Development of compact fast neutron spectrometer based on GEM technology

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Outline

- NS-GEM Motivation
- NS-GEM spectrometer design
  - Requirements, possibilities and limitations
  - Geant4 simulations
- Test beam results
- Plans for the future
- Summary

Neutron spectrometer (NS-GEM) – motivation

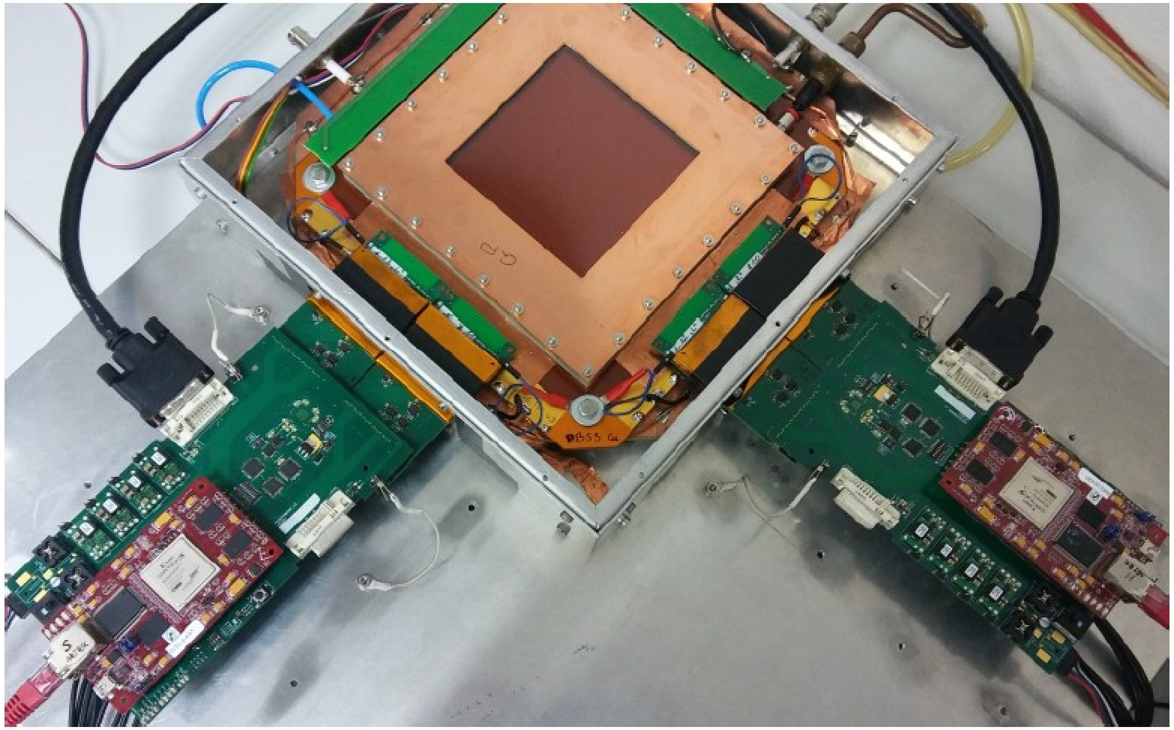
- Compact neutron spectrometer for fusion plasmas at ITER
  - lack of space in the HRNS spectrometer area
- Spectrometer key features:
  - Radiation hardness
  - Low sensitivity to γ-rays
  - Neutron detection within energy range 2 – 20 MeV
- Design assumptions:
  - Application of GEM (Gas Electron Multiplier) technology
  - Redesign of our own already existed and extensively tested GEM detection system
  - Support with commercially available components

1) reasonable timescale

2) costs minimisation

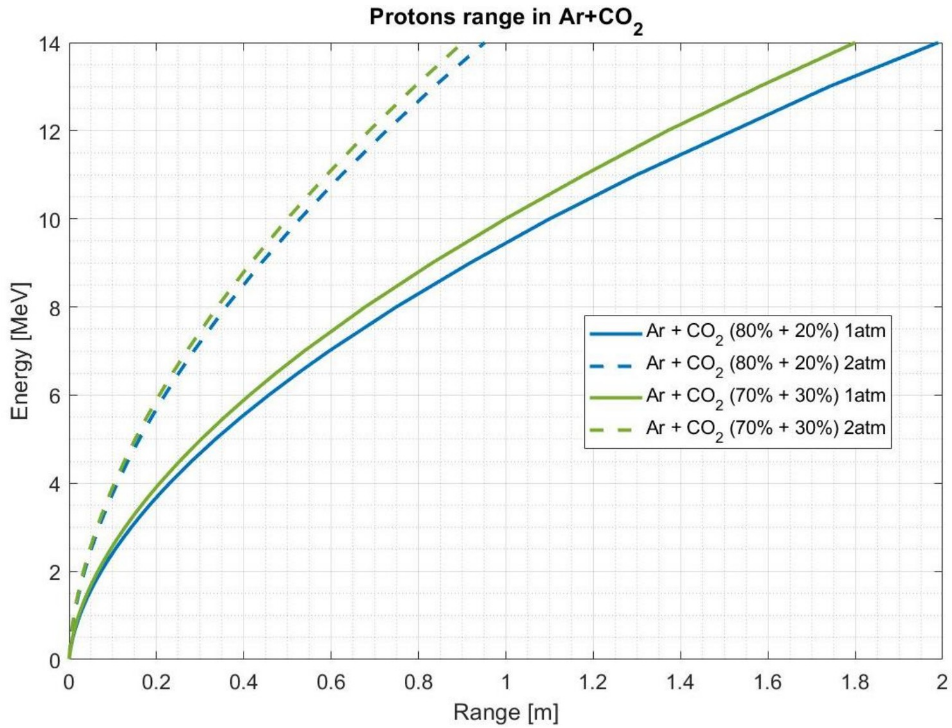
Detection system with triple-GEM at AGH

- Detection area 10 x 10 cm^2
- 2D strip-like readout
- Custom design DAQ acquisition system



TPR in NSGEM spectrometer

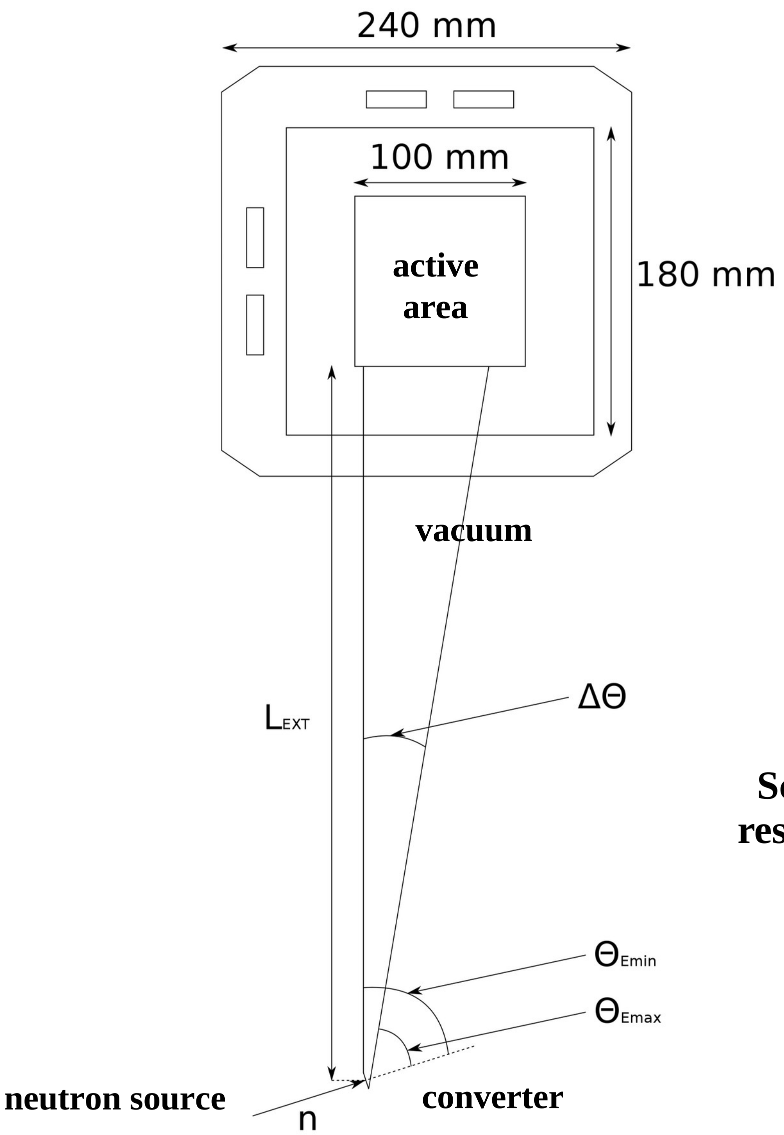
- Thin Proton Recoil technique → $E_n = \frac{E_p}{\cos^2\theta}$
- 14 MeV neutron generator at IFJ Laboratory
- Proton range in active detector volume →



For 10 cm long GEM detector operating at 1 atm only protons with energy up to 2.5 MeV can be stopped completely in the active detector volume

If E_N = 14 MeV → $\theta > 65^o$

Spectrometer design – version I



- Detection of protons recoiled at $\theta > 65^{o}$ ($E_P < 2.5$ MeV)
- Vacuum chamber to limit the error of θ determination
- Plenty of extended simulations to study:
  - Proton scattering and energy deposition
  - Influence of drift thickness, gas mixture, extension arm length
  - Detection efficiency, system energy resolution

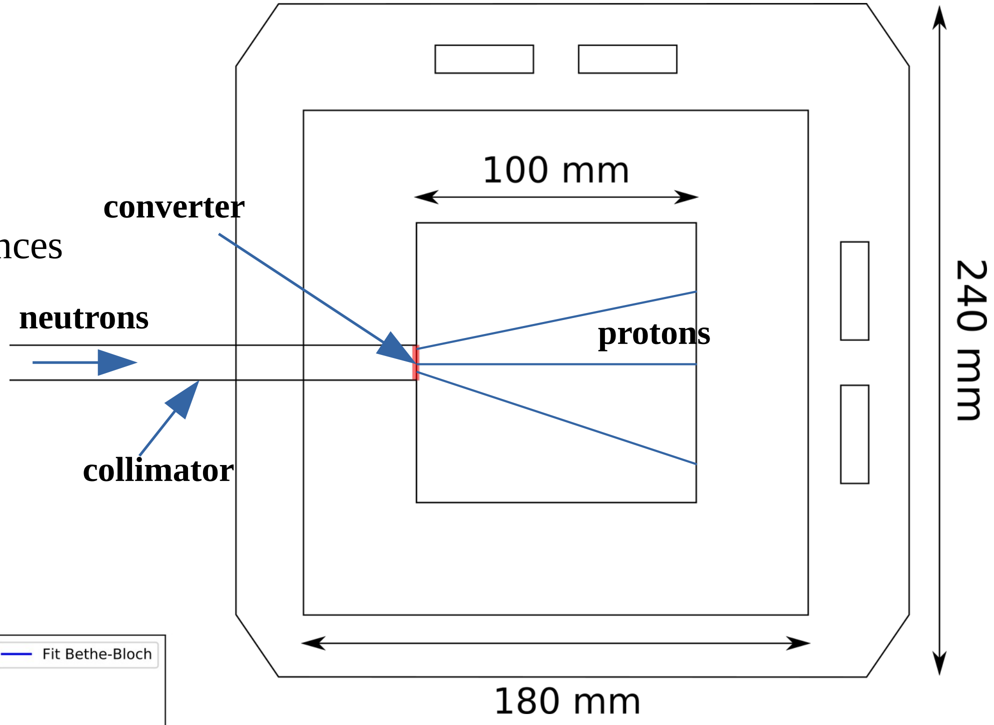
Scattering of protons with such low energies within the converter (0.1mm) results in system energy resolution at 100 % FWHM level (goal at 5 % level)

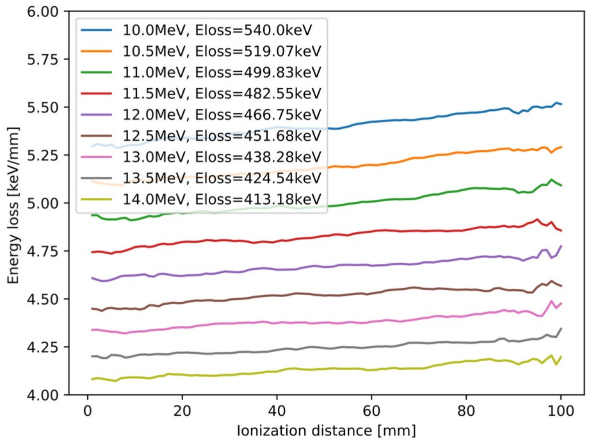
Rejection of the measurement concept and ...

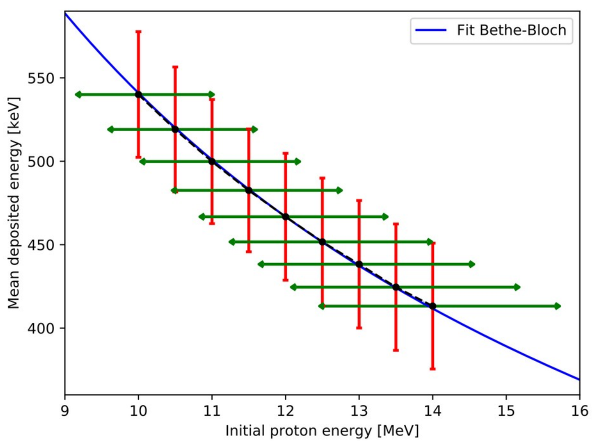
Spectrometer design – version II

Reconstruction of protons energy from dE/dx

- Measurement of partial energy deposition of high energy protons and reconstruction of its initial energy based on dE/dx curve
- Energy loss characteristic for initial proton energy and ionization distances
- Advantages:
  - Simpler spectrometer construction (no vacuum chamber)
  - Angle of acceptance: $\theta < 20^{o}$ → $10 < E_P < 14$ MeV
  - Increase of detection efficiency



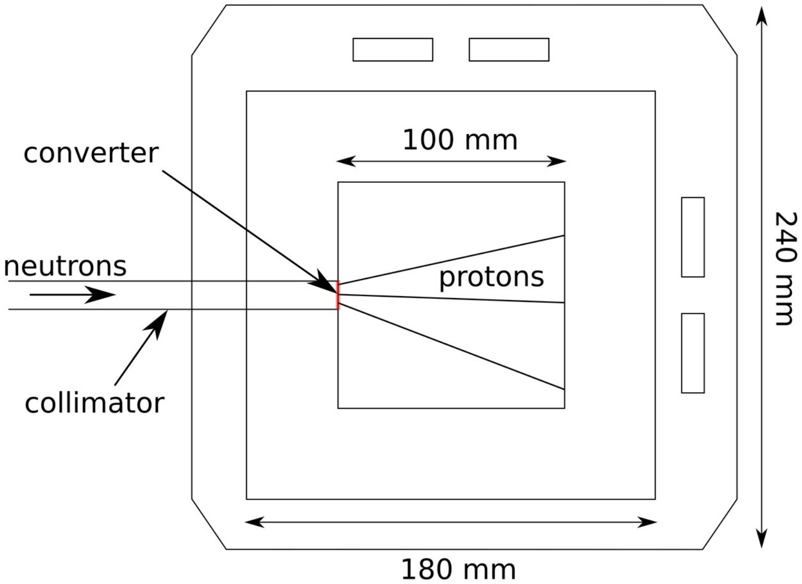


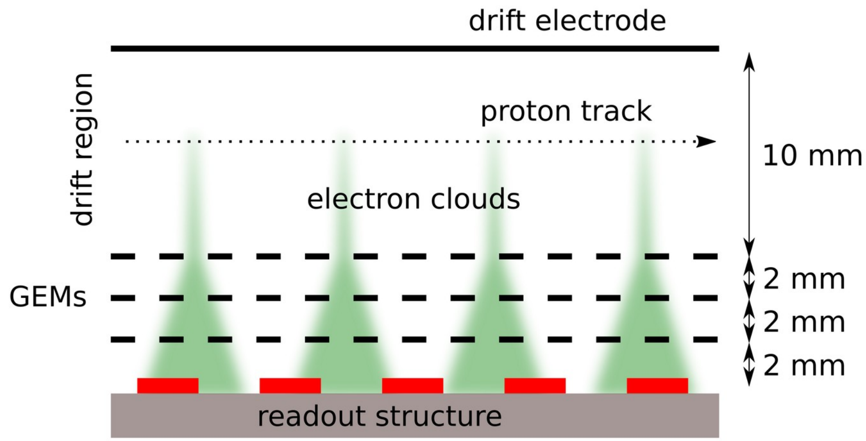


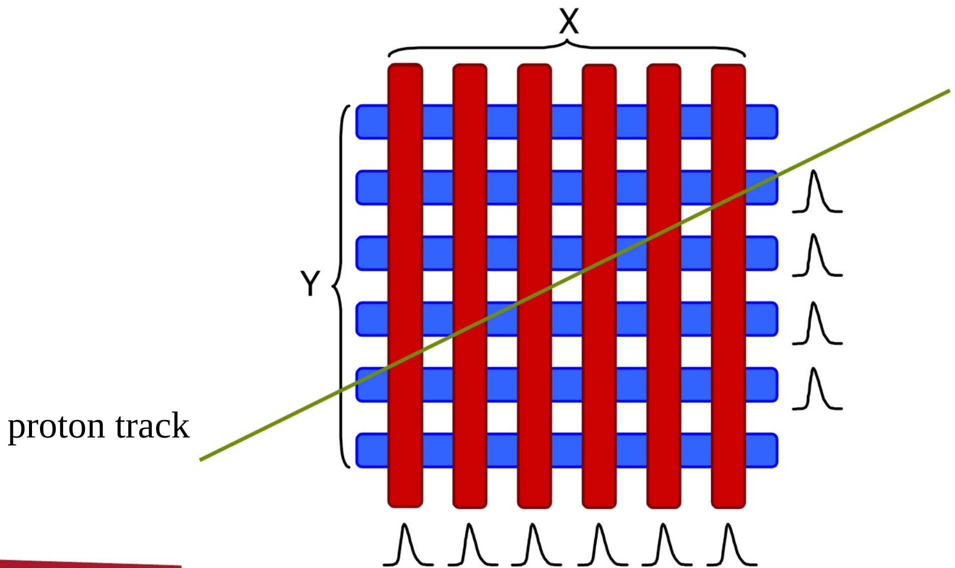
Significant fluctuations but...

$$\sigma\left(\frac{dE}{dx}\right) \sim L^{-0.37}$$

NS-GEM – working principle summary







Proton track reconstruction

↓

All the signals registered within specific arbitrary selected time window (time coincidence)

Energy measurement

Trajectory reconstruction

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

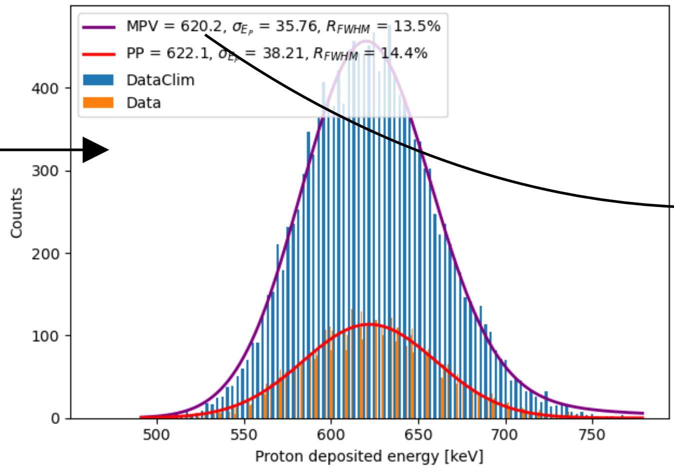
Calibration curves generation – idea

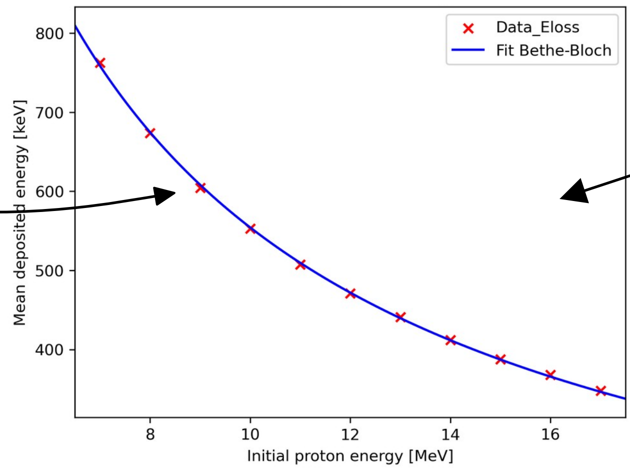
Proton energy loss in NS-GEM detector depends on:

- Its initial energy
- Track length ← → angle and origin of the generation at the converter
- Converter thickness

To create a lookup table with energy loss to initial proton energy conversion one need to simulate proton energy loss over different its energies and track length (angle and point of generation)

Proton energy loss for specific angle and track length





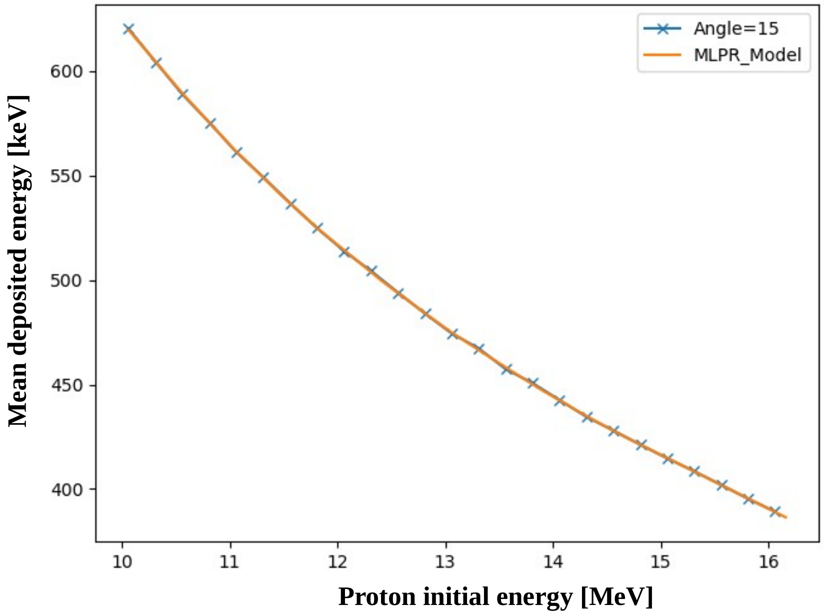
Calibration curve dedicated for specific angle and track length

Calibration curves generation – fitting the model

As for low proton energies, proton energy loss do not follow anymore Bethe-Bloch formula, it is impossible to generate and fit proper calibration curves for such proton energy range.

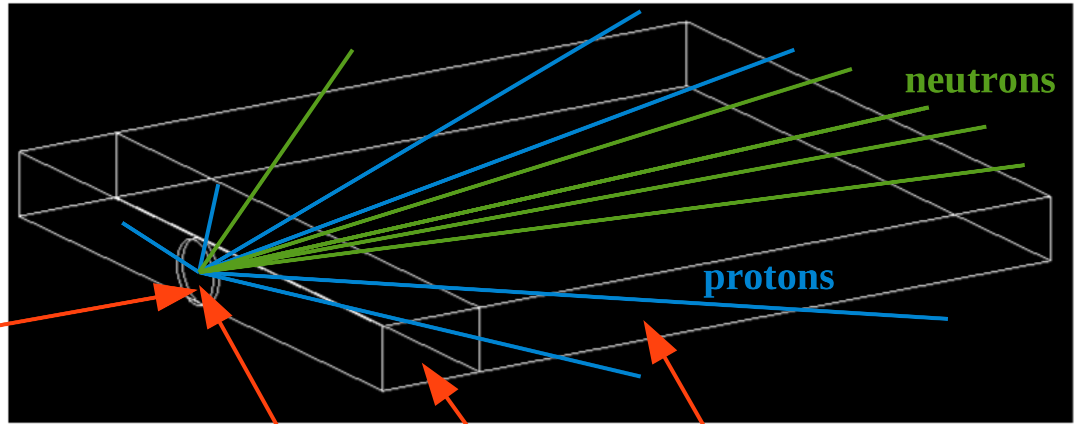
Thus to provide valid calibration curves in a wide proton energy range, fitting algorithm based on neural network has been tested and applied to MPV data.

- MLPRegresor from scikit-learn python library
- 5 layers with 200 neurons each
- activation = relu
- solver = lbfgs
- model.loss_ < 0.09

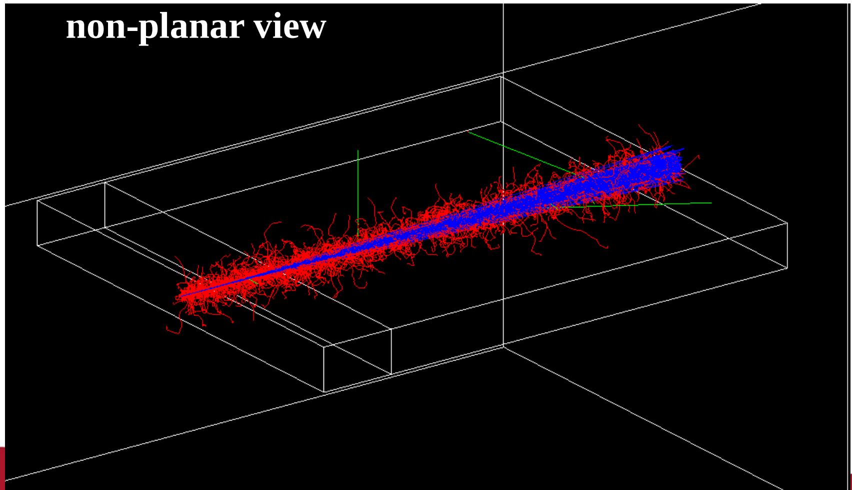


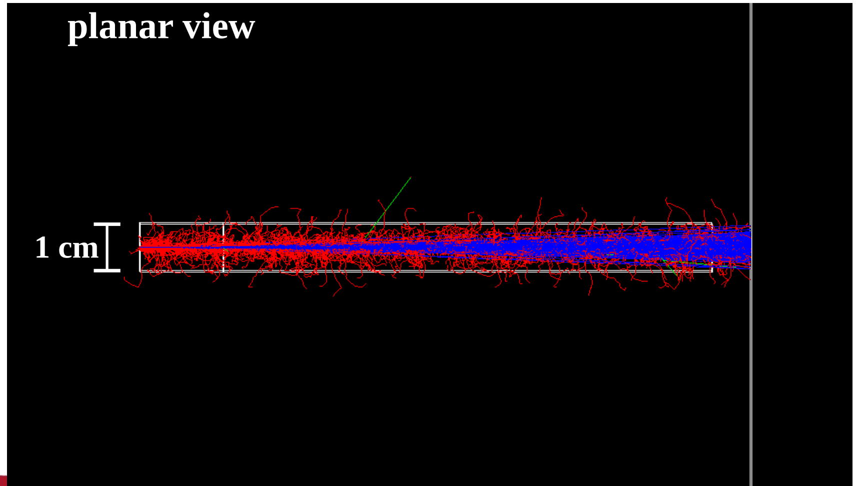
Geant4 simulation

To model the proton transport through the detector volume in detail, the dedicated Geant4 simulation model has been prepared



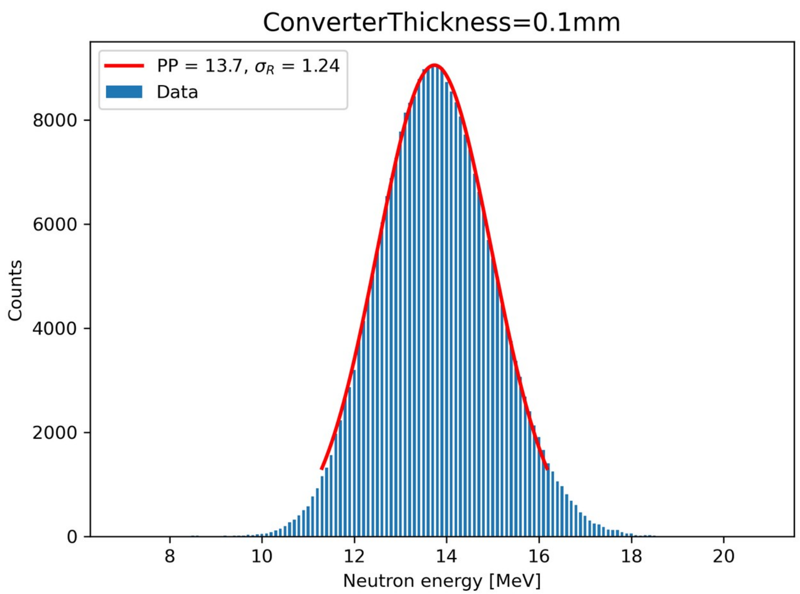
Exemplary Monte Carlo results of:
1000 14 MeV protons (blue)
with δ-electrons (red)
and kaons/neutrons (green)
detection





Neutron cumulative spectrum energy resolution – Geant4 simulation

Neutron cumulative spectrum (sum over the 0 – 20 deg angles) energy resolution calculated taking into account: scattering and dE/dx deposition fluctuation in the detector volume

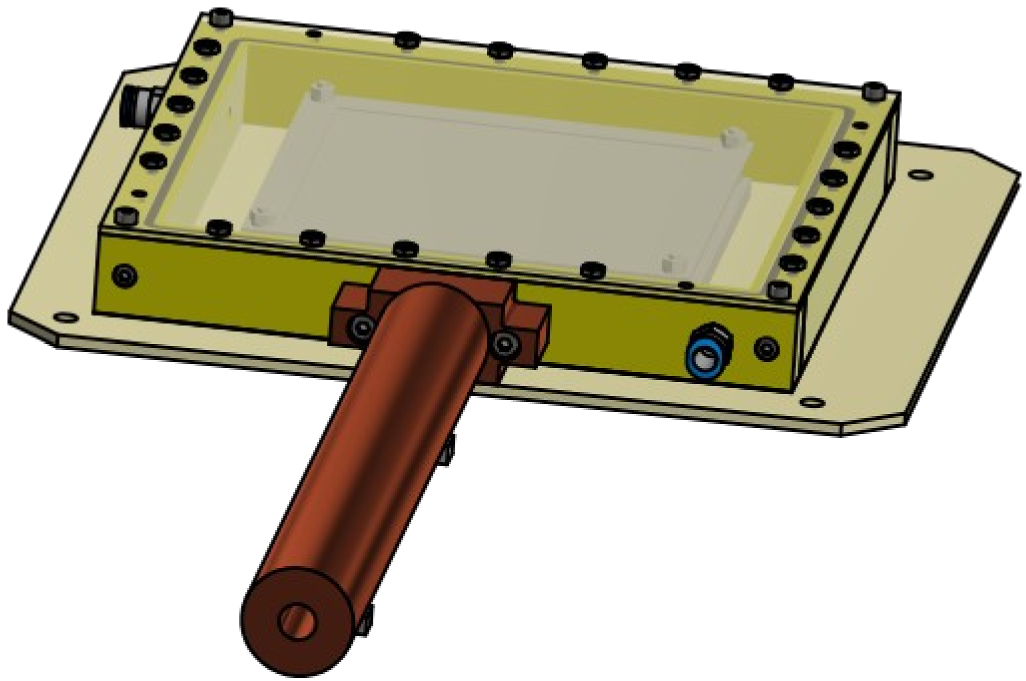


Converter Thickness [mm]	Energy resolution [%]	
	1 atm. pressure	2 atm. pressure
0.1	21.3	14.6
0.25	20.4	15.3
0.5	22.1	17.5

Thickness of the converter seems not so crucial in case of such short detector...

Mechanical construction of the NS-GEM detector

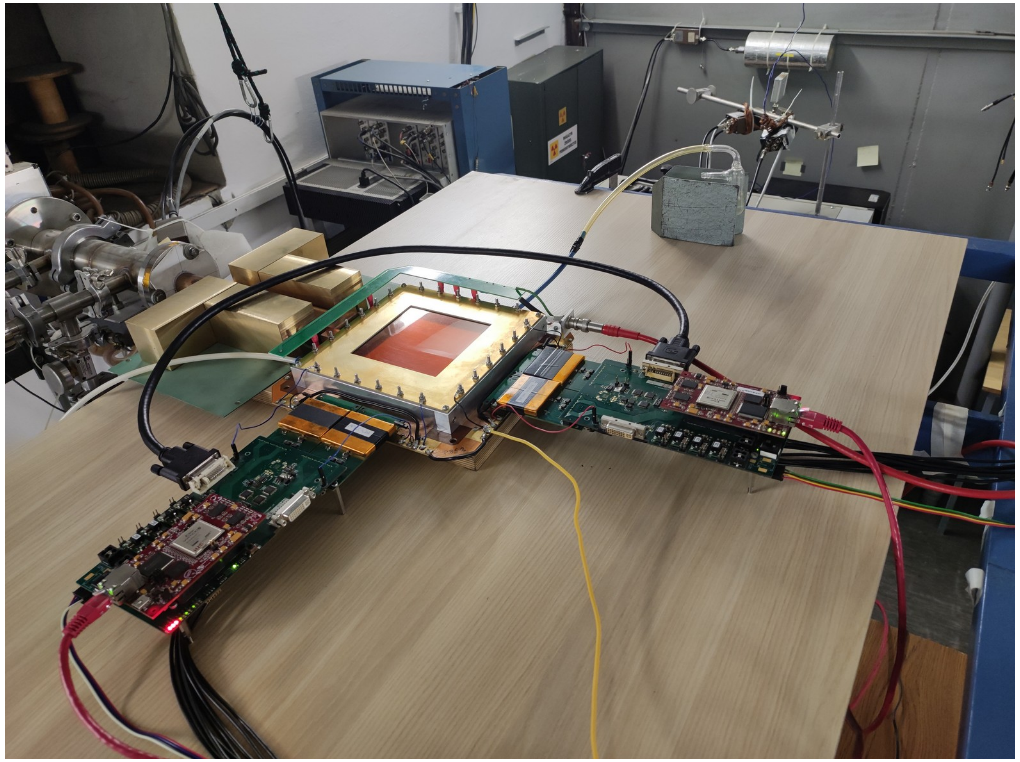
- Manufacturing of the final mechanical construction of the NS-GEM spectrometer
- Results of cooperation of researchers at:
  - AGH (W. Dąbrowski / B.Mindur group)
  - PK (R. Kantor group)
  - IFJ (M.Scholz group)
- Assembling the NS-GEM detector with the readout system
- Initial tests and calibration with X-ray
- Development of algorithms for continuous track reconstruction

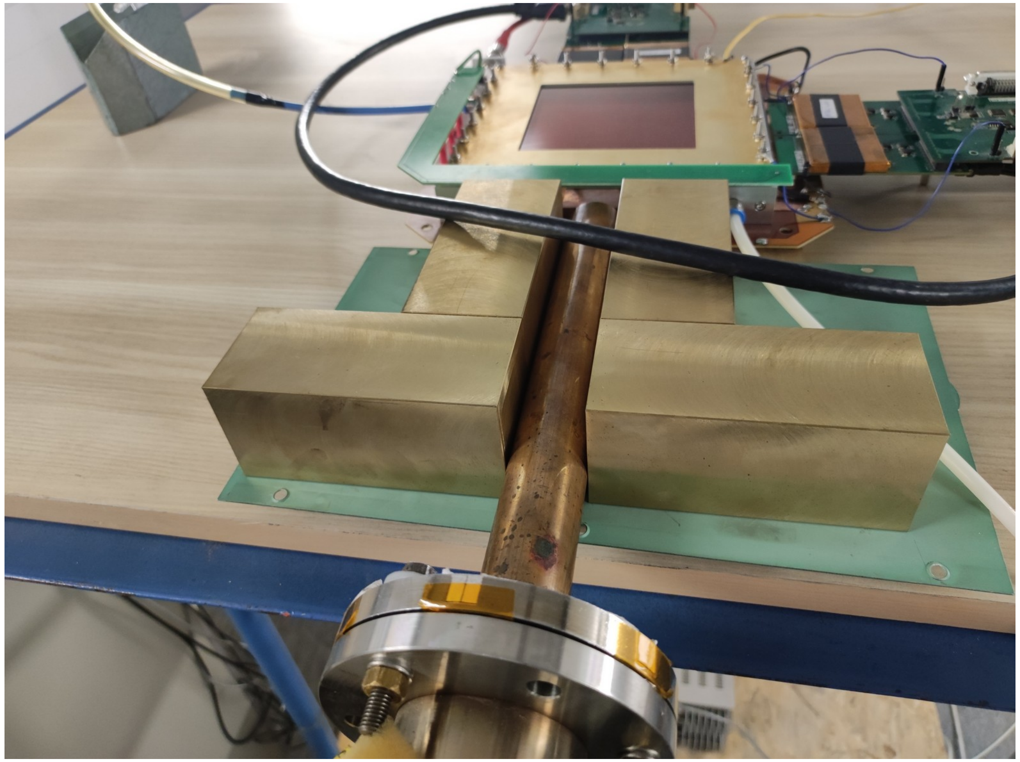


NS-GEM measurement setup at IFJ*

Measurement parameters:

- neutron source of 14 MeV neutrons
- ^{55}Fe radiation source
- converter thickness of: 0.13, 0.23, 0.5 mm
- Electric drift field in the drift region: 0.5, 1.8 kV/cm

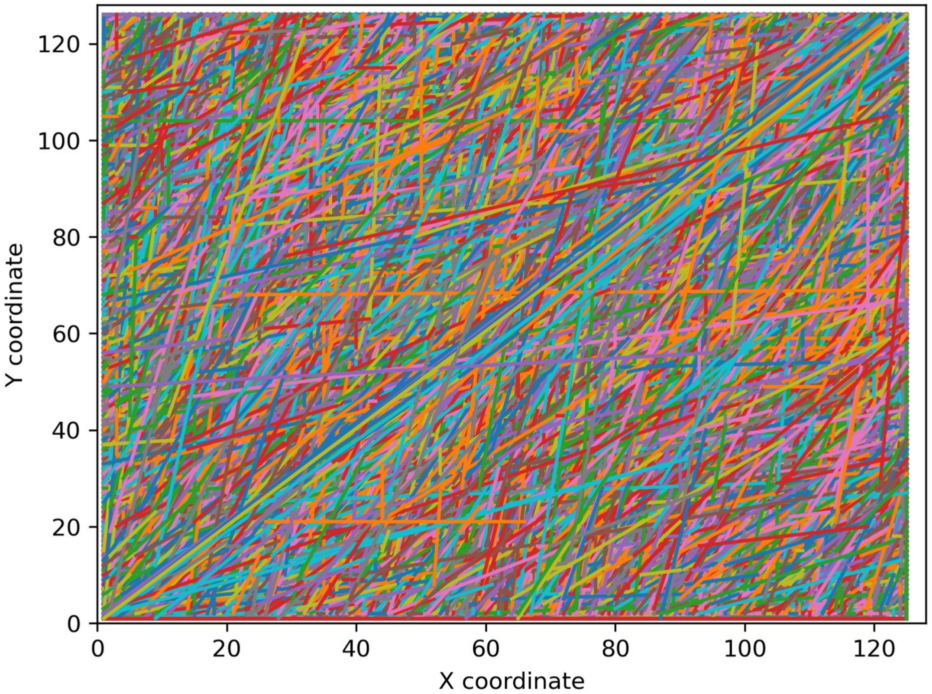




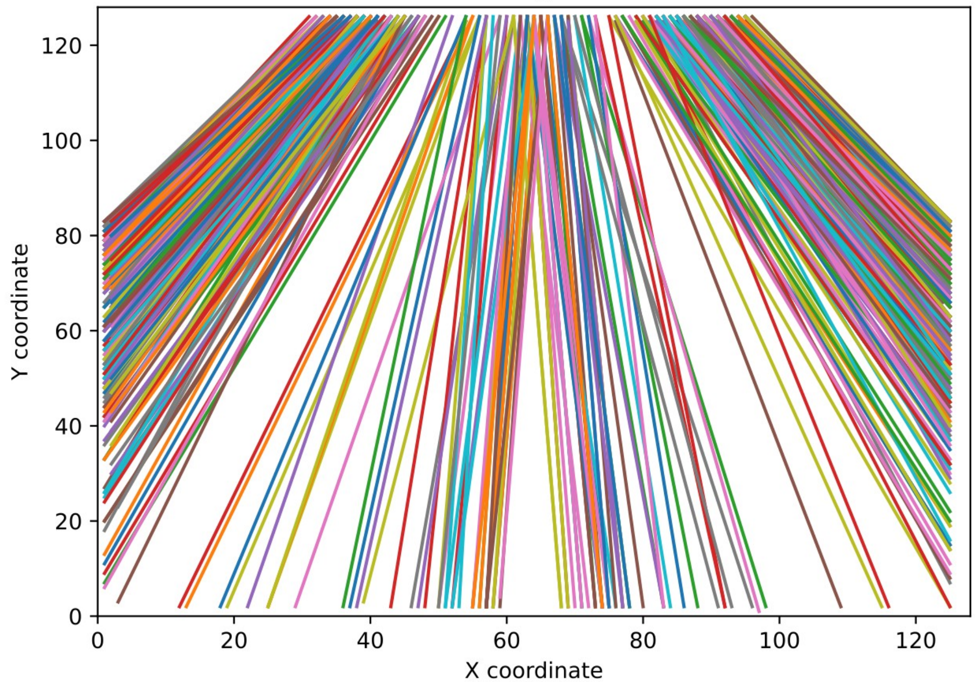
***IFJ – Institute of Nuclear Physics PAN in Krakow**

Reconstruction of the proton tracks

All reconstructed events



Reconstructed tracks originated in the converter



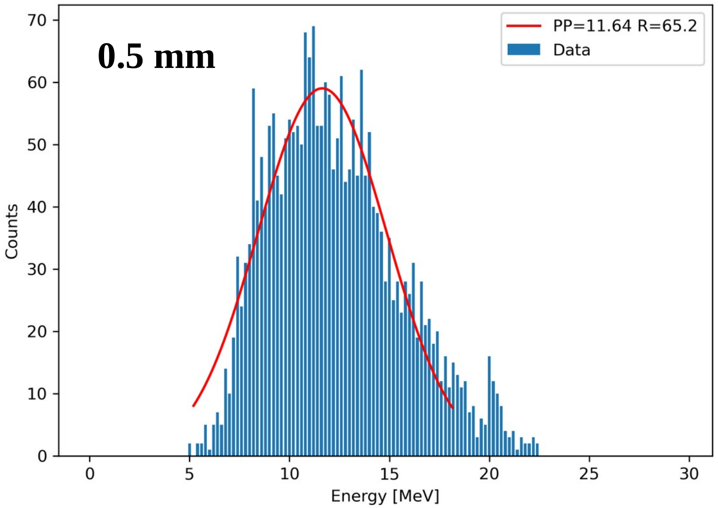
Valid track candidate criteria:

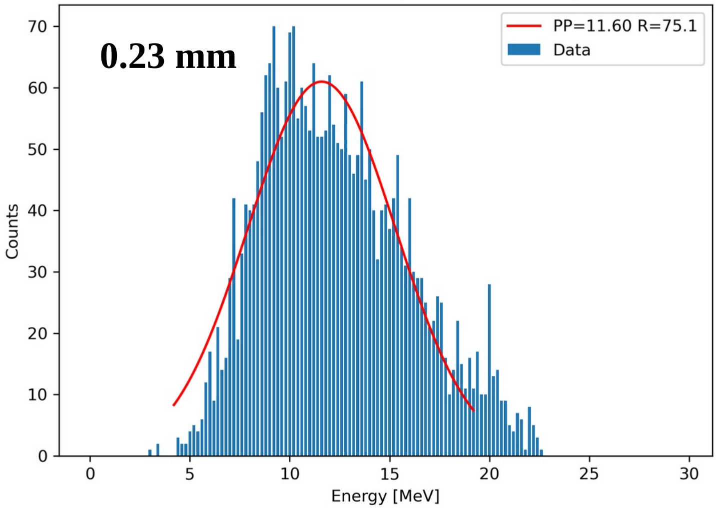
- origin point in the converter
- long enough track
- recoil angle in the range of 0 to 20 deg
- not saturated energy signal

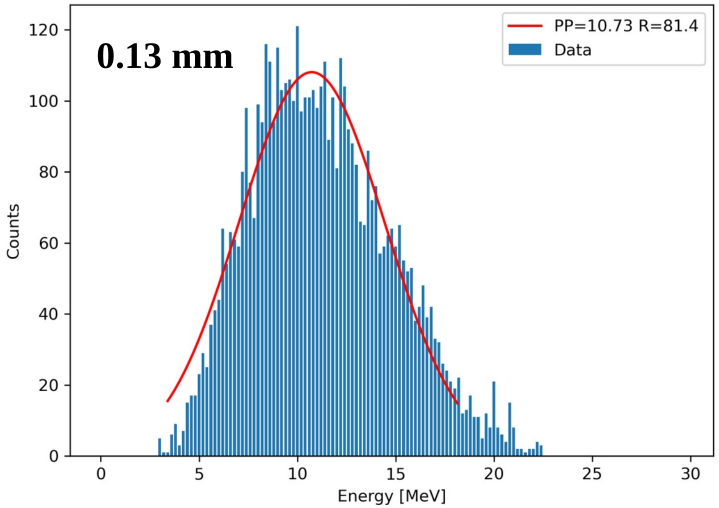
15 minute of measurement ≈ 200 tracks

Reconstructed neutron spectra – measurement summary

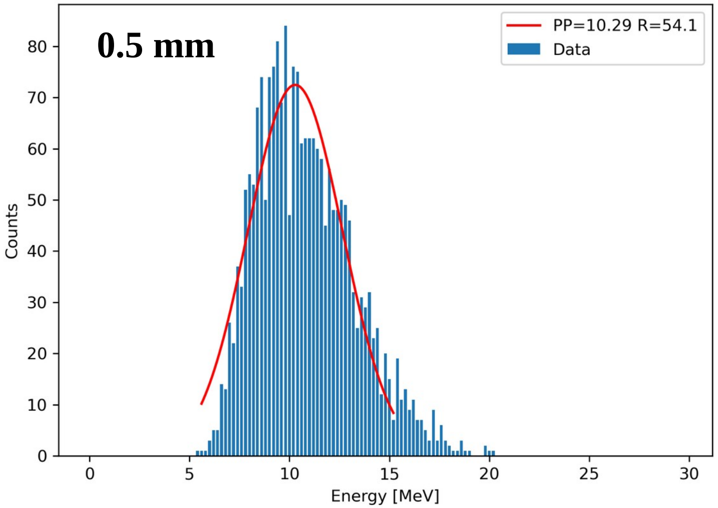
E_{drif}=0.5 kV/cm

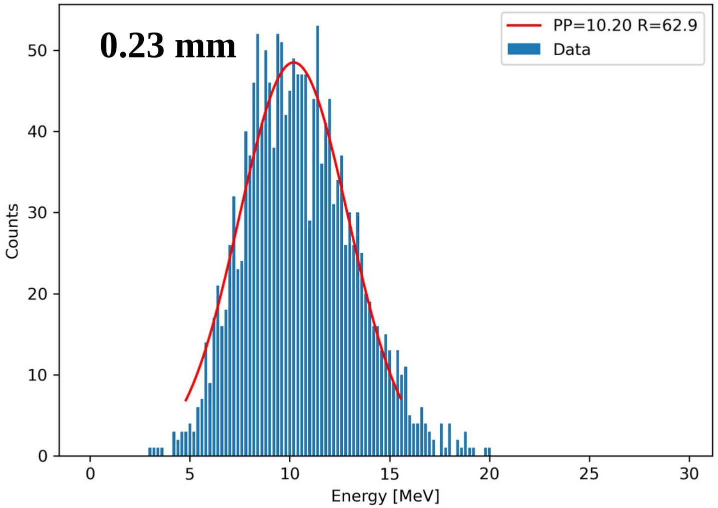


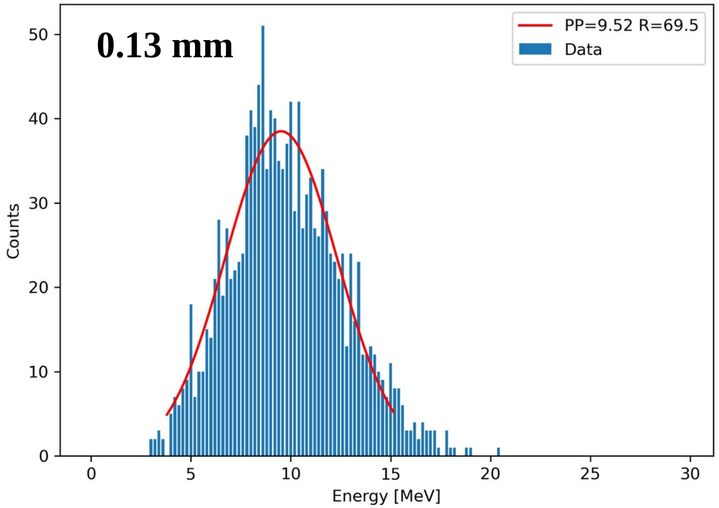




E_{drif}=1.8 kV/cm



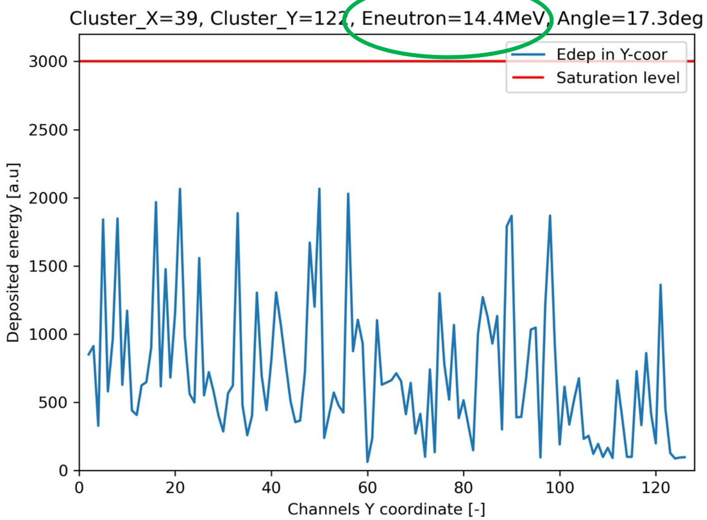


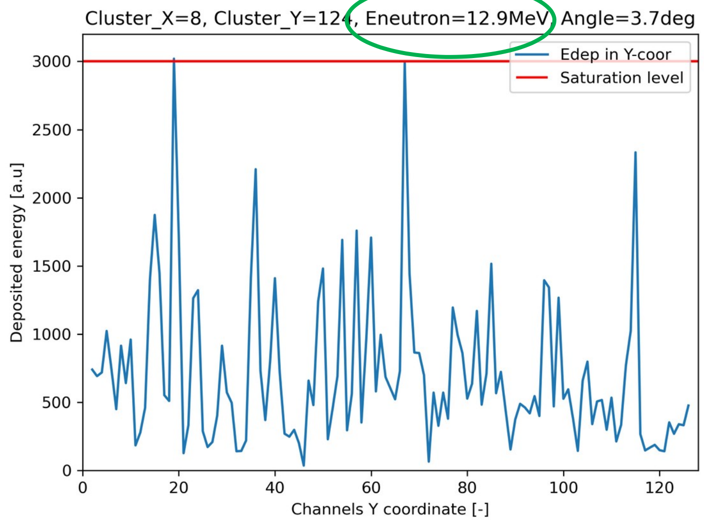


<u>What is the reason of observed 14 MeV neutron spectra shift?</u>

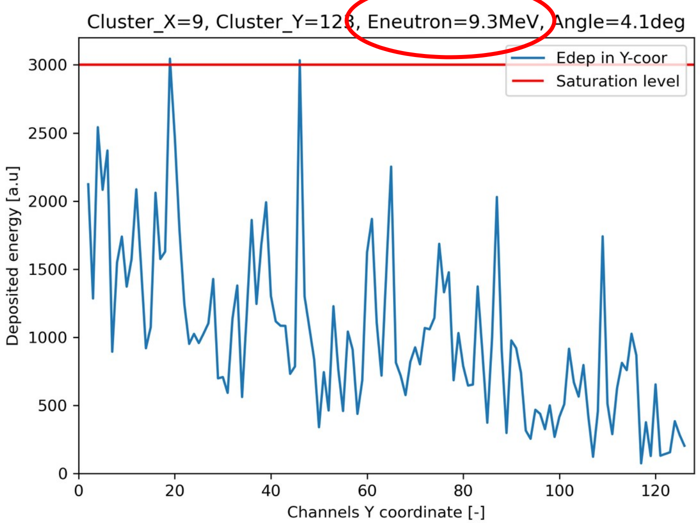
Proton energy deposition along the track - visual inspection

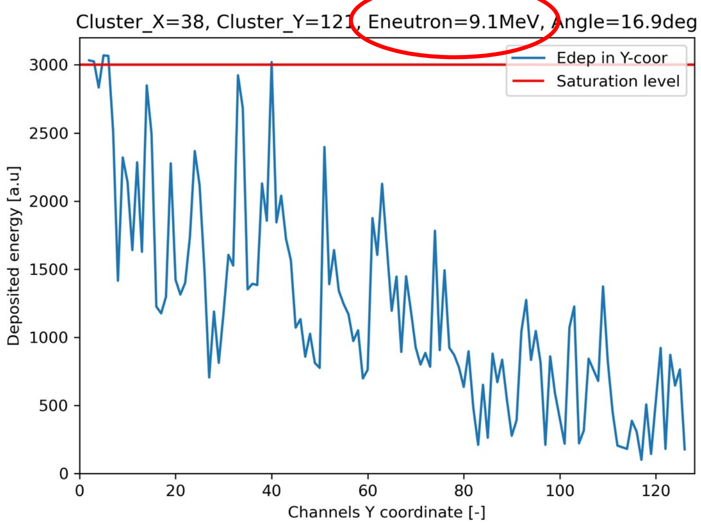
Correct neutron energy reconstruction

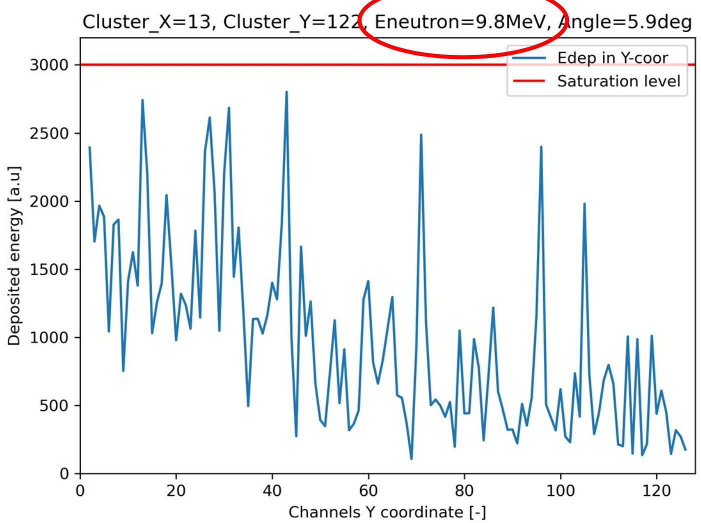




Incorrect neutron energy reconstruction





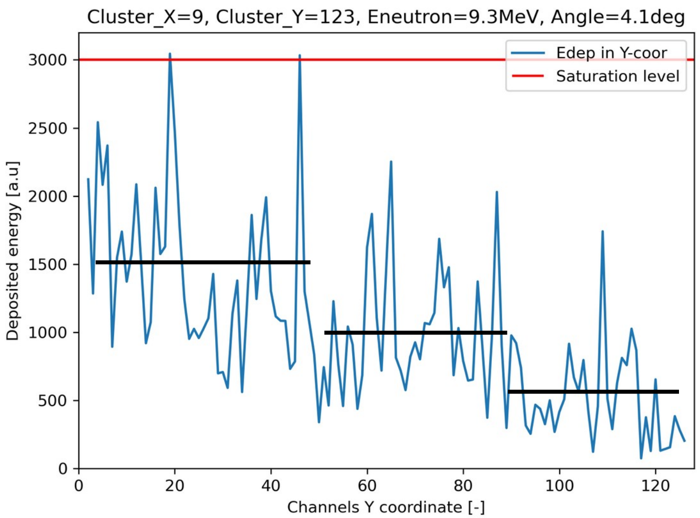


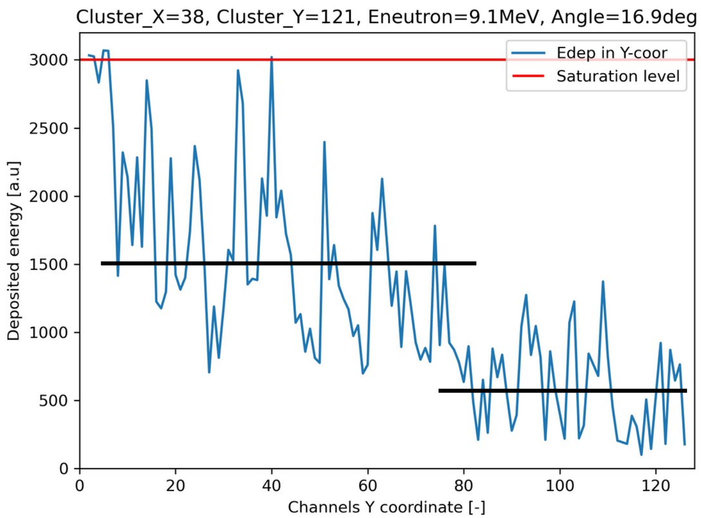
Observation: Tracks with correct neutron energy reconstruction tend to have flat proton energy deposition pattern.

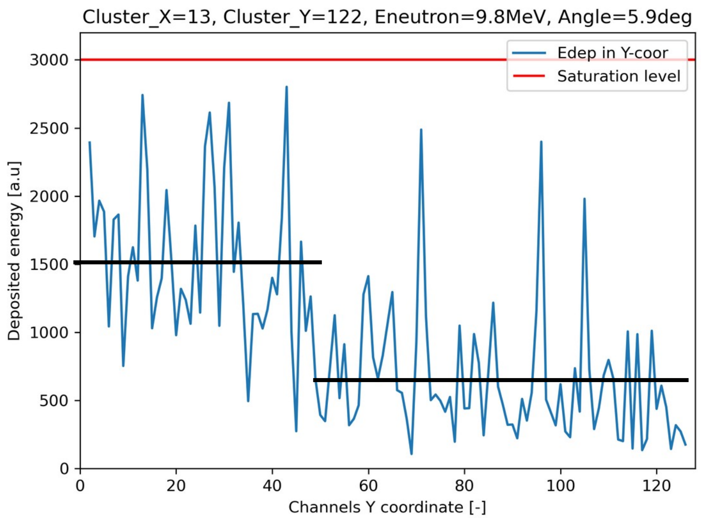
Proton energy distribution pattern - physical mechanism explanation

Hypothesis:

- During the proton energy deposition, signal coming from additional particles (most probably protons recoiled from GEM foils) is registered increasing the proton deposited energy. Due to strip-type readout it is impossible to distinguish both signals.
- In most cases, extra signal starts at some length of the detector and last until its end. Some particles may also origin from backscattering in kapton foil on the inner surface of the frame.
- Overestimated proton energy deposition translates to lower initial proton energy calculation (calibration curve) and underestimated reconstructed neutron energy.

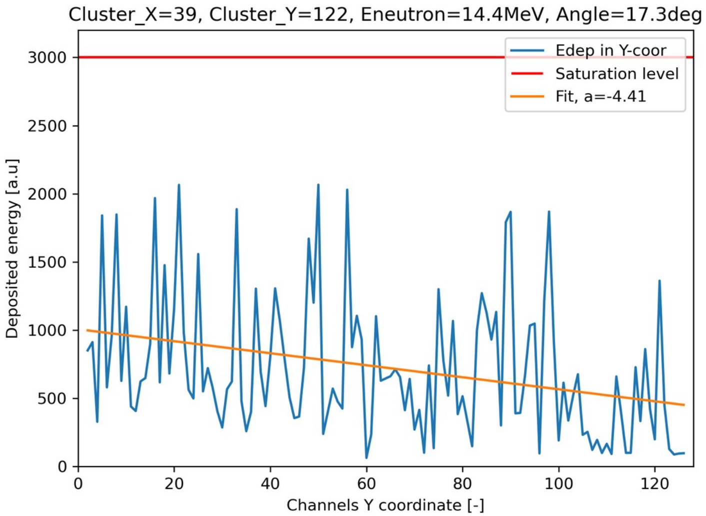


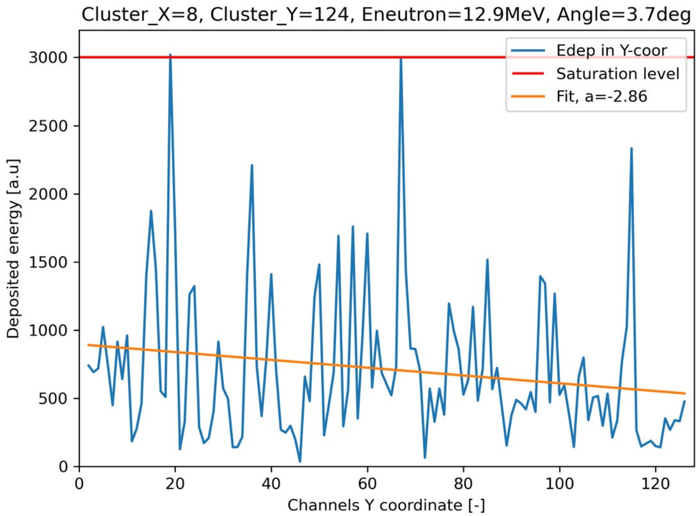


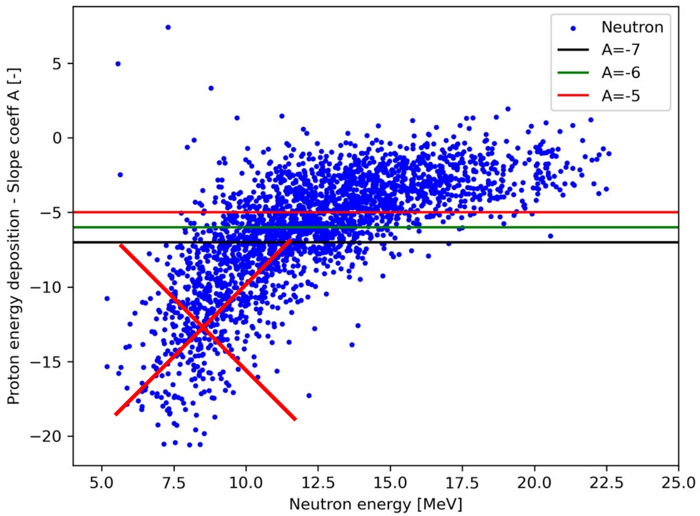


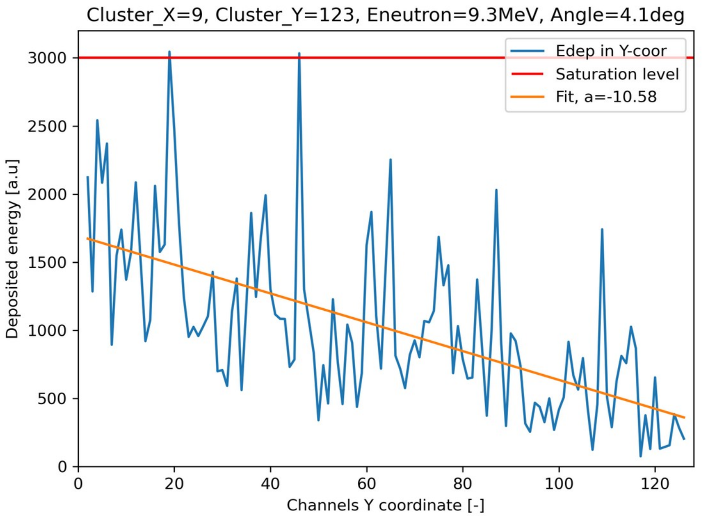
Proton energy deposition pattern – slope fit & discrimination

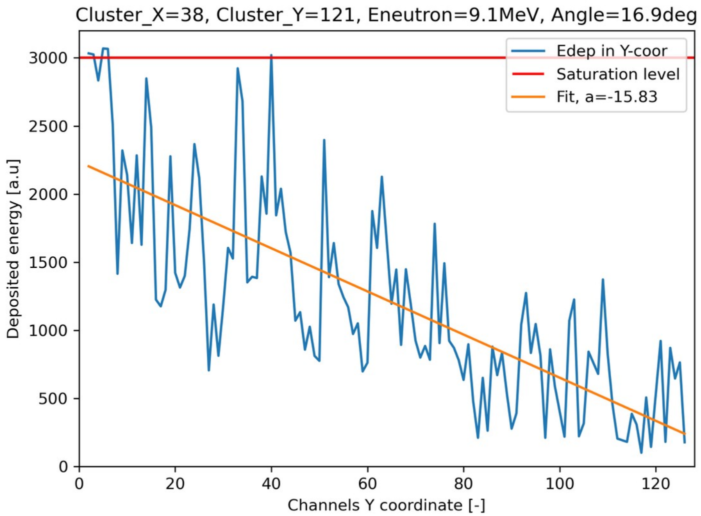
Can we discriminate proton tracks based on deposition pattern slope?

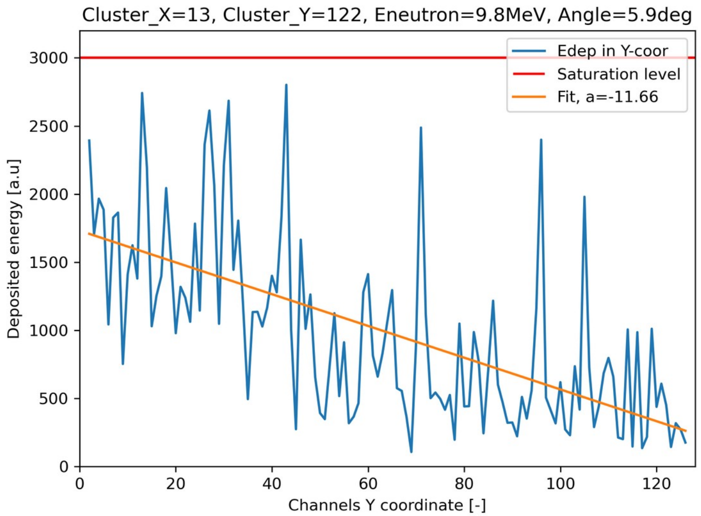












Neutron energy resolution - filtration summary

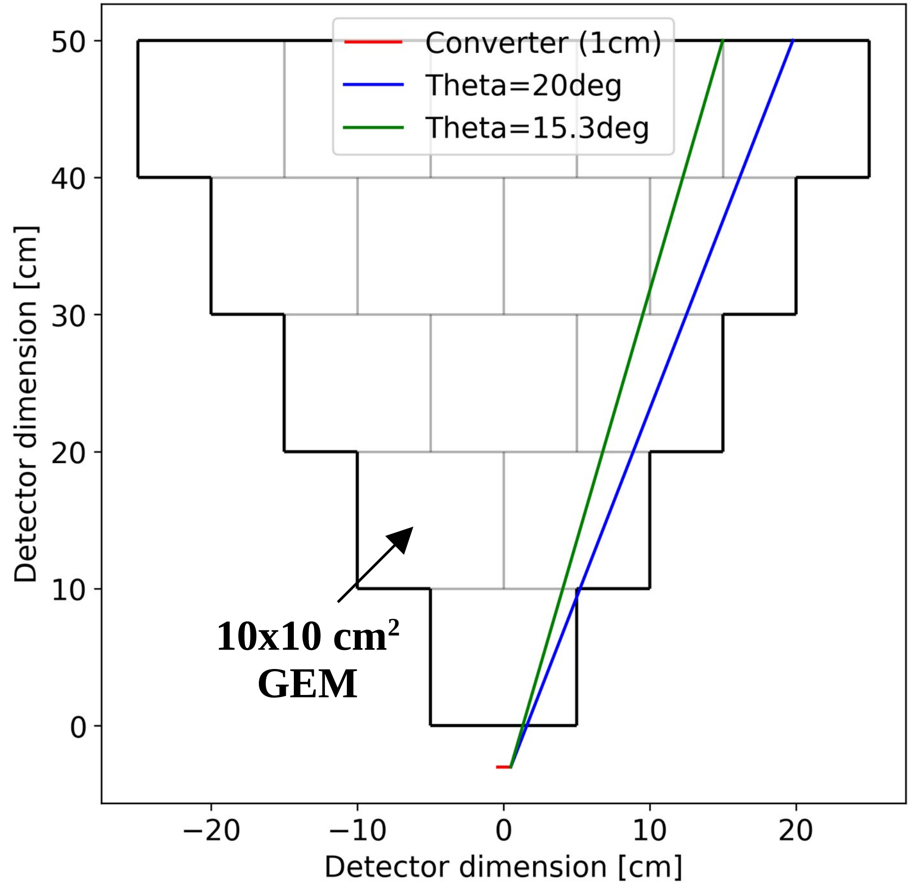
Converter thickness [mm]	Before cut		After cut	
	E_{drif}=0.5 kV/cm	**E_{drif}=1.8 kV/cm**	**E_{drif}=0.5 kV/cm**	**E_{drif}=1.8 kV/cm**
0.5	65.2	54.1	47.8	36.8
0.23	75.1	62.9	57.4	42.6
0.13	81.4	69.5	52.6	43.8

Filtration improves neutron energy resolution by about 20% of FWHM

Geant4 simulation results → 22%

Plans for the future

- Redesign of existing setup to pad-type readout, repeating the experiments and prove the conclusions
- Modular detector design
- Multiplication of standard size GEM enclosed in common gas chamber
- Pixel-type (pad) readout structure
- Challenging but possible (cost & human resources)



Summary

- Neutron spectrometer based on GEM technology has been worked out and manufactured
- Spectrometer performances has been simulated and finally validated during the real experiments
- Main functionality (neutron spectrometry) of the designed system has been proved
- Obtained system energy resolution is significantly worse compared to simulated one but… …the reason is understood
- Strip-type readout structure makes it impossible to fully discriminate the valid proton tracks from the background
- Pixel-type (pad) readout structure is necessary
- Work on standard 10x10 cm^2 with pad type readout are ongoing
- Modular detector design as a plan for the future