RAD Conference Proceedings, vol. 8, pp. 89-95, 2024
ISSN 2466-4626 (online) | DOI: 10.21175/RadProc.2024.17
www.rad-proceedings.org

A COMPREHENSIVE BEAMLINE FOR PROTON AND ION BEAMS ACCELERATED VIA LASER-PLASMA INTERACTION: THE APPROACH IMPLEMENTED AT THE I-LUCE FACILITY

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Abstract. *The potential for developing compact, high-brightness particle and radiation sources has significantly advanced laser technology, particularly by enhancing laser efficiency and repetition rates. This progress is evident in the new generation of ultra-fast, high-power laser systems operating at high repetition rates, which have been installed across the world. A new high-power laser facility, "I-LUCE" (INFN Laser Induced Radiation Acceleration), is currently entirely under construction at LNS-INFN (Laboratori Nazionali del Sud – Istituto Nazionale di Fisica Nucleare) in Catania, Italy. This paper provides an overview of the I-LUCE facility, highlighting its main features and potential. It also includes a detailed description of the beamline designed for proton and ion beam transport and selection, as well as a thorough description of the diagnostic and dosimetric systems developed for dosimetric and radiobiological applications.*

Keywords: *Laser-driven particles acceleration, beamline, proton acceleration, dosimetry, diagnostic*

1. Introduction

The acceleration of particles via the coherent interaction of high-power lasers with matter has emerged as a promising alternative to conventional methods. Traditional accelerators, such as cyclotrons, tandems, and synchrotrons, use large and costly machines that generate strong electric and magnetic fields to produce monoenergetic particle beams with low angular spread [1-3].

Conversely, high-power laser interactions with solid targets represent a novel approach for multi-species production and acceleration. This technique involves focusing an ultra-short, high-power laser (up to 10 PW) on a micrometer-sized spot on a solid target of varying thickness. The resulting laser-target interaction forms a transient plasma, accelerating electrons, protons, and various ions to energies in the MeV–GeV range. Currently, lasers of high-peak powers of 1–10 PW are achieved by increasing the laser energy and/or reducing pulse duration, enabled by Chirped Pulse Amplification (CPA) technology. This advancement in laser technology, typically operating at wavelengths close to 1 µm (for Nd Glass lasers) or 800 nm (for Ti:Sapphire lasers), has significant implications for particle acceleration, nuclear fusion, medicine and high-energy density science [4].

In addition, improvements in target fabrication and laser performance have stimulated interest in the use of laser-accelerated protons for dosimetry and radiobiological applications. Notable international collaborations, such as the Extreme Light Infrastructure (ELI) consortium, ELI Beamlines in Prague [5], the Oncooptics project at OncoRay in Dresden [6], and the BELLA-i project at LBNL [7], underscore the global effort in this field.

At LNS-INFN in Catania, the development of a new high-power laser facility, I-LUCE (INFN-Laser Induced Radiation Production), is underway. Supported by the Italian PNRR (Piano Nazionale di Ripresa e Resilienza) programs EuAPS (EuPRAXIA Advanced Photon Sources), Samothrace (Sicilian Micronanotech Research and Innovation), and ANTHEM Advanced Technologies for Human-Centered Medicine), I-LUCE aims to explore advanced particle acceleration techniques and nuclear reactions in plasma. The facility will employ high-power laser systems with capabilities up to 320 TW and 23 fs pulse duration. I-LUCE will focus on the generation of radiation from solid, liquid, or gaseous materials with novel and compelling properties.

As the first open-user facility of its kind in Italy, I-LUCE will enable researchers to carry out experiments with laser-driven radiation and explore warm dense matter regimes. The facility will feature a laser with pulse rates from 2.5 Hz to 10 Hz and powers ranging from 40 TW to 320 TW. Additionally, one experimental area will be dedicated to the study of interactions between laser-generated plasma and ions from conventional accelerators, making I-LUCE the most powerful and versatile laser facility in Italy, with applications in multidisciplinary and basic sciences.

Furthermore, a dedicated beamline will be constructed to transport and select proton and ion

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beams. This beamline will be equipped with advanced diagnostic and dosimetry systems for real-time monitoring of beam parameters and future research in dosimetry and radiobiology. This paper offers a detailed overview of the I-LUCE facility, emphasizing its development of beamlines for proton and ion beam transport and selection.

2. I-I-LUCE FACILITY

The I-LUCE facility will consist of several distinct areas (see Figure 1):

1. *Laser System*: an ISO-7 clean zone housing the laser system, including the optical compressor.
2. *Experimental Areas*: divided in two sections, E1 and E2, each containing a different in-vacuum interaction chamber designed for specific experimental purposes.
3. *Utility Room*: this room will contain the power supplies for the laser system and its cooling systems.
4. *Control Area*: this area will be dedicated to house the control system, allowing for remote operation of both the laser system and experimental chambers.

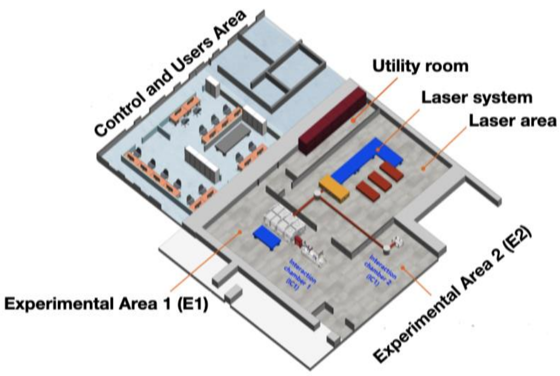

Figure 1. 3D model of the I-LUCE facility at INFN-LNS. The right section comprises the laser area, the utility room (housing the power supplies), and the two experimental areas, E1 and E2. The left section is allocated for the control rooms and a specialized optical laboratory.

The design of the I-LUCE high-power laser system is based on the THALES LAS QUARK family, an ultrashort pulse femtosecond, Titanium-Sapphire (Ti:Sa) laser system. This design utilizes an innovative combination of components, including the oscillator, stretcher, amplifier, and temporal compressor under vacuum. The system will provide two distinct outputs: one will be a high-repetition-rate (HRR) beamline delivering 40 TW with 23 fs pulses, 1.5 J energy, and a 10 Hz repetition rate, while the primary beamline will be a low-repetition-rate (LRR) laser delivering 320 TW with 23 fs pulses, 8 J energy, and a 2.5 Hz repetition rate. The I-LUCE facility is designed to direct the laser beam into two distinct interaction areas called E1 and E2. E1 will primarily focus on particle acceleration. A beamline will be installed and optimized to select, transport, and focus proton beams with energies between 5 and 40 MeV, enabling in-air experiments.

The I-LUCE laser target system will feature a motorized five-axis setup, enabling up to 900 shots per irradiation session before target replacement. Dose per shot, adjustable by modifying target properties, laser parameters, or selected energy, offers flexibility for tailoring irradiation to experimental needs, such as delivering approximately 2 Gy per shot at 15 MeV with a 40 MeV cutoff energy.

A station for electron acceleration in the Laser Wakefield Acceleration regime will be also installed, featuring gas-jet and capillary systems, online diagnostics, and a selection system for electrons with energies up to 3 GeV. Stand-alone experiments using high-intensity laser beams will also be conducted to investigate phenomena such as neutron production and X-ray laser generation. Conversely, E2 will offer a globally unique experimental setup that combines the interaction of heavy ion beams produced by the existing Superconductive Cyclotron and Tandem accelerators at LNS with the generated plasma. For moderate laser intensities (up to 40 TW), E2 will also support experimental runs dedicated to studies on nuclear fusion and the stopping power in plasma.

3. THE BEAMLINE TO TRANSPORT PROTON BEAMS

Optically accelerated ion beams are characterized by high intensities, a variety of ion species with multiple charge states, broad energy spectra, and energy-dependent angular distributions. To make these beams suitable for multidisciplinary applications, the primary objective of the beam transport system is to control the beam energy and angular distributions and ensure the reproducibility of the delivered beam spot size and dose distribution. This control is critical for conducting precise dosimetry measurements and radiobiological irradiations in pre-clinical studies.

The proposed technical solution is based on a modular system for beam focusing, which is followed by a final energy selection stage. Figure 2 shows the layout of the beam transport line, which includes the interaction chamber and, further downstream, the irradiation point. The transport and focusing system is equipped with a diagnostic and dosimetry systems consisting of various devices positioned both in air and in vacuum.

3.1. Focusing and Energy Selection System

The beamline for transporting proton and ion beams consists of two main sections: the particle collection section and the energy selector. The particle collection section aims to collect the maximum number of particles while minimizing beam angular divergence. The compact design is of paramount importance, as it must fit within the interaction chamber (where the laser-plasma interaction occurs) and be positioned close to the target. To meet these requirements, a series of quadrupoles with permanent magnets was developed. Additionally, a mechanical system was implemented to adjust the distances between the

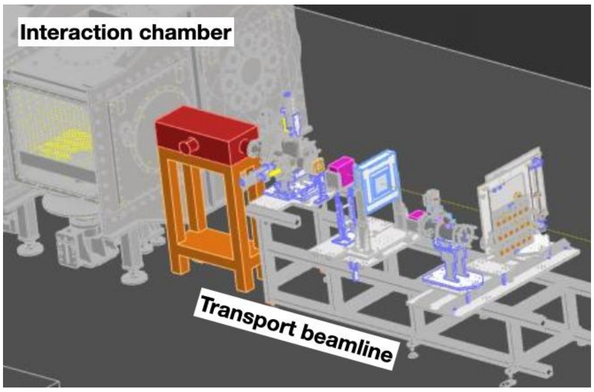

Figure 2. 3D model of the transport beamline designed for the I-LUCE facility. Proton beams generated in the interaction chamber will be energy-selected and transported to the interaction point in air.

quadrupoles, allowing for precise fine-tuning of the focal point for the desired energy.

Permanent magnet quadrupoles were selected for the I-LUCE beamline due to their compactness, cost-effectiveness, and ability to optimize particle collection and reduce angular divergence, meeting the facility's initial operational needs. Unlike solenoids, which offer high acceptance and energy-dependent focusing but lack precise energy discrimination, PMQs provide a simpler, more efficient solution. This choice prioritizes operational feasibility while leaving room for more advanced focusing systems in future upgrades.

Concerning the second section of the beamline, it was considered that the beam emerging from the collection system may still contain unwanted energy components. Consequently, an energy selection device for final energy refinement was developed. Following a detailed description of these two transport elements is reported.

Both the quadrupoles and selector were tested with conventional and laser-driven beams, showing good precision and consistency when compared to simulations. Due to the permanent magnets used, no fluctuations are expected in beam transport, with any dose variations likely arising from the laser-driven beam generation process.

The beam angular divergence is mitigated by using quadrupoles as collimators and two additional collimators (with variable diameters from 10 mm to 15 mm) in the ESS, while no collimators are placed after ESS, although a final nozzle will be added before the irradiation point to define emittance, and beam profile dimensions were studied by varying the distance between the exit kapton window and the irradiation point by +/- 50 mm, showing a 2mm variation in the beam FWHM.

3.1.1 Permanent Magnet Quadrupoles

Given the considerable difficulties posed by the high levels of electromagnetic interference present in the laser interaction environment, a specific design has been developed for permanent magnet quadrupoles (PMQs) shielded with mu-metal layers. These quadrupoles employ a hybrid Halbach cylindrical

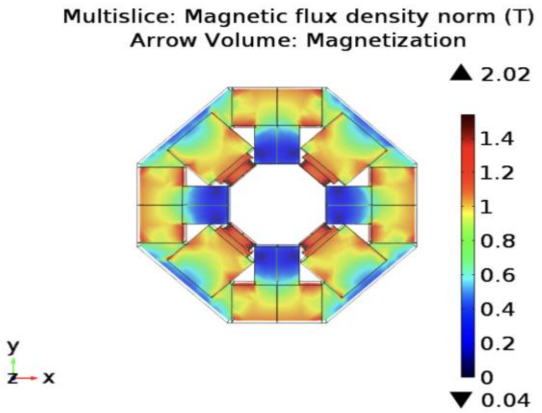

Figure 3. 3D model of magnetic flux density of one element of the PMQ collection system.

array comprising eight sectors, as illustrated in Figure 3.

The poles are oriented at an angle of 45° with respect to the horizontal axis and are attached to four iron sections that are nearly saturated and serve both as structural support and as magnetic flux guides. The magnetic properties of each quadrupole are determined by the BH curve of the materials used, with NdFeB N50 employed for the magnets and XC10 iron for the other components. Each magnet is individually oriented for permanent magnetization [8].

The entire collection system consists of two long permanent magnet quadrupoles, each measuring 80 mm in length, and two shorter PMQs of 40 mm in length. The maximum field gradients achieved are approximately 114 T/m and 100 T/m, respectively. A fourth quadrupole was incorporated into the triplet configuration to more effectively accommodate lower energy ranges within the system's operational range, spanning from 1 to 30 MeV.

3.1.2 Energy Selector System

The Energy Selector System (ESS) consists of a series of four dipole magnets with alternating polarity, similar to a bunch compressor (see Figure 4). Within each dipole, particles are deflected by the magnetic field, resulting from the Lorentz force. However, the combined effect of the dipole sequence, in conjunction with a central collimator, is to selectively allow particles within a specified energy range to pass through.

The sequence of dipoles is designed to separate protons of varying energies, while eliminating plasma electrons that may have entered the ESS. Specifically, upon entering the first two dipoles, the proton beam undergoes spectral dispersion in the radial plane. This configuration enables a clear separation of particle trajectories based on their energy: higher-energy particles experience less deflection compared to those with lower energies. The particles that pass through the slit are subsequently refocused by the opposing gradients of the third and fourth dipoles' magnetic fields [9,10].

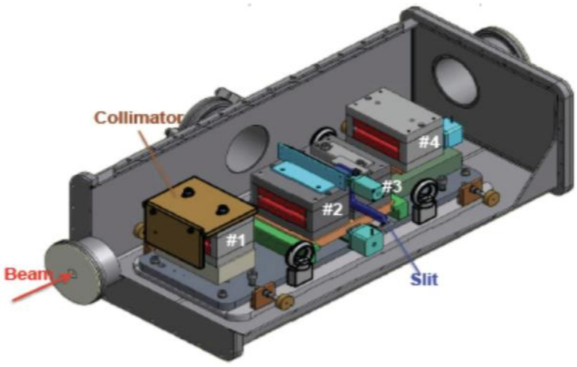

Figure 4. 3D model of the Energy Selection System. The drawing includes the four magnets, the vacuum chamber in which they are housed, and the motorization system for the magnets.

The ESS has a length of approximately 600 mm, including two collimators positioned 25 mm upstream of the first dipole and downstream of the fourth dipole, respectively. The collimators are designed to minimize particle spatial mixing, a common issue associated with the wide angular distribution characteristic of laser-driven proton beams. Each ESS dipole is composed of a soft iron yoke and NdFeB permanent magnets, which are capable of generating a magnetic field of up to approximately 0.8 T. The central twin magnets can be remotely adjusted transversely by 50 mm via a roller guide system. This allows the device to select protons within the energy range of 1 to 60 MeV. Its adaptable design includes transverse and longitudinal adjustments of magnets to maintain beam quality and minimize angular spread, while offering potential for future modifications to select other ion species.

The calibration of dipole magnets in the ESS ensures precise energy selection by measuring and adjusting the magnetic field profile, achieving uniformity along the radial direction and correcting beam trajectory deviations. Energy-specific selection is achieved using a collimating slit, with calibration performed at multiple proton energies to validate magnetic field maps and verify Monte Carlo simulations, optimizing the transport line for the I-LUCE facility's laser-driven proton beams.

3.2. Diagnostics and dosimetry systems

3.2.1 Time of Flight detectors

Due to the highly distinctive characteristics of laser-driven ion beams - such as their short pulse durations (0.1–1 ns), high peak currents (10^10 to 10^12 protons per pulse), and extremely high dose rates in a single pulse (10^9 Gy/min) - in contrast to traditionally accelerated beams, innovative diagnostic methods and devices are necessary [11].

The diagnostic system currently under development at I-LUCE will consist of polycrystalline and single-crystal diamond detectors, as well as Silicon Carbide (SiC) detectors, with surface areas ranging between 2 mm and 5 mm in diameter, and thicknesses from 10 µm to 500 µm. Diamond and SiC detectors have demonstrated promising capabilities in time-of-flight (TOF) measurements of high-energy laser-driven proton beams. These capabilities include good time (order of hundreds ps) and energy resolution (order of 1%), high radiation hardness capable of withstanding fluxes of up to 10^9 protons per bunch, and wide range of capacitance (0.1 - 20 pF).

These properties make them especially suitable for timing measurements of high-intensity particle bunches at high repetition rates. The detectors will be placed strategically along the beamline to facilitate monitoring both the laser-plasma interaction and the beam transport efficiency (see Figure 5).

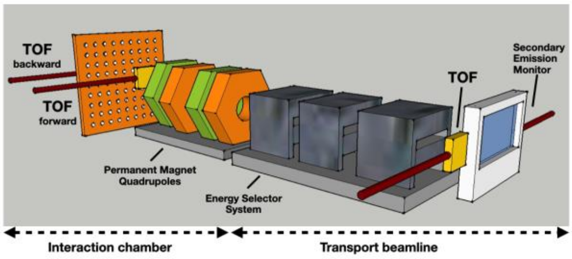

Figure 5. 3D model of the transport beamline. The beam divergence will first be controlled and reduced by the PMQ system located inside the interaction chamber. The beam will then undergo energy selection through the ESS system. The entire process will be monitored by a set of detectors, including three TOF detectors, which will monitor the interaction and transport of the beam in air.

Near the target, two different detectors will be positioned: one in the backward direction to monitor shot-to-shot reproducibility in terms of particle count and energy distribution, and another in the forward direction, mounted on an actuated system to measure the energy spectrum and optimize the operating configuration for the PMQ and ESS systems. Finally, a solid-state detector in TOF configuration will be placed on an actuated system to monitor the energy spectrum downstream of the entire transport system.

3.2.2 Relative dosimetry

The dosimetry system is designed to provide real-time dose measurements at the irradiation point in air using four online detectors that form the relative dosimetry system:

- an Integrated Current Transformer;
- a Secondary Emission Monitor;
- a Scintillator-based Monitoring;
- a Dual-Gap Ionization Chamber.

The output from the aforementioned detectors will be calibrated to dose measurements through a Faraday Cup, which serves as an absolute dosimeter. This will be positioned in air at the end of the beamline (see Figure 6).

Additionally, passive detectors, such as radiochromic films, will also be employed, as their response is well-established to be independent of dose rate. These detectors will be used in two configurations: as a single detector to accurately measure the transverse dose distribution profiles, and

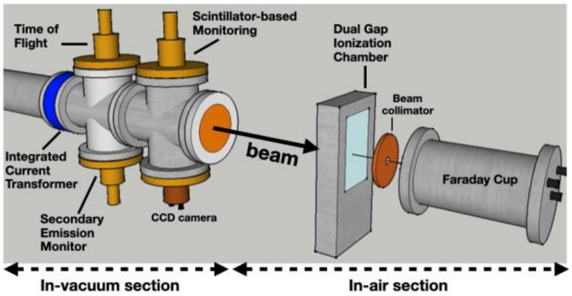

Figure 6. 3D model of the dosimetry system, which consists of a vacuum section and an air section for performing relative dosimetry. Absolute dosimetry will be carried out using a Faraday Cup detector.

in a stack configuration to obtain energy information of the accelerated protons via an iterative deconvolution procedure [4]. In addition, a detector based on Silicon Carbide technology (named PRAGUE) will be used to monitor both the incident spectra and the percentage depth dose distribution at the irradiation point. A comprehensive description of all the detectors is provided below.

The dosimetry calibration involves three steps: initial beam characterization with radiochromic films (to determine the beam's energy spectrum and spot size), absolute dosimetry using the Faraday Cup, and relative dosimeter calibration for real-time monitoring. This ensures accurate dose delivery and precise control for advanced radiobiological and dosimetry experiments.

Integrated current transformer (ICT)

The ICT is an online detector designed to accurately measure the charge of very short pulses in a non-destructive way. The device operates as a capacitively shorted transformer in conjunction with a fast readout transformer, both of which are integrated into a common magnetic circuit. The magnetic cores are made from thin ribbons of cobalt/molybdenum amorphous alloy, interleaved with nickel/iron crystalline alloy. The operating principle is straightforward: a current is induced in the magnetic core when the particle beam passes through the detector. The charge generated within the detector can then be directly correlated to the beam's current measurement. Furthermore, with appropriate calibration, the current can be converted into dose measurements.

Secondary Emission Monitoring (SEM)

The SEM detector consists of a thin tantalum foil with a thickness of 15 µm. The detector is electrically isolated from the rest of the beamline by a polymethylmethacrylate frame. An actuator enables the SEM detector to be moved in and out of the beamline axis. The SEM functions by measuring secondary electron emission, which is produced when multi-MeV charged particles traverse the tantalum foil. The resulting signal is directly proportional to the incident beam current and, when appropriately cross-calibrated with a reference dosimeter, can provide real-time data related to the dose delivered at a specific point [12].

Scintillator-based Beam Monitoring (SBM)

The SBM is a detector system that combines a CCD camera and a scintillator to monitor the beam profile, uniformity and positioning in real time. Specifically, it uses a 50 mm × 50 mm EJ-204 plastic scintillator screen (1 mm thickness) from Eljen Technology, renowned for its high scintillation efficiency, rapid response, and good attenuation length. The scintillation light produced by the proton beam is captured by a CCD camera (Bigeye G-283 Cool, Allied Vision Technologies GmbH, Germany) coupled with a Xenon 0.95/25 lens (Schneider Kreuznach GmbH, Germany). To prevent direct irradiation of the CCD chip, a mirror positioned at a 45° angle and 80 mm behind the scintillator reflects the emitted light. Additionally, through a precise calibration procedure, the system can also provide lateral dose distribution information [13].

Dual Gap Ionization Chamber (DGIC)

The DGIC is an innovative device designed for real-time dose monitoring on a shot-to-shot basis. It comprises two consecutive ionization chambers with inter-electrode gaps of 5 mm and 10 mm, respectively. Each chamber is powered by an independent voltage supply, with a range of −1,000 to +1,000 V and −2,000 to +2,000 V, respectively. The inclusion of the second chamber, with its differing collection efficiency, enables compensation for ion recombination effects that may occur due to the extremely high dose rates expected (MGy to GGy per second).

Proton range measure using silicon carbide (PRAGUE)

The PRAGUE device consists of a multilayer of Silicon Carbide detectors arranged in a stacked configuration. The system, which includes both the SiC detectors and the associated readout electronics, is designed to operate effectively under extremely high dose rate conditions. The system offers high spatial resolution for depth dose distribution measurements, due to the use of advanced solid-state detectors based on p-n junction technology. These detectors have an active thickness of 10 µm, are fully depleted, and measure 15x15 mm². The PRAGUE detector will be positioned in air at the irradiation point, providing crucial data on the range of incident particles and enabling real-time reconstruction of the depth dose distribution curve. Additionally, an appropriate deconvolution procedure will allow for the reconstruction of the incident proton spectrum.

3.2.3 Absolute dosimetry

To avoid the saturation effects commonly observed with traditional dosimeters when used with laser-driven ion beams, a novel Faraday Cup (FC) has been designed and realized for absolute dosimetry. The design incorporates geometric solutions aimed at improving charge collection efficiency and reducing uncertainties related to charge collection, as explored in [14]. An additional electrode with a distinctive beveled shape, positioned coaxially and internally to the standard electrode, has been introduced. The resulting electric field within the FC combines the fields from the two coaxial electrodes, creating an asymmetric electric field that mitigates the adverse effects of secondary electrons generated by the interaction of protons with the thin entrance window and the cup material itself.

4. Conclusion

The facility is projected to become fully operational at LNS by 2028, contingent upon the completion of the laser system's construction and installation, in addition to the experimental area and transport beamline. The facility will provide dedicated beam time for nuclear physics and multidisciplinary research, fostering open access for collaborative national and international projects.

The I-LUCE beamline is designed to transport protons and various ion species (e.g., helium, lithium, carbon) at 1–30 MeV/n, offering adaptability for diverse experiments. However, current laser-driven ion acceleration technology is optimized for protons, and producing heavier ions at high energies with sufficient yields remains a technical challenge, requiring advancements in laser-target interaction and target design

The beamline for transport and selection of proton beams was designed and constructed with the primary objective of investigating radiobiological and dosimetry applications. Each component is meticulously engineered to achieve high shot-to-shot reproducibility, precise dose delivery, and quasi-monoenergetic beam spectra at the irradiation site. The diagnostic and dosimetry systems have been designed to monitor, with high precision, all key beam parameters, including particle fluence, angular divergence, delivered dose, energy spectra, as well as beam uniformity and positioning.

The dosimetry detectors are designed to provide comprehensive online beam characterization. The ICT monitors beam current non-invasively, suitable for low-current conditions. The SEM offers higher sensitivity and helps homogenize the lateral dose distribution. The DGIC provides precise dose measurements at the irradiation point, while the SBM gives real-time data on beam position and lateral dose distribution, ideal for higher beam currents. Each detector is optimized for specific beam characteristics, ensuring accurate dosimetry assessments.

These features make the beamline particularly suited for future users engaging in biomedical research with the novel beams generated by laser-matter interactions.

Additionally, the modular design of the I-LUCE beamline allows for easy upgrades and modifications, ensuring long-term adaptability and versatility. Planned upgrades include an irradiation station for small animals with online dosimetry monitoring and a configuration for generating polychromatic beams and multiple ion species, simulating Galactic Cosmic Rays for space research. The modularity also supports adding advanced transport elements, such as higher-order focusing optics, to enhance beam quality for future experimental needs.

Acknowledgements: *The establishment of the I-Luce facility has been made possible through the funding provided by three Italian programs under PNRR (Piano Nazionale Ripresa Resilienza): EUAPS (EuPRAXIA Advanced Photon Sources), SAMOTHRACE (Sicilian Micro and Nano Technology Research and Innovation Center), and ANTHEM (Advanced Technologies for Human-centered Medicine).*

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