Laser-driven proton-boron fusion reactions for alpha-particle production

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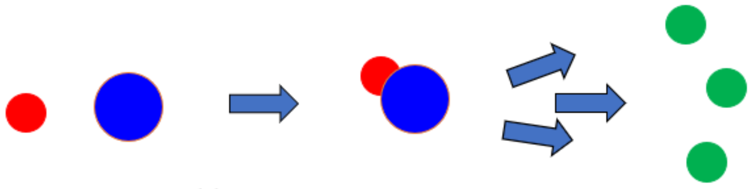
p-11B fusion reaction: Background and purpose

- α-particles are produced by the proton-boron nuclear fusion reaction:

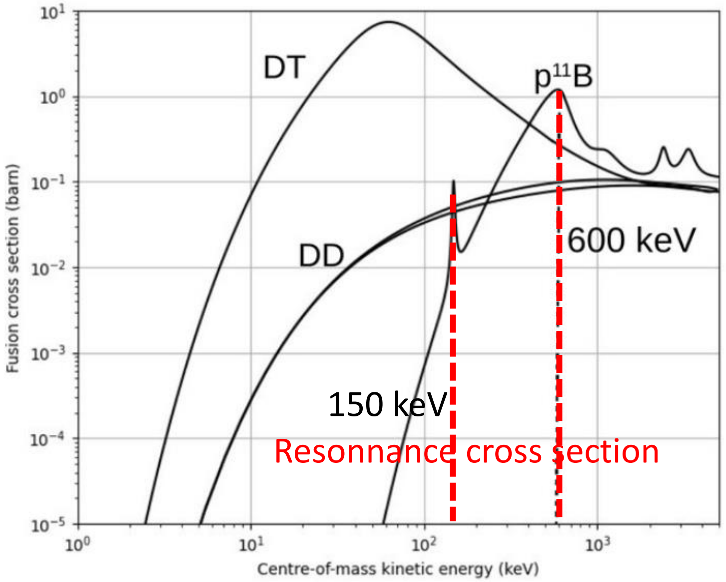


$$H + B^{11} \rightarrow 3\alpha + 8.7\ MeV$$

- The proton-boron nuclear reactions is interesting for multiple applications

  - fusion for energy : quasi aneutronic reaction
  - α production
    - ➛ for cancer therapy[1]
    - ➛ for radioisotope production[2]

Fusion Cross Section



<u>This reaction requires very high temperature</u>

➔Conventional compression approach is not possible to ignite fuel

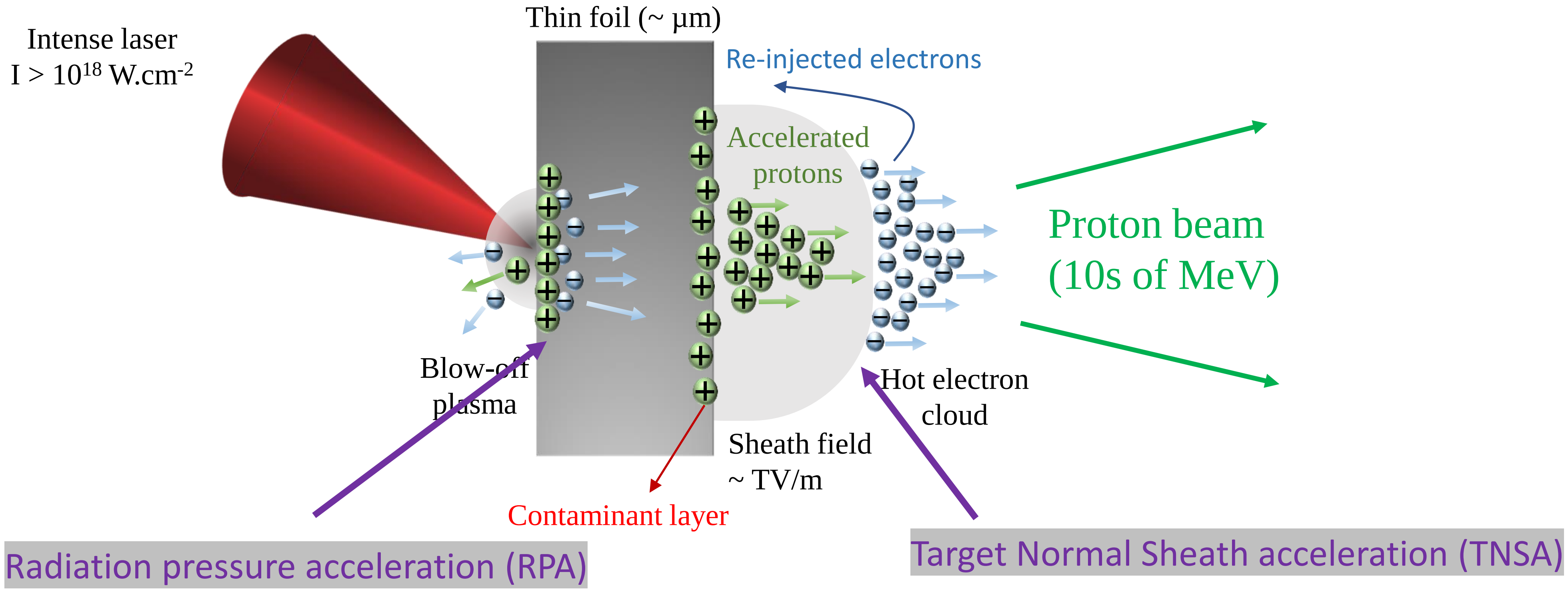
➔ Laser initiated p-^{11}B nuclear fusion reaction

[1]Cirrone et al, Sci. Rep. 8, 1141 (2018) [2]Szkliniarz et al, Applied radiation and istopes (2016)

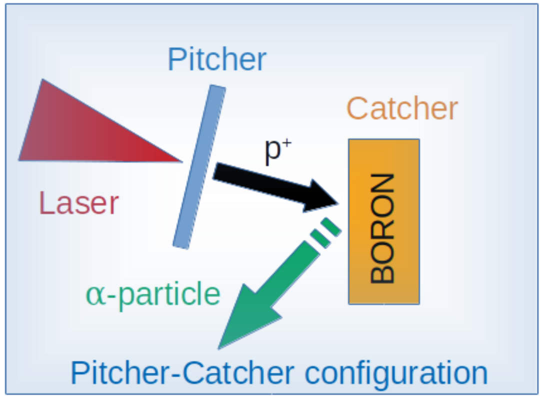
Protons are accelerated by several mechanisms during laser-matter interaction

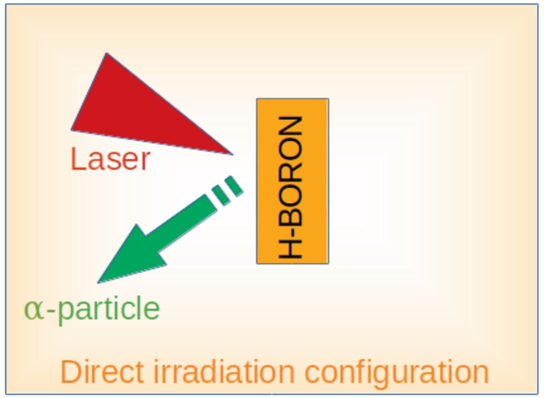
➔ Protons accelerated at the <u>rear side</u> of the target by **Target Normal Sheath acceleration (TNSA) mechanism**

➔ Protons accelerated at the <u>front side</u> of the target by **Radiation Pressure Acceleration (RPA) mechanism**

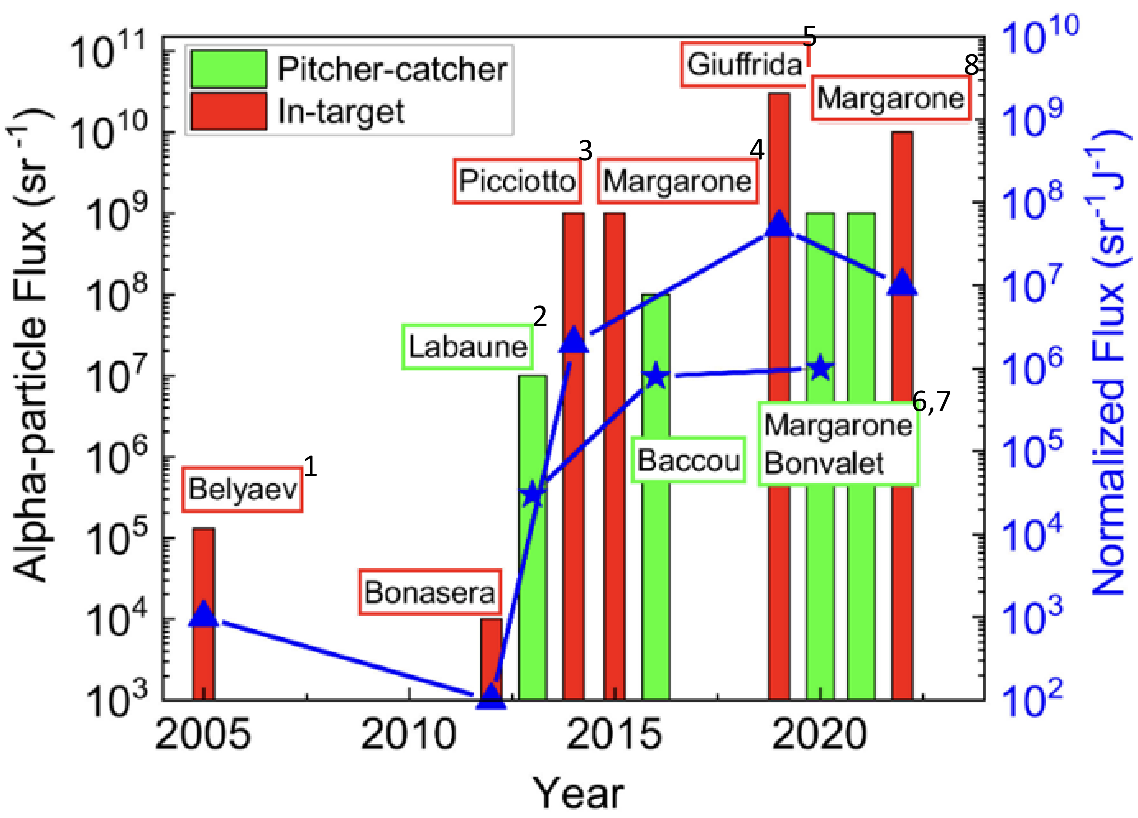


Two main approaches to trigger p-^{11}B fusion reactions in laser-matter experiments





The experimental progress in p–B fusion



➔ Since Belyaev work in 2005, using **laser-driven proton acceleration**, the p-B reaction yield has continuously increased up to a few 10^{10} α/sr in 2020[5] .

[1] V.S. Belyaev et al., Phys. Rev. E, (2005) [2] C. Labaune et al., Nat. Commun. 4, (2013) [3] A. Picciotto et al., Phys, Rev. X 4, (2014)
[4].D. Margarone et al, Plas. Phys. Contr. Fus. 57, 014030 (2015) [5] L. Giuffrida et al., Phys. Rev. E101, (2020) [6] D. Margarone et al Front. Phys. 8, 345 (2020)
[7] J. Bonvalet et al, Phys. Rev. E 103, 053202 (2021), [8] D. Margarone et al Applied Sciences 12, 1444 (2022)

α-particle measurement is challenging in Laser-initiated p-^{11}B nuclear fusion

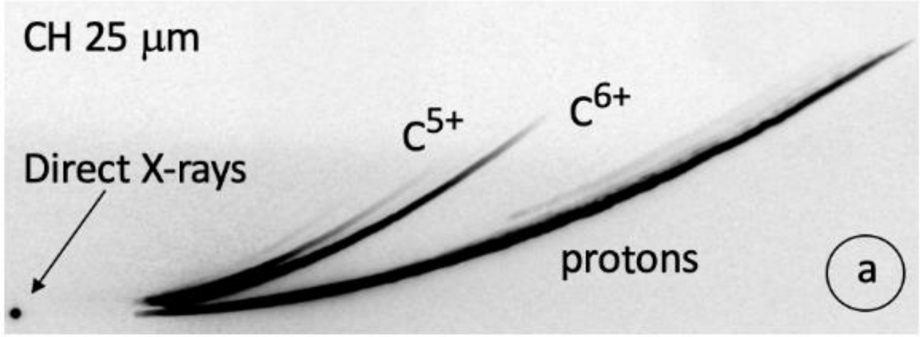
Complementary diagnostics must be used to accurately measure α-particles

- ➔ ***Low reaction rate*** *(10^{-5} α-particle/H^+ produced)* and ***other ion species from contaminant layer*** *interfere with alpha detection*

- ➔ *Only α* **produce at surface of the target** can escape and be detected (5 MeV α-particles cross 20µm thick Boron)

Thomson Parabola Spectrometer(TP):

➔ E and B field deflect vertically and horizontally the incoming charge particle: parabolic traces
➔ Discrimination of ions according to Z/A: the α-particle spectrum hidden by other ions with same Z/A (C, N, …)



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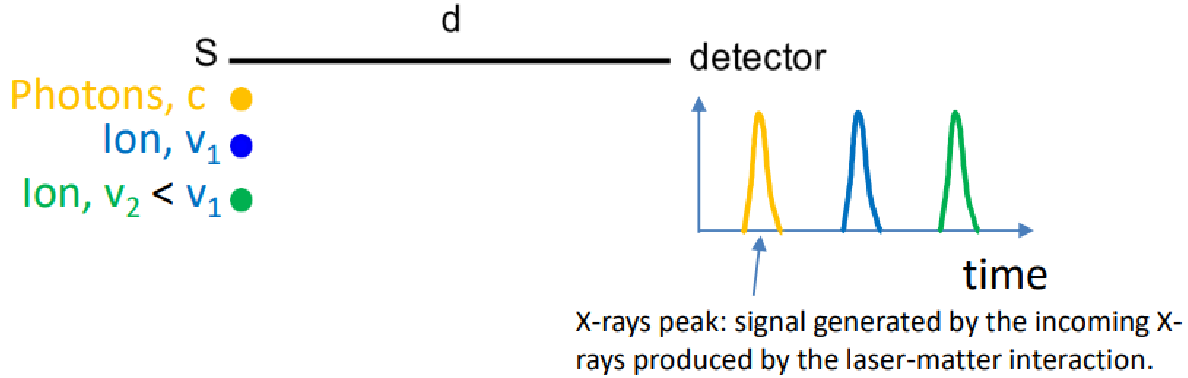
Time of flight (TOF):

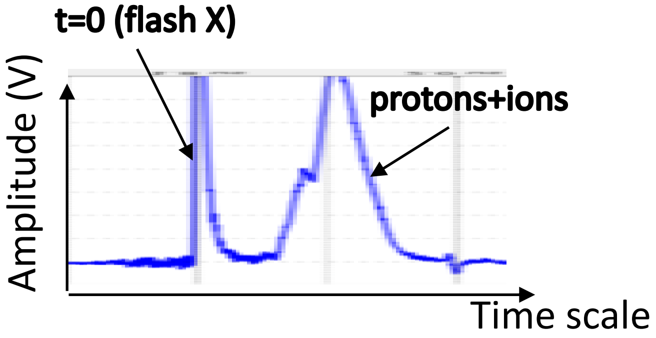
➔ information on particle velocity obtained with their time of arrival on detector at some distance from the target:

➔ easily identifies energetic protons but toughly the following ions

➔ No discrimination on particles but only on their velocities Mass/energy ratio.

➔ Bunch α/heavy ions/H^+ mixed





Signal from oscilloscope

α-particle measurement is challenging in Laser-initiated p-^{11}B nuclear fusion

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The **Solid-state nuclear track detector** (**CR39**):

➔ exposition to ionizing radiation generates local damaging i.e. tracks after etching

➔ detect a single ion with energy information according to hole diameter

➔ Relation between diameter track and energy is overlapping between ions

- ➔ Problem of discrimination

protons

Doubts C/N/alphas ?

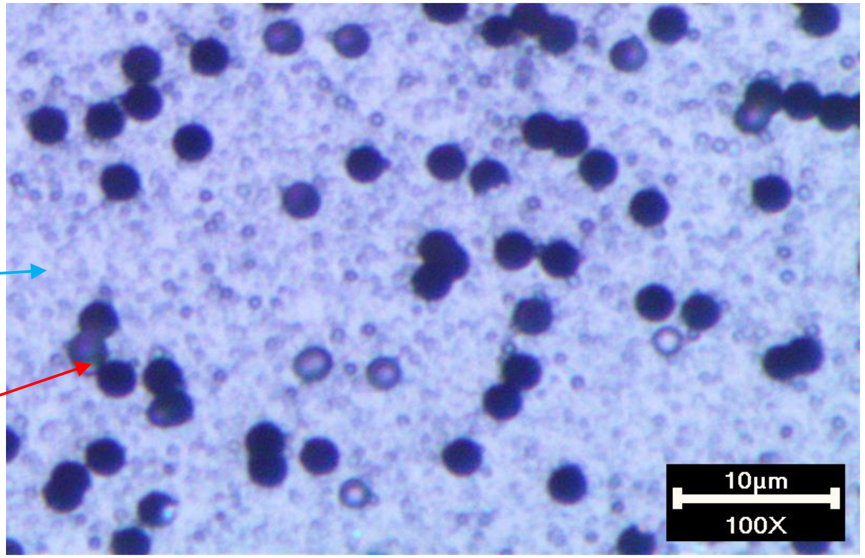


Image of Cr39 after etching from microscope x100

α-particle measurement is challenging in Laser-initiated p-^{11}B nuclear fusion

Complementary diagnostics must be used to accurately measure α-particles

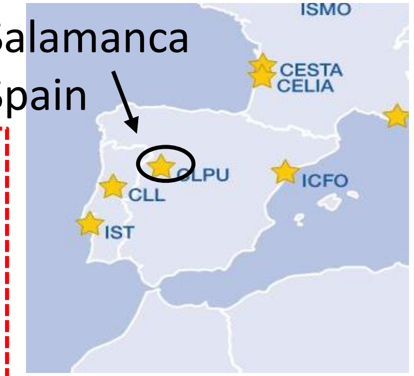
- ➔ ***Low reaction rate*** *(10^{-5} α-particle/H^+ produced) and* ***other ion species from contaminant layer*** *interfere with alpha detection*
- ➔ *Only α* **produce at surface of the target** can escape and be detected (5 MeV α-particles cross 20µm thick Boron)

➔Use of <u>shielding</u> / <u>filte</u>r can help to <u>discriminate</u> the α-particle contribution

Al filter [um]	**Cut-off energy [MeV]**		
	H	**α**	**C**
5	0,47	1,6	5,75
10	0,75	2,8	11,5
15	1	4	17,5

Experimental campaign at CLPU laser facility (March 2023)

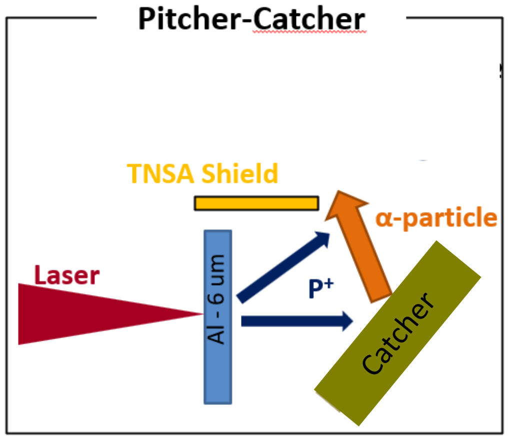
- Use of **high power** and **high repetition rate** laser VEGA-3 [1,2]
  - ➔ Highly improved statistics
  - ➔ Better control of the parameters and measurements of studied processes

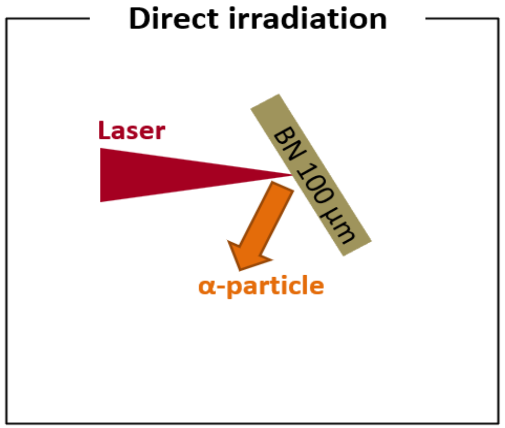


1PW VEGA-3 parameters:
30 Joules
30 femtoseconds
1 Hz repetition rate

- **Objectives**
  - ➔ Improve α-production and detection with two experimental schemes
  - ➔ Test new target type
  - ➔ Comparison of fusion products yield

- **2 set-up configurations**
  1) Laser driven proton acceleration on B type targets: **Pitcher-catcher**
  2) direct laser-target irradiation of B type targets: **Direct irradiation**

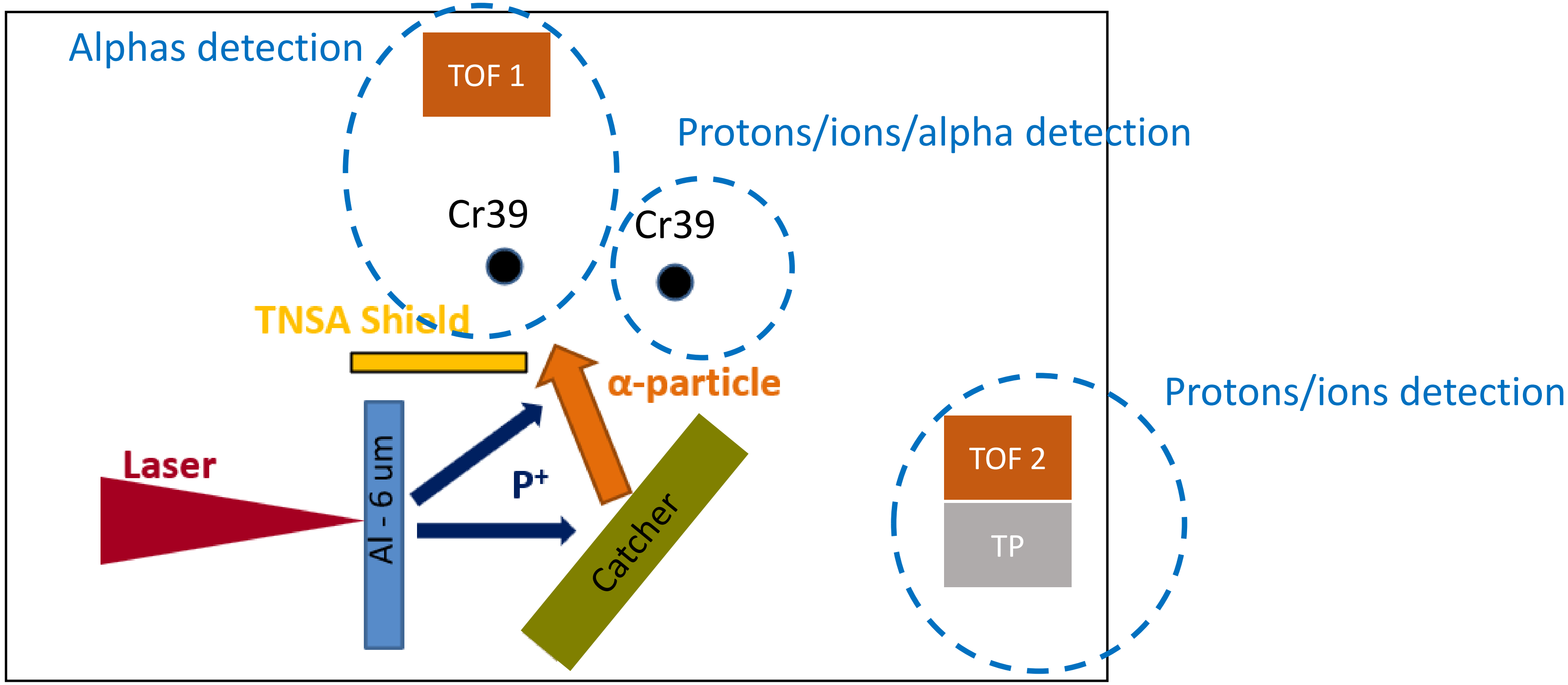




[1] C. Méndez et al., Fourth International Conference on Applications of Optics and Photonics,11207 (2019)

[2] Volpe L. et al., High Power Laser Science and Engineering, 7 e25 (2019)

Pitcher-catcher configuration set-up

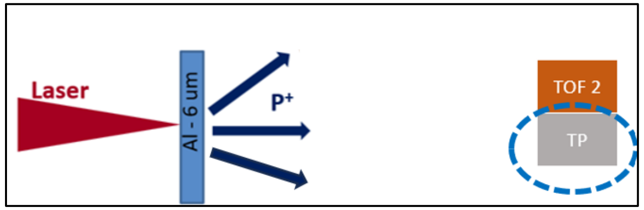


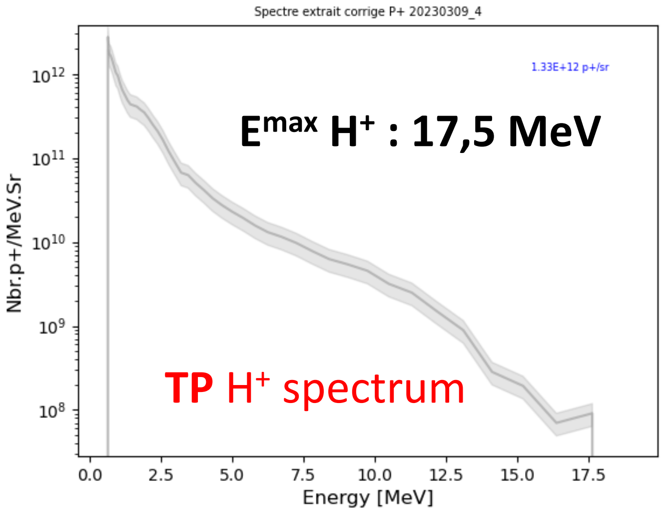
Catcher targets: *BN (5mm)*

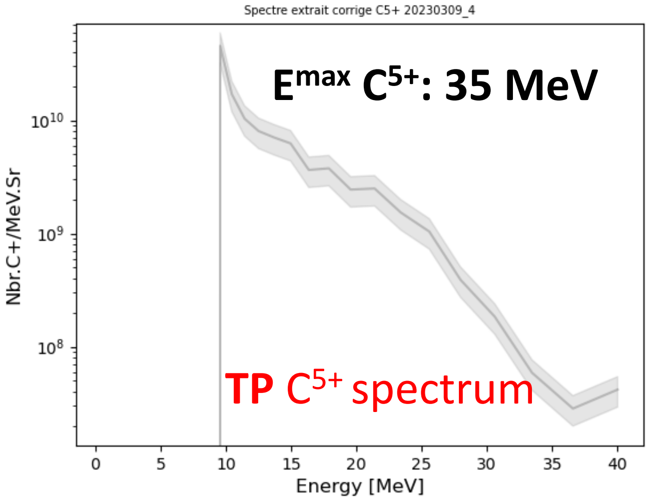
Diagnostics (in situ)*: Thomson Parabola (TP); Time of Flight (TOF) ;* ***Cr39***

Laser-target interaction was first optimized and TNSA proton characterized

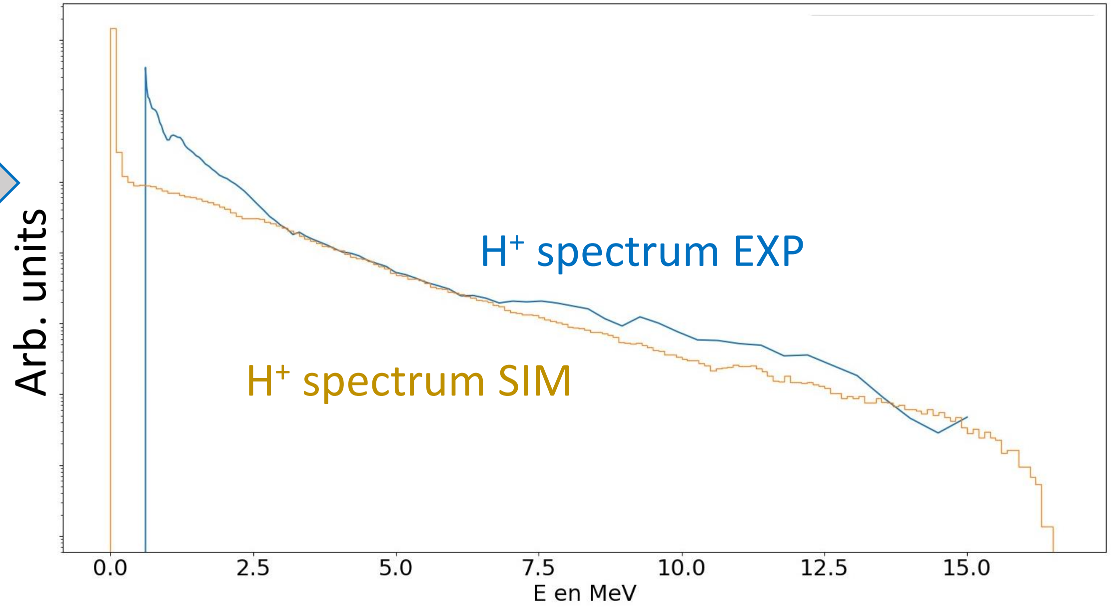
➔Experimental proton spectrum was reconstructed thanks to TP diagnostic







Comparison H^+ spectrum Exp /Simu (PIC)

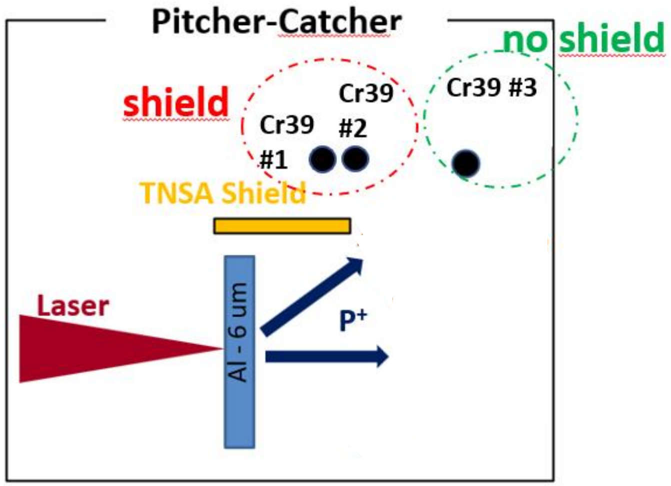


➔TP Experimental spectrum helps to constrain the simulation parameters

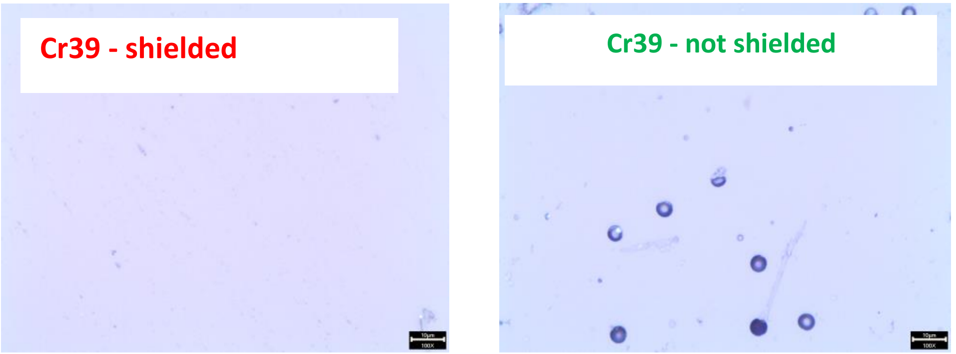
In TNSA, several ion species are accelerated at the rear side of the target

Ions from contaminant layer (H, C, N, O….) can interact with the detectors➔ difficult to separate α-particles contribution

➔**TNSA shielding** between pitcher target and Cr39/TOF detectors to protect from contaminants interaction



TNSA Shield



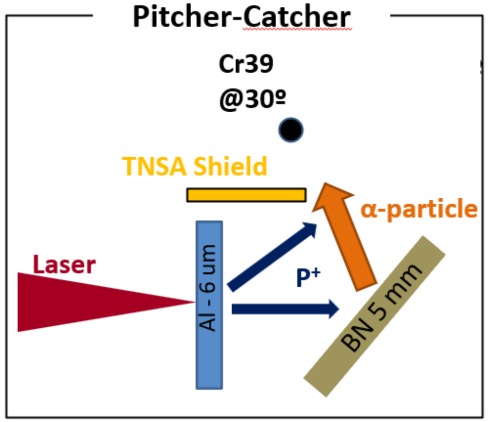
A shielding was placed between the pitcher target and one of the **Cr39** to prevent TNSA emission

On Cr39, TNSA shielding efficiency proven during reference shot **without catcher target**

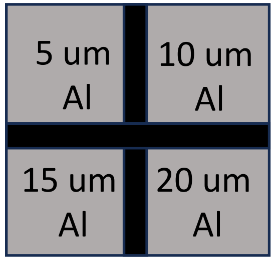
When adding the catcher target, other particles can reach the detectors

➔ions from contaminant layer interact with the catcher ➔ presence of **diffused particles and secondary nuclear reactions products on the detectors**

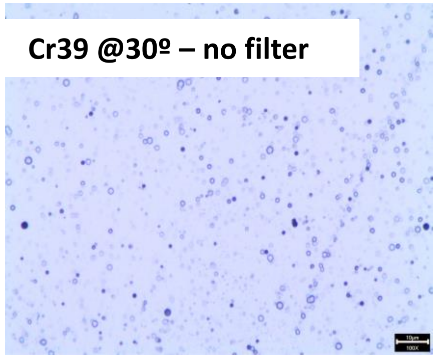
➔Use **filters** to discriminate between α and other ion species

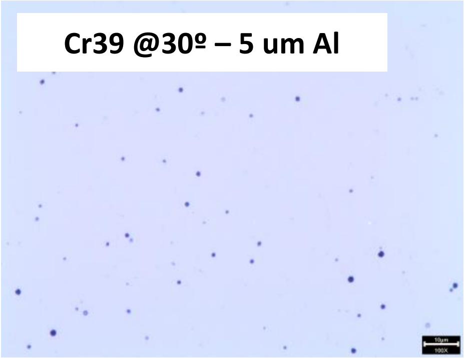


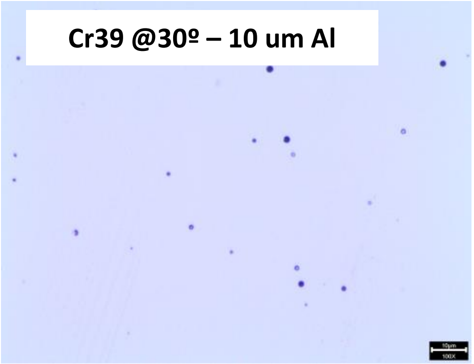
Cr39 design holder



Cr39 images on microscope x100







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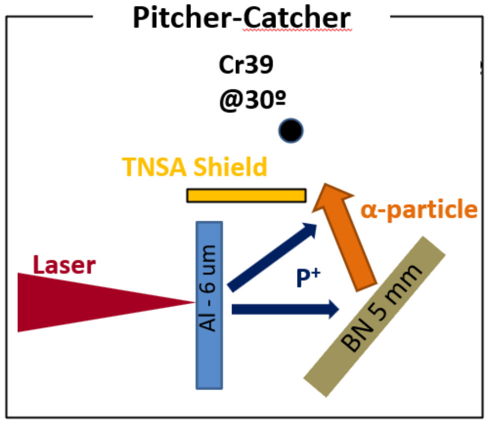

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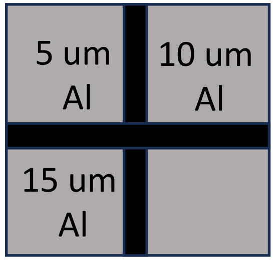

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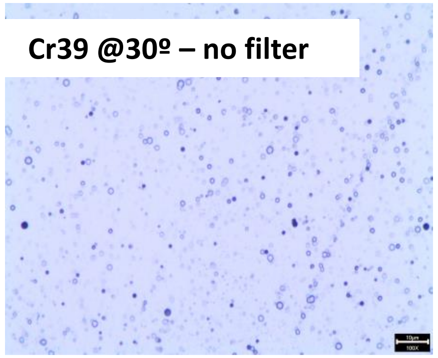
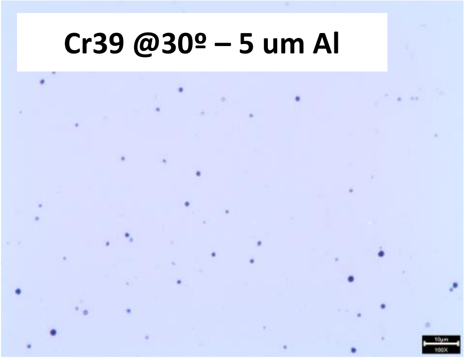
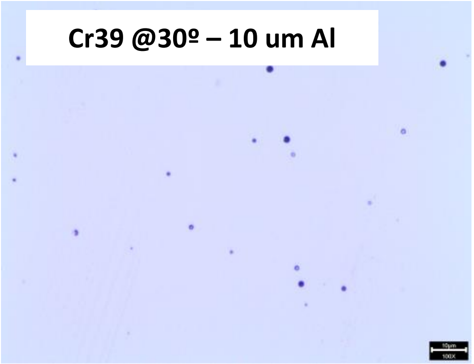
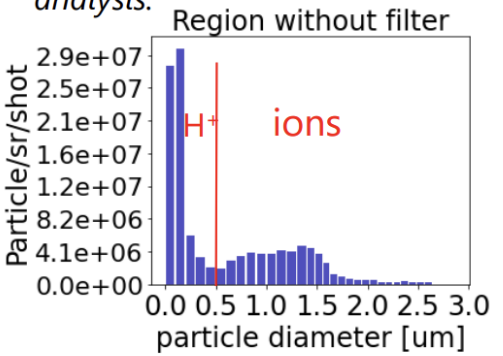






Extracted histogram from Cr39 analysis.

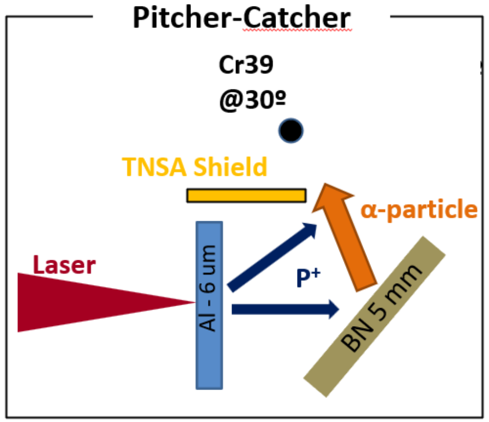


➔Possible discrimination between H+ and ions on histogram, but not between ion species

When adding the catcher target, other particles can reach the detectors

➔ions from contaminant layer interact with the catcher ➔ presence of **diffused particles and secondary nuclear reactions products on the detectors**

➔Use **filters** to discriminate between α and other ion species



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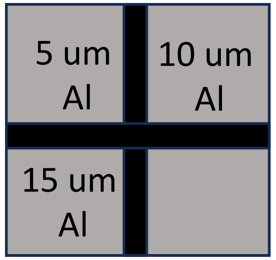
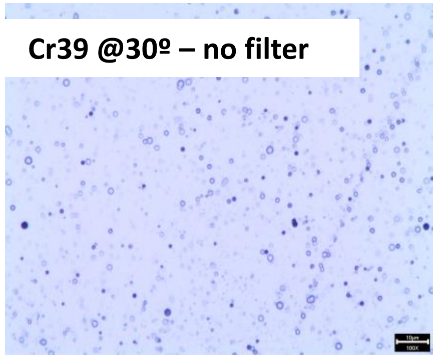
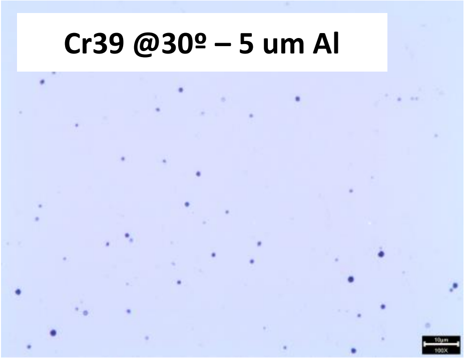
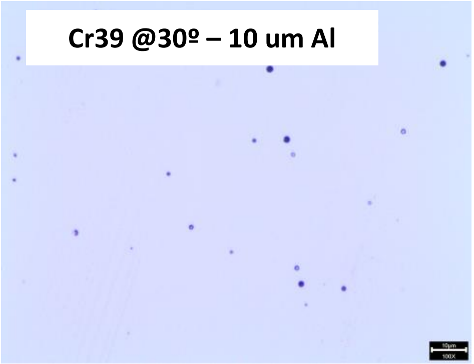


Cr39 images on microscope x100







Al filter [um]	**Cut-off energy [MeV]**		
	H	**α**	**C**
5	0,47	1,6	5,75
10	0,75	2,8	11,5
15	1	4	17,5

➔Possible discrimination between H+ and ions on histogram, but not between ion species

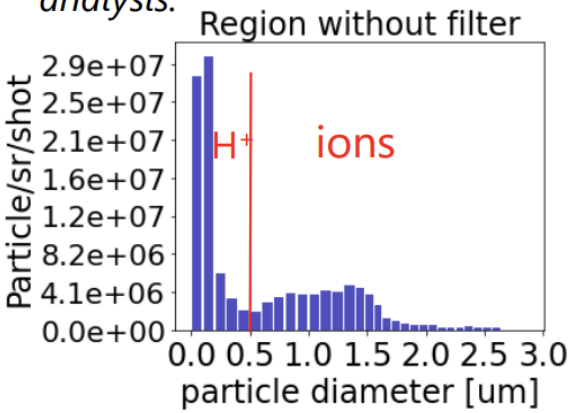
➔Filter thickness should stop heavy ions and so allows discriminating between ion species

Reconstruction of α-particle spectrum with Cr39 thanks to calibration

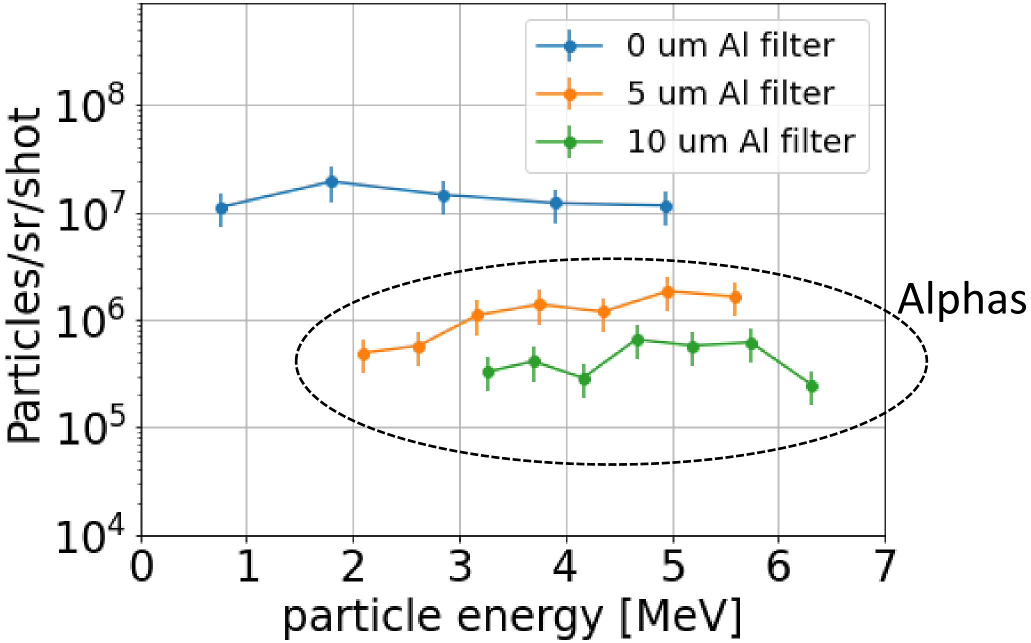
A calibration of Cr39 with α-emitting source and Accelerator beam has been done

➔conversion **track diameter to energy**
➔Allows for **α spectrum reconstruction**

Extracted histogram from Cr39 analysis.



Experimental spectra - Cr39



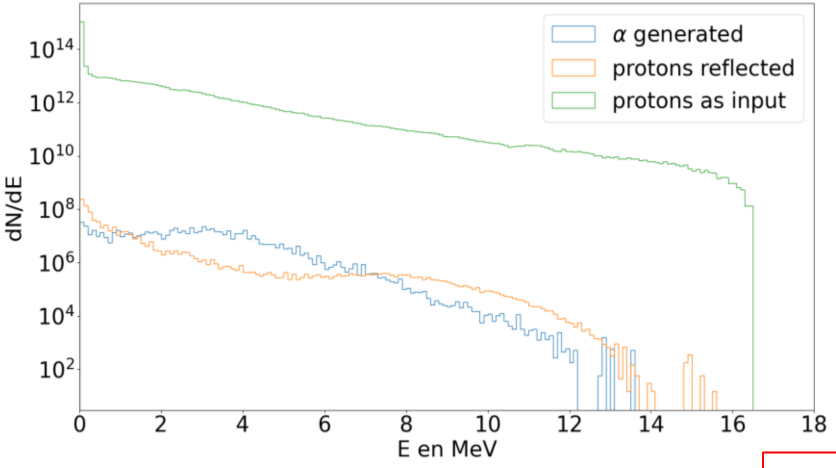
Total alpha number/sr/shot	
	Exp. data
>1,6 MeV (5 umAl)	1e7
> 2,8 MeV (10 um Al)	3,5e6
> 4 MeV (15 um Al)	8e5

➔ Strong gap between regions with/without filter

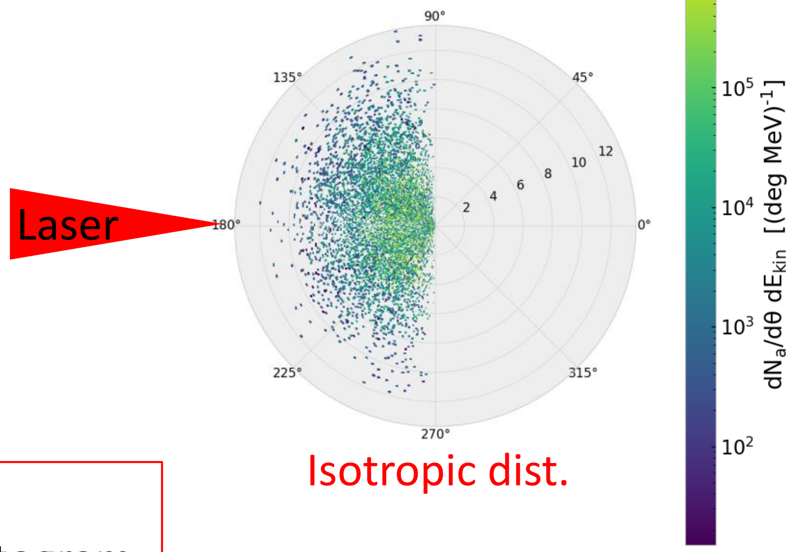
➔ Other particles contribution ?

Simulations confirm the first conclusions on α-particle contributions

Emitted α and diffused H^+ spectra from catcher target with respect to injected H^+ (Monter Carlo and Smilei)

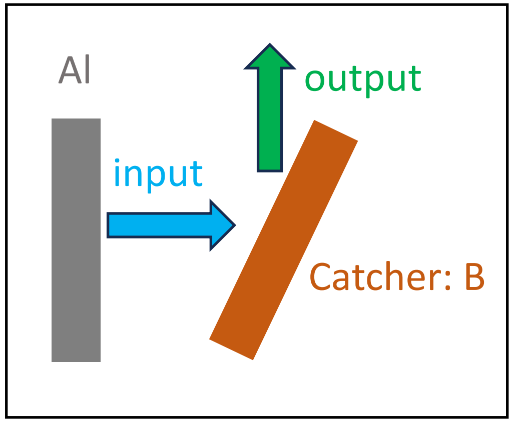


α angular distribution



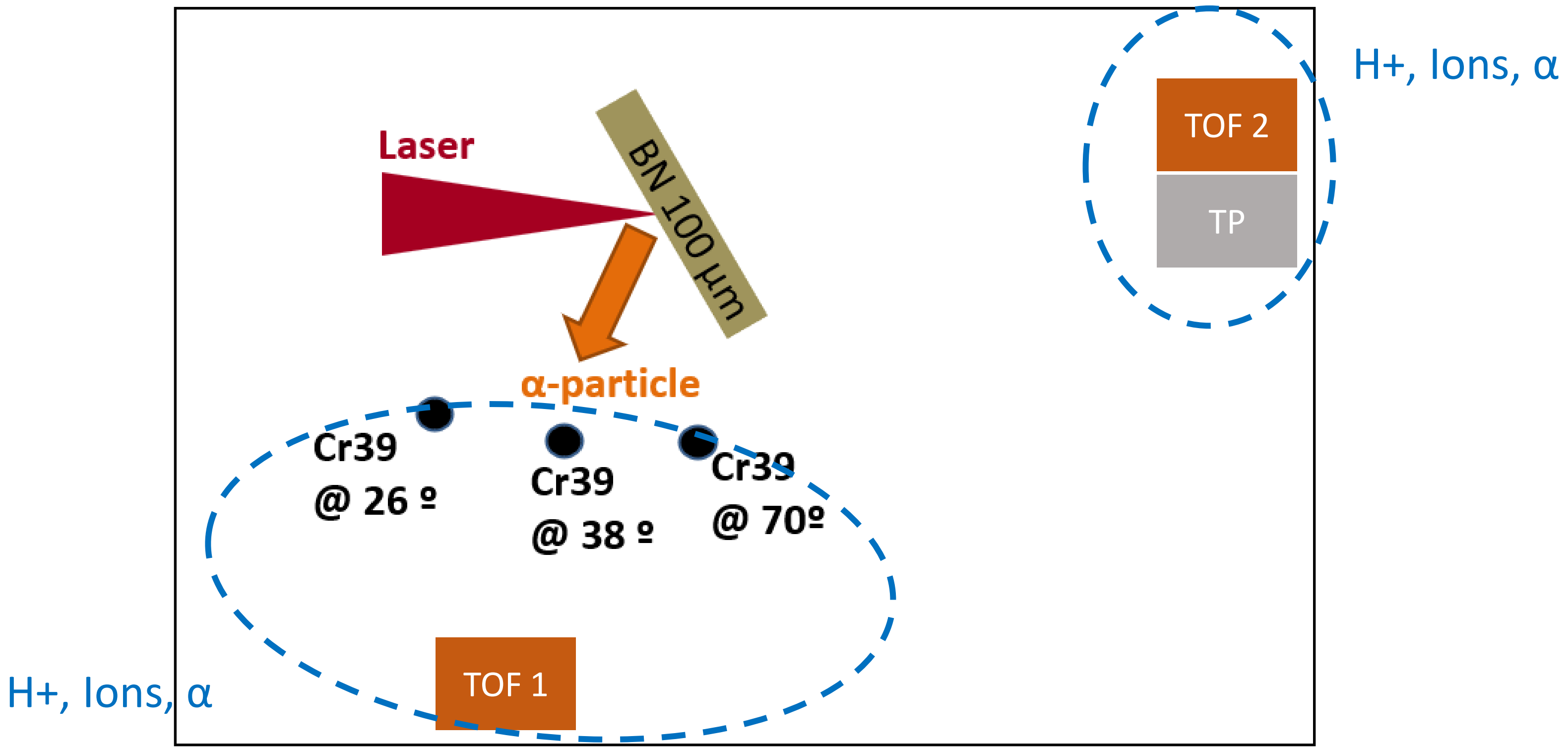
- ➔ Other contribution comes mainly from H^+
- ➔ Proton are easy to distinguish on Cr39 histogram

Particle contribution simulation (fluka)



- ➔ α emitted / H^+ emitted ≈ 2.5$10^{-5}$ (3 MEV) - 5.10^{-5}(10 MEV)
- ➔ H^+ (diffused+nuclear)/ H^+ emitted ≈ 2.10^{-5} (3MEV H^+) - 8.10^{-5}(10MEV H^+)
- ➔ C diffused/ C emitted ≈ 10^{-6}
- ➔ B from C or H^+ emission negligeable ≈ 10^{-7}
- ➔ Fragmentation C starts at 12 MeV (H^+ and α negligeable)

Direct irradiation configuration set-up



***Catcher targets: CH-**BN (2µm-100µm)*

➔ use of CH deposition as a front layer allows to know the H content in front layers

➔This can allow better comparison with numerical simulations

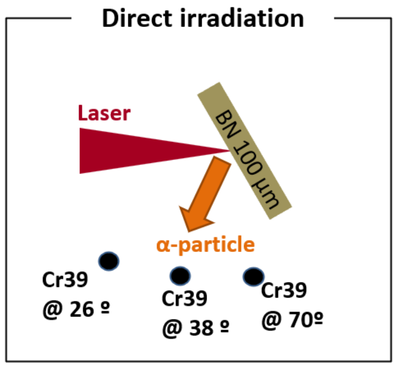
Diagnostics (in situ)**: Thomson Parabola (TP); Time of Flight (TOF) ; **Cr39

In direct irradiation, the detectors detect all particles accelerated from target front side

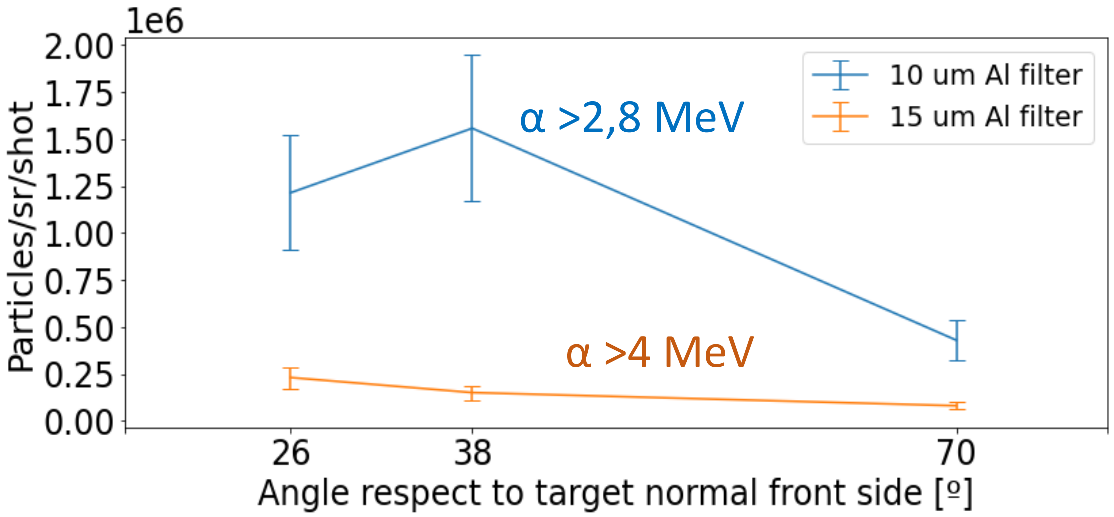
Ions from contaminant layer localizes at the front target side are also emitted by TNSA mechanism

➔ We placed the Cr39 at **3 different angles to distinguish isotropic/no isotropic emissions**

➔ We used **2 filter thickness** (10 and 15 um Al)



Angular distribution comparison of ions detected by CR39 for filtered regio with 10 um (blue) and 15 um (red) Al thickness.



Total alpha number/sr/shot			
	Exp. data		
	@26º	@38º	@70º
> 2,8 MeV (10 um Al)	1,2e6	1,6e6	4,3e5
> 4 MeV (15 um Al)	2,3e5	1,5e5	8,1e4

Al filter [um]	**Cut-off energy [MeV]**		
	H	**α**	**C**
5	0,47	1,6	5,75
10	0,75	2,8	11,5
15	1	4	17,5

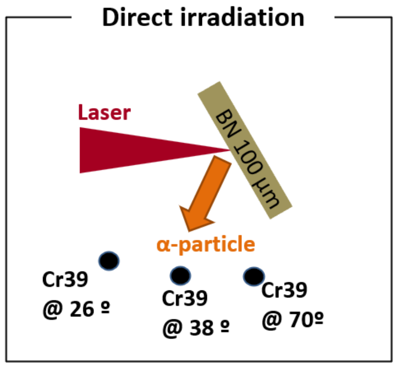
➔Tendency curve for 10 um Al and 15 um Al seems in agreement with isotropic distribution of α particle

➔Only carbons with energy > 11,5 MeV can reach the Cr39 detector in the region of 10 um Al filter

➔Only carbons with energy > 17,5MeV can reach the Cr39 detector in the region of 15 um Al filter

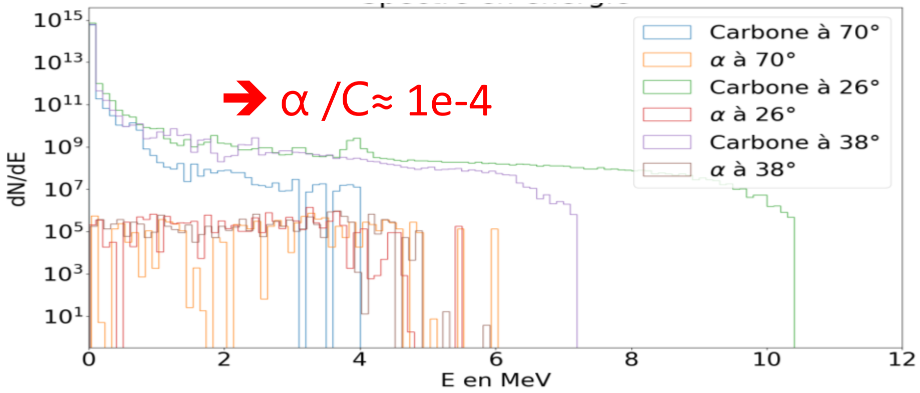
Simulations estimate the ions distribution and energy at the detector positions

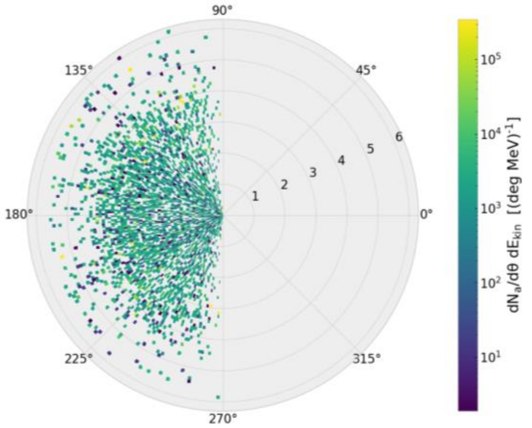
➔According to simulation, max Carbon energy up to 10.5 MeV at 26º respect to normal front side target ➔We expected all carbons to be stopped by 10 and 15 um Al filters



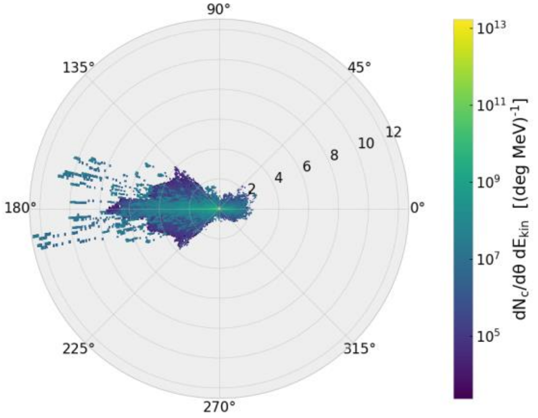
Al filter [um]	Cut-off energy [MeV]		
	H	α	C
5	0,47	1,6	5,75
10	0,75	2,8	11,5
15	1	4	17,5

FRONT SIDE: Carbon and α spectrum

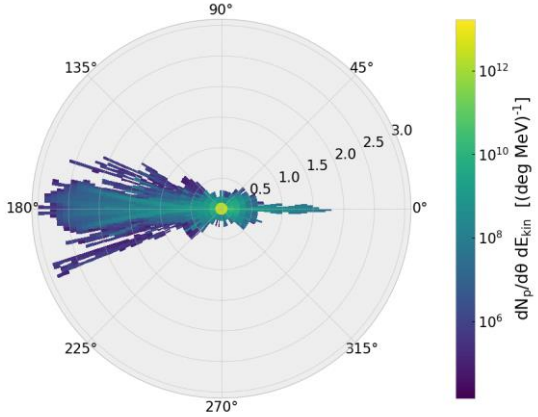




α angular dist.



C angular dist.



H+ angular dist.

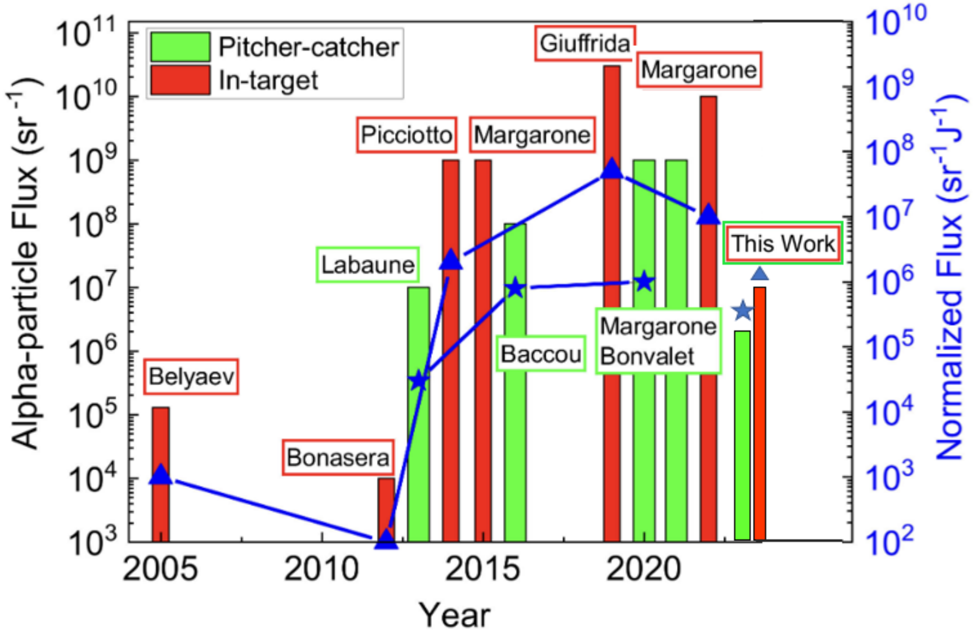
Conclusion and Perspectives

- Laser induce p-^{11}B fusion reaction has been tested on HRR laser installation
- Two configurations (Pitcher-Catcher and Direct irradiation) set-up have been tested
- Source of Alpha estimated per joule is comparable to previous experiments

➔ Using the HRR could allow to get a high brightness α-particle source

Pitcher-catcher: 3.5e6 α/sr/shot (α > 2,8MeV@30º)

Direct irradiation : 1.6e6 α/sr/shot (α > 2,8MeV@38º)



<u>**Perspectives**</u>

- Next step is to realise laser-driven α source at HRR for the production of radioisotopes
- **Radioisotopes ^{43}Sc via the reaction ^{40}Ca(α,p)^{43}Sc is a positron emitter and considered as the "radioisotope of the future" in the field of imaging.**

[1] K.Szkliniarz, et al. Applied Radiation and Isotopes 118, 182 (2016)

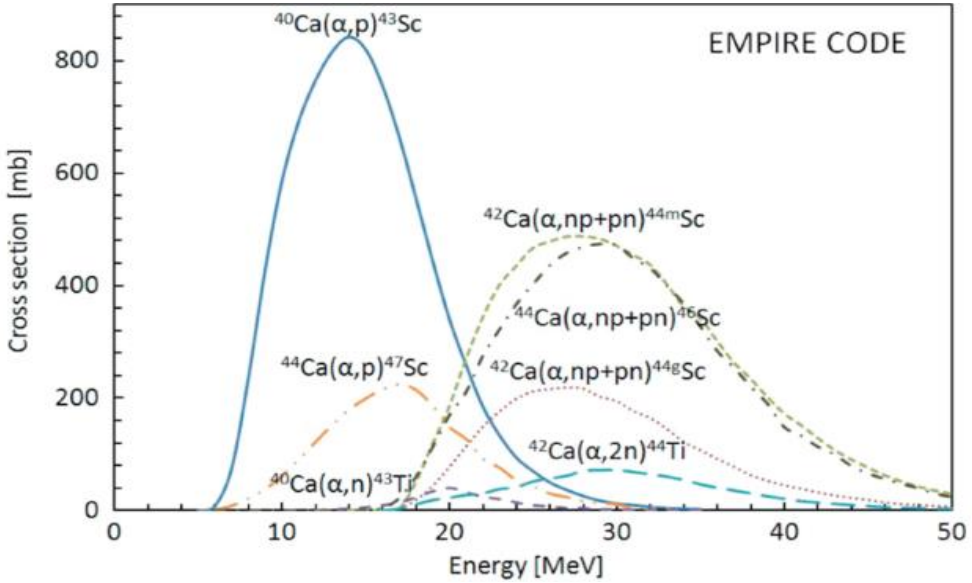
[2] M. I. K. Santala, et al. 2001. Applied Physics Letters, 78(1)

Thank you

Email: marine.huault@usal.es

Acknowledgements:

Scandium radioisotope production using α-particle beam



➔ **Radioisotopes ^{43}Sc via the reaction $^{40}Ca(\alpha,p)^{43}Sc$ considered as the "radioisotope of the future" in the field of imaging *.**

Radionuclides of scandium: - **scandium-43 and scandium-44 ($^{43/44}Sc$)** ➔ as positron emitters
- **scandium-47** (^{47}Sc) ➔ beta-radiation emitter

Laser-initiated $^{11}B(p,\alpha)2\alpha$ nuclear reaction

<u>The α-particle measurement is challenging</u>

➔ Nuclear reactions induced by α-particles/protons could be used as diagnostics

- gamma peaks can only be measured after shot with a **High Purity Germanium radiation detector (HPGe)**

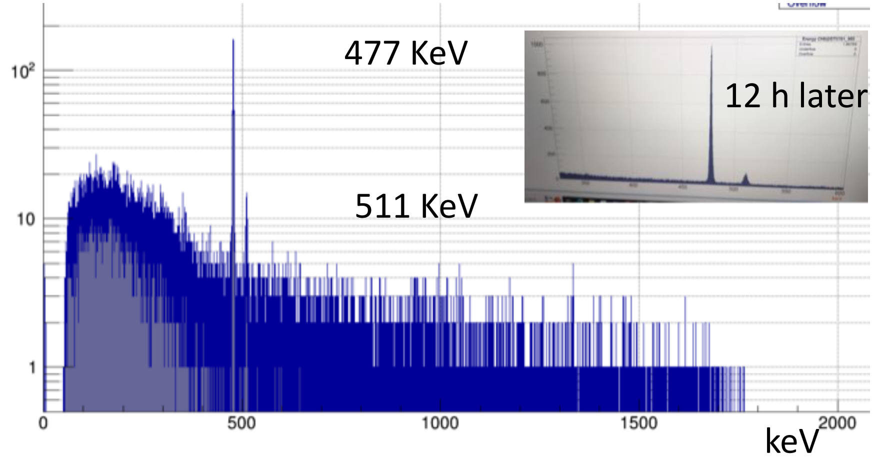
➔possible in the pitcher-catcher geometry,

➔complicated in the directed irradiation because a part of the matter is ablated

ex : $p + {}^{10}B \rightarrow {}^{11}C^* \rightarrow {}^{7}Be^* + \alpha \rightarrow {}^{7}Li + \gamma$ (477 KeV)

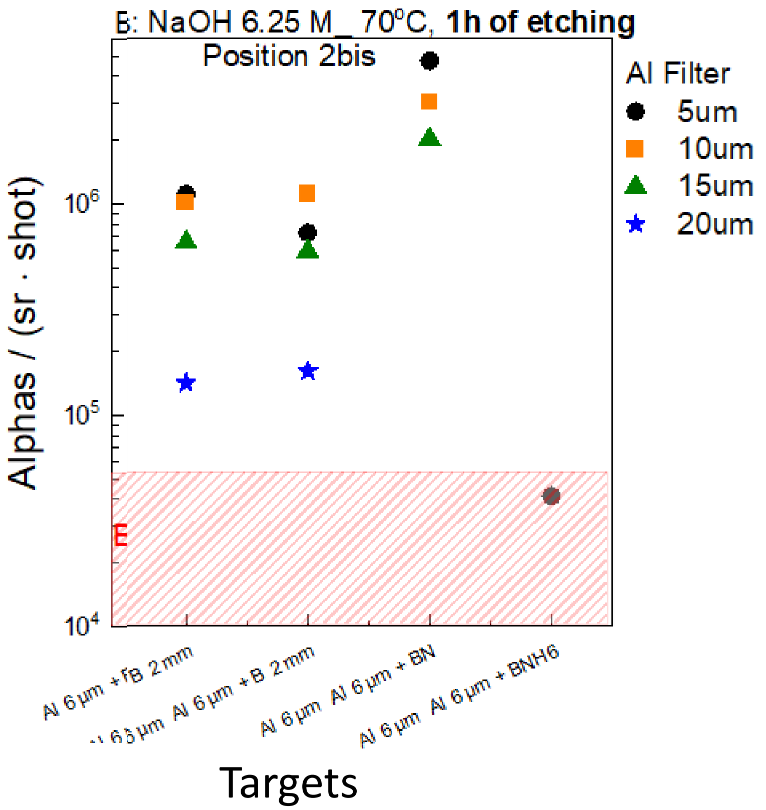
$p + {}^{11}B \rightarrow {}^{11}_{6}C + n \rightarrow ({}^{11}_{5}B + e+ \ + \nu) + n$ (511 KeV)

$\alpha + {}^{40}Ca \rightarrow {}^{43}Sc + \gamma$ (373 KeV)

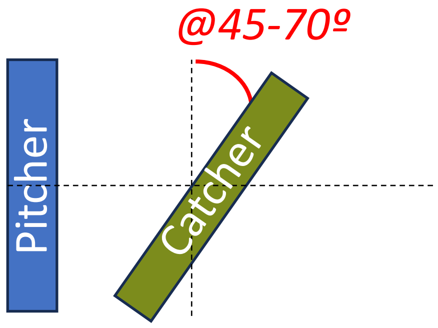


Experimental campaign at CLPU laser facility (March 2023)

- Pitcher-catcher configuration: Comparison between targets



➔ Several target have been tested with different angle and composition
B @45º (2mm) ; BN @70º (5mm) ; BNH6 @60º (1mm)



➔ high angle between catcher –pitcher can enhance the p-11B fusion reaction at the Surface of the catcher
➔ Alpha are generated in Surface of the catcher and can escape easily the target