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A TRANSPORT BEAMLINE SOLUTION FOR LASER-DRIVEN PROTON BEAMS

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Abstract

Laser-target interaction represents a very promising field in several potential applications, from nuclear physics to medicine. On the other hand optically accelerated particle beams are characterized by some extreme features, often not suitable for several applications, as an high peak current, a poor shot-to-shot reproducibility and a wide energy and angular distribution. Therefore many efforts are currently ongoing for the development of specific beam transport devices in order to obtain controlled and reproducible output beams. In this framework, this work want to report about a transport beamline solution dedicated to laser-driven beams and made of two main sections: a quadrupole-focusing device and an energy selector system. A test beam-line consisting of prototypes has been realised at INFN-LNS (National Institute of Physics-South National Laboratories, Ct, I) and partially tested with conventional accelerated proton beams. Moreover, some of these prototypes have been already tested with laser-driven beams.
Several simulations have been also performed using the Geant4 Monte Carlo toolkit, in order to best exploit the beamline potentiality. Preliminary simulations of a transported beamline to select 5 MeV and 24 MeV proton beams are here reported.

INTRODUCTION

Nowadays, the interest in particle acceleration from ultra intense lasers is strongly growing, thanks to the huge number of potential applications and to the possibility to investigate new physics regimes and phenomena. In particular, it is becoming evident that, in the next future, laser-driven acceleration could represent a different and perhaps more effective alternative as respects to the actual conventional particle accelerators. It could bring to more compact and less expensive acceleration systems and, consequently, to a larger spread of radiation beams around the word [1]. Such reasons are stimulating the interest of many physicists for the improvement and the optimisation of the interaction regimes as well as of the overall quality of these new kinds of beams. Beyond the improvement at the laser-target interaction level, many efforts are spent for the development of specific beam transport devices. Interesting options with microlens, magnetic chicanes, quadrupoles, solenoids and radio frequency cavities are reported in literature [2], however for all these approaches, there are different crucial parameters, as the acceptance angle of the transport system that, considering the wide input divergence, limits the number of output particles. In this framework, this paper reports about a Monte Carlo study of a transport beamline solution for laser-accelerated proton beams.

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TRANSPORT BEAMLINE

Ions accelerated by laser-matter interaction are characterized by high intensities, multiple species and charge states, wide energy spectrum and large energy-dependent angular distribution. Therefore, in order to make these nonconventional beams suitable for multidisciplinary applications, mainly in terms of reproducible and controlled output features, the design of specific transport elements seems to be mandatory. Bearing in mind these purposes, a transport beamline prototype has been designed and already realized at INFN-LNS. It consists of two main elements: a collecting-focusing sector and an energy selector system (ESS). Both elements have been separately tested with conventional protons up to 12 MeV, delivered by the TANDEM system of INFN-LNS and INFN-LNL. The ESS has been also tested with non-conventional beams at the Queens' University of Belfast, where the TARANIS laser system is installed [3]. Results will be reported elsewhere.
As regarding the quadrupole system, it should be able to collect, focus and pre-select in angle and energy the accelerated particles (fig. 1).

It is composed of four remotely controlled permanent quadrupoles with magnetic field gradients of 110T/m and 114T/m, 20mm bore and with lengths of 40 and 80mm, respectively [4]. This system allows to cover a wide energy operational range, from 0 up to 30MeV.
The final beam energy refinement is then obtained by means of the second transport device.

It is mainly composed of a central slit and four permanent dipoles with alternating polarity. Thanks to the magnetic field of the first two dipoles, particles with different energies are spatially separated on the radial plane. Then the central

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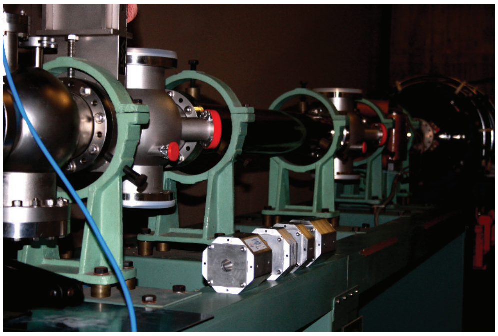

Figure 1: The four quadrupoles at INFN-LNS.

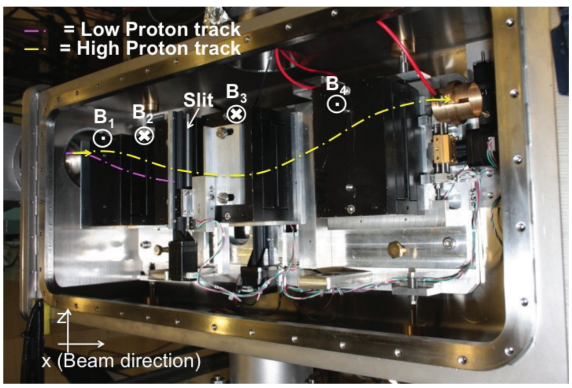

Figure 2: The energy selector system during the calibration test at INFN-LNS.

slit, a moveable beam stopper with an aperture, stops particles with unwanted energy. Finally the last two dipoles put selected protons back to the input beam axis. Figure 2 shows the ESS with the four dipoles (in black). The dot-dashed lines represent the path of different energy particles inside the selector.

The ESS is composed of one Aluminum slit 8 mm thick, four dipoles, with a maximum magnetic field of about 8 KGauss on a gap of 10 mm, and two Al collimators, placed 25 mm upstream and downstream from the first and the last dipole, respectively [5, 6, 10]. The two central dipoles are mounted on a roller guide system that allows their movement in the transversal direction (orthogonal to the beam direction) for a maximum excursion of 50 mm. The possibility to move the central dipoles has a double advantage: maintain the desired particles path inside the uniform region of the magnetic fields and increase the operational energy range up to 60 MeV.

The fourth dipole can be moved as well, back and forth along the longitudinal direction (the beam axis direction) for a maximum excursion of 50 mm. This movement is crucial for the compensation of the field asymmetry, that allows to maintain the direction of the particles leaving the ESS identical to the incident one [7].

Geant4 Simulation

In order to fully characterize the beamline, a simulation tool of the above described systems has been developed using the Geant4 (GEometry ANd Tracking) Monte Carlo toolkit [8]. It is a C++ object-oriented code that provides advanced functionalities for all typical domains, from the high energy to the medical one.

The developed code has been based on the freely released Hadrontherapy advanced example [9] and it has been publicly added in the 10.1 Geant4 distribution as a specific module for laser-driven beams (see figure 3).

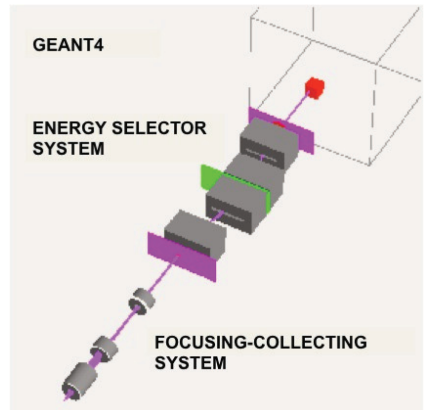

Figure 3: The transport beamline for laser-driven charged particles of the hadrontherapy advanced example of the GEANT4 toolkit.

Each element has been simulated with the real sizes, materials and properties. As regarding the magnetic fields, they have been treated using grid maps, obtained by OPERA and COMSOL simulations, with a linear interpolation between near points. In order to check and set some simulation parameters for the best compromise between accuracy and CPU time, particle tracking and beam emittance have been compared with three reference codes outputs (COMSOL, OPERA and TraceWin). The output beam features have been also compared with the preliminary experimental results.

PRELIMINARY STUDY FOR A TYPICAL LASER DRIVEN PROTON BEAM

Bearing in mind the main tasks of a transport beamline for laser-driven beams, several Monte Carlo simulations have been performed and a preliminary study is here reported. It has been performed using, as input, a typical laser-driven proton beam, with an exponential shaped energy spectrum defined in [0-55] MeV (see fig. 5) and an energy-dependent angular function. In order to reproduce the real experimental data [11], higher energy particles have been simulated with a narrower angular distribution, for instance 5 and 25 MeV protons have been described with an angular divergence of ± 20 deg and ± 5 deg, respectively.

Considering [0-30] MeV as the operational energy range of the whole transport beamline, the setup has been optimized in order to have 5 and 24 MeV as selected output energies. As first step, a set of simulations has been performed using only

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the ESS (Φ_{in}=8mm, Φ_{out}=6mm, 1×8 mm^2 slit aperture [1]), placed 60 mm far from the source point. As second step the focusing system has been added to the energy selector. Figure 4 reports the two different configurations preliminary optimized for the two energies.

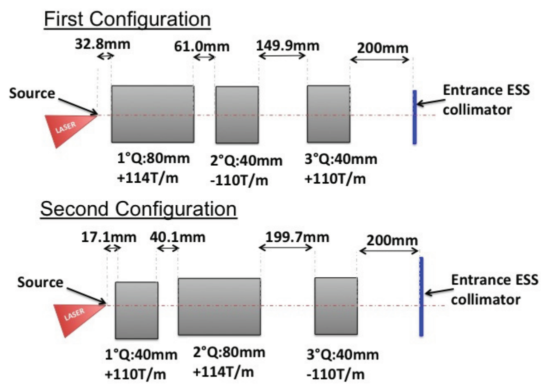

Figure 4: Details of the final PMQs setups, optimized for a 5 MeV (top) and 24 MeV (bottom) proton beam transmission.

The output beams have been then evaluated downstream the second ESS collimator, in terms of energy spectrum, fitted with a gaussian function, and transmission efficiency, as ratio between the output and the input number of particles considered in the same energetic window. Figure 5 shows the output energy spectra, obtained when only the ESS or the whole transport beamline (TBL) have been simulated. In the same plot, the input spectrum has been reported in an appropriate log scale, as well.

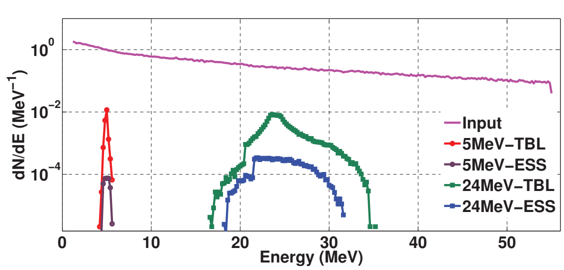

Figure 5: Input and output energy spectra, obtained when only the ESS or the whole transport beamline (TBL) have been simulated.

A quantitative evaluation of the output beams characteristics is reported in table 1.

CONCLUSION

A transport beamline prototype dedicated to laser-driven protons has been designed and realized at INFN-LNS. It consists of two main section: a focusing system and an energy selector. In order to characterize each element, preliminary tests with conventional and non conventional beams have been already performed. For this purpose, also a Monte Carlo simulation tool with a realistic implementation of each section has been developed. This paper want to report about a preliminary study performed using, as input, a typical laser-driven proton beam characterized by a wide energy and angular distribution. The beamline has been optimized in order to select 5 MeV and 24 MeV protons. Obtained results show how only the energy selector system coupled to the focusing system (TBL) allows to select output beams with defined energy spectra and transmission efficiencies. Next step foresees to test of the whole transport beamline with conventional as well as with laser-accelerated beams.

Table 1: Output Beam Characteristics for the Two Selected Energies

	E [MeV]	FWHM	Transmission Efficiency
ESS	5	14.1 %	0.007 %
TBL	5	5.2 %	1.2 %
ESS	24	25.9 %	0.1 %
TBL	24	13.5 %	2.3 %

[1] Collimators and slit sizes have been chosen in order to best exploit the energy selector gap, avoiding the inhomogenius part of the field, near the magnets

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REFERENCES

[1] S. Bulanov et al., *Oncological hadrontherapy with laser ion accelerators*, *Phys. Lett. A*, **299**, 240 (2002).

[2] A. Macchi, M. Borghesi and M. Passoni, *Ion acceleration by super intense laser-plasma interaction*, *Reviews of Modern Physics*, **85**, 751 (2013)

[3] T. Dzelzainis et al., *The TARANIS laser: A multi-Terawatt system for laser-plasma investigations*, *Laser and particles beams*, **28**, p. 451-461, ISSN: 0263-0346 (2010)

[4] M. Maggiore et al., *Transport and Energy selection of laser produced ion beams for medical and multidisciplinary applications*, *Proceedings of IPAC2014* (2014)

[5] M. Maggiore et al., *Innovative handling and transport solutions for laser-driven ion beams*, *AIP Conf. Proc.* **1546**, pp. 34-43 (2013)

[6] V. Scuderi et al, *Development of an Energy Selector System for laser-driven beam applications Nucl. Instr. Meth. A* **740** - 87 (2014)

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[7] A. Tramontana et al., *The Energy Selection System for the laser-accelerated proton beams at ELI-Beamlines*, *Journal of Instrumentation* **9**, C05065 (2014)

[8] S. Agostinelli et al., *GEANT4 - a simulation toolkit*, *Nucl. Instr. and Meth. in Phys. Res. A* Vol. **506**, 3, 250-303 (2003)

[9] G.A.P. Cirrone et al. *Implementation of a new Monte Carlo-GEANT4 simulation tool for the development of a proton therapy beam line and verification of the related dose distributions*, *IEEE Trans. Nucl. Sci.* **52(1)** pp. 262-265 (2005)

[10] F. Romano et al., *Monte Carlo Simulation for the Transport Beamline*, *AIP Conf. Proc.* **1546**, pp. 63-69 (2013)

[11] K. Zeil et al, *The scaling of proton energies in ultrashort pulse laser plasma acceleration*, *New Journal of Physics* **12**, 045015 (2010)