Assessment of neutron production using the high-energy PETAL laser

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Outline

Laser-driven neutron sources

Pitcher-catcher technique
Characteristics and applications

Design of the experiment

Preliminary calculations
Diagnostics
Setup

First results of neutron production

Shot details
Activation diagnostic
Neutron Time-of-flight

Conclusions & prospects

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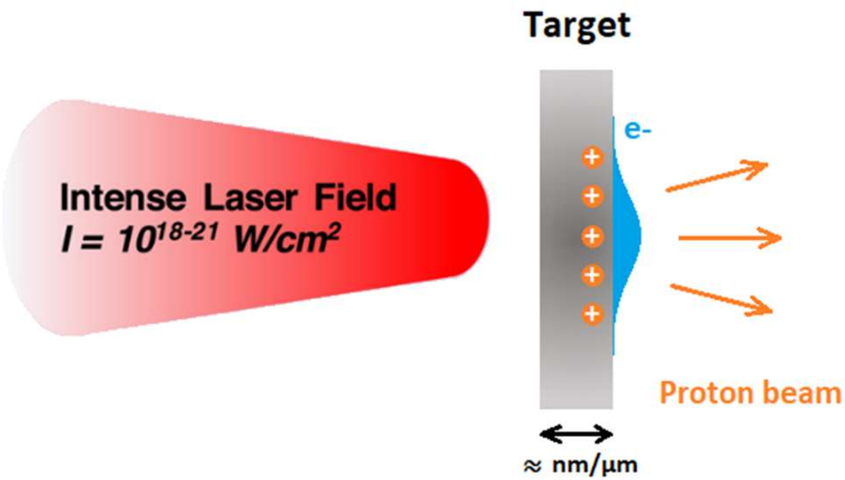
Pitcher-catcher technique

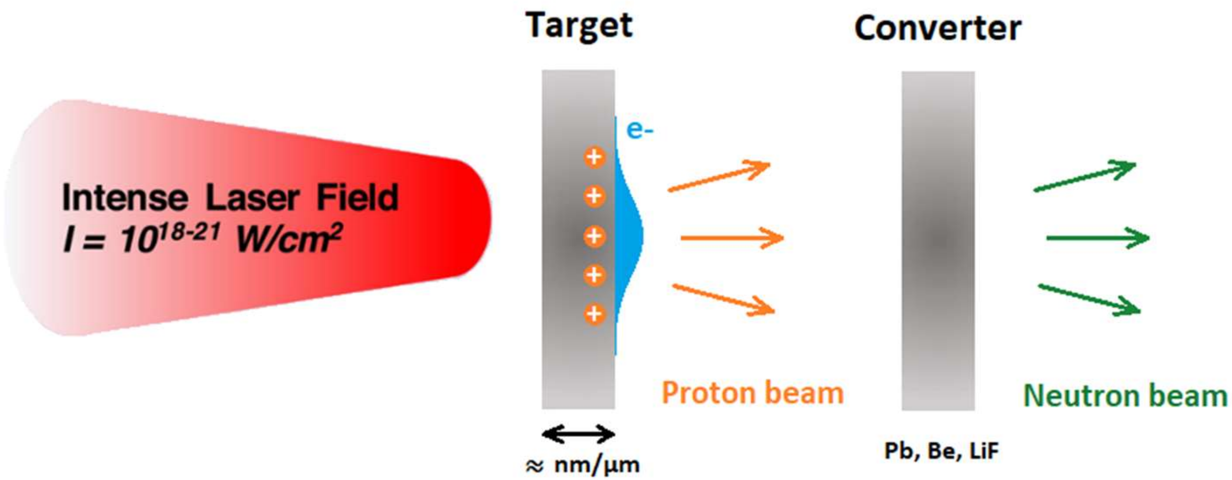
Neutron production from a laser-induced proton beam



≈ 10s MeV

Pitcher-catcher technique

Neutron production from a laser-induced proton beam



Characteristics

New neutron sources:

+ compact sources

- radiological constraints

Characteristics

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+ compact sources

- radiological constraints

Unique characteristics:

Short and intense emissions

Fast neutrons

Characteristics

New neutron sources:

+ compact sources

- radiological constraints

Unique characteristics:

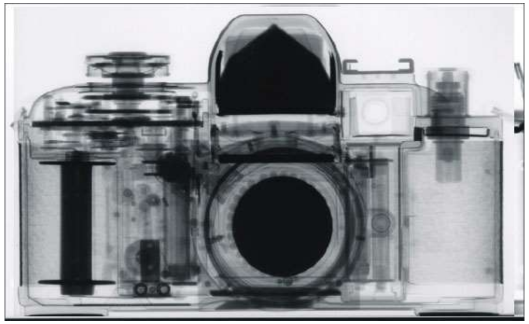
Short and intense emissions

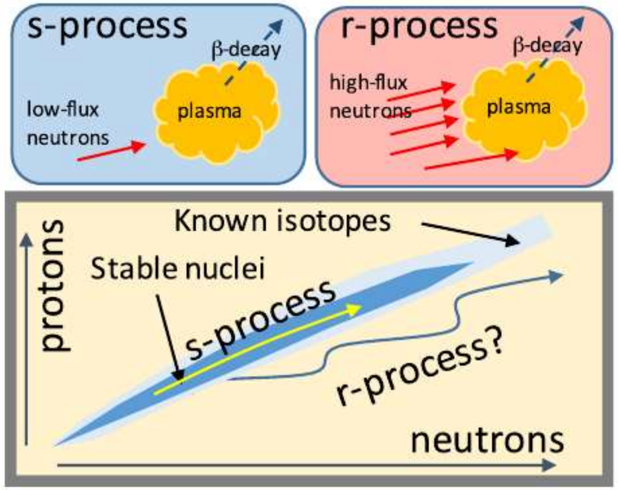
Fast neutrons

Facility	Peak neutron flux $[n/(cm^2\ s)]$	Average neutron flux $[n/(cm^2\ s)]$	Neutron bunch duration	Repetition rate (Hz)	
ILL (reactor-based)	$\sim 10^{15}$	$\sim 10^{15}$	(Continuous)	(Continuous)	
SNS (accelerator-based)	$\sim 10^{16}$	$\sim 10^{12}$	$\sim 1\ \mu s$	60	
Present-day lasers	10^{18}–10^{19}	5×10^5–5×10^6	~1 ns	5×10^{-4} (1 shot/30 min)	→ **APOLLON 0.6 PW**
Upcoming multi-PW lasers	10^{22}–5×10^{24}	10^{11}–5×10^{13}	**~1 ns**	1.6×10^{-2} **(1 shot/min)**	→ **APOLLON 10 PW**

Applications

Neutron radiography
Radiotherapy (BNCT)
Astrophysics: r-process
…





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 a-decay

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

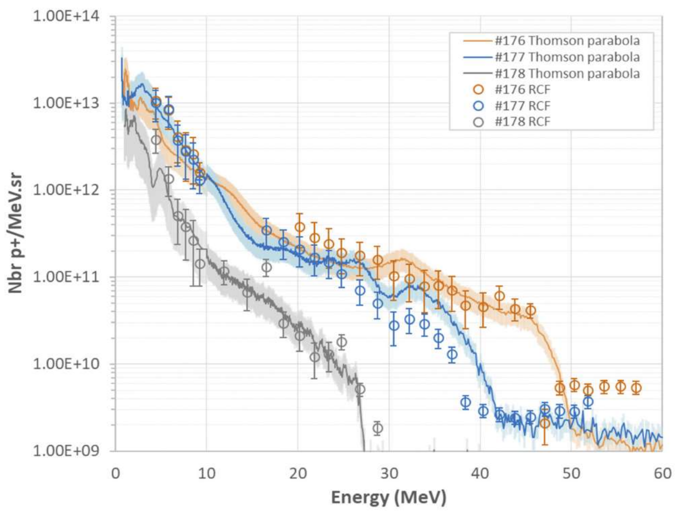
Outline

Preliminary calculations

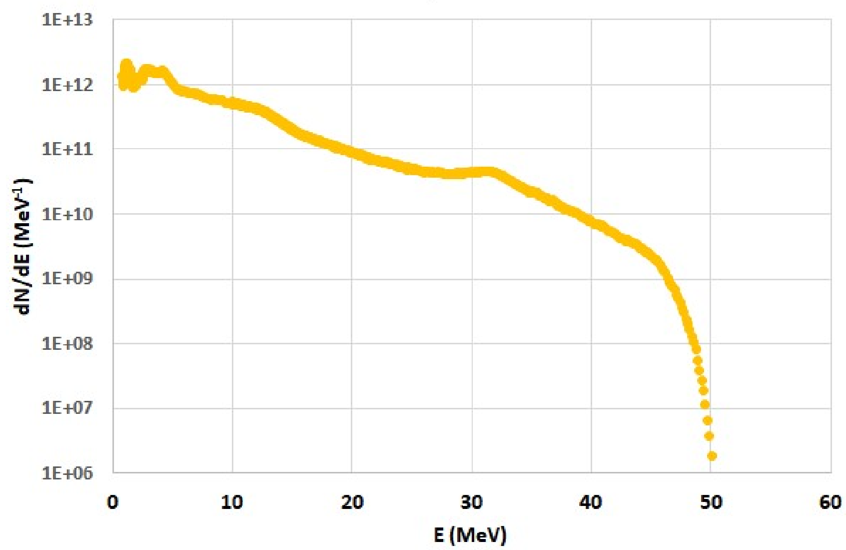
Proton spectrum: - Shot #176 (450J, 50 µm CH + 1µm Al)
- Cutoff energy ≈ 51 MeV
- 1.4×10^{13} protons/shot

"Enhanced ion acceleration using the high-energy petawatt PETAL laser"
D. Raffestin et al. (2021)

Differential energy spectrum



Proton spectrum

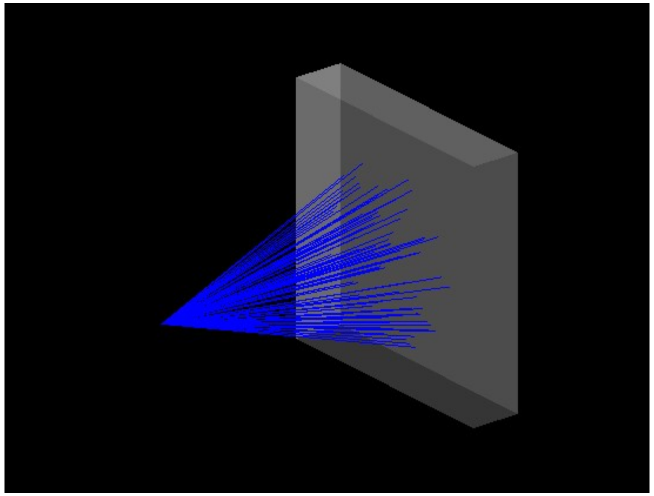


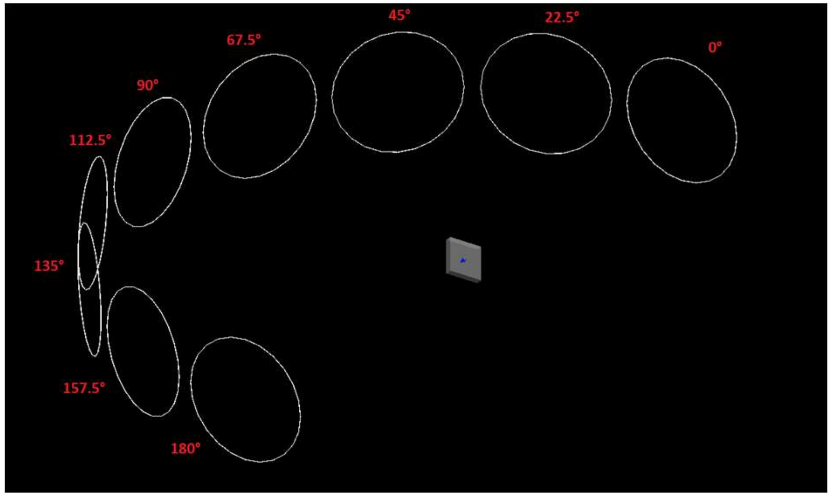
Converter dimension optimization

Converters: LiF (e=2 → 7mm), Pb (e=1,5 → 3mm) and LiF+Pb

Virtual detectors: 0° → 180° / 10cm² / 10cm from converter
4π sr sphere

Physics list "QGSP_BIC_AllHP": TENDL for proton-induced reactions and ENDF for neutron-induced reactions





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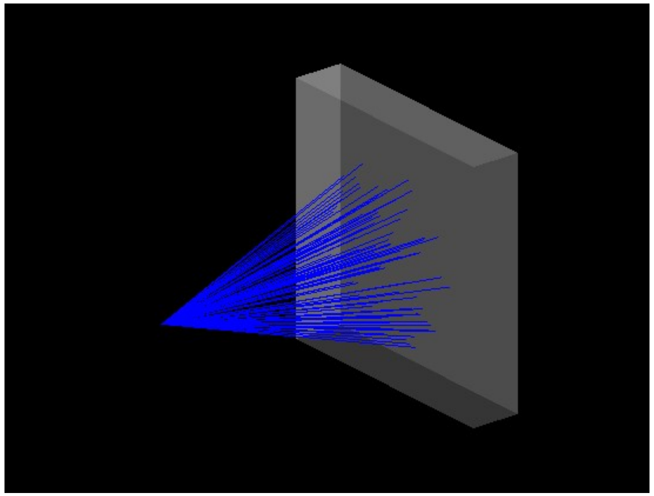

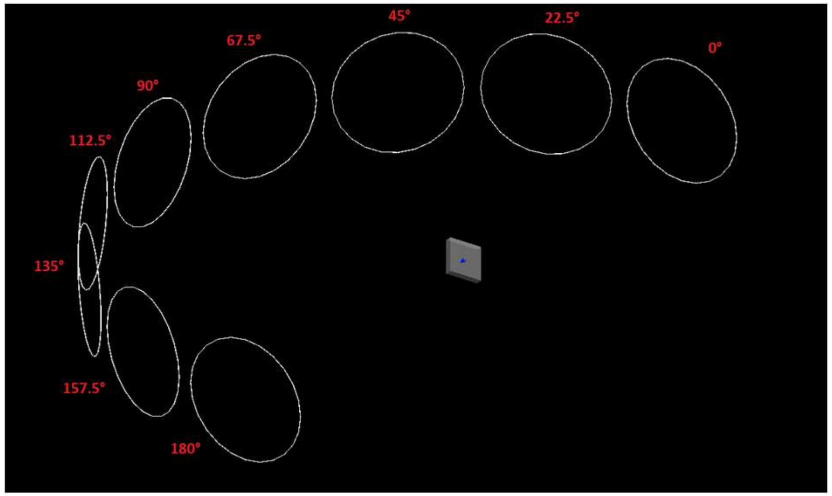

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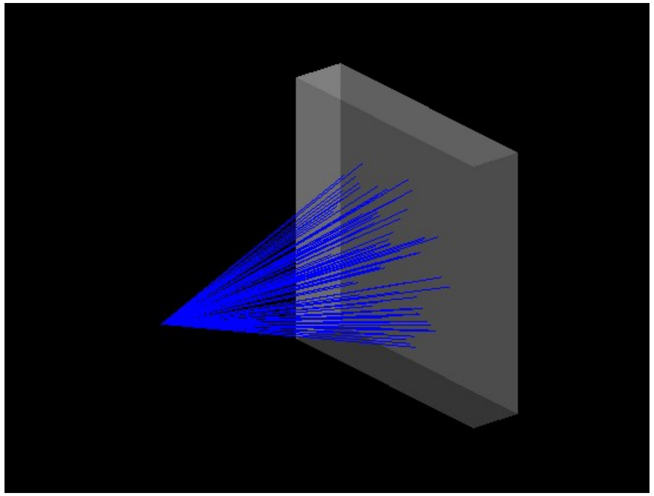
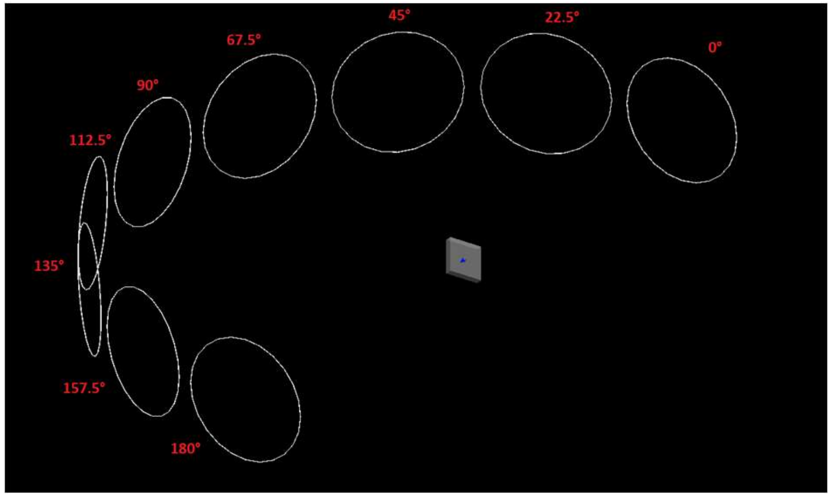
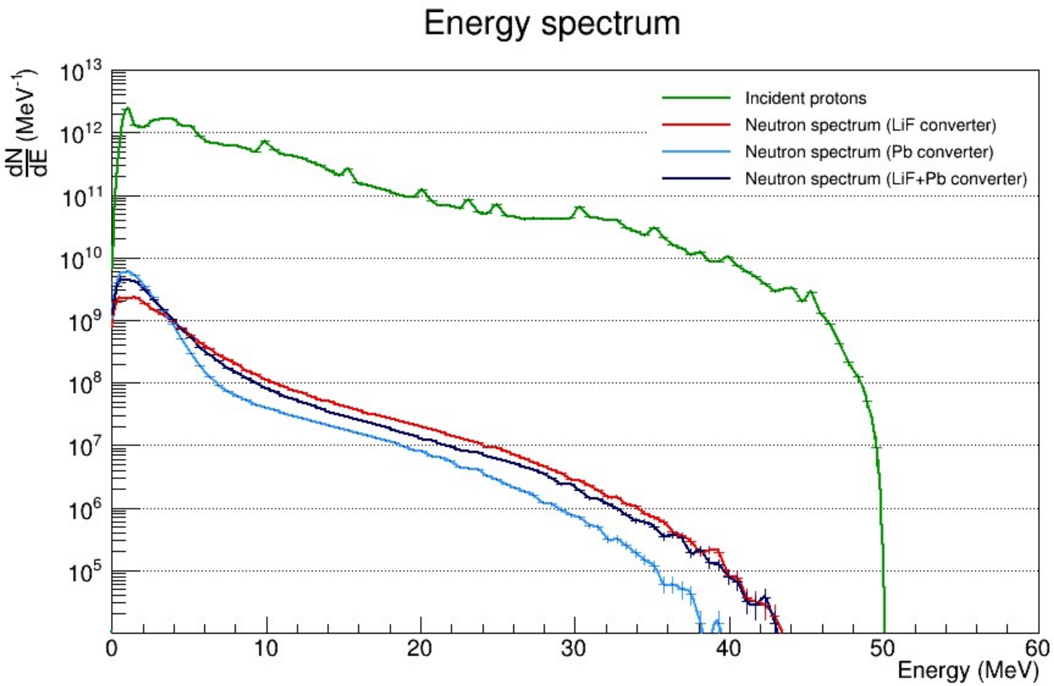




Simulation of neutron emissions

Best results for: **LiF (e=4mm), Pb (e=2mm)** and **LiF (e=1mm) + Pb (e=1,5mm)**

- ➢LiF : 9.866×10^{9} neutrons ($\bar{E}$ = 3.50 MeV)
- ➢Pb : 1.509×10^{10} neutrons ($\bar{E}$ = 2 MeV)
- ➢LiF+Pb : 1.395×10^{10} neutrons ($\bar{E}$ = 2.57 MeV)

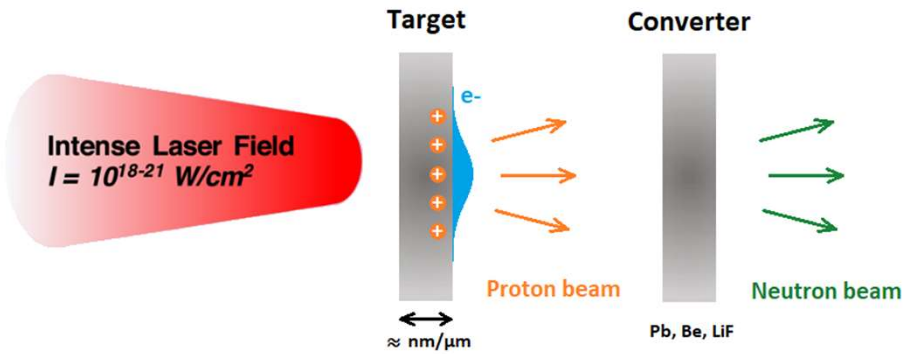


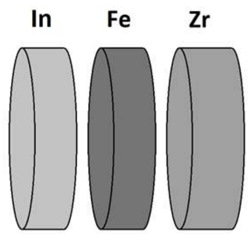
Neutron production yield ≈ 1/1000

Diagnostics

Two types of neutron detectors:

- Activation diagnostic

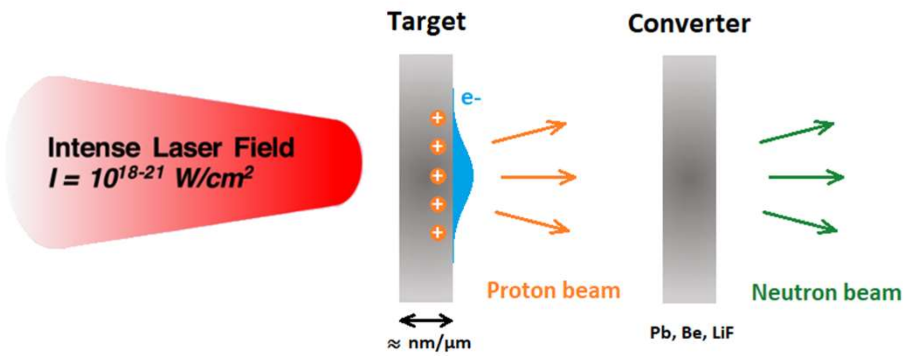


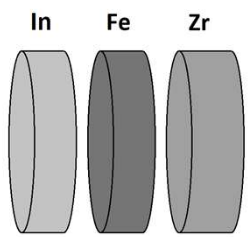


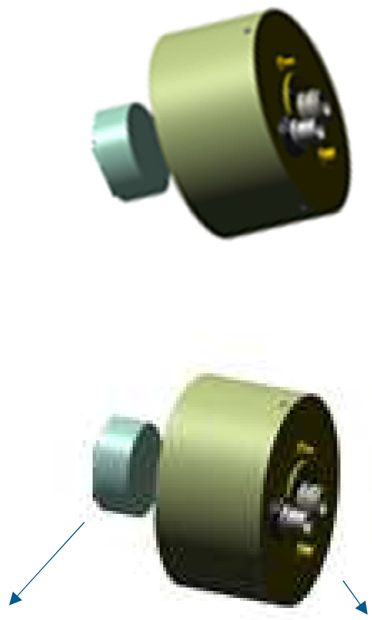
Diagnostics

Two types of neutron detectors:

- Activation diagnostic
- Time-of-flight detectors (BC422Q)







Activation diagnostic

Activation of samples using different reactions to retrieve neutron energy

Several criteria for samples selection:

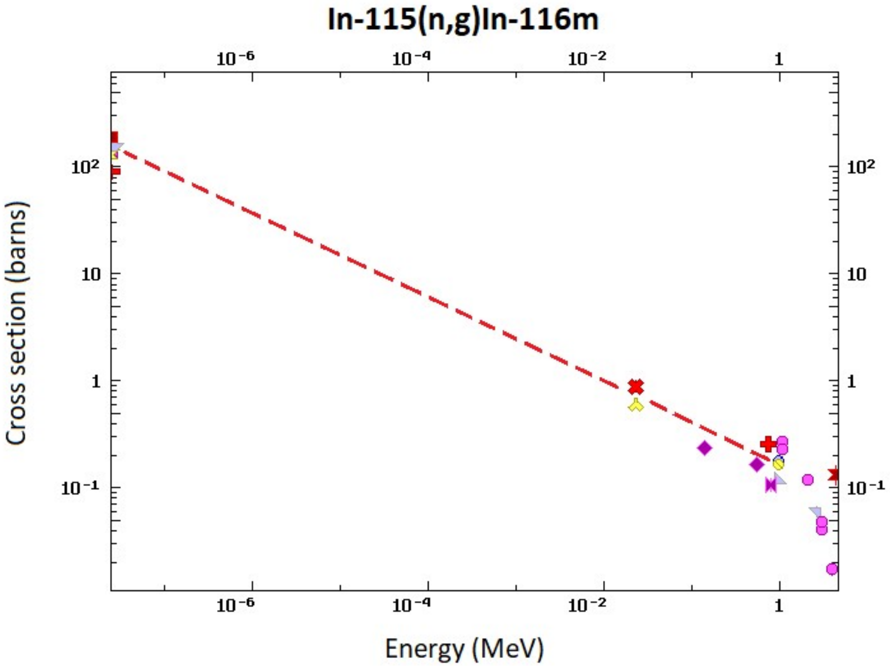
- Reactions with interesting cross-sections and spanning a wide spectrum
- Radionuclides with high intensity gamma emissions
- …

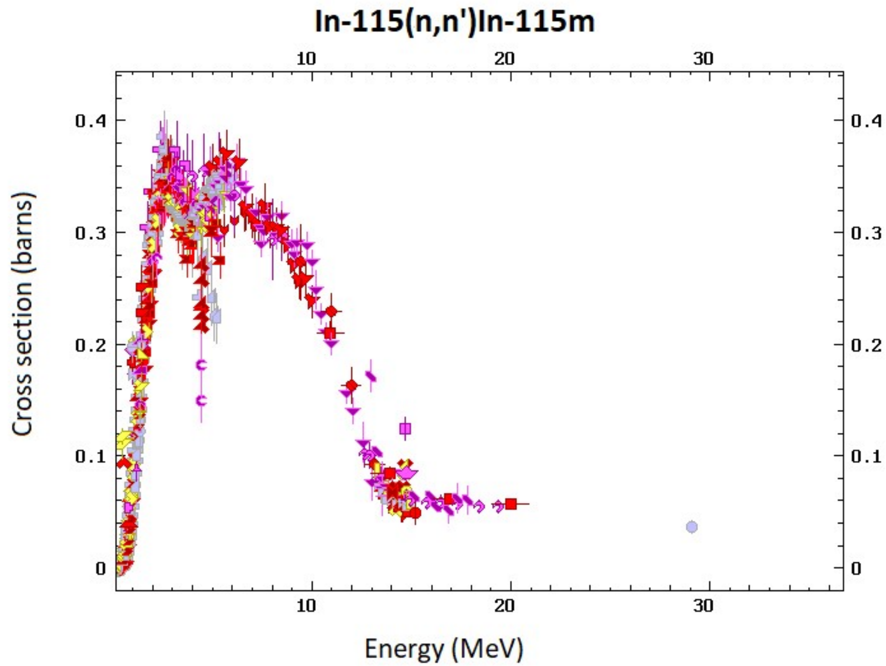
Layer #1	Layer #2	Layer #3	Layer #4	Layer #5
(n,g) reactions Au, Cd, Cu, Mn, Ni, Sn, W, Zn, …	(n,n') or (n,p) reactions Al, In, Ni, Rh, S, Zn	(n,a) reactions Al, Fe, Mg	(n,2n) reactions Co, Cu, Nb, Ni, Sc, Y, Zr	(n,3n) or (n,4n) reactions Bi

Activation samples

Geant4 activation simulations to find best samples:

- Indium

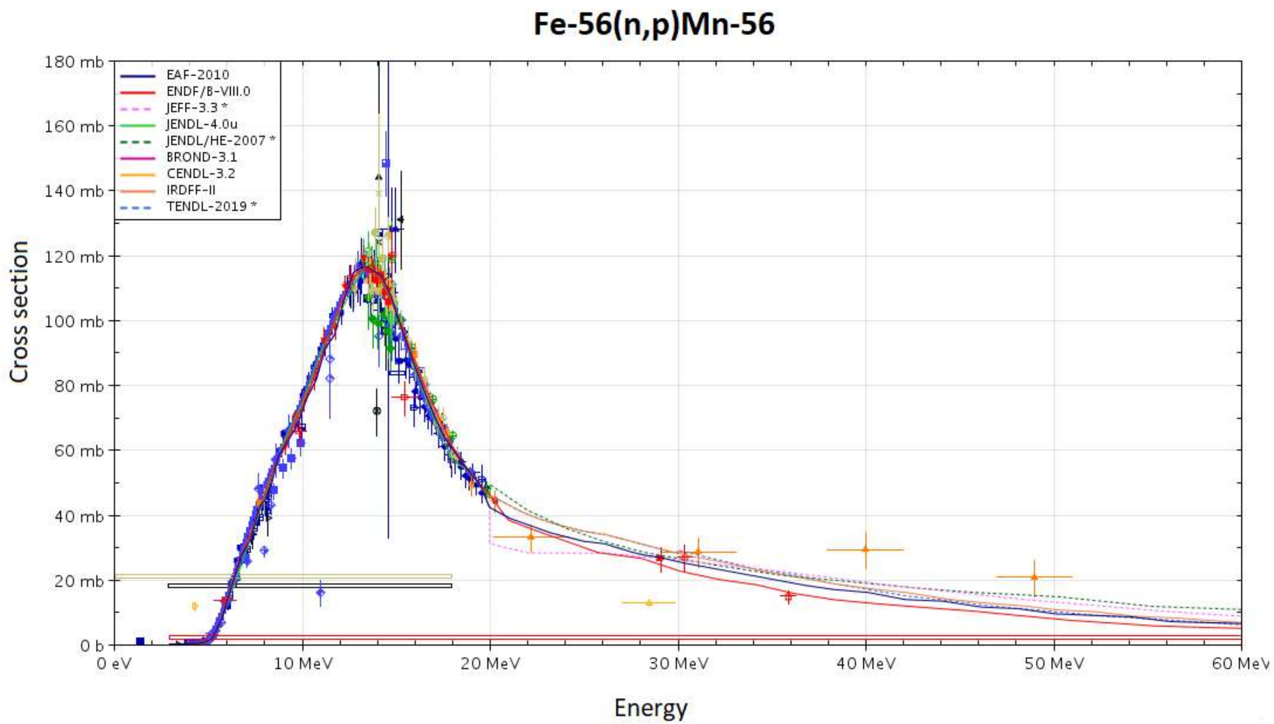




Activation samples

Geant4 activation simulations to find best samples:

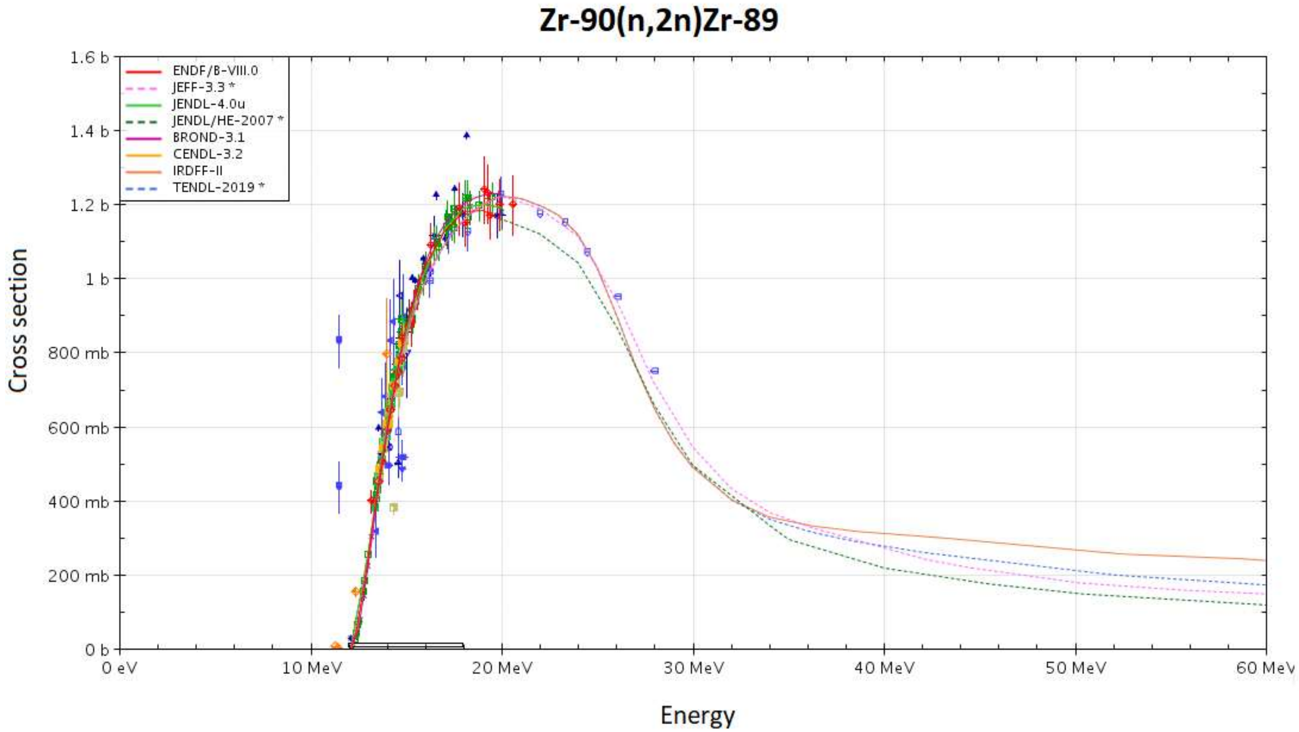
- Indium
- Iron



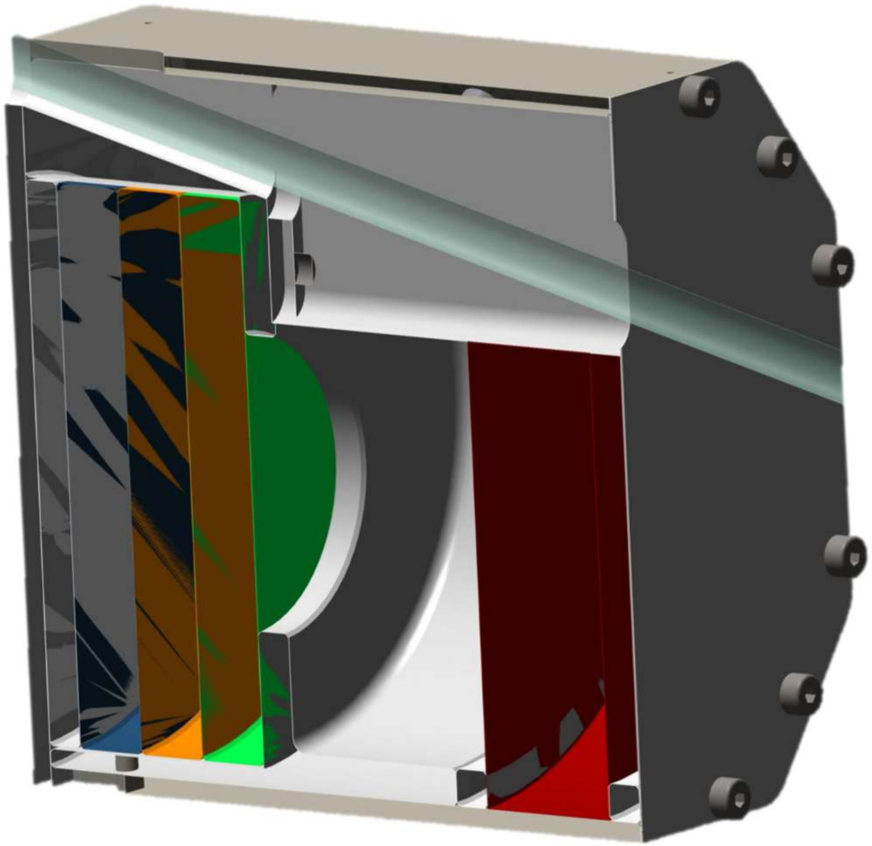
Activation samples

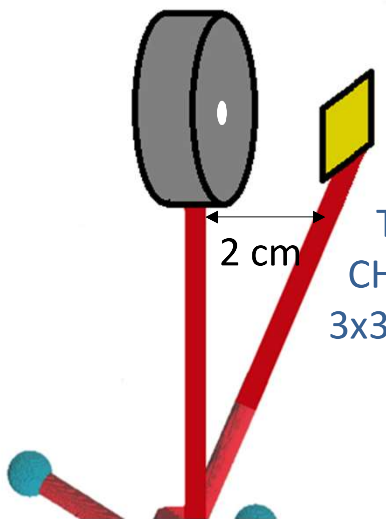
Geant4 activation simulations to find best samples:

- Indium
- Iron
- Zirconium



Setup





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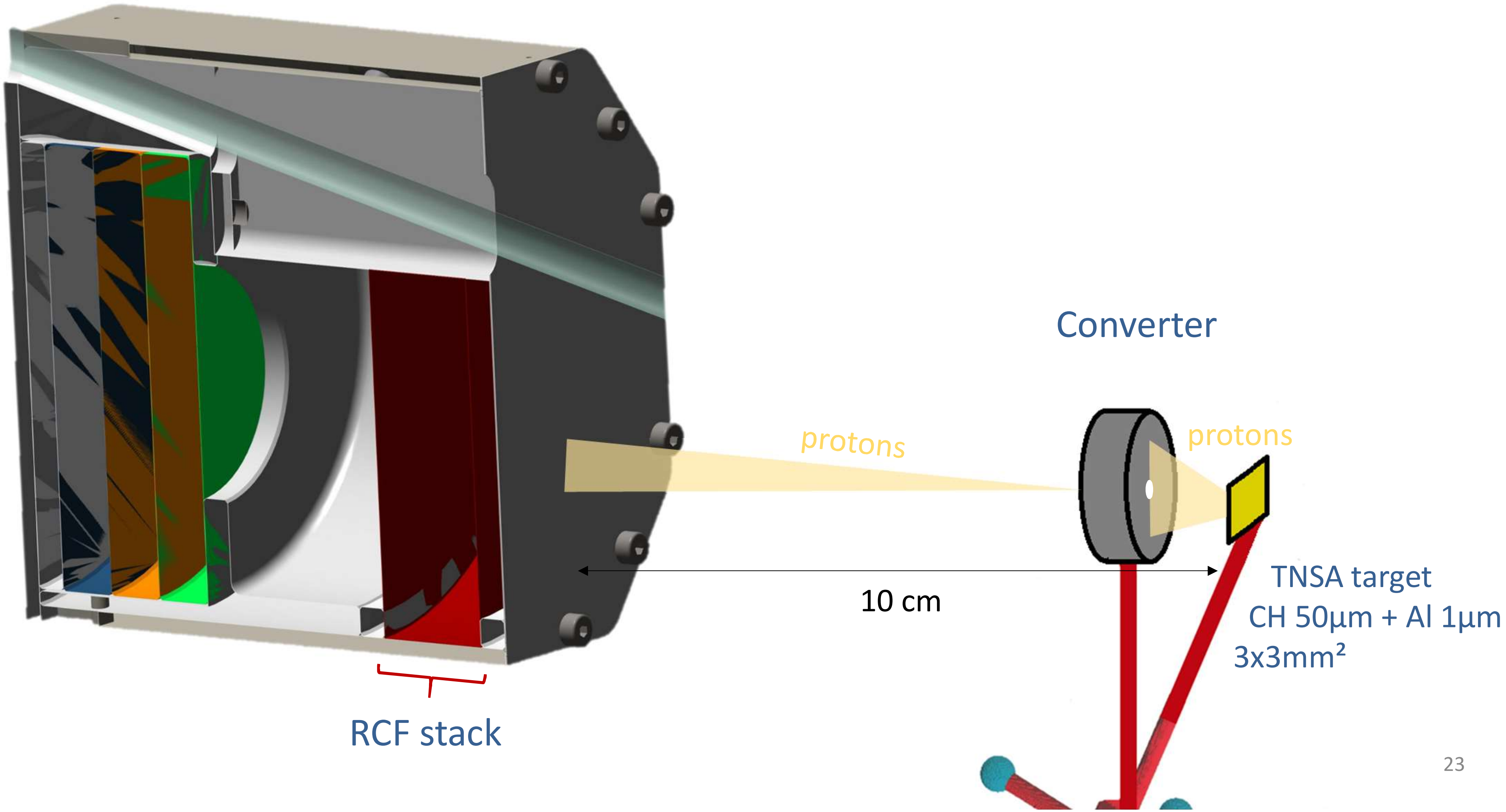
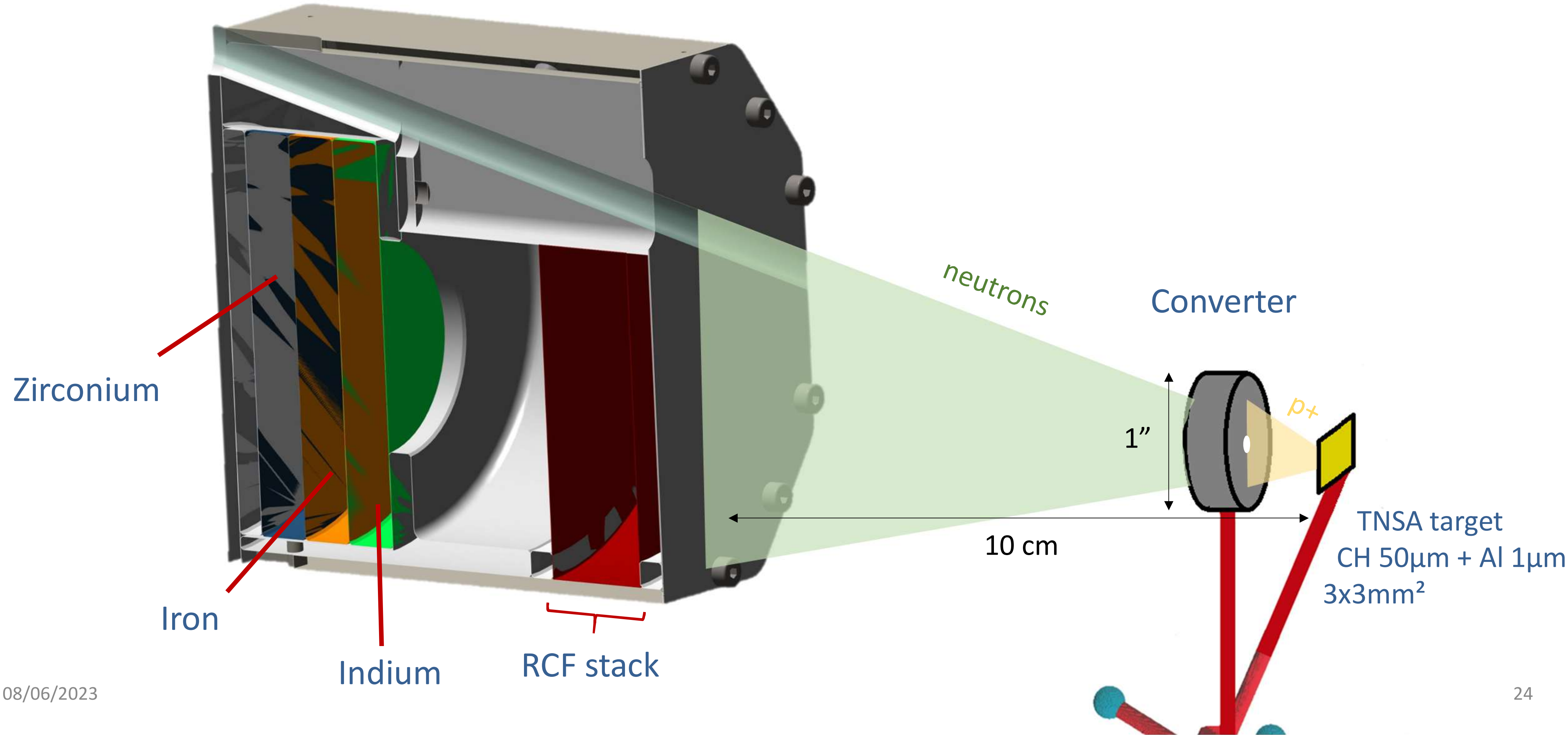
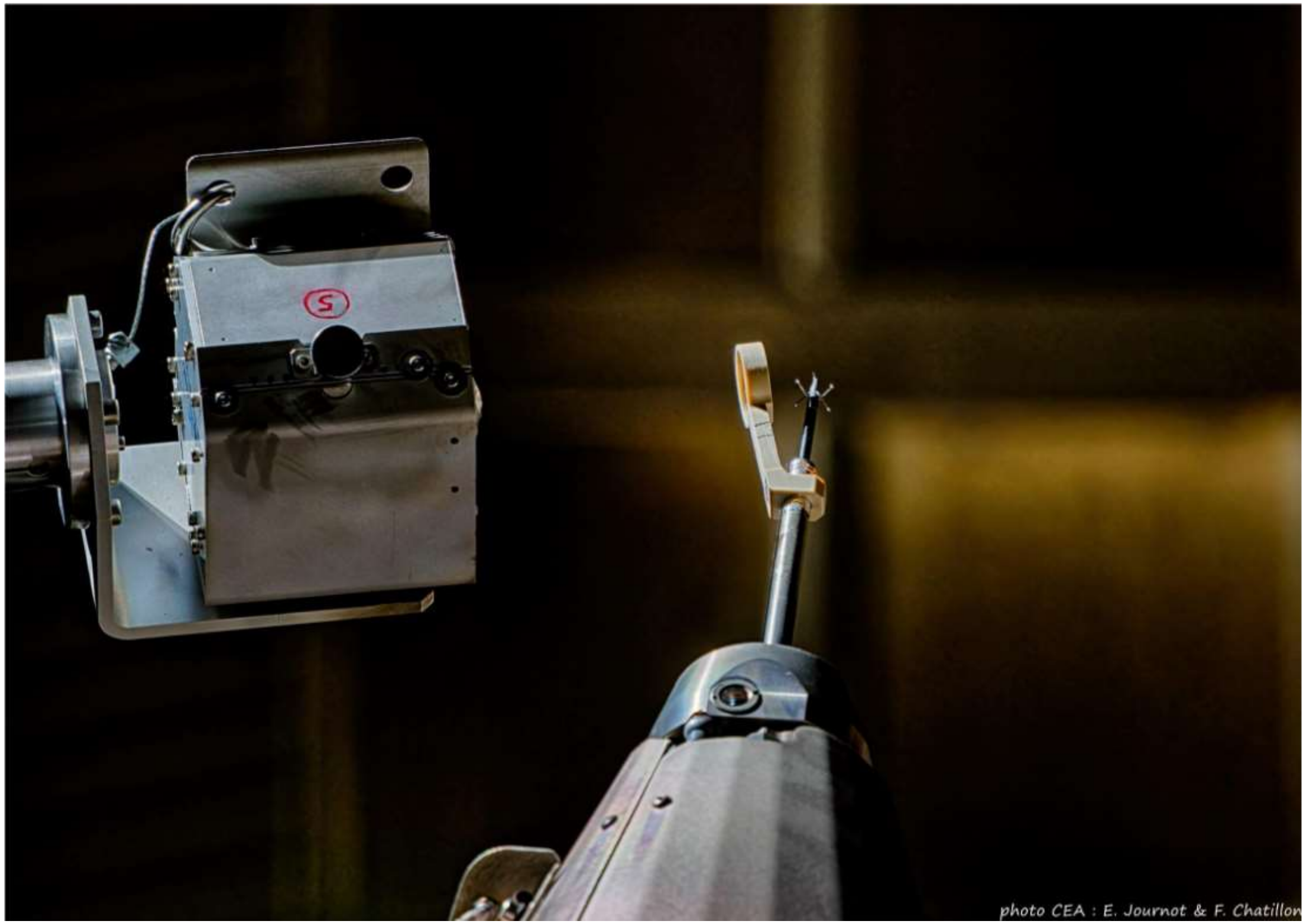

Converter
protons
protons
TNSA target
CH 50µm + Al 1µm
3x3mm²
10 cm
RCF stack

Setup



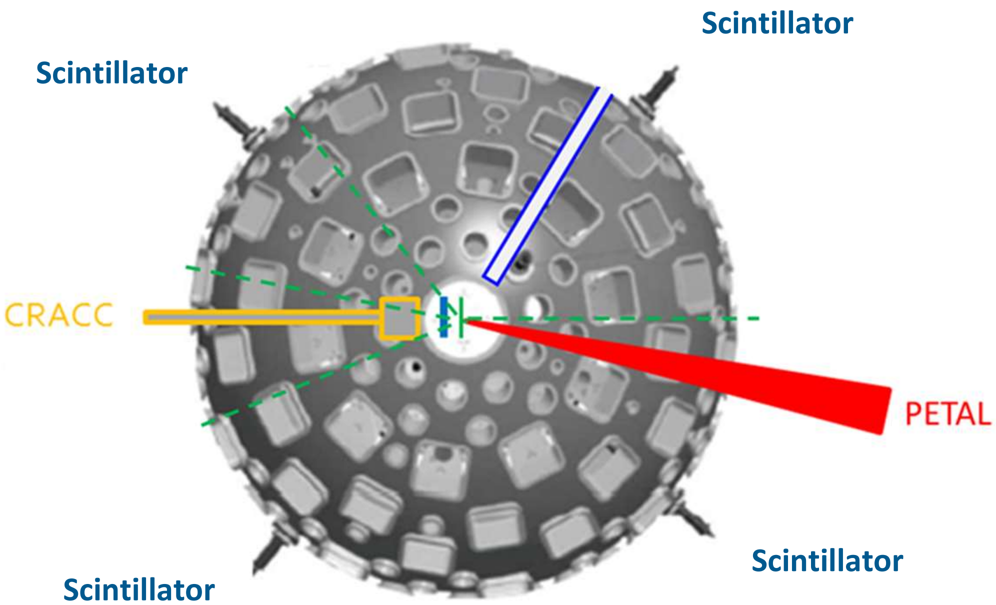
Zirconium
Iron
Indium
RCF stack
neutrons
Converter
1"
p+
10 cm
TNSA target
CH 50µm + Al 1µm
3x3mm²

Setup



Setup

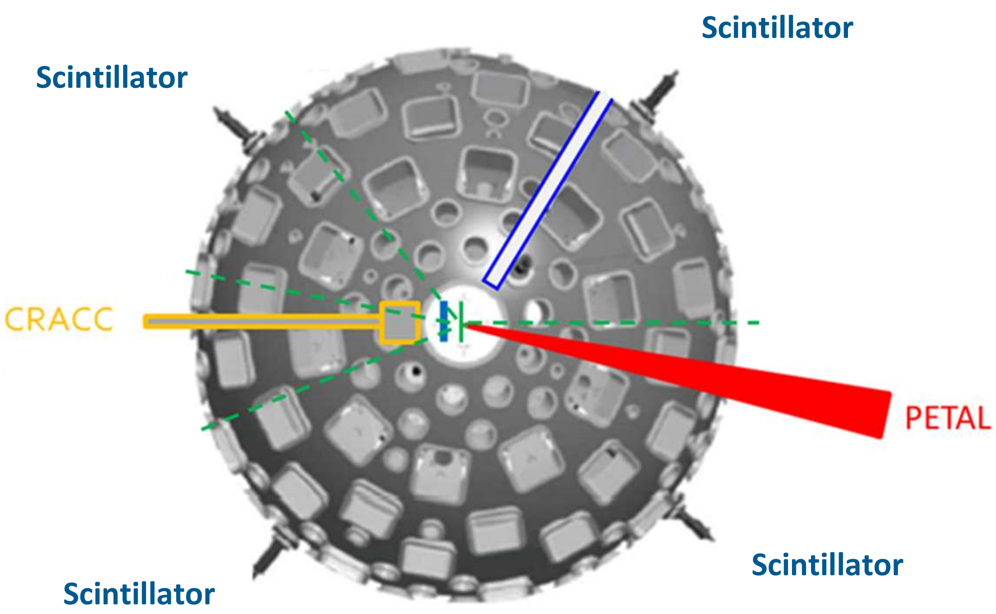
4 scintillators on the equatorial plan



Top view

Setup

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



Top view

Side view

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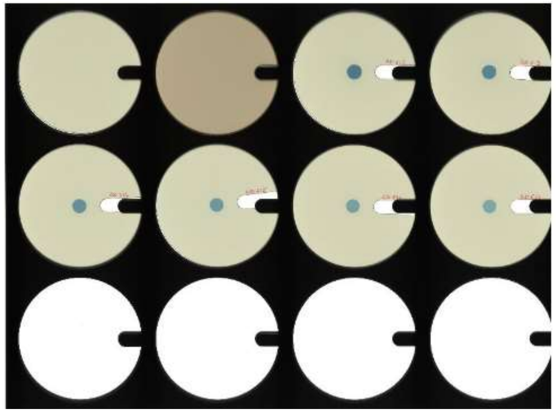
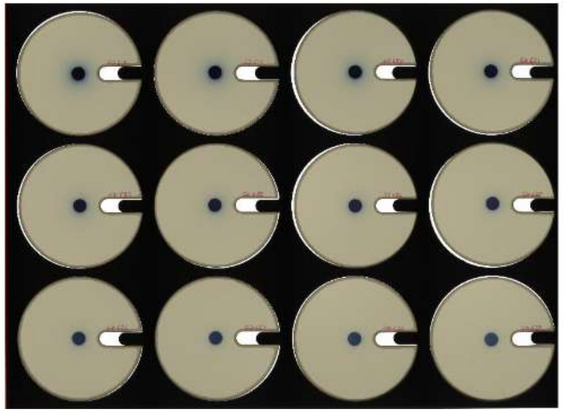
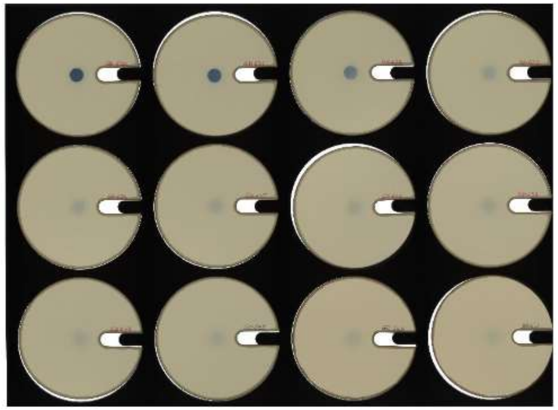
Shot details

	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







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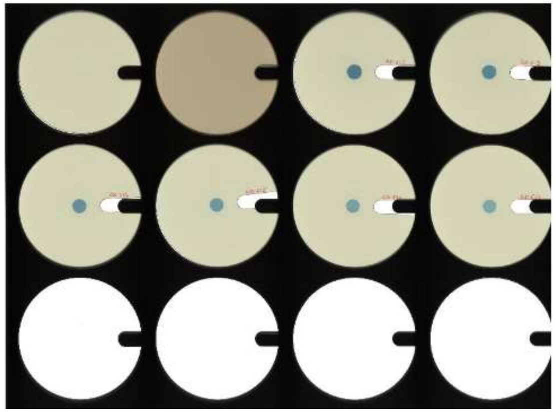
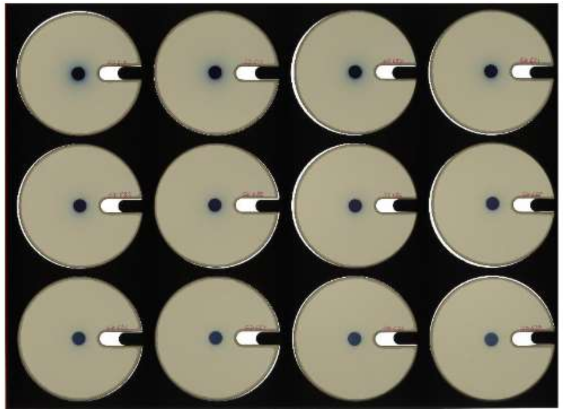
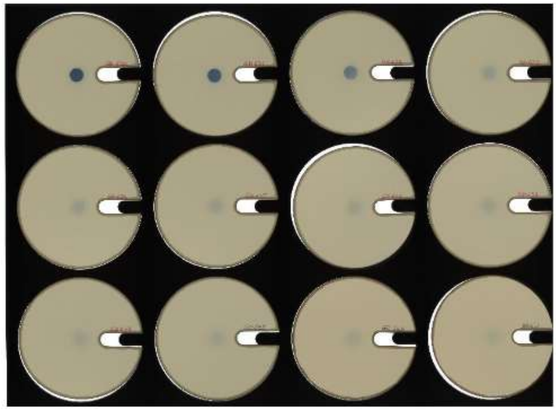
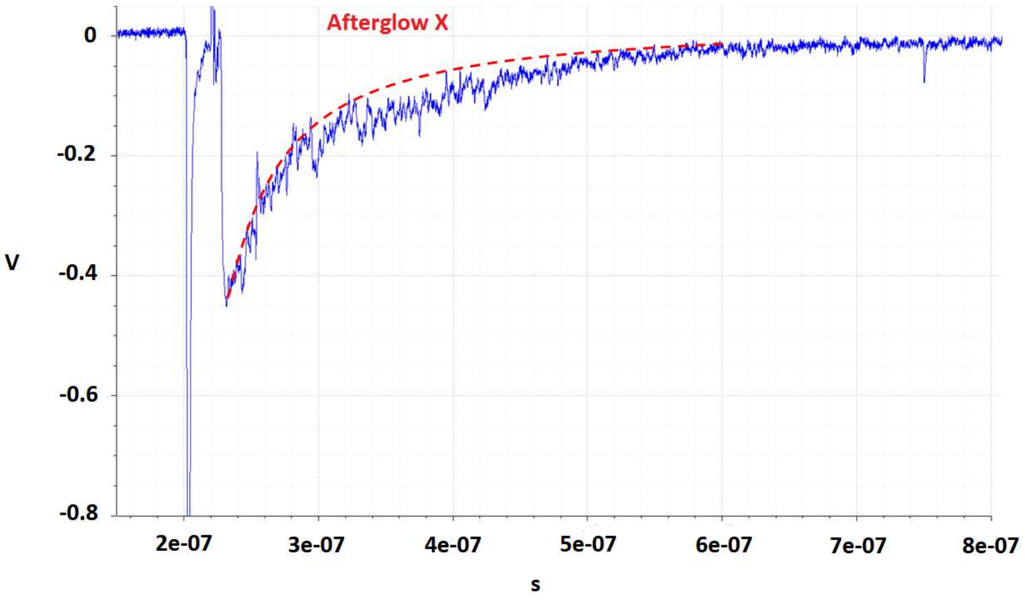




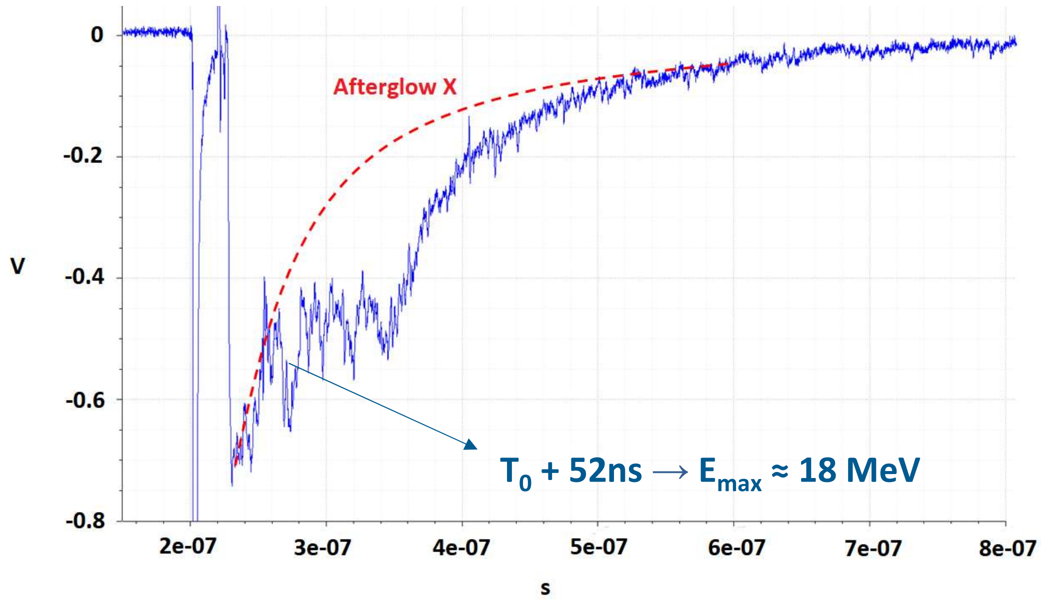
Neutron Time-of-flight

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

Shot #1 - Pb converter



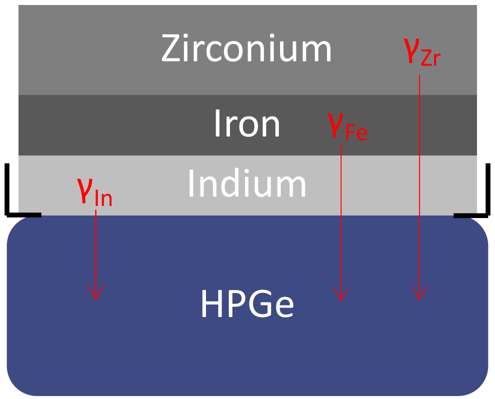
Shot #3 – hybrid converter LiF + Pb



Activation diagnostic

Gamma spectrometry of the activation samples:

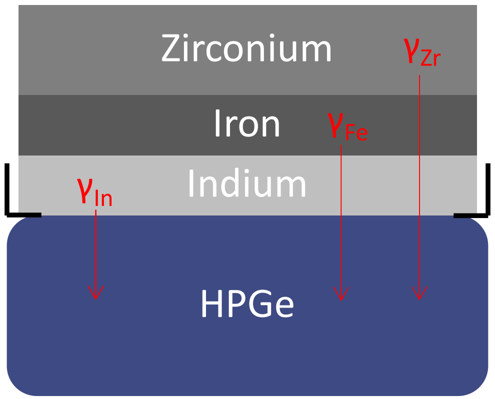
- Measurement time → 22h

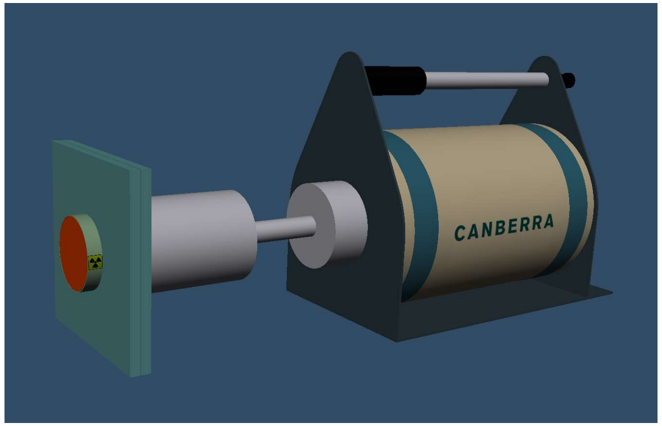


Activation diagnostic

Gamma spectrometry of the activation samples:

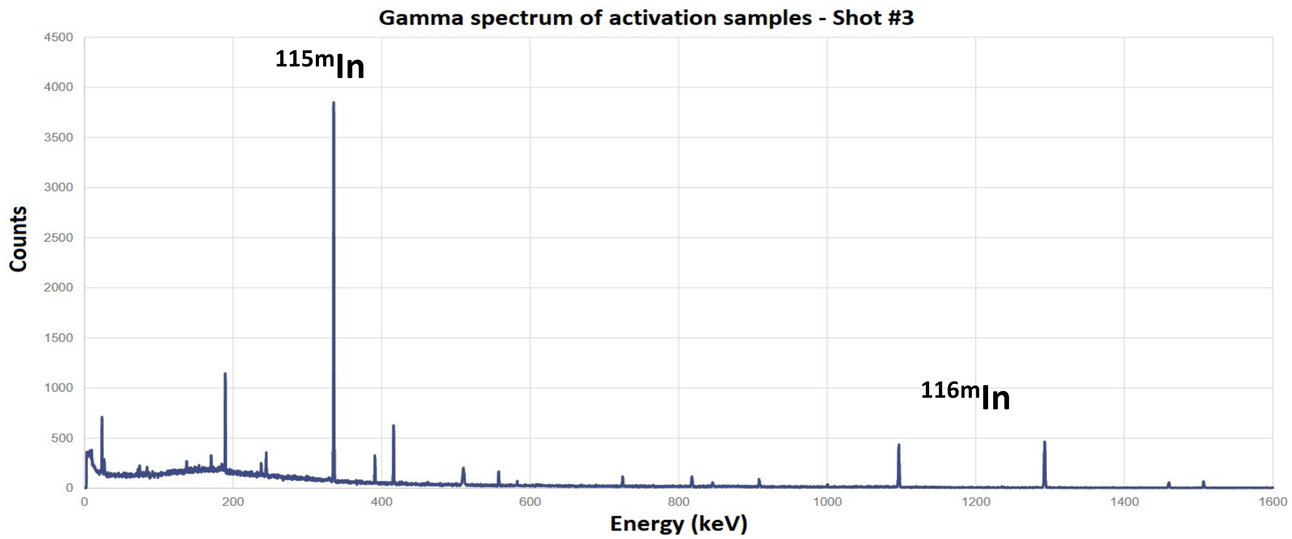
- Measurement time → 22h
- Detection efficiency calculated with ISOCS software





Activation diagnostic

Material	Reaction	Half-life	E_X (keV)	Shot #1 - $A_{mes.}$ (Bq)	Shot #3 - $A_{mes.}$ (Bq)
In	$^{115}In(n,g)^{116m}In$	54.29 min	1293.6	21.86 ± 1.49	190.5 ± 3.43
	$^{115}In(n,n')^{115m}In$	4.49 h	336.2	5.23 ± 0.22	48.05 ± 0.43
Fe	$^{56}Fe(n,p)^{56}Mn$	2.58 h	846.8	0	3.12 ± 0.39
Zr	$^{90}Zr(n,2n)^{89}Zr$	78.41 h	909.2	0.60 ± 0.08	1.46 ± 0.12



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Measurements: 4.7×10^7 neutrons/sr [1-10 MeV] 4.3×10^8 neutrons/sr [1-10 MeV]

Activation diagnostic

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Measurements: 4.7×10^7 neutrons/sr [1-10 MeV] 4.3×10^8 neutrons/sr [1-10 MeV]

Simulations: 1.3×10^9 neutrons/sr [1-10 MeV] 1.4×10^9 neutrons/sr [1-10 MeV]

Shot details

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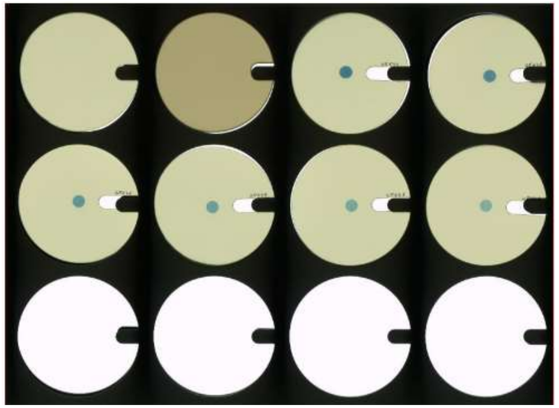

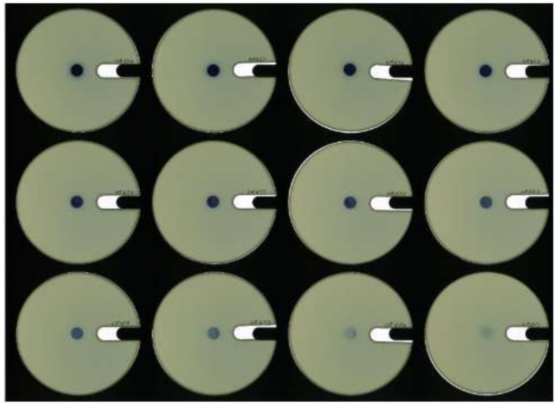

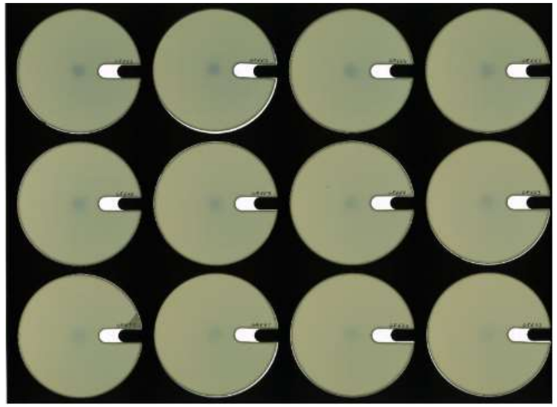

Activation diagnostic

Material	Reaction	Half-life	E_γ (keV)	Shot #2 - $A_{mes.}$ (Bq)	Shot #3 - $A_{mes.}$ (Bq)
In	$^{115}In(n,g)^{116m}In$	54.29 min	1293.6	211.5 ± 5.29	190.5 ± 3.43
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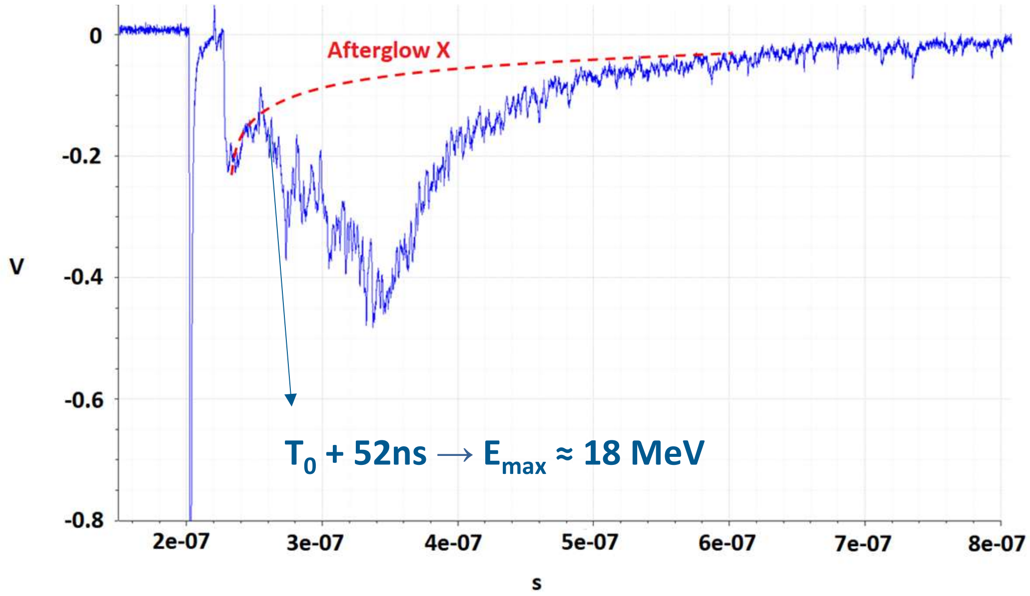
Zr	$^{90}Zr(n,2n)^{89}Zr$	78.41 h	909.2	0	1.46 ± 0.12

Measurements: **$3.5x10^8$ neutrons/sr [1-10 MeV]** **$4.3x10^8$ neutrons/sr [1-10 MeV]**

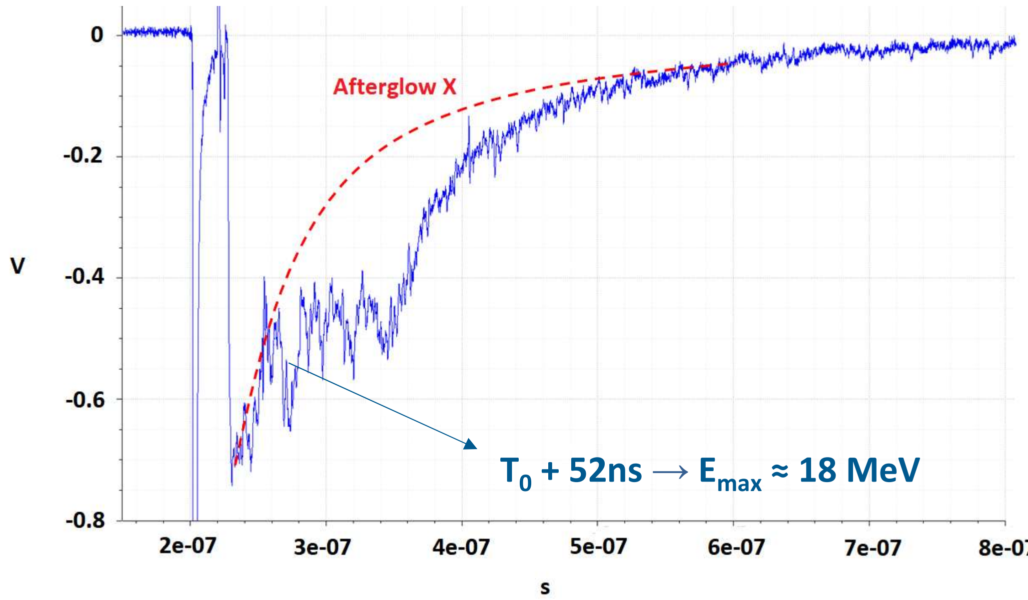
Neutron Time-of-flight

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

Shot #2 - LiF converter

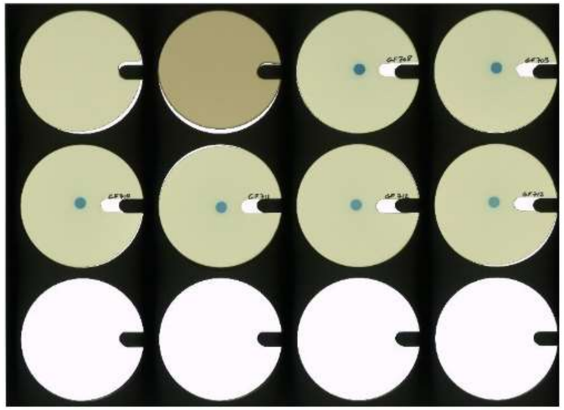
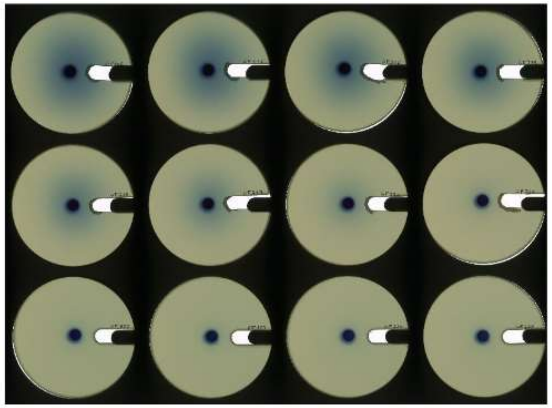
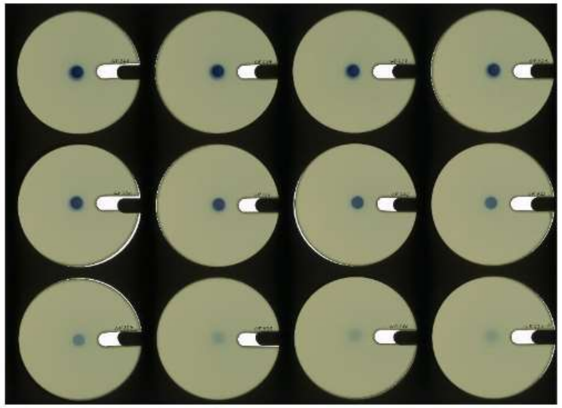


Shot #3 – hybrid converter LiF + Pb



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

Activation diagnostic

Material	Reaction	Half-life	E_γ (keV)	Shot #4 - $A_{mes.}$ (Bq)	Shot #3 - $A_{mes.}$ (Bq)
In	$^{115}In(n,g)^{116m}In$	54.29 min	1293.6	267.7 ± 5.09	190.5 ± 3.43
	$^{115}In(n,n')^{115m}In$	4.49 h	336.2	75.60 ± 0.53	48.05 ± 0.43
Fe	$^{56}Fe(n,p)^{56}Mn$	2.58 h	846.8	6.54 ± 0.48	3.12 ± 0.39
Zr	$^{90}Zr(n,2n)^{89}Zr$	78.41 h	909.2	6.01 ± 0.19	1.46 ± 0.12

Measurements: **6.8×10^8 neutrons/sr [1-10 MeV]** **4.3×10^8 neutrons/sr [1-10 MeV]**

Outline

Laser-driven neutron sources

Pitcher-catcher technique
Characteristics and applications

Design of the experiment

Preliminary calculations
Diagnostics
Setup

First results of neutron production

Shot details
Activation diagnostic
Neutron Time-of-flight

Conclusions & prospects

Conclusions & prospects

PETAL 2023 experiment

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

⟶ Possibility to adjust the neutron production using different converters

⟶ Demonstration of the interest of hybrid converters

Prospects

⟶ Development of an activation spectrometer

⟶ Mettre en œuvre les applications (neutron capture or radiography)

Conclusions & prospects

PETAL 2023 experiment

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

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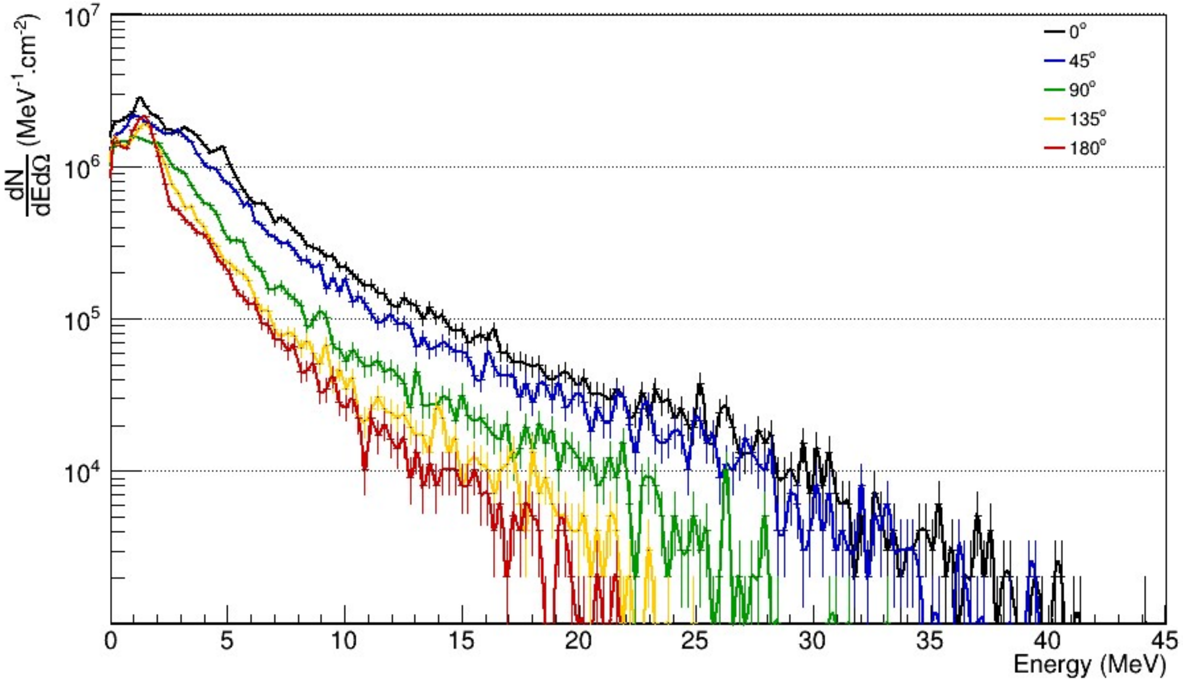
Geant4 simulation

LiF converter (4 mm)

→ Total : 9.869×10^{9} neutrons   ($\bar{E}$ = 3.50 MeV)

- 0° : 1.280×10^{7} neutrons/cm^{2} ($\bar{E}$ = 4.41 MeV)
- 45° : 1.035×10^{7} neutrons/cm^{2}
- 90° : 6.457×10^{6} neutrons/cm^{2}
- 135° : 5.571×10^{6} neutrons/cm^{2}
- 180° : 5.194×10^{6} neutrons/cm^{2}

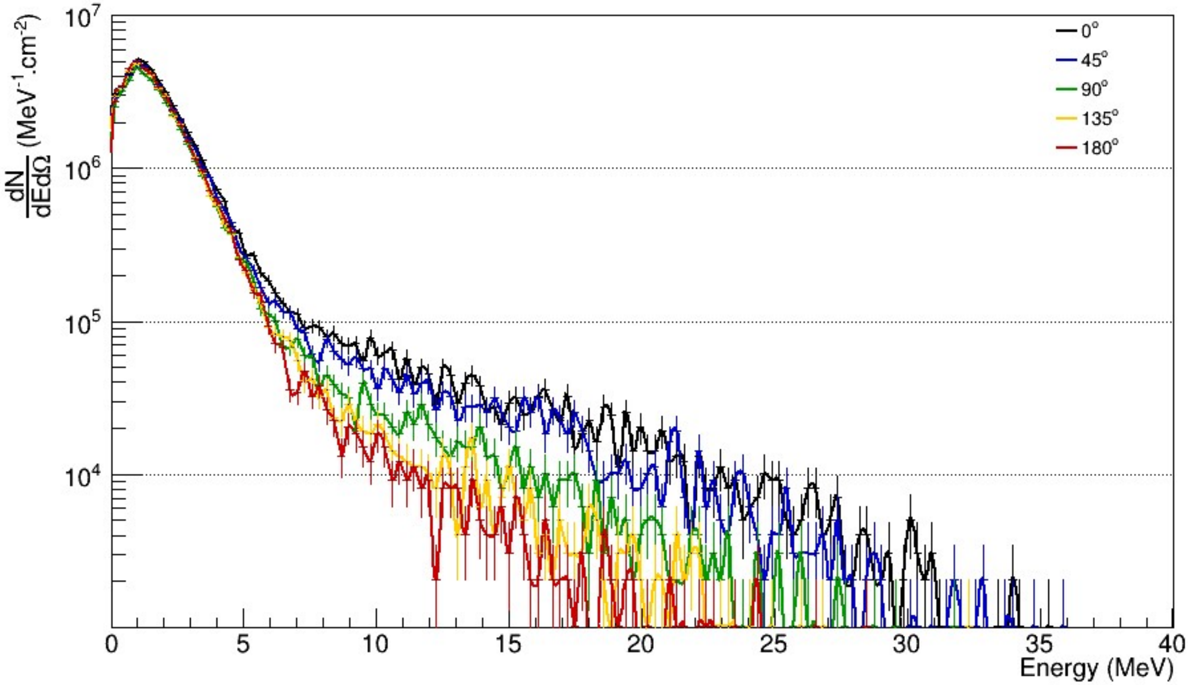


Geant4 simulation

Pb converter (2 mm)

→ Total : 1.509×10^{10} neutrons ($\bar{E}$ = 2 MeV)

- 0° : 1.312×10^{7} neutrons/cm² ($\bar{E}$ = 2.35 MeV)
- 45° : 1.229×10^{7} neutrons/cm²
- 90° : 1.086×10^{7} neutrons/cm²
- 135° : 1.154×10^{7} neutrons/cm²
- 180° : $1,160 \times 10^{7}$ neutrons/cm²

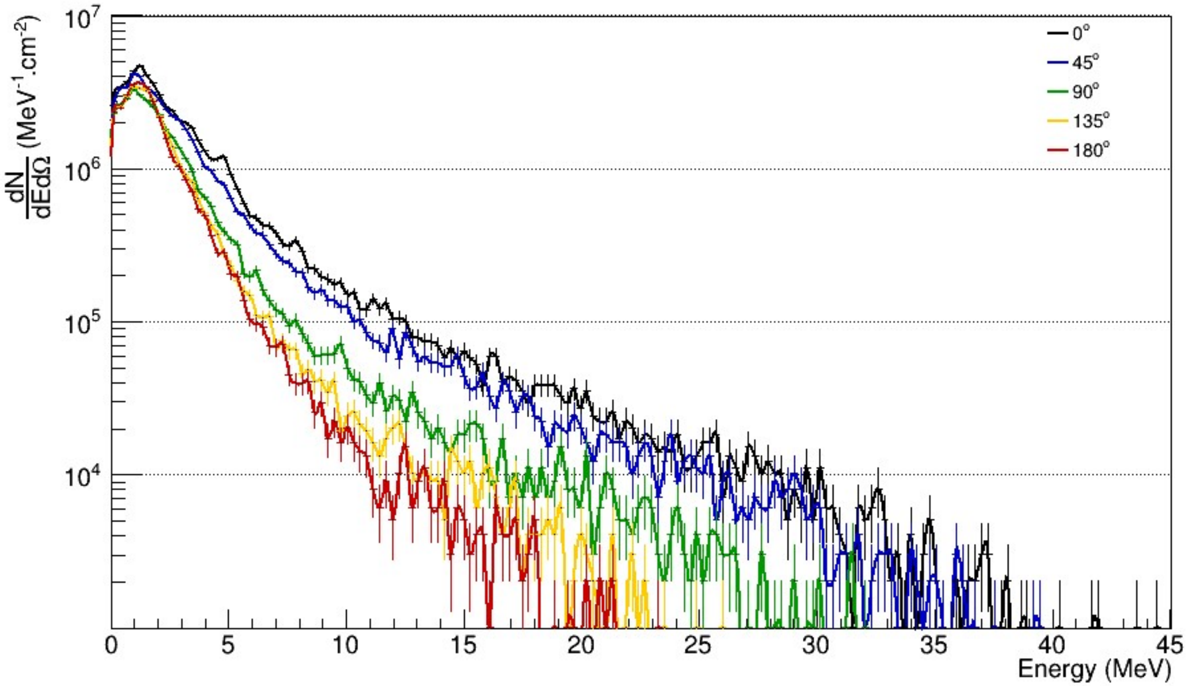


Geant4 simulation

LiF (1 mm) + Pb (1.5 mm)

→ Total : 1.395×10^{10} neutrons ($\bar{E}$ = 2.57 MeV)

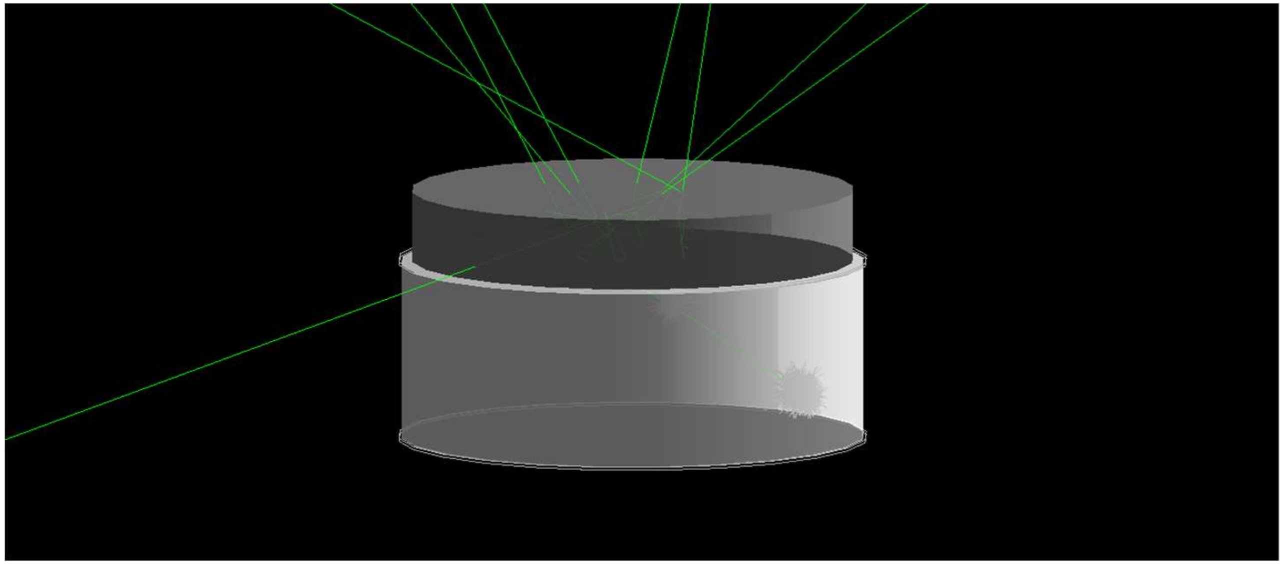
- 0° : 1.587×10^{7} neutrons/cm² ($\bar{E}$ = 3.29 MeV)
- 45° : $1{,}035 \times 10^{7}$ neutrons/cm²
- 90° : $6{,}457 \times 10^{6}$ neutrons/cm²
- 135° : $5{,}571 \times 10^{6}$ neutrons/cm²
- 180° : $5{,}194 \times 10^{6}$ neutrons/cm²



Thickness optimization

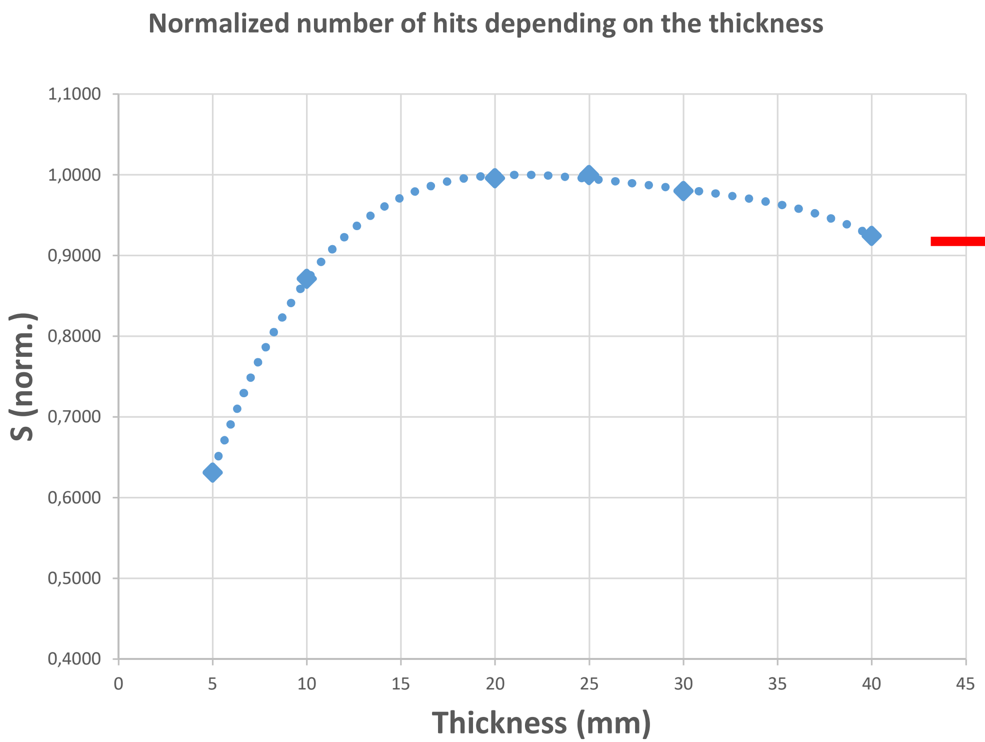
Geant4 simulations of gamma-ray emissions from samples of varying thicknesses

→ Number of nuclei created vs self-absorption effect



Activation samples

Thickness optimization: indium sample



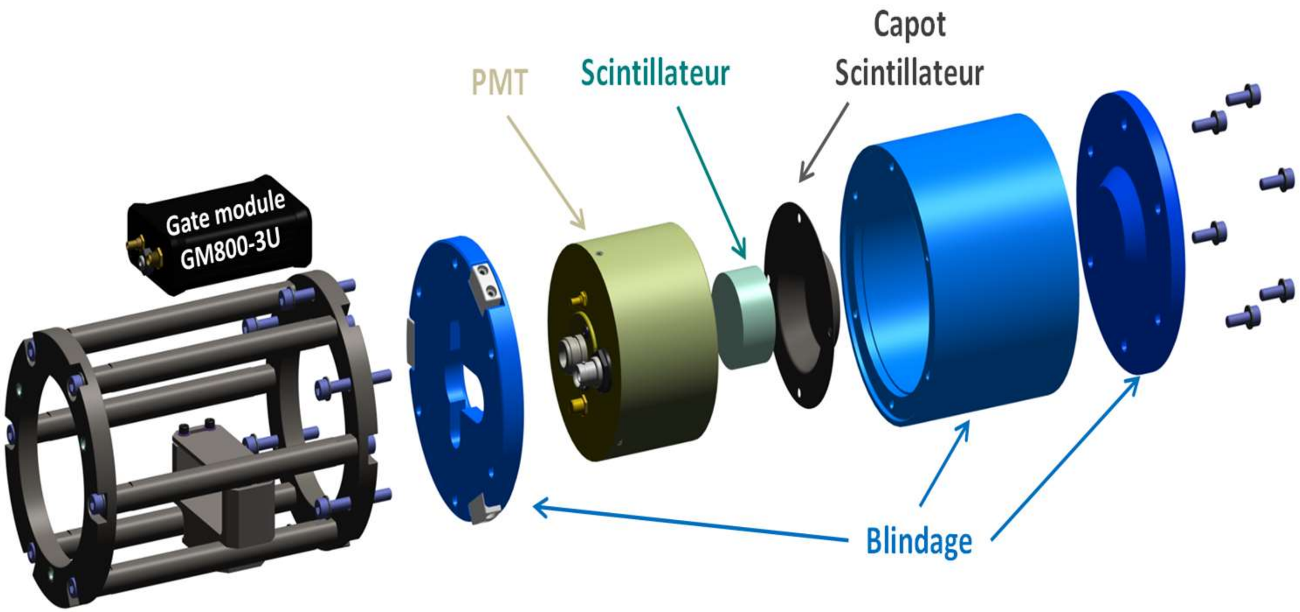
→ Optimum thickness ≈ 20 mm

10 mm → $A_0(^{115m}In)$ = 50,99 Bq & $A_0(^{116m}In)$ = 364,69 Bq

Time-of-flight detectors

- 40 mm diameter PVT-based scintillators (BC422Q)
- At 3.8 m from TCC
- Gated PMT: 4x GPMT140 (low gain)

  2x GPMT240 (high gain)



Simulations

Convertisseurs		LiF 4mm		Pb 2mm		LiF 1mm + Pb 1,5mm	
Réactions		(n,X)	(g,X)	(n,X)	(g,X)	(n,X)	(g,X)
Échantillon n°1 **In** **D=3 pouces** **e=10 mm**	^{115m}In	27,48 Bq	0,018 Bq	21,10 Bq	0,166 Bq	29,18 Bq	0,139 Bq
	^{116m}In	17,03 Bq	0,253 Bq	24,25 Bq	3,04 Bq	26,08 Bq	2,52 Bq
	^{113m}In	0,374 Bq	0,447 Bq	0,118 Bq	5,40 Bq	0,258 Bq	4,58 Bq
Échantillon n°2 **Fe** **D=3 pouces** **e=10 mm**	^{56}Mn	5,05 Bq	0,016 Bq	1,60 Bq	0,143 Bq	3,78 Bq	0,116 Bq
	^{54}Mn	0,005 Bq	0,0003 Bq	0,002 Bq	0,004 Bq	0,004 Bq	0,004 Bq
	^{55}Fe	0,002 Bq	0,006 Bq	0,001 Bq	0,076 Bq	0,001 Bq	0,063 Bq
Échantillon n°3 **Zr** **D=3 pouces** **e=15 mm**	^{89}Zr	0,232 Bq	0,773 Bq	0,072 Bq	9,40 Bq	0,175 Bq	7,85 Bq
	^{97}Zr	0,024 Bq	0,0005 Bq	0,032 Bq	0,005 Bq	0,035 Bq	0,004 Bq
	^{91}Sr	0,008 Bq	0 Bq	0,002 Bq	0,0004 Bq	0,005 Bq	0 Bq