Characterization of neutron generation at APOLLON

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IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

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ÉCOLE POLYTECHNIQUE

Apollon

Outline

APOLLON facility overview

Experimental rooms, beam characteristics

Laser-accelerated protons

Proton spectrometry via Thomson Parabola using CMOS sensors
Laser energy/protons transfer optimization (Double plasma mirror)

Neutron generation

Pitcher-catcher technique
Neutron production simulations

Neutron detection

Several diagnostics

Prospects and future developments

Laser energy increasing and improvement of neutron production

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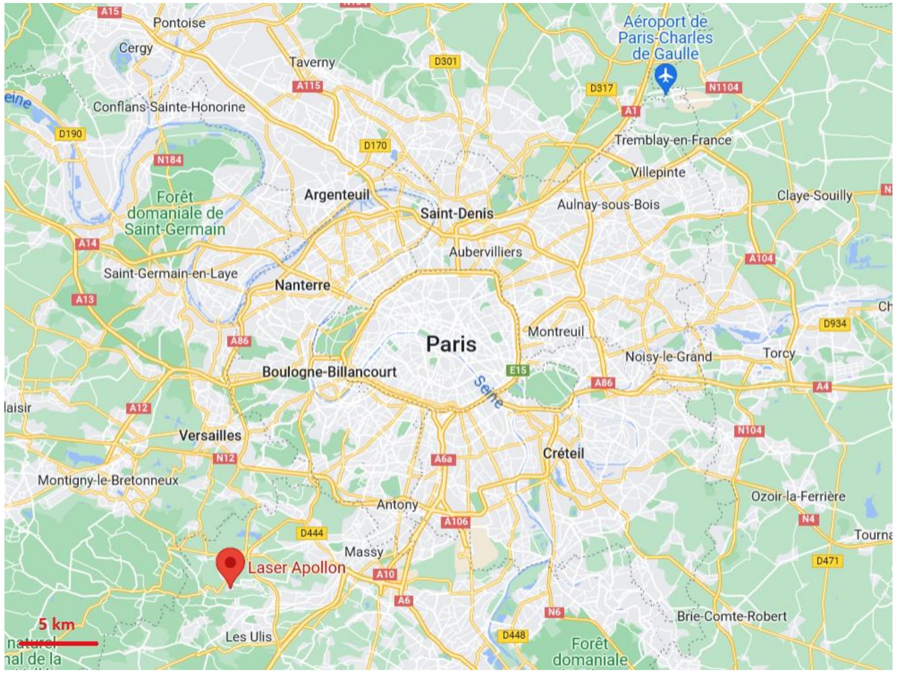
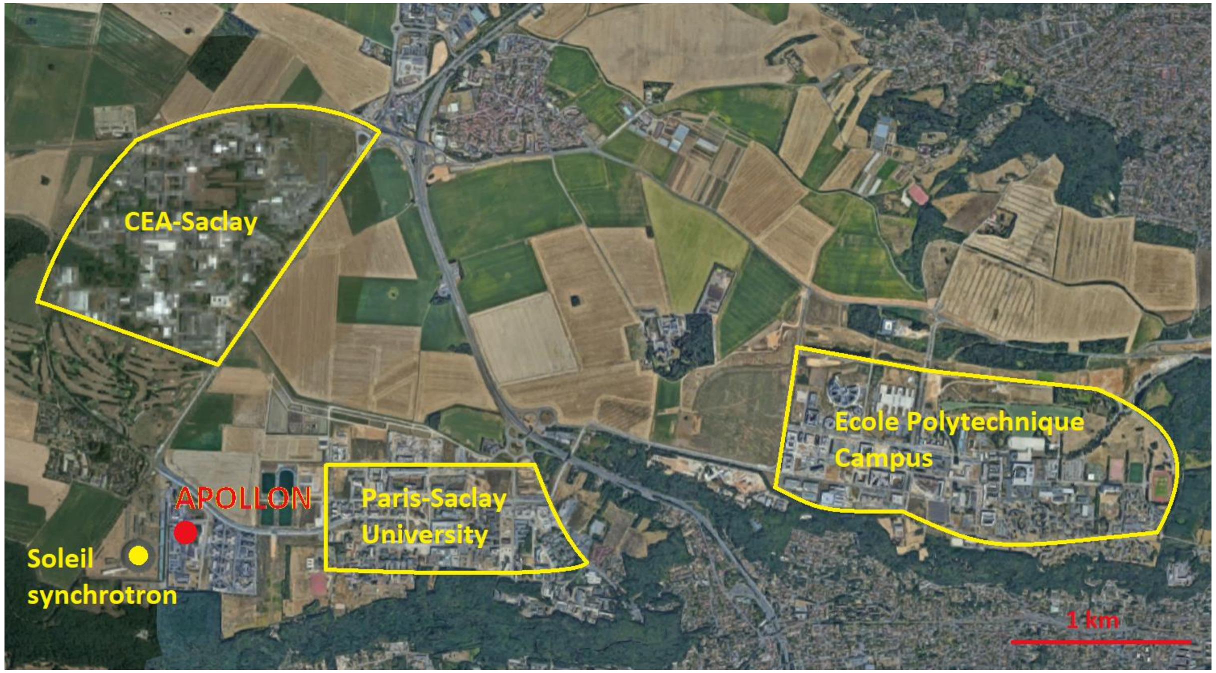
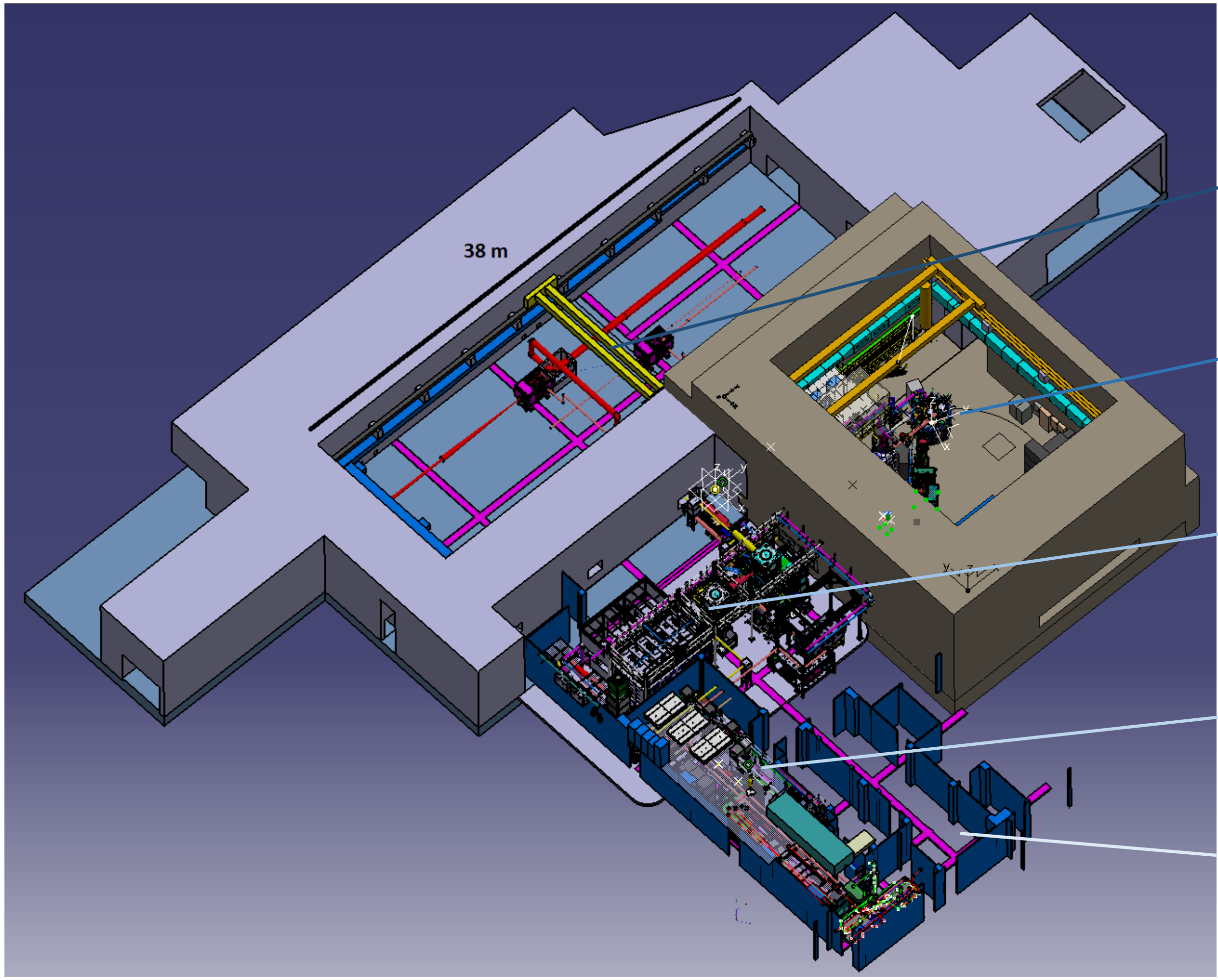
Location of APOLLON

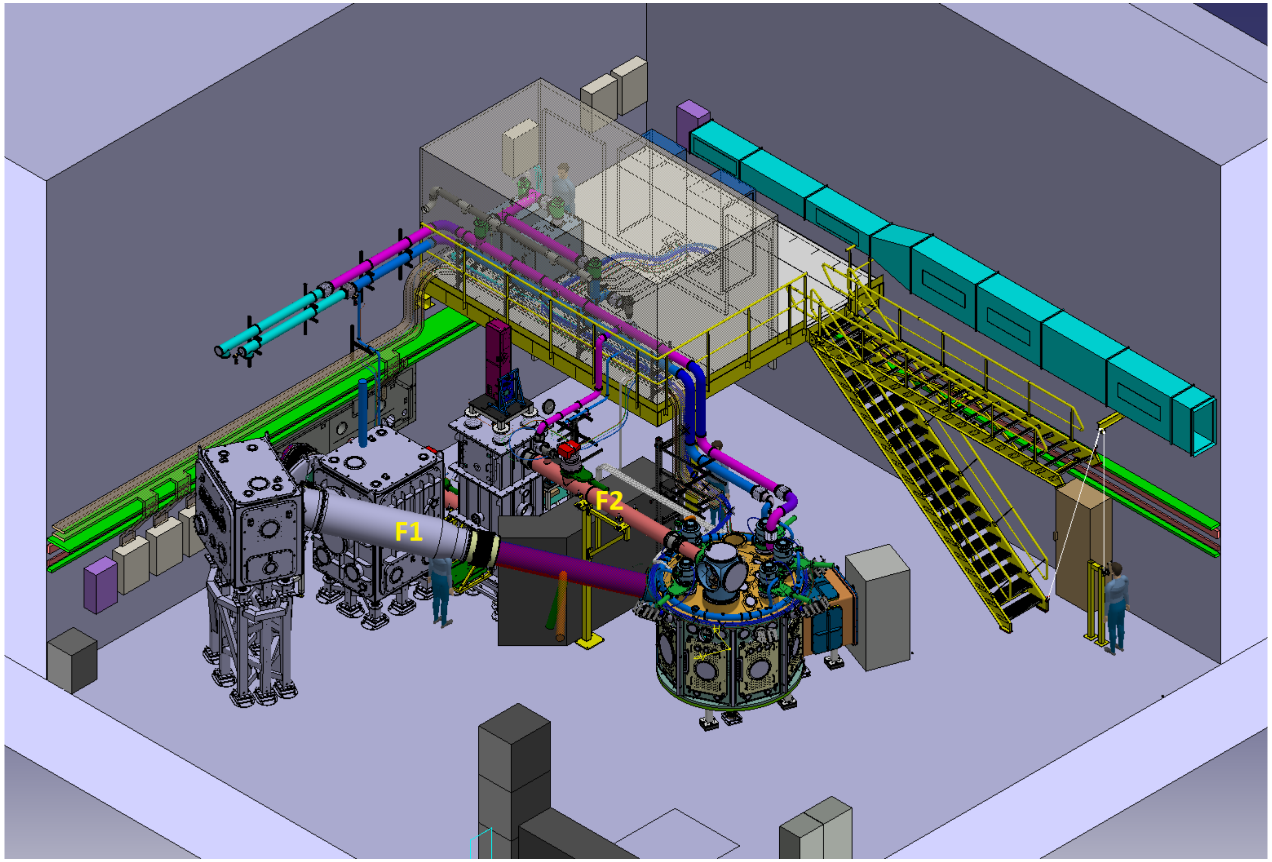




Facility structure



Details of the Short-Focal Area



OPCPA front end

5 Ti:Sapphire amplification stages

F2 – secondary beam (15J, 24fs → 0.6PW)

F1 – main beam (220J, 22fs → 10PW)

max. 1 shot/min

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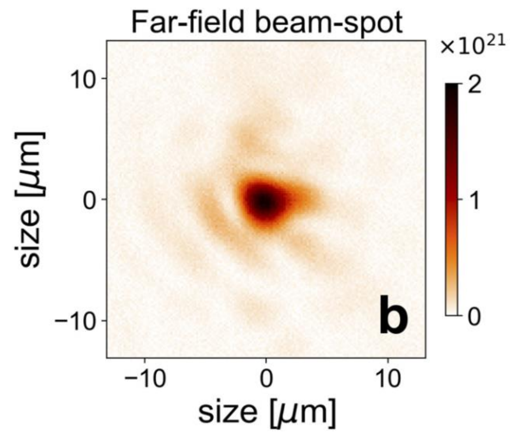
Commissioning of F2 beam in 2021

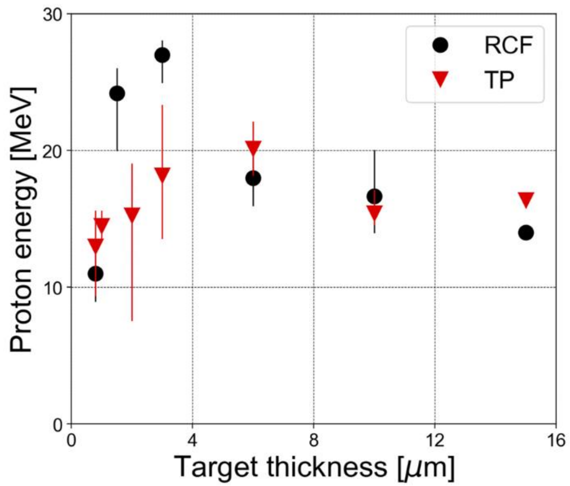
“K. Burdonov et al., Matter Radiat. Extremes 6, 064402 (2021)”

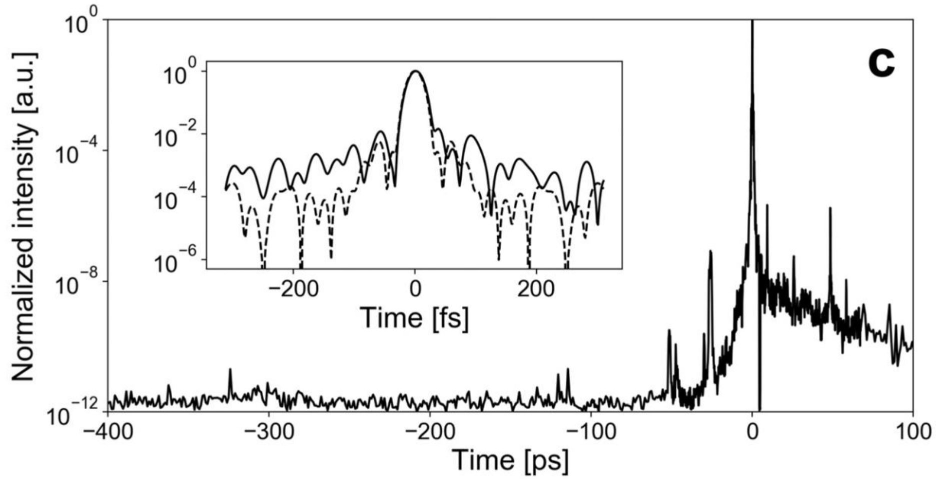
Pulse duration : 24 fs
On-target laser energy : ≈ 10J

About 41% of laser energy within a disk of 2.8 µm FWHM

→ ≈ 2x10^{21} W/cm²

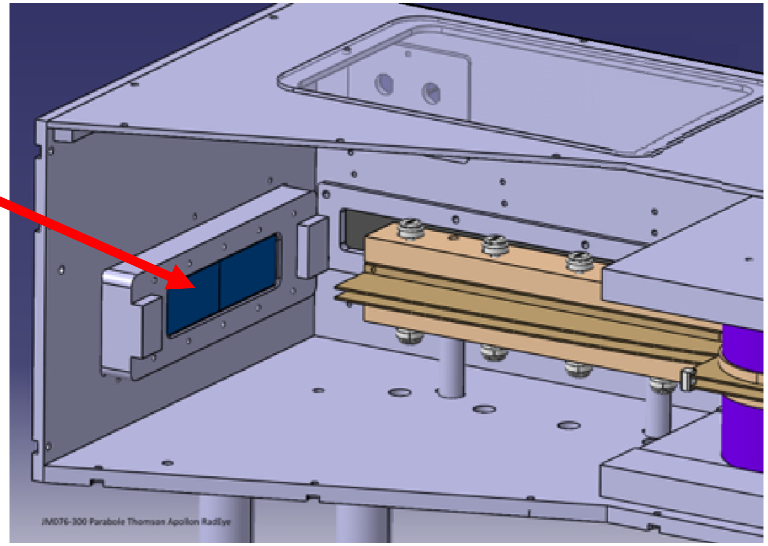






Real-time proton spectra acquisition

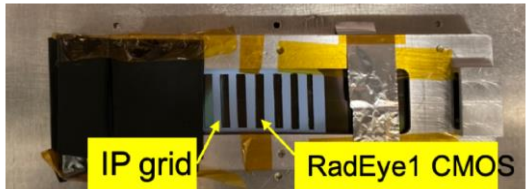
Thomson Parabola using CMOS sensors

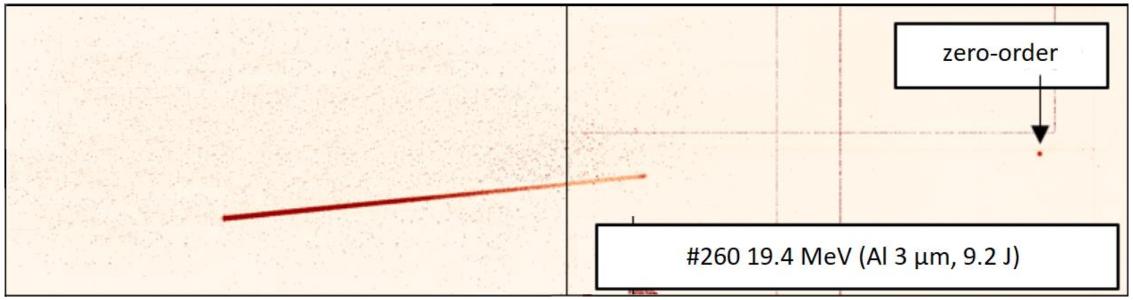


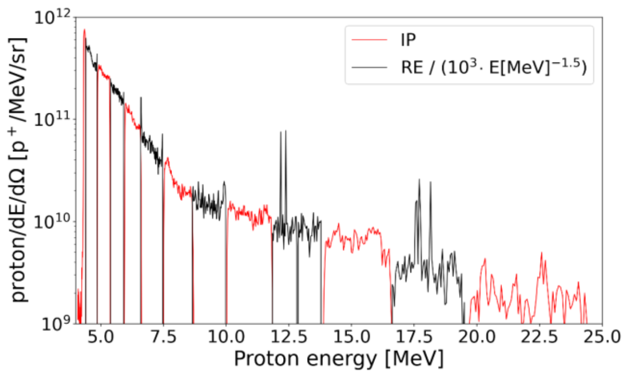
Acquisition in real-time
No need to break the vacuum

→ useful for high-repetition rate lasers

More sensitive than IP



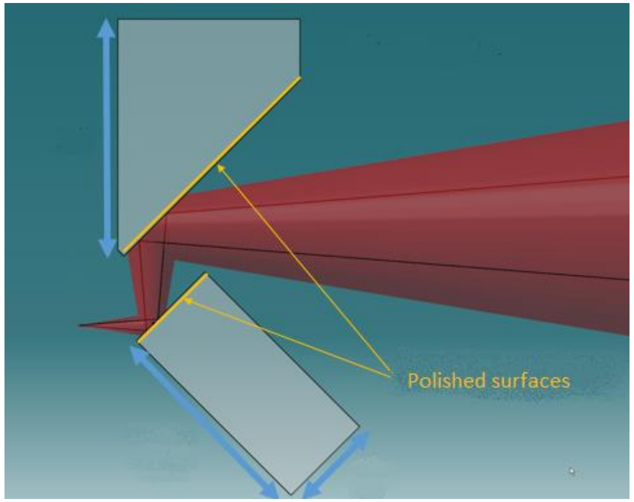


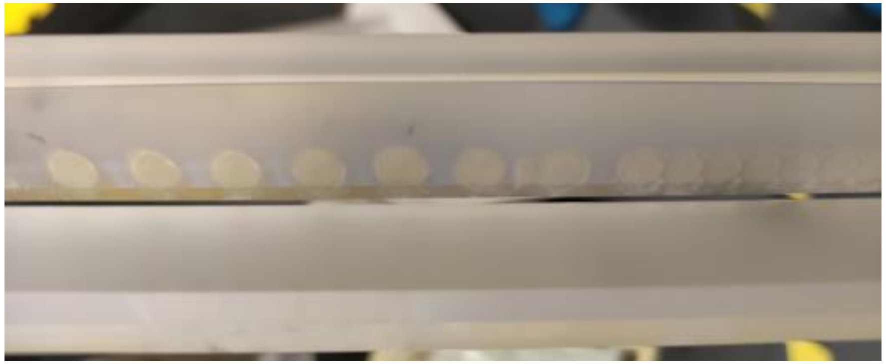


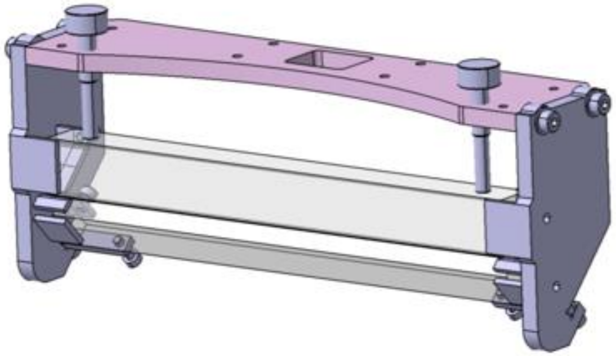
Ultra-high contrast possible with DPM

Double Plasma Mirror (DPM) improves laser contrast and induces:

→ possibility to shoot thinner targets (from several µm to tens of nm)







Ultra-high contrast possible with DPM

Double Plasma Mirror (DPM) improves laser contrast and induces:

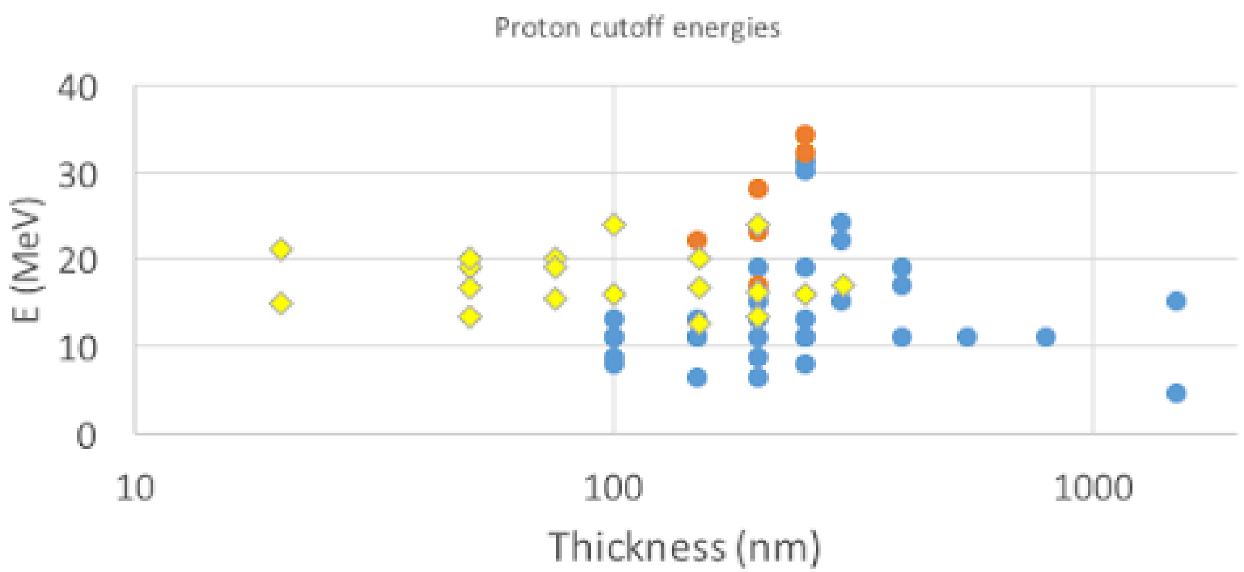
→ possibility to shoot thinner targets (from several µm to tens of nm)

→ better proton cutoff energies (from 28 to 36 MeV)

→ **improvement in neutron production yield**

→ Reduction in production of gamma-rays

But loss of on-target energy (efficiency ≈ 60% → ≈ 6 J/shot)



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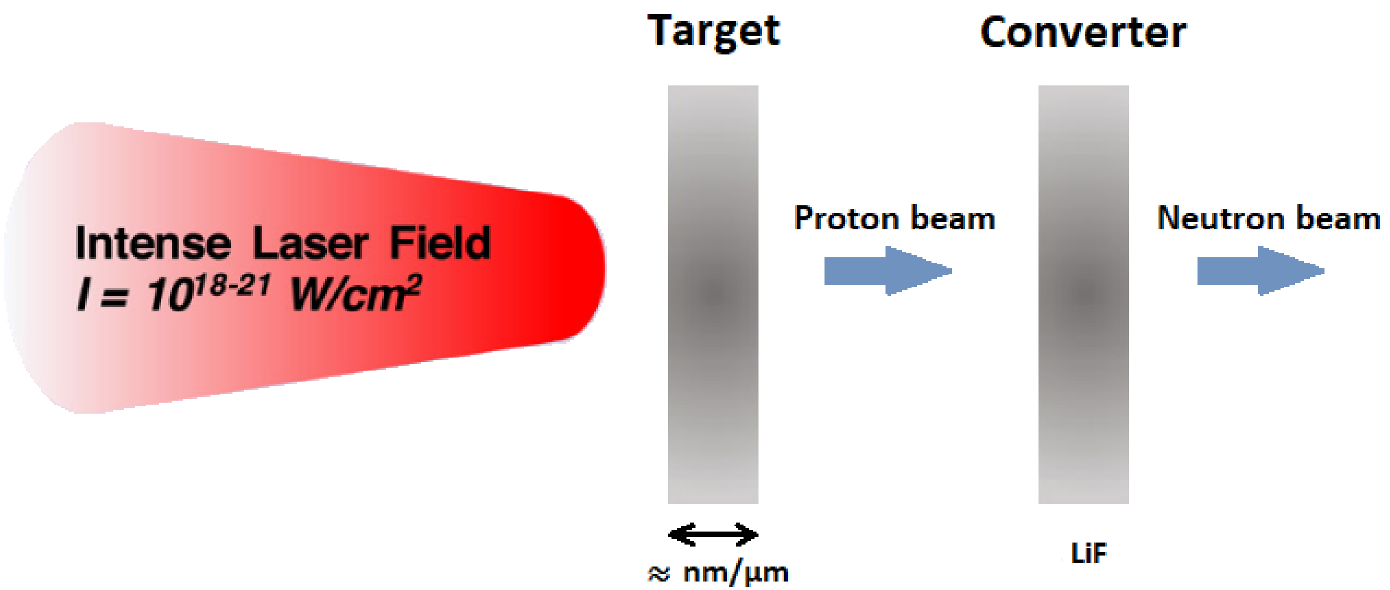


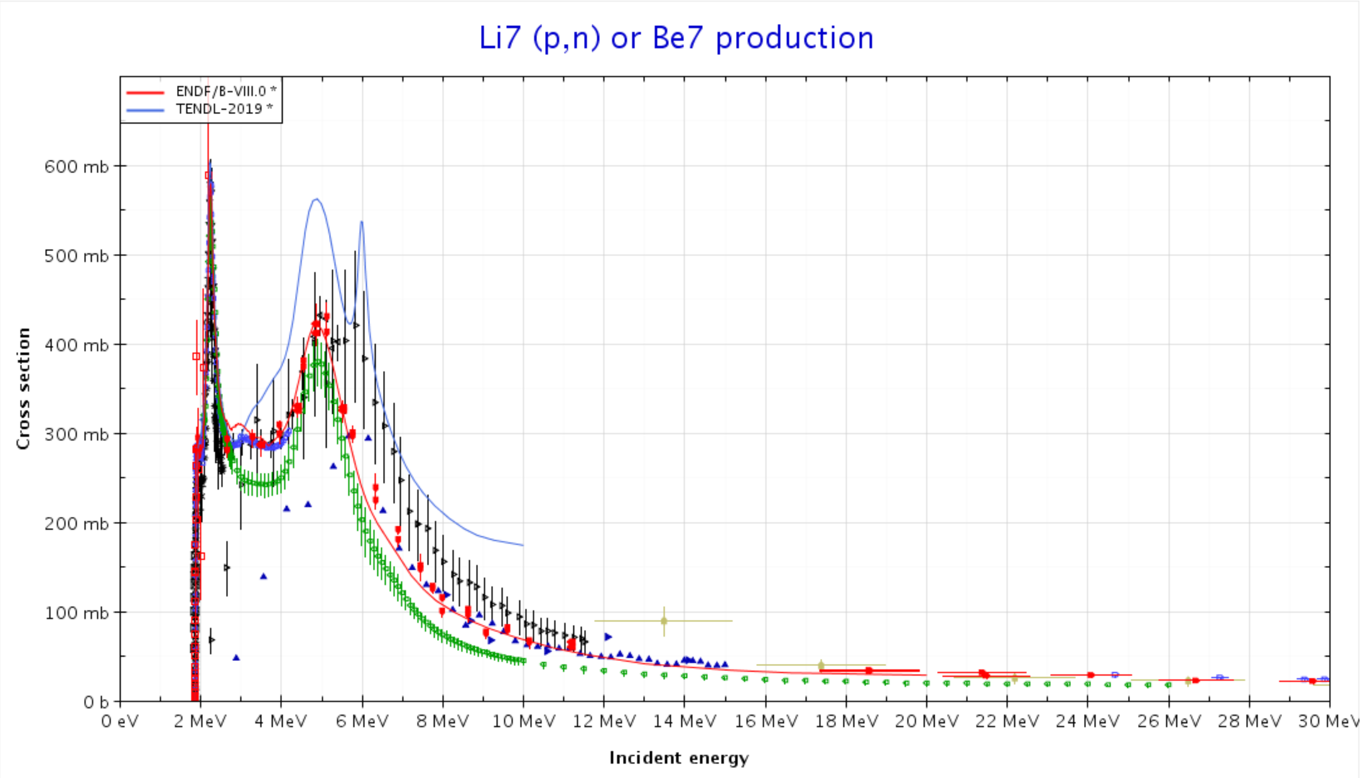
Neutron generation

Pitcher-catcher technique on low-Z materials

N_p (E > 10 MeV) < 1% of total proton number

N_p (2 < E < 10 MeV) > 33%

→ **Low-Z materials are preferred**



Simulation of neutron emissions

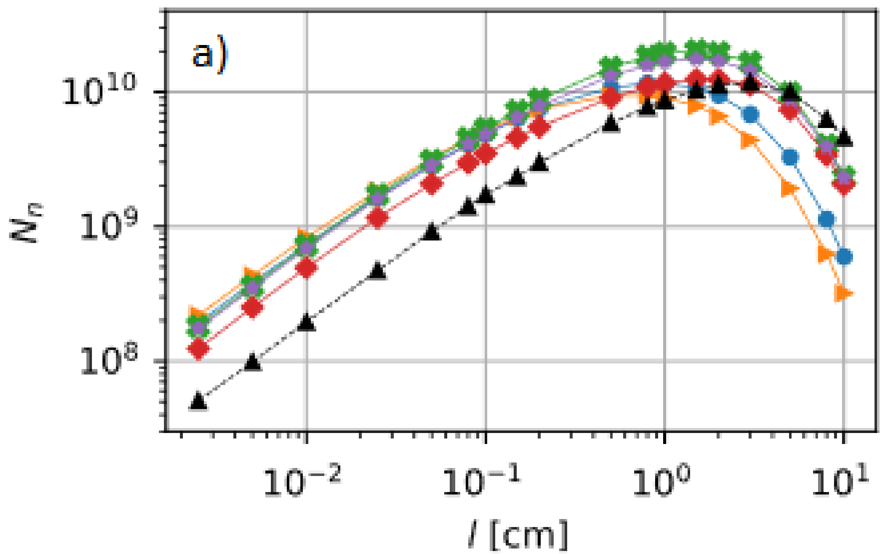
"V. Horný et al., Scientific Reports 12, 19767 (2022)"

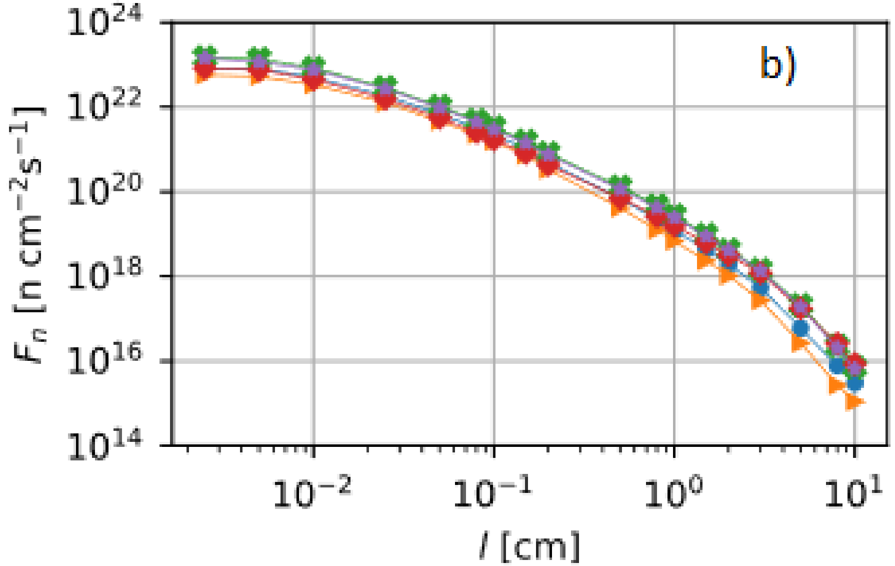
Fluka simulations (Vojtech Horný, LULI) of neutron emissions using low-Z converter :

→ Possibility to optimize certain properties according to applications (e.g. flux for r-process study)

Optimization of the total yield only :

→ To test our detection capabilities

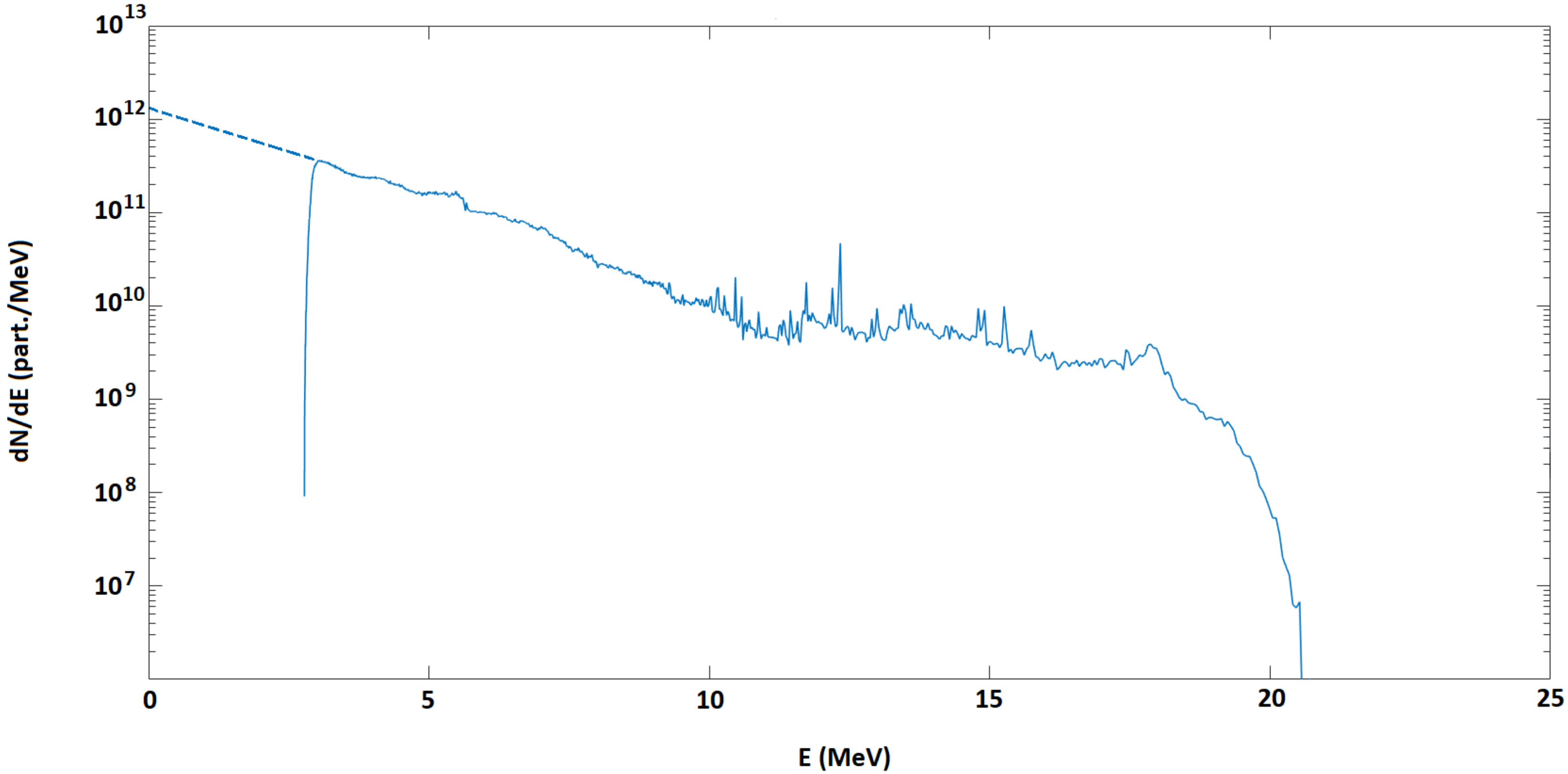




Actual proton spectrum

Proton spectrum :

- typical direct shot (without DPM) with 12J on-target energy (1.5 µm Al)
- Cutoff energy : 20.6 MeV
- extrapolated at low energy
- 3.2x10^{12} protons/shot (3.4x10^{11} protons between 5 MeV and cutoff energy)

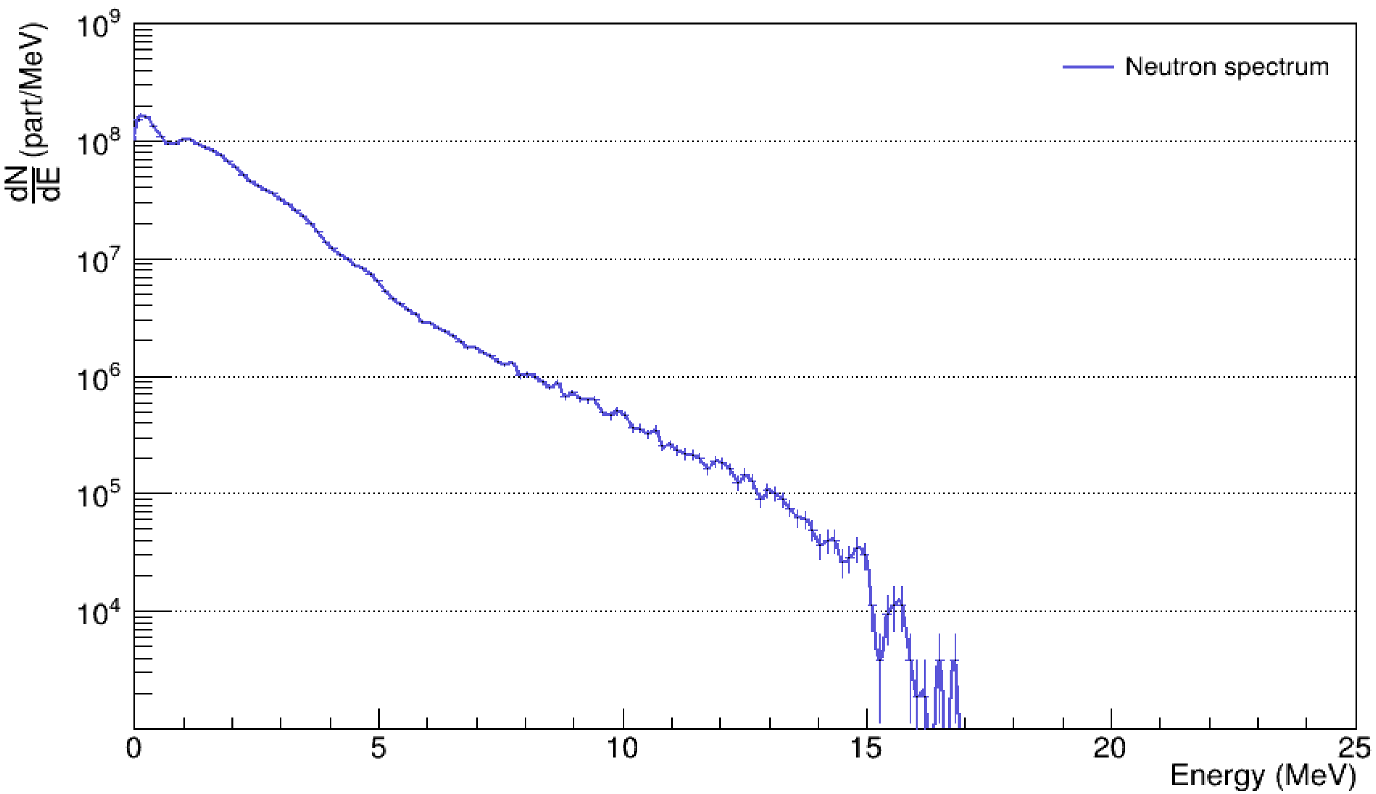


Simulation of neutron emissions

GEANT4 simulations (Physics List "QGSP_BIC_AllHP")

4mm thick LiF converter

→ Total number of neutrons : **2.947x10^{8} neutrons/shot**

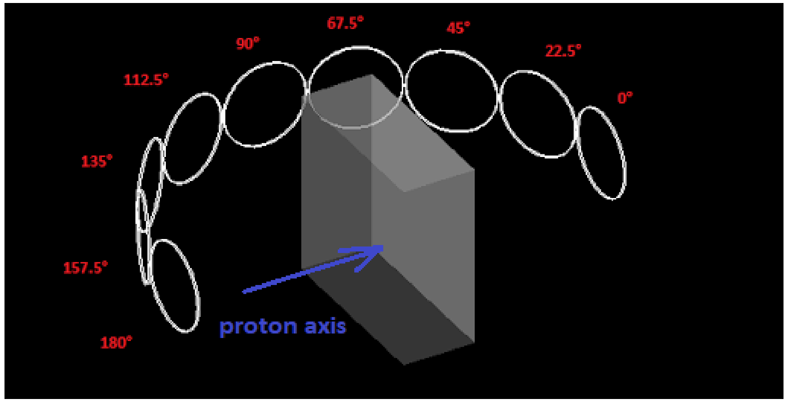


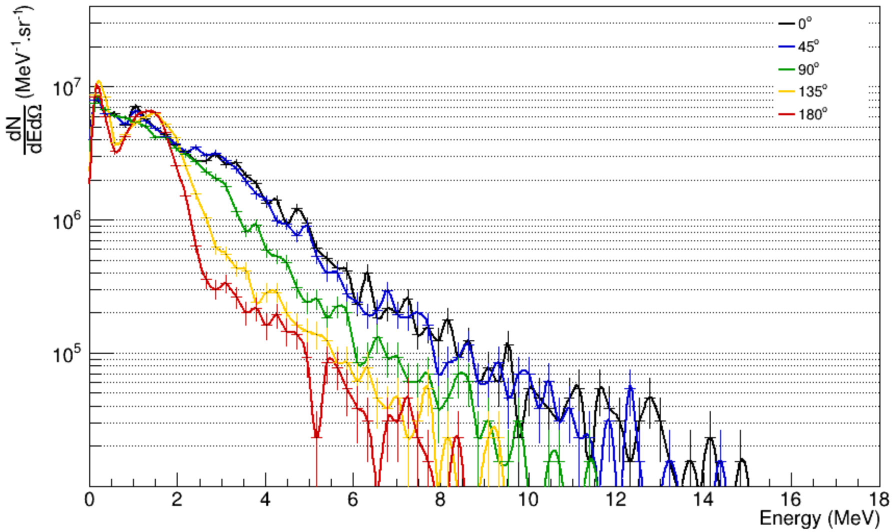
Simulation of neutron emissions

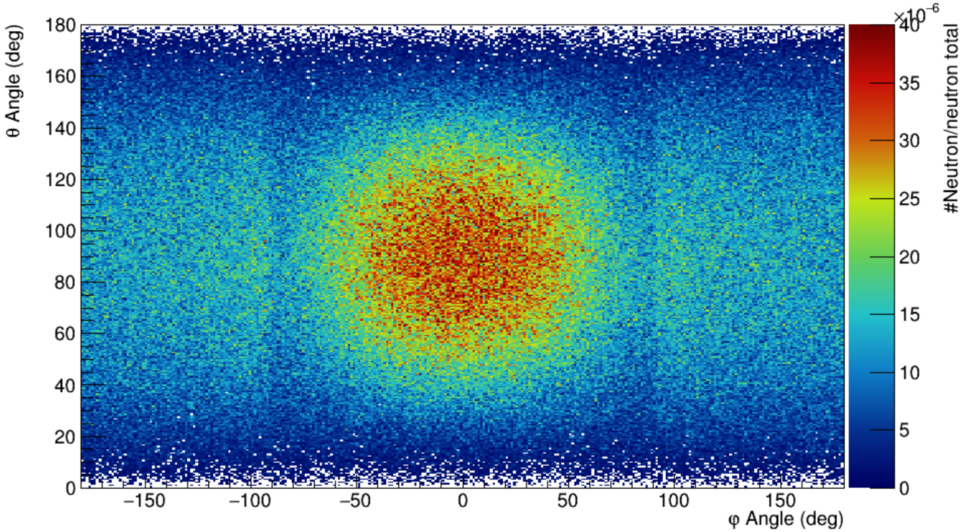
GEANT4 simulation: angular distribution

- 1.913x10^7 neutrons/sr at 0°

- 1.872x10^7 neutrons/sr at 45°
- 1.553x10^7 neutrons/sr at 90°
- 1.215x10^7 neutrons/sr at 180°







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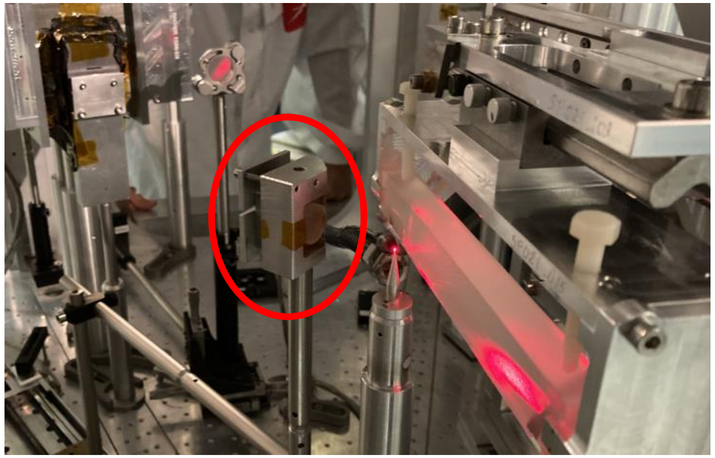
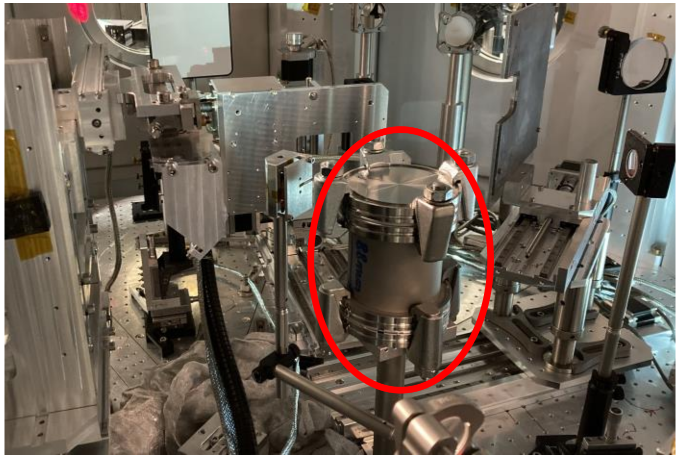
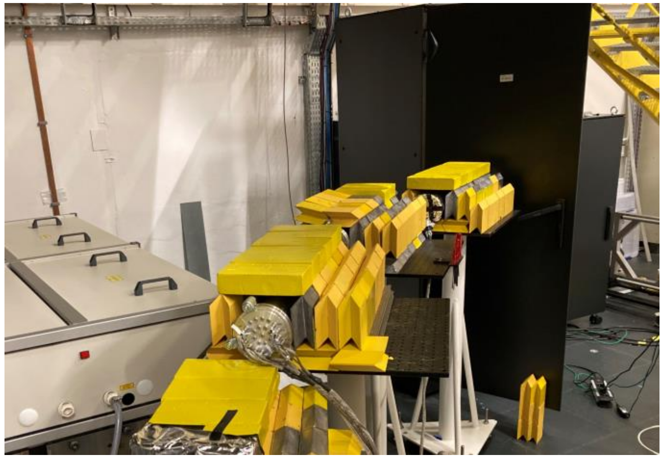
Diagnostics

Three types of detectors

- Activation samples
- Bubble detectors
- Time-of-Flight detectors







Activation samples

→ Activation of samples using different reactions to retrieve neutron energy

Several criteria for samples selection:

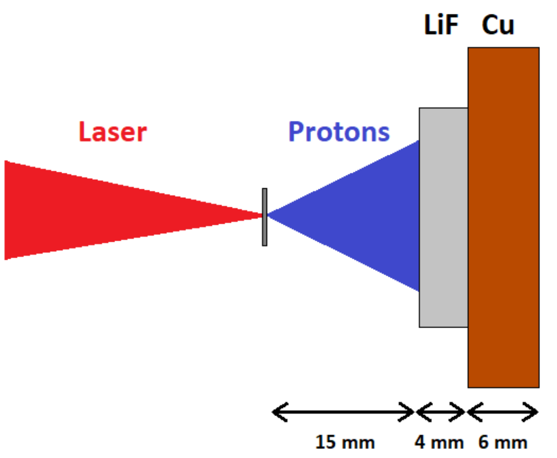
- Reactions with interesting cross-sections and spanning a wide spectrum
- Radionuclides with high intensity gamma emissions
- …

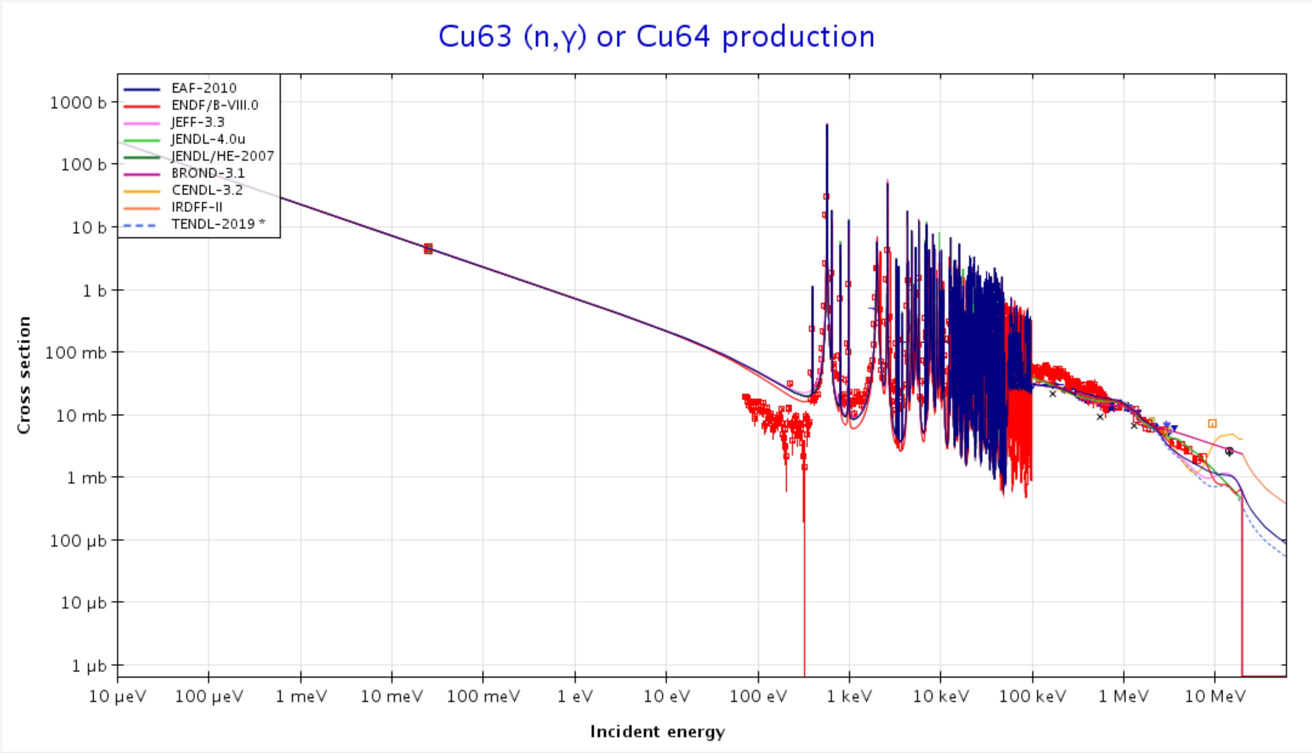
Layer #1	Layer #2	Layer #3	Layer #4	Layer #5
(n,g) reactions Au, Cd, Cu, Mn, Ni, Sn, W, Zn, …	(n,n’) or (n,p) reactions Al, In, Ni, Rh, S, Zn	(n,a) reactions Al, Fe, Mg	(n,2n) reactions Co, Cu, Nb, Ni, Sc, Y, Zr	(n,3n) or (n,4n) reactions Bi

Activation samples

GEANT4 activation simulations to find best samples:

- Copper

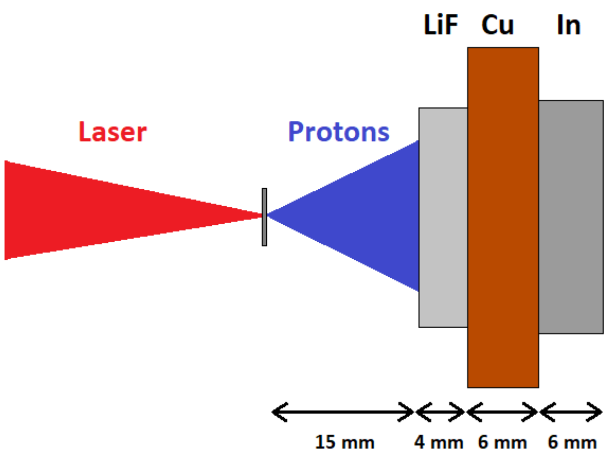


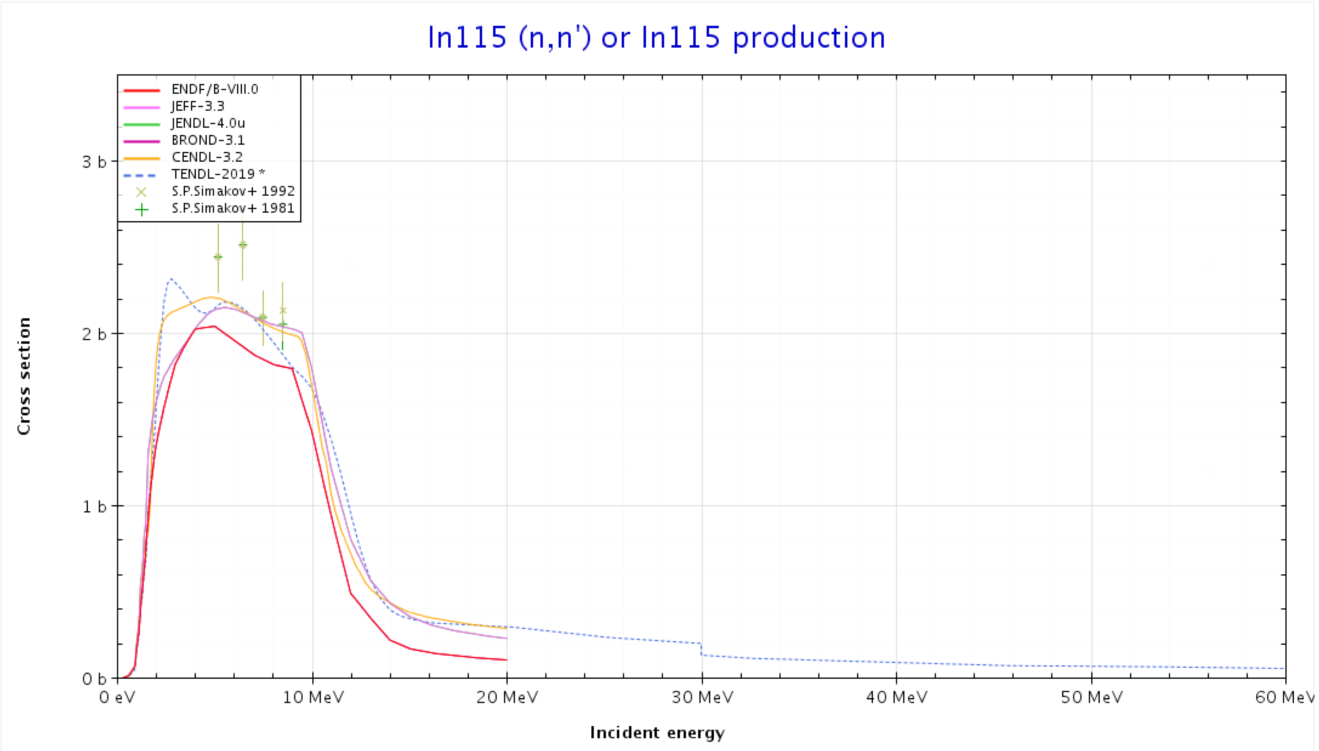


Activation samples

GEANT4 activation simulations to find best samples:

- Copper
- Indium

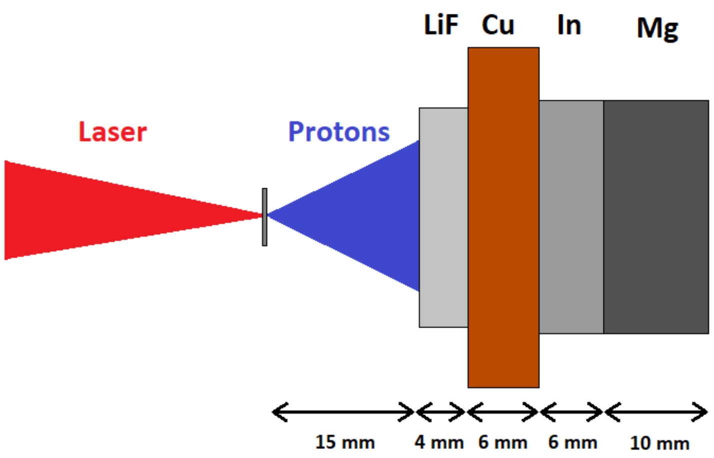


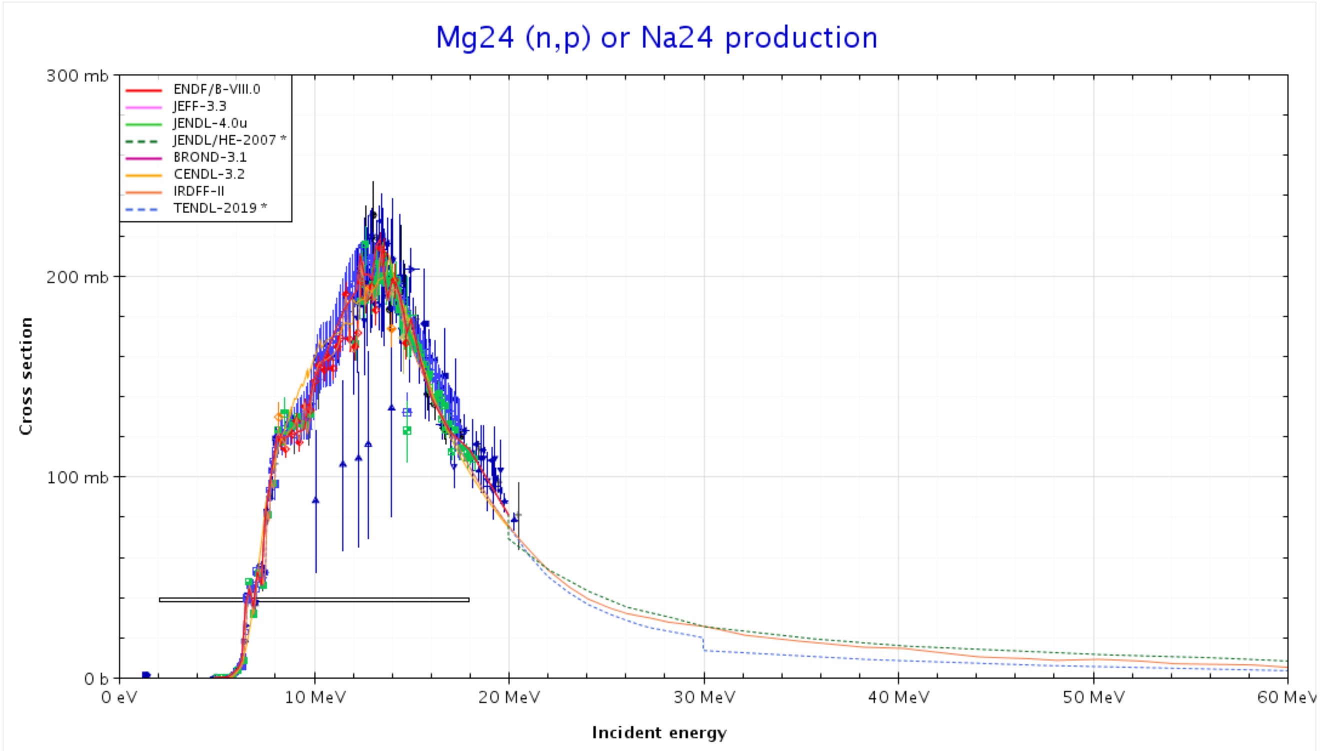


Activation samples

GEANT4 activation simulations to find best samples:

- Copper
- Indium
- Magnesium

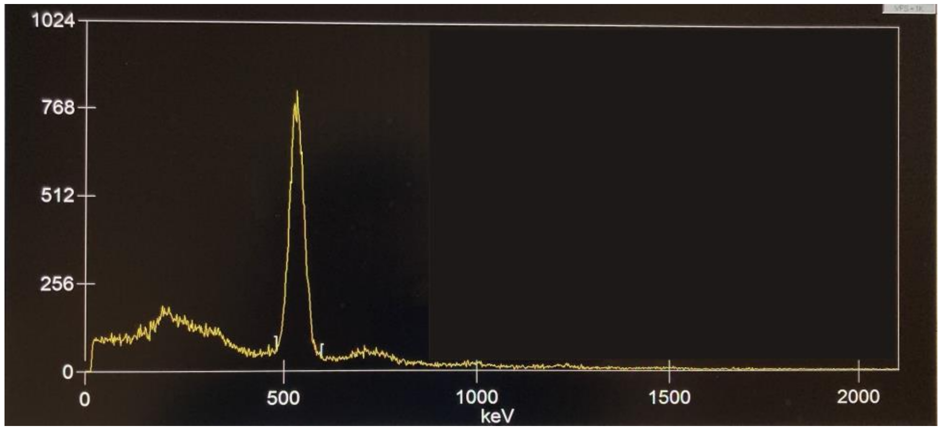




First results for activation diagnostic

Same activation samples for a session of 20 shots to accumulate activities

Material	Reaction	Half-life (h)	E_X (keV)	$A_{mes.}$ (Bq)	$A_{sim.}$ (Bq)
Cu	$^{63}Cu(n,g)^{64}Cu$	12.701	511	*(waiting for calibration)*	29.06



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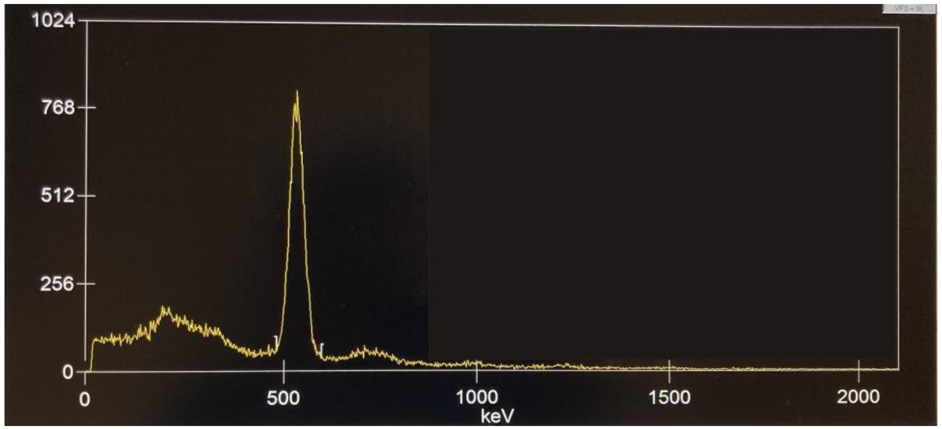
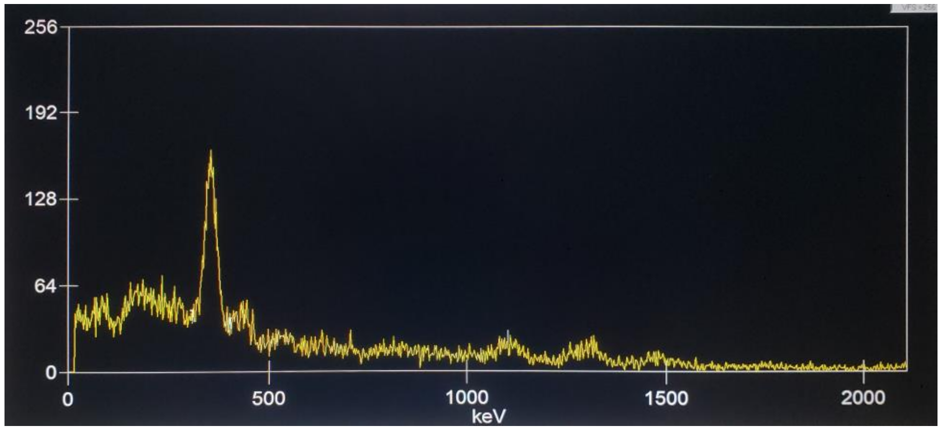
In	$^{115}In(n,n')^{115m}In$	4.486	336.2	22.72 ± 3.16	42.92





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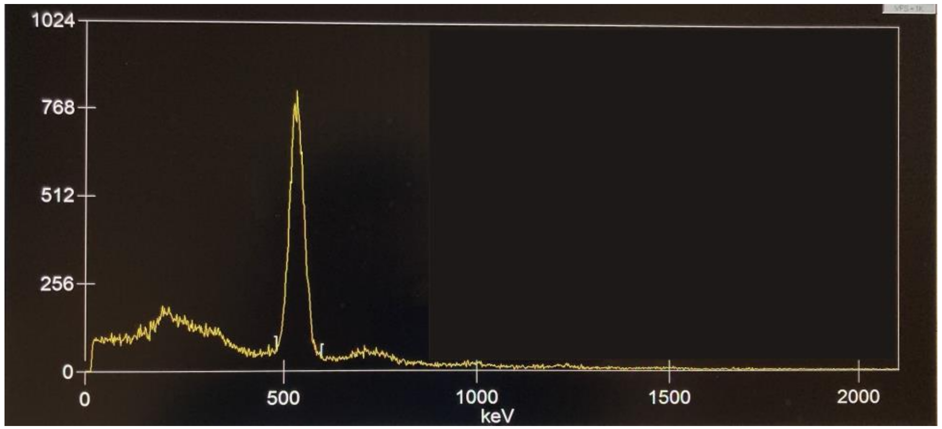
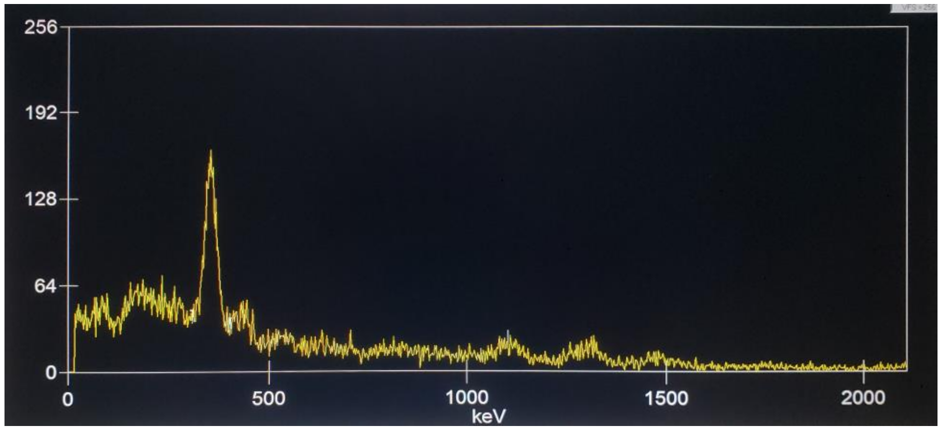
In	$^{115}In(n,n')^{115m}In$	4.486	336.2	22.72 ± 3.16	42.92
Mg	$^{24}Mg(n,p)^{24}Na$	14.997	1368.6	< LoD*	0.34

Interesting values at ~ 10J

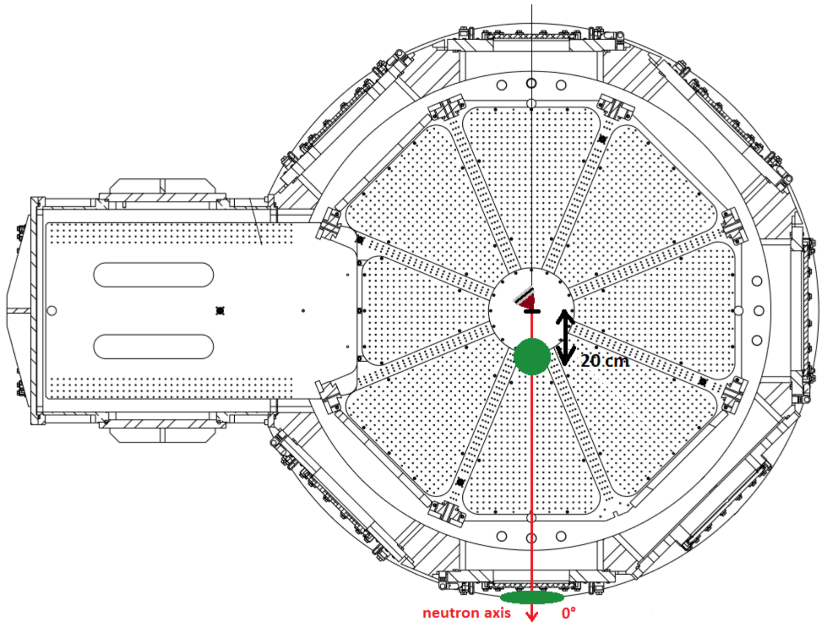


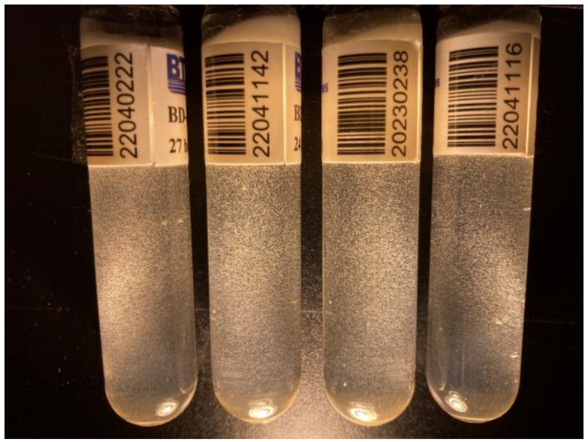


Bubble detectors

- 2 set of bubble spectrometer placed 20 cm from the converter (during the same session of 20 shots)

- Bubble dosimeters taped to the chamber and filmed by a camera to see neutron generation shot-to-shot

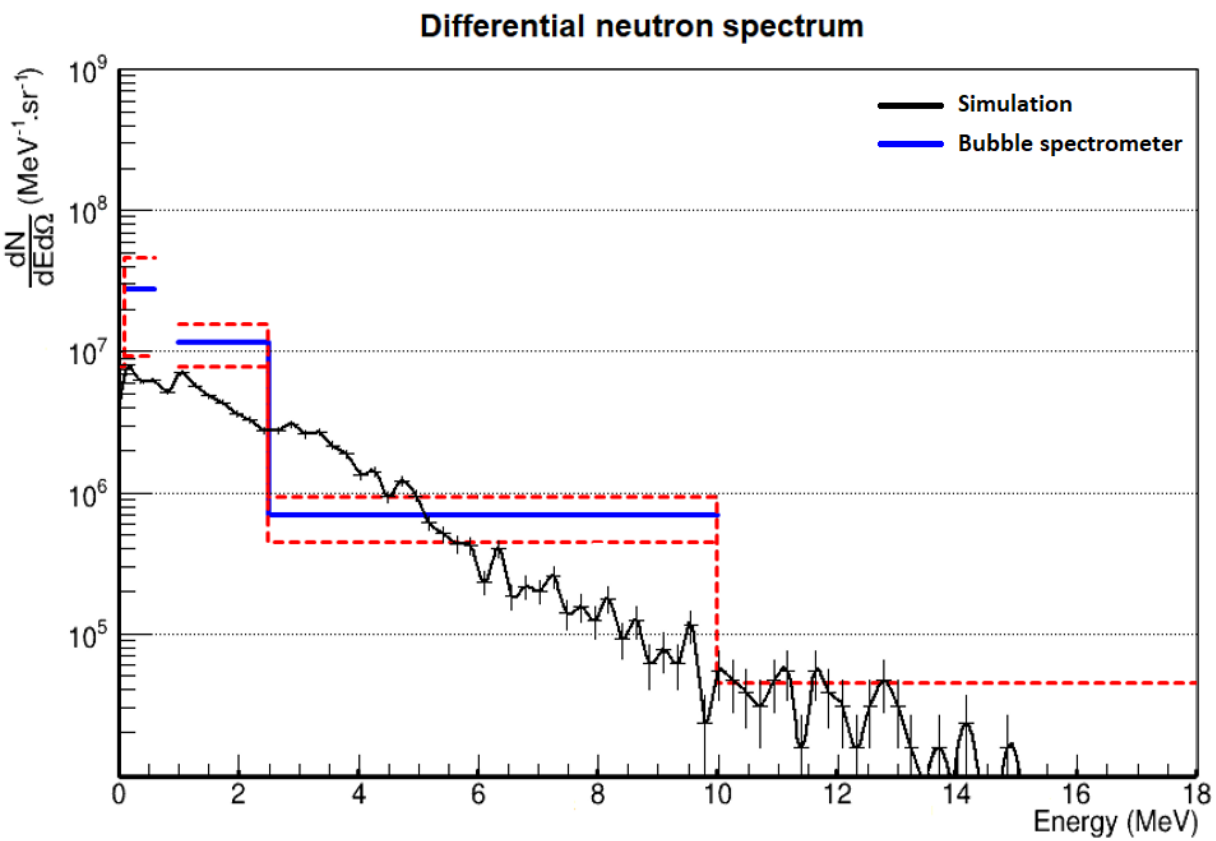




Bubble detectors

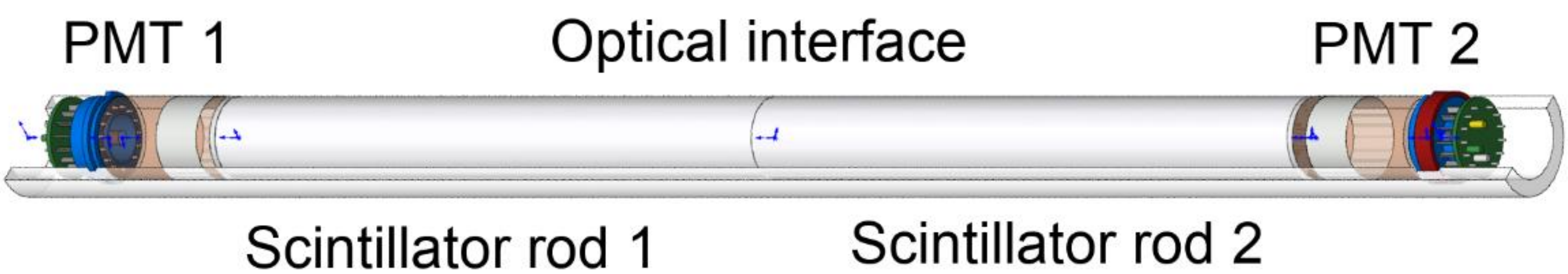
→ Measured neutron spectrum greater than simulated one, unlike the activation diagnostic.

→ Bubble detectors don’t seem totally insensitive to gamma-rays.



Time-of-flight detectors

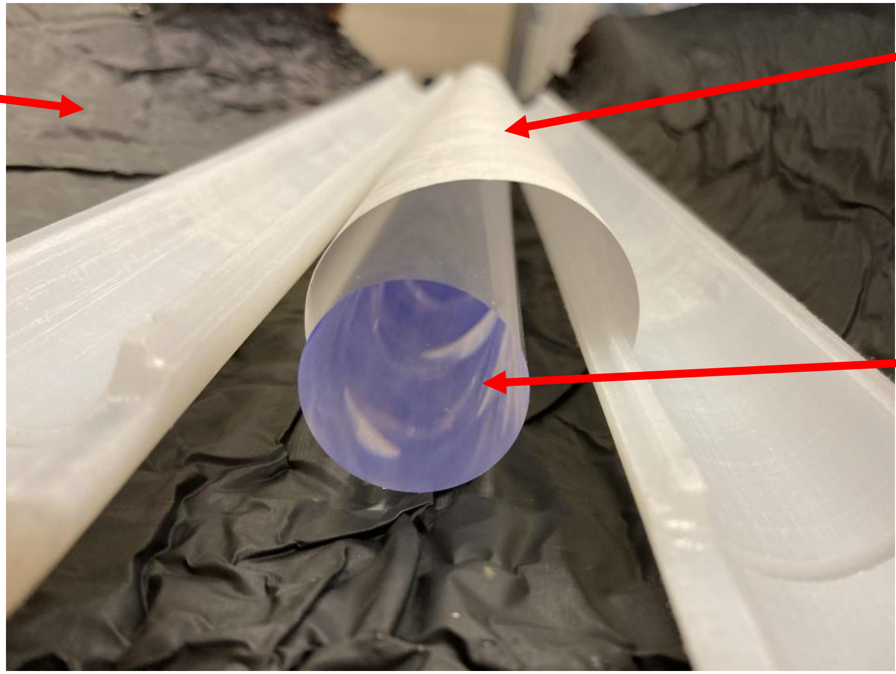
- PVT-based scintillators (EJ-254)
- 1” diameter, 40cm long cylinders with PMT on either side



Time-of-flight detectors

- PVT-based scintillators
- 1" diameter, 40cm long cylinders with PMT on either side

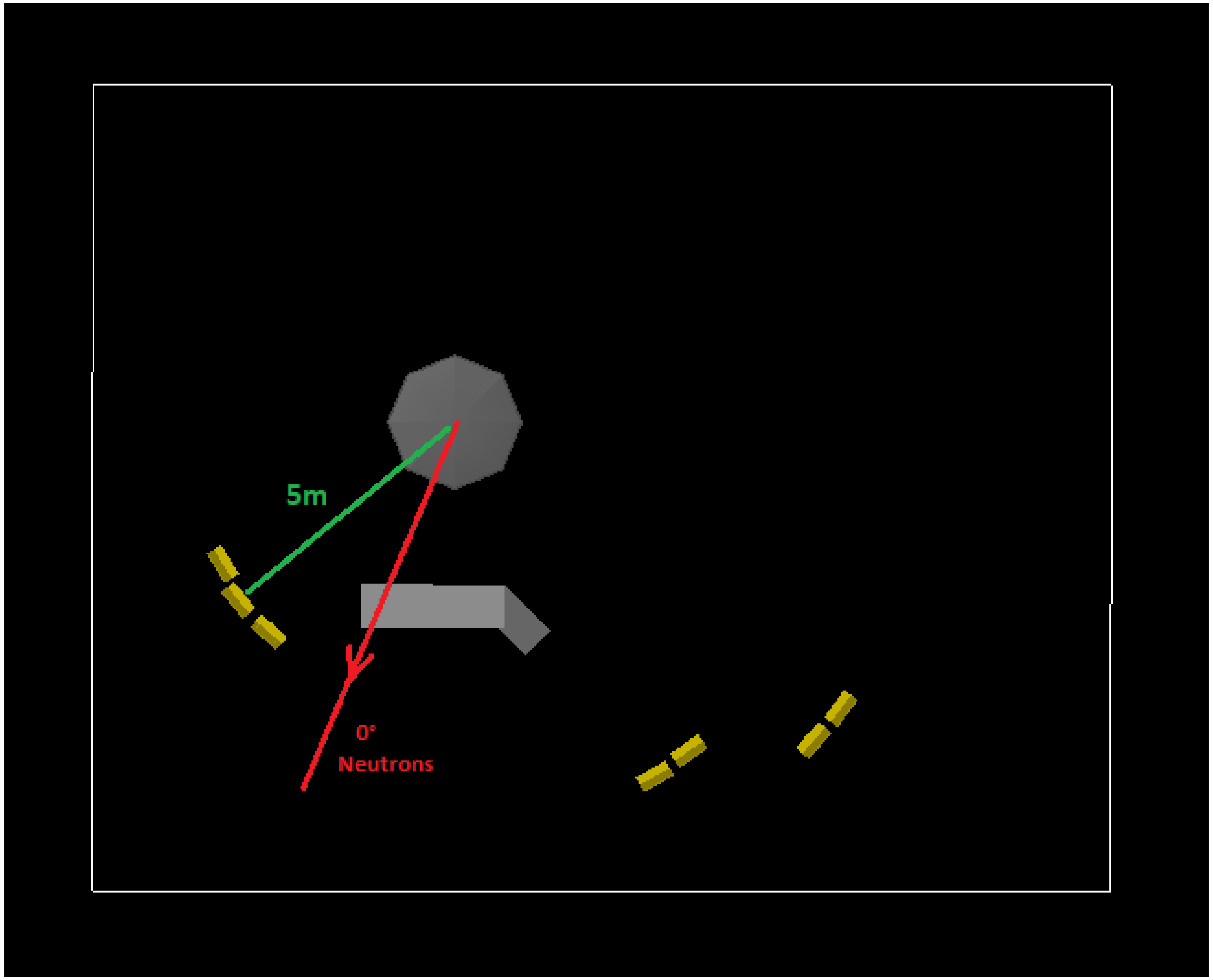
Black aluminum



Reflective paper

Scintillator

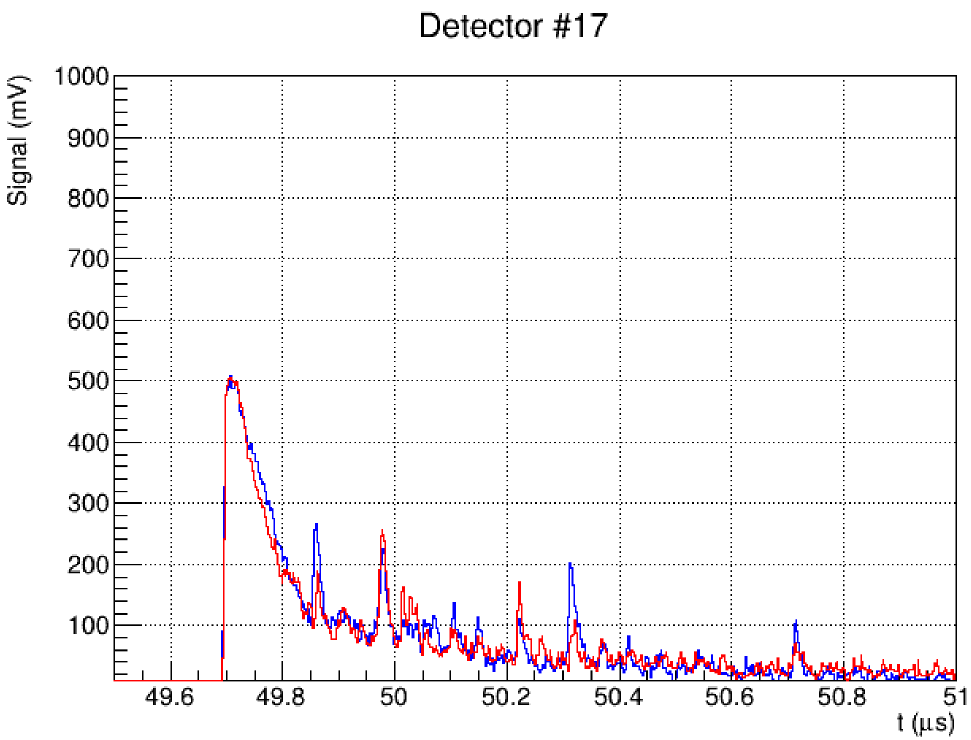
Time-of-flight detectors



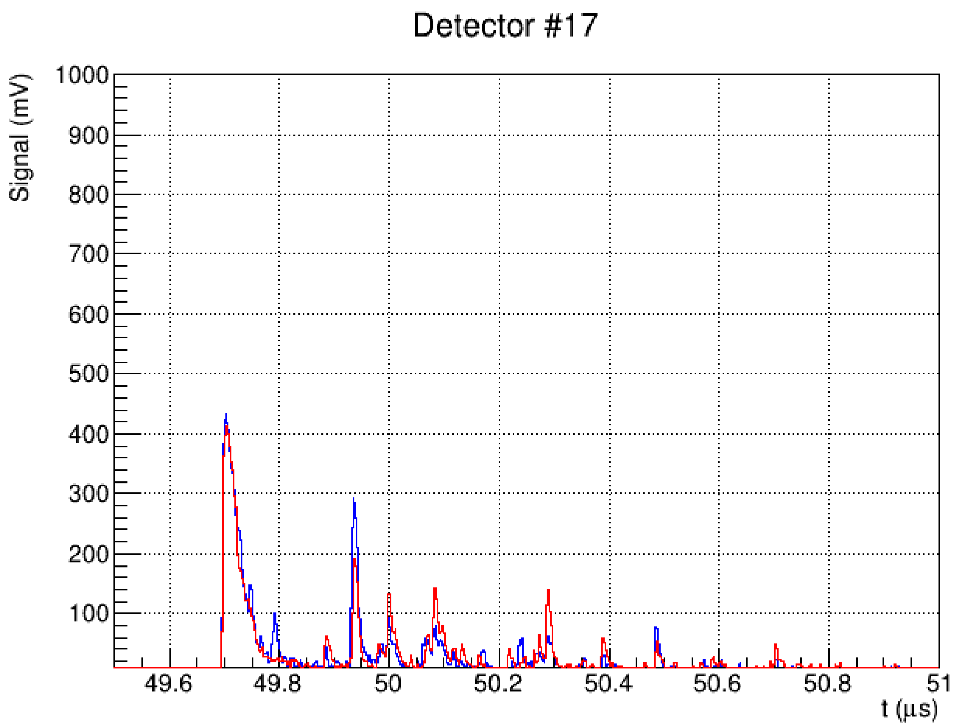
Gamma flash with and without DPM

Shots without converter, same cutoff energy: ≈ 21 MeV

without DPM (1.5µm Al)



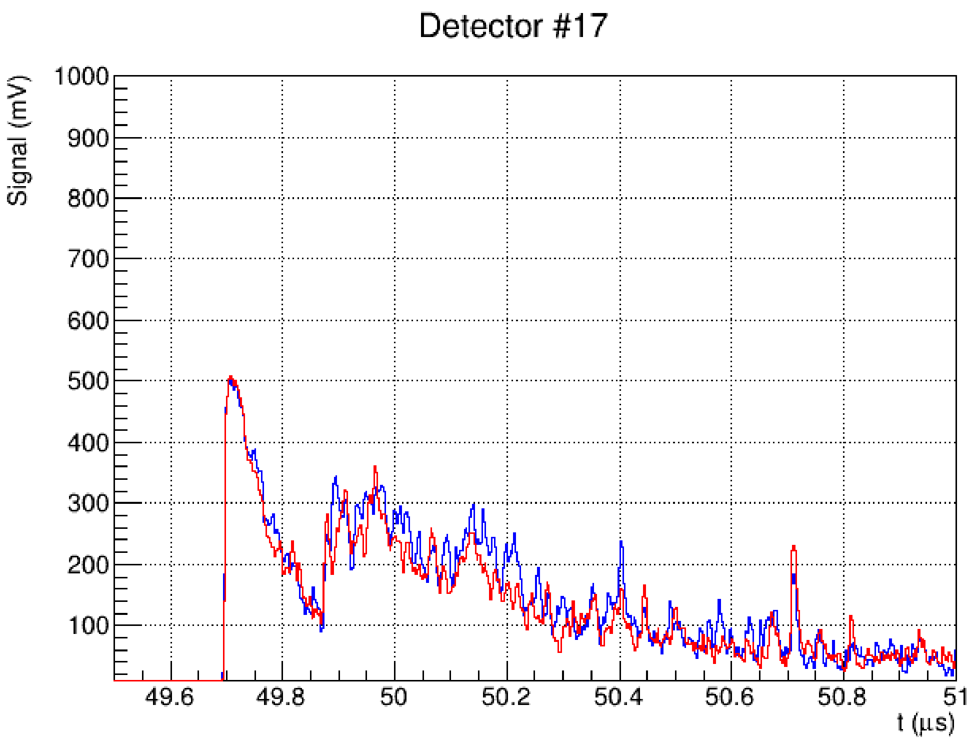
with DPM (300nm Si)



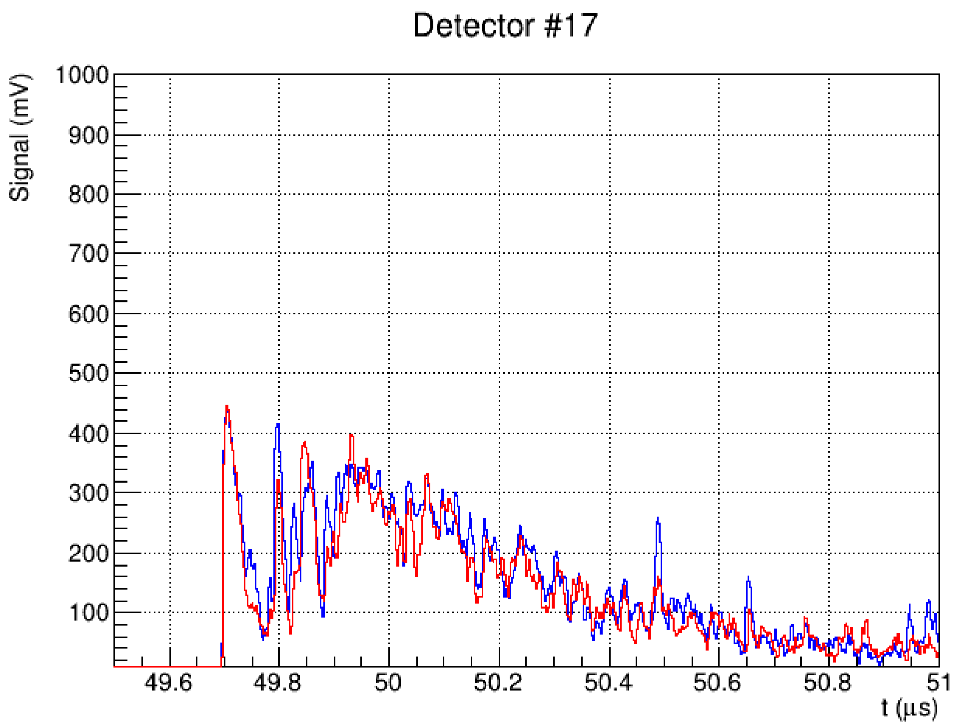
nToF signal with and without DPM

Shots <u>with</u> converter, same gamma flash as before

without DPM (1.5µm Al)

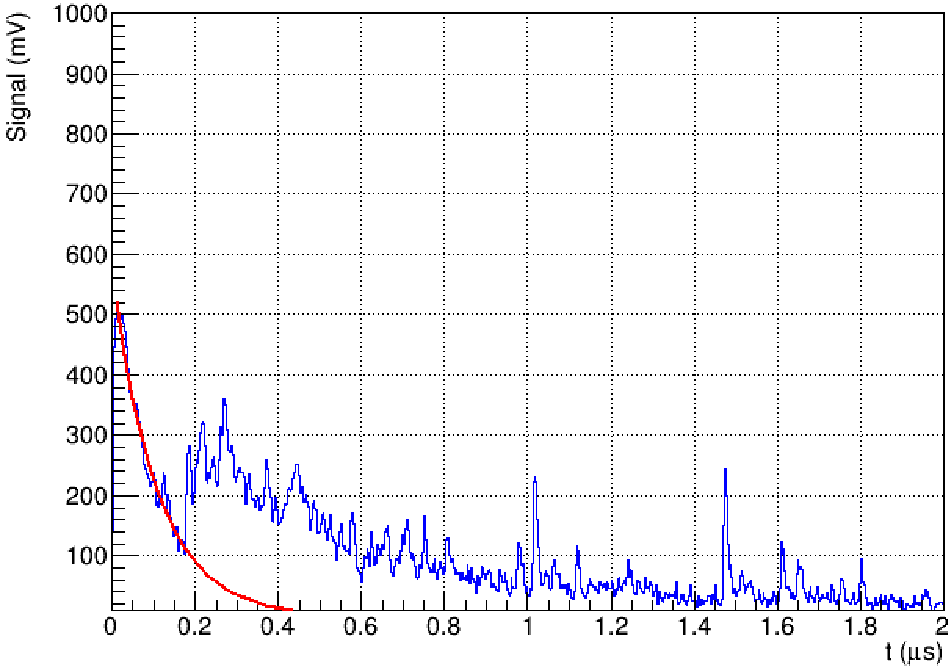


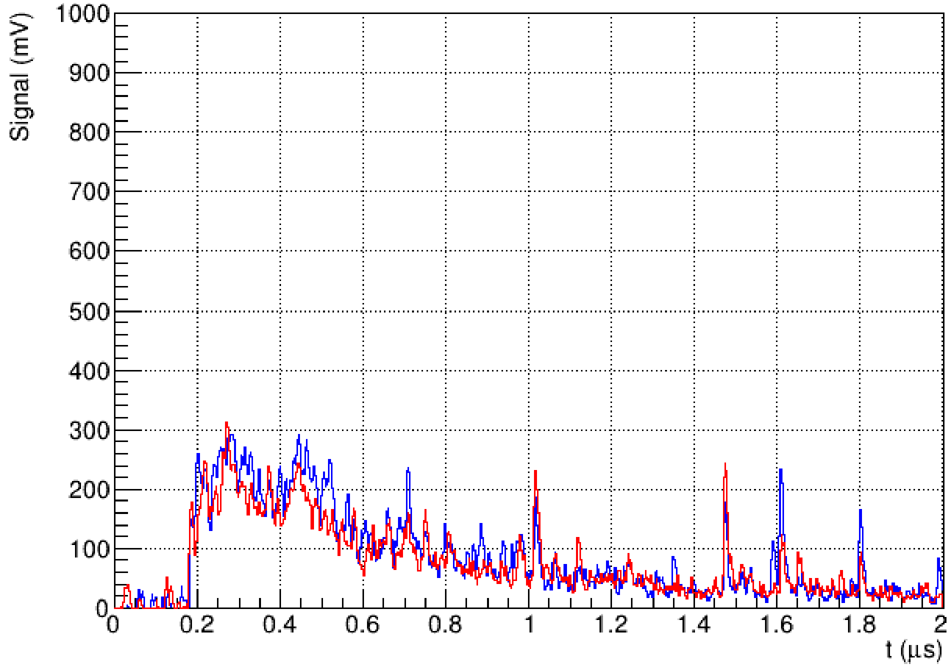
with DPM (250nm Si)



nToF signal analysis

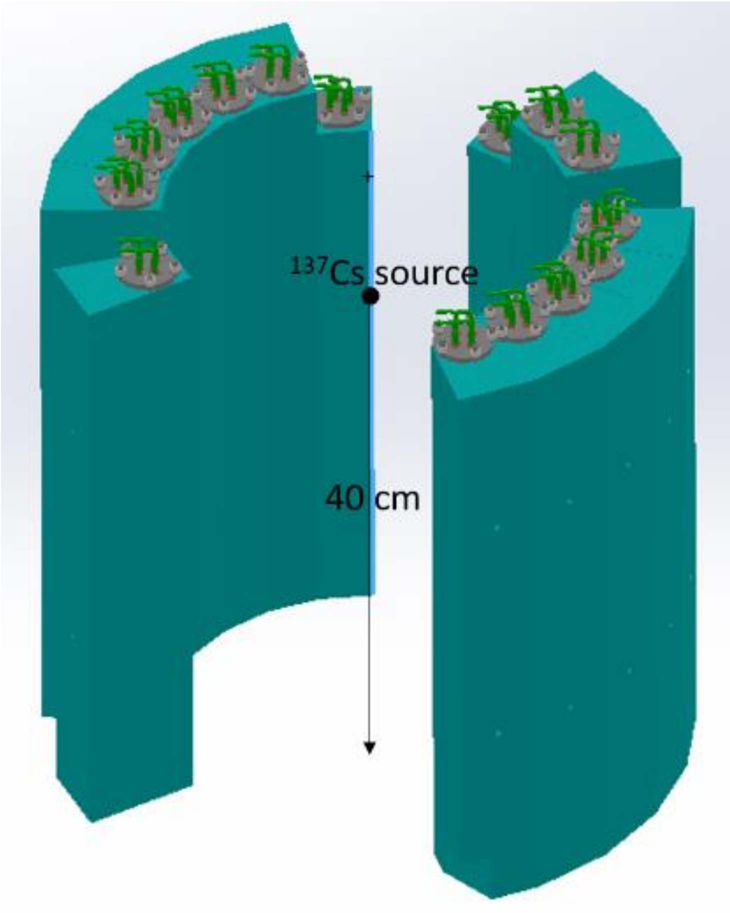
Gamma flash subtraction





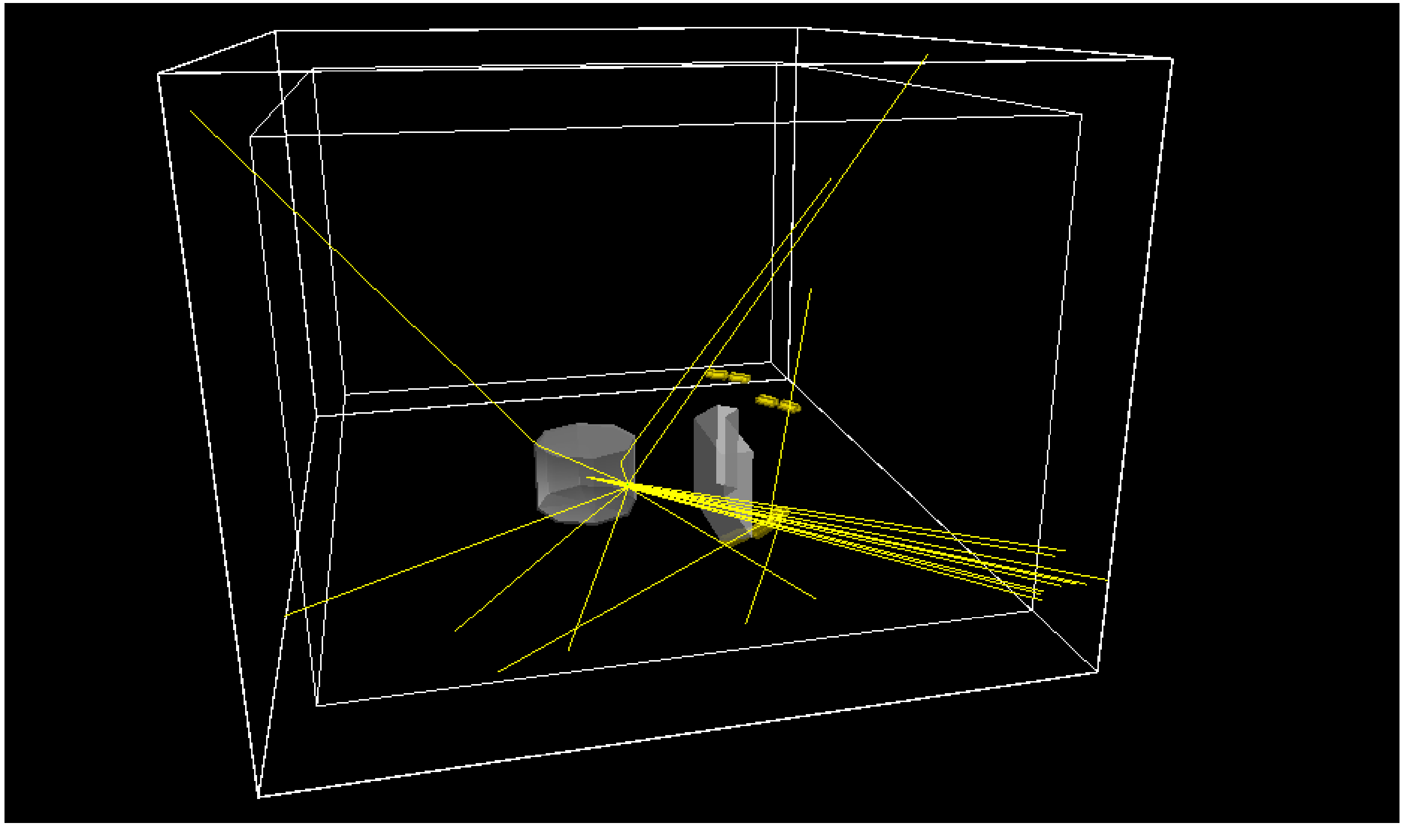
Calibration

mV/pC signal → number of scintillation photons



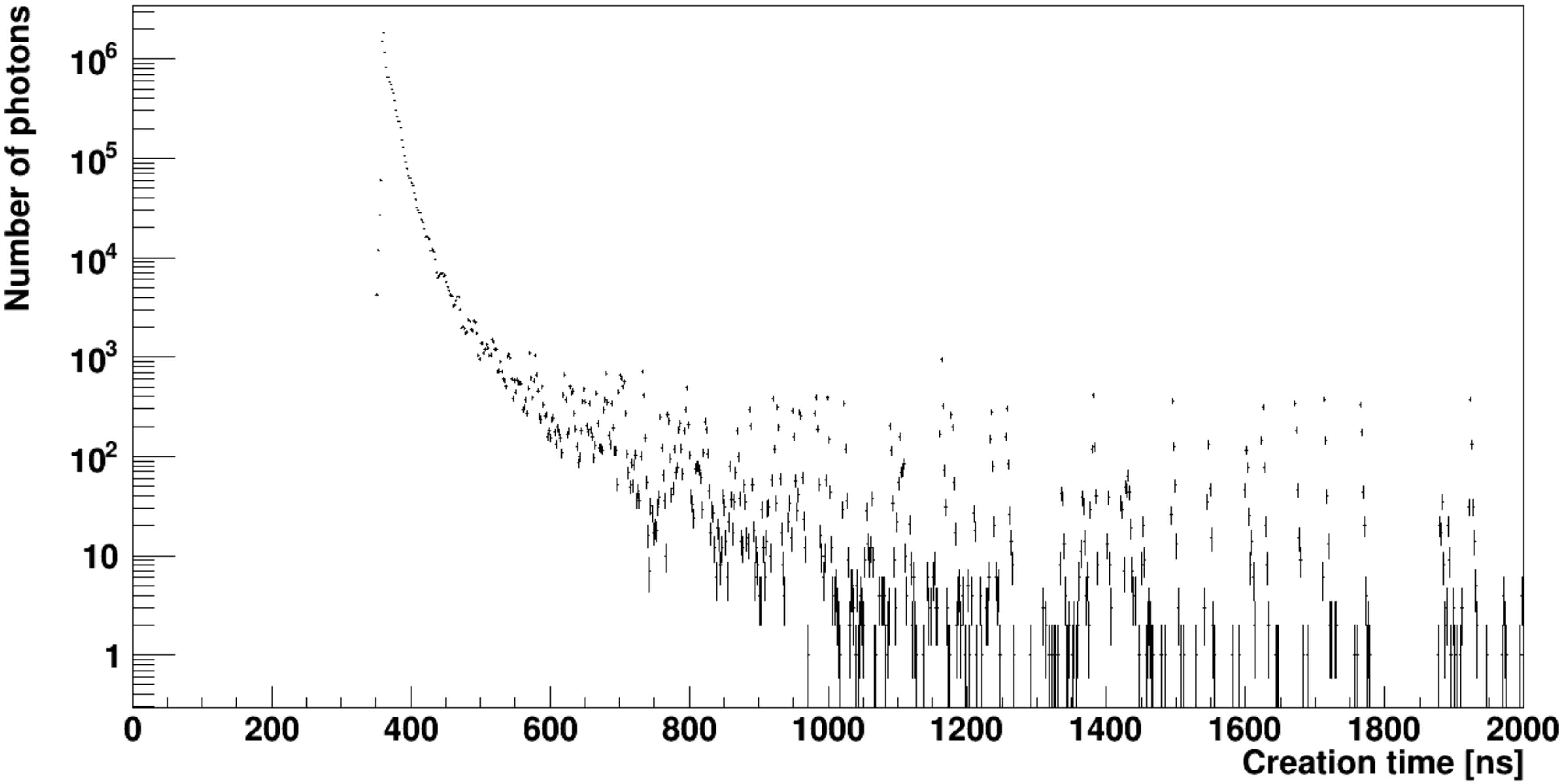
Efficiency calibration

Number of scintillation photons → Number of neutrons



Efficiency calibration

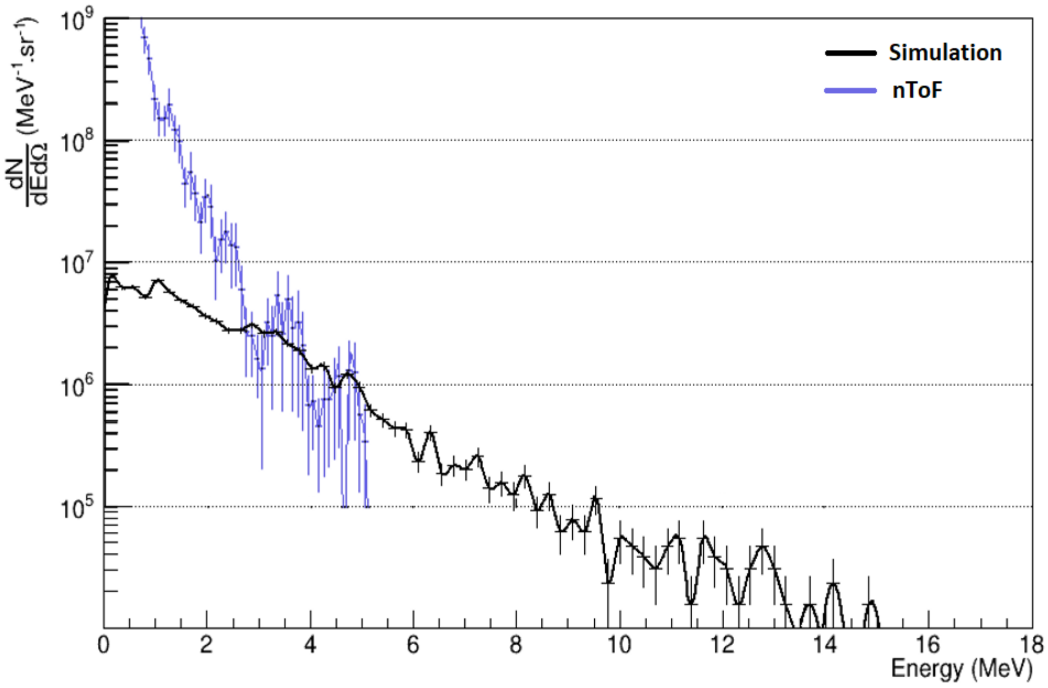
Simulations of scintillation signal with neutrons of different energies



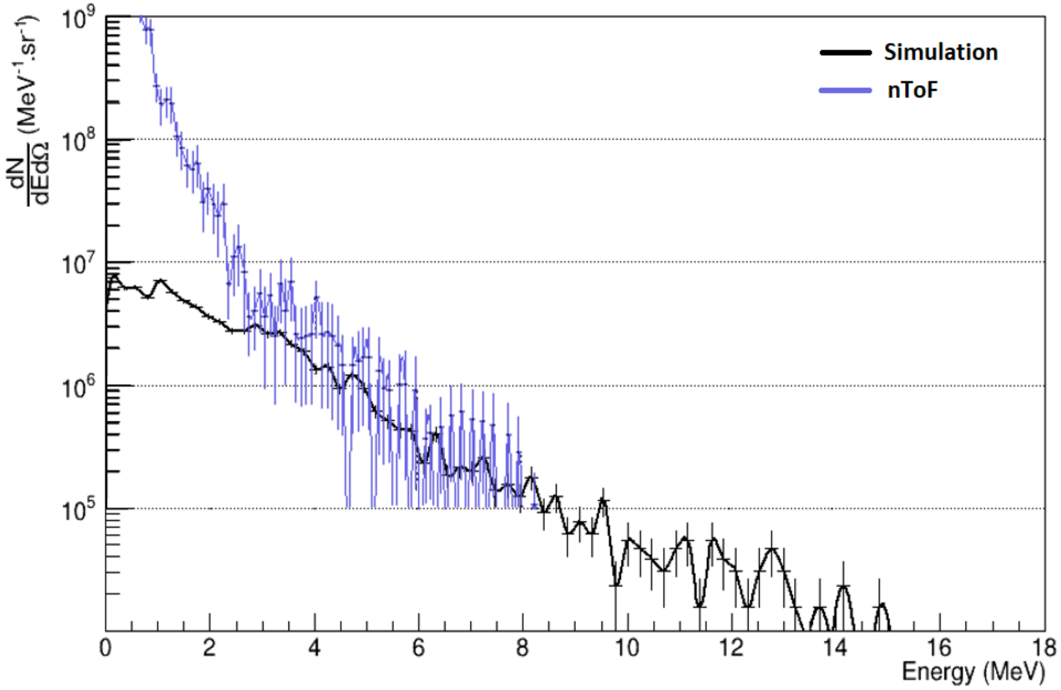
nToF spectrum

More high energy neutrons with DPM

without DPM (1.5µm Al)



with DPM (250nm Si)



Outline

APOLLON facility overview

Experimental rooms, beam characteristics

Laser-accelerated protons

Proton spectrometry via Thomson Parabola using CMOS sensors
Laser energy/protons transfer optimization (Double plasma mirror)

Neutron generation

Pitcher-catcher technique
Neutron production simulations

Neutron detection

Several diagnostics

Prospects and future developments

Laser energy increasing and improvement of neutron production

Future perspectives

3 PW shots: more protons and higher cutoff energy expected

→ improvement of neutron production yield

→ possibility to reach spallation reactions using high-Z material converters (like Pb)

More neutrons = better nToF signal, better precision on bubble detectors and more activation in the activation spectrometer.

10 PW shots → early 2024

Thank you for your attention

INSTITUT DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE