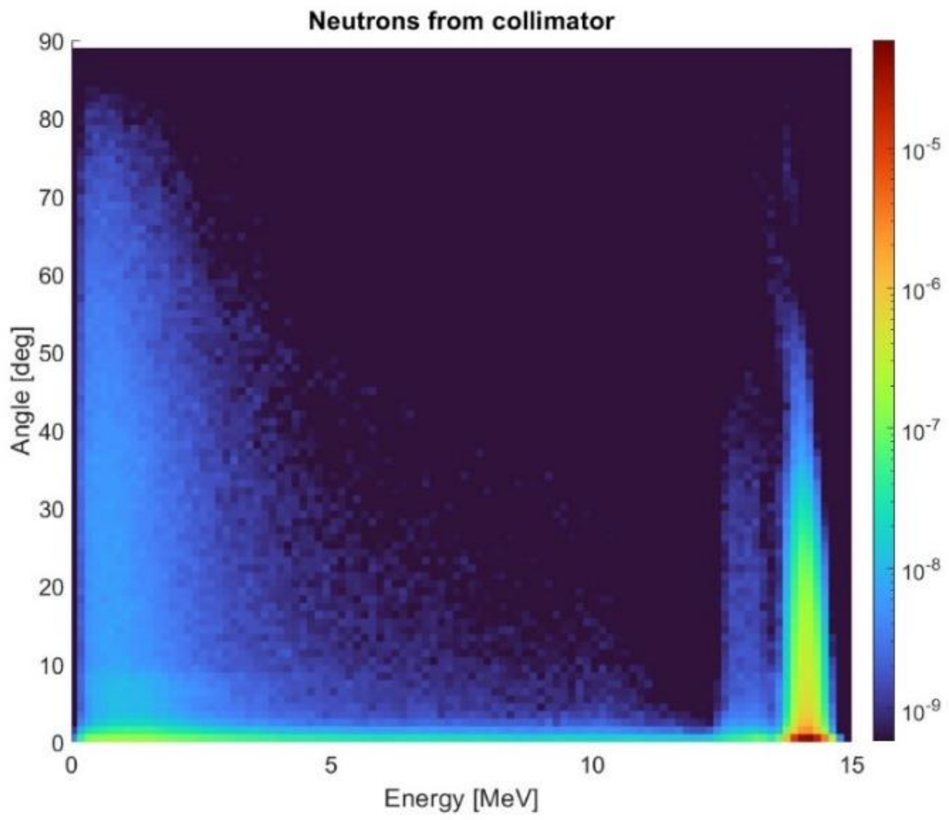
3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

Neutrons from the collimator

- For 14 MeV and all angles:
  - 1.505e-04 n/ surf / sn
- For E < 14 MeV and all angles:
  - 1.776e-05 n/surf/sn
- For all directions and all energies:
  - 1.683e-04 n/surf/sn

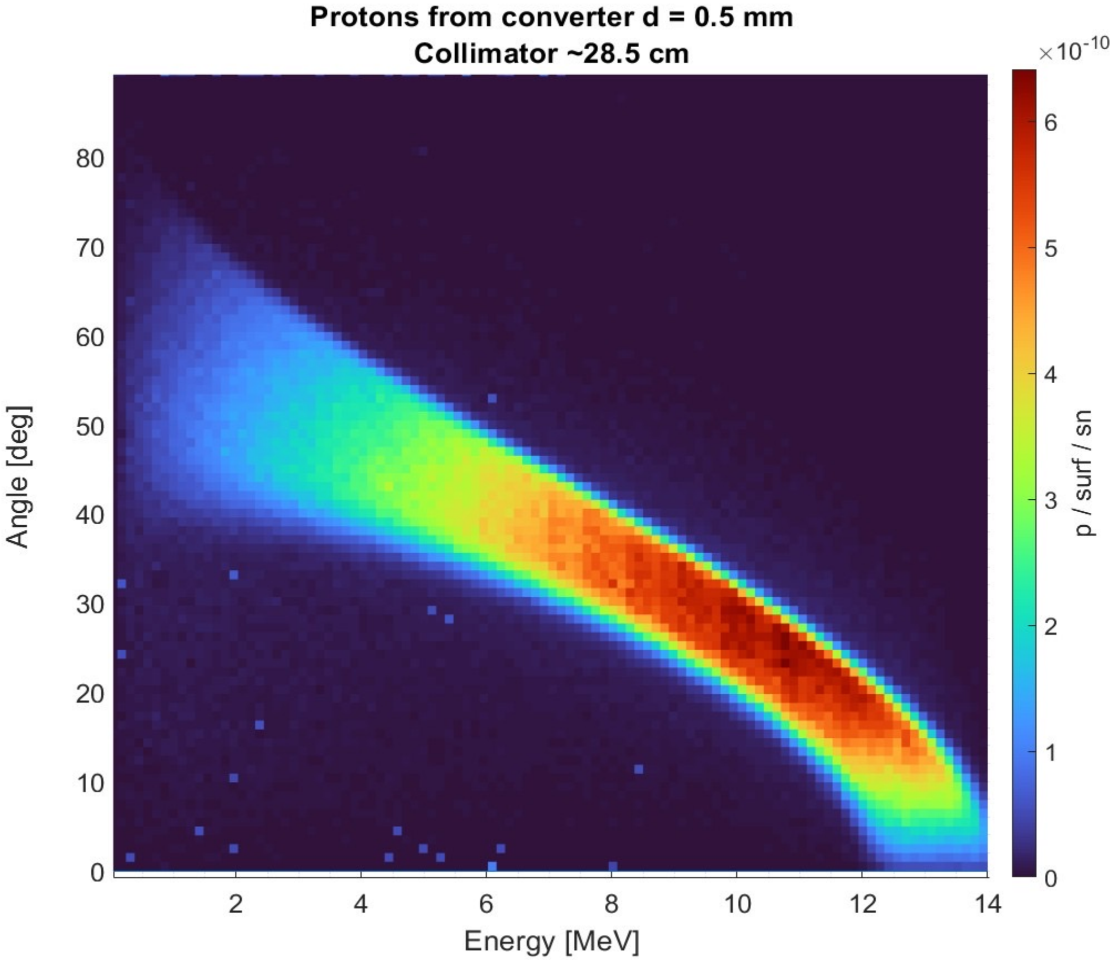
$N_{14MeV/AllE} = 89\%$

$N_{14MeV/E<14MeV} = 8.5$



3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

Protons from the converter



Number of protons produced in the converter:

Neutrons from the source: **~ 7.5 x 10^7 n/s**

For ideal case:

- All angles: 4.942 x 10^{-7} p/surf/sn -> **~ 37 p/s**
- 0-35 deg: 2.817 x 10^{-7} p/surf/sn -> **~ 21 p/s**

For real case:

- All angles: 5.39 x 10^{-7} p/surf/sn -> **~ 40 p/s**
- 0-35 deg: 3.072 x 10^{-7} p/surf/sn -> **~ 23 p/s**

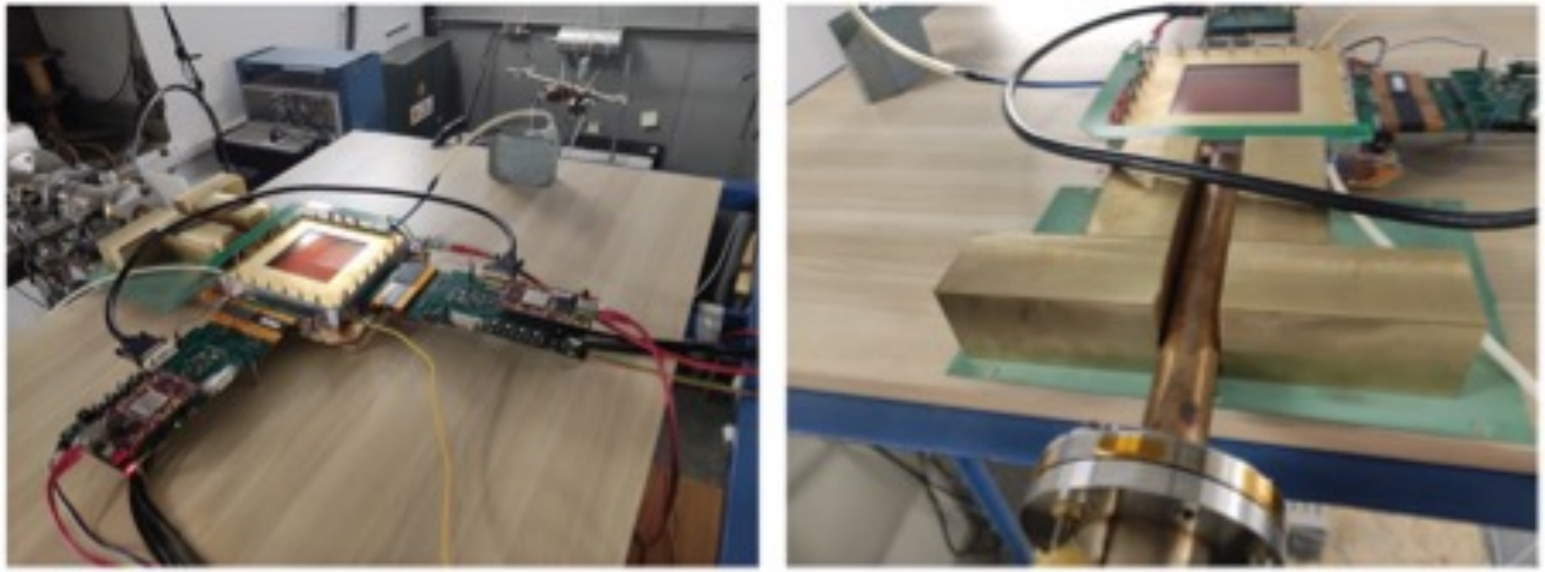
Real case = neutrons are emitted at a full angle from the source (background)

converter d= 0.5 mm

3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

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

Detector system set up in the IGN-14 laboratory

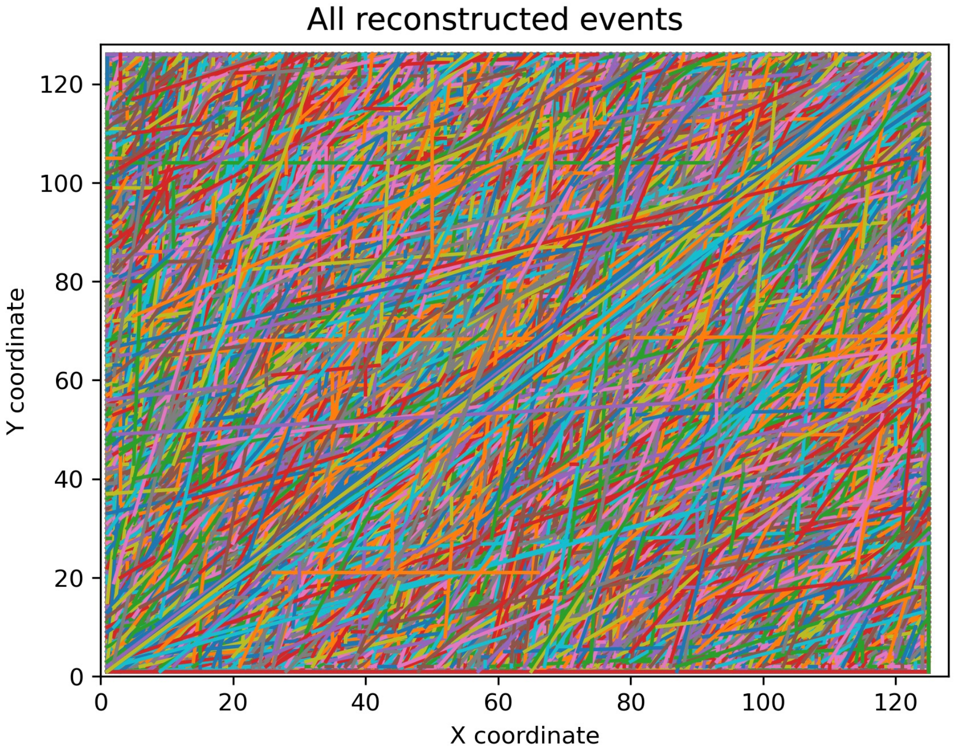


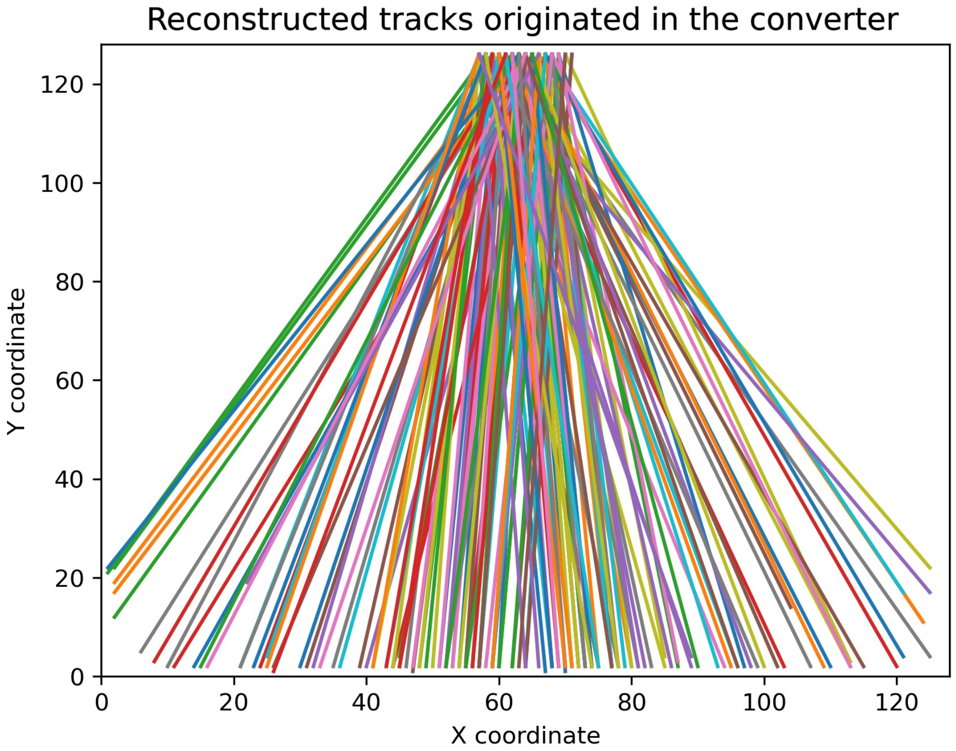
For performed tests 25 cm collimator and 0.5 mm converter has been used. Data have been collected for 3 hours in 15 minutes periods.

3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

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

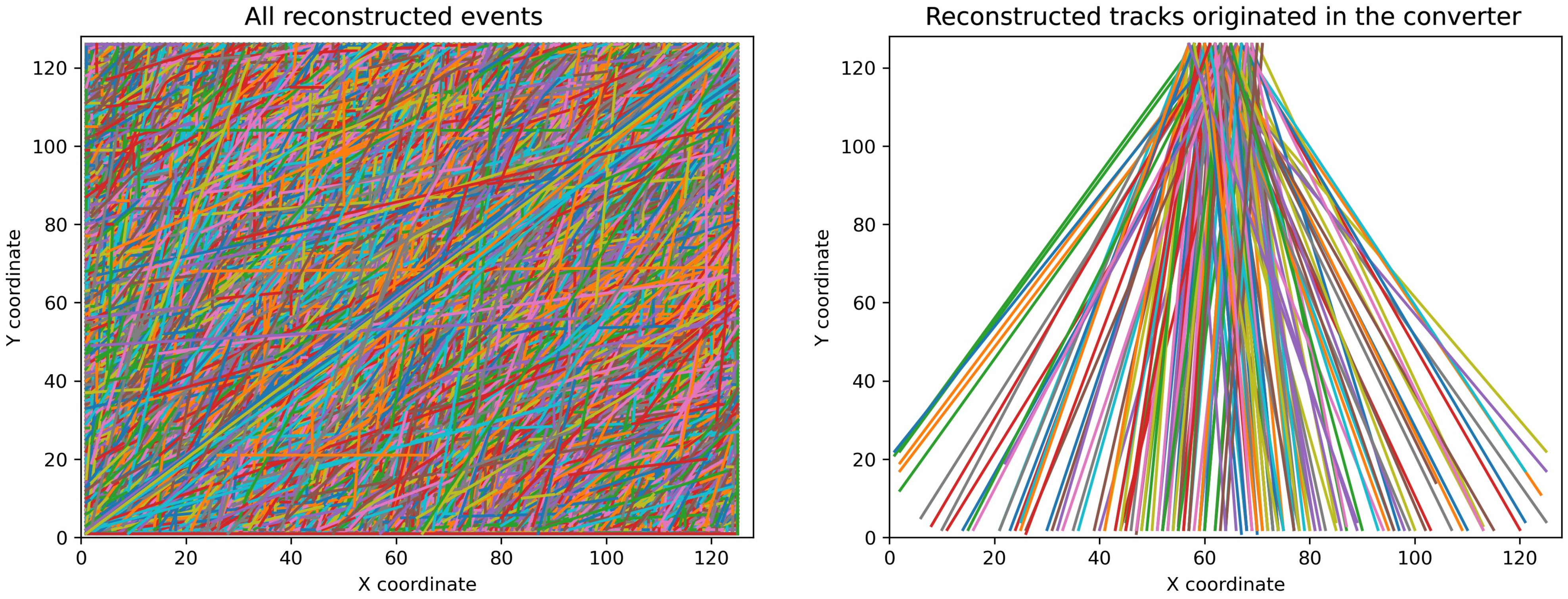
Critical aspect of the analysis is the algorithm for proton tracks reconstruction as we have to deal with a huge amount of background signals originating in detector material by scattered neutrons. In order to filter out this redundant events, several requirements were imposed on the reconstructed events. In particular, proton track candidate has to meet the following criteria: origin point in the converter, long enough track, and recoil angle in the range of 0 to 35 deg.





3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

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



The next step in data analysis is estimation of the total energy losses in the detector volume, which is the sum of signal amplitudes recorded along the track.

3. NG-14 MeV neutron generator: NS-GEM demonstrator neutron tests.

- The demonstrator detector has been designed, built and used for first measurements in the IGN-14 neutron generator.
- Elaborated procedures for recoil proton tracks reconstruction have been proved to be very efficient and robust ever for very large background of signals.
- Measurements of energy losses dE/dx requires further optimisation of the detector working parameters.

Modifications/changes to the project required in 2024.

At the moment we do not anticipate.

In 2023 we mentioned

Possible risk that may be associated with the implementation of the project in 2023:

- Prolonged procedure for purchasing additional tritium targets for ING14;

We started with this procedure at the beginning of 2023, and the October we obtained answer from Sodern – ArieneGroup:

Temat: RE: Rćf./Ref. : SODERN proposal ref. DAF/CT/PC/PK- TUB 22- 0597
Data: 2023-10-23 09:24
Od: LACROIX Jean-Sebastien <jean-sebastien.lacroix@sodern.fr>
Do: aldabrowska <aleksandr
The production of the 4 targets has been slightly postponed : scheduled
second week of January. Delivery expected by end of January.
Best regards,
Jean-Sébastien LACROIX
Key Account Manager / Project Manager
Sodern - ArianeGroup
20 avenue Descartes
94450 Limeil Brévannes, France
T. +33 (0)1 45 95 72 33

Others:

- French student in the 2nd year of an engineering school (equivalent to the first year of a master's degree) at ENSICAEN in Caen in the north of France.
- 4-month internship in the : Department of Radiation Transport Physics (NZ61) at the IFJ PAN Institute from April to August 2023.
- The purpose of the internship was to model a recoil proton thin-foil system and a detector for measuring fusion neutrons by observing the spectrum of energy deposited by protons in the detector after converting neutrons into protons in a polyethylene thin-foil.

Based on the results of the internship the draft of the article to the J of Fusion Energy was prepared:
„AI-supported modeling of a simple TPR system for fusion neutron measurement"

During the implementation of the project in 2023, four technical notes were prepared. On the basis of these notes, an annual report was prepared with applications for implementation in the next year of the project implementation.

Articles and presentations:

1. 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 DOI: 10.1088/1748-0221/18/05/C05001
2. M. Scholz*, W. Dąbrowski, U. Wiącek, A. Jardin, B. Łach, K. Drozdowicz, U. Woźnicka, A Kurowski, A. Kulińska, D. Mazon, Proton-recoil spectrometer for fast neutron spectrum based on GEM gas detector, EPS 2023, Bordeaux
3. M. Scholz, U. Wiącek, K. Drozdowicz, A. Jardin, U. Woźnicka, A. Kulińska, A. Kurowski, W. Dąbrowski, B. Łach, D. Mazon, Status of the GEM detector as a compact neutron spectrometer for fusion plasmas, 44th Meeting of the ITPA Topical Group on Diagnostics, 6-9 November 2023, ITER Organization site

Additional information

Collecting meetings data:
https://wiki.euro-fusion.org/wiki/Project_No12