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Status of the ELIMED Beamline at the ELIMAIA facility

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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, characterize 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 the 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 dipoles to select particles within a narrow energy range. Here, the actual status of the design and development of these magnetic systems is described.

KEYWORDS: Accelerator Subsystems and Technologies; Accelerator Applications; Beam dynamics; Beam Optics

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1 Introduction

In the recent years laser-target interaction has gained interest as laser-based accelerators could represent a promising and competitive alternative to conventional accelerating machines [1–6]. In this view the first high-power laser user oriented facility, ELI-Beamlines, is under develpment in Czech Republic within the ELI infrastructure and it will provide different beamlines for users interested in applications of laser-driven beams. In particular one of the beamlines, the ELIMAIA (ELI Multidisciplinary Application of laser-Ion Acceleration) beamline, will be addressed to users interested in multidisciplinary applications of laser-produced ions, with a particular care for medical applications with the aim to demonstrate the clinical applicability of this new acceleration technique. Laser-driven ion beams are not directly suitable for most applications because of the large angular and energy spread and, to fulfill the project goals the INFN-LNS has been officially appointed for the design and realization of a transport beamline able to produce a controllable beam and also to perform an accurate diagnostic and dosimetry. This system, named ELIMED (MEDical and multidisciplinary application at ELI-beamlines) is made of a set of magnetic elements for the beam handling and selection and a set of diagnostics devices for the beam characterization and dosimetry measurements. In this contribution a description of the design process and the status of the magnetic elements realization are reported.

2 The ELIMED Collection system

The first part of the beamline has been designed in order to collect most of the particles within a certain energy range and properly inject them in the next selection section. The design process started with the analytical definition of the Energy Selection System (ESS), as described in [7]. It will be a double-dispersive mode magnetic chicane working on a single reference orbit. The reference orbit parameters are used to simplify the ESS description as a set of collimators and to define the proper matching conditions in order to limit the losses of the energy range to be selected in the collection system. The resulting envelope for 60 MeV protons obtained during this preliminary study is shown in figure 1. The matched beam has to be focused at the selection slit position in the horizontal plane (matching condition on the transport matrix $M_{12} = 0$) and an almost parallel beam in the vertical plane (matching condition on the transport matrix $M_{44} = 0$). A setup of 5 Permanent Magnet Quadrupoles (PMQs) of different lengths guaranties the tunability necessary to satisfy these conditions for all energies in the range 3 – 70 MeV. Two of the quads are 80 mm long, two others are 120 mm and the remaining one is 160 mm, all five with a 36 mm bore diameter and a gradient of 100 T/m to increase the acceptance and minimize losses. Every time a different energy is selected the optics of the collection system is retuned, mainly by changing the PMQs relative distances, but also changes in PMQs sequence, polarity and number are possible.

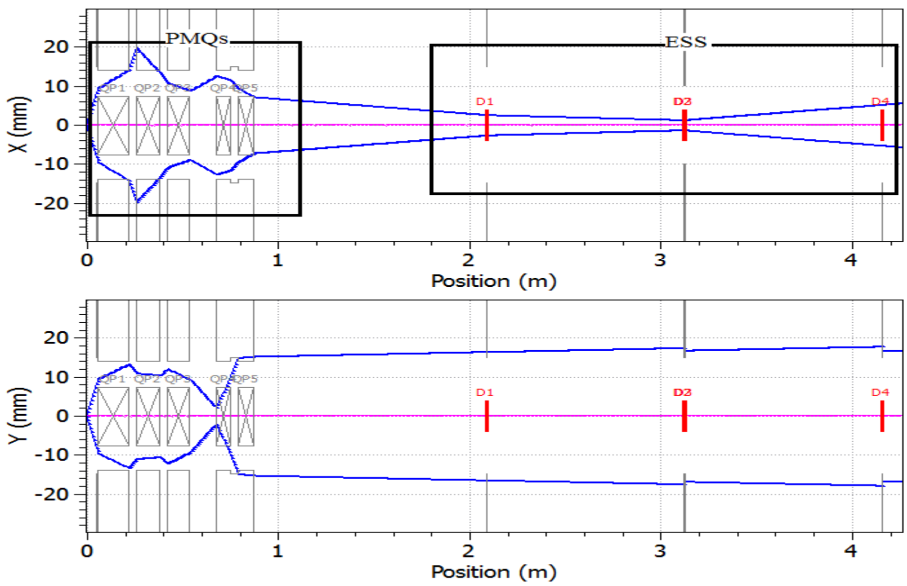

Figure 1. Matched beam obtained using a simplified ESS scheme featuring a set of five permanent magnet quadrupoles. A 60 MeV proton beam is used in this simulation.

The preliminary design is deeply described in [7] where the magnets are analyzed from different points of view in order to understand their feasibility and the requirements on the field quality. The most critical point is represented by the extremely high attraction/repulsion forces between magnets which also introduce more constraints on the system tunability. In the preliminary design a 40 mm minimum distance is necessary to cope with forces not higher than 7 kN between magnets, [7]. The PMQs manufacturing is almost completed and the final design has been optimized by SigmaPhi, providing a simplified magnetic configuration with an internal Halbach array of 149 mm outer diameter made of high coercitivity and lower remanence magnetic material and an external array of rectangular blocks with an outer diameter of 266 mm made of lower coercitivity and high remanence magnetic material. This configuration allows to avoid demagnetization issues for the blocks and also to have smaller magnets and, as a consequence, a strong reduction of forces: about 2.5 kN for a distance of 30 mm between quadrupole. The l.h.s. of figure 2 shows the 120 mm PMQ assembled and r.h.s. of figure 2 shows the full system complete with mechanics.

The final design has been validated against requests on field gradient and gradient uniformity, calculation being performed by two different teams using two different codes (Sigmaphi/OPERA 3D and INFN-LNS/COMSOL) and the results are shown in the following figures 3 and 4 where also field requirements are reported. The plots, especially the one in figure 4, show that the field quality

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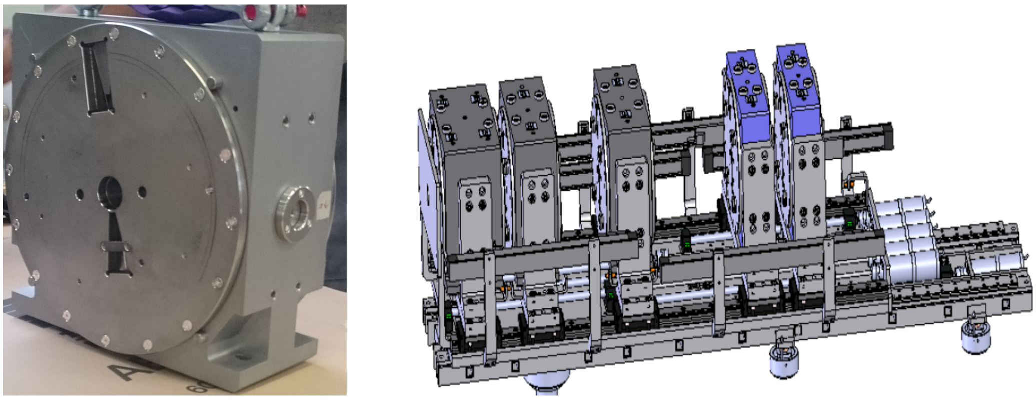

Figure 2. L.h.s.: 120 mm long PMQ assembled. R.h.s.: full system complete with mechanics.

of the new simplified design complies with the request coming from the preliminary feasibility study [7]. Difference between the two code results are due to mesh nodes number (higher in OPERA) and, to a scaling factor of about 0.5 % for the maximum gradient value. The harmonic content evaluated with the two codes is also very similar with a total contribution of about 8 units with respect to the main $b2$ harmonic.

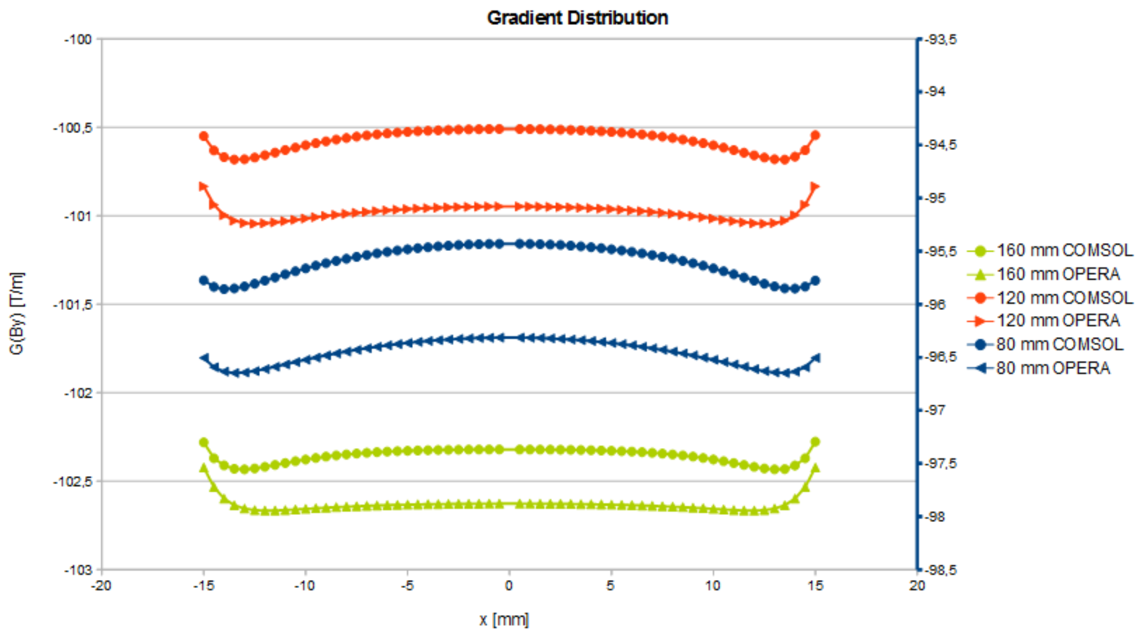

Figure 3. Gradient distribution calculated with OPERA 3D and COMSOL for the 3 types of quadrupoles. Scale on the right side is referred to the 80 mm quads gradient.

3 Energy Selector and additional transport elements

The Energy selector has been designed considering the reference orbit parameters and also taking into account the emittance growth due to the PMQs system, this highlight the strict connection

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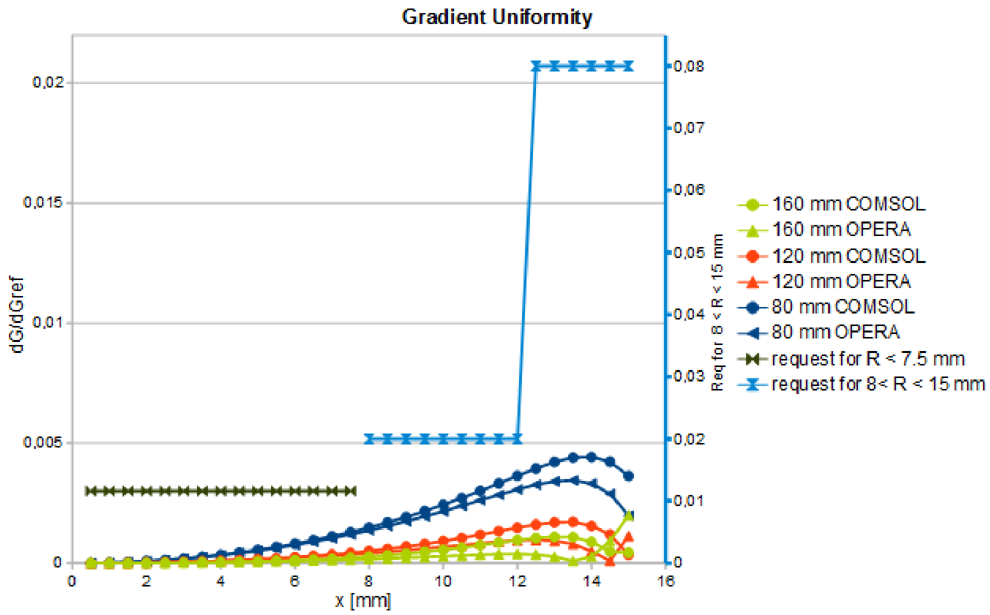

Figure 4. Gradient uniformity calculated with OPERA 3D and COMSOL for the 3 types of quadrupoles and comparison with requested values. Scale on the right side is referred to the request for $R > 7.5$ mm.

between the two systems. Detailed description is provided in [8], which will be used as a starting point for the final design and optimization by SigmaPhi. It will be a double-dispersive mode, large acceptance magnetic chicane with a transmission efficiency of 100 % if the energy range to be selected is properly injected and its energy resolution can be easily changed with the slit aperture size. It has been also designed to work as an active energy modulator changing the field shot-by-shot. The beamline is completed with an electromagnetic quadrupole doublet with a maximum gradient of 10 T/m over a magnetic bore of 70 mm and two double axis correctors. Figure 5 shows the whole transport elements and their relative distances. The additional transport element are standard pieces of optics but are important to refine the beam shape, size and uniformity before delivering the ion bunch to the users. As shown in figure 6 the beam uniformity is strongly improved focusing the particles and cutting the beam halo with a collimator. In this case losses are not relevant.

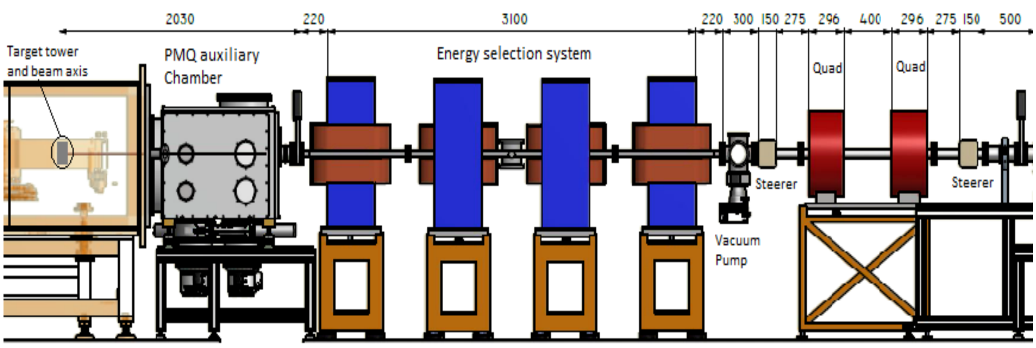

Figure 5. Scheme of the whole ELIMED beamline. Beam direction is left to right, PMQs are not reported as they are partially set in the auxiliary chamber.

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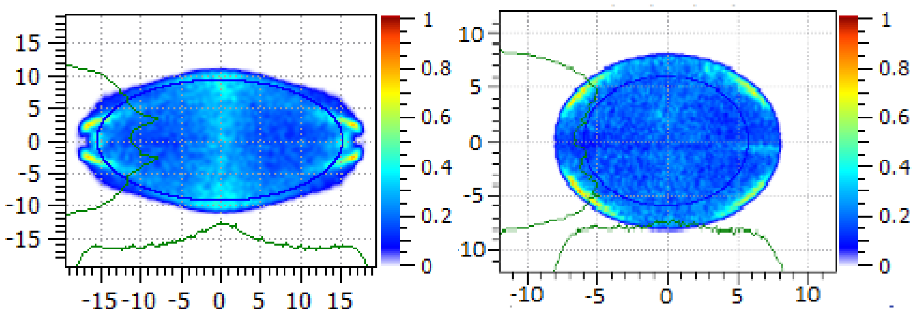

Figure 6. 60 MeV proton beam profile at the ESS output (l.h.s., at the vacuum pump position in figure 5) and at the beamline output (r.h.s., after the second steerer in figure 5).

4 Conclusion

The beamline realization is still in progress, the PMQs will be completed within the end of 2016 and deliver to LNS for characterization with Tandem and Cyclotron beams. The other elements, ESS and the standard lenses, are under engineering at SigmaPhi and the final design will be provided in the next months. They are expected to be delivered at LNS in the second half of 2017 where the whole beamline wil be characterized, calibrated and tested before the installation at ELI-Beamlines in Prague.

References

[1] V. Malka et al., *Practicability of protontherapy using compact laser systems*, *Med. Phys.* **31** (2004) 1587.

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

[3] S.V. Bulanov, et al., *Laser ion acceleration for hadron therapy*, *Phys.-Usp.* **52** (2014) 1149.

[4] S.V. Bulanov and V.S. Khoroshkov, *Feasibility of Using Laser Ion Accelerators in Proton Therapy*, *Plasma Phys. Rep.* **28** (2002) 453.

[5] T. Esirkepov et al., *Highly Efficient Relativistic-Ion Generation in the Laser-Piston Regime*, *Phys. Rev. Lett.* **92** 4 (2004) 1750031.

[6] A.V. Kuznetsov et al., *Efficiency of ion acceleration by a relativistically strong laser pulse in an underdense plasma*, *Plasma Phys. Rep.* **27** (2011) 211.

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

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

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