PARTICLE-IN-CELL SIMULATION FOR EXPERIMENTAL ION ACCELERATION BY FS LASER-GENERATED PLASMA

G. Costa and L. Torrisi

Dipartimento di Scienze Fisiche, MIFT, Università di Messina, V.le F.S. D'Alcontres 31, 98166 S. Agata, Messina, Italy

University of Messina

Outlines

- Laser-Matter interaction (BPA – TNSA – RPA)
- Experimental TOF measurements
- PIC (Particle-in-Cell) approach (Electron Density, Electric Field of ion acceleration, ion energy spectra)
- Experimental-Theoretical comparison
- Conclusions and Future Perspectives

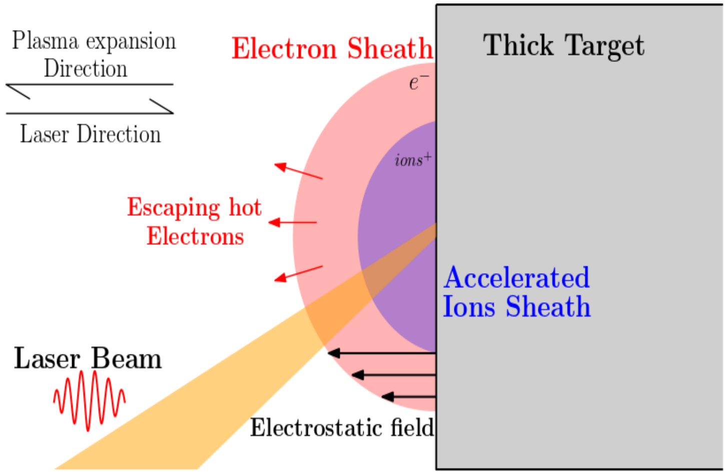
Laser-Matter Interaction

When a pulsed laser beam with an intensity greater than $10^8 \div 10^{10}$ W/cm^2 hits a target, atoms, particles, molecules, clusters and more are ejected from it.

Ion Acceleration Regime

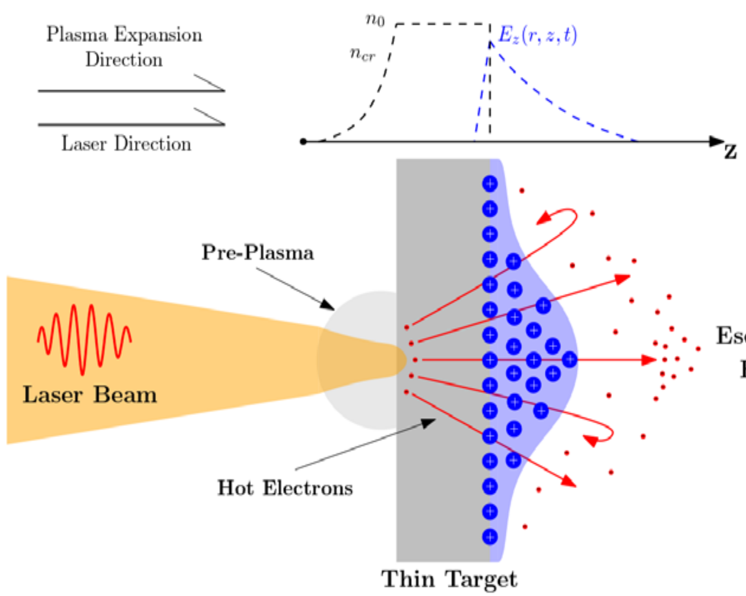
Backward Plasma Acceleration (BPA)

$10^8 \div 10^{14}$ W/CM^2



Target Normal Sheath Acceleration (TNSA)

$10^{15} \div 10^{20}$ W/CM^2

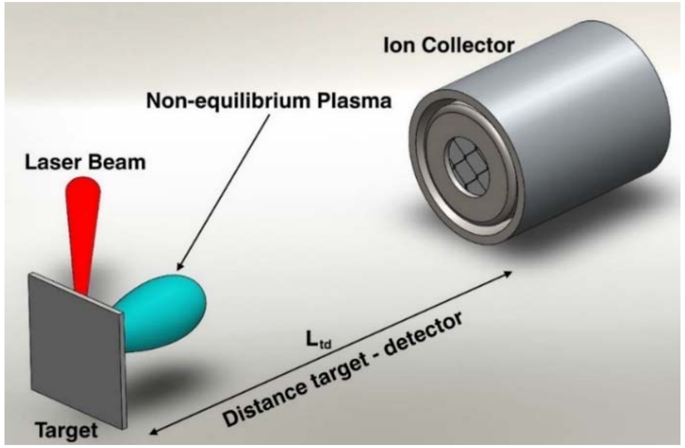


$$E = \sqrt{\frac{n_e k T}{\epsilon_0}}$$

Radiation Pressure Acceleration (RPA)

$>10^{20}$ W/CM^2

Time of Flight (TOF)

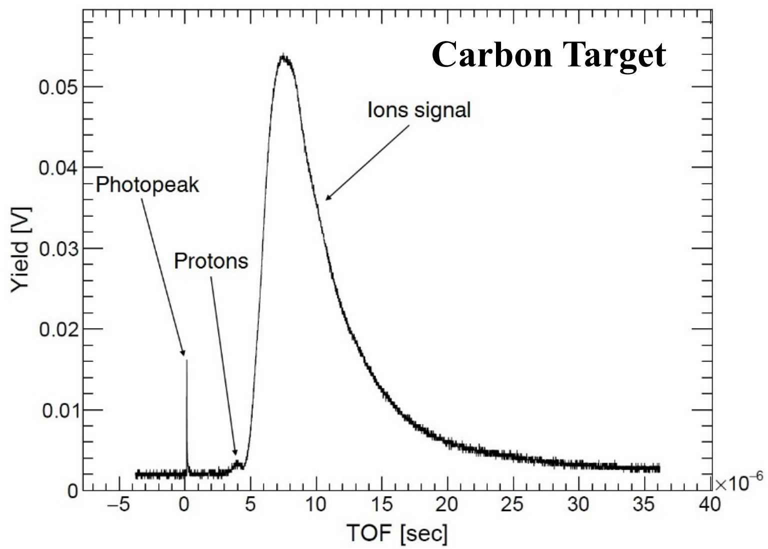


Time of Flight Technique

Time Of Flight (TOF) technique can be used for the particles velocity and/or energy evaluation of a plasma generated by Laser. It consists in evaluating the time necessary for an ion to travel a known distance.

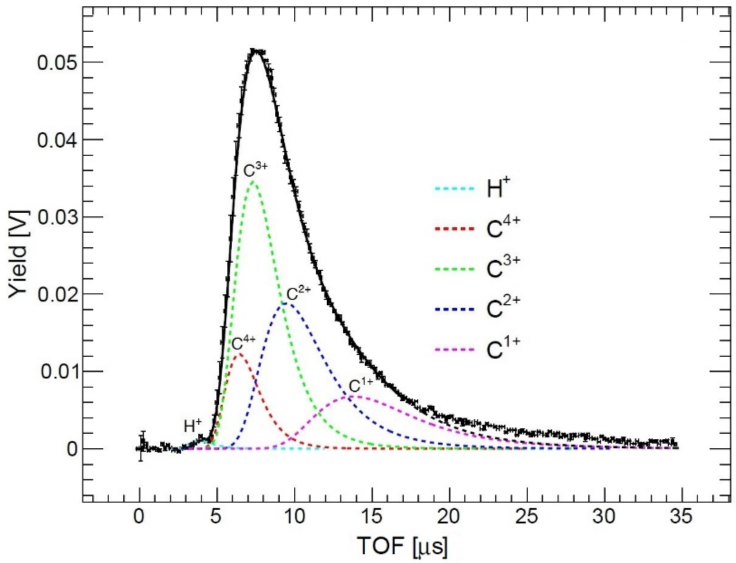
$$\bar{v} = \frac{L_{td}}{TOF} \quad \rightarrow \quad \bar{E} = \frac{1}{2} m \bar{v}^2$$

CBS(t) $\rightarrow$ $$f(TOF) = A\sqrt{\left(\frac{m}{2\pi k_B T}\right)^3} \frac{L_{td}^4}{TOF^5} \exp\left[-\frac{m}{2k_B T}\left(\frac{L_{td}}{TOF} - \sqrt{\frac{\gamma k_B T}{m}} - \sqrt{\frac{2zeV}{m}}\right)^2\right]$$



CBS(t)

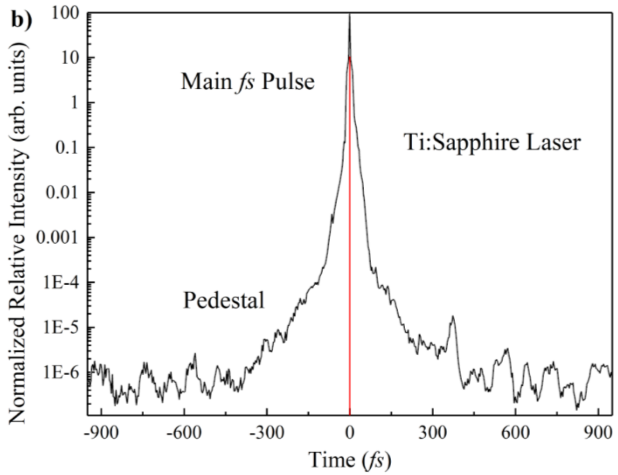
Deconvolution

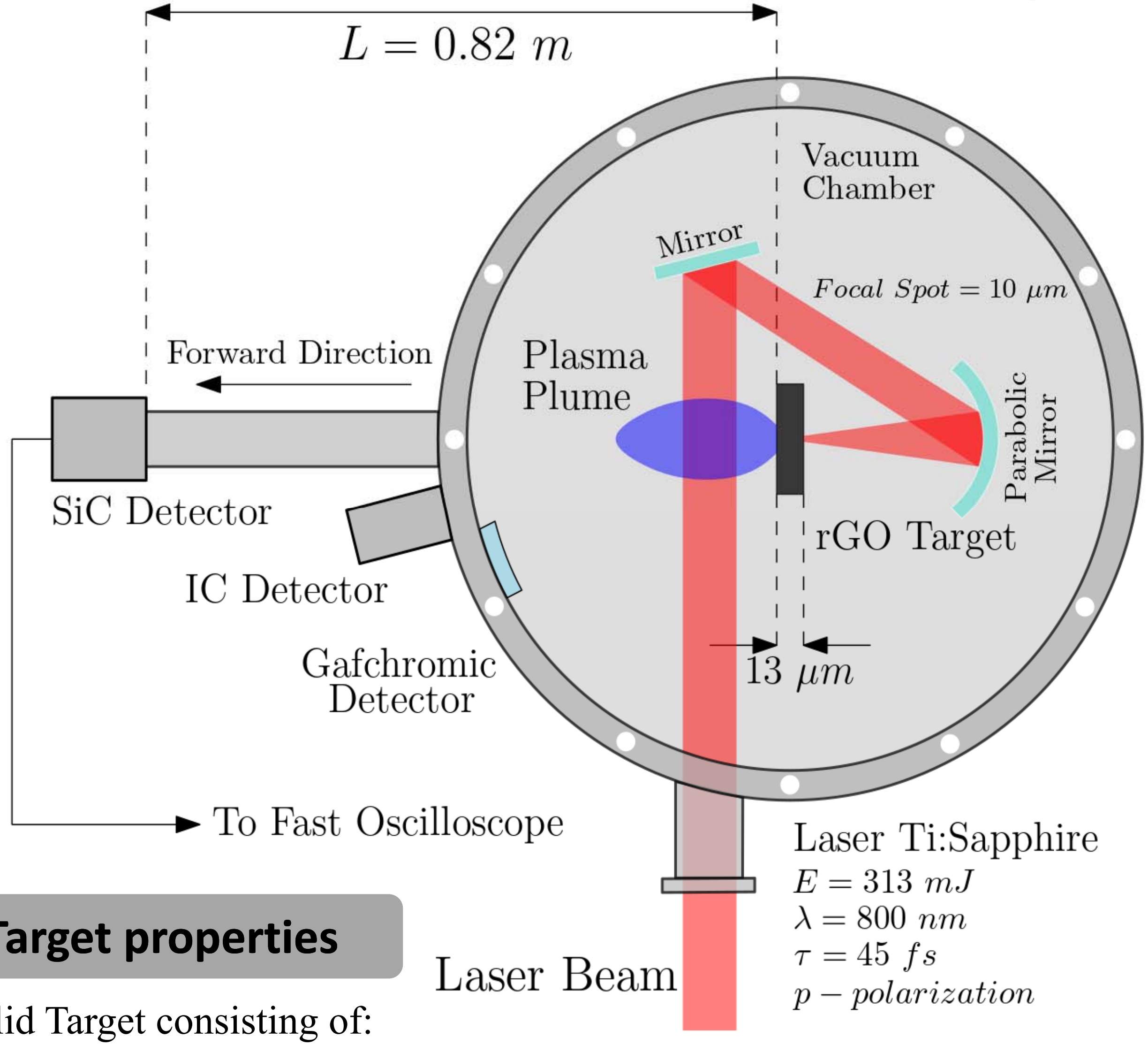


Experimental Setup

Laser features

- **Laser Ti:Sapphire**
- Wavelength: 800 nm
- Pulse duration: 45 *fs*
- Energy: 313 mJ
- Intensity: 10^{18} W/cm^2





Irradiation Condition

- Vacuum: ~ 10^{-6} mBar
- Incidence at ~ 0°
- Laser Spot: ~ 70 µm^2

Target properties

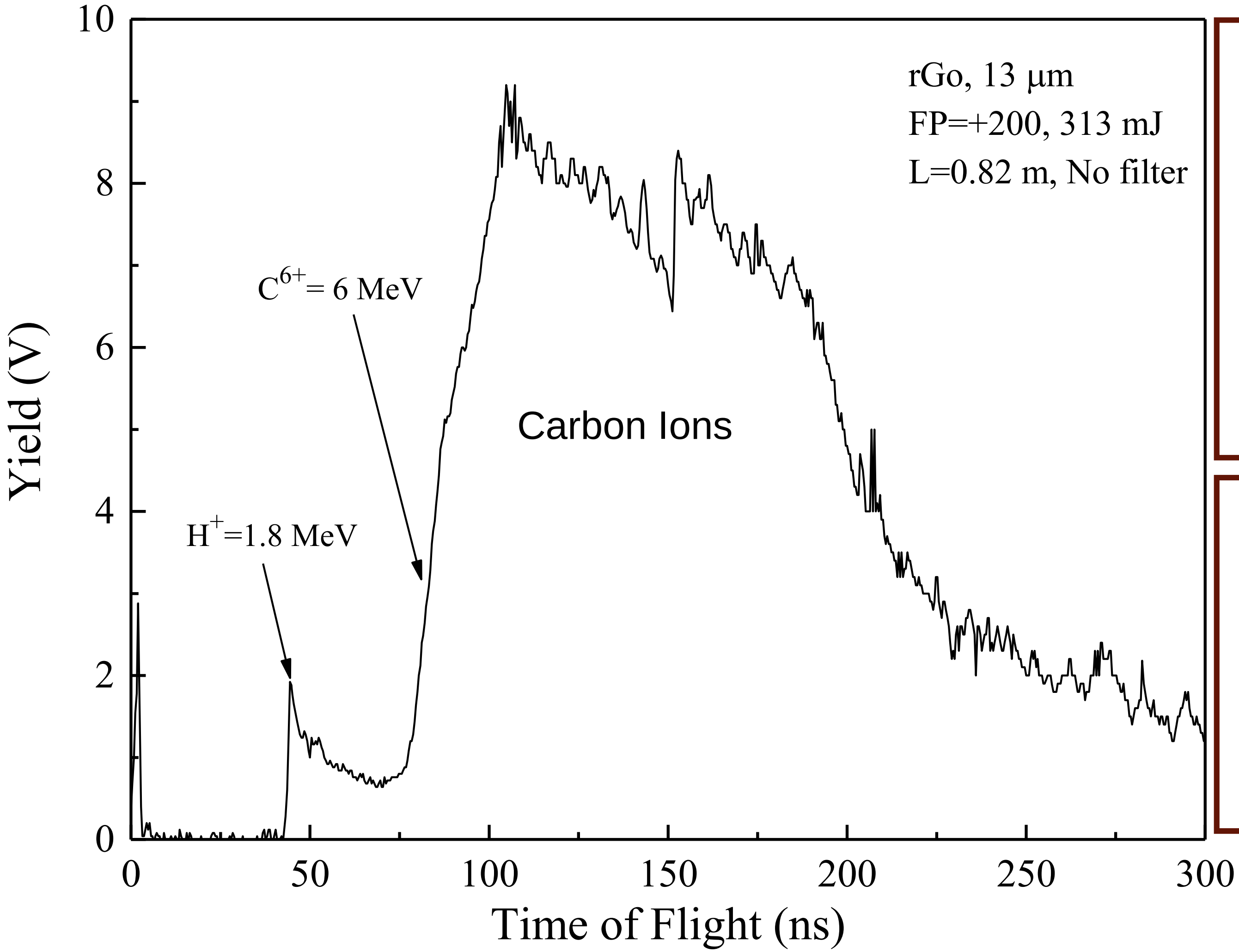
Solid Target consisting of:

- rGO (13 µm)

IPPLM of Warsaw (PL)

Experimental Result

By irradiating the GO foil using a single laser shot we obtain the following TOF spectrum



CBS Approach

$$\frac{E}{z} \cong const$$

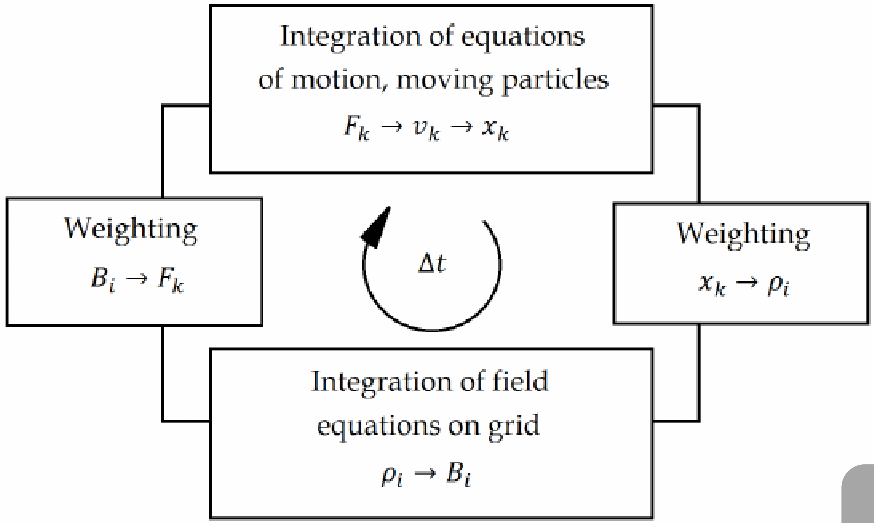
$E(H^{+}) = 1.8$ MeV
$E(C^{6+}) = 10.8$ MeV

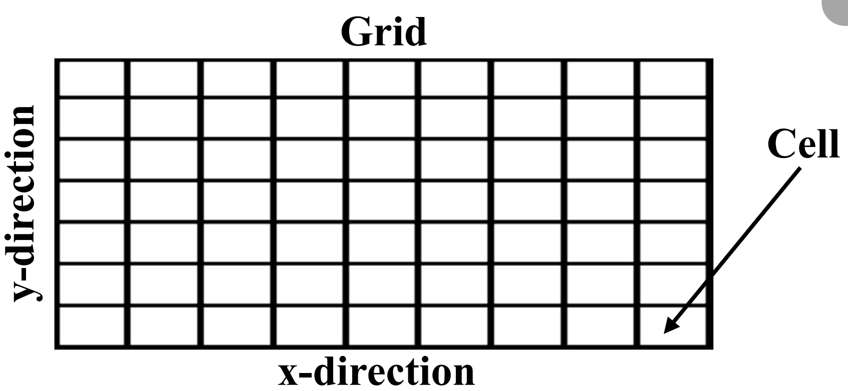
TNSA Approach

$E(H^{+}) = 1.8$ MeV
$E(C^{6+}) = 6$ MeV

Particle-in-Cell Approach

We compare experimental results with 2D-Particle in Cell (PIC) simulation by use EPOCH code. PIC-EPOCH code simulates collisionless plasma kinetics.





Core of the Solver

Field Solver

Particle Pusher

Lorentz Force

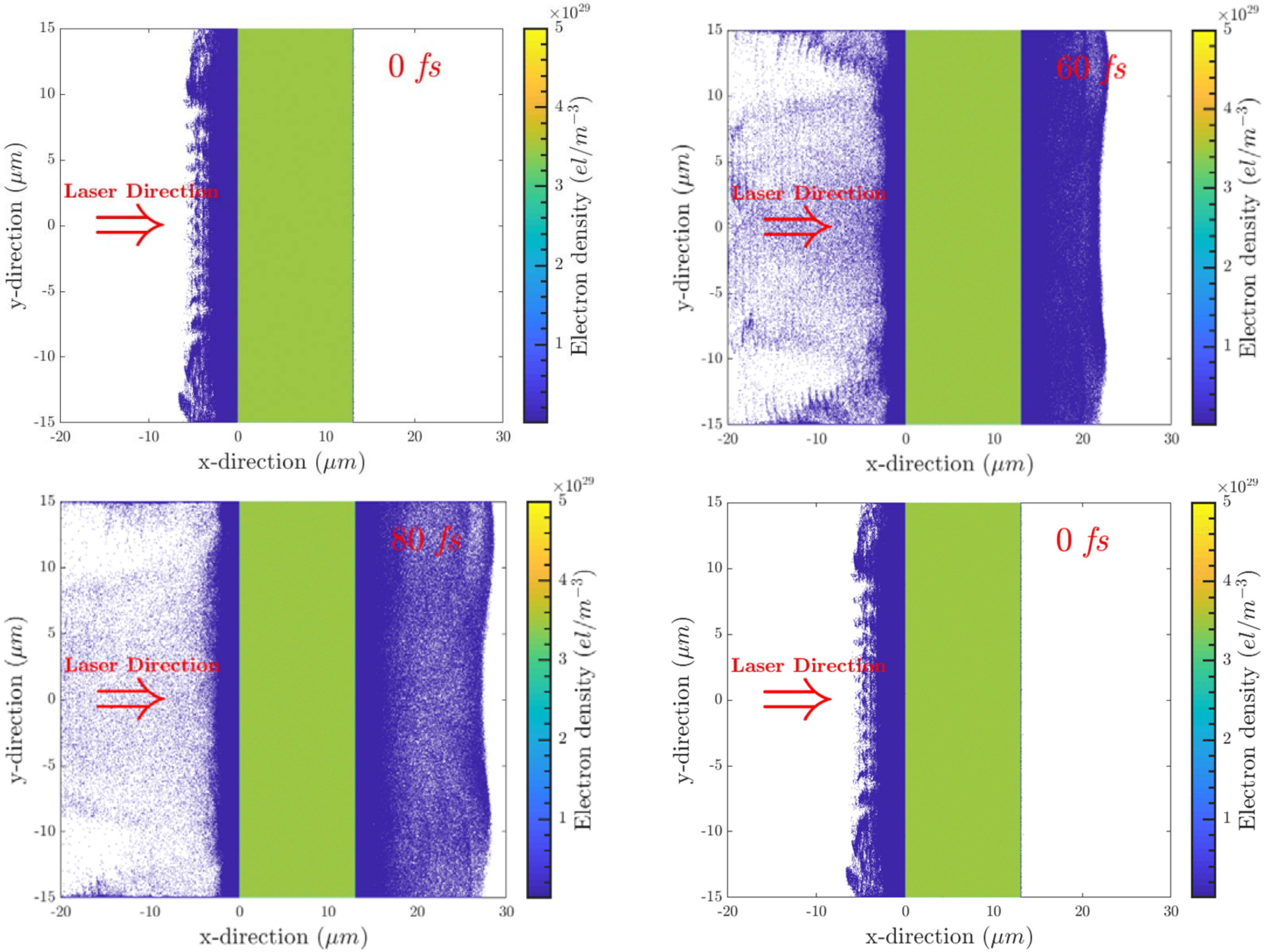
$$\boldsymbol{p}_\alpha^{n+1} = \boldsymbol{p}_\alpha^{n} + q_\alpha \Delta t \left[\boldsymbol{E}^{n+\frac{1}{2}}\left(\boldsymbol{x}_\alpha^{n+\frac{1}{2}}\right) + \boldsymbol{v}_\alpha^{n+\frac{1}{2}} \times \boldsymbol{B}^{n+\frac{1}{2}}\left(\boldsymbol{x}_\alpha^{n+\frac{1}{2}}\right) \right]$$

Particle-in-Cell Simulation

The simulation box is set to dimension of 50 µm × 30 µm (x-direction × y-direction), from -20 µm to 30 µm in x-direction and between ±15 µm in y-direction. The box contains square cells with size of 10 nm.

Input Paramaters

- Laser Parameters
- Foil size = 13 µm
- Preplasma = 2 µm
- Foil density
- Particle per cell:
  - ➢ Electron = 80
  - ➢ Proton = 2000
  - ➢ Carbon = 1500



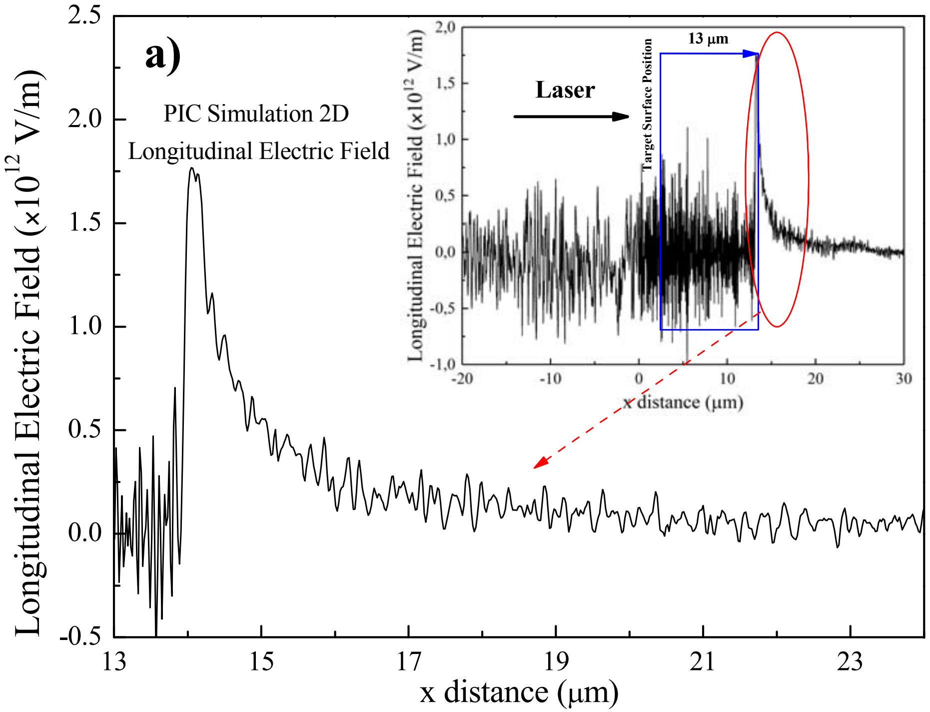
Output Paramaters

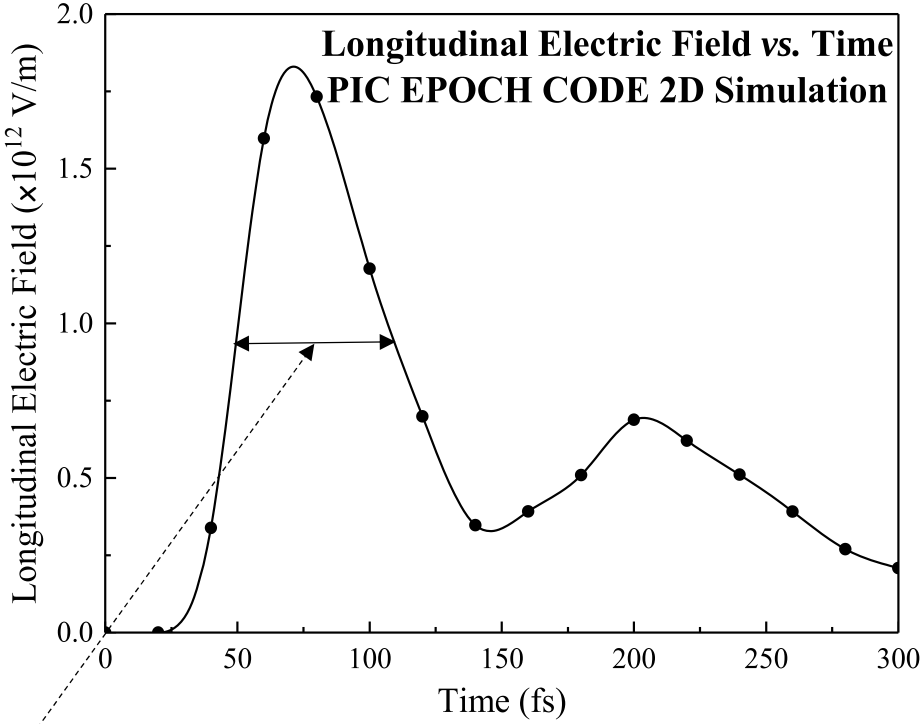
- Electric Field
- Particle Density
- Particle Energy
- and others…

Electric field driven acceleration

The longitudinal electric field, in x-forward direction indicating a peak value of about 1.75 x 10^{12} V/m at about 60 *fs* from the laser shot.

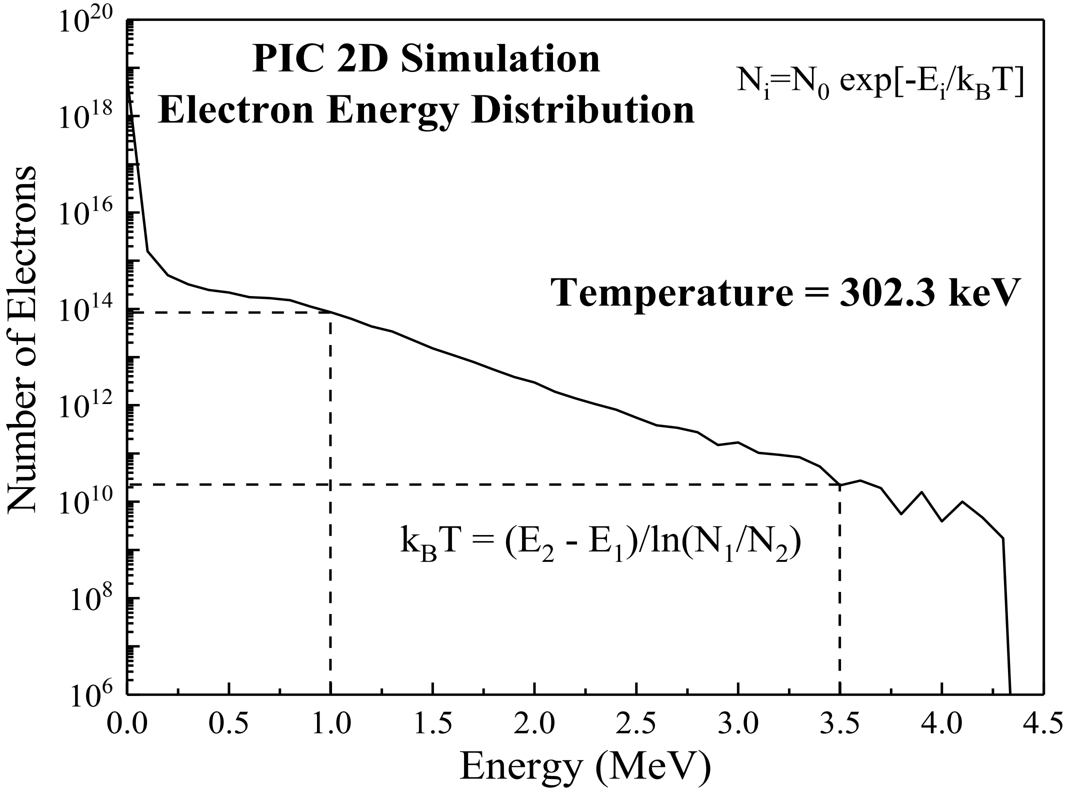
$$1.75 \times 10^{12} \left({}^{V}\!/_{m} \right) \cdot 1 \times 10^{-6} (m) = 1.75\ MV \quad \Rightarrow \quad E(H^{+}) = 1.75\ MeV$$





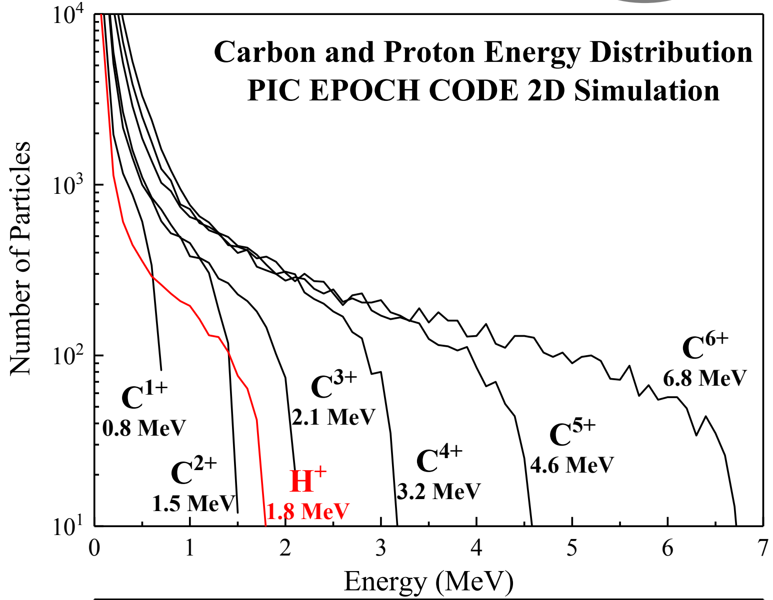
It is responsible for the forward ions acceleration; FWHM ~ 50 *fs* comparable with the duration of the laser pulse (45 *fs*).

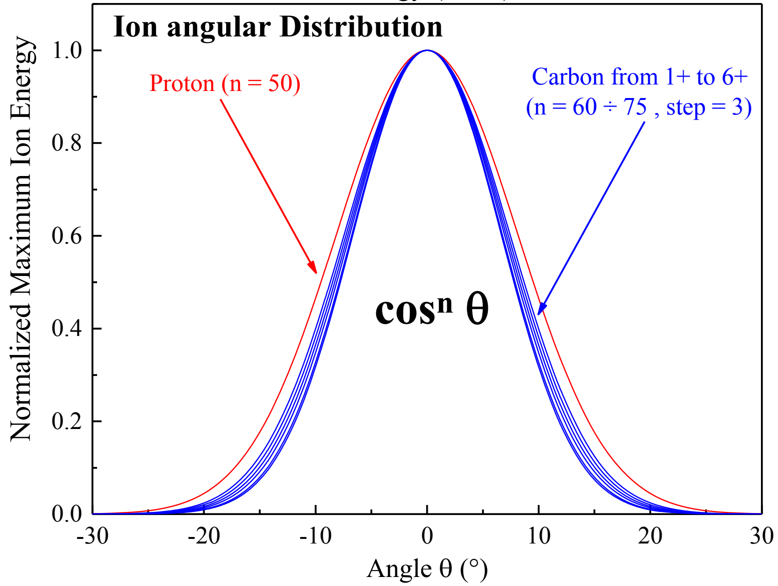
Electrons and Ions Energy



The Plasma Temperature is in agreement with the theoretical evaluation:

$$kT = m_0c^2\left(\sqrt{1+\frac{I_0\lambda_L^2}{1.37\cdot 10^{18}}}-1\right)\cong 354\ keV$$

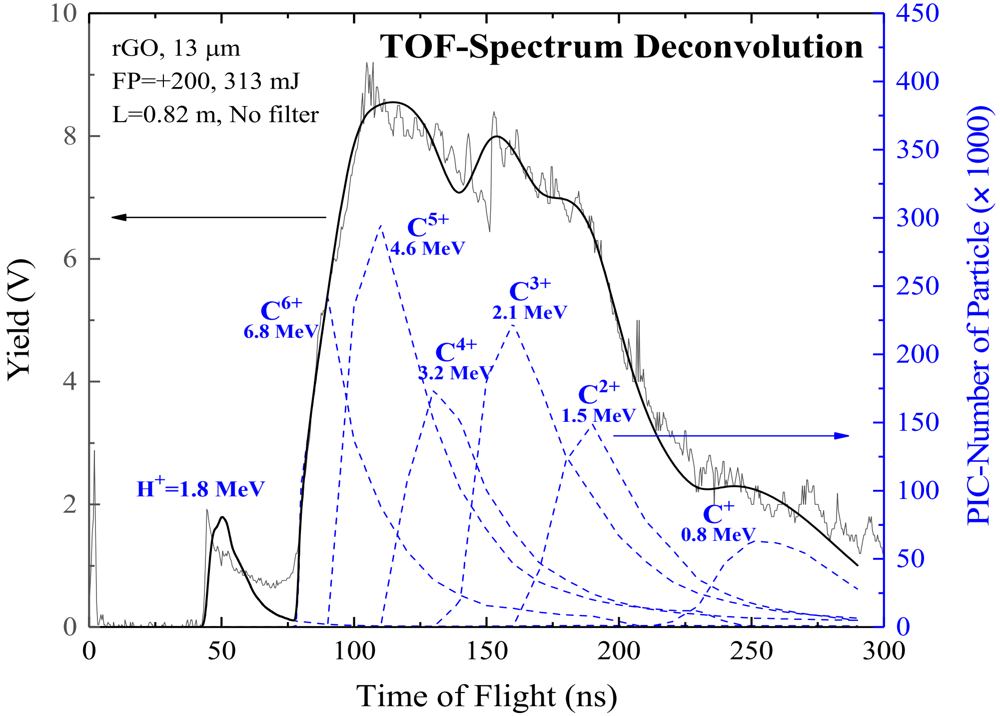




L. LASKA, et al. *Laser and Particle Beams*, **26**, 555–565 (2008).

M. ROTH AND M. SCHOLLMEIER, *Springer International Publ*, 231-270 (2016).

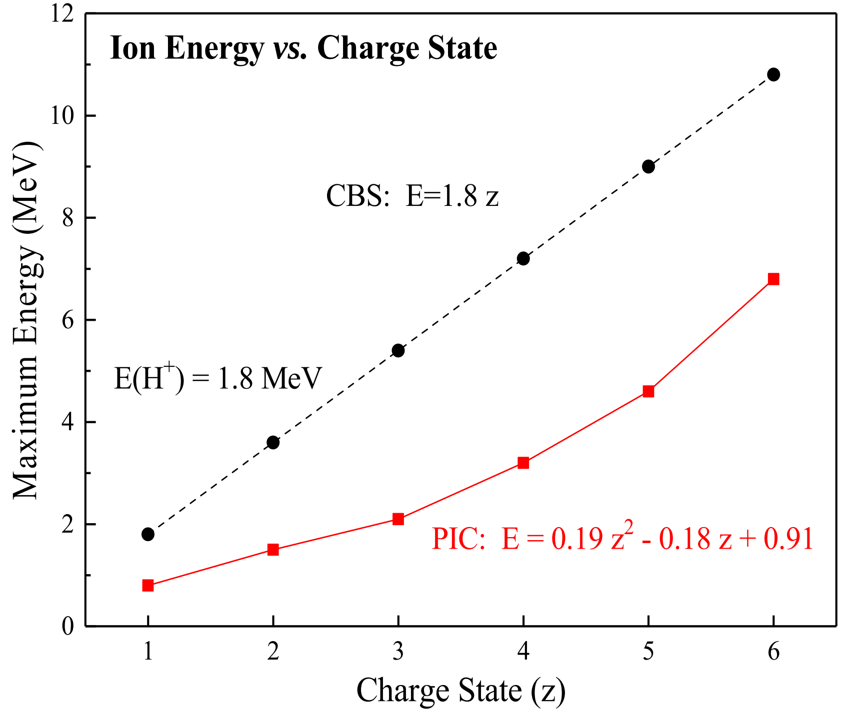
Deconvolution



Correlating the PIC ion energy distributions with the angular distribution of particles, it is possible to deconvolve the TOF ion spectrum in the different ion contributions. Higher ionized states of carbon ions are responsible of the maximum contribution, due to their angular distribution more peaked with respect to the lower charge states and to the protons.

Comparison between CBS and PIC Results

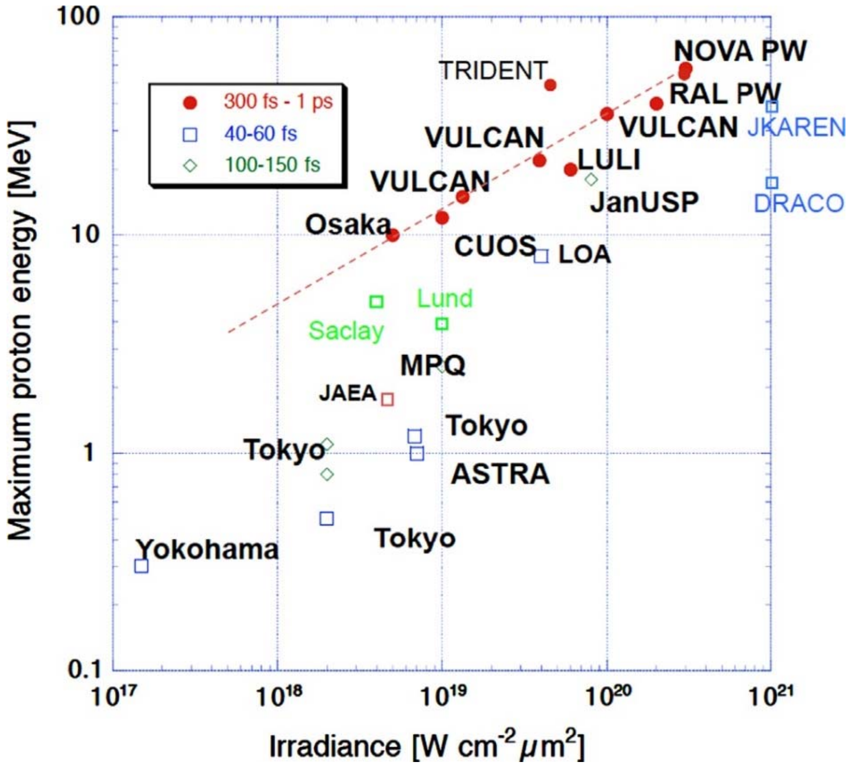
CBS is applicable to lower laser intensities and to higher laser pulse durations, as reported in the literature, and demonstrates that its application for intensities above 10^{18} W/cm^2 can be only approximated.



L. TORRISI. *Rad. Eff. and defects in Solids* **171**(1-2), 34-44 (2016).

Conclusions

- TNSA Regime can accelerate protons approaching energy of hundreds MeVs.
- Comparison between the particle-in-cell method and the experimental results allows to understand what is happening within the system, evaluating electric fields, density profiles and more.
- CBS energy distribution is valid for long laser pulses; for shorter pulses, the electric acceleration field decay rapidly and the ions are not all affected by the same field.



Future Perspectives

We will continue to compare the experimental results at higher ions energies with the PIC method, in order to study the dynamics of laser-matter interaction and optimize them.

M. Borghesi. *Nucl. Instr. and Meth. in Phys. Res. Sec. A* **740**, 6–9 (2014).

A. Macchi, A. Sgattoni, S. Sinigardi, M. Borghesi and M. Passoni. *Plasma Physics and Controlled Fusion*, **55**(12), 124020 (2013).

M. Passoni, V.T. Tikhonchuk, M. Lontano and V.Yu. Bychenkov. *Physical Review E*, **69**(2), 026411 (2004).

Acknowledgements

Dr. Ing. Jan Pšikal (*Czech Technical University in Prague, Czech Republic*)
Dr. Marcin Rosiński (*Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland*)

Thank you for your attention!