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ADVANCED BEAM TRANSPORT SOLUTIONS FOR ELIMAIA: A USER ORIENTED LASER-DRIVEN ION BEAMLINE

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Abstract

Laser-target acceleration represents a very promising alternative to conventional accelerators for several potential applications, e.g. in nuclear physics and medicine. However, some extreme features, such as a wide energy and angular spread, make optically accelerated ion beams not immediately suitable for multidisciplinary applications. Therefore, in addition to improvement of laser-target interaction, a large effort has been recently devoted to the development of specific beam-transport devices in order to obtain controlled and reproducible output beams within the ELIMAIA user beamline development at ELI-Beamlines. The transport beamline will be composed by three sections for the collection, selection and final shaping of the transported beams. The collection section is made of a set of super-strong high field quality permanent magnet quadrupoles with large acceptance to minimize beam losses and a gradient of 100 T/m over a 36 mm net bore able to correct the angular dispersion and focus laser driven ions. The beam selection is done by a magnetic chicane made of C-shaped electromagnetic dipoles able to select beams with an high resolution and to work as an active energy modulator (up to 300 MeV for protons and carbon ions up to 70 MeV/u). The final beam shaping is done by two steerers and two electromagnetic quadrupoles. In this contribution the actual status of the beam transport line is described together with the preliminary test performed with conventional accelerators at INFN-LNS. The feasibility study of a possible upgrade will be also reported.

INTRODUCTION

Laser-driven ion beams are a promising alternative to conventionally accelerated particle beams [1–7] even if they are not directly suitable for most applications because of the large angular and energy spread. Several efforts have been already put in order to develop beam-transport lines able to produce a controllable beam from laser accelerated particles [8–11]. Moreover, studies on the radiobiological effectiveness of laser driven protons have been also carried out, showing promising results [12]. A collaboration between ELI-Beamlines and INFN-LNS (ELI-Beamlines [13]) was launched to realize the beam transport, the dosimetric and the irradiation section of the ELIMAIA (ELI Multidisciplinary Application of laser-Ion Acceleration) beam-line dedicated to ion acceleration. ELIMED represents the section of ELIMAIA addressed to the transport, handling and dosimetry of laser-driven ion beams and to the achievement of stable, controlled and reproducible beams that will be available for users interested in multidisciplinary and medical applications of such innovative technology. The transport and dosimetric beam-line has been installed at ELIMAIA in Jul 2018, Fig.1, and it is made of three main elements: a collection system, namely a set of Permanent Magnet Quadrupoles (PMQs) placed close to the laser-interaction point, an energy selection system (ESS) based on four resistive dipoles, and a set of conventional electromagnetic transport elements for the final focusing of the beam before the injection in the in-air dosimetric station [14–16]. The beam-line will be working for laser-produced ions up to 70 MeV/u and for protons up to 300 MeV, offering, as output, a controllable beam in terms of energy spread (varying from 5 % up to 20 %), angular divergence and hence, manageable beam spot size in the range 0.1 – 10 mm, and acceptable transmission efficiency of about 10 %.

Figure 1: The ELIMAIA beamline with description of each section.

In order to fulfill the project requirements the two main elements of the beam-line, the PMQs system and the ESS, have been optimized. The aim of the collection system is to collect the accelerated ions within a certain energy range, correct their angular divergence and inject them into the selection system which will cut the particle outside the energy range of interest. The beams coming out from this first part of the beam-line (PMQs+ESS) will have characteristics closer to conventional beams and, hence, easier to be transported and shaped with conventional electromagnetic lenses (quadrupoles), which will be placed in the last part of the in-vacuum beam-line. The above description of the proposed beam-line, makes it clear that the ESS is the core element. It has been designed and realized as a single reference trajectory device based on four resistive dipoles with wide acceptance and, its laminated core allows the use

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of the chicane as an active energy modulator system. The performances of the ESS are strictly related to the input beam features. Hence, the collection system has been realized to properly inject the beam component to be selected in the ESS using five permanent magnet quadrupoles (PMQs). PMQs lenses have the advantage to be relatively compact with an extremely high field gradient, of the order 100 T/m, within a reasonable big bore of few centimeters. The PMQs system allows to collect most part of the particles with wide divergence produced in the laser-target interaction process, providing a beam of good quality in terms of controlled size and divergence. For these reasons the interest in the application of PMQs in the handling of laser produced beams is growing in recent years [17–19]. Several PMQs designs have been proposed, based on pure Halbach scheme [20] or hybrid devices using saturated iron to guide the magnetic field [21, 22]. Moreover, PMQs can be placed in the vacuum chamber, which means close to the laser-target interaction point, allowing a good collection and transmission efficiency. In this contribution we present the installed beamlines at the ELIMAIA facility and a possible upgrade is also proposed.

THE COLLECTION SYSTEM

The PMQs system consists of five quadrupoles described in Table 1, [23]. The system has to work for the collection of a wide range of ion energies from 3MeV/u up to 70MeV/u and inject a certain beam component in the ESS, hence, it has to be versatile in order to respect the transfer matrix element constraints required for the proper injection, i.e. a waist on the radial plane close to the selection slit position ($M_{1,2} = 0$) and a parallel beam on the transverse plane ($M_{4,4} = 0$) [24, 25] and it has to ensure a reasonably good transmission efficiency. Hence, the PMQs have been designed and realized with a big bore of 36 mm, a strong field gradient and high uniformity within the 75 % of its surface. The net bore is reduced to 30 mm in diameter as a 3 mm thick shielding pipe for magnet protection is set in the aperture. The quadrupoles are based on a standard trapezoidal Halbach array [26] surrounded by a external array made of rectangular magnetic blocks. The choice of this layout results to be robust with a very good field quality and, at the same time, a cost effective alternative to a pure Halbach array. The PMQs are set on a mechanical system which for changing the magnetic lenses relative position and, hence, for tuning the optics according the energy to be transported; it also allows an easy alignment of the magnets. The system is shown in Fig. 2.

Table 1: PMQs Main Features

PMQs	Geometric Length	Field Gradient	Bore Diameter
1	160 mm	101 T/m	30 mm
2	120 mm	99 T/m	30 mm
2	80 mm	94 T/m	30 mm

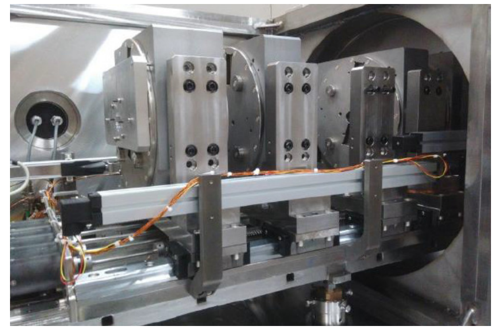

Figure 2: PMQs with their mechanical system.

THE ENERGY SELECTION SYSTEM

The definition of the ESS reference orbit, resolution and required fields for H^+ and C^{+6} are shown in Fig. 3. It is based on four resistive dipoles with alternating field [27], similar to a bunch compressor scheme, and its main trajectory parameters are calculated according to the description proposed in [28]. The main feature of the ESS are summarized in Table 2. The upper panel of Fig. 3 shows the trajectory within the four dipoles (colored lines). The selected path will guarantee a fixed energy resolution of about 5 % if a 5 mm aperture slit is used. This resolution is independent form the particle energy and ion species, as shown in Fig. 3 LHS of the bottom panel. What have to be changed, in order to put particles with different energy on the reference trajectory is the magnetic field, as shown in Fig. 3 RHS of the bottom panel, which have to vary between 0.085 up to 1.2 T for protons with energy ranging between 3 and 300 MeV, while it has to reach the value of 1 T for carbons (C^{+6}) with energy of 70 MeV/u. The proposed layout allows to vary the energy resolution changing the slit aperture size. The ESS has laminated cores for the dipoles and offer also the possibility to work changing the excitation current with the same repetition rate of the laser, 1 Hz. The current ramping in the coils will produce eddy currents circulating in the vacuum chamber that can cause an effective sextupole field superimposed to the dipole field [29–32]. Hence, the main dipole field distortions due to the current ramp have been investigated [27] showing no relevant effect on the main dipole component when the field is stable.

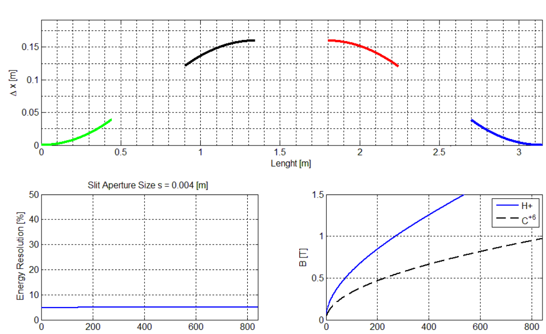

Figure 3: ESS reference orbit, resolution and required fields for H^+ and C^{+6}.

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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	**Field uniformity**	**Curvature radius**	**Drift length**	**Max Current density**
100 mm	< 0.5 %	2.593 m	500 mm	2.53 A/mm^2

Figure 4: ESS installed at INFN-LNS for calibratiion.

The whole system was calibrated using standard accelerator beams at INFN-LNS, Fig. 4.

ELIMAIA UPGRADE: HIGH ENERGY THOMSON PARABOLA

The possibility to use the first dipole of the ESS as magnetic deflection sector of a Thomson Parabola spectrometer [33, 34] is a simple solution for having an on-axis diagnostics system with extremely high energy resolution for protons up to 300 MeV and for carbon ions up to 900 MeV. The large horizontal space inside the vacuum chamber also offer the possibility to install two electrostatic dipoles, as shown in Fig. 5.

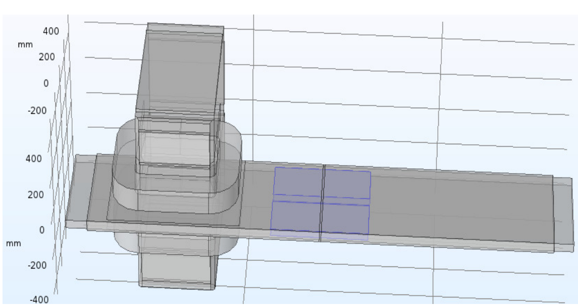

Figure 5: Setup of two electric field inside in the ESS vacuum chamber.

This solution would optimize the performances of the device. In fact, one sector would have a large dynamics range but a limited energy resolution of about 10 %, the other sector would have a limited dynamics range but the resolution can be up to 1 %. The simulated spectrogram for the large-dynamics, low-resolution sector is shown in Fig. 6.

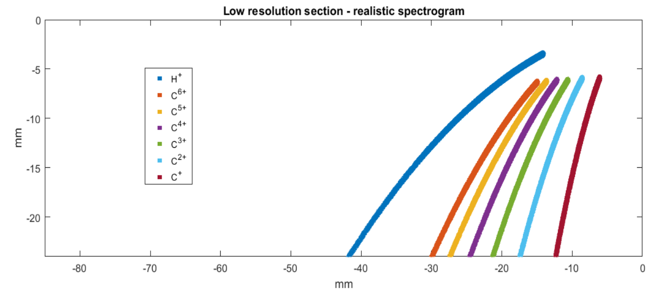

Figure 6: Realistic spectrogram obtained using the large-dynamics, low-resolution sector

In order to have the correct charge separation it will be necessary to use a small collimating system with an aperture of 0.2 or 0.1 mm which is still under design and, most importantly, the proper electric field strength should be achieved considering that 30 mm clearance in the ESS vacuum chamber must be guaranteed. Due to this relatively large gap the voltage on the electrode should be of 100 kV and this lead to some issues with the choice of the proper insulator and connection between electrodes and high voltage feedthoroughs. Even if few promising solutions have been already identified it would be necessary to carry on some prototyping before the final realization. A detailed study of this upgrade will be presented elsewhere.

CONCLUSION

The actual status of the ELIMED beam transport line is here reported. The transport line has been installed as a part of the ELIMAIA user beam line at ELI after testing the most important elements with conventional beam at INFN-LNS accelerators. The possibility to use the chicane as a Thomson Parabola spectrometer is also proposed. This would be the first upgrade of the ELIMAIA beamline.

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REFERENCES

[1] V. Malka *et al.*, "Practicability of protontherapy using compact laser systems", *Med. Phys.*, vol. 31, p. 1587-92, Jun. 2004.

[2] S. V. Bulanov *et al.*, "Oncological hadrontherapy with laser ion accelerators", *Phys. Lett. A*, vol. 299, p. 240247, 2002.

[3] S. V. Bulanov *et al.*, "Laser iona acceleration for hadron therapy", *Physics-Uspekhi*, vol. 52, p. 1149-1179, 2014.

[4] S. V. Bulanov *et al.*, "Feasibility of using laser ion accelerators in proton theraphy", *Plasma Physics Reports*, vol. 28, p. 453-456, 2002.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPTS005

[5] T. Esirkepov *et al.*, “Highly Efficient relativistic-ion generation in the laser-piston regime”, *Phys. Rev. Lett*, vol. 92, p. 1750031, 2014.

[6] A. V. Kuznetsov *et al.*, “Effciency of ion acceleration by a relativistically strong laser pulse in an underdense plasma”, *Plasma Phys. Rep.*, vol. 27, p. 211, 2011.

[7] F. Schillaci *et al.*, "ELIMED, MEDical and multidisciplinary applications at ELI-Beamlines", *J. Phys.: Conf. Ser.*, vol. 508, p. 012010, 2013.

[8] V. Scuderi *et al.*, "Development of an energy selector system for laser-driven proton beam applications", *NIMA, Proceeding of EAAC Workshop 2013*, vol. 740, p. 87-93, 2014.

[9] M. Maggiore *et al.*, "Transport and energy selection of laser produced ion beams for medical and multidisciplinary applications", presented at IPAC’14, Dresden, Germany, Jun. 2014, paperTUPME034, unpublished.

[10] S. Busold *et al.*, "Commissioning of a compact laser-based proton beam line for high intensity bunches around 10 MeV", *Phys. Rev. ST Accel. Beams*, vol. 17, p. 032801, 2017.

[11] U. Masood *et al.*, "Spectral and spatial shaping of a laser-produced ion beam for radiation-biology experiments", *Phys. Rev. Accel. Beams*, vol. 20, p. 41-52, 2014.

[12] L. Pommarel *et al.*, "A compact solution for ion beam therapy with laser accelerated protons", *Appl. Phys. B*, vol. 117, p. 41-52, 2014.

[13] ELI - Extreme Light Infrastructure Whitebook,

[14] D. Margarone *et al.*, "ELIMAIA: A Laser-Driven Ion Accelerator for Multidisciplinary applications", *Quantum Beam Sci*, vol. 2, p. 8, 2018.

[15] F. Schillaci *et al.*, "ELIMED: MEDical application at ELI-Beamlines. Status of the collaboration and first results", *Acta Polytechnica*, vol. 54, p. 285-289, 2014.

[16] G.A.P. Cirrone *et al.*, "ELIMED, future hadrontherapy applications of laser-accelerated beams", *NIMA*, vol. 730, p. 174-177, 2013.

[17] S. Becker *et al.*, "Characterization and tuning of ultrahigh gradient permanent magnet quadrupoles", *Phys. Rev. ST Accel. Beams*, vol. 12, p. 102801, 2009.

[18] H. Sakakki *et al.*, "Simulation of Laser-Accelerated Proton Focusing and Diagnosis with a Permanent Magnet Quadrupole Triplet", *Plasma Fusion Res.*, vol. 5, p. 009, 2010.

[19] M. Schollmeier *et al.*, "Controlled Transport and Focusing of Laser-Accelerated Protons with Miniature Magnetic Devices", *Phys. Rev. Lett*, vol. 101, p. 055004, 2008.

[20] K. Halbach "Physical and optical properties of rare earth cobalt magnets", *NIM*, vol. 187, p. 109, 1981.

[21] T. Mihara *et al.*, "Superstrong Adjustable Permanent Magnet for a Linear Collider Final Focus", *Proc. of the 12th Linear Accelerator Conference*, SLAC Report No. SLAC-PUB-10878.

[22] F. Schillaci *et al.*, "Errors and optics study of a permanent magnet quadrupole system", *JINST*, vol. 10, p. T05001, 2015.

[23] F. Schillaci *et al.*, "Design of the ELIMAIA ion collection system", *JINST*, vol. 10, p. T12001, 2015.

[24] H. Wollnik, "Optics of Charged Particles", *Academic Press, Inc.*, 1987.

[25] F. Schillaci, "Feasibility Study of an Energy Selection System for laser driven-ion beams in the energy range of 3 – 60 MeV/u", unpublished

[26] K. Halbach, "Design of permanent multipole magnets with oriented rare earth cobalt material", *NIMA*, 169, p. 1, 1980.

[27] F. Schillaci *et al.*, "Design of a large acceptance, high efficiency energy selection system for the ELIMAIA beam-line", *JINST*, vol. 11, p. P08022, 2016.

[28] P. Castro "Beam trajectory calculations in bunch compressors of TTF2", Berlin, Germany, Desy Tecnical Note 2003-01, 2003.

[29] J. C. Bergstrom *et al.*, "Effects of Eddy Current Induced Sextupole Moments in the Booster During Ramping", Saskatoon, Canada, *CLS Design note* – 3.2.69.2 Rev. 0, 2000.

[30] S. A. Bogacz *et al.*, "Chromaticity Compensation – Main Injector Sextupole Strengths", Fermilab, USA, *Main Injector note* MI-0056, April 1991.

[31] T. Toyama *et al.*, "The Eddy-current-induced Head-tail Instability at the KEKE-PS", *Proc. PAC’99*, New York, 1999.

[32] N .S. Sereno, "Eddy-current-induced Multipole Field Calculations", *Advanced Photon Source Note* LS-302, 2003.

[33] J. J. Thomson, "Rays of positive electricity",*Philos. Mag*. Vol. 21, p. 225-249, 1911.

[34] F. Schillaci, *et al.*, "Calibration and energy resolution study of a high dispersive power Thomson Parabola Spectrometer with monochromatic proton beam", *JINST* Vol 9, T10003, 2014.