Fluence and energy optimization of laser-driven proton beams for medical applications: the ELIMED project

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Abstract

Nowadays, laser-driven ion beams generated by the interaction of high power lasers with solid targets represent a fascinating attraction in the field of the new acceleration techniques. The ELIMED project aims to demonstrate the potential medical applicability of optically accelerated proton beams. Design and development of beam transport, selection and dosimetric prototypes for laser-driven proton beams will be presented in this contribution.

The Elimed network

Over the last decades, charged particle acceleration using ultra-intense and ultra-short laser pulses has been one of the most attractive topics in the relativistic laser-plasma interaction research. 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].

In the near future, different acceleration regimes will be investigated at the Extreme Light Infrastructure (ELI)-Beamlines facility in the Czech Republic. ELI-beamlines will be dedicated to different applications of laser generated photon and particle beams, from high-resolution X-ray imaging to multidisciplinary applications of laser-driven charged particles. One of the most challenging ideas driving recent activities consists on using laser-target interaction as a source of high-energy ions for medical applications. High interest of the scientific community towards laser driven ion schemes stems from the fact that conventional ion accelerators, beam transport lines and gantry systems are complex and expensive. More compact laser-based accelerators could significantly increase the availability of high-energy ion beams and provide particle therapy to a broader range of patients. In this context, an international network named ELIMED (Eli-Beamlines MEDical applications) has been launched by INFN-LNS and ASCR-FZU researchers [3, 4]. The ELIMED main purpose consists in demonstrating that laser-driven high energy proton beams can be used for multidisciplinary applications investigating, particularly, new approaches for future applications in the medical field. Medical application represents, indeed, a good candidate as user demonstration case since the beam requirements needed for therapeutic treatments are the most demanding. Nevertheless, due to the peculiar features of the laser-driven ion beams available nowadays (i.e. very high flux, extremely short bunch duration, broad energy spectra and angular distributions), before any medical applications might start several challenges, starting from laser-target interaction and beam transport development, up to dosimetric and radiobiological issues, need to be overcome.

A brief discussion on the transport beam line prototype, we started to design and develop aiming to deliver a laser-generated proton beams with optimized properties and adequate repetition rates, will be presented in this work.

Transport beam line ideas and energy selection

The beam transport as well as the energy selection of optically accelerated ion beams represent one of the critical points of the whole system in order to make such kind of beams suitable for medical purposes. The transport beam line, therefore, must be able to collect, select and deliver charged particles up to 60 MeV energy, which corresponds to the lowest energy limit for the shallow tumor treatment. In contrast to conventional accelerators the beams produced in high intensity laser-matter interaction, available nowadays, are typically characterized by a $\pm$25 degrees of angular divergence and a 100 % energy spread, but a small transversal emittance since the beam spot is less than 1mm. The main goal in the design of the transport system is to collect the largest fraction of the beam in order to maximize the transmission efficiency and optimize the energy selection.

A first layout of the transport beam line prototype consists of a focusing element coupled with a magnetic system that will provide the energy selection of the previous focused beam [5]. The focusing element has been designed and is currently under construction at the INFN-LNS in Catania. The purpose of such element will be to reduce the initial angular divergence of the particle beam accelerated from the target improving the transmission efficiency of the entire transport system. The prototype will consist of three permanent magnetic quadrupoles. In order to obtain a focusing effect on both transversal planes at least two quadrupoles are needed, a third lens is suitable for matching the focal point on vertical and horizontal directions so that a common waist can be achieved after the focusing. By using quadrupole devices with 100 T/m gradient, 20 mm bore and length of 40 and 80 mm, up to 30 MeV proton beam can be efficiently focused.

A prototype of the key component of the whole beam line, the Energy Selector System (ESS), able to control and select the laser-driven proton beams has already been developed at the INFN-LNS [5, 6]. The compact device consists of a series of four permanent dipole with alternating polarity (the first and the fourth with same polarity whereas the second and the third have opposite sign) providing the radial separation of the charged particles with different energies. By means of a movable slit placed between the second and the third dipole, the particles with suitable energy can be selected and transported to the exit of the device. The prototype has been calibrated in the energy range between 2 and 12 MeV using mono-energetic proton beams provided by electrostatic accelerators at the LNS-INFN (Catania) and LNL-INFN (Legnaro) laboratories. According to the preliminary results and the energy resolution extracted, the ESS prototype can operate in the energy range between 2 and 60 MeV allowing to select a proton beam with an energy spread ranging from few % up to 30%. The ESS has been also successfully characterized for the first time with the laser-driven proton beam available at the TARANIS laser facility, Queen's University of Belfast (UK). Moreover, in order to obtain realistic predictions of the transmission efficiency, energy spread, fluence per pulse and dose expected at the irradiation point, a complete Geant4 Monte Carlo simulation of the ESS has been performed [7].

The whole collecting/selection system, consisting of the quadrupole and the ESS prototypes, will be characterized during the 2014 at the TARANIS laser facility to transport and select a laser-driven proton beam in the energy range between 4-8 MeV.

Relative and absolute dosimetry

The definition of detectors, methods and procedures for absolute and relative dosimetry of optical-accelerated ions represents a crucial step toward the medical use of this new kind of beams. Due to the typical laser-driven beam characteristics, i.e. burst duration of the order of 0.1-10 ns with a flux ranging from 10^{10}-10^{12} particles per bunch and extremely high dose rate, dosimetry is extremely challenging. So far no protocol for dose measurements with optical-accelerated beams has been established. Hence, one of the ELIMED task, will be the definition of procedures aiming to obtain an absolute dose measurement at the end of the transport beam line with an accuracy as close as possible to the one required for clinical applications (i.e. of the order of 5 % or less). Relative dosimetry procedures must be established, as well, since they are required to verify the beam dose distributions and monitor the beam fluency and the energetic spectra during the irradiation. Different online and offline detectors for relative dosimetry, as for instance secondary emission monitor, transmission ionization chambers and radiochromic films will be developed and tested in order to perform a fully dosimetric characterization of laser-accelerated proton beams [8]. In particular, for the absolute dose measurements, a Faraday cup prototype specifically designed for high dose rate and intense beams has been designed and tests with laser-driven proton beams are currently ongoing.

ACKNOWLEDGMENTS

This work has been performed under the LILIA (Laser Induced Light Ion Acceleration) project funded by INFN and under the Czech Republics Ministry of Education, Youth and Sports to the ELI-Beamlines (CZ.1.05 / 1.1.00 / 02.0061), Laser Gen (CZ.1.07 / 2.3.00 / 20.0087), Laser Gen (CZ.1.07 / 2.3.00 / 20.0279) and Laser Gen (CZ.1.07 / 2.3.00 / 30.0057) and under the institution Fyzikalni ustav, AV CR,v.v.i.

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