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ANGULAR-RESOLVED THOMSON PARABOLA SPECTROMETER FOR LASER-DRIVEN ION ACCELERATORS

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Abstract

Laser-plasma driven accelerators have become reliable sources of low-emittance, broadband and multi-species ion beams, presenting cut-off energies above the MeV-level. We report on the development, construction, and experimental test of an angle-resolved Thomson Parabola (TP) spectrometer for laser-accelerated multi-MeV ion beams which is able to distinguish between ionic species with different q/m ratio. The angular resolving power is achieved due to an array of entrance pinholes and it can be simply adjusted by modifying the geometry of the experiment and/or the pinhole array itself. The analysis procedure allows for different ion traces to cross on the detector plane, which greatly enhances the flexibility and capabilities of the detector. A full characterization of the TP magnetic field has been implemented into a relativistic code developed for the trajectory calculation of each beamlet. High repetition rate compatibility is guaranteed by the use of a MCP or plastic scintillator as active particle detector. We describe the first test of the spectrometer at the 1 PW VEGA 3 laser facility at CLPU, Salamanca (Spain), where up to 15 MeV protons and carbon ions from a 3-micron laser-irradiated metallic foil are detected. A second set of experimental measurements is shown, where highly magnified traces are obtained which leads to a possible transversal beam emittance estimation.

INTRODUCTION

Since the invention of the Chirped Pulse Amplification [1], the range of accesible light intensities on focus for ultra-bright lasers has only increased. Such enhancement paved the way for laser-plasma particle accelerators (LPA), mainly focused on ions [2] and electrons [3]. The applications of such accelerated beams profit from the low-emmitance and ultrashort duration of the beams, wel-fitted characteristics for practical employments. Specifically, since the demonstration of collimation and monochromatisation of LPA multi-MeV ion beams [4, 5], their potential employments have attained plenty of attention, including ultrafast proton probing [6], isochoric heating of dense plasmas [7], fast ignition of inertial confinement fusion reactions [8] and medical purposes [9] among others.

Due to the specific LPA beam characteristics, one of the most widely used diagnostics for laser-driven ion accelerators are Thomson Parabola (TP) spectrometers [10]. First developed by Thomson in 1907, they are in-line diagnostics which sort the particles depending on their energy, momentum and charge-to-mass ratio. The latter is specially useful in LPA scenario where the acceleration of multi-species beam is frequent. The main drawback of TPs is the incapability of deconvolving the spatial distribution of the measured beam as only a particular angle of the beam with an insignificant spread is evaluated because of the use of an entrance pinhole mask. Previous studies with different detectors, focused on analysing the spatial structure of the beams, showed that the most common laser based ion acceleration mechanism, the Target Normal Sheath Acceleration or TNSA [2], emits extraordinarily low-emittance beams from a source with a diameter as big as a few hundreds of micrometers and a total beam divergence of 20°. In order to retrieve spatial information about the beam other methods could be use, as stacks of radiochromic films or scintillators [11] which nevertheless fail when attempting to have fine spectral resolution. We present a multi-pinhole Thomson Parabola spectrometer, which combines sharp spectral and angular accuracy, besides the ionic species sorting capability.

DESIGN

Thomson Parabola spectrometers work according to magnetic an electric sector spectrometer principles. The entrance pinhole selects a beamlet composed by ions with specific q/m. Parallel (or anti-parallel) magnetic (B) and electric (E) dipoles deflect the ions in orthogonal directions. Such particles are detected in a two-dimensional spatially resolved particle-sensitive detector. In paraxial approximation with perfect fields, the particles will draw a parabolic trace onto the detector (given simply by Lorentz force) as

$$y^2 = \frac{q}{m}\frac{B^2 l_2 l_3}{E}x, \qquad (1)$$

where l_2 dipole length, l_3 the particle free-flight distance after the deviation, being the fields parallel to the x-axis. As seen, different charge-to-mass ratio particles will describe different traces and the position of the particle onto the trace will describe its kinetic energy.

We propose a modification of the basic TP design which consist on the substitution of the entrance pinhole by a mask in which several pinholes are drilled. The array of holes chops the incoming beam into several beamlets which are simultaneously detected, resulting in a tomography-like spectral measurement with tunable spatial-resolved information [12]. Figure 1 shows the basic device design.

Previous works [13–15] showed similar measurement strategies but most of the cases dismissing the electric field (and therefore the q/m differentiation) or limited their detec-

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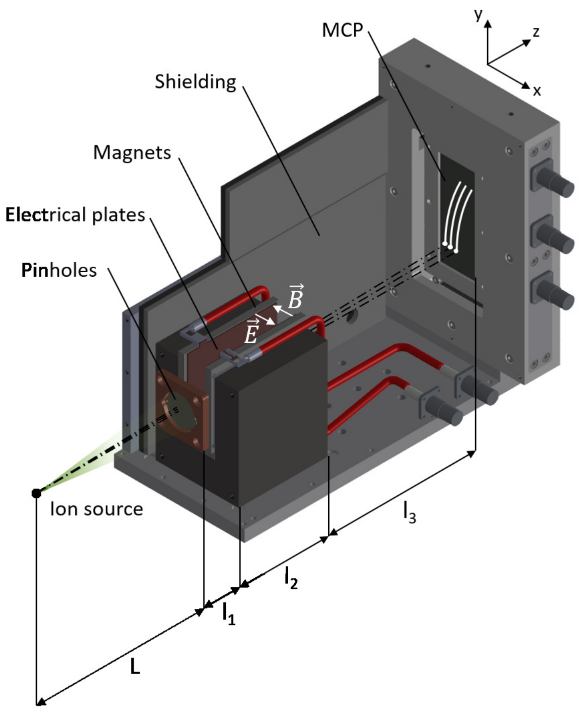

Figure 1: Multi-pinhole TP spectrometer design.

tion geometries in order to avoid crossing traces on the detector [16]. We propose a more general approach of such device which can apply the electric and magnetic field for identifying different q/m ions and measuring their spectrum at different beamlets backed by a generic post-processing methods which accounts for trace crossing. A three-dimensional numerical solver was developed for trajectory simulation and provides the expected traces and the energy-position relation for the required species, which includes a Hall probe characterization of the magnetic field. In the presented configuration proton energies between 300 keV and 25 MeV are accessible; uncertainty at 20 MeV has been estimated to be around 1 MeV.

Trace crossings at the detector produce peak artifacts in the spectrum. Interpretation of such events starts with the identification of the species involved in each cross. Only artifacts producing significant distortion are treated; the peaks that are still observable after applying a Gaussian smoothing over the data are removed, by removing the relevant peak width and performing a linear interpolation between the gap edges. Such interpolation is considered to follow the data trend within its root main squared deviation.

EXPERIMENTAL TESTS

In this section we show two experimental tests of the detector performed under different experimental conditions. Both were performed at the VEGA 3 petawatt laser facility at Centro de Láseres Pulsados (CLPU, Spain). VEGA 3 is a Titanium:Sapphire system ($\lambda = 0.8$ µm) which delivers p-polarized pulses, up to 30 J and as short as 30 fs. The pulses are focalized by a F/11 off-axis parabolic mirror into a 10 µm full width at half maximum, which implies an averaged laser intensity over 10^{19} W/cm^2. The target was a micrometric-thick Al planar foil irradiated at 10° from the target normal in the horizontal plane.

Low Spatial Resolution Test

In this first commissioning test ion acceleration was detected by the multi-pinhole set at a distance from the source $L = 508$ mm. A microchannel-plate (MCP) attached to a phosphor screen was used as active detector, which has the advantage of being well-fitted for high repetition rate (HHR) operation. As shown in Fig. 2, traces were imaged onto a scientific CMOS with a calibrated imaging system. The mask in this case was made of a W substrate with $n = 3$ drilled pinholes of $d = 200$ µm evenly separated by $a = 3$ mm.

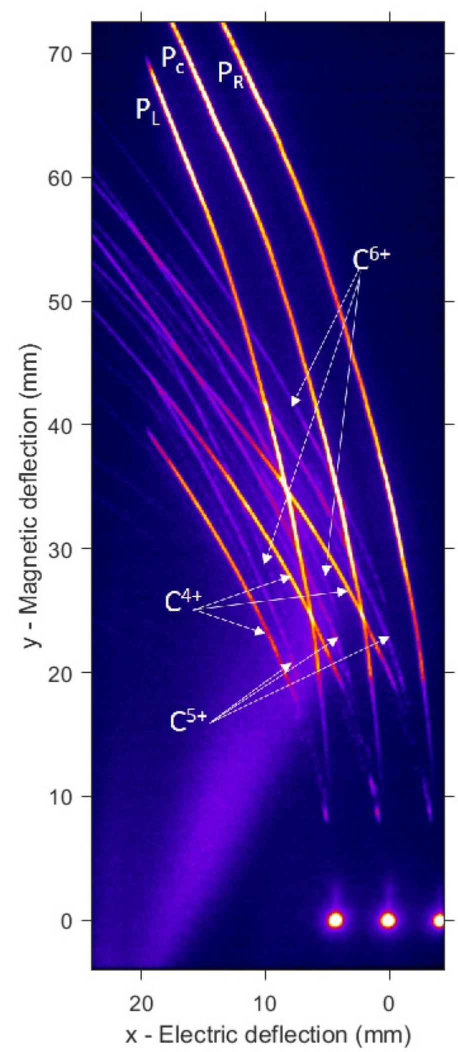

Figure 2: Multi-pinhole TP traces from a single laser shot at VEGA 3.

A single beamlet proton spectrum is plotted in Fig. 3, together with the traces intersection signal which are removed.

In such geometrical configuration, the separation between the angles probed ($\alpha \approx a/(L) = 0.3°$) is small when com-

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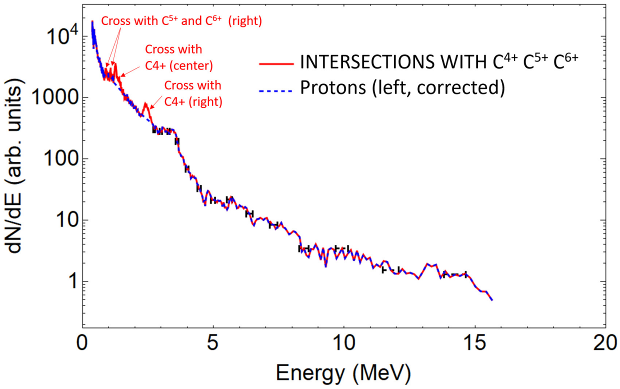

Figure 3: Left beamlet proton (P_L) spectrum from Fig. 2. Dashed blue: corrected spectrum. Red: raw spectrum.

pared to the total divergence of the beam. Therefore modest differences between different beamlet spectra are expected. Such conjecture is confirmed after the data analysis, as seen in the spectra shown in Figs. 4 and 5. For sake of comparison Fig. 6 shows the spectra of different ion species of the same beamlet.

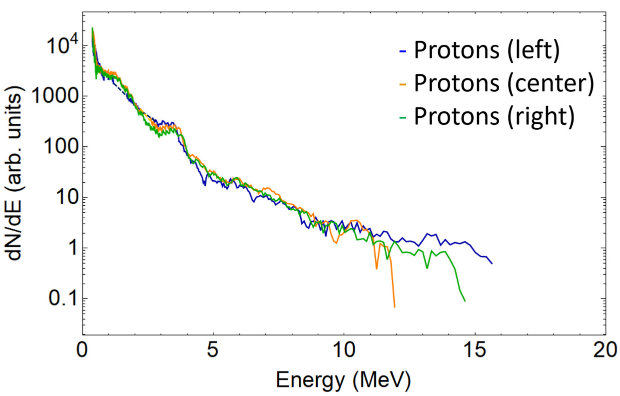

Figure 4: Left, center and right proton beamlets (P_L, P_C and P_R) spectra from traces of Fig. 2.

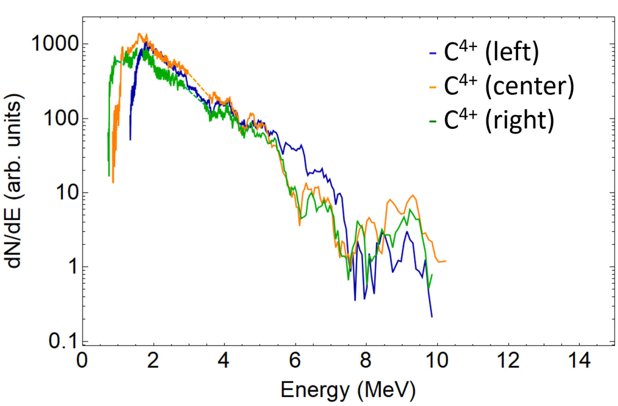

Figure 5: Left, center and right C^{4+} beamlets spectra from traces of Fig. 2.

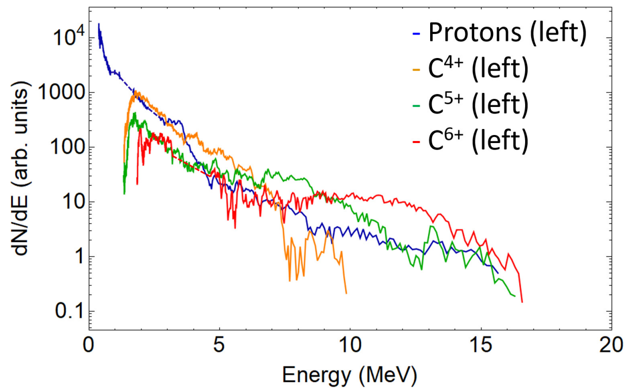

Figure 6: Left beamlet spectra for protons P_L and C^{4+}, C^{5+} and C^{6+} from traces of Fig. 2.

High Spatial Resolution Test

The results of a second test are shown, whose goal was attempting to improve as much as possible the spatial resolution of the detector. For such purpose, the experimental geometry was accordingly modified mainly by bringing the detector closer to the interaction point ($L = 15$ mm, $n = 13$, $a = 500\,\mu$m, $d = 100\,\mu$m). Such change results in larger beam area measured and greater angular separation between beamlets ($\alpha = 2°$) and higher acceptance of each pinhole, therefore producing thicker traces. For this case a HHR-compatible scintillating screen BC-400 was directly used as active detector. A 12 µm thick pokalon (plastic) foil was used to protect the scintillator from optical radiation and simultaneously shield it against heavier ions. As only protons where detected after the shielding, q/m was unique for all particles and electric field was switched off. A Lanex scintillating screen was used for measuring the x-ray non-deflected reference point of each pinhole.

Figure 7 shows the typical proton traces of this experimental test. Observable cut-off energy is approximately 15 MeV, similarly as in the previous test. Clear features (as trace thickness and direction) are identified to change at different energies. Following the working principle of the pepper-pot method [17], from such data it is in principle possible to infer, in a restricted area of the full beam profile, the spectrally-resolved horizontal phase-space of the beam and therefore estimate the local rms horizontal emittance ϵ considering that

$$\epsilon_x = \sqrt{< x^2 >< x'^2 > - < xx' >^2}, \qquad (2)$$

where x is the particle transverse position and x' its transverse momentum.

CONCLUSION

A newly developed diagnostic tool is presented. Its operation is based on the Thomson Parabola working principle and therefore able to differentiate between ionic species and presents a fine and wide spectral range of detection, which makes it well-fitted to measure characteristics of typical laser-driven ion beams. Furthermore, tomography-like

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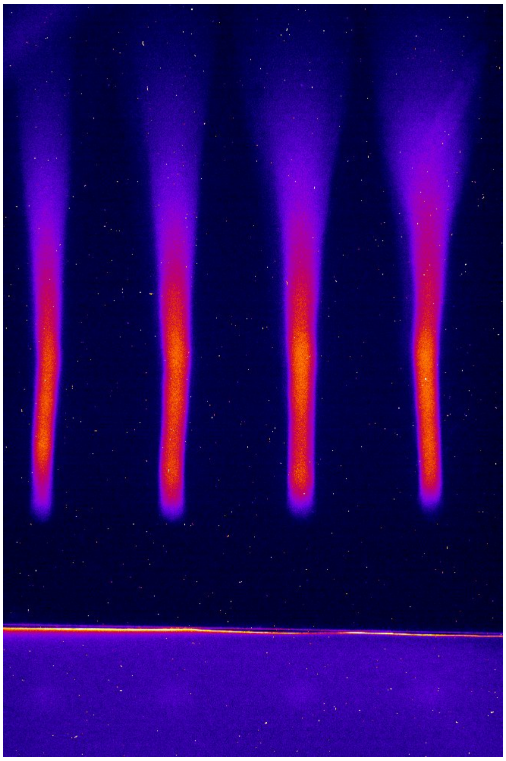

Figure 7: Proton traces at highly magnified experimental test.

measurements of the beam with varying angular resolution—depending on the detecting geometry—can be performed thanks to a mask of entrance pinholes. A post-processing method is introduced, making it possible to account for trace crosses at the detector plane. Moreover, a feasible method for specie/spectrum-resolved (restricted) phase-space estimation with the device is presented. Such simultaneous study of beam parameters makes this tool practical for characterization of LPA beams, which present a high degree of laminarity [18] and therefore are well adapted for possible application after beamline transport [19].

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