Thomson Spectrometer for ionic acceleration study
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Abstract - This report describes the development of a powerful and self-consistent technique to be used as a diagnostic tool for the ionic acceleration study in laser-generated plasmas.

INTRODUCTION
Recent developments in laser technology allow to generate high-density and high-temperature plasmas by means of laser-matter interaction, therefore it is possible to produce and accelerate ion beams in the multi-MeV energy range \cite{1}, \cite{2}. An important diagnostic for analysing these ion beams is the Thomson Parabola Spectrometer (TPS) \cite{3}. This is used to measure the energy spectra of different ion species in a given solid angle. Magnetic and electric fields are used to detect ions according to their velocity and charge-to-mass ratio. It is a particularly useful diagnostic of laser-plasma interactions in which a range of ion species are accelerated. This spectrometers are usually equipped with CR-39 or radiochromic films as the position-sensitive ion detector, which allows to obtain information on energy, number of ions, etc., but do not show the image instantly. Otherwise, with a microchannel plate coupled to a phosphor screen (MCP-PH) and a conventional reflex camera it is possible to observe online the spectrogram and in single shot measurements. Moreover, MCPs allow to detect even low number of ions with a spatial resolution of some tens of microns. The spectrogram analysis is difficult because is necessary determine the spectrogram origin location and the spatial resolution depending on the trace width. For this reason TPS are often used in series with time-of-flight detectors. By means of the calibration of TPS we have developed a powerful and self-consistent technique for spectrogram analysis \cite{3}. In this contribution we report on the results of an experimental measurement performed with a TPS developed at INFN-LNS \cite{4}.

EXPERIMENTAL SET-UP
Different measurements were carried out at INFN–LNS and at CNR–INO. At LENS laboratory (Laser Energy for Nuclear Sciences) in Catania a Q-switched Nd:YAG laser with $10^{12}$ W/cm\textsuperscript{2} laser intensity, 1064 nm fundamental

wavelengths, 6 ns pulse duration, operating in single shot mode, was employed to ablate a 2 mm thick aluminum target in order to produce the plasma.

At ILIL (Intense Laser Irradiation Laboratory) in Pisa a femto-source Ti:SA oscillator with a 200nm bandwidth and 20fs pulse duration was used. The laser beam irradiates solid thin foils in Target Normal Sheath Acceleration (TNSA) regime in order to generate non-equilibrium plasma in forward direction i.e. in the rear side of the target. Ion acceleration emitted from plasma was monitored employing the TPS. It is composed by two pinholes to collimate the ions; the first is 1 mm in diameter and the second, 10 cm distant, is 100 \textmu m in diameter. Later, a deflection sector composed by an electric and a magnetic field partially overlapping with each other is placed. The applied magnetic fields and an electric voltage was applied across two deflecting plates, producing an electric field orthogonal to the direction of the incident ions. After passing the drift region, which allows to increase the particles deflection and separation among different traces, the ions position is detected using a imaging system. A microchannel plate coupled to a phosphor screen 2 cm in diameter and a reflex camera is used to acquire the produced light \cite{4}.

Working principle
The resulting ion dispersion, assuming uniform magnetic (B) and electric (E) fields, can be calculated using the follows equations \cite{5}:

$$x_m = \frac{Q e B m \left(\frac{L_m + L_e}{2}\right)}{\sqrt{2mE_{kin}}}$$

$$y_e = \frac{Q e E_e \left(\frac{D_m + D_e}{2}\right)}{2E_{kin}}$$

(1)

where $x_m$ and $y_e$ are the deflection measured with respect the origin, $Q$ is the charge state of the ion, $e$ is the charge of the electron, $m$ is the ions mass, $E_{kin}$ is the kinetic energy, $B$ and $E$ are the applied magnetic and electric fields, $L_m$ and $L_e$ are the geometric length of the magnet and the electrodes, $D_m$ and $D_e$ are the drift between the end respectively of the magnet or of the electrodes and the detector.
Combining the equation of magnetic and electric deflections it get the parabolic equation:

\[
y_e = \frac{mE_y}{QeB^2r^2_m}\left(D_m + \frac{L_m}{2}\right)^2
\]

which means that ions with the same charge-to-mass and different energies are deflected on a parabolic trace on the detector screen. Because the magnetic and electric deflections have a hyperbolic dependence on the energy, it is possible, note the deflection, to derive the kinetic ions energy from the equations (1) and (2) as follows:

\[
E_{\text{kin}} = \frac{A_m}{x_m^2} \quad \text{or} \quad E_{\text{kin}} = \frac{A_e}{y_e}
\]

**RESULTS**

In this section, analysis of spectrograms is described. The spectra contain a bright halo, which constitutes the origin of the parabolic ion traces, due to x-radiation and neutral particle produced by the laser-plasma interaction propagating straight through the electromagnetic field and parabolic traces associated to protons and other ions outgoing from the bright region.

Along a parabola, the energy gradually decreases from the origin towards the edge of the detector. In the spectrograms, the electrical and magnetic deflections are normalized to the respective fields in order to no have dependence from the spectrometer geometry.

In particular, the image shown in Fig. 1 represents a typical TPS spectrum obtained by irradiating a 2 mm thick Al target.

Protons and ions aluminium are observed: the proton maximum energy is 5 keV, while the Al ions have a maximum energy of 35 keV.

It is no possible to well-spatially resolve the aluminium charge states because the TPS is optimized for higher energy. In Fig. 2 is shown the spectrogram obtained irradiating a Mylar thin target at intensity of \(10^{19}\) W/cm\(^2\) (TNSA regime).

**CONCLUSION**

Thomson Parabola spectrometer can provide useful detailed information on physical processes, ion species and charge states generated in single-shot laser experiments. Moreover, the use of MCP as the position-sensitive detector gives us the ability to measure the ion image online, immediately after the laser shot.

By means of the calibration of TPS it was possible obtain the kinetic energy of different ion species with a self-consistent technique.

**REFERENCES**