Measurements with an innovative high energy resolution Thomson Parabola Spectrometer

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Abstract

In recent years a new concept of particle acceleration has gained interest. It is based on high power, short pulse lasers interacting with thin metal foils. In the interaction process the target is suddenly ionized and the charge separation, originating from different phenomena, can efficiently accelerate ions and in particular protons from the target impurities. The peculiar characteristics of laser-driven beams are extremely promising and, moreover, the laser-based accelerators are expected to be more compact and less expensive than conventional machines. Recently, a great interest has been devoted to the multidisciplinary applications of this new kind of beams, in particular to the development of a new concept of hadrontherapy centers. In order to reach this goal a new project, maned ELIMED (MEDical and multidisciplinary application at ELI-Beamlines), has been launched between FZU (Fizikalny Ustav, CZ) and LNS-INFN (Laboratori Nazionali del Sud - Istituto Nazionale di Fisica Nucleare, IT). Several European research institutes with expertise in different fields are now involved in the project. In the development of a dedicated beam transport line, beam diagnostic is a crucial task since it allows to control and select the different beam components in terms of energy and q/m and, also, to have information on the laser-matter interaction. An high energy resolution Thomson Parabola Spectrometer (TPS) has been already realized and successfully tested at PALS in 2012. Recently, the TPS has been upgraded and tested in other experimental runs allowing to obtain better results.

Introduction

Charged particle acceleration is one of the main applications of high power lasers. High-current multi-MeV proton beams are expected to be produced in the interaction of ultra intense

($10^{18}\,\mathrm{W/cm^2}$) short pulse ($30\,\mathrm{fs} - 10\,\mathrm{ps}$) laser with thin solid foils [1]. Up to now, the highest proton energy have been reached using the Target Normal Sheath Acceleration (TNSA) mechanism [2]. In TNSA an intense laser pulse is focused on a thin metal foil so that the energy is transferred to electrons on the front target surface. These electrons propagate through the target generating an intense electrostatic field of the order of some TV/m which is responsible for proton acceleration. The proton bunch has a duration of the order of the laser pulse and is characterized by a large angular divergence ($20^\circ - 30^\circ$) and an exponentially decaying energy distribution ranging from few KeV to a maximum cut-off value. Other acceleration mechanisms have been studied in literature, as for instance the so called Radiation Pressure Acceleration (RPA) [4]. Radiation pressure effects dominate over the TNSA regime for laser intensities greater than $10^{23}\,\mathrm{W/cm^2}$; this regime is expected to be available within the ELI (Extreme Light Infrastructure) project [5]. ELI is an European large scale infrastructure based on three laser facilities located in different countries and dedicated to different research fields from nuclear physics to the attosecond physics. One of the facility, named ELI-Beamlines, is already under construction in Prague (CZ). It will be dedicated to applications of the laser generated photon and ion beams in several fields from high-resolution X-ray imaging to hadrontherapy. One of the secondary sources available at ELI-Beamlines will be dedicated to the demonstration of the applicability of laser driven protons and/or ions for multidisciplinary researches, including future clinical applications, as suggested in [6], thanks to the development and the realization of a beam transport line. A collaboration between groups of researchers from different European countries has been established with the name of ELIMED (MEDical and multidisciplinary application at ELI-Beamlines); a complete description of the project can be found in [7]. Since one of the crucial task to fulfill within the project is the realization of a beam diagnostic system, a TPS has been developed at LNS (IT).

The LNS Thomson Parabola Spectrometer

The TPS is a widely used beam diagnostic system and the basic working principle is described in details in [9, 10]. It is based on mutually parallel electric and magnetic fields acting perpendicularly on a collimated ion beam. The Lorentz force separates the different ion species according to their q/m resulting in a set of parabolic traces on the detection plane. Each parabola corresponds to a well identified ion species. Electric and magnetic deflections depend on energy and momentum of the particles, therefore, in a single measurement it is possible to obtain information on energy, momentum and species of the ions. A new Thomson Parabola has been recently developed at LNS with high dispersive power (up to $20\,\mathrm{MeV}$ protons). The deflection sector consists of electric and magnetic fields partially overlapped so to have a more compact system. The magnetic field is generated by two resistive coils placed inside an H-shaped iron structure ensuring a very good field uniformity. The resistive coils allow to increase the dynamics and the energy resolution of the device since the field intensity can be changed by varying the current. This represents an advantage with respect to the use of permanent magnet based dipoles. The electromagnet length is 15 cm and the maximum field achievable is 2500 gauss. The electric field is produced by two 7 cm long copper electrodes placed 6 cm downstream the magnetic field centre. Using the maximum voltage value it is possible to reach an electric field of 19 KVolt with a 1.8 cm gap, ensuring a very high dispersion power. The possibility of tuning both fields increases the energy range the spectrometer can measure, thus it can be used for detecting very low energy particles. A complete scheme of the deflection sector can be found in [8]. The collimation system consists of two pinholes: the first collimator is a 2 cm thick double layer of copper and lead with a 1 mm hole. It is also used to shield from neutral radiation coming from the plasma. The second pinhole is a 1 mm thick aluminum layer with 100 μm hole. The distance between the two pinhole is 10 cm. The collimation system is designed to let the beam enter out-off the central device axis, in order to exploit the entire surface of the MCP detector, placed at the end of the TPS. In such a way, the low energy part of the ion traces, where the different parabolas are more separated, can be detected by the imaging system so that the spatial resolution is increased. The imaging system consists of an MCP, a phosphorous screen and a conventional reflex camera. Data reduction has been performed using two ad hoc MATLAB based softwares, developed by our group. The simulation tool solves the second order differential equations reproducing the particle motion in the TPS from the collimator to the detector plane. The semi-automatic analysis part of the tool allows to fit the traces, detected with the imaging system, using a second order polynomial function reproducing the parabolic shape of the experimental curves. The tool gives a reference frame with electric (y) and magnetic (x) deflections, the q/m for each trace and the maximum ion energy, corresponding to the parabola experimental point closest to the brightest spot of the spectrogram, i.e. the spectrogram origin. The bright halo is mainly due to the neutral radiation produced in the laser-plasma interaction. The TPS has been successfully tested at PALS laboratory (Prague, CZ) in the 2012, using the ASTERIX IV laser system. After some technical improvements, it has been recently used in another experimental run at the same laboratory and also at the FLAME facility (Frascati, IT). A typical spectrogram is shown in Fig. 1. As it can be seen in the picture, the TPS allows to resolve the different parabolic traces, in particular the first parabola on the right is the proton trace with a maximum energy extracted from the analysis of 540 KeV. The other parabolas are the traces due to the carbon ions, from C^{1+} to C^{6+}, as it has been confirmed from the q/m value obtained with the MATLAB based tools. Moreover, as it has been described in [11], during the last run performed at PALS, a slotted CR-39 detector has been placed upstream the MCP.

The parabolic traces on the track detector are complementary to the TPS parabolas. Therefore, the combined information from the two detectors will allow to calibrate the TPS imaging system in terms of particle number and energy. The data analysis is still in progress.

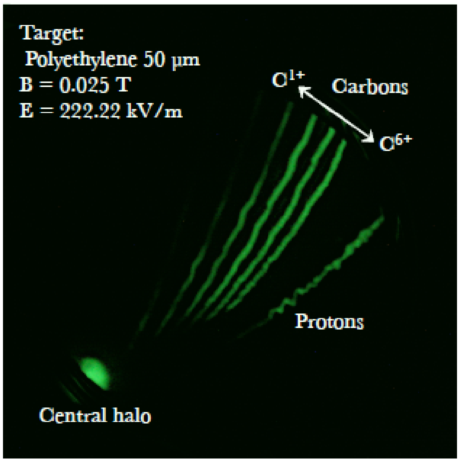

Figure 1: Typical spectrogram.

Conclusion

The TPS described in this work represents a starting point for the realization of a device suitable for high energy ion beams expected to be available at ELIMED in 2017. The calibration performed with the CR-39 is crucial to complete the information retrived with the TPS.

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References

[1] G. Mourou, et al., Rev. Mod. Phys. **78**, 309 - 371, (2006).

[2] S. C. Wilks, et al, Physics of Plasmas **8**, 2 (2001)

[3] M. Passoni, et al., New J. of Phys. **12**, 4 (2009)

[4] A. Macchi, A. Benedetti, NIMA **620**, 1 (2010)

[5] Authors, V., ELI - Extreme Light Infrastructure. White Book. Science and Technology with Ultra-Intense Lasers (2011).

[6] S. V. Bulanov, et al., Plasma Phys. Rep. **28**, 5 (2002)

[7] G. A. P. Cirrone, et al, NIMA preprint, DOI: 10.1016/j.nima.2013.05.051.

[8] G.A.P. Cirrone, et al., Rad. Eff. Def. Solids **165**, 6 - 10 (2010)

[9] M. J. Rhee, Rev. Sci. Instrum. **55**, 8 (1984)

[10] K. Harres, et al., Rev. Sci. Instrum. **79**, 9 (2008)

[11] Prasad et al., NIMA **623**, 2 (2010)