Study of target heating induced by fast electrons in mass limited targets

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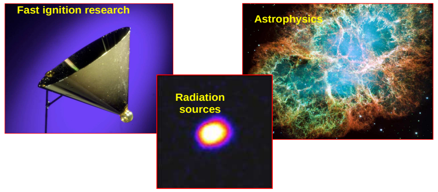
High Energy Density Physics

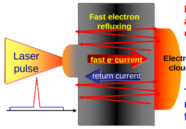
The experiment goal is the creation of extreme states of matter defined High Energy Density Matter (HEDM) at solid density via fast electrons energy deposition.

A step forward in many research fields



Fast electrons

The interaction of Ultra High Intensity lasers with matter leads to the generation of fast electron beam that propagates in target



For intensities up to 10^{17} W/cm² many accelerating processes occur at the plasma critical density:

$$n_{cr} = \gamma \frac{1.1\times10^{21}}{\lambda^2(\mu\mathrm{m})}\mathrm{cm}^{-3}$$

The fast electron energy in the intensity range 10^{17}-10^{19} W/cm² is given by the Beg formula:

$$T_{hot} = 100keV \times \left(\frac{I(W/cm^2)}{10^{17}}\right)^{1/3} \lambda^2(\mu m)$$

The fast electron distribution function shape is still under investigation, for the calculations it will be assumed maxwellian

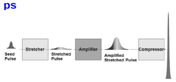
$$f(E) \approx E^{1/2}\exp(-E/T_{hot})$$

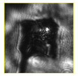
or even a relativistic Maxwellian

Isochoric heating

The isochoric heating requires the energy to be delivered istantaneously compared with the typical time scale length of plasma expansion, typically ~ $10^2 - 10^3$ ps

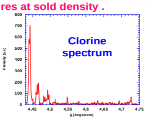
Ultra high intensity laser are devices capable to produce such fast heating due to the very short pulse duration and to focalize the energy in very small regions



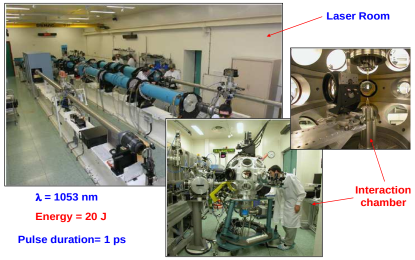


Mass limited targets are necessary to concentrate the energy in a small amount of matter, reaching high temperatures at sold density .

High resolution spectroscopic analysis is required to determine the plasma temperature and density



50 TW Alisé facility



λ = 1053 nm

Energy = 20 J

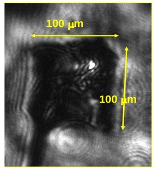
Pulse duration= 1 ps

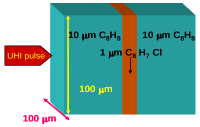
Mass limited targets

Low Z plastic material has been used for mass limited targets. It allows the study of plasmas close to the ICF and astrophysical conditions

M = 200 ng

V = 2.1×10^{-7} cm³





With 10J of laser energy we reach the HEDM condition:

$$\frac{10J}{2.1\times10^{-13}m^3} \approx 5\times10^{13}J/m^3$$

Targets

Other kind of targets have been used to study polarization spectroscopy and fast electron transport

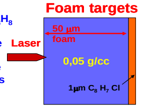
2mm x 2mm x2mm targets   m ≈ 9×10^{-3} g

The 1 μm $C_2H_2Cl_2$ tracer layer is buried in C_8H_8 at different dephts from 0 to 10.5 μm to study the VDF shape on the surface and inside the target

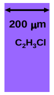
10.5 μm overcoating are compared with mass limited targets

Foam targets

Targets made of C_8H_8 foam have been used to study the fast electron propagation. The 1μm tracer layer is on the back.



Thick C_2H_3Cl (PVC) targets, for diagnostic alignment and to get a Clorine spectrum from the critical layer

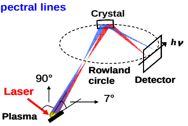


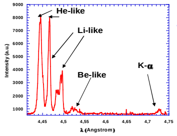
Spectrometer

A thoroidally bent Bragg crystal spectrometer has been used to collect the high energy spectral lines

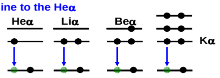
The spectrometers look at the target front side with an angle of 7° to the target surface collecting the normal and parallel polarization

The Heα line is reflected at 41.7° Bragg angle



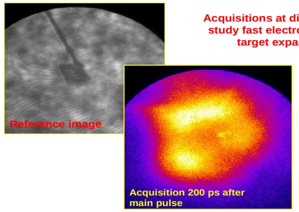


The high energy Clorine spectrum is recorded, in the range 4.4 Å - 4.75 Å, from the "cold" Kα line to the Heα



Gated optical imager

The Gated Optical Imager (GOI) is composed by a CCD camera looking in the visible domain coupled with a ultra-fast shutter that allows acquisitions with a temporal window width of 120 ps FWHM

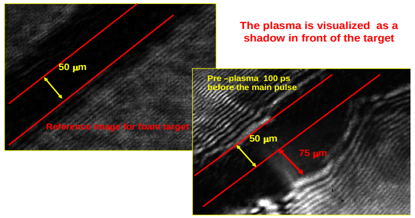


Acquisitions at different time delay to study fast electron propagation and target expansion velocity

The GOI is looking at the target rear surface with an angle of 38° to the normal

Transverse shadowgraphy

A 2ω, 537 nm, compressed probe beam passes transversely on target. reflected by plasma which density is $n_e \geq n_c = (2\omega)^2\varepsilon_0 m_e/e^2$ revealing th
dense plasma on target front side

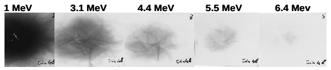


The plasma is visualized as a shadow in front of the target

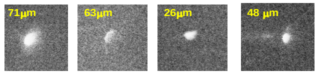
RCF and Pin Hole

Proton signal from foam targets is the most energetic

e accelerating field is: $E \sim \frac{T_e}{e\lambda_{de}}$ Depends on fast electron temperature and density

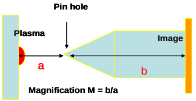


n the Pin Hole images of massive and foam targets results that the average spot size is ~ 50μm, this value will be assumed as laser focal spot size

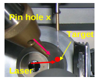


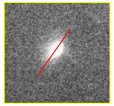
Pin Hole X

Pin hole x looking at the target front side, acquiring the x ray emission from the high density plasma

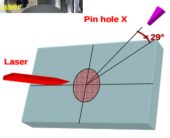


Magnification M = b/a





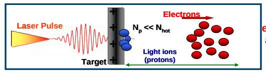
The longest axis corresponds to the plasma size



The Pin Hole X was looking with an incidence angle of 29°

Proton diagnostic

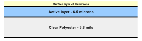
The fast electrons reaching the target rear side set up a huge electric field that accelerates ions from the target rear surface



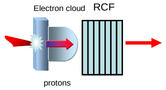
The generated quasi static electric field is up to 1 Mev/μm and it can accelerate protons up to several MeV

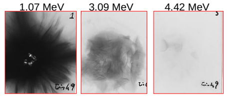
This model is known as Target Normal Sheath Acceleration (TNSA)

To diagnose protons, stack of radio chromic film (RCF) have been used



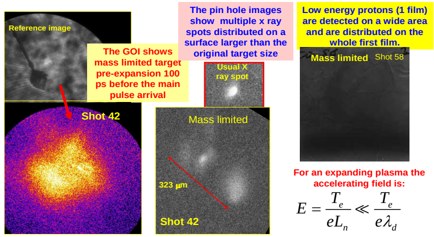
The active layer becomes dark showing the proton path





Pre-pulse effect

A strong pre-pulse effect on mass limited target has been clearly observed by all the diagnostics



The GOI shows mass limited target pre-expansion 100 ps before the main pulse arrival

The pin hole images show multiple x ray spots distributed on a surface larger than the original target size

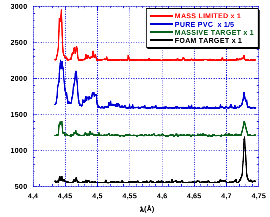
Low energy protons (1 film) are detected on a wide area and are distributed on the whole first film.

For an expanding plasma the accelerating field is:

$$E = \frac{T_e}{eL_n} \ll \frac{T_e}{e\lambda_d}$$

Spectra comparison

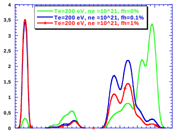
From the spectra appears clear that the highest temperature is reached w
mass limited targets, looking at the ratio between He α and Li satellites. T
"cold" Kα signal increases when ionization decreases

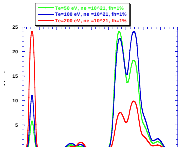


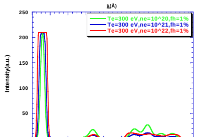
Simulations

Simulations are required in order to determine the plasma temperature

Three parameters have been varied: the background electron T_e, the fast ctrons fraction f_{hot} and the electron density N_e

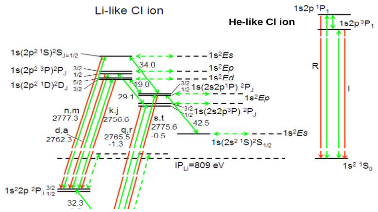






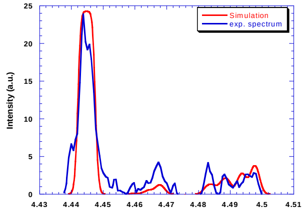
Kinetic Model

Graphical representation of the kinetic matrix . Green arrows represent collisional transitions while red arrows radiative transitions



Spectra matching

The spectrum for mass limited target best matches with the simulation for $N_e = 10^{21}/cm^3$, T_e=300 eV, T_{hot} =100 keV, f_h= 0.1%



Energy balance

Assuming a focal spot diameter of 50μm as measured from the pin hole images and a laser energy of 12 J it's possible to calculate the main pulse intensity on target : 6 x10^{17} W/cm²

The hot electron temperature is given by the Beg's formula:

$$T_{hot}(keV) = 100\times\left(\frac{I(W/cm^2)}{10^{17}W/cm^2}\right)^{1/3}\lambda^2(\mu m) \approx 200keV$$

The total number of electrons in the target is **7x10^{16}** and the ion number is **Ni ~ 1/3 Ne**, taking into account the energy in the pre –pulse **E_{pre} = 1.8J** and **0.74 J** of ionization energy we found that the total energy on target is:

$$E_{tot} = E_{pre} + E_{ion} + E_{be} + E_{ion} + E_{hot} = 9.3J$$

Omega EP

Omega EP laser facility represents a unique opportunity to improve the experiment, thanks to the larger energy – intensity on target.

If we consider the Omega EP Maximum Intensity beam ~2x10^{20}W/cm² , assuming contrast ratio of 10^{-7}, the pre-pulse intensity is almost equal to the Alisé one.

The ablation pressure produced by a 2x10^13W/cm² beam is given by

$$P_a(Mbar) = 12\times\left(\frac{I(W/cm^2)}{10^{14}W/cm^2}\right)^{2/3}\times\lambda_{\mu m}^{-2/3} = 4Mbar$$

The correspondent shock wave velocity in C_8H_8 plastic is 31000 m/s and the tra
layer would be reached 320 ps after the pre-pulse action. There are three possibilities to keep high density

Cut the pre pulse or strongly reduce its intensity to decrease the

Reduce the pre pulse duration, i.e using fast pockels cell

Use tamped targets to preserve the tracer layer at solid density, keeping the mass