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Cirrone, G. A. P., Catalano, R., Cuttone, G., Margarone, D., Schillaci, F., & Petringa, G. (2020). Generation control and application of flash radiation beam from laser-matter interaction: The ELIMAIA-ELIMED beamline. *Il Nuovo Cimento C* , *43*(1), [15].

Published in:
Il Nuovo Cimento C

Document Version:
Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:
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Download date:27. Sep. 2023

IL NUOVO CIMENTO **43 C** (2020) 15
DOI 10.1393/ncc/i2020-20015-6

COLLOQUIA: FATA 2019

Generation control and application of flash radiation beam from laser-matter interaction: The ELIMAIA-ELIMED beamline

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received 2 March 2020

Summary. — One of the main direction proposed by the community in the field of laser-driven ion acceleration is to improve particle beam features in order to demonstrate reliable approaches to be used for multidisciplinary applications. The mission of the laser-driven ion target area at ELI-Beamlines (Extreme Light Infrastructure) in Czech Republic, called ELI Multidisciplinary Applications of laser-Ion Acceleration (ELIMAIA) is to provide stable, fully characterized and tunable beams of particles accelerated by petawatt-class lasers and to offer them to the user community for multidisciplinary applications. The focusing, selecting, measuring and irradiating parts of ELIMAIA constitute the so-called ELIMED (ELI MEDical and multidisciplinary applications) portion. In this work, the status of the ELIMED/ELIMAIA beamline will be reported along with a complete description of the main dosimetric systems and transport elements.

1. – Introduction

The idea of coherent acceleration 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 when 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 $3 \times 10^{18}\,\mathrm{W/cm^2}$ to $3 \times 10^{20}\,\mathrm{W/cm^2}$) laser pulses. The typical experimental set-up used in these experiments consists of a high-power laser beam impinging on a thin solid target from which particles, in both directions with respect to the laser incident direction, are

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(*) Corresponding author. E-mail: `catalano@lns.infn.it` accelerated. In particular, the peculiarities of the proton emitted in the forward direction (*i.e.*, in the opposite direction with respect to the laser-irradiated target surface) 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 fundamental research as well as in the possible multidisciplinary applications. Due to the extreme characteristic of particles emitted in a laser-matter interaction process, and owing to their still not controlled reproducibility, the need of a specific system to control their divergence and energy and to measure on-line their fluxes, it is necessary to spread their use in the nuclear physics and interdisciplinary community. In particular, the potential ability of these beams to release high doses in very short times (dose rates up to 10^9 Gy/sec have been already reported [5,6], indeed) makes them of particular appeal for new tumor radiation schemes as the flash radiotherapy [7,8]. 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, was established in 2012. The main aim of the collaboration, named ELIMED (ELI-Beamlines MEDical applications) [9], is to investigate the feasibility of designing and realizing 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 beamline dedicated to the ion acceleration and multidisciplinary applications. The ELIMED beamline, which was 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. – Ion acceleration by laser-matter interaction

The generation of fast particles from the lasers-matter interaction was firstly observed in the 60s, when the first experiments with a laser irradiating a solid target were performed [10]. Those experiments showed that plasma created on the target surface is a source of ions of energies up to several keV. In parallel with the development of lasers of increasing power, higher ion energies were then achieved and, nowadays, tens of MeVs energies have been recorded, *e.g.*, for protons. The possibility to obtain such regimes was made possible thanks to the introduction, in the laser development technology, of the Chirped Pulsed Acceleration (CPA) [11] technique. The CPA allows for the generation of ultra-intense and ultra-short laser pulses, a condition that is at the basis of the laser-plasma interaction and laser-induced particle acceleration. Since the invention of CPA the ability to increase the energy of ultra-short pulses dramatically improved and now it is possible to produce pulses with a duration of few femtoseconds (10^{-15} sec) and a maximum intensity above 10^{22} W/cm^2. The mechanism of ion acceleration by laser-matter interaction is well studied and figured out at least up to intensities of 10^{19}–10^{20} W/cm^2. When a laser pulse reaches a solid, an over-dense plasma slab is obtained and several energy absorption mechanisms can be involved. The laser energy accelerates and heats plasma electrons. At the same time, in particular if a normal incidence is considered, the laser ponderomotive force pushes inner electrons from the surface creating a charge separation which produces intense electrostatic fields (order of TW/m) that, in turn, are able to accelerate the electrons and ions present in the target. This acceleration mechanism is called Target Normal Sheath Acceleration (TNSA) [12]. The accelerated protons come from the rear surface and the accelerating field is generated by the expansion of the electrons around the target [13]. Other regimes as the Radiation Pressure Acceleration (RPA) have been theoretically proposed and are currently under experimental tests, in which the radiation pressure of the laser is dominant on the heating process and the forward accelerated bunch is composed mainly by the ions of the target and comes from the irradiated surface. The laser-target interaction mechanisms produce a flux of particles such as protons, electrons and ions with very high peak current (up to 10^{13} protons) within a bunch duration of a few nanoseconds [14].

3. – Beam transport elements of the beamline

Laser-driven ion beams represent a promising alternative to conventional ones. Unfortunately, due to their extreme features, like the wide energy and angular distributions, and their extremely high intensity, they are not directly usable for most applications. In order to overcome these intrinsic limitations, an appropriate transport beamline together with the corresponding dosimetric system, has been designed to collect, select and transport laser-accelerated beams up to 60 MeV/u. It will offer, as output, a controllable beam in terms of energy spread (5% up to 20% for higher energy), angular divergence, variable beam spot size (in the range 0.1–10 mm) and acceptable transmission efficiency (namely 10^6–10^{11} ions/pulse, assuming 10^9–10^{12} ions/pulse produced at the source energy range of interest).

The transport beamline is composed of two main elements: a collection system composed of five permanent magnet quadrupoles (PMQs) and an energy selection system (ESS) made of four conventional resistive dipoles. The main aim of the collection system is to collect particles within a certain energy range, to reduce the beam angular divergence and to inject the particles in the ESS. The ESS will hence provide the additional energy selection needed to generate a quasi-monochromatic beam.

Particles coming out from this first section of the beamline (PMQs+ESS) will have characteristics similar to the conventional beams. They can be hence transported in a relatively easy way, adopting conventional magnetic lenses, such as resistive quadrupoles and steerers, which will be placed in the last section of the beamline. The conventional transport section of the beamline represents the last tract in vacuum. After that the ions will exit in air through a thin (15 μm in thickness) Kapton window and will reach the irradiation point after traversing about three meters of air. The in-air section will contain all the dosimetric devices necessary to perform the absolute and relative dosimetry needed for a reliable and reproducible sample irradiation. The ELIMED dosimetric system was designed and realised in order to deal with very fast (tens of nsec) and very intense (order of 10^7 ions per bunch). It will be composed by different devices (see sect. **5**) together permitting an accurate evaluation of the absorbed dose also in conditions of extremely high dose rates where ions recombination effects do not permit the use of conventional dosimetric detectors. Figure 1 shows the ELIMED section of the ELIMAIA beamline installed at the ELI-Beamlines facility (Dolnì Brezani, CZ).

3˙1. *Section one: The permanent magnetic quadrupoles (or PMQs).*

– Magnetic lenses are used in conventional particle accelerator facilities to deflect, focus and correct the beam along the transport lines. Permanent magnets systems (like quadrupoles or PMQs) have the advantage of being relatively compact with extremely high field gradients (up to 100 T/m) with quite large bore of a few centimetres. A PMQs system allows col-

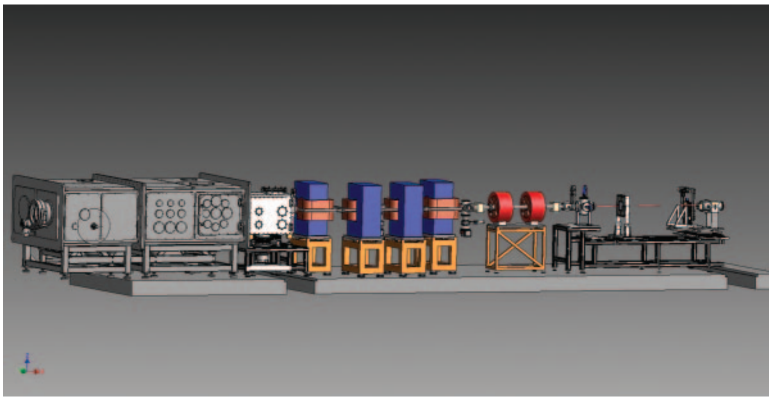

Fig. 1. – Visualization of the ELIMED section of the ELIMAIA beamline.

lecting the 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. The design proposed for the collection system of the laser-driven-ion beamline for multidisciplinary applications for the ELIMED tract of the ELIMAIA beamline has the main aim to collect a wide range of ion energies from 3 MeV/u up to 60 MeV/u and inject the beam in the ESS with a quite good quality. The system has hence to be versatile and has to ensure a reasonably high transmission efficiency.

3·2. *Section two: The energy selection system (or ESS).* – The ESS layout is based on four resistive dipoles with alternating fields, mimicking the configuration of a typical bunch compressor scheme. The proposed scheme would allow to vary the energy resolution changing the slit aperture size, which is an advantage as, at higher energy, laser-produced particles are less abundant and a bigger slit is necessary to keep the transmission efficiency acceptable. The ESS is designed to select protons with energies up to 300 MeV and heavier ions with energies up to 60 MeV per nucleon. The ESS works on a fixed reference orbit, *i.e.*, varying only the magnetic field (and not the slit position) from 0.63 T up to 1.2 T, hence it will be possible to cover the entire expected ion energy range. The energy spread of the selected particles will linearly depend on the slit aperture size.

4. – Monte Carlo simulations

Geant4 (GEometry ANd Tracking) simulation software is one of the most widely used Monte Carlo codes for particle interaction and transport in the matter. This toolkit is currently used in several fields, from high energy physics to medical physics and space science, thanks to its advanced functionalities in the geometrical description and to a wide and well-tested set of physics models. Thanks to its robustness, versatility and reliability of the implemented physical processes, Geant4 has been chosen as the most appropriate code for the ELIMED transport and dosimetry beamline simulation. The ELIMED application was developed following two main requirements:

- provide preliminary predictions in order to support the design of the beamline elements and detectors;

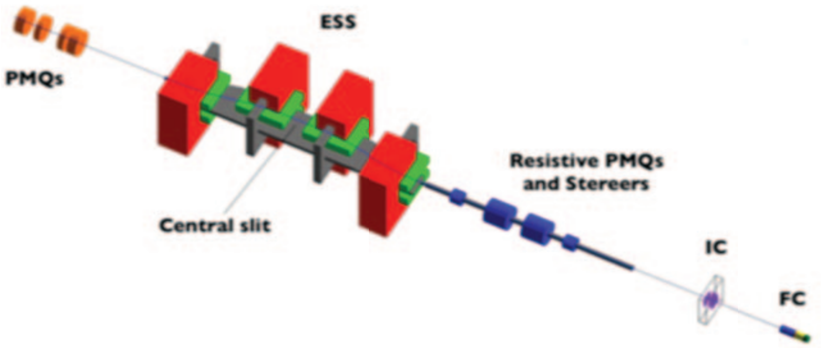

Fig. 2. – Visualization of the complete beamline model as simulated by a Geant4 Monte Carlo simulation [15].

- provide the users with a tool capable of predicting particle transport, fluences and doses at different positions along the beamline.

In order to fulfill the requirements, the ELIMED application has been conceived as a complex and modular code, in which the different geometrical components, as well as their functionalities can be switched off/on according to the specific purpose of the simulation. In fig. 2, the scheme of the whole ELIMED beamline simulated with Geant4 is reported.

5. – Dosimetric system

The dosimetric system, together with the sample irradiation system, represents the key element of the in-air section of the ELIMED beamline. It has been realized to fulfill the particular characteristics (extremely high dose and short time per pulse) of laser-accelerated beams, maintaining the requirements for its use in multidisciplinary experiments like biology irradiation, dosimetric tests and detector characterization (*e.g.*, dose rate independence and real-time measurements with an accuracy within 5%). The dosimetric system is composed of a Faraday Cup (FC), specifically designed to measure the beam charge with high accuracy and extract the absolute dose for pulsed and extremely intense laser-driven beams, a secondary emission monitor (SEM) and a multi-gap in-transmission ionization chamber (IC) for relative dosimetry measurements. A detailed description of the dosimetric devices and procedures can be found elsewhere [15]. In order to overcome saturation effects, characterizing the conventional dosimeters at laser-driven extreme regimes, an innovative FC has been designed for the ELIMED beamline. It is an absolute dosimeter collecting and counting the charged particles entering the detector and, according to its operating principle, it is not affected by the extremely high dose rates of laser-driven beams. The designed FC has been inspired by similar detectors already developed for ion beam dosimetry [16, 17], adopting innovative geometrical solutions aiming to optimize the charge collection efficiency and reduce the uncertainties related to the charge collection for highly pulsed beams [18]. The generated electric field inside the FC is a combined effect produced by two coaxial electrodes: the external electrode is a metallic hollow cylinder, where a positive voltage can be applied, while the internal one is an inner peculiar beveled cylinder, where a negative voltage can be

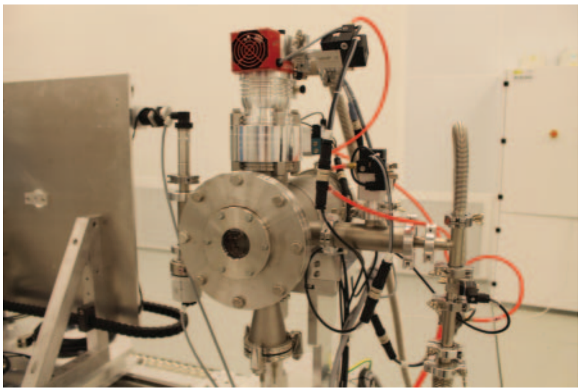

Fig. 3. – Faraday Cup dosimeter installed at ELIMAIA.

applied. 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 able to maximise the deflection of the secondary electrons generated by the interaction of the protons with the entrance window and the cup material itself. In fig. 3 a picture of the realized FC installed at ELIMAIA is reported.

Once the absolute dose is measured, an on-line in-transmission IC detector will be used for monitoring the dose and delivering the required amount onto the user sample, once cross-calibrated against the FC absolute dosimeter. In particular, in order to overcome general recombination effects for the high dose rates of laser-driven beams, a prototype of multi-gap chamber, composed of two different gaps of increasing thickness, characterized by different recombination factors and efficiencies, has been designed for relative dosimetry measurements at the ELIMED beamline. The presence of the second gap, close to the first one, will allow to correct for any ion recombination effect, if a very high voltage between the electrodes is applied. Passive devices for relative dose measurements, radiochromic films (RCF, HD-V2 type) and solid state nuclear track detectors (CR-39 type) will be employed at the ELIMED beamline as well. RCF and CR-39, in particular, can be used both as a single detector or in stack configuration in order to obtain information on the energy spectrum of the accelerated protons [19, 20]. The use of RCF films, if properly calibrated, also allows performing an accurate measurement of the released dose at the irradiation point. Finally, since CR-39 detectors show a relatively low saturation level (10^6 particles per shot), thermoluminescent dosimeters (TLD) will be used for the final stage of the ELIMED project, when a dose of 1 Gy per shot is expected, being able to reach an overall accuracy of the order of 5% on the absolute dose.

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This work has been supported by the project ELI —Extreme Light Infrastructure— phase 2 (CZ.02.1.01/0.0/0.0/15-008/0000162) of the European Regional Development Fund, by the Ministry of Education, Youth and Sports of the Czech Republic (project No. LQ1606) and by the projects “advanced research using high intensity laser produced photons and particles” (CZ.02.1.01/0.0/0.0/16-019/0000789) and “high field initiative” (CZ.02.1.01/0.0/0.0/15-003/0000449) of the European Regional Development Fund. This work has been also supported by the ELIMED project of the INFN fund.

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