Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

Modulations on Thomson parabolic-like ion-patterns caused by laser-matter produced ElectroMagnetic Pulses

F. Filippi, B. Grau, M. Scisciò, M. Cipriani, M. Alonzo, P.L. Andreoli, G. Cristofari, E. Di Ferdinando, E. Domenicone, S. Agarwal, C. Altana, S. Arjmand, D. Bortot, P. Gajdoš, L.G. Guardo, M. Krupka, G. Messina, S. Mirabella, G. Morello, M. Nocente, F. Odorici, A. Pappalardo, G. Pasquali, G. Petringa, R. Rinaldi, S. Singh, A. Trifirò, C. Verona, G.A.P Cirrone, and F. Consoli

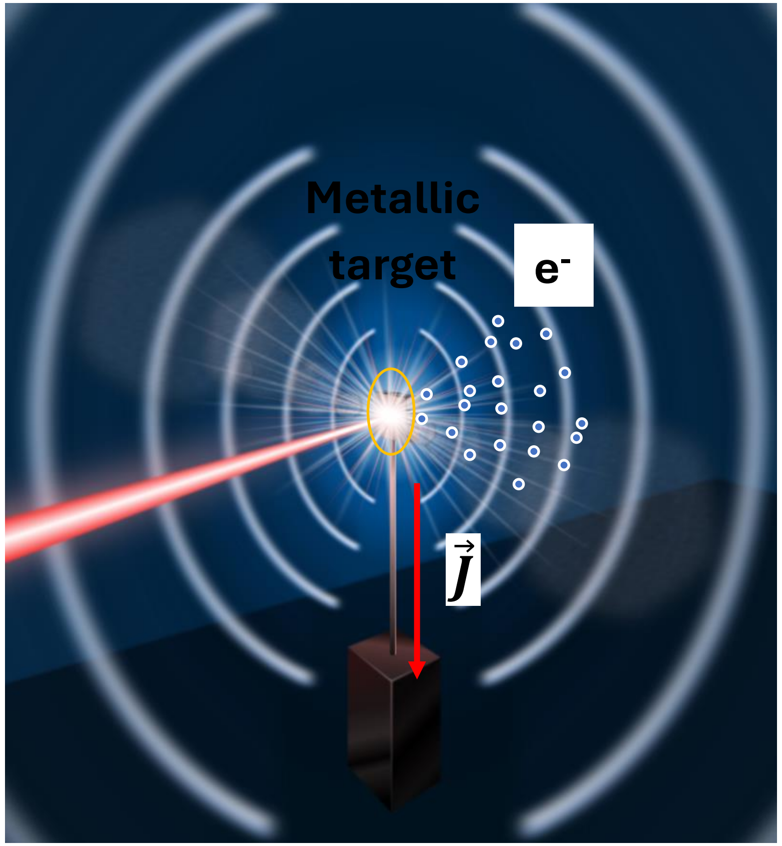
7th European Advanced Accelerator Conference (EAAC2025)

Outline

1. ElectroMagnetic Pulses (EMPs) in high intensity laser environment
2. Thomson Parabola as tool to characterize ions/EMPs (and laser-target interaction mechanisms)
3. Experimental measurements of ions/EMPs
4. Conclusions and future works

Electro-Magnetic Pulses (EMPs)

The principal source of EMPs is the **neutralization current**: when the laser hits the target, electrons are ejected due to various mechanisms, leading to a discharge in the target.



laser

Intensity
$\sim 10^{18}$–10^{20} W·cm^{-2}

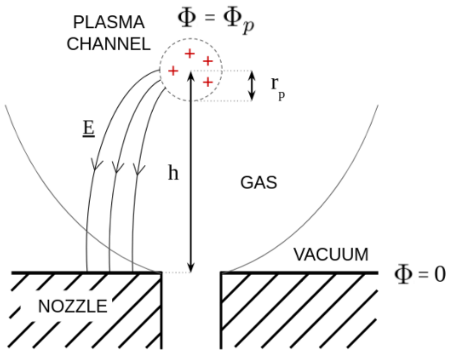
Consoli F et al. "Laser produced electromagnetic pulses: Generation, detection and mitigation", High Power Laser Sci. Eng. 8 (2020) e22. DOI: 10.5286/edata/1

The **electrons** are heated and accelerated by the laser pulse leaving most of the ions behind.

This induces a **current** through the target's stalk to the chamber's floor and walls, which may undergo to several reflections, generating EMPs.

Neutralization current may pass through the gas of a **gas jet**!

Bradford, P., et al. "Laser Interactions with Gas Jets: EMP Emission and Nozzle Damage." arXiv e-prints (2024): arXiv-2403.



EMPs can be emitted also by the plasma surface sheath oscillation, transient charged layers due to photoionization...

Electro-Magnetic Pulses (EMPs): hazardous or beneficial?

EMPs scale with **laser energy** and mostly with **laser intensity**.

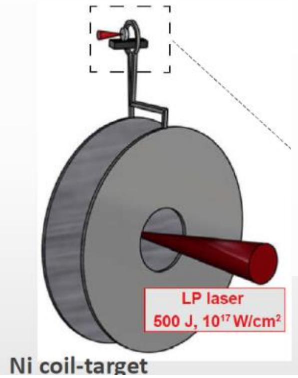
They have a **remarkable intensity** (up to the **MV/m** order and beyond) a **broad frequency range** from **MHz to THz**.

Issues:

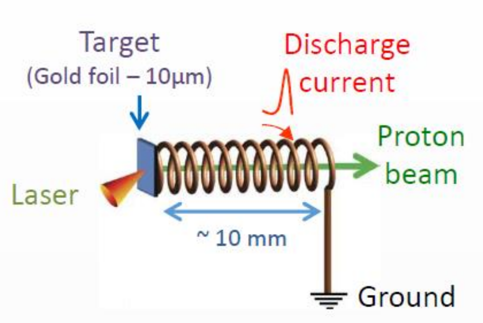
- saturation/damaging of electronic equipment
- EM noise in the diagnostics
- Personnel protection

Applications:

- provide a “signature” of the laser-matter interaction
- manipulation of accelerated charged particles
- medical, biological, astrophysical and material studies



J. Santos et al., NJP 2015



S. Kar et al., Nat. Comm. 2016

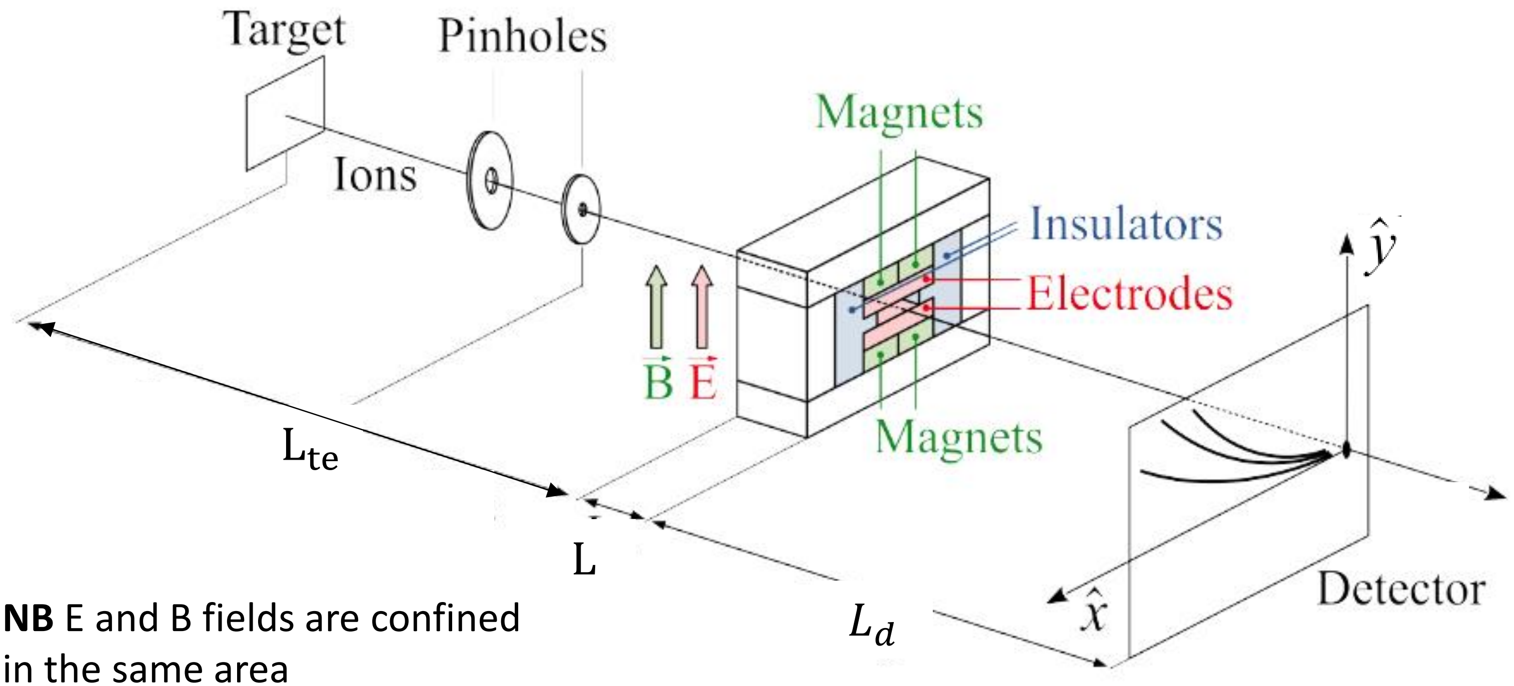
To measure this intense electromagnetic field, different detectors or probes are currently used: antennas, D-DOT, B-DOT, Electro-Optical probe…

Techniques for accurately measuring, controlling and tuning EMPs are being investigated

The effects of the EMPs are visible on several diagnostics! Mostly as ‘noise’

Thomson Parabola (TP): working principle

Thomson Parabola (TP) Spectrometer is commonly used diagnostic affected by EMPs
In ENEA (Frascati) we designed a TP to be placed very close to the interaction point, inside the vacuum chamber.



NB E and B fields are confined in the same area

Table 1. Key physical parameters of the TS.

Electrode length	25 mm
Electrode gap	5 mm
Drift space	197 mm
Max. measured magnetic field	0.405 T
Max. voltage	±3.9 kV
Inner (outer) pinhole diameter	0.35 mm (2 mm)

Spect. Proton range 100 keV–10 MeV

It has been optimized to screen X-rays on the detector and EMPs in the high voltage cables (still, they affects the measurements).

The E and B fields of the TP allow to deflect ion species with different mass-to-charge ratio ($\frac{A}{Z}$) on different trajectories.

Each parabolic trace corresponds to one $\frac{A}{Z}$ ratio.

Di Giorgio G, et al., JINST 15 C10013; DOI: 10.1088/1748-0221/15/10/C10013
M. Sciscìò et al. J. Inst. 17, (2022) C01055

Thomson Parabola (TP): fundamental equations

Particles passing through the TP will be deflected by both an electrostatic field and a magnetostatic field generated by electrodes and magnets, which will separate the particles based on their charge-to-mass ratio.

$$\begin{cases} x = R_i - R_i\sqrt{1-\left(\frac{L}{R_i}\right)^2} + \dfrac{1}{R_i\sqrt{1-\left(\frac{L}{R_i}\right)^2}} \\ y = \dfrac{q_i E R_i^2}{2 m_i v_i^2}\left[\sin^{-1}\left(\frac{L}{R_i}\right)\right]^2 + \dfrac{q_i E R_i L_D \sin^{-1}\left(\frac{L}{R_i}\right)}{m_i v_i^2\sqrt{1-\left(\frac{L}{R_i}\right)^2}} \end{cases}$$

$$R_i = m_i v_i / q_i B$$

bending radius of the particle trajectory

Hp:

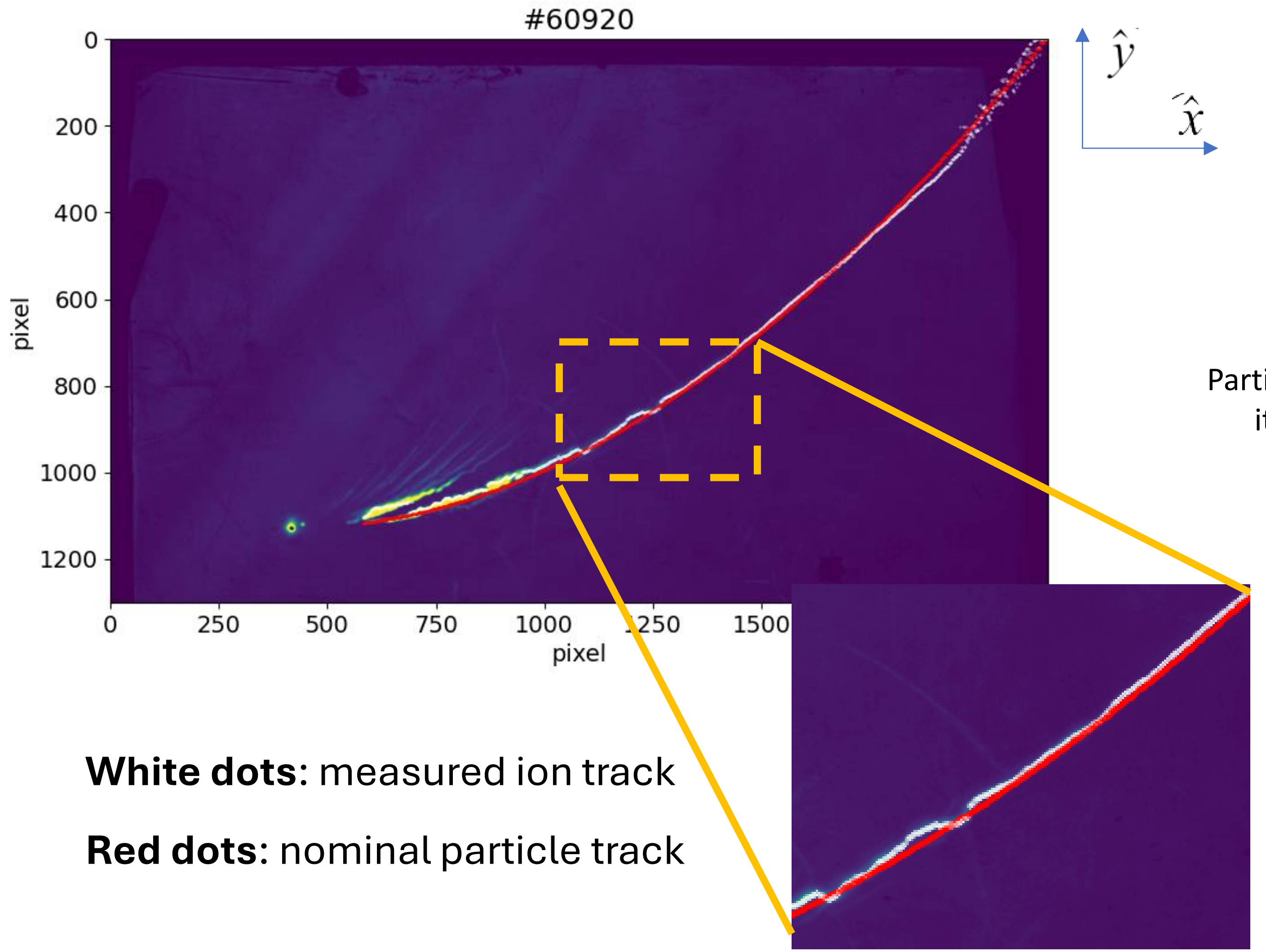
- $^{L}/_{R_i} \ll 1$ (displacement of the particle along the y axis due to magnetic field is negligible)
- **Non-relativistic particles**

$$\begin{cases} x = \dfrac{q_i B}{m_i v_i}\, L\left(\dfrac{L}{2} + L_d\right) \\ y = \dfrac{q_i E}{m_i v_i^2}\, L\left(\dfrac{L}{2} + L_d\right) \end{cases}$$

EMPs could alter the deflecting fields, leading to <u>modulation of the expected traces </u>(and possible superposition of them)

Grepl, F et al., Appl. Sci. 2021, 11, 4484. DOI: 10.3390/ app111044846020

Thomson Parabola (TP): effects of the EMPs on signal



On the **y axis**, the particles are deflected by the superposition of the imposed electric field E and the electric field of the EMP, ΔE

$$y + \Delta y = \frac{q_i(E + \Delta E)}{m_i v_i^2} L \left(\frac{L}{2} + L_d\right)$$

Particle deviation from its nominal pos.

$$\Delta E = \frac{m_i v_i^2}{q_i L} \frac{1}{\left(\frac{L}{2} + L_d\right)} \Delta y$$

On the **x axis**, the particles are dispersed by their velocity (i.e. their kinetic energy)

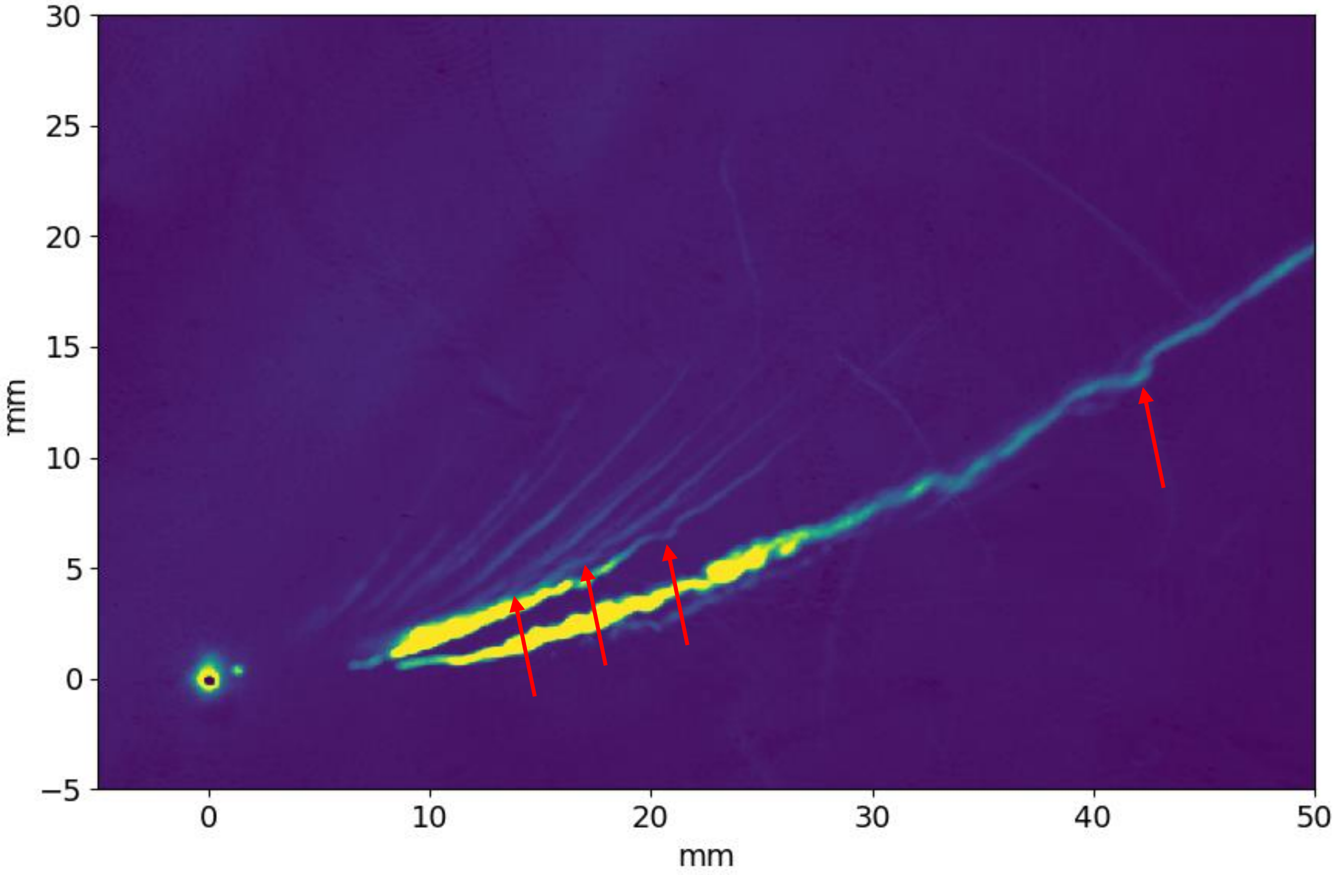
$$x = \frac{q_i B}{m_i v_i} L \left(\frac{L}{2} + L_d\right)$$

White dots: measured ion track

Red dots: nominal particle track

Thomson Parabola (TP): effects of the EMPs on signal

At different kinetic energies corresponds different **Time of Flight** (ToF) of the particles.



non-relativistic ion kinetic energy $E_i = \frac{1}{2} m_i v_i^2$

Time-of-Flight $t = \frac{L_{TE}}{v_i}$

Target-electrodes distance (L_{TE})

Ion velocity (v_i)

We can recognise the same patterns on the different ion tracks, tracking straight lines where particles have the same ToF (and **experience the same ΔE**)

$$y = t \frac{E}{B\, L_{TE}} x$$

Lines on the detector where particles have the same ToF are described by this equation

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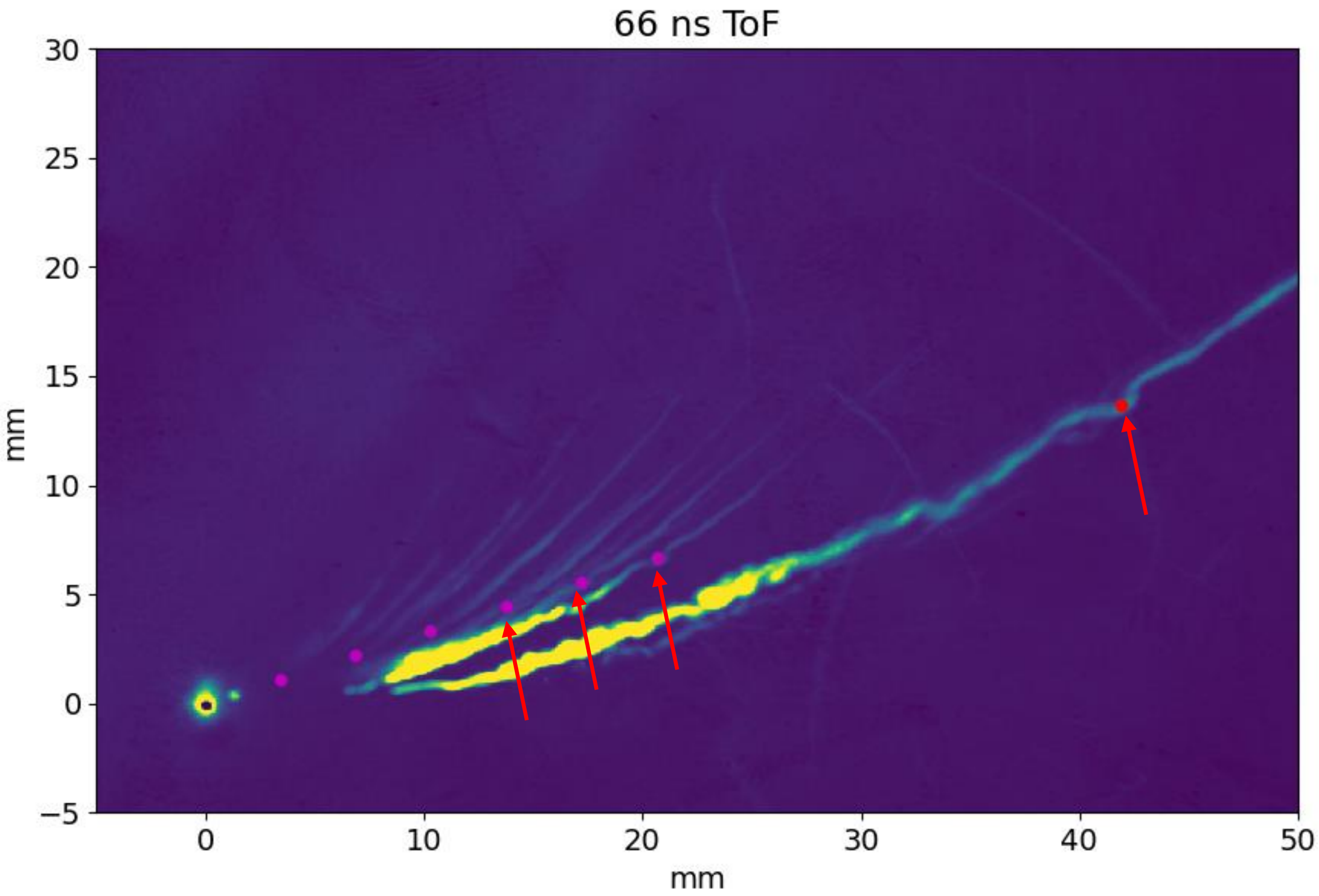

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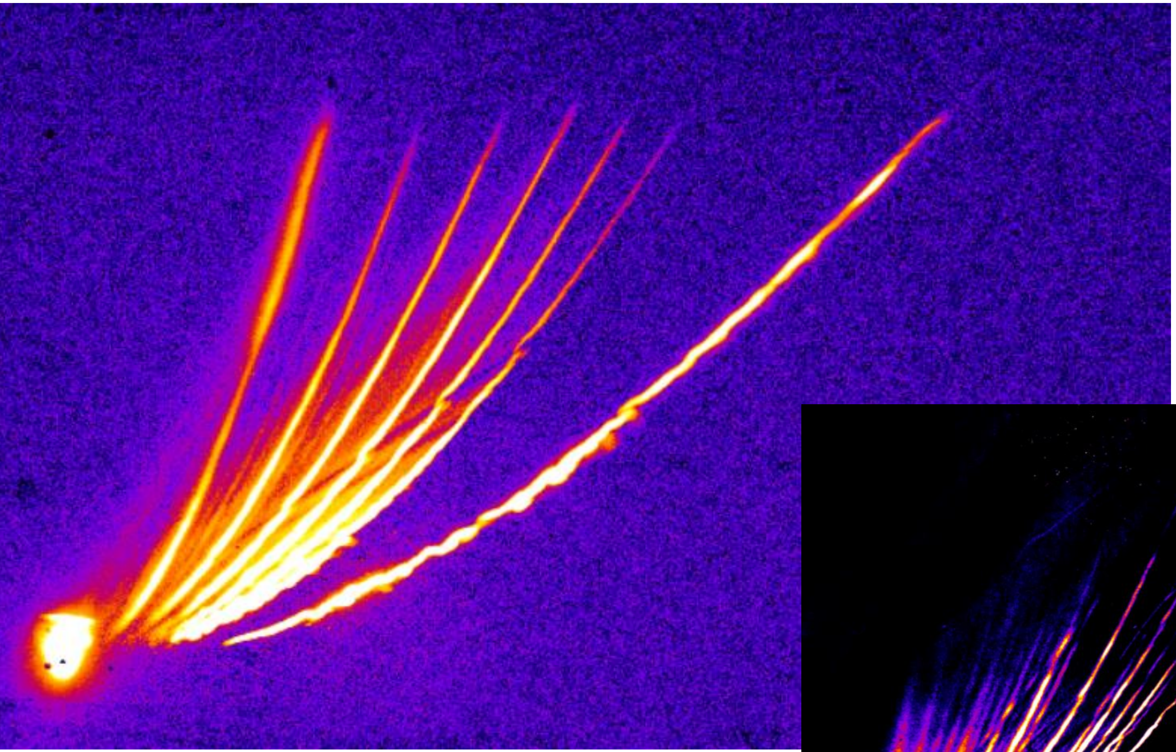

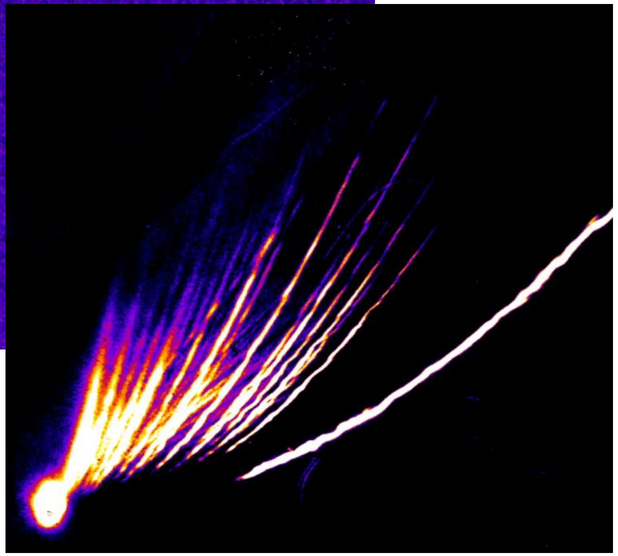

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Experimental measurements of ions/EMPs: pB fusion experiment

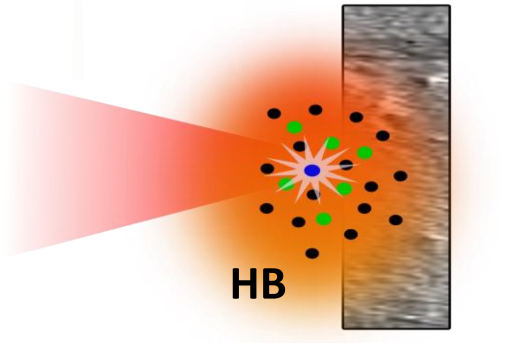
We tested this methods during the pB fusion experiment at PALS

$p^{11}B$ nuclear fusion reaction: $p + {}^{11}B \rightarrow 3\alpha + 8.7$ MeV

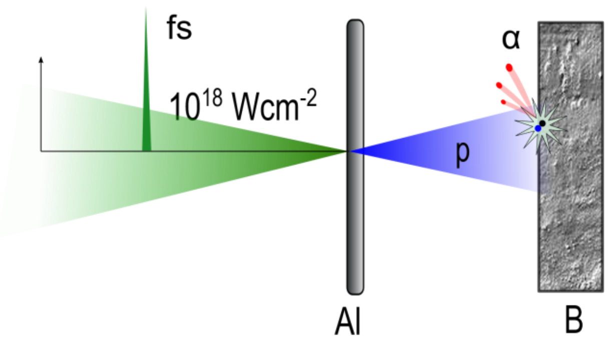
- No/few neutrons are produced
- No need for radioactive reactant
- Energetic alpha particles are obtained

Fusion reaction initiated by high energy lasers
two main schemes are adopted:

"In target" scheme

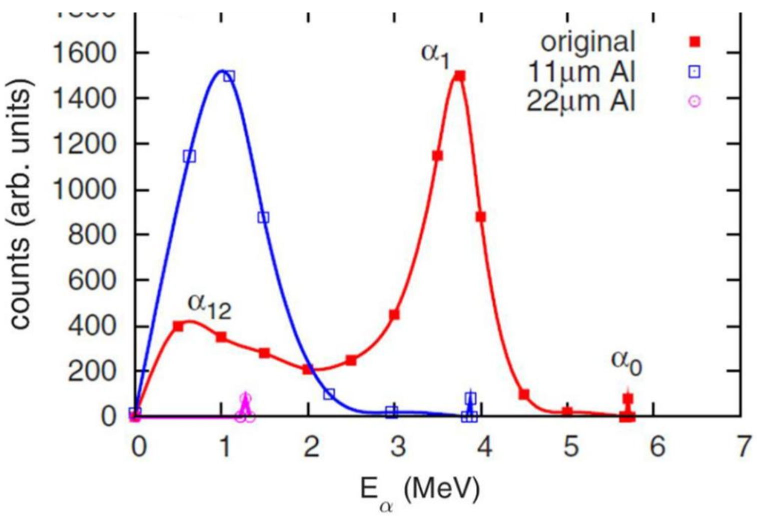


"pitcher-catcher"



Nuclear fusion rates are determined also by the produced alphas: needs for detection and characterization of the produced alphas (**TP in close proximity to the target**!).

Kimura et al., Phys. Rev E 79, 038401 (2009)



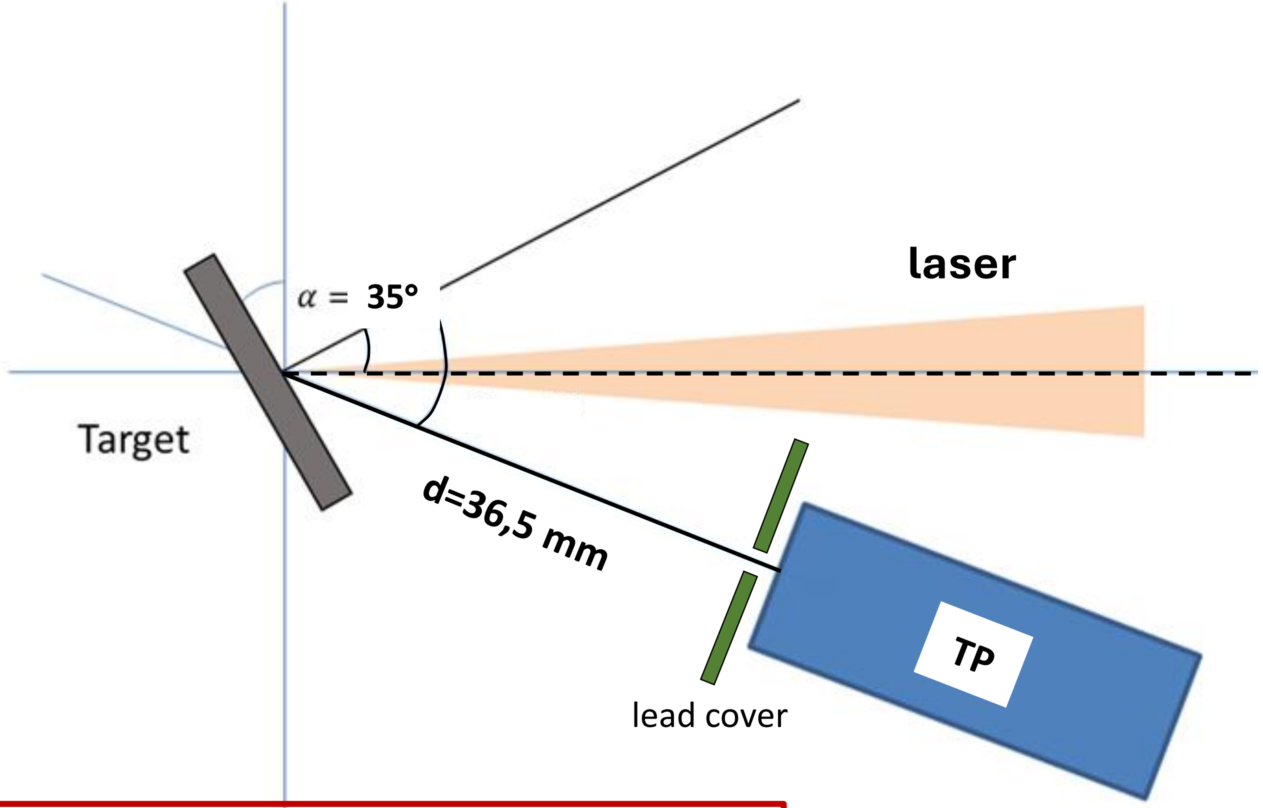
Not only for energy production:
interest for both ***medical applications*** and ***astrophysics research***

F. Consoli et al. *Front. Phys.* 8, (2020) 561492
P. Cirrone et al. *Sci. Rep.* 8 (2018) 1141

EMPs are a concerning **problem** for future reactors. As well, they can give a **deep insight** of the mechanisms of laser-matter interaction

Experimental measurements of ions/EMPs: pB fusion experiment

Experimental setup at the PALS facility



TP at close proximity to the target, inside the target chamber!

EMPs affects the measurements!

Laser parameters:
Wavelength λ = 1315 nm
Pulse duration τ ≈350 ps
Pulse energy between 600 J and 700 J Intensity on target $I \approx 10^{16}\ W/cm^2$

Target: Foam Target 100mg/cc HB.

The **maximum voltage** applied to the electrodes of the TP was of ΔV = 4,2 kV (resulting in an electric field E ≈ 1 MV/m).

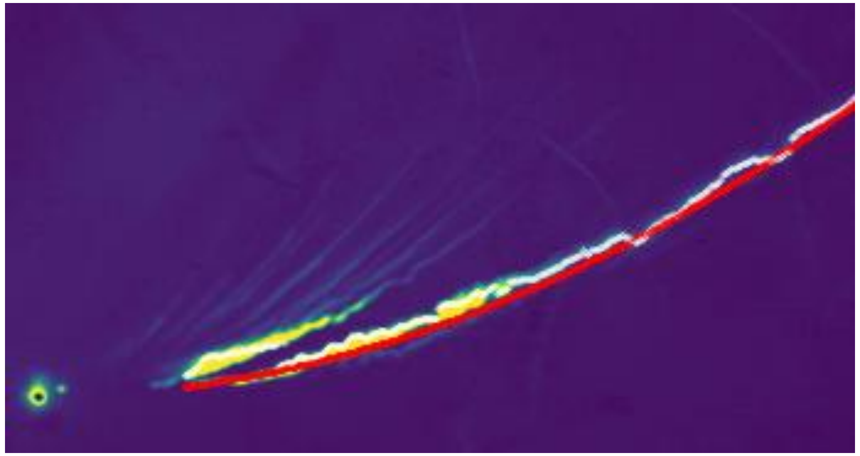
Detector on TP: BAS-TR type Imaging Plate (IP) with no filter on the sensitive surface.

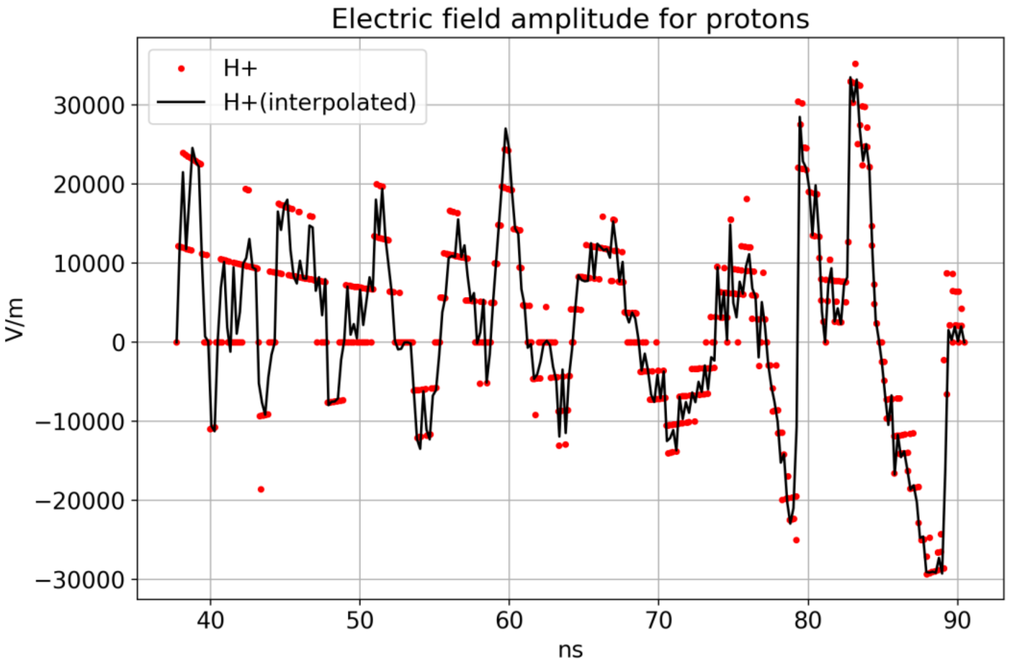
Experimental measurements of ions/EMPs

We identified the centre of the proton's parabola (white dots), then we compare its shift Δy to its nominal position (red dots).

Then we retrieved the temporal evolution of the EMP electric field ΔE

$$\Delta E = \frac{m_i v_i^2}{q_i L} \frac{1}{\left(\frac{L}{2} + L_d\right)} \Delta y$$





NB **slower particles** are more deflected by the same field than faster particles.

This leads to a **better electric field resolution** at lower energies.

Moreover, at lower energies there is a **better temporal resolution** (particles are more dispersed).

Courtesy of Benoist Grau

Conclusions and future works

Conclusions

- EMPs are both hazardous and beneficials in laser-matter interaction experiments
- This analysis leads to a temporal and spectral analysis of the emitted fields.
- It will allow a deeper insight into the laser-plasma interaction dynamics, as well as in the mechanisms of generation of the EMPs.

Future work:

- We will compare the measurement of the EMPs obtained with the TP with D-DOT/B-DOT
- We will use a different TP, with different proton spectrum (proton energy range 5 keV to 2MeV) to analyse slow particles spectra

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THANK YOU FOR YOUR ATTENTION!

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