CELIA

Energetic α-particle sources produced through proton-boron reactions, by high-energy, high-intensity laser beams

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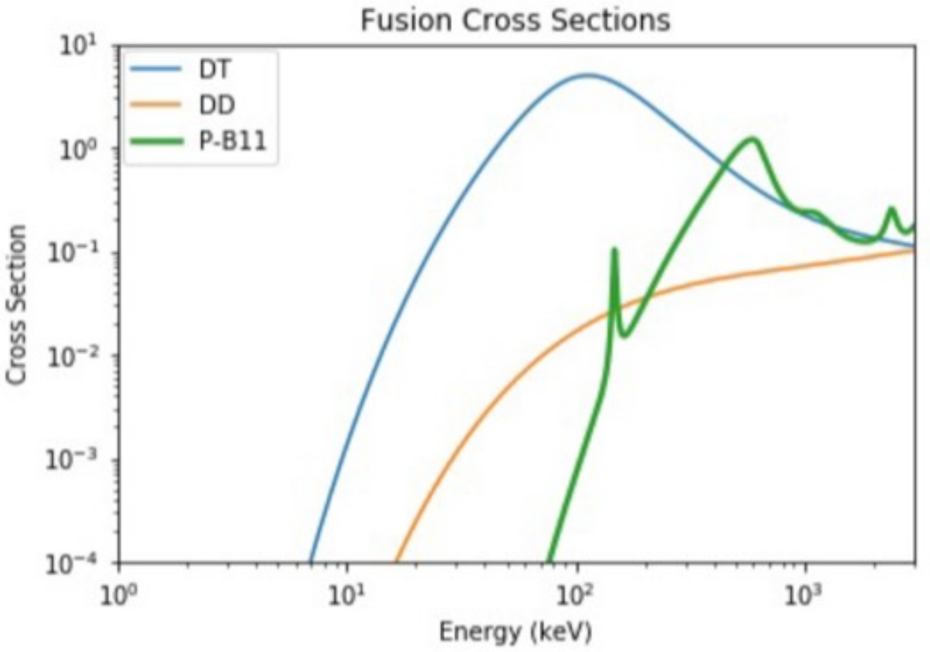
The background and purposes

The proton-boron fusion reactions present interest due to multiple applications in various fields

- ❑ fusion for energy : quasi aneutronic reaction but requires very high temperature
  - ➛ non classical/thermal scheme to ignite fuel *
- ❑ α production ($p + {}^{11}B \rightarrow \alpha + {}^{8}Be \rightarrow 3\alpha$)
  - for cancer therapy**
  - for radio-isotope production



Through our last laser experiment, we aimed at

- ❑ producing a bright and energetic α-particle source
- ❑ better understanding the α-particle production and transport
- ❑ testing our numerical tool chain

*Hora et al, High Power Laser Sci. Eng. 4 e35 (2016)
Belloni, Plasma Phys. Cont. Fusion 63, 055020 (2021)

**Cirrone et al, Sci. Rep. 8, 1141 (2018)

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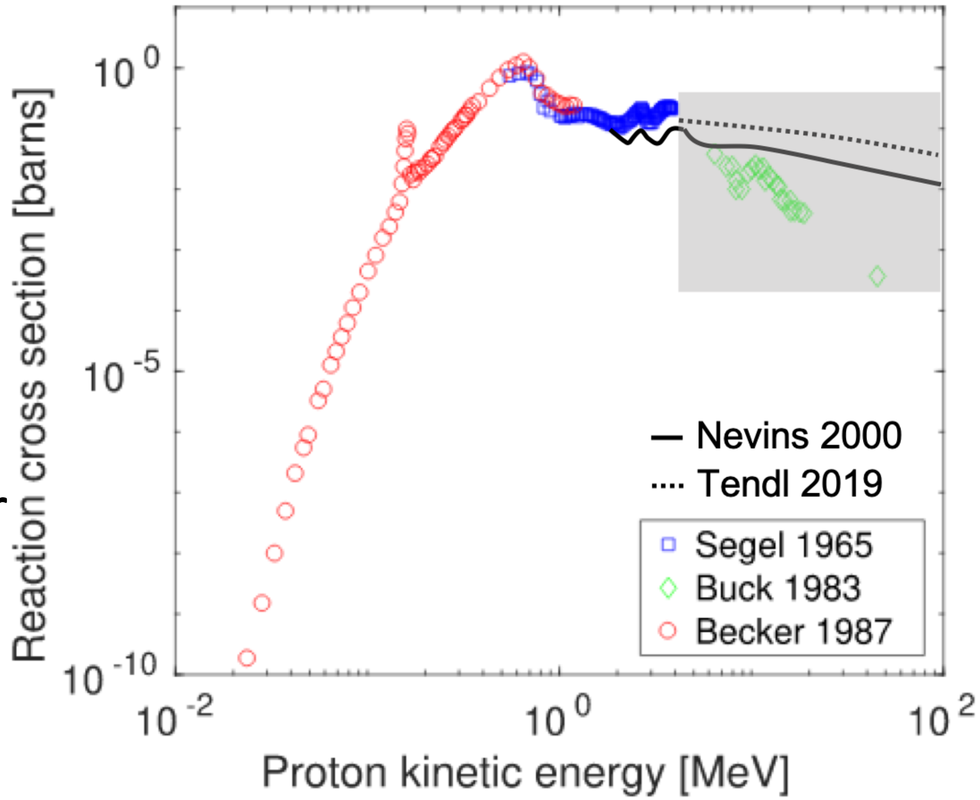

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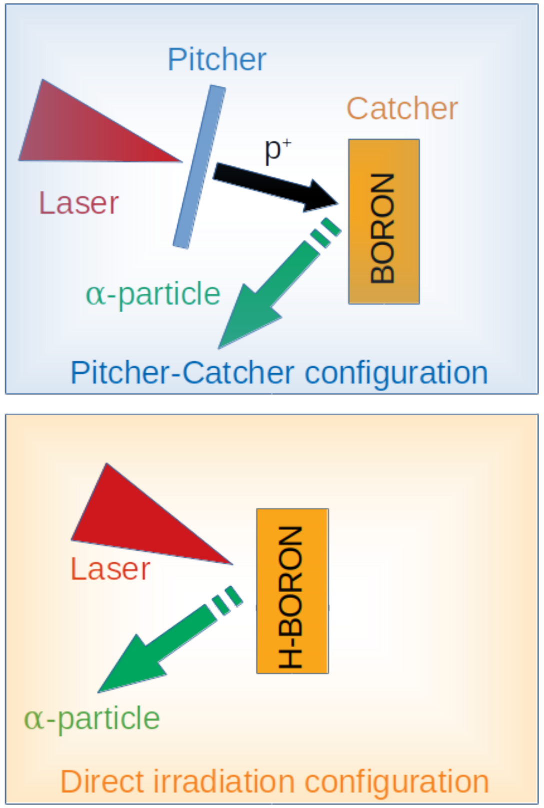
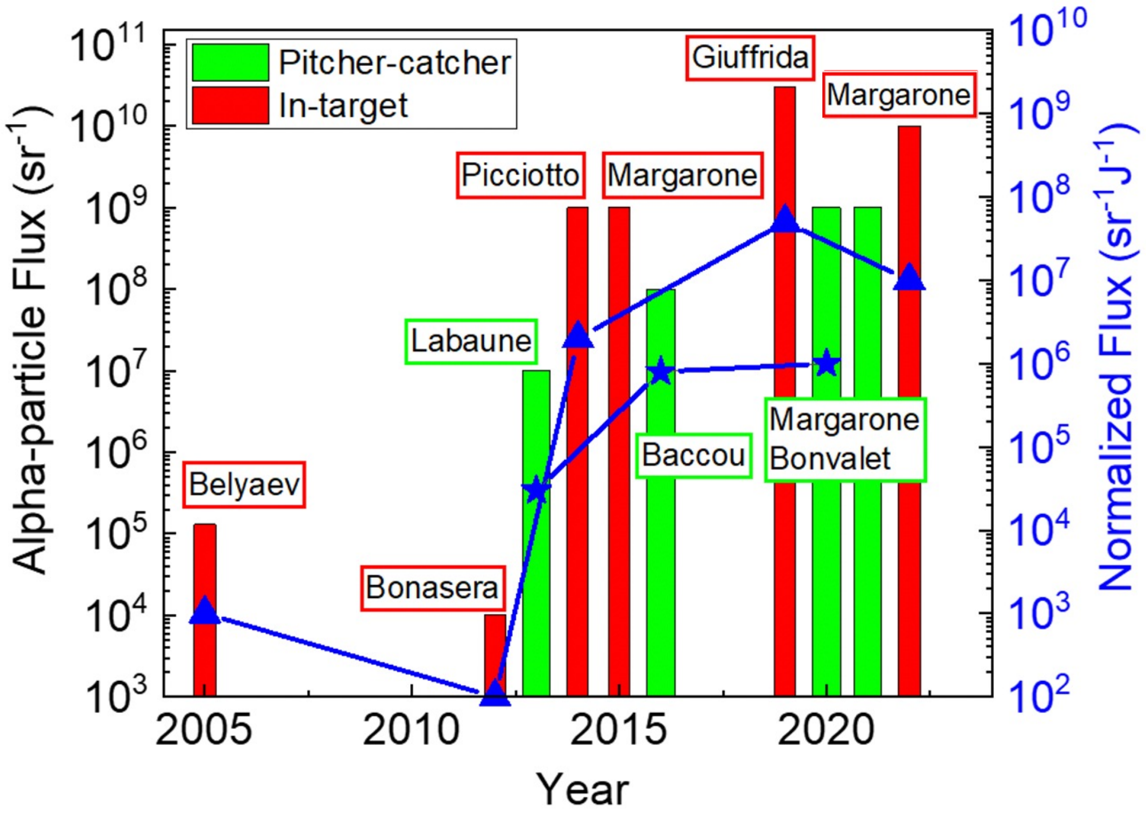
Since Belyaev work in 2005, using laser driven protons, the p-B reaction yield has continuously increased up to a few 10^{10} α/sr in 2020[4] .

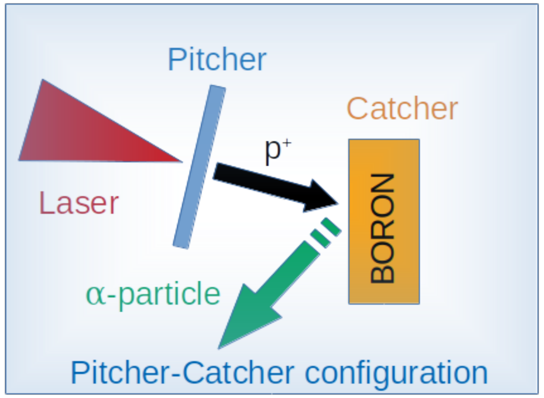


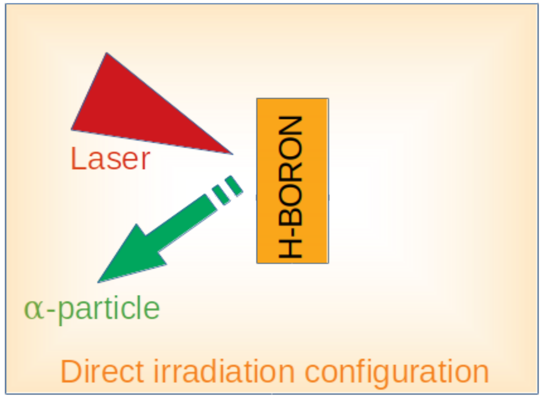


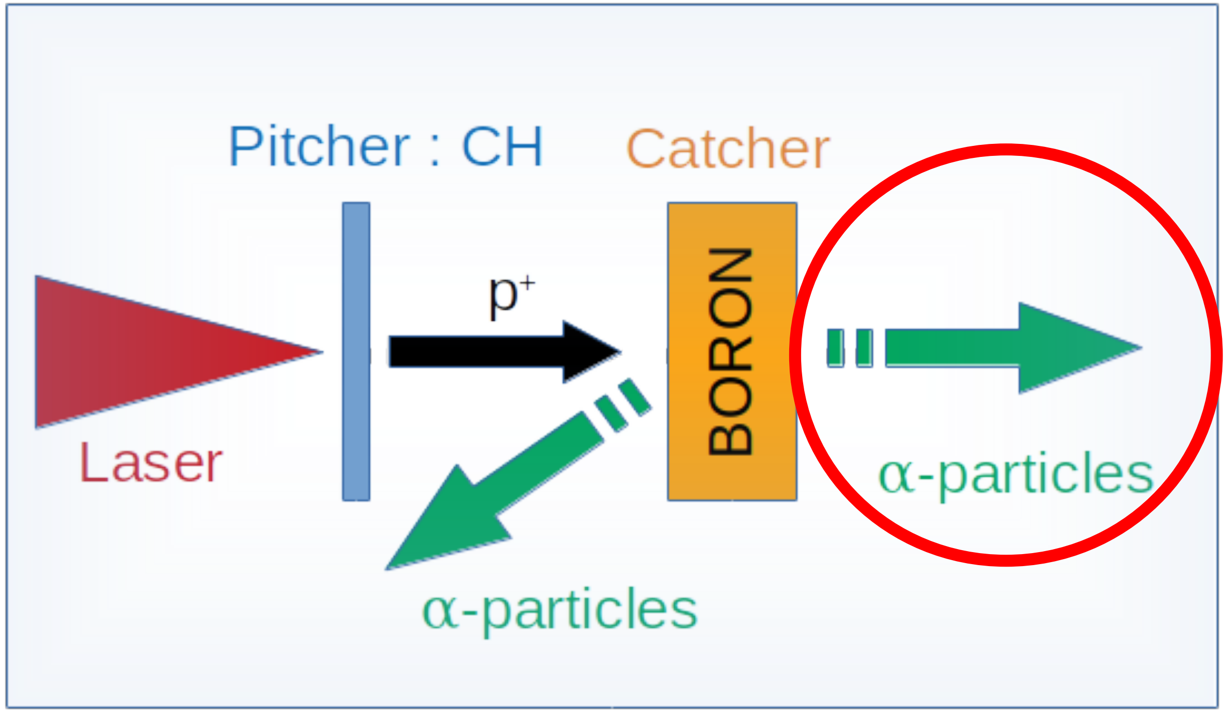
The last and best results[4] has been obtained using sub-ns laser pulse with a modest intensity

[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)

Our goal was not to only produce a large number of α-particles but also to create an external, clean and energetic α-particle beam for other applications (radio-isotope)



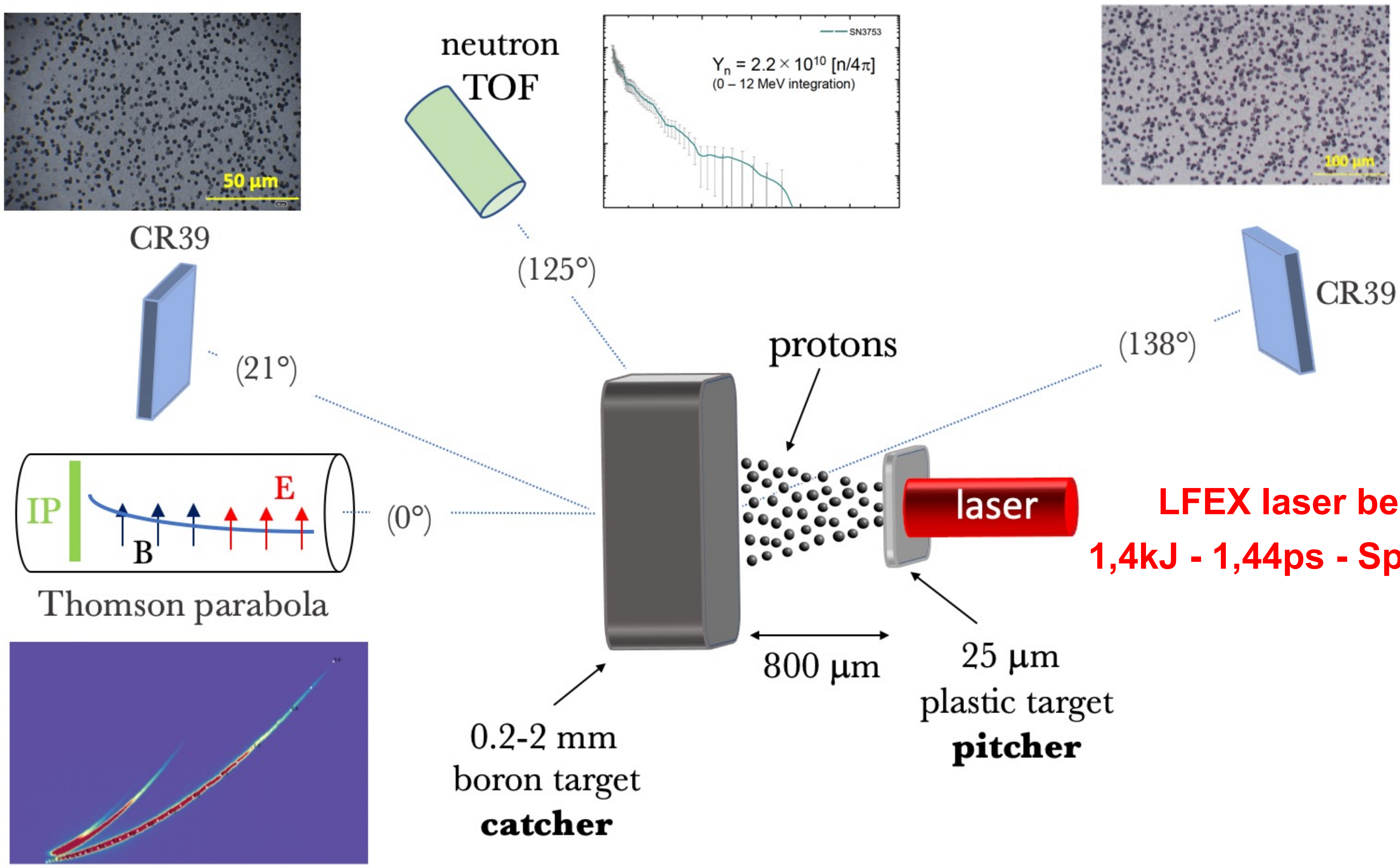




In a pitcher-catcher configuration, using thin boron targets, energetic α-particles may be induced at the rear side, by kinetic energy transfer from incident protons

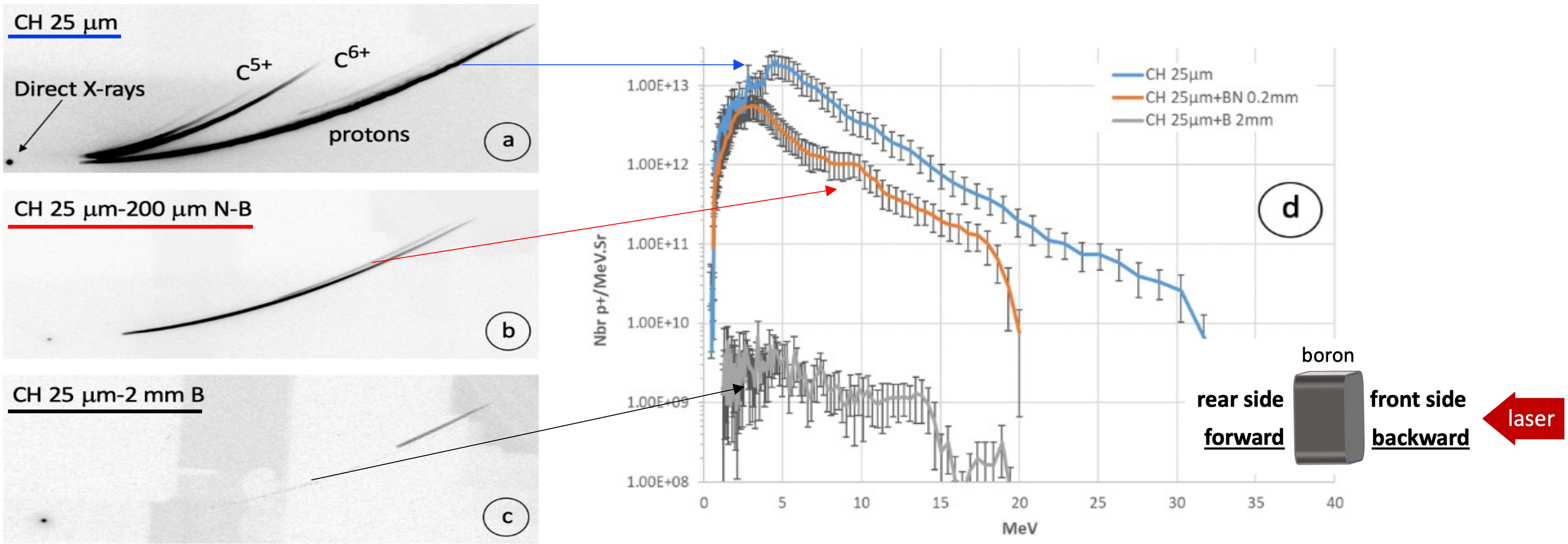
The boron target stops carbon ions from CH target

The experiment has been carried out at the LFEX laser facility at Osaka, Japan in 2020



LFEX laser beam :
1,4kJ - 1,44ps - Spot 60µm

Thomson Parabola: energetic protons, up to 30 MeV have been measured



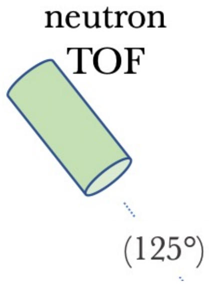
Without the secondary boron target, protons and carbon ions are clearly visible.

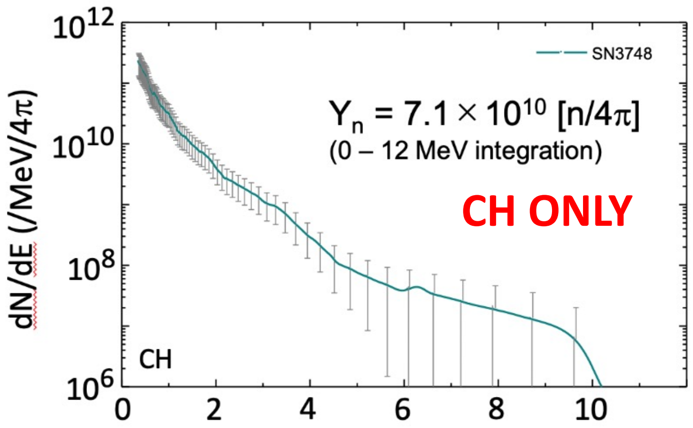
Even after 2 mm of boron, protons are still detectable in the forward direction.

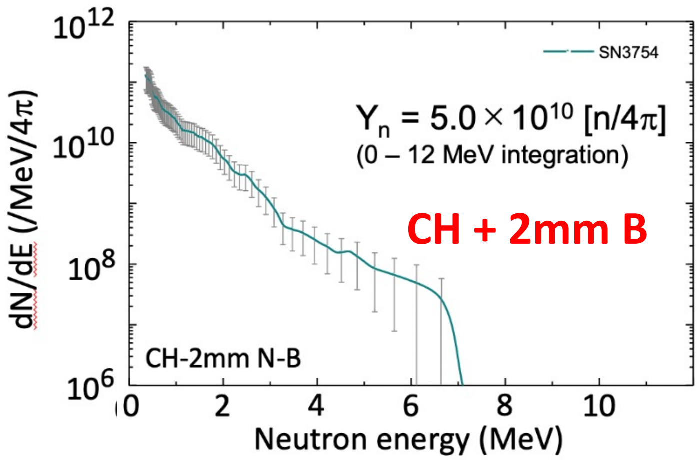
For the 2 mm case, some TP structures are visible showing the noise limit.

No α-particle are visible meaning their amount is below the TP detection threshold

The presence of the boron target does not change the neutron energy distribution





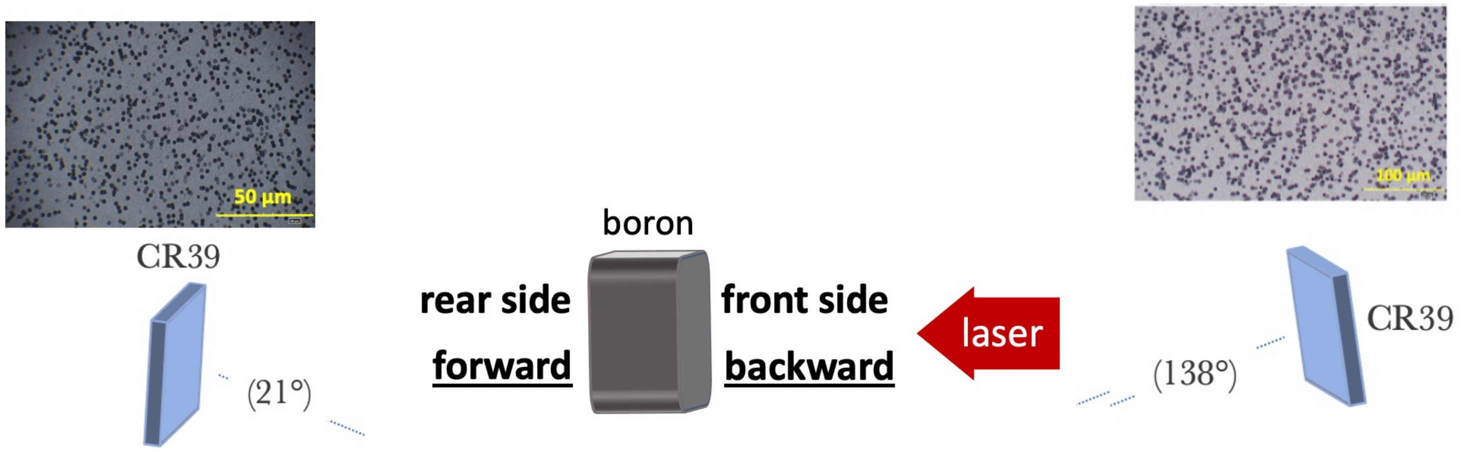


5-7 10^{10} neutrons (4 π) have been detected w/ or w/o the boron target

Neutrons mainly produced in the target chamber interaction by protons and gammas (^{56}Fe [g,n] and ^{56}Fe[p,n])

The p-B reactions look aneutronic

Thanks to CR-39, we measured α-particles in the backward and also forward directions



10^8-10^9 α-particles/sr have been detected

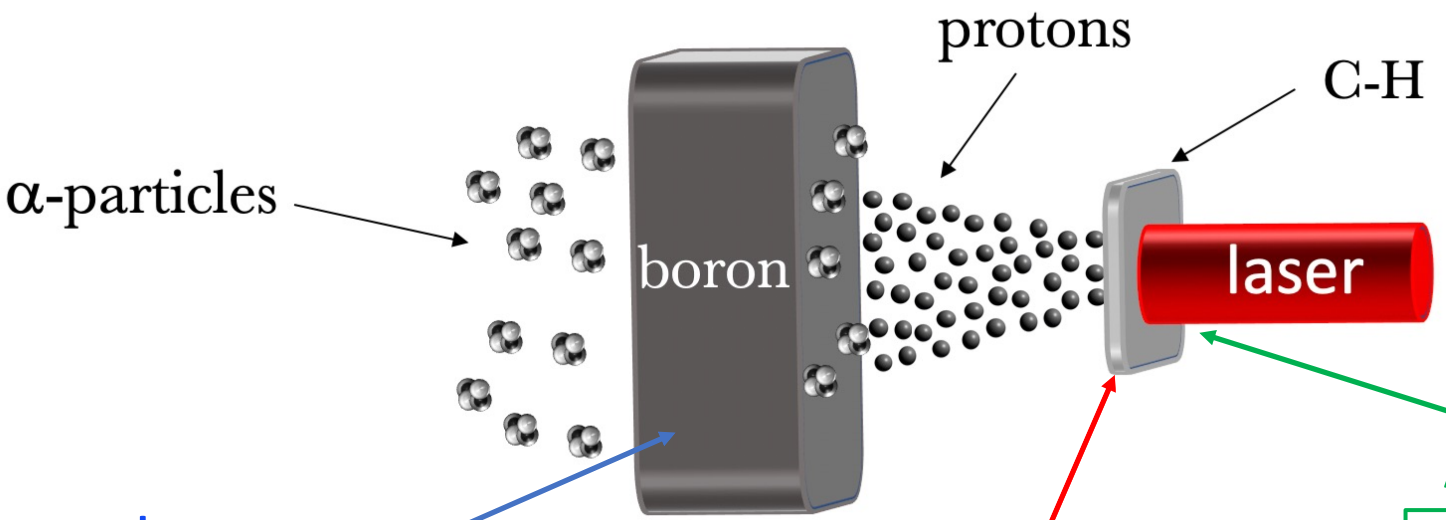
CR39, were covered by 10 and 30 μm of Al layers, allowing to extend energy range up to 10 MeV

Even with the thicker target, energetic α-particles have been measured at the rear side (forward dir.)

TABLE I. α-particle counts /sr on CR39

CR position	138° / 48.3 cm	
energy range	5. - 7. MeV	8.1 - 9.9 MeV
B 2 mm	$1.3\times10^8 \pm 4.5\%$	$4.44\times10^7\pm50.\%$
NB 0.2 mm	-	$2.4\times10^9 \pm 18.\%$
CR position	21° / 35.9 cm	
energy range	5. - 7. MeV	8.1 - 9.9 MeV
B 2 mm	-	$1.6\times10^6 \pm 40.8\%$
NB 0.2 mm	$7.2\times10^8 \pm 5.3\%$	$4.59\ \times10^7 \pm 16.7\%$

The chain of numerical codes used to simulate the experiment



ASE - preplasma

Hydro Code (CHIC[1])

Nuclear reactions and transport

Monte Carlo Code (FLUKA [3])

Laser-plasma interaction and Ion acceleration

PIC Code (SMILEI[2])

In the pitcher catcher scheme, each "step" can be simulated separately !

The hydro-profiles may be used to initialize the PIC code, according to the laser prepulse

The PIC phase space of protons is used to initialize the M-C code

[1] J. Breil et al. Comp, and Fluids, (2011)
[2] J. Derouillat et al. Comput. Phys. Com. (2018)
[3] A. Ferrari et al. (2005)

The 2 D radiation hydrodynamic code, CHIC*

- ✓ second order cell centered Lagrangian scheme
- ✓ ALE scheme
- ✓ unstructured meshes
- ✓ classical or nonlocal thermal conduction
- ✓ nine points scheme
- ✓ thermal coupling
- ✓ detailed radiation transport
- ✓ opacities
- ✓ real Equation of State (QEOS and Sesame)
- ✓ 3D ray tracing for laser propagation
- ✓ thermonuclear burn
- ✓ self-generated magnetic fields
- ✓ Kinetic module M1

*J. Breil et al, J. Comp. Phys. 224, 785 (2007) J. Breil et al, Computers & Fluids 46, 161 (2011)

a Collaborative, Open-Source, Multi-Purpose Particle-In-Cell Code for Plasma Simulation

Open-source & Collaborative
https://github.com/SmileiPIC/Smilei

Modern & High-performance
C++/Python3 • MPI/OpenMP • SIMD • HDF5/OpenPMD
a platform for Exascale (GPU porting under way)

Community-Oriented
advanced documentation • online tutorials • post processing & visualization tools
training workshops • summer school & master trainings

Multi-Physics & Multi-Purpose
advanced physics modules: collisions, ionization, radiation, QED, reduced geometry/envelop
broad range of applications: from laser-plasma interaction to space/astrophysical plasmas

MAISON DE LA SIMULATION

FLUKA: version 2020.0.4

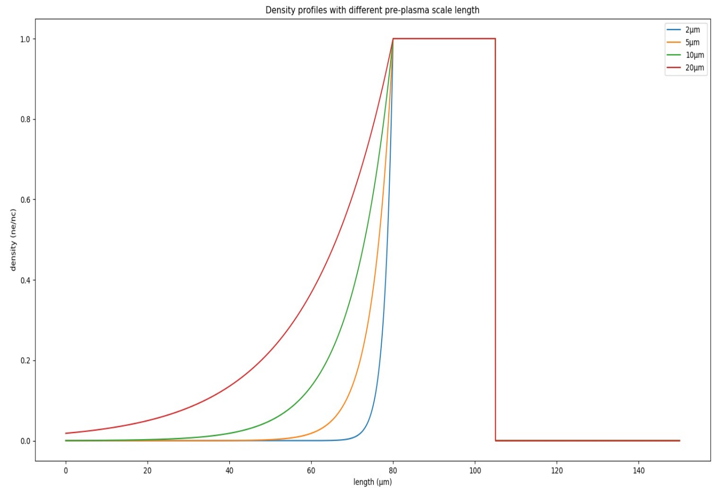
The FLUKA Monte-Carlo code accurately modelizes transport and interactions of electrons, ions, neutrons and photons from relativistic energies down to a few keV.

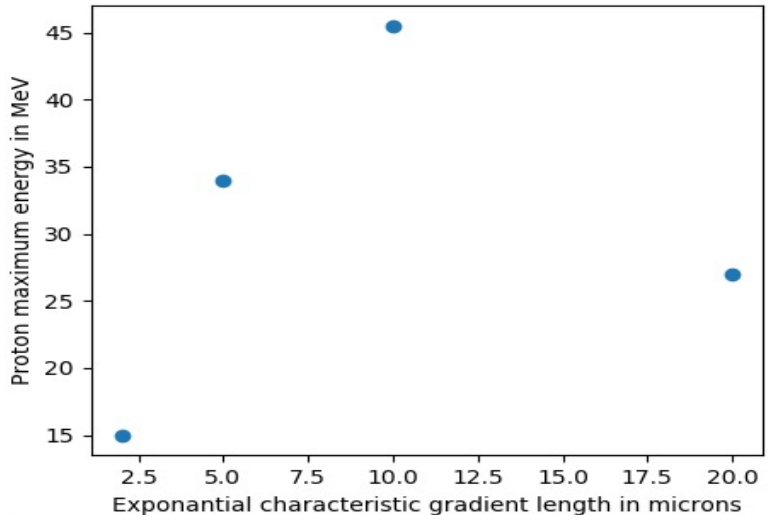
FLUKA is continuously being benchmarked with models and experimental data, including nuclear cross sections. But not obvious to obtain information from FLUKA team.

The material is assumed cold !

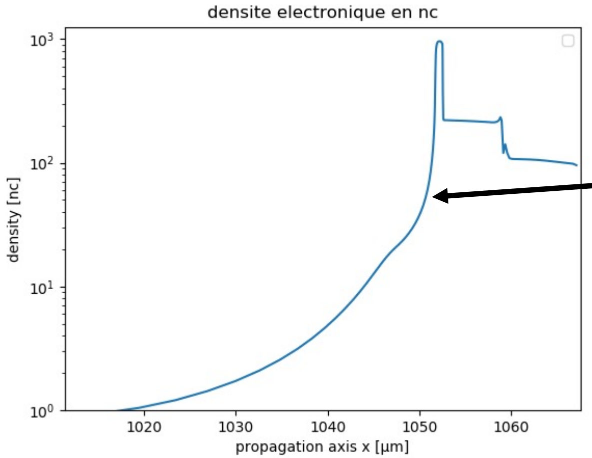
First step: reproduce the proton spectrum with the PIC code

A pre-plasma induced by ASE strongly modifies the particle acceleration (1D)



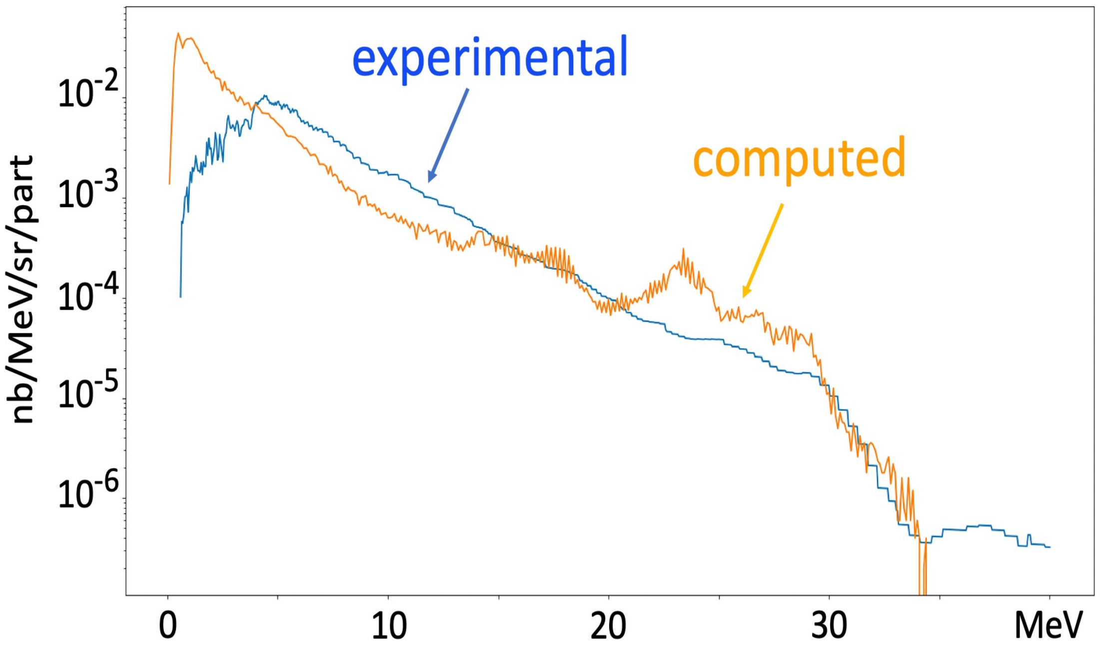


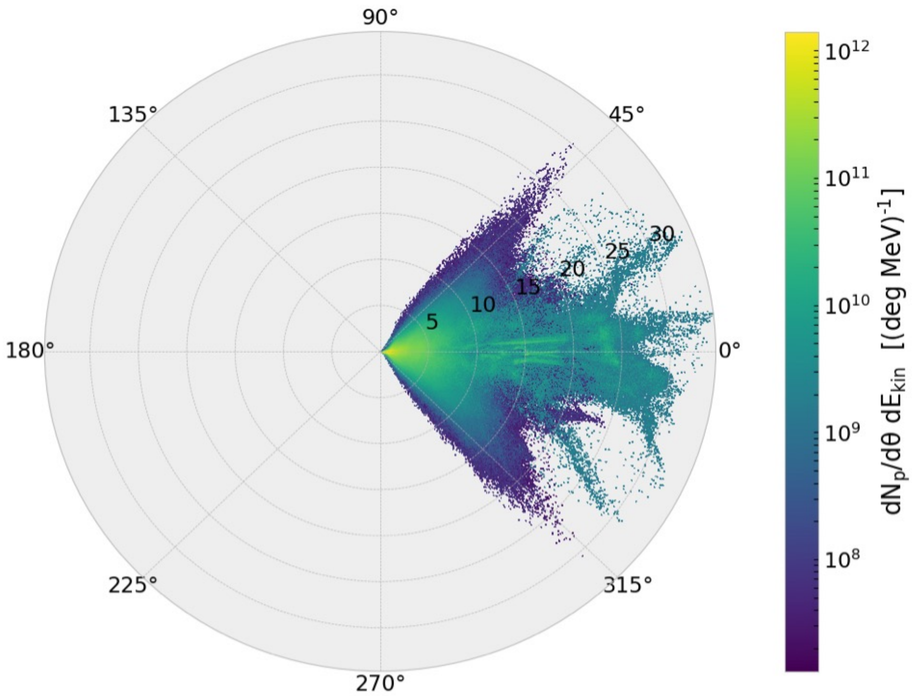
A gradient length of ~7 µm or 15µm reproduces the maximum proton energy



The CHIC code gives in 2D the following profile, corresponding to a gradient length of 22 µm.

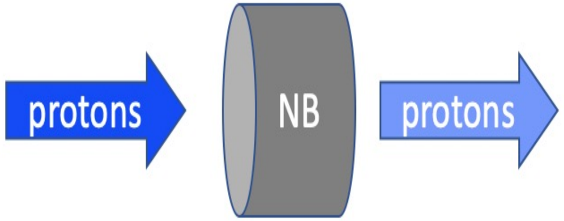
Shapes, maximum energies and proton numbers are in fair agreement



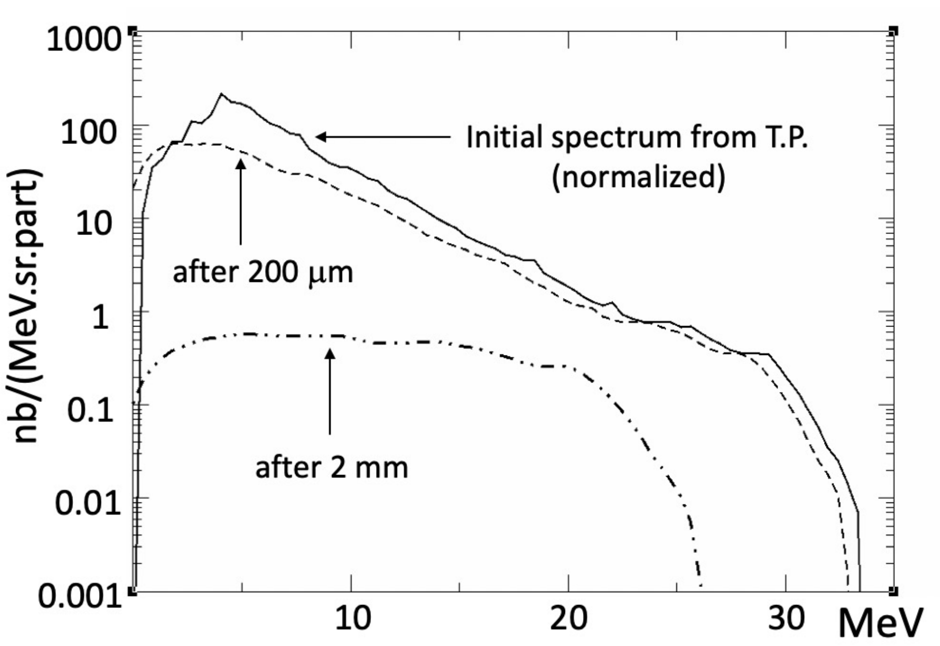


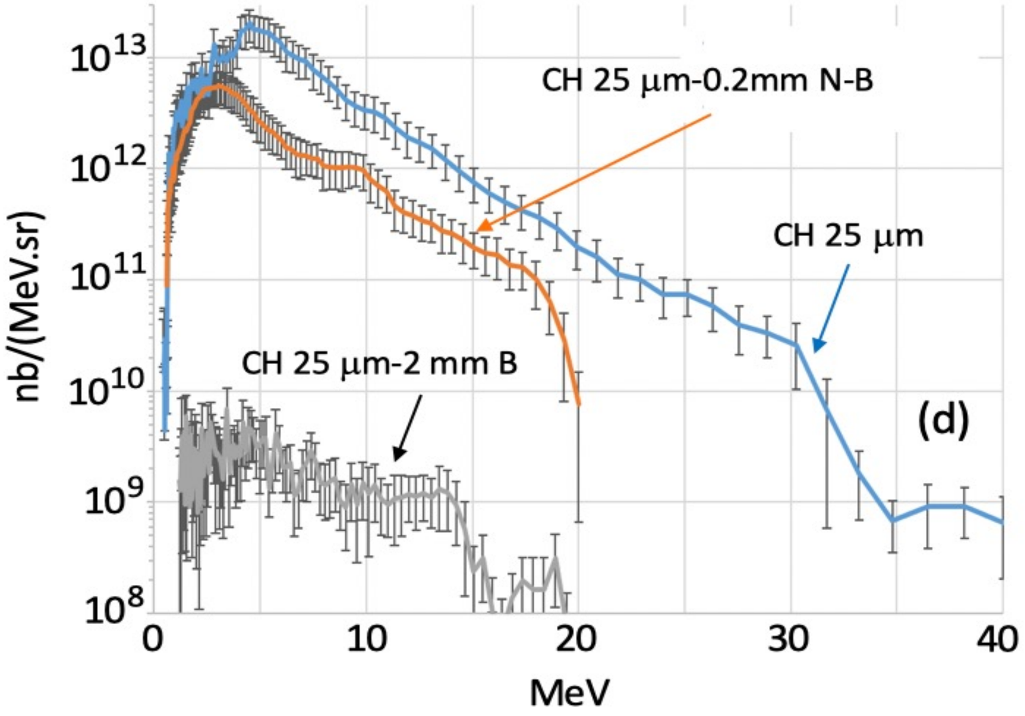
Simulation results may be used to access non-measured data : experimental spectrum obtained along the laser axis without information on angular distribution

We use the computed angular distribution combined with exp. energy distribution to initialize the MC computation



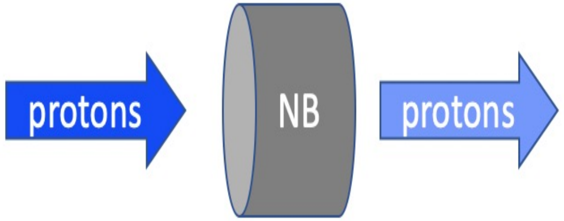
Protons spectra after boron target crossing have been measured and can be compared with the simulations



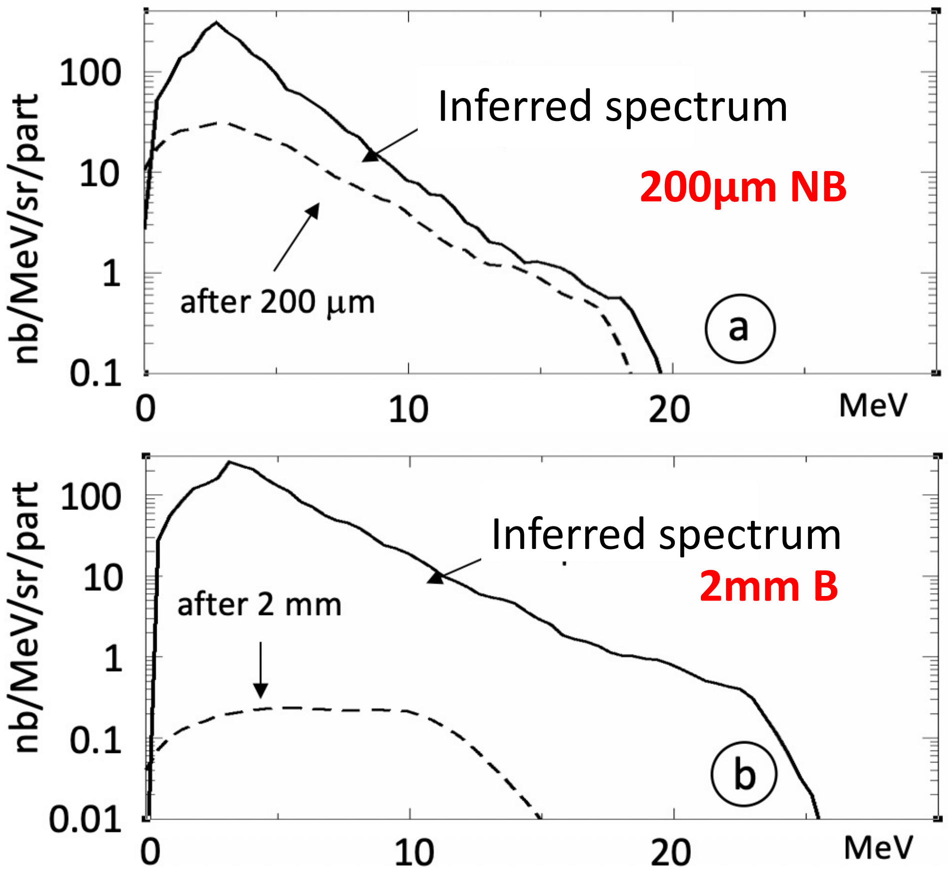


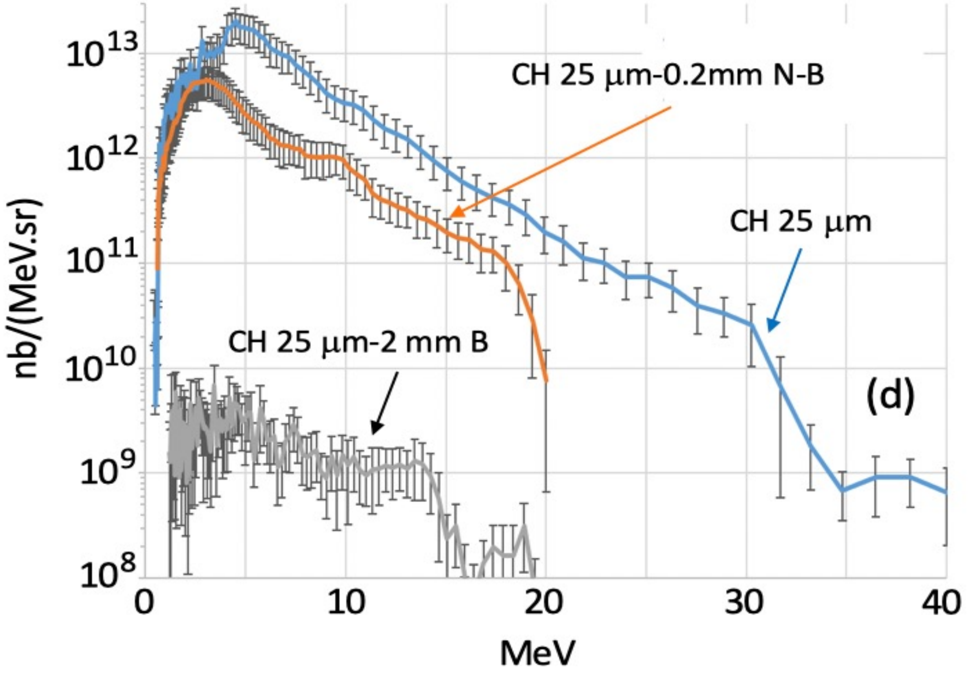
One obtains good tendency but the numbers and maximum energies are not correct after target crossing

Thanks to simulations, we can revert the process to infer corresponding injected proton spectra



shot-to-shot fluctuations may modify the injected proton spectrum



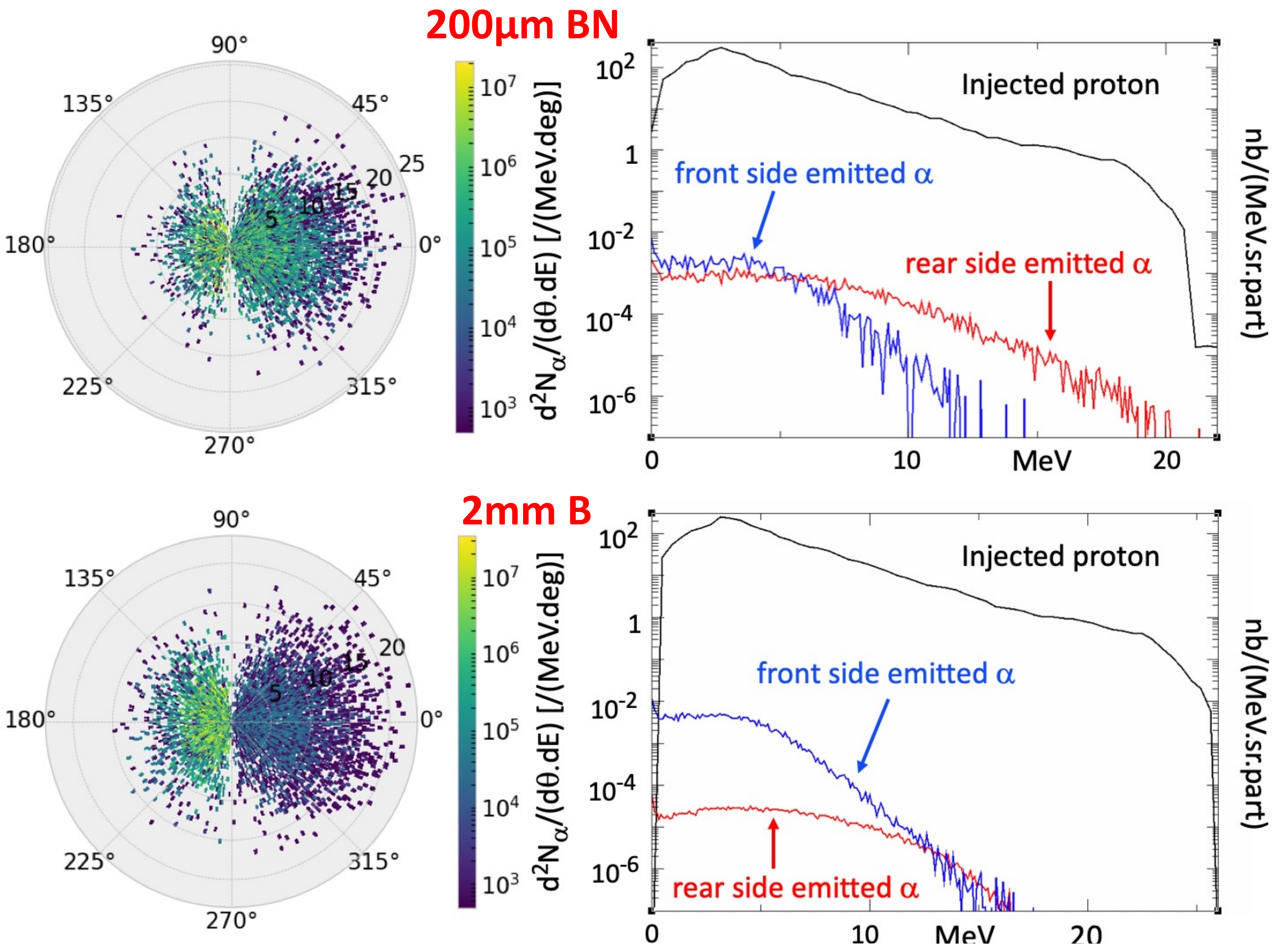


After 200 µm and 2 mm, resp. 18% and 0.2%, of incident protons cross and exit the rear side of the boron target

We can reproduce proton spectra after 200 µm and 2 mm and so we know the injected proton spectra

➞ we can now calculate α-particle production

High energy α-particles, up to 20 MeV, are produced at the target rear side.



The high energy of α-particles is due to a kinetic energy transfer from incident protons. These energies can be confirmed analytically through energy and momentum conservation equations

α-particle energies are higher at the rear side for 200 µm and comparable for the 2mm due to energy losses by protons

For the 200 µm (2 mm) target, for one proton, 7.3 10^{-6} (2.4 10^{-7}) α-particle exit the rear side
➞below the Thomson Parabola threshold

Given 10^{14} incident protons, only ~7 10^8 α-particles exit from the 200µm target

The direct comparison between CR-39 and simulations is rather good

experiment . α-particle counts /sr on CR39

CR position	138° / 48.3 cm	
energy range	5. - 7. MeV	8.1 - 9.9 MeV
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simulation α-particle counts /sr in simulations

CR position	front side	
energy range	5. - 7. MeV	8. - 10. MeV
B 2 mm	3.7×10^8	3.3×10^7
NB 0.2 mm	1.5×10^8	7.8×10^6
CR position	rear side	
energy range	5. - 7. MeV	8. - 10. MeV
B 2 mm	5.4×10^6	4.9×10^6
NB 0.2 mm	1.5×10^8	9.5×10^7

Differences may be explained by different assumptions like 2D PIC simulation, nuclear cross section accuracy, number of incident proton because the low-energy part of the spectrum is not measured (a 5 MeV proton cannot cross 200 μm of boron) …

Summary

A bright and energetic proton source has been used to produce, at the front side and also rear side of a boron target, energetic α-particle sources

In the pitcher-catcher scheme, the catcher acts as a filter, removing ion species: cleaner α source

Simulation chain reproduces pretty well the mechanisms of α-particle production and transport

The 200 μm boron target generates the best results but the thickness could be better adapted to the proton spectrum and proton energy lost.

The direct irradiation scheme is the next challenge:

- how do we separate processes to use different codes?
- how do we implement the nuclear cross sections in the PIC code (in progress w/ p-B^{11})?
- how do we infer/measure proton spectrum?