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A growing interest of the scientific community towards multidisciplinary applications of laser-driven beams has led to the development of several projects aiming to demonstrate the possible use of these beams for therapeutic purposes. Nevertheless, laser-accelerated particles differ from the conventional beams typically used for multiscipilinary and medical applications, due to the wide energy spread, the angular divergence and the extremely intense pulses. The peculiarities of optically accelerated beams led to develop new strategies and advanced techniques for transport, diagnostics and dosimetry of the accelerated particles. In this framework, the realization of the ELIMED (ELI-Beamlines MEDical and multidisciplinary applications) beamline, developed by INFN-LNS (Catania, Italy) and that will be installed in 2017 as a part of the ELIMAIA beamline at the ELI-Beamlines (Extreme Light Infrastructure Beamlines) facility in Prague, has the aim to investigate the feasibility of using laser-driven ion beams for multidisciplinary applications. In this contribution, an overview of the beamline along with a detailed description of the main transport elements as well as the detectors composing the final section of the beamline will be presented.

1. Introduction

Over the last decades, charged particle acceleration using ultraintense and ultra-short laser pulses has been one of the most attractive topics in the relativistic laser-plasma interaction research [1,2].

Since the first experiments on laser-matter interaction, wide theoretical and experimental progresses have been carried out, confirming the possibility to accelerate multi-MeV ion beams from the interaction of high-intensity laser pulses (from 10^{18} to 10^{20} W/cm^2) on thin solid targets [3–5]. So far different acceleration regimes [6–11], such as the Target Normal Sheath Acceleration (TNSA) [12–14], the Radiation Pressure Acceleration (RPA) [15–17] and the Break-Out Afterburner (BOA) [18], have been studied and several experimental results, obtained mainly within the TNSA regime, have been reported in the literature [12–14]. Some of the peculiarities of the accelerated protons might be of interest for different kind of applications, including the medical ones. In particular, high fluxes per shot a broader energy spectra, if well controlled, could provide an alternative and powerful tool for dose delivery, representing a new opportunity for the therapeutic purposes of charged particles. Indeed, one of the most challenging ideas driving recent activities consists on using laser-target interaction as a source of high-energy ions for possible future medical applications [20,21]. Nevertheless, despite the great enthusiasm driven by the recent results, before clinical application of laser-accelerated particles several tasks need to be fulfilled. Several international collaborations and experiments have been launched in the last years aiming to explore the feasibility of using laser-driven sources for potential medical applications and many research centers have been involved in the investigation of laser driven therapy and applications, as for

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instance the Queens University Belfast Consortium, the OncoRay National Center for Radiation Research in Oncology, Dresden, The

Munich Centre for Advanced Photonics (MAP), the ion Acceleration Program at BNL ATF and UCLA, 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 [22]. In this framework, a collaboration between the INFNLNS (National Institute for Nuclear Physics – Laboratori Nazionali del Sud, Catania, Italy) and the ASCR-FZU (Institute of Physics of the Czech Academy of Science), in charge for the ELI-Beamlines facility implementation, has been established in 2011. ELI-Beamlines started in 2012 the realization of a high-power laser facility, where one of the experimental hall, named ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration) will be dedicated to the multidisciplinary experiments with laser-accelerated protons and ions. ELIMED (ELIBeamlines MEDical and multidisciplinary applications) represents the beam transport and dosimetric section of the ELIMAIA room and will be designed, realized and installed at ELI-Beamlines by LNS-INFN within the end of 2017. Its purpose is to provide to the interested scientific community a user-oriented facility where accurate dosimetric measurements and radiobiology experiments can be performed [23].
In the following sections, a description of the ELIMED beamlines, with a detailed discussion of the transport elements as well as of the detectors, will be presented.

2. The ELIMED transport beam line

To fulfil the mentioned goals and deliver the accelerated beams with the requirements necessary for multidisciplinary applications, the following issues have to be taken into account designing the ELIMED beamline: to make the optically accelerated beams suitable for multidisciplinary applications and to find innovative solutions for the detectors development for laser-driven ions.
The first goal will be achieved studying and designing specific transport elements that allow collecting and selecting the accelerated particles. The second one will be achieved developing new solutions to perform accurate dose and energy spectra measurements and, consequently, well-controlled sample irradiations. According to these requirements, three main sections are foreseen for the ELIMED beamline: the first and the second one, in vacuum, composed by magnetic elements for the transport and selection of the accelerated particles, and the third section in air, a dosimetric system for real time monitoring of the delivered dose on samples at the irradiation point (Fig. 1). Moreover, detectors for diagnostics will be placed respectively after the collection system and at the end of the in-vacuum transport beamline to measure the properties of the transported beams, namely beam emittance, fluence and energy spectra.
Concerning the collection and selection, the in-vacuum transport beam-line that will be installed at ELIMAIA consists of three main elements: a collection system, namely a set of Permanent Magnet Quadrupoles (PMQs), placed close to the laser-target interaction point, an Energy Selection System (ESS) based on four resistive dipoles, and a set of conventional electromagnetic transport elements, two quadrupoles and two steering magnets.
The beam-line has been designed to deliver laser-driven ions up to 60 MeV=u, offering, as output, a controllable beam in terms of energy spread (varying from 5% up to 20% for the highest energies), angular divergence and, hence, variable beam spot size between 0.1–10 mm with a reasonable transmission efficiency (namely 10^6 10^{11} ions=pulse). The final beam dimension can be achieved using a conventional doublet of quadrupoles with a maximum gradient of 5 T/m and a bore of 70 mm and eventually using collimators.
In order to fulfil the project requirements, the two main elements of the in-vacuum section, the PMQs system and the ESS, have to be optimized. The aim of the collection system is to collect the largest fraction of the accelerated ions within a certain energy range, reduce their angular divergence and inject them into the selection system, which will cut the particles outside the energy range of interest. The beams coming out from this first part of the beam-line (PMQsþESS) will have reduced angular and energy spreads, therefore, they are easier to be transported and shaped with conventional magnetic lenses, such as resistive quadrupoles and steerers. They will be placed in the last part of the in-vacuum beam-line. However, although the transport elements will allow to obtain beams selected in energy and with small divergence, the beam properties are still far from the typical features characterizing the conventional accelerated beams, from the point of view of the temporal structure. Indeed, the transported laseraccelerated ion beams will be characterized by very high intensities per pulse, i.e. up to 10^7 10^{10} particles per bunch, and very short temporal profile (ns), compared to 10^8 10^9 particles/s accelerated by conventional clinical machines. This results in an extremely high dose rates, i.e. 10^6 10^9 Gy=min (vs 10–50 Gy/min in conventional proton therapy). In these conditions, innovative detectors have to be developed and new dosimetric procedures

need to be assessed in order to deliver the dose with an accuracy as closer as possible to the one required in medical applications. Moreover, the whole ELIMED beamline has been simulated with the Monte Carlo Geant4 code for particle tracking in the matter [24,25]. 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 [26]. Moreover, once the final configuration of the beamline is accurately reproduced, the Geant4 simulations will be used to predict the particle transport at specific positions along the beam line and to evaluate dose, fluence and particle distribution in the in-air section, where the experiments will be performed.

2.1. The collection system

The PMQs system consists of five quadrupoles as described in Table 1 [27,28]. The system has to collect a wide range of ion energies,

Fig. 1. Layout of the ELIMED beamline with the three different sections.

Table 1
PMQs main features.

No. of PMQs	Geometric length (mm)	Field gradient (T/m)	Bore diameter (mm)
1	160	101	30
2	120	99	30
2	80	94	30

from 3 MeV/u up to 60 MeV/u, and inject a given beam component in the ESS. Therefore, it has to be versatile in order to ensure a good transmission efficiency. A big bore of at least 36 mm with a strong field gradient and high uniformity is necessary. The net bore of 36 mm is reduced to 30 mm in diameter due to a 3 mm thick shielding pipe for magnet protection. Considering these requirements, the quadrupoles are based on a standard trapezoidal Halbach array [29,30] surrounded by two external hybrid arrays made of rectangular magnetic blocks and iron. The inner array is mainly responsible for the field quality of the quadrupole whereas the external arrays are necessary to increase the volume of the permanent magnet material and to reach the required field gradient. A scheme of the PMQs layout is shown in Fig. 2.

This layout results to be robust with a good field quality and a cost effective alternative to a pure Halbach array. As shown in Fig. 2 the two external arrays are placed within an iron frame which has the role of supporting the structure as well as a magnetic flux guide. The inner array consists of two different permanent magnet alloys with different characteristics. In fact, in those sectors the external magnetic field $\vec{H}$ is higher than the main magnetic material coercitivity and, to avoid demagnetization, materials with different coercitivity are used. The field analysis, performed as described in [31], shows a gradient uniformity better than 2% and an integrated field uniformity better than $<0.3\%$ within a radius of 12 mm [27,28].

2.2. The energy selection system

The ESS is based on four resistive dipoles with alternating field, similar to a bunch compressor, and the main trajectory parameters are calculated according to the description proposed in [32]. The main features are listed in Table 2. The total geometrical length of the system is 3.1 m and the reference particle path length is 3.168 m with a maximum radial deflection of 160 mm at the center. The selection path guarantees a fixed energy resolution of about 5% if a 5 mm aperture slit is used. The resolving power does not depend on the particle energy or ion species. In order to deflect particles with a specific energy along the reference trajectory the magnetic field has to be changed. It has to be varied between 0.085 and 1.2 T, which corresponds respectively to an energy ranging between 3 and 350 MeV for protons and between 3 MeV/u and 100 MeV/u for carbon ions (C^{+6}). The proposed layout allows to vary the energy resolution by changing the slit aperture size, which is an advantage particularly when selecting higher energies: in this case, indeed, laser-driven particles are less abundant, and they can be selected with a broader spectrum (corresponding to a bigger slit aperture) to keep the transmission efficiency acceptable.

The pole shape has been designed in order to fulfil the requirements of Table 2. It ensures the required field uniformity and effective length for the whole range of magnetic fields [34,35]. The whole system is shown in Fig. 3 where it is also shown the reference particle trajectory. The system will be provided with two collimators upstream and downstream the selection, necessary to avoid spatial mixing of particles with large divergence and to refine the energy selection at the exit of the system. They will be placed 200 mm upstream and downstream the ESS, and will have a 30 mm diameter. In [27] is demonstrated the necessity to use a magnetic chicane to control the energy distribution of the selected beam, as a simple collimation system on the focal point does not allow a proper selection.

Fig. 2. PMQs layout for the 60 MeV reference beam. From the left: 160 mm long quad 101 T/m, 120 mm long quad 99 T/m, 120 mm long quad 99 T/m, 80 mm long quad þ94 T/m, 80 mm long quad 94 T/m. Different colors indicate the different material used. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Table 2
ESS dipole features.

Dipoles	B field	Length	Effective length	Gap
4	0.085–1.2 T	400 mm	450 mm	59 mm
GFR	B uniformity	Curvature radius	Drift length	Max J
100 mm	o0:5%	2:593 m	500 mm	2:53 A=mm2

Fig. 3. Energy selector with vacuum chamber and reference trajectory.

2.3. Beam transport simulation

In the present section, the preliminary beam-transport simulation results for the selection of 60 MeV protons are reported. The beam-line is configured as in Fig. 4. The selection slit, placed at 3.8 m from the target, is a rectangular aperture with 40 mm height and 20 mm width in order to obtain an energy spread of 20%.

The simulated input beams show a typical TNSA-like distribution, both in terms of energy and divergence (see [27] for details): beam spot size of 40 μm at the source and an angular divergence with a FWHM of 5° at 60 MeV, corresponding to an emittance of 0.29 Pi.mm.mrad [Norm] and twiss parameter α ¼ 0:0032 and β ¼ 0:0001 mm=Pi:mrad. The transmission efficiency of the system results to be 12%, namely about 10^7 particles per laser shot. The beam divergence is considerably reduced to 0:31 after the selection, allowing to transport and shape the beam using conventional resistive quadrupoles. These conventional elements, placed at the end of the in-vacuum section, will transport the beam down to the in-air part of the beam-line, with the characteristics required for the dosimetric measurements. In fact, using two resistive quadrupoles with an effective length of 331.5 mm and a maximum gradient of 10 T/m, the output beam results to be quite uniform and similar to conventional accelerated ion beams after additional collimation, as shown in Fig. 5. The beam divergence is of about 3 mrad.

2.4. The in-air section: dosimetry and sample irradiation

According to the beam transport simulations discussed in the previous section and considering the worst case for particle production at the target, a total of 10^7 protons are transported per pulse at 60 MeV at the end of the in vacuum section, with a final collimator of 10 mm of diameter. This configuration corresponds to about 2 cGy per pulse that, assuming a repetition rate of 1 Hz, would provide a pulsed proton beam with an average dose rate of about 1.2 Gy/min, which represents the minimal requirement for typical radiobiology experiments. To perform such kind of experiments, the dosimetric system has to allow on-line dosimetry measurements with a level of accuracy within 5%. These peculiarities do not allow to use conventional detectors typically employed and suggested in the international protocols for dosimetry, due to ion recombination effects [36]. So far, a great number of proposals and studies investigating the possible medical applications of laser-accelerated protons achieving the accuracy required by clinical constraints have been started, see e.g. [37,38]. In the ELIMED beam line, we are realizing detectors that are dose-rate independent and specifically designed to work in a typical laser-driven environment, also characterized by not-negligible electromagnetic pulses [39].

In particular, for relative dosimetry we are realizing a secondary electron monitor (SEM) and a multi-gap ionization chamber (IC); for absolute dosimetry, a Faraday cup (FC) specifically designed to decrease uncertainties in the collected charge has been realized [40]. Moreover, a sample irradiation system (SIS) will be installed at the end

Fig. 4. Scheme of the simulated beamline with envelop of 60 MeV protons.

Fig. 5. Beam spot at the beam line output, before injection in the in-air section. Color bar is referred to particle energy in MeV. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

of the in-air section, allowing the positioning of the cell samples with a sub-millimetric precision (Fig. 6).

The SEM is a thin metallic foil detector, whose working principle is based on the secondary electron emission (SEE). It will be mounted in a vacuum chamber, placed at the end of the in-vacuum beam line section, upstream the kapton window.

The multi-gap IC is an innovative prototype designed to real-time measure the dose delivered per pulse, without affecting the beam transport downstream at the irradiation point. It is an in-transmission air-filled chamber and it will be cross-calibrated against the FC absolute dosimeter. The presence of a second gap close to the first one allows to correct for ion recombination effects caused by the very high dose rate per pulse. The working principle of this detector is based on the idea that the recombination effects can be corrected once the collection efficiency f in specific conditions is known. After a calibration procedure of the two gaps, the collection efficiencies of the gaps f_1 and f_2 as a function of the voltage can be obtained. Finally, a relation between f_1 and the ratio f_1/f_2 can be experimentally determined and the collected charge can be corrected for each pulse.

The FC has been designed including an additional electrode with a particular geometrical shape to further repel the secondary electrons and to increase the accuracy of the measured charge. Together with the collected charge, the effective beam area and the energy spectrum have to be retrieved for the measurement of the absolute dose with a FC. They can be both obtained using radiochromic films (RCF) that, in case of energy spectra measurements, have to be used in stack configuration. These dosimeters, although allow to obtain spatial dose distributions with high spatial resolution, are passive detectors, thus they need a post processing analysis. To have real-time information we foresee to use scintillating fibres for the beam spot measurement and stack of scintillators for the energy spectra.

3. Conclusion

In this contribution an overview of the ELIMED section of the ELIMAIA beamline that will be installed at the ELI-Beamlines facility in Prague has been presented. Feasibility studies of both the collection and selection systems have been carried out and they will be realized within 2016. The detectors for diagnostics have been recently acquired: energy spectra measurements will be performed with CVD (Chemical Vapor Deposition) diamonds and employing the TOF (Time of Flight) technique. The dosimetric system, set in the in-air section of the ELIMED beam line, has been realized and both detectors for diagnostics and dosimetry have been preliminary tested with conventional proton beams accelerated at 62 MeV by the Superconducting Cyclotron of the LNS-INFN in Catania. Some of them have been tested also with optically accelerated beams and further experimental campaigns in laser-driven facilities have been planned for 2016. The ELIMED beam line section will be delivered and assembled in Prague (CZ) at the end of 2017, and it will offer the possibility to study the biological properties and the potentialities of laser-driven ion beams with well controlled systems. By means of the transport devices and the diagnostics/dosimetric systems we are developing, precise dosimetric measurements and accurate cell sample irradiations will be possible at the ELIMAIA beam line, giving the opportunity to study the peculiarities of laser-driven beams for a possible future application for therapeutic purposes.

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Fig. 6. Layout of the in-air section of the ELIMED beam line, where the detectors for dosimetry and the sample irradiation system are placed.

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