Neutron Imaging Detectors using Ultra-Thin Converter Layers

LIBPhys-UC

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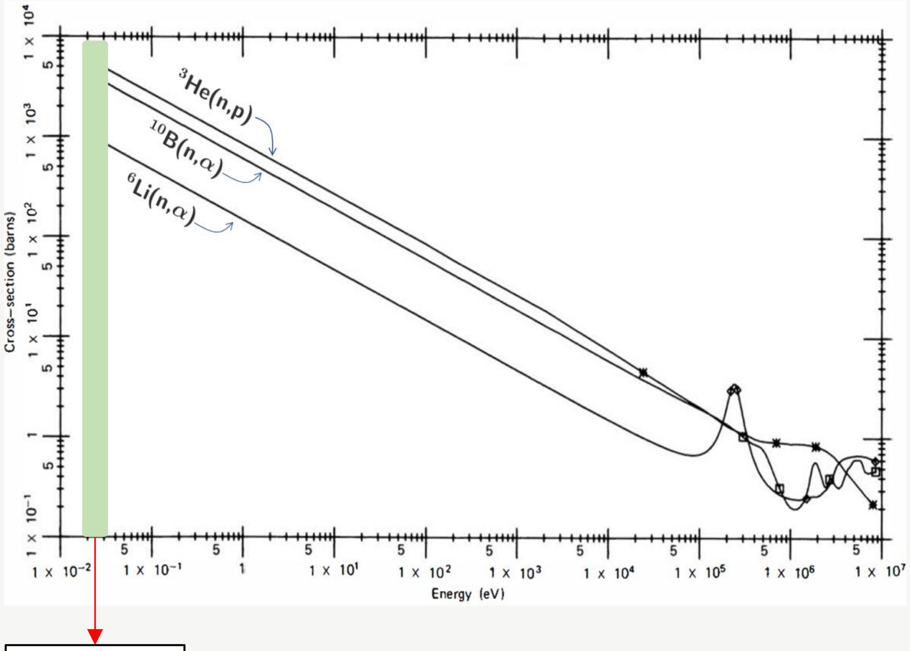
Neutron: the challenges

- No net charge - > Interactions with matter are limited to nuclear and magnetic interactions
- Detection is made via nuclear capture reactions, mostly with ^{3}He, ^{10}B and ^{6}Li.



$\sigma_{thermal}$

Nuclear capture (between a stationary nucleus and a slow neutron) followed by nuclear fission:

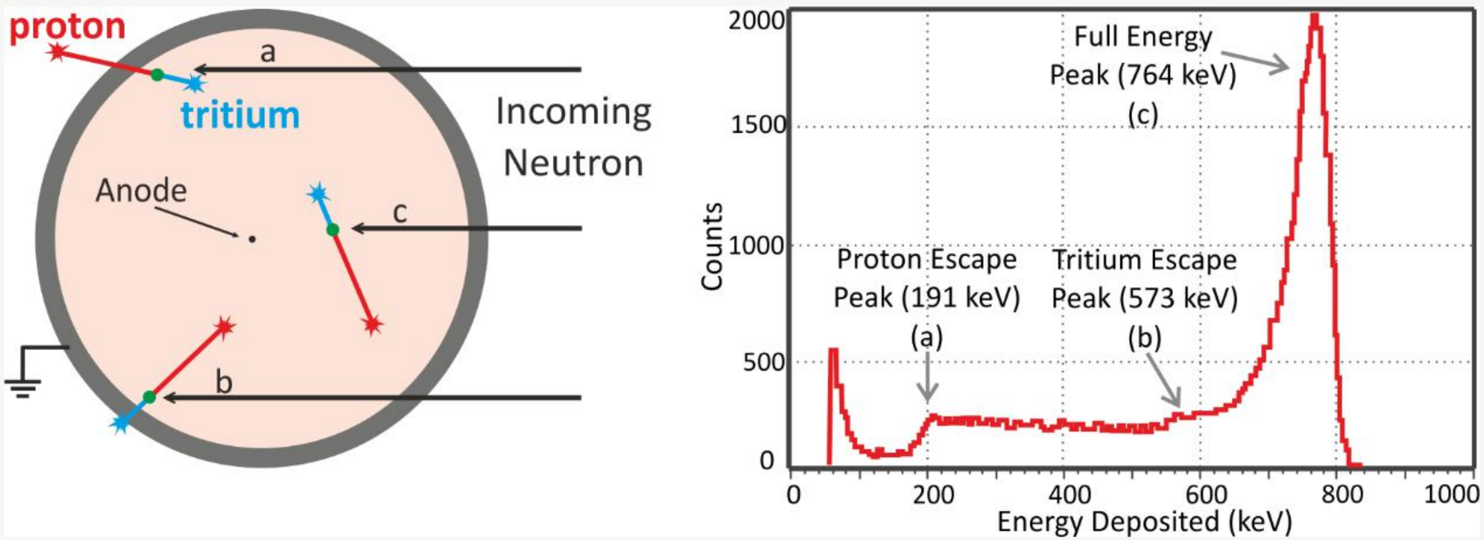
Two secondary (highly ionizing particles) are emitted in opposite directions

^{3}He detectors

- high cross section
- good gamma ray discrimination
- is non-toxic
- relatively affordable gas

^{3}He proportional counters are the "workhorse" for neutron detection

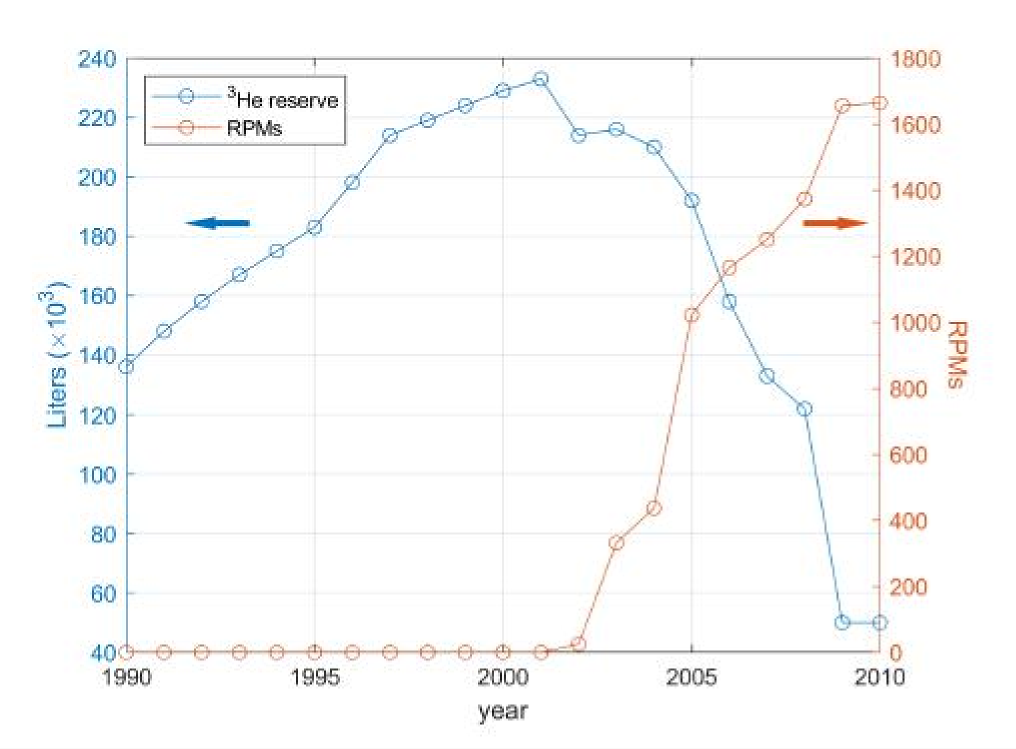
$$n + {}^3He \rightarrow {}^3H\ (191\ keV) + p(573\ keV);\ Q = 764\ keV$$



- Full energy peak well distinguish
- Wall effects can be minimized

^{3}He shortage crysis

Following the security concerns in the 00's the need for Radiation Portal Monitors depleted the ^{3}He reserves.

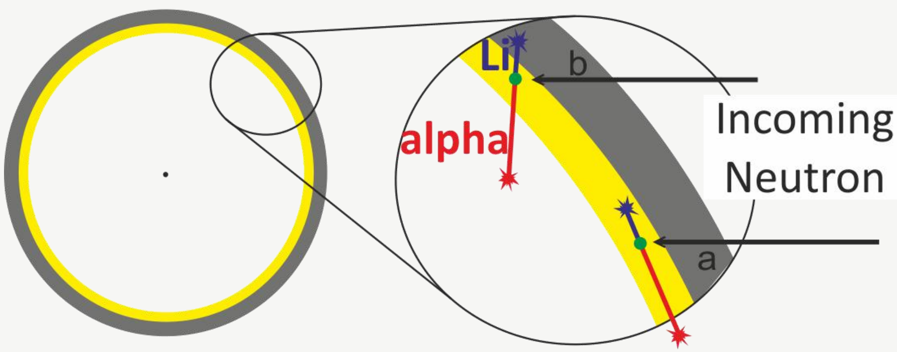


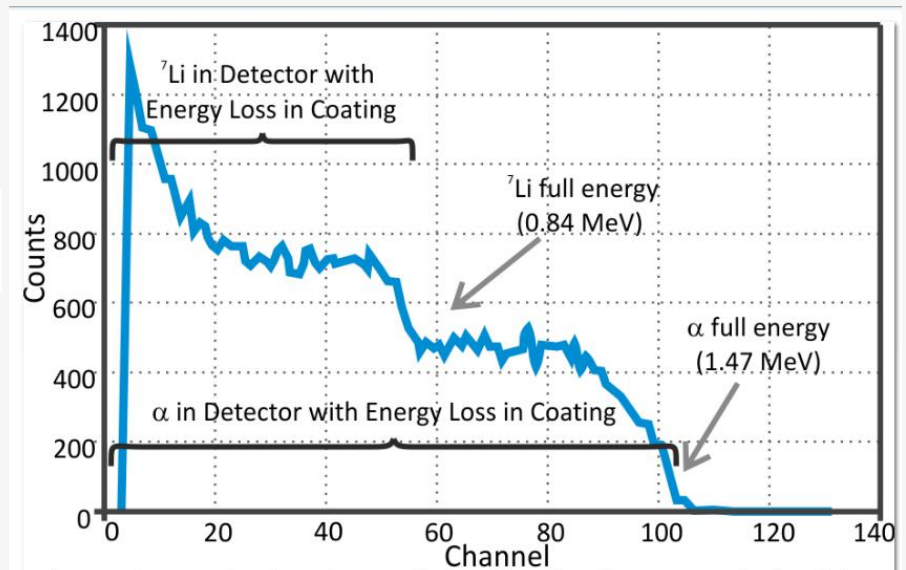
80 $/l => 1000 $/l

^{10}B layers

$$n + {}^{10}B \rightarrow {}^{7}Li\ (0.84\ MeV) + {}^{4}_{2}\alpha\ (1.47\ MeV);\ Q = 2.31\ MeV(\mathbf{94}\%)$$

$$\rightarrow {}^{7}Li\ (1.05\ MeV) + {}^{4}_{2}\alpha\ (1.77\ MeV);\ Q = 2.79\ MeV(6\%)$$



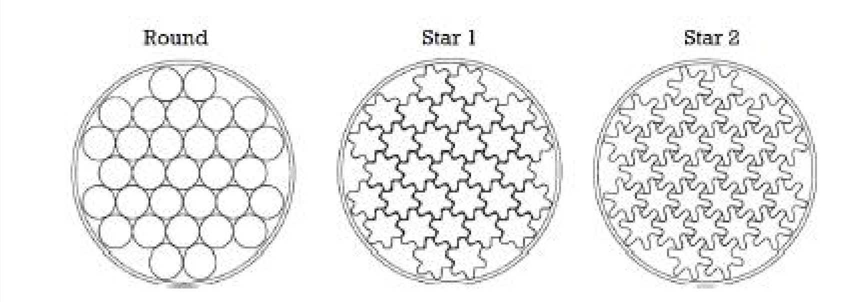


- Higher Q than ^{3}He;
- Natural abundance of ^{10}B: ~20%.
- Two-step distribution
- Single layer detection efficiency limited to 4-5%

^{10}B layers

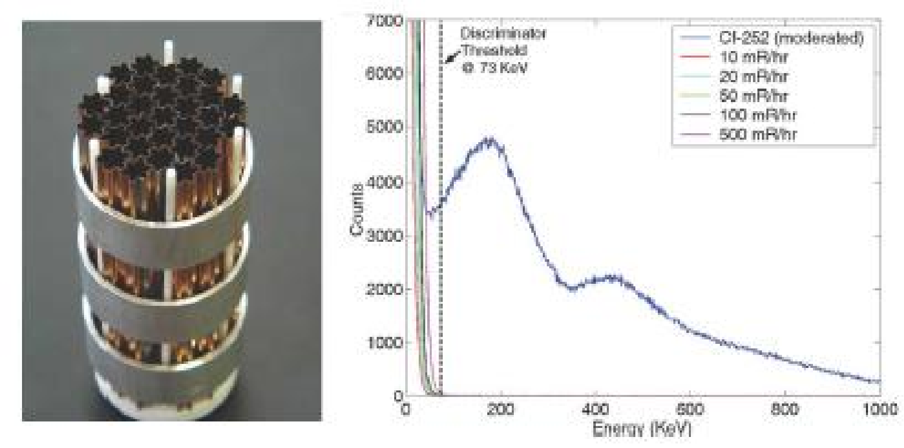
Main concern was detection efficiency.
Most common solution is to combine several detection elements.
Several detector names show that property (Cascade, Multi-Blade).

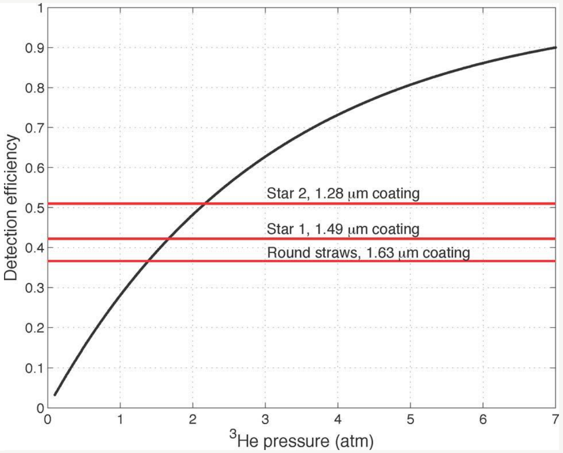
Boron coated straw detectores:



Combines several individual proportional counters, each coated with a ^{10}B layer.

Shape of the proportional counter was optimized and **detection efficiency of ~50%** is possible, comparable to the one of ^{3}He detectors.

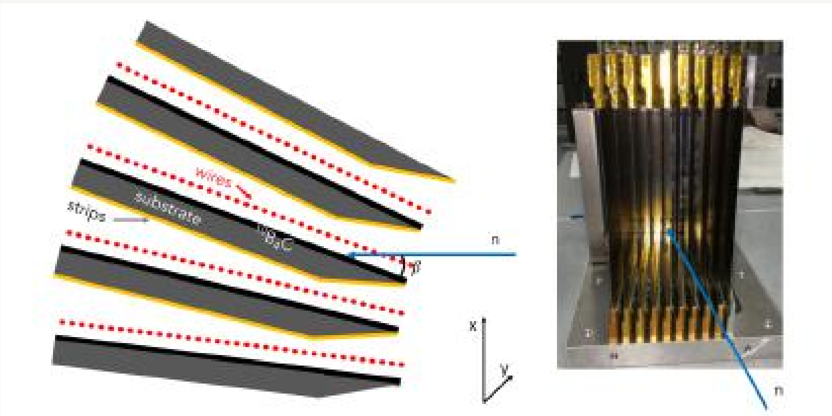




[Jeffrey L. Lacy et al., *The Evolution of Neutron Straw Detector Applications in Homeland Security*, IEEE TNS, 60-2, April 2013]

^{10}B layers

Multi-Blade (Estia and Freia reflectometers at European Spallation Source):



Overcomes some of the ^{3}He Counters limitations, namely the **spacial resolution** and **counting rate**.

Readout is achieved by MultiWire Proportional Counters (MWPC).

FWHM = 3.16 mm

[F. Piscitelli, *Boron-10 layers, Neutron Reflectometry and Thermal Neutron Gaseous Detectors*, PhD Thesis
F. Piscitelli et al., *The Multi-Blade Boron-10-based neutron detector for high intensity neutron reflectometry at ESS*, 2017 JINST 12 P03013]

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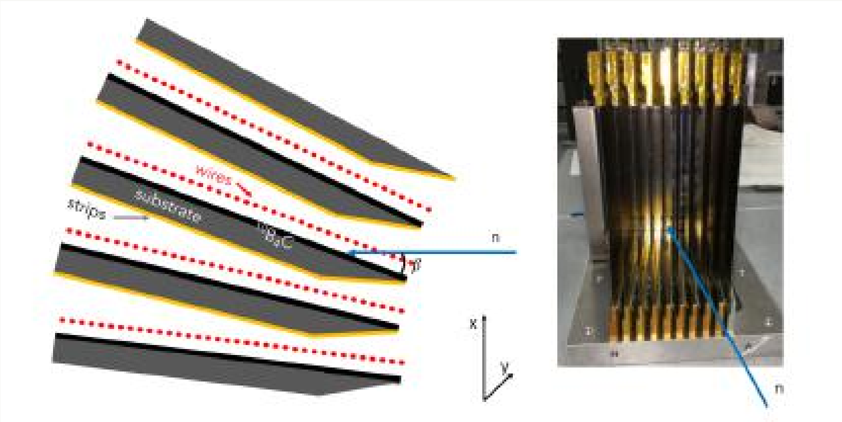

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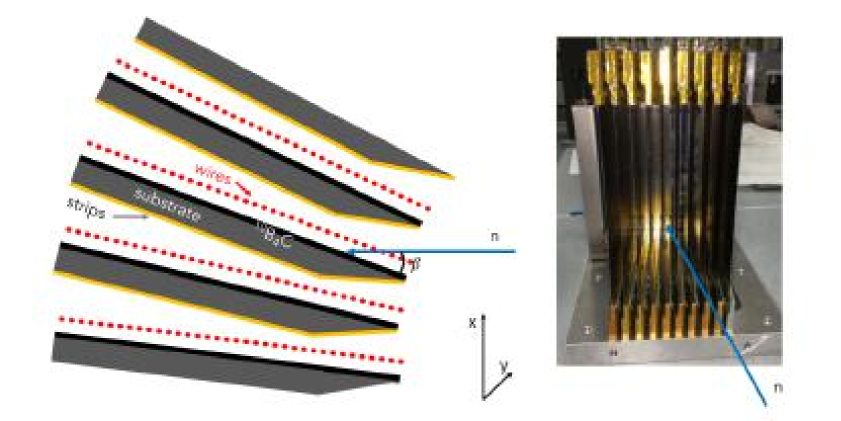

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some concerns in a modular design:

- uniformity of detector response (overlap between different substrates, coating uniformity, substrate flatness and parallax errors)
- if the sample-detector distance changes, the cassettes inclination should change too, if we want to avoid dead spaces.

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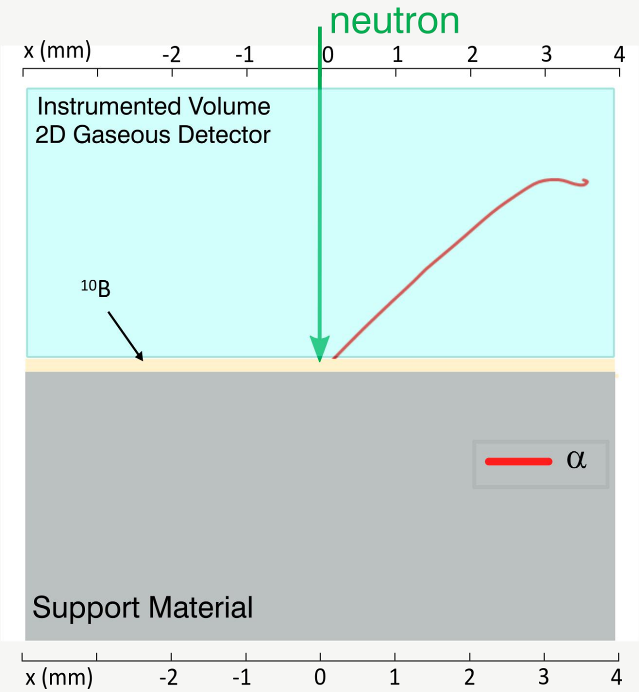

State of the Art (SoA) neutron **Position Sensitive** gaseous detectors employ a **thick layer of a material with ^{10}B atoms** for neutron conversion.

An incoming neutron reacts with a ^{10}B atom, releasing two products, **emitted back-to-back**:

$$n + {}^{10}B \longrightarrow \begin{matrix} I \\ II \end{matrix} \begin{cases} {}^{7}Li(0.84\ \text{MeV}) + \ {}^{4}\alpha(1.47\ \text{MeV}); & Q = 2.31\ \text{MeV}\ (94\%) \\ {}^{7}Li^{*}(1.01\ \text{MeV}) + \ {}^{4}\alpha(1.78\ \text{MeV}); & Q = 2.79\ \text{MeV}\ (6\%) \end{cases}$$

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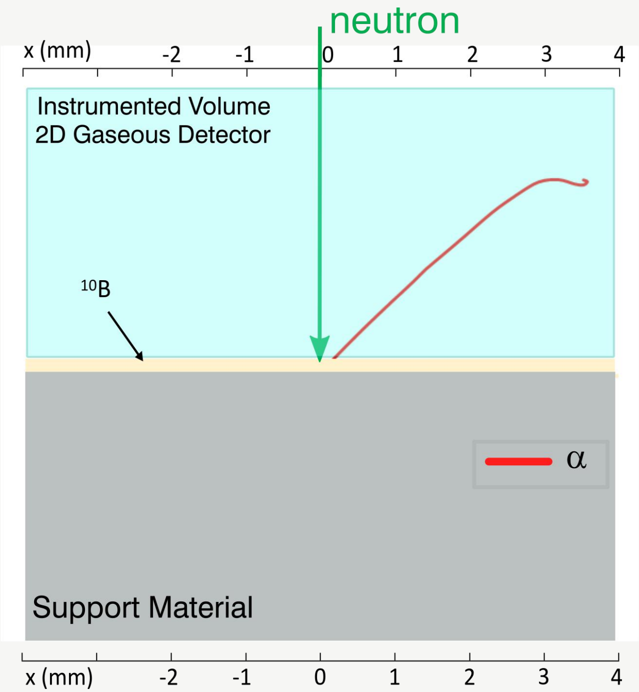

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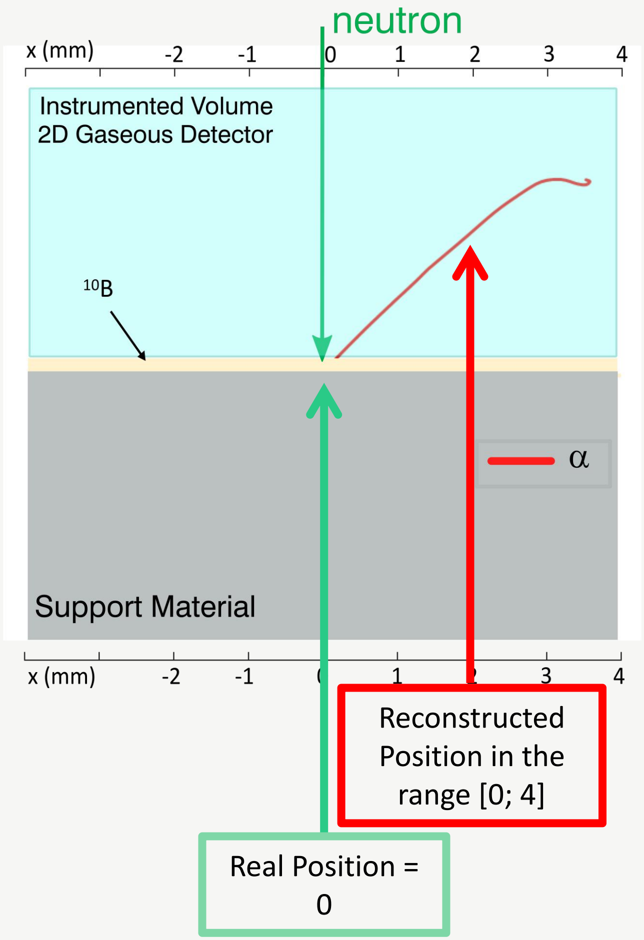

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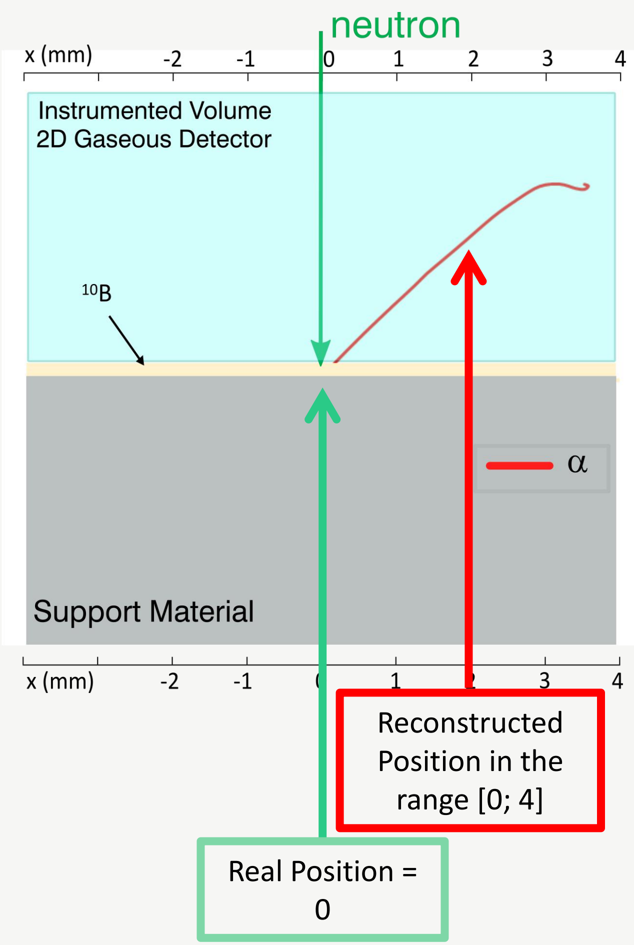
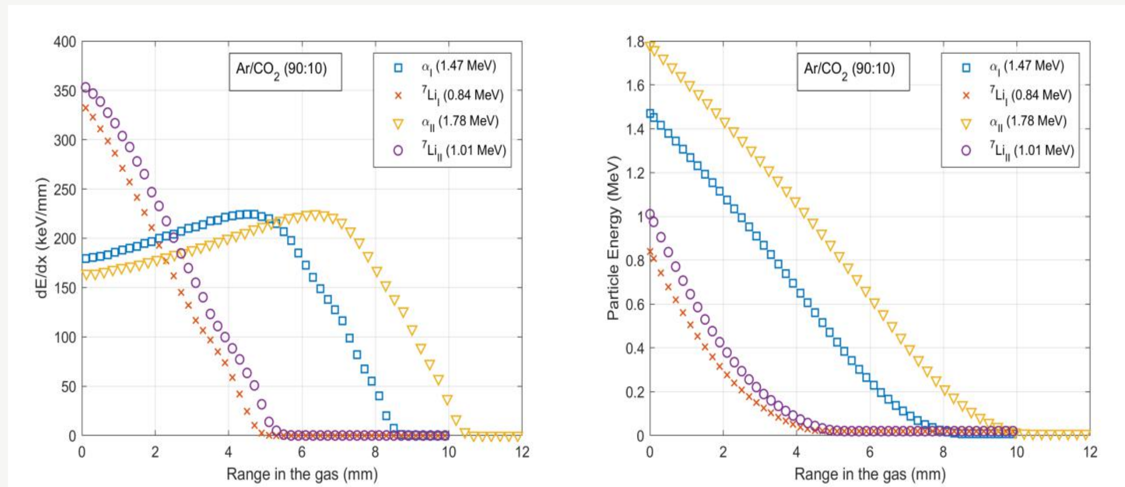
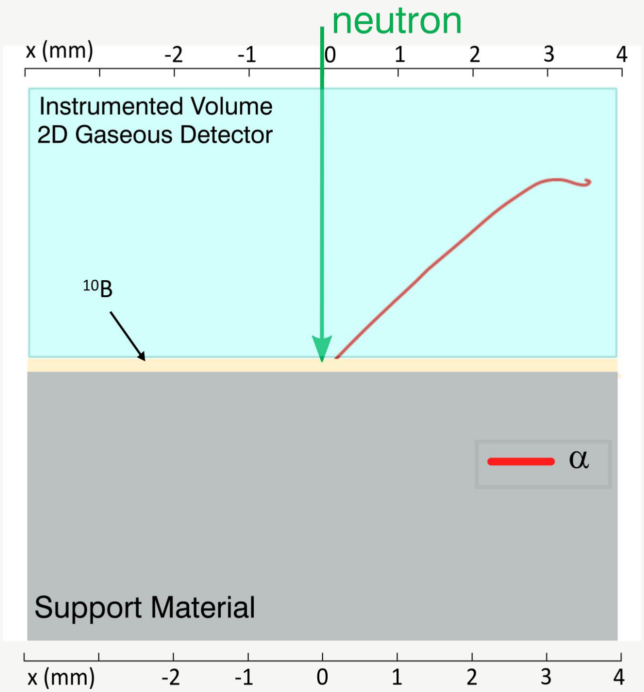




- Gas ionizations (track profile) are energy dependent
- Particle energy is dependent on the depth at which the neutron capture took place

range of several mm in most gases -> main contribution to the uncertainty in determining the neutron interaction site.

NeuThin concept



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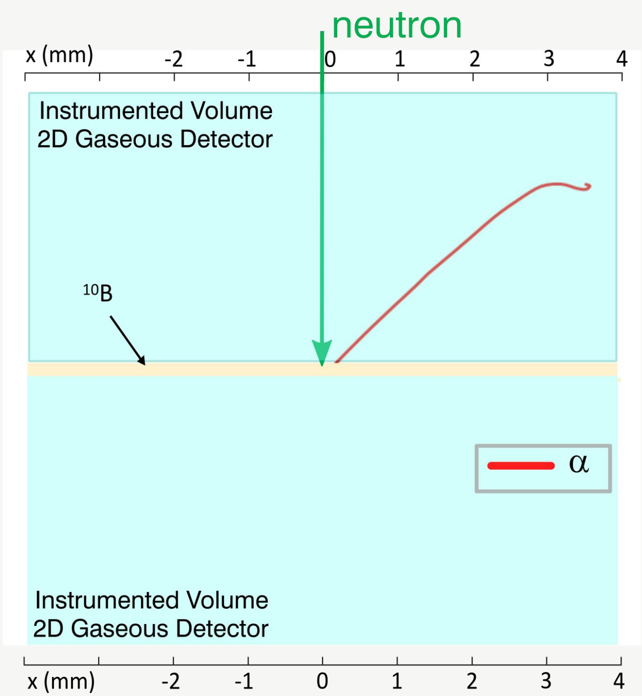

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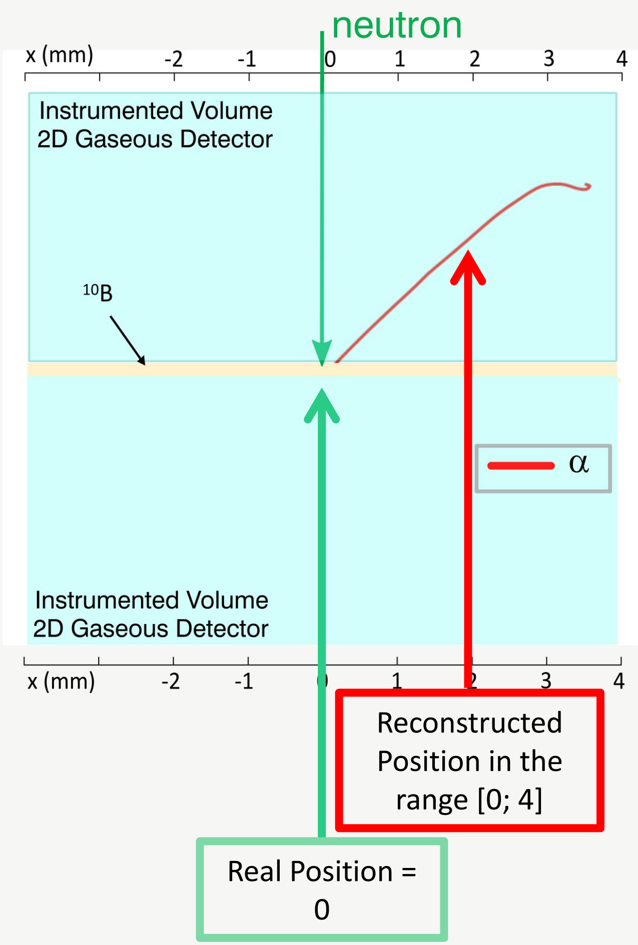

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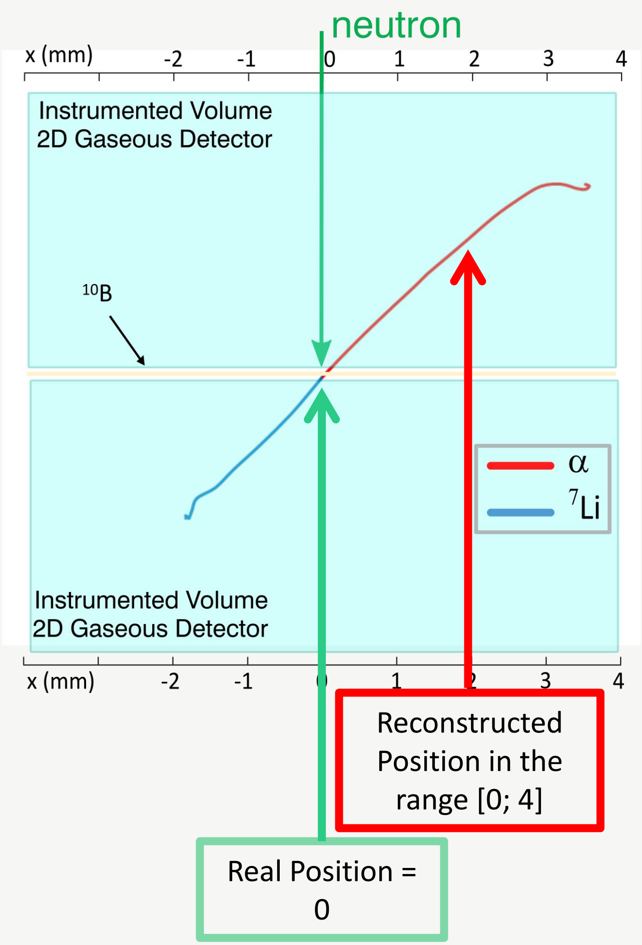

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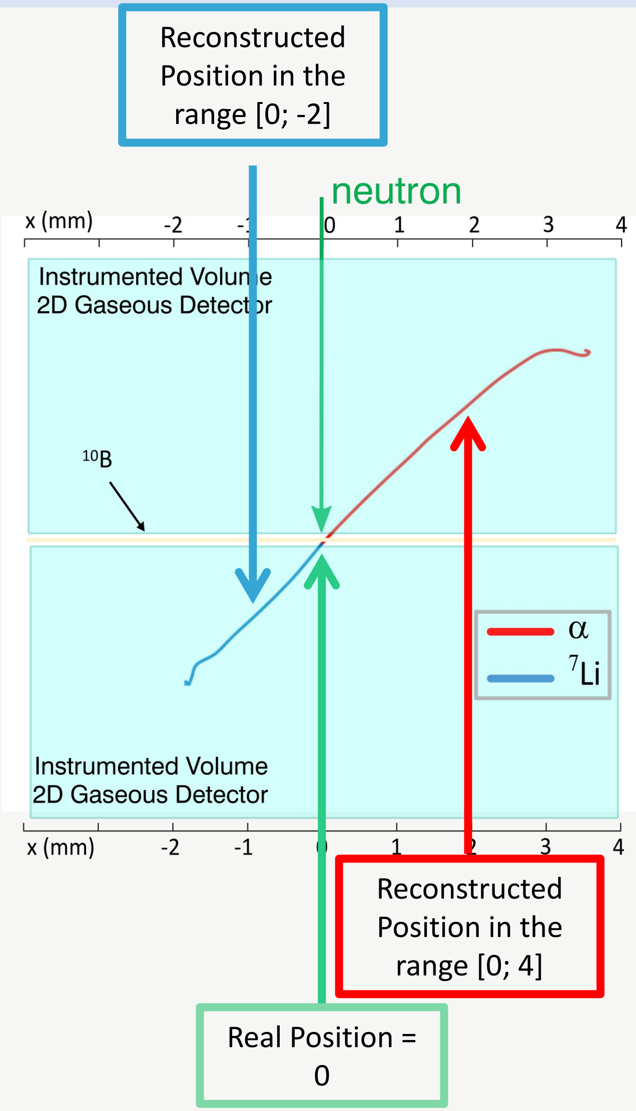
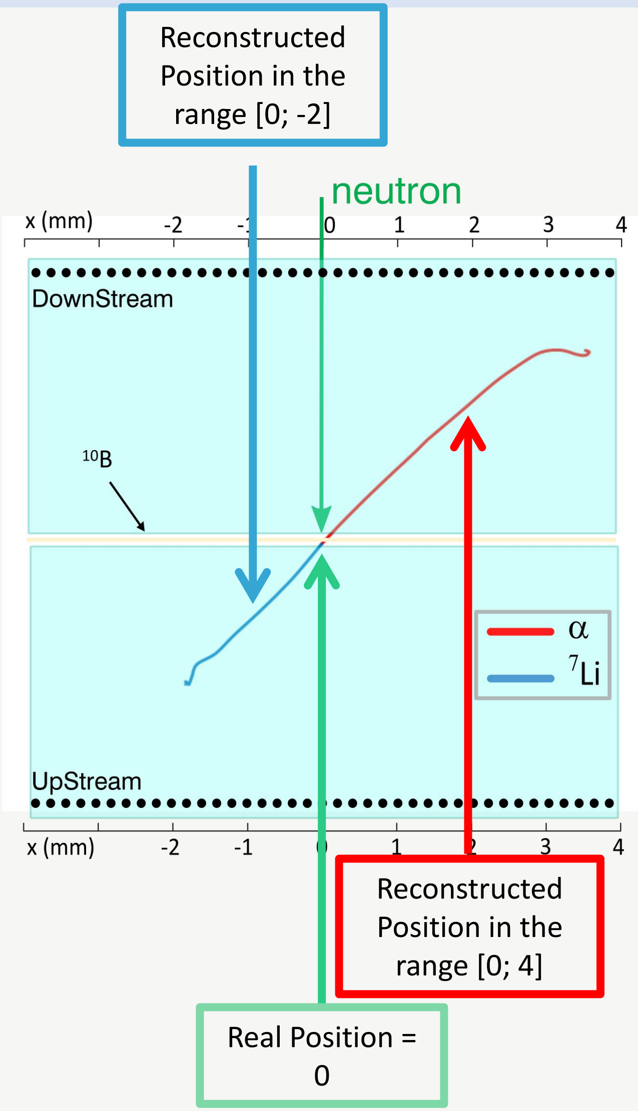


Two position sensitive gaseous detectors, instrumenting both sides of the converter foil, are required.

$X_{DownStream}$ $X_{UpStream}$

NeuThin concept



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The information provided by them is averaged in order to determine the position where the neutron interacted with the ^{10}B atom:

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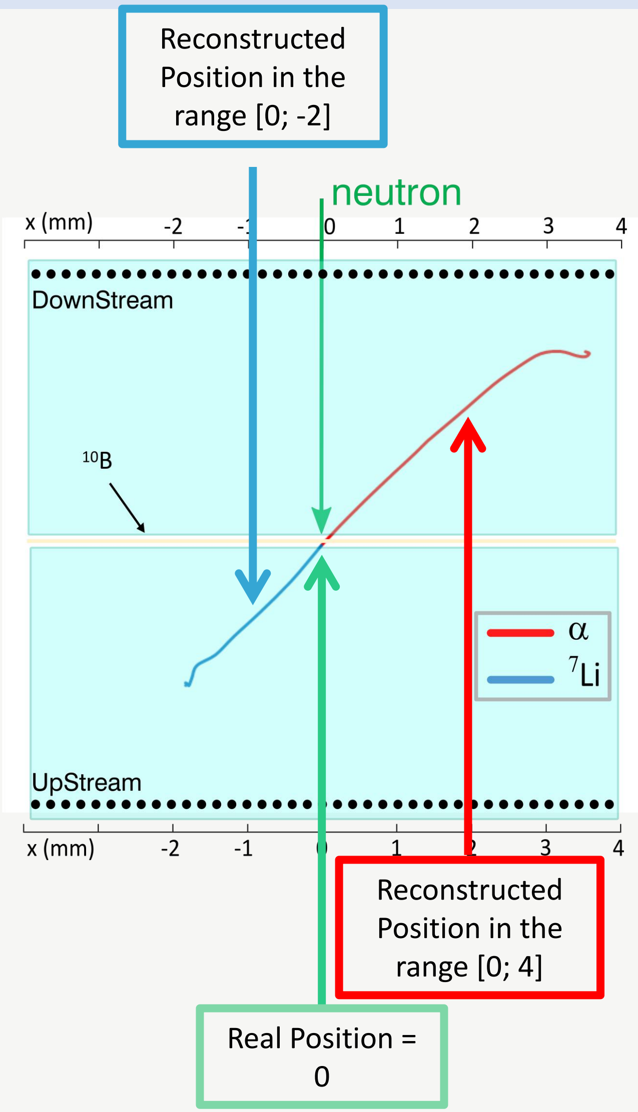

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Important Requirements:

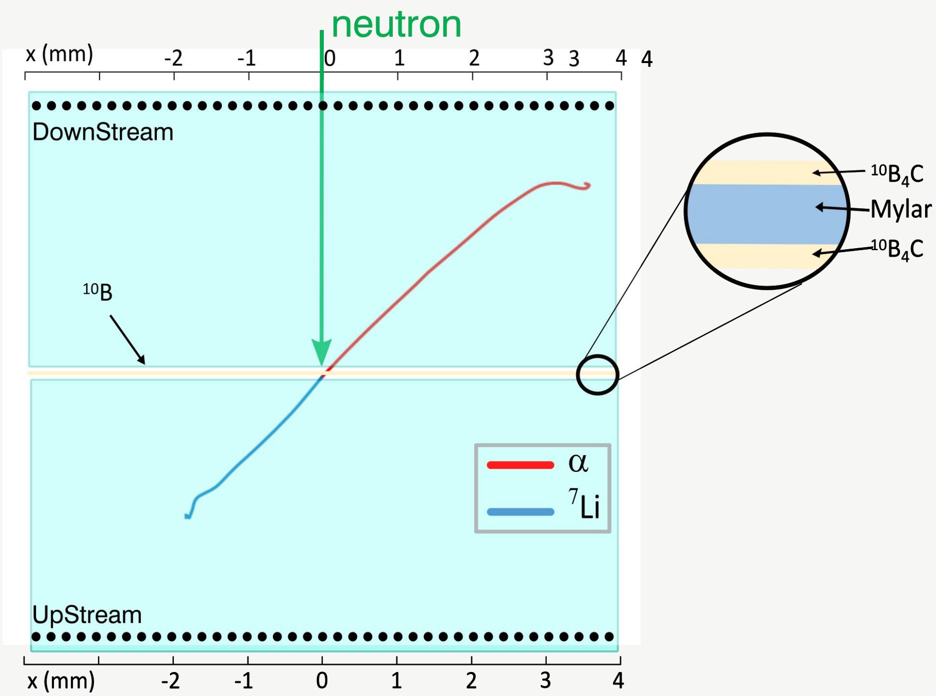
- thin ^{10}B layers (nm scale)
- deposited in a material “transparent” to the ^{7}Li and alpha particle

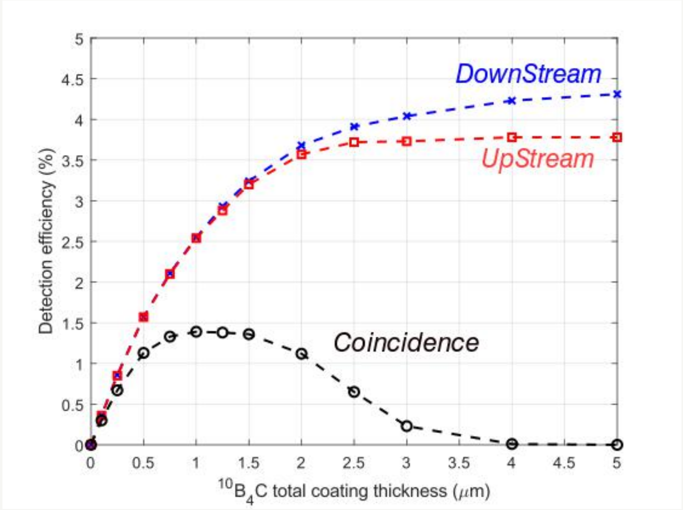
? Efficiency
? Stability

NeuThin Simulations

The **converter foil** (^{10}B + support material) must be made of materials that maximize the simultaneous escape probability of the reaction products.

The need for a coincident detection limits the choice of materials for NeuThin.





A B_4C layer (500 nm thick) on each side of 0.9 micron thick Mylar film.

NeuThin detection efficiency ~ -1.5 %

NeuThin Simulations

How much can we improve?

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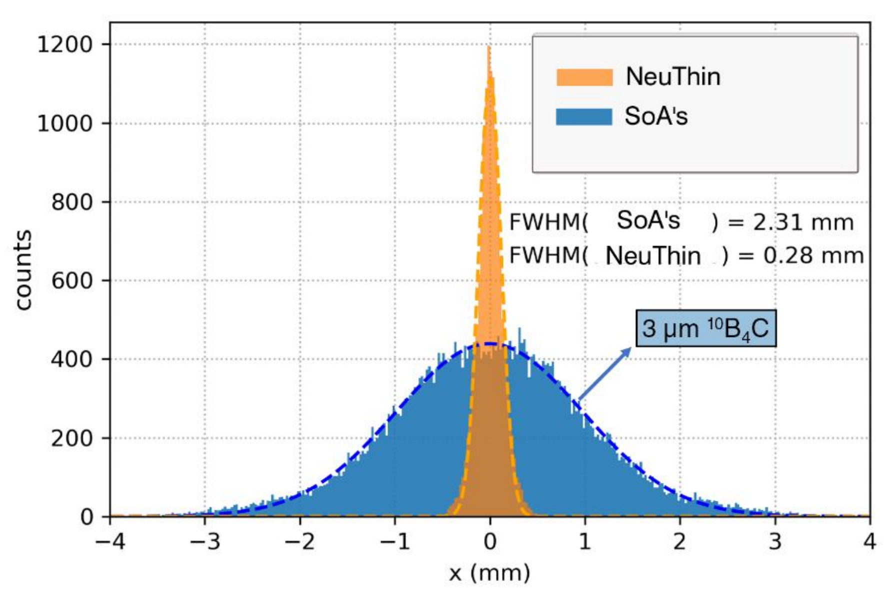

Simulations indicate the potential for position resolution improvement by a factor of ~8.

[N. F. V. Duarte et al., *Improving position resolution of neutron detectors with ultra-thin B_4C foils*, (2022) JINST_010T_0122]

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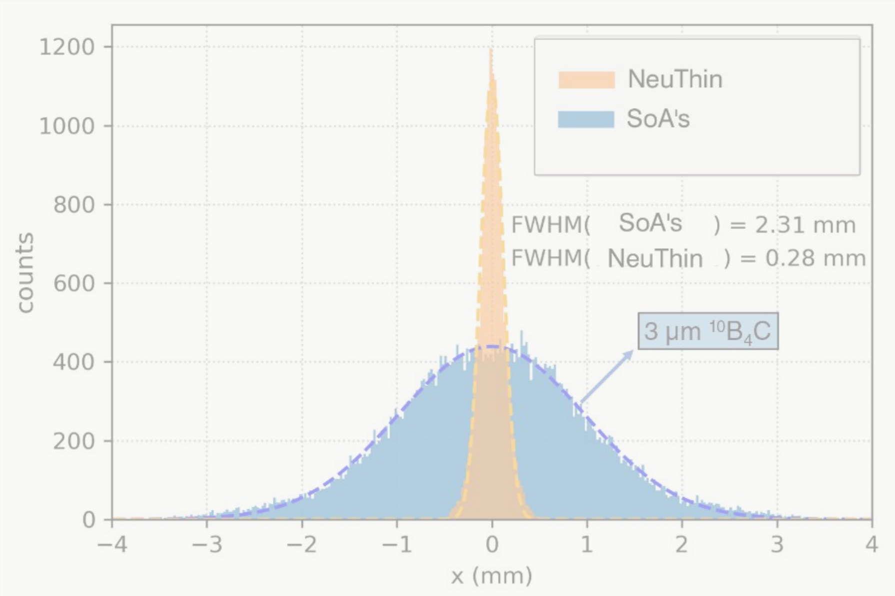

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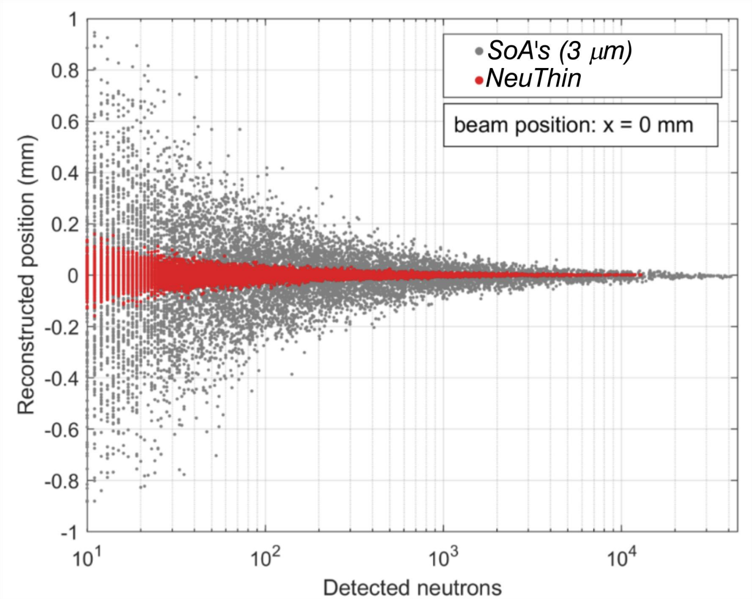
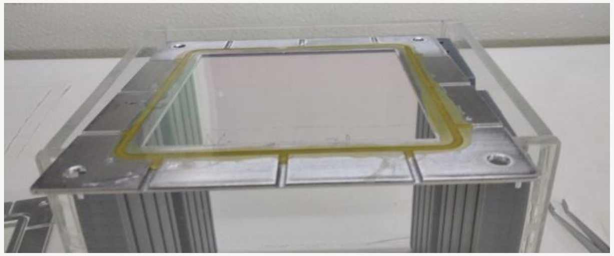


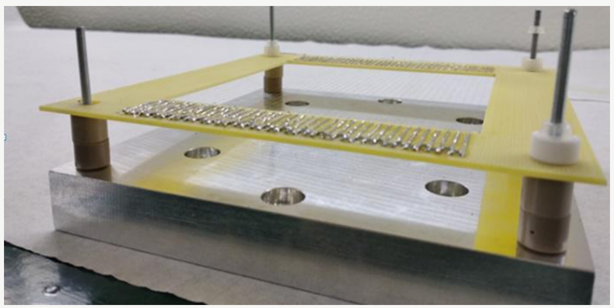
NeuThin converges to the "true position" for lower number of detected neutrons, opening the door to a reduction in the exposure time.

Can it compensate for the "loss" of detection efficiency with NeuThin ? ...
... should we stop talking about detection efficiency and instead use exposure time as metric?

[N. F. V. Duarte et al., *Improving position resolution of neutron detectors with ultra-thin B_4C foils*, (2022) JINST_010T_0122]

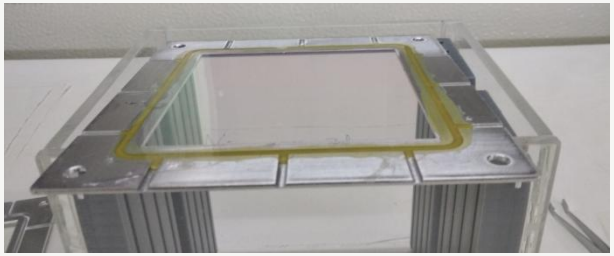
NeuThin detector

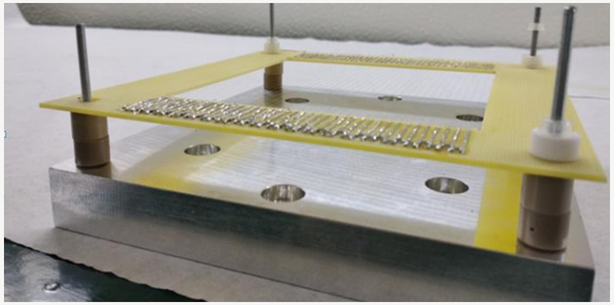




First experimental tests made in August 2022 at PSI SINQ Narziss beam-line.
Several detector configurations (converter foils) have been tested.

NeuThin detector

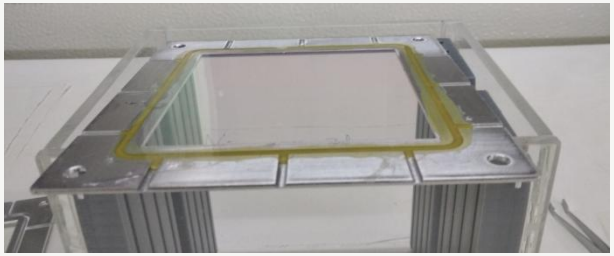


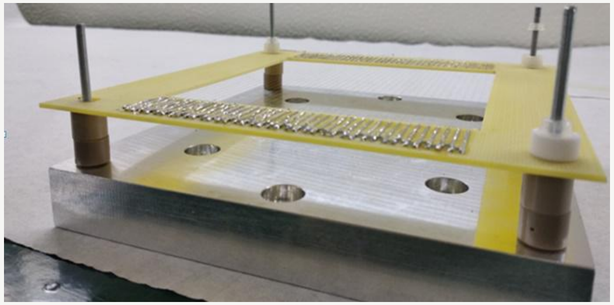


MWPC's :

- 10×10 cm^2
- 25 mm tungsten wires, 1.8 mm spacing
- 1D position via resistive line readout

NeuThin detector





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Converter Foils				
Produced at	Substrate	Coating		Area
		Material	**Thickness***	
International Iberian Nanotechnology Laboratory (INL - **Braga**), Portugal	Mylar (0.9 μm)	nat. Boron	2 layers (500 nm)	10×10 cm^2
Lebow, USA	---	nat. Boron	1 μm	⌀ 1 cm
Paul Scherrer Institute (**PSI**), Switzerland	Mylar (0.9 μm)	$^{10}B_4C$	2 layers (≥ 500 nm)	3×3 cm^2

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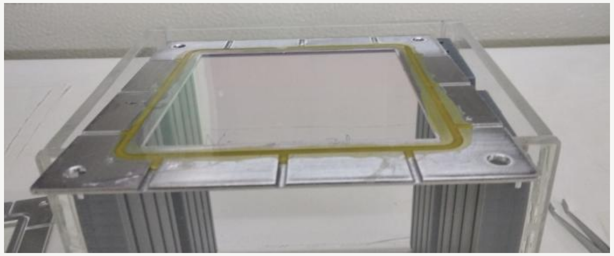

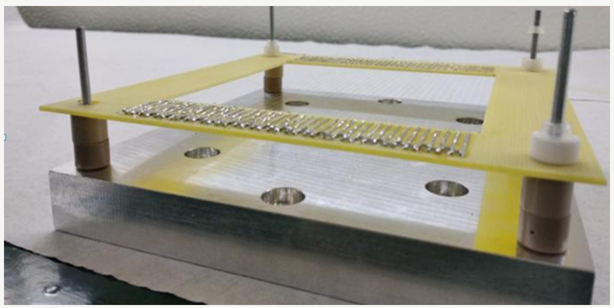

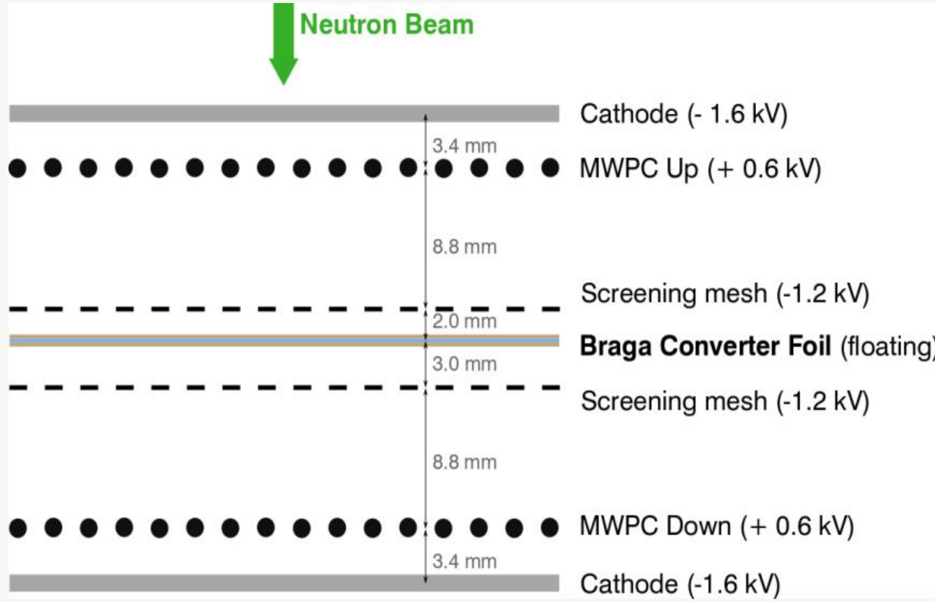

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NeuThin Results

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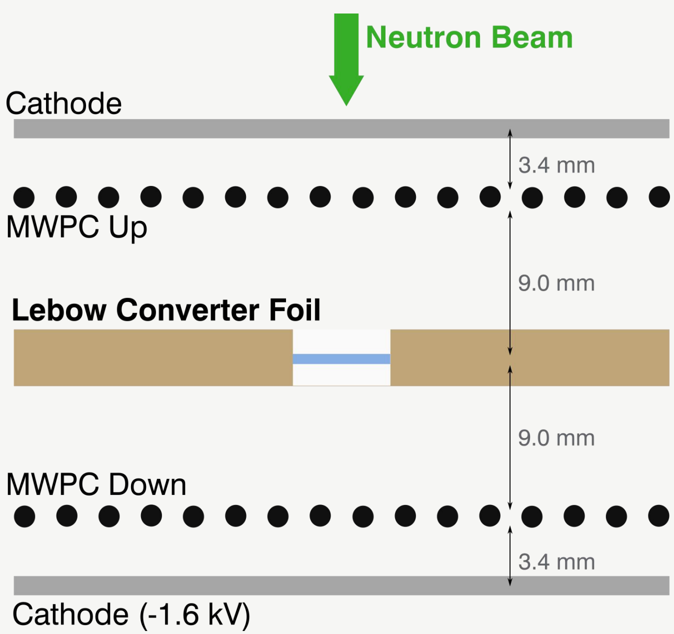

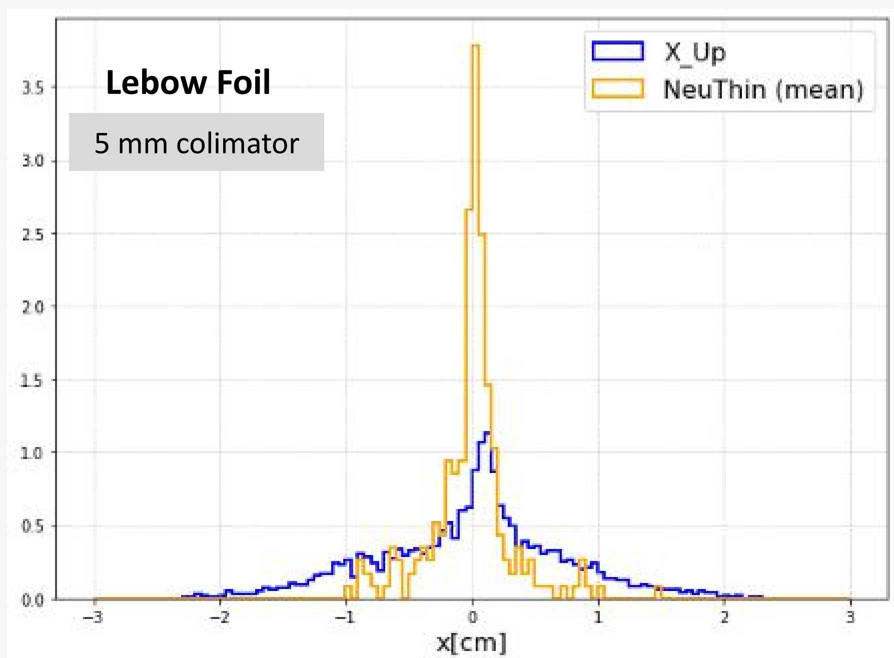

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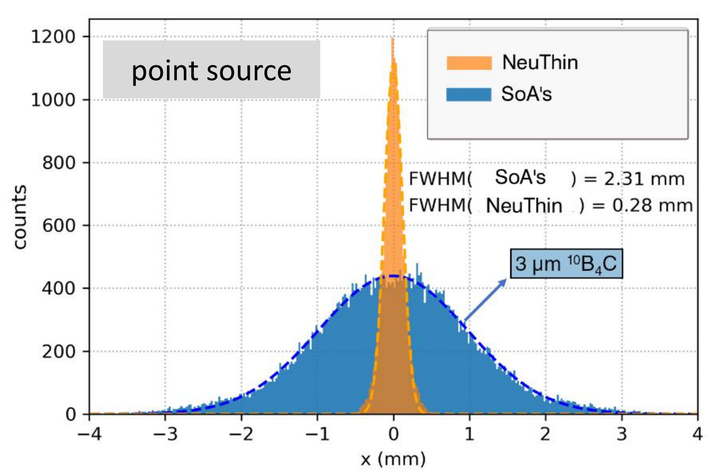
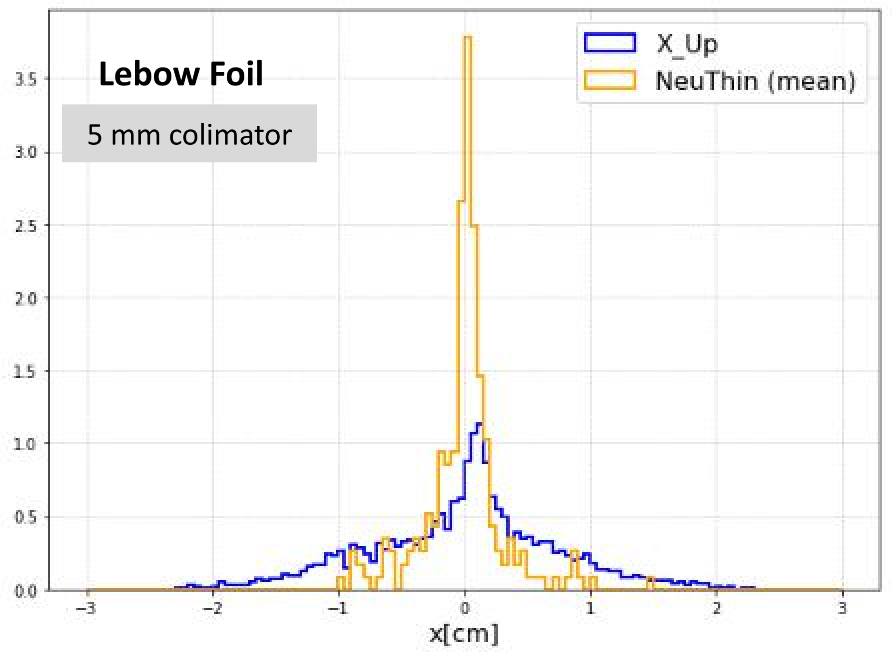
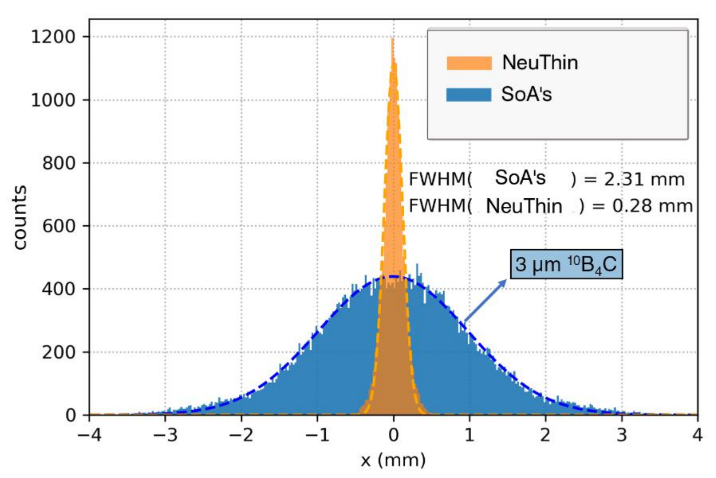




NeuThin Results

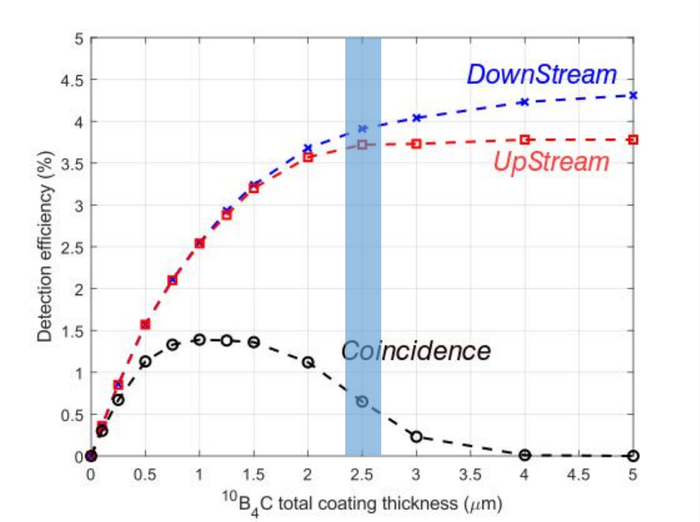
foil	acquisiton time (s)	beam (mm)	efficiency (%) Up	Down	NeuThin	position (FWHM) Up	Down	NeuThin	NeuThin Improv. Fact.	Coinc. Eff. (%)
Braga Foil	93.72	05 mm	0.32	0.37	0.05	0.64	1.01	0.63	1.59	14.30
LeBow 1 cm	64.45	05 mm	0.32	0.46	0.01	0.28	0.17	0.14	2.06	2.58
PSI-Strech	20.92	05 mm	0.47	1.98	0.03	0.36	0.23	0.31	1.18	1.37

✓ Improvement factor is now of 2 (compared with 8 from simulations)



NeuThin Next Steps

foil	acquisiton time (s)	beam (mm)	efficiency (%) Up	Down	NeuThin	position (FWHM) Up	Down	NeuThin	NeuThin Improv. Fact.	Coinc. Eff. (%)
Braga Foil	93.72	05 mm	0.32	0.37	0.05	0.64	1.01	0.63	1.59	14.30
LeBow 1 cm	64.45	05 mm	0.32	0.46	0.01	0.28	0.17	0.14	2.06	2.58
PSI-Strech	20.92	05 mm	0.47	1.98	0.03	0.36	0.23	0.31	1.18	1.37



- ✓ Improvement factor is now of 2 (compared with 8 from simulations)
- ✓ The low values for the coincidence efficiency seems to indicate that the thickness of the deposits on the converter foils has exceeded the optimum value

NeuThin Next Steps

foil	acquisiton time (s)	beam (mm)	efficiency (%)			position (FWHM)			NeuThin	
			Up	Down	NeuThin	Up	Down	NeuThin	Improv. Fact.	Coinc. Eff. (%)
Braga Foil	93.72	05 mm	0.32	0.37	0.05	0.64	1.01	0.63	1.59	14.30
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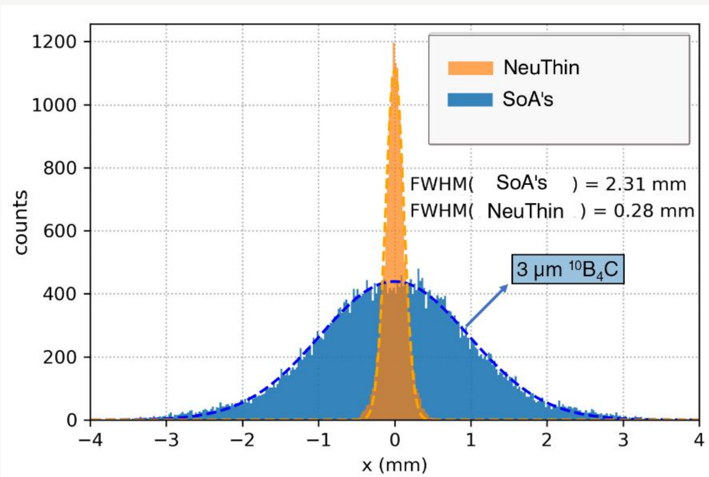

- ✓ Improvement factor is now of 2 (compared with 8 from simulations)
- ✓ The low values for the coincidence efficiency seems to indicate that the thickness of the deposits on the converter foils has exceeded the optimum value

Next Steps:

- **Optimize foils**: make the Braga foil conductive (coating nm Al) -> remove the need for screening meshes
- **Optimize foils**: new depositions on Mylar ($^{10}B_4C$, smaller thickness's)
- Detector development (better MWPC, calibrations, cascade several elements)

Neutron Imaging Detectors using Ultra-Thin Converter Layers

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NeuThin Results