DESIGN OF A COLLECTION AND SELECTION SYSTEM FOR HIGH ENERGY LASER-DRIVEN ION BEAMS

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Abstract

Laser-target acceleration represents a very promising alternative to conventional accelerators for several potential applications, from the nuclear physics to the medical ones. However, some extreme features, not suitable for multidisciplinary applications, as the wide energy and angular spreads are typical of optically accelerated ion beams. Therefore, beyond the improvements at the laser-target interaction level, a lot of efforts have been recently devoted to the development of specific beam-transport devices in order to obtain controlled and reproducible output beams. In this framework, a three years contract has been signed between INFN-LNS (IT) and Eli-Beamlines-IoP (CZ) to provide the design and the realization of a complete transport beam-line, named ELIMED, dedicated to the transport, diagnostics and dosimetry of laser-driven ion beams. The transport devices will be composed by a set of super-strong permanent magnet quadrupoles able to collect and focus laser driven ions up to 70 MeV/u, and a magnetic chicane made of conventional electromagnetic dipole to select particles within a narrow energy range. Here, the design and development of these magnetic systems is described.

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 done in order to develop beam-transport line able to produce a controllable beam from laser accelerated particles [8–11]. In 2014 FZU (ELI-Beamlines [12]) launched a public tender 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. INFN-LNS has been officially appointed through a three years contract for its delivery. ELIMED will represent 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, in the future, will be available for users interested in multidisciplinary and medical applications of such innovative technology. The transport and dosimetric beam-line that will be installed at ELIMAIA will be made of three main elements: a collection system, namely a set of Permanent Magnet Quadrupoles (PMQs) that will be 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. The beam-line will be working for laser-produced ions up to 70 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, manageable beam spot size in the range 0.1 − 10 mm, and acceptable transmission efficiency (about 10^7 ions/pulse). In order to fulfill the project requirements the two main elements of the beam-line, the PMQs system and the ESS, have to be 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 and steerers, 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 as a single reference trajectory device based on four resistive dipoles with wide acceptance. The performances of the ESS are strictly related to the input beam features. Hence, the collection system has been designed 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 beam handling of laser produced beams is growing in recent years [13–15]. Several PMQs designs have been proposed, based on pure Halbach scheme [16] or hybrid devices using saturated iron to guide the magnetic field [17,18]. 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 even if, in the early stages of the laser ion accelerator development, the angular spread of the beam is estimated in a few tens of degrees. The

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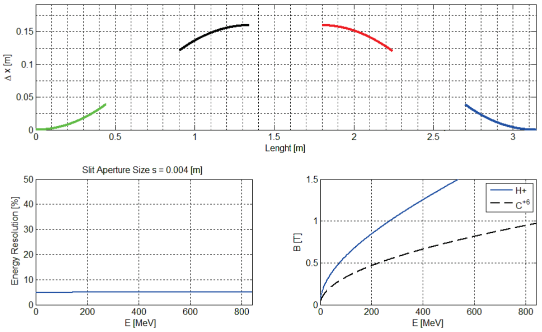

Figure 1: Definition of the design trajectory of the ESS, resolution and required fields for H^+ and C^{+6}.

Table 1: 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

design and optics study of the PMQs and of the ESS systems are described in this contribution.

THE ENERGY SELECTION SYSTEM

A sketch of the ESS is shown in Fig. 1. Its layout is based on four resistive dipoles with alternating field, similar to a bunch compressor scheme, and its main trajectory parameters are calculated according to the description proposed in [19]. The main feature of the ESS are summarized in Table 1. The upper panel of Fig. 1 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.1 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.1 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 80 MeV/u. The proposed layout allows to vary the energy resolution changing the slit aperture size.

The pole shape has been designed in order to respect the requirements of Table 1 and considering that, in order to keep the system as compact as possible, the magnet efficiency is 98 %. The pole radial shimming studied allows to limit the iron saturation to the pole periphery and to ensure the required field uniformity for each value of B [20, 21]. Moreover, magnetic saturation in the vicinity of the longitudinal edge results in a small decrease in the effective length with the increasing of the excitation current. Hence, the effective length will be varying in a wide range as the dipoles of the chicane will be working at different fields. A suitable longitudinal Rogowski profile [22] can avoid saturation issues and also reduces the effective length variation for different fields. In these magnets, the Rogowski profile has been approximated with two straight lines and this approximation reduce the effective length variation between 451 mm and 448 mm, moreover, the longitudinal profile has no saturation as shown in Fig.2. The whole system is shown in Fig.3 where also it is evident that the reference particle beam moves within the GFR of each dipole. The system has two collimators, necessary to cut unwanted particle with energy outside the spread to be selected and injected in the chicane with big angles and to refine the selection at the exit of the system; they will be set 200 mm upstream and downstream the ESS, and will have a diameter of 30 mm.

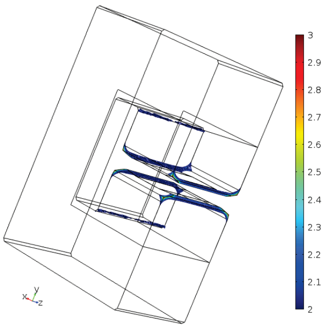

Figure 2: Saturated regions in the Rogowski shaped dipole.

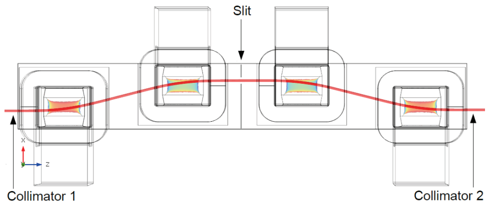

Figure 3: Energy Selector with vacuum chamber and reference trajectory. Colour surface marks the GFR of each dipole.

The ESS will 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 [23–26]. Hence, the main dipole field distortions due to the current ramp have been investigated. Time dependent simulations are extremely expensive in terms of computational resources and time, thus a conservative case has been considered: the current is ramped from zero up to 273 Amp/turn in 0.28 s, which means a maximum field of 1.5 T. This choice is related to the fact that higher magnetic flux variations cause higher induced currents in the chamber wall. The simulation is performed on a period of one second, namely between two laser shots, and considering only two dipoles. The induced current density has a maximum value of $1.15 * 10^6$ A/mm^2 and after 0.13 sec the current ramp starts, and at 0.31 sec it is reduced to zero. The total harmonic content of the dipole have been analyzed during the current ramp, following the formalism proposed in [7].

Table 2: 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

As expected, the sextupole harmonics dominates over the other components and when the eddy currents extinguish, the total harmonic content is restored to the same value of the static case.

THE COLLECTION SYSTEM

The PMQs system consists of five quadrupoles as described in Table 2, [27]. The system has to work for the collection of a wide range of ion energies from 3 MeV/u up to 60 MeV/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 ($M_{4,4} = 0$) [28, 29] and it has to ensure a reasonably good transmission efficiency. A big bore of at least 36 mm with a strong field gradient and high uniformity within the 75 % of its surface is also necessary. The net bore is reduced to 30 mm in diameter as a 3 mm thick shielding pipe for magnet protection has to be set in the aperture. Considering these requirements the quadrupoles designed are based on a standard trapezoidal Halbach array [30] surrounded by two external hybrid arrays made of rectangular magnetic blocks and iron. A scheme of the PMQs layout is shown in Fig. 4.

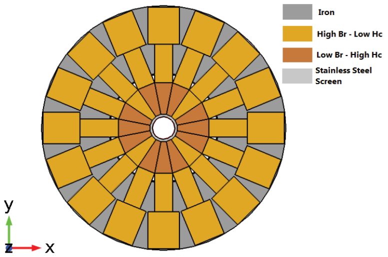

Figure 4: PMQ layout. Different colors are for different materials used.

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. As can be seen in Fig. 4, the inner array is made of two different permanent magnet alloys with different characteristics in order to avoid demagnetization issues. The field analysis, reported in Table 3 for the long (160 mm) quadrupole, and it is compared with the same magnet realized as a pure Halbach array.

BEAM TRANSPORT SIMULATION

In the following, the preliminary beam-transport simulation results for the selection of 60 MeV protons are reported.

Table 3: Field Uniformity of the 160 mm PMQ and Comparison with Pure Halbach Design

	Gradient Uniformity		Integrated Gradient Uniformity	
	PMQ 160 mm	**Pure Halbach**	**PMQ 160 mm**	**Pure Halbach**
@$R = 7.5$ mm	< 0.25 %	< 0.1 %	< 0.035 %	< 0.03 %
@$R = 12$ mm	< 2 %	< 1.5 %	< 0.3 %	< 0.3 %
@$R = 14.5$ mm	< 8 %	< 3 %	< 0.7 %	< 0.6 %

The beam-line is set as in Fig. 5 where the particles in the energy range of interest (54 – 66 MeV) are in black; blue and green traces are for lower and higher energy particles. The selection slit, set at 3,8 m from the target, is a rectangular aperture with height of 40 mm, same as the inner ESS vacuum chamber height, and 20 mm width in order to produce an energy spread of 20 %. The lower panel of the plot is a magnification of the last part of the ESS and justify the necessity to use the presented chicane. In fact, the spectrum is still large due to the spatial mixing of particles with big angles in the first half of the system.

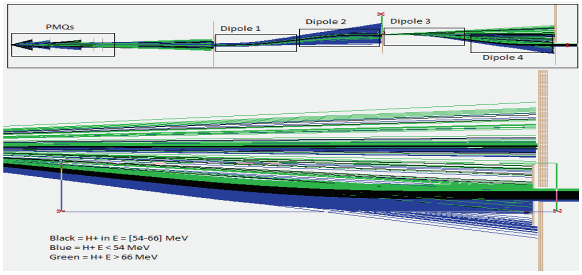

Figure 5: TNSA-like protons motion in the beamline. Simulation performed with SIMION8.0.

The input spectrum is typical TNSA exponential decreasing, as simulated with PIC code, with a cut off at 105 MeV, black line in Fig.6, the angular divergence has been modeled as a function of the energy and, for the particle in the range of interest, it has a FWHM of 5°. The transmission efficiency of the system results to be of 12 % as shown in Fig. 6 where the blue line indicates the particles produced in the energy range of interest at the source and the green line the output spectrum. The beam divergence is considerably reduced to 0.3°, which makes it possible to transport and shape the beam using conventional resistive quadrupoles that will be used to prepare the beam with the right features for the injection in the in-air part of the beam-line where dosimetric studies will be performed.

CONCLUSION

The design of the ELIMED beam-line is here reported showing good features of the magnetic elements. A preliminary beam transport simulation has been also reported showing good beam-line performances. The magnets will be manufactured in the next months, the test with conventional

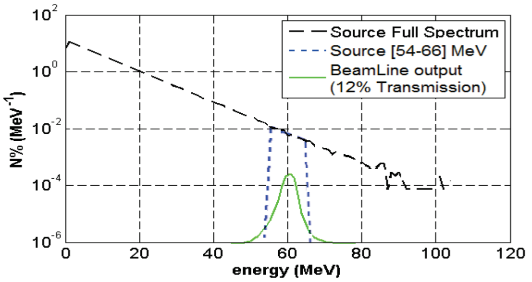

Figure 6: TNSA-like proton spectrum from PIC simulations (black line), particles in the energy range of interest (blue line) and selected spectrum (green line).

beam at INFN-LNS accelerators will be performed before the installation of the systems at the ELI-Beamlines facility in Prague (CZ) expected at the end of the 2017.

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