LPAW 2025

Experimental and computational evaluation of alpha particle production from laser-driven proton–boron nuclear reaction in hole-boring scheme

M. Huault [1] , T. Carrière [2] , H. Larreur [1,2] , Ph. Nicolaï [2] , D. Raffestin [2] , D. Singappuli [2] , K. Batani [3] , M. Cipriani [4] , F. Filippi [4], M. Scisciò [4], C. Verona [5] , L. Giuffrida [6] , V. Kantarelou [6] , S. Stancek [6] , N. Boudjema [1] , R. Lera [7] , J.A. Pérez-Hernández [7] , L. Volpe [7,8] , A. Bonasera [9], M.R.D. Rodrigues [9] , D. Ramirez Chavez [9] , F. Consoli [4] , D. Batani [2]

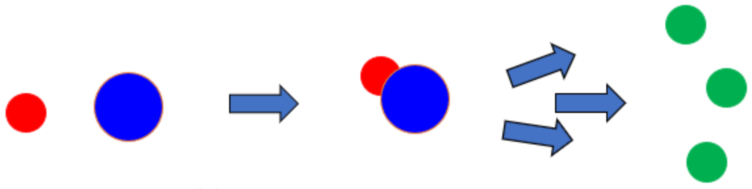
VNiVERSiDAD D SALAMANCA

CELIA Centre Lasers Intenses et Applications

[1]USAL [2]University of Bordeaux, CNRS/CELIA/CEA [3]IPPLM [4]ENEA [5]DIIEM [6]ELI-Beamlines [7] CLPU [8]ETSIAE [9]Texas A&M Cyclotron Institute

p-^{11}B fusion reaction: Background and purpose

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



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

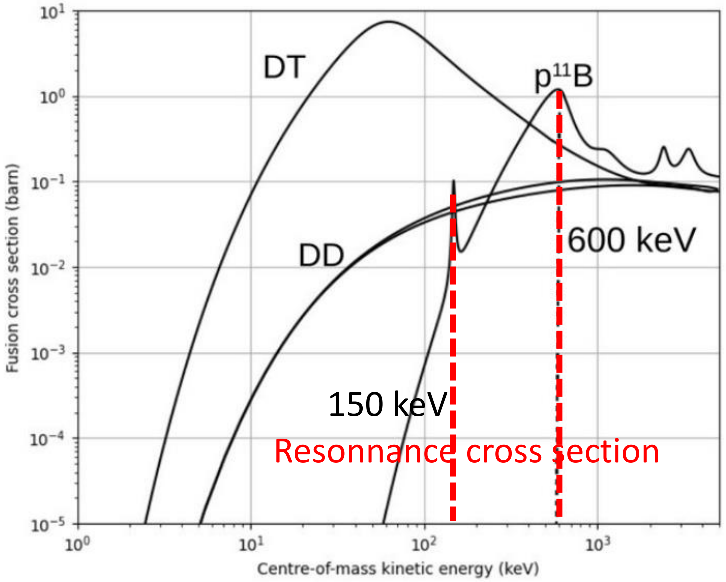
- The proton-boron nuclear reactions is interesting for multiple applications
  - fusion for energy : quasi aneutronic reaction
  - α-production:
    - ➛ for cancer therapy[1]
    - ➛ for radioisotope production[2]

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

➔Conventional compression approach is not possible to ignite fuel

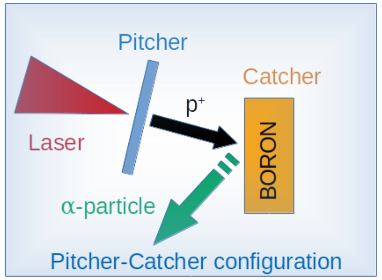
➔ Laser initiated p-^{11}B nuclear fusion reaction

Fusion Cross Section



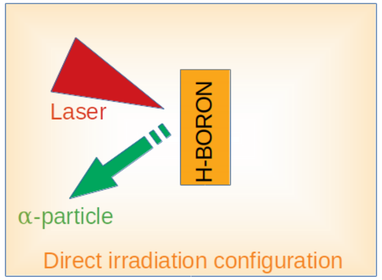
[1]Cirrone et al, Sci. Rep. 8, 1141 (2018)   [2]Szkliniarz et al, Applied radiation and isotopes (2016)

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



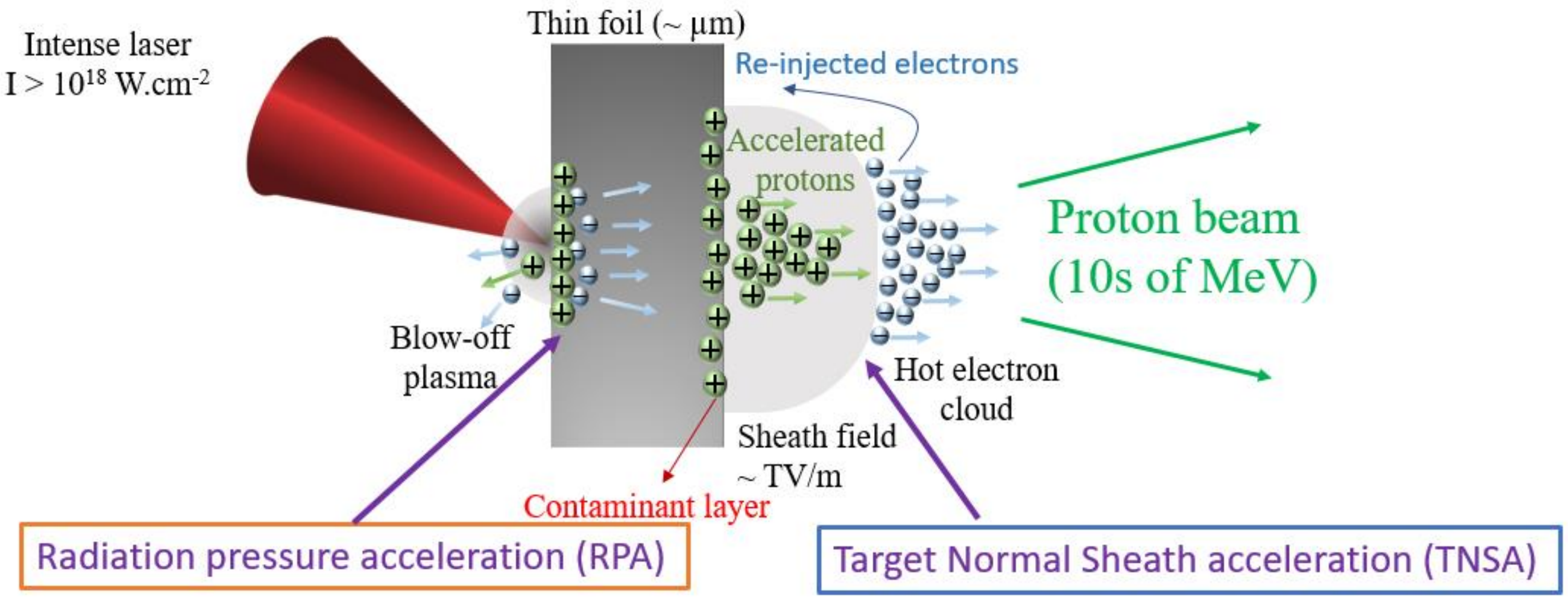
- ***Pitcher-catcher configuration***

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



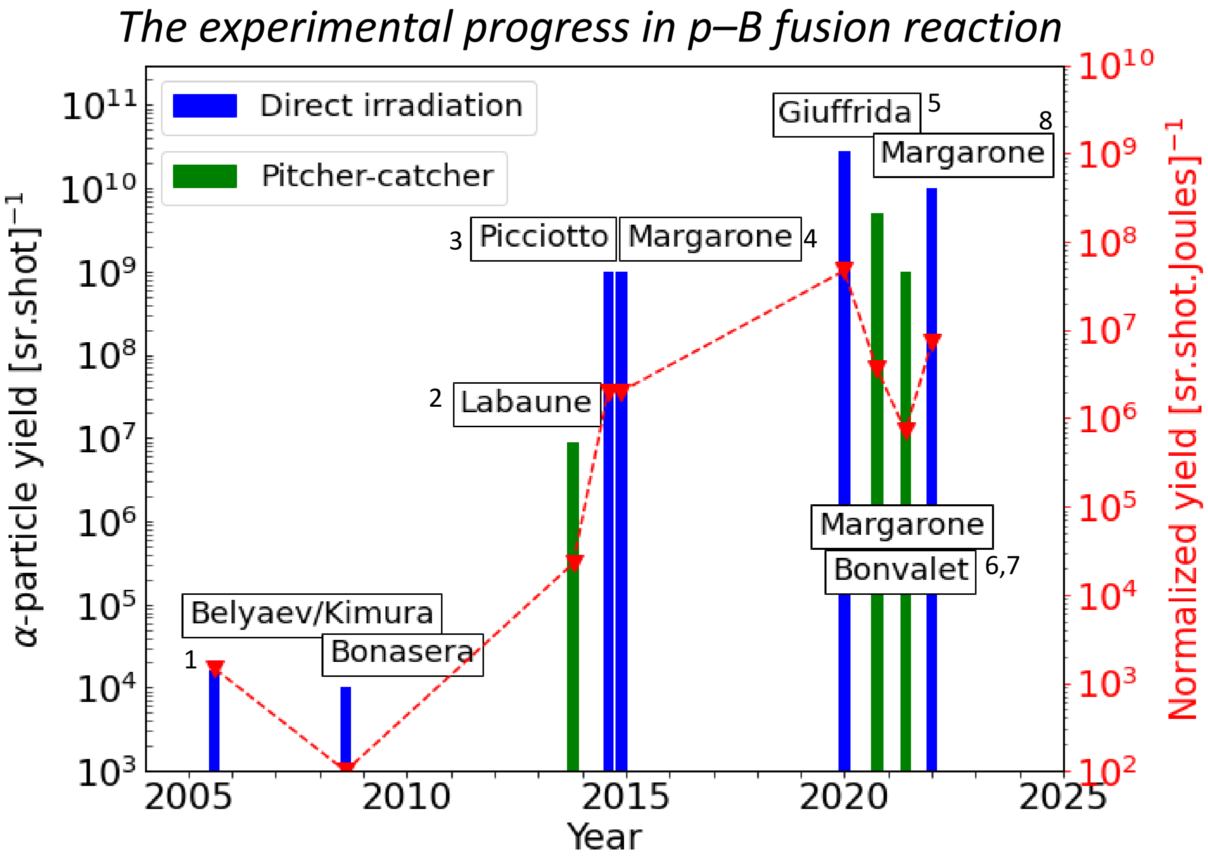
- ***Direct irradiation configuration***

➔ Protons accelerated at the front side of the target by **Radiation Pressure Acceleration mechanism (RPA-Hole Boring)**



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

➔ 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/shot 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)

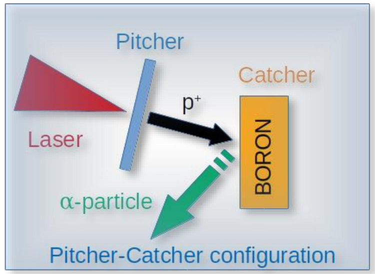
Experimental campaign at CLPU laser facility (March 2023)

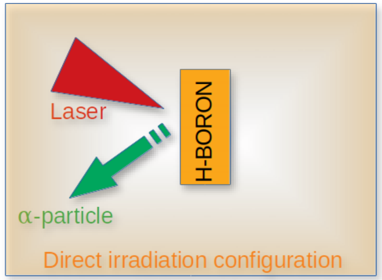
- Use of **high power** and **high repetition rate** laser VEGA-3 [1,2]

➔ Highly improved statistics
➔ High repetition rate compensate the lower α-production due to lower laser energy of VEGA-3

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

- **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**





Objectives

➔ Improve α-production and detection with two experimental schemes
➔ Use the Pitcher-catcher scheme to validate our codes and help interpreting in a second step the direct irradiation scheme

[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)

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

Complementary diagnostics must be used to accurately measure α-particles

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

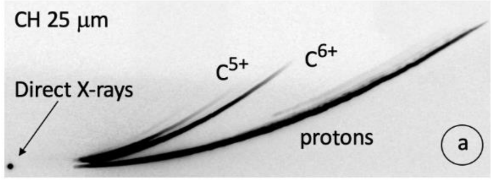
α-particle measurement is challenging in Laser-initiated p-^{11}B nuclear reaction

Complementary diagnostics must be used to accurately measure α-particles

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

➔ ***Thomson Parabola Spectrometer(TP)***

- E and B fields deflect vertically and horizontally the incoming charge particle: parabolic traces
- Discrimination of ions according to charge-mass ratio Z*/A: α spectrum hidden by other ions with same Z*/A (C^{6+}, N^{7+},…)



Typical parabolic traces on screen

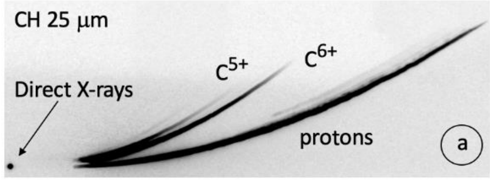
α-particle measurement is challenging in Laser-initiated p-^{11}B nuclear reaction

Complementary diagnostics must be used to accurately measure α-particles

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

➔ ***Thomson Parabola Spectrometer(TP)***

- E and B fields deflect vertically and horizontally the incoming charge particle: parabolic traces
- Discrimination of ions according to charge-mass ratio Z*/A: α spectrum hidden by other ions with same Z*/A (C^{6+}, N^{7+},…)

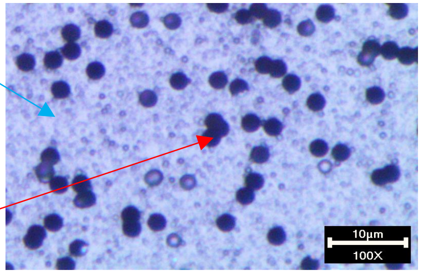


Typical parabolic traces on screen

➔ ***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 track diameter
- Discrimination according to track diameter: Same track diameter corresponds to several ion species at different energies

protons



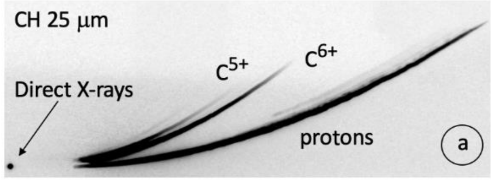
Doubts α/heavy ions ?

Image of Cr39 after 1H etching from microscope x100

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

Complementary diagnostics must be used to accurately measure α-particles
- ***Low reaction rate*** *(10^{-5} α-particle/H^+ produced)*
- ***Other ion species from contaminant layer*** *interfere with α-particle detection*
- *Only* ***α produced near the target surface*** *can escape and be detected (5 MeV α-particles cross 20 µm thick Boron)*

➔ ***Thomson Parabola Spectrometer(TP)***
- E and B fields deflect vertically and horizontally the incoming charge particle: parabolic traces
- Discrimination of ions according to charge-mass ratio Z*/A: α spectrum hidden by other ions with same Z*/A (C^{6+}, N^{7+},…)



Typical parabolic traces on screen

➔ ***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 track diameter
- Discrimination according to track diameter: Same track diameter corresponds to several ion species at different energies

protons

Doubts α/heavy ions ?

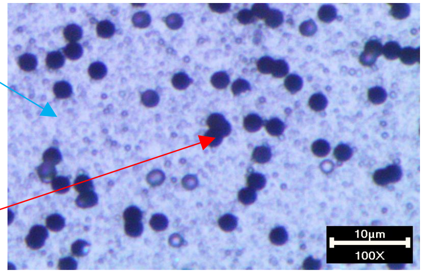
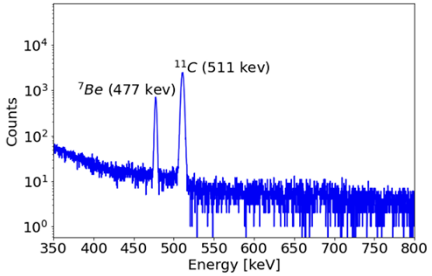
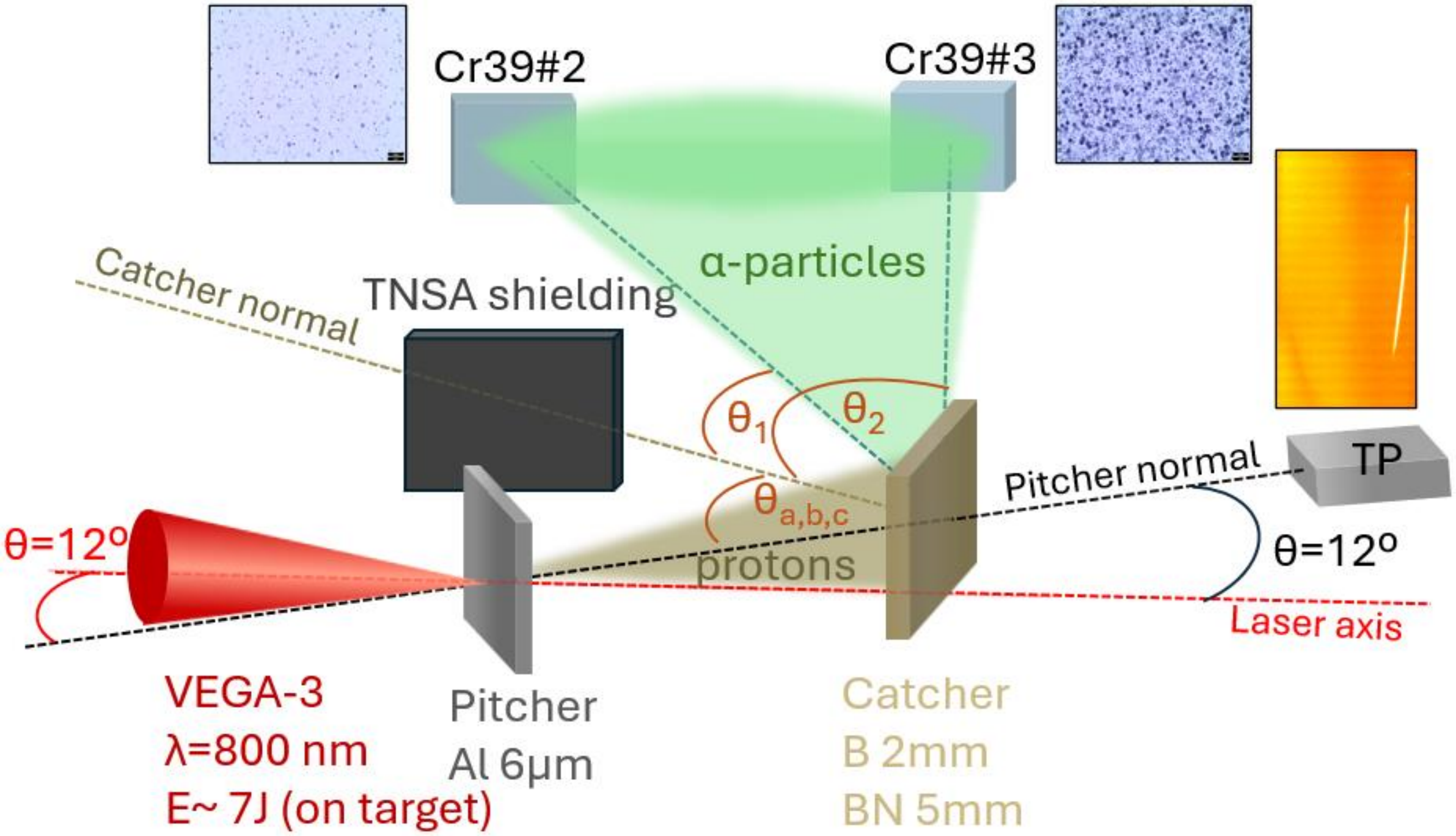


Image of Cr39 after 1H etching from microscope x100

➔ ***High Purity Germanium radiation detector (HPGe) :*** **Nuclear reactions induced by α-particles/protons**
- possible in the **pitcher-catcher** geometry
- complicated in **the direct irradiation** due to ablated matter when the laser interacts with the target



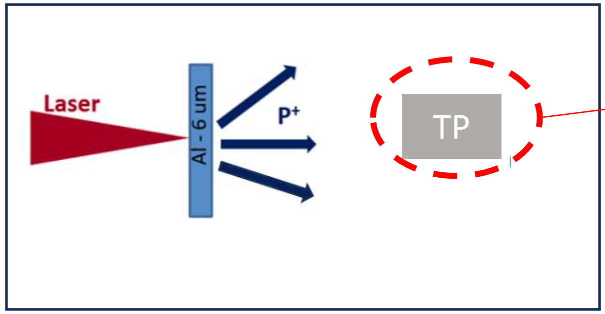
Pitcher-catcher configuration



Diagnostics: TP, CR39, HPGe

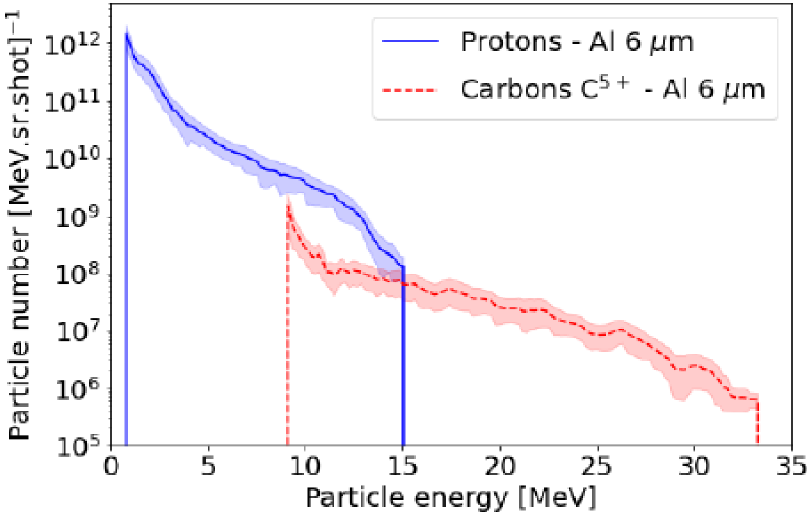
Catcher: B (2mm) @ 45º ; BN (5 mm) @70º

Pitcher-catcher: TNSA protons were first optimized and characterized

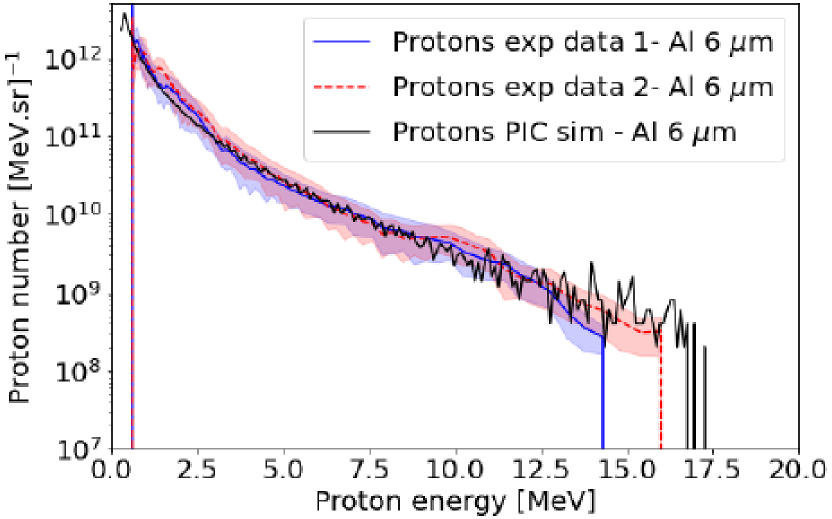


Experimental TNSA proton spectrum was reconstructed thanks to TP diagnostic

Exp. Proton/Carbon spectrum (TP)



Comparison Proton spectrum Exp. /Simu (PIC)

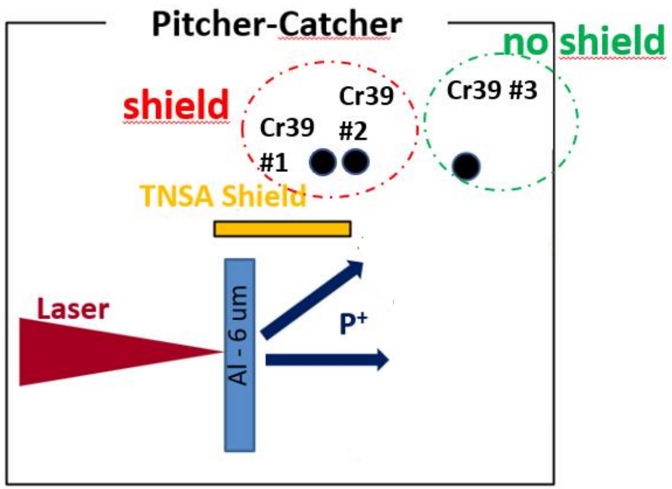


➔Experimental proton spectrum helps to constrain the simulation parameters

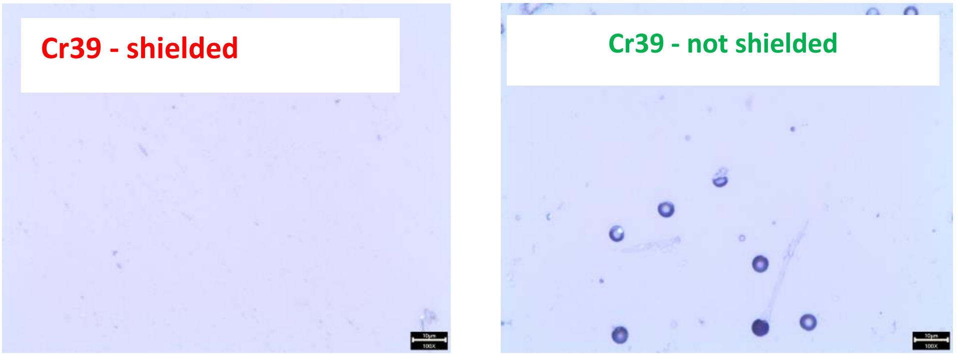
Pitcher-catcher: In TNSA, several ion species accelerated at the rear side of the target

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 detectors to protect from contaminants interaction



TNSA Shield



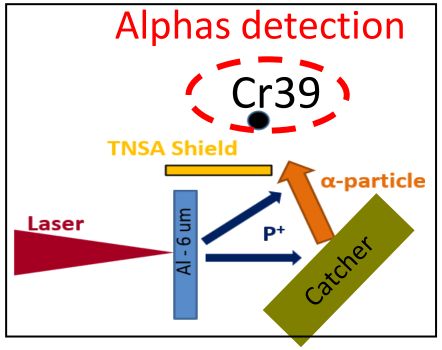
A shielding was placed between the pitcher target and ones of the **Cr39** to prevent TNSA emission

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

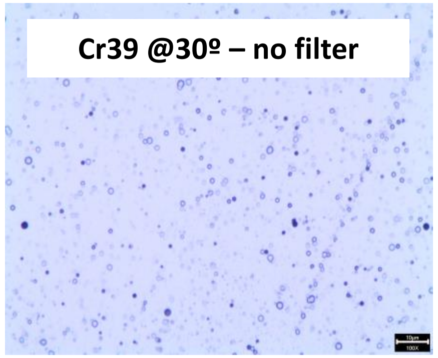
Pitcher-catcher: When adding the catcher target, other particles can reach the Cr39 detectors

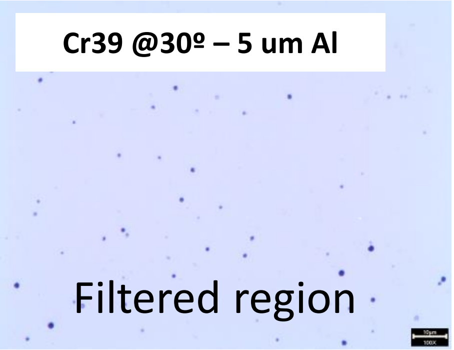
Ions from contaminant layer interact with the catcher :

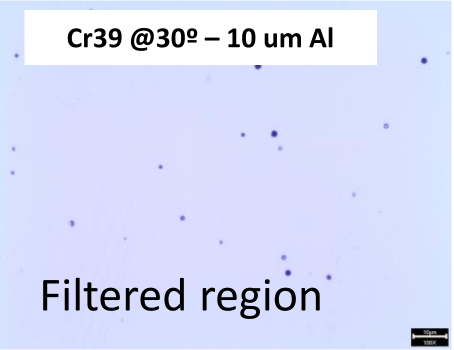
➔ presence of **diffused particles and secondary nuclear reactions products on the detectors**



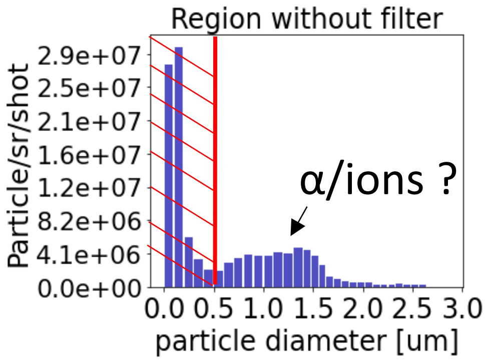
Cr39 images on microscope x100



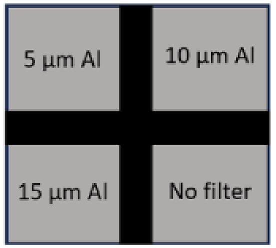




Extracted histogram from Cr39 analysis



Cr39 design holder



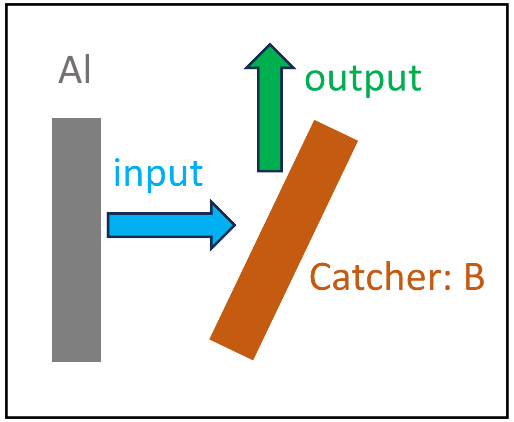
Al filter [um]	Cut-off energy [MeV]		
	H	α	C
5	0.47	1.6	5.75
10	0.75	2.8	11.5
15	1	4	17.5

<u>After 1H etching:</u>

- possible discrimination between H^+ and ions on histogram, but not between ion species
- **Filter in front of Cr39 should stop heavy ions and so allows discriminating between ion species**

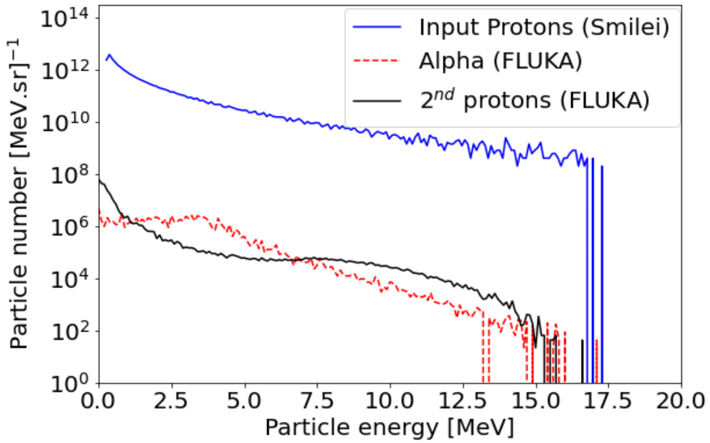
Pitcher-catcher: Simulations confirm multi-species contribution on Cr39 with majority of α-particles

Particle contribution simulation (fluka)



- ➔ Alpha emitted / input proton ≈ 10^{-5}
- ➔ Proton (diffused+nuclear)/ input proton ≈ 10^{-5}
- ➔ Carbon diffused/ input carbon ≈ 10^{-6} @45º(B) and ≈ 10^{-5} @70º(BN)
- ➔ Boron from Carbon or proton: ≈ 10^{-7}
- ➔ Carbon fragmentation starts at 12 MeV (➔ protons and α negligeable according to carbon experimental spectrum)

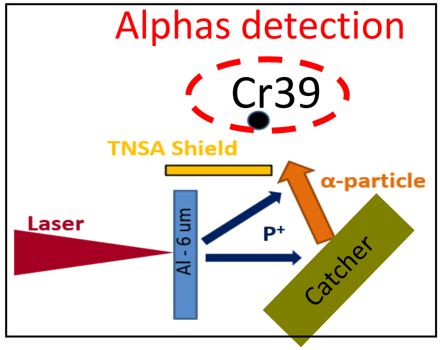
- ➔ For 5 um Al filter region, Carbon contribute up to 10% for catcher @45º and 50% for catcher @70º
- ➔ Other contributions come mainly from protons
- ➔ Proton are easy to distinguish on Cr39 histogram



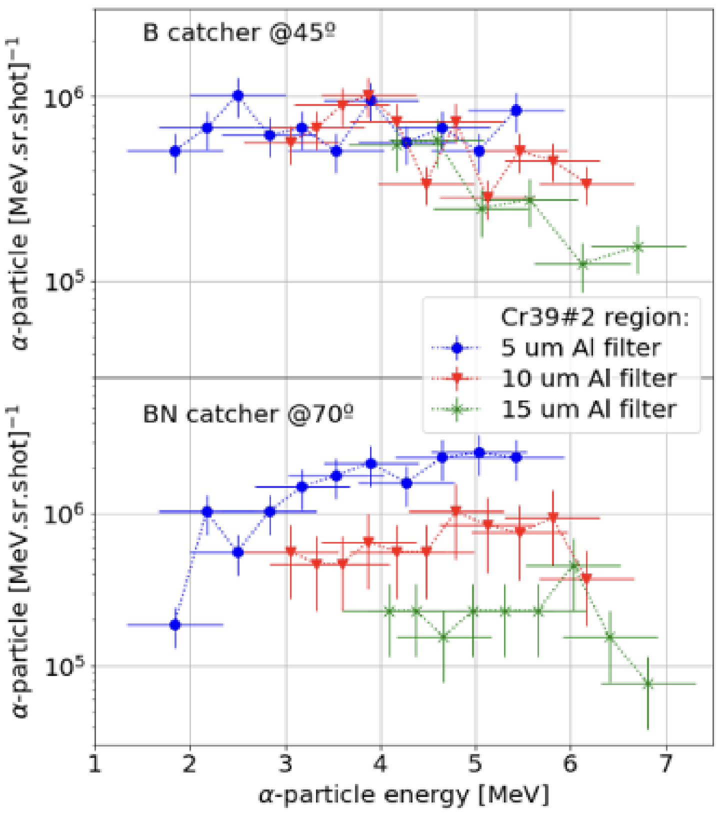
Pitcher-catcher: Reconstruction of α-particle spectrum with Cr39 thanks to calibration

Calibration of Cr39 with α-emitting (^{239}Pu source + Accelerator beam AIFIRA)

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



Experimental spectra - Cr39



	Catcher	Angle respect to pitcher normal [°]	α-particle number [sr.shot]$^{-1}$ in Cr39 #2 region:		
			5 um Al	10 um Al	15 um Al
exp	B_1	45	3.0e6*(3.3e6)	2.9e6	1.6e6
sim			6e6	4e6	1e6
exp	B_2	48	2.7e6*(3.0e6)	2.1e6	1.3e6
sim			6e6	4e6	1e6
exp	BN	70	3.8e6* (7.5e6)	3.2e6	9.5e5
sim			5e6	3e6	1e6

*value corrected with carbon contribution

Cr39 results in close agreement with simulation

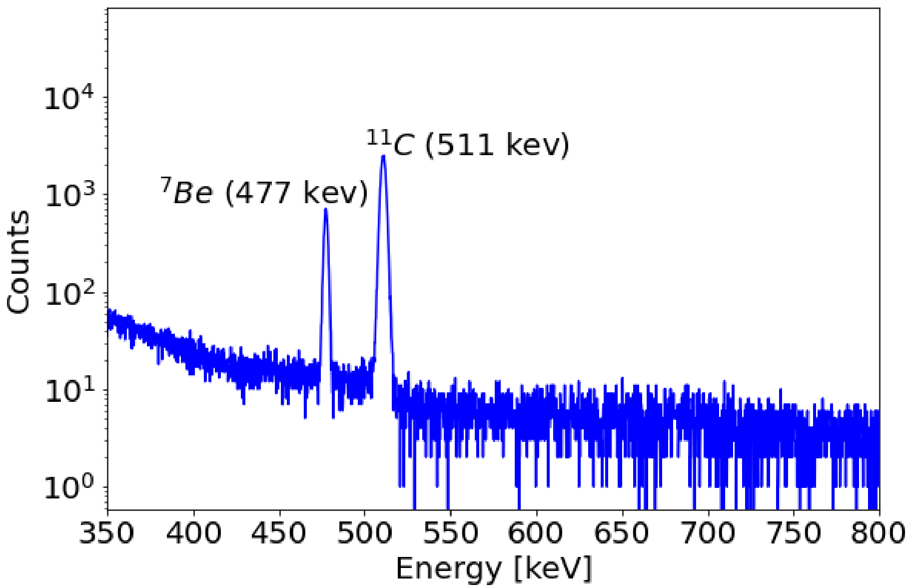
Pitcher-catcher: HPGe analysis in close agreement with simulations

Nuclear reactions induced by α-particles/protons used as diagnostic:

- ${}^{1}_{1}p + {}^{11}_{5}B \rightarrow {}^{11}_{6}C + {}^{1}_{0}n \rightarrow ({}^{11}_{5}B + e^{+} + \nu_e) + {}^{1}_{0}n$ (Annihilation peak)

  $e^{+} + e^{-} \Longrightarrow \gamma + \gamma$ **(511 KeV)**
- ${}^{1}_{1}p + {}^{10}_{5}B \rightarrow {}^{11}_{6}C^{*} \rightarrow {}^{7}_{4}Be/{}^{7}_{4}Be^{*} + {}^{4}_{2}\alpha \rightarrow {}^{7}_{4}Li + \gamma$ **(477 KeV)**

Measured γ-spectra from BN catcher with the HPGe diagnostic.



Experimental data:

$$N = \frac{A}{\lambda} \Rightarrow$$

$$N({}^{7}Be) = 5.3 \times 10^{6}/\text{shot}$$
$$N({}^{11}C) = 1.6 \times 10^{7}/\text{shot}$$

Simulations:

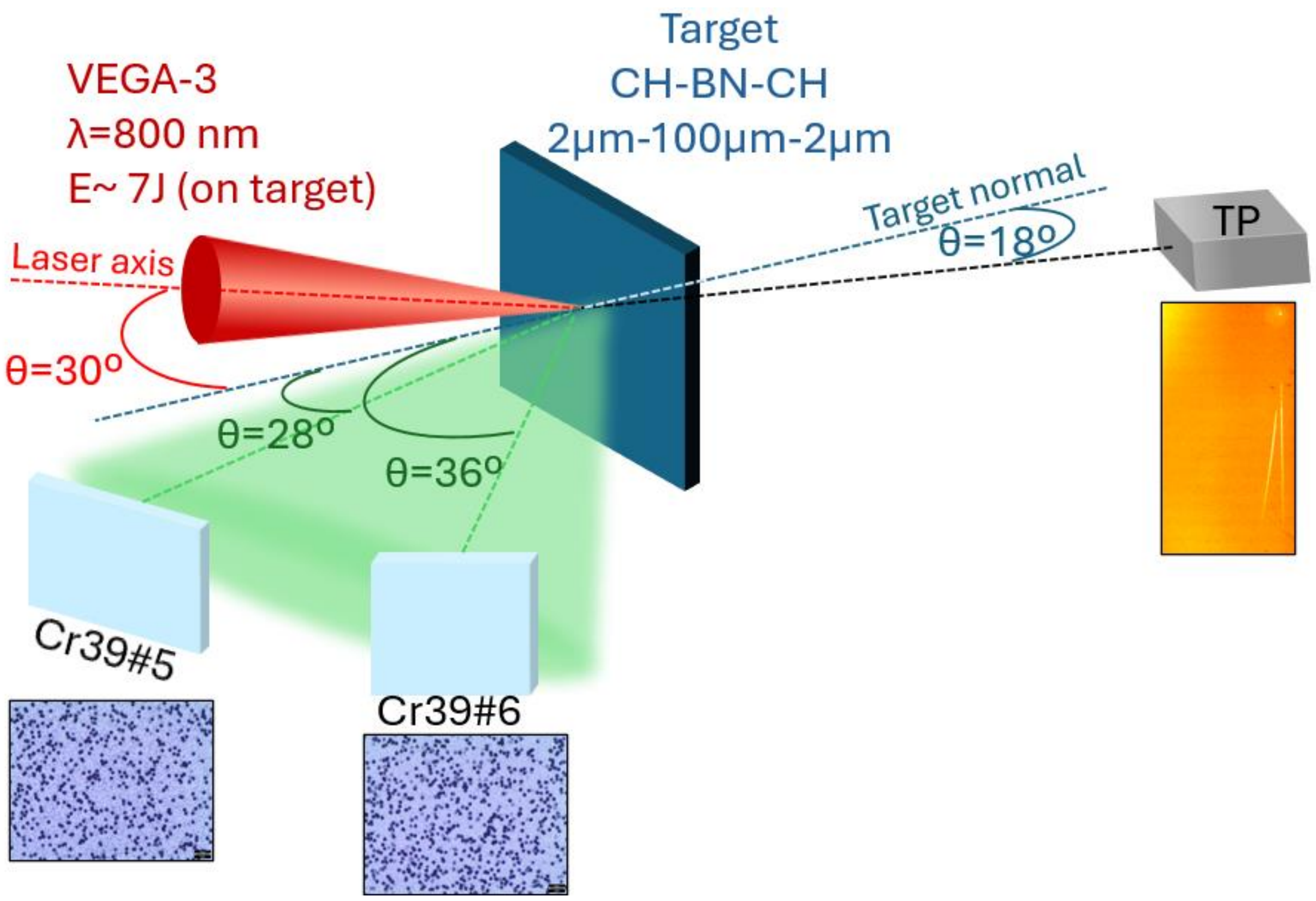
N (^{7}Be)= 1×10^{7}

N (^{11}C)= 2×10^{7}

SIM/EXP → X1.9 X1.3

HPGe results in close agreement with simulation

Direct irradiation configuration



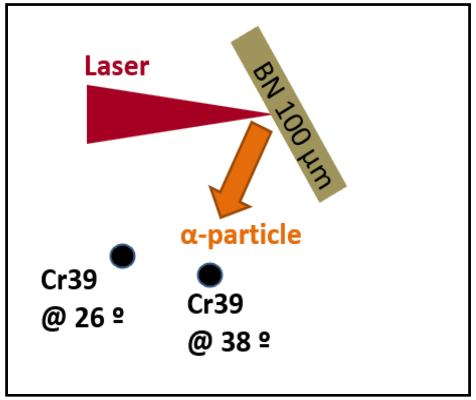
Diagnostics: TP, CR39

Target : CH-BN-CH (2um-100um-2um) @30º

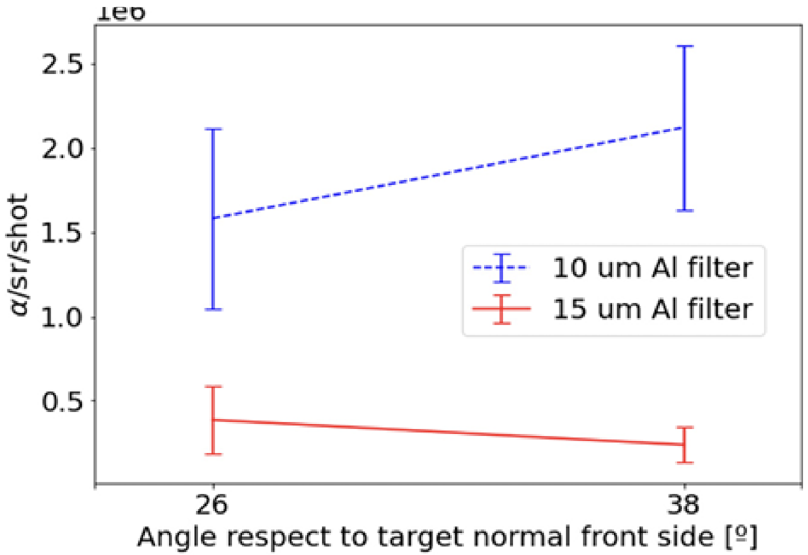
In Direct irradiation, diagnostics detect all particles accelerated from target front side

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

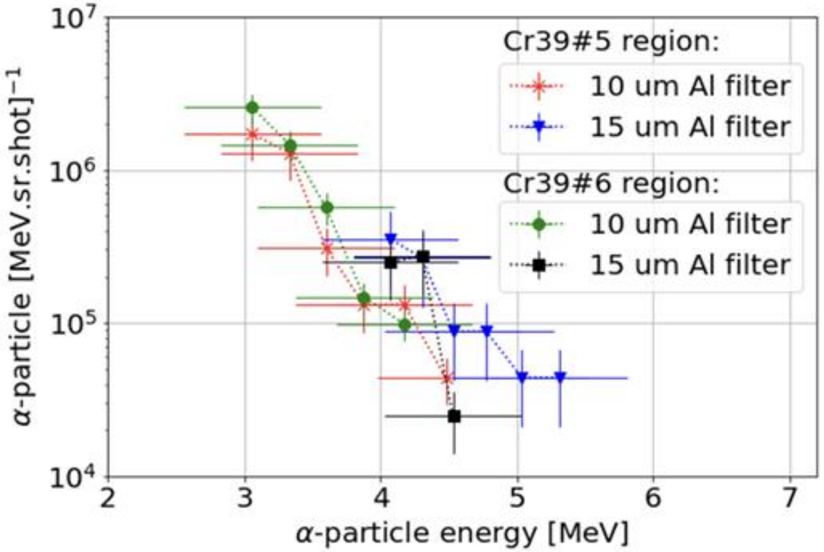
- We used Cr39 with **2 filter thickness regions** (10 and 15 um Al)
- We placed the Cr39 at 2 **different angles to distinguish isotropic/non isotropic emissions**



Angular distribution of α-particles - Cr39



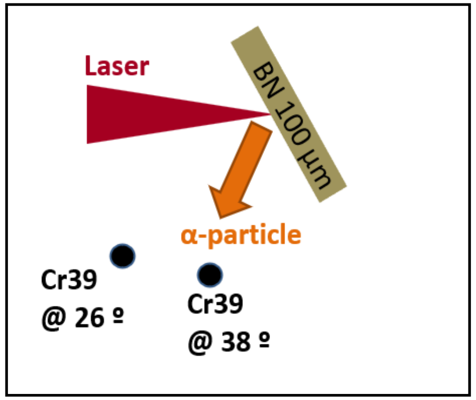
Experimental α-spectra - Cr39



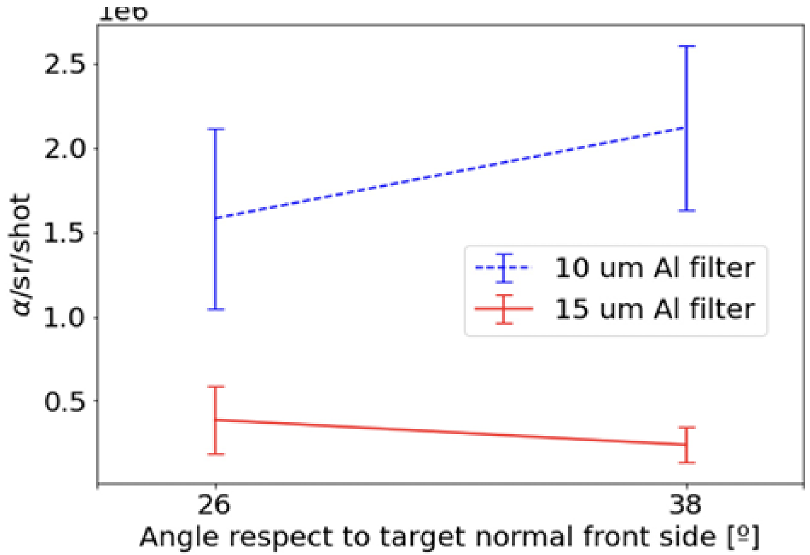
In Direct irradiation, diagnostics detect all particles accelerated from target front side

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

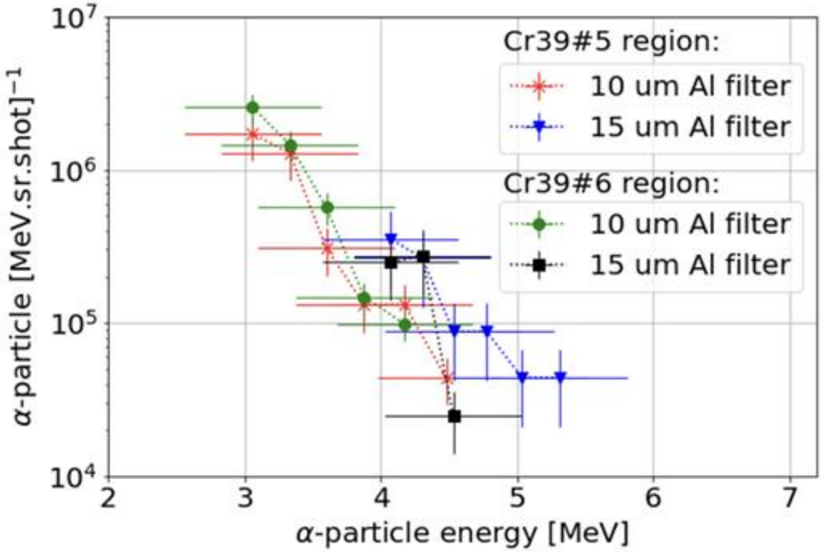
- We used Cr39 with **2 filter thickness regions** (10 and 15 um Al)
- We placed the Cr39 at 2 **different angles to distinguish isotropic/non isotropic emissions**



Angular distribution of α-particles - Cr39



Experimental α-spectra - Cr39

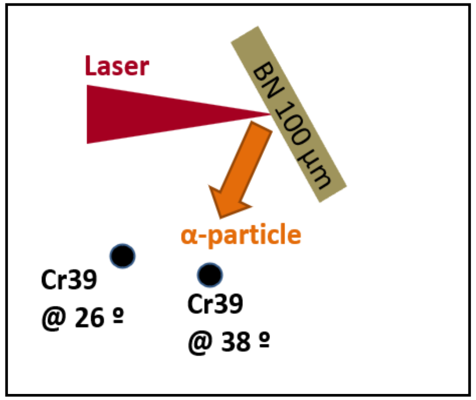


Tendency curves for 10 um Al and 15 um Al regions in agreement with isotropic distribution of α particle

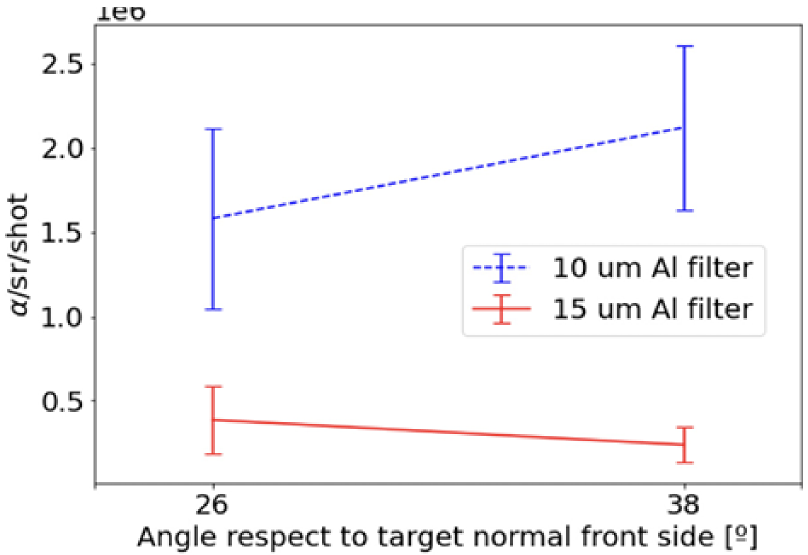
In Direct irradiation, diagnostics detect all particles accelerated from target front side

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

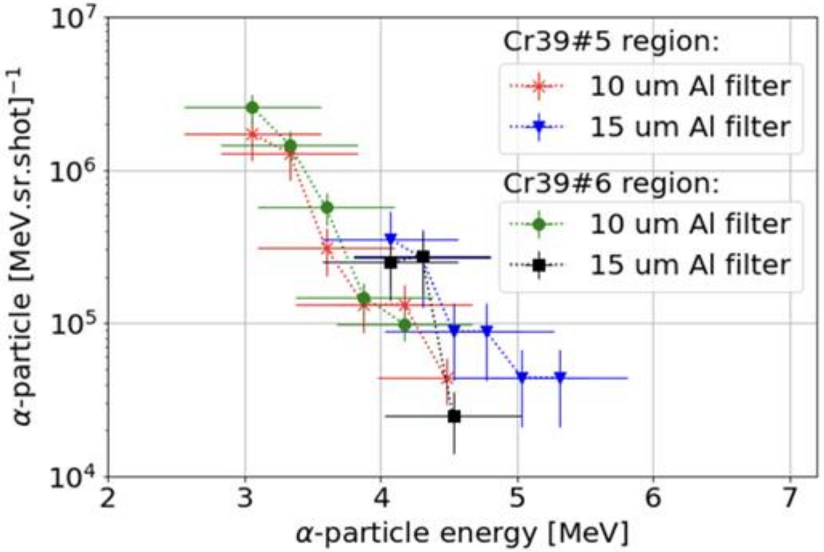
- We used Cr39 with **2 filter thickness regions** (10 and 15 um Al)
- We placed the Cr39 at 2 **different angles to distinguish isotropic/non isotropic emissions**



Angular distribution of α-particles - Cr39



Experimental α-spectra - Cr39



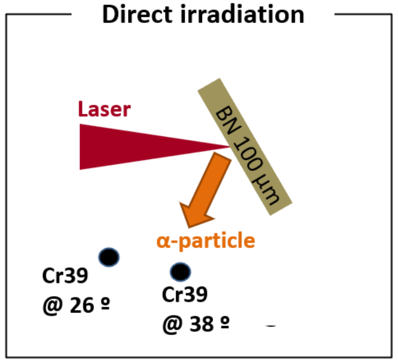
	Target	angle of target respect to laser axis [°]	α-particle number [sr.shot]$^{-1}$ in Cr39 region: 10 um Al	15 um Al
			Cr39#5	
exp			1.6e6	3.9e5
			Cr39 #6	
exp	CH-BN-CH	30	2.1e6	2.4e5
sim	CH-BN-CH	30	4e5	1e5

Tendency curves for 10 um Al and 15 um Al regions in agreement with isotropic distribution of α particle

➔ carbons need energy > 11.5 MeV to reach the region of 10 um Al filter
➔carbons need energy > 17.5MeV to reach the region of 15 um Al filter

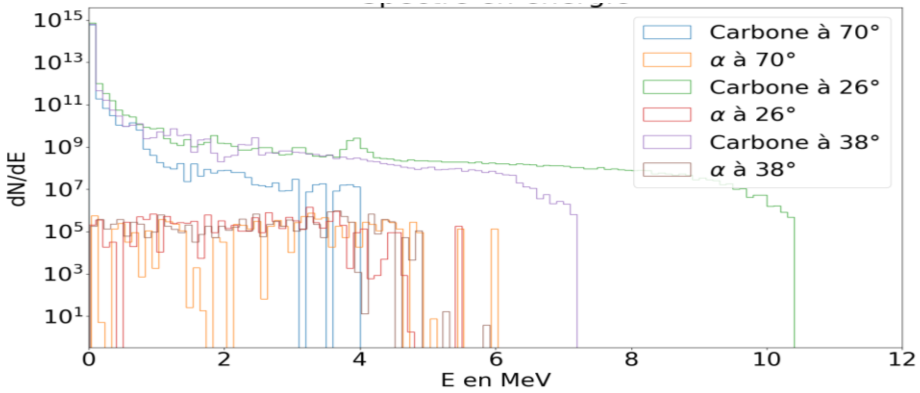
Simulations estimate the ions distribution and energy at the detector positions

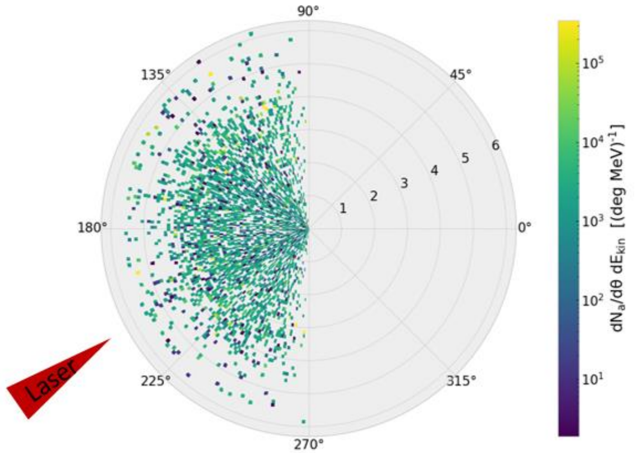
According to simulation, max Carbon energy up to 10.5 MeV at 26º respect to normal front side target ➔**We expected all carbons to be stopped by 10 and 15 um Al filters**



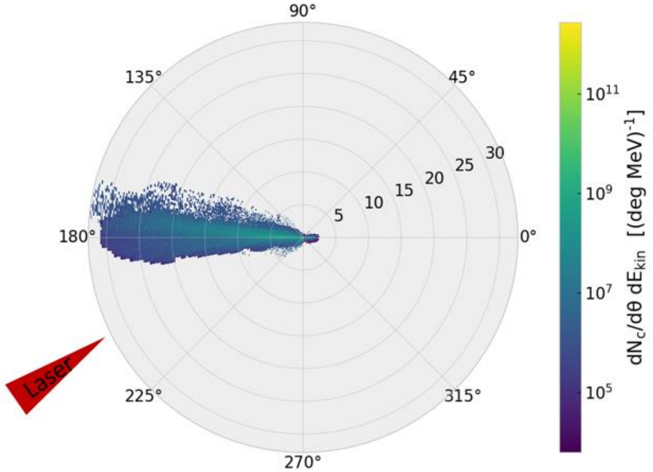
Al filter [um]	Cut-off energy [MeV]		
	H	α	C
5	0.47	1.6	5.75
10	0.75	2.8	11.5
15	1	4	17.5

FRONT SIDE: Carbon and α spectra

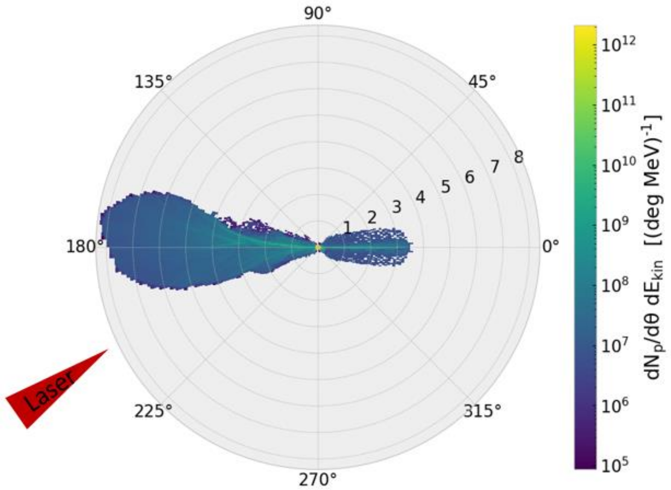




α angular dist.



Carbons angular dist.



Protons angular dist.

Conclusion and Perspectives

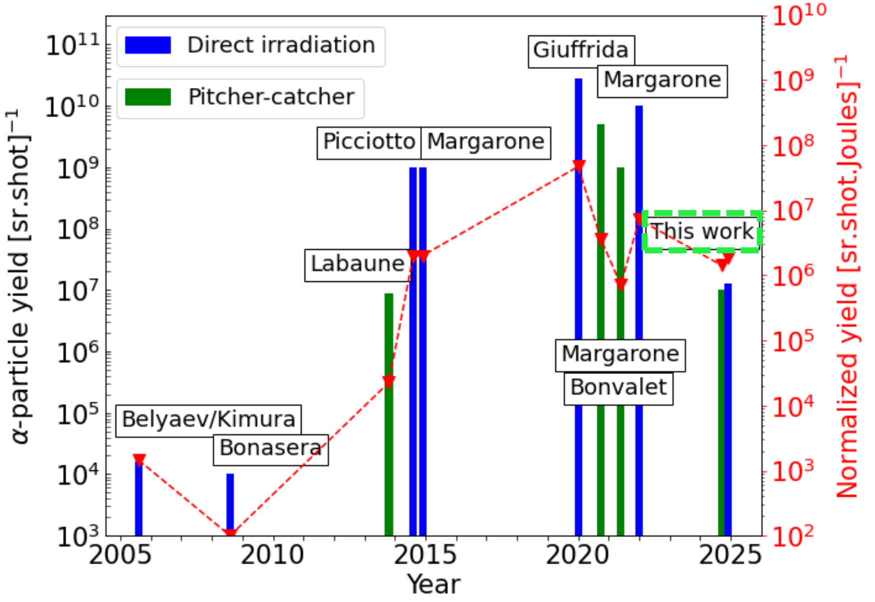
- Laser induced p-^{11}B fusion reaction has been tested on HRR laser installation
- Two configurations (Pitcher-Catcher and Direct irradiation) set-up have been tested
- Validation of our code in pitcher-catcher scheme gives confidence in the interpretation of results in direct irradiation
- Source 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:
3e6 α/sr/shot (α > 2.8MeV) ➔1e7 α/sr/shot with Simulation

Direct irradiation :
2.1e6 α/sr/shot (α > 2.8MeV) ➔1.3e7 α/sr/shot with Simulation

More info about this study: ***Huault et al Phys. Plasmas 32, 013102 (2025)***
https://doi.org/10.1063/5.0238029



Perspectives

- 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.**

Thank you

Email: marine.huault@u-bordeaux.fr

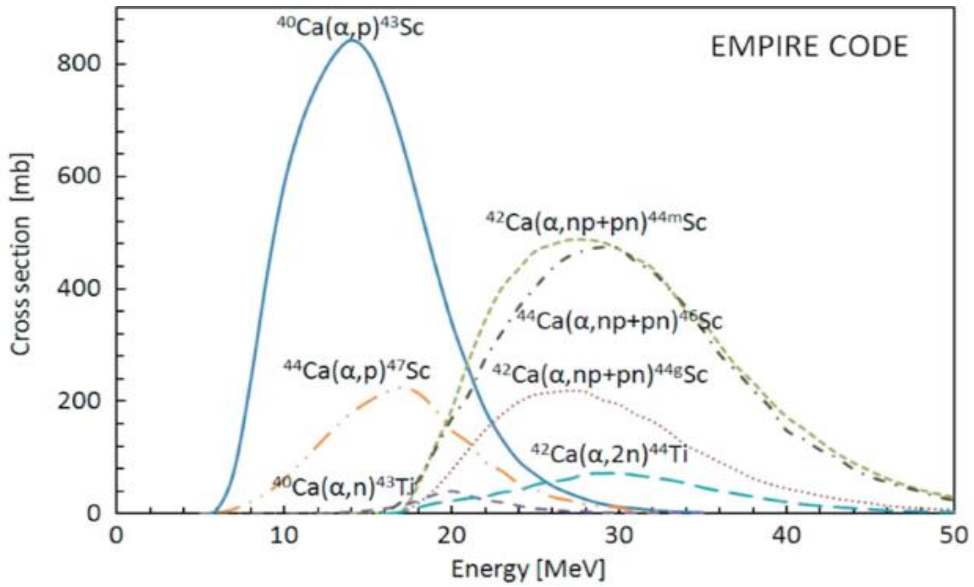
Acknowledgements:

RADNEXT
HB11 ENERGY
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Participating groups:

CELIA
CLPU CENTRO DE LÁSERES PULSADOS
INFN
ENEA
VNiVERSiDAD D SALAMANCA
eli beamlines
IFPiLM
ATM CYCLOTRON INSTITUTE

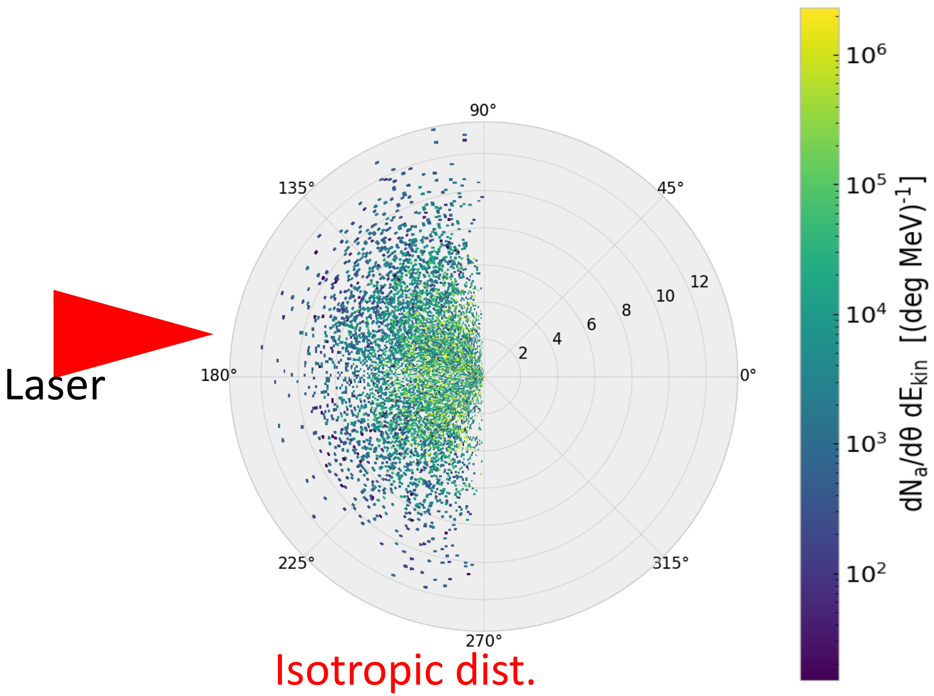
Scandium radioisotope production using α-particle beam



➔ **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

α angular distribution from catcher



Isotropic dist.

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

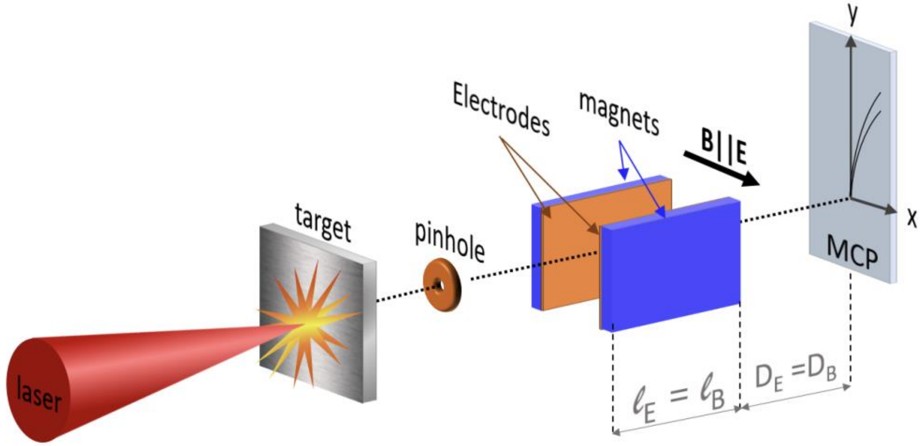
Complementary diagnostics must be used to accurately measure α-particles

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

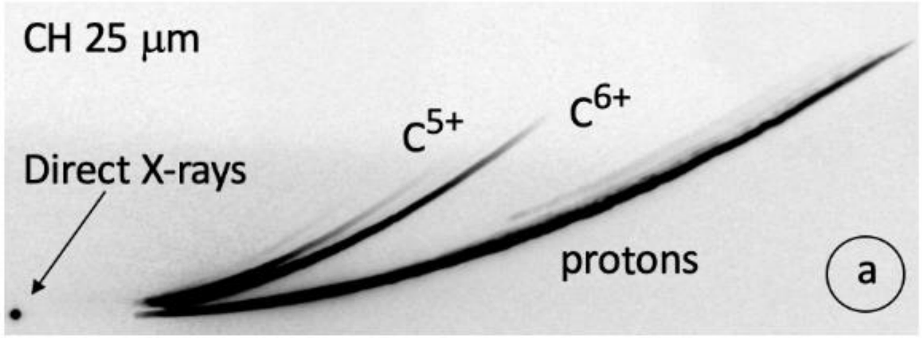
Thomson Parabola Spectrometer(TP)

➔ E and B field deflect vertically and horizontally the incoming charge particle: parabolic traces

➔ Discrimination of ions according to charge-mass ratio Z*/A: α spectrum hidden by other ions with same Z*/A (C^{6+}, N^{7+},…)



TP working principle



Typical parabolic traces on screen

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

Complementary diagnostics must be used to accurately measure α-particles

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

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 track diameter
➔ Discrimination according to track diameter: Same track diameter corresponds to several ion species at different energies

Cr39 is the most reliable diagnostic for direct measurement of α-particles

protons

Doubts α/heavy ions ?

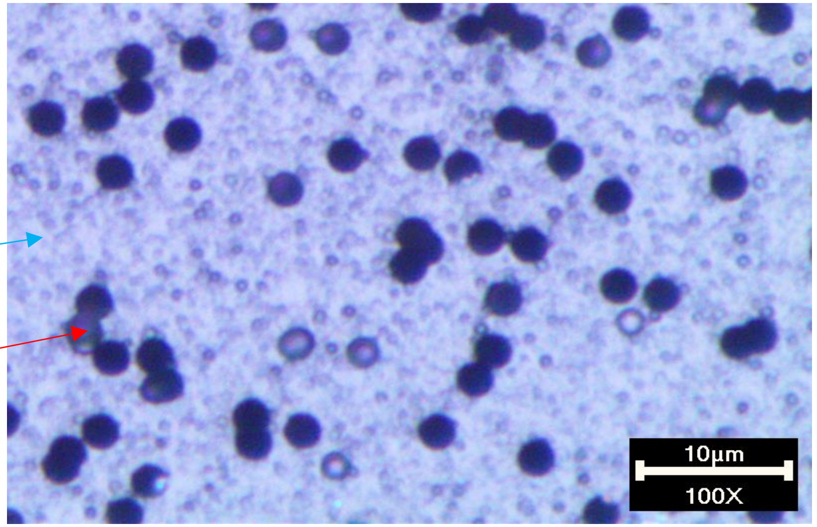


Image of Cr39 after 1H etching from microscope x100

➔ Filters are needed to separate the ion contributions
➔ Calibration is needed to reconstruct α spectrum

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

Complementary diagnostics must be used to accurately measure α-particles

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

High Purity Germanium radiation detector (HPGe)

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

- $^{1}_{1}p + ^{11}_{5}B \rightarrow ^{11}_{6}C + ^{1}_{0}n \rightarrow (^{11}_{5}B + e^{+} + \nu_e) + ^{1}_{0}n$ (Annihilation peak)

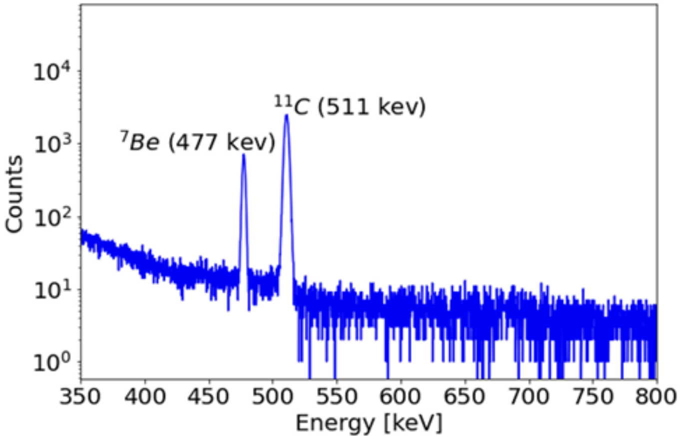
  $e^{+} + e^{-} \Longrightarrow \gamma + \gamma$ **(511 KeV)**

- $^{1}_{1}p + ^{10}_{5}B \rightarrow ^{11}_{6}C^{*} \rightarrow ^{7}_{4}Be/^{7}_{4}Be^{*} + ^{4}_{2}\alpha \rightarrow ^{7}_{4}Li + \gamma$ **(477 KeV)**

Gamma peaks can be measured after shots with ***HPGe***

➔possible in the pitcher-catcher geometry

➔complicated in the direct irradiation due to ablated matter when the laser interacts with the target



cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

HB11 ENERGY

RAD NEXT

PARTICIPATING GROUPS

CELIA
Centre Lasers Intenses et Applications

CLPU
CENTRO DE LÁSERES PULSADOS

ENEA

VNiVERSiDAD D SALAMANCA

INFN Laboratori Nazionali del Sud

eli beamlines

INSTYTUT FIZYKI PLAZMY I LASEROWEJ MIKROSYNTEZY
IM. SYLWESTRA KALISKIEGO

TEXAS A&M UNIVERSITY
Cyclotron Institute