Hydrogen boron fusion in confined geometries

D.Batani

University of Bordeaux

Институт за општу и физичку хемију

О ИНСТИТУТУ ⌄ ИСТРАЖИВАЊА ⌄ ПРИВРЕДА ⌄ РЕПОЗИТОРИЈУМ РАДОВА

Почетна / О институту / Научно - стручни скупови

Научно - стручни скупови

5th International Workshop on Proton-Boron Fusion

Belgrade 8 – 11 September 2025

Hydrogen boron fusion in confined geometries

2022-2026 For the Next 50 YEARS

université de BORDEAUX

CA 21128 PROBONO

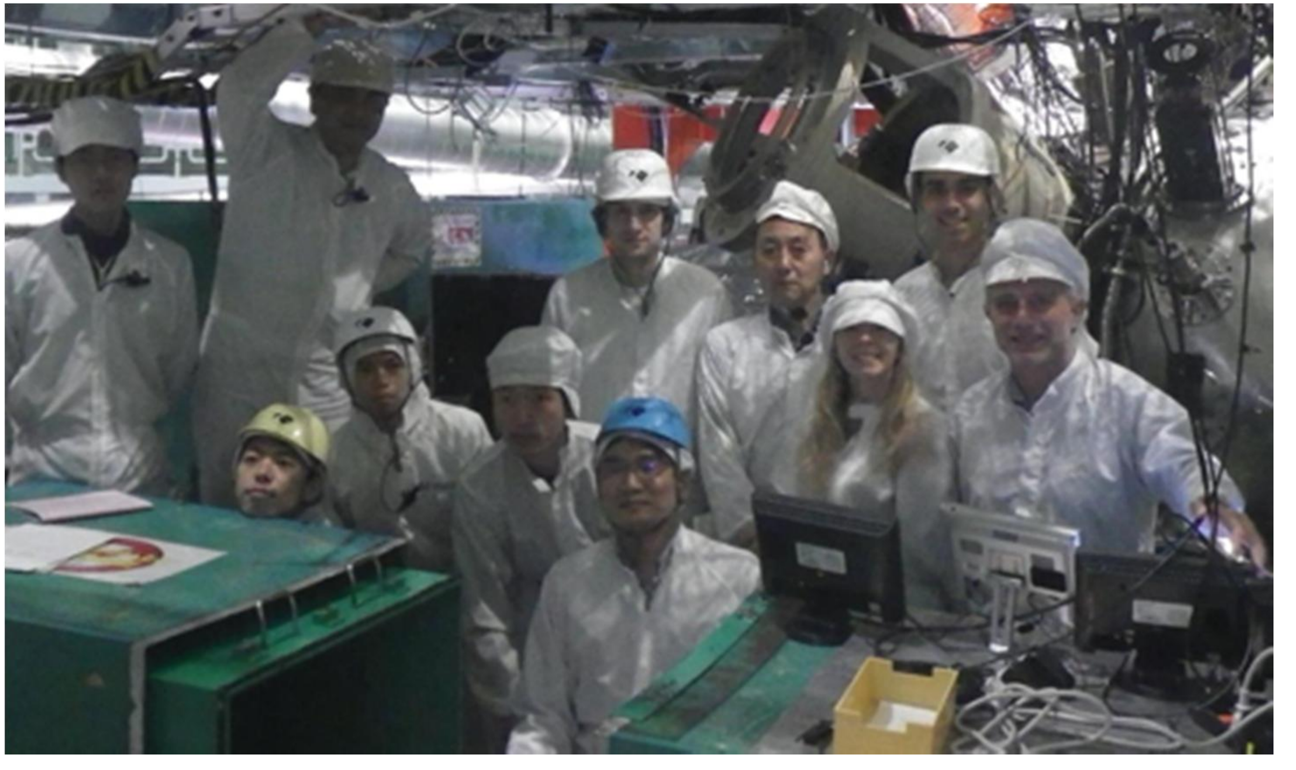
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

eli beamlines

HB11 ENERGY LASER BORON FUSION

DEAKIN UNIVERSITY

IFPiLM INSTYTUT FIZYKI PLAZMY I LASEROWEJ MIKROSYNTEZY IM. SYLWESTRA KALISKIEGO



Experiment at the laser Gekko, Osaka

Hydrogen boron fusion in confined geometries

Dimitri Batani[1], Marco Tosca[2,3], Lorenzo Giuffrida[2], Daneile Margarone[2], Philippe Nicolai[1], Clement Caizergues[1], Didier Raffestin[1], Evgenij Filippov[4], Sergey Pikuz[4], Katarzyna Batani[5], Qiran Cai[6], Srikanth Mateti[6], Ying (Ian) Chen[6], Kohei Yamanoi[7], Alessio Morace[7]

[1] University of Bordeaux, CELIA, Domain du Haut Carré, 43 Rue Pierre Noailles, 3405 Talence, France.

[2] ELI Beamlines Facility, The Extreme Light Infrastructure ERIC, Dolnî Brežany, Czech Republic

[3] Charles University, Faculty of Mathematics and Physics, Department of Macromolecular Physics, Prague, Czech Republic.

[4] HB11 Energy Holdings Pty, Freshwater 2096, Australia

[5] Institute of Plasma Physics and Laser Microfusion (IPPLM), Warsaw, Poland

[6] Institute for Frontier Materials, Deakin University, Waurn Ponds, Victoria 3216, Australia

[7] Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita 565-0871, Japan

Just published

HIGH POWER LASER
SCIENCE AND ENGINEERING

10.1017/hpl.2025.10055

Tosca Batani Giuffrida Nicolai Caizergues
Margarone Raffestin Filippov Pikuz Batani
Cai Mateti Chen Yamanoi Morace

Motivation

- In pitcher-catcher laser-driven hydrogen boron fusion experiments, the ratio of produced α particles to protons is usually $10^{-3} – 10^{-4}$
- How can we get more α particles for incoming protons ?
- A closed geometry might due it, because of multiple passage of protons in the foil of boron compound and because the geometry might produce electric and magnetic fields stronger than in the case of planar foils. Such fields could further increase the confinement of the plasma particles.

- Detection of α-particles in a TP using CR39

Experiments at LFEX 2022

Two experiments were done in 2022, PI Alessio Morace (ILE staff member)

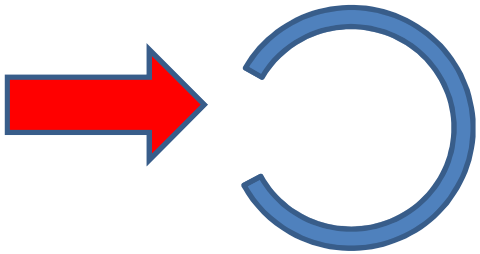
In the experiment, the LFEX laser delivering 1.5 kJ in 1 ps at 1 μm

Several kind of targets were shot:

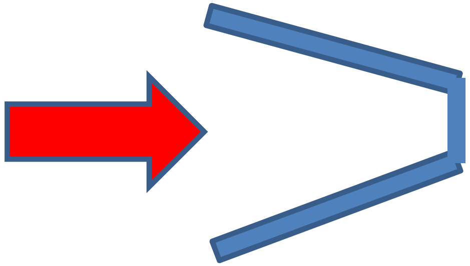
- Empty spheres with plastic / boron oxide walls, realized at ILE, Osaka, Japan.
- Boron nitride cylinders, produced at Deakin University, Australia.

Experiments at LFEX 2022

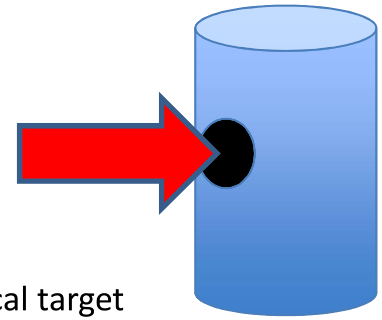
We compared different geometries



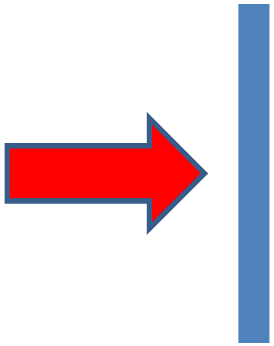
Sphere target



Wedge target

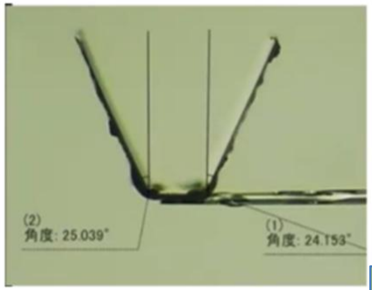


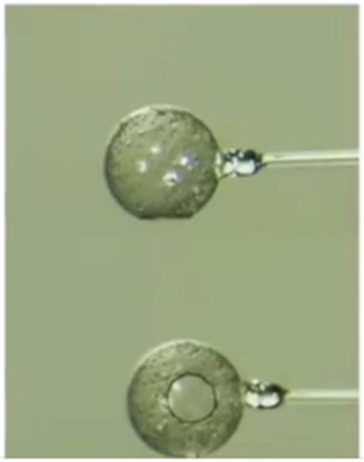
Cylindrical target

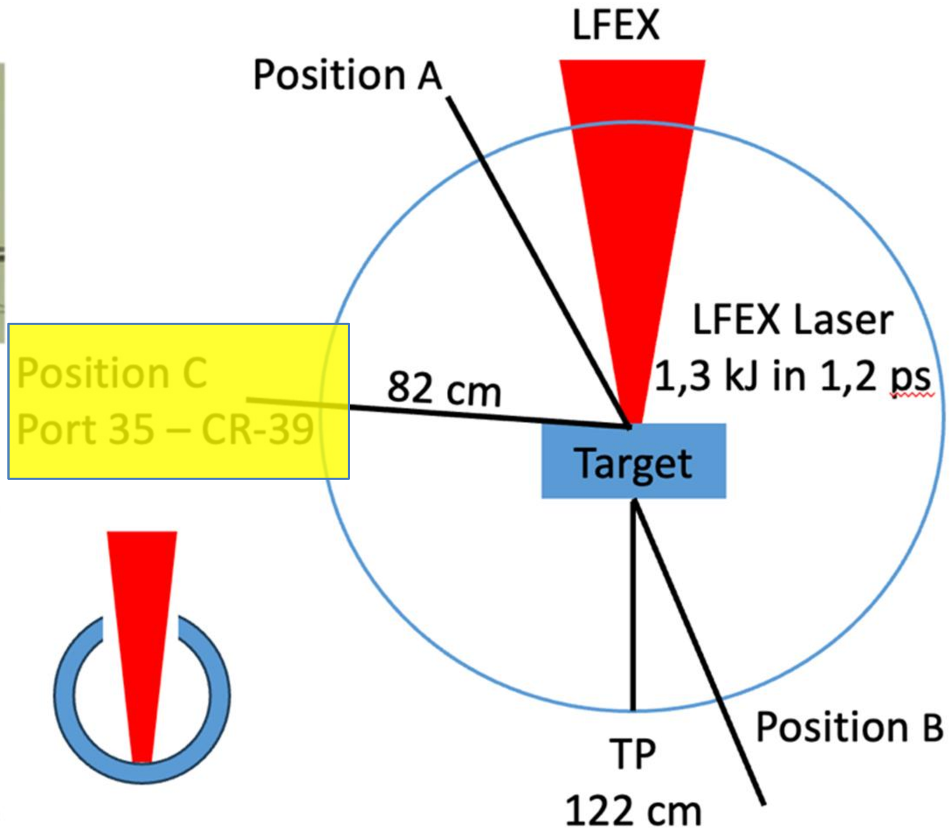


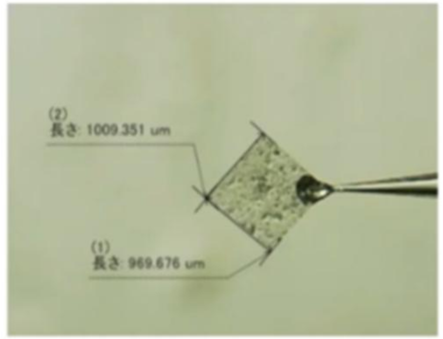
Flat foil

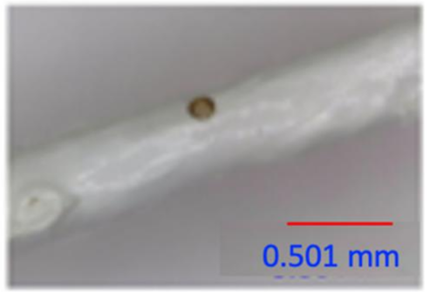
Experiments at LFEX 2022











Position A corresponds to 10° from the front target normal,
B to 10° from the rear target normal,
C to 80° from the front target normal

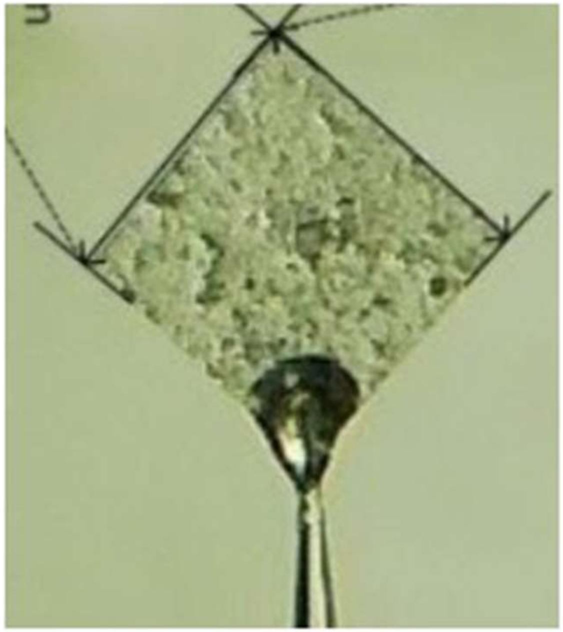
Experiments at LFEX 2022

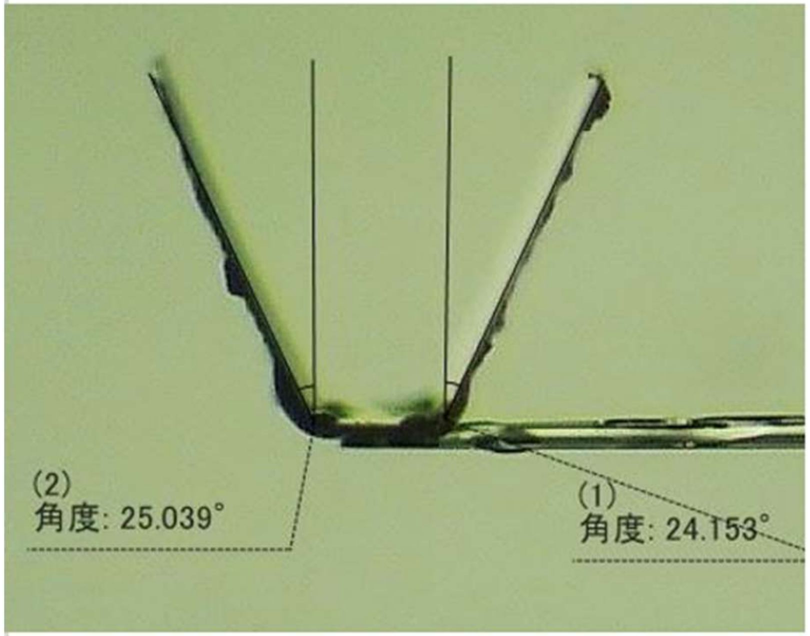
[redacted]

Summary of performed shots with indications of working diagnostics (√). In total there were 21 shots, nine of which were on spheres, three on wedges and four on flat foils.

Imaging plate (IP) were used as detectors in the TP apart from two shots where they were replaced by CR-39 foils.

Targets





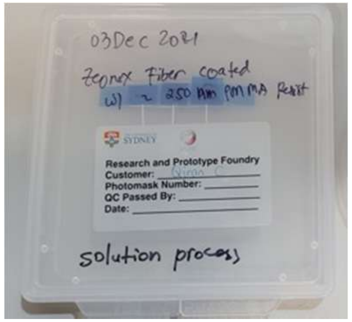
1 mm size

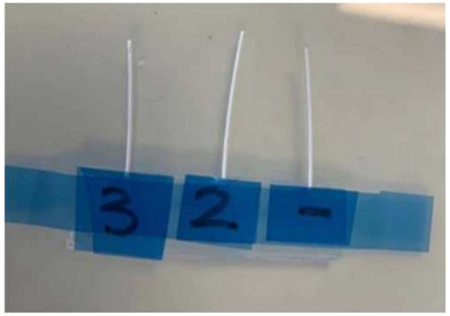
500 µm diameter

18 µm foil

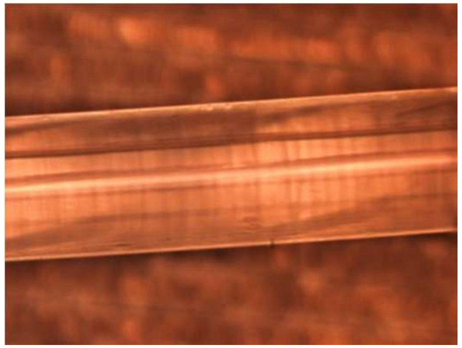
Cylindrical targets (Deakin)

1. Zoenex (500um) + PMMA (250 nm)

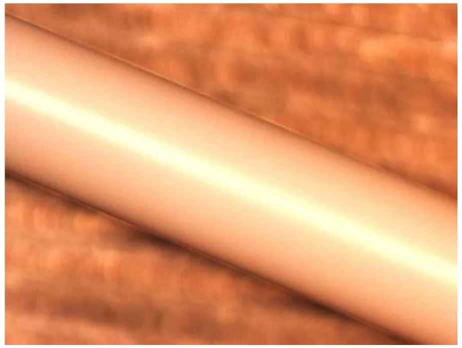




Before coating



after coating



Three Zoenex + PMMA samples have been prepared:

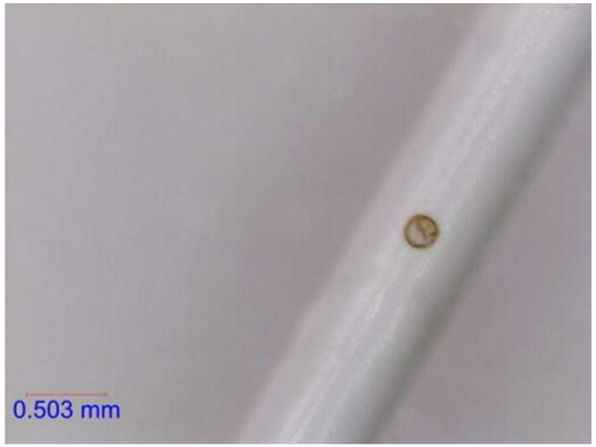
Sample 1: BNNS + PVA coating. Thickness: 7-10 µm

Sample 2: BNNS + PVA coating. Thickness: 10-15 µm

Sample 3: BNNS+ PVA coating. Thickness: 15-20µm

Z2C sent to ILE

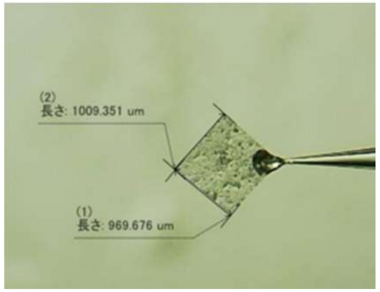
Z2D – sent to ILE



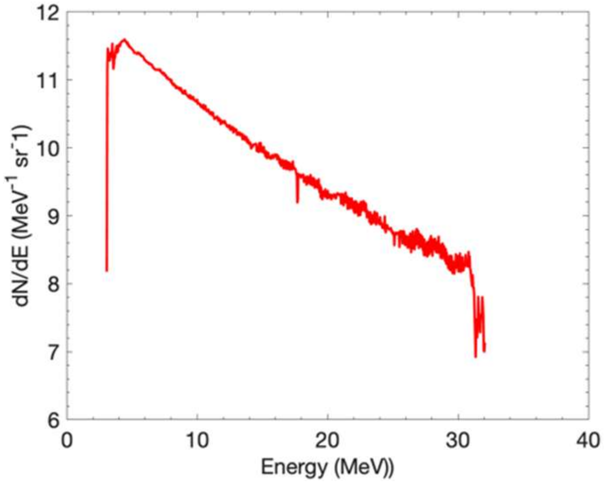
Zeonex Sample 2 –10-15 µm BN + 250 nm PMMA (Cyclohexane – 10h hours at room temperature)

Experimental results

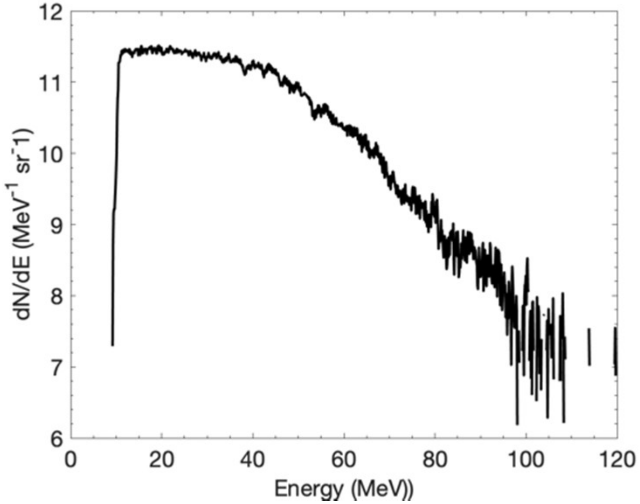
Shot 1 (LFEX shot 4366)
Energy 1189 J
Flat B-doped CH



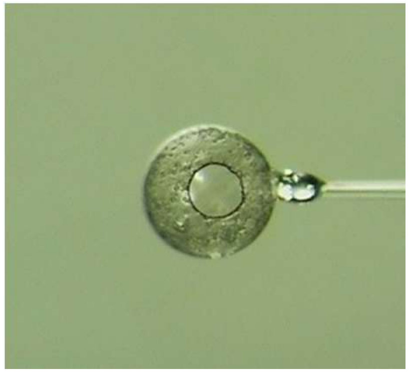
Protons

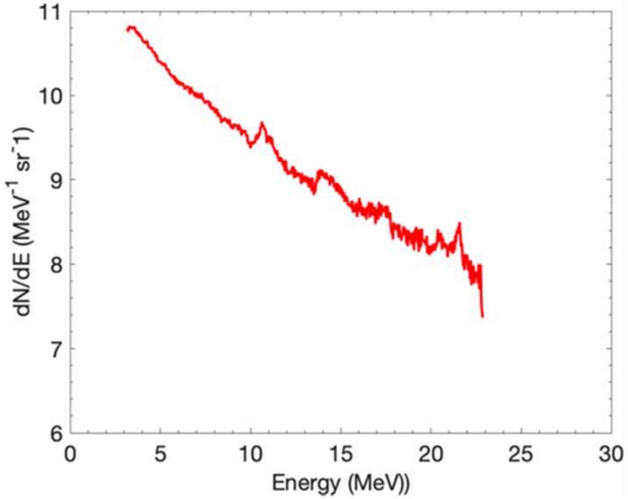


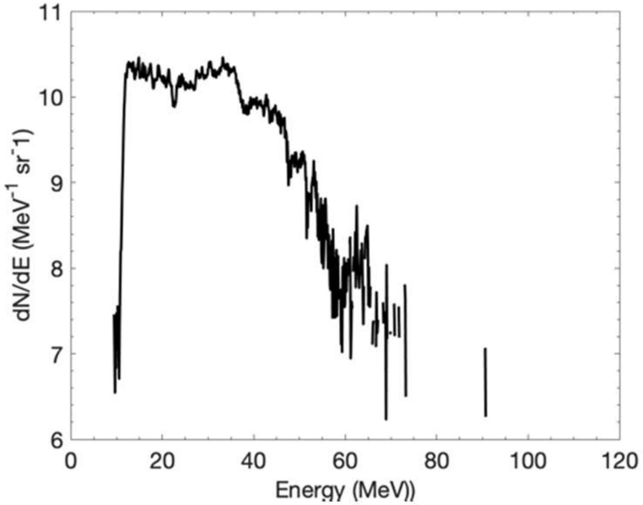
Carbon 6+



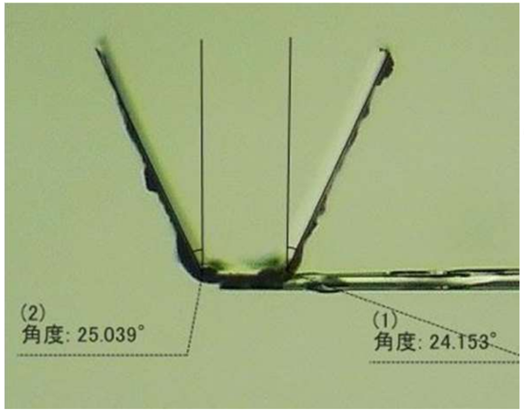
Shot 2 (LFEX shot 4367)
Energy 1189 J
Open B-doped shell

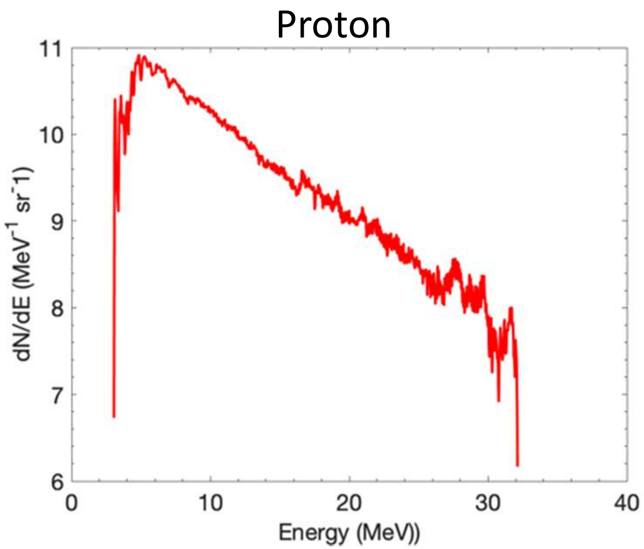


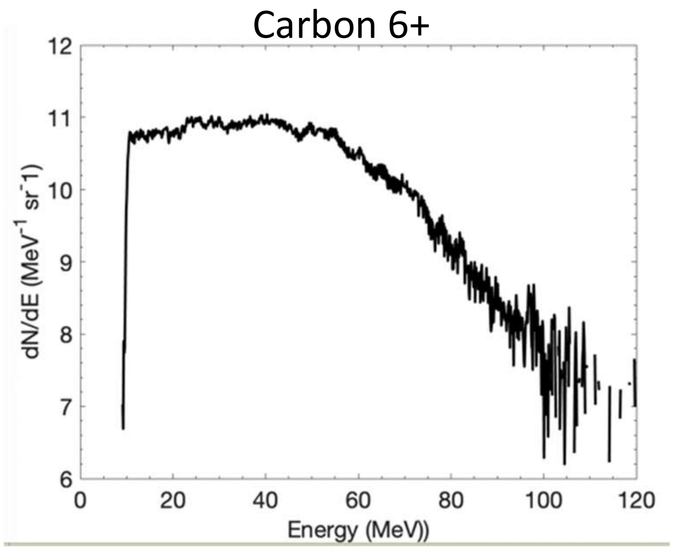


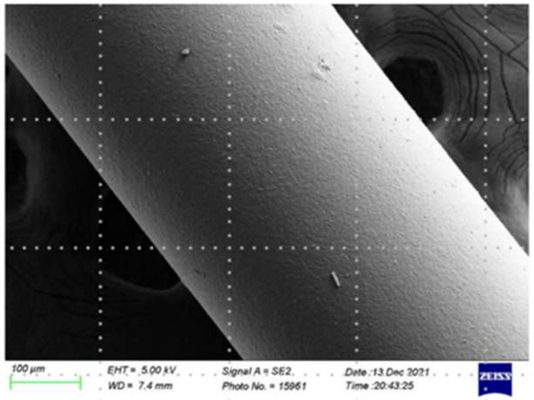


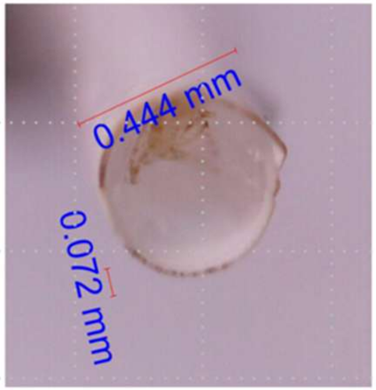
Shot 3 (LFEX shot 4368)
Energy 1236 J
Wedge vertical attachment





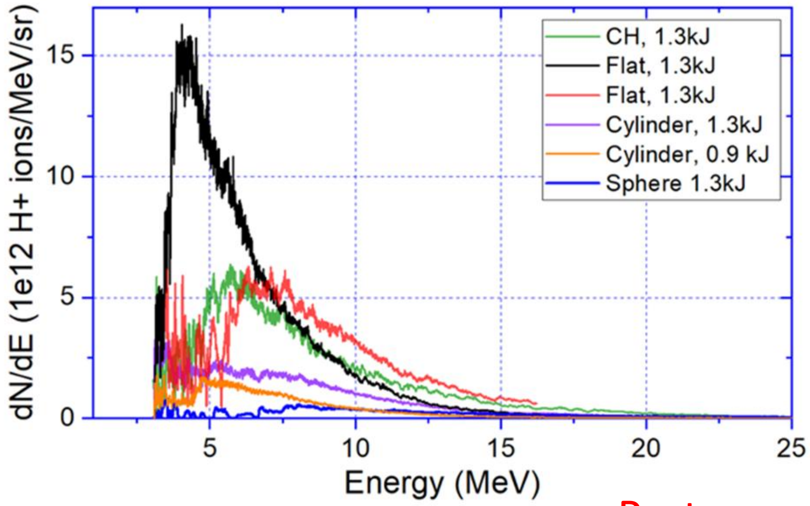




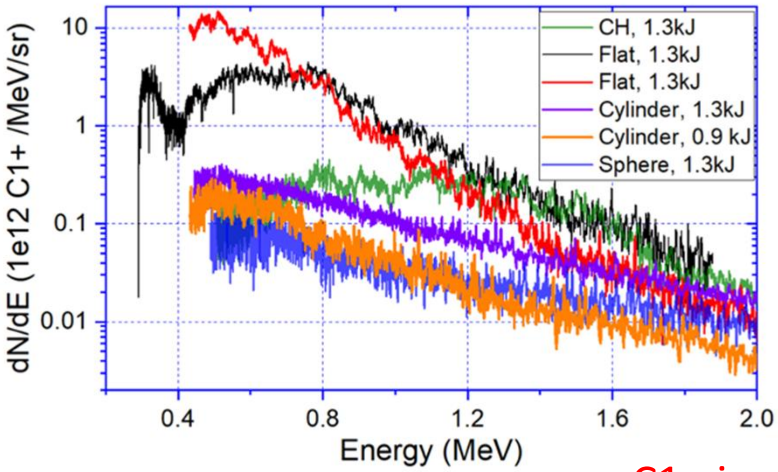


Boron Nitride cylinders produced at Deakin Univ.

Experimental results

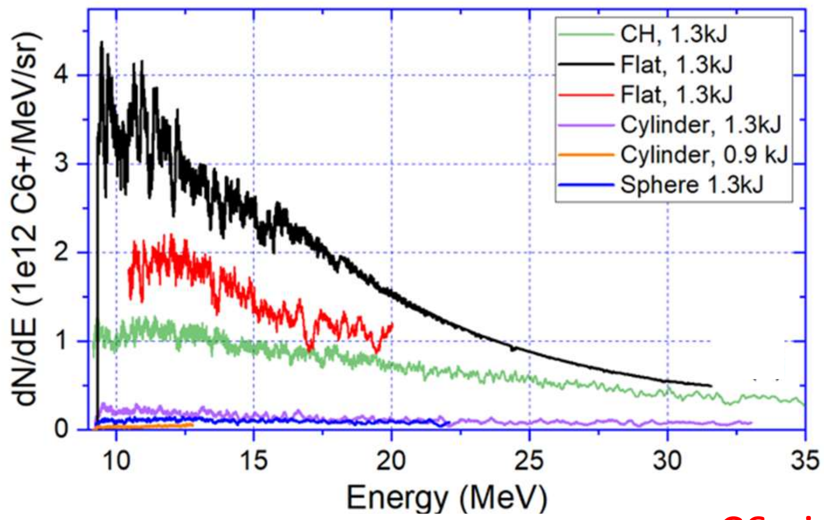


Protons



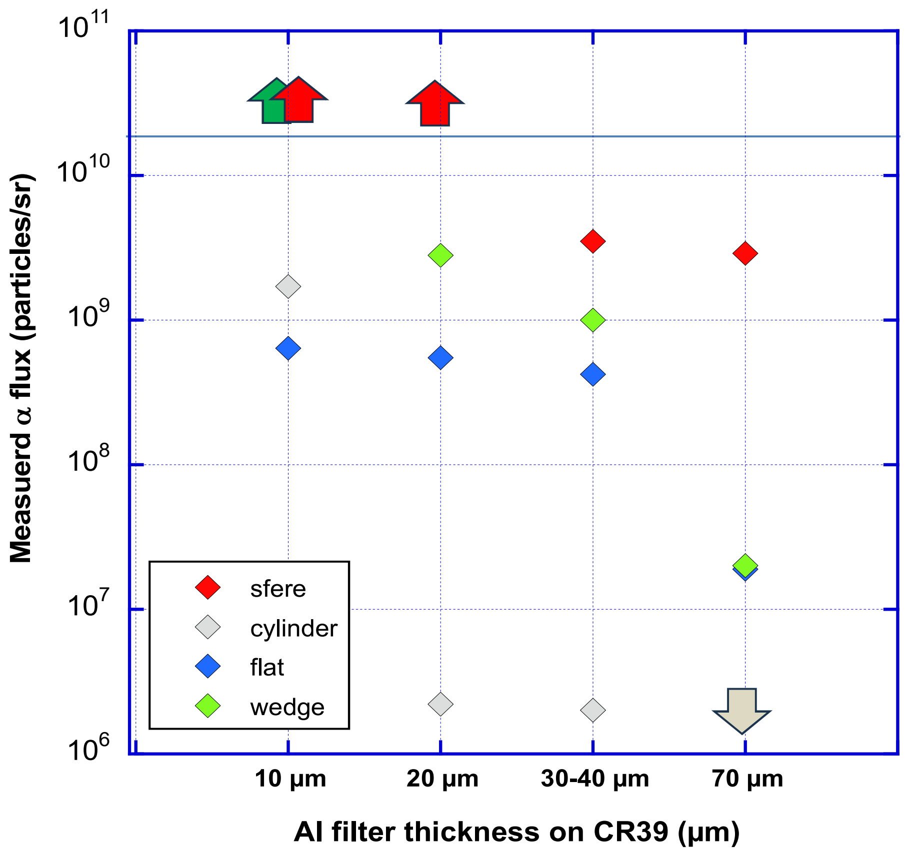
C1+ ions

Thomson parabola results for protons, C^{1+} ions, and C^{6+} ions. The spectral range was limited by the edge of the detector and the merging point of all tracks (for C^{6+} ions) where it is not possible to distinguish different ion species.



C6+ ions

Experimental results



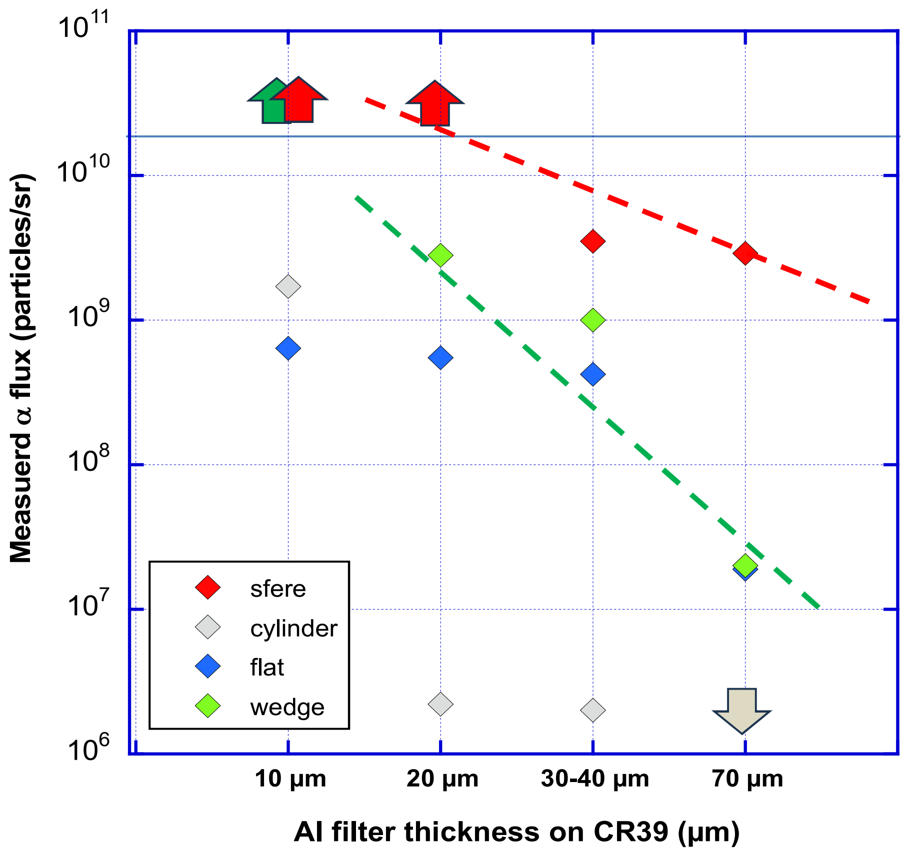
Problems:

- detection of α-particles with CR39 is ambiguous (we mainly rely on CR39 in position C, 80° from the front target normal, where «ion pollution» is expected to be negligible)
- CR39 were sometimes saturated, or they did not show any signal above background

However, there is a clear indication that the confined geometry increases α-particle yield

Ion	Cutoff energy [MeV] Al filter thickness [µm]				
	10	20	40	50	70
H	0.77	1.24	1.94	2.23	2.74
He	2.75	4.71	7.60	8.79	10.89
C	11.65	22.19	38.29	44.99	56.80

Experimental results

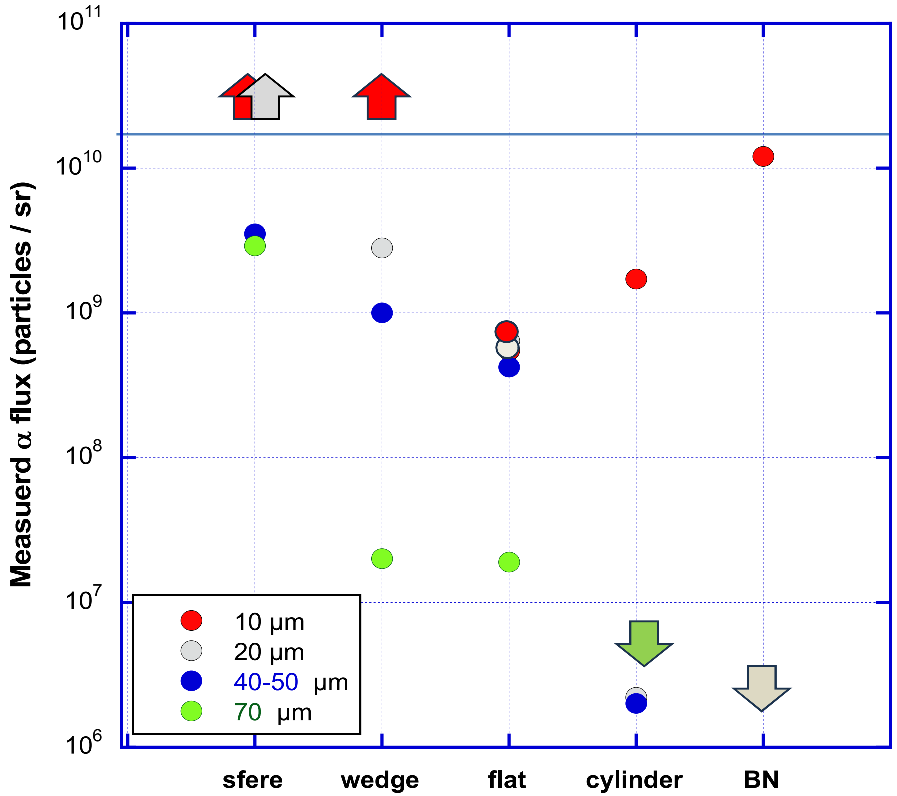


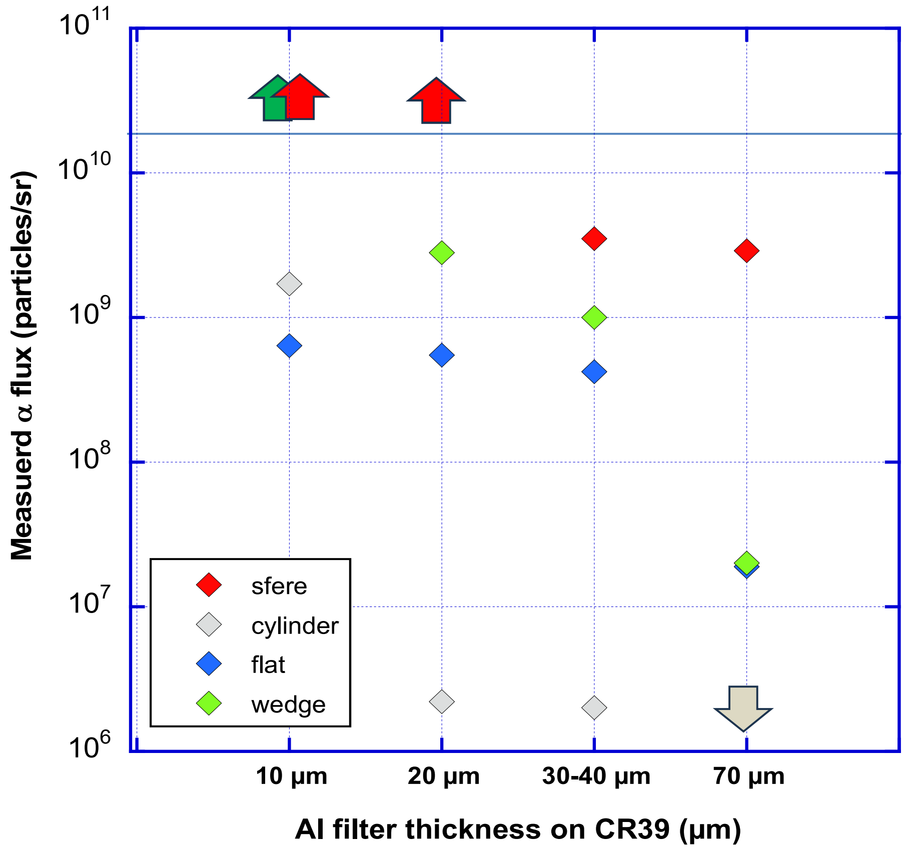
Evidence of more energetic spectrum ?

Ion	Cutoff energy [MeV] Al filter thickness [µm]				
	10	20	40	50	70
H	0.77	1.24	1.94	2.23	2.74
He	2.75	4.71	7.60	8.79	10.89
C	11.65	22.19	38.29	44.99	56.80

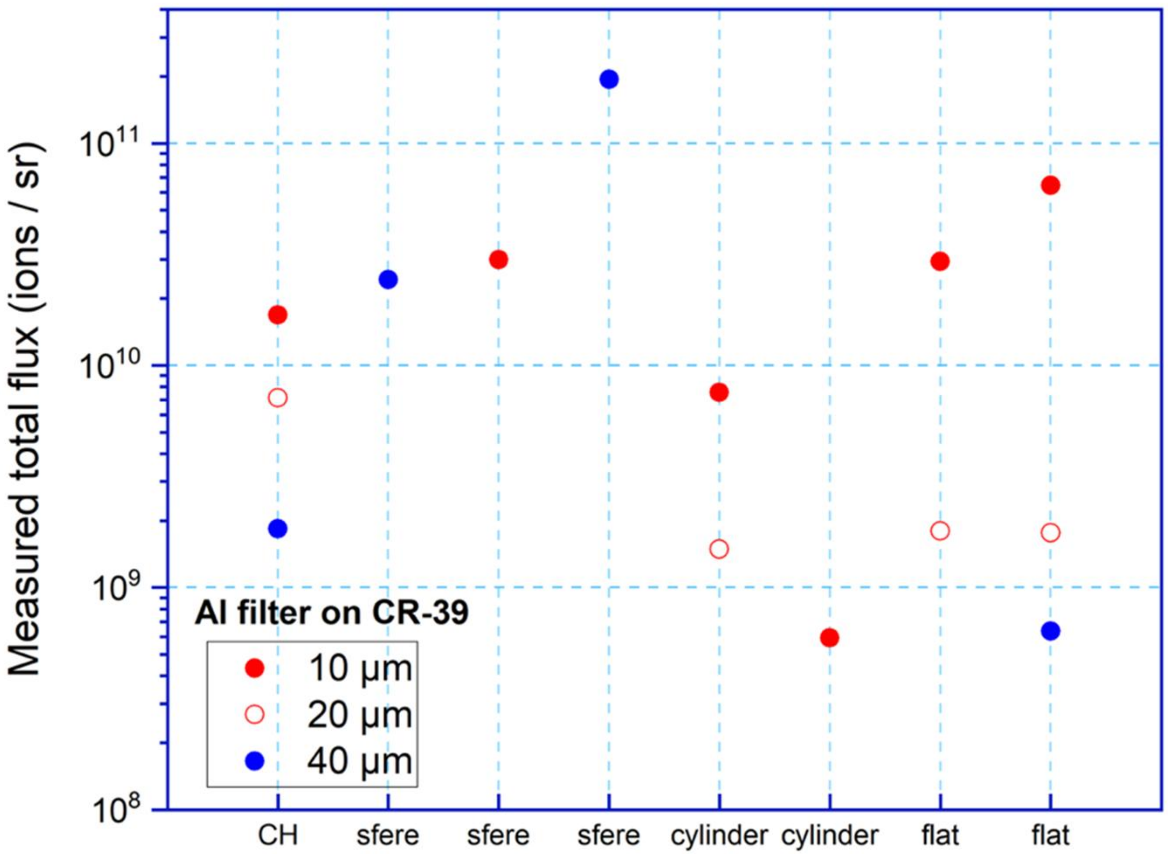
Experimental results

α-particle yield: CR39 in position C, 80° from the front target normal





Experimental results

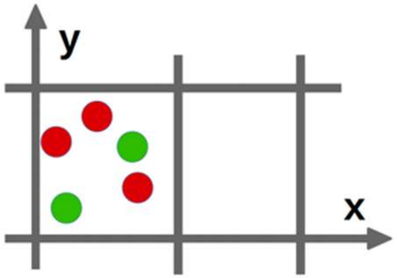


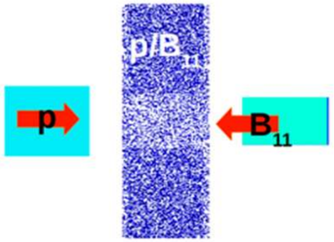
Total ion flux on CR-39 measured in position B for the 8 LFEX shots performed in the July 2022 experimental campaign

LFEX 2022 - simulations

Simulations at CELIA have been performed with the PIC code SMILEI where proton boron nuclear reactions have been implemented

Smilei)

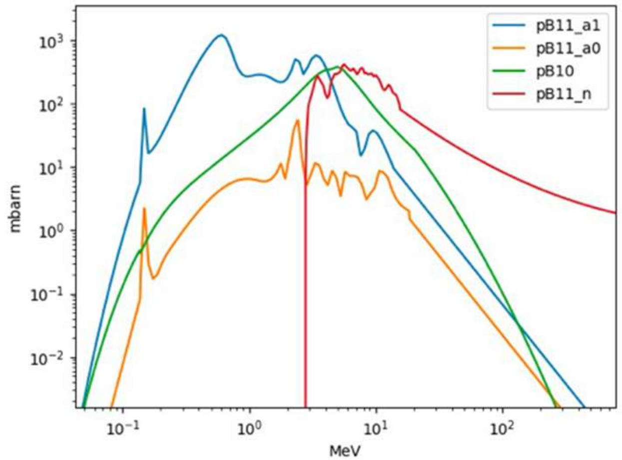




One starts to post-process nuclear reactions into SMILEI, by computing

$$\Sigma_{(1,2)}\,\sigma[(\mathbf{p}_1-\mathbf{p}_2)^2].w_1.w_2.\mathbf{V}_{1-2}$$

σ is the nuclear cross section,
V is the relative velocity between particles,
w is the particle weight.

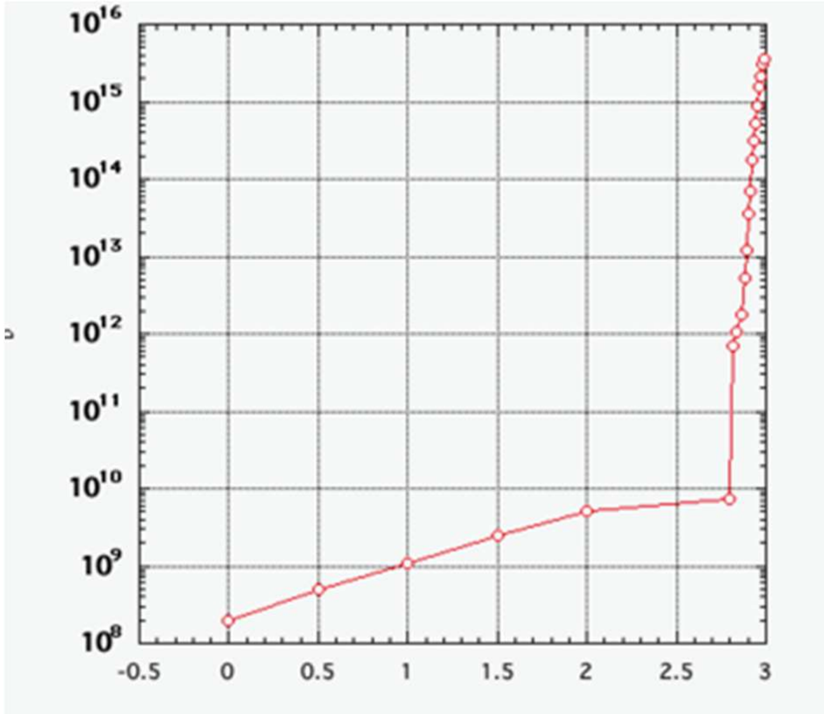


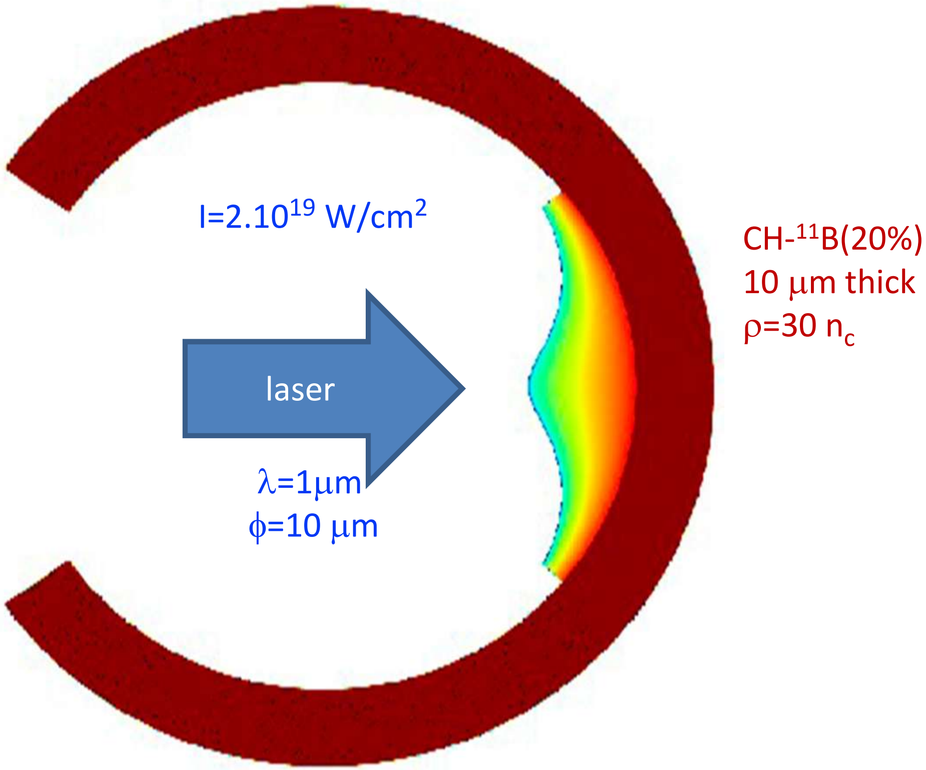
One just computes nuclear reactions, α-particles are not created

There is no depletion of the proton/boron particles due to fusion reactions, meaning probability of interaction must be small.

LFEX 2022 - simulations

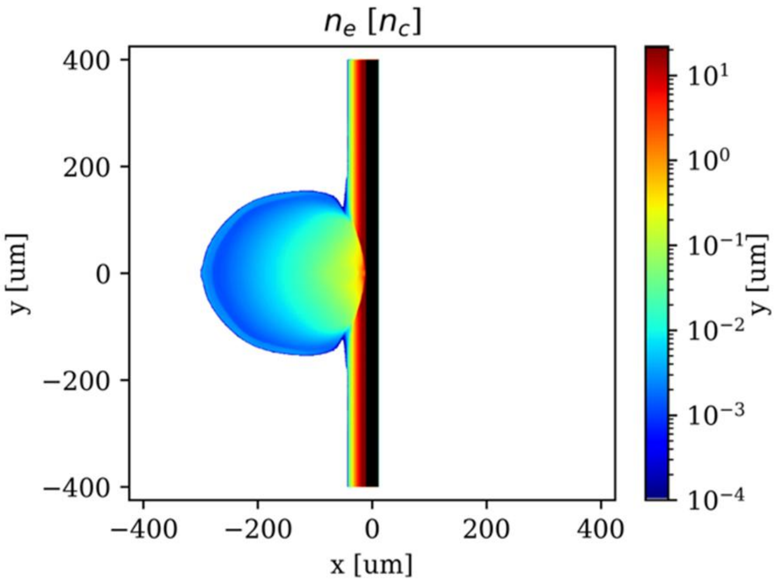
Plasma expansion simulated with the code CHIC taking into account the shape of LFEX laser prepulse

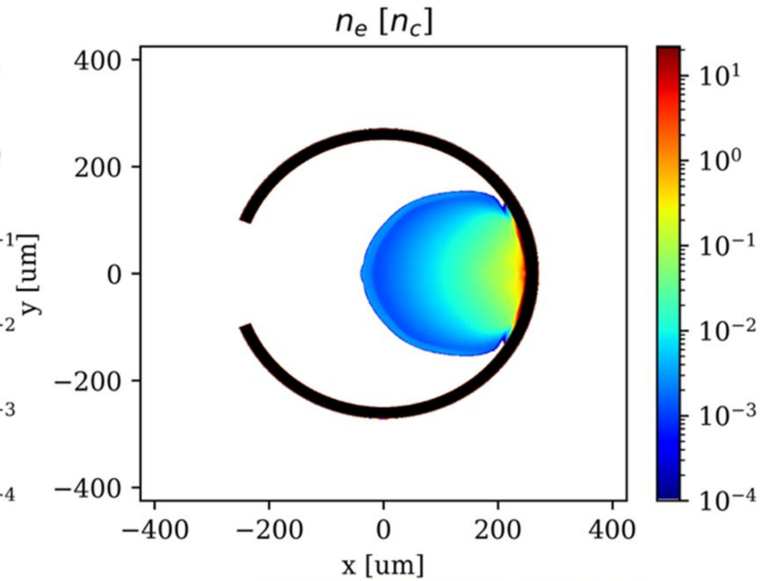


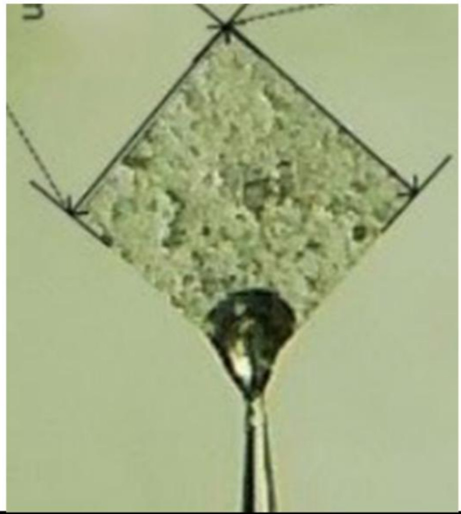


The increase is very rapid: from 7 10^9 W/cm^2 up to 3 10^{15} W/cm^2 in 0.17 ns

LFEX 2022 - simulations







Initial electron density in the planar and in the spherical geometry

LFEX 2022 - simulations

At the arrival of main LFEX laser peak, the laser interacts with the preplasma cloud and creates additional plasma.

Protons and boron ions are produced inside a boron sphere (these are accelerated due to both TNSA and hole boring mechanism).

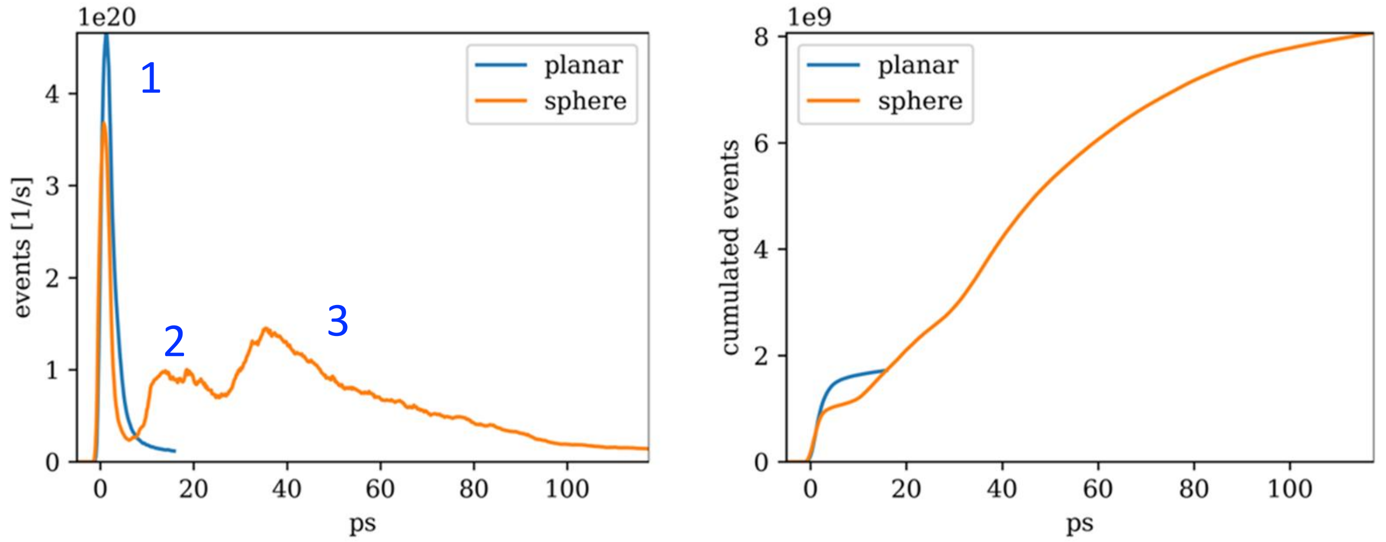
The plasma expansion is associated to the generation of strong magnetic fields which may act to confine this plasma cloud.

This effect can be particularly strong in the case of confined geometry

LFEX 2022 - simulations

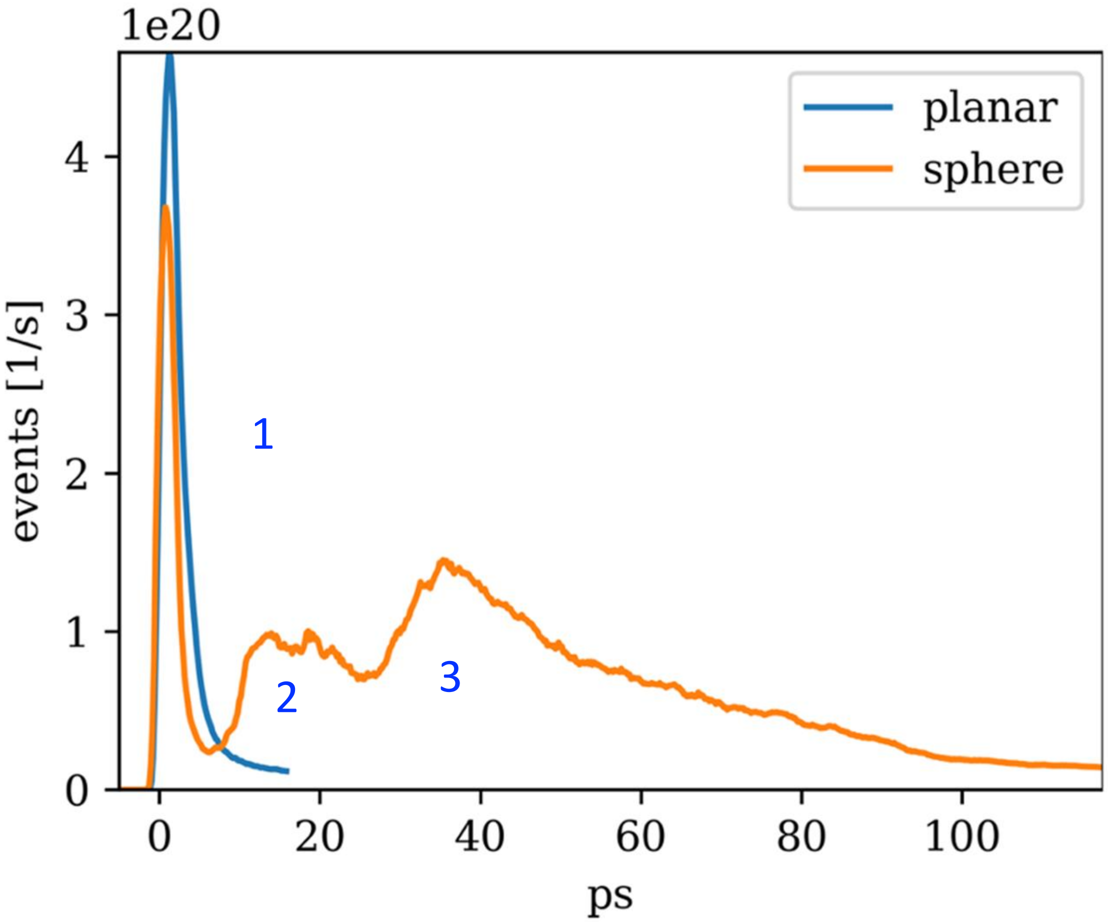
The spherical geometry increases the reaction rate, taking advantage of different acceleration processes

Contrarily to the planar target, the whole spherical target is source of nuclear reactions. The time evolution of reactions does not present only one peak (like with the planar target) but three, spaced in time by a few ps.



Evaluation of p-B11 fusion events in planar vs. spherical geometry. (left) Time evolution of fusion rate (right) Time integrated yield. For the spherical case we see three characteristic phases corresponding to the first emission peak, an intermediate bump, the final peak.

LFEX 2022 - simulations

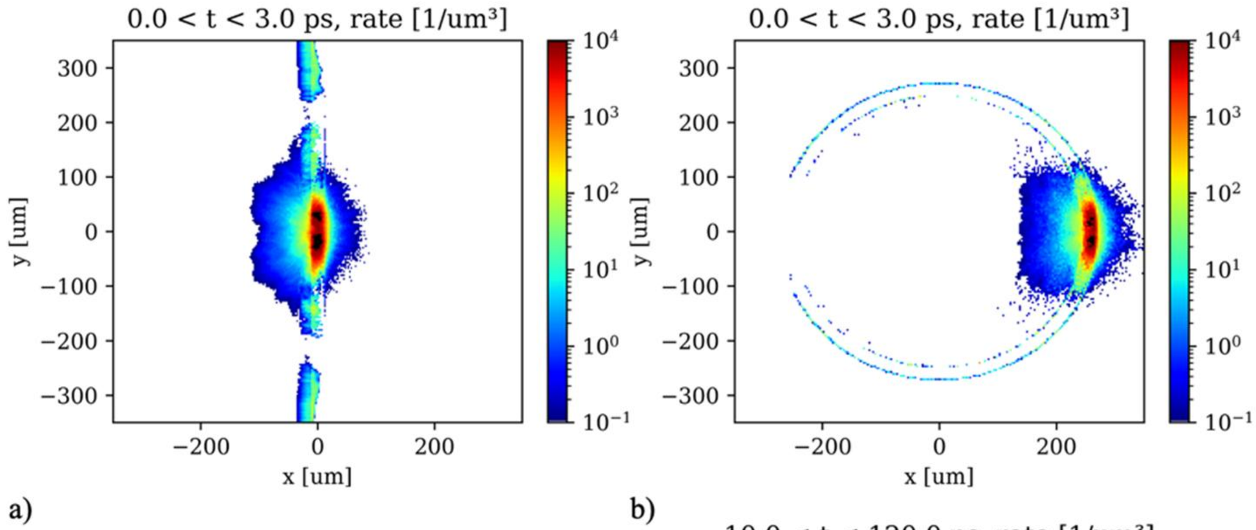


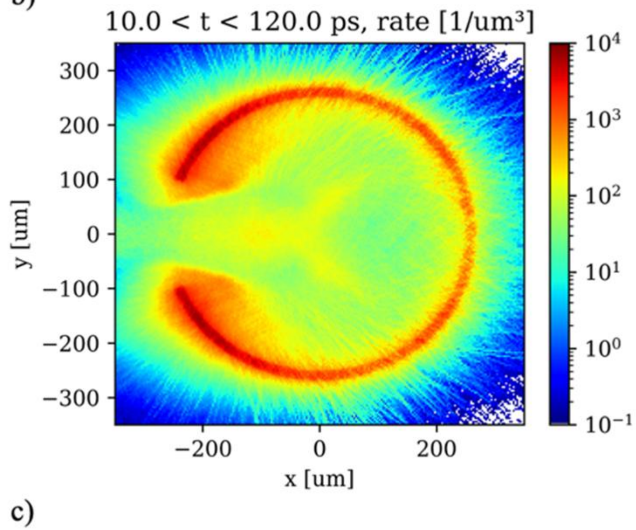
The first peak (1) corresponds to the HB acceleration of protons and borons through the bottom wall.

The second peak (2) to the backward TNSA of protons interacting with the inner wall close to the entrance. Typically, a 4 MeV proton takes ~20 ps to cross the sphere (500 μm).

The third peak (3) to the backward TNSA of borons interacting with the inner wall. A 10 MeV boron takes ~50 ps to cross the sphere.

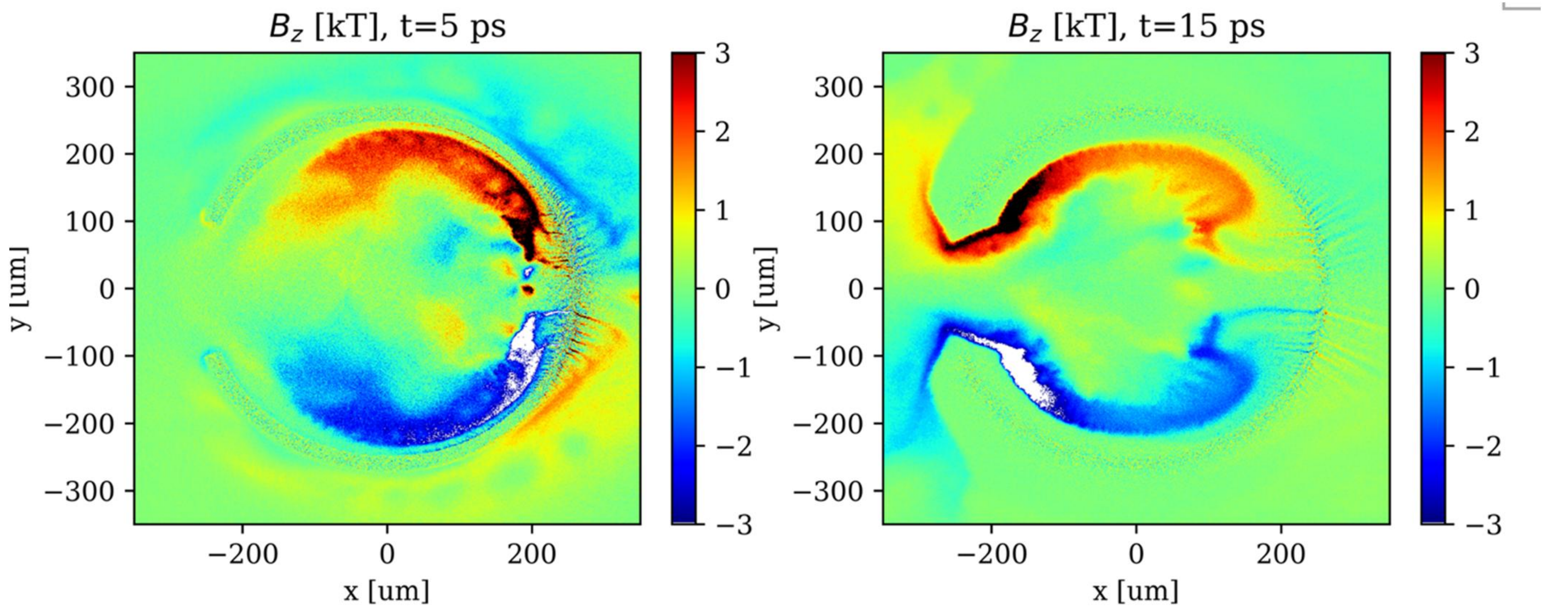
LFEX 2022 - simulations





Spatial location of fusion events (a) for planar geometry (b,c) for spherical geometry. Here (a,b) refer to the time of the first emission peak, (c) refers to emission at later times.

LFEX 2022 - simulations



Magnetic fields in the sphere case at two different times

Magnetic fields are generated inside the cavity and last over tens of ps.

LFEX 2022 - simulations

Are these enough to contribute to the enhancement of α-particle yield?

Larmor radius

[redacted]

Large fields of typical ~2 kTesla (= 2 10^7 Gauss) intensity appear inside the cavity and last over tens of ps.

For 600 keV protons the corresponding Larmor radius is ~4 10^{-3} cm = 40 µm.

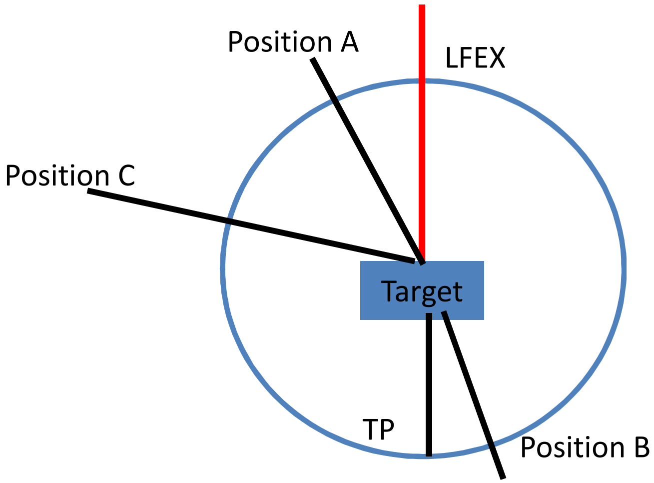
Instead for 3 MeV $^{11}B^{1+}$ ions the Larmor radius (~300 µm) exceeds the dimensions of the sphere.

Moreover, these fields are only present in the low-density plasma in the interior of the sphere, regions for which the fusion probability is weak due to low density.

Therefore, particle confinement does not seem to play a significant role here

Conclusions

- Spheres seem to provide higher fluxes of α particles as compared to flat foils. This seems to be in agreement with simulation results
- The α-particle spectrum seems to shift towards higher energies
- Analysis of data is difficult.
  Many CR39 are saturated. Others below noise
  Discriminating α-particle and ions in Cr39 (and in TP) is difficult
- Targets production is an issue (Spheres were low quality). Cylinders were successfully produced at Deakin but reliable production of many cylinders is an issue
- New simulations codes have been developed which allows interpretation of experimental results (PIC code SMILEI with HB fusion reactions)
- Need better / more diagnostics to measure produced α particles.
- Is there a way to increase the magnetic field action on target size and laser parameters, so that confinement becomes relevant?

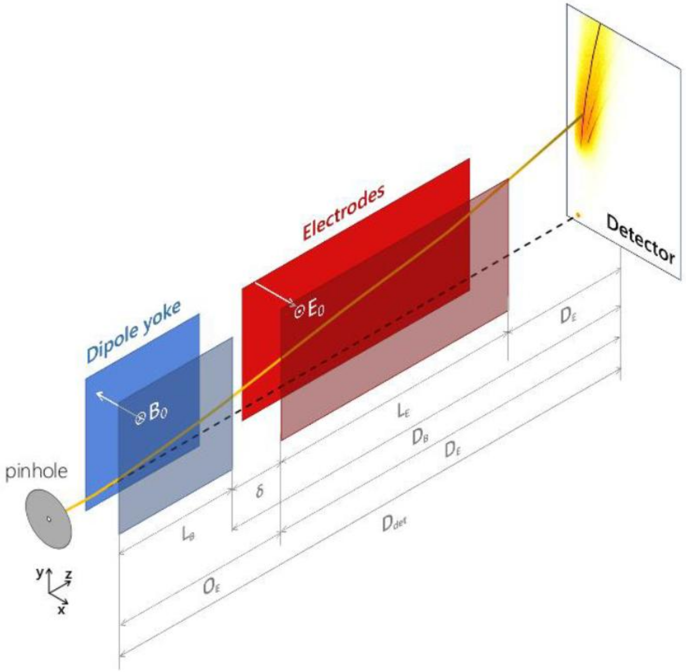


Unambiguous detection of α-particles on Thomson Parabola

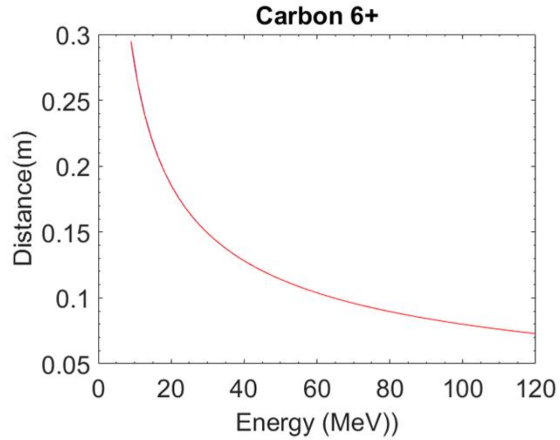
	Energy	Target	CR Position A-157cm	CR Position B - 178,5 cm	PET	PC	CR Position C - 148 cm	PET	PC	T. Parabola	Comments
Shot 1	1,3kJ	CH	55	63	x	x	56	x	x		good TP
Shot 2	1,350kJ	Sphere	54	58	✓	x	57	✓	✓		good TP
Shot 3	1,26kJ	Flat	65	64	✓	x	66	✓	✓		Broken filters (10-20um) mask PC or PET 11. TP Voltage = -3,1-2,9=6 kV
Shot 4	1,301kJ	Sphere	59	60	x	✓	61	✓	✓		Same filters now on broken
Shot 5	1,350kJ	HB11, Cilinder	70	71	x	✓	69	✓	✓		
Shot 6	0,876kJ	HB11, Cilinder	74	75	x	✓	73	✓	✓		
Shot 7	1,254kJ	B-2mm	x	x	x	x	x	x	x	x	Philippe Configuration, no TP and CR
Shot 8	1,277kJ	Flat	27	78	✓	x	77	✓	✓		
Shot 9	0,710kJ	Sphere	53	13	✓	x	40	✓	✓	L008	CR used as IP with filter of 11um

Thomson parabola

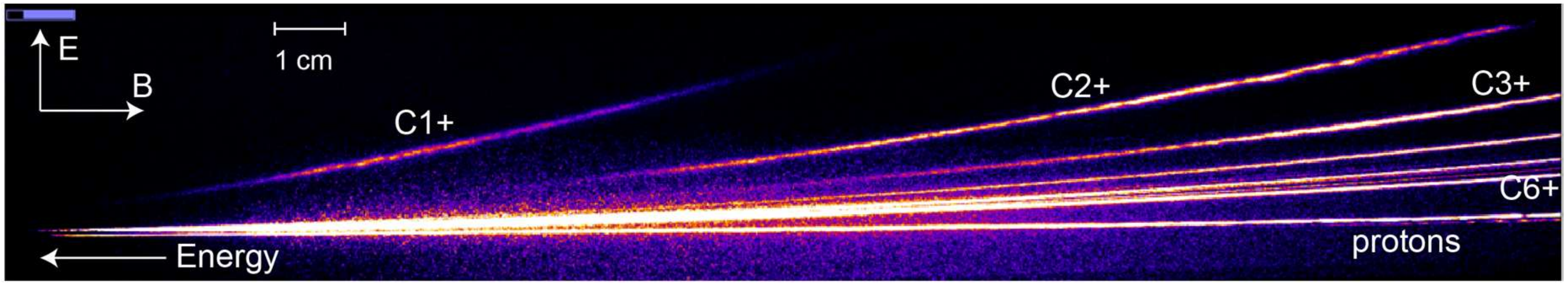
- **Pinhole Diameter**: 300 μm
- **Target Distance**: 110 ± 2 cm
- **Solid Angle**: 8.26×10^{-9} sr
- **Magnetic Field**: 0.75 T
- **Electric Field**: 3.5×10^{5} V/m



omson Parabola

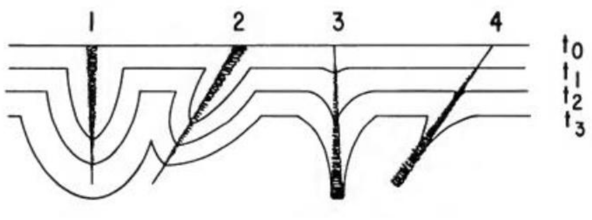


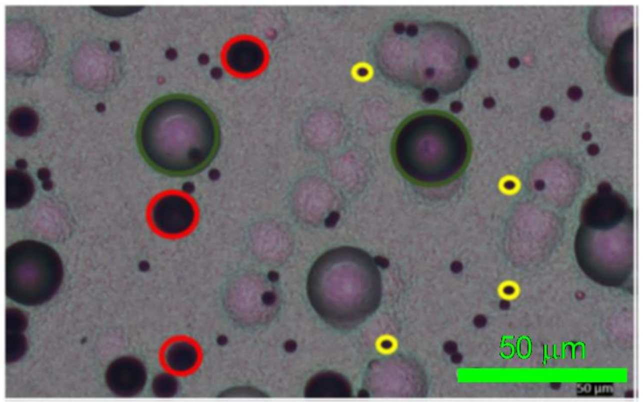
$$y = \frac{m}{q}\frac{E_0 L_E\left(\frac{L_E}{2}+D_E\right)}{B_0^2 L_B^2\left(\frac{L_B}{2}+D_B\right)^2}x^2$$

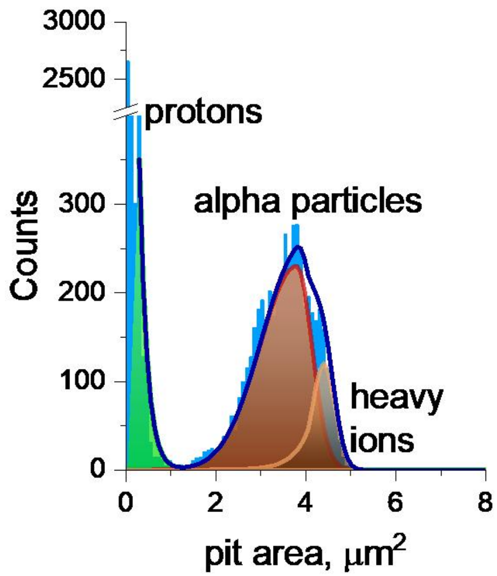


CR-39 detectors

- Chemical etching in 6.25 M NaOH at 70°C
- Detects micrometer-scale tracks left by ions
- Discrimination based on track size







TP signal on CR-39

Mid Energy

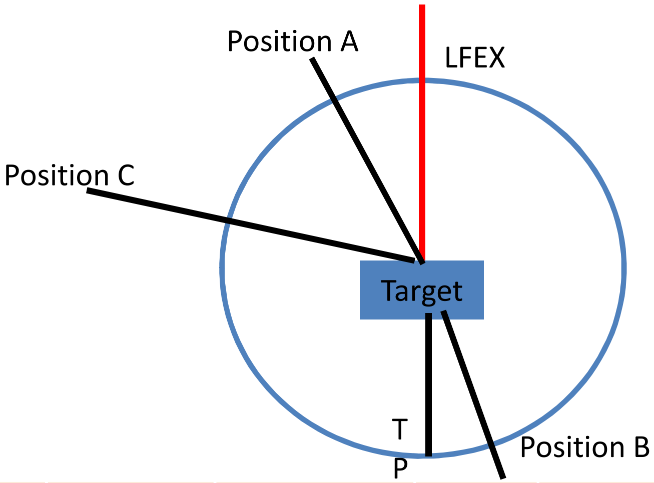
Ion	MeV
H+	1,9
He+	7,6
C6+	22,7

Low-Mid Energy

Low Energy

Overview

TP signal on CR-39

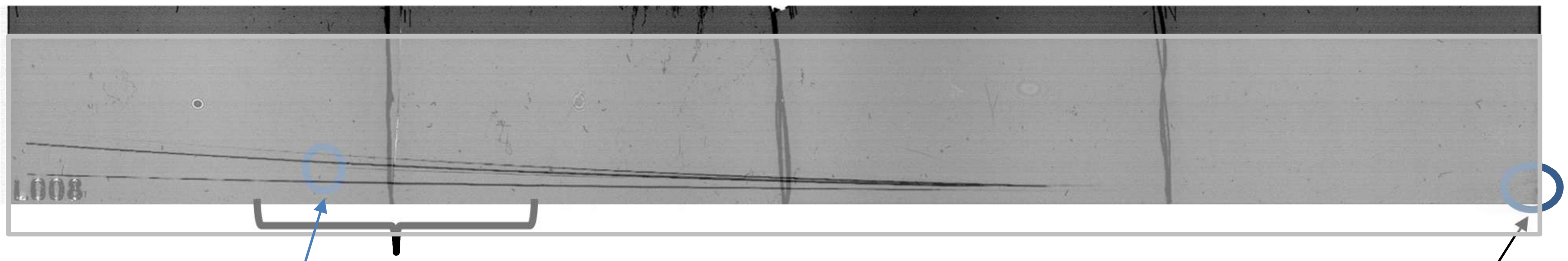


LFEX experimental campaign

	Energy	Target	CR Position A-157cm	CR Position B - 178,5 cm	PET	PC	CR Position C - 148 cm	PET	PC	T. Parabola	Comments
Shot 1	1,3kJ	CH	55	63	x	x	56	x	x		good TP
Shot 2	1,350kJ	Sphere	54	58	✓	x	57	✓	✓		good TP
Shot 3	1,26kJ	Flat	65	64	✓	x	66	✓	✓		Broken filters (10-20um) mask PC or PET 11. TP Voltage = -3,1-2,9=6 kV
Shot 4	1,301kJ	Sphere	59	60	x	✓	61	✓	✓		Same filters now on broken
Shot 5	1,350kJ	HB11, Cilinder	70	71	x	✓	69	✓	✓		
Shot 6	0,876kJ	HB11, Cilinder	74	75	x	✓	73	✓	✓		
Shot 7	1,254kJ	B-2mm	x	x	x	x	x	x	x	x	Philippe Configuration, no TP and CR
Shot 8	1,277kJ	Flat	27	78	✓	x	77	✓	✓		
Shot 9	0,710kJ	Sphere	53	13	✓	x	40	✓	✓	L008	CR used as IP with filter of 11um all over

TP signal on CR-39

Shot 9, sphere target



Expected location of the pinhole

Ion	Cutoff energy [MeV] Al filter thickness [μm]		
Al thickness	10	11	12
H	0.77	0.82	0.87
He	2.75	2.98	3.20
C	11.65	12.82	13.97

TP signal on CR-39

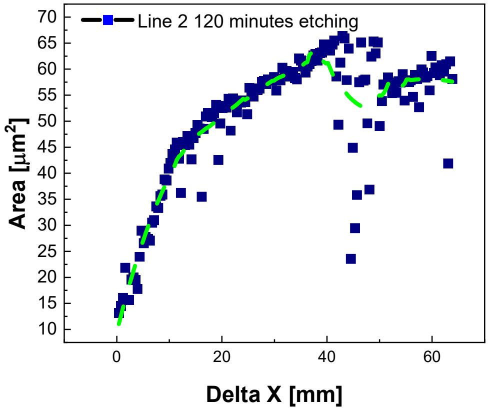
Shot 9, comparison line 1 and 2

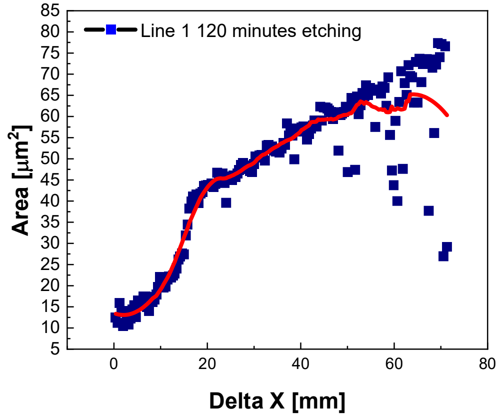
- Each dot is average size of the traces in the single image
- 200 images taken in series

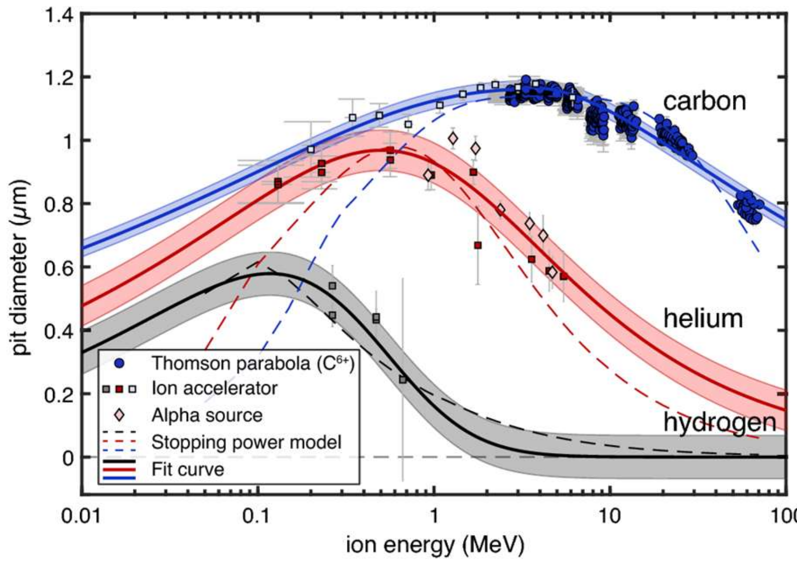
1 ion specie on the TP

Standard calibration trend for ions

Proof of 2 different species on the same line



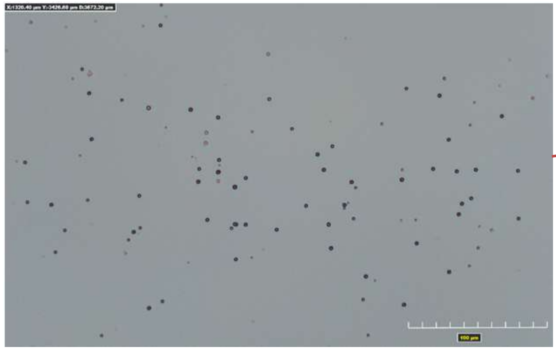


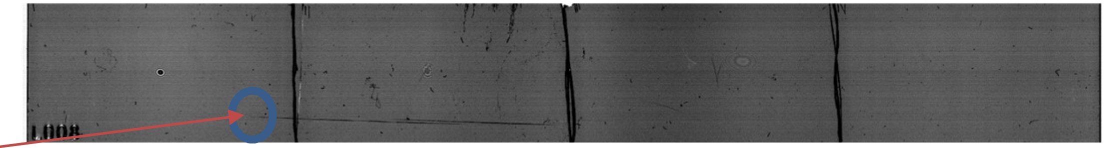


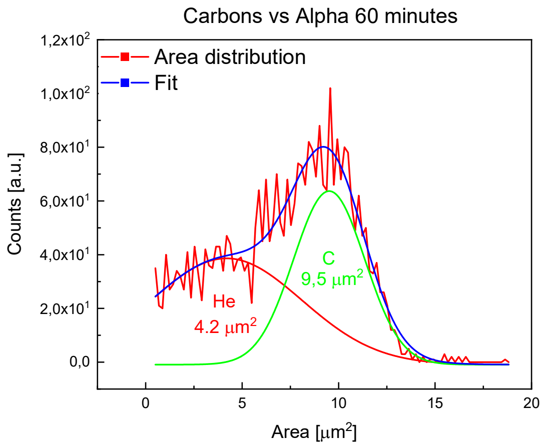
Schollmeier, *et al. Sci Rep* **13**, 18155 (2023)

TP signal on CR-39

Shot 9, analysis line 1





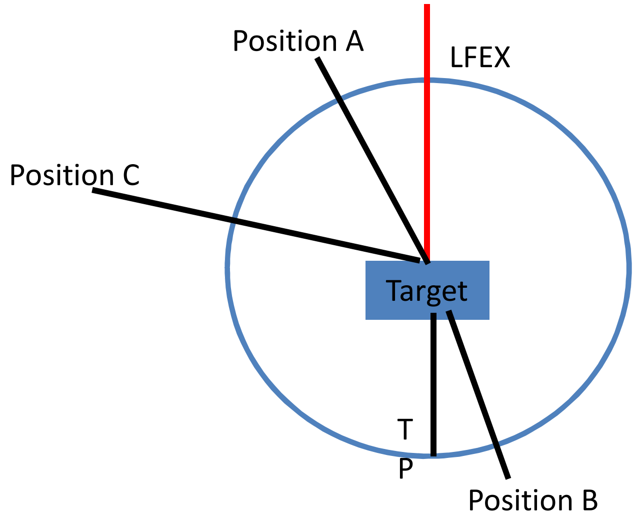


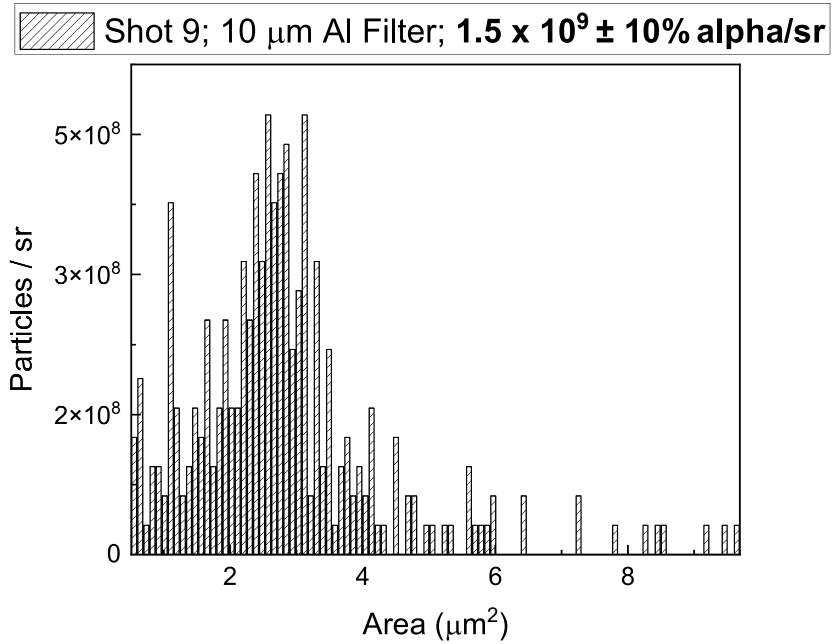
Calibration NaOH 6.25M

Energy α [MeV]	1h etching
0.6	3.12±0.40
0.93	6.07±0.37
1.09	4.60±0.34
1.4	2.52±0.44
3.15	3.02±0.33
3.7	2.07±0.37

- A total of 228 tracks has been counted as α–particles, 3.35 x 10^9 /sr
- Energy before the filter 3.7 – 4.0 MeV
- Experimental proof of detection of α particles using CR-39

Shot 9, comparison with position C





CR39 with 10 µm Al filter non-saturated (low energy shot)

α-detection on TP with CR-39

Challenges

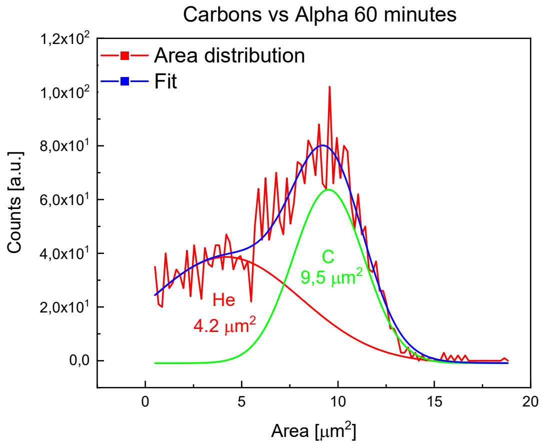
- Time-consuming analysis
- Specific setup parameters may not be transferable
- Requires high ion yield for clear detection
- Limited energy resolution

Proposed improvements

- Improving the software for counting α particles
- Multiple filters of different thicknesses can be used to reconstruct an energy spectrum
- Improving the etching station based on the dimension of the CR-39

Conclusions

- Limits of the α particle's detection
- New method of detection of α particles
- Successfully detected α particles in the TP using CR-39
- Measured 3 x 10^9 α particles/sr at 4.5 MeV



Acknowledgements

PROBONO Cost Action CA-21128 “PROton BOron Nuclear fusion: from energy production to medical applicatiOns

COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career and innovation. (www.cost.eu)