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ELIMED, MEDical and multidisciplinary applications at ELI-Beamlines

F Schillaci[1,2]**, A Anzalone**[1]**, G A P Cirrone**[1,2]**, M Carpinelli**[3]**, G Cuttone**[1]**, M Cutroneo**[9]**, C De Martinis**[10]**, D Giove**[10]** G Korn**[2]**, M Maggiore**[2,4]**, L Manti**[5]**, D Margarone**[2]**, A Musumarra**[1]**, F M Perozziello**[5,]** I Petrovic**[6]**, P Pisciotta**[1]**, M Renis**[7]**, A Ristic-Fira**[6]**, F Romano**[1]**, F P Romano**[1,11]**, G Schettino**[8]**, V Scuderi**[1,2]**, L Torrisi**[1,9]**, A Tramontana**[1,7]**, S Tudisco**[1]

[1] INFN-LNS, Catania, Italy
[2] Institute of Physics of the ASCR, ELI-Beamlines Project, Prague, Czech Republic
[3] Università di Sassari, Dipartimento di Chimica e Farmacia e INFN, Sassari, Italy
[4] INFN-LNL, Legnaro, Italy
[5] Università Federico II di Napoli, Dip.to di Fisica and INFN Sezione di Napoli, Napoli, Italy
[6] University of Belgrade, Vinca Institute of Nuclear Sciences, Mihajla Petrovica 12-14, Belgrade, Serbia
[7] Università di Catania, Catania, Italy
[8] National Physical Laboratory, Hampton Road — Teddington, TW11 0LW — UK
[9] Università di Messina, Messina, Italy
[10] Università di Milano and INFN Sezione di Milano, Milano, Italy
[11] IBAM – CNR, Catania, Italy

e-mail: francesco.schillaci@ct.infn.it

Abstract. ELI-Beamlines is one of the pillars of the pan-European project ELI (Extreme Light Infrastructure). It will be an ultra high-intensity, high repetition-rate, femtosecond laser facility whose main goal is generation and applications of high-brightness X-ray sources and accelerated charged particles in different fields. Particular care will be devoted to the potential applicability of laser-driven ion beams for medical treatments of tumors. Indeed, such kind of beams show very interesting peculiarities and, moreover, laser-driven based accelerators can really represent a competitive alternative to conventional machines since they are expected to be more compact in size and less expensive. The ELIMED project was launched thanks to a collaboration established between FZU-ASCR (ELI-Beamlines) and INFN-LNS researchers. Several European institutes have already shown a great interest in the project aiming to explore the possibility to use laser-driven ion (mostly proton) beams for several applications with a particular regard for medical ones. To reach the project goal several tasks need to be fulfilled, starting from the optimization of laser-target interaction to dosimetric studies at the irradiation point at the end of a proper designed transport beam-line. Researchers from LNS have already developed and successfully tested a high-dispersive power Thomson Parabola Spectrometer, which is the first prototype of a more performing device to be used within the ELIMED project. Also a Magnetic Selection System able to produce a small pencil beam out of a wide energy distribution of ions produced in laser-target interaction has been realized and some preliminary work for its testing and characterization is in progress. In this contribution the

status of the project will be reported together with a short description of the of the features of device recently developed.

1. Introduction

Laser ion acceleration has gained interest over the last years and a wide variety of applications has been proposed to exploit the power of high-current multi-MeV ion (especially proton) beams produced in high-power ($>10^{18}$ W/cm^2) short-pulse (30 fs – 10 ps) laser interaction with thin solid foils [1,2]. Several acceleration mechanisms have been already discussed in literature such as Target Normal Sheath Acceleration (TNSA) regime [3], Coulomb Explosion (CE) [4, 5], Radiation Pressure Acceleration (RPA) [6]. The highest proton energies with best characteristics have been experimentally reached using the TNSA regime as the laser energies required for the other regimes are not available yet. In TNSA an intense laser is focused on a several microns thick target where many processes involving energy transfer between the laser main pulse and the target electrons can occur and, as a consequence, a population of hot electrons with a mean free path larger than the target thickness is produced. Hence, they can cross the target itself setting up an intense electrostatic field due to the charge imbalance between positive ions at rest in the target and the electron sheath expanding at its rear surface, namely in the laser incidence direction [7]. In this field of several TV/m, predominantly protons are accelerated showing a large divergence angle [8] and an exponentially decaying energy spectrum with a spread up to 100 %, these characteristics depending on the laser as well as on target parameters [9]. This would require the development of an angular and energy selection system to make such beams suitable to different applications or the utilization of different mechanisms of laser proton acceleration. There are other acceleration regimes than TNSA which have been identified and investigated with simulations, as the high power laser required for this regimes are not available yet. A part from the TNSA, very promising results have been obtained for the Radiation Pressure Acceleration regime (RPA) which is different for thick (hole boring) and thin (light sail) targets [10 - 13]. Radiation pressure effects start to be progressively more important at very high intensities and they dominate over TNSA at laser intensities $I > 10^{23}$ W=cm^2. The RPA regime could be achieved within the ELI (Extreme Light Infrastructure) project whose main goal is to develop the first petawatt class lasers with very short pulses (from the femto down to the zepto-second regime) with excellent shot-to-shot reproducibility in order to accelerate particles in the ultra-relativistic energy range [14].

2. ELIMED Network

ELI is an European large scale infrastructure developed within the ESFRI process and based on three laser facilities located in different countries and dedicated to different research fields from nuclear physics to the attosecond physics. One of this facility is being implemented in Prague (Czech Republic) and it is named ELI-Beamlines and will be mainly dedicated to applications of the laser produced photon and particles beams in several fields such as high-resolution X-ray imaging, exotic physics etc. One of the secondary sources available at ELI-Beamlines will be dedicated to Multidisciplinary Application of laser-Ion Acceleration, thus the acronym used as name for the beam line is ELIMAIA. An experimental hall of the ELI-Beamline building has been already assigned for the development and the realization of a transport beam-line and will be available for users interested in studying the applicability of laser-driven ions in different fields, including future clinical applications, as suggested in [15]. Around the ELIMAIA beam line a network between groups of researchers from different European and non-European countries has been launched under the name of ELIMED (MEDical application at ELI-Beamlines). One of the motivation of the project is based on the fact that the actual hadrontherapy centres are based on conventional accelerators, such as cyclotrons or synchrotrons which are huge, complex and, hence, expensive machines, both in terms of financial and human resources. These are the reasons why only few centres are available around the

world and the request of proton therapy treatments cannot be fully satisfied. On the other hand, laser-based accelerators could be a competitive alternative as they can be smaller in size and less expensive. Design of miniaturized systems have been already proposed in literature [16] in which the laser-driven ion part is combined to a conventional beam transport system, or in which the acceleration occurs inside a moving gantry [17].

In this context and with the aim to develop a new approach in hadrontherapy, the ELIMED network has been established. The project officially started with a Memorandum of Understanding (MoU) signed between ASCR-FZU and INFN-LNS within the ELI-Beamlines project [18]. The purpose of the MoU is to start a research program whose main aim is to study, design and realize an irradiation facility for dosimetric and radiobiological studies with the high energy proton/ion beams which will be produced at ELI-Beamlines. Several institutes have shown interest in the project and have joined the network. The INFN researchers will be involved in the development of new dosimetric techniques suitable for very high dose-rates, the characterization of laser-driven beams [19], the development of a proton/ion transport line and the carrying out of in-vitro radiobiological studies. Moreover, INFN researchers will be involved in the beam diagnostics with a new Thomson-like spectrometer, whose first prototype has been already accomplished and some results are presented in the following. The energy selection of the beam is an INFN concern as well, and it is crucial in order to produce a beam with spectral and spatial characteristics similar to the ones required for clinical applications. A magnetic system has been realized for this purpose and will be also presented.

3. **The first prototype of high dispersive power Thomson Parabola Spectrometer**
The Thomson Parabola Spectrometer is a widely used beam diagnostics device. The working principle, deeply described in literature [20-23], is based on parallel electric and magnetic fields acting on a well collimated ion beam and the Lorentz force splits the different ion species according to their q-over-m ratio. The result on the detection plane is a set of parabolic traces each of them corresponding to a well determined ion species. Moreover, electric and magnetic deflections are related to the energy and momentum of the particles. Hence a complete set of information on the beam is obtained in a single measurement.

A new Thomson Parabola have been developed at LNS with high dispersive power (up to 20 MeV protons) and high energy resolution. Its deflection sector is made of partially overlapping electric and magnetic fields in order to have a more compact system. The magnetic field is produced by two resistive coils set inside and H-shaped iron matrix ensuring a very good field uniformity. The resistive coils allow to increase the dynamics and the resolution of the device as the field intensity can be changed according to the current used, which is an advantage with respect to the use of permanent magnet based dipoles. The length of the electromagnet is 15 cm and the maximum achievable field is 2500 gauss, corresponding to a 86.2 A current. The possibility to tune the fields increase the energy range detectable from the spectrometer, as it can be used for very low energy particles reducing also the errors in energy evaluation. The electric field is produced by two 7 cm long copper electrodes starting at 6 cm from the magnetic field centre. The electrodes have been designed to stand an electric potential of 30KVolt, ensuring a very strong electric field which which means a very high dispersion power and hence good separation between different ion traces and an very high energy limit (about 40 MeV/amu). A scheme of the deflection sector is available in [24]. The beam is collimated using two pinholes: the first one is an 1 mm hole on a 2 cm thick double matrix of brass and lead which screens from neutral radiation coming from the plasma, the second one is a 100 μm hole on a 1 mm thick aluminium matrix. The distance between the two pinhole is 10 cm. The collimator allows to have the beam entering out-off the central device axis, in order to exploit the whole surface of the MCP detector set at the end of the spectrometer. In this way it is possible to increase the spatial resolution as the low energy part of ions traces, where different parabolas are more separated, is detected by the imaging system. The MCP is the main part of the imaging system which is also made of a phosphor screen and a conventional reflex camera.

The system is completed by a MATLAB based simulation and analysis tool. The simulation part of the tool solves the second order differential equations to describe the particle motion in the spectrometer from the collimator to the detector plane. Computational errors are reduced using the effective magnetic and electric lengths and a symplectic integrator to solve the particle motion. The semi-automatic analysis part of the tool allows to fit traces, detected with the imaging system using a second order polynomial function expressing a parabolic shape of the experimental curves. The tool gives a reference frame with electric (y) and magnetic (x) deflections, the q-over-m ratio for each trace and the maximum ion energy, corresponding to the experimental point closest to the spectrogram center, due mainly to neutral radiation produced in the laser-plasma interaction.

The spectrometer has been successfully tested at PALS laboratory (Prague, Cz) in the 2012, using the ASTERIX IV laser system [25] and, after some improvement it has been recently used for another experimental run at the same laboratory. An example of spectrogram is shown below.
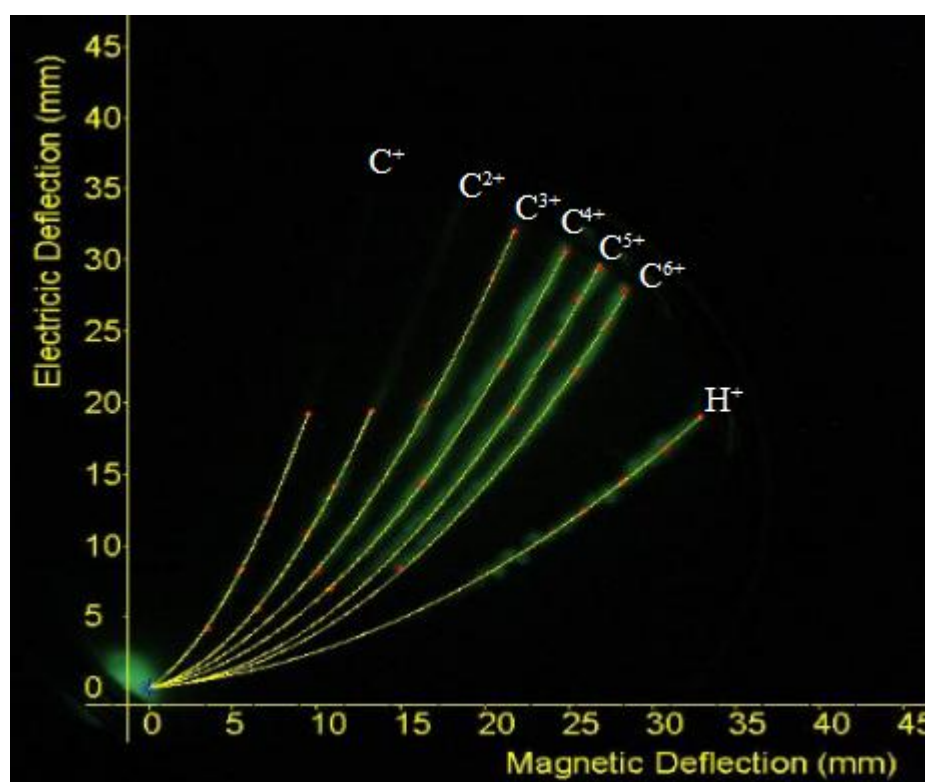
Figure 1. Analysed spectrogram with the MATLAB tool. Each traces on the image is fitted with a second order polynomial, the output of the code are the q/m ration and the electric and magnetic deflections.

The spectrogram has been acquired using a 50 μm thick target of PET (Polyethylene terephthalate) and the Thomson Parabola was set on the target normal in backward direction. Protons parabola is the first from the right side and their maximum energy is about 0.7 MeV. The other set of parabolas is due to carbon ions (C^{+6} to C^{+1}) with maximum energy of q*0.7 MeV, being q the charge state. In the spectrogram it is also evident that the central spot, due to neutral radiation passing the collimator, falls close to the edge of the detector.

During the last experimental run some slotted CR-39 have been used in series with the MCP in order to perform a calibration of the imaging system [26] and to have information on the particle energy spectra. Result will be reported elsewhere.

Moreover an energy calibration of the system will be performed within the end of this year at the LNS Tandem beam in the energy range 6-12 MeV.

4. The Energy Selection System

As stated above, protons from TNSA regime have a huge energy spread and, in view of the potential use of these beams for medical applications, a magnetic energy selection system [27] (ESS) has been realized in order to select particles in a narrow and controlled energy range. An energy calibration have been already performed at LNS using the Tandem beam in the energy range [4-12] MeV in order to characterize the device and validate the GEANT4 simulations. Data analysis is in progress and related results will be published elsewhere. The calibration is crucial for the preparation of the first experimental run already scheduled at the Center for Plasma Physics at Queen's University in Belfast (UK) where the TARANIS laser system is used to accelerate protons up to 12 MeV [28]. The ESS is a magnetic chicane and consists of four dipoles based on permanent magnets producing a field of ~0,85 T each. The second and the third magnetic fields are parallel to the first and fourth but oriented in the opposite direction. The fields configuration allows to radially defocus the beam in the first two dipoles. In this way it is possible to have a good separation between the particle trajectories at different energy in correspondence of the central pair of magnets where, by means of a moving slit collimator, the particles with the desired energy are selected. The particles passing through the slit are then refocused by the opposite gradient of the third and fourth dipoles. More details can be found in [29-31]. The field profile have been mapped along three selector axes and its integral is not exactly zero, as expected. Hence the beam coming out from the device won't be parallel to the selector axis. The issue, due to manufacturing errors, can be fixed displacing the forth dipole back and forth. During the calibration the right position of the last magnetic field have been also evaluated. The energy spread and the amount of particles passing through the slit depends on the size of the aperture. The lower the energy spread, the lower the number of particles will be transported through the energy selector as it needs to use a smaller slit size. On the other hand bigger slit size means lower selection efficiency but higher transmission efficiency. The energy of the proton beam can be tuned by moving transversely the slit position between 30 mm and 8 mm from the target normal axis. A roller guide system, where the central twin magnets are placed, allows to radially displace the two dipoles in order to increase dynamics and select the lowest energy particles. The lower energy limit is hence related to the reflection of particles on the first dipole and is less than 1 MeV. The energies at which the system can work vary within the wide range of 1 MeV and 60 MeV. The energy spread reachable by using 1 mm slit aperture ranges from 3 % for low energy (1 MeV) up to 20 % for the highest (60 MeV). The whole system is almost 600 mm long and will be placed into a dedicated vacuum chamber. Two additional collimators are placed both upstream and downstream the selector system; the first collimator is used to select the beam in angle in order to avoid spatial mixing of particle with different energies inside the device, the second one would refine the beam collimation and selection as well.

Selection and transmission efficiencies of the magnetic system can be improved if a beam transport element is designed in order to inject the beam in the chicane with proper characteristics. A magnetic lenses system is under studying for this purpose.

5. Conclusions

The ELIMED preparatory phase has already started and several researchers are already involved in the development and study of the detectors and transport devices. As described above, the Thomson Parabola for beam diagnostics have been used in two different experimental run at PALS Laboratory showing good response, the Energy Selector System characterization has been completed and it will be tested with optically accelerated ion beams within the end of the year. Hence, the actual status of the project makes us confident that the planned schedule will be followed without significantly delay for, at least, the first phases. The whole project is of outstanding importance as, if the goal will be reached, it would be possible to perform proof-of-principle experiments devoted to demonstrate new concepts for non-conventional hadrontherapy centres which would be less expensive in terms of realization and operating costs, as they would be less complex than conventional centres, and smaller

in size. Hence, it would be possible to develop more facilities around the world which would allow a widespread availability of hadrontherapy centres as required by current demand for this type of treatment.

Acknowledgements

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