Proton and alpha stopping power in laser-generated plasma: a systematic study proposed within the FUSION project

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INFN and University of Florence

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Physics case

Proton-Boron fusion in laser-generated plasma

$$\boxed{\mathrm{p}+{}^{11}\mathrm{B}\longrightarrow 3\alpha + 8.7\mathrm{MeV}}$$

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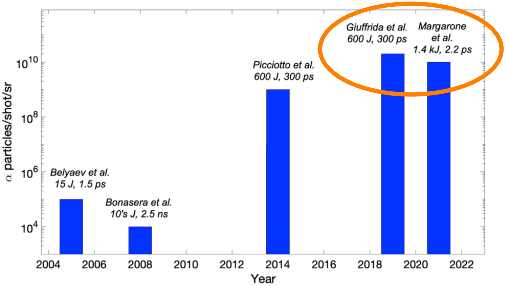
  $\longrightarrow$ significant progressive increase in the reaction yields (reaching α fluxes up to $\sim 10^{10}$ particles/sr per shot)



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  $\longrightarrow$ significant progressive increase in the reaction yields (reaching α fluxes up to $\sim 10^{10}$ particles/sr per shot)
- R&D needed to maximise the reaction rate (e.g. target development...)
- At present, an extensive systematic investigation of laser-based $p^{11}B$ fusion is still missing
  $\longrightarrow$ necessary for a deeper understanding of the physics at the basis of the reaction in plasma

The FUSION project

Objectives of the project

The FUSION project

FUsion StudIes of prOton boron Neutronless reaction in laser-generated plasma

Presented to the CSN5 of INFN, 10 INFN sections involved, in collaboration with ELI-Beamlines (CZ), HILASE (CZ), Physic Institute of Czech Academy of Science (CZ)

National responsibles: G.A.P. Cirrone (INFN-LNS), F. Consoli (ENEA)

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- optimisation of the setup to maximise the $p^{11}B$ reaction rate in plasma, developing new-generation solid targets, exploiting different laser systems
- development of innovative diagnostic systems for plasma and radiation
- simulation and modelling of the phenomena at the basis of the reaction

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- simulation and modelling of the phenomena at the basis of the reaction
- characterisation of proton and alpha stopping power in plasma

Stopping power of ions in plasma

Why experimental data are needed

An accurate modelling of the stopping power of ions in plasma is needed for many applications:

- Fusion power research:
  - α-heating mechanism for Inertial Confinement Fusion
  - ion-driven fast ignition scheme
- Accelerator physics (e.g. plasma strippers)
- Plasma diagnostics exploiting ions
- Study of astrophysical phenomena (e.g. stellar energy transport)
- High-energy-density physics (HEDP) investigations

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Low-energy regime: $v_p \approx v_{th}^e$, around the Bragg peak

- strong projectile-plasma electron coupling: a detailed treatment of close collisions leads to a sensibly different energy loss
- sparse database, generally with uncertainties on plasma temperature

Stopping power of ions in plasma

An intuition within the SSM

In a Standard Stopping Model approach:

$$-\frac{dE}{dx} = \frac{4\pi e^4 Z_{eff}^2}{m_e v_p^2}\left[\underbrace{n_{be} \ln\left(\frac{2m_e v_p^2}{\bar{I}}\right)}_{\text{bound } e^-} + \underbrace{n_{fe} G\left(\frac{v_p}{v_{th}^e}\right) \ln\left(\frac{2m_e v_p^2}{\hbar\omega_{pe}}\right)}_{\text{free } e^-} \right]$$

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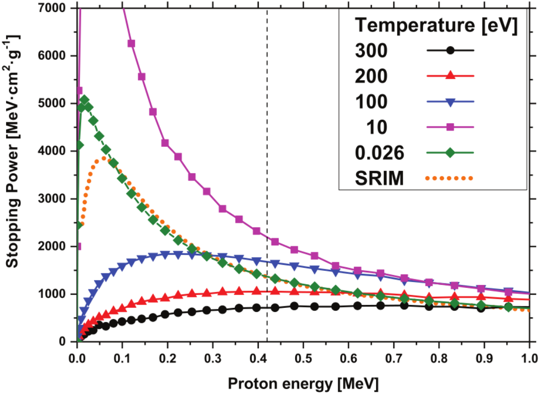
- At higher temperatures $v_p/v_{th}^e < 1 \Rightarrow G(v_p/v_{th}^e)$ decreases

Stopping power of ions in plasma

Effect of plasma temperature and density

For increasing temperature, $\frac{dE}{dx}$ decreases → regions of reduced stopping power (recently observed)



L. González-Gallego *et al.*, Phys. Plasma 28, 043103 (2021)
S.N. Chen *et al.*, Nat. Sci. Rep. 8, 14586 (2018)

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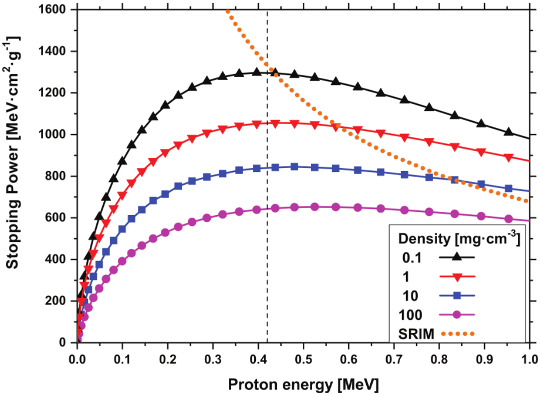
For increasing temperature, $\frac{dE}{dx}$ decreases $\rightarrow$ regions of reduced stopping power (recently observed)

Also the free e^- density affects $\frac{dE}{dx}$, that decreases with increasing density.

$\rightarrow$ Enhanced/reduced stopping power intervals are shifted.



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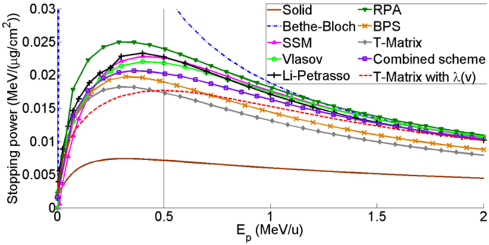
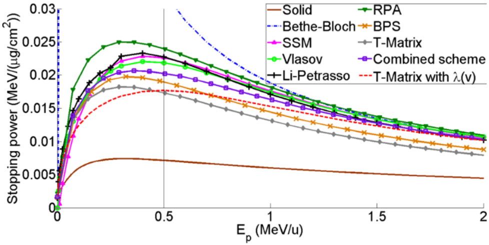
Stopping power of ions in plasma
Stopping power models



Assuming different models can drastically change the stopping power, particularly in the Bragg peak region.

→ W. Cayzac *et al.*, Phys. Rev. E 92, 053109 (2015)



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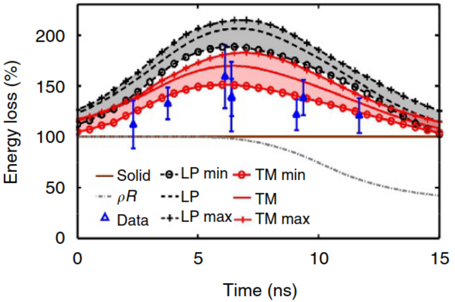
Energy loss calculated assuming stopping models, Z_{eff} models and plasma condition simulations, e.g.:
W. Cayzac *et al.*, Nat. Comm. 8, 15693 (2017) ←

- shaded bands → uncertainties in free e^- density and temperature
- experimental data disprove some stopping models



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- Proton and α-particle energy loss in plasma is of great interest:
  - for protons, Z_{eff} is essentially 1 → stopping power model selection
  - for p+B fusion development, stopping power for low-energy protons (main resonance at ~600 keV) is important
  - α-particle stopping power modelling is directly relevant for ICF (M. Temporal *et al.*, Eur. Phys. J. D 71, 132 (2017))

FUSION: energy loss of ions in plasma

Proposed setup

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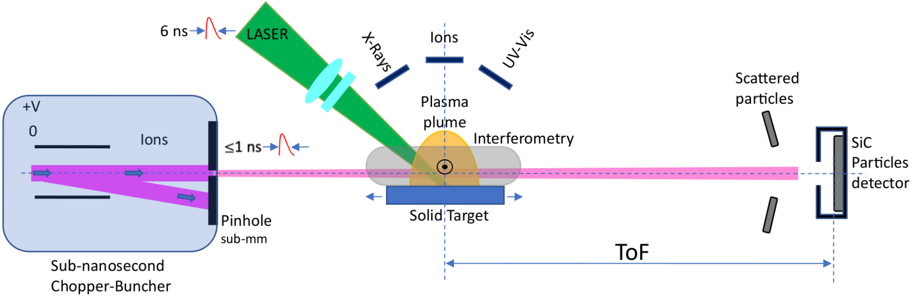
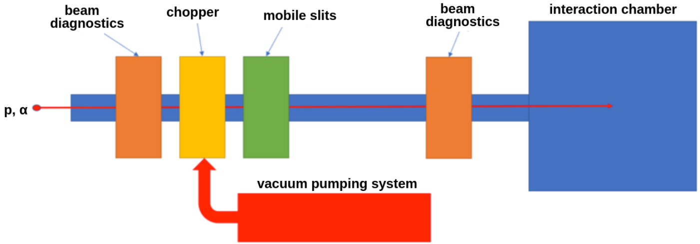


The proposed setup exploits 0.5-3 MeV proton and α bunched microbeams delivered by conventional accelerators, crossing a plasma plume generated under vacuum by a laser beam interacting with a solid target.

FUSION: energy loss of ions in plasma

Beam chopper system

Low-energy proton and α beams provided by Singletron electrostatic accelerator (Physics Dept., Catania University).



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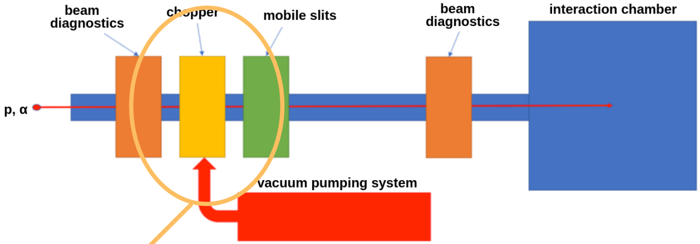
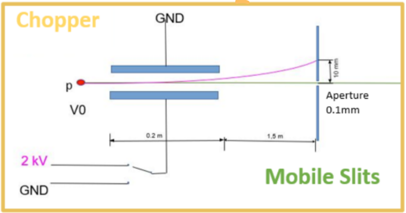




Chopper-buncher system

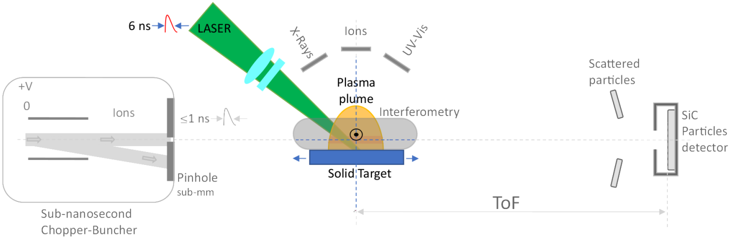
→ pulsed beam (sub-ns bunches)

Electrostatic deflector (two metallic plates with fast-switching voltage) + adjustable slits

the deflector bends transversely the beam → small number of ions passing through the slits for a short Δt (< plasma evolution scale)

FUSION: energy loss of ions in plasma

Laser and target



- Different laser system with respect to the other FUSION activities:

Energy	**Pulse duration**	**High repetition rate**
2 J per pulse	6 ns	10 Hz

Laser light focused to reach power densities $\sim 10^{12-13}$ W/cm^2

- Thick targets ~mm (e.g. boron nitride BN)

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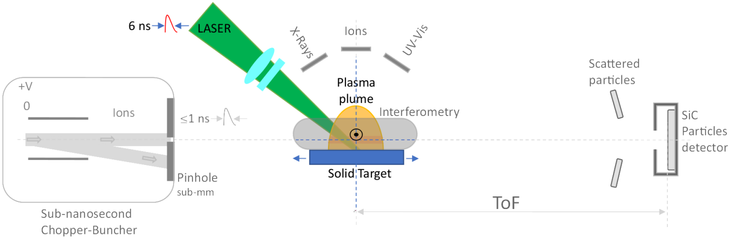

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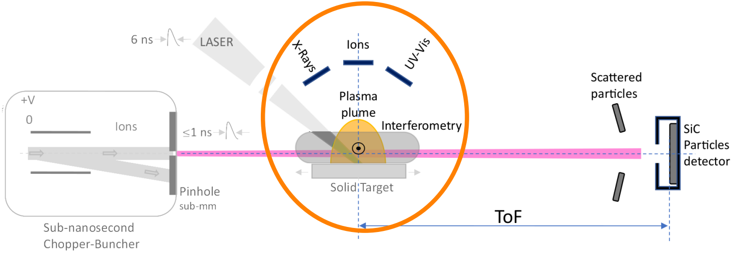
- Smart 3-axis micrometric target movimentation for both optimal focusing and repetition mode operation



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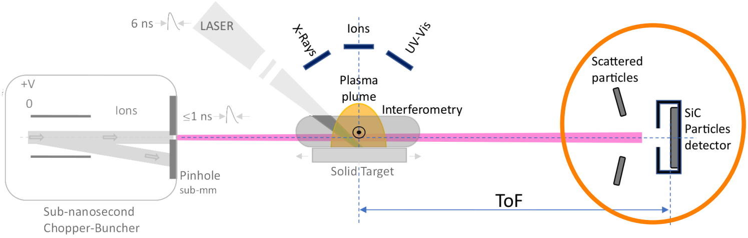
- Plasma parameters (i.e. temperature and density) extracted after the initial expansion via a dedicated diagnostic system (i.e. X-ray spectrometers and optical interferometers)



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Energy loss measurements:

- ToF measurements using SiC detectors (insensitive to visible light)

DAQ and synchronisation

- Data acquisition system for detectors and diagnostics based on fast digitizing boards.
- Global Timing and Synchronization system based on CAEN V1495 programmable logic driving all the devices during measurement
  - Trigger logic management
- Remote control of DAQ and trigger parameters, bias voltages etc.

Plasma temperature and density	**Ion** energy loss

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Plasma temperature and density	⟷	**Ion** energy loss

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- Stopping power in plasma deduced by comparing the energy loss information to the simulations

Conclusions

Looking forward...

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