Transport and dosimetric solutions for the ELIMED laser-driven beam line

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ABSTRACT

Within 2017, the ELIMED (ELI-Beamlines MEDical applications) transport beam-line and dosimetric systems for laser-generated beams will be installed at the ELI-Beamlines facility in Prague (CZ), inside the ELIMAIA (ELI Multidisciplinary Applications of laser–Ion Acceleration) interaction room. The beam-line will be composed of two sections: one in vacuum, devoted to the collecting, focusing and energy selection of the primary beam and the second in air, where the ELIMED beam-line dosimetric devices will be located. This paper briefly describes the transport solutions that will be adopted together with the main dosimetric approaches. In particular, the description of an innovative Faraday Cup detector with its preliminary experimental tests will be reported.

1. Introduction

Many experimental evidences as well as theoretical argumentations demonstrate that proton/ion beams acceleration (up to hundreds of MeVs) based on the interaction of high power (order of PW) lasers with matter can represent a concrete future alternative in the field of particle acceleration [1].

Laser-driven beams, nevertheless, show different (and in some case 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 [2] are the main features of a typical laser-driven beam accelerated in the so-called TNSA (Target Normal Sheath Acceleration) regime that represents the most known and experimentally investigated laser-induced acceleration mechanism [3]. During the last decades, laser-driven ion acceleration has gathered more and more interest as it represents a new future perspective in fundamental, nuclear as well as in the applied physics. As a main consequence, laser-based accelerators, indeed, could significantly increase the availability of high-energy ion beams and induce a wider spread of particle therapy based facilities around the world. Moreover, a careful study of the laser–target interaction processes, as well as of the potential multidisciplinary applications of laser driven beams, is the main aim of several recently risen projects. Among these are the LIBRA (Laser Induced Beams of Radiation and their Applications) project [4] at the Queen's University of Belfast (UK); the onCOOPtics [5], (High-Intensity Lasers for Radiooncology) a cooperation between the centers of innovation OncoRay in Dresden and the Helmholtz-Zentrum Dresden-Rossendorf (HZDR); the MAP network [6], Munich-Centre for Advanced Photonics, Munich. In this contest, a new collaboration between the INFN-LNS (Nuclear Physics Laboratory, Catania, Italy) and ASCR-FZU (Institute of Physics of the Czech Academy of Science) in charge of the ELI-Beamlines facility implementation has been launched in 2012 [7]. The collaboration was called ELIMED (ELI-Beamlines MEDical applications) and its main aim is to investigate the concrete possibility to design and realize a complete transport beam-line for optically accelerated beams to be used for multidisciplinary and medical applications. The study and the development of new detectors for absolute and relative dosimetry along with new radiobiological investigations will be also considered in the project. At the end of 2012, the ELIMED initiative was presented at the ISAC

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(International Scientific Advisory Committee) of ELI-Beamlines and finally accepted at the end of 2013. In 2013 the ELI-Beamlines Institute officially started the realization of the ELIMAIA (ELI Multidisciplinary Applications of laser–Ion Acceleration) experimental hall, representing the ELI-Beamlines areas specifically dedicated to the ion acceleration and to their applications. Finally, as a result of a public tender, launched in 2014 by the FZU (ELI-Beamlines), the INFN-LNS has been officially appointed to realize the beam transport, the dosimetric and irradiation section in the ELIMAIA room. In summary, ELIMED will definitively represent the section of the ELIMAIA activity addressed to the transport, handling and dosimetry of the laser-driven beams and to the achievement of stable, controlled and reproducible beams that will be in future available to all the users interested in the multidisciplinary and medical applications of such innovative technology. In the first part of this paper we briefly describe the solution we are studying for the final beam-line: a set of permanent quadrupoles for the beam focusing and an energy selector composed of four magnetic dipoles and two collimators. In the second part, we describe the adopted dosimetric system based on the innovative Faraday Cup realized at INFN-LNS and its preliminary tests.

2. The ELIMED approach for the ELIMAIA beam line

2.1. Beam transport solution: permanent quadrupoles and energy selector

Ions accelerated by laser–matter interaction are characterized by high intensities, multiple species and charge states, a wide energy spectrum and a large energy-dependent angular distribution. Therefore, in order to make these non-conventional beams suitable for multidisciplinary applications, the design of specific beam line transport elements, coupled to appropriate diagnostic devices, is mandatory.

The main aims of the transport elements will be the control of the optically accelerated ions final energy and angular distributions, the beam-line reliability as well as the flexibility and reproducibility of the final beam spot size and the final dose distribution. Bearing in mind these purposes, the ELIMED beam transport solution that will be proposed for the ELIMAIA beamline will consist of two main elements: a collecting-focusing system and an energy selector.

The first element, placed few cm downstream the target, collects, focuses and pre-selects in angle and energy, the accelerated particles. It will be composed of a set of permanent quadrupoles whose movement, along the beam line direction, will be performed by independent motors remotely controlled. Three quadrupoles are, indeed, necessary in order to focus the beam on both transversal planes and match the focal points in a common waist. An additional quadrupole can be possibly added to cover a wider energy operational range. In particular, quadrupoles with magnetic field gradients of 110 T/m and 114 T/m, 20 mm bore and respectively with lengths of 40 and 80 mm, will be adopted to efficiently collect and focus ion beams up to 30 MeV.

The final beam energy refinement is obtained by means of the second transport device: the energy selection system (ESS). It is composed of two collimators, four permanent dipole magnets with alternating polarity and a central slit that allows us to select particles with a specific energy.

A first prototype of this transport beam-line has been already designed, simulated (using both analytical and Monte Carlo approaches) and realized. The ESS prototype has been already calibrated with conventional proton beams and tested with laser-driven protons up to 10 MeV at the TARANIS facility [8] of the Queen's University in Belfast (UK). More details on the ESS can be found elsewhere [9–12]. The quadrupoles system has been recently realized on the basis of the INFN-LNS original design and its characterization under conventional as well as laser-driven ion beams will be performed in the course of 2015.

Although the described beam-line is designed to efficiently work with laser-driven proton beams with energies up to 30 MeV, this solution will conceptually be the same of the final ELIMED beam-line that will be installed at the ELIMAIA hall of ELI-Beamlines in Prague (CZ) [13].

2.2. Dosimetric solutions for ELIMED

A precise knowledge of the absolute dose, released by the incoming radiation, is essential in many applications. This is the case, for example in medical applications, like radiotherapy or nuclear medicine, where the dosimetric accuracy of a radiation treatment is a crucial prerequisite in order to estimate the correspondence between planned and delivered dose. It is in fact demonstrated that an uncertainty higher than 5% in the absorbed dose evaluation can compromise the effectiveness of a radiation treatment as well as the patient health. Dosimetric international protocols, where the use of specific detectors and procedures are recommended, have been already established since 2000 for conventional clinical ion beams [14]. On the other hand, due to their features (very high dose rate [15], very low reproducibility) no recommendations are available today for dose evaluation for laser-driven beams. Nevertheless as the wordwide availability, the maximum energy and intensity of laser-driven beams are continuously growing, during the last decade many researchers started several investigations on targets, detectors and procedures, in order to achieve an accurate evaluation of the dose released by laser driven ion beams. This represents a crucial step for the future use of these beams in multidisciplinary experiments like biology irradiation, dosimetric tests and detector characterizations. Currently, two main classes of dosimeters are under investigation for laser-driven beams: solid state detectors (such as nuclear-track detectors, radiochromic films, and fluorescent image-plates) and ionimetric detectors like Faraday Cups (FC) and ionization transmission chambers for high dose-rate beams. Nuclear track detectors are very useful absolute dosimetry permitting the direct measure of particle fluence independent from the particle dose rate. Nevertheless they show a relatively low saturation level and their use is not feasible for particle fluency greater than 10^6 particles per shot, the thermoluminescent approach will be used for the ELIMED dosimetry.

As CR39 detectors show a relatively low saturation level (they cannot be used for fluence greater than 10^6 particles per shot) the hermoluminescent approach will be used for the final stage of the ELIMED project, when a dose of one Gray or more per shot is expected. Thermoluminescent dosimeters (TLD) are dose-rate independent and can permit an absolute dose measure with an overall accuracy of the order of 5%. TLD800 model will be firstly characterized as they permit measurement in a very broad dose range.

For the absolute dosimetry system, an innovative Faraday Cup (FC) has been recently designed and developed within the ELIMED collaboration. Its technical design was inspired to similar detectors already developed for ion-beam dosimetry [16,17], but innovative geometrical solutions have been adopted in order to further improve the overall charge collection efficiency.

2.2.1. The new laser-driven Faraday Cup

The FC realization has been possible thanks to several preliminary studies performed in order to optimize shape, dimensions, materials and electric field features. These studies have been carried out using the COMSOL FEM (Finite Element Method) software, the Simion FEA (Finite Element Analyze) software and, also, the Monte Carlo Geant4 [18,19] simulation toolkit with the main aim to optimize the FC as absolute dosimeter for ion-beams and to maximize its performances also for laser-driven ions.

Fig. 1 shows the final FC configuration with its details. It is about 400 mm long with an internal radius of 20 mm. The main components are a 25 μm kapton window, a 5 mm thin mass ring, a 180 mm steel suppressor and a 100 mm aluminium cup. Since the ionization of the residual gas could affect the FC measurements, an high vacuum, of about 10^{-5} mbar, is required as working condition.

A Faraday Cup allows the evaluation of the absolute dose (Gy) released in water (D_w) from a proton beam, according to the expression

$$D_w = \frac{1}{A} \cdot \frac{\int (S(E)_w) N(E)\, dE}{\int (N(E)\, dE)} \cdot \frac{Q}{e} \cdot 1.602 \times 10^{-10}\ \text{(Gy)} \qquad (1)$$

where A (cm^2) is the effective beam area, $S(E)_W$ the mass stopping power in water (MeV cm^2 g^{-1}) at a given energy E, Q (C) is the measured charge and e is the elementary charge. As well known [16], the value of total collected charge Q can be strongly affected by both the secondary electrons generated at the entrance window by the beam–kapton interaction and the back-scattered ones, produced by the beam collision with the cup material. The former, if able to reach the cup, lead to an underestimation of the total charge while the latter, if generated with sufficient energy to leave the collecting cup, cause a charge overestimation. In order to maximize the charge collection accuracy, following the work of Thomas et al. [20], a special-shaped electric field has been designed. It is generated by the combined effect produced by two coaxial electrodes. The external electrode is a metallic hollow cylinder while the internal one is a peculiar beveled cylinder (Fig. 2).

The cylindrical symmetry of the electric field provided by the external electrode is broken due to the presence of the internal one. The resulting effect is a strongly asymmetric electric field, characterized by a significant transversal component (dotted line of Fig. 3) able to maximize the deflection of the secondary electrons generated by both the entrance window and the cup. The three components of the electric field shown in Fig. 3 are generated, by means of the COMSOL software, applying a bias of −600 V to the internal electrode and of +600 V to the external one.

2.3. Preliminary experimental tests

A typical high power laser–matter interaction, and the subsequent plasma production is, unfortunately, accompanied by the emission of an intense electromagnetic pulse (EMP) which propagates inside and outside the interaction chamber [21]. This EMP interferes with the diagnostic devices affecting their response. Therefore, it results so evident that, preliminary to the dose evaluation, a systematic study of the electromagnetic noise due to the laser pulse has to be performed. In the particular case of a dosimeter, such as the Faraday Cup, the electromagnetic pulse produces, indeed, a not-negligible noise signal that, if not carefully evaluated, does not allow a correct charge measurement [22]. A noise characterization, mainly in terms of proper frequencies and amplitude of the pulse signal entering in the chamber during the laser shot, is hence mandatory in order to develop a dedicated

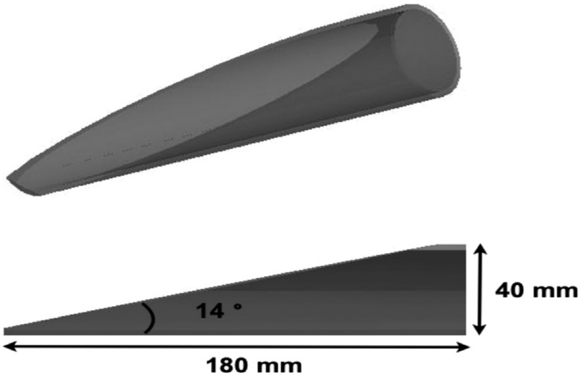

Fig. 2. 3D view and dimension of the internal electrode of the Faraday Cup.

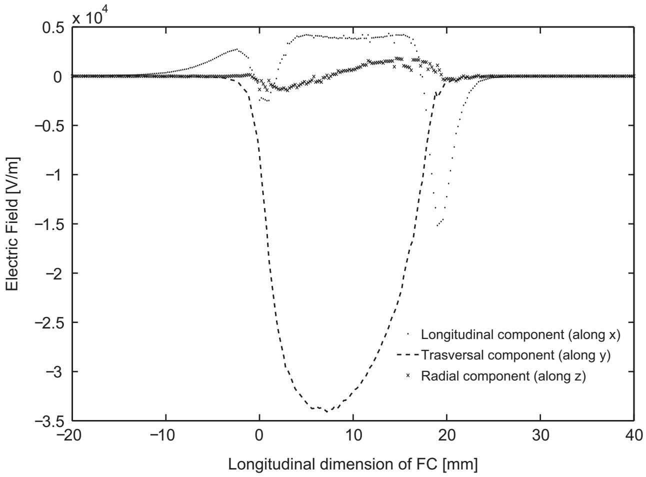

Fig. 3. The transversal, longitudinal and radial components of the FC electric field, obtained using the COMSOL software, as a function of the longitudinal dimension of the FC.

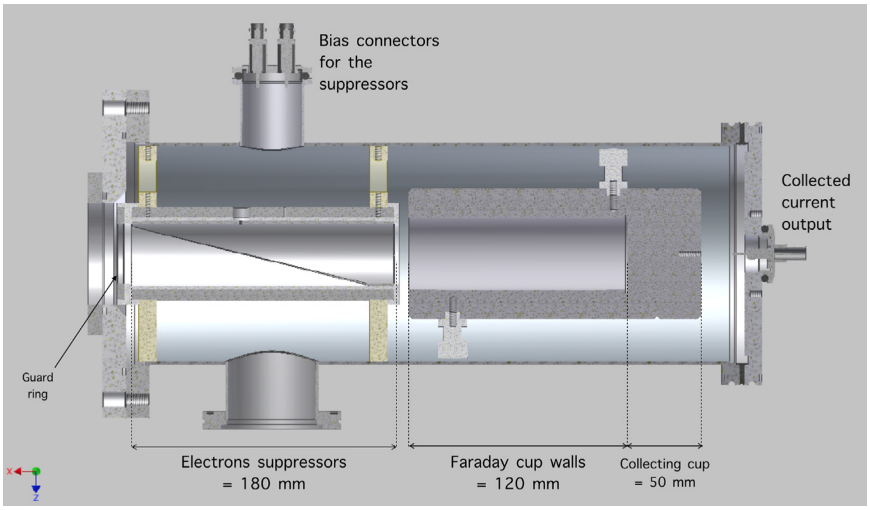

Fig. 1. Schematic layout of the Faraday Cup (FC) detector. The current collected in the cup is sent to an electrometer for integration.

electronic system (hardware and software) for the absolute dose measurement. The developed Faraday Cup has been preliminary tested in an experimental campaign, at the PALS laboratory (Prague, CZ), where a 2TW laser system (about 1KJ of energy delivered on target and a time duration of 300 ps) is available. The FC signal was registered with a 2 GHz Le Croy Digital Oscilloscope in two different configurations: the FC was both placed outside the interaction chamber and directly connected to it. Fig. 4 shows the FC noise signal and the corresponding Fourier transforms, registered with the FC placed outside the chamber, 5 m far from the interaction chamber. As one can see, a significant contribution at high frequencies ranging from hundreds of MHz up to few GHz is evident.

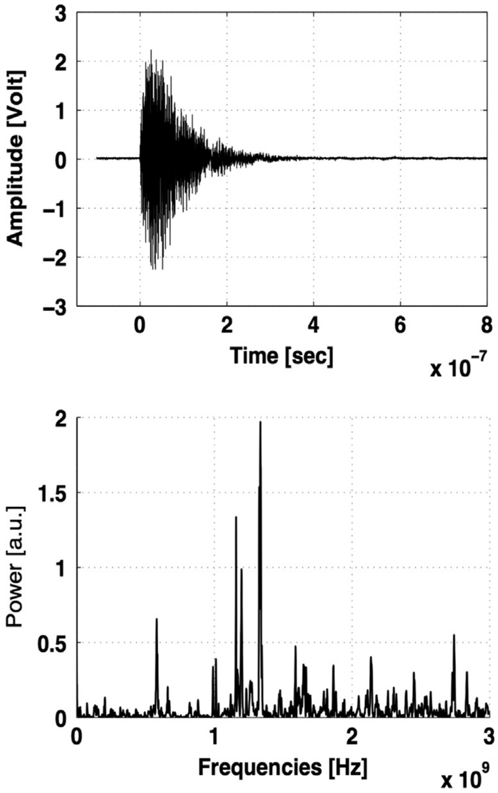

Fig. 4. Faraday Cup signal (top figure) registered with the detector located outside the interaction chamber, about 5 m far from the target. The corresponding Fourier transform plot is reported in the bottom plot.

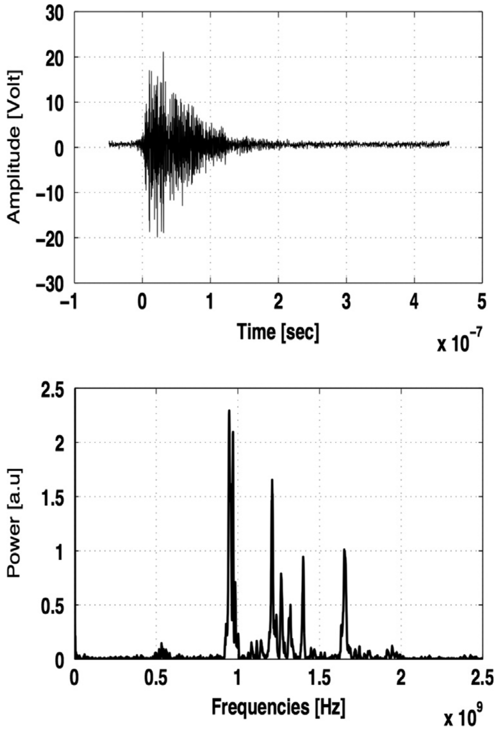

Fig. 5. Faraday Cup signal (top figure) registered with the detector connected to the interaction chamber, at 30° with respect to the target normal in the backward direction. The corresponding Fourier transform plot is reported in the bottom plot.

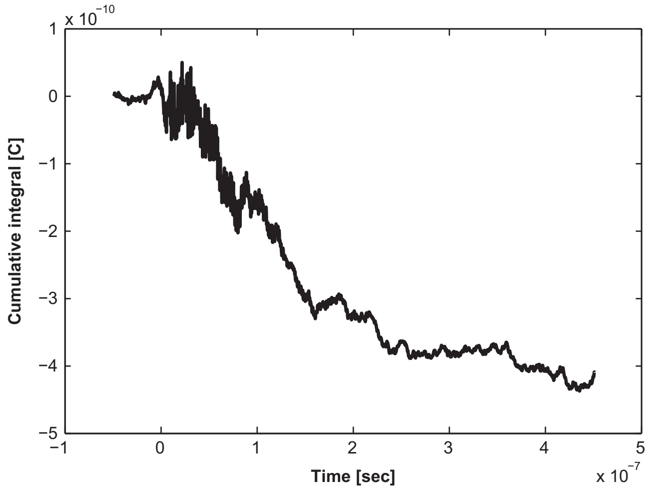

Fig. 6. The cumulative integration of the signal obtained with the FC connected to the interaction chamber (Fig. 5).

The registered frequencies are induced by the charge oscillations generated by the laser–target interaction, during the collision. The most of these frequencies can be attributed to the electromagnetic pulse propagation inside the interaction chamber, as already reported in refs. [21,23,22,24]. The interaction chamber, mounted at the PALS laboratory, can be considered, in first approximation, as a spherical cavity with 1 m diameter. Effectively, the frequencies from few hundreds of MHz up to 1 GHz can be attributed to the resonance frequencies of the electromagnetic pulse propagating inside a spherical cavity, according to what has been found in [24]. However, the presence of a great number of small-scale structures in the interaction chamber, as for instance flanges, glass windows, as well as detectors connected to the chamber, causing a not-perfect roundness of the target chamber, determines a non-ideal EMP propagation [21,24].

In the second configuration, in order to also investigate the FC response in accelerated particle presence, the FC was directly connected to the interaction chamber, at 30° with respect to the target normal in the backward direction. In Fig. 5 the signal acquired, in this case, by means of the oscilloscope is shown. As one can clearly see, the electromagnetic noise seems to be predominant with respect to the charge signal, not allowing the evaluation of the total collected charge. Nevertheless, a cumulative integration of the whole signal reveals the presence of a charge contribution that, although very small, can be separated by the huge background.

Fig. 6 shows the cumulative integration of the current signal shown in Fig. 5. For those signals where only the EMP is present, due to its identical positive and negative contributions to the integral, a null final cumulative value is expected. As shown in 6, on the contrary, the cumulative has a decreasing-negative trend, indicating a continuous negative contribution to the integrated signal.

This result suggests the necessity to perform a thorough study to allow the separation of the noise contribution from the physical signal. A possible solution can consist in the use of appropriate electronic circuits, as filters or amplifiers, optimized to remove and/or reduce the higher frequencies of signal related to the EMP.

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