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Abstract. Nowadays, one of the biggest challenges consists in using high intensity laser-target interaction to generate high-energy ions for medical purposes, eventually replacing the old paradigm of acceleration characterized by huge and complex machines. In order to investigate the feasibility of using laser-driven ion beams for multidisciplinary application, a dedicated beam transport line will be installed at the ELI-Beamlines facility in Prague (CZ), as a part of the User-oriented ELIMAIA beam-line dedicated to ion acceleration and their potential applications. The beam-line section dedicated to transport and dosimetric endpoints is called ELIMED (ELI-Beamlines MEDical and multidisciplinary applications) and will be developed by the INFN-LNS.

1. Introduction

In the last few decades, charged particle acceleration using ultra-intense and ultra-short laser pulses has gathered a strong interest in the scientific community. Indeed, it could represent the future of particle acceleration and open new scenarios in multidisciplinary fields as, in particular, the medical one. Recently, high interest of the scientific community is driven from the fact that more compact laser-based therapy units could dramatically increase the availability of high-energy proton and carbon ion beams, and provide particle therapy to a broader range of patients [1, 2]. Furthermore, laser-based hadrontherapy would offer the advantage of having a unique integrated system, as for instance the possibility to perform treatments with different types of radiation sources: protons, heavier ions (He, Li, C), electrons, X/gamma rays and neutrons.

A variety of mechanisms underlying laser-driven ion acceleration exists dependant on the properties of the laser pulse and on the target geometry [3]. So far, most of the experimental results obtained refer to the TNSA regime [3], although features associated to several of the other mechanisms have recently emerged from experiments. Recently, it has been theoretically shown that PW-class lasers can accelerate protons to a few hundred MeV, thus fulfilling the medical requirements for particle energy. However, generation of an ion source that would simultaneously meet the maximum energy, energy spread, number of particles per bunch and repetition rate requirements for its application in hadrontherapy, is still a challenge. Laser-driven beams are, indeed, characterized by very intense (10^8-10^{12} particles per bunch) ultra-short (~ ps) particle pulses and ultra-high pulse dose rate (up to 10^{12} Gy/min) compared to conventional clinical proton beams (10^7-10^{10} particles/s and dose-rate up to 10-50 Gy/min) [3]. Besides, they have broad energy (up to 100% compared to 0.1-1%) and angular distributions and substantial intensity (charge) fluctuations from pulse to pulse. Thus, beyond standard requirements such as shot-to-shot operational stability, a reliable and precise dosimetric characterization of laser-accelerated particle beams is needed.

Several international collaborations and experiments have been launched in the last years and many research centers are currently involved in the investigation of laser driven therapy and applications and a more complete and extensive review on these research projects along with the specifications of the laser systems and technical approaches involved can be found in an ICFA Publication [4]. In this framework, a collaboration, named ELIMED, between the INFN-LNS (National Institute for Nuclear Physics - Laboratori Nazionali del Sud, Catania, Italy) and the ASCR-FZU (Institute of Physics of the Czech Academy of Science) has been established in 2011. The ELIMED project (ELI-Beamlines MEDical and multidisciplinary applications) aims to demonstrate the validity of new approaches based on laser-driven ion sources for potential future applications in medical and other multidisciplinary fields, including hadrontherapy.

2. The ELIMED beam-line

In 2018, a User-oriented beam-line, ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration) equipped with diagnostics and dosimetry end-points will be commissioned at the ELI-Beamlines facility in the Czech Republic with the main goal to perform proof-of-principle experiments, dosimetry measurements and radiation biology investigations at high repetition rate. The INFN-LNS is in charge for the development, realization and installation of the beam-line section, called ELIMED from the collaboration, dedicated to the beam transport and energy selection, diagnostics and dosimetry of the laser-driven ion beams. The purpose is to provide to the scientific community interested in multidisciplinary and medical applications a stable controlled and reproducible beam. The ELIMED beam line consists of two main sections: the first one, in vacuum, dedicated to transport, collection and diagnostics of the accelerated beam and the second one, in air, addressed to the relative and absolute dose measurement [5]. Fig. 1 (left) shows a technical drawing of the whole ELIMED beamline. In particular, in the first section, a focusing quadrupole (PMQs) system [6] will be placed downstream the target allowing beam collection and focusing, followed by a resistive energy selector system (ESS) dedicated to the beam selection in terms of species and energy. The PMQs system consists of a 5 permanent magnet quadrupoles based on a hybrid Halbach scheme, with a 100 T/m gradient [6]. The radial field uniformity is better than 3%, while the longitudinal uniformity is better than 1%. The system will be placed downstream the target, it is modular and it can be adapted for the collection and optimization of reference beams with different energies (3-70 MeV protons) to be injected in the energy selection system. The energy selection system consists of 4 resistive C-shaped dipoles allowing the selection of a single reference trajectory in chicanes. Thanks to such layout the resolving power of the system depends only on the selection slit width (ranging between 1 and 20 mm to obtain energy spreads from 1 up to 20%). The resistive magnets will work with variable fields from 0.085 to 1.2 T ensuring the selection for C+6 up to 70 MeV/u and protons up to about 300 MeV.

In the in-air section of the ELIMED beam line, a dosimetric system composed by detectors for relative and absolute dosimetry will be installed (Fig. 1, right). Dose delivery with a 5% accuracy has to be ensured at the sample irradiation point; in order to fulfil this task, taking into account the extremely high dose rate per pulse, it is mandatory to design and realize dose-rate independent detectors. In particular, a secondary electron monitor (SEM) and a multi-gap ionization chamber (IC), dedicated to the on-line in-transmission relative, dosimetry will be realized. The multi-gap IC allows correcting for the ion recombination effects providing reliable dose measurements also for extremely variable intensities per pulse. These detectors will be calibrated using a Faraday cup (FC) for absolute dosimetry specifically designed to decrease uncertainties in the collected charge. After the calibration procedures, a sample irradiation system (SIS), placed at the end of the in-air section, will allow cell sample irradiations with a sub-millimetric precision.

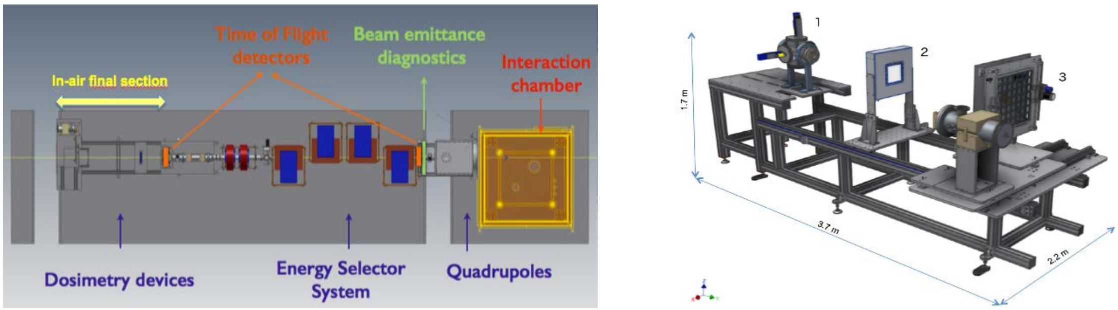

Figure 1. Left: schematic layout of the ELIMED beam line. Right: in-air section equipped with the SEM (1), the multi-gap IC (2) and, at the sample irradiation point, the FC and the SIS (3).

3. Geant4 Monte Carlo simulation of the ELIMED beamline and preliminary results

A complete Monte Carlo (MC) application of the ELIMED beamline has been developed with the Geant4 (GEometry ANd Tracking) toolkit [7]. Monte Carlo simulations have been widely used to support the design of some elements composing the beam line and to preliminary study the response of detectors. Moreover, once the final configuration of the beamline will be accurately reproduced, the Geant4 simulations will be used to predict the particle beam characteristics at specific positions along the beam line and to evaluate dose, fluence and particle distribution in the in-air section, where the irradiation will be performed.

Initially, the PMQs focusing system has been simulated using analytical transport codes, such as SIMION [8] and COMSOL [9], which allowed to design the geometry configuration and to fix the number of quadrupoles, their magnetic field features, their size and their optics dynamics. Then, the focusing system has been completely simulated also with Geant4, implementing the magnetic field maps created with the analytical transport software.

As discussed in the previous section, in order to deliver a controlled proton beam with energies up to 60 MeV/u and limit the energy spread, the focusing elements will be coupled with an innovative energy selection system. The energy selector system geometry has been fully reconstructed in the GEANT4 application and the magnetic field map grid of the single dipole, provided by COMSOL software, has been imported in the simulation.

For both the PMQ and the ESS the particle transport through the system has been simulated and compared with the results obtained with analytical transport softwares. The detailed results of such comparisons will be published elsewhere.

Once the final version of the ELIMED application has been validated and the whole beam line has been successfully implemented, in order to study the expected energy spectra, fluence and dose distributions, top-bottom simulations have been performed. These results aim to demonstrate the reliability of the simulated model, which now can be used to predict the necessary information at the different endpoints in the ELIMAIA beam line. The source input parameters have been extracted from PIC simulation corresponding to a typical TNSA spectrum with a maximum energy cut-off of about 100 MeV with an initial angular divergence ranging from about 40° half-angle for lowest energies and about 5° half-angle for the highest energy components. A preliminary simulation study to investigate the energy spreads and the transmission efficiencies achievable after the selection has been performed for different energies selected and for different selection slit widths. In particular, the energy spectra were registered after the ESS section, with all magnetic fields (i.e. quadrupoles, energy selector) configured to transport a given energy proton beam and the slit aperture set to 5 mm, 10 mm and 20 mm. Fig 2 (left) shows the energy spectra acquired just after the ESS varying the slit width using the beamline configuration properly tuned to transport 5 MeV protons.

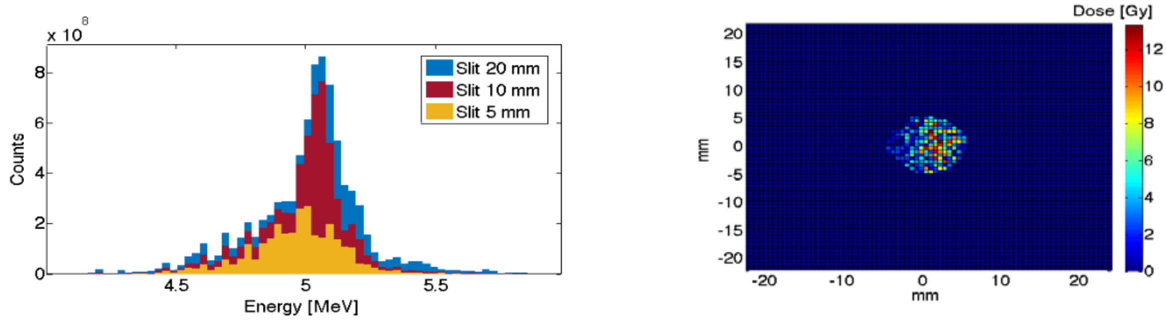

Figure 2. Left: energy spectrum for 5 MeV protons registered after the ESS with a 20 mm (blue), 10 mm (red) and 5 mm (yellow) slit aperture; the counts reported have been normalized on the real number of protons emitted obtained by the PIC. Right: spatial dose distribution in water for one shot.

The energy resolutions have been extracted from a gaussian fit of the energy spectra shown in figure 2. The energy resolution, obtained with the three slit configurations, ranges from 4 to 6 %. The transmission efficiencies, evaluated as the ratio of the transmitted (output) and the emitted (input) protons within the energy range 5 ± 0.25 MeV, are 2, 4.5 and 6% for 5, 10 and 20 mm slit aperture, respectively. The results indicate how the transmission efficiency strongly depends on the slit width and, as a consequence, a compromise for the slit width has to be found in order to assure a transmission of about 10% and at the same time a significant number of protons in the in air final section at the sample irradiation point. Moreover, a preliminary estimation of the 2D spatial dose distribution in water for one shot is shown in the same figure (right), demonstrating that sample irradiation with an acceptable beam homogenenity can be carried out.

A more extensive simulation study is currently on-going for the transport and selection of 30 MeV and 60 MeV proton beams; these energies are, indeed, more relevant to asses all the clinical aspects. In both cases, longitudinal transversal dose distributions at the irradiation point will be also retrieved from the simulations.

4. Acknowledgments
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