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

ENR-TEC.01.IPPLM-T001 - D001

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Introduction

Project objective:

Design and development of a high-resolution neutron spectrometer based on the GEM detector for fusion reactors

Tasks specifcation:

- Theory and modeling: NS-GEM synthetic diagnostics: performance analysis and evaluation of NS-GEM measurement capabilities.
- NS-GEM demonstrator: Modernization of the design and testing of the NS-GEM demonstrator.
- NG-14 MEV Neutron Generator: NS-GEM Demonstrator Neutron Tests.

Introduction

❑ 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:

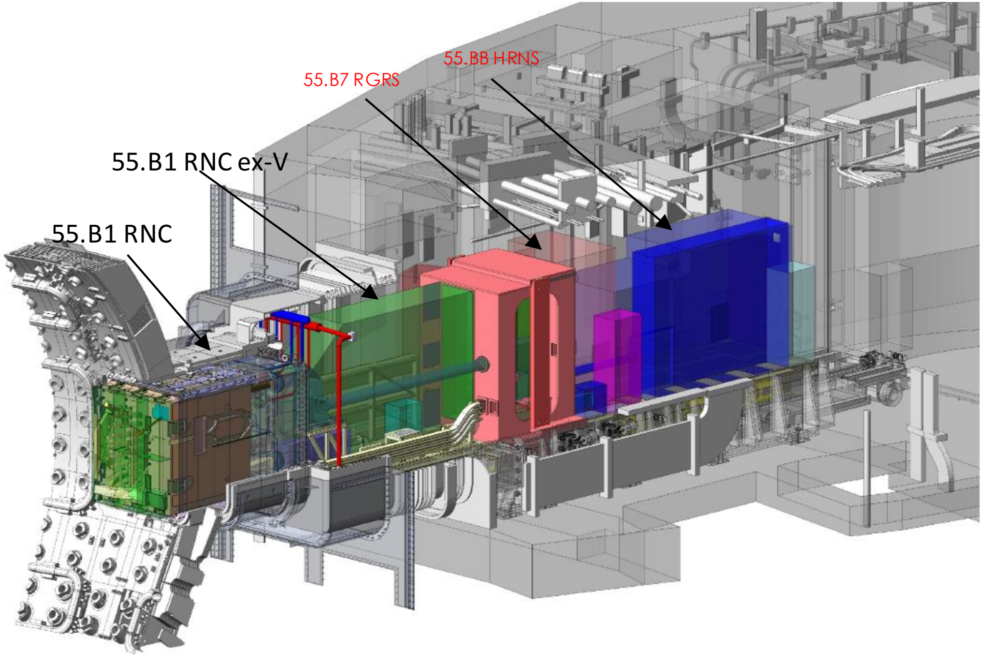
- Time resolved neutron yield monitor
- Activation system
- Neutron profile camera
- Neutron spectrometer

❑ 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

Systems 55.BB HRNS

Location: ***EP#1, PCSS*** *(Port Cell Support Structure)*

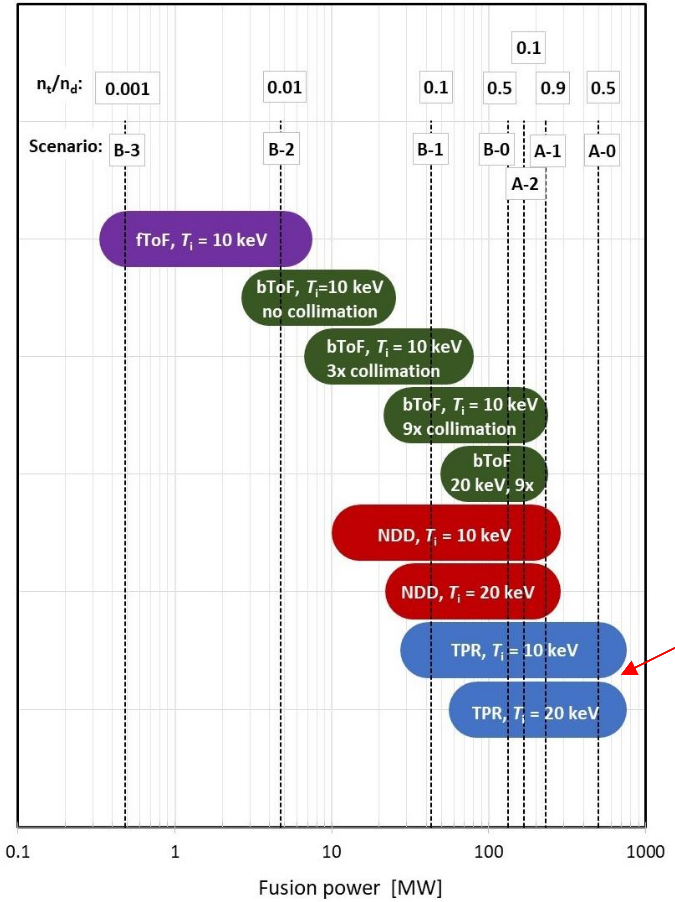


[M. Scholz et al. (2019) Nucl. Fusion 59 065001]

PSB 55.BB

Primary design driver: ***M020***

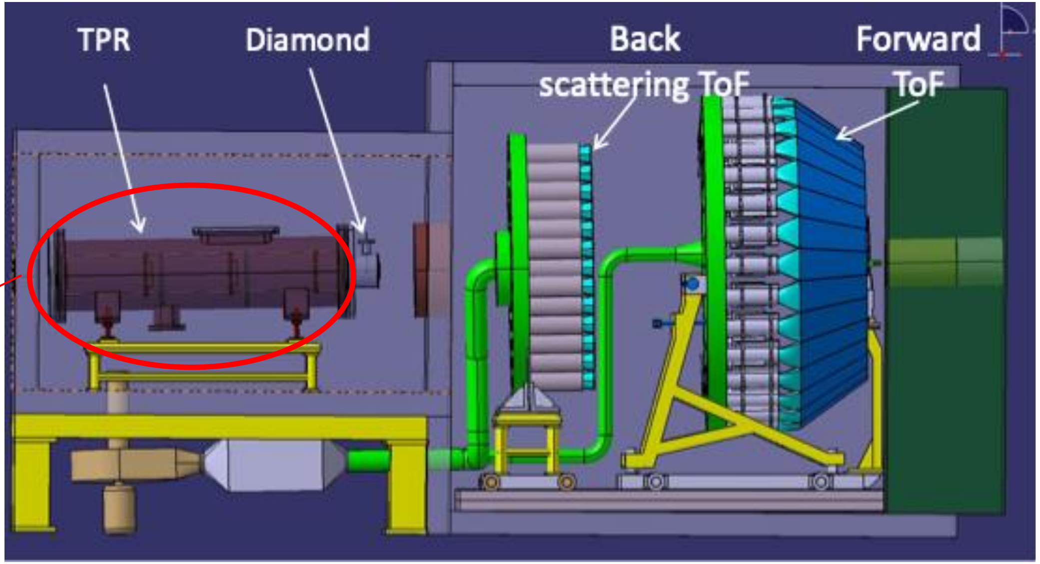
- *Prediction of fuel ion ratio n_t/n_d with uncertainty of less then 20% for a measurement time window of 100 ms. For parameter range: $0.01 < n_t/n_d < 10$.*



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

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:

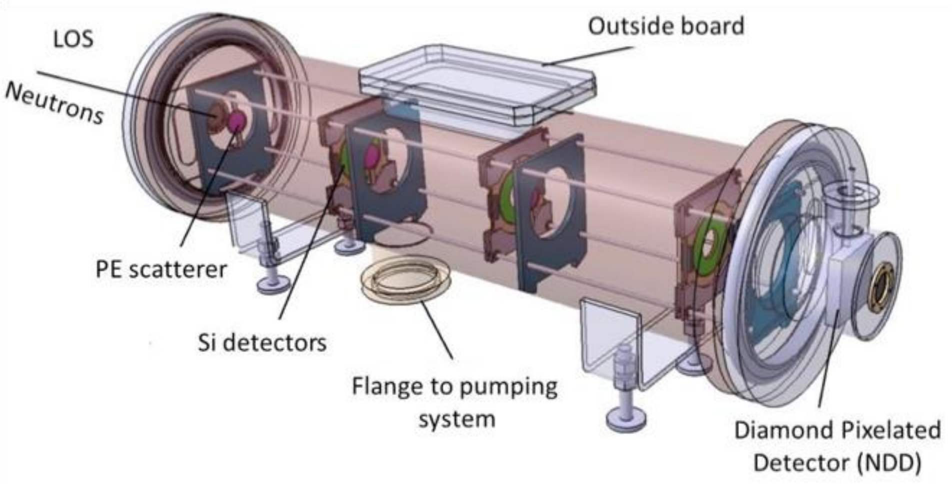
- **Thin Proton Recoil (TPR)**
- **Neutron Diamond Detectors**
- **Back-scattering Time-of-Flight (bToF)**
- **Forward Time-of-Flight (fToF)**



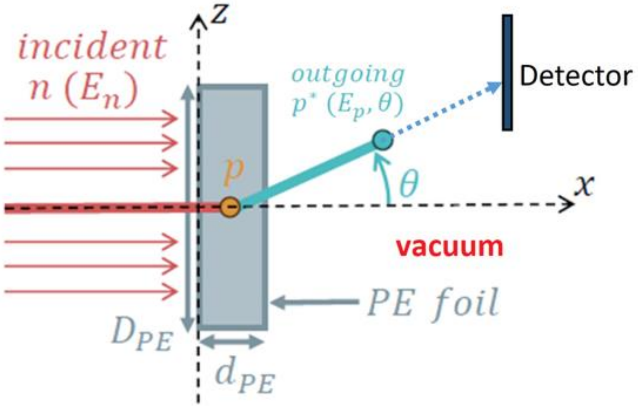
Thin-foil Proton Recoil (TPR)

- **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.

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



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



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

New idea of TPR technique

The basic motivation of the project

Changing the Si detector to a Gas Electron Multiplier (GEM) detector!

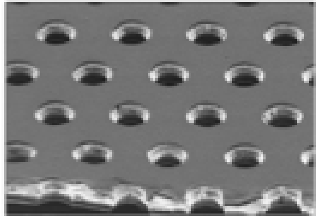
The basic idea of using a compact NS-GEM detector in the TPR system relies on estimating the proton energies by measuring their specific energy losses dE/dx and recording proton tracks in the GEM active volume, to then reconstruct the energy spectrum of incident neutrons.

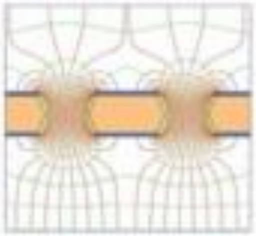
Gas Electron Multiplier (GEM) detector

GEM – a gaseous type of detector invented in 1997 by F. Sauli for high energy physics (HEP) applications.

The key detector component (GEM foil) is made of Kapton polyimide foil both sided with copper and perforated with double conical holes arranged in a hexagonal shape.

Microscopic photo

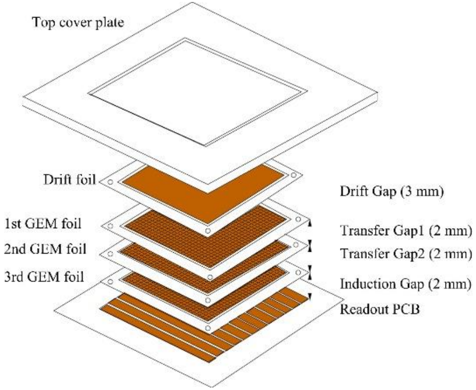




The key performances:

- High effective gain and low discharge probability,
- Robustness with respect to aging processes (radiation hardness),
- Large detection area,
- Spatial resolution at the level of 50 µm,
- Time resolution less than 10 ns,
- Energy resolution at the level of 20% FWHM for 5.9 keV Kα line of 55Fe source,
- Relatively low cost technology,
- Different types of readout structures (strips, pads, mixed).

Schematic view

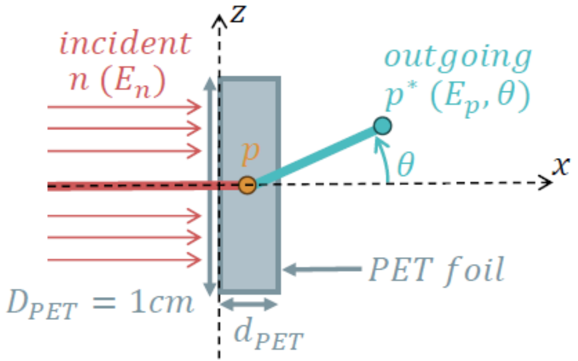


R. N. Patra et al., "Measurement of basic characteristics and gain uniformity of a triple GEM detector", NIM-A, 2017, 862, 25 – 30.
F. Sauli, "Development and applications of gas electron multiplier detectors", NIM-A, 2003, 505, 195 – 198.

Neutron Spectrometer based on GEM (NS-GEM)

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.

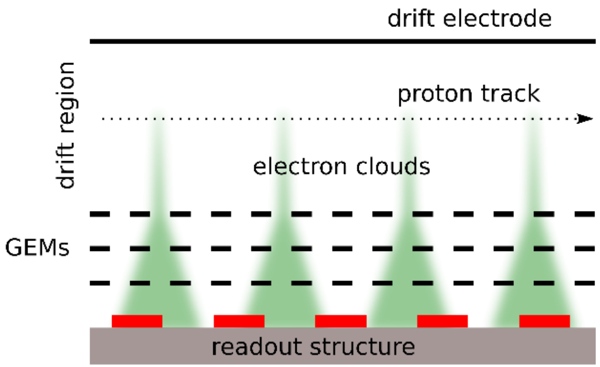
Thin-foil Proton Recoil (TPR)



+

$$E_p = E_n \cos^2 \theta$$

Gas Electron Multiplier (GEM)

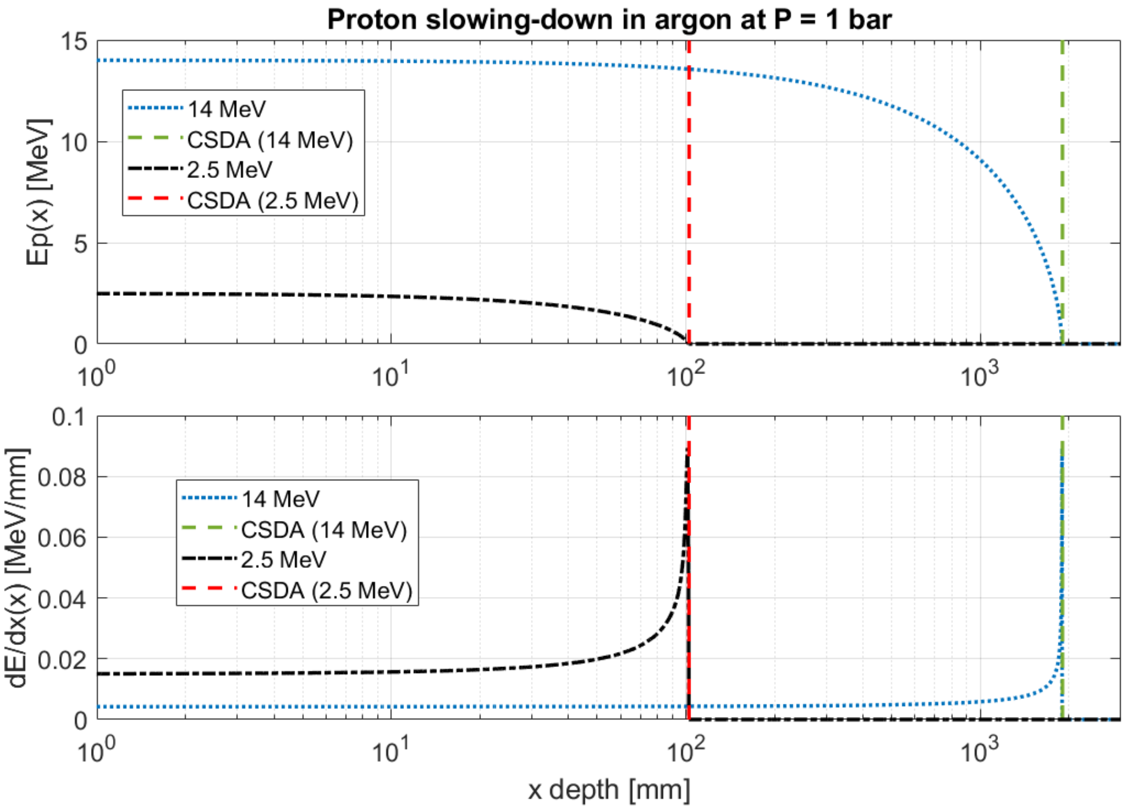


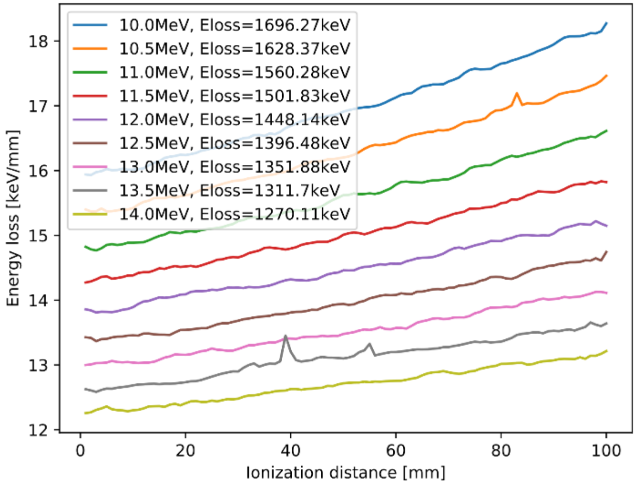
Detection idea:

- Neutron collimation
- Conversion neutron → proton in polyethylene (PE)
- 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

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.





→ *dE/dx* approach

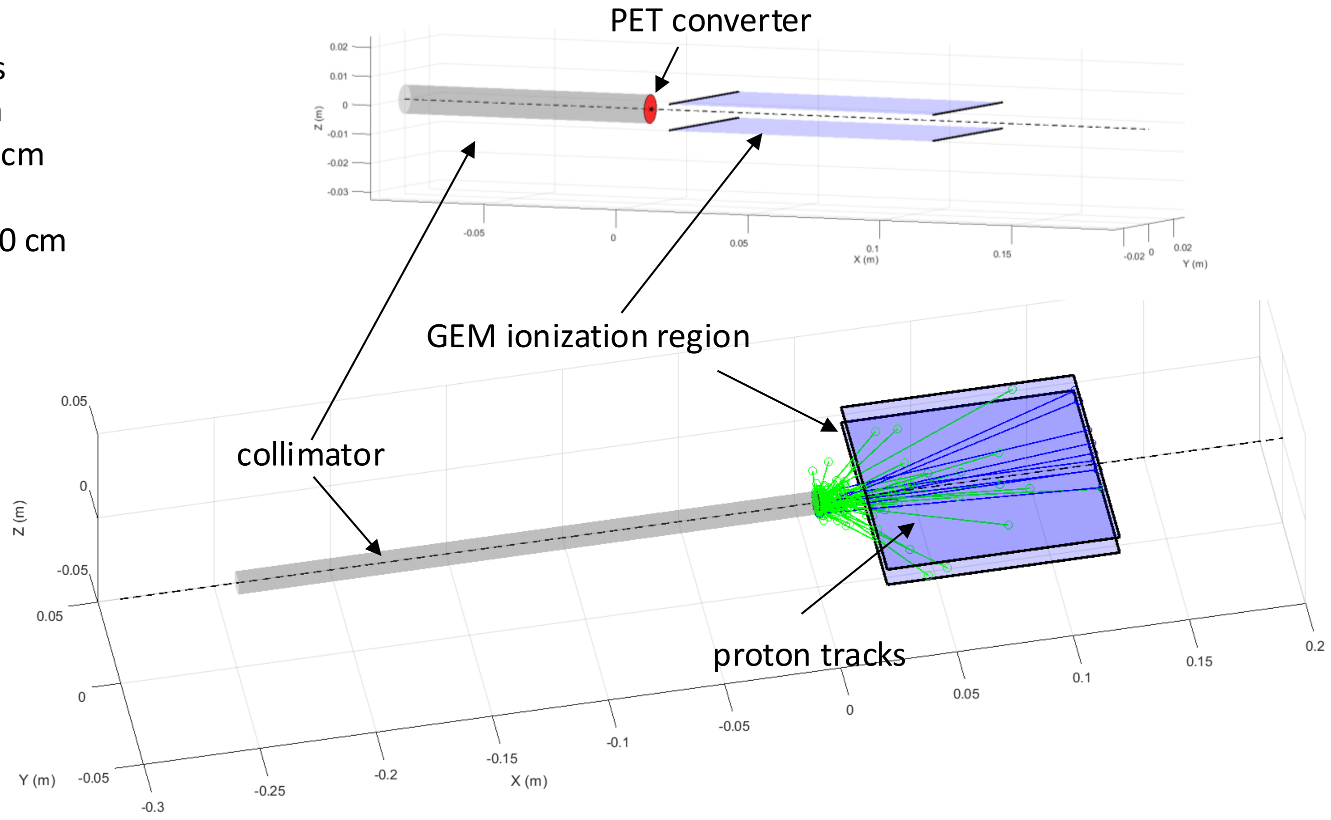
Partial absorption before the Bragg peak

NS-GEM prototype modeling

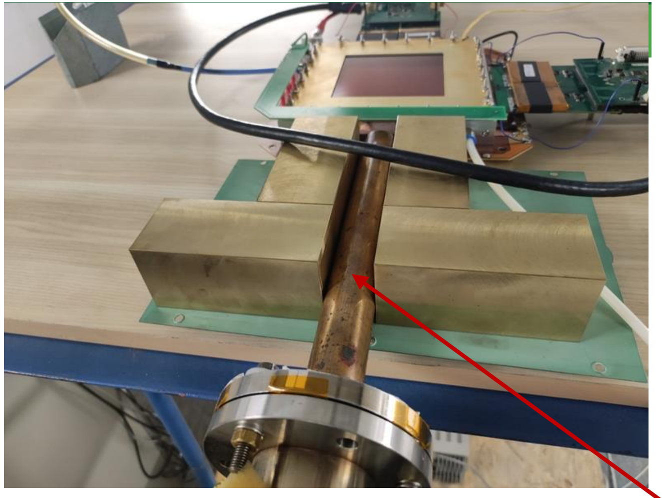
A simplified geometrical model of the NS-GEM prototype was implemented with Matlab.

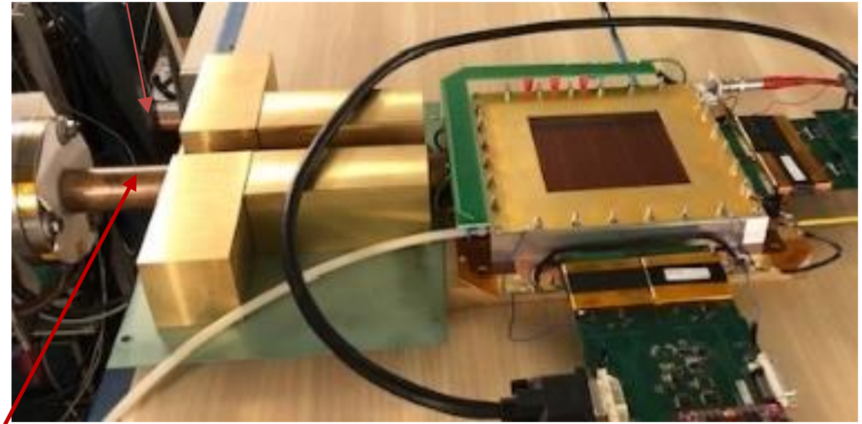
<u>Parameters</u>:

- IGN-14 DT source: $6{\cdot}10^7$ n/s
- Collimator: L=28cm, d=1cm
- PET: thickness=0.5mm, d=1cm
- Distance PET-GEM = 3 cm
- GEM XY dimensions: 10 x 10 cm
- GEM Z height = 0.9 cm



NS-GEM detector at the IGN-14 experimental stand





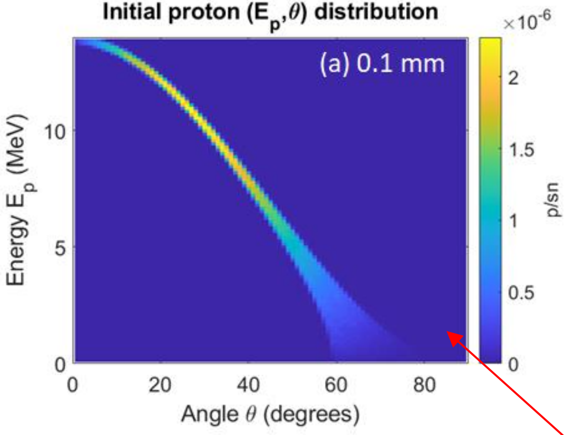
Neutron source

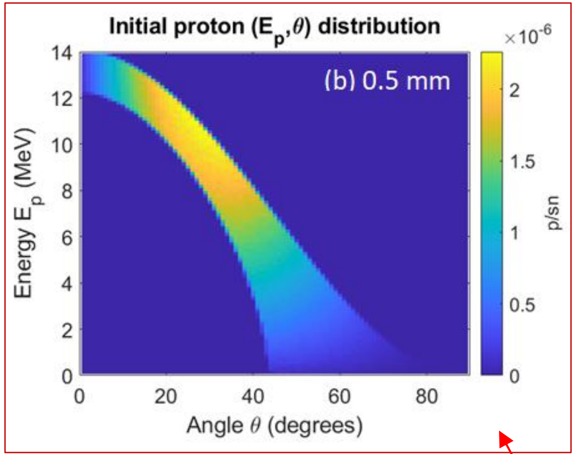
Collimator

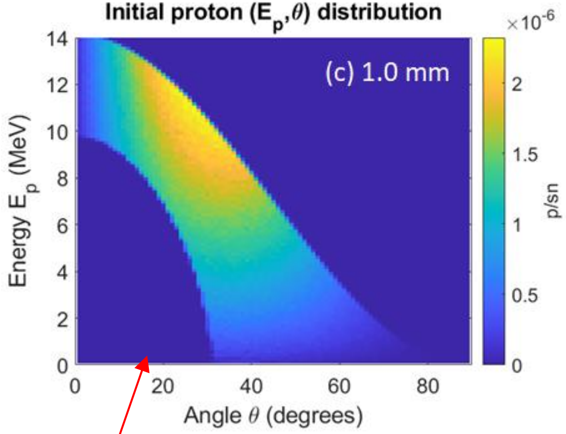
GEM detector

Polyethylene (PE) foil - neutron→proton conversion

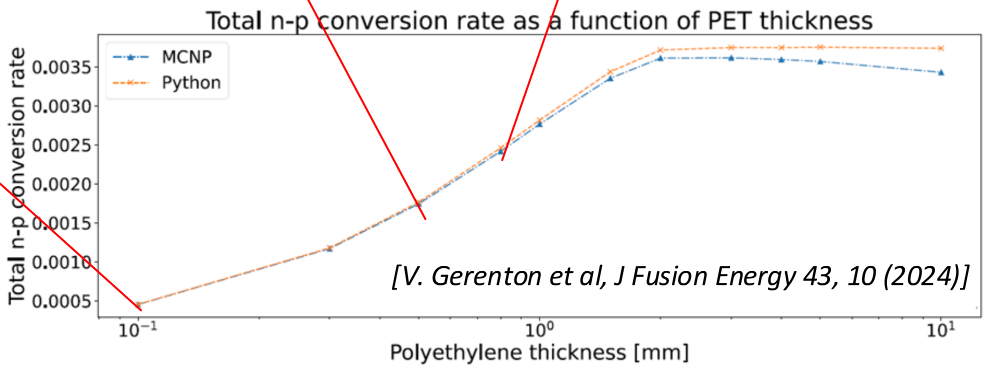
Conversion rate and proton energy-angle distribution exiting the polyethylene (PE) foil





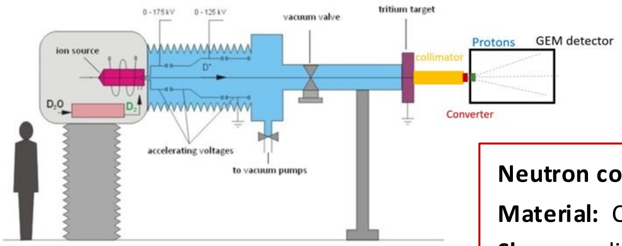


- Calculated based on cross-sections available in NIST and JENDL/HE-2007 libraries,
- The n-p conversion rate increases with PE thickness. Saturation for PE foils thicker than ~1 mm, due to significant neutron absorption,
- Trade-off between n-p conversion rate and loss of resolution in the range [0.1 – 1.0 mm].



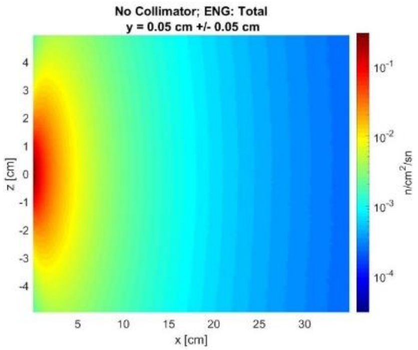
NS-GEM demonstrator and measurement strategy

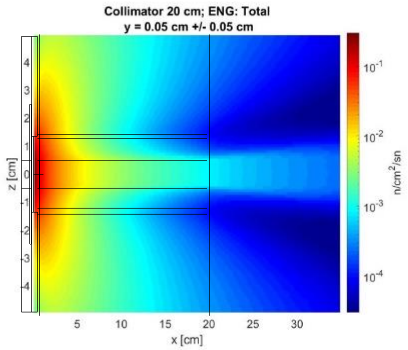
Optimisation of the neutron collimator



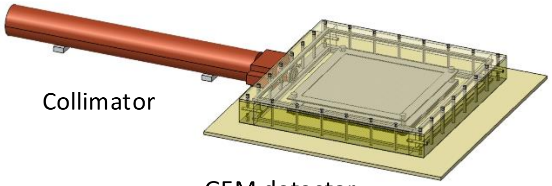
Fast neutron generator IGN-14

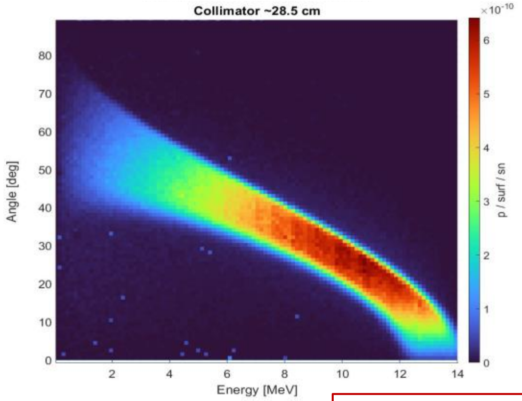
Neutron collimator
Material: Cu,
Shape: cylinder,
inner $\varnothing_1$ =1 cm,
outer $\varnothing_2$ = 2.5 cm,
Length: at least L_C = 20 cm





Selection of the neutron-proton converter





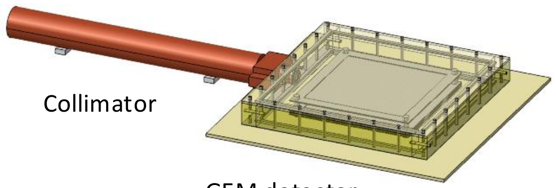
Neutron – proton converter
Material: PE hydration, PE
Thickness: d= 0.13 mm,
0.23 mm,
0.5 mm

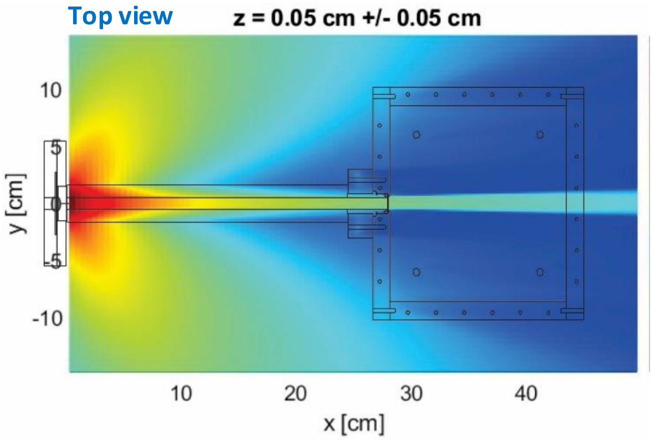
Number of protons from the 0.5 mm converter:

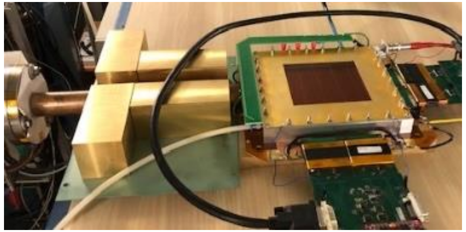
Assuming **~7.5 x 10^7 n/s** from the source
- For all angles: ~5.4 x 10-7 p/surf/sn -> ~40 p/s
- For (0-35) deg: 3.1 x 10-7 p/surf/sn -> ~23 p/s

NS-GEM demonstrator and measurement strategy

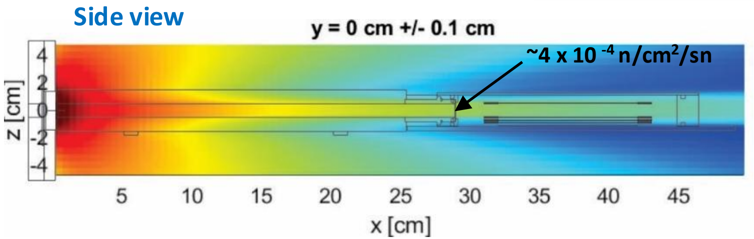
Neutrons in the NS-GEM detector at the IGN-14 experimental stand

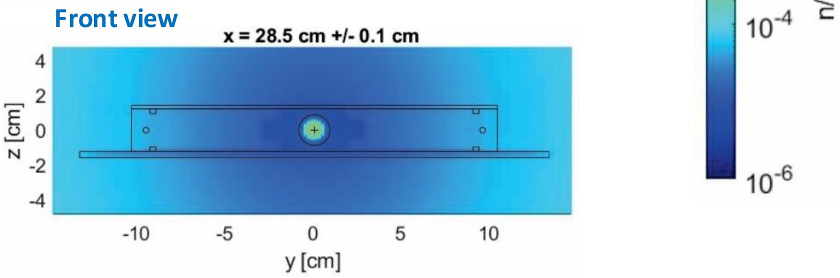






Collimator length: ~28.5 cm

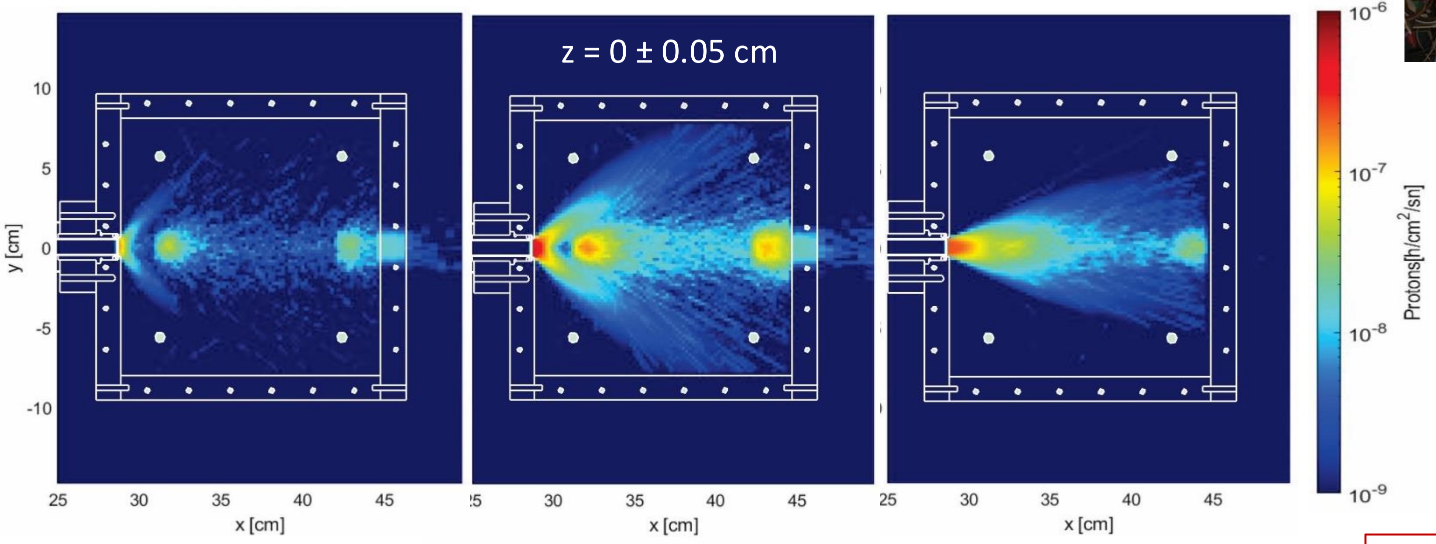




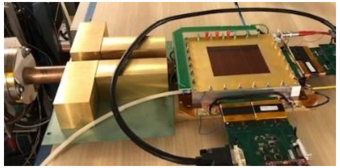
MCNP6.2
MeshTally: 2 mm x 2 mm x 1 mm

Protons in the NS-GEM detector at the IGN-14 experimental 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



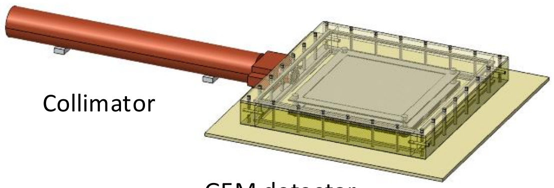
$$En = \frac{Ep}{cos^2\theta}$$

Protons from the n/p converter

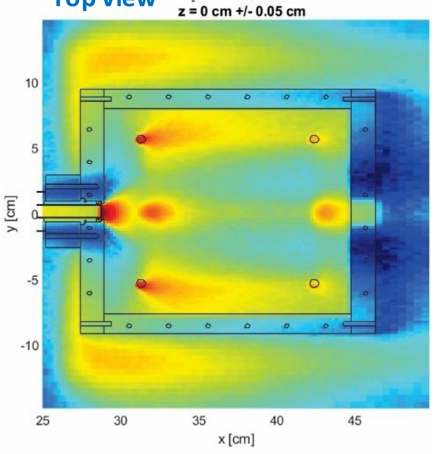
MCNP6.2
MeshTally: 2 mm x 2 mm x 1 mm

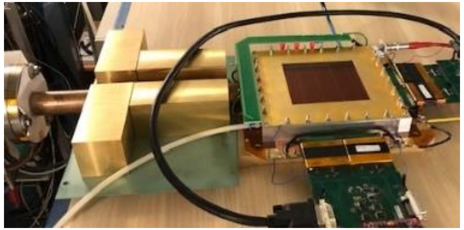
NS-GEM demonstrator and measurement strategy

Protons in the NS-GEM detector at the IGN-14 experimental stand

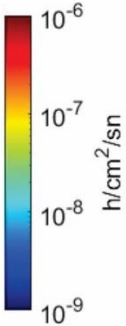


Top view

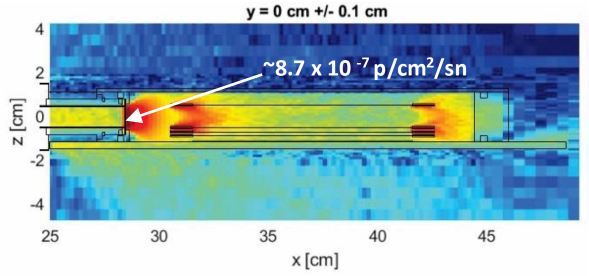




Collimator length: ~28.5 cm

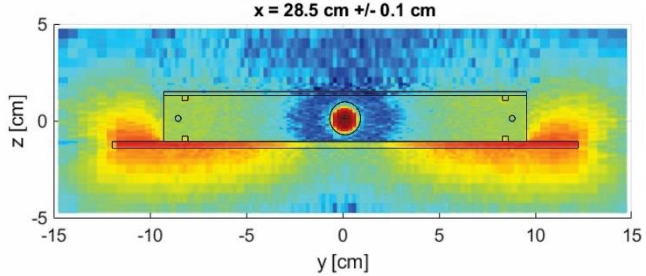


Side view



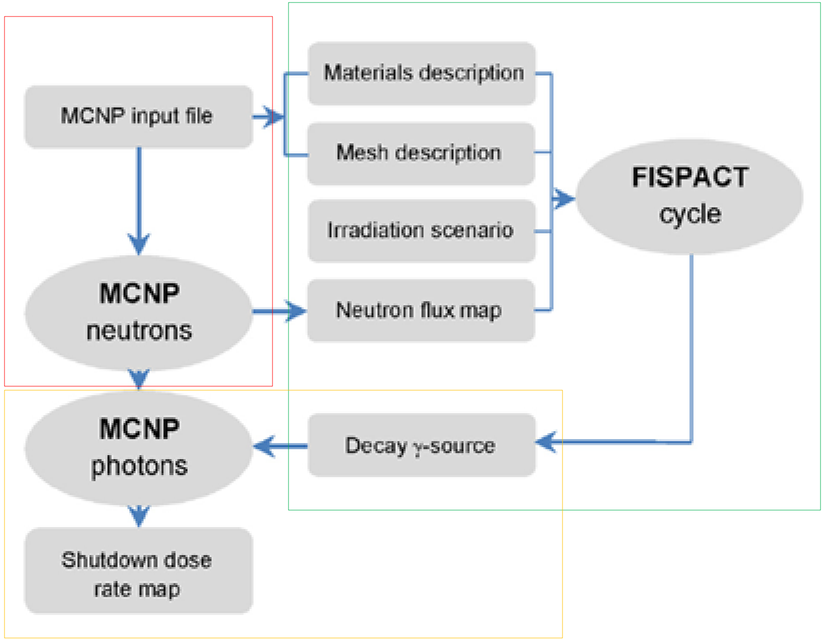
Protons from the n/p converter & construction elements

Front view



MCNP6.2
MeshTally: 2 mm x 2 mm x 1 mm

Methodology



[Adapted from P. Pereslavtsev et al. 2013]

The procedure of these calculations consists of seven steps:

1. Calculation of the neutron flux spectra in the 175 VITAMIN-J group structure for all non-void cells of the considered geometry model using MCNP code with FENDL-2.0/A activation cross-section data.

2. Material detection in the whole geometry divide into small elements (mesh).

3. Processing of MCNP input file to get material information.

4. Preparing inputs for FISPACT.

5. FISPACT activation calculations.

6. Calculations of the decay gamma source distribution using FISPACT.

7. Calculation of the decay gamma sources spectrum and intensity in MCNP.

Modelling of Activation of NS-GEM

Assumption for calculations

Irradiation History for SA2

Type of Operation	Duration	Wall Load (kWm^{-2})	Fluence = Duration * Wall Load ($kWym^{-2}$)	Fusion Power n + α (MW)	Repetition
No Plasma	1 y	0	0	0	Once
Hydrogen Plasma	5 y	0	0	0	Once
DD Operation	2 y	3	6	2.68	Once
DT Operation	10 y	23.1	231	20.6	Once
Shutdown	0.667 y (8 months)	0	0	0	Once
DT Operation	1.325 y (16 months without one day)	46.5	62	41.5	Once
DT Operation (Last Day of ITER Operation)	0.000124 y (3920 s)	0	0	0	17 times
	0.000013 y (400 s)	560	0.00728	500	
	0.000124 y (3920 s)	0	0	0	3 times
	0.000013 y (400 s)	784	0.01019	700	
	Total time = 20 y		Total Fluence ≈ 300 $kWym^{-2}$		

[Adapted from M. Loughlin et al., 2009]

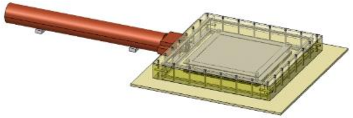
Modelling of Activation of NS-GEM

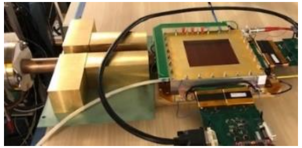
Results

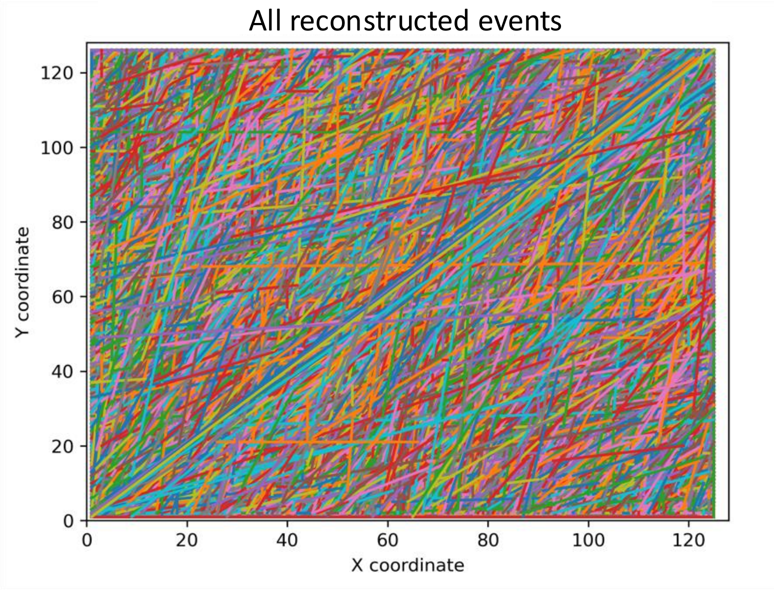
		Neutron Generator (after 1h, 10^8 n/(m^2*s) at detector entrance)			ITER (after 20 years, 1.11 *10^{13} n/(m^2*s) at Cuboid entrance)		
Number	Activated material	Spec. Activity [kBq/kg]	Mass [kg] (roughly)	Activity [kBq]	Spec. Activity [kBq/kg]	Mass [kg] (roughly)	Activity [kBq]
1	Stainless Steel	0.11	0.05	0.01	0.89	0.05	0.05
2	FR-4	0.66			2.83		
3	Kapton	0.37	0.03	0.01	726.30	0.03	20.55
4	Copper (collimator)	1.24	0.40	0.50	251 000.00	0.40	100 977.30
5	Aluminium 1050A (case of detector)	3.04	3.00	9.13	2.86	3.00	8.58
6	PE converter	0			8.28		
7	Aluminium Alloy 7075-0 (back side case of detector)	2.74	0.70	1.92	119 000.00	0.70	83 300.00
8	Epoxy resin (bootom plate of detector)	0.03			1.84		
		Total	4.50	11.56	Total	4.50	184 306.48

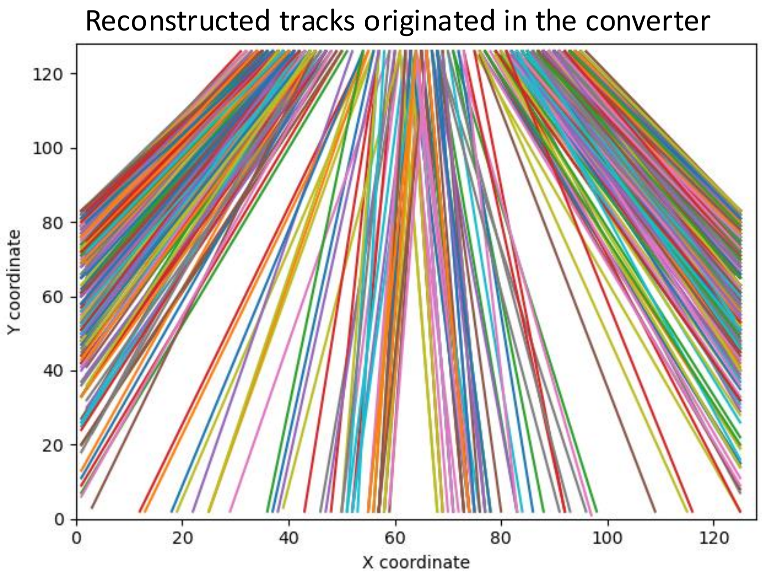
Reconstruction of the proton tracks

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



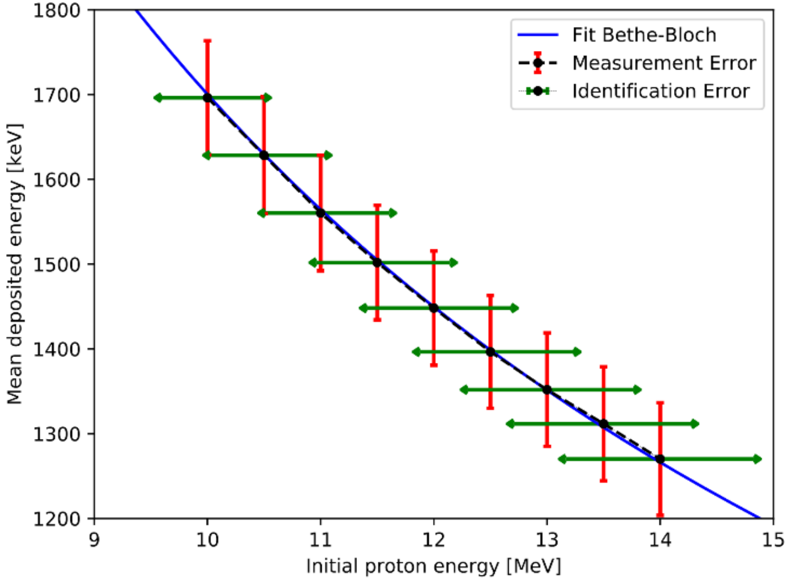




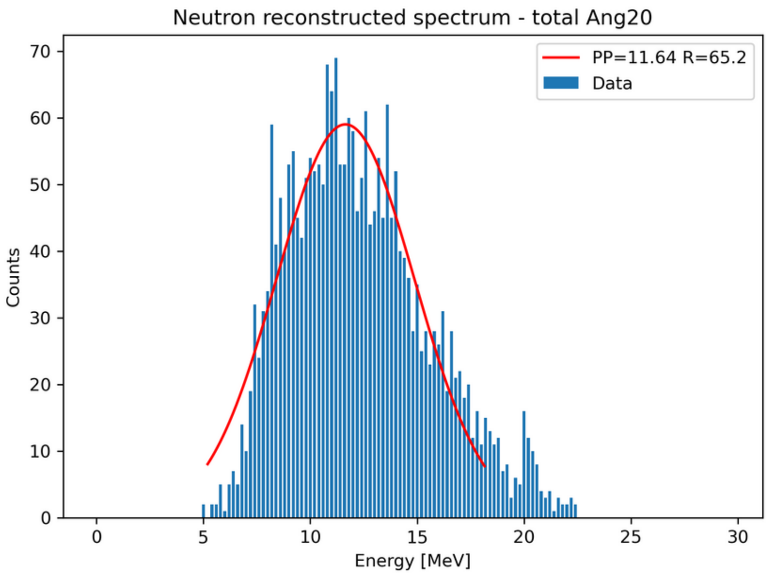


Reconstruction of neutron spectrum

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



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



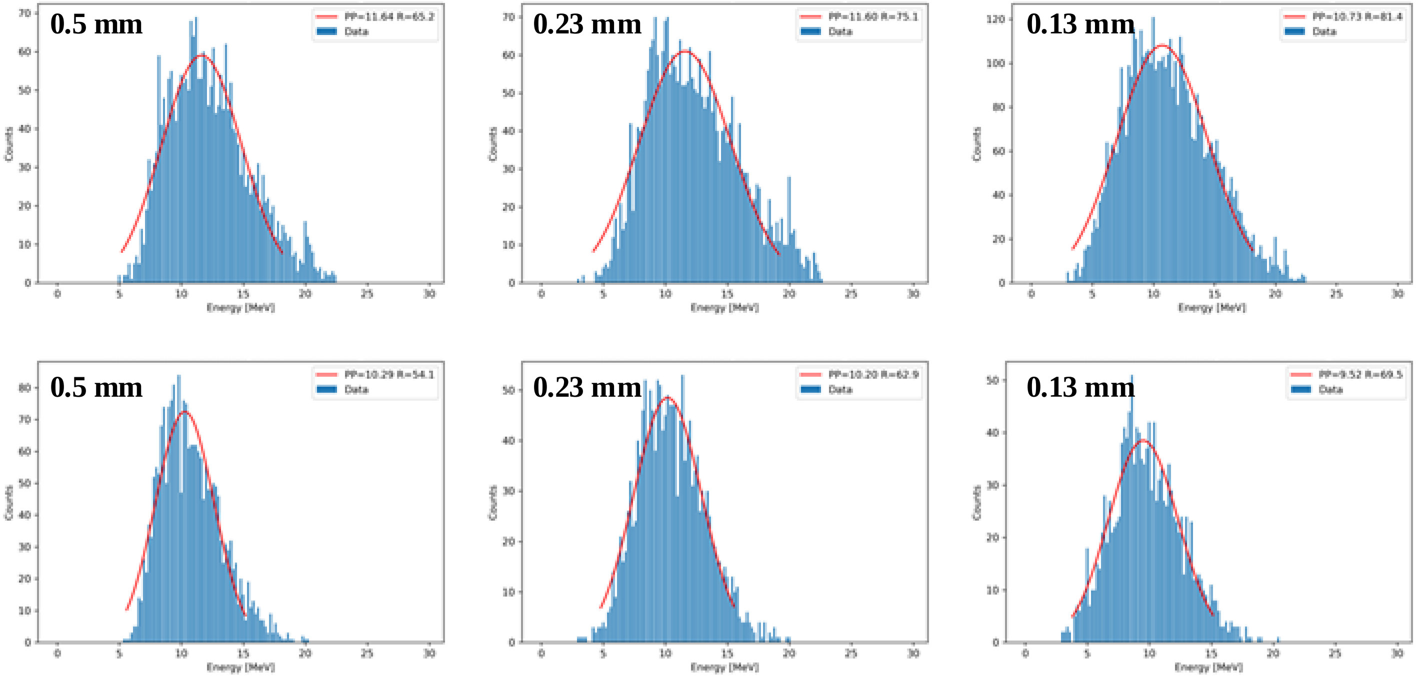
Issue of energy reconstruction (energy shift) – likely related to readout electronics (crosstalk between the readout planes), but it needs to be studied further

Reconstruction of neutron spectrum

Neutron spectra summed over 0 - 20 degree angles

E_{drif}=0.5 kV/cm

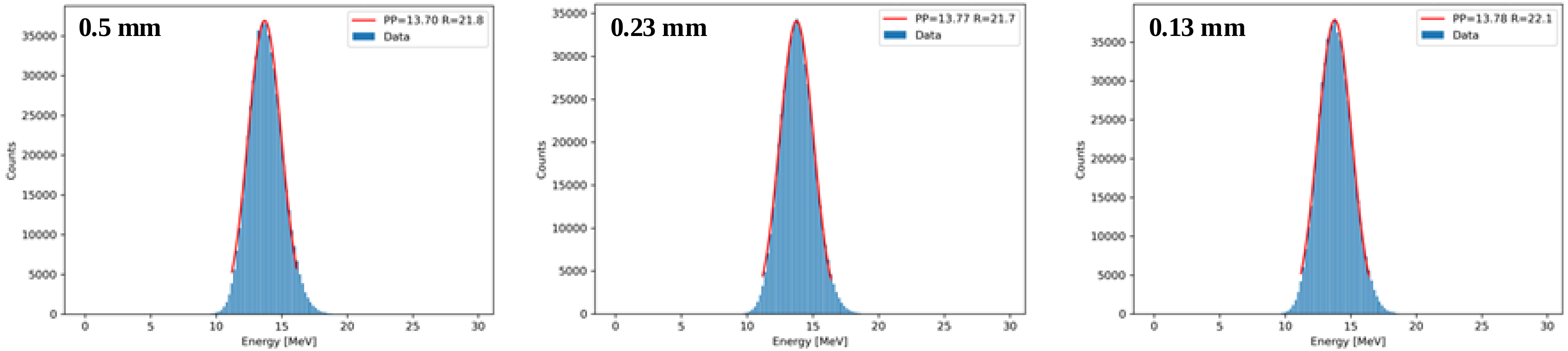
E_{drif}=1.8 kV/cm



Energy shift - we have some hypotheses related to readout electronics (crosstalk between the readout planes), but they need to be studied further!

Reconstruction of the proton tracks – Geant4 modelling

Neutron spectra summed over 0 - 20 degree angles



Total energy resolution at the level of 22% FWHM expected for all of the considered converters.

NS-GEM energy resolution

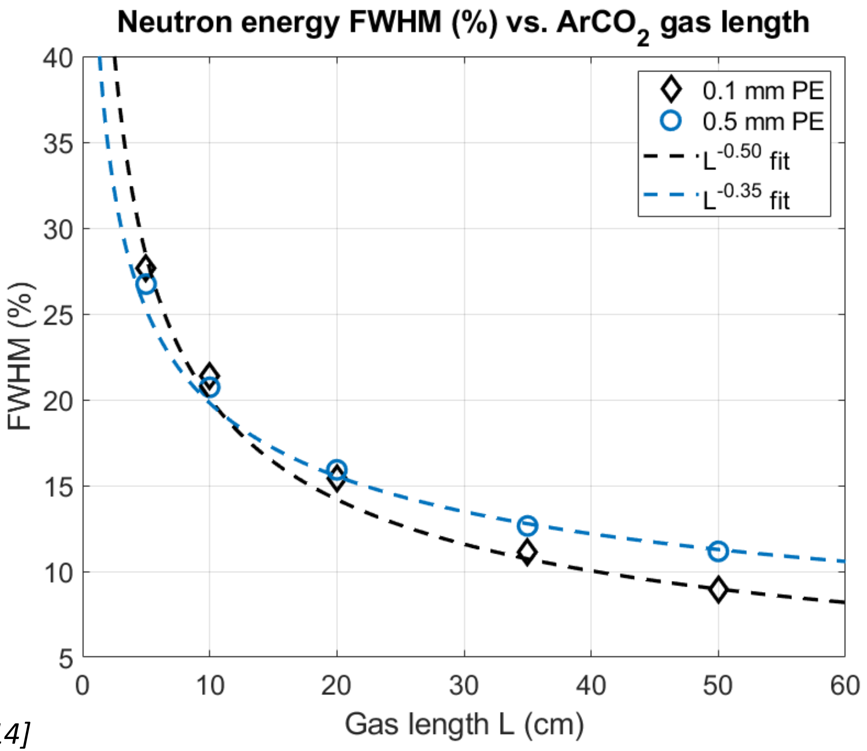
- Estimated neutron energy resolution FWHM as a function of the $ArCO_2$ (70-30, 1 bar) gas length for incident 14 MeV neutrons on the NS-GEM prototype.

- Solutions to get to the required resolution: minimize proton scattering and get closer to the Bragg peak.

✓ Thinner PE foil, down to 0.1 mm or lower

✓ Work at higher gas pressure > 1 bar

✓ Extend depth of gas mixture > 50 cm (larger detector)



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

Discussion and Summary

Energy shift observed in the experiment:

- we have some hypotheses related to readout electronics (crosstalk between the readout planes), but it needs to be studied further

Conclusions from the modelling:

Solution to get to the required resolution: **minimize proton scattering and get closer to the Bragg peak**.

✓ Thinner PE foil, down to 0.1 mm or lower.

✓ Work at higher gas pressure > 1 bar.

✓ Extend the depth of the gas mixture > 50 cm (larger detector).

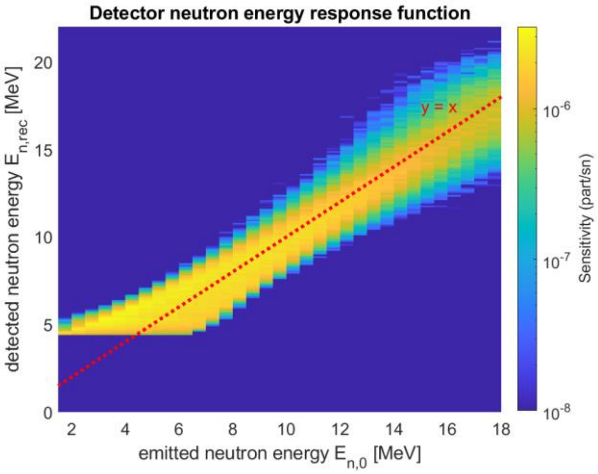
Another path that may be investigated in the future:

Add a stopping material between the PE foil and the GEM detector, to get protons closer to the Bragg peak (however, compromise to be found between proton stopping efficiency and loss of resolution by scattering in such material…)

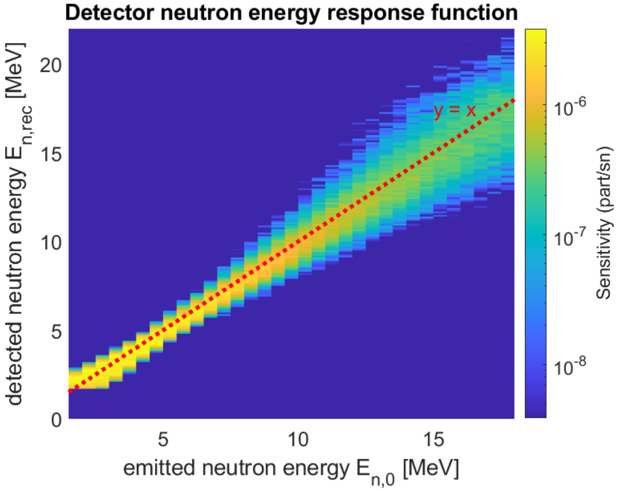
NS-GEM energy response function

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

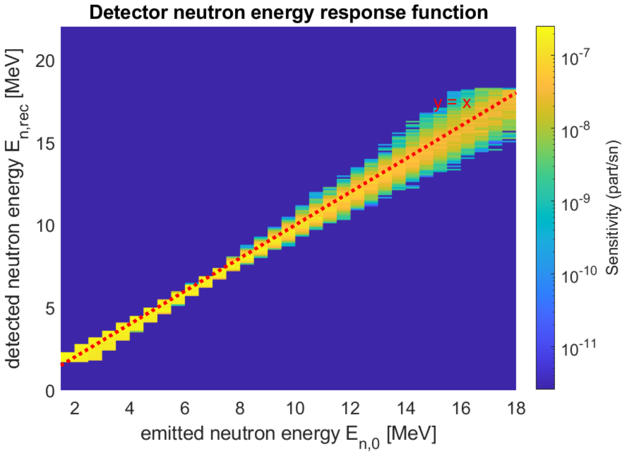
0.5 mm, 10 cm gas depth
(+PE-GEM gap 3 cm)



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



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

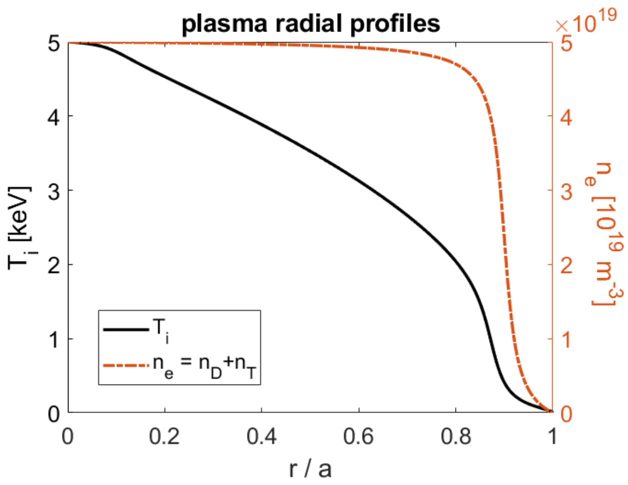


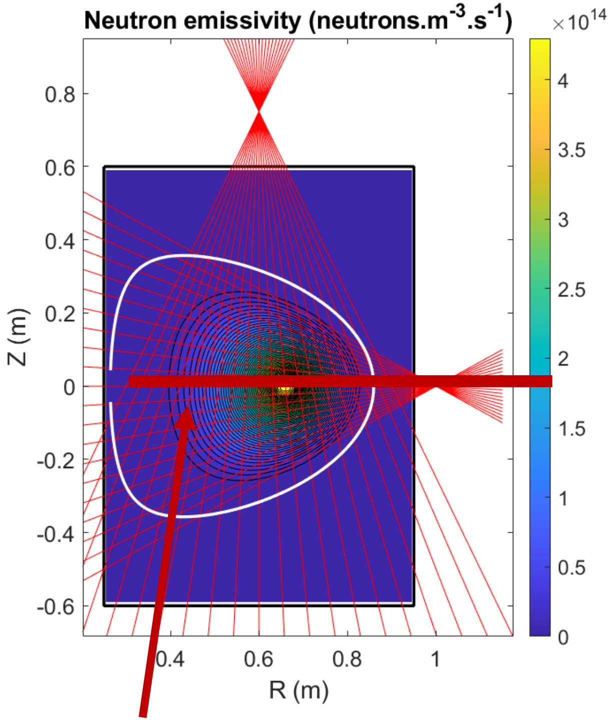
→ Energy resolution can be increased at the cost of efficiency (decreased count rate)

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

NS-GEM synthetic diagnostic in tokamak environment

An artificial tokamak environment was created with analytical magnetic equilibrium to test the NS-GEM synthetic diagnostic with different plasma scenarios DD, TT, and DT reaction rates calculated assuming Maxwellian distributions



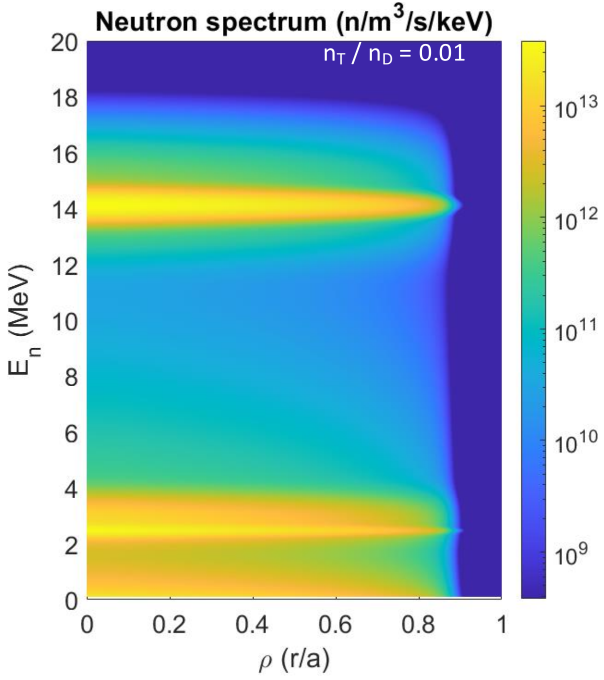


Test along a central horizontal LoS

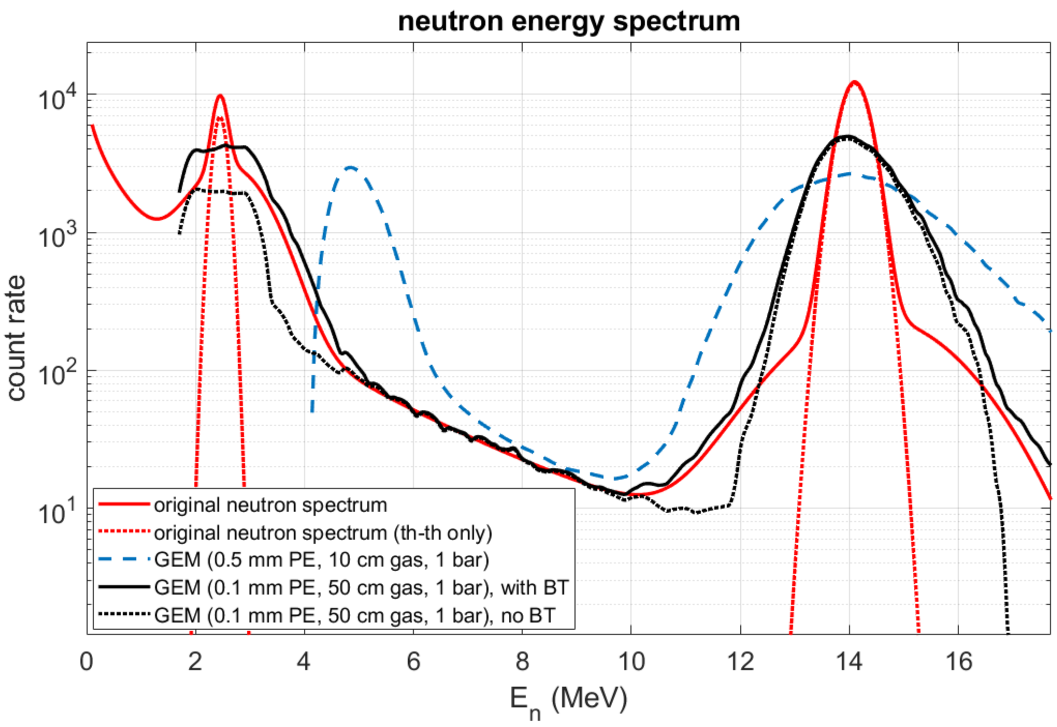
NS-GEM synthetic diagnostic in a tokamak environment

For testing NS-GEM reconstruction: scattering and beam-thermal components were added with analytical functions that mimic expected line-integrated spectra on the HRNS collimator.

[Scholz NF 2019]



Simulation of NS-GEM neutron spectrum reconstruction



- Resolution of ion temperature is very challenging.
- Resolving the non-thermal component of spectra is a more accessible parameter.
- A very compact NS-GEM (0.5 mm PE, 10 cm gas, 1 bar) such as the prototype tested at IGN-14 cannot resolve such plasma parameters.

Summary & perspectives

- NS-GEM demonstrator successfully built and actively being tested on 14 MeV neutron generator,
- Reconstruction algorithm being analysed to improve the experimental proton energy determination,
- Ongoing modelling activities to determine further steps to improve energy resolution for tokamak applications (PE thickness, gas pressure, detector length…). Balance to be found between energy resolution and efficiency of the detector,
- Test with 2.5 MeV neutrons (D target) or test on other devices (e.g. direct proton beam with Van de Graaff, higher neutron flux on more powerful generator) could be foreseen,
- We are open to collaboration on this topic.

https://wiki.euro-fusion.org/wiki/Talk:Project_No12

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