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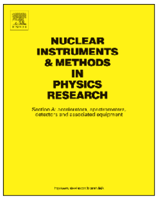

Development of an energy selector system for laser-driven proton beam applications

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ABSTRACT

Nowadays, laser-driven proton beams generated by the interaction of high power lasers with solid targets represent a fascinating attraction in the field of the new acceleration techniques. These beams can be potentially accelerated up to hundreds of MeV and, therefore, they can represent a promising opportunity for medical applications. Laser-accelerated proton beams typically show high flux (up to 10^{11} particles per bunch), very short temporal profile (ps), broad energy spectra and poor reproducibility. In order to overcome these limitations, these beams have be controlled and transported by means of a proper beam handling system. Furthermore, suitable dosimetric diagnostic systems must be developed and tested. In the framework of the ELIMED project, we started to design a dedicated beam transport line and we have developed a first prototype of a beam line key-element: an Energy Selector System (ESS). It is based on permanent dipoles, capable to control and select in energy laser-accelerated proton beams. Monte Carlo simulations and some preliminary experimental tests have been already performed to characterize the device. A calibration of the ESS system with a conventional proton beam will be performed in September at the LNS in Catania. Moreover, an experimental campaign with laser-driven proton beam at the Centre for Plasma Physics, Queens University in Belfast is already scheduled and will be completed within 2014.

1. The elimed project

Over the last decades a lot of effort, both from theoretical and experimental point of view, has been devoted to charged particle acceleration using high power lasers. High current multi-MeV proton beams can be produced and accelerated from the interaction of ultra-intense (higher than 10^{18} W/cm^2) short pulse (from 30 fs to 10 ps) laser with thin solid foils [1,2]. Several acceleration regimes have been studied so far in literature as for instance Target Normal Sheath Acceleration (TNSA) [3], Coulomb Explosion [4,5], Radiation Pressure Acceleration [6], Magnetic Vortex Acceleration [7,8] and Shock Wave Acceleration [9,10]. Moreover, other acceleration schemes, generated by the combination of different regimes, like the Break-Out-Afterburner [12] and the Directed Coulomb Explosion [13,14], have been recently proposed.

In the near future, different laser-driven ion acceleration regimes will be investigated at the Extreme Light Infrastructure (ELI)-Beamlines facility in the Czech Republic. The facility represents one of the three pillars of the ELI pan-European project and is already under construction in Prague. The ELI-Beamlines facility will deliver ultra-short, high-energy laser pulses for the generation and application of high-brightness X-ray sources and accelerate charged particles for fundamental research and for multidisciplinary applications, including the medical field. In this framework, an international joint collaboration named ELIMED (MEDical and multidisciplinary applications at ELI-Beamlines) [11] has been proposed and established by INFN-LNS and ELI-Beamlines (IoP-ASCR) researchers. The ELIMED purpose consists in demonstrating that laser-driven high energy proton beams can be potentially used for multidisciplinary applications and, in particular, this includes also the investigation of new approaches for future laser-driven proton beam application in the hadron-therapy field. Actually, clinical applications have been addressed to be a good candidate as user demonstration case since the beam

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requirements needed for therapeutic treatments are the most demanding. So far the proliferation of hadron-therapy facilities has been limited since they are based on conventional accelerators that are huge and expensive machines both in terms of space and economic resources. A significant effort is ongoing today in the physics community to achieve the required ion beam parameters for medical applications reducing the facilities overall cost and complexity compared to currently employed accelerator. On the other hand, the laser-based accelerators can really represent a future alternative for hadron-therapy since they combines several advantages. Indeed, they can be more compact and cost-efficient than conventional accelerator and, moreover, thanks to laser-driven ion beam peculiarities, new potential treatment modalities can be explored.

The ELIMED preparatory phase started in 2013 and is planned to be completed in 2016. During the preparatory phase a beam transport line (BTL) prototype, able to deliver beams fulfilling specific requirements like a wide energy and fluency range and a variable spot size, will be developed and realized. A complete characterization of the BTL prototype will allow to handle and control the beam conditions in order to deliver beams stable and reproducible in terms of energy and fluency distributions. After the preparatory phase, two phases of the project have been identified on the basis of the expected values for the laser-accelerated proton beam energy: phase 1 (30–60 MeV) and phase 2 (60–250 MeV). During the phase 1 of the project, which is planned to start at the end of 2016, proton beams with energy up to 60–70 MeV are expected to be delivered using a 30 fs, 1 PW laser on thin solid foils within the TNSA regime. Therefore, the ELIMED phase 1 aim is to perform proof-of-principle experiments to demonstrate the validity of new approaches for potential future application of laser-accelerated proton beams in the medical field, being the radiation treatment of diseases lying within 3 cm in depth (i.e. 60 MeV proton range in the tissue-equivalent) such as the ocular tumors a demonstration case, as well as the use of such non-conventional proton beams for other multidisciplinary applications.

In this work a detailed description of the state of the art regarding the ESS realization (Section 3), the first preliminary experimental test (Section 3.1) and the Monte Carlo simulation (Section 3.2) performed on the device will be given.

2. The beam transport line

The potential availability, in the next years, of laser-driven charged particles suitable for hadron-therapy applications opens new and fascinating technical perspectives in the fight against tumors. However, before any clinical treatment phase might start a big effort in different research fields as for instance laser–target interaction, beam transport and selection device development will be required. Moreover, since no dosimetry protocol has been already established for laser-driven proton beams it will require development and testing of innovative detector for absolute and relative dosimetry, beam diagnostics together with the study of biological effects.

The laser-accelerated ion beams are characterized by very peculiar features depending on the laser as well as on the target parameters. Up to now, a lot of work has been dedicated to the experimental investigation of the TNSA acceleration mechanism and the maximum energy of protons accelerated from solid targets in the TNSA regime is 67.5 MeV [1]. The laser intensity currently available on target, about 10^{21} and 10^{22} W/cm^2 [3,4,6], limits the maximum achievable ion energy, nevertheless the next generation laser facilities will allow higher intensities leading, therefore, towards higher ion energies. On the other hand, other ion beam parameters, such as emittance, brilliance and energy range, have to be improved and controlled for specific applications. The TNSA regime allows to deliver proton beams highly laminar and with very low emittance. However, on the other hand the broad energy spectrum and the large angular divergence represent a concern for application requiring beam transport to a secondary target. Moreover, these features might be particularly critical and have to be precisely handled and controlled to make such kind of beams suitable for those applications, as the hadron-therapy case, that require sufficient high energies coupled with the need of having a sufficiently large number of particles in the energy of interest.

Several groups around the world have already started preliminary investigations on the validity and the methodology of using laser-driven ion source for cell irradiation experiments [15–17]. These studies aim to establish a procedure for cell handling, irradiation and dosimetry, compatible with a laser–plasma interaction environment. Furthermore, the use of laser-driven ion beams for clinical treatment purposes may result in non-continuous dose rates, which are several orders of magnitude higher than those usually delivered with conventional beams (up to 10^9 Gy/s). Therefore, due to their peculiarities, laser-driven ion beams represent a new frontier as far as the dosimetric systems are concerned. Based on these assumptions, we started to design and realize a first prototype of a BTL that will allow to deliver laser-accelerated proton beams with optimized properties and sufficient rates to perform first dosimetric and radiobiological irradiations with such kind of beams [18–20]. The BTL design and development aim to study innovative solutions for a beam transport system in order to characterize and control the particle beams in terms of collection, focusing and energy selection and to investigate the feasibility for multidisciplinary application. A schematic layout of the BTL prototype can be found in Ref. [19]. The BTL consists of a laser–target interaction area, a section dedicated to the beam handling and the diagnostic system and a final part devoted to the dosimetry system and the cell irradiation point. During the first phase of the project proton beams will be accelerated within the TNSA regime up to hundreds of MeV as cut-off limit, thus a BTL able to transport and deliver protons with energy up to about 60 MeV, which corresponds to the lowest energy limit for the shallow tumors treatment, has to be developed. An intermediate phase has been also foreseen aiming to deliver a proton beam with energy up to about 30 MeV.

The initial section of the BTL for laser-driven ion beam delivering has to be tunable in order to ensure capturing and collecting beams within a broad incident energy range and also a variable energy spread. Moreover, the BTL has to be characterized by a large acceptance to control the large chromatic emittance due to the energy spread of the transported beam and deliver to the irradiation point a sufficient number of particles. Furthermore, in order to meet the different experimental setup requirements the modularity of the beam transport elements is also an additional key point. The proposed beam handling configuration consists of 3 main elements: a solenoid producing a pulsed high magnetic field for collecting the charged particles produced from the target, two triplet quadrupole sections for focusing and transport and, then, a final energy selection that will be provided by means of a proper magnetic device. Depending on the transmission efficiency and on the energy spread which has to be achieved, different layouts for the BTL development have been investigated [20]. One possible solution consists in using a compact pulsed high magnetic field solenoid with a 40 mm bore diameter and a reduced length (100–150 mm), placed few centimeters downstream the target, coupled with standard resistive quadrupoles with a 60 mm bore diameter used in a triplet configuration. Thanks to the large acceptance of this system, such configuration will ensure focusing on both transverse planes reducing the initial divergence of