Laser-Plasma Micro-accelerator for Health and Energy Applications in the framework of SAMOTHRACE project

C. Altana[1], S. Arjmand[1], D.L. Bonanno[1], R. Catalano[1], G.A.P. Cirrone[1], M.S. Musumeci[1], L. Pandola[1], A.D. Pappalardo[1], G. Petringa[1], G. Torrisi[1], J.J. Suarez Vargas[1], S. Tudisco[1]

[1] INFN-LNS, Via Santa Sofia, 62 – 95125, Catania

E-mail: altana@lns.infn.it

Abstract - High-intensity lasers can generate compact, energetic ion bems via Target Normal Sheath Acceleration (TNSA), reaching tens of MeV and enabling the development of compact, high-brightness ion sources. Within the SAMOTHRACE ecosystem, WP1-Spoke5 is developing a miniaturized ion accelerator for medical and energy applications. It is composed by an ion target station that supports up to 900 targets at 3 Hz, with sub-micrometer positioning accuracy and full EMP compatibility. Ion diagnostics based on a Thomson Parabola Spectrometer (TPS), optimized for detecting protons up to 70 MeV will operate in low- and high-energy configurations, achieving energy resolutions of 2–5%. The micro-accelerator will be installed at the I-LUCE (INFN–Laser indUCEed radiation production) facility at INFN-LNS.

I-LUCE (INFN-Laser indUCEd radiation production) facility

The I-LUCE facility at the Laboratori Nazionali del Sud of INFN represents a significant advancement in high-power laser technology and its applications in both fundamental and applied research.

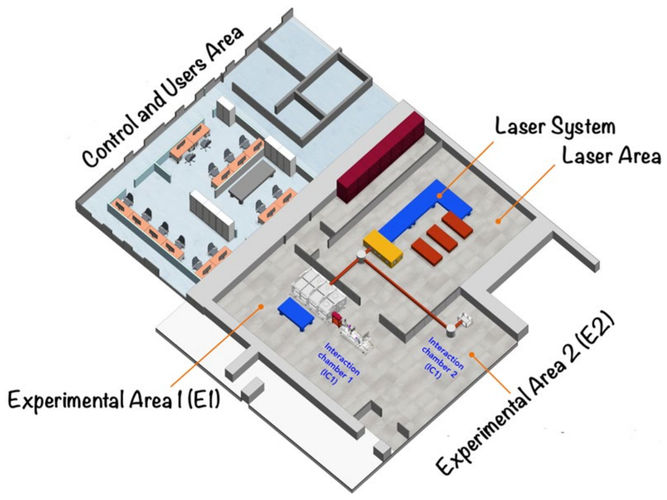
The I-LUCE facility includes two experimental halls.

Experimental area 1 (E1) is dedicated to:

- Proton acceleration via TNSA with energies between 5 and 60 MeV
- Electron acceleration via LWFA between 800 MeV and 3 GeV
- Beamline optimized for particle selection, transport, and focusing
- Target and detectors testing

Experimental area 2 (E2) is dedicated to:

- Advanced studies in plasma and nuclear physics
- Conventional ion–plasma interaction experiments
- Warm Dense Matter investigations
- Stopping power and cross-section measurements in plasma



The I-LUCE facility is equipped with an ultrafast Ti:Sapphire laser system designed for high-intensity, high-repetition-rate experiments.

The laser delivers **two output beamlines**, with different power levels and repetition rates:

- **45 TW Beamline**
  - Pulse energy: **1.5 – 8 J**
  - Pulse duration: **25 fs**
  - Repetition rate: **10 Hz**
- **350 TW Beamline**
  - Pulse energy: **1.5 – 8 J**
  - Pulse duration: **25 fs**
  - Repetition rate: **2.5 Hz**

THALES

Laser Power	**45 – 320 TW**
Laser Energy per Pulse	**1.5 – 8 J**
Laser Pulse Duration	**23 – 25 fs**
Laser intensity	**10^{18} – 10^{21} W/cm^2**
Repetition Rate	**2.5 – 10 Hz**
Strehl Ratio	**>80% with Deformable Mirror**

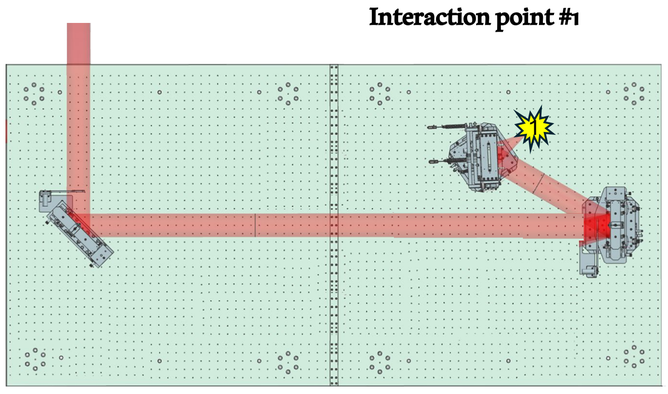
Miniaturized ion accelerator in SAMOTHRACE project

➢ Optical path for laser beam transport

Within the **SAMOTHRACE project**, the optical beam path for ion acceleration was designed for the interaction chamber located in **Experimental Area E1**.

The optical setup inside the interaction chamber in Experimental Area E1 enables precise laser delivery to two different interaction points for ion acceleration, each optimized for different applications.

Interaction point #1



➢ **Interaction Point #1** enables key research activities such as:

· Plasma characterization

· Beamline optimization

· Target testing

· Detector testing

Key optical components include:

A. Turn Mirror for 45° AOI:

- Reflects the laser beam along the chamber axis
- Enables symmetric access to both interaction points without repositioning upstream optics

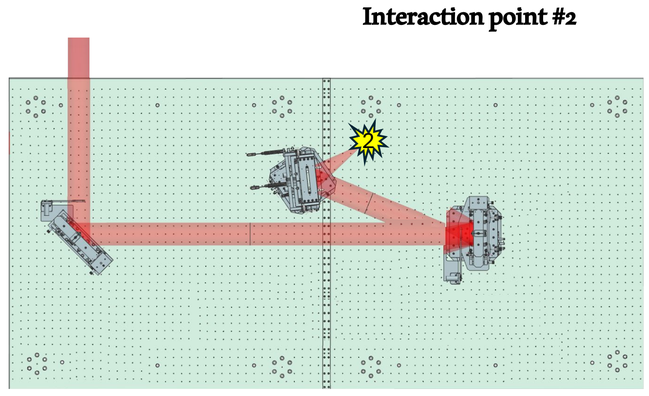
B. Rotatable Turn Mirror with variable AOI:

- Acts as a local switchyard
- Can be positioned at two predefined locations inside the chamber, allowing beam delivery to either Interaction Point #1 or #2.

C. Off-Axis Parabolic Mirrors (OAPs) for Focusing **with FS = 270 mm or FS = 400 mm:**

- Selection of OAP depends on focusing needs and beam shaping for ion acceleration experiments

Interaction point #2



➢ **Interaction Point #2** enables advanced applications by integrating **focusing quadrupoles** and a **magnetic energy selector** inside the vacuum chamber:

· Ion beam dosimetry

· Radiobiological studies

· Nuclear reaction experiments

➢ Target station and focus monitoring

A dedicated positioning system has been developed to enable **micrometric alignment of solid targets** with respect to the laser focus, ensuring high reproducibility and flexibility for ion acceleration experiments.

The focus monitoring system is designed to ensure extremely precise positioning of the target with respect to the laser focus, using high-precision optical diagnostics.

Key Features:

Five Degrees of Freedom movement with high resolution and speed:

- **X–Y translation**:
  · Range: ±105 mm
  · Resolution: 10 µm
  · Speed: >20 mm/s
- **Z-axis translation**:
  · Range: 25 mm
  · Resolution: 1 µm
  · Speed: <10 mm/s
- **Tilt & Rotation**:
  · Angular Range: ±2°
  · Angular Resolution: 20 µrad

This system ensures **precise and repeatable target positioning**, crucial for maximizing laser-target interaction efficiency and beam reproducibility.

SourceLAB

Images courtesy of SourceLAB

Key Features

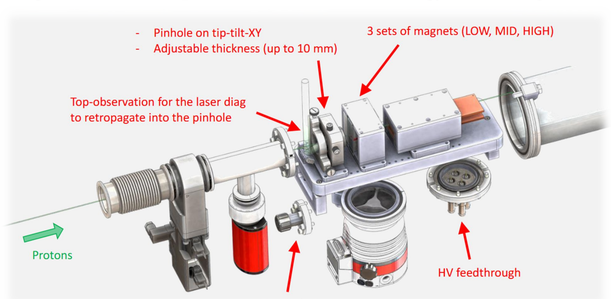
- **Alignment Laser**
  · A reference laser beam, co-linear with the main IR beam, is focused onto the target surface
  · The light scattered from the surface is used for focus diagnostics
- **High-Magnification Lens**
  · A lens with ~×50 magnification captures the scattered spot
  · Enables mapping of ~50 µm displacements on the target surface to the full camera sensor
- **Imaging Camera**
  · An 8-bit CCD camera records the laser spot reflected from the target
  · Provides high-resolution visual feedback on target focus
- **Adjustable Field of View**
  · The system allows imaging of a surface area up to Ø2 mm
  · Suitable for aligning different target types
- **Focus Resolution**
  · Sub-micrometer resolution along the Z-axis (<1 µm)
  · Ensures target positioning accuracy better than 15 µm

➢ Ion diagnostic

Thomson Parabola Spectrometer (TPS) is designed to characterize laser-accelerated ions by separating different ion species based on their energy and charge-to-mass ratio (E/q and m/q).

Key Features:

- **Pinhole:**
  · Defines beam geometry and limits angular spread
  · Enables spatial resolution of ion trajectories
  · Typically <1 mm wide for improved resolution
- **Electrostatic plates:**
  · Generate a uniform electric field perpendicular to ion path
  · Deflect ions vertically according to their energy-to-charge ratio (E/q)
  · High voltage operation to allow analysis of ions up to tens of MeV
- **Permanent dipole magnet:**
  · Provides magnetic field perpendicular to both beam and electric field
  · Deflects ions horizontally depending on mass-to-charge ratio (m/q)
  · Field strength chosen to resolve protons and heavier ion species
- **Drift region:**
  · Allows full spatial separation of ion species
  · The combination of E and B fields results in a parabolic ion dispersion
- **Detector system:**
  · MCP (Microchannel Plate) coupled to a phosphor screen
  · Readout via fast CCD camera
  · Ensures single-shot capability and high spatial resolution
- **Field shielding and housing:**
  · Entire system is enclosed in vacuum to prevent ion scattering
  · Shielding installed to block light and electron background



Images courtesy of SourceLAB

Specifications:

- Detection of protons with a maximum energy of 70 MeV
- Possibility to operate in low (10 MeV) and high energy (70 MeV) regime by varying the specifications of the system

SourceLAB