Theoretical and numerical investigation of ion acceleration in the interaction of high energy and high intensity attosecond pulses with solid targets

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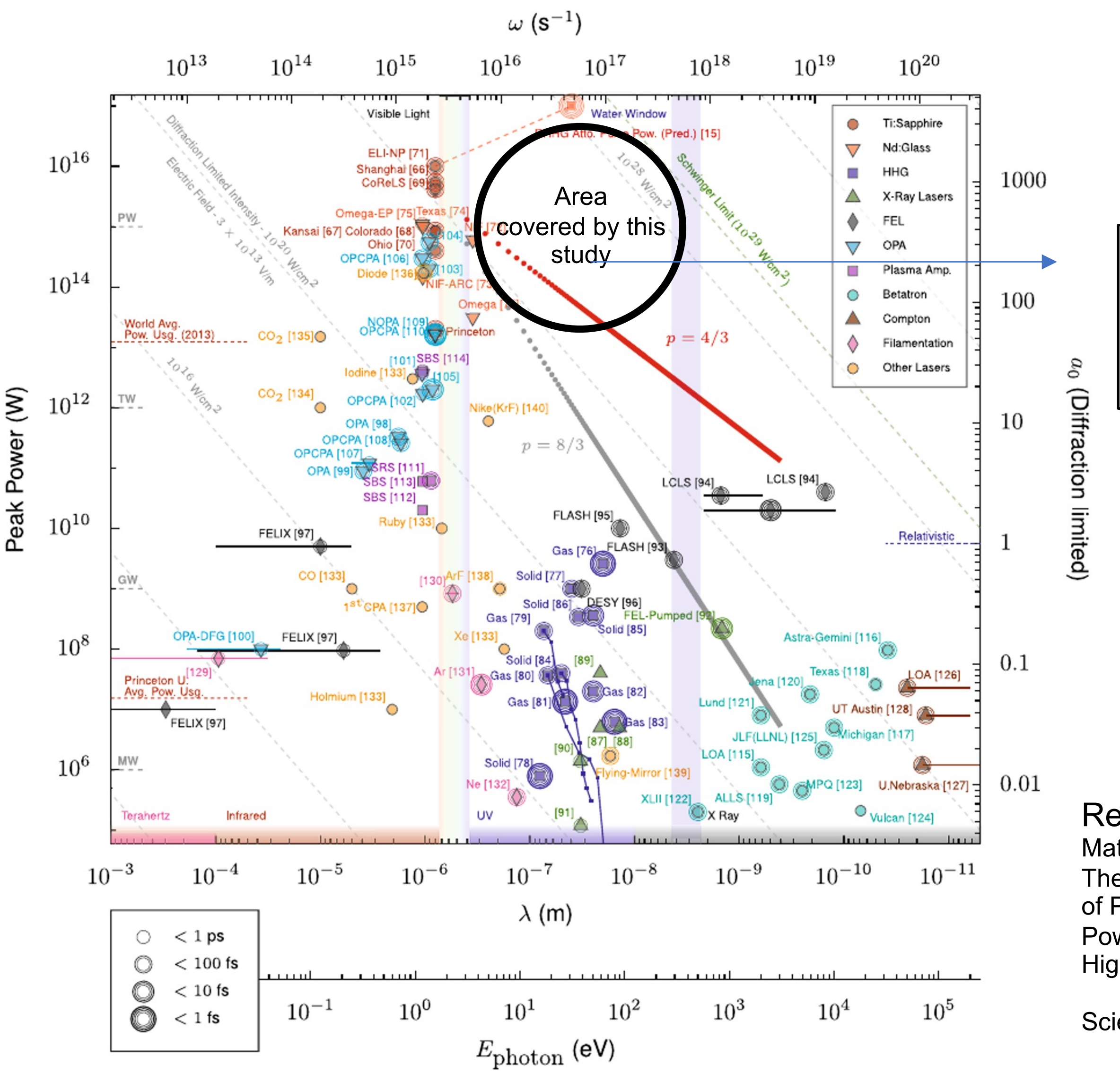
Outline

- Context and motivations: high energy attosecond pulses
- Particle-In-Cell simulations of the interaction of a high energy attosecond pulse with a solid proton-Boron target
- Optimization of longitudinal proton acceleration
- Application to proton-Boron fusion
- Conclusions and perspectives

Context



Energetic attosecond pulses : λ=1-100 nm, E_l=0.1-10 J

Ref.:
Matthew R. Edwards & Julia M. Mikhailova, The X-Ray Emission Effectiveness of Plasma Mirrors: Reexamining Power-Law Scaling for Relativistic High-Order Harmonic Generation

Scientific Reports, 10:5154 (2020)

Extreme compression of high power laser pulses to X-rays

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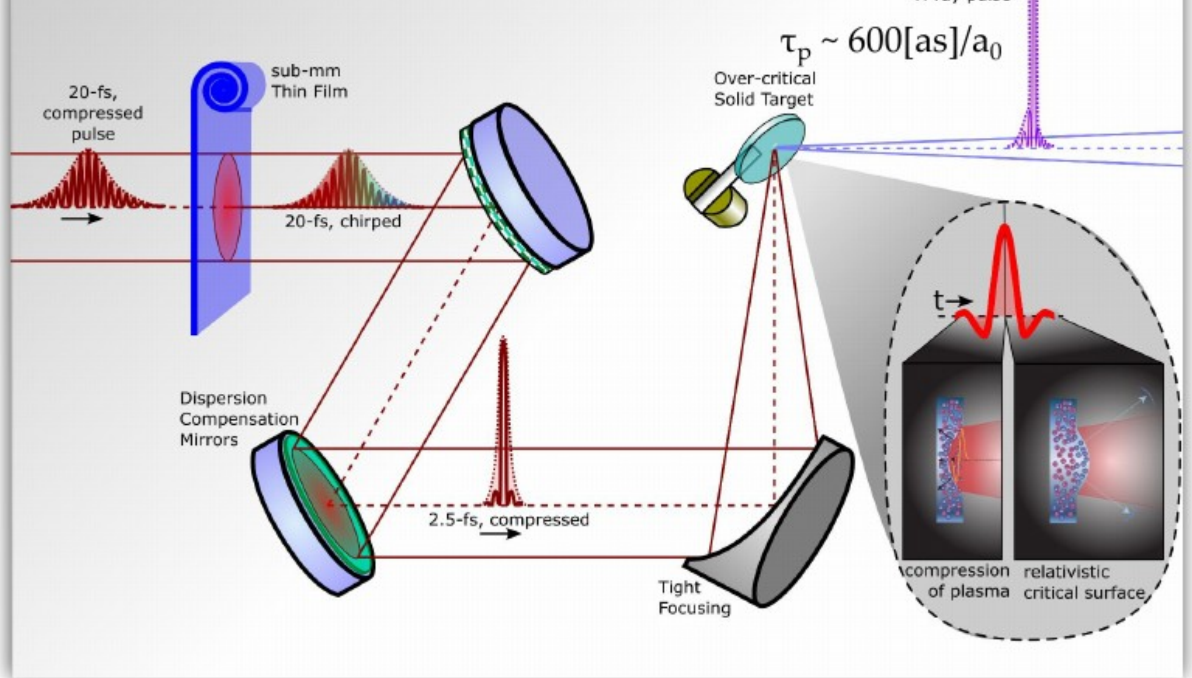
NIR laser



Courtesy of J. Wheeler

N. M. Naumova, et al., Phys. Rev. Lett. 92, 063902-1 (2004).

Single of few-cycle attosecond pulse with $I>10^{25}$ W/cm^2

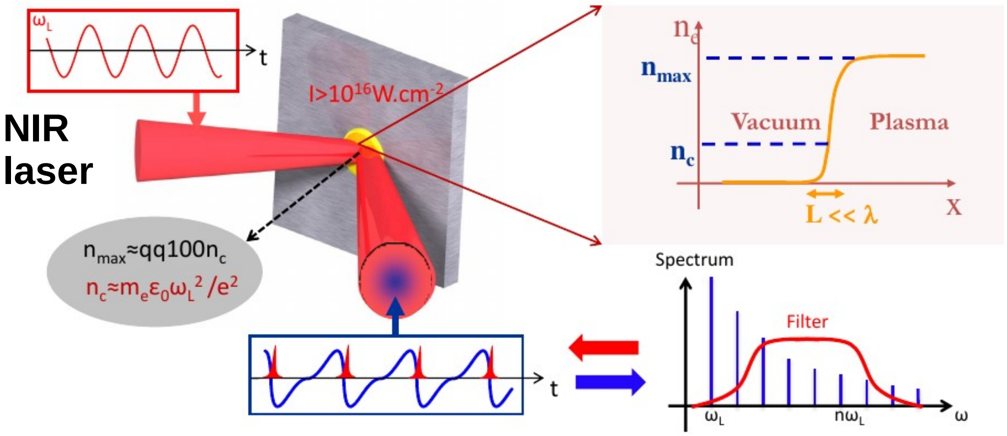
Plasma mirror efficiency for 2.5 to 5 fs NIR (10^{22} W/cm^2) pulse: between 45 and 55%

High repetition rate => kHz
Joule energy level
=> Small laser facility

Preliminary experiments on the first stage at INRS with the team of J.C. Kieffer

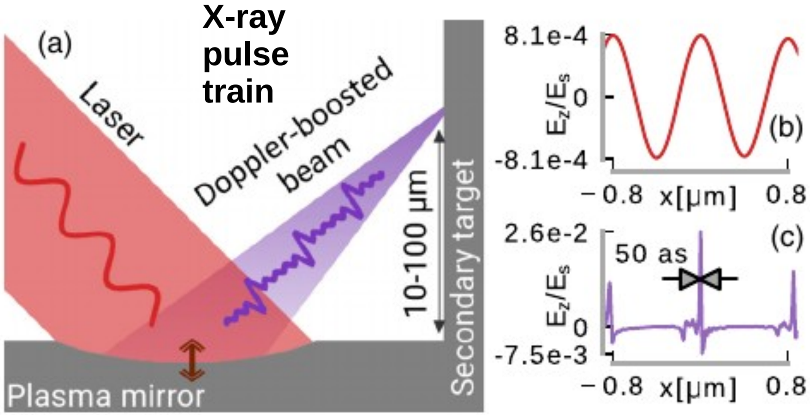
High harmonic generation on plasma mirrors

Vincenti H. ELISS Conf. 2016



Relativistic plasma mirror
Attosecond pulses generation

Fedeli L. *et al.* PRL **127**, 114801 (2021)
Vincenti H. PRL, **123**, 105001 (2019)



High intensity attosecond pulses
Produce by **focusing** relativistic plasma mirror

Attosecond pulse train

$$I > 10^{25}\mathrm{W/cm^2}$$

Plasma mirror efficiency: for 20 fs NIR pulse (10^{22} W/cm^2): 30 %
High repetion rate kHz

Attosecond pulse interaction with a Hydrogen-Bore slab

Current laser pulse parameters

$\boldsymbol{\lambda_L = 10\ \mathrm{nm}}$ $I_L = 2.71 \times 10^{26}\ \mathrm{W.cm}^{-2}$

$a_L = 140$

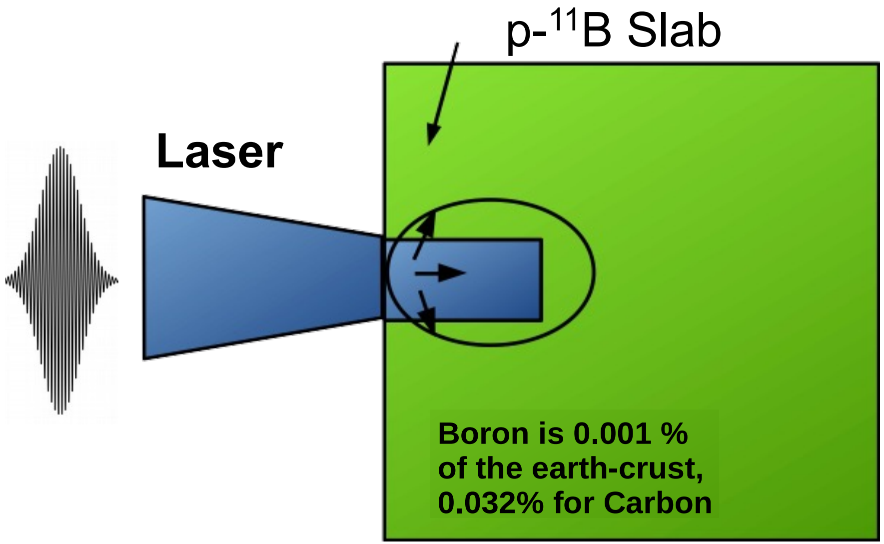
$\mathrm{FWHM}_{(\mathrm{intensity})} = 330\ \mathrm{as}$ $\mathrm{Spot} = 10\ \lambda_L$

$\mathcal{E}_L = 10\ \mathrm{J}$

H-^{11}B target   Solid HB target

$n_{e0} = 3 \times 10^{23}\ \mathrm{cm}^{-3} \simeq 0.03 n_c$

The laser energy in the pulse scales as λ

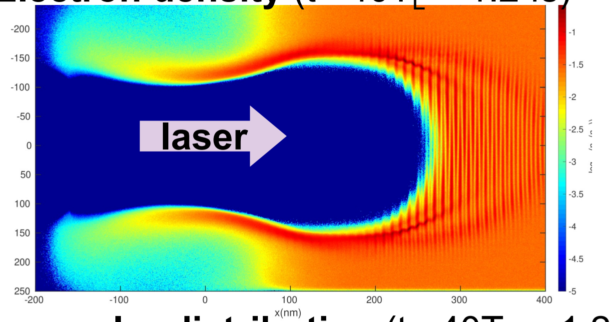


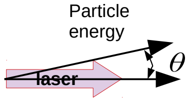
Because the attosecond pulse is in UV-X range
The solid target is transparent (sub-critical)

Attosecond pulse interaction with matter
PIC simulations

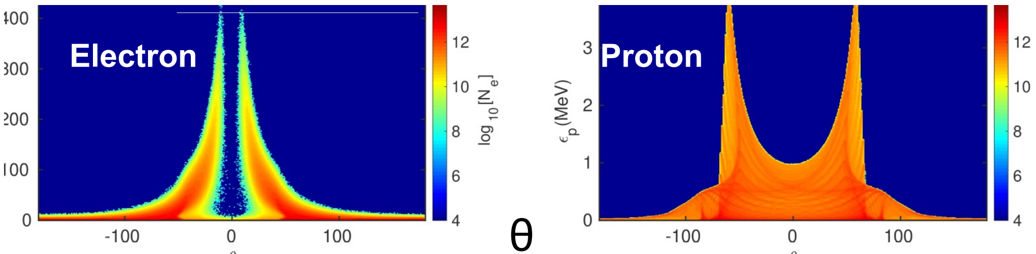
R. Capdessus

Electron density (t= $40T_L$ = 1.2 fs)

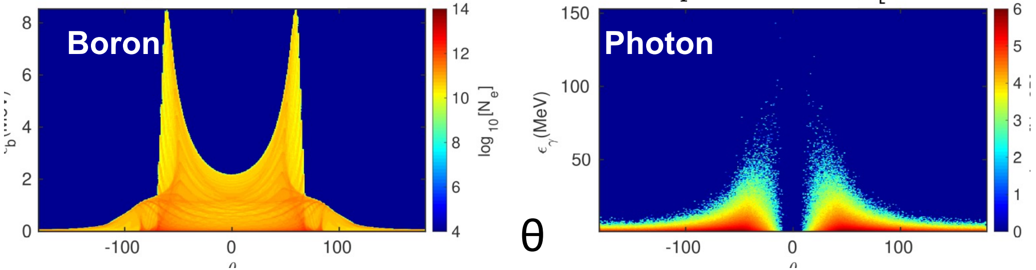




Energy angular distribution (t= $40T_L$ = 1.2 fs)



$E_{B0} = 8$ MeV $\quad E_{p0} = 3$ MeV



2D PIC Simulations with EPOCH

Current parameters

$\boldsymbol{\lambda_L} = \mathbf{10\ nm} \quad I_L = 2.71 \times 10^{26}\ \mathrm{W.cm^{-2}}$

$a_L = 140$

$\mathrm{FWHM}_{(\mathrm{intensity})} = 330$ as & $\mathrm{Spot} = 10\lambda_L$

$\mathcal{E}_L = 10$ J

Solid pB target

B & H target $n_{e0} = 3 \times 10^{23}\ \mathrm{cm^{-3}} \simeq 0.03 n_c$

- Electron are swept out of the channel
- Proton and Boron ions are accelerated mainly transversely to several MeV and also longitudinally to MeV

Preliminary model of transverse ion acceleration

For example $\mathrm{E_L} = 10\,\mathrm{J}, \lambda_0 = 10\,\mathrm{nm}\,(120\,\mathrm{eV})$

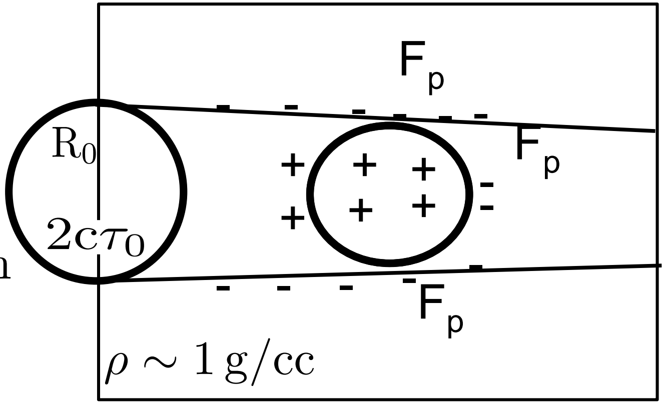
Gaussian pulse: FWHM $2\mathrm{R} = 100\,\mathrm{nm}, \tau = 333\,\mathrm{as}$

$\rho \sim 1\,\mathrm{g/cc}$ $\quad \mathrm{n_e/n_c} \sim 0.03$

The solid target is sub-critical
or we need to pre-compress the target.

$\mathrm{I_0} = 2.7 \times 10^{26}\mathrm{W/cm^2}, \mathrm{a_0} = 140$

$2c\tau_0 = 120\,\mathrm{nm}$



- **Electron acceleration by radial ponderomotive force**
- **Ion acceleration by electric field (charge separation)**

Transverse Ion acceleration*

$$\mathrm{v_{i_{max}}} \sim \frac{\mathrm{Zm_e}}{\mathrm{A}\sqrt{2}\,\mathrm{m_p}} \frac{\mathrm{c^2}\tau_0}{\mathrm{R_0}} \frac{\mathrm{a_0^2}}{\sqrt{1+\frac{\mathrm{a_0^2}}{2}}}$$

$$\mathrm{E_{ion_{max}}} = \frac{\mathrm{Am_p}}{2}\mathrm{v_{i_{max}}^2}$$

Proton $\mathrm{E_{ion_{max}}} \sim 3.1\,\mathrm{MeV}$

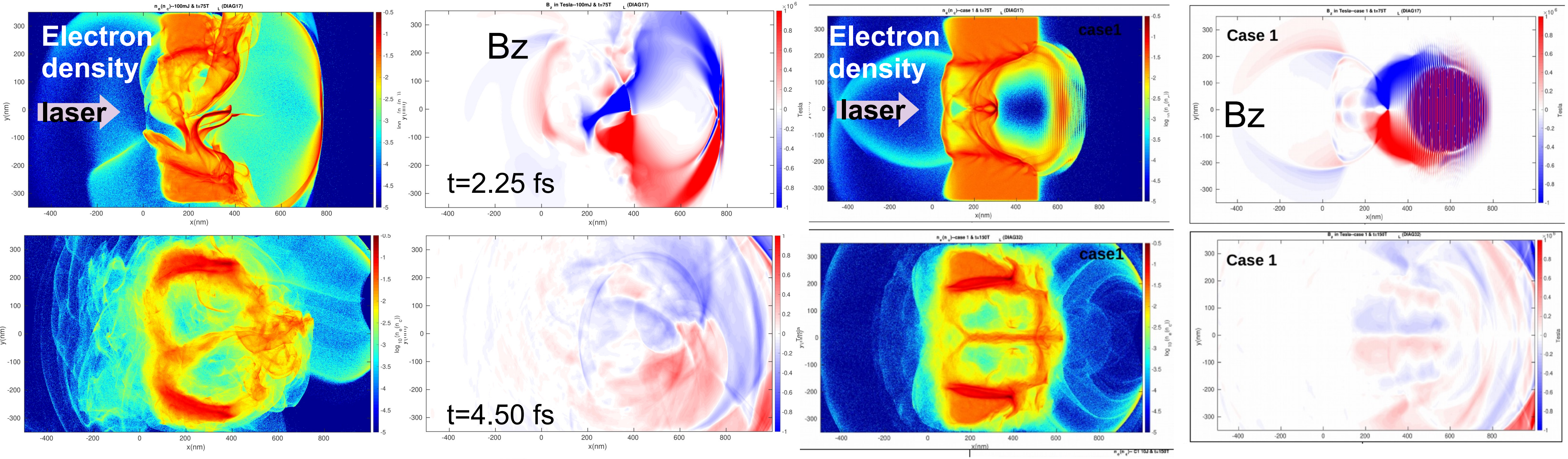
Boron $\mathrm{E_{ion_{max}}} \sim 7.1\,\mathrm{MeV}$

Model agrees with simulations

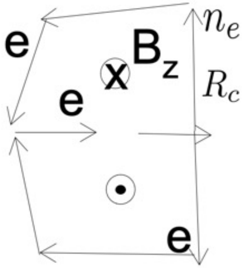
* Sarkisov G. S. et al. PRE **59**,6 (1999)

Attosecond pulse interaction with matter
Huge self-generated magnetic fields

1 optical cycle (1 J) 500 nm 10 optical cycle (10 J)



Magnetic field generation due to high electron currents along a loop



Maxwell Ampère law: $n_e \simeq 0.01\ n_c = 10^{23}\mathrm{cm}^3$

$$B_z \simeq\ 4\pi\ eR_c n_e \frac{v_e}{c} \qquad B_z \simeq 1000\ \mathrm{kT}$$

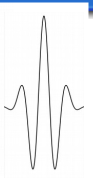
$$B_z\mathrm{simu} \simeq 1000\ \mathrm{kT}$$

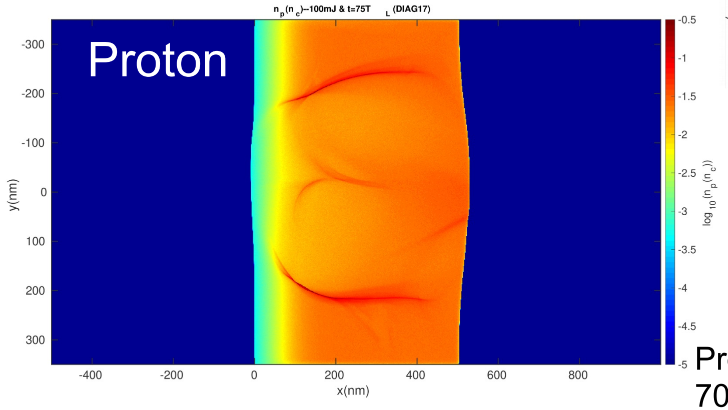
$$\frac{v_e}{c} \simeq 1 \quad R_c \simeq 200\ \mathrm{nm}$$

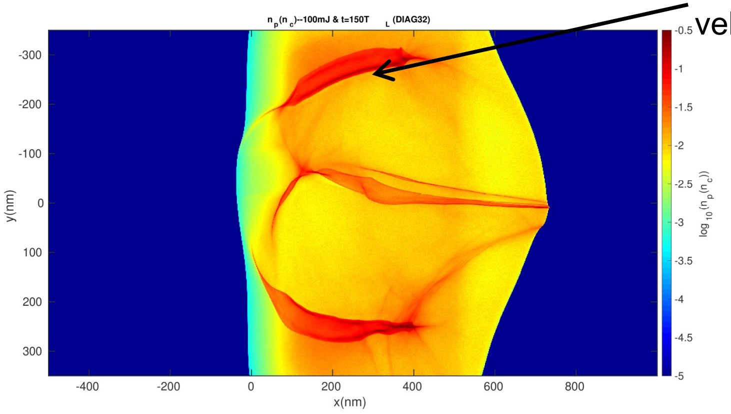
Electrons are strongly magnetized

High velocity structure ~ 0.1 c
Shock structure generation or piston ?

1 optical cycle (1J)







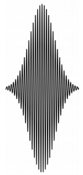
2.25 fs

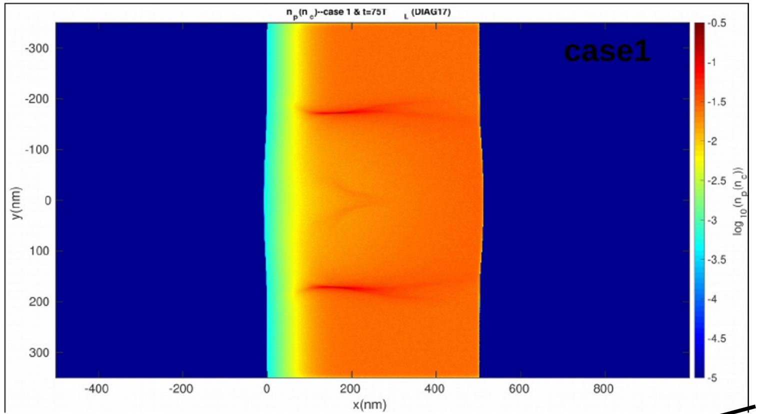
Proton front:
70 nm/2.25fs
velocity = 0.1c

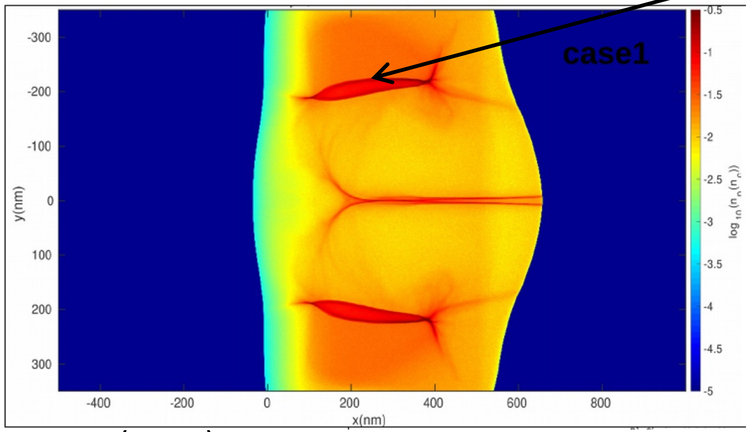
4.50 fs

Proton compressed
30 times

10 optical cycle (10J)





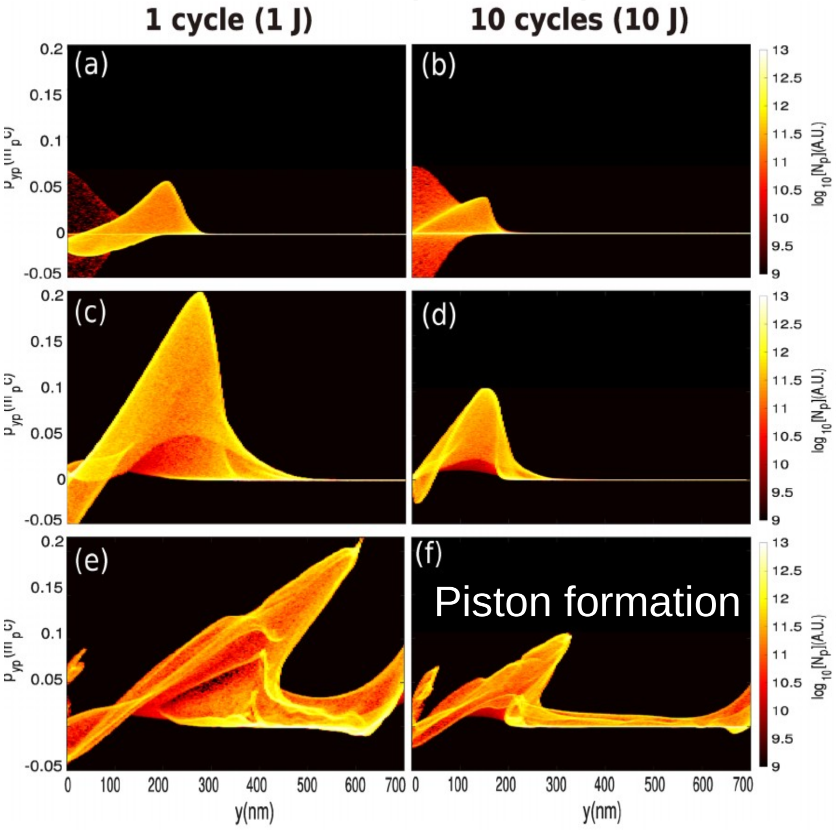


Proton front:
40 nm/2.25fs
velocity = 0.06c

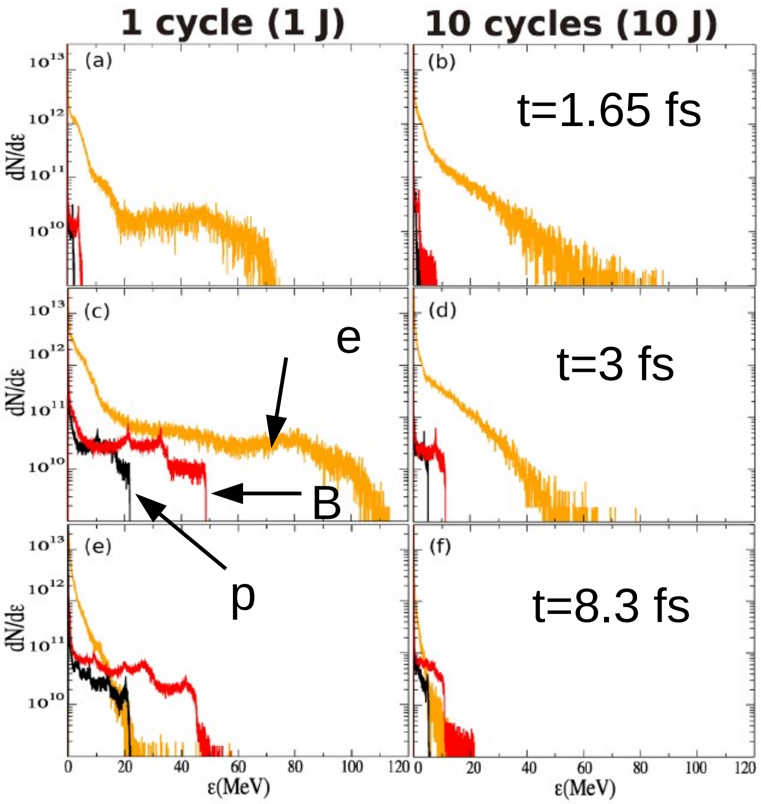
X. Ribeyre et al. Scientific Reports 12:4665 (2022)

Piston and particles spectra evolution

Transverse phase space



Energy distribution



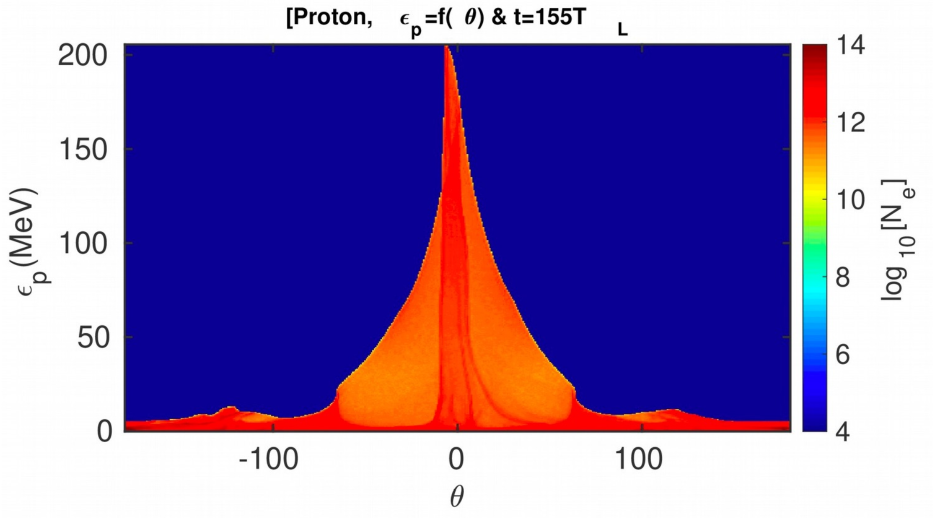
	Single-cycle	10-cycles
Laser energy	1 J	10 J
Proton	0.085%	0.0057%
Boron	0.2%	0.013%

Single cycle is
15 more effecicient

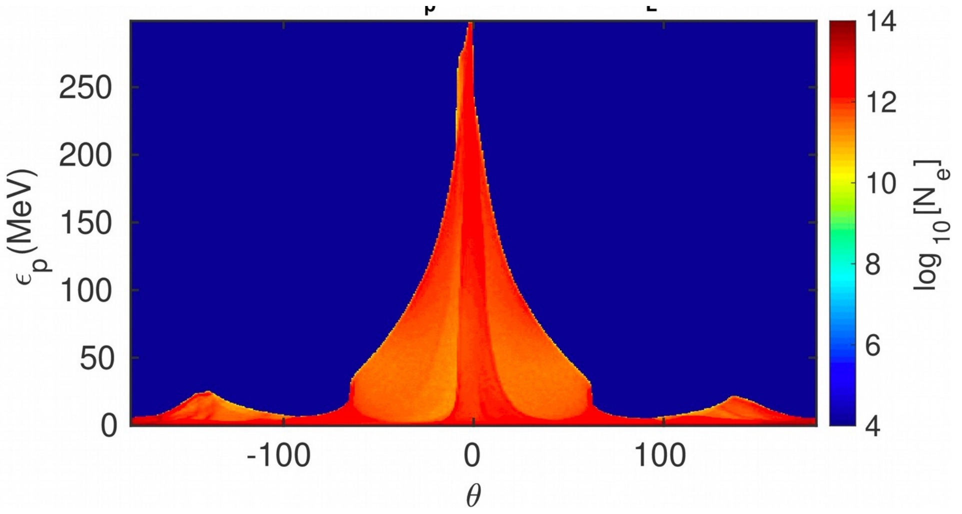
Ref. Ribeyre X. et al. Scientific Reports 12:4665 (2022)

Optimization of longitudinal proton acceleration pB target

$\lambda_L = 10$ nm $\quad a_o = 140 \quad \mathrm{FWHM}_{(\mathrm{intensity})} = 330$ as $\quad \mathrm{Spot} = 10\ \lambda_L$



Proton energy angle distribution after 4.95 fs for a 1 J single cycle case

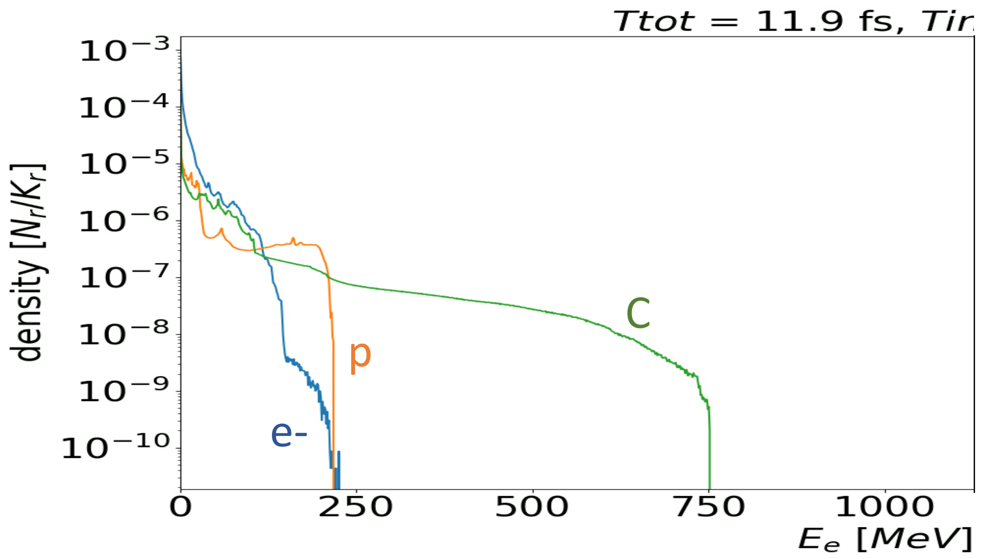


Proton energy angle distribution after 4.95 fs for a 10 J single cycle case

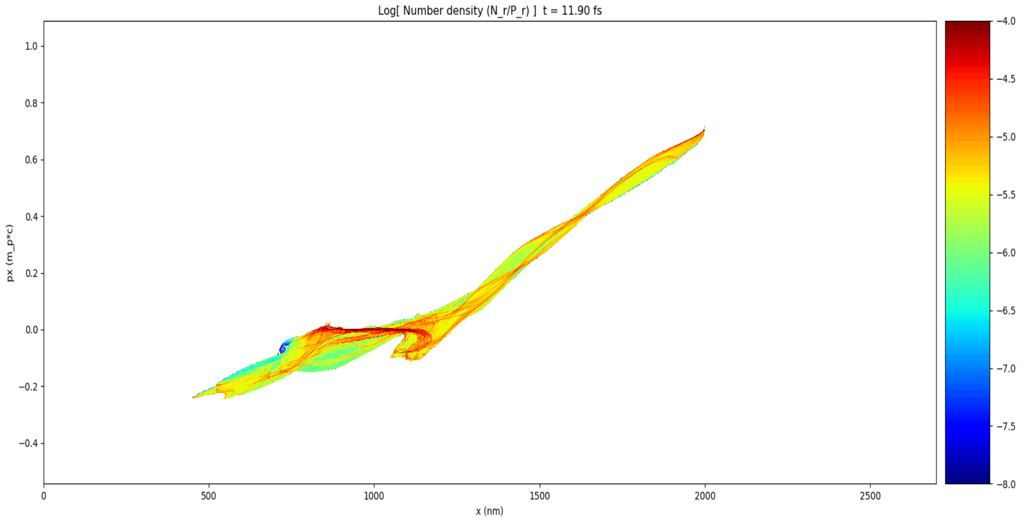
Optimization of longitudinal proton acceleration 500 nm thick CH target

F. Brun

$\lambda_L = 10$ nm $a_0 = 140$ $\mathrm{FWHM}_{(\mathrm{intensity})} = 330$ as $\mathrm{Spot} = 10\ \lambda_L$ SMILEI



Proton, e- and C spectra after 11.9 fs for a 1 J single cycle case

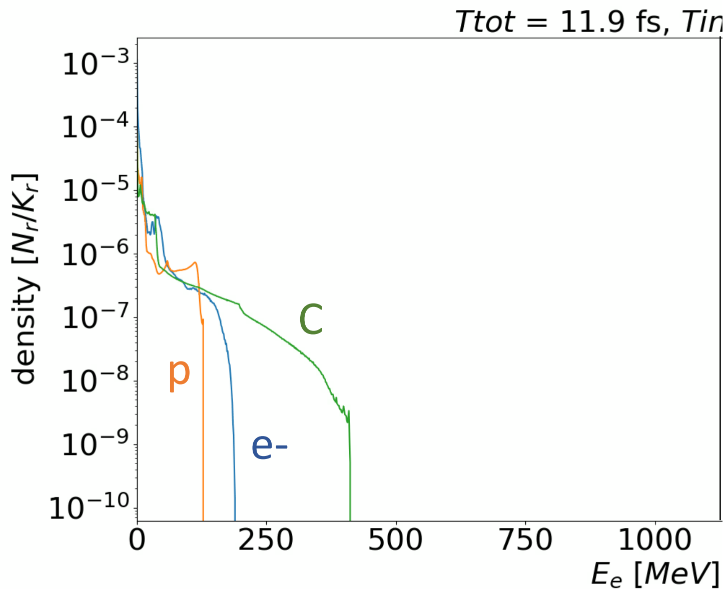


Proton x-p_x phase space 11.9 fs for a 1 J single cycle case

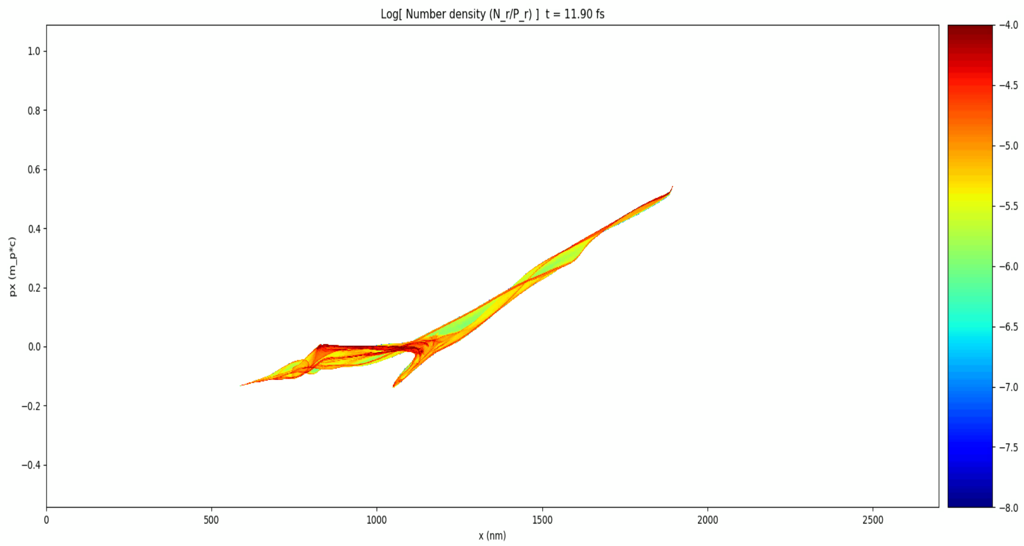
At this wavelength a solid target acts as an underdense target with sharp boundaries.

Optimization of longitudinal proton acceleration 500 nm thick CH target

$\lambda_L = 10$ nm $a_0 = 140$ $\mathrm{FWHM}_{(\mathrm{intensity})} = 330$ as $\mathrm{Spot} = 10\ \lambda_L$ SMILEI



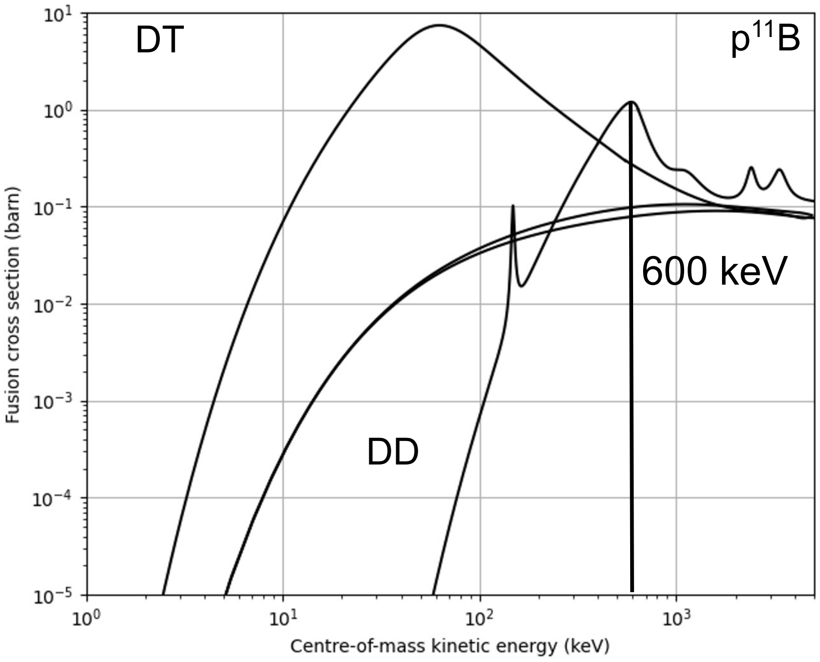
Proton, e- and C spectra after 11.9 fs for a 10 J ten-cycle case



Proton x-p_x phase space 11.9 fs for a 10 J ten-cycle case

Application to aneutronic Fusion

Fusion cross section



$$\mathrm{D} + \mathrm{T} \rightarrow \alpha\,(3.5\mathrm{MeV}) + \mathrm{n}\,(14.1\mathrm{MeV}) \qquad \mathrm{Q_{DT}} = 17.6\,\mathrm{MeV}$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\,(1.01\,\mathrm{MeV}) + \mathrm{p}\,(3.03\,\mathrm{MeV})$$
$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{H_e}\,(0.82\,\mathrm{MeV}) + \mathrm{n}\,(2.45\,\mathrm{MeV})$$

Aneutronic fusion

$$\mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\alpha\,(8.6\,\mathrm{MeV}) \qquad \mathrm{Q_{pB}} = 8.6\,\mathrm{MeV}$$

Proton-Boron resonance 600 keV

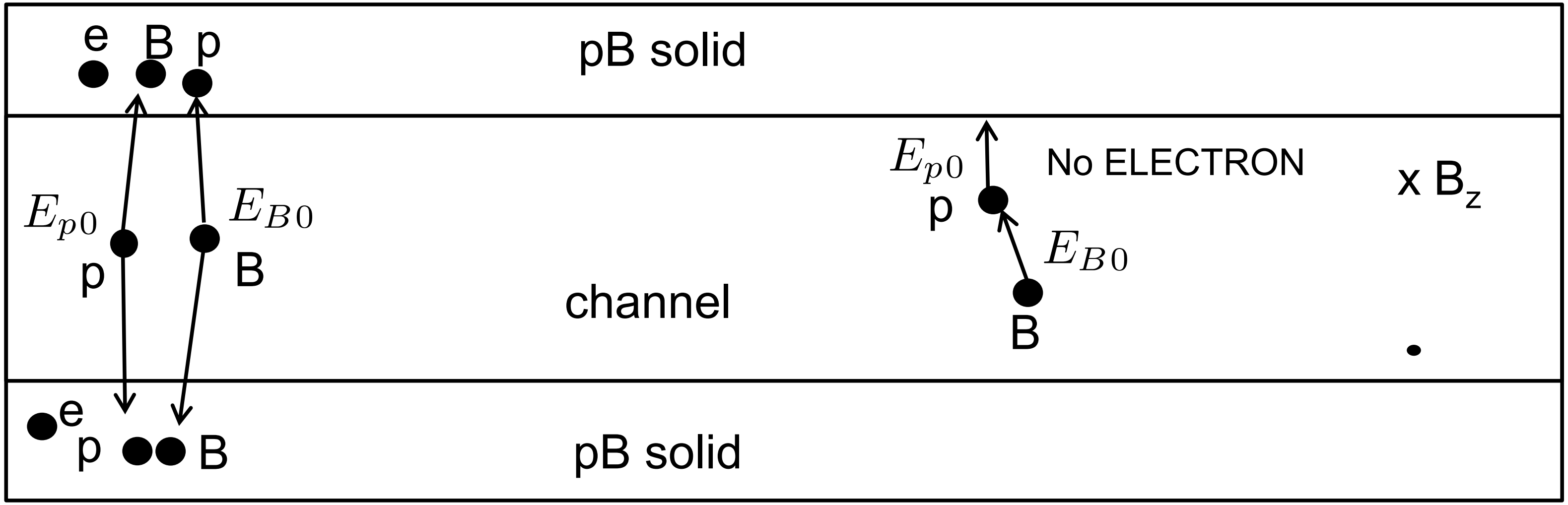
Need to accelerate Proton and Boron ions to higher than 600 keV to produce the most efficient fusion reaction rate

Go toward non-thermal fusion = kinetic fusion

* Giuffrida L. et al. PRE **101,** 013204 (2020)

** Margarone D. et al Frontiers in Physics **8**, 343 (2020)
*** Bonvalet J. et al PRE **203**, 053202 (2021)

Alpha production estimation p→ pB
Modelisation: outside and inside the channel



Electron Stopping dominates (Bethe & Bloch)

$$E_{p0} = 3 \text{ MeV}$$
$$\rho_{pB} \sim 1 \text{ g/cc}$$

Nuclear Stopping dominates (Rutherford)

$$E_{cm} = 1 \text{ MeV}$$
$$\rho_{pB} \sim 1 \text{ g/cc}$$

(5% laser initial energy 10 J) For 0.5 joules in proton beam :

$$E_{\alpha tot} = 0.23 \text{ mJ}$$

$$E_{\alpha tot} = 0.3 \text{ J}$$

Similar model as in Giuffrida L. et al. PRE 101 (2020)

X. Ribeyre et al. Scientific Reports 12:4665 (2022)

Conclusions and perspectives

- The interaction of high energy attosecond pulses with matter is still a mostly unexplored regime of laser-plasma interaction.
- It has a strong potential to efficiently produce high energy secondary sources (electrons, ions, photons).
- Single-cycle pulses can efficiently accelerate ions transversally which could be interesting for pB fusion.
- An advantage for longitudinal ion acceleration, aside from the energy efficiency, is that it is possible to use solid targets as underdense targets with sharp boundaries.

- Work on the generation of the required laser pulses in experiments: see also Stimulated-Raman-scattering amplification of attosecond XUV pulses by Andreas Sundström et al. Phys. Rev. E 106, 045208 (2022)/
- 3D simulations.
- Sensitivity to the CEP in the single–cycle case.
- High energy photons are produced and it would also be interesting to optimize the photon beams produced.
- To go further on the pB fusion application: need for integrated multi-scale numerical simulations.

Thank you for your attention !