α particle sources production through proton-boron nuclear reactions initiated by UHI lasers

SMILEI and FLUKA Simulations

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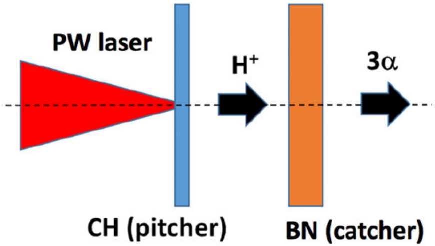
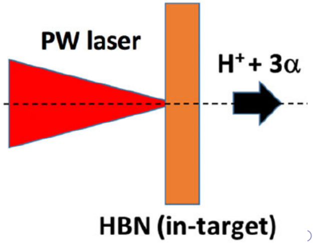
Introduction and Context

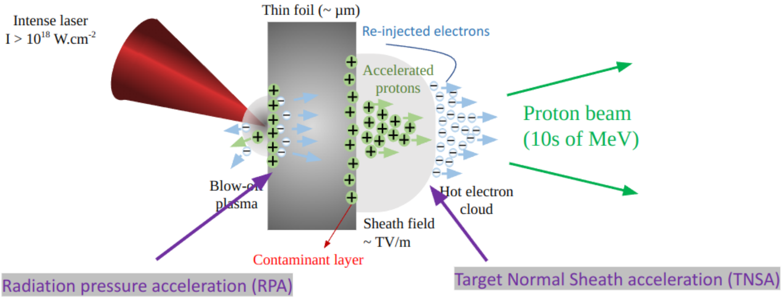
Objective: Production of secondary α particle sources by means of intense lasers (UHI)
- 2 experimental campaigns have taken place on the VEGA-III laser (November 2022 and March 2023) $\Longrightarrow$ Comparison of experimental results with numerical simulations (PIC: SMILEI and MONTE-CARLO: FLUKA) to better understand the underlying processes.
- Two schemes have been studied: Pitcher-Catcher with TNSA protons reacting on a secondary Boron or Boron Nitride (BN) target and Direct Irradiation with HB ions reacting inside one hydrogenated-Boron target





Ion acceleration by UHI lasers ($> 10^{18}$W.cm^{-2}) Hole-Boring (HB) and Target normal sheath acceleration (TNSA)

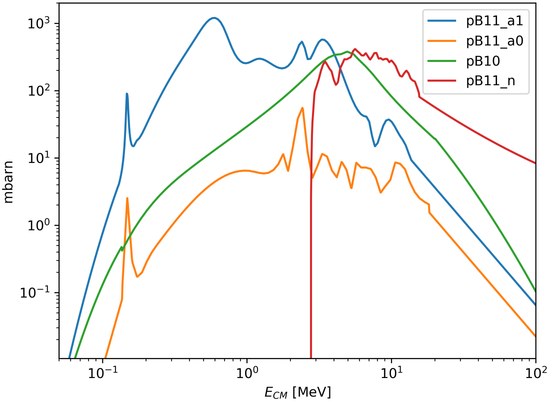
HB -> Radiation pressure of the laser that will push the electrons and ions



TNSA -> electrostatic sheath field due to electrons being moved by the laser-solid interaction will accelerate protons up to 10s of MeV

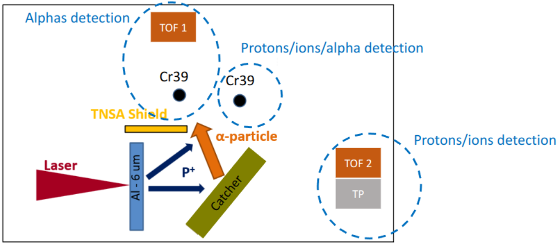
figure : courtesy of M.Huault

Proton-Boron reactions and interests for laser-plasma interaction

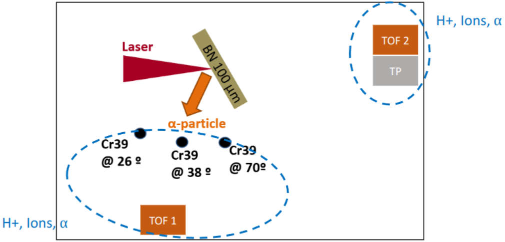


- $\sigma > 1$ barn at $E_p = 675$ keV
- no neutrons for $E_p < 3$ MeV
- ^{10}B is 20% of natural Boron and also yields α particles by reaction p-^{10}B, for experiments $\Longrightarrow$ ^7Be, ^{11}C isotopes easily detectable

CLPU campaigns for alpha particle generations using both ion acceleration mechanisms



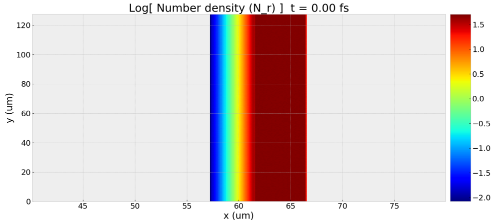
⟹ Pitcher-catcher scheme with 1 cm shielding



⟹ Direct irradiation scheme

See talks "new results 1" this afternoon at 14h.

Laser and target parameters for 2D PIC simulations



E_L	7 J (25% of 28 J)
λ	0.8 μm
I_L	$2.1 \times 10^{19} W.cm^{-2}$
τ_L	200 fs
L_{target}	5 μm
ℓ_{pp}	0.1 μm (0.5 here)
n_e	50 n_c

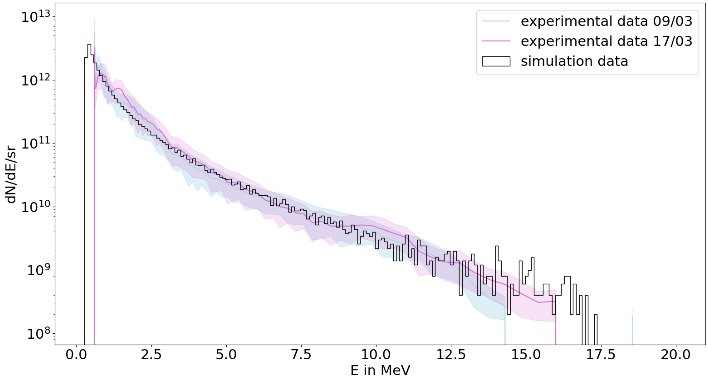
2D PIC simulations using the SMILEI[1] collaborative code

Target: ionised Al 5 μm + pre-plasma caracterised by an exponential slope, with Hydrogen as contaminants at the rear side over 100 nm thickness.
$\Longrightarrow$ Difficulty of modelling the pre-plasma due to high-contrast and no experimental measurements done

[1] J. Derouillat et al. (2018). "Smilei : A collaborative, open-source, multi-purpose particle-in-cell code for plasma simulation". In: *Computer Physics Communications*. DOI: https://doi.org/10.1016/j.cpc.2017.09.024

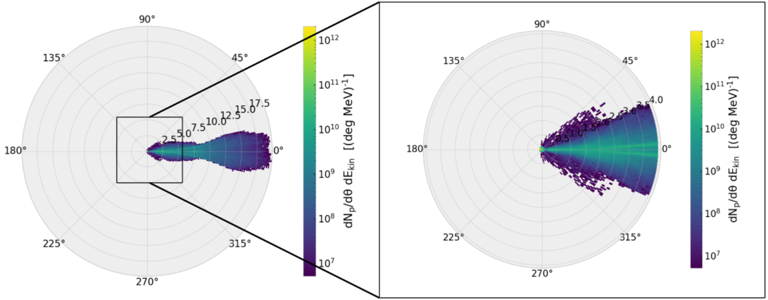
TNSA protons spectrum : PIC simulations and experimental spectra from Thomson Parabola on the rear side

$N_p^{sim} = 2.0 \times 10^{12}$ protons/sr, $N_p^{exp} = 1.4 \times 10^{12}$ protons/sr



$E_{p,simu}^{max} = 17$MeV -> Spectrum used as input in FLUKA simulations
$E_{p,exp}^{max} \approx 18$MeV during the 2022 campaign and $E_{p,exp}^{max} = 15 - 16$MeV during March 2023 campaign with scaling laws giving $E_p^{max} \approx 15$MeV

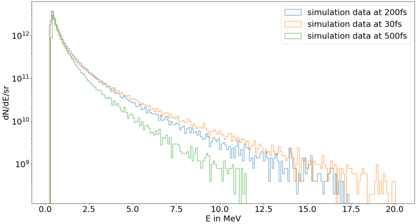
Angular distribution of TNSA protons, zoom at lower energy to show contributions at high angles



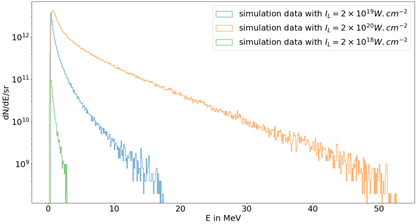
- Leftside, full angular proton distribution not integrated in time, rightside, zoom on the low energy part (4 MeV), high number of particles even at high angles : 45° but energy quite low (1-2 MeV), problematic of saturation of detectors in the chamber -> use of shielding.

Parametric studies to possibly explain shot variations $\Longrightarrow \mathrm{I_L}, \ell_g, \tau_L$

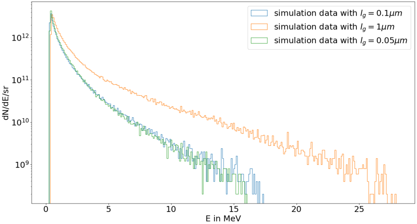
Pulse duration variation τ_L



Energy variation $\mathrm{I_L} \propto \mathrm{E_L}$



Pre-plasma variation ℓ_g

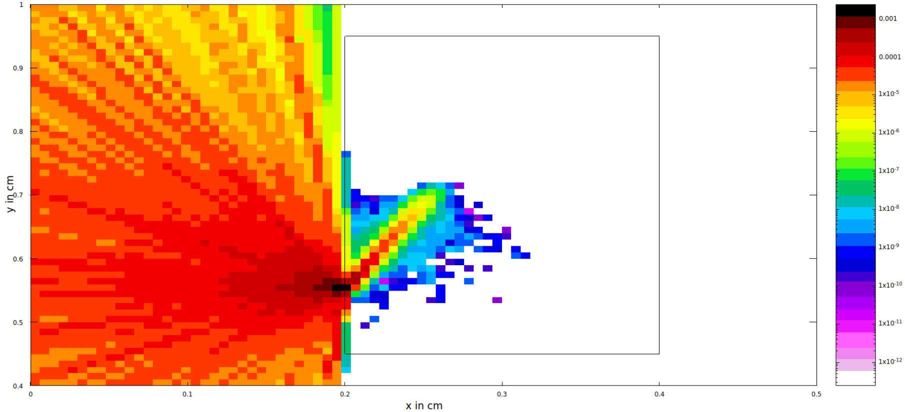


- For τ_L and ℓ_g we obtained the most stable results both numerically and experimentally for the base parameters
- Higher number at lower proton energy needs more intense beams for a given $\tau_L \longrightarrow \nearrow \mathrm{E_L}$ and/or $\searrow \Phi_L$

FLUKA simulation for proton-boron reaction, trajectory of alpha particles inside the target and at the front face

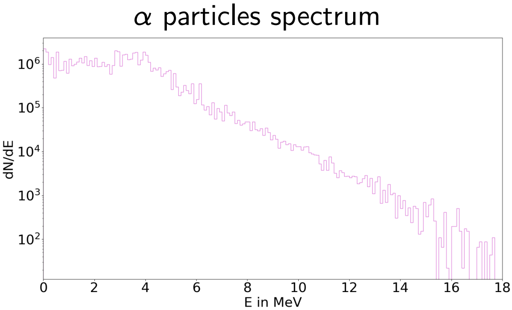
Boron nitride target 2 mm thick with a proton incident angle of $\approx 70°$
$\Longrightarrow$ 5 MeV α particles travels 20 μm of solid Boron

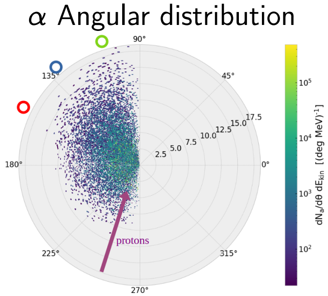
Normalised density of α particles in the simulation after interaction



Alpha particles spectrum, angular distribution and number per steradian at different detector angles

Irradiation of TNSA proton beam on a 2 mm BN target



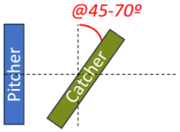


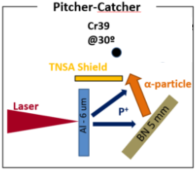
$\Theta_{detector}$ \ N/sr	sim
30°	3.1 10^7
54°	2.7 10^7
77°	1.5 10^7

$\Longrightarrow$ For a high incident angle, angular distribution less isotropic due to kinetic energy transfer by accelerated protons

Study of incidence proton beam angle influence on alpha particle production and differences between Boron and Boron Nitride targets

	N/sr at 30°	
@	BN	B
15°	$8.7\ 10^6$	$2.6\ 10^7$
45°	$1.5\ 10^7$	$3.9\ 10^7$
70°	$3.1\ 10^7$	$7.4\ 10^7$





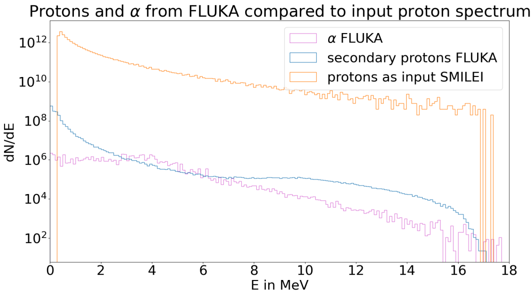
$\Longrightarrow$ Dependence in angles $\approx$ 3 times more for 70° than 15°

$\Longrightarrow$ Difference between B and BN as catcher due to density difference

Comparison with experimental CR39 data :

N/sr at 30°	BN at 70°	B at 45°
simulation > 2,8 MeV (=10μm Al filter)	$6\ 10^6$	$1\ 10^7$
experimental > 2,8 MeV (=10μm Al filter)	$4\ 10^6$	$2.5\ 10^6$

Lists of particles counted as output from FLUKA code



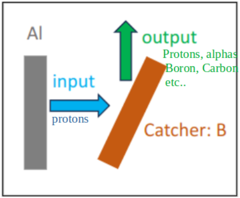
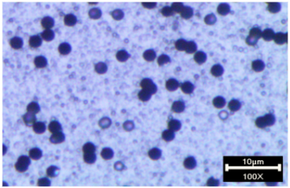


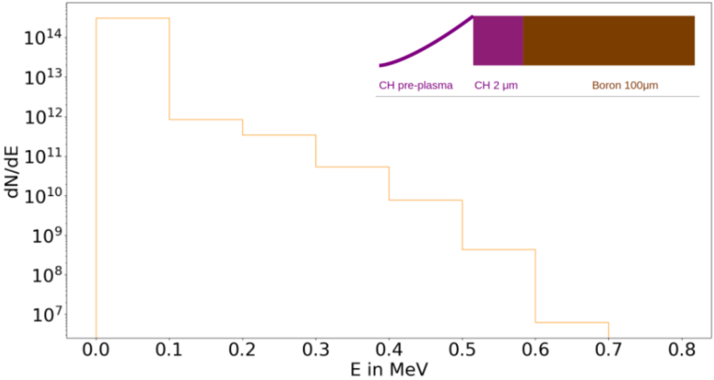
Image of CR39 with many species



- α emitted / protons input: $\approx 10^{-5}$
- secondary protons from catcher / protons input: $\approx 10^{-5} - 10^{-4}$
- Carbon from catcher / Carbon input: $\approx 10^{-6}$
- Boron from catcher / protons or Carbon input: $\approx 10^{-7}$
- Same number of Nitrogen and Boron ejected from catcher for BN

Proton spectrum for the Hole-Boring mechanism on a thick $100\mu m$ Boron target coated with $2\mu m$ CH layer

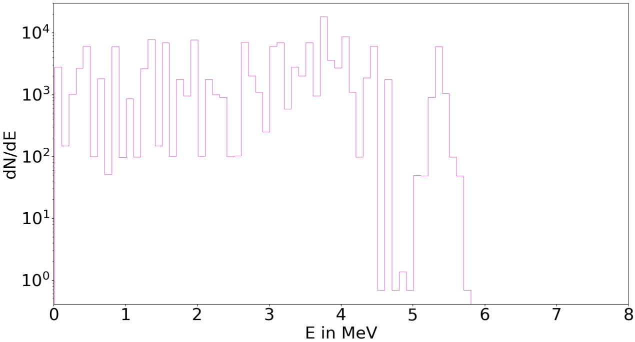
Preliminary results: $N_p^{sim} = 1.0 \times 10^{13}$ protons/sr



$\Longrightarrow$ High number of particles but mainly at low energy (lower than the cross section in the code as seen earlier) which will then give a low number of alpha particles

Preliminary results for hole-boring α particles with direct irradiation scheme, and comparison with experimental data

$N_\alpha^{sim} \approx 1.0 \times 10^5 \alpha/sr$, $N_\alpha^{exp} \approx 1.0 \times 10^6 \alpha/sr$ after 10 μm Al filter



As discussed earlier, low number of α particles (more than ten times less than experimentally) because low energy and low number of protons (with the biggest proton contribution below the threshold of cross section of the FLUKA code)

Conclusions and perspectives

- We obtained good agreement between simulation and experiment for proton acceleration in the TNSA scheme
- Amount of α particles between experiments and simulations are in fair agreement for the pitcher-catcher configuration
- Hole-Boring simulations need to be improved to be compared to experiments
- Implementation of the needed nuclear physics in SMILEI to limit issues due to code chaining, is in progress

Acknowledgments

- GDR APPEL for financial support in going to the SMILEI workshop
- GENCI project number 12889 for computational time on the TGCC
- GPR LIGHT and Région Nouvelle Aquitaine for PhD funding
- ED SPI / University of Bordeaux for general funding
- This contribution is based upon work from COST Action CA21128-PROBONO "PROton BOron Nuclear fusion: from energy production to medical applicatiOns", supported by COST (European Cooperation in Science and Technology - www.cost.eu)

FLUKA Cross sections, version 2021.2.8

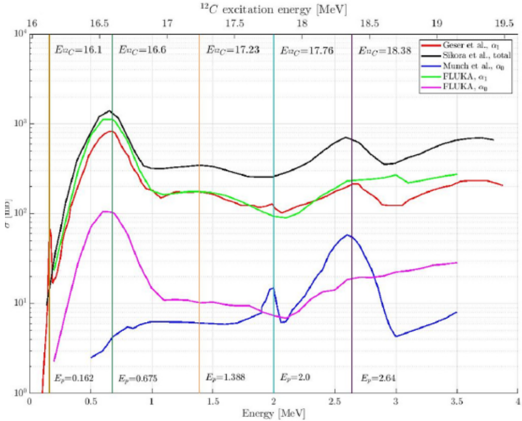
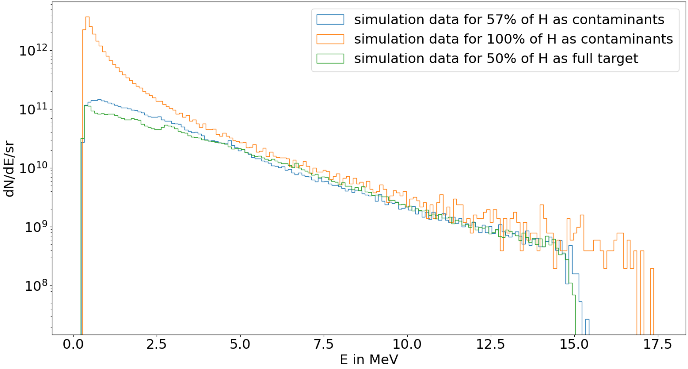


Figure from D. Mazzucconi et al. (2023). "Proton boron fusion reaction: A novel experimental strategy for cross section investigation". In: *Radiation Physics and Chemistry* 204

Issues of accurately modelling the contaminants layer of an Al target and comparison to CH target for proton spectrum

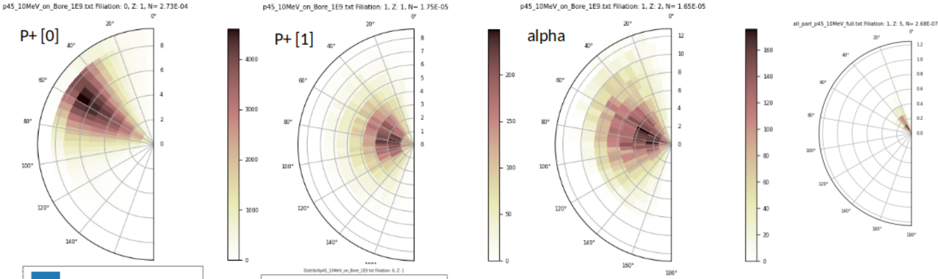


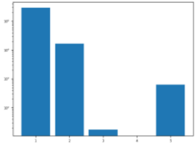
$\Longrightarrow$ O,C,H contaminants modelling fail to reproduce low energy spectrum

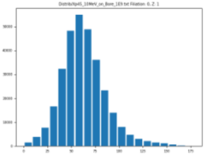
$\Longrightarrow$ Using only H atoms is much closer to experimental reality

$\Longrightarrow$ CH mix (50%-50%) gives similar results as the first case

Geant4. Protons 10MeV, 45°, 1E9 particules sur Bore (densité 2.37)

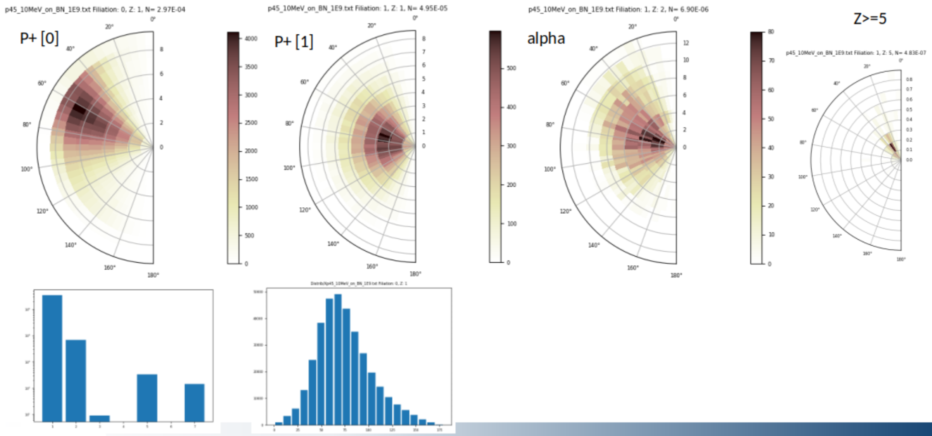






Distribution p+ (filiation 0 et 1)

Geant4. Protons 10MeV, 45°, 1E9 particules sur BN (densité 2.25)



Distribution p+ (filiation 0 et 1)

CELIA

Collaborations

Many people have been involved in the two experiments and have talks at this workshop, later today:

- Fabrizio Consoli at 11:50: *"Advanced Time-of-Flight detection methodologies for fast real-time ion diagnostics in laser-triggered proton-boron experiments"*
- Massimiliano Sciscio at 14:00: *"Laser-Initiated 11B(p,α)2α fusion reactions in petawatt-scale, high-repetition-rate laser facilities"*
- Marine Huault at 14:20: *"Laser-driven proton-boron reaction for alpha particles production"*
- Aldo Bonasera at 14:40: *"Radioisotopes production using lasers: from basic science to applications"*
- Katarzyna Batani at 15:00: *"Generation of radioisotopes using high-repetition, high-intensity lasers"*
- Howel Larreur poster session at 15:40: *"Optimisation of catcher target thickness in laser-driven proton-boron fusion experiments"*