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Characterization of neutron emissions produced by ultra-intense lasers

Ronan Lelièvre

W. Yao, T. Waltenspiel, I. Cohen, D. Michaeli, I. Pomerantz, C. Gautier,
F. Trompier, Q. Ducasse, G. Boutoux, X. Davoine, A. Allaoua, J. Fuchs

Laboratoire pour l'Utilisation des Lasers Intenses (LULI - CNRS)
Laboratoire de micro-irradiation, de métrologie et de dosimétrie des neutrons (LMDN - IRSN)

Outline

Laser-driven neutron sources

Pitcher-catcher technique
Characteristics
Applications

Neutron production at Apollon

Characteristics
Setup & diagnostics
Results

Neutron production at PETAL

Setup & diagnostics
Results

Conclusions & prospects

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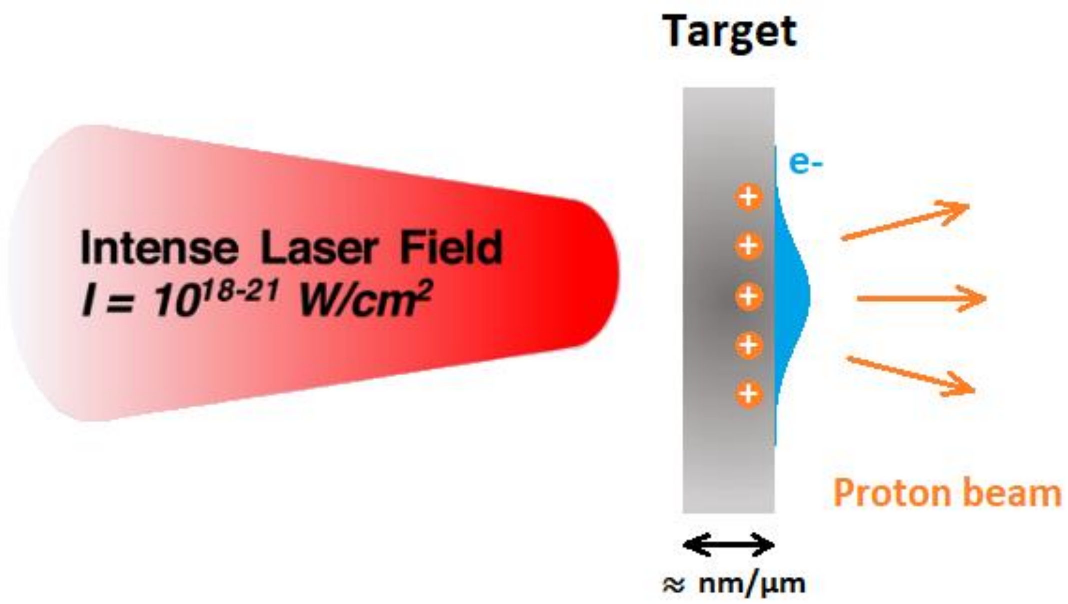
Pitcher-catcher technique

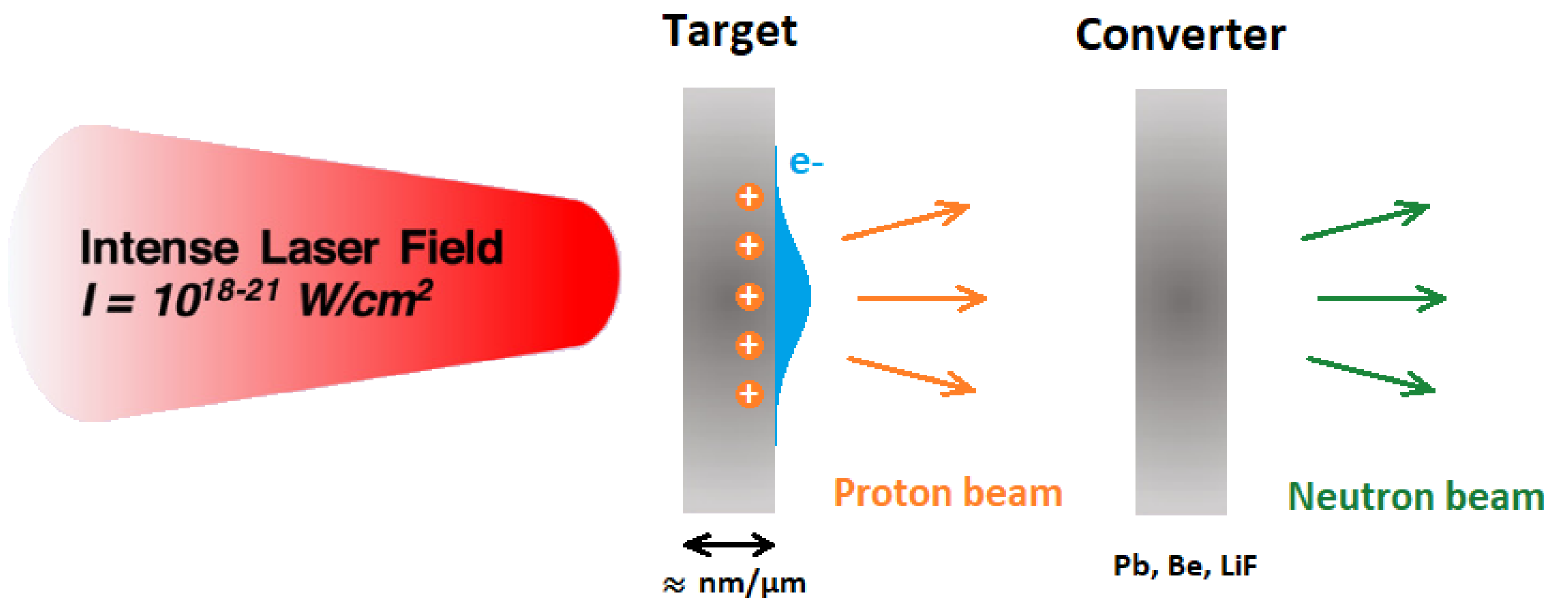
Neutron production from laser-induced proton beams



≈ 10s MeV

Pitcher-catcher technique

Neutron production from laser-induced proton beams



Characteristics

New neutron sources:

+ compact sources

- radiological constraints

Unique properties:

Fast neutrons (> MeV)

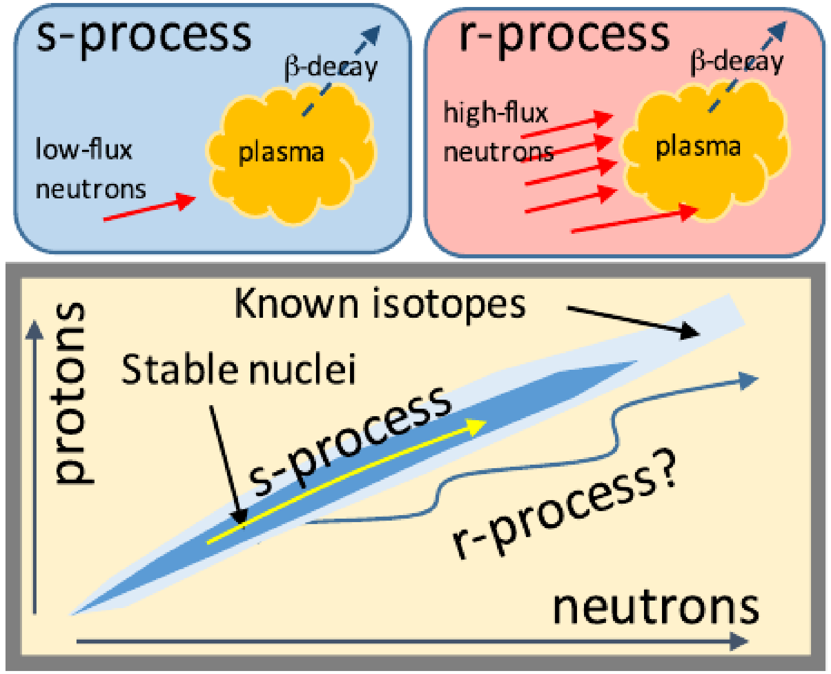
Short and intense emissions (< ns)

Facility	Peak neutron flux [$n/(cm^2\ s)$]	Average neutron flux [$n/(cm^2\ s)$]	Neutron bunch duration	
ILL (reactor-based)	$\sim 10^{15}$	$\sim 10^{15}$	(Continuous)	
SNS (accelerator-based)	$\sim 10^{16}$	$\sim 10^{12}$	$\sim 1\ \mu s$	
Present-day lasers	10^{18}–10^{19}	5×10^{5}–5×10^{6}	~ 1 ns	→ **APOLLON 2 PW**
Upcoming multi-PW lasers	10^{22}–5×10^{24}	10^{11}–5×10^{13}	~ 1 ns	→ **APOLLON 10 PW**

Applications

Astrophysics: r-process

→ Creation of heavy nuclei



s-process and β^--decay

$$ {}^{A}_{Z}X + {}^{1}_{0}n \rightarrow {}^{A+1}_{Z}X \rightarrow {}^{A+1}_{Z+1}Y + e^- + \bar{\nu}_e $$

s-process works only up to ^{209}Bi, because ^{210}Po undergoes α-decay

$$ ^{210}\mathrm{Po} \rightarrow {}^{206}\mathrm{Pb} + {}^{4}\alpha $$

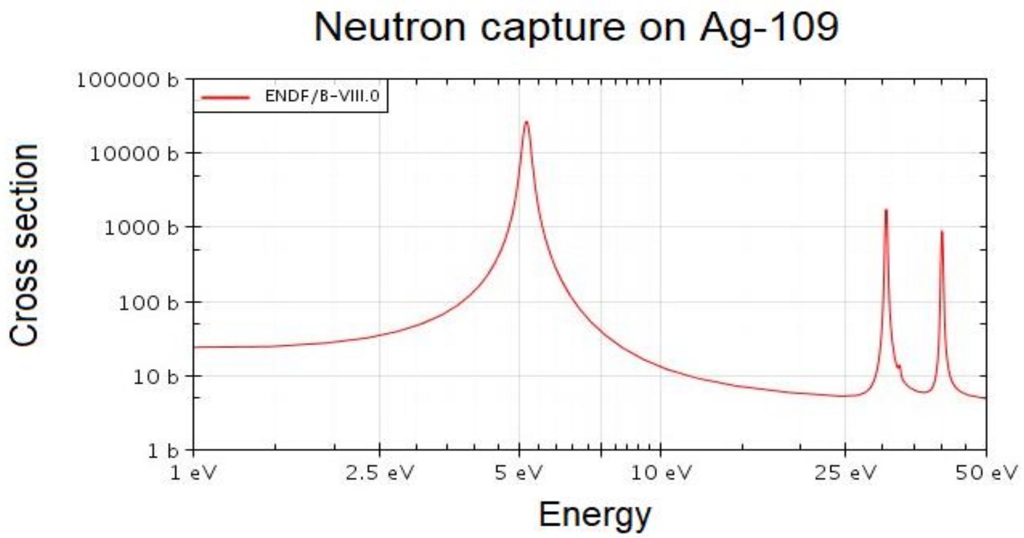
S. N. Chen et al., Matter Radiat. Extremes 4, 054402 (20)

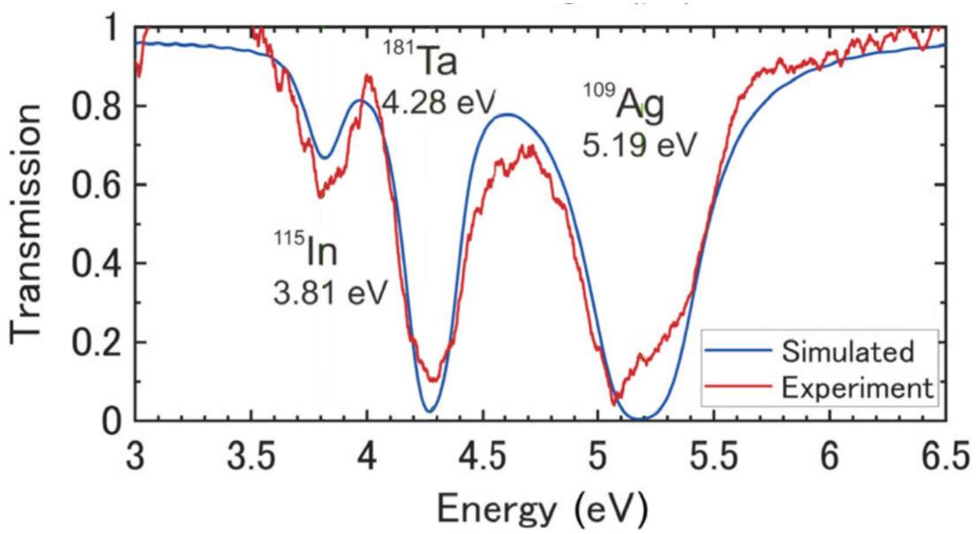
Applications

Neutron Resonance Spectroscopy (NRS)

→ Non-destructive material analysis

→ Shock temperature measurements





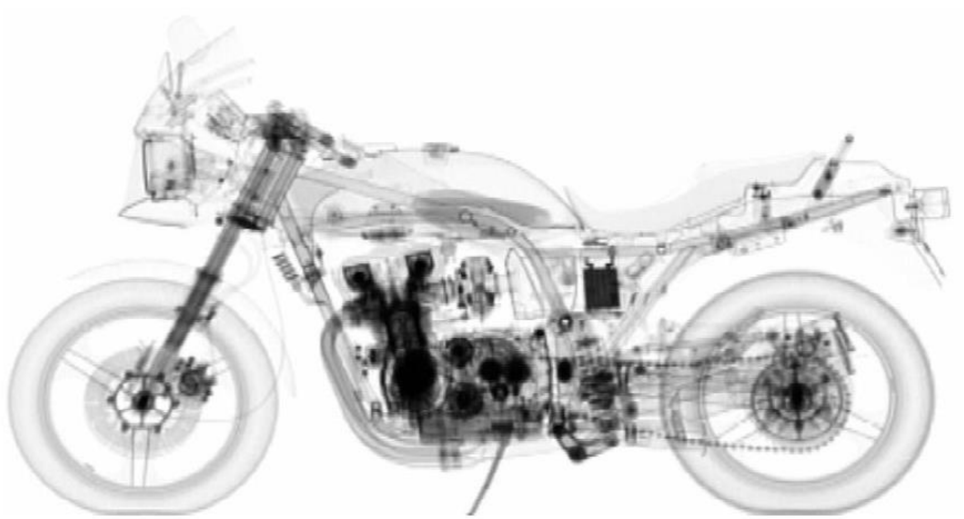
A. Yogo et al., Phys. Rev. X 13, 011011 (2023)

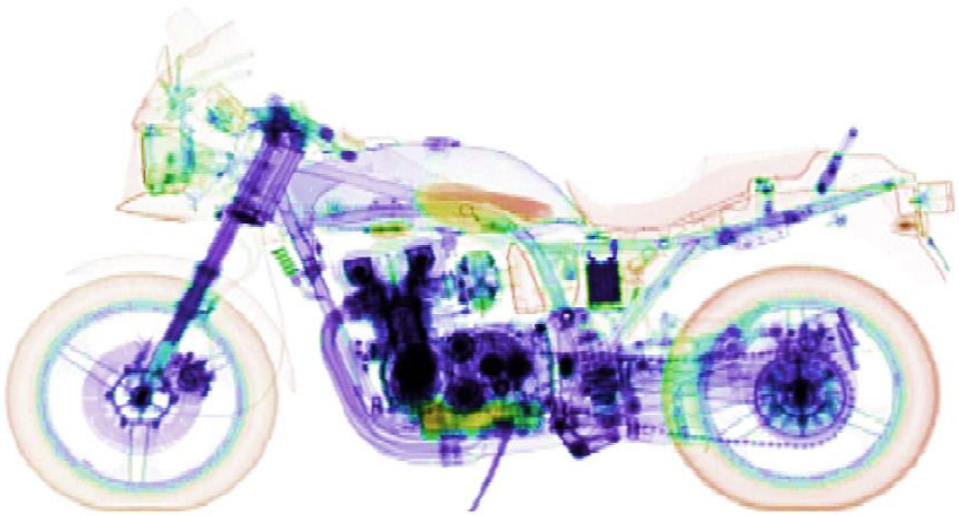
Applications

Neutron radiography / Dual radiography

→ Container inspection (explosives, narcotics, …)

→ Archaeological objects





J. Eberhardt et al., Non-intrusive Inspection Technologies 6213, 621303 (2006)

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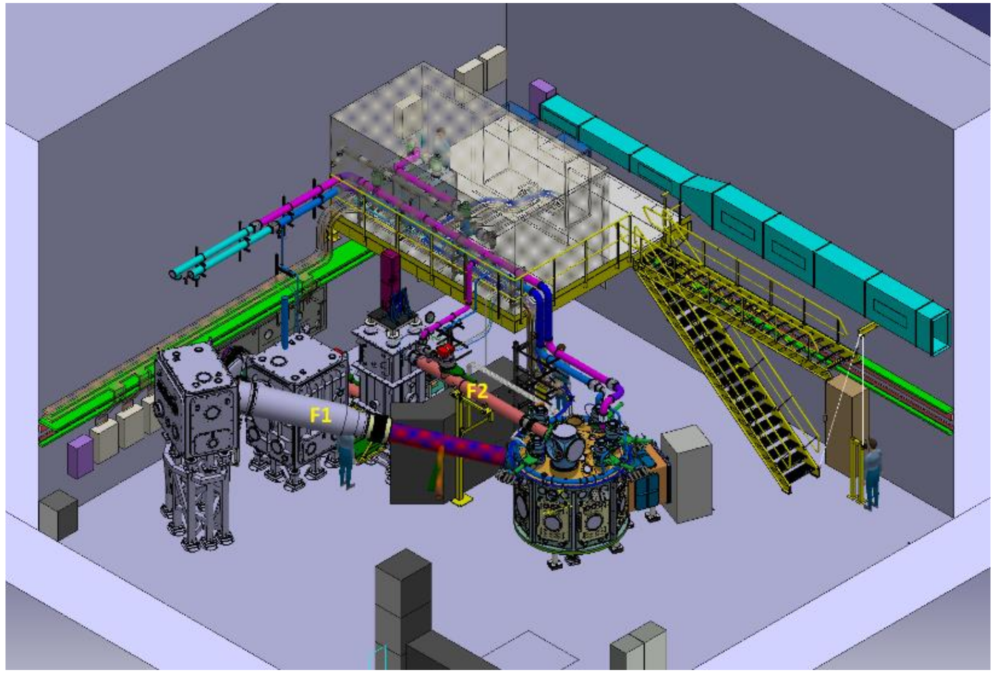
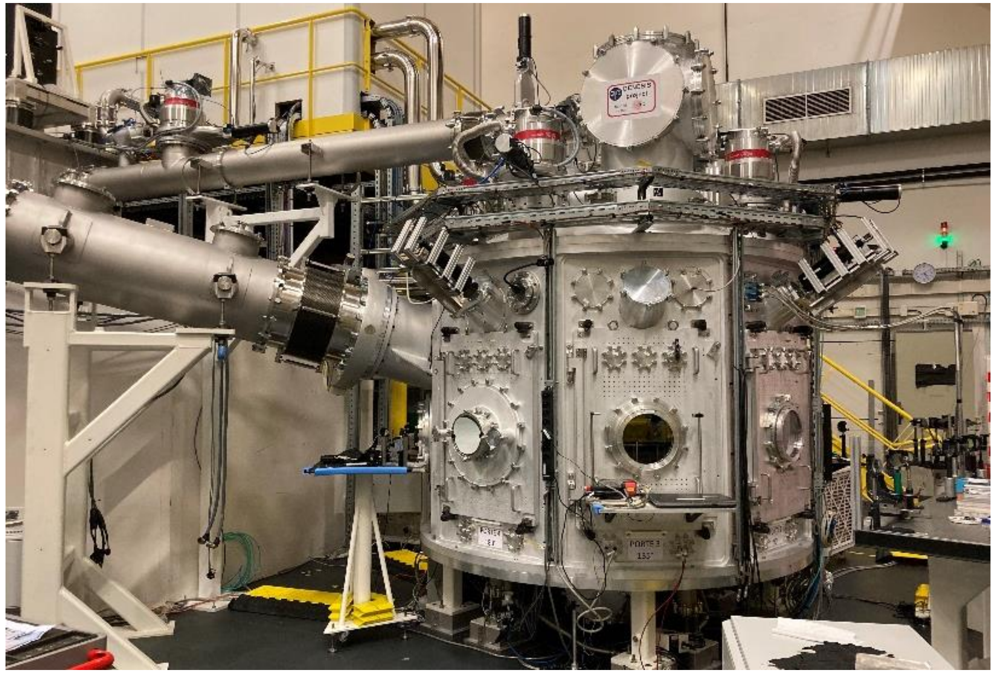
Apollon laser

	Focal spot	*Intensity*
Main beam F1 (42 J, 22 fs ⟶ ≈ 2 PW) ⟶	2.3×2.5 µm	≈ 1.10^{22} W/cm²
Secondary beam F2 (11 J, 24 fs ⟶ ≈ 0.5 PW) ⟶	2.8×3.7 µm	≈ 2.10^{21} W/cm²





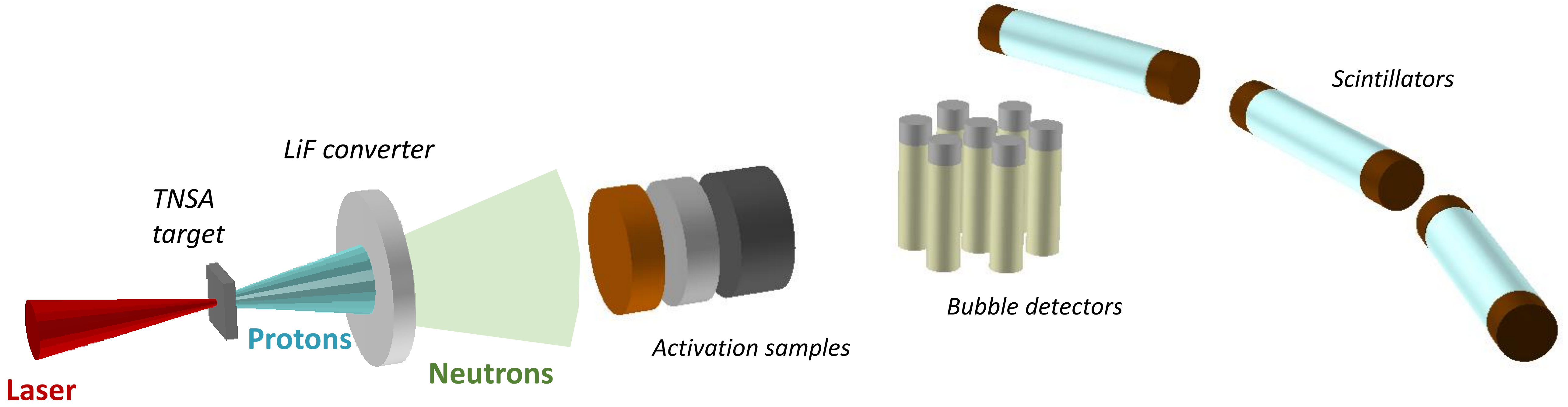
Diagnostics

3 types of detectors:

→ Activation samples

→ Bubble detectors

→ Scintillators (Time-of-Flight detectors)



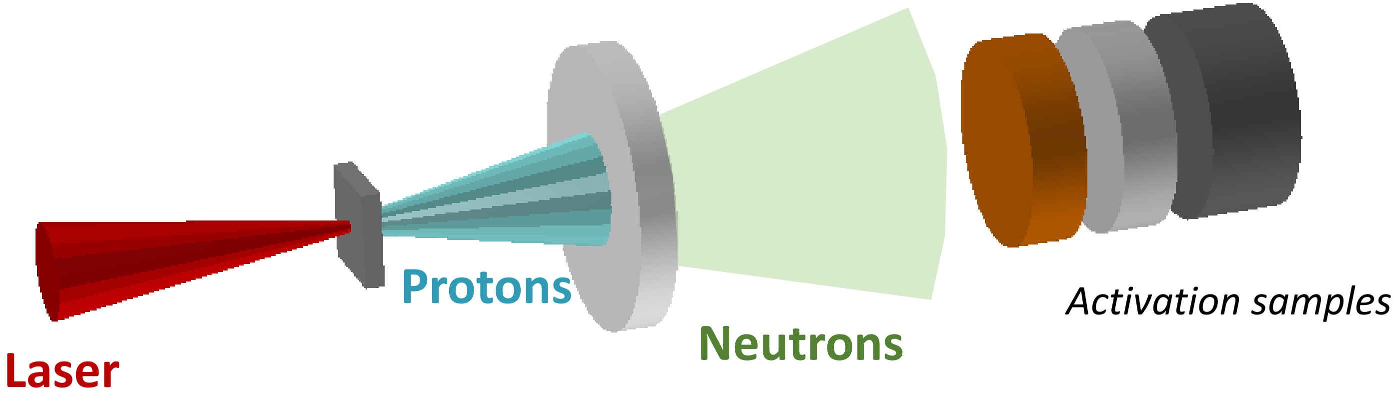
Activation samples

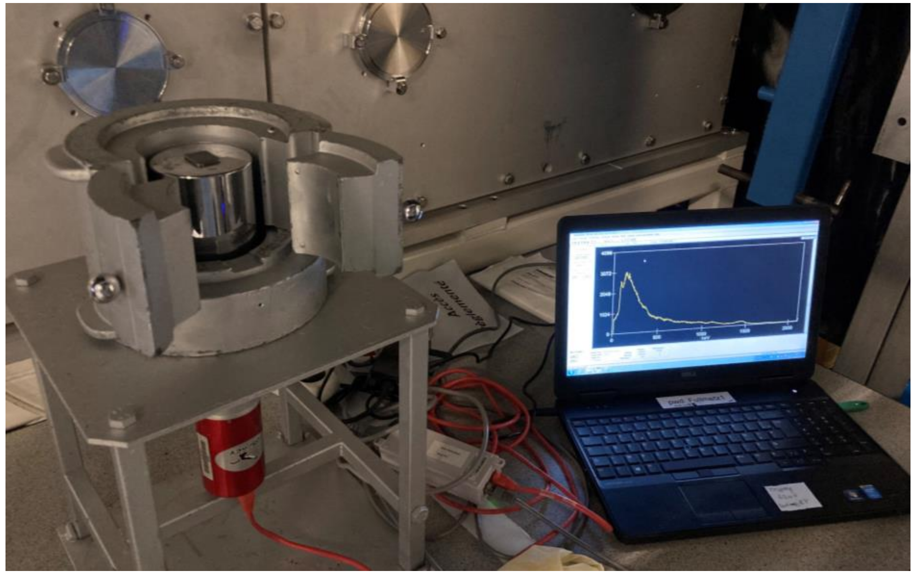
Neutron-induced reactions in different materials

→ Production of radionuclides

→ Measured by gamma spectrometry: quantity of radionuclides

→ Considering cross sections: Information about neutron energy distribution





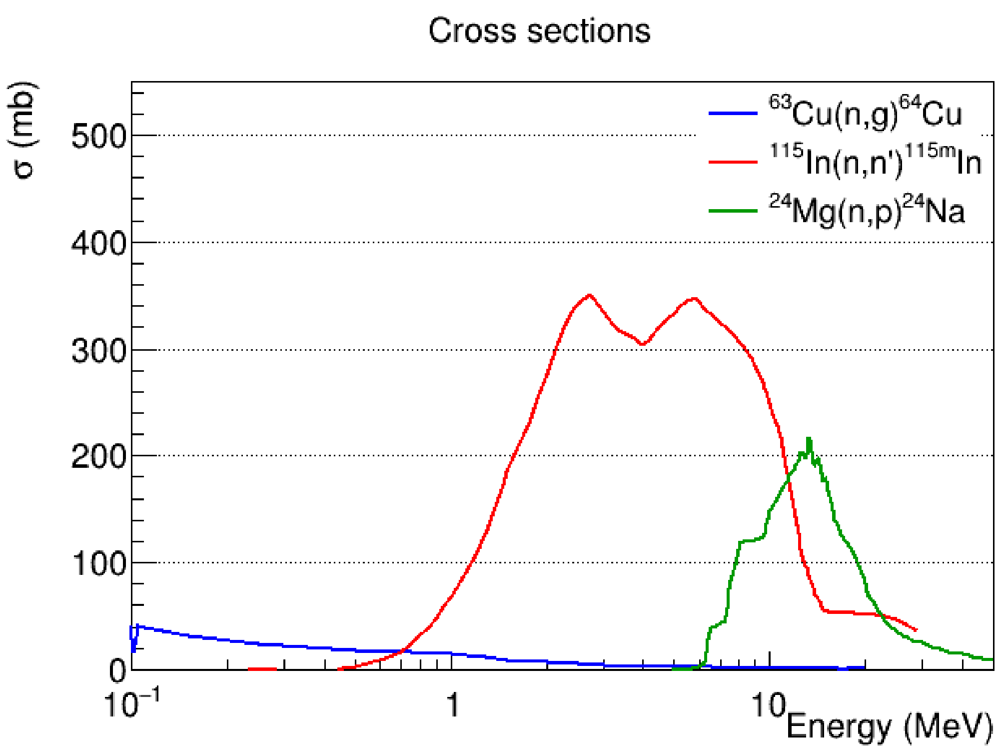
Activation samples

Several criteria for diagnostic design:

⟶ Reactions with interesting cross-sections, spanning different energy ranges

⟶ Radionuclides with high intensity gamma-ray emissions

⟶ Half-lives



Activation samples

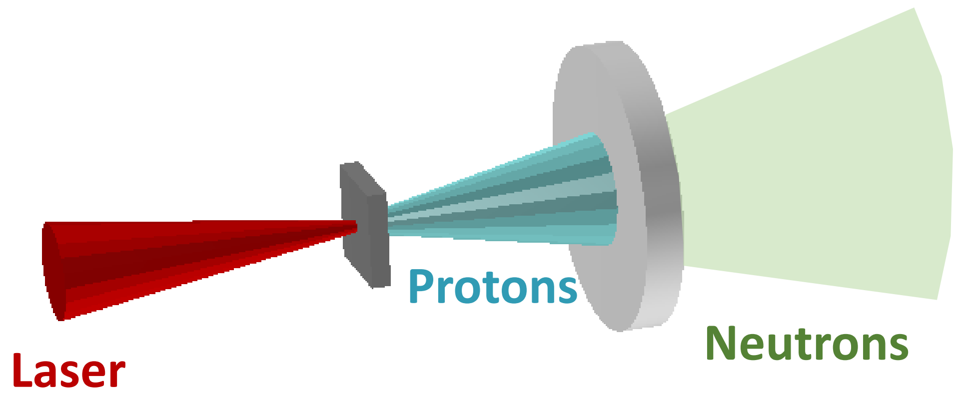
Results

Material	Reaction	Sensibility range	$A_{mes.}$/shot (Bq)	
			F2 experiment	F1 experiment
LiF	$^{7}Li(p,n)^{7}Be$	-	5.53 ± 0.3	47.4 ± 3.0

≈ 3.142×10^{8} neutrons/shot

x 8.6

≈ 3.670×10^{7} neutrons/shot



Activation samples

Results

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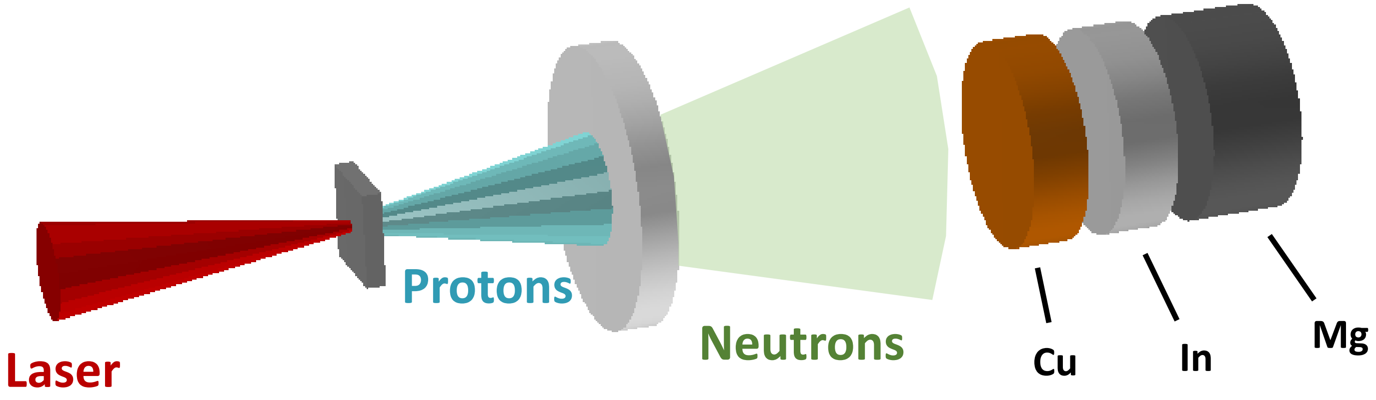
			F2 experiment	F1 experiment
LiF	$^{7}Li(p,n)^{7}Be$	-	5.53 ± 0.3	47.4 ± 3.0
Cu	$^{63}Cu(n,g)^{64}Cu$	[0 - <1 MeV]	17.6 ± 1.2	35.81 ± 2.15
In	$^{115}In(n,n')^{115m}In$	[2 - 10 MeV]	0.93 ± 0.13	6.36 ± 0.45
Mg	$^{24}Mg(n,p)^{24}Na$	[6 - 25 MeV]	0	0.99 ± 0.05

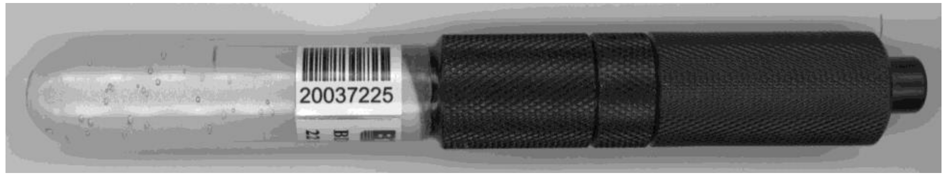
≈ 1.750×10^{7} neutrons/sr/shot

x 10.4

≈ 1.689×10^{6} neutrons/sr/shot



Bubble detectors



Dosimeter

[100 keV – 20 MeV]

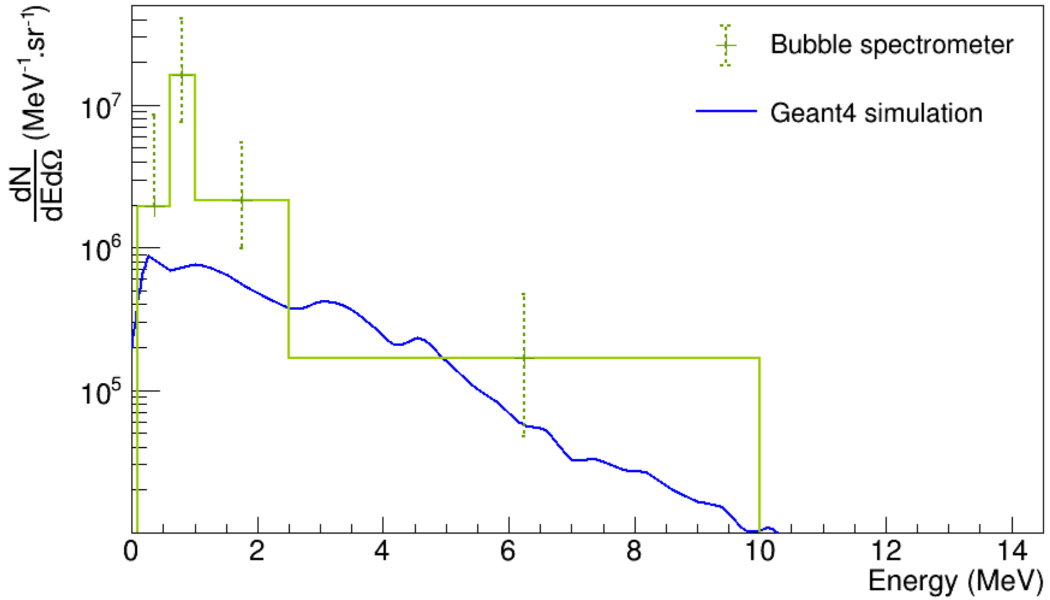
Spectometer

[10 keV – 20 MeV]

F2 experiment: **4.373x10⁶ neutrons/sr/shot**

F1 experiment: **4.703x10⁷ neutrons/sr/shot**

x 10.8



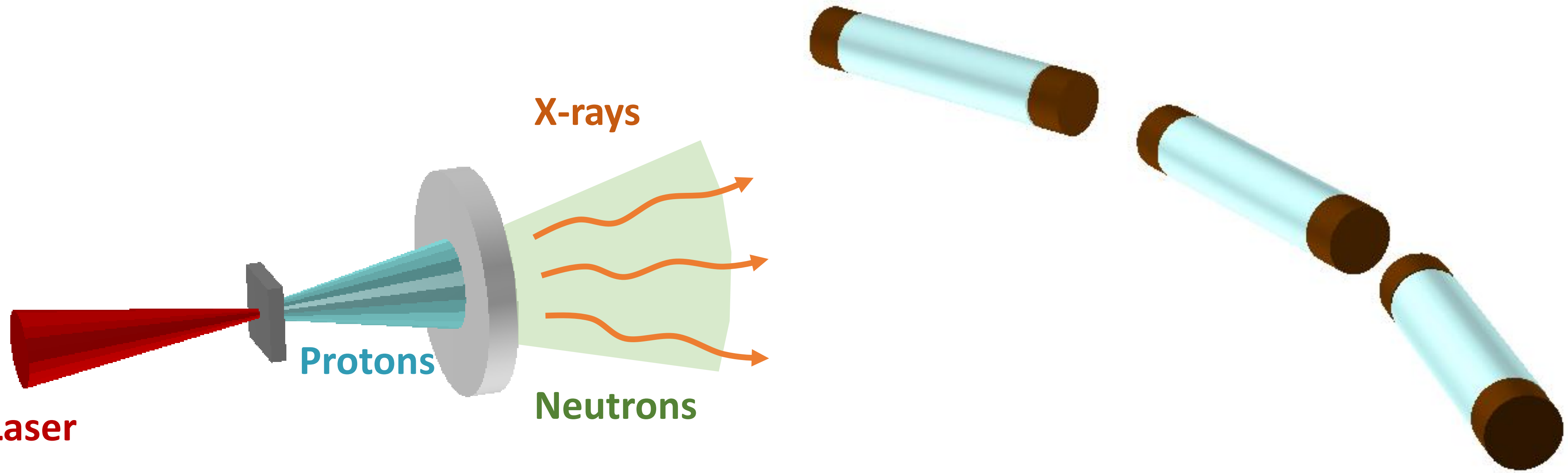
Scintillators

→ Ultra-fast organic scintillators

EJ-254: 1” diameter and 40cm long

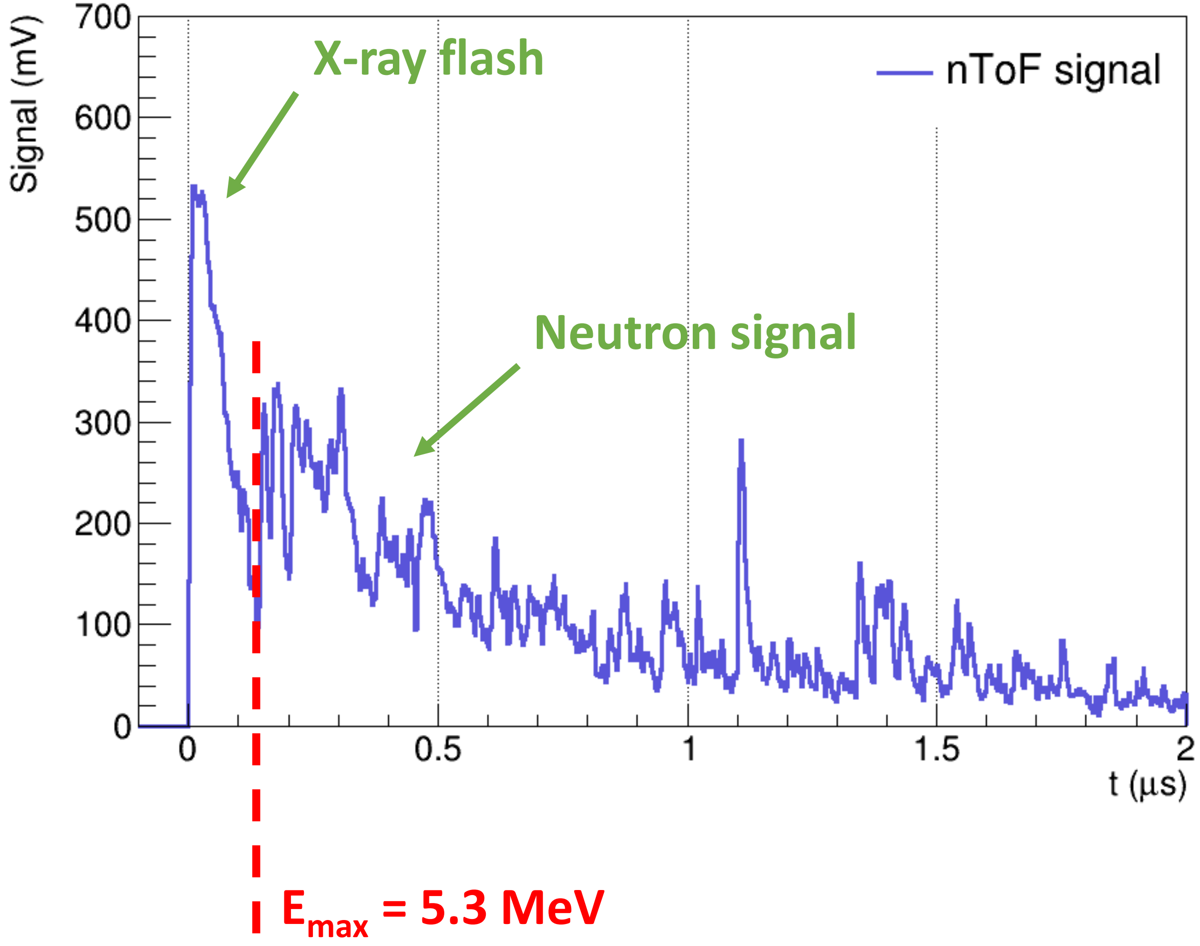
1 PMT on each side

→ neutron Time-of-Flight (nToF) technique

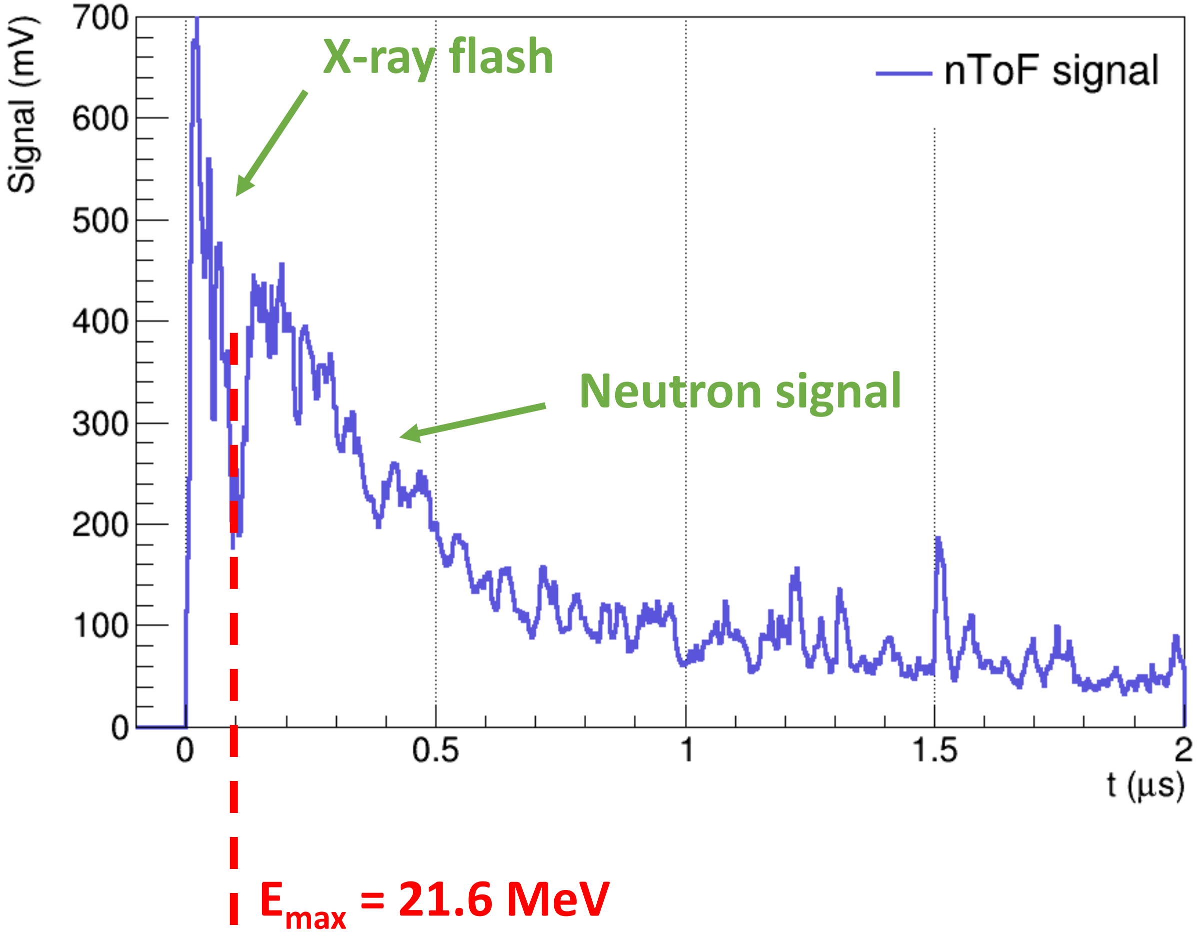


Time-of-Flight detectors

F2 experiment (11 J, 24 fs ⟶ ≈ 0.5 PW)



F1 experiment (42 J, 22 fs ⟶ ≈ 2 PW)



Double Plasma Mirror *(DPM)*

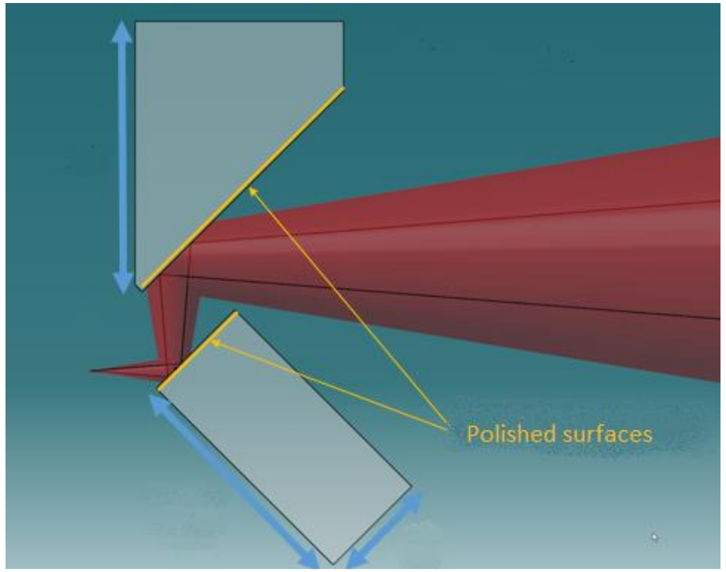
Laser contrast enhancement (F2 beam) inducing:

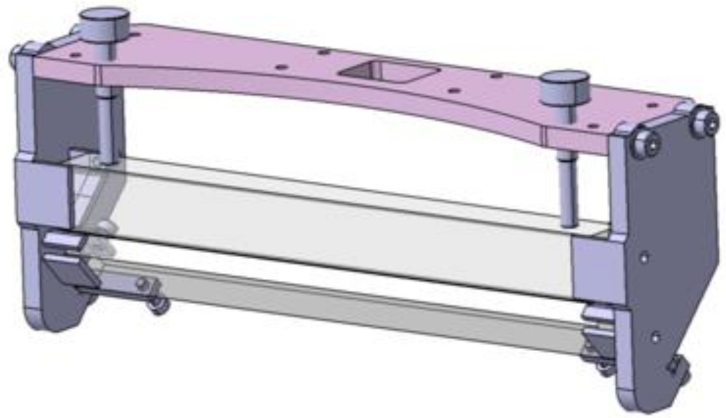
⟶ less on-target energy *(52% reflectivity)*

⟶ better laser/target interaction

⟶ possibility to shoot on thinner targets *(from few µm to tens of nm)*

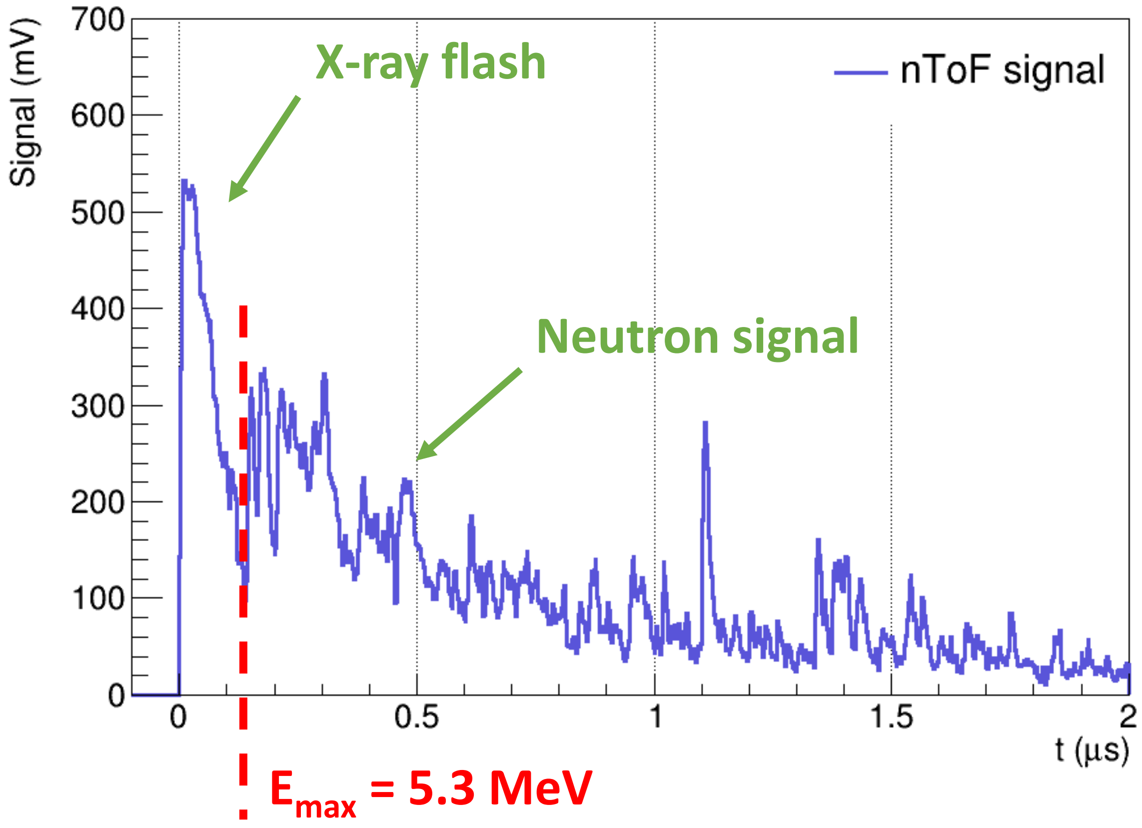
⟶ better proton cutoff energies *(from 25 to 36 MeV)*



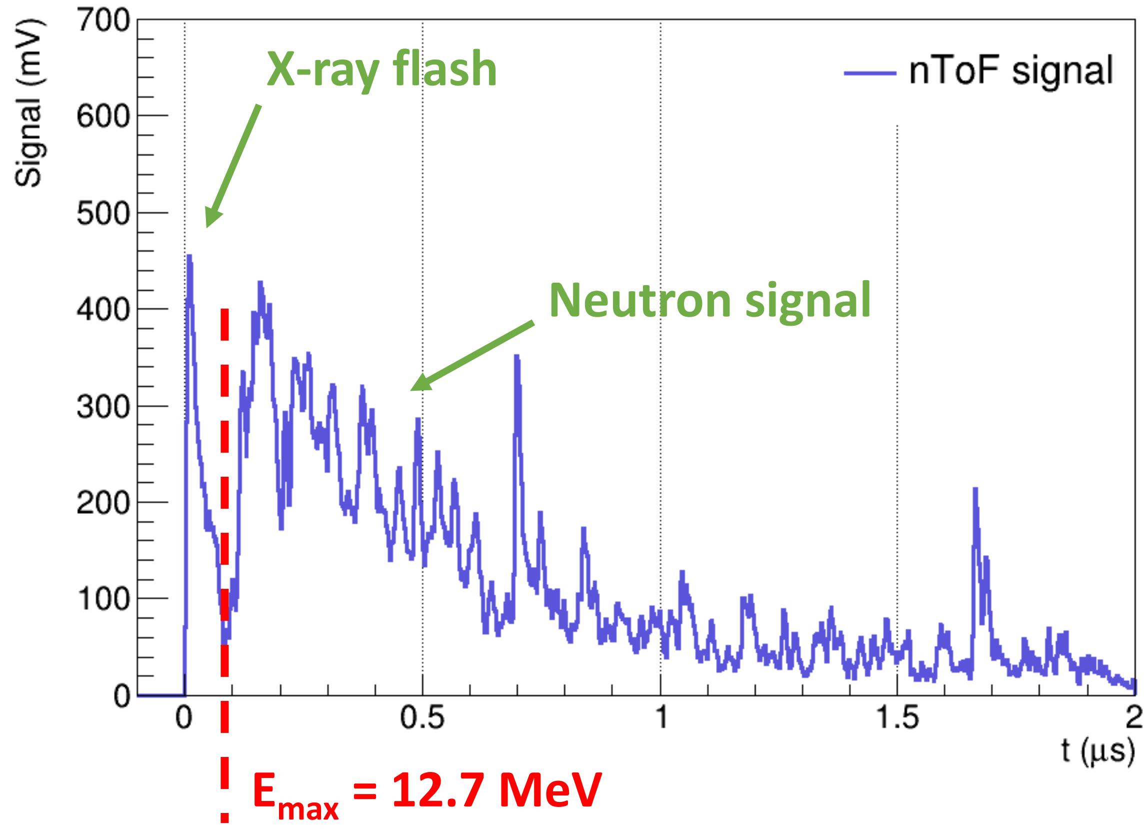


Time-of-Flight detectors

F2 experiment without DPM



F2 experiment with DPM



→ Less X-ray emissions with DPM

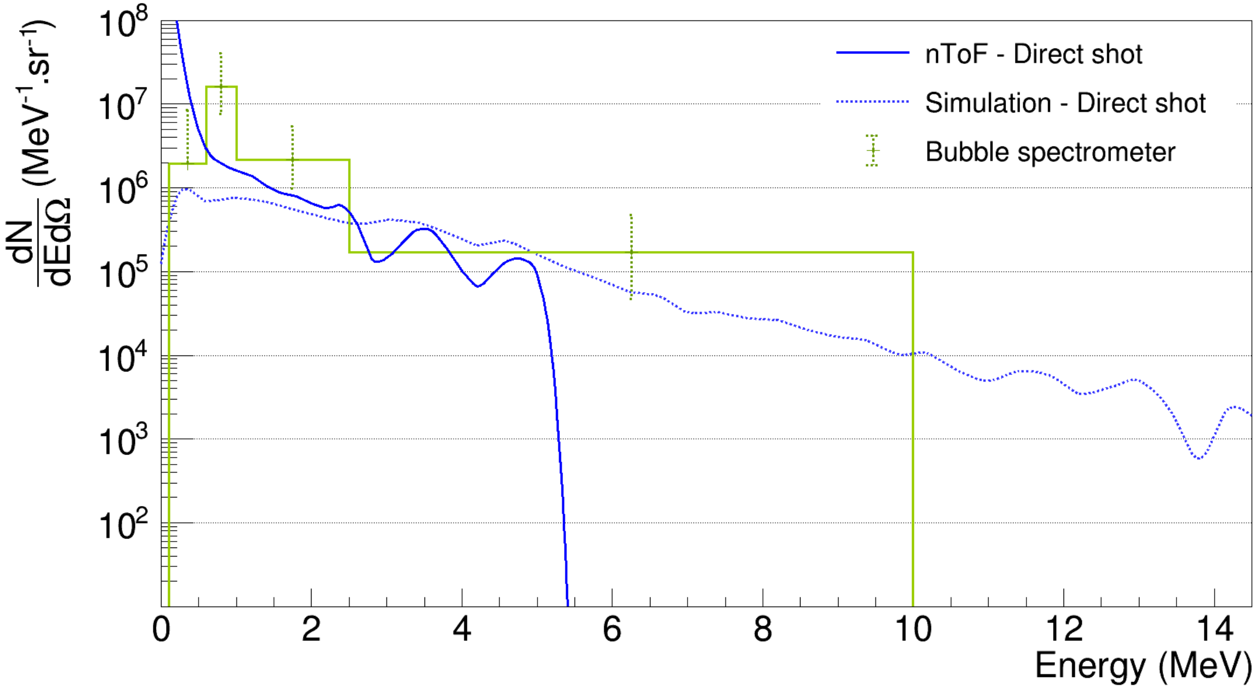
→ Similar neutron emissions

→ Better neutron cutoff energy

Neutron spectra

Deconvolution procedure using Geant4 simulations

F2 experiment without DPM



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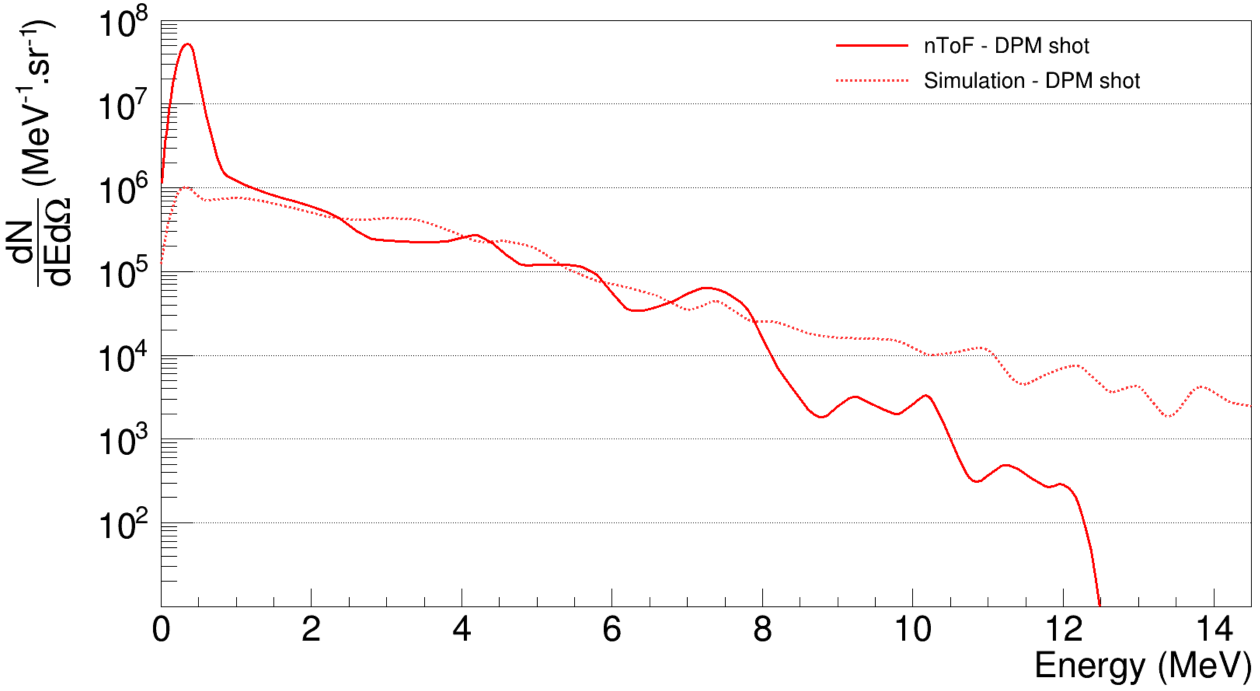

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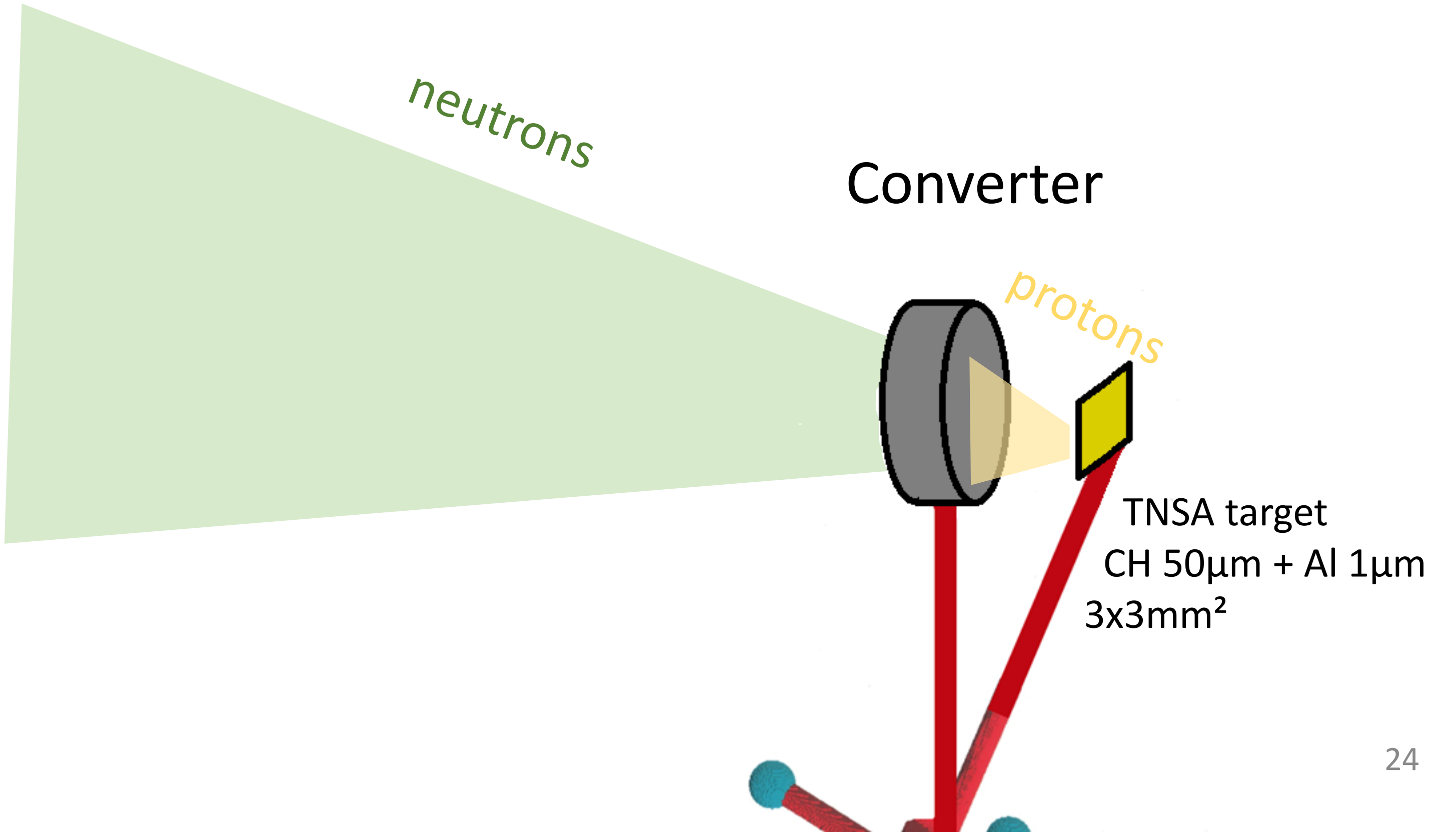
PETAL *(350J, 0,6-1 ps)*

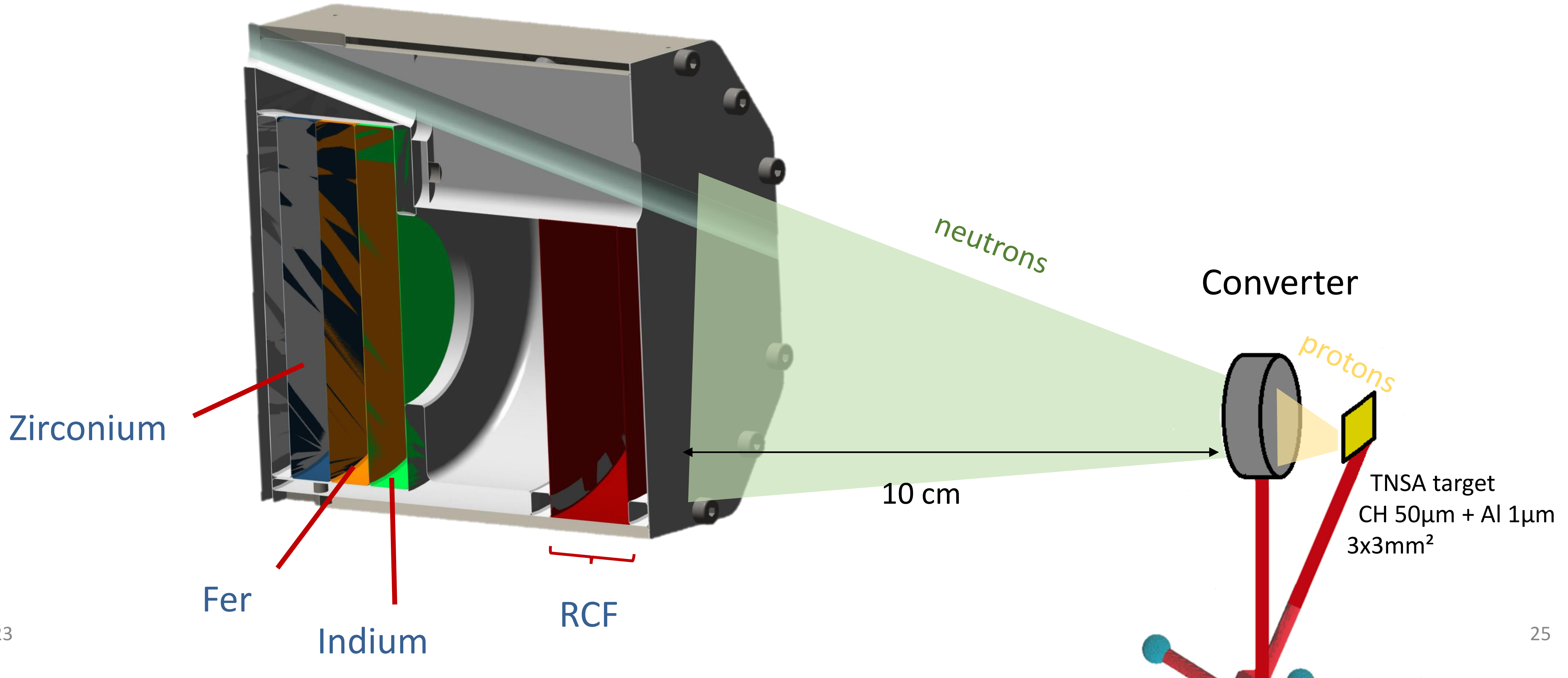
Production and characterization of neutron emissions

Different converters (LiF, Pb, LiF + Pb)



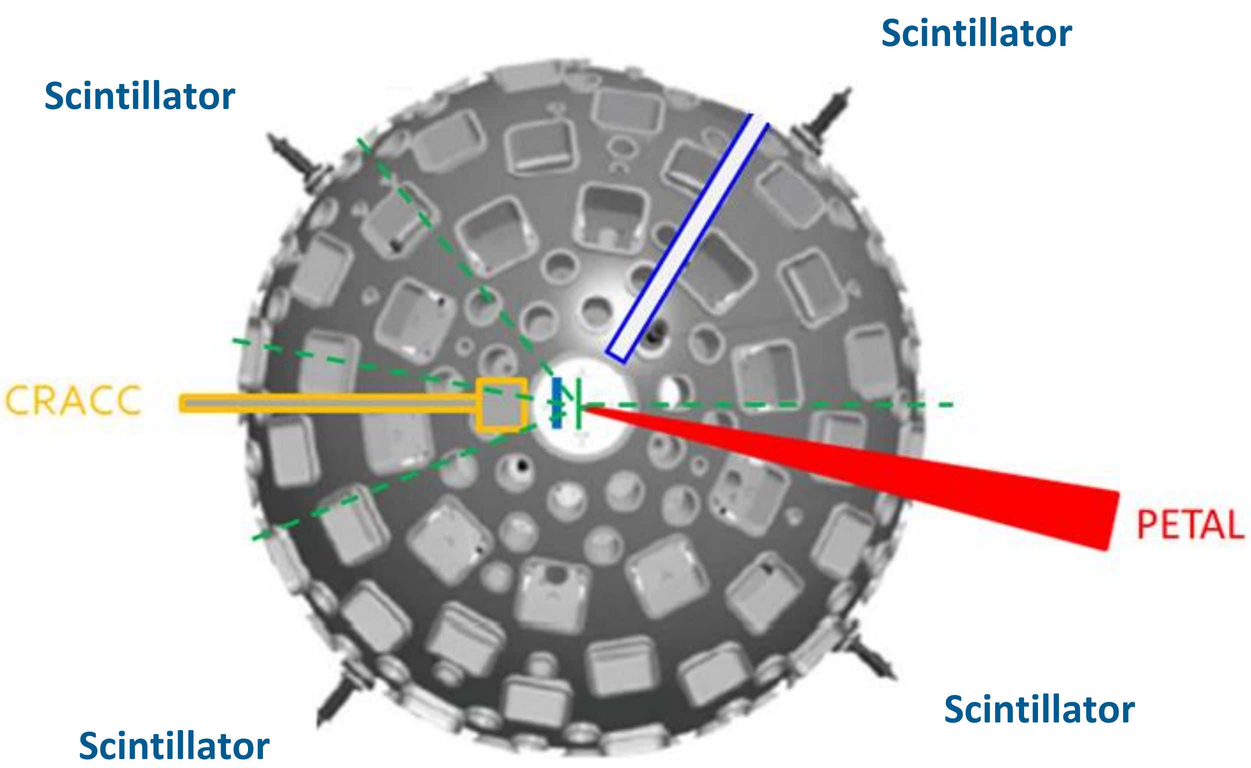
Diagnostics

Activation samples



Diagnostics

4 scintillators on the equatorial plan + 2 scintillators on the near-polar axis



Top view

Side view

Activation samples

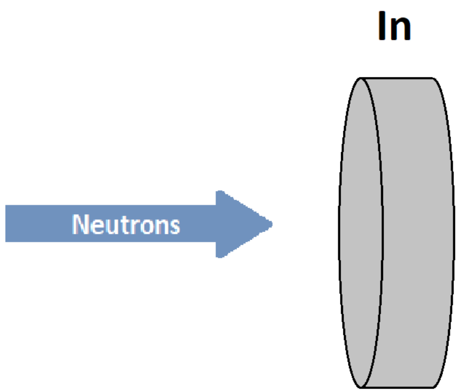
Results: 4 shots

Proton cutoff energies from 32 to 47 MeV

Material	Reaction	Sensibility range	$A_{mes.}$/shot (Bq)			
			Shot #1 - Pb	Shot #2 - LiF	Shot #3 – LiF+Pb	Shot #4 – LiF+Pb
In	$^{115}In(n,n')^{115m}In$	[2 - 10 MeV]	5.23 ± 0.22	38.71 ± 0.39	48.05 ± 0.43	75.60 ± 0.53
Fe	$^{56}Fe(n,p)^{56}Mn$	[6 - 25 MeV]				
Zr	$^{90}Zr(n,2n)^{89}Zr$	[12 - 35 MeV]				

≈ 6,8x10^{8} neutrons/sr

Simulation ≈ 1,4x10^{9} neutrons/sr



Activation samples

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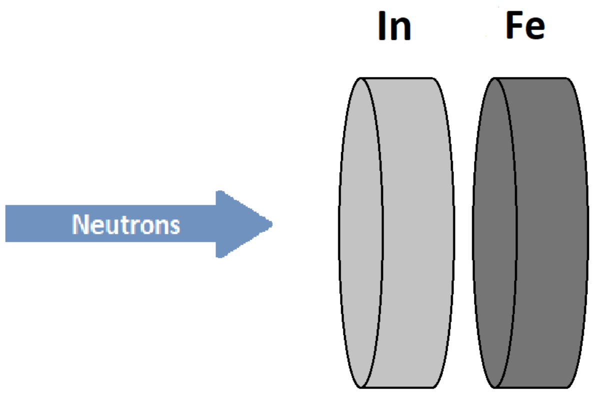
Fe	$^{56}Fe(n,p)^{56}Mn$	[6 - 25 MeV]	0	1.30 ± 0.35	3.12 ± 0.9	6.54 ± 0.48
Zr	$^{90}Zr(n,2n)^{89}Zr$	[12 - 35 MeV]				



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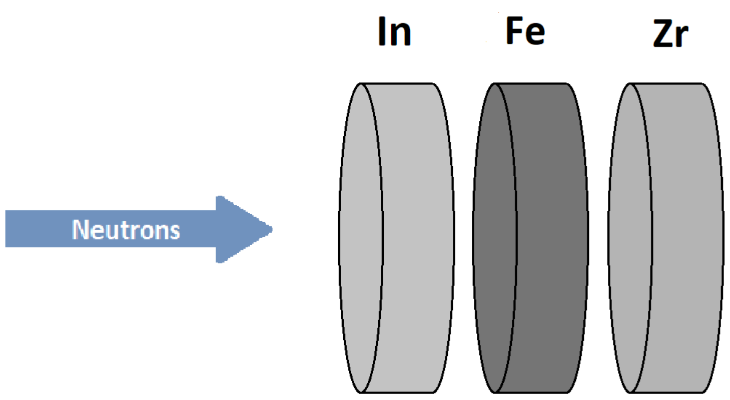
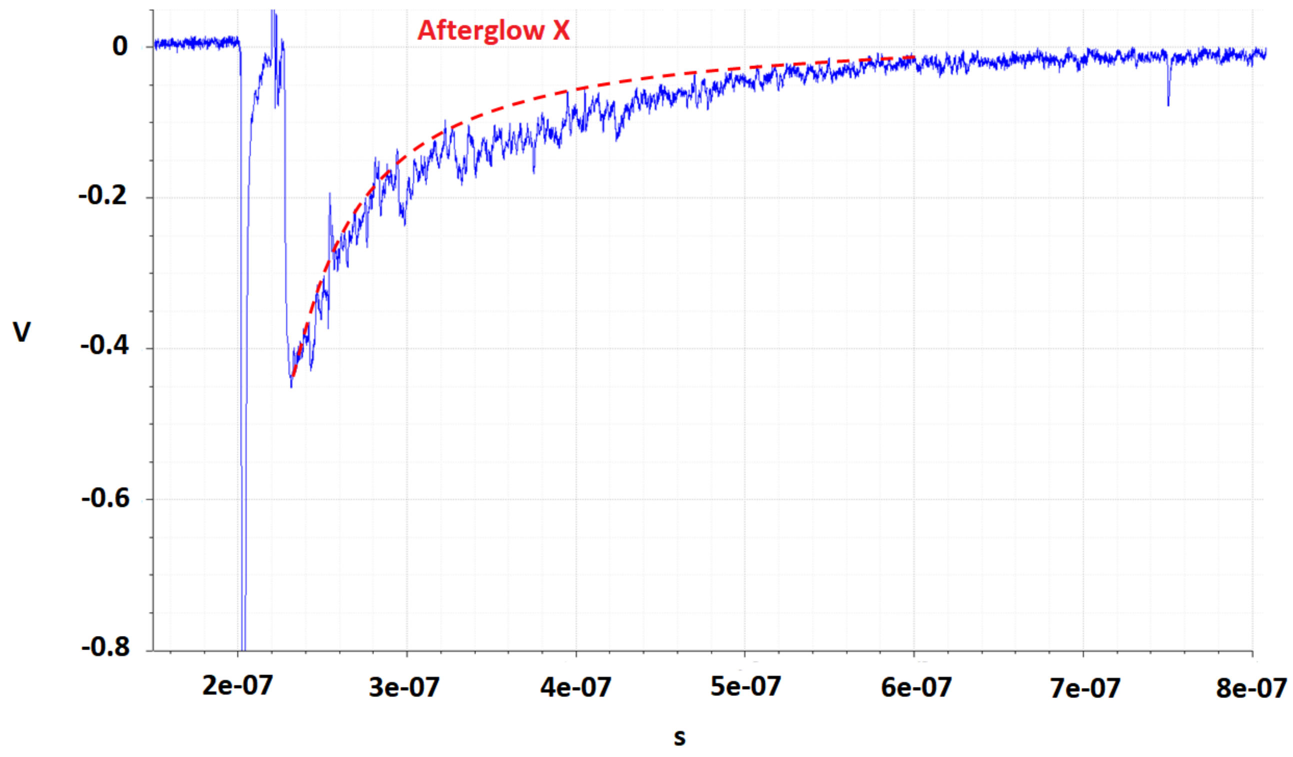
Zr	$^{90}Zr(n,2n)^{89}Zr$	[12 - 35 MeV]	0.60 ± 0.08	0	1.46 ± 0.12	6.01 ± 0.19



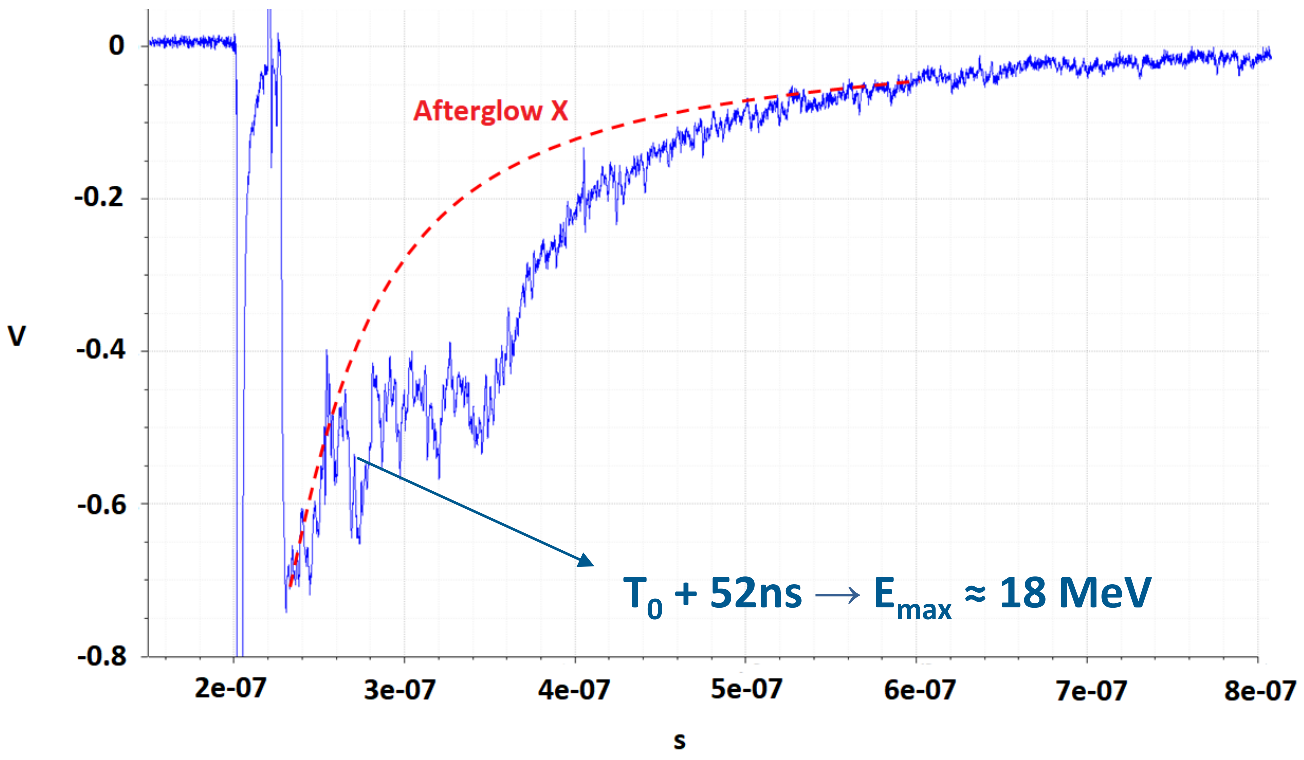
Time-of-Flight detectors

Scintillator 448 (placed behind the converter, 45deg from the normal axis)

Tir 1 – convertisseur Pb



Tir 3 – convertisseur hybride LiF+Pb



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Apollon experiments

⟶ First quantitative measurements

F2: 3.7×10^7 n/shot, 4.4×10^6 n/sr/shot at 0°

F1: 3.1×10^8 n/shot, 4.7×10^7 n/sr/shot at 0°

⟶ Neutron emissions $\propto E_{laser}^{1.5}$

⟶ Good agreement between experimental and simulation results

⟶ Possibility to adjust the neutron/X-ray ratio with the DPM

PETAL experiment

⟶ First measurements of neutrons produced by the pitcher-catcher technique

~ 8×10^9 n/shot, 6.8×10^8 n/sr/shot at 0°

⟶ Demonstration of the interest of hybrid converters

Prospects

$\longrightarrow$ Increasement of laser energy:

Possibility to reach the spallation regime using high-Z converters

Enhancement of neutron production (possible applications ??)

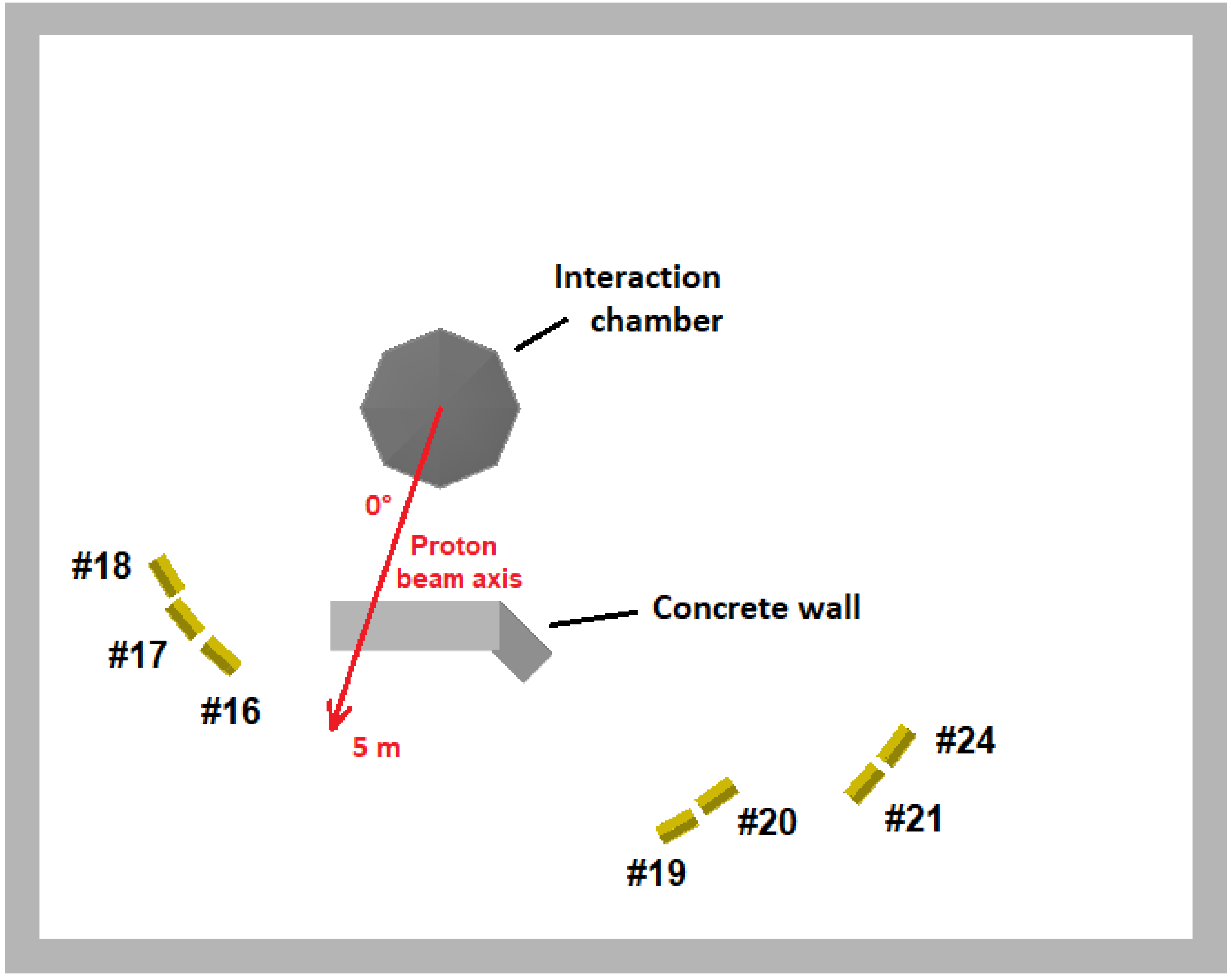
$\longrightarrow$ Optimization of neutron production using different converters

$\longrightarrow$ Investigation of X-ray emission mechanisms to optimize the neutron/X-ray ratio

$\longrightarrow$ Development of an activation spectrometer

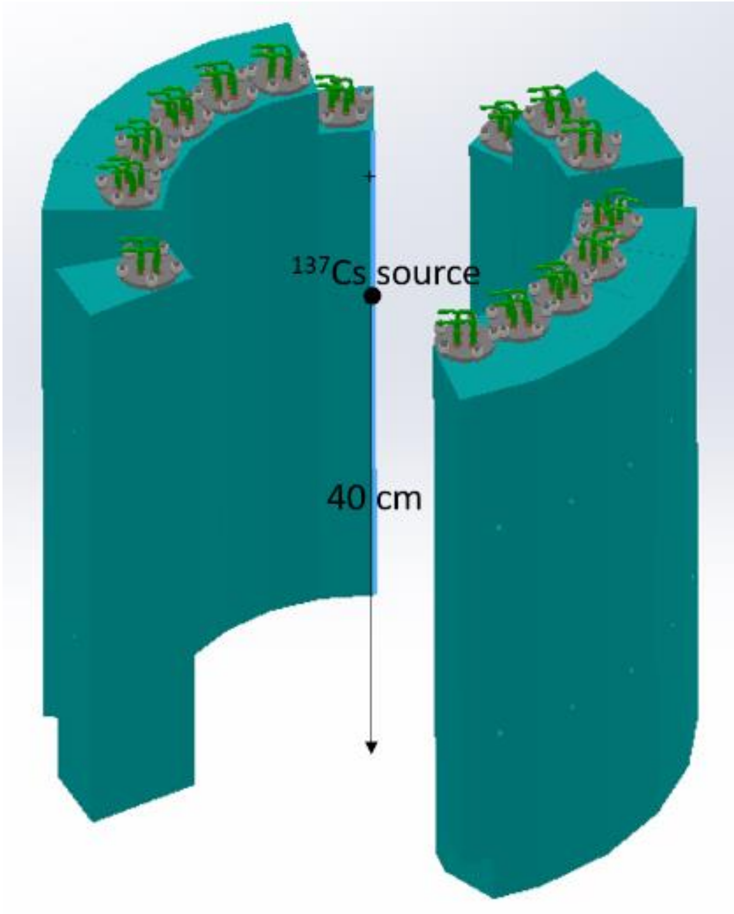
Thank you for your attention

Time-of-Flight detectors



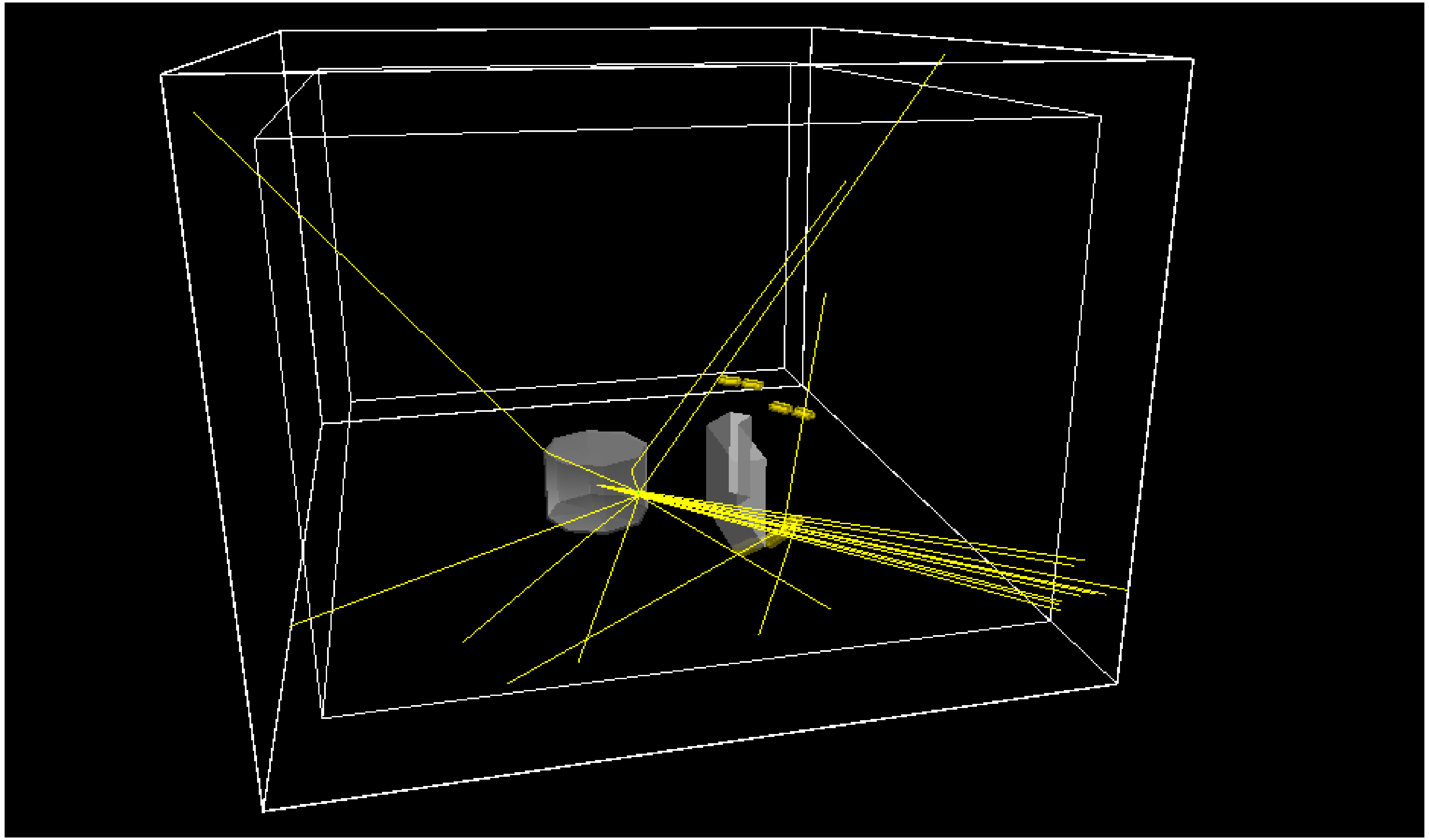
Energy calibration

mV/pC signal → number of scintillation photons



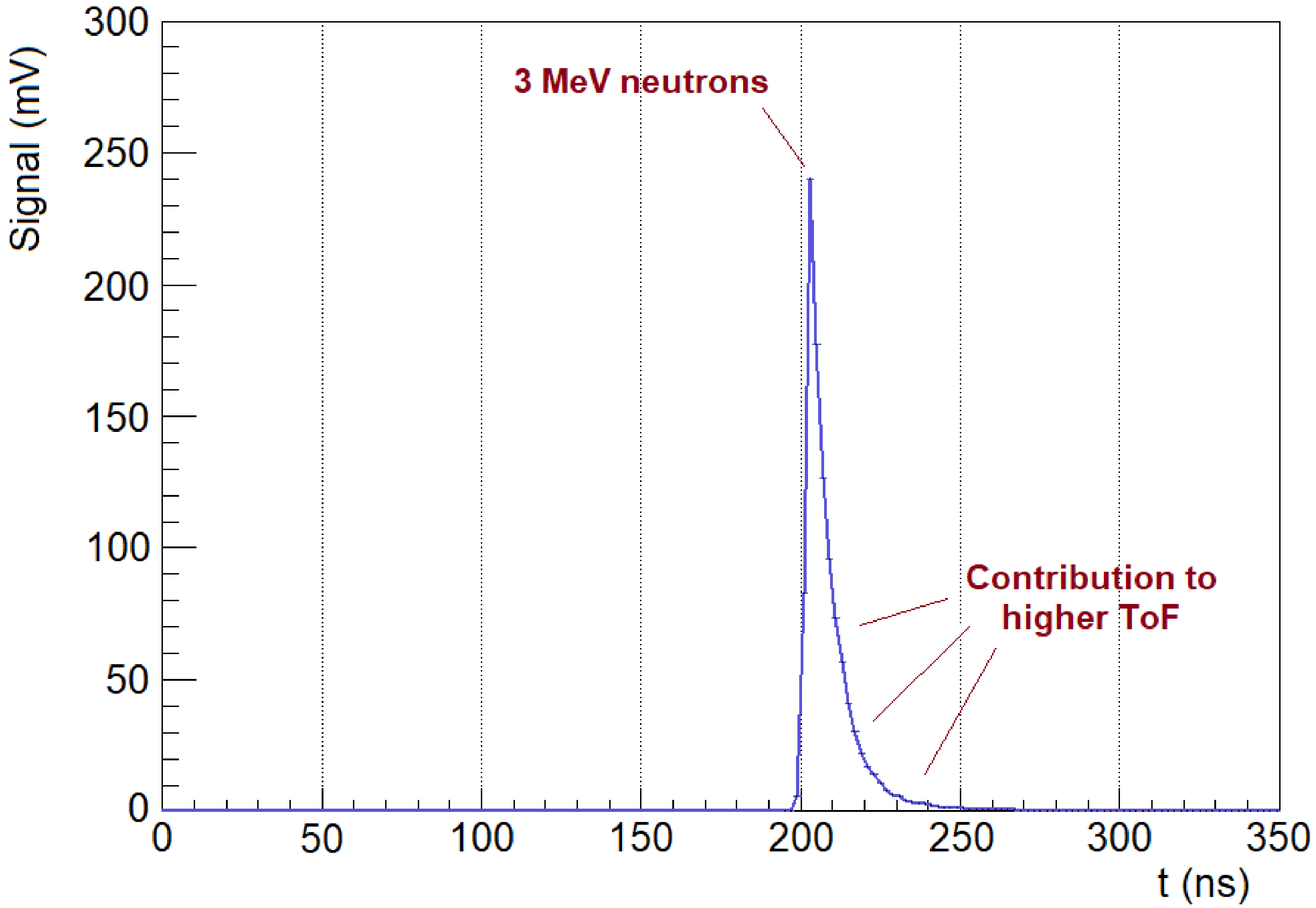
Efficiency calibration

Number of scintillation photons ⟶ Number of neutrons *(Geant4 simulations)*



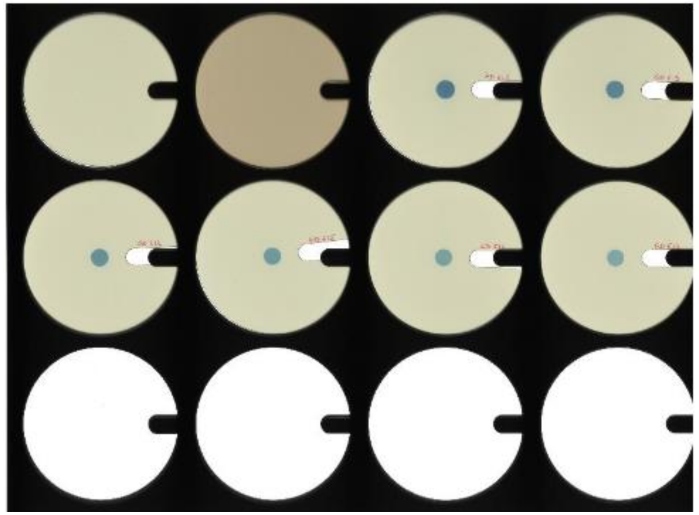
Efficiency calibration

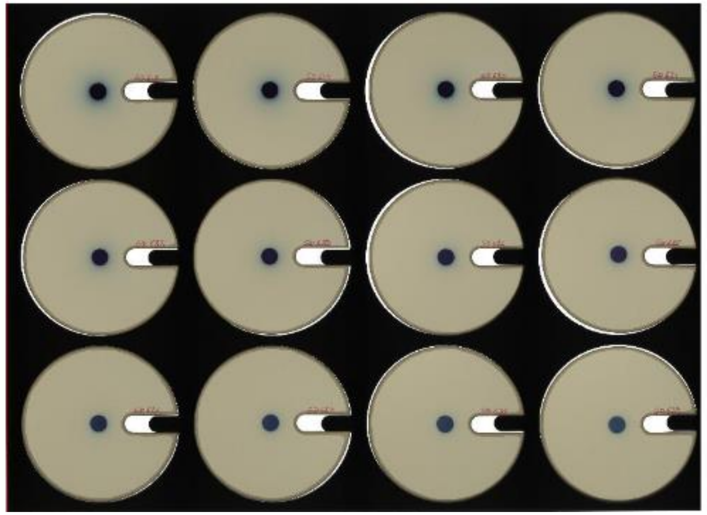
Simulation of scintillation signal with neutrons of different energies

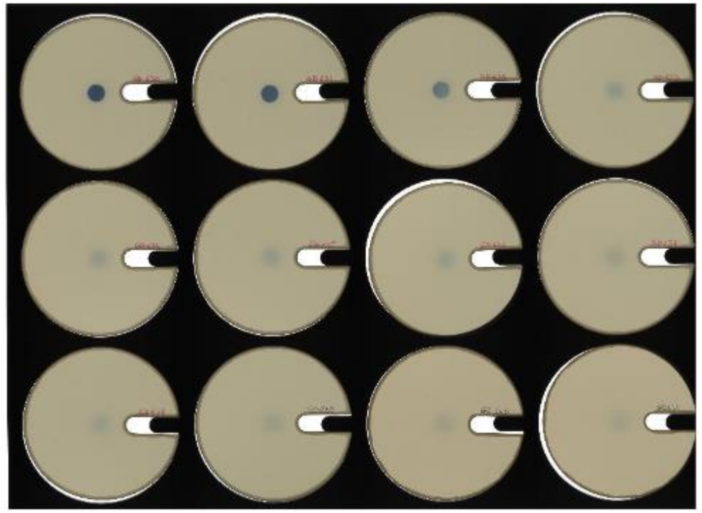


Shot details

	Shot #1 Pb converter	Shot #2 LiF converter	Shot #3 LiF + Pb converter	Shot #4 LiF + Pb converter
On-target energy (J)	347	358	345	340
Pulse duration (fs)	1000	1000	800	630
Intensity (W/cm²)	3.1×10^{18}	4.1×10^{18}	2.95×10^{18}	7.2×10^{18}
Proton cutoff energy (MeV)	30	25	28	35
Converter	Pb	LiF	LiF + Pb	LiF + Pb

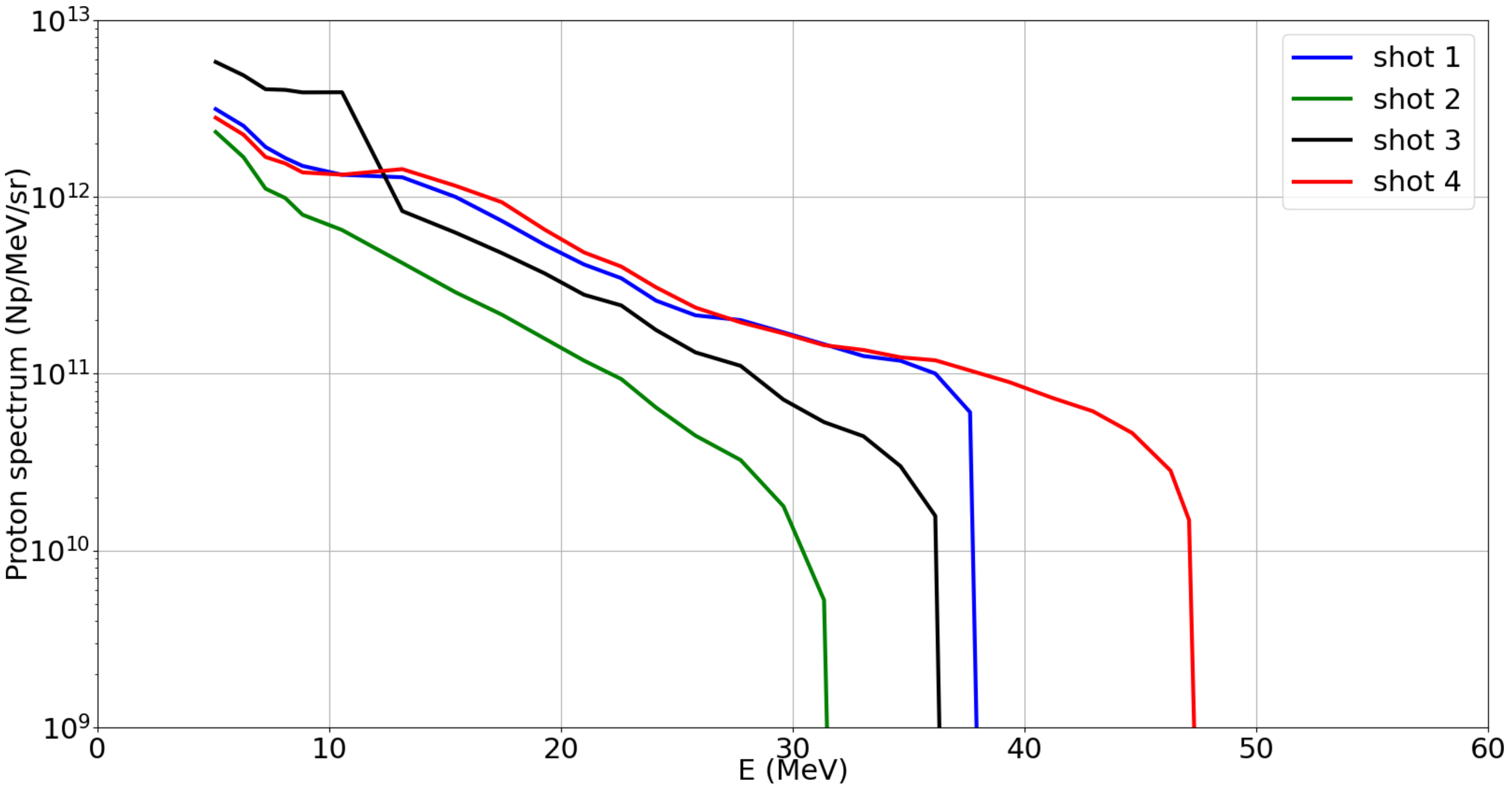




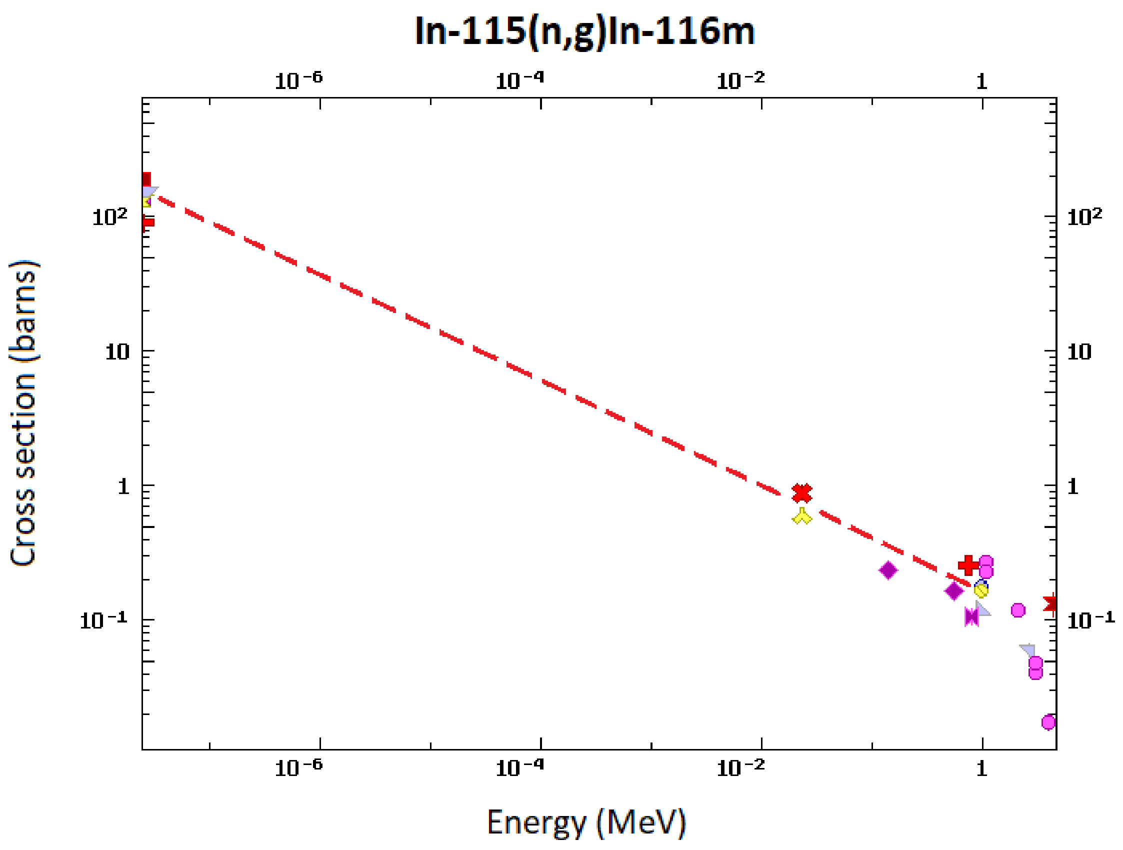


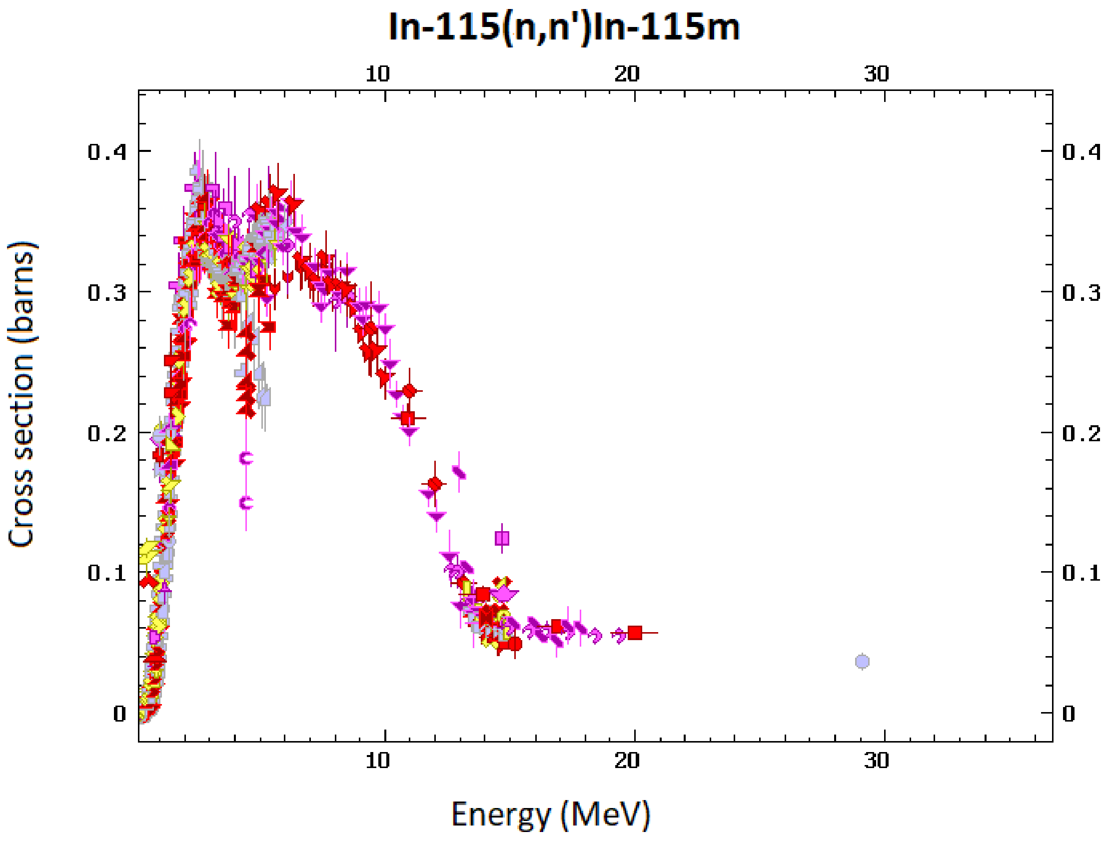
Proton spectra – PETAL

Proton spectra obtained with RCF films

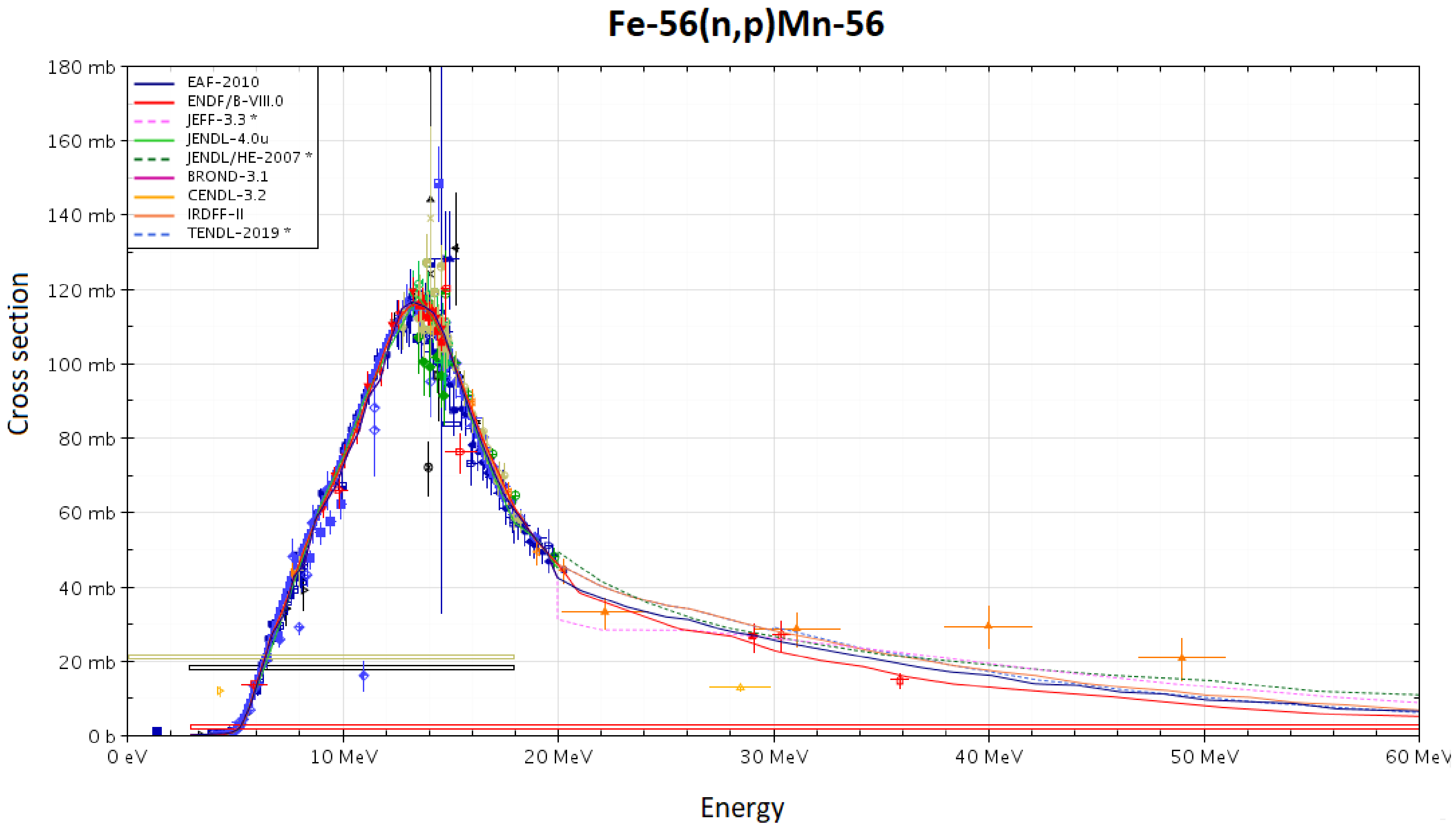


Activation samples





Activation samples



Activation samples

Zr-90(n,2n)Zr-89