STATUS, PLANS AND POTENTIAL APPLICATIONS OF THE ELIMED BEAM LINE AT ELI-BEAMLINES

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Abstract

Charged particle acceleration using ultra-intense and ultra-short laser pulses has gathered a strong interest in the scientific community and it is now one of the most attractive topics in the relativistic laser-plasma interaction research. Indeed, it could represent the future of particle acceleration and open new scenarios in multidisciplinary fields, in particular, medical applications. One of the biggest challenges consists of using, in a future perspective, high intensity laser-target interaction to generate high-energy ions for therapeutic purposes, eventually replacing the old paradigm of acceleration, characterized by huge and complex machines. The peculiarities of laser-driven beams led to develop new strategies and advanced techniques for transport, diagnostics and dosimetry of the accelerated particles, due to the wide energy spread, the angular divergence and the extremely intense pulses. In this framework, INFN-LNS (Italian Institute of Nuclear Physics, Catania (I)) in collaboration with ELI-Beamline Institute (Dolny Brezany, CZ) will realise, within 2017 the ELIMED (ELI-Beamlines MEDical and multidisciplinary applications) beamline. ELIMED will be the first Users' addressed transport beamline dedicated to the medical and multidisciplinary studies with laser-accelerated ion beams. In this paper, a progress status of the beamline with its main diagnostic elements, will be presented.

TUMOUR RADIATION TREATMENT WITH ION BEAMS

The use of energetic protons (energy sufficient to reach a tumour located in the human body) in medical applications was firstly suggested by by Robert Wilson in 1946 [1] and in 1954 that the first patients were finally treated treated. Nowadays, according to the Particle Therapy Cooperative Group statistics (PTCOG [2]) there are 58 centers actives and 32 are under construction. Since first treatment, in 2014 about 135.000 patients have been already treated with hadrontherapy. In Italy the first hadrontherapy facility ([3,4]) started its operations in 2002. Since then two additional facilities have been developed and started their operation in Italy on the last years: the CNAO foundation [5] where proton and carbon beams of 250 MeV and 450 AMeV are available; and the proton therapy facility in Trento [6]. Even if hadrontherapy, from many different reasons and aspects, is still a pioneering technique, nevertheless its relevance in the clinical world and superiority as respect the conventional radiation is evident for many clinical cases. It represents the election therapy in most of the choroidal and iris melanomas occurrences. In the case of the pediatric medulloblastoma, where the whole brain and spinal chord is irradiated, protontherapy greatly reduces the dose in the health tissue and sensibly reduce the associated risks of secondary tumour occurrence. In the breast cancer treatment, finally, is becoming more and more evident that, the use of protons, produces evident advantages like the reduction of the occurrence of lung secondary tumours and general coronary diseases. The reader is suggested to read the excellent following list of publications reporting the current status of hadrontherapy and its principal advantages and drawbacks: [7], [8], [9], [10], [11], [12], [13], [14], [15] and references therein. Despite the evident advantage over conventional radiotherapy, the spread of Hadrontherapy (and, consequently, the patient access to it) is limited by high costs (ranging between 130-150 Meuro [7]) and complexity of these centres. In this framework the authors of [7] and [14] clearly state that further in the future we will probably see the "*the first proton single room facility based on the illumination of a thin target with powerful (*10^{18}*-*10^{20} *W cm*$^{-2}$*) and short (30 fs to 50 fs) laser pulse*" The basis of their statement is a shared optimism that the cost and size of laser-based proton therapy centers might be greatly reduced in the future [9]. At present the overall challenges that must be addressed for laser-driven ion beam radiotherapy is to develop well-controlled, reliable, energetic ion beams of very high quality that can meet the stringent medical requirements adopted in the clinical practice.

POTENTIAL MEDICAL APPLICATIONS OF LASER-DRIVEN BEAMS: THE ELIMED BEAMLINE AT ELI-BEAMLINES

Charged particle acceleration using ultra-intense and ultra-short laser pulses, in the last few decades, has gathered a strong interest in the scientific community and it is now one of the most attractive topics in the relativistic laser-plasma interaction research [16]. Indeed, it could represent the future of particle acceleration and open new scenarios in multidisciplinary fields. In particular, one of the most

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challenging ideas driving recent activities consists in using high intensity laser-target interaction to generate high-energy ions for medical purposes, eventually reducing cost and sizes of the old paradigm of acceleration, characterized by huge and complex machines [17] [18] .

Indeed, a development of more compact laser-based therapy centres could lead to a widespread availability of high-energy proton and carbon ion beams providing hadron therapy to a broader range of patients [17], [18] .

Nevertheless,great enthusiasm driven by the recent results, before clinical application of laser-accelerated particles several tasks need to be fulfilled. The pulse properties of laser-driven proton beams differ significantly from those provided by conventional accelerators in pulse duration, peak current, pulse dose rate and energy spectrum. Thus, among obvious properties such as operational stability, many scientific and technical challenges must be met first to demonstrate the feasibility of unique laser-driven capabilities and a reliable and precise physical and dosimetric characterisation of laser-driven beams has to be established before starting any medical application.

Different acceleration regimes, as for instance Target Normal Sheath Acceleration (TNSA) predominant at intensity of 10^{18}-10^{21} W/cm [19], [20], Radiation Pressure Acceleration (RPA) [21], [16] and Break-Out Afterburner (BOA) [22], have been investigated, so far. Nevertheless, due to the available laser intensities most of the experimental results reported in literature are mainly related to the study of the acceleration parameters relevant to the TNSA scheme [19], [20] . In this work we will not discuss the different acceleration processes in detail, a more extensive and complete review on this subject can be found for instance in [23], [24]. Typical TNSA ion distribution shows a broad energy spread, exceeding 100%, much larger compared to the 0.1-1% energy spread typical of ion beams delivered by conventional accelerators, a wide angular distribution with an half-angle approaching 30° which is very different from the typical parallel beam accelerated by the conventional machine and a very high intensities per pulse, i.e. up to 10^{10}-10^{12} particles per bunch, as well as a very short temporal profile (ps) compared to 10^{7}-10^{10} particles/s of conventional clinical proton beams. Moreover, the cutoff energy value can be likely considered as a spectrum feature still strongly dependent to the shot-to-shot reproducibility and stability and up to now, the maximum proton energy obtained with a solid targets in the TNSA regime is about 70 MeV [25].

In the last decades, the study on the optimization of the laser-driven source features has been coupled to the experimental investigations carried out on target structures [26], [27] and recently also very innovative technologies [28]. Different types of structured target have been recently developed and tested aiming to improve the characteristics of the optical-accelerated beam at the source, for example some of the most recent works on nanostructured foils [26], [27] have shown an enhancement in the maximum proton energy obtained, an increment in the conversion efficiency coupled to an improvement of the beam spatial profile. These results are particularly promising along the pathway for achieving laser-driven ion beams matching the parameters required for different multidisciplinary application, including the medical one.

In this framework, a collaboration between the INFN-LNS (Nuclear Physics Laboratory, Catania, Italy) and the ASCR-FZU (Institute of Physics of the Czech Academy of Science), responsible for the ELI-Beamlines facility implementation, has been established in 2011. The main aim of the collaboration, named ELIMED (ELI-Beamlines MEDical applications), is to demonstrate that high energy optically accelerated ion beams can be used for multidisciplinary applications, including the hadron therapy case, designing and assembling a complete transport beam-line provided with diagnostics and dosimetric sections that will also enable the Users to apply laser-driven ion beams in multidisciplinary fields. In 2012, ELI-Beamlines started 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 ion and proton acceleration and will host the beam-line dedicated to their application. In 2014, a three-years contract has been signed between INFN-LNS and ELI-Beamlines to develop and realize the ELIMAIA beamline section dedicated to the collection, transport, diagnostics and dosimetry of laser-driven ion beams. This section, named ELIMED as the collaboration, will be entirely developed by the LNS-INFN and will be delivered and assembled in the ELIMAIA experimental hall within the end of 2017. One of the purposes of the ELIMAIA beamline is to provide to the interested scientific community a user-oriented facility where accurate dosimetric measurements and radiobiology experiments can be performed [29] .

LASER-DRIVEN PROTONS TRANSPORT: THE ELIMED BEAM LINE ELEMENTS

The technical solution proposed for the realization of the ELIMED beam line is based on a modular system, which allows adapting and combining the devices depending on the different phases of the project and the different user's requirements. Three different sections of the ion beam line have been identified for its implementation: the Ion Beam Collection and Diagnostics; the In-Vacuum Ion Beam Selection, Transport and Diagnostics and the Dosimetry and sample Irradiation systems [30]. A schematic layout of the ELIMED section along the ELIMAIA beamline is shown in Figure 1.

The beam transport line consists of an in vacuum section dedicated to the collection transport and selection of the optically accelerated particles. In particular, few centimetres downstream the target, a focusing system based on permanent magnet quadrupoles (PMQs) will be placed.

The PMQs system is based on a particular layout, in which a pure Halbach array is mixed with hybrid Halbach arrays, is due to the fact that permanent magnet alloys are very brittle material and the realization of trapezoidal blocks is problem-

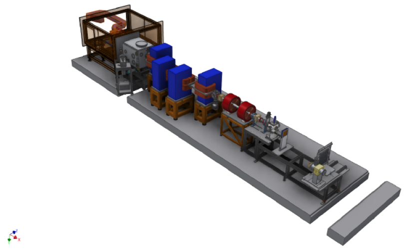

Figure 1: Layout of the ELIMED beam-line with the three different sections.

atic from the mechanical point of view. The design, results to be robust with a very good field quality and, at the same time, easier to realize, compared to a pure Halbach array. Two external arrays are set within an iron frame which has the function of supporting structure as well as magnetic flux guide. The inner array is made of two different permanent magnet alloys with different characteristics. This is due to the fact that the magnetic flux in the bore has a maximum value of about 1.8 T and, for such high flux values, local demagnetization phenomena can occur, where the magnetic field components Hx and Hy have opposite direction respect to the permanent magnets magnetization direction and a value higher than the material coercitivity. This issue can be solved mixing materials with different coercitivity in some strategic places of the array. In particular in the proposed design the main magnetic material is NdFeB N48H with remanence B_r=1.39 T and coercitivity H_c=1273 kA/m and NdFeB N38UH (B_r=1.26 T and H_c=1990 kA/m), the high coercitivity component, set in the point at risk of demagnetization. Since the field strength is fixed for each magnet, the PMQs system will be provided with mechanical stages allowing modifying the relative distance of each quadrupole along the beam direction (i.e. the longitudinal axis) and, thus, the focal point position as function of the beam energy. A complete description of the designed system along with the study of the PMQs optics for different energies is given in ref. [31].

The focusing system will be coupled to a selector system (ESS) dedicated to the beam selection in terms of species and energy.

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 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}) [33].

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 whole ELIMED beamline has been also simulated with the Monte Carlo Geant4 code for particle tracking in the matter [34], [35] . 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 [36]. 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. According to the beam transport simulation results, performed for the 60 MeV case with the beamline elements designed for ELIMAIA and considering a typical TNSA-like distribution with a cutoff energy of about 120 MeV and an angular divergence with a FWHM of 5 deg at 60 MeV, it is possible to deliver 60 MeV proton beam with a 20% energy spread with a rather uniform 10 x 10 mm spot size, beam divergence less than 0.5 deg and achieving a transmission efficiency of about 12%.

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%. Moreover, accurate measurements of the absolute dose delivered by the incoming radiation are a crucial requirement for several applications, as for instance the hadrontherapy one. However, the very high dose-rate and the limited shot-to-shot reproducibility characterizing the laser-driven ion beams, do not allow to easily performing dose measurements, with the required accuracy, using conventional devices. Indeed, several effects have to be considered with high intensity, pulsed ion beams, as the gas recombination, the dose-rate dependence and the not-negligible electromagnetic pulse. Therefore, since no dosimetry protocol has been established, new technologies and innovative dosimeters must be developed in order to perform a correct dose measurement with laser-driven ion beams. The in-air section of the ELIMED beamline dedicated to dosimetry and irradiation, will be composed of three main elements: a secondary emission monitor (SEM) and a multi-gap transmission ionization chamber (IC), will be used for relative dose measurements, whereas a Faraday Cup (FC), specifically designed to decrease the uncertainties in the collected charge has been realized [37] and will be placed at the irradiation point for absolute dose measurements. Moreover, a sample irradiation system (SIS) will be installed at the end of the in-air section, allowing the positioning of the cell samples with a sub-millimeter precision. 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 correcting 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 f1 and f2 as a function of the voltage can be obtained. Finally, a relation between f1 and the ratio f1/f2 can be experimentally determined and the collected charge can be corrected for each pulse. Obtaining an accurate measurement of the absolute dose using a FC, requires a precise measurement of: the total charge carried by the beam, the proton beam energy spectrum and the effective beam area, needed to extract the fluence distribution [38]. A typical Faraday Cup, used for ion beam dosimetry [38], consists of a thin entrance window, a suppressor electrode aimed to repel secondary electrons and a collecting cup, able to stop the impinging primary beam and to collect the total charge. Additionally, our FC design, inspired by similar detectors already developed for ion beam dosimetry [39], contains a second beveled electrode, coaxial and internal to the standard one, aimed to optimize the charge collection efficiency and reduce the uncertainities, related to the charge collection, caused by the secondary electrons produced. Indeed, the second inner electrode produces an electric field with a very high transverse component, generated in the suppressor section, capable of deflecting the secondary electrons produced in the entrance window and of collecting the ones generated in the cup. The beam area and energy spectrum, needed for dose evaluation, will be measured using Gafchromic films [40] . These dosimeters, although allow to obtain spatial dose distributions with high spatial resolution, are passive detectors, thus they need a post processing analysis. Further alternative solutions based optical fiber and spectrometer consisting of scintillator stacks to perform, respectively, on-line beam spot and energy spectrum measurements are currently under investigation. The detailed description of the Faraday Cup and the preliminary results obtained using conventional proton beams are discussed in [30].

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.

ACKNOWLEDGEMENTS

This work has been performed within the ELIMED activities supported by the V committee of INFN (Italian Institute for Nuclear Physics), the MIUR (Italian Ministry of Education, Research and University) and by the ELI-Beamlines Con-305 tract no S 14-187, under Laser Gen (CZ.1.07/2.3.00/30.0057). This research was also supported by the Ministry of Education, Youth and Sports of the Czech Republic (ELI-Beamlines reg. No. CZ.1.05/1.1.00/02.0061) and by EPSRC (grants n. EP/K022415/1, EP/J500094/1 and EP/L002221/1). The partial support of Czech Science Foundation (project No. 15-02964S) is gratefully acknowledged. We would like also to kindly thank Prof. M. Borghesi for interesting discussions and useful suggestions.

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