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*Article*

# Design and Status of the ELIMED Beam Line for Laser-Driven Ion Beams

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**Abstract:** Charged particle acceleration using ultra-intense and ultra-short laser pulses has gathered a strong interest in the scientific community and it is now one of the most attractive topics in the relativistic laser-plasma interaction research. Indeed, it could represent the future of particle acceleration and open new scenarios in multidisciplinary fields, in particular, medical applications. One of the biggest challenges consists of using, in a future perspective, high intensity laser-target interaction to generate high-energy ions for therapeutic purposes, eventually replacing the old paradigm of acceleration, characterized by huge and complex machines. The peculiarities of laser-driven beams led to develop new strategies and advanced techniques for transport, diagnostics and dosimetry of the accelerated particles, due to the wide energy spread, the angular divergence and the extremely intense pulses. In this framework, the realization of the ELIMED (ELI-Beamlines MEDical applications) beamline, developed by INFN-LNS (Catania, Italy) and installed in 2017 as a part of the ELIMAIA beamline at the ELI-Beamlines (Extreme Light Infrastructure Beamlines) facility in Prague, has the aim to investigate the feasibility of using laser-driven ion beams in multidisciplinary applications. ELIMED will represent the first user's open transport beam line where a controlled laser-driven ion beam will be used for multidisciplinary and medical studies. In this paper, an overview of the beamline, with a detailed description of the main transport elements, will be presented. Moreover, a description of the detectors dedicated to diagnostics and dosimetry will be reported, with some preliminary results obtained both with accelerator-driven and laser-driven beams.

**Keywords:** laser-driven ion; ELIMED beamline; medical applications; magnetic transport elements; dosimetry; electromagnetic pulse

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## 1. Introduction

The concept of coherent acceleration, that can be advised as the starting idea of the new particle acceleration approach, based on the high-intensity laser matter interaction, was introduced for the first time in 1957 by Veksler [1]. Ever since, enormous theoretical, as well as experimental progress, has been achieved in this field until the year 2000, which can be considered the *annus mirabilis* of laser-driven ion acceleration. In 2000 three experiments [2–4] reported on the generation of intense and energetic (up to 58 MeV) proton beams from solid targets irradiated with high-intensity (from $3 \times 10^{18}$ W/cm$^2$ to $3 \times 10^{20}$ W/cm$^2$) laser pulses.

The typical experimental set-up used in these experiments consists of a high power laser beam impinging on a thin solid target; thanks to the laser-matter interaction charged particles are accelerated in both directions with respect to the laser-irradiated target surface. For the first time, protons were emitted as a rather collimated beam, along the target normal direction rather than in the isotropic and low-brilliance emission typical of previous experiments [5,6].

So far different acceleration regimes, for instance target normal sheath acceleration (TNSA) [7], the radiation pressure acceleration [8], "Light sail" acceleration [9], "Laser piston" acceleration [10], "Break-out afterburner" acceleration [11], have been studied and several experimental results on laser driven ion energies [12–14], obtained mainly within the TNSA regime, have been reported in literature.

The peculiarities of the proton emitted in the forward direction (*i.e.* in the opposite direction with respect to the laser-irradiated target surface) in these new experiments were extremely promising suggesting that laser-driven proton/ion acceleration might represent a new opportunity in the particle acceleration field and generating also a huge interest in both fundamental research as well as in the possible multidisciplinary applications.

Actually, laser accelerated beams show different and, in some cases, extreme characteristics with respect to the conventional ones. A very high peak current, a broad energy spectrum, a wide angular distribution and a rather small transverse and longitudinal emittance are the main features of a typical laser-driven ion beam generated in the so-called TNSA (Target Normal Sheath Acceleration) acceleration regime, which represents the most known and experimentally investigated laser-induced acceleration process.

In this framework, a collaboration between the INFN-LNS (Nuclear Physics Laboratory, Catania, Italy) and the ASCR-FZU (Institute of Physics of the Czech Academy of Science), in charge for the ELI-Beamlines facility implementation, has been established in 2012. The main aim of the collaboration, named ELIMED (ELI-Beamlines MEDical applications), is to investigate the feasibility to design and realize a beam transport line for optically accelerated beams to be used for multidisciplinary and medical applications. In 2013 the ELI-Beamlines Institute started the realization of a facility in Prague, where one of the experimental halls, called ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration), will host the beam line dedicated to the ion acceleration and multidisciplinary applications. The ELIMED beam line, which will be developed by LNS-INFN, will represent the section of the ELIMAIA activity addressed to the transport, handling and dosimetry of the laser-driven ion beams allowing the achievement of stable, controlled and reproducible beams that, in the future, will be available for all the users interested in multidisciplinary and medical applications of such innovative technology.

## 2. Overview of the ELIMAIA Beam Line

As already pointed out, the ELIMED main goal is the realization of a beam transport line (from the laser-target interaction chamber to the final sample irradiation point) and a number of dosimetric endpoints that will enable the users to apply laser-driven ion beams (protons, alpha-particles and carbon/lithium ions) in multidisciplinary fields. The technical solution proposed for the realization of the ELIMED beam line is based on a modular system, which allows adapting and combining the devices depending on the different phases of the project and the different user's requirements. Three different sections of the ion beam line have been identified for its implementation: the Ion Beam Collection and Diagnostics; the In-Vacuum Ion Beam Selection, Transport and Diagnostics and the Dosimetry and sample Irradiation systems.

Laser-driven ion beams are characterized by high intensities, several species with multiple charge states, broad energy spectra and energy-dependent angular distributions. Therefore, in order to make these beams suitable for multidisciplinary purposes, the main task of the beam transport line will be to control the particle energy and angular distributions as well as the flexibility and reproducibility of the delivered beam spot size and dose distribution. The requirements needed to perform accurate dosimetric measurements and radiobiological irradiations for pre-clinical studies imply that the transported beam must fulfill specific characteristics. Indeed, these preparatory pre-clinical studies, which are based on *in vivo* irradiations on mice, have to be done with a level of accuracy on delivered dose close to the one characterizing human tumor treatments. The specific characteristics of the transported beams are mainly related to the beam flatness and symmetry at the irradiation point, which have to be within 3%.

In particular, the purpose of the collecting and focusing section is to reduce the initial angular divergence of the particle beam accelerated from the target improving the transmission and the selection efficiency of the entire transport system. The focusing element will consist of a set of permanent magnet quadrupoles (PMQs) [15–17] based on a hybrid Halbach array in order to maximize the magnetic field strength, quality and uniformity by keeping the system as compact as possible. A quadrupole set is necessary to obtain a focusing effect on both transversal planes, as well as for a suitable matching with selection system acceptance. The PMQs system will be placed few cm downstream the target. Since the field strength is fixed for each magnet, the PMQs system will be provided with mechanical stages allowing modifying the relative distance of each quadrupole along the beam direction (*i.e.* the longitudinal axis) and, thus, the focal point position as a function of the beam energy. The moving system will be provided with a remote control.

The energy selection system is the critical element of the whole beam line. The beam accelerated by the laser-target interaction, after the collecting and focusing section, might still show a broad energy spectrum. Therefore, it is important to realize a system able to select ion beams with controlled energy spread and kinetic energy. The energy selector system (ESS) proposed will be placed along the beam transport line, downstream from the PMQs system. The ESS will consist of tunable resistive conductors allowing varying the performances depending on the ion species to be selected. It will be based on a resistive coil system with alternating field gradient. A set of resistive quadrupoles placed downstream from the ESS will allow recovering both vertical and radial focusing of the beam after the selection. Two steering magnets (in both vertical and horizontal directions) will allow for control of the beam direction after the selection and correcting of any possible beam misalignments.

The beam transport elements, as it has been established in the signed contract, will be characterized and tested using conventional accelerated and laser-driven ion beams. An experimental hall at the INFN-LNS has been entirely dedicated to the ELIMED project in order to perform all the tests required for the ELIMED beam line using proton beams delivered by the Tandem and by the Superconducting Cyclotron (CS) (LNS, Catania, Italy).

After the main beam transport elements, diagnostics elements specifically optimized to measure the beam emittance for laser-driven ions will be used for the on-line characterization of the collected beam. Complementary diagnostics systems such as Silicon Carbide (SiC), Diamond or Secondary Emission Monitor (SEM) detectors will be provided. This detector will be used in Time of Flight (ToF) configuration, providing a spectral analysis of the accelerated and transported ions.

A precise knowledge of the absolute dose, delivered by the incoming radiation, is crucial in several applications, as for instance the hadrontherapy ones, where the dosimetric accuracy is a key prerequisite. Indeed, for clinical accelerator-driven proton beams, the dose uncertainties at a reference depth in water with calibrated plane-parallel ionization chambers are 2.3%, according to the Code of Practice for Dosimetry IAEA TRS-398 of 2006. Nevertheless, the pulse properties of laser-driven ion beams differ significantly from those commonly provided by medical accelerators in pulse duration, peak current and correspondingly pulse dose rate and energy spectrum. Thus, detectors must be dose-rate independent allowing measuring very intense and short pulses without suffering from saturation effects and guarantying the required accuracy also for high intense beam pulse. Furthermore, it is mandatory to develop on-line beam monitoring and relative dosimetry systems, suitable to operate with high intense beam pulse and strong electromagnetic noise, ensuring a negligible beam perturbation. In order to fulfill all the requirements new detection devices and techniques must be designed and developed. The solution proposed to perform relative and absolute dose measurements implies different alternative approaches, as for instance SEM detectors [18], CR39 solid-state track detectors [19], Gafchromic films [20], transmission ionization chamber for high intense beams [21] and Faraday Cups (FC) [22].

Figure 1 shows a schematic layout of the ELIMED beam line where the elements composing the three different sections are clearly visible in their preliminary design.

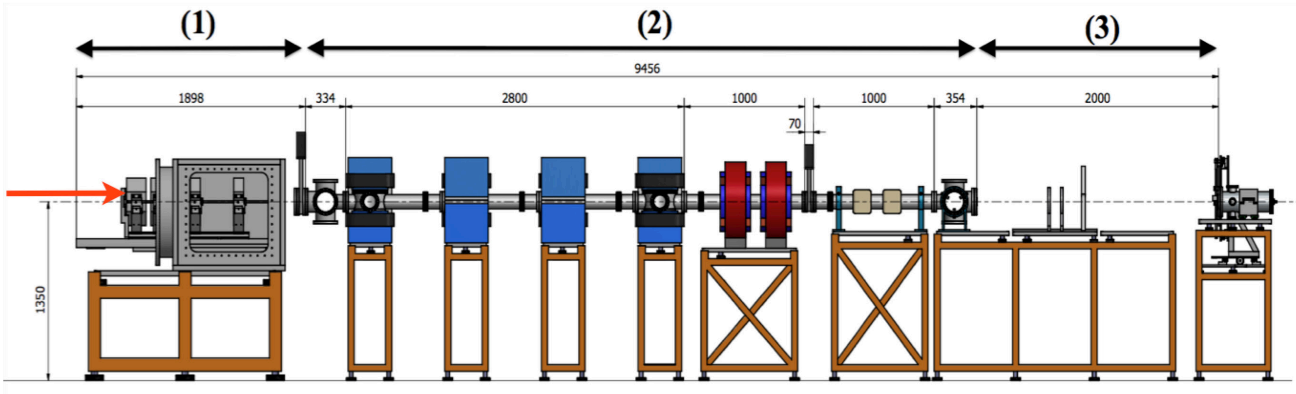


**Figure 1.** Scheme of the ELIMED beam line showing the three different sections: (**1**) ion beam collection and diagnostics; (**2**) in-vacuum ion beam selection, transport and diagnostics; (**3**) dosimetry and sample irradiation. Distances are in mm.

Monte Carlo (MC) simulations will play a key role for the realization of the ELIMED beam line transport elements and for the development of the detectors. Indeed, MC results allow accurate designing of some key elements, particularly for the in-air section of the beam line, and to predict the particle transport, as well as the fluence and dose at given points of interest. Moreover, radioprotection studies can be carried out in order to design appropriate shielding solutions. For the simulation of ELIMED beam line the MC toolkit GEANT4 (GEometry ANd Tracking) [23] will be used. GEANT4 is one of the most versatile and widespread codes used today for particle tracking, as well as being widely used for different physical applications. It is a C++ object oriented toolkit allowing the simulation of particle interactions with matter. It provides advanced functionalities for all the typical domains of detector simulation: geometry and material modelling, description of particle properties, physical processes, tracking events and run management, user interface and visualization. Initially developed for High Energy Physics experiments (HEP) simulation, GEANT4 is now widely used also for multidisciplinary applications and, in particular, medical physics. It allows the tracking of any charged and uncharged particle relevant for radio diagnostics and radiation therapy.

The ELIMED collaboration already designed and realized a beam transport line prototype composed by a quadrupole-based focused-system and by an energy selector allowing to transport and select up to 30 MeV protons.

The design and realization of the three different sections of the ELIMED beam line, as well as the development of the diagnostics/dosimetry detectors and the MC simulations, will be carried out in parallel. The beam line, after dedicated tests with conventional accelerator beams and laser-driven beams, will be finally assembled at ELI-Beamlines at the end of 2017.

## 3. Elements of the Beam Line Prototype

### *3.1. The Focusing System Prototype*

The permanent magnet quadrupoles (PMQs) prototype, designed and realized at the INFN-LNSS, consists of two PMQs of 80mm length and two PMQs of 40 mm length with an active bore of 20 mm and 1 mm thick shielding pipe, placed inside the bore for the protection of the magnets. The magnetic field gradient is about 100 T/m [17]. The system has been designed to improve the transmission and the selection efficiencies of a magnetic energy selector prototype based on four permanent magnet dipoles with alternating field gradient (see section 3.2 for a detailed description).

The PMQs are based on a hybrid Halbach cylindrical array with eight sectors, as shown in Figure 1. The poles are set at 45° with respect to the horizontal axis and are attached to four iron sections, almost saturated, used as supporting structure as well as magnetic flux guides. The poles have a rectangular main body (13 × 14 mm$^2$) with two smaller pieces close to the bore, which allow increases of the field and, hence, the gradient inside the bore itself. The T-like magnets between two poles are modeled as three independent squared pieces (10 × 10 mm$^2$). The magnetic features of each section of the quadrupole have been evaluated from the BH curve of the materials, NdFeB N50 for the magnets and iron XC10 for the other four parts. Each magnet has its own direction for the permanent magnetization (see red arrows in Figure 2).

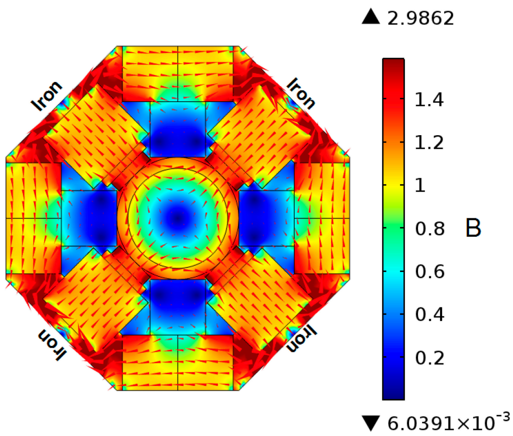


**Figure 2.** The layout of the PMQs system prototype based on hybrid Halbach design.

Design based on hybrid Halbach design with standard rectangular magnetic blocks. Field maps are simulated with 0.5 mm step and scaled according to the measurements provided by the SigmaPhi Company (Vannes, France) during the manufacturing process [17].

The system can be used for focusing and collecting protons up to 30 MeV, although, according to the simulation results, the best performances can be achieved for energies lower than 20 MeV. An example of particle tracing performed using the code for optics calculation TraceWin [24], in the PMQs system optimized for the 5 MeV proton injections in the energy selector prototype is shown in Figure 3. The ESS is simulated as a three collimator system in line: collimator 1 and 2, with a 10-mm diameter aperture, are used to remove from the beam particles with large divergence, the slit is a rectangular aperture of 1 × 10 mm and is responsible for the energy selection and the selected energy resolution. The focusing system ensures a transmission efficiency of about 1%–2% for the whole beam line.

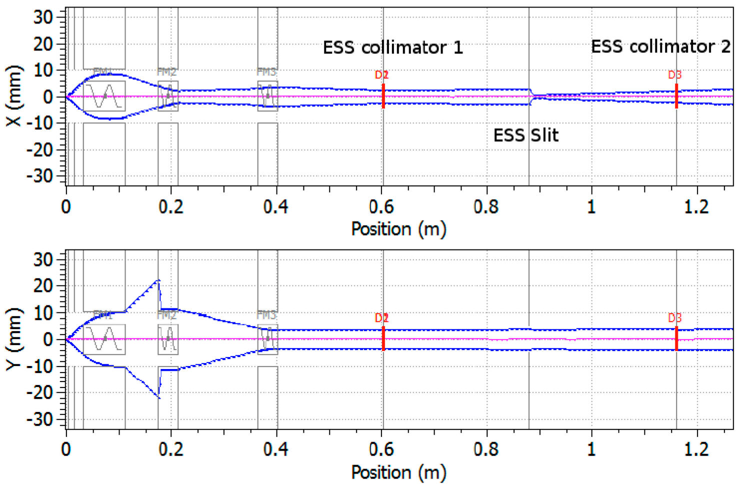


**Figure 3.** Horizontal envelop (**upper panel**) and vertical envelop (**lower panel**) of the beam line for a monochromatic beam (5 MeV) with a spot size of 100 µm and 170 mrad half angle divergence.

The PMQs prototype has been tested with 10 MeV proton beam delivered by the Tandem accelerator at the LNS. Figure 4 shows the comparison between the 10 MeV proton beam spot distribution predicted by the beam optics simulations and the experimental data taken using Gafchromic film, EBT3 type. As one can see from the comparison, a good agreement between the simulation and the measured spot size has been obtained.

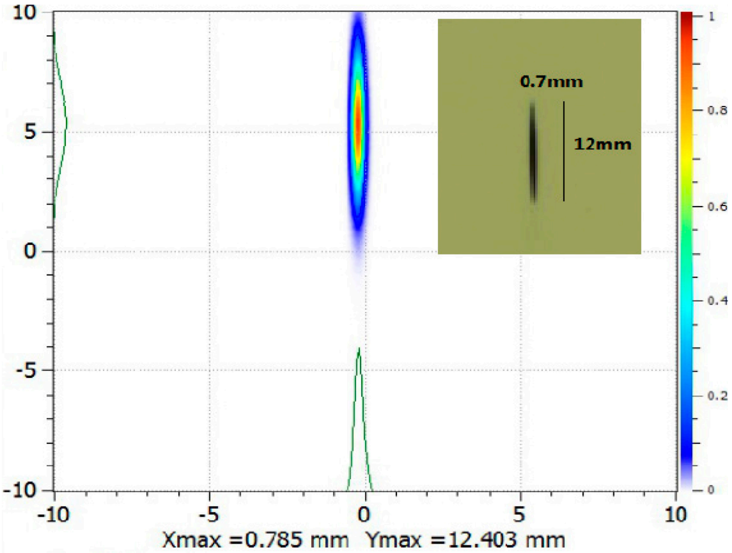


**Figure 4.** Comparison between the simulation results and the experimental measurements (inset) for the 10 MeV proton beam spot along the PMQs system.

A new system, characterized by higher field uniformity and capable of focusing ions with energies up to 60 MeV/n, has been recently designed for the ELIMED section of the ELIMAIA beam line. It will consist of 5 PMQs with the characteristics described in the Table 1. This is the lowest proton energy of interest for medical applications, for instance, eye melanoma are treated worldwide with 60 MeV proton beams. This is the reason why transport and selection of 60 MeV/n ions represents our first goal in the feasibility studies related to the applications of laser driven ion beams for therapeutic purposes.

After few years of operation, different acceleration regimes will be investigated at the ELIMAIA facility reaching higher energies and, hence, extending the studies at least up to 250 MeV, which is the maximum energy used in proton therapy.

**Table 1.** The ELIMED PMQs system features.

| *n*° of PMQ | 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 |

The layout of the PMQs is shown in Figure 5. It is based on a standard trapezoidal Halbach array surrounded by two external hybrid arrays made of rectangular block and iron. The inner array is mainly responsible for the field quality of the quadrupole, the external arrays are necessary to increase the volume of the permanent magnet material to reach the required field gradient.

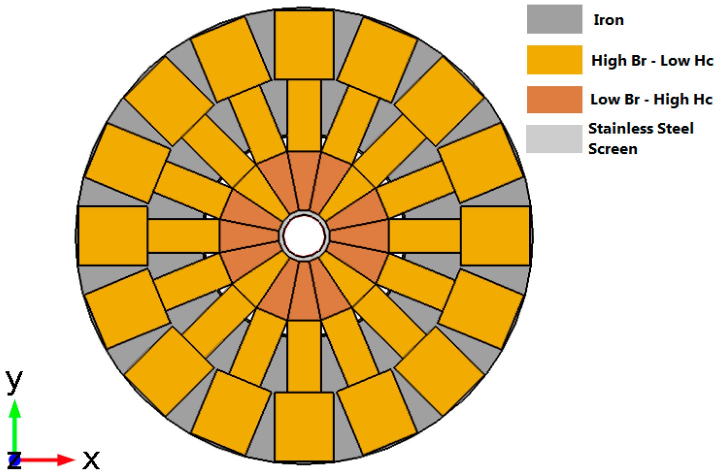


**Figure 5.** ELIMED PMQs layout.

*3.2. The Energy Selector System Prototype*

A prototype of an energy selector system (ESS), designed and developed at the INFN-LNS a few years go [25], is based on four permanent magnet dipoles with alternating fields, similar to a bunch compressor chicane [26]. Each dipole is 88 mm long; the drift space between the central and peripheral dipoles is 85 mm whereas a 10 mm drift distance separates the central dipoles. In such drift space, the particles with different energies are dispersed along the radial plane and a moving slit is used to select ions within a certain energy range. Figure 6 shows a scheme of the ESS prototype together with the parameters for the calculation of the path length of a proton inside the magnetic chicane, for the calibration equation and for the acceptance of the system.

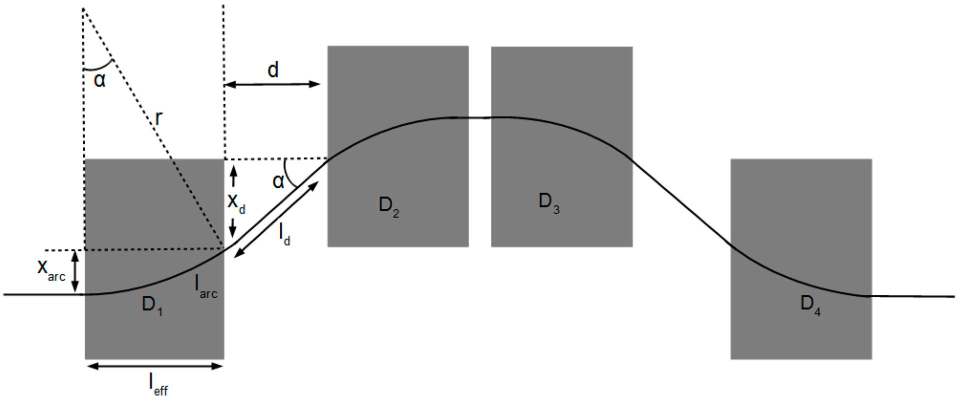


**Figure 6.** Scheme of the ELIMED ESS prototype.

The ESS prototype has been successfully calibrated using accelerator-driven proton beams with FWHM energy spread of 0.5% in the energy range between 2.5 and 5 MeV at the Laboratori Nazionali di Legnaro (LNL) in Padova and between 4.5 and 12 MeV at the LNS in Catania. Figure 7 shows an example of the experimental results of the slit positions as a function of the energy measured in the energy range available at the LNL, along with a comparison with theoretical predictions. Based on the parameters shown in Figure 6, the equation describing the slit position as a function of the energy can be derived:

$$T = \sqrt{\left(\frac{qx(\Delta x - tan\alpha_2}{\frac{(1-cos\alpha_1)}{B_1} + \frac{(1-cos\alpha_2}{B_2}}\right)^2 + M_0{}^2c^4} - E_0 \quad (1)$$

where $q$, $M_0$ and $E_0$ are charge, mass and rest energy of the ion beam, respectively, $\Delta x$ is the slit position, $\alpha_i$ and $B_i$ are the bending radius and the magnetic field of the first and the second dipoles, respectively. As shown in Figure 7 (lower panel) the Equation (1) can evaluate the ion energy in a very good agreement with the experimental measurements (upper panel).

The energy resolution of the system can be estimated from the derivative of Equation (1) as shown in Equation (2).

$$E_{res} = \left(\frac{dT}{dx}\right) \times \Delta x = \frac{\left(\frac{qc}{\frac{1-cos\alpha_1}{B_1} + \frac{1-cos\alpha_2}{B_2}}\right) \times \sqrt{(E_0+T)^2 - M_0{}^2c^4}}{E_0 + T} \times \Delta x \quad (2)$$

According to the scaling factor, the experimental results indicate that the system can select protons with an energy resolution of about 30% at 30 MeV ensuring a better resolution for lower energies.

The experimental results have also been compared with the GEANT4 predictions showing a rather good agreement and allowing a fine-tuning of the simulation parameters.

The ESS prototype has been also characterized with laser-driven proton beams at the TARANIS laser facility (Queen's University, Belfast, UK). During the test experiment two energies, 4.5 and 7 MeV, have been selected using the selection system. Energy spreads, fluence, angular divergence, spot sizes of the proton beam coming out from the energy selection system have been measured for both energies selected. Preliminary results show energy spreads of about ±7% and ±8% for 4.5 and 7 MeV, respectively. The measured average fluence is $5 \times 10^6$ p/cm$^2$ when a 4.5 MeV proton beam is selected and about $10^6$ p/cm$^2$ in the case of 7 MeV protons. The results of this experiment will be published elsewhere.

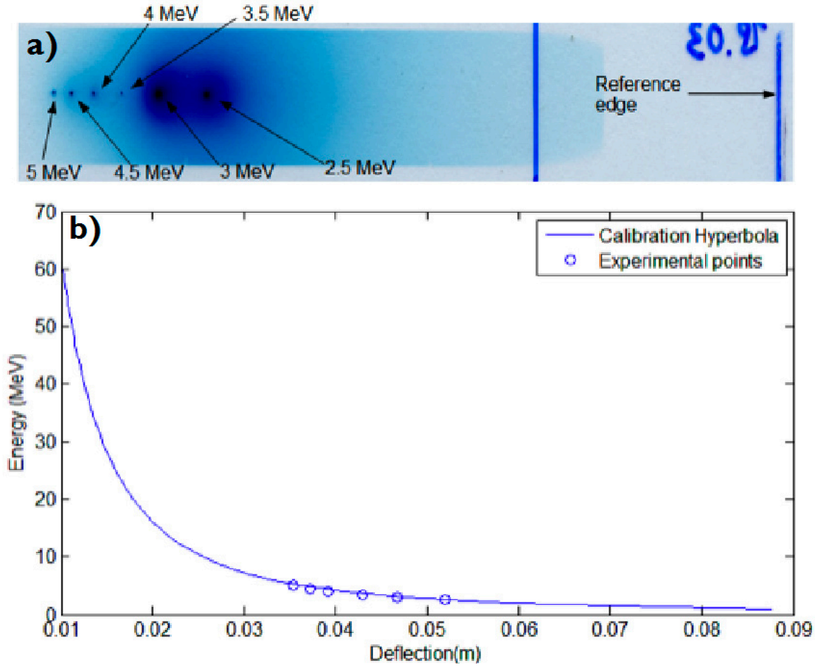


**Figure 7.** (**a**) Experimental measurements of the slit position as a function of the energy, using accelerator-driven proton beam in the energy range between 2.5 and 5 MeV and (**b**) comparison with the calibration Equation (1) of the energy selection system.

The predicted transmission efficiency of the ESS prototype is quite low (few particles out of ten thousands). Nevertheless, the PMQs system coupled to the ESS will allow increased efficiency up to 1%–2% and also selecting beam more precisely since the energy selection is particularly sensitive to the particle divergence. The beam optics simulation of the whole system, composed by the PMQs and ESS prototypes, is shown in Figure 8.

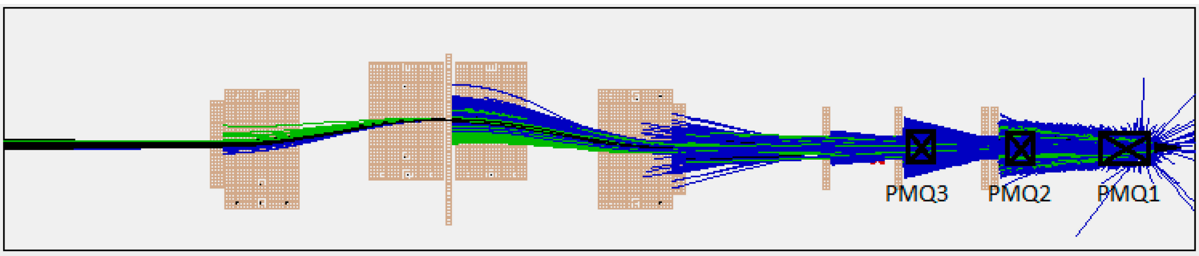


**Figure 8.** The results of the full beam optics simulation for 5 MeV proton selection (black trajectories). Blue traces represent lower energies and green trajectories represent higher energies. A proton beam is transported from the right to left direction.

A new energy selection system dedicated to the ELIMED section of the ELIMAIA beam line will be designed by the end of the year. It will be based on four electromagnets and will allow the selection of proton and carbon beams up to a maximum energy of 60 MeV/n with a maximum energy spread of 30%.

### *3.3. On-line Beam Diagnostics and Dosimetry*

The pulse properties of optically accelerated ion beams differ significantly from those commonly provided by conventional accelerators in pulse duration, peak current and correspondingly pulse dose rate and energy spectrum. Thus, among obvious properties, such as operational stability, the development of innovative techniques for diagnostics and dosimetry represents a crucial step towards multidisciplinary applications of laser-driven beams with the required uncertainty.

Typical laser-driven beam specifications report proton burst duration of the order of 0.1–1 ns, with intensity ranging from $10^{10}$ to $10^{12}$ p/burst. Therefore, the detectors developed for the on-line beam monitoring systems and for the relative dosimetry have to be dose-rate independent, in order to be able to measure very intense and short pulses without saturation effects and suitable to operate in presence of a strong electromagnetic pulse (EMP). Different alternative approaches will be followed in the development of detectors for on-line non-invasive beam current monitoring.

Different diagnostics detectors will be placed, in particular, after the focusing and the selection systems. A detector, based on the well-known pepper pot method, will be specifically designed and optimized for single shot emittance measurement of the laser-driven proton beam after the PMQs system. On the other hand, particle identification and fluence/current measurements will be performed using Silicon Carbide (SiC), CVD diamond detectors and secondary particle emission detectors (SEM), based on the secondary electron emission from a thin metallic foil hit by ion beams. These radiation-hard detectors, suitable to work in harsh radiation environments, will be used in ToF mode for plasma ion intensity and energy distribution measurements in the energy range between few MeV/n up to 60 MeV/n. They will be placed at different distances from the target along the beam-line, in particular, after the PMQs system and after the energy selection device at the end of the in-vacuum section of the beam-line. The high temporal resolution and the fast response of SiC and CVD detectors, together with the high signal-to-noise ratio characteristics, already tested in the previous experimental campaign at PALS and at TARANIS laser facilities, will allow determining the energy of the identified selected ions with resolution of about 20% for the maximum energy selected (*i.e.* 60 MeV/n).

So far, no protocol for absolute dosimetry for optically accelerated ion beams has been established. In order to fulfill this task, a reliable and accurate dosimetric characterization of laser-driven charged particle beams has to be performed. Therefore, devices and procedures to develop a calibration method for absolute dose evaluation have to be implemented.

The device proposed to perform absolute dose measurements will consist of a Faraday Cup (FC) specifically designed to measure the beam charge with high accuracy and extract the absolute dose for pulsed laser-driven beams. Indeed, thanks to the linear response with respect to the beam intensity and the dose rate independent signal, a FC is expected to allow charge collection with high level of accuracy, also in case of high pulsed and extremely intense beams.

A FC prototype [27] for absolute dosimetry with high-pulsed ion beams has been recently designed and realized at the INFN-LNS within the ELIMED project. The FC technical design has been inspired to similar detectors already developed for ion-beam dosimetry [22,28], adopting innovative geometrical solutions in order to further improve the overall charge collection efficiency [29].

In the absolute dose measurement using a FC, the main uncertainty sources are related to the precise measurements of the total charge carried by the beam, of the proton beam energy spectrum and of the effective beam area, needed to extract the fluence distribution. Each of these quantities has to be separately and accurately evaluated. An issue related to the total charge measurements is represented by the emission of secondary particles, usually electrons, produced by the interaction of the protons with the entrance foil and the cup material itself. The emitted secondary electrons may be either collected or leave the cup, affecting the collected charge measurements. The secondary electrons produced in the vacuum window former may lead to a total charge underestimation, while those produced within the cup material, if produced with sufficient energy, may leave the collecting cup and cause a charge overestimation. In order to maximize the charge collection measurement accuracy by increasing the probability of capturing the secondary electrons emitted, shape, sizes, materials and electric field characteristics have been modeled and determined, with the help of the GEANT4 MC simulations and electrostatic ion trajectory software, such as the COMSOL FEM (Finite Element Method) [30] and the Simion FEA (Finite Element Analyse). These studies aimed to increase the efficiency and reliability of the FC design as a charged particle current detector. Figure 9 shows the final FC prototype configuration with all the geometrical details. The FC prototype technical details and the simulation results on the electric field generated can be found in ref. [27].

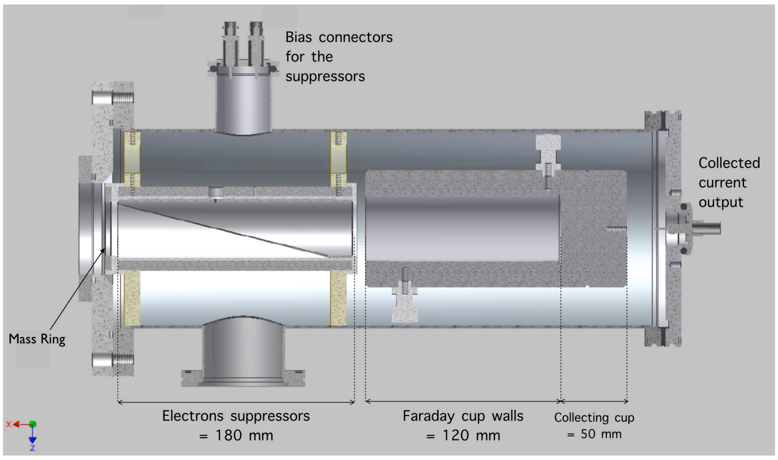


**Figure 9.** Technical drawing of the FC prototype realized at the INFN-LNS.

Typical FC detectors have cylindrically symmetric components and employ coaxial electrostatic fields to recapture the ejected electrons. In the FC prototype, the electric field results by the combined effect of two coaxial electrodes. The external electrode is a metallic hollow cylinder and the internal one, follows a similar design presented by Thomas *et al.* [29], is a peculiar beveled cylinder. The addition of this element breaks the electrostatic coaxial symmetry of the field, provided solely by the external electrode, by introducing a relevant transverse electric field component, as it can be seen in Figure 10, which allows recapturing secondary electrons improving the deflection of the secondary electrons emitted by both the entrance window and the cup.

In order to investigate the FC prototype response, an experimental campaign has been performed using the 62 MeV proton beams delivered by the superconducting cyclotron (CS) at the CATANA protontherapy facility [31] at the INFN-LNS (Catania, Italy). A complete characterization of the FC prototype charge measurement varying the bias applied to the suppression electrodes, the proton beam incident current and the dose delivered has been also performed. The FC prototype has been placed about 9 cm downstream from the final collimator along the beam-line, a 20 mm diameter collimator has been used for the measurements. The FC operating vacuum was $10^{-5}$ mbar. The FC current signal as a function of the collecting time was measured using of the electrometer Keithley 6517A.

In order to compare the secondary electron suppression efficiency using the external electrode alone and the two coaxial electrodes together, the characterization of the FC prototype charge collection as a function of the applied voltage has been performed using both configurations. The voltage has been varied from −4000 Volt to 4000 Volt. Each charge measurement has been performed delivering a given dose of 15 Gy. The dose released has been monitored using the online transmission ionizations chambers. Figure 11 shows some preliminary results of the collected charge as a function of the applied voltage. Each charge measurement has been obtained integrating the current signal for the time interval required to deliver 15 Gy.

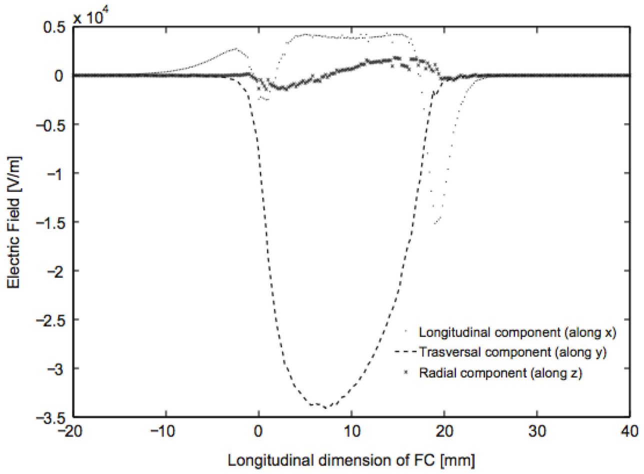


**Figure 10.** Transversal, longitudinal and radial components of the FC prototype electric field as a function of the FC longitudinal size, obtained using the COMSOL software (COMSOL, Brescia, Italy).

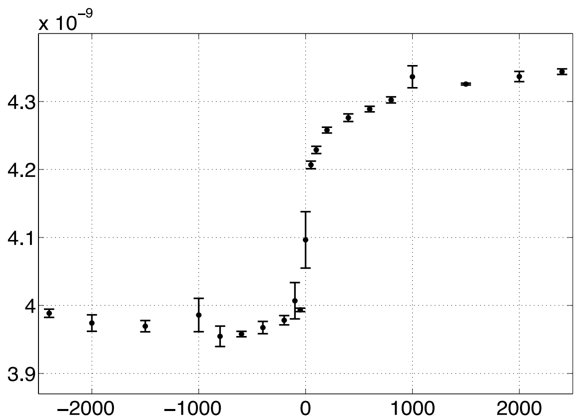


**Figure 11.** Charge collected by the FC prototype as a function of the bias applied to the external electrode.

As one can see, a typical flat voltage response plateau in the negative voltage range between −2400 V and −400 V can be observed; on the other hand, for positive voltages a collected charge dependence increasing with the voltage applied is evident. The charge collection response observed in the FC prototype is in agreement with the typical behavior of standard FCs used for absolute dosimetry [22,28]. The analysis of the charge measurement data using the internal beveled electrode is still on going. Nevertheless, based on a preliminary comparison the electric field resulting from the two coaxial electrodes improves the electron suppression efficiency.

Recently, characterizations of the electromagnetic pulse (EMP) effect on the FC prototype signal has been carried out at the PALS laser facility, in Prague (Czech Republic) and at the TARANIS laser facility at the Queen's University in Belfast (UK). Typically, a high power laser-matter interaction and the subsequent plasma production are accompanied by the emission of an intense EMP, which propagates inside and outside the interaction chamber [32] interfering with the diagnostic devices and affecting their response. Therefore, particularly for a dosimeter, it is crucial to perform a systematic study, in terms of frequencies and amplitude of the EMP generated by the laser pulse, to perform accurate dose evaluations. Indeed, the EMP produces a not-negligible background signal that, if not carefully characterized, does not allow a precise charge measurement [32].

The FC prototype has been tested by using a laser-driven proton beam during an experiment [27] performed at the PALS laboratory (Prague, Czech Republic), where a 2 TW laser system (about 1 KJ of energy delivered on target and a time duration of 300 ps) is available. The FC was mounted inside the experimental hall at approximately 2 and 5 m from the interaction chamber for a characterization of the EMP propagating outside of the chamber and directly connected to the interaction chamber at 30° in the backward direction with respect to the target normal axis. The FC signal was registered with a 2 GHz Le Croy Digital Oscilloscope. Figure 12 shows a typical FC signal registered during the experiment.

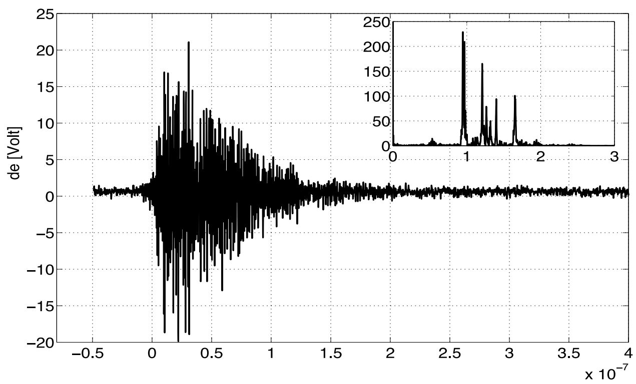


**Figure 12.** A FC signal registered during the PALS experiment. The inset shows the Fast Fourier transformation of the signal.

As one can see from the inset in Figure 12, the EMP is characterized by frequency components from few hundreds of MHz up to 2 GHz. Based on the frequency analysis, the significant noise signal results from the EMP propagation inside the interaction chamber [33,34] and seems to be predominant with respect to the charge signal, affecting the measurement of the total collected charge. Nevertheless, the cumulative integration of the FC signal, as shown in Figure 13, reveals the presence of a charge contribution that, although very small, can be separated by the huge EMP noise contribution [27]. Indeed, even though the EMP signal is present, a null final cumulative value is expected due to their identical positive and negative contributions to the integral. On the other hand, for those signals registered when the FC is mounted on the interaction chamber (*i.e.* along the plasma emission direction) a signal generated by the incoming charged particles accelerated from the target is expected to be present together with the typical EMP contribution. Therefore, as it can be observed in Figure 13, the cumulative of those signals deviates from a null final integral showing a decreasing-negative trend, which indicates a continuous negative contribution to the integrated signal.

This result indicates the necessity to perform a thorough study to allow the separation of the noise contribution from the physical signal. The use of appropriate electronic circuits, as filter amplifiers, and also proper EMP shielding will allow removing or reducing the higher frequency contributions related to the EMP.

The analysis of the data taken during the experimental campaign performed at the TARANIS laser facility at the Queen's University in Belfast (UK) is currently on going and the results will be published elsewhere.

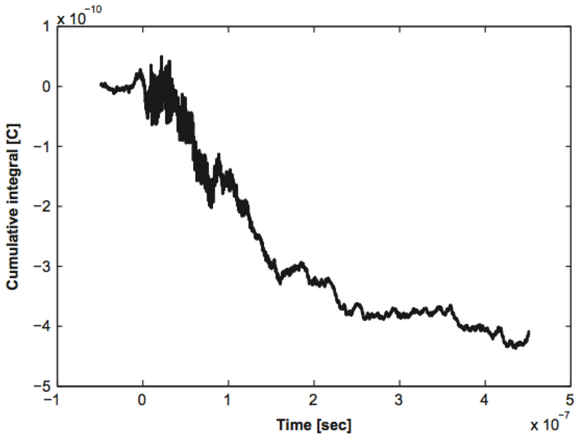


**Figure 13.** The cumulative integration of the FC signal.

## 4. Conclusions

In this paper an overview of the ELIMED beam line section, that will be installed at the ELI-Beamlines facility in Prague, has been presented. In particular, the prototypes of the quadrupoles and of the energy selector (ESS) have been shown and some results of the tests performed with both accelerator-driven and laser-driven beams have been discussed. The focusing properties of the quadrupole prototype have been tested at the INFN-LNS in Catania with 10 MeV proton beams, confirming the performances predicted by the beam optics simulations. The energy selector prototype has been calibrated at INFN-LNS and INFN-LNL with proton beams in the energy range between 2.5 and 12 MeV, demonstrating that this system can select protons with an energy resolution of 30% at 30 MeV, ensuring a better resolution at lower energy. Moreover, the ESS has been also characterized with laser-driven proton beams at the TARANIS facility in Belfast (UK), obtaining energy spreads of 7% and 8% selecting, respectively, 4.5 and 7 MeV proton energies. For both devices, respectively involved in the focusing and selection of the laser-driven ion beams, a feasibility study has been carried out in order to realize the final versions to be assembled in 2017 along the ELIMAIA beam line in Prague. The feasibility study of the new quadrupoles has been already completed and the characteristics have been described in detail in this paper. The design of the final version of the ESS is still in progress.

Concerning the diagnostics, different solutions will be adopted and implemented for the ELIMAIA beam line in Prague, involving the use of SiC, CVD diamonds and SEM detectors, used in ToF mode for proton energy distribution measurements in the energy range between few MeV/n up to 60 MeV/n. Some of them have been tested during previous experimental campaigns at PALS and TARANIS to characterize them in the laser environment. In the same environment, a prototype of a FC, built with innovative solutions for the internal electrode, has been also tested in order to characterize the EMP and analyze its frequency components. These studies are of crucial importance since the EMP, typically present in the laser-driven ion facilities, can affect the measurements as it is predominant over the detector signals. In particular for the FC, the obtained results would support adopting specific solutions to disentangle such EMP contributions from the physical signal, for instance filter amplifiers and/or dedicated EMP shielding. A dosimetric characterization of the FC has been also carried out with accelerator-driven beams at INFN-LNS. In particular, the FC response, as a function of the applied voltage to the electrode for the electron suppression, has been measured for voltages ranging between −4000 V and 4000 V. A typical flat response has been observed between −2400 V and −400 V, as confirmed by other authors.

Most of the activities related to the prototypes have been carried out aiming to preliminarily study and characterize the physical properties of laser-driven ion beams and optimize the final versions of the main transport elements, as well as the detectors. The ELIMED beam line section will be delivered and assembled in Prague, where a first user's facility dedicated to multidisciplinary studies will offer the possibility to study the biological properties and the potentialities of laser-driven ion beams with well controlled systems. By means of the transport devices and the diagnostics/dosimetric systems, precise dosimetric measurements and accurate cell sample irradiations will be possible at the ELIMAIA beam line, giving the possibility to study the characteristics of these beams from the clinical point of view and, therefore, provide a deeper understanding of their peculiarities for a possible future use in the medical field.

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## Author Contributions

G. A. Pablo Cirrone, Giacomo Cuttone, Francesco Romano, Francesco Schillaci and Valentina Scuderi worked on the text and organized the structure of all the paper. G. A. Pablo Cirrone, Renata Leanza, Francesco Romano and Giada Petringa, Georg Korn and Daniele Margarone worked on the dosimetric aspects of the paper. Francesco Romano, Giuliana Milluzzo and Antonella Tramontana worked on the Monte Carlo simulations; Francesco Schillaci and Mario Maggiore provided the beam transport simulations; Michele Costa and Giuseppe Gallo worked on the beamline design; Antonino Amato, Giuliana Milluzzo, Giuseppina Larosa and Valentina Scuderi carried out the time of flight

measurements; Giacomo Candiano, Rosanna Manna and Valentina Marchese last but not least, worked on the dosimetric acquisition with radiochromic films and CR39 detectors.

## Conflicts of Interest

The authors declare no conflict of interest.

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