

Neutron Field Characterization: Spectral and Fluence for AB-BNCT and BSA optimization

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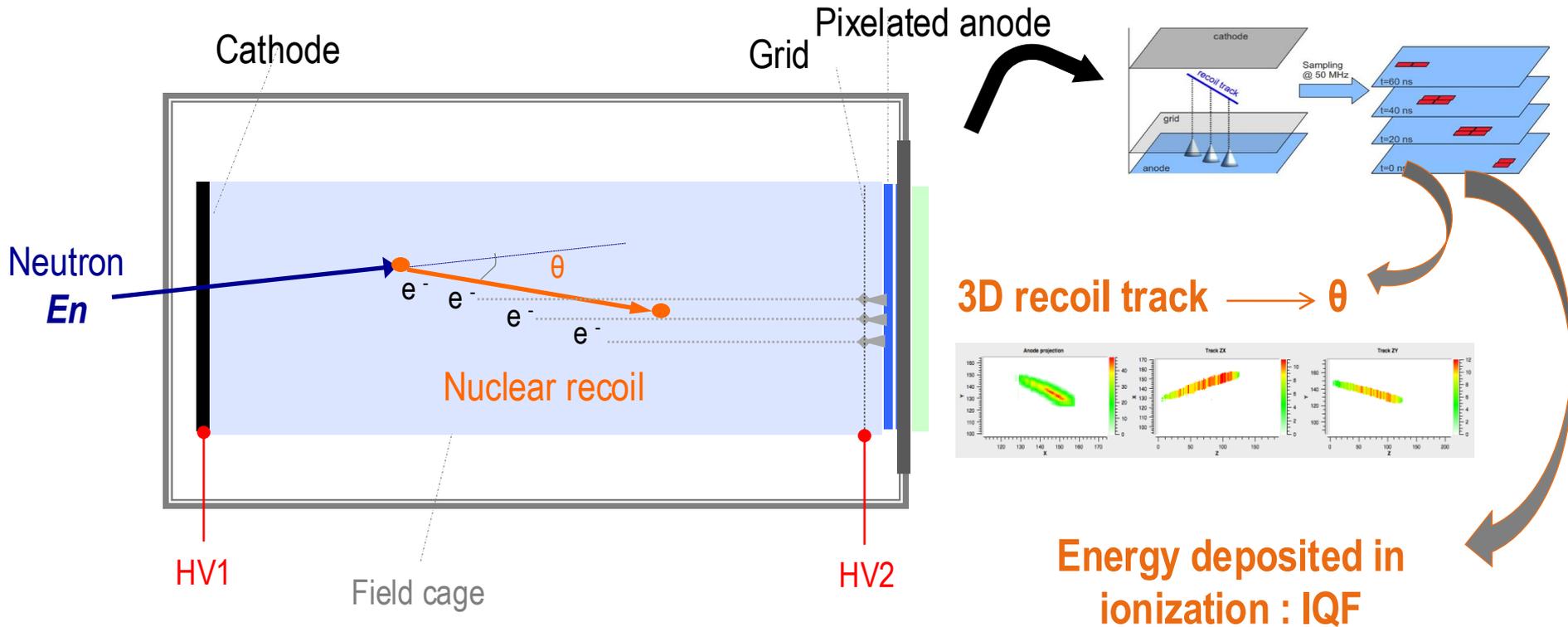
Enya Mobio (PhD), Amokrane Allaoua

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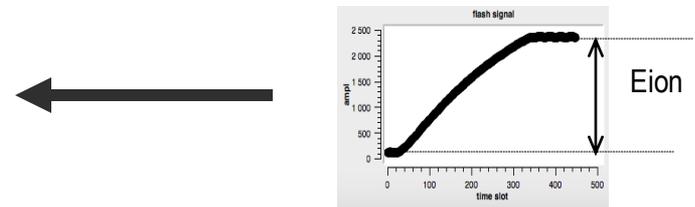
ASNR(ex-IRSN)-France

How can we measure a neutron energy produced by a non-pulsed beam ?

➤ 3D-nuclear recoil camera + Ionization Quenching Factor (IQF)



From θ , E_{ion} , and the IQF,
we get the neutron energy E_n

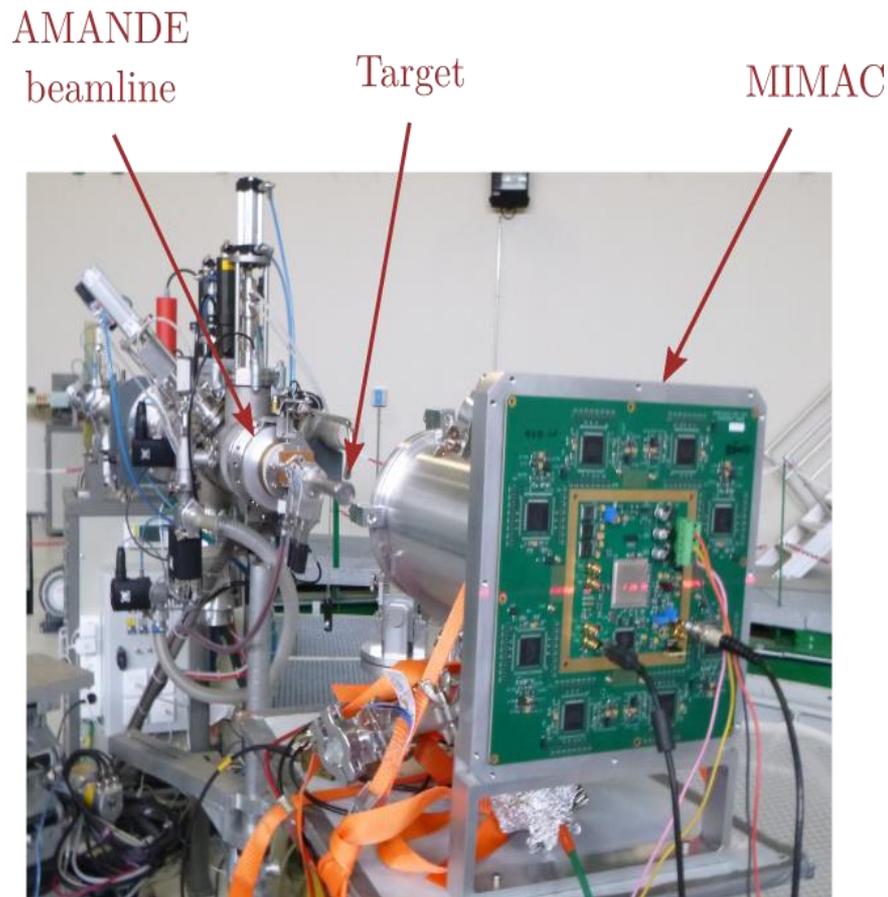


Demonstration of the directional detection with mono-energetic neutron fields

- The AMANDE facility (ASNR (ex-IRSN)-Cadarache) provides mono-energetic neutron fields
- The energy of a mono-energetic neutron field is defined by the angle of **each nuclear recoil** track with respect to the neutron direction...

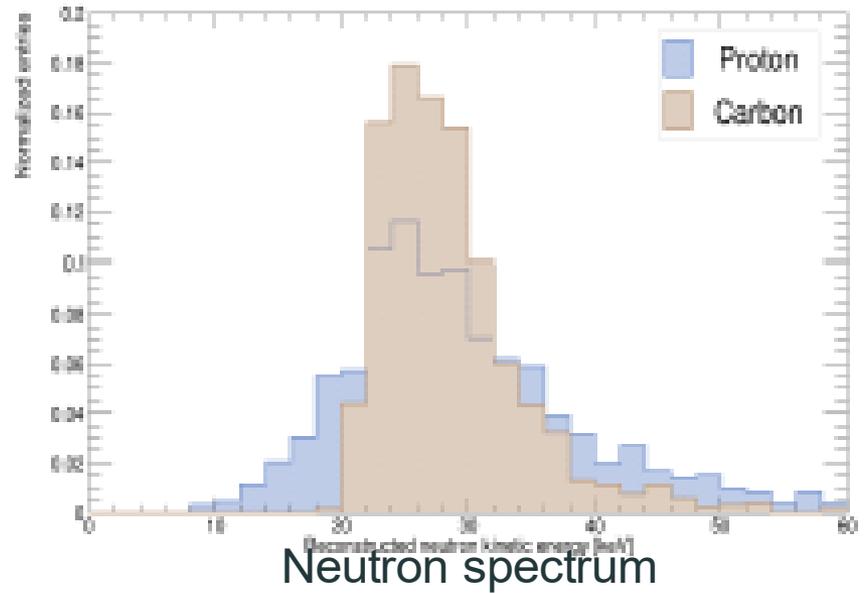
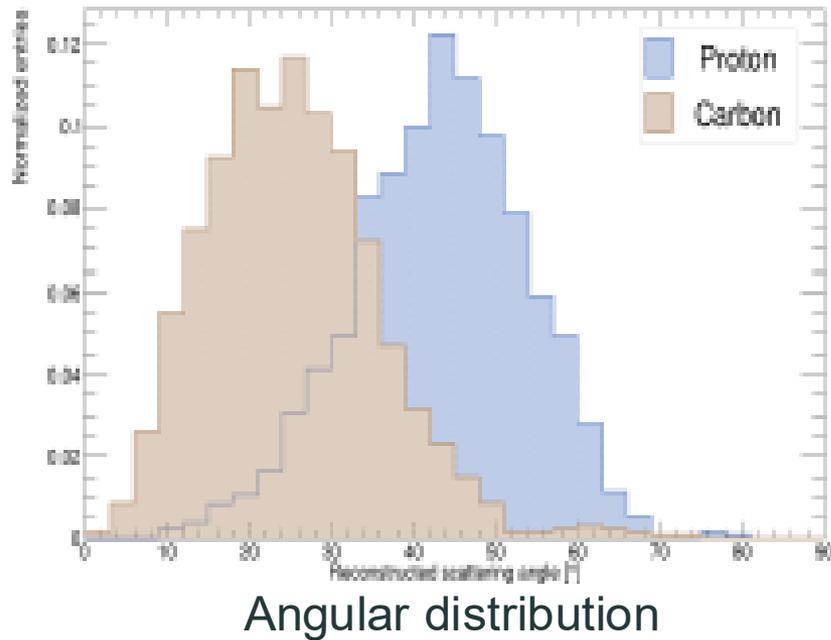
But the ionization energy of the recoil is different of its kinetic energy...

It is quenched !!

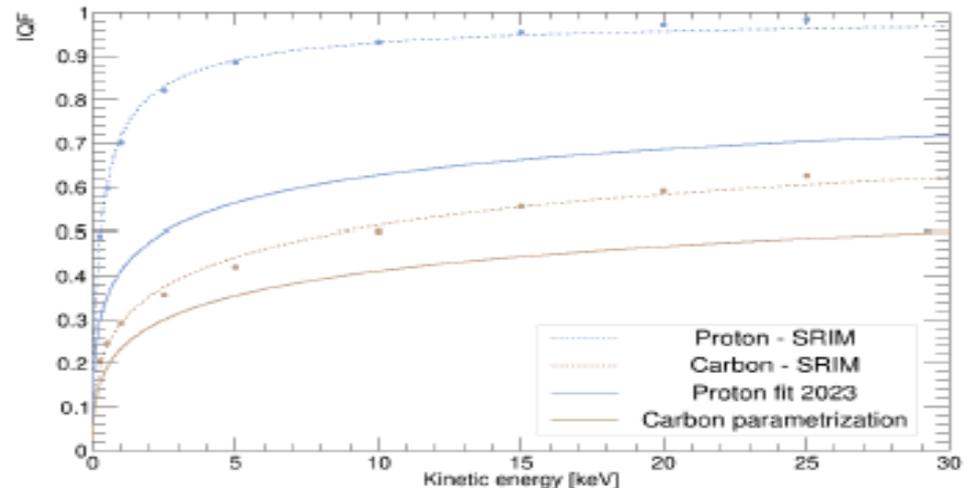


At low energies... 27 keV neutron field Proton and carbon recoils give the same neutron energy !

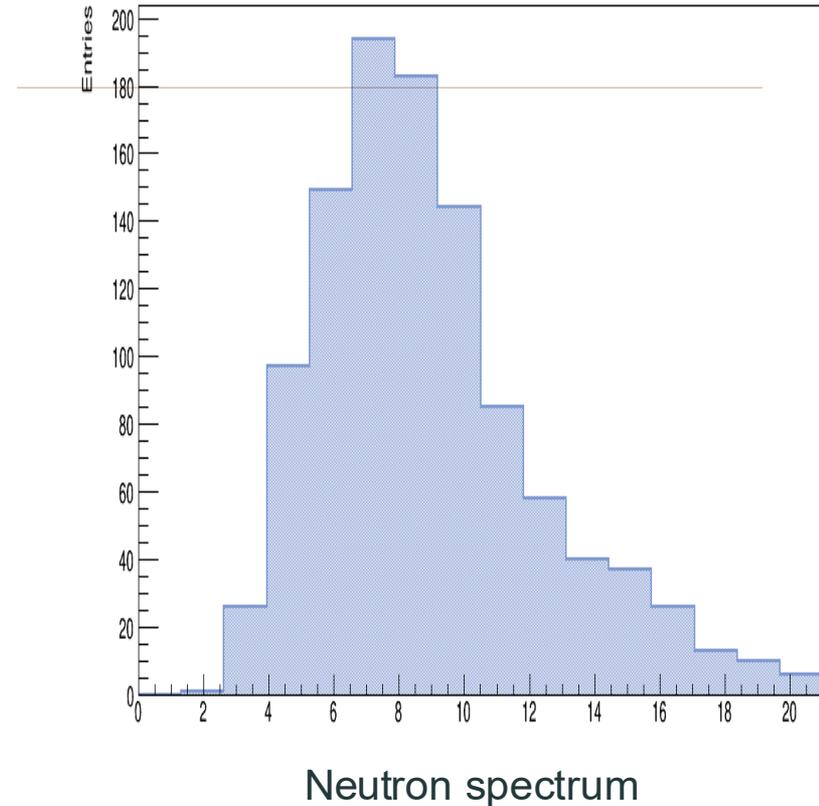
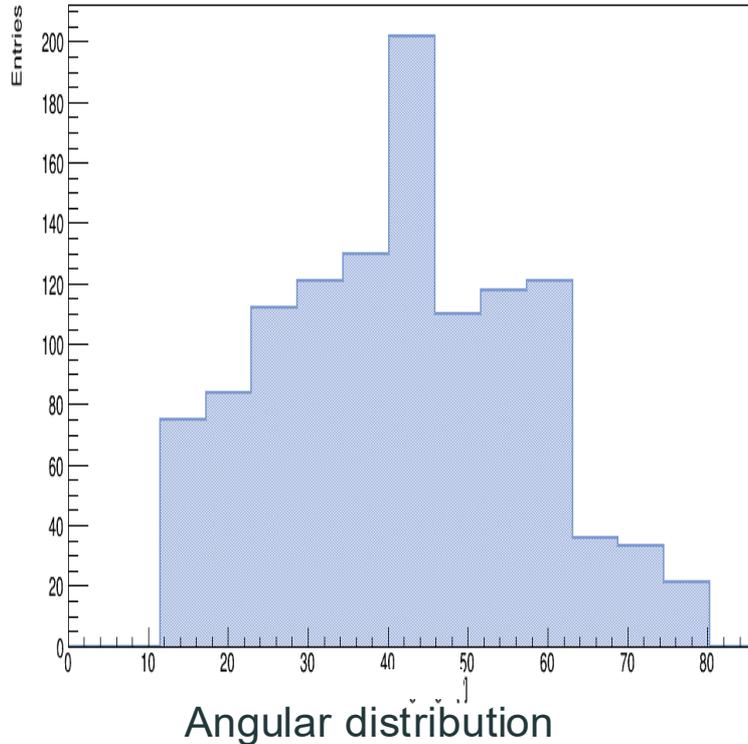
C. Beaufort *et al* 2024 *JINST* 19 P05052, [arXiv:2312.12842](https://arxiv.org/abs/2312.12842)



The kinetic energy is reconstructed with the Ionization quenching factor measured by COMIMAC



A mono-energetic Epithermal neutron field (8 keV) Neutron spectrum reconstruction from proton recoils



Directional performances at 8 keV

Cyprien Beaufort et al. JCAP08(2022)057

Polyenergetic measurement with ${}^9\text{Be}(d(1.45\text{ MeV}),n)$

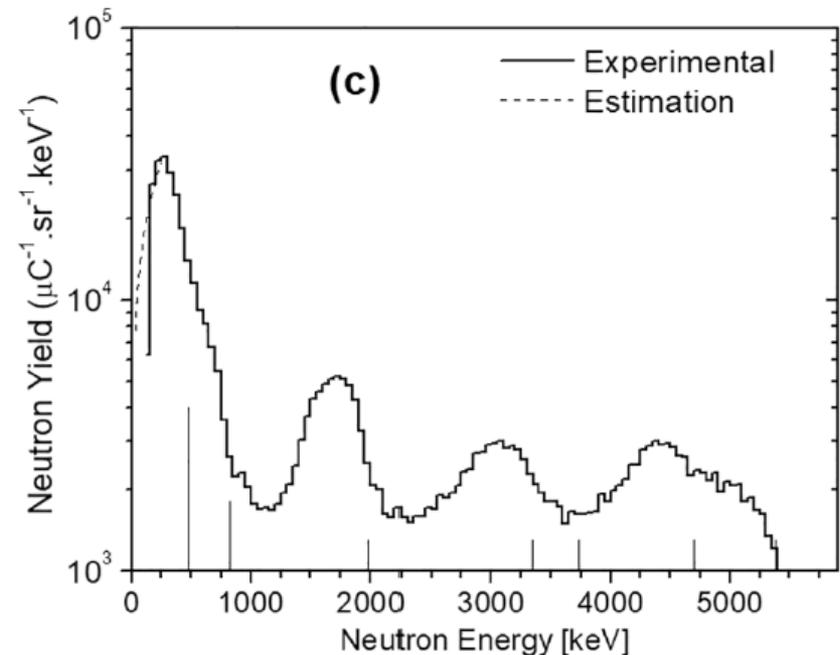
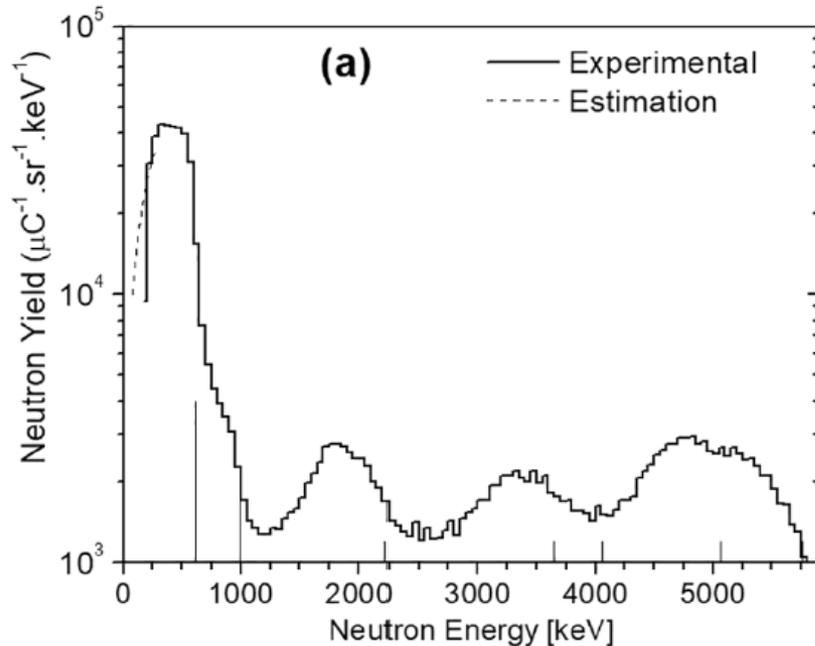
Angular distribution
for an AB-BNCT nuclear reaction

INFN LNL
(Legnaro - Italy)

700 mbar
He/CO₂ (5%)

Spectrum measured at 0 deg

Spectrum measured at 60 deg



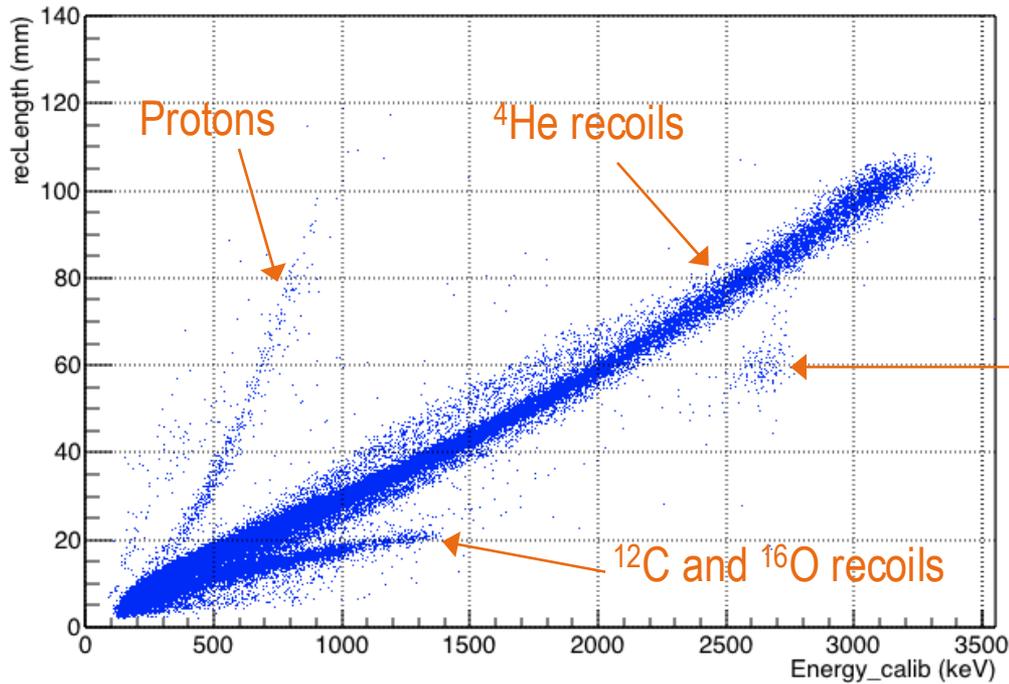
M.E. Capoulat, N.Sauzet *et al.*

« Neutron spectrometry of the ${}^9\text{Be}(d(1.45\text{ MeV}),n){}^{10}\text{B}$ reaction for accelerator-based BNCT »

NIM B, vol. 445, pp. 57-62, 2019

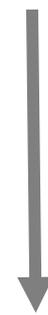
Selection of ^4He nuclear recoils : $\text{D}(\text{d}(1.8 \text{ MeV}),\text{n})$

Discrimination from protons, ^{12}C , ^{16}O , and (n,α) reactions

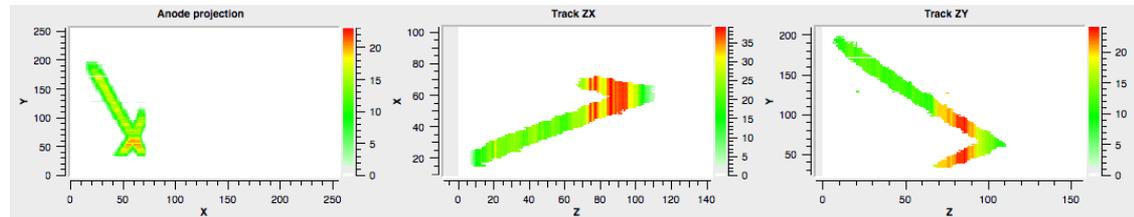


700 mbar He/CO_2 (5%)

$^{16}\text{O}(\text{n},\alpha)^{13}\text{C}$

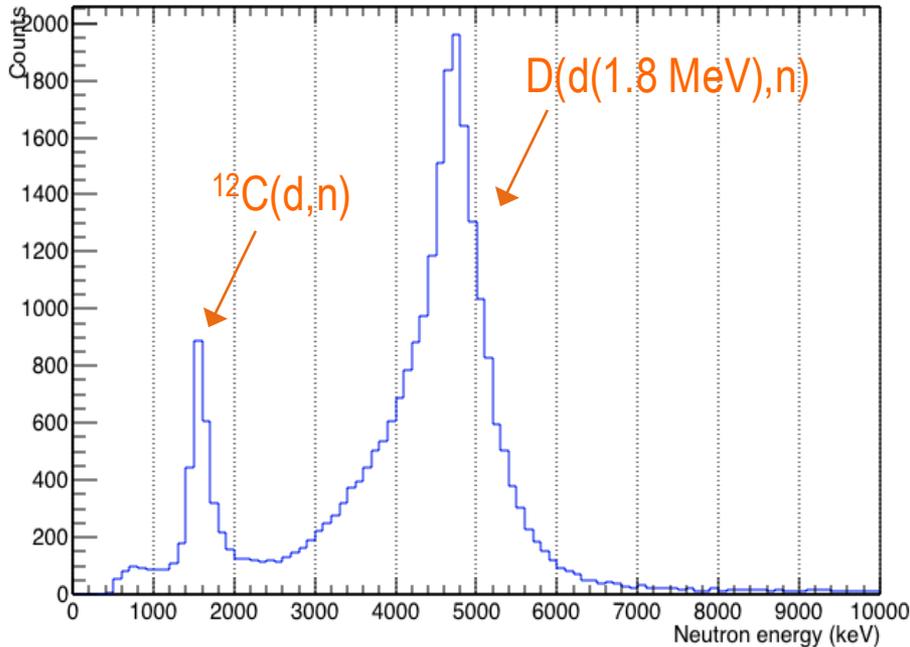


IRSN / AMANDE
(Cadaraache)



Monoenergetic measurements : detection of target pollutions

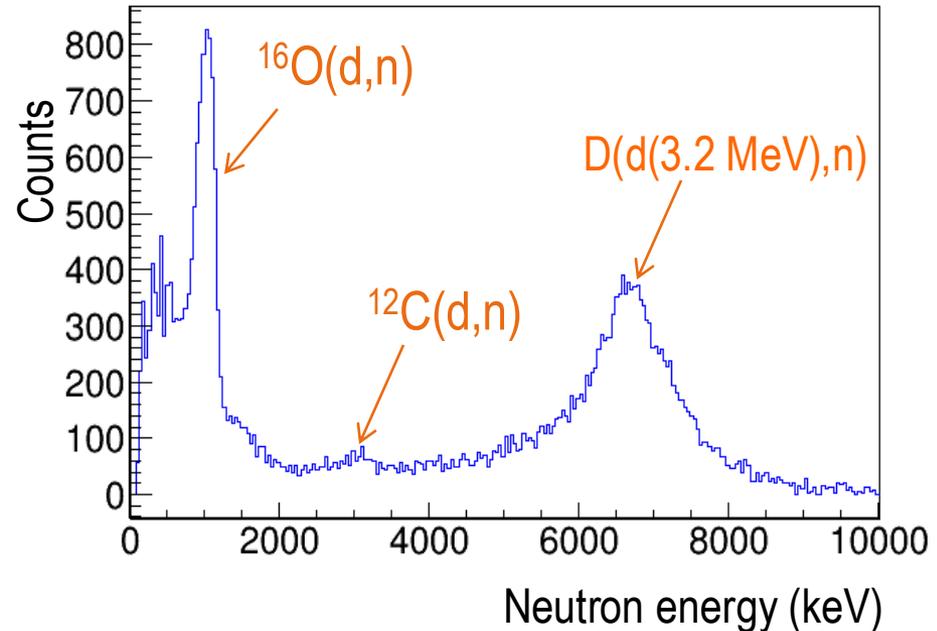
D(d(1.8 MeV,n) : neutrons of 5 MeV



NPL/(UK)

700 mbar He/CO₂ (5%)

D(d(3.2 MeV,n) : neutrons of 6.5 MeV

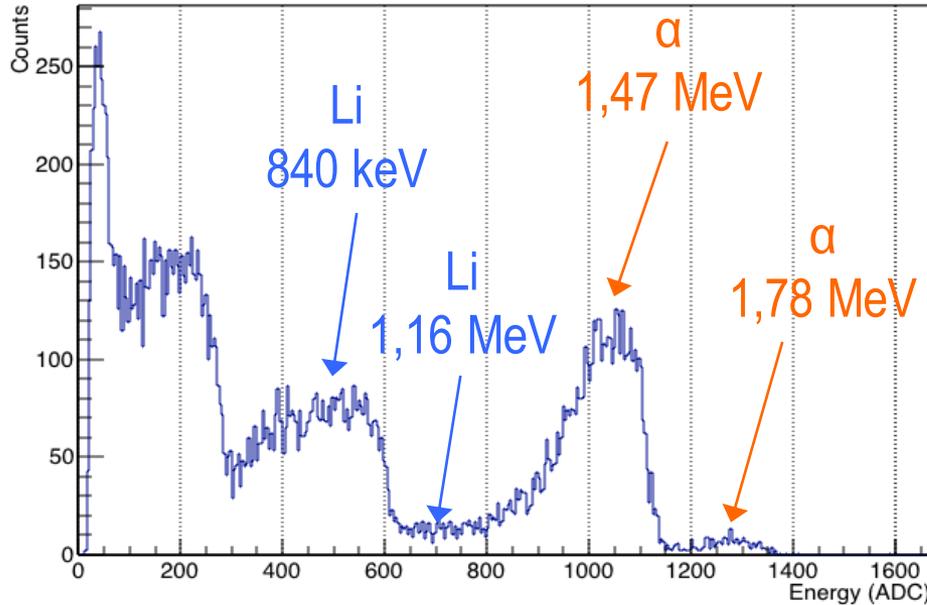


IRSN / AMANDE
(Cadarache)

The targets have in general pollutions not well determined generating neutrons not taken into account in simulations... We have to characterize the neutron field produced at the target

Energy calibration, Thermal neutron fluence and Active BNCT Phantom

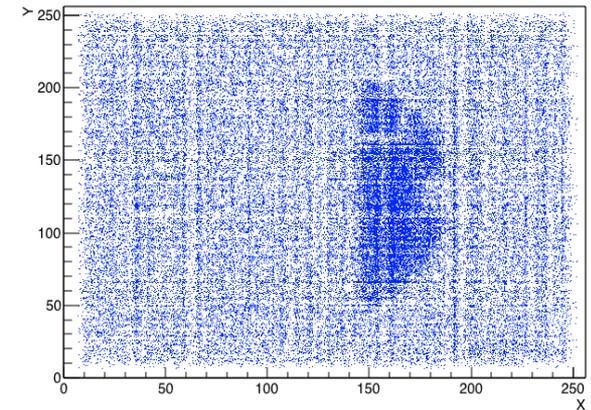
Detection of α and ${}^7\text{Li}$, resulting from thermal neutron capture on a B_4C layer



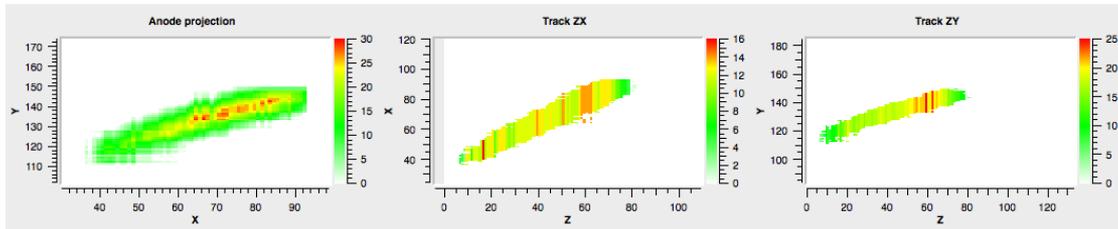
B_4C layer
on the cathode
(500 nm thick)



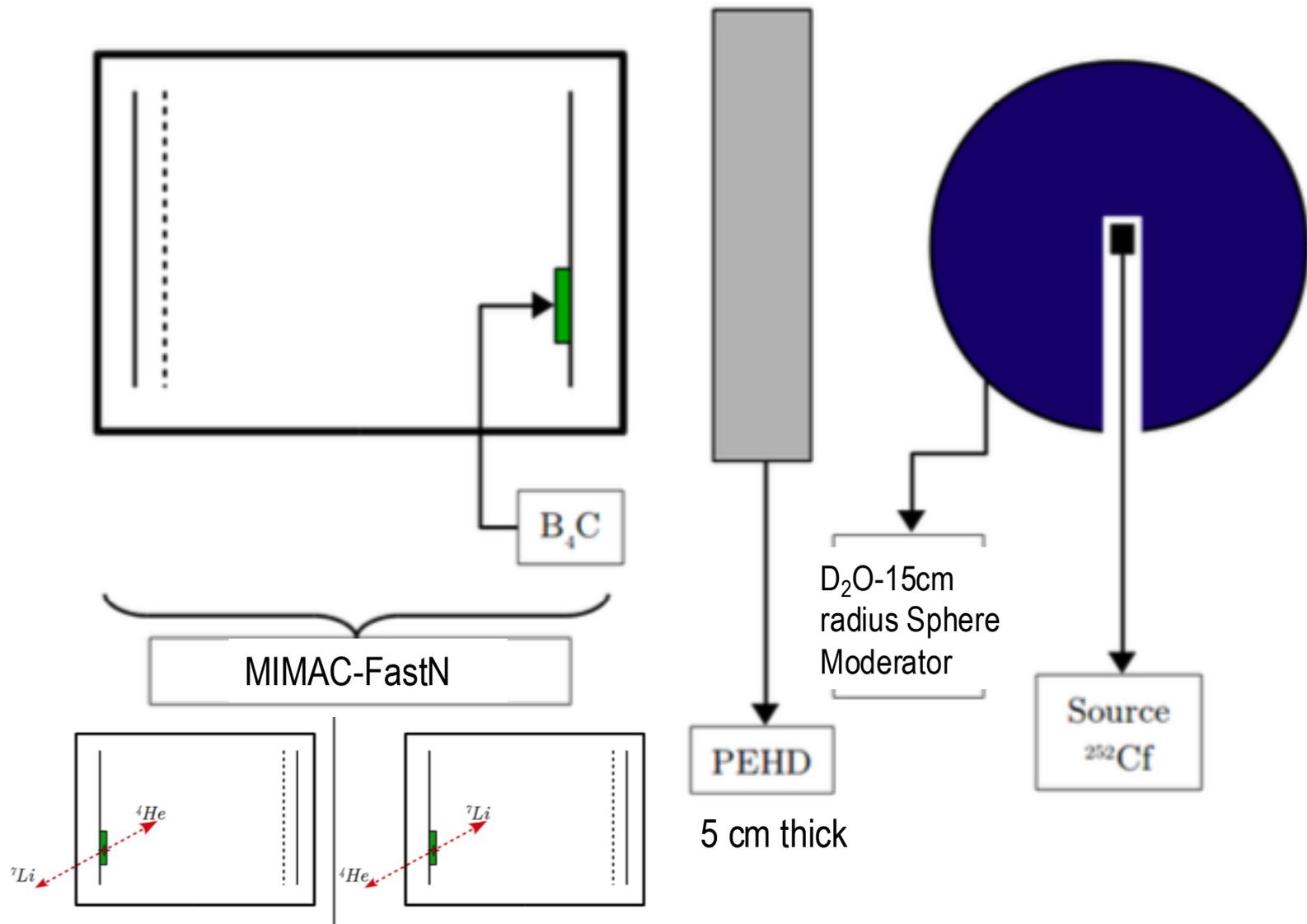
Anode projection : track start



Alpha track



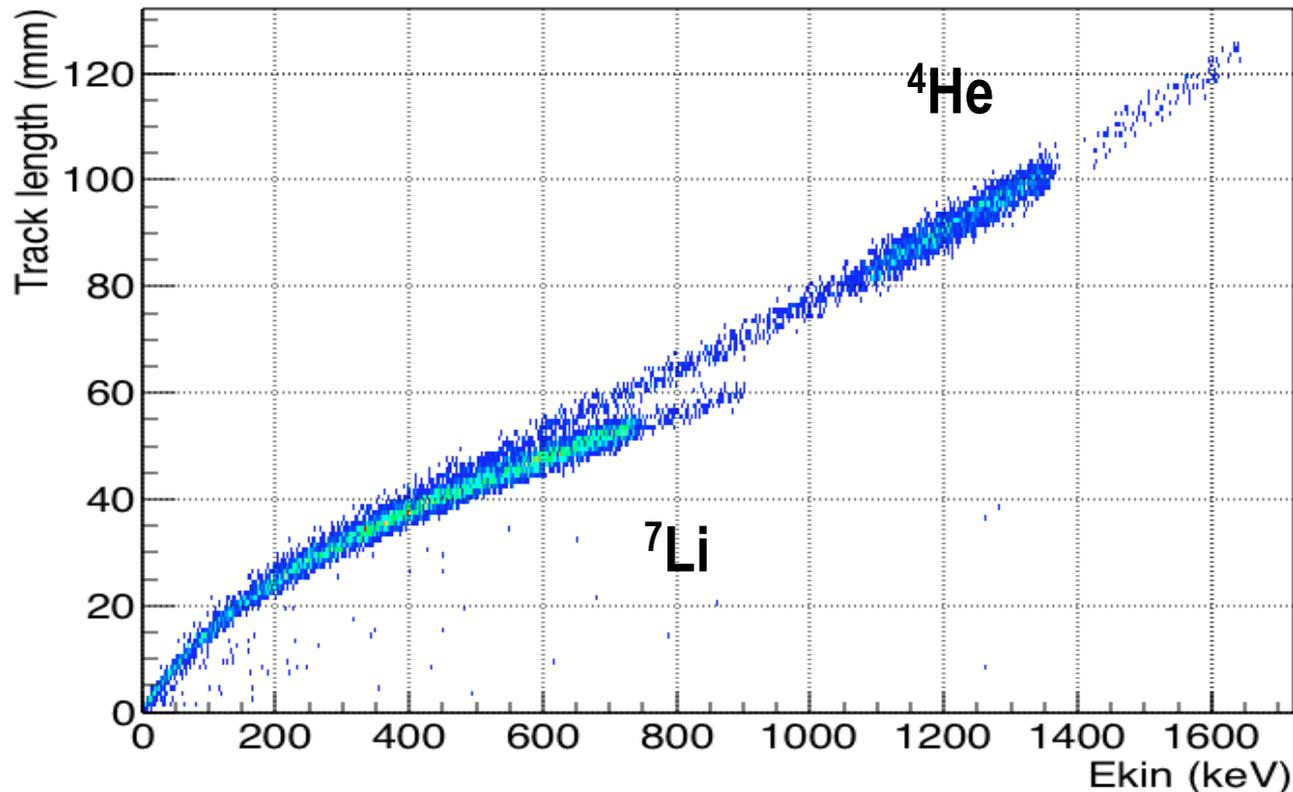
Experimental Set-up (schematic) to test the Active-Phantom Mode



Geant4 Simulation of the MIMAC-FastN-Active Phantom

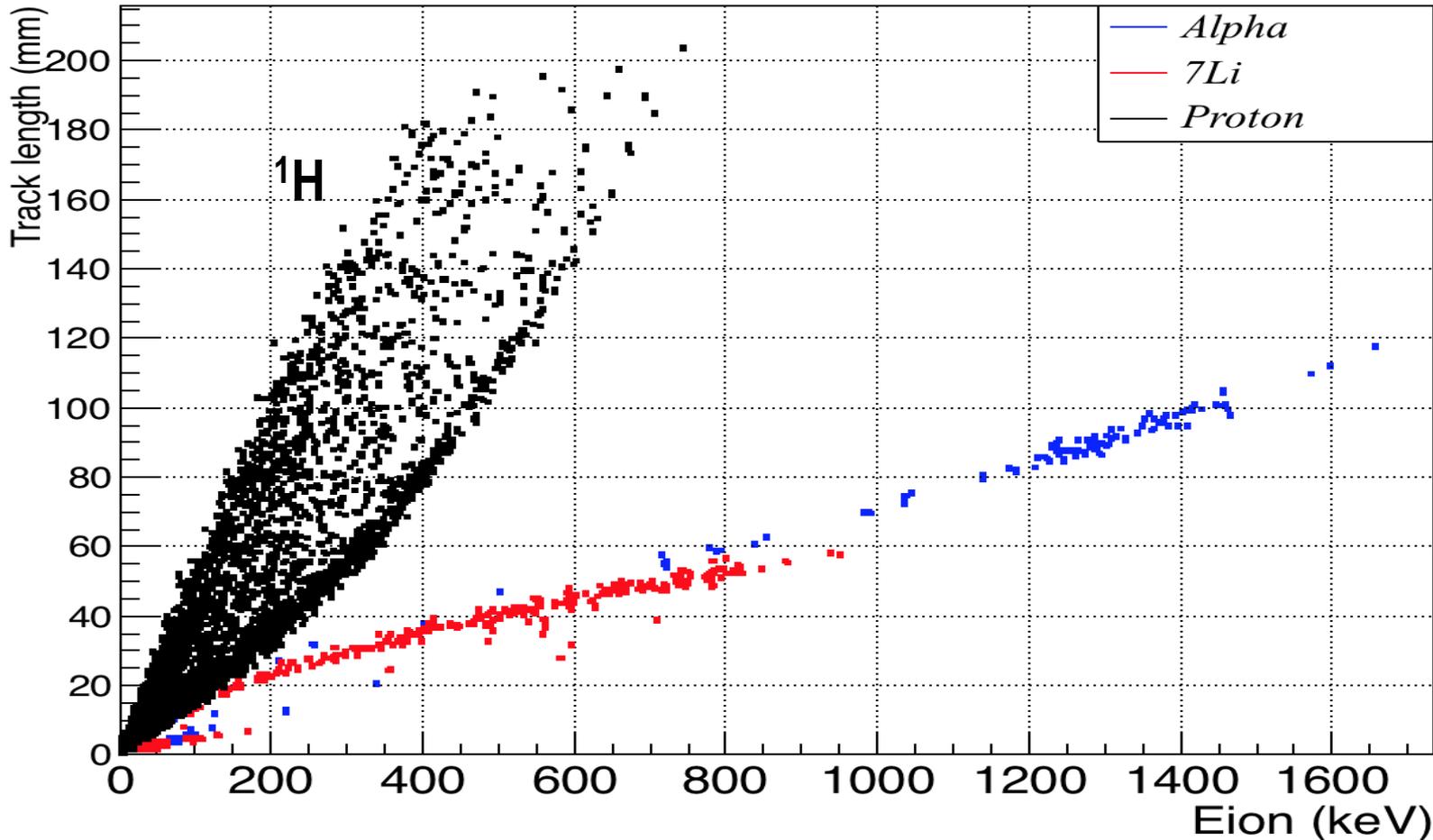
Clear separation of the alpha and ${}^7\text{Li}$ branches with the both components each

Track length totally included in the $\text{C}_4\text{H}_{10} + 50\% \text{CHF}_3$ at 30 mbar



Geant4 Simulation showing all the recoils produced and stopped inside the active volume

The proton background is easily discriminated with respect to the alpha and lithium nuclear recoils in $C_4H_{10} + 50\% CHF_3$ at 30 mbar



Experimental Set-up

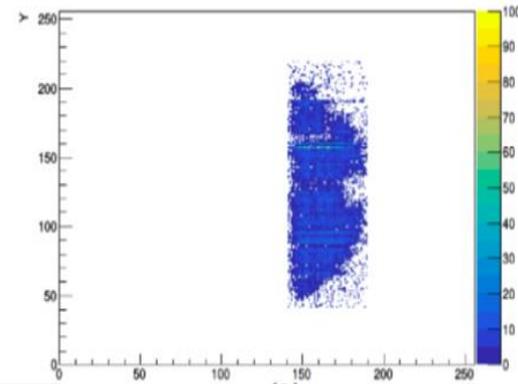
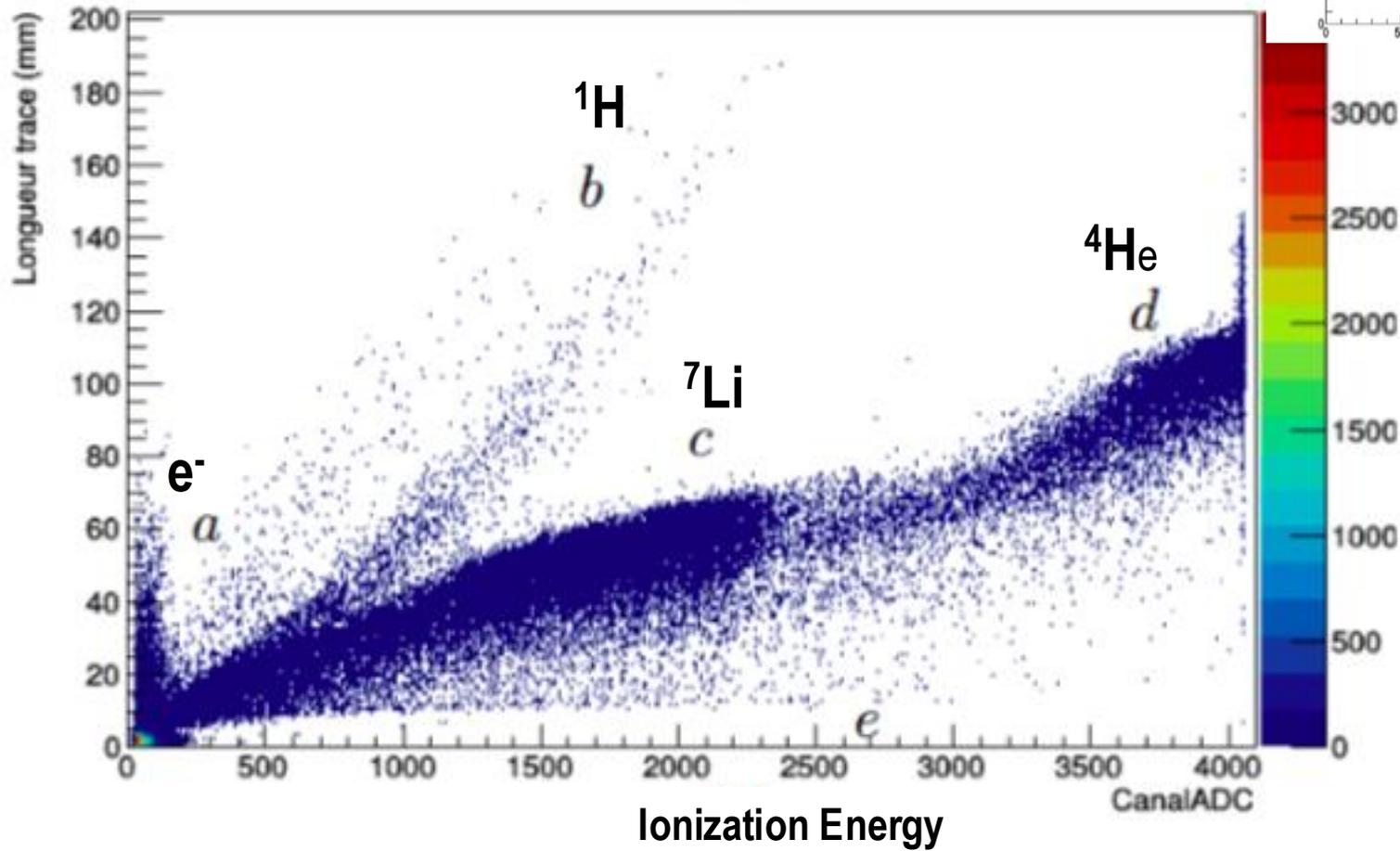
Set-up at the IRSN-Cezane facility at Cadarache (France)
Bruno Asselineau, Michaël Petit, Thibaut Vinchon



Neutron Capture on ^{10}B with MIMAC-Active Phantom mode

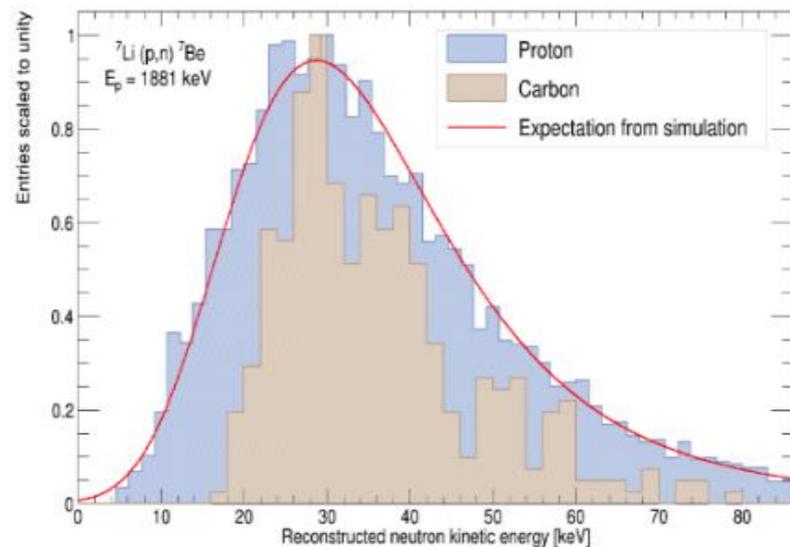
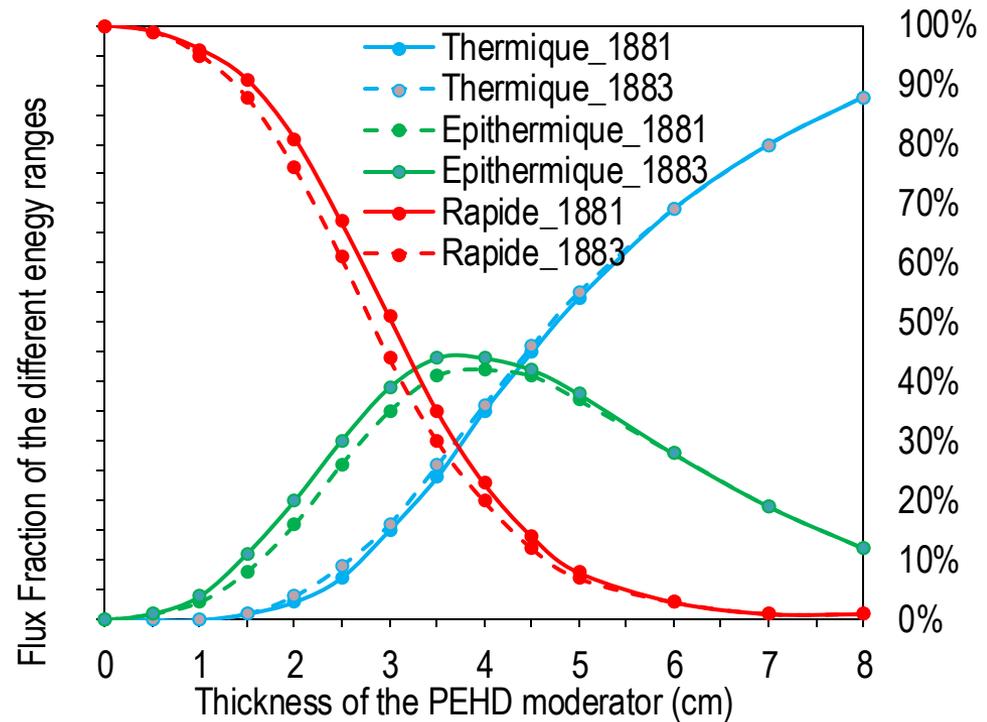
Data from the MIMAC-Active Phantom using the
Experimental Set-up shown before with
 $\text{C}_4\text{H}_{10} + 50\% \text{ CHF}_3$ at 30 mbar

Track length (mm) vs. Ionization Energy (ADC channel)



A complex epithermal neutron field characterization

At AMANDE facility, with a near threshold ${}^7\text{Li}$ (p (E=1.881 MeV),n) reaction



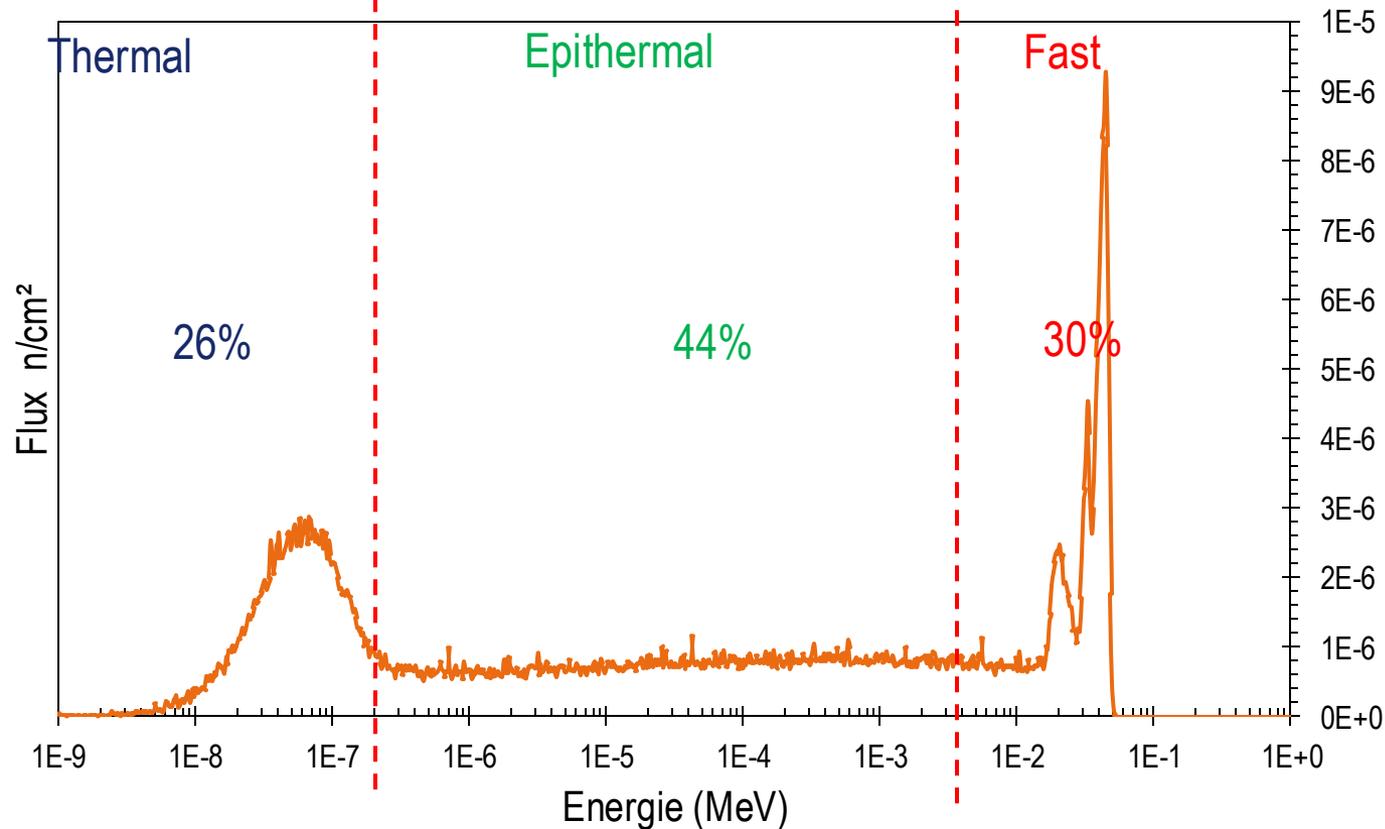
C. Beaufort et al.
JINST, P05052 (2024)

Daniel Santos



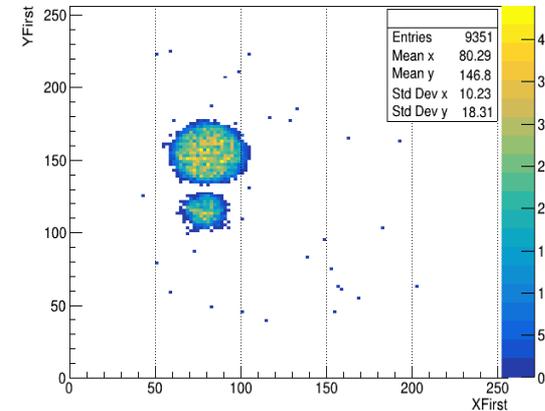
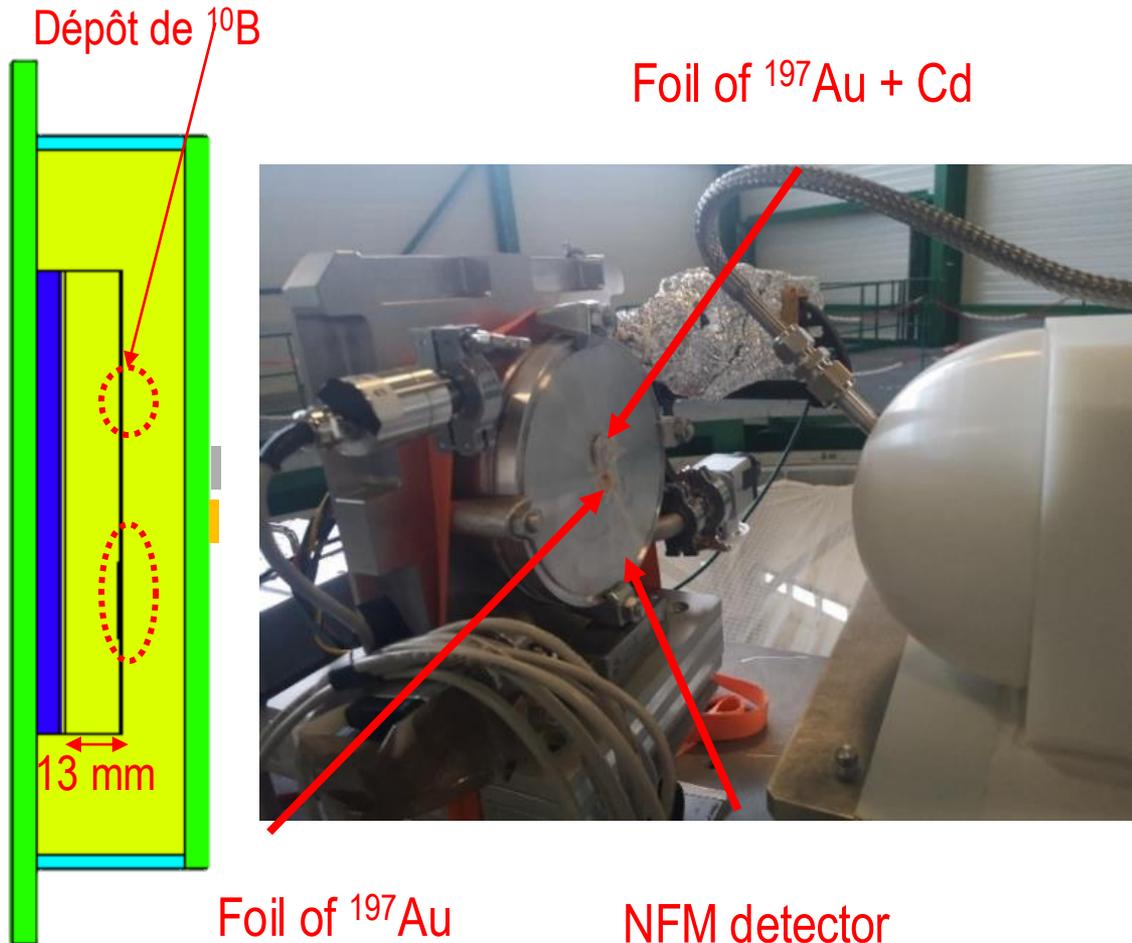
Spectral distribution after neutron moderation

Spectral distribution (MCNP simulation) of the neutron flux coming out the moderator (3,5 cm thickness)

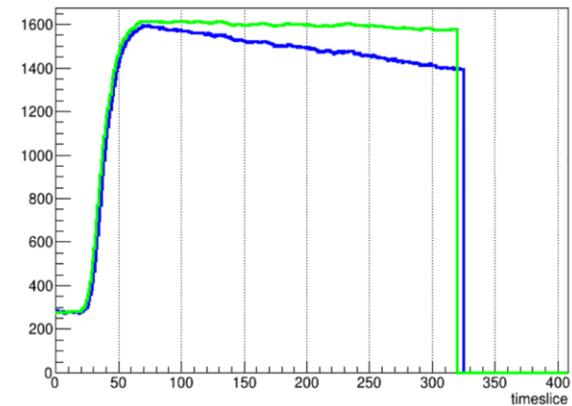


E. Mobio et al. (2025)

Neutron flux measurements by the Gold foil Activation method and by the Neutron Flux Monitor (NFM) detector

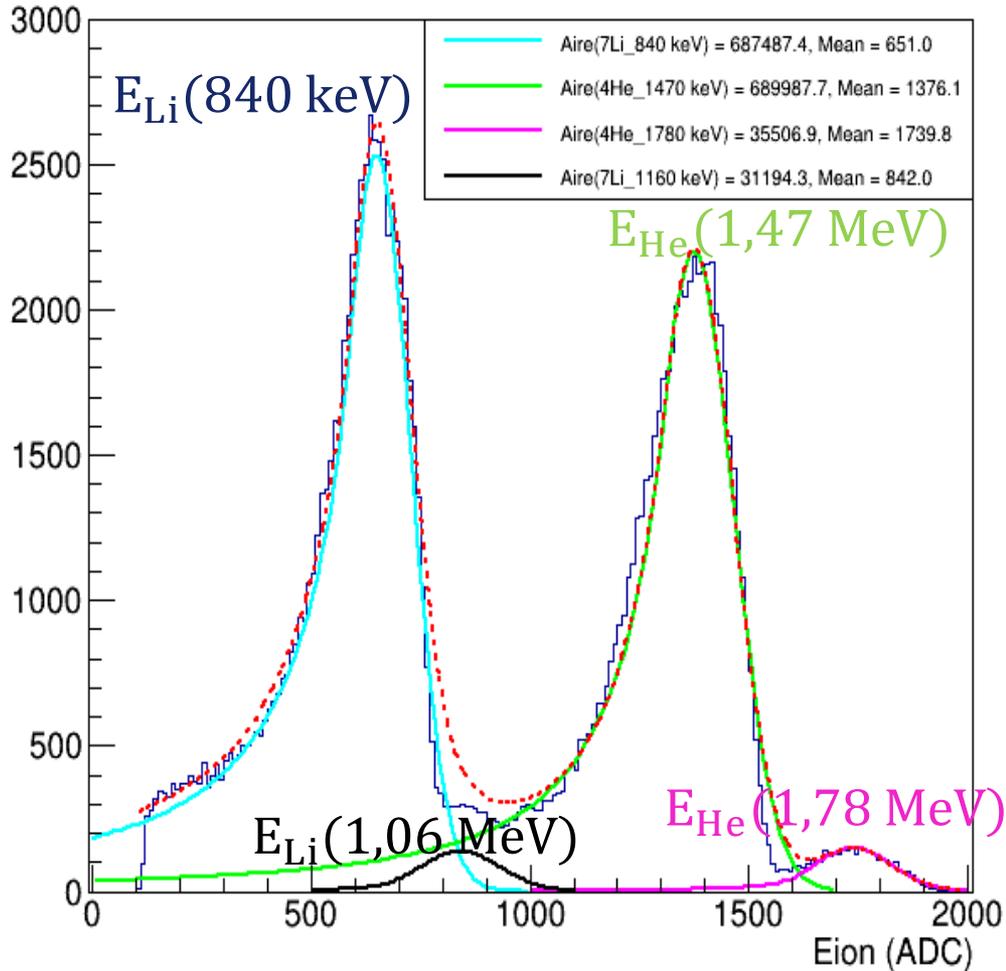


Distribution of the first measurement of the 3D-tracks



FADC profile of an alpha (1.24 MeV) event as a function of the sampling (20 ns)

Alpha and ${}^7\text{Li}$ energies measured with the NFM



$A_{{}^7\text{Li}} = A_{{}^4\text{He}}$
(difference < 1%)

Thermal and Epithermal Fluence Results

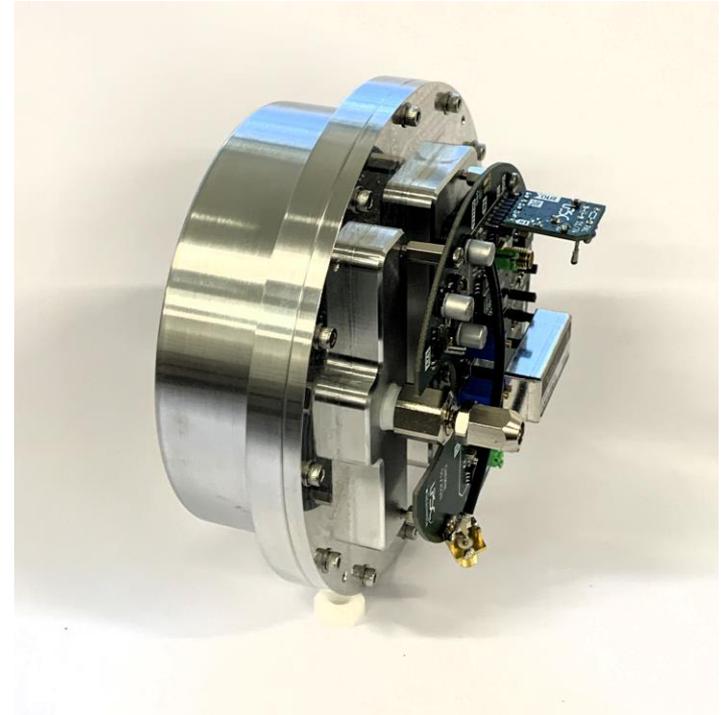
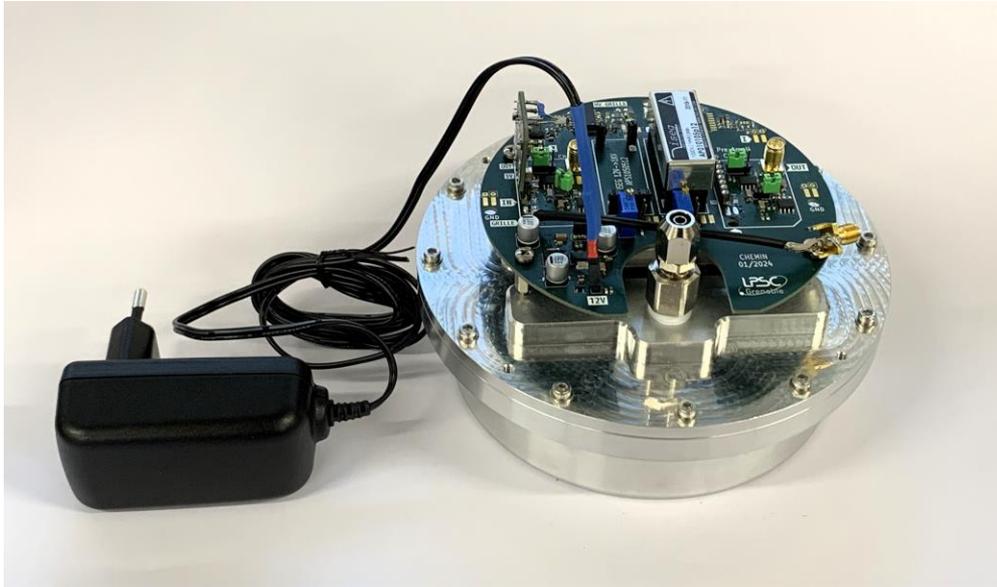
From the Activation of Gold foils and the Neutron Flux Monitor detector compared with the MCNP simulation calculation

		Φ_{th} (n.cm ⁻² .s ⁻¹)	C/E	Difference	Φ_{epi} (n.cm ⁻² .s ⁻¹)	C/E	Diff
¹⁹⁷ Au	Calcul	$(7,52 \pm 0,32).10^2$	0,68	- 46%	$(1,06 \pm 0,05).10^3$	1,25	+20%
	Exp.	$(1,10 \pm 0,08).10^3$			$(8,53 \pm 0,84).10^2$		
NFM	Calcul	$(5,66 \pm 0,25) .10^2$	0,94	- 6 %	$(9,08 \pm 0,40).10^2$	0,94	- 6 %
	Exp.	$(6,03 \pm 0,34).10^2$			$(9,64 \pm 0,55).10^2$		

Enya Mobio (LMDN (ASNR)), PhD thesis (April 2025)

NFM (Neutron Flux Monitor) Detector

Ready to be used...



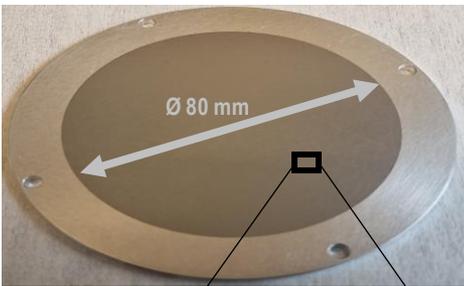
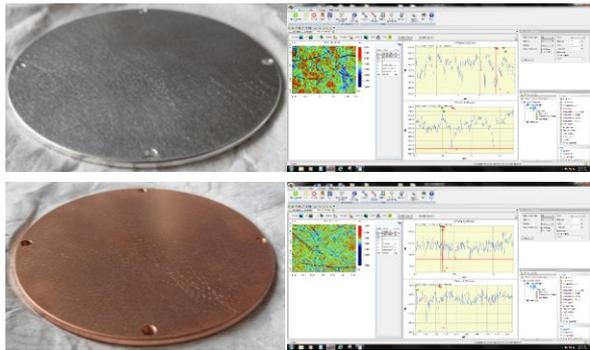
Including a Boron layer very well measured (thickness, surface and homogeneity !!)

Multi-layer deposition PAPVD (plasma-assisted)

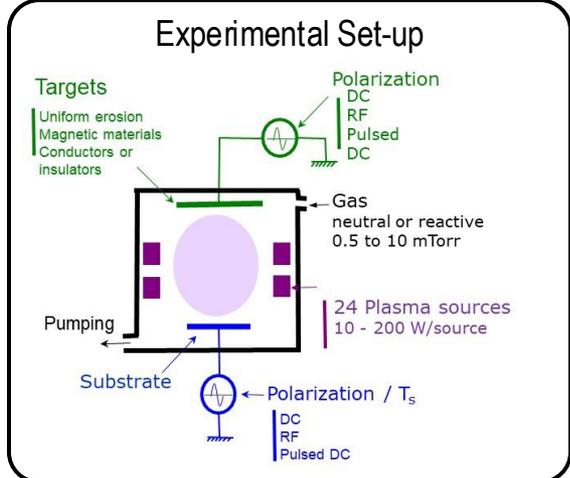
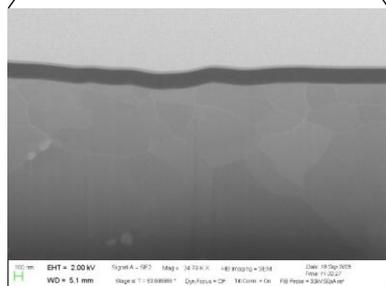
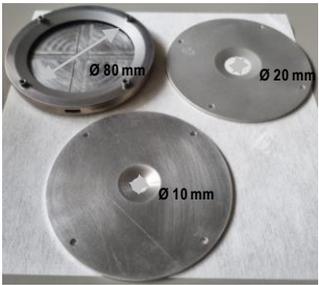
LPSC – Alexandre BES, Ana LACOSTE

Cathode availables Al et Cu

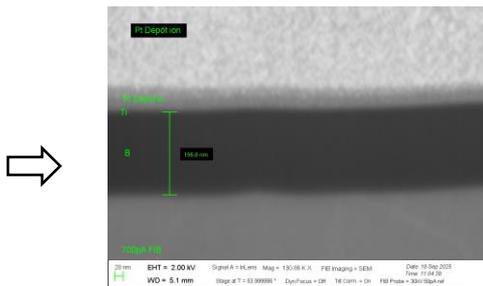
Roughness between 1 et 3 μm



Masks of 10, 20 and 80 mm diameter



Production of a layer of $200 \pm 5 \text{ nm}$ of natB + 10 nm of Ti on an Aluminium cathode



Topology Optimization of Neutron Moderators

BSA design methodologies

What criteria does the community use to design BSAs?

Method 1: in the past, BSA often designed so that the **neutron field at its exit verified some in-air FOMs**. E.g. $\phi_{\text{epi}} > 5e8 \text{ cm}^{-2}\text{s}^{-1}$ (intensity), $D_{\text{fast}}/\phi_{\text{epi}} < 2e-13 \text{ Gy}\cdot\text{cm}^2$ (purity), etc.

Issue: in-air FOMs found too restrictive, can eliminate BSAs with best therapeutic performance
IAEA TECDOC 2001: in-air FOM "values [...] are specifically not suggested as 'requirements' or 'recommendations' that have to be achieved by a system provider"

→ **method 1 becoming obsolete**

Method 2: a therapeutic target is chosen, often a GB of a few cm^3 placed at a depth of $\sim 3\text{-}4 \text{ cm}$ in a patient's head. BSA then designed to **maximize $D_{\text{tum}}/D_{\text{brain}}$ or a TCP**.

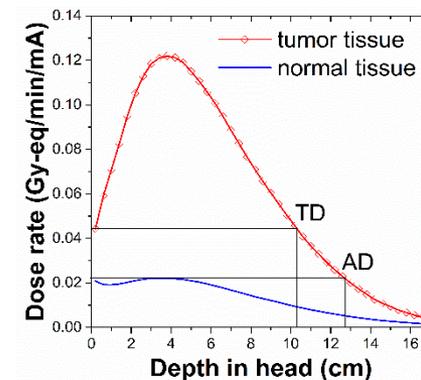
Issue: arbitrariness of the choice of tumor configuration

→ **expected design suboptimality for treating other tumor configuration**

Method 3: BSA designed to **maximize dosimetric FOMs, most often AD (Advantage Depth) or TD (Treatment Depth)**.

TD gives a **range of depth** in body where tumor tissue receives at least 2 times the max. dose in normal tissue

→ **common methodology, extensively explored in literature**

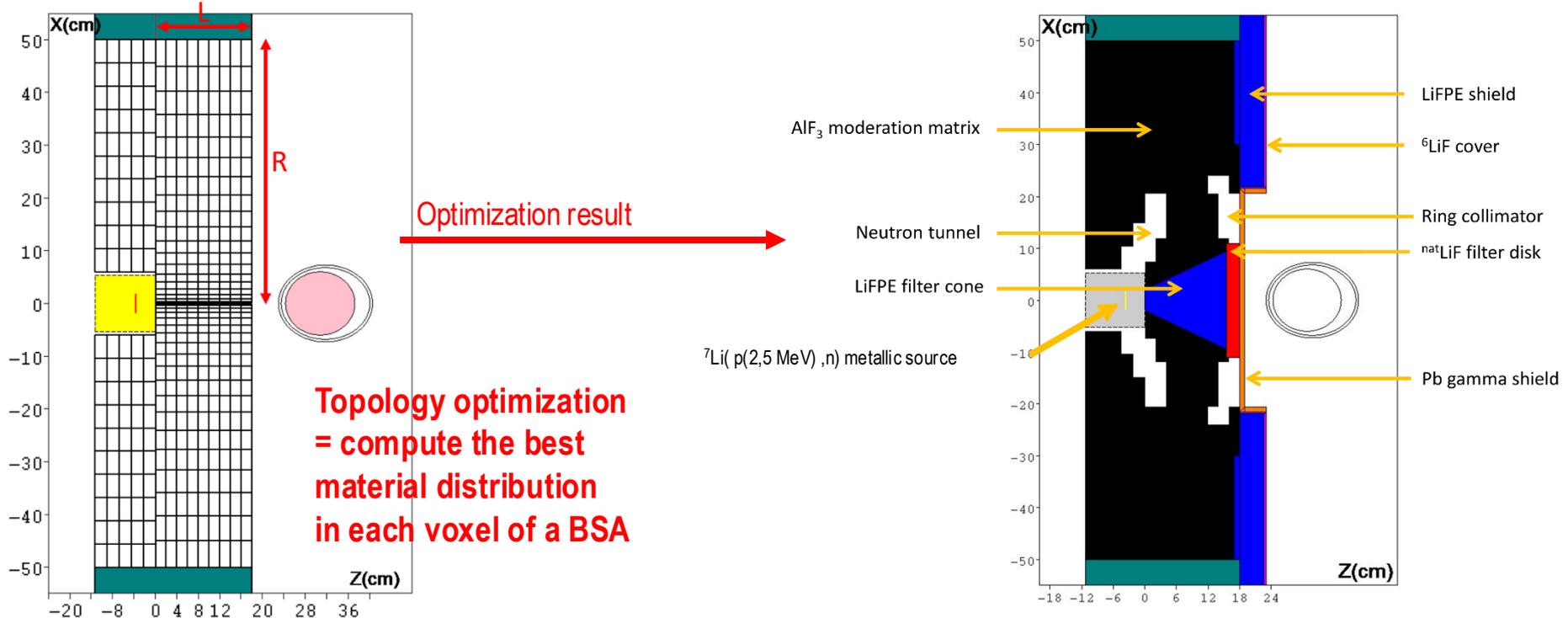


Modern BSA design calculation methods

S. Chabod et al., Phys. Med. Biol. 2025, 70 (3), pp.035008

Breakthrough in recent years: recent developments in algorithms (machine learning, topology optimization, etc.) now allow unbiased computations of the structures of BSAs.

Ex of result: TopOpt computation of the best BSA structure that **max TD s.t. TT < 1h** for GB



State of the art of BSA design using method 3

Progress in the dosimetric performance of BSAs over the past 30 years

Study	Source	C _B (ppm)	AD (cm)	TD (cm)
Bleuel et al. 1998	BMR Reactor	13	8.4	NA
	⁷ Li(p(2.4 MeV),n)	13	9.9	NA
Riley et al. 2003	MIT Reactor	18	9.7	7.8
Kononov et al. 2004	⁷ Li(p(2.3 MeV),n)	18	9.1	7.0
Kim et al. 2009	⁷ Li(p(2.5 MeV),n)	10	8.1	6.0
Tanaka et al. 2009	KU Reactor	15	8.4	NA
	KU Reactor	18	8.6	NA
	⁹ Be(p(30 MeV),n)	15	8.9	NA
	⁹ Be(p(30 MeV),n)	18	9.1	NA
Inoue et al. 2014	⁹ Be(p(8.0 MeV),n)	10	7.5	5.0
Minsky et al. 2014	⁷ Li(p(2.3 MeV),n)	15	9.5	7.0
Capoulat et al. 2014	⁹ Be(d(1.45 MeV),n)	15	9.6	7.8
Capoulat et al. 2017	¹³ C(d(1.45 MeV),n)	15	10.0	7.8
Koay et al. 2018	W(p(50 MeV),n)	18	9.3	NA
Torres-Sánchez et al. 2021	⁷ Li(p(2.1 MeV),n)	18	9.74	7.85
Bae et al. 2022	⁹ Be(p(10 MeV),n)	18	9.0	7.2
Zhang et al. 2023	⁷ Li(p(2.3 MeV),n)	18	11	NA
Rong et al. 2024	⁷ Li(p(2.8 MeV),n)	18	8.24	6.5
Verdera et al. 2024	⁴⁵ Sc(p(2.918 MeV),n)	18	9	7
Chabod et al. 2025	⁷Li(p(2.5MeV),n)	18	12.7	10.3

C_B = Boron-10 concentration in blood

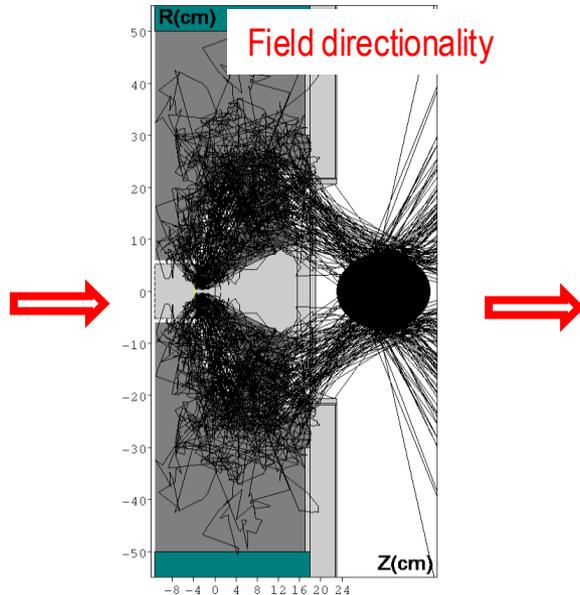
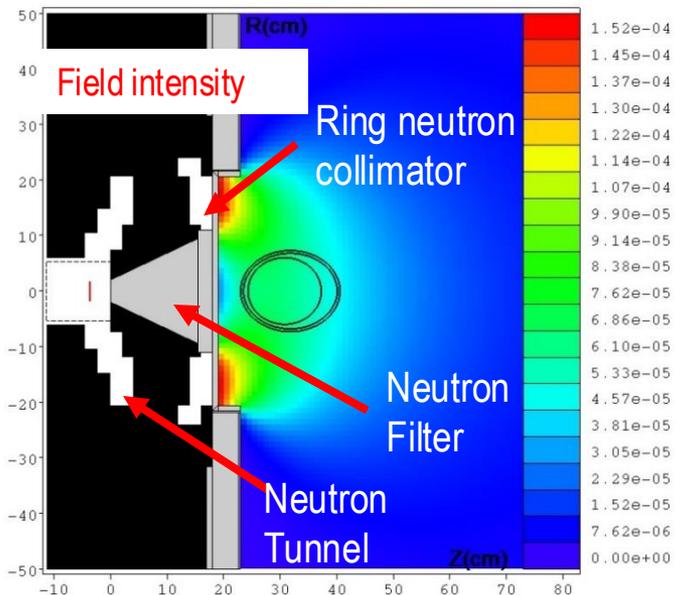
NA = value not published and cannot be reconstructed in the absence of published dose profiles

Results: AD increased by only 1.1 cm in 20+ years, TD by only 0.05 cm.

Characterization of advanced neutron fields

Modern BSAs generate complex neutron fields $\varphi(r, E, \underline{\Omega})$, that combine directionality ($\underline{\Omega}$), space (r) and energy (E) distribution of neutrons to better control tumors & side effects.

Ex: field generated by a BSA that max TD for a 30 mA ${}^7\text{Li}(p(2,5 \text{ MeV}), n)$ source



Field performances

AD = 12.7 cm
 Previous best value obtained so far : 11 cm

TD = 10.3 cm
 Previous best value obtained so far : 7.8 cm

$D_{\text{tum}} @ 4 \text{ cm depth} = 206 \text{ Gy-Eq/h}$

S. Chabod et al., Phys. Med. Biol. 2025, 70 (3), pp.035008

General problem: how to characterize such BNCT neutron fields?

Some improvements for AB-NCT concerning the Neutron Field (NF) characterization and the BSA used to define it :

- 1- Spectral and fluence measurements of the NF produced by a non-pulsed particle beam
- 2- Monitoring the fluence as a function of time giving access to the eventual degradation of the target and a real-time dose calculation
- 3- Standardization of measurements will give access to the comparison of the different NF produced by the different facilities and the doses delivered
- 4- An active phantom allowing measurements of the number of captures on a controlled amount of ^{10}B at different “depths” is available
- 5- Optimal Moderators (BSA) are now possible...

A new generation of AB-BNCT could start !!

$$D_T = D_B + D_n + D_p + D_\gamma$$

Total absorbed dose (D_T) in Gy (Joule/kg) = (Total Ionization released in a volume of mass m) / (mass m)

Each dose component of the total dose is associated to a different nuclear reaction:

$^{10}\text{B}(n,\alpha)^7\text{Li}$ a neutron capture reaction to the called boron dose D_B ,
considering the ionization energy released by the alpha particle and lithium nucleus

$^1\text{H}(n,n')^1\text{H}$ an elastic collision reaction to the called neutron dose D_n ,
considering the ionization energy released by the hydrogen resulting from
the elastic neutron scattering,

$^{14}\text{N}(n,p)^{14}\text{C}$ a neutron capture reaction to the called proton dose D_p ,
considering the ionization energy released by the proton and the carbon nucleus,

$^1\text{H}(n,\gamma)^2\text{H}$ a radiative capture reaction on ^1H plus the residual gamma from ^{10}B capture reaction
and all the gamma rays coming out from the BSA...
to the called gamma dose D_γ , considering the energy transferred by the photon by pair
production, Compton, and photoelectric processes.

Biological Dose in Gy[RBE]

Taking into account the Relative Biological Effectiveness (RBE)

$$\underline{D_w = w_c \cdot D_B + w_p \cdot D_n + w_n \cdot D_p + w_\gamma \cdot D_\gamma}$$

RBE factors for BPA boron carrier

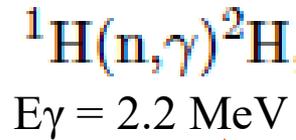
tissue	tumour	brain	skull	skin
w_c	3.8	1.3	1.3	2.5
w_n	3.2	3.2	3.2	3.2
w_p	3.2	3.2	3.2	3.2
w_γ	1	1	1	1

Jeffrey A Coderre et al, Derivations of relative biological effectiveness for the high-LET radiations produced during boron neutron capture irradiations of the 91 rat gliosarcoma in vitro and in vivo.

International Journal of Radiation Oncology* Biology* Physics, 27(5) :1121–1129, 1993.

Dose [Gy]= Ionization Energy released [Joule] / mass unit [kg]

« Total absorbed dose »



$$D_T = D_B + D_n + D_p + D_\gamma$$

Elastic collisions !!

