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A transport beamline solution for laser-accelerated proton beams at ELI-Beamlines

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Summary. — Nowadays, laser-driven acceleration represents an innovative research field. In this context and within the ELI-Beamlines framework, the ELIMED project has been established in order to realize a transport beamline with a dosimetric and a radiobiological section for medical and multidisciplinary applications. In this paper, a transport solution with permanent magnetic quadrupoles and an energy selector system (ESS) has been presented. In particular, preliminary study of the ESS transmission efficiency with laser driven proton beams as input will be presented.

PACS 52.65.Pp – Monte Carlo methods.
PACS 41.75.Jv – Laser-driven acceleration.
PACS 41.85.Lc – Particle beam focusing and bending magnets, wiggler magnets, and quadrupoles.

1. – Introduction

Optical acceleration represents an innovative solution for the multi-MeV ion beams generation, especially respect to conventional accelerators. During last decades many worldwide researchers are focusing their attention on this field. It, indeed, could represent a future new perspective in the fundamental nuclear as well as in the applied physics, like experimental and medical. The current hadrontherapy centers, for instance, are based on conventional accelerators, such as cyclotrons or synchrotrons, which are huge, complex and expensive machines, both in terms of financial and human resources. These are the reasons for the limited spread of protontherapy centers around the world and for the not fully satisfaction of the therapy treatments request. On the other hand, laser-based accelerators could be a competitive alternative as they can be smaller in size and less expensive [1].

These optically accelerated beams show different and sometimes extreme features as respect the conventional ones. A very high peak current, a broad energy spectrum, a wide angular distribution, a non reproducibly and a rather small transverse and longitudinal emittance are indeed the main characteristics of the most experimentally investigated regime, the so called Target Normal Sheath Acceleration (TNSA) [2]. Therefore in order to have a widespread use of these non conventional beams in multidisciplinary applications, new acceleration regimes as well as innovative ion beam handling methods are under investigation. In particular many recently proposed projects are focusing their attention on two options: the upgrading in the target manufacturing and the consequently laser-target interaction optimization or the design of new transport beam line solutions.

In this contest, the new ELIMED collaboration (ELI-Beamlines MEDical and multidisciplinary applications) between the INFN-LNS (Nuclear Physics Laboratory, Catania, Italy), the ELI-Beamlines facility (Prague, Czech Republic) and the FZU Institute of the Academy of Sciences of the Czech Republic has been launched in 2012. Its main aim is to study, design and realize a complete transport beamline for laser-accelerated beams suitable for multidisciplinary and medical applications [3,4]. The study and the development of new dosimetric detectors coupled to innovative radiobiological studies are also considered in the project.

During the 2013 the ELI-Beamlines Institute officially started the realization of the ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration) experimental area, that is one of the ELI-Beamlines halls dedicated to the applications of the laser-accelerated ion beams. Finally, as result of a public tender launched in 2014 by ELI-Beamlines, the INFN-LNS has gained the possibility to realize the transport beamline and the dosimetric section of ELIMAIA. In the next future the stable, controlled and reproducible laser-driven beams will be completely available to all the users interested in any multidisciplinary applications [5].

In this contest, this paper want to report about a possible solution for a laser-driven beamline, able to transport and handle up to 30 MeV protons. The solution is designed to be scalable for higher-energy beams, too. In the first part the studied beamline, composed of a set of permanent quadrupoles coupled to an energy selector, is briefly described. In the second part, the attention is focused on the energy selector and on its transmission efficiency, evaluated for a typical proton beam generated in the TNSA regime.

2. – Beamline solution

Ions accelerated by laser-matter interaction in the TNSA regime are characterized by high intensities, wide energy spectra and large energy-dependent angular distributions. Therefore, in order to make these non-conventional beams suitable for several applications, the design of a specific beam line seems to be one of the mandatory options. The main aims are the realization of a flexible and reliable transport line for the beam energy, angular and dose distributions control.

Bearing in mind these purposes, we have designed our transport solution that will be conceptually the same of the final ELIMAIA beam-line [6, 7]. It is composed by two main sections: a collecting-focusing system and an energy selector (fig. 1). The first part should collect and pre-select in energy the accelerated particles emitted from the target. It consists of three/four permanent quadrupoles system located just downstream the target. In particular, quadrupoles with magnetic field gradients of 110 T/m and 114 T/m, 20 mm bore and lengths of 40 and 80 mm, respectively, have been realized in order to cover a wide energy range, from 1 MeV up to 30 MeV.

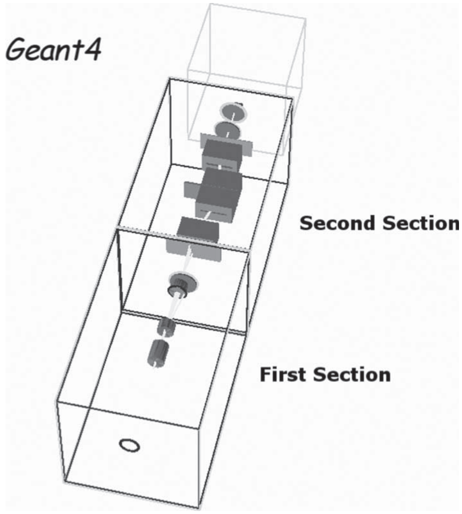

Fig. 1. – The transport beam line simulated with the Geant4 toolkit [15, 16].

The final beam energy refinement is downstream obtained, thanks to an Energy Selection System (ESS). It is based on the well know principles of energy-dependent spatial separation of a charged particles beam traveling in a magnetic fields [8-10]. In detail it consists of two collimators, four permanent dipole magnets with alternating polarity, each with an absolute maximum field value of 0.8 T in a 10 mm gap, and a central slit for the selection of the desired energy. More informations can be found elsewhere [11-14].

The shortly described transport beam-line has been already designed, simulated, using Monte Carlo approaches (Geant4 toolkit [15,16]) and realized at INFN-LNS (Catania, I). In particular, the ESS has been already calibrated with conventional beams at the INFN-LNS and INFN-LNL (National Laboratories of Legnaro, I) and tested with laser-driven protons (10 MeV as energy cutoff) at the TARANIS facility of the Queen's University of Belfast (UK). Regarding the quadrupole system, its characterization is currently ongoing.

3. – The Energy Selector System

We have focused our attention on the ESS simulative study using different laser-accelerated–like proton beams as input. In particular, in order to evaluate how the transmission efficiency and the output energy spread depend on the input beam features, mainly in terms of angular and energy distributions, a set of Geant4 simulations has performed.

In detail, the input energy spectrum was considered decreasing exponential shaped, with a cut-off value at 8.2 MeV, as reported in fig. 2, in agreement with a typical TNSA energetic distribution [17, 18].

Regarding the divergence, we have chosen an angular energy-dependent function, just like a real proton beam [19]. As shown in fig. 3, we have treated the angle-energy relation with a step function characterized by 5, 10, 15, 20, 25 and 29 deg as angle value for energy equal to zero [20-22].

For the ESS setup, we have used two, 3 mm in thickness, Al collimators with $\Phi = 3$ mm and 6 mm for the input and output collimator, respectively, and a 3 mm Al slit with a 1 mm $\times$ 8 mm aperture. The input beam axis was placed 42 mm far from the central dipole axis.

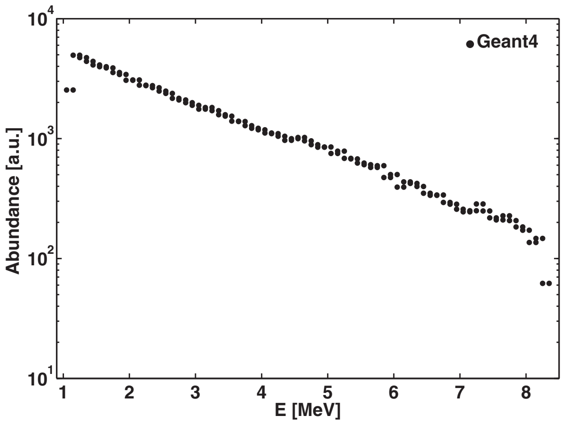

Fig. 2. – Energy spectrum of the laser-driven proton beam used as input of the Geant4 simulations set.

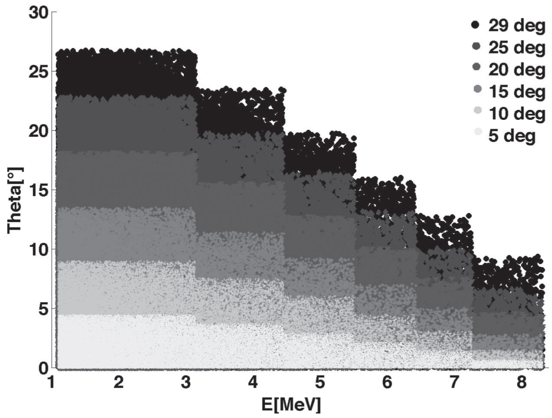

Fig. 3. – Angle energy-dependent step functions used as input beam divergence of the Geant4 simulations set.

3·1. *The transmission efficiency.* – Using the described ESS setup and input proton beams, several simulations have been performed, conveniently moving the slit aperture in order to select 4, 5 and 7 MeV. The output beam has been then evaluated just beyond the last collimator in terms of number of particles and energy spread, when a gaussian fitting is applied. Finally the transmission efficiency has been calculated as the ratio between the number of output *vs.* the input particles, evaluated in the output energy range.

The obtained data show how the energy spreads are not dependent on the input angle distribution, instead of the transmission efficiency values. They are reported in table I and in fig. 4.

As shown, fixing the Angle coordinate (in degrees), the step angular function allows to obtain a higher transmission efficiency value for the higher energies that are, indeed, produced in narrower angular shells (fig. 3).

TABLE I. – *The ESS transmission efficiency obtained for* 4, 5 *and* 7 *MeV using, as input, different laser-driven proton beams.*

Energy [MeV]	5 deg	10 deg	15 deg	20 deg	25 deg	29 deg
$4.1 \pm 6\%$	0.17%	0.06%	0.03%	0.015%	0.009%	0.0066%
$5.0 \pm 6\%$	0.5%	0.12%	0.049%	0.026%	0.015%	0.01%
$7.0 \pm 8.5\%$	3.09%	0.59%	0.19%	0.077%	0.04%	0.026%

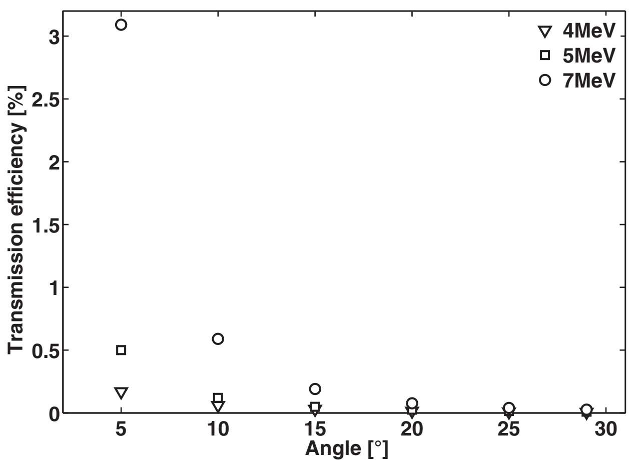

Fig. 4. – The ESS transmission efficiency evaluated when 4, 5 and 7 MeV are the selected energies. The transmission efficiency is reported as a function of the input angle value for energy equal to zero.

On the other hand, fixing the energy value, we have a decreasing trend of the transmission efficiency for bigger input angle values, *i.e.* the transmission efficiency decreases from the "29 deg" to the "5 deg" case.

Unfortunately, simulations outputs reports low transmission efficiency values independently from the input beam divergence and from the selected energy. The necessity to insert a quadrupole system in the beamline solution appears now mandatory.

4. – Conclusion

The ELIMED project has been launched within the ELI-Beamlines framework. Its goal is the development of a transport beamline for laser-driven ion beams with the related diagnostics. The beamline will be installed in the ELIMAIA experimental area of ELI-Beamlines (Prague, Cz). The actual status of the work is focused on the experimental characterization of the energy selector system with laser-driven proton beams in order to study how the transmission efficiency depends on the input beam divergence and on the output selected energy, just like the presented simulative work.

In the next phases of the project, the experimental characterization of the transport beam line (*i.e.* the energy selector coupled to the focusing system) will be completed with conventional as well as with laser-driven beams. Preliminary Geant4 simulations have been already performed, showing, for the laser-driven case, an increase in the transmission efficiency as respect to the cases treated in this paper.

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