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LASER DRIVEN USER FACILITIES AND STATUS OF I-LUCE AT LABORATORI NAZIONALI DEL SUD OF INFN (ITALY)

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Abstract. *Laser-driven ion acceleration has emerged as a promising technology in accelerator physics, offering a compact alternative to conventional machines. By utilizing the interaction of high-intensity laser pulses with plasma, ions can be accelerated to high energies over short distances, enabling a wide range of applications in medical therapy, materials science, and nuclear physics. This paper provides an overview of the current facilities worldwide where laser-driven ion acceleration is being studied and implemented, and where laser-driven beams are made available to users for fundamental and applied research. It specifically focuses on the ELI-Beamlines facility (Dolní Břežany, Czech Republic) and the I-LUCE initiative facility (Catania, Italy), which aims to establish a laser facility at the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS). The main characteristics of these facilities and their generated beams are briefly discussed.*

Keywords: *Ion Acceleration, Laser-Driven Ion Acceleration, Target Normal Sheath Acceleration, High-Power Laser, Medical Application*

1. LASER-DRIVEN ION ACCELERATION

Laser-driven ion acceleration is a rapidly evolving field that leverages the interaction between ultra-intense laser pulses and matter to produce high-energy ion beams. This technology emerged from early research into laser-produced plasma in the 1960s [1,2], with a breakthrough occurring around the year 2000. At that time, collimated beams of MeV protons were successfully generated from thin foil targets irradiated by high-power, short-pulse lasers (≤1 ps) [3,4,5]. Since then, laser-driven ion acceleration has become one of the most actively studied areas within plasma physics, holding immense potential for scientific research, technology, and medical applications. When an ultra-intense laser strikes a solid or gaseous target, it starts to create a plasma, generating a hot-electron population via the ponderomotive force. These electrons are then pushed through the target to its rear. These electrons form a sheath, creating a strong electrostatic field that accelerates surface ions (typically protons) normal to the target. This process produces a forward-directed, high-energy ion beam, with the most energetic ions in the central part. A simplified layout of this mechanism is illustrated in Figure 1. One of the significant advantages of this approach is the compactness of the system, making high-energy ion acceleration feasible in smaller laboratories compared to conventional accelerators.

Recent advancements in high-power, ultra-fast laser systems have significantly enhanced the efficiency, precision, and control of laser-driven ion acceleration. Improvements in laser technology, including higher repetition rates and greater precision in terms of the laser focal spot position in laser-target interactions, have expanded the capabilities of these systems. Additionally, innovations in target design, such as thin foil configurations, and advancements in plasma diagnostics are helping to optimize the acceleration process, further increasing the achievable ion energies [6].

As the technology progresses, laser-driven ion acceleration is increasingly viewed as a viable option for various applications. Potential uses span fundamental physics experiments, industrial processes, and medical treatments, including tumor therapy [7]. The establishment of the I-LUCE (**I**NFN-**L**aser **I**nd**UCE**d Radiation Production) facility at INFN-LNS (Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud) in Catania, Italy will further support these advancements, providing a dedicated platform for particle and ion acceleration through advanced laser-driven interactions with matter [8].

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1.1 Laser-Driven Ion Acceleration Mechanisms

Laser-driven ion acceleration operates through several key mechanisms, each offering different advantages and challenges. A simple scheme of a laser-driven ion accelerator is shown in Figure 1. This accelerator includes a short-pulse, high-intensity laser and a target, such as a thin foil, positioned in a vacuum chamber. The separation between electrons and ions created in the laser-matter interaction creates an intense electric field between the electron and ion layers, which pulls the ions forward, following the electron layer. The strength of this field can reach extremely high values (up to tens or even hundreds of GV/cm), allowing ions to be accelerated to high energies over sub-millimeter distances—many orders of magnitude shorter than in conventional RF-driven accelerators. Consequently, the laser-driven accelerator can be much smaller and simpler in design. Additionally, the ion pulse duration can be very short, and the resulting dense, compact ion bunches can achieve high intensities and powers.

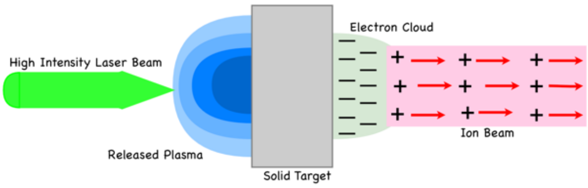

Figure 1. A basic diagram of a laser-driven ion accelerator

The primary forces that a laser beam generates in plasma, which are responsible for accelerating ions to high speeds over very short distances, can be broadly divided into two types: electromagnetic (EM) forces and hydrodynamic forces. When the laser intensity is high (greater than $10^{15}\frac{\mathrm{W}}{\mathrm{cm}^2}$) or very high (greater than $10^{18}\frac{\mathrm{W}}{\mathrm{cm}^2}$), multiphoton ionisation processes induce atoms ionization and generate hot electrons that can be separated by the positive charged ions. This causes the generation of extremely powerful fields, which in turn accelerate electrons at relativistic energies and ions up to the 100 MeV scale over sub-millimeter distances. Systems in which EM forces play the primary role in ion acceleration are often referred to as laser-driven electromagnetic accelerators. The core mechanism behind these EM forces is the Lorentz force, given by

$$\bar{F} = q\bar{E} + q(\bar{v} \wedge \bar{B}) \quad (1)$$

where q is the particle's charge, $\bar{v}$ is its velocity, and $\bar{E}$ and $\bar{B}$ represent the electric and magnetic fields of the laser in the plasma. This force primarily acts on electrons rather than ions due to their much smaller mass. When electrons are displaced from ions by this force, they create a powerful electric field between themselves and the ions. This electric field then accelerates the ions, which often move in sync with the electron cloud. The extreme strength of this field enables ions to reach high speeds over very short distances and in brief time intervals.

The specific details of ion acceleration vary based on the properties of both the laser pulse and the target, with multiple known mechanisms for laser-driven ion acceleration. These include target normal sheath acceleration (TNSA) [9,10,11], radiation pressure acceleration (RPA) [9,10,12], collisionless electrostatic shock acceleration (CESA) [6,13,14], ion solitary wave acceleration (ISWA) [15,16], coulomb explosion acceleration (CEA) [17,18], laser break-out afterburner (BOA) [9,10,19,20], and skin-layer ponderomotive acceleration (SLPA) [21,22,23]. Each of these mechanisms has been extensively studied and is optimized for different laser and target conditions.

The robust laser-driven ion acceleration mechanism, which has been extensively explored in the last two decades, is known as TNSA. In this process, an ultra-intense laser pulse interacts with a solid target, heating electrons to relativistic velocities. These electrons quickly escape from the rear surface of the target, leaving behind a positively charged region. The resultant strong electrostatic field, or sheath field, accelerates ions at the rear surface of the target, propelling them forward.

TNSA has enabled the production of ion beams with energies reaching tens of MeV per nucleon, making them suitable for various applications, including radiation therapy and proton therapy [24]. Its efficiency depends on the temperature of the hot electrons and the thickness of the target. Advances in thin foil targets and improvements in laser contrast allow for enhanced ion energy and improved beam quality in TNSA-based systems.

Another promising mechanism is radiation pressure acceleration (RPA). Unlike TNSA, RPA relies on the radiation pressure P=I/c, where I is the laser irradiance (in W/m²), and c is the speed of light in vacuum. This pressure transfers momentum to the target electrons, which are collectively accelerated. The resulting electron-ion separation generates a strong electrostatic field capable of accelerating protons and ions. This process is particularly efficient in thin targets and allows for the acceleration of ions with a narrower energy spread than TNSA. However, the requirements for stable RPA—such as extremely high-intensity laser pulses and ultra-thin, homogeneous targets—make it technically challenging. Nevertheless, RPA offers exciting potential for achieving higher ion energies with respect to the TNSA approach and many research groups are working on its practical implementation.

Break-out afterburner (BOA) is another advanced mechanism that operates when the laser pulse becomes so intense that the target becomes relativistically transparent. In this scenario, the laser breaks through the plasma, and the ions are accelerated by both the sheath field, generated by the laser ponderomotive force and the laser pressure itself, which continues to interact with the target even after transparency is reached. The BOA mechanism can produce ion energies much higher than TNSA, with some experiments reaching into the multi-hundred MeV range. Thin, over dense targets are particularly effective in BOA setups, as they maximize the interaction between the laser and the plasma. However, the complexity of maintaining the laser-plasma interaction stable and controlled (in terms of focus position, focus dimension, energy on target, etc.) remains a significant challenge for practical applications of BOA. In BOA and RPA, protons within the bulk of the material are directly accelerated, unlike in TNSA, where only surface contaminants undergo acceleration.

2. High-Power Laser Story and Motivation

The development and advancement of high-power lasers have revolutionized particle acceleration, offering a compact and efficient alternative to traditional methods. Since the 1960s, breakthroughs like chirped pulse amplification (CPA)—a technique that stretches and compresses laser pulses to achieve unprecedented intensities—have propelled laser systems to multi-terawatt (TW) and petawatt (PW) scales. These advancements enable the generation of extreme electric fields in tabletop setups, making laser-driven ion acceleration a promising tool for applications ranging from cancer therapy to next-generation particle accelerators. By harnessing the power of high-intensity lasers, new possibilities are being unlocked for precision medicine, materials science, and fundamental physics research.

2.1. Status of High-Power Laser Facilities in the World

The global landscape of high-power laser facilities has advanced significantly, driven by ambitious initiatives to explore new frontiers in laser-driven ion acceleration. These facilities offer unprecedented capabilities in generating high intensity pulses up to powers of the 10 PW scale [25], creating conditions suitable for ion acceleration, and facilitating breakthrough research in medical, industrial, and scientific applications. Below, we outline the capabilities and focus areas of four prominent high-power laser facilities where irradiation beamlines for secondary generated laser-driven ion beams are present: ELI-Beamlines (Czech Republic), DRACO at HZDR (Dresden), BELLA Centre at LBNL (USA), and I-LUCE (Italy).

The Extreme Light Infrastructure (ELI)-Beamlines facility houses the ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration) beamline. ELIMAIA operates with laser peak powers of up to 1 PW, laser pulse duration of 30 fs, repetition rate of up to 1 Hz, and intensities exceeding $10^{21}\frac{\mathrm{W}}{\mathrm{cm}^2}$, thus, providing unique access to users exploring both laser-driven ion acceleration mechanisms and their applications. At ELIMAIA the ELIMED (ELI MEDical and multidisciplinary applications) section is specifically dedicated to laser-driven ion beam transport, dosimetry, and user sample irradiation for multidisciplinary applications with a special focus on pre-clinical research (radiation biology, medical physics, and innovative approaches to hadron therapy) [25,26,27]. ELIMED aims to translate high-power laser-driven ion technology into potentially viable clinical solutions, as well as to explore novel irradiation effects in radiobiology and materials testing.

The Dresden high-intensity laser laboratory, part of the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in Germany, focuses on advancing the fundamental understanding of laser-driven particle acceleration [28]. Facilities like DRACO (Dresden laser acceleration source) and its two-beam setup enable experiments with peak powers up to 1 PW, laser pulse duration of 30 fs, and intensities on the order of $10^{21}\frac{\mathrm{W}}{\mathrm{cm}^2}$. Research here aims to generate stable, high-quality ion beams, particularly suited for applications in particle physics and radiobiology.

The Dresden facility has made considerable progress in beam shaping, targetry, and optimizing laser-ion interactions, contributing valuable insights into the scalability and stability of laser-driven acceleration mechanisms for various scientific applications.

The Berkeley Lab Laser Accelerator (BELLA) facility at Lawrence Berkeley national laboratory in the United States is a pioneering center in the field of laser-based particle acceleration, particularly in laser-plasma acceleration for high-energy electron beams [29]. BELLA operates at peak power levels of 1 PW with short pulse durations (40 fs), achieving intensities in the $10^{21}\frac{\mathrm{W}}{\mathrm{cm}^2}$ range. Its primary aim is to develop compact accelerator solutions that can generate particle beams with energies comparable to conventional, large-scale accelerators. While much of BELLA's focus has traditionally been on electron acceleration, recent efforts are expanding towards ion acceleration, targeting applications in high-energy physics and advanced imaging techniques. The BELLA facility's high repetition rate and precision beam control make it a leading site for pushing the energy frontier in laser-driven acceleration.

All the aforementioned facilities have been developed to study and characterize these new beams, which also hold potential for various applications. In particular, the prospect of using laser-driven ions for cancer treatment, isotope production [30], industrial applications (such as implantation and lithography) [31], and cultural heritage preservation (e.g., PIXE applications) makes these facilities especially valuable for future research.

3. The ELIMAIA-ELIMED BEAMLINE

The ELIMAIA beamline at ELI-Beamlines is designed to provide high-energy ion beams accelerated by petawatt-class lasers, aimed at multidisciplinary applications. Ion beams produced through laser-matter interactions exhibit high intensities, a range of ion charge states, broad energy spectra, and energy-dependent angular distributions. Managing these characteristics requires a beamline capable of controlling particle energy and angular distribution precisely. The ELIMAIA beamline comprises two main sections: the ion accelerator and the ELIMED sections. Figure 2 presents the entire ELIMED ion beam transport section. The beamline connects to the interaction chamber (the vacuum chamber on the top left), where ion beams are accelerated from a thin target and captured by a permanent quadrupole system. This section is followed by the energy selection system (ESS), the beam-shaping section, and finally, the beam is delivered to the in-air dosimetry station [32].

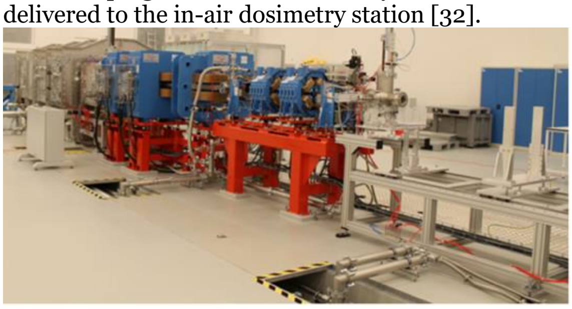

Figure 2. The full transport section of the ELIMED ion beam

3.1 ELIMED Components and Functionality

Three main components compose the ELIMED beamline.

Ion Capture and Focusing: The initial section of ELIMED captures and collimates ions, addressing the high divergence typical of laser-accelerated ion beams. Using a set of permanent magnet quadrupoles (PMQs), it focuses the ion beam on both transverse planes, ensuring alignment with the subsequent ESS. PMQs help reduce beam divergence and match it to the ESS's acceptance for efficient transmission.

Energy Selection System: This subsystem refines the ion beam's energy range, consisting of four resistive dipoles arranged in an alternating magnetic field configuration. The magnetic characteristics of these dipoles can be tuned depending on the energy and type of ions selected. A slit after the second dipole narrows the beam's energy spread further. The ESS can select proton energies up to 250 MeV and Carbon ions up to 60 MeV per nucleon [33]. Diagnostic elements, such as solid-state detectors, are used to monitor the beam along the beamline, with devices like diamond and silicon carbide detectors operating in a time-of-flight (TOF) setup.

Dosimetry Systems: Accurate shot-to-shot dose measurement is a key feature of ELIMED. Its absolute dosimetry system is built for dose-rate independence and provides online measurements with an error rate below 5%. Three main devices are used: a secondary electron monitoring (SEM) unit, a multi-gaps ionization chamber (MGIC), and a faraday cup (FC) for absolute dosimetry. Additionally, passive detectors like CR39 and radiochromic films are utilized to calibrate and benchmark active dosimetry systems. Since laser-driven ion beams have broad energy spectra and high divergence, multiple transport stages are essential. In the dedicated vacuum chamber, the ion collection section captures ions within a specific energy range and injects them into the ESS. This collection section includes five high-gradient PMQs (50 T/m), placed on a displacement system to adjust to varying ion energies.

After this, the magnetic chicane ESS, composed of four C-shaped electromagnetic dipoles, selectively filters ions by energy. The chicane has a fixed trajectory with variable magnetic fields (0.063 – 1.22 T) to accommodate different ion energies, and the beam's energy spread correlates with the slit's width, with a 10 mm slit resulting in a 10% FWHM spread.

Finally, a beam shaping section fine-tunes the beam with two resistive quadrupoles (gradients up to 10 T/m) and alignment elements, providing precise focusing onto the user sample. The use of laminated cores in the dipoles minimizes hysteresis effects and allows for rapid adjustments to magnetic fields. The ESS can be adapted as a Thomson parabola (TP) spectrometer by using the first dipole and additional electrostatic deflectors in the selector chamber, enhancing diagnostic capabilities with a wide dynamic range and broad charge separation, albeit with moderate energy resolution (~10%).

4. I-LUCE FACILITY

The I-LUCE facility at INFN-LNS is an advanced European initiative focused on producing very-high energy electron (VHEE) beams, as well as proton beams and neutron production, for a range of medical and scientific applications. Aiming to push the boundaries of laser-driven particle acceleration, I-LUCE combines state-of-the-art laser and plasma technology. Figure 3 offers a 3D view of the facility, highlighting its structure designed specifically for advanced high-intensity laser research and particle acceleration experiments. The facility covers a total area of 407.5 m² divided into two sections: one measuring 19.6 m by 16 m (313 m²) and the other 10.5 m by 9 m (94.5 m²).

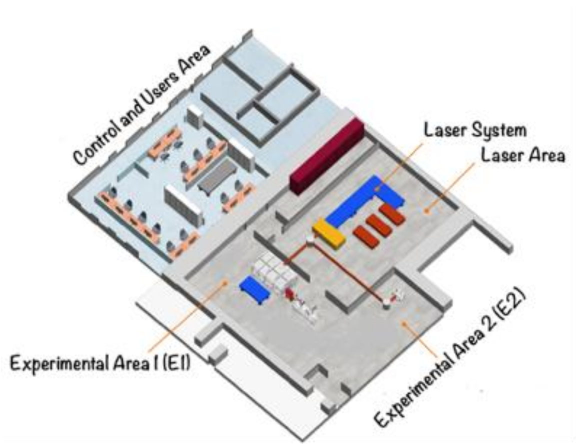

Figure 3. A 3D model of the I-LUCE facility at INFN-LNS. The total area of the facility is 407.5 m²

The laser system is based on the THALES LAS QUARK series, an ultrashort pulse femtosecond Titanium-Sapphire (Ti:Sa) laser. This system includes a complex configuration of components, such as an oscillator, stretcher, amplifier, and a vacuum-based temporal compressor. Key specifications are outlined in Table 1.

Table 1. Main characteristics of I-LUCE laser system

Parameter	Value
Power [TW]	45 – 320
Energy per Pulse [J]	1.05 – 7.7
Pulse Duration [fs]	23
Intensity [$\frac{W}{cm^2}$]	$10^{20} - 9 \cdot 10^{20}$
Repetition Rate [Hz]	2.5 – 10
Contrast at 100 [ps]	1:10^{10}

The I-LUCE laser system is built with dual output modes to accommodate a wide range of experimental applications. The high-repetition-rate (HRR) beamline delivers 45 TW with 23 fs pulses, 1.05 J energy operating at a 10 Hz repetition rate. Meanwhile, the primary low-repetition-rate (LRR) beamline provides 320 TW with 23 fs pulses, 7.7 J energy, at a 2.5 Hz repetition rate. Both laser outputs will have a contrast of 1:10^10 at 100 ps while a plasma mirror system will be developed to still improve the contract after the laser commissioning. Enclosed in an ISO-7 clean area, the laser system and optical compressor are protected from contaminants, ensuring precision and stability for high-power beam production.

The facility consists of two main experimental areas, E1 and E2 (see Figure 3), each with in-vacuum interaction chambers tailored for specific research needs. E1 is dedicated to proton and electron acceleration, with both lines integrated into a single chamber. For proton acceleration, E1 features a beamline that supports the TNSA mechanism, optimizing the selection, transport, and focusing of proton beams with energies between 5 and 40 MeV, supporting in-air experimental setups. Additionally, E1 supports electron acceleration via the laser wakefield acceleration (LWFA) technique [34], utilizing various gas sources, such as plasma-discharge capillaries [35,36] and gas-jet systems [37]. Equipped with online diagnostics like spectroscopy [38] and interferometry [39], the setup enables real-time monitoring. This configuration aims to produce electron beams with energies ranging from 100 MeV to 3 GeV, complemented by a selection system for fine-tuning electron energies. This area will also support high-intensity laser experiments focused on phenomena such as neutron production and X-ray laser generation.

Meanwhile, E2 provides a unique setup, combining both ions from conventional accelerators (ranging from any Z, with energies between 4 AMeV and 80 AMeV) and heavy ion beams from LNS's existing Superconductive Cyclotron and Tandem accelerators with plasma generated in the interaction chamber. For laser powers up to 45 TW, E2 will also facilitate research on ion interactions with plasma, including studies on stopping power and nuclear fusion. This setup makes E2 a valuable platform for advancing both conventional ion beam research and laser-driven ion acceleration. Equipped with advanced diagnostics such as TOF spectrometers and plasma imaging systems, E2 will enable detailed analysis of ion-plasma interactions and support further development of ion beam applications in various scientific fields.

The facility's utility room houses the laser amplifier power supplies and cooling systems, ensuring continuous, stable operation of the laser components under high demand. Additionally, a dedicated control area allows for remote operation of the laser and experimental zones, enabling precise, real-time adjustments and safe management of the high-power systems. As a state-of-the-art facility, I-LUCE marks a significant advancement in Europe's pursuit of research in laser-driven particle acceleration. Its flexible laser outputs and innovative experimental configurations establish I-LUCE as a vital platform for scientific progress, especially in particle acceleration, plasma physics, and nuclear research.

The facility's ability to provide both high-repetition and low-repetition beams makes it ideal for a wide range of experimental applications, from particle therapy to high-energy physics studies. Furthermore, it lays a strong foundation for the future use of laser-driven technologies across medicine, industry, and fundamental science. The I-LUCE control room is currently operational, and construction of the laser system, led by THALES group, is underway. We expect the laser area to be ready by early 2026, with the full installation completed later that year.

5. Conclusion

In conclusion, laser-driven ion acceleration represents a transformative approach in the field of particle acceleration, combining compact design with high-energy output. Since its inception and significant advancements in the early 2000s, this technology has evolved through the development of various mechanisms such as TNSA, RPA, and BOA. Each mechanism leverages ultra-intense laser interactions with matter to achieve ion acceleration, presenting unique benefits and challenges. Advancements in laser technology, target design, and plasma diagnostics continue to enhance the performance and feasibility of these systems. Facilities like I-LUCE at INFN-LNS play a crucial role in advancing laser-driven ion acceleration. Scheduled to be fully operational by 2028, I-LUCE will be one of Italy's most powerful laser facilities and among the few globally to offer both ions from conventional accelerators and ions from laser-plasma sources. The facility will also include a dedicated interaction chamber to study the interactions between conventional ions and laser-generated plasma, making this capability almost unique worldwide. As these efforts move forward, the potential for broad applications in scientific research, industry, and medical treatments becomes increasingly promising, ushering in a new era for particle acceleration technology.

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