The I-LUCE high power laser facility at INFN-LNS: status and perspectives for ultrafast applied physics

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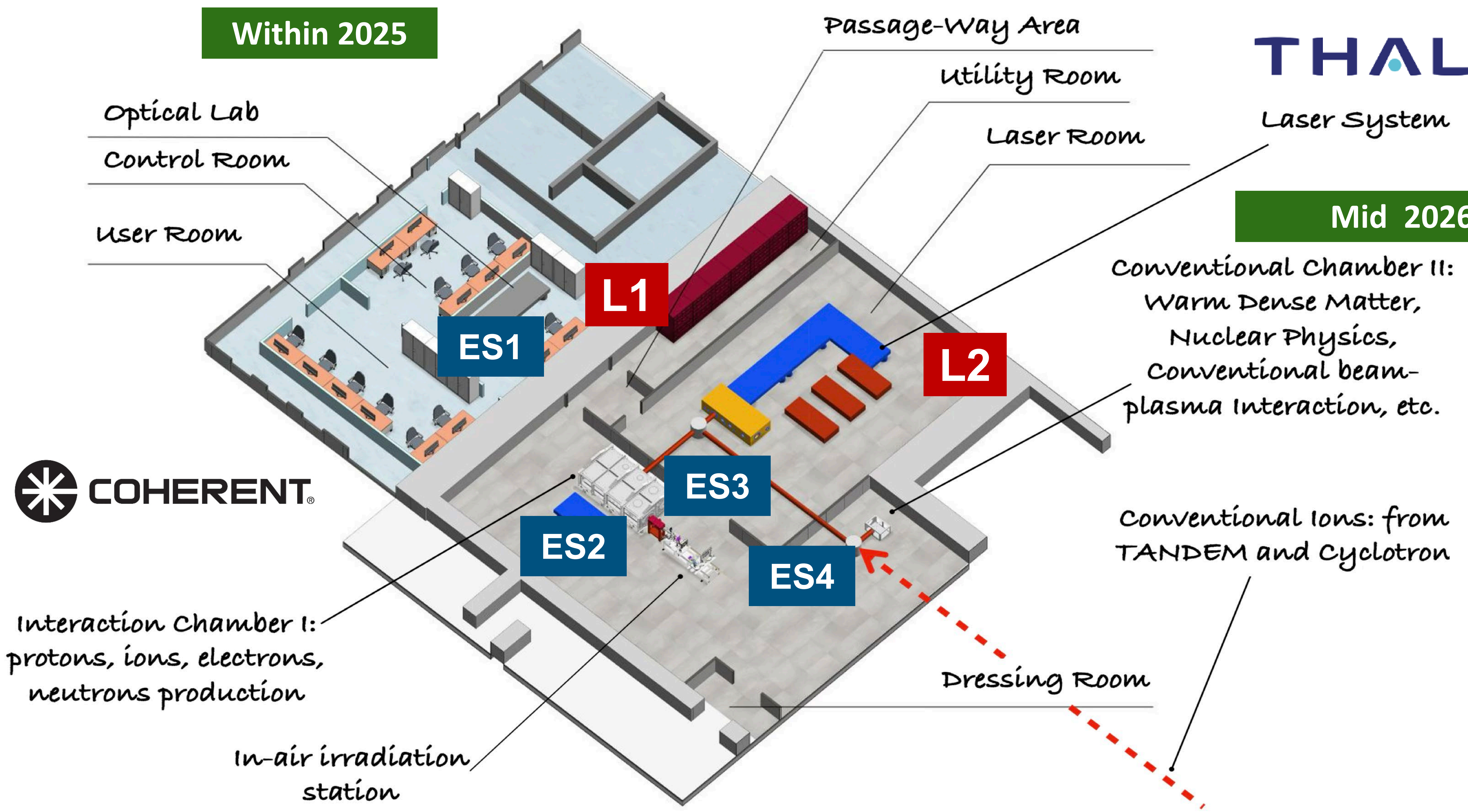
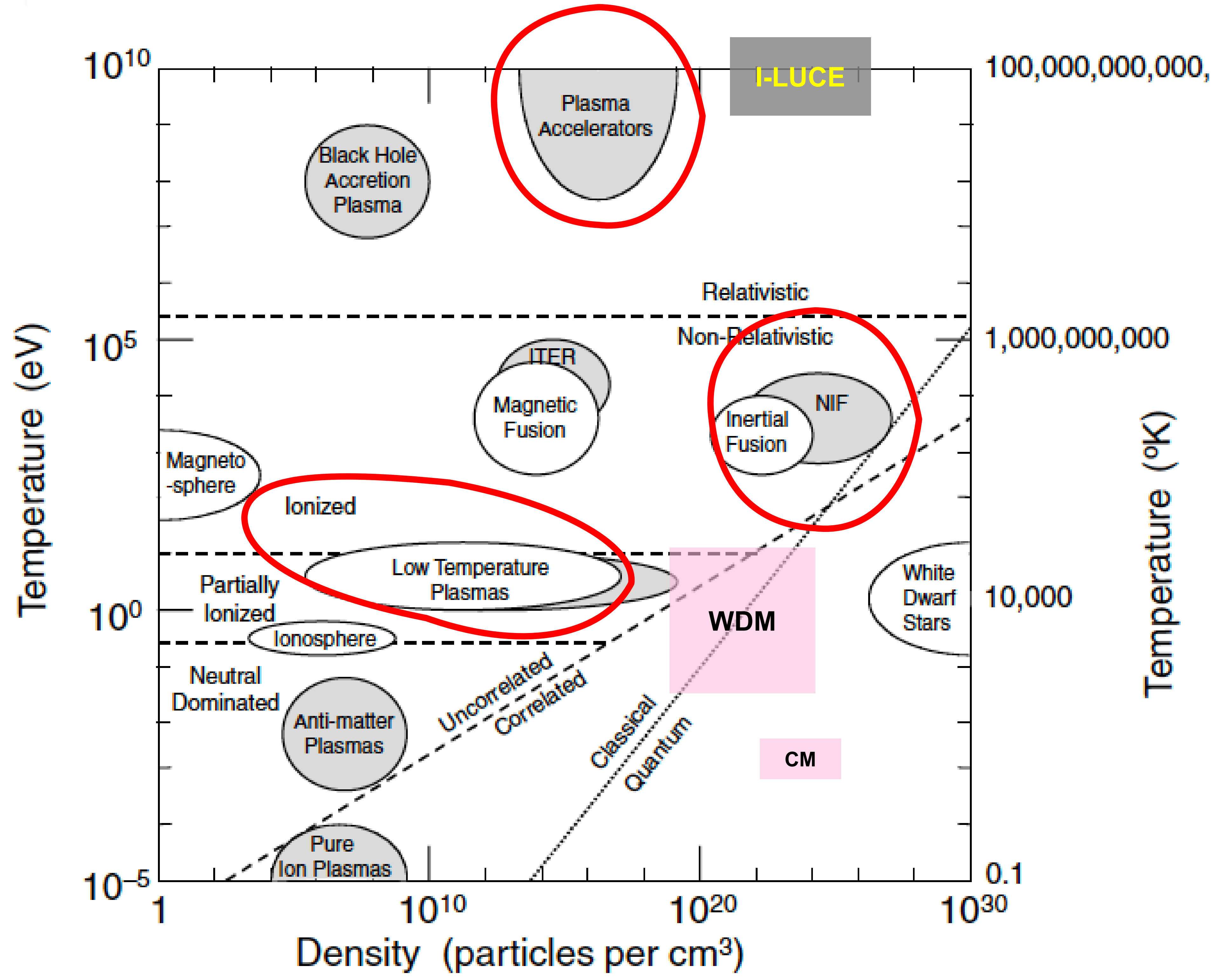
Offices and
laboratories
Laser bay
27 AMeV Tandem accelerator
80 AMeV superconducting
cyclotron

I-LUCE



- Two **laser systems** (L1 and L2)
- Three **laser outputs**
- Four **experimental stations** (ES1, ES2, ES3 and ES4)



Electron temperature [K]	$10^{10} – 10^{11}$ (MeV range)
Electron density [cm^{-3}]	$10^{21} – 10^{24}$
Ion temperature [K]	$10^{7} – 10^{9}$
Compressed matter density [cm^{-3}]	Up to 10^{26}

Astrella femtosecond laser (L1)

COHERENT

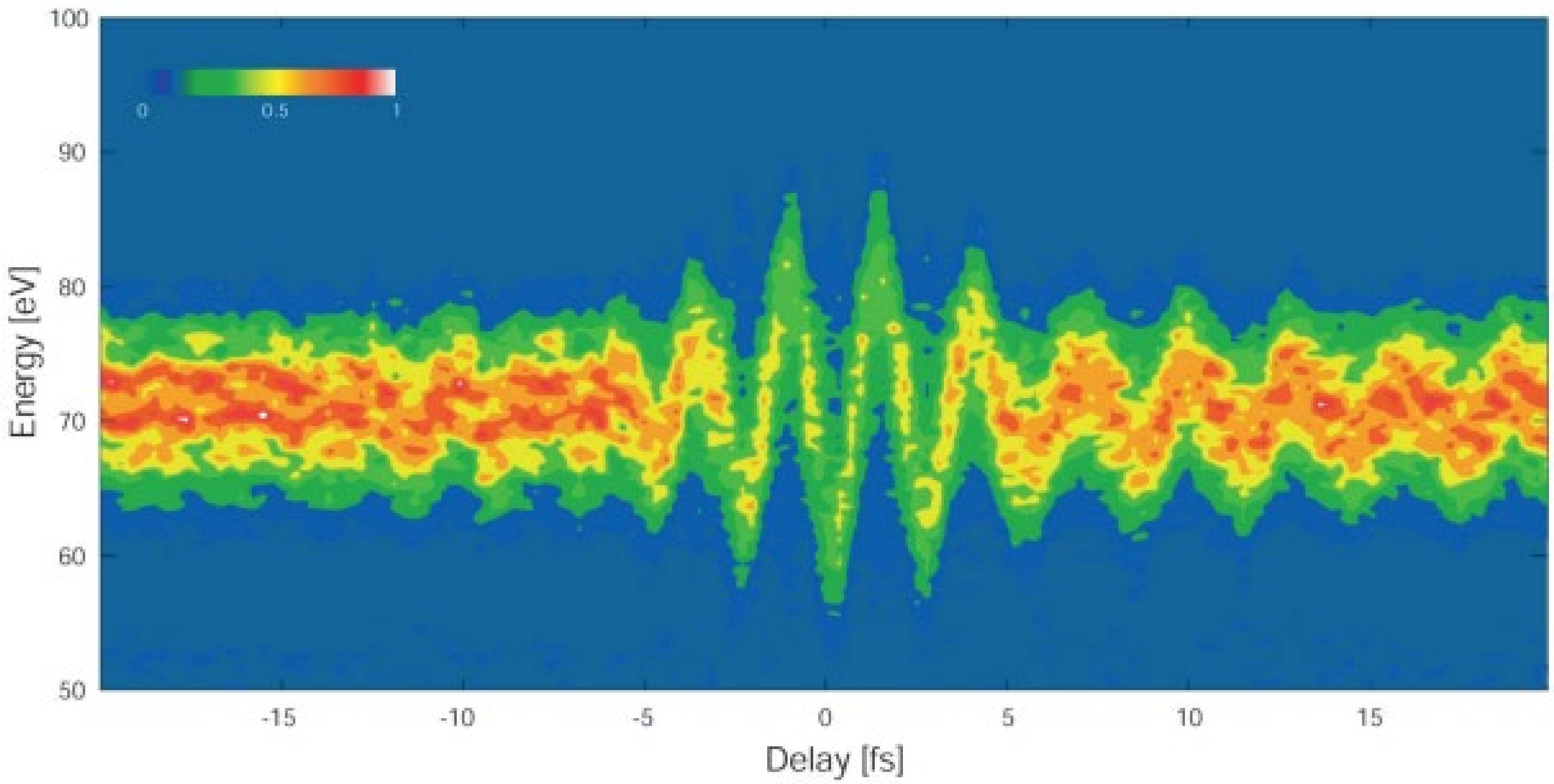
Laser Parameter	Values
Output Energy [mJ]	5-10
Pulse Duration [fs]	35 (7 or less after beam compression)
Repetition Rate [Hz]	1000
Spectrum (FWHM) [nm]	$\geq$ 70
Central Wavelength [nm]	800
Beam Profile	Gaussian; $M^2 < 1.23$
Power stability [RMS]	0.5
Contrast Ratio	$> 10^3$ (pre-pulse); $> 10^2$ (post-pulse)
Beam diameter (mm)	13
Maximum Intensity on Target [W/cm^2]	$5 \times 10^{17} – 10^{18}$

Potential applications:

- test bench for detectors to be employed with the main laser system
- low power laser for high resolution plasma diagnostics of L2
- stand-alone laser system

Electric field temporal visualization

$$E(t) = -\frac{\partial A}{\partial t}$$



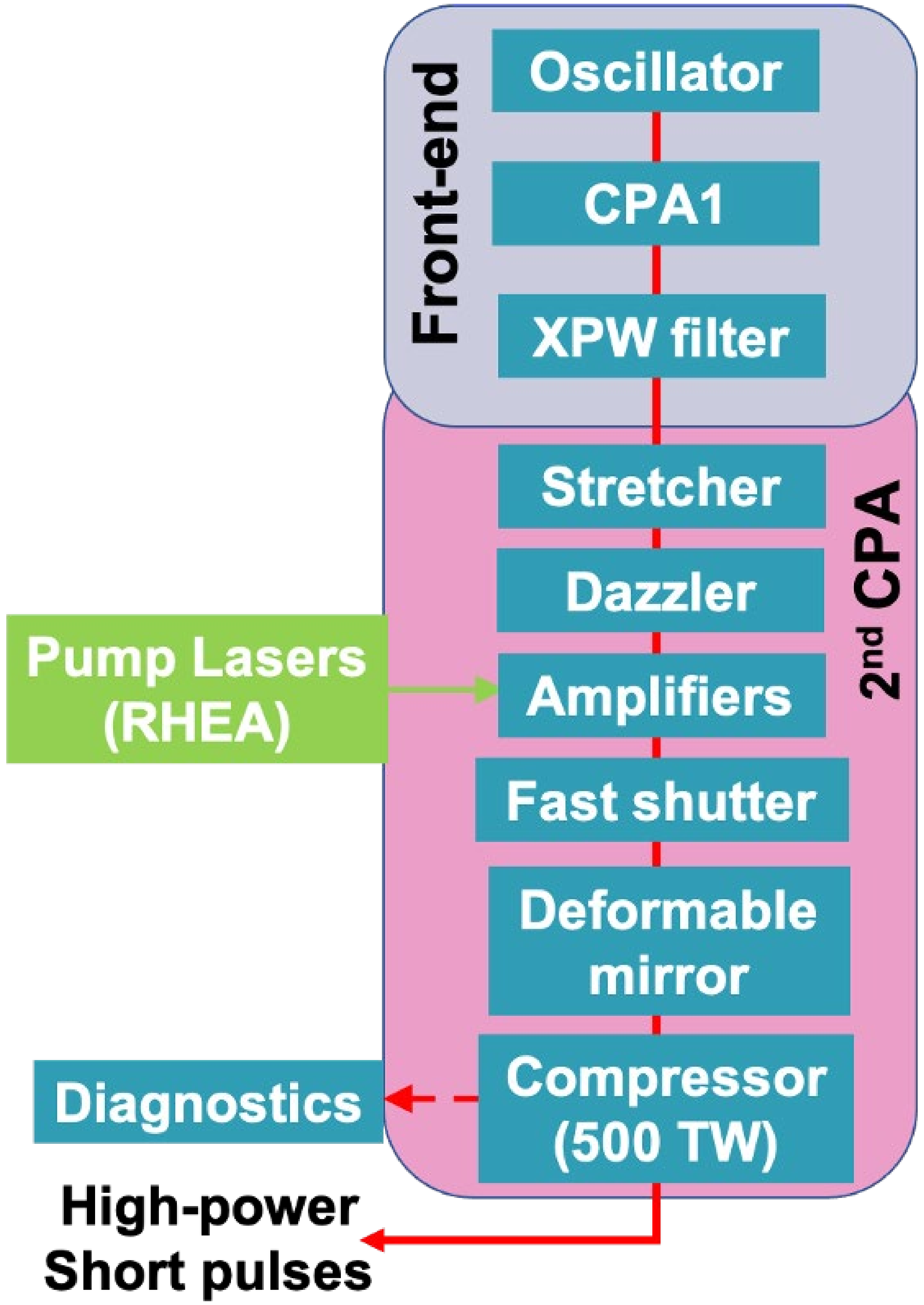
M Schultze et al 2007 New J. Phys. 9 243

The I-LUCE two laser systems (L2)

Thales Quark System 320 TW

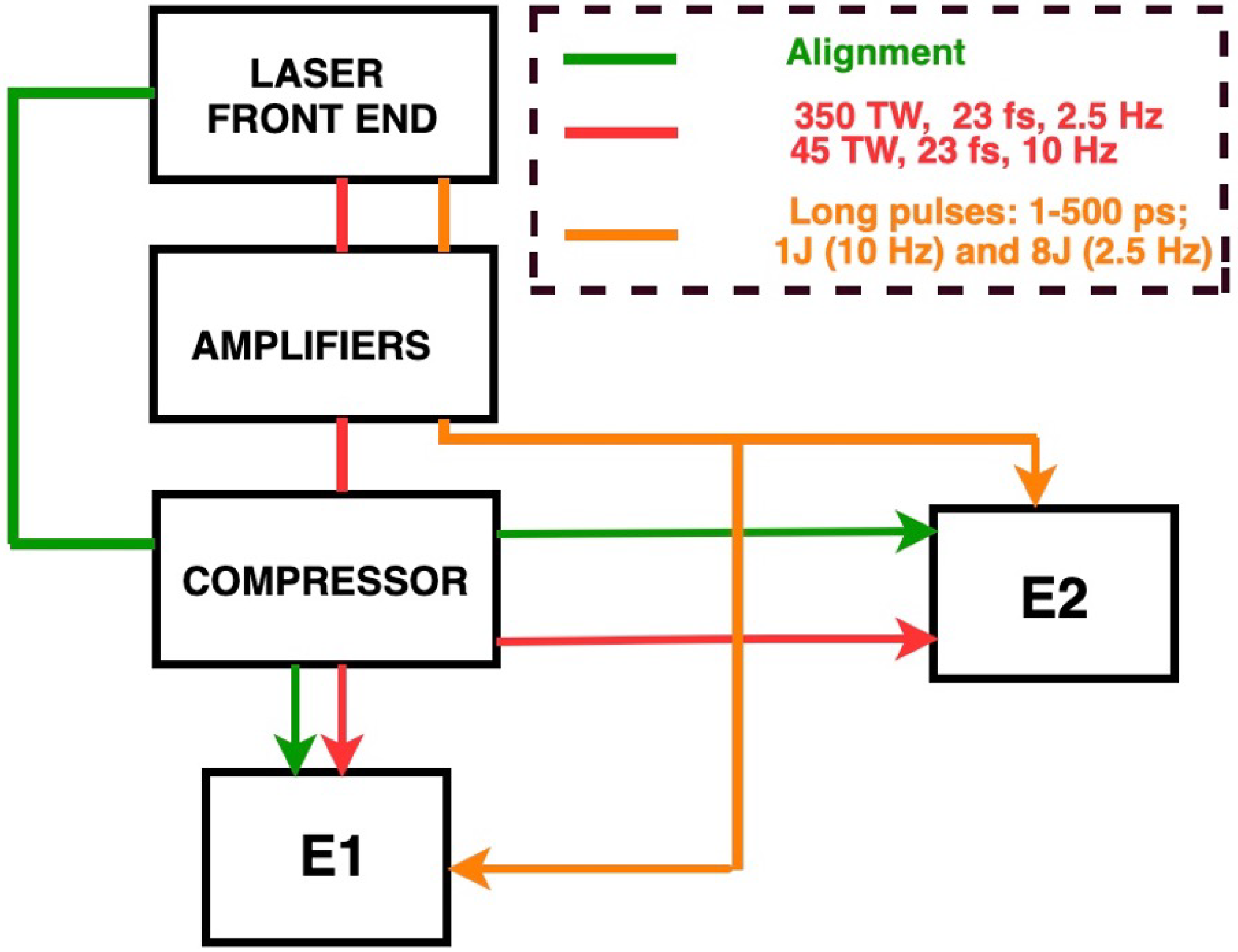
Laser Parameter	Low Power Mode	High Power Mode
Output Energy [J]	≥ 1.5	≥ 8
Pulse Duration [fs]	≤ 23	≤ 23
Peak Power [TW]	45	320
Repetition Rate [Hz]	10	2.5
Focusing surface [um^2]	36	36 or better
Spectrum (FWHM) [nm]	≥ 40	≥ 40
Central Wavelength [nm]	800 ± 10	800 ± 10
Beam Profile	Super Gaussian Top Hat	Super Gaussian Top Hat
Strehl Ratio	> 80% with deformable mirrors	> 80% with deformable mirrors
Contrast Ratio @ ps	< $1{:}10^8 – 1{:}10^{10}$	< $1{:}10^8 – 1{:}10^{10}$
Energy stability [% rms]	≤ 1.5	≤ 1.5
Maximum Intensity on Target [W/cm^2]	1×10^{20}	9×10^{20}

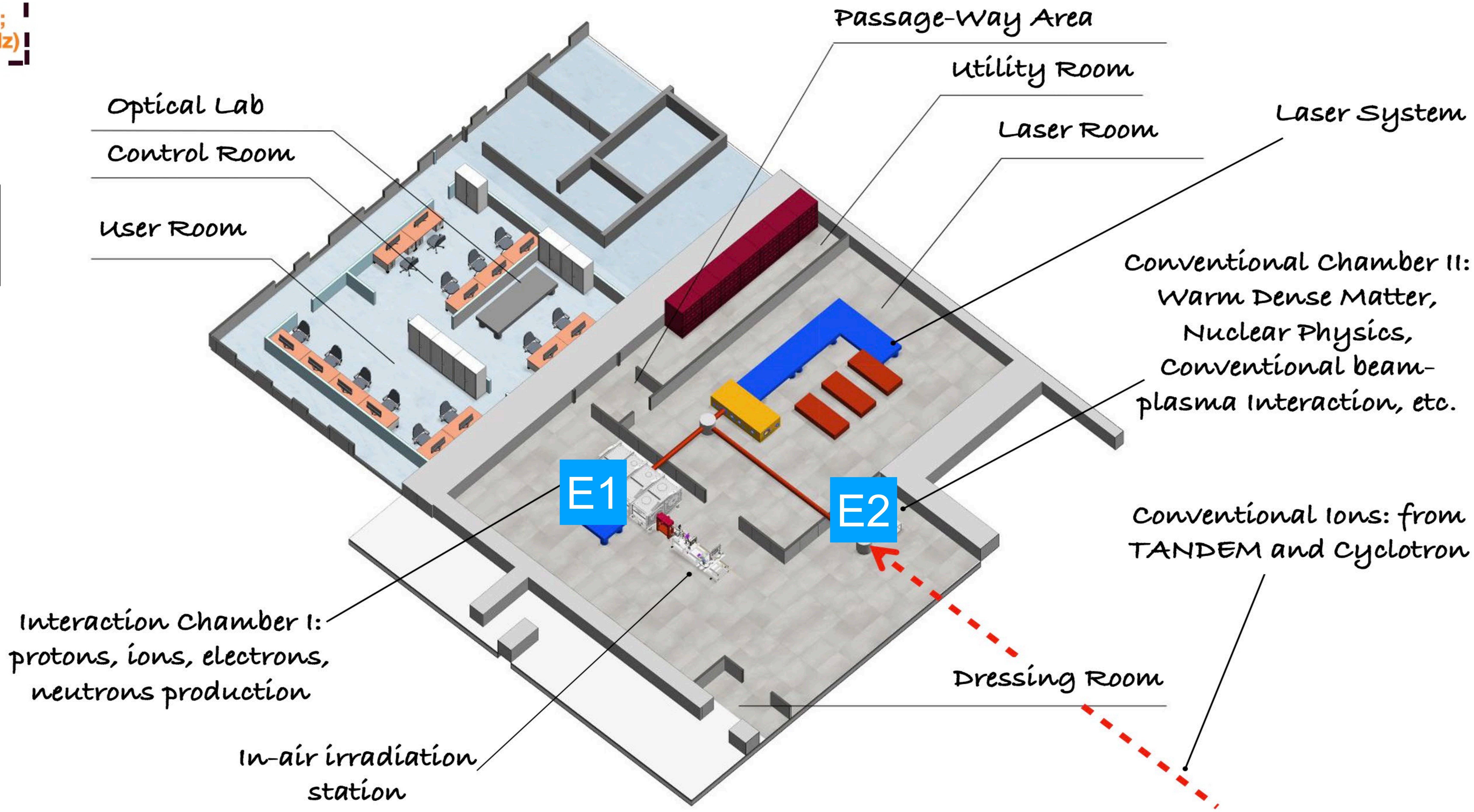
Thales Quark System 320 TW



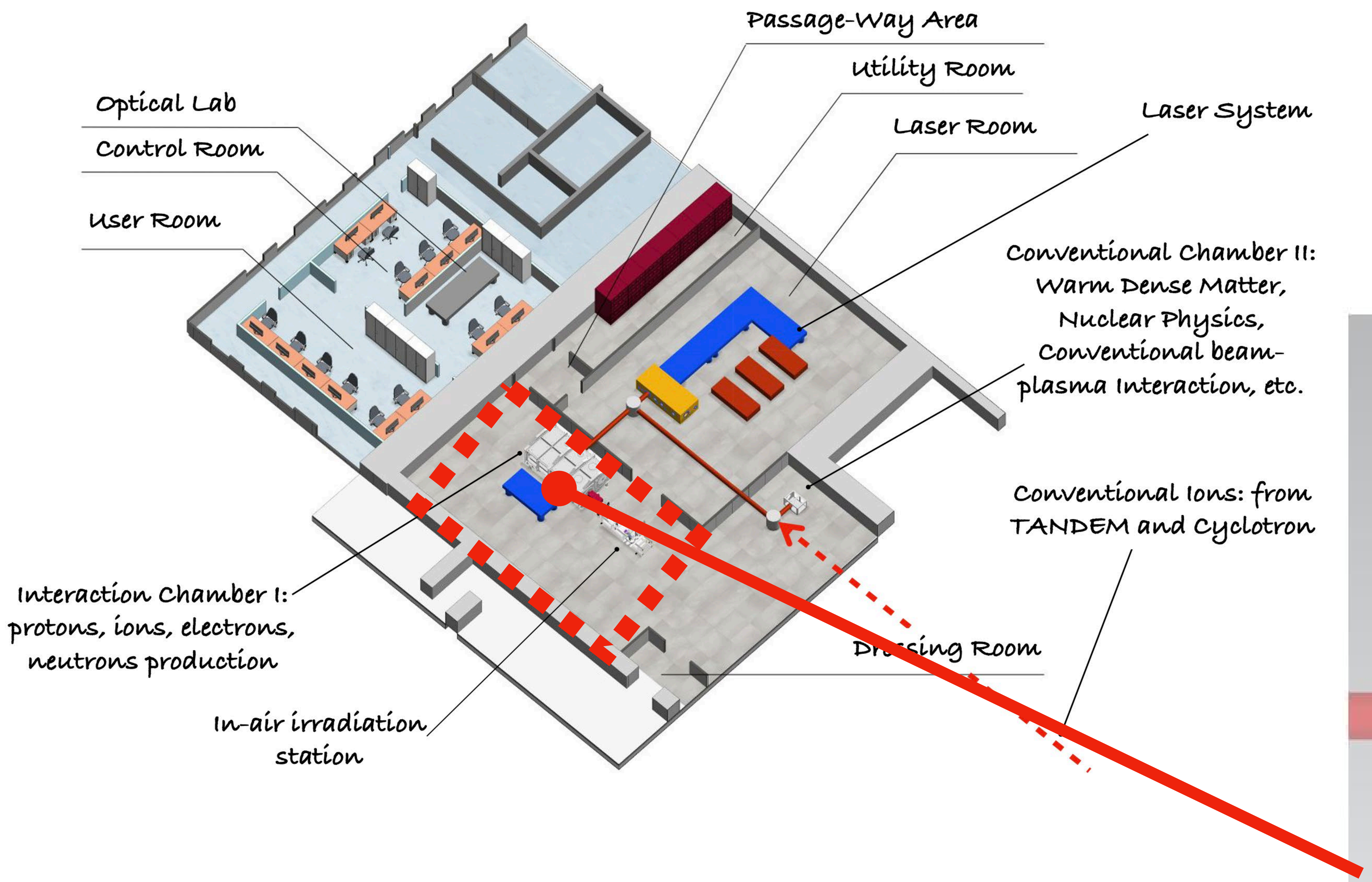
THALES

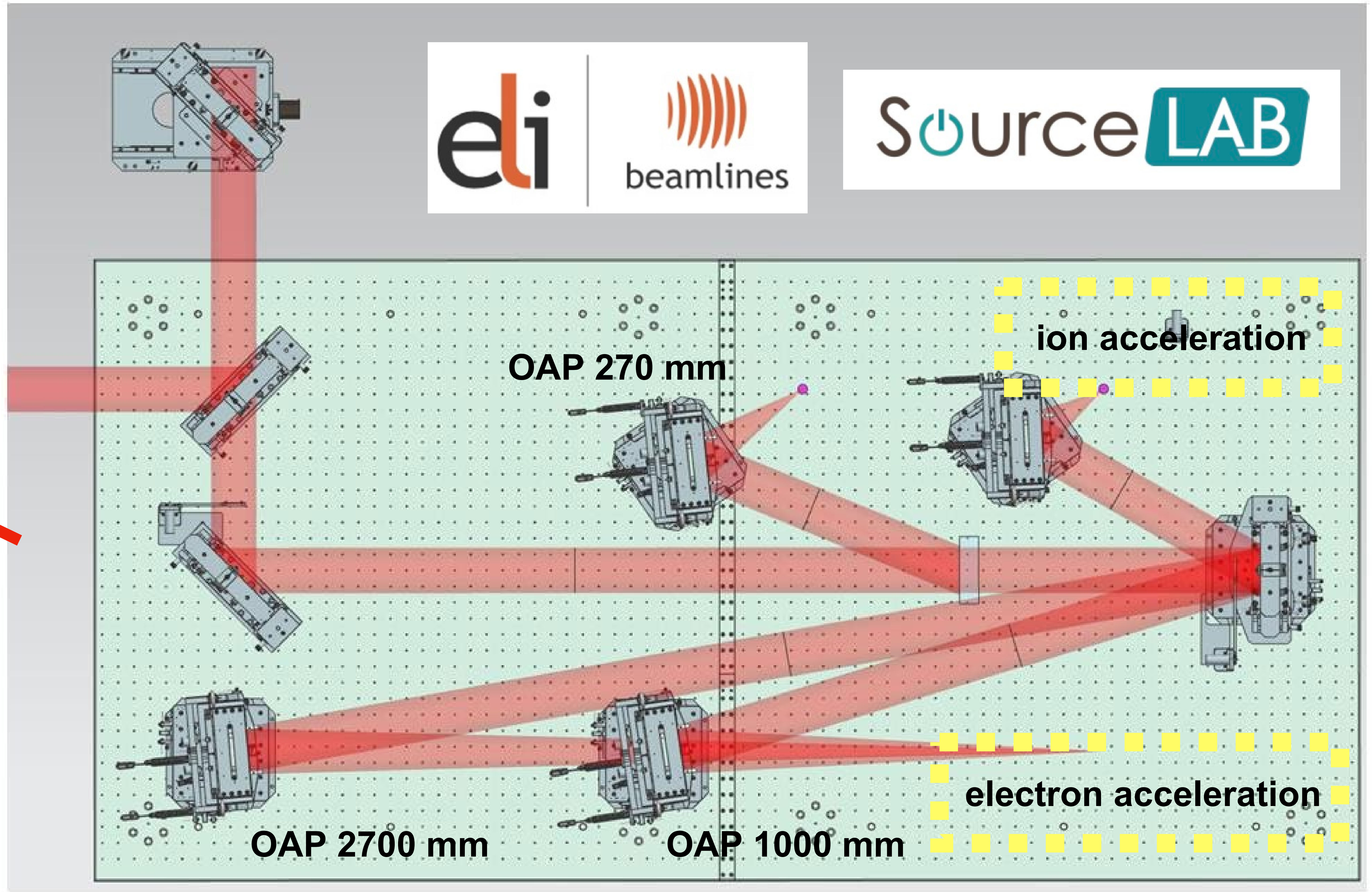
Beam transport to the experimental area





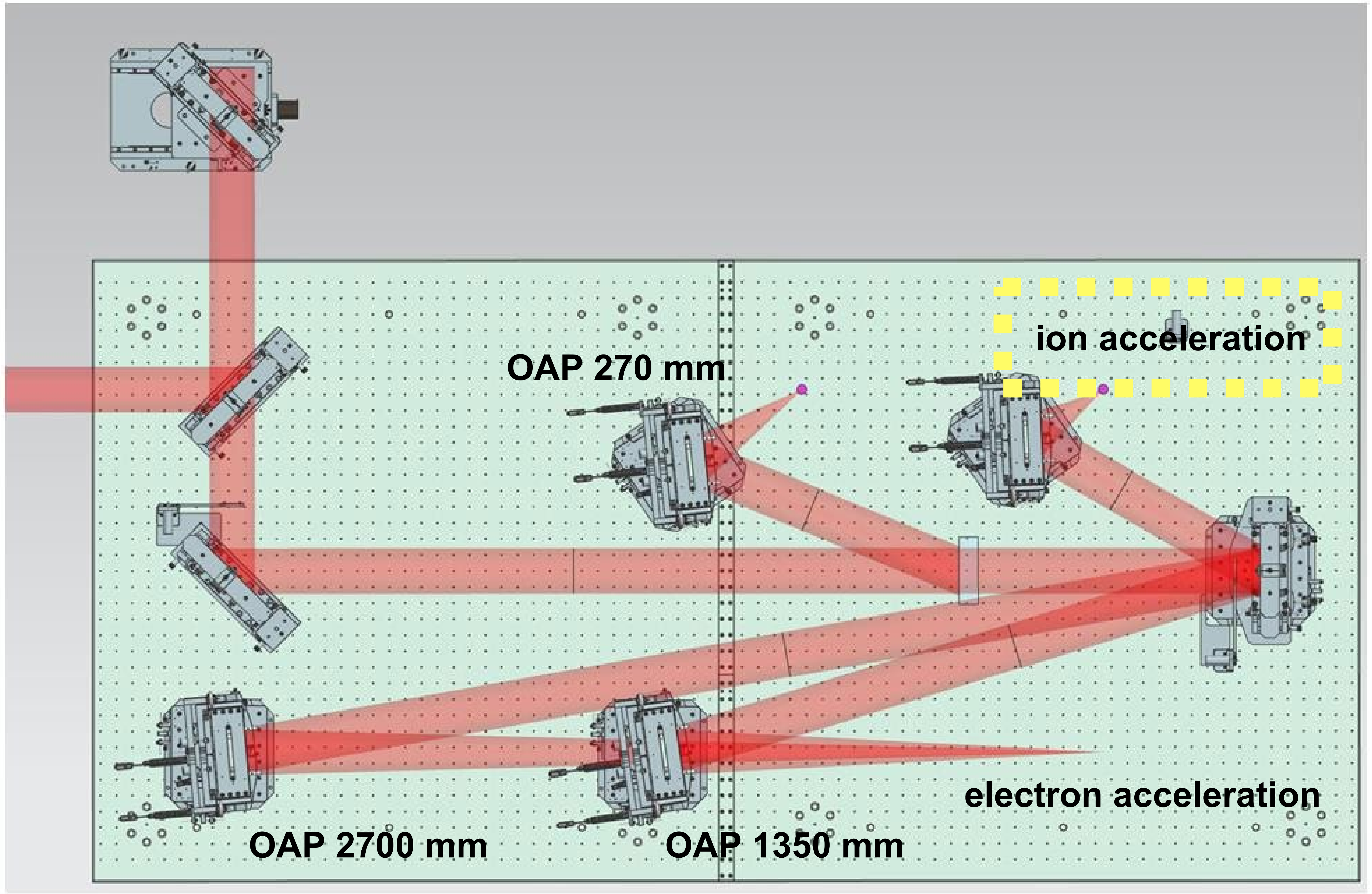
The radiation production interaction chamber

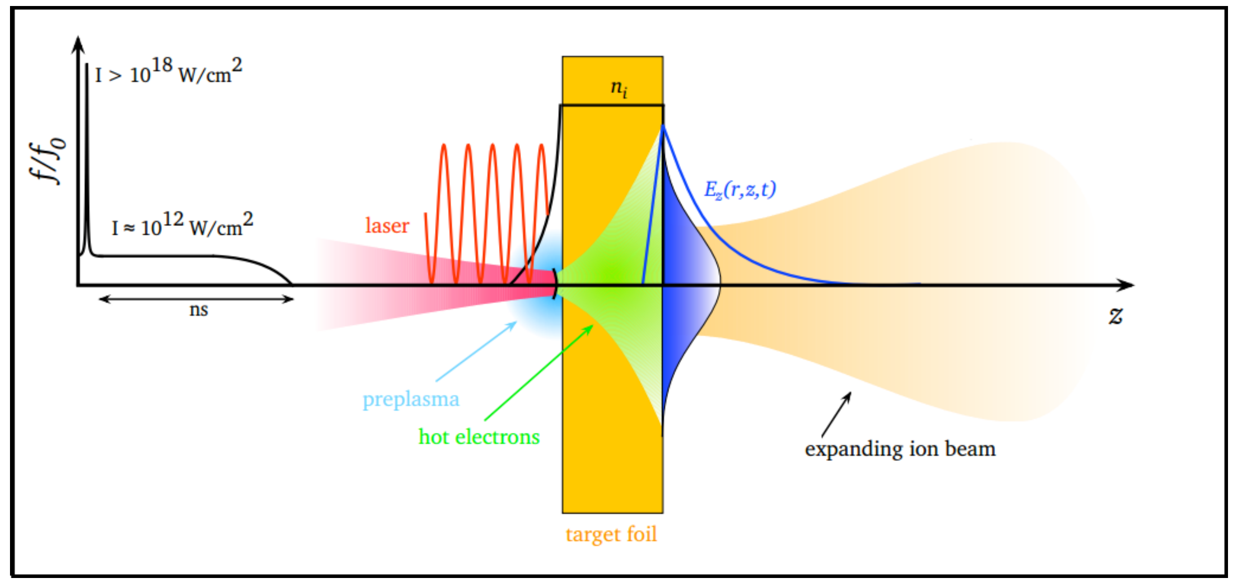




- one interaction chamber for proton/ions and electrons
- a partially reflective mirror (beam splitter)
- three different interaction points in the first phase

Ion acceleration station

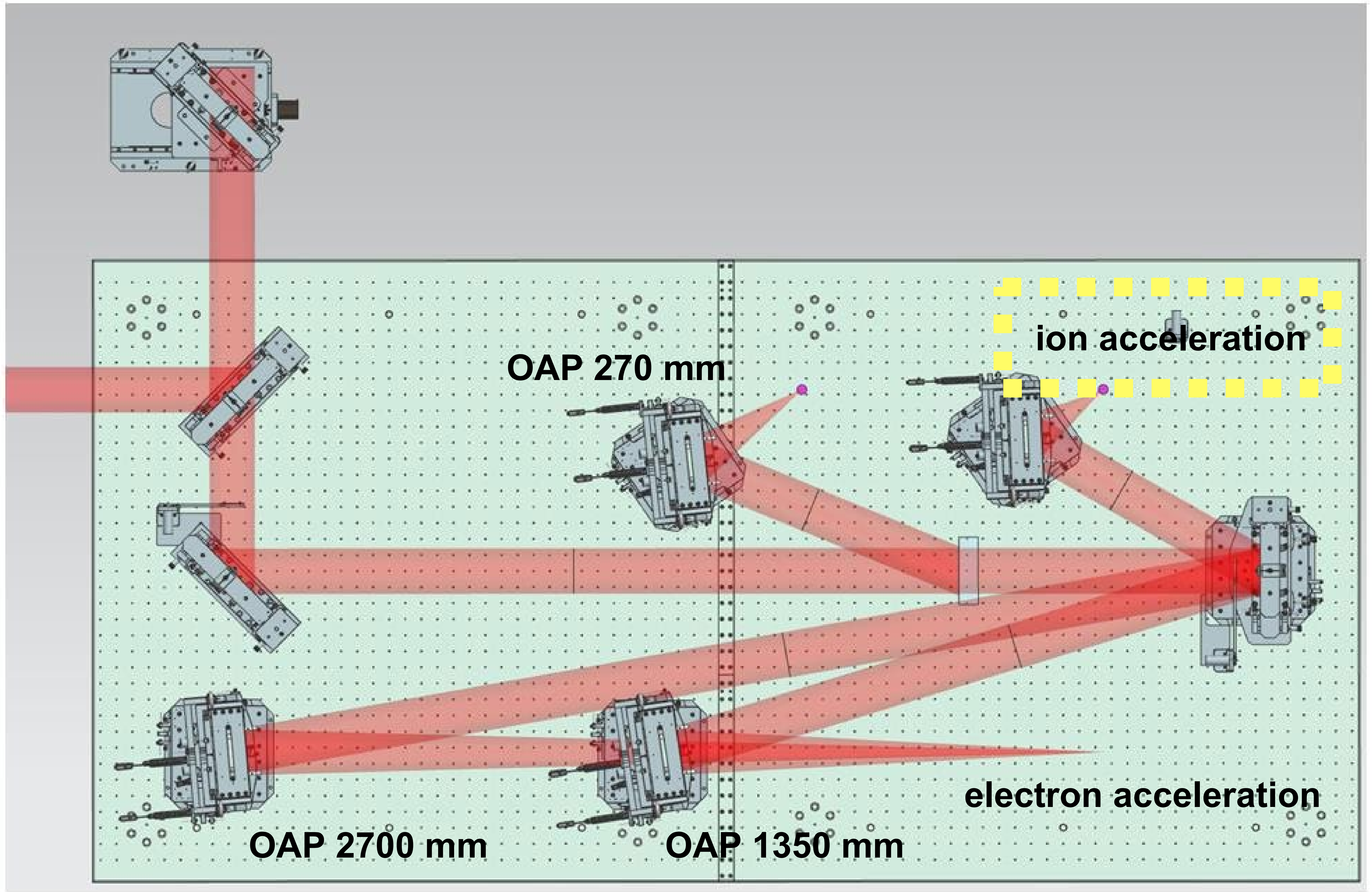




- Up to 900 targets
- Max repetition rate: 3 Hz
- Five degrees of freedom
- XY = 105 mm @10 µm resolution, >20 mm/s
- Z = 25 mm @1 µm resolution, < 10 mm/s
- Tilt and rotation, ±2° @ 20 µrad resolution
- EMP compatible

Micrometric <u>precision</u> and <u>repeatability</u> are guaranteed for the five degrees of freedom

Ion acceleration station



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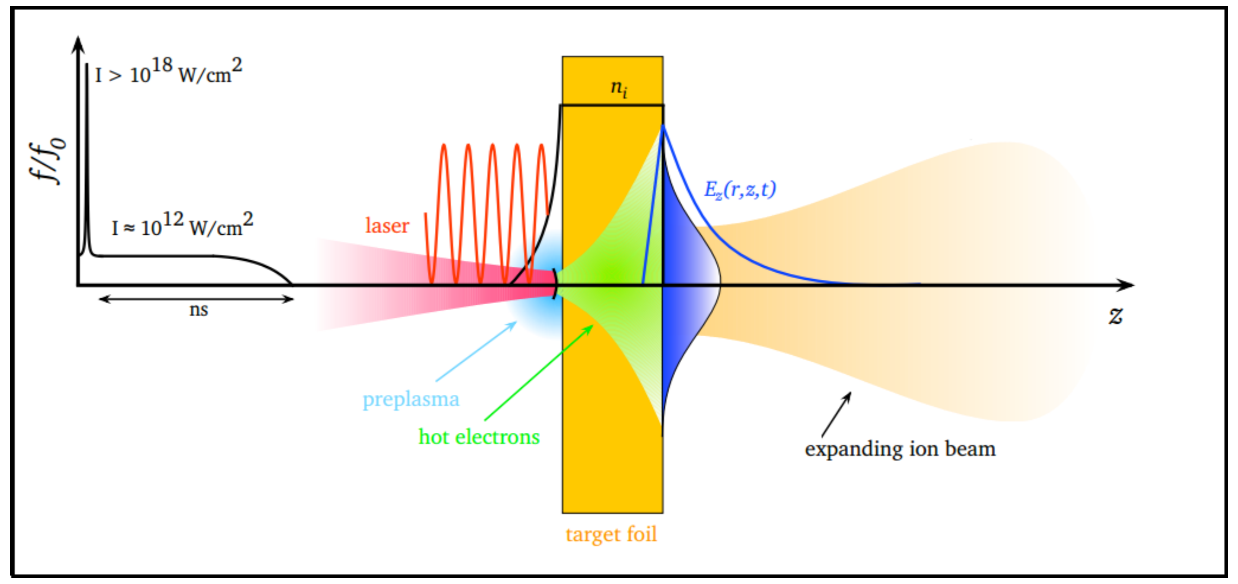
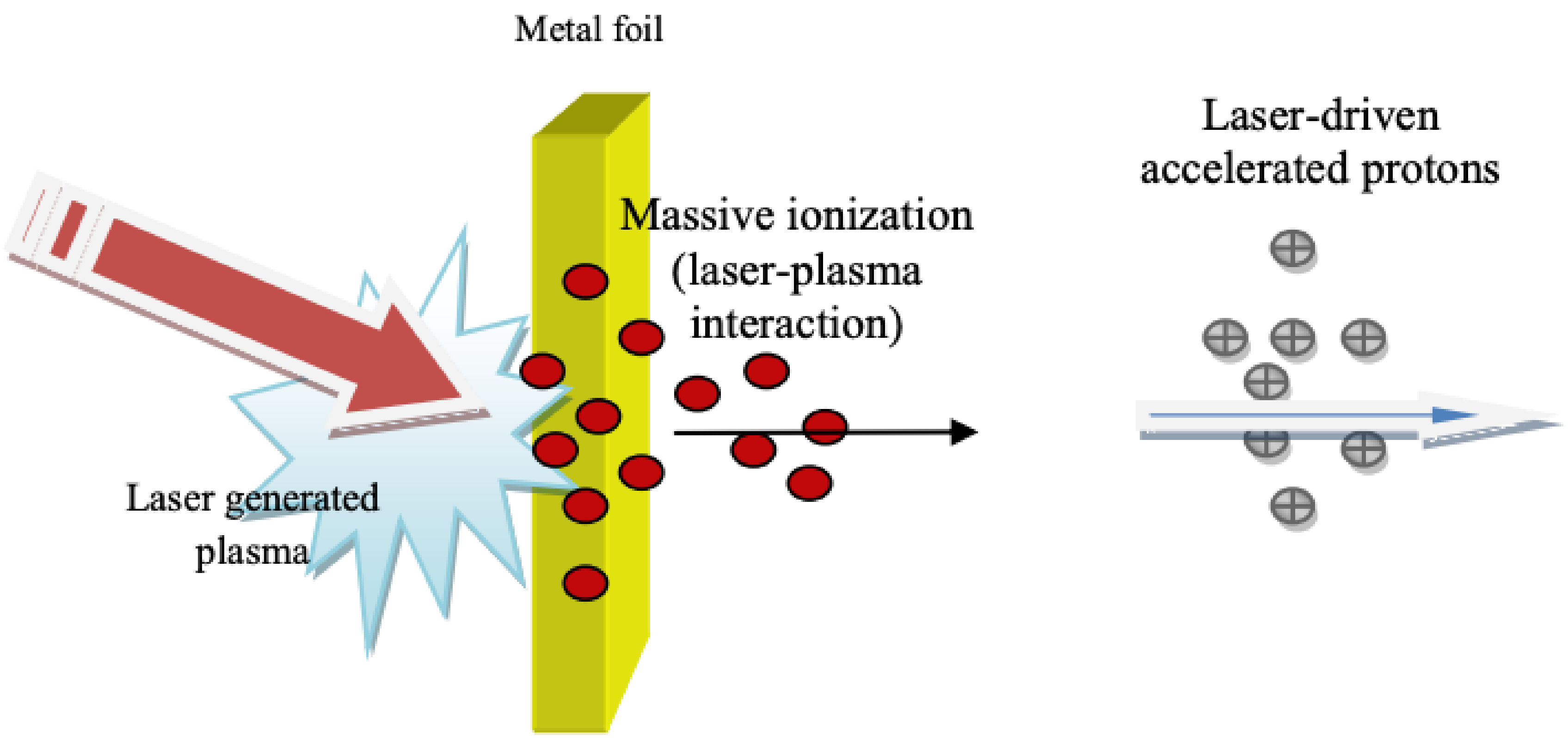
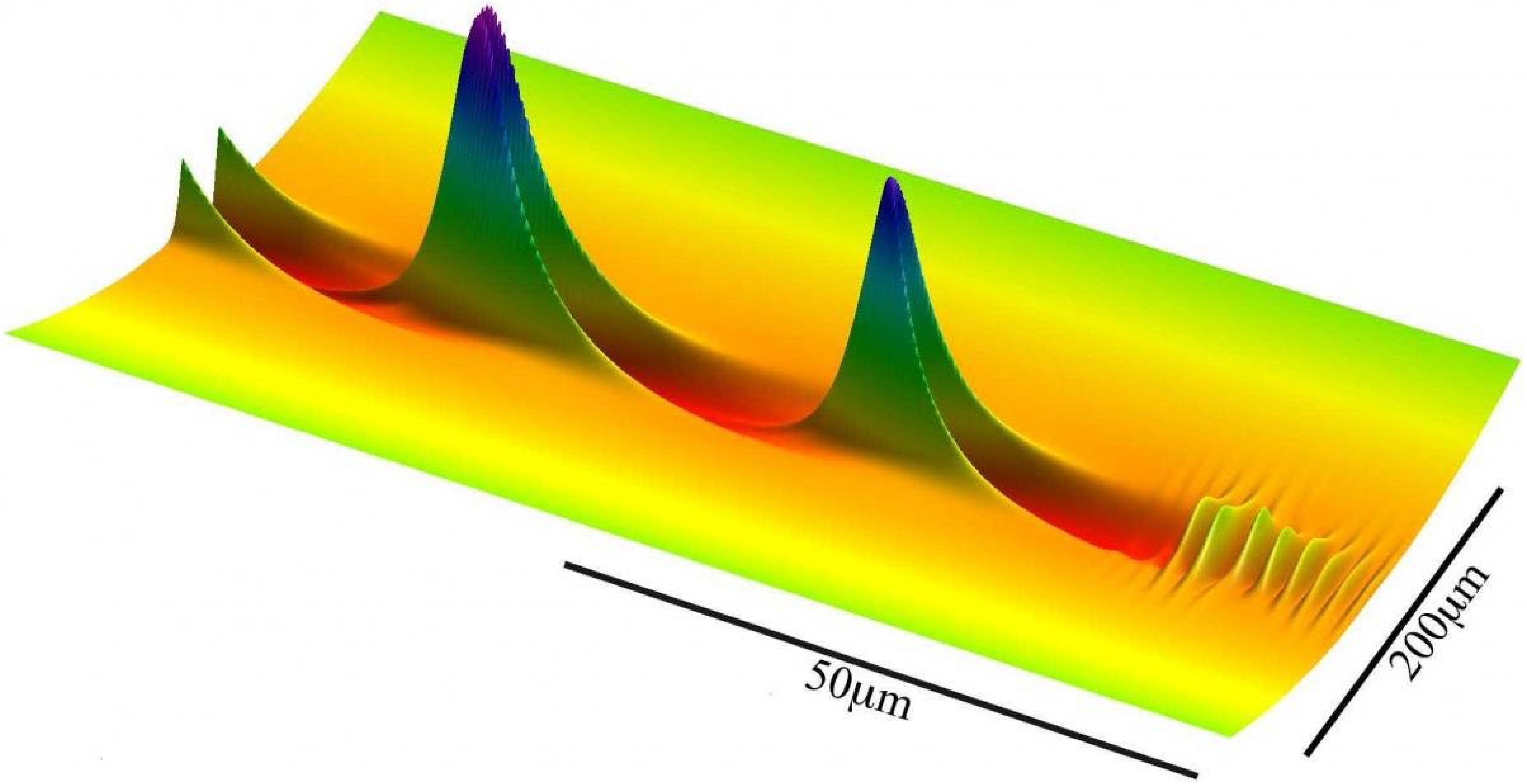


Particles acceleration principles

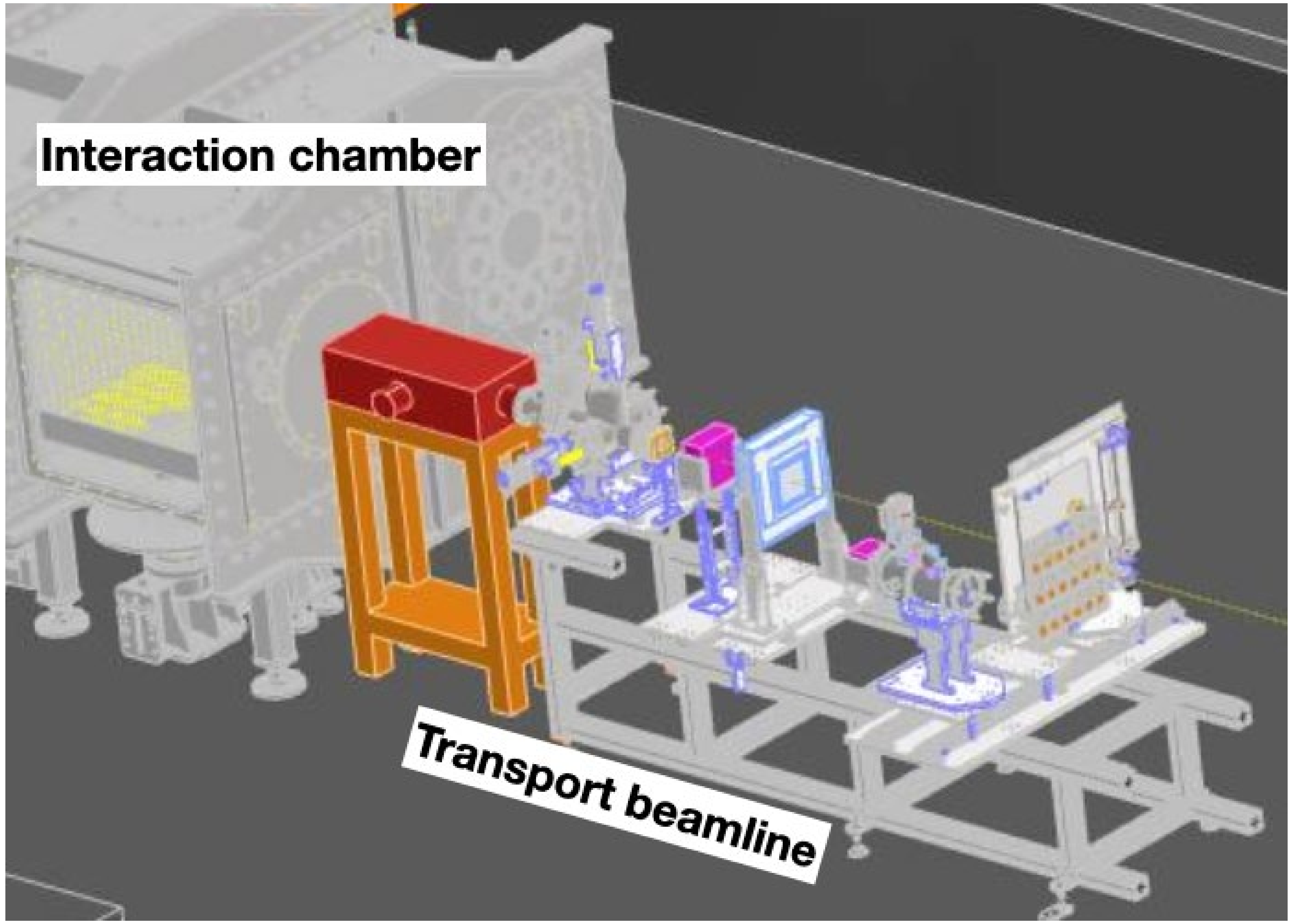


Target Normal Sheath Acceleration (TNSA)



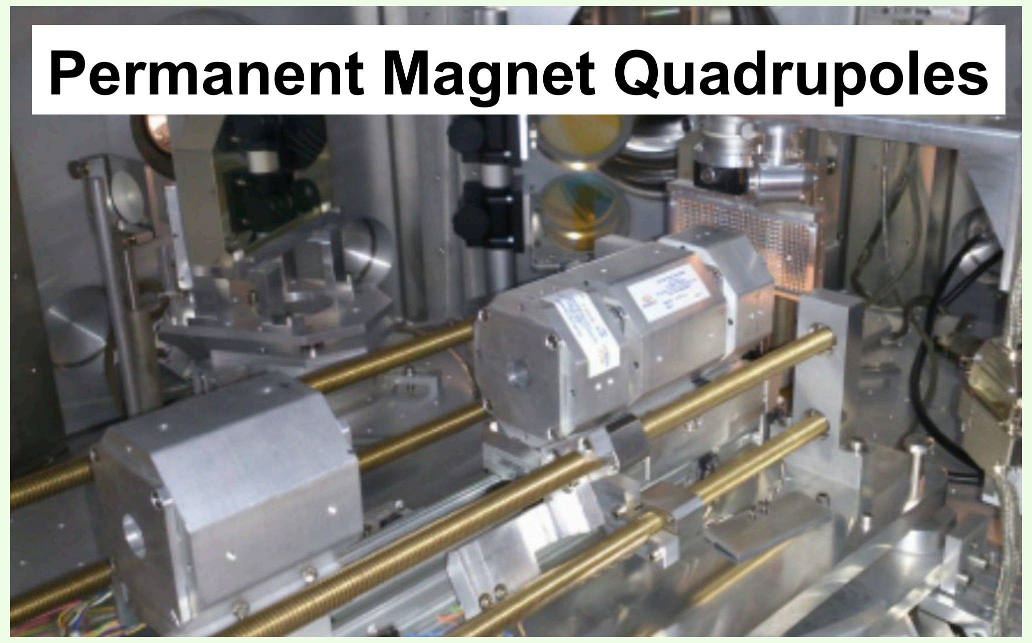
Laser-wakefield acceleration (LWFA)

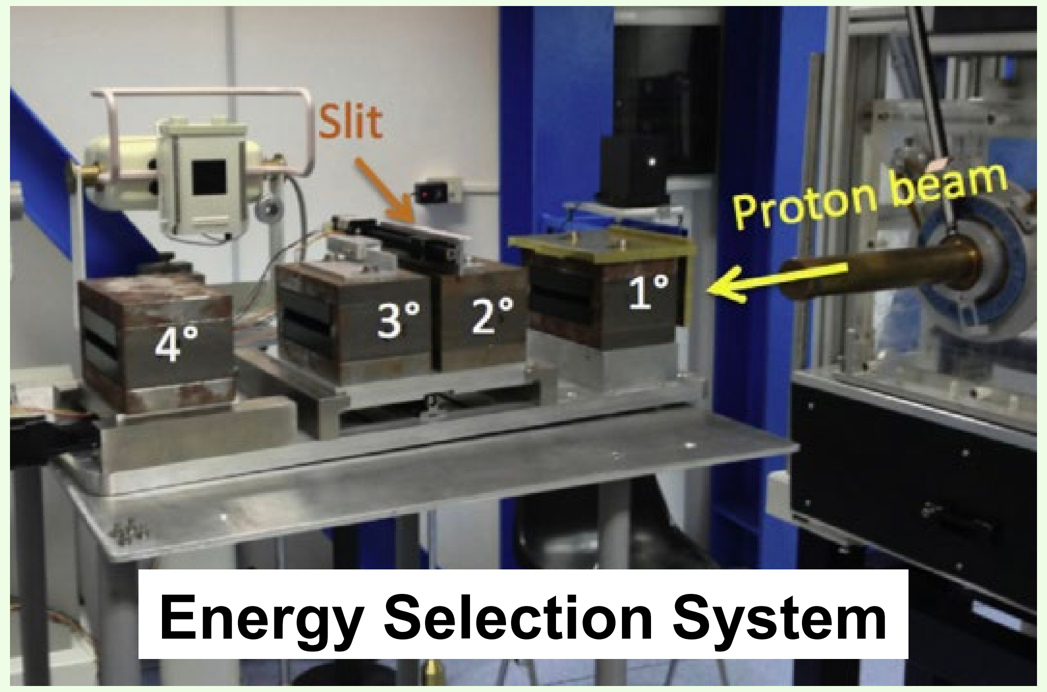
Transport beamline and diagnostic for ion beams



Protons /Ions	Max energy	50 MeV
	Particle per pulse (at 30 MeV)	10^{11} MeV^{-1} sr^{-1}

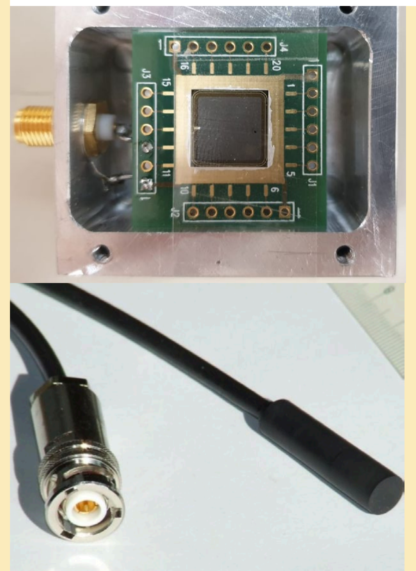
Transport System



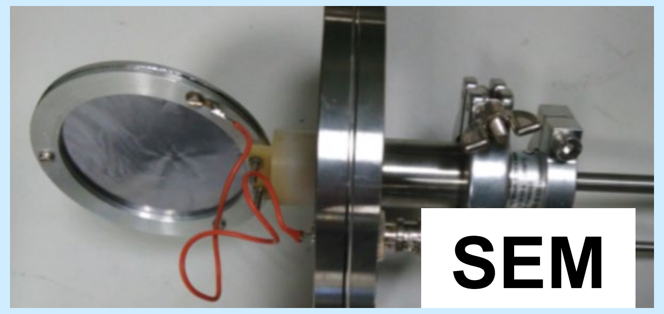


Transport up to 30 MeV with an energy revolution of 5 %

Diagnostic System



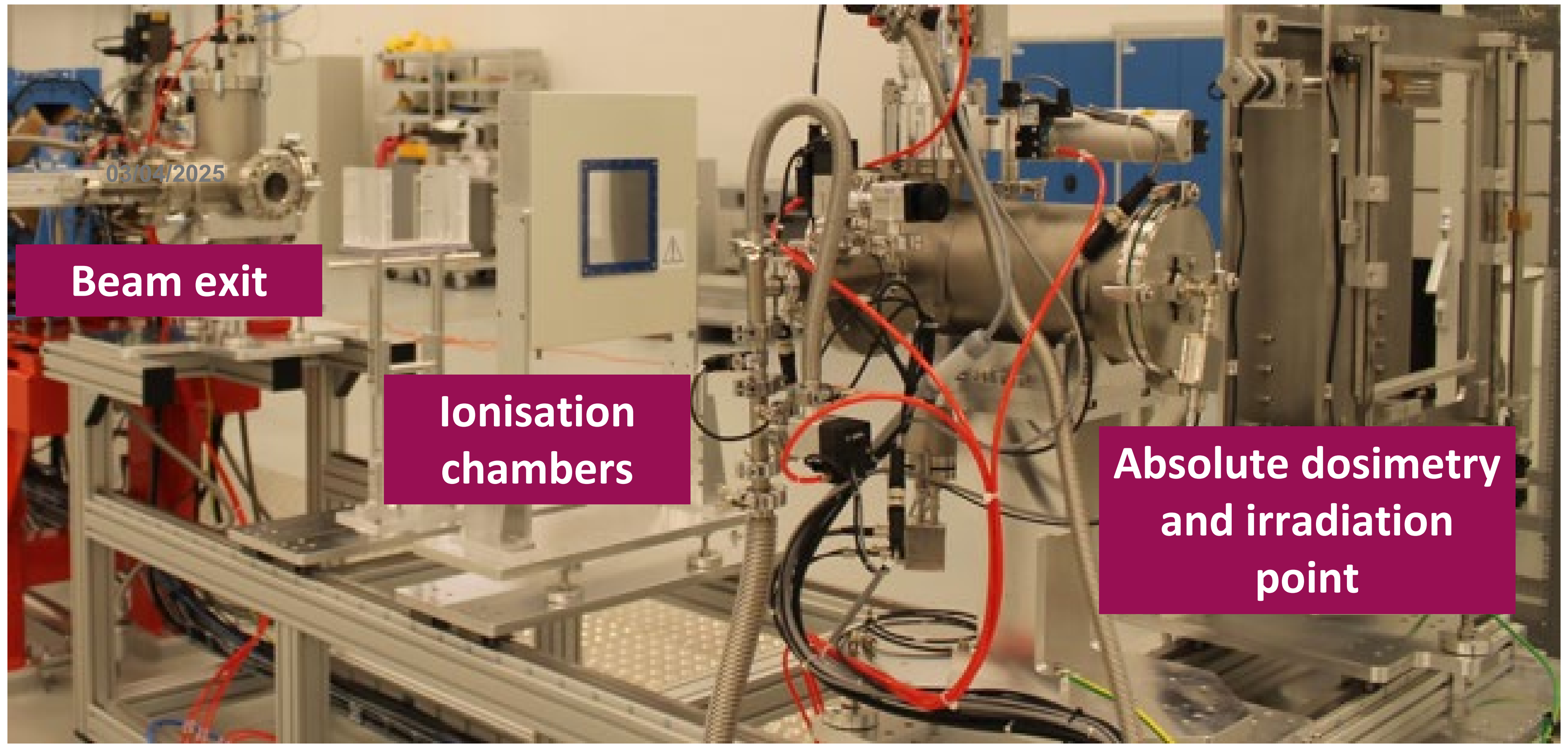
Dosimetric System

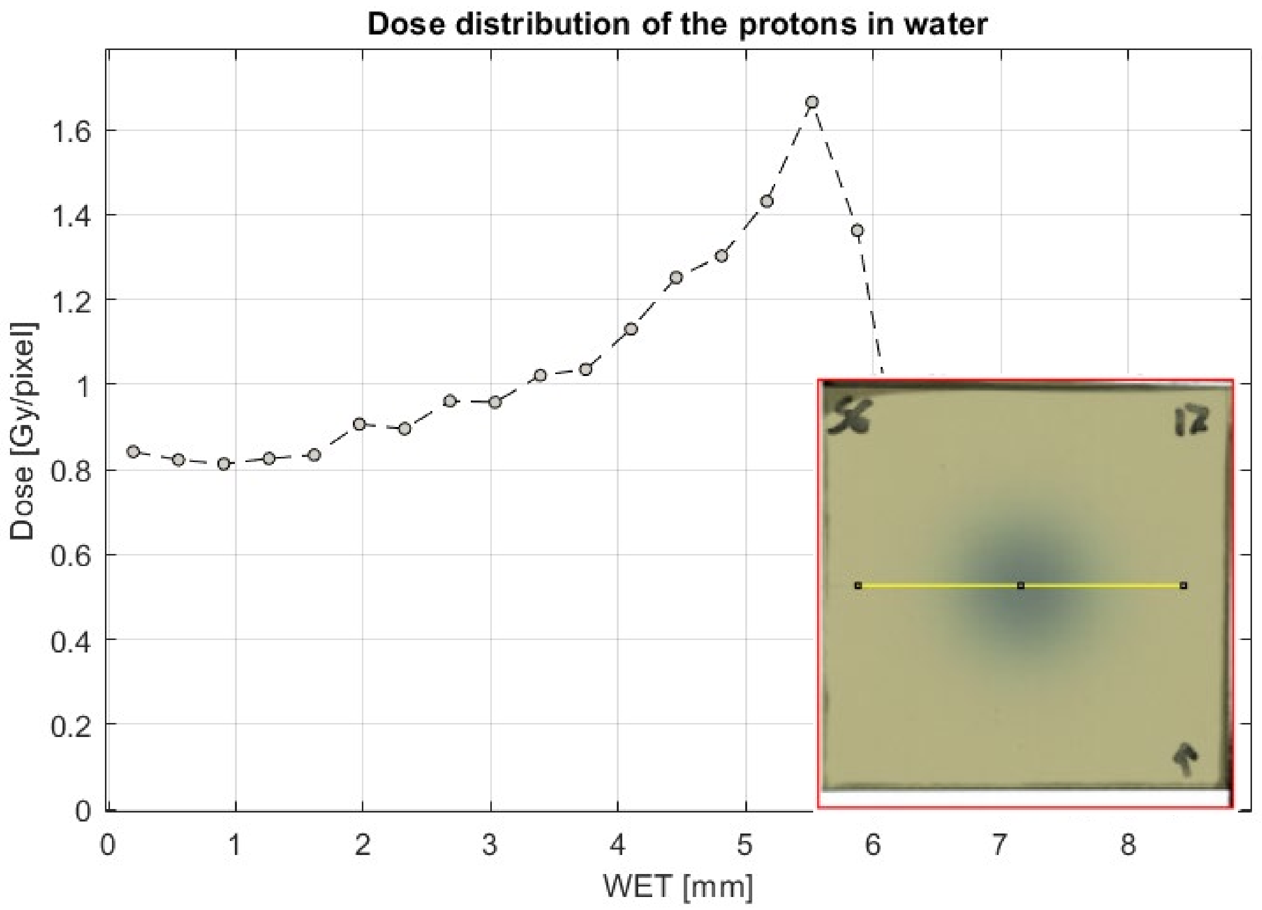


A Thomson Parabola Spectrometer (TPS) is currently under construction

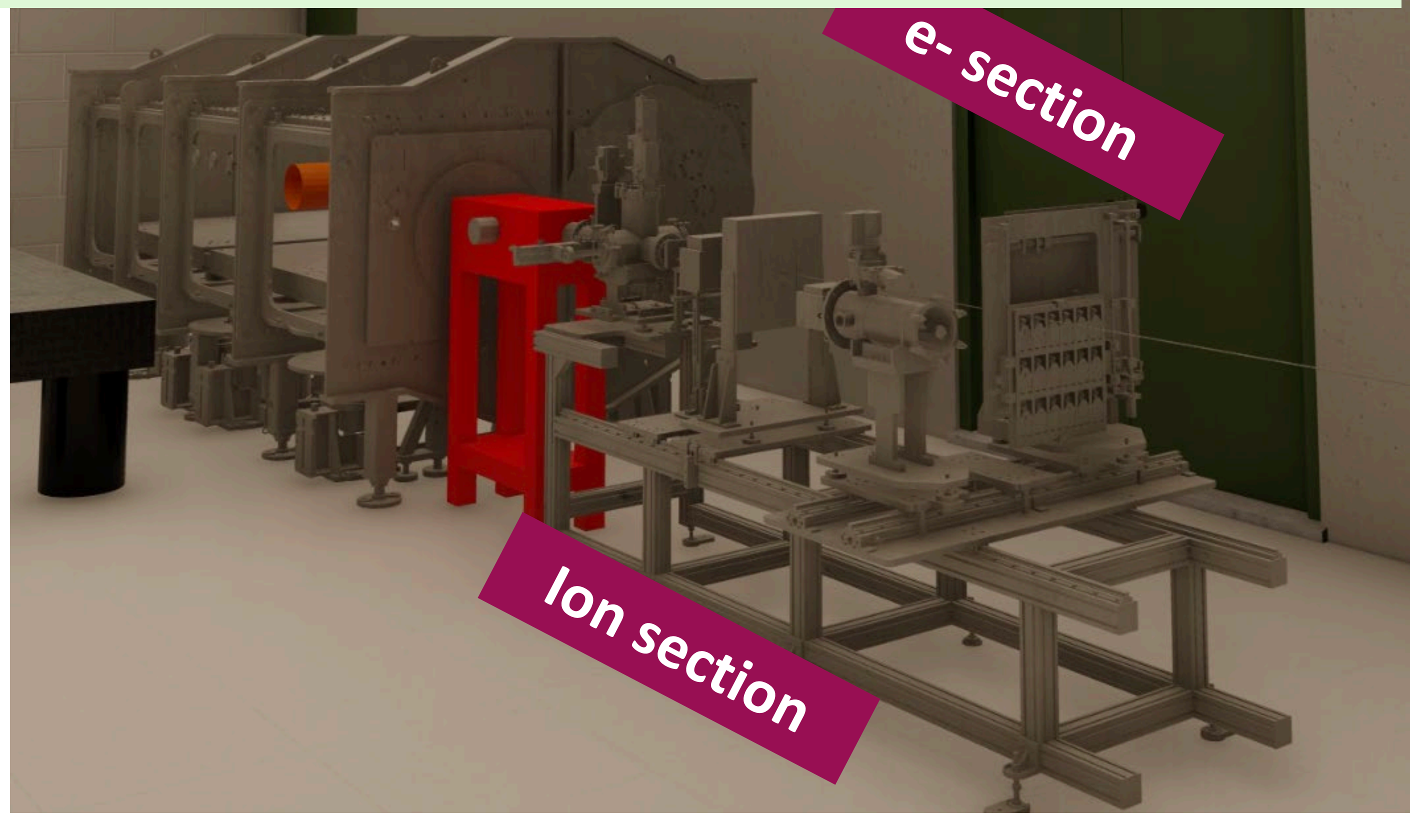
From past to future: 2018 ->

INFN-LNS realised and is commissioning the first Users-open beamline for laser-driven ion beams



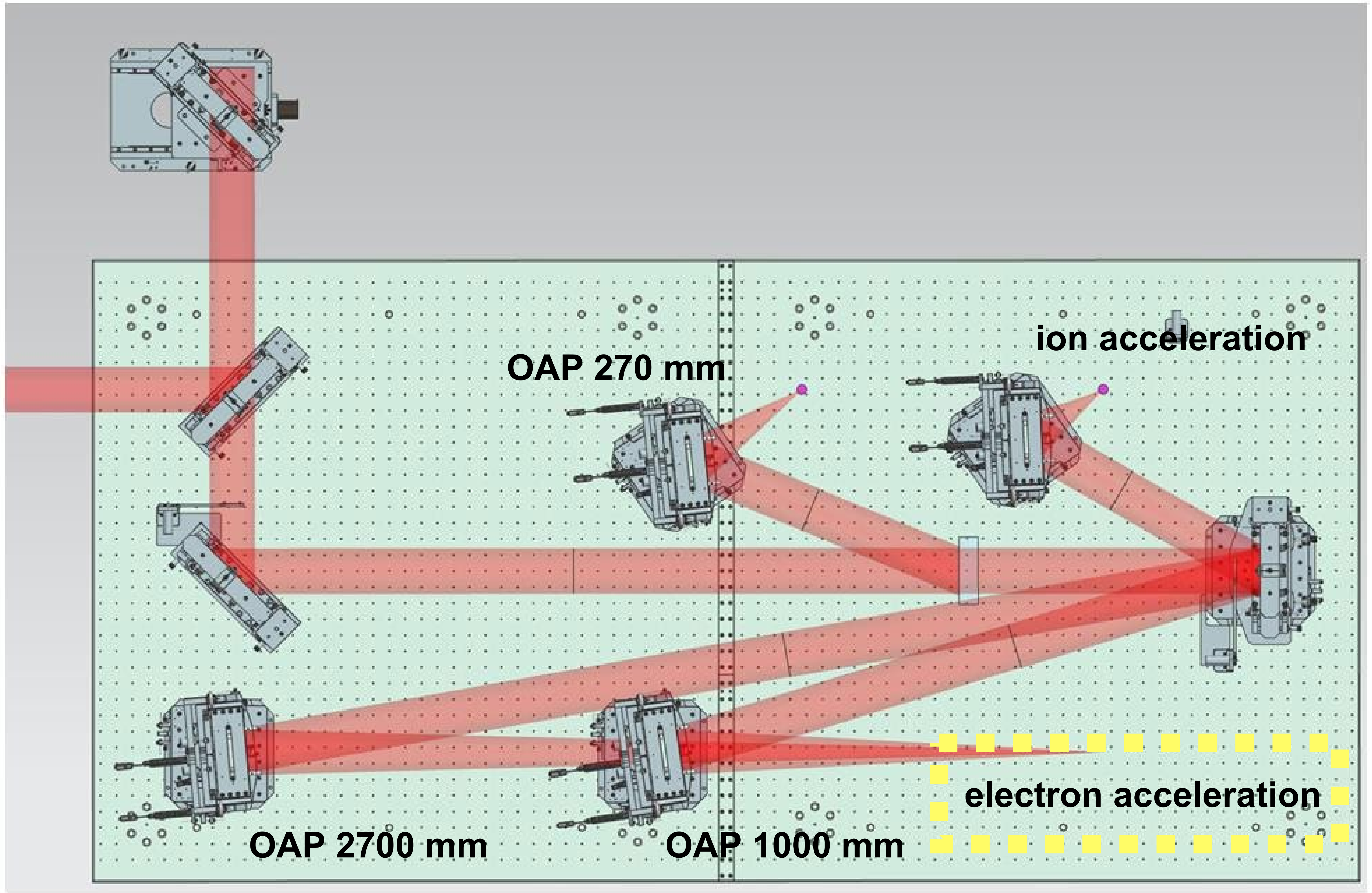


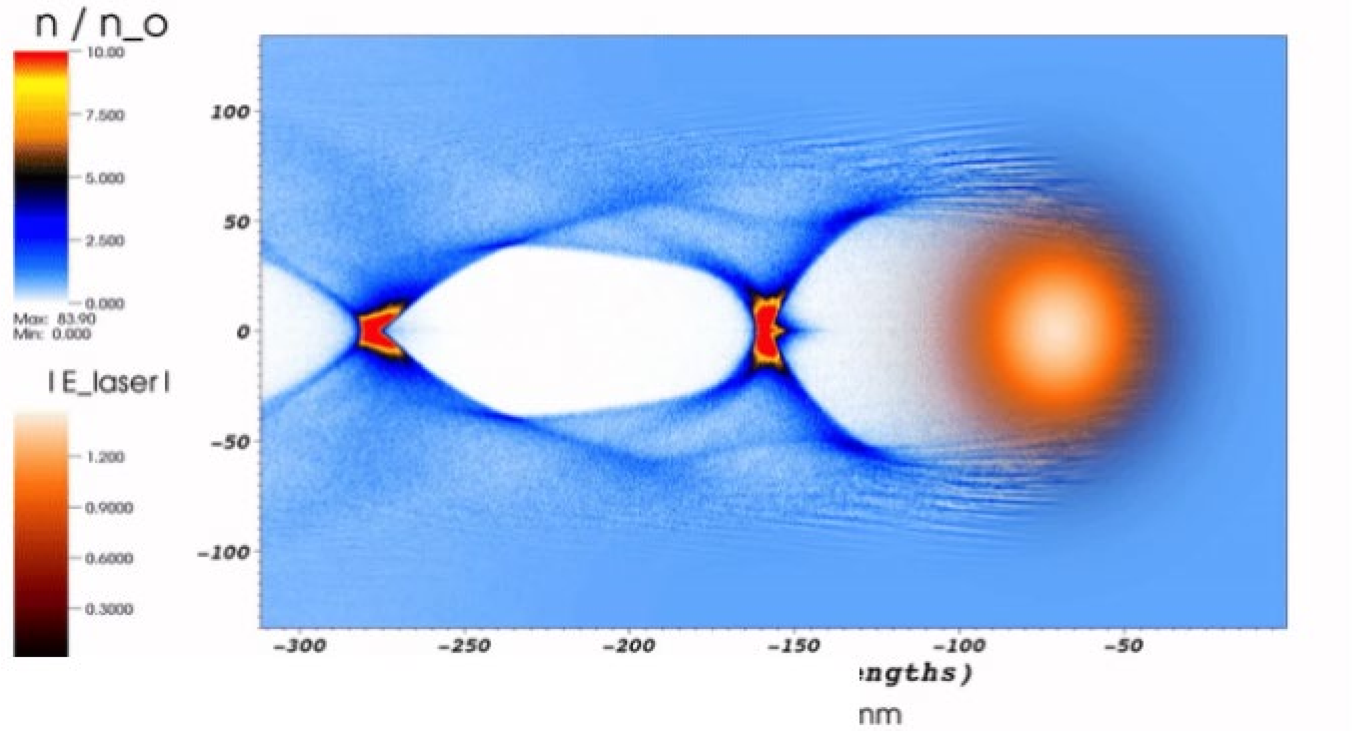
Protons up to 60 MeV; 10^9 pr shot



- *GAP Cirrone et al., Laser Driven User Facilities and Status of I-LUCE at Laboratori Nazionali del Sud of INFN (ITALY) , RAD Conference Proceedings, 2025, (Accepted).*
- *GAP Cirrone et al., Beam Delivery Methods for Laser-Driven Proton Sources, NIMA 2025 (Submitted).*
- *G Petringa, et al., A comprehensive Beamline for Proton and Ion Beams Accelerated via Laser-plasma Interaction: the Approach Implemented at the I-LUCE Facility, RAD Conference Proceedings, 2025 (Accepted).*

Electrons acceleration station

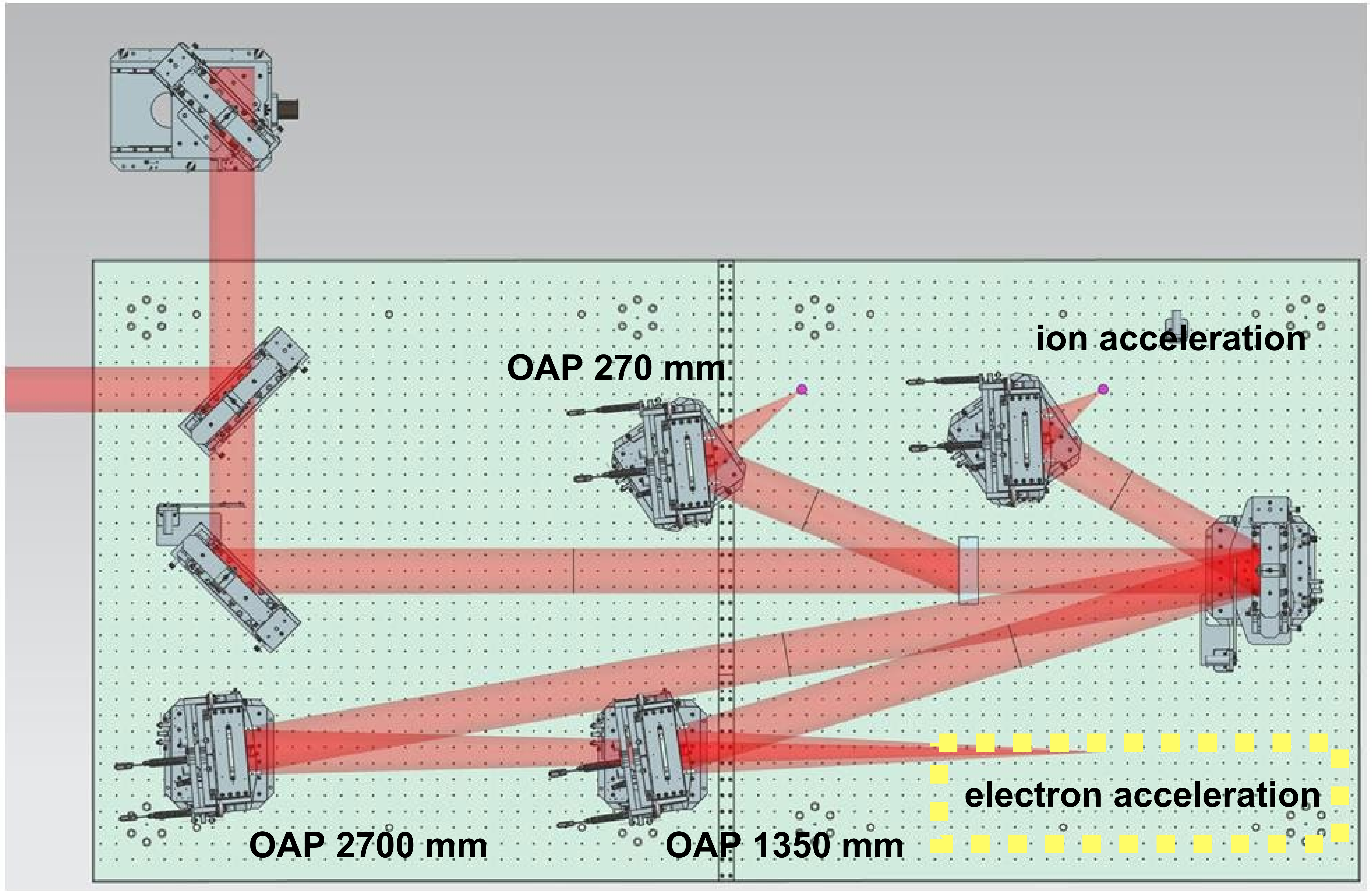


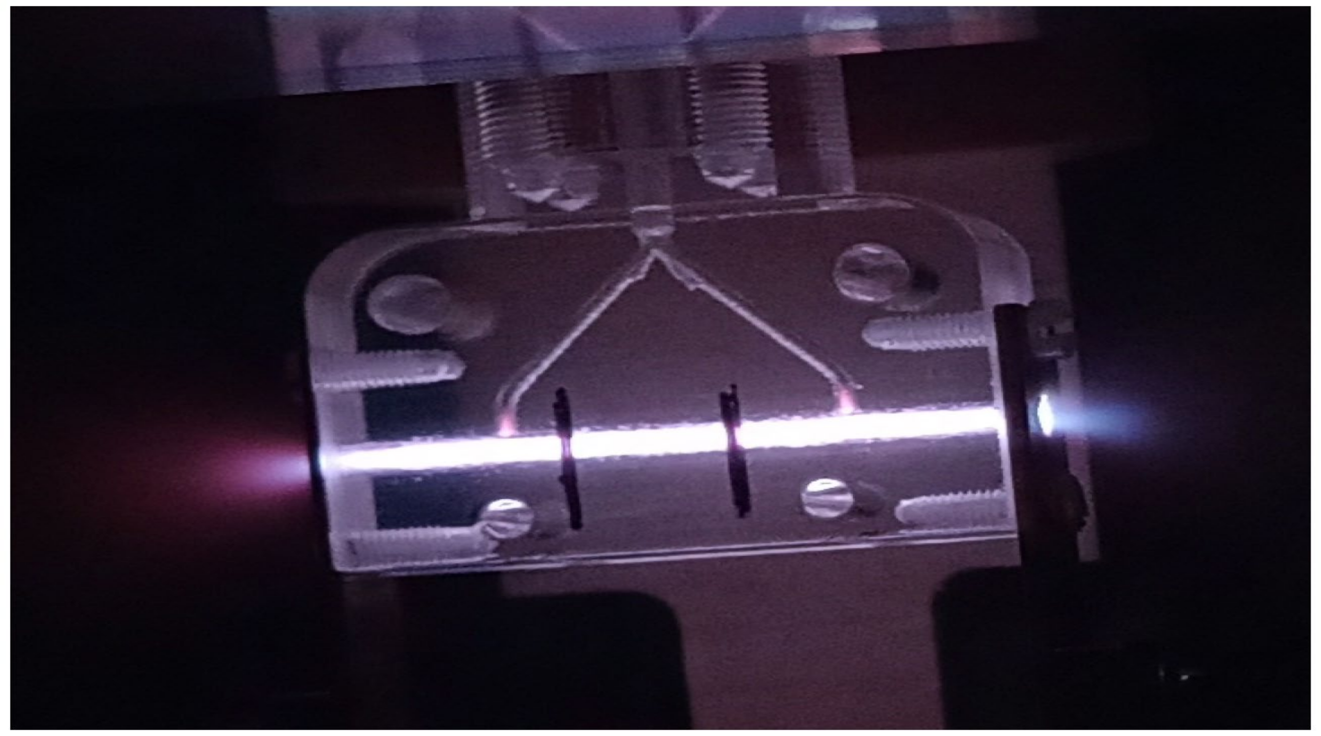


Two different approaches will be adopted, based on gas sources and LWFA mechanism:

- Plasma Discharge Capillary
- Gas jet system

Electrons acceleration station





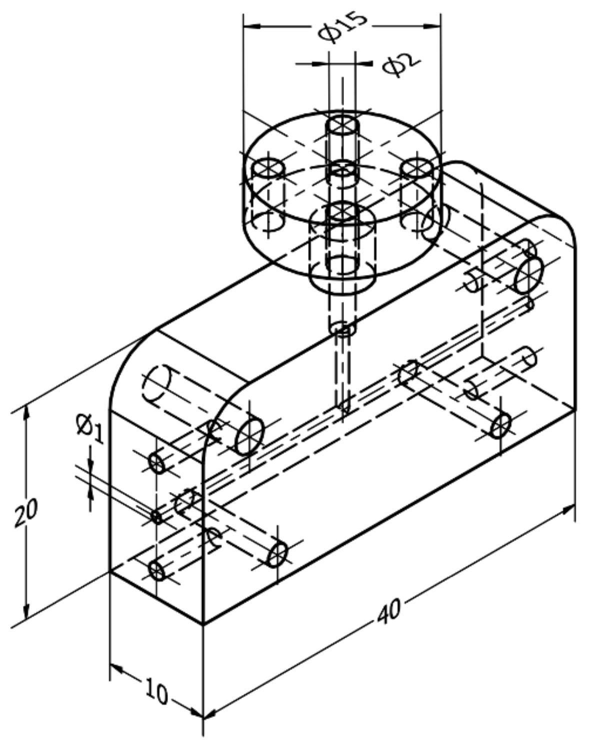
Courtesy: INFN-LNF

Two different approaches will be adopted, based on gas sources and LWFA mechanism:

- Plasma Discharge Capillary

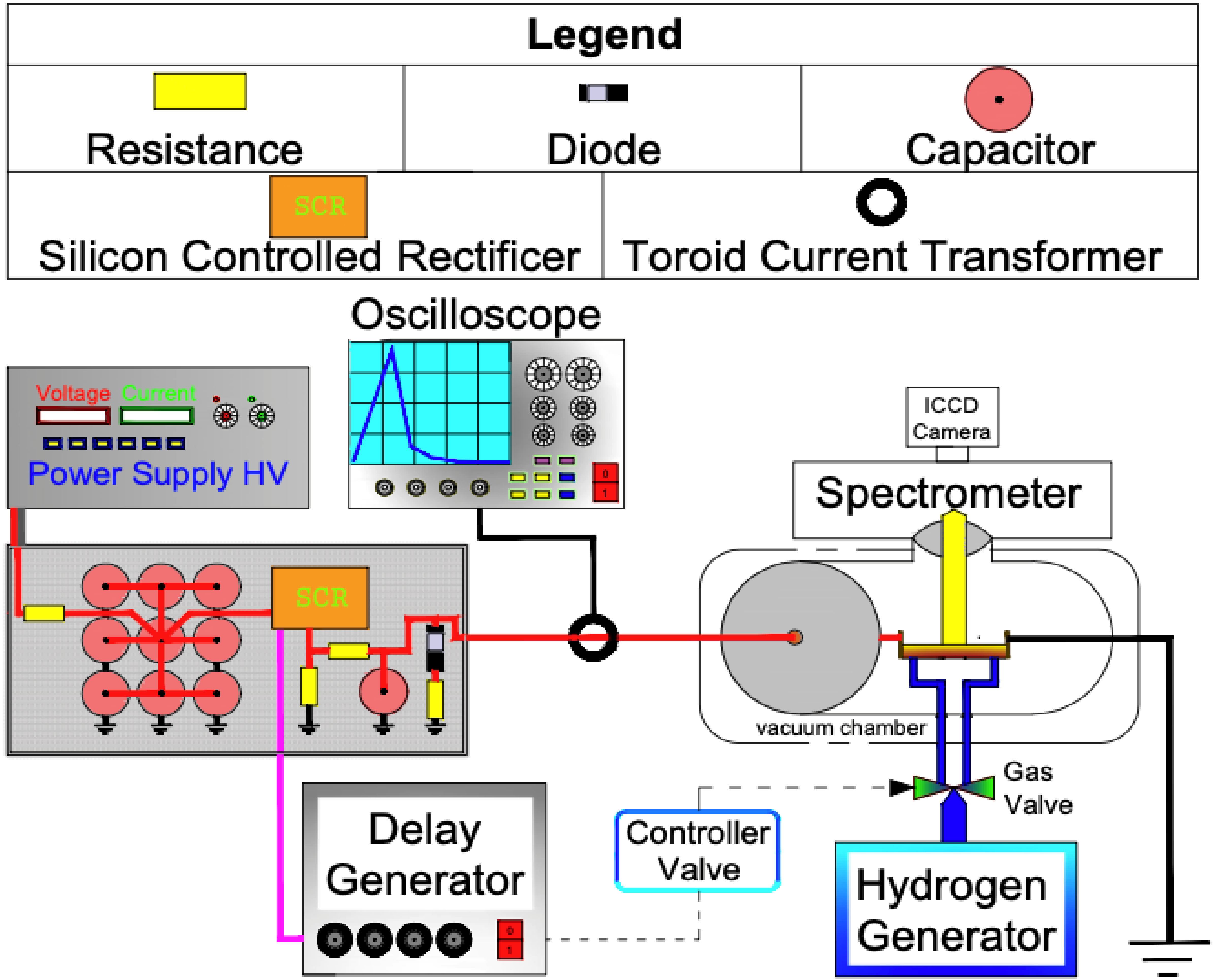
- Gas jet system

- **a small diameter tube**
- **a HV discharge is applied across the gas-filled capillary forming a plasma with a pa-parabolic transverse density profile**
- **the laser pulse is focused into the plasma channel pushing away electrons from the plasma and creating a region of positive**
- **this forms a strong electrical longitudinal field (10-100 GV/m)**
- **the electrons are finally accelerated to high energies over just few centimeters**



Electrons	Max energy	3 GeV
	Particles per pulse	10^9

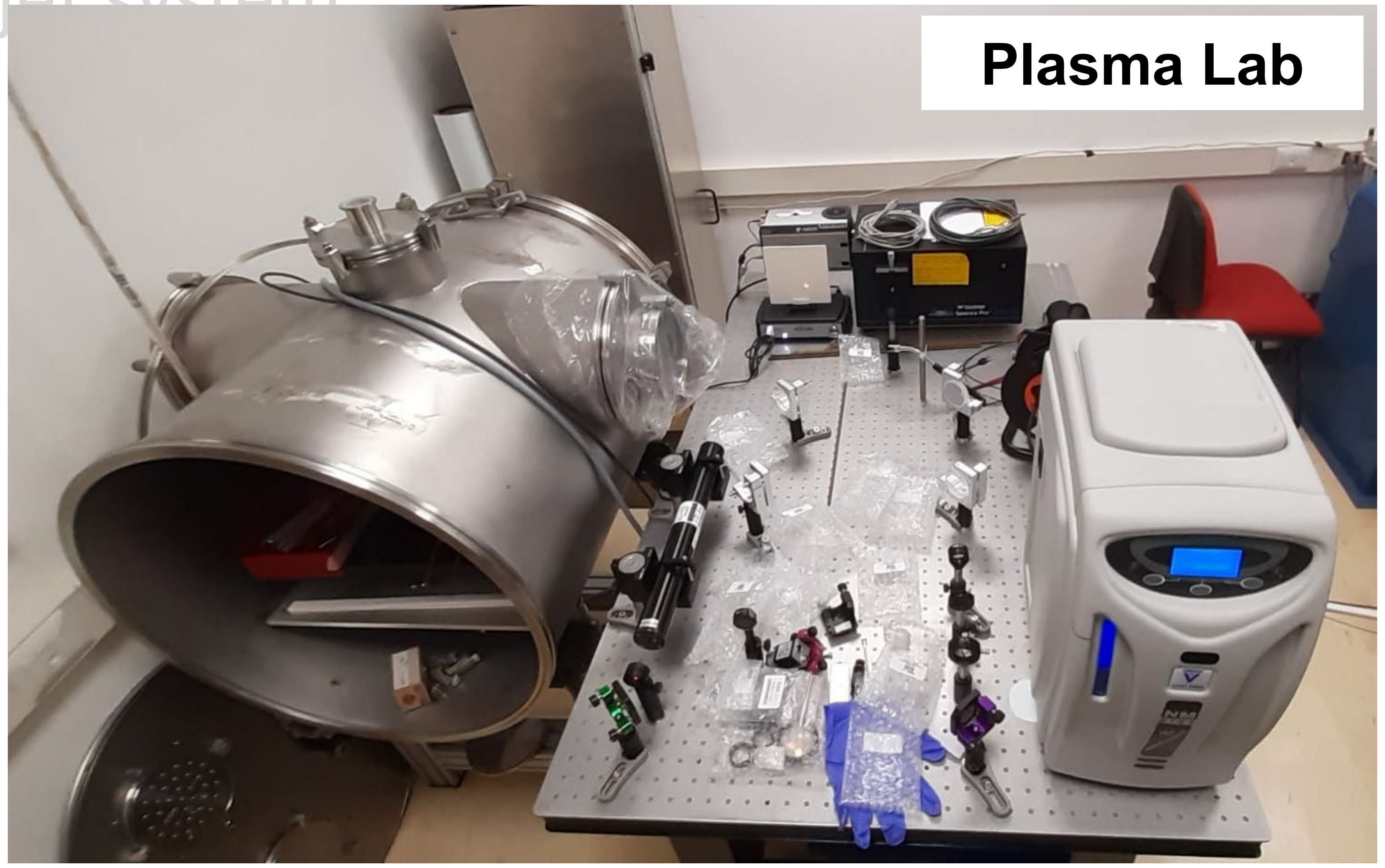
Electrons acceleration station



Two different approaches will be adopted, based on gas sources and LWFA mechanism:

ouse

- Plasma Discharge Capillary (INFN-LNS in-house development)
- Gas jet system



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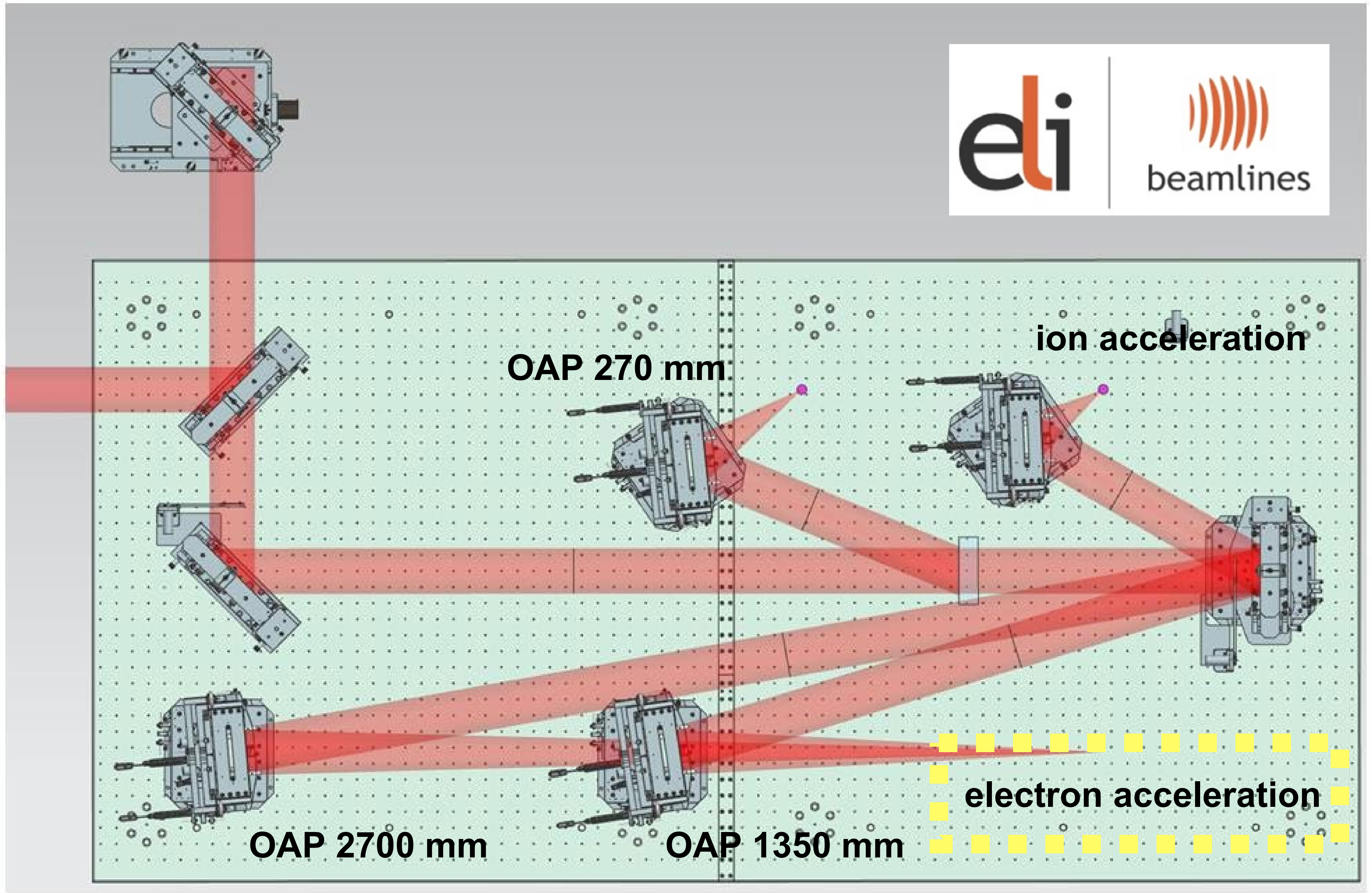
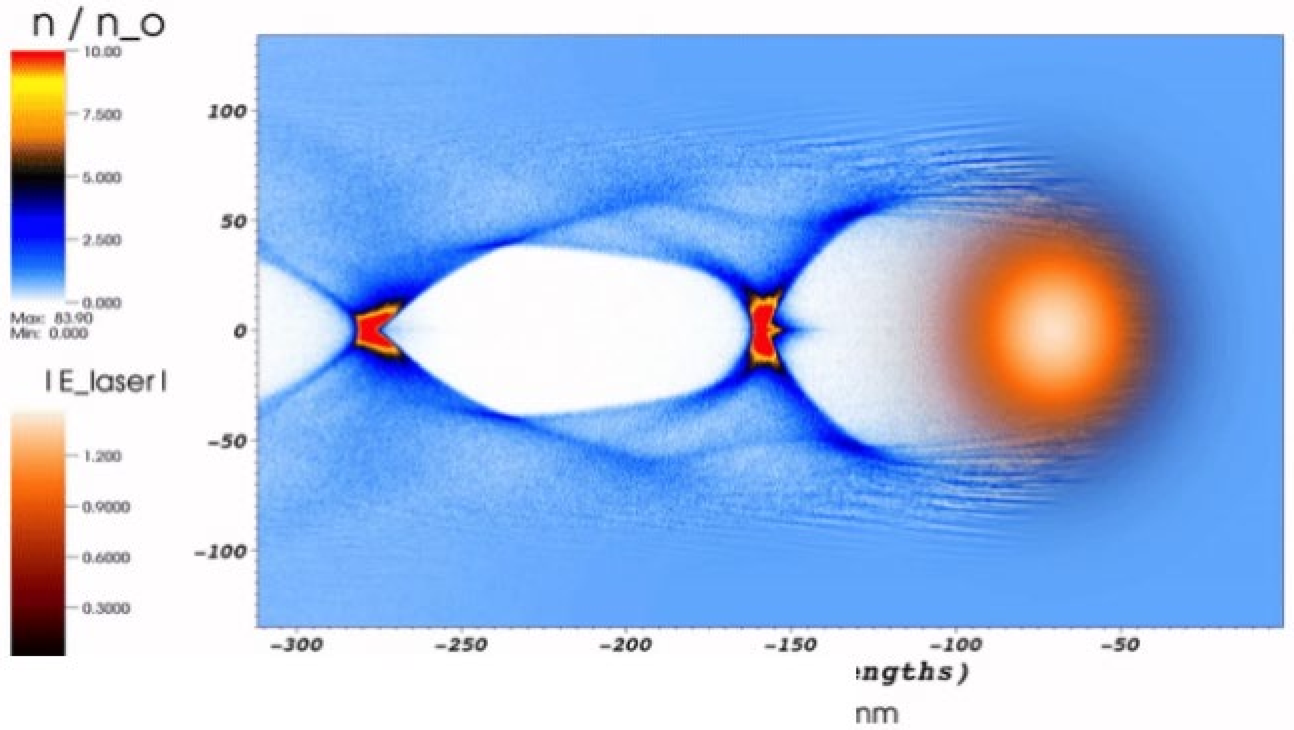
Electrons acceleration station





Two different approaches will be adopted, based on gas sources and LWFA mechanism:

- Plasma Discharge Capillary

- Gas jet system

- supersonic gas-jet injection into a vacuum chamber using a special nozzle
- the gas, usually He or a mix of He and N with a carefully controlled density, serves as the target that will form the plasma
- the high-intensity and ultra-short laser pul-se is focused directly onto the gas-jet, thus stripping electrons from the gas and crea-ting the plasma
- the electrical longitudinal field accelerates electrons to high energies

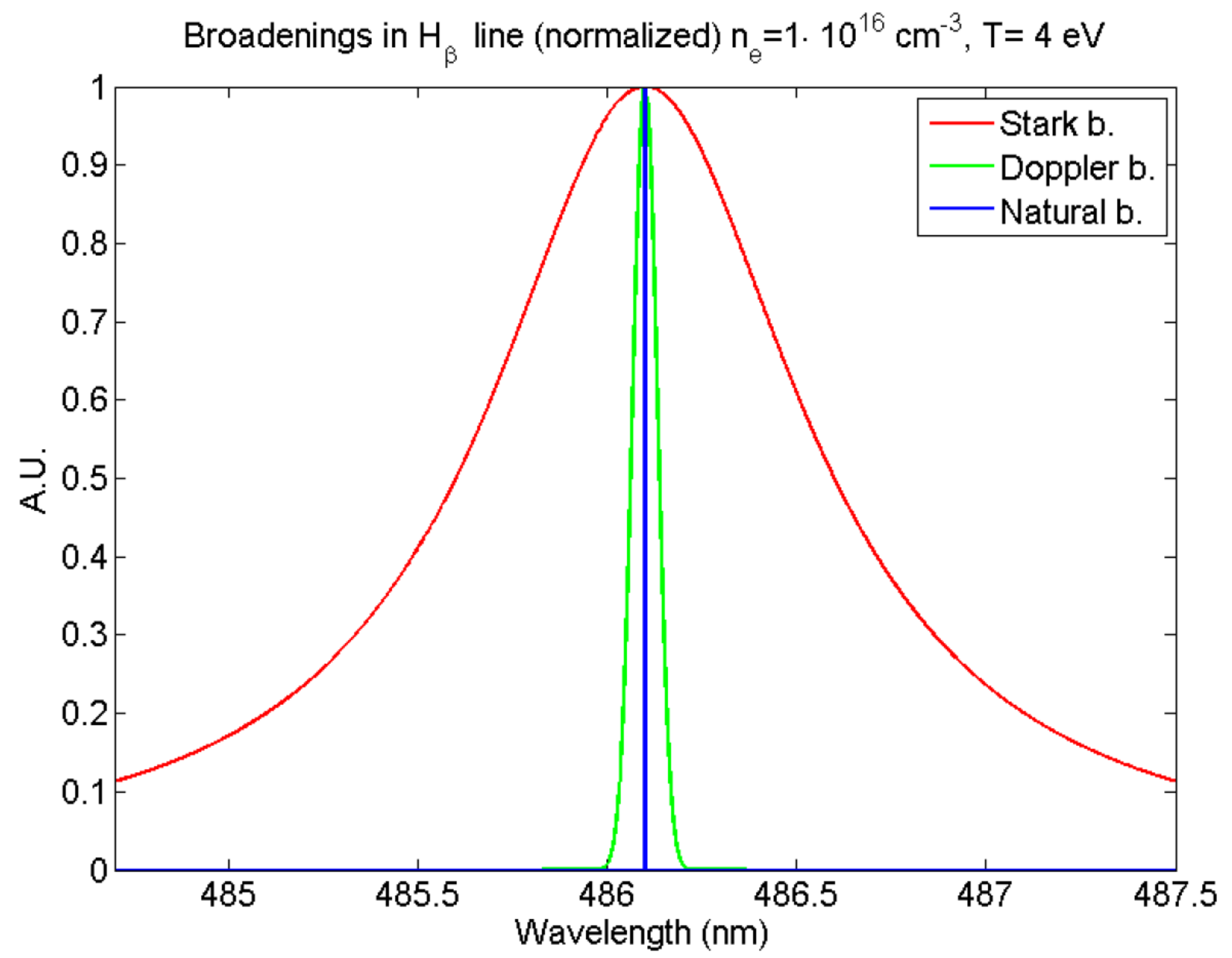
SourceLAB

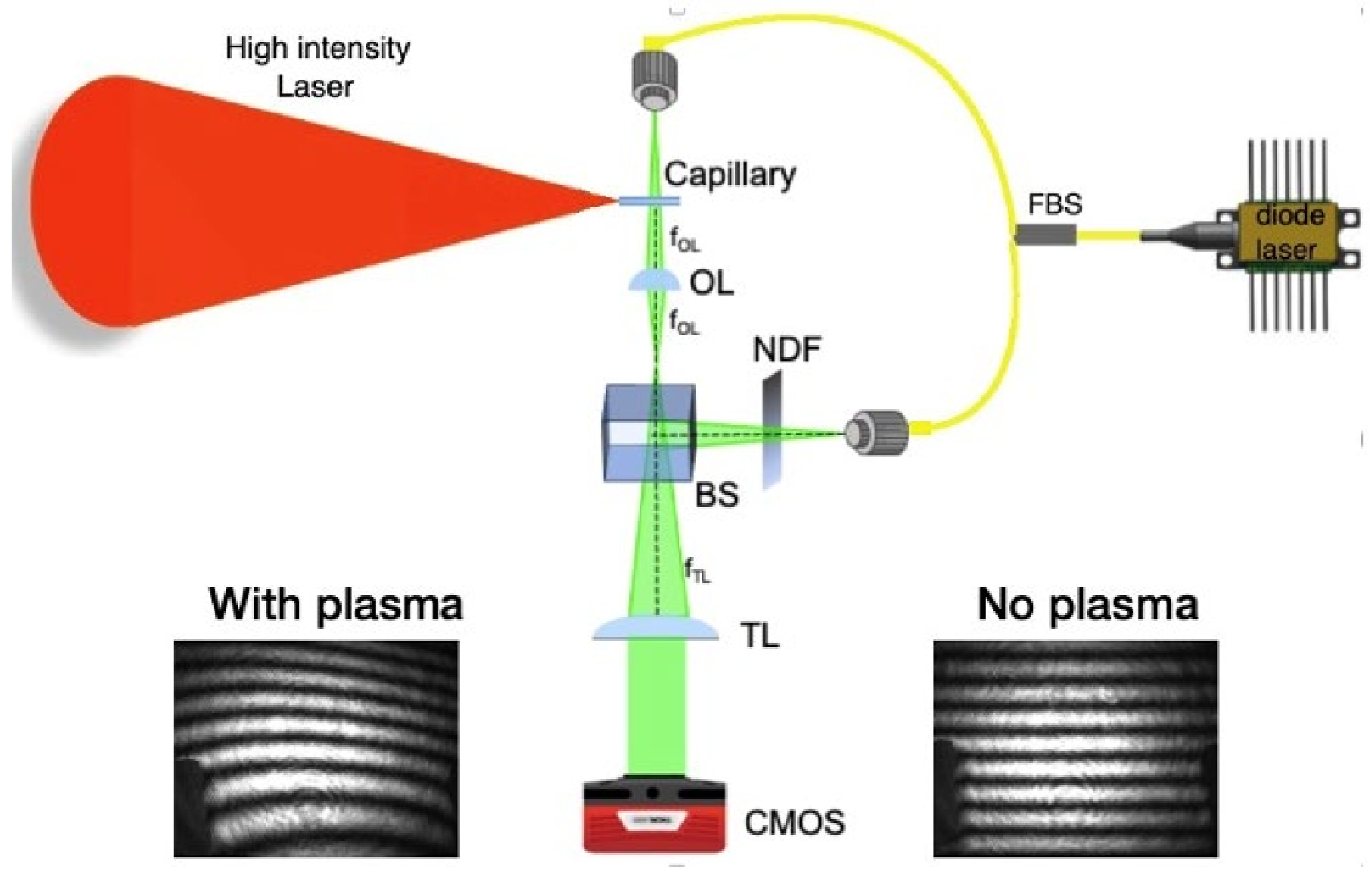
Electrons	Max energy	3 GeV
	Particles per pulse	10^9

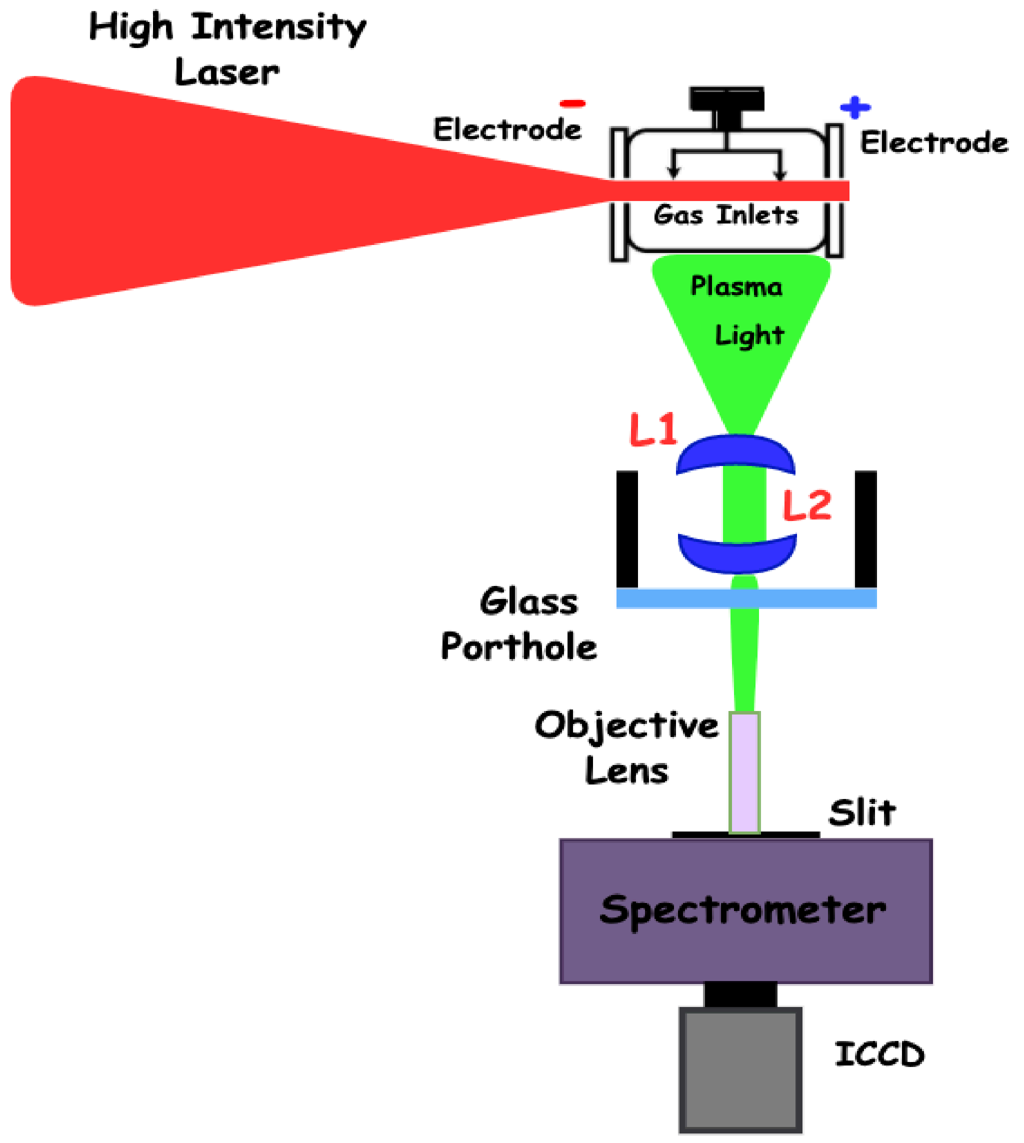
Electrons acceleration station

Diagnostic Systems:

- **Optical Emission Spectroscopy**
- **Interferometry (Mach-Zehnder)**
- **Wavefront sensors**
- **Near and far field beam spatial profiles**



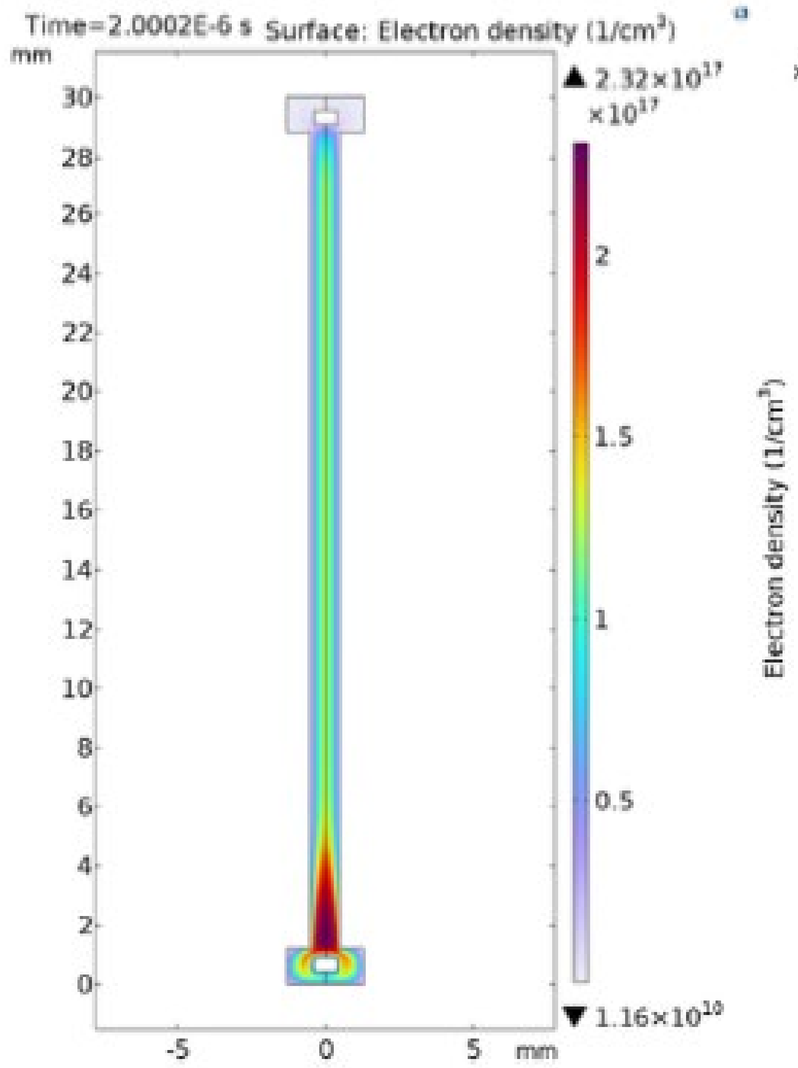


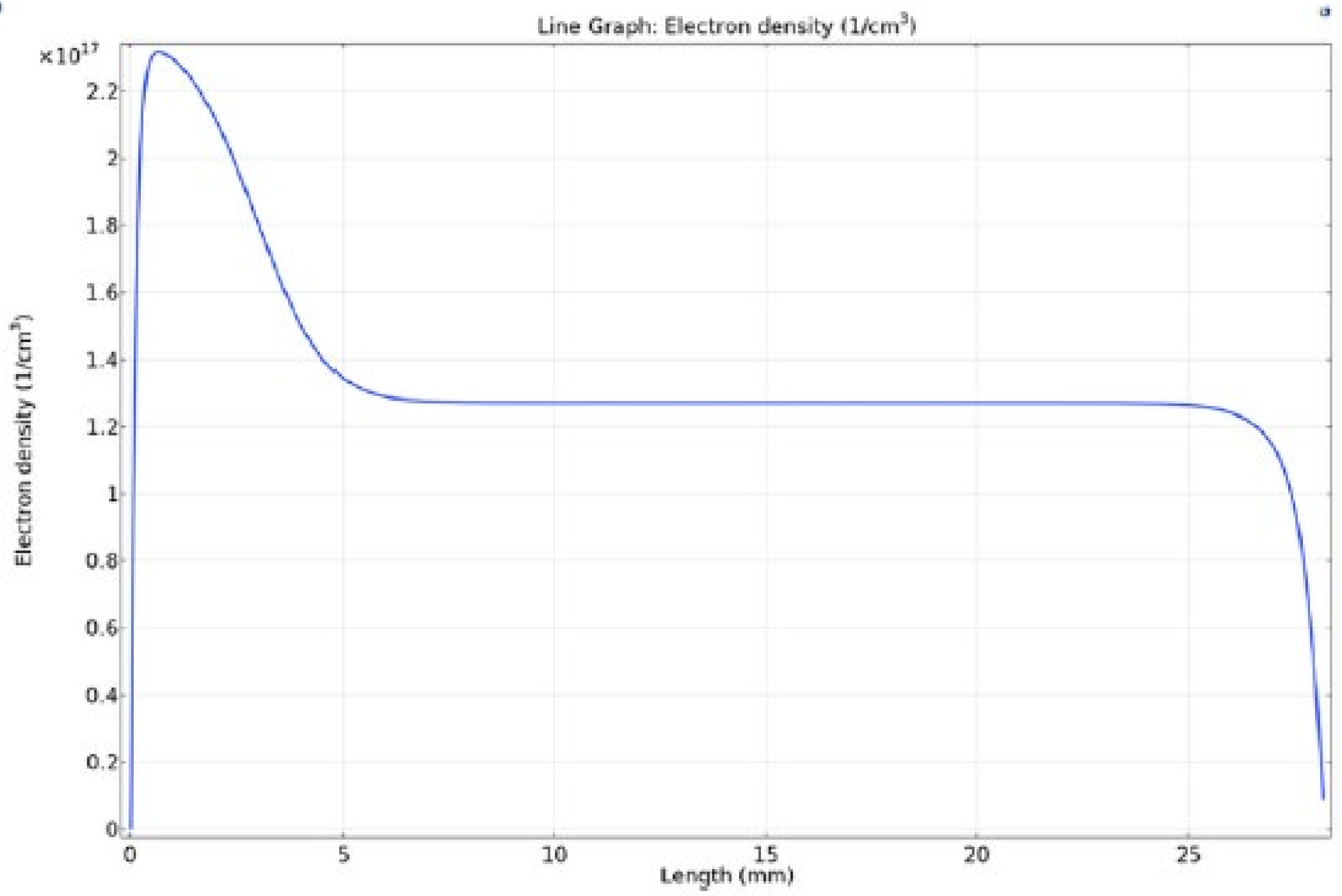


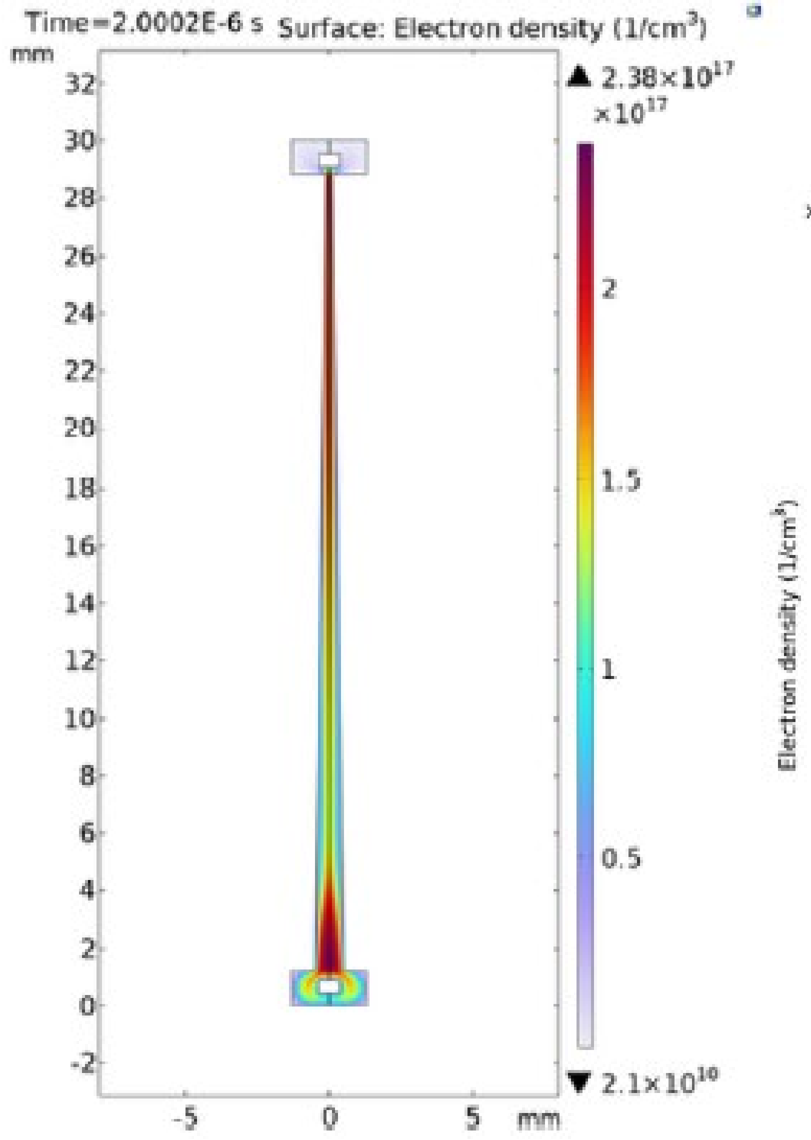
Mach Zehnder Interferometer

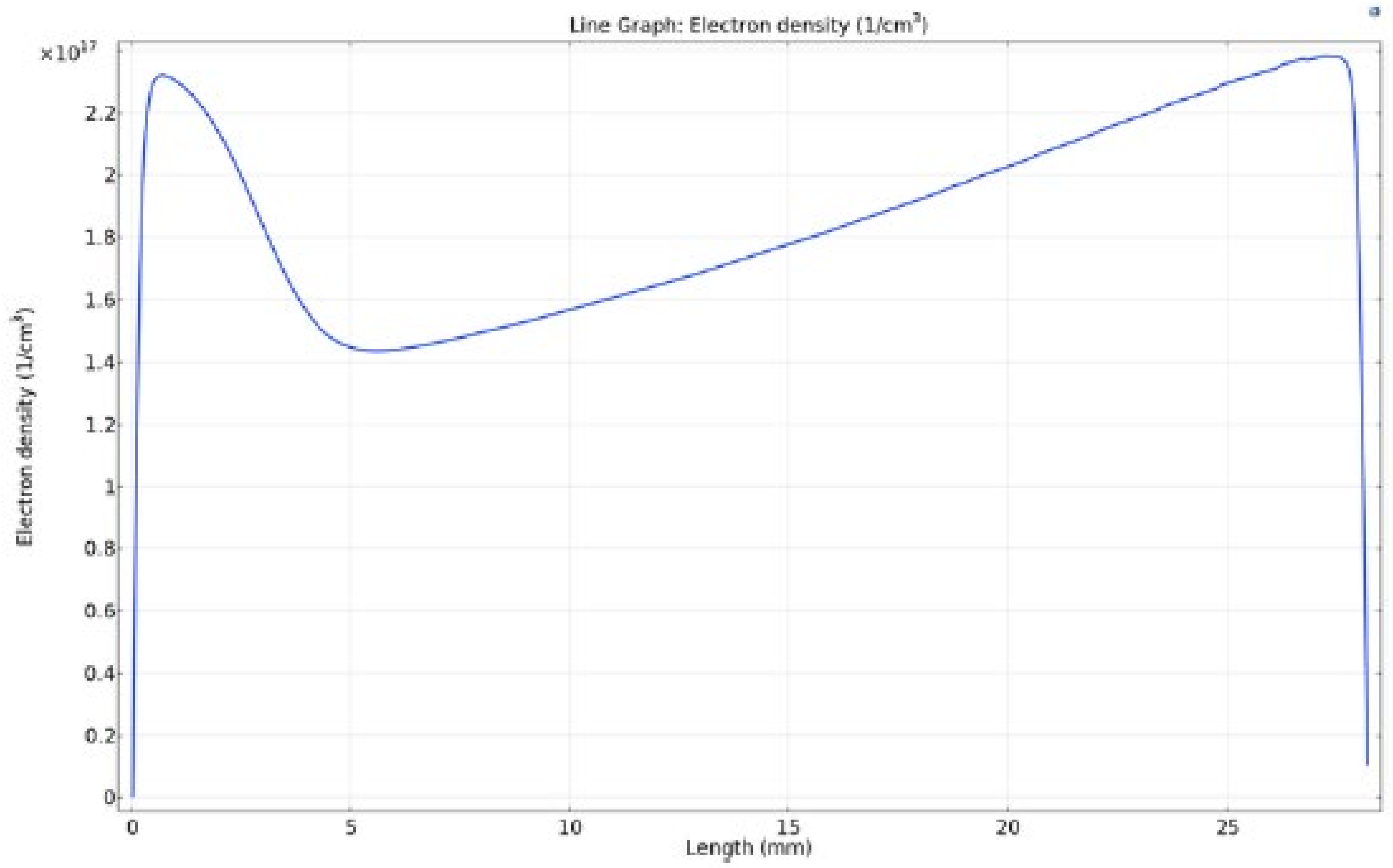
Spectroscopy system

Electrons acceleration station









Plasma Discharge in Capillary with COMSOL MULTIPHYSICS

3cm-long capillary filled with argon gas with two different longitudinal profiles:

- 1mm-diameter (top)
- tapered one featuring a 1 mm entrance and a 200 um exit diameters (bottom)
- 10 mbar, 15 kV
- R=20 Ω, C= 5 nF

An increased plasma density at the capillary exit which compresses the plasma, enhancing coupling with the accelerating fields and optimizing electron injection and acceleration.

Further characterization → multi-ramping shapes and dual gas injection profiles.

Metric	Sharp	Tapered	Charge
Mean Energy [MeV]	136.1	158.3	+16.3%
Energy Spread [%]	30.1	21.1	−29.9%
Peak Energy [MeV]	165.8	184.5	+11.3%
Charge [pC]	20.7	23.9	+15.7%
ε_x [μm]	10.3	8.1	−21.5%
ε_y [μm]	11	2.7	−74.9%
Bunch FWHM [fs]	115.4	59.1	−48.7%

Better beam quality

Arjmand et al., Preformed plasma waveguides: Enabling high-energy electron beams for FLASH radiotherapy, NIMA (2025)

I-LUCE Laser parameters and expected beams (L2)

Laser Power	45 TW	
Energy per pulse	≥ 1.5 J	
Pulse Duration	≤ 23 fs	
Focusing surface	36 um^2	
Max power density (at the target)	1.21×10^{20}	
Contrast Ratio @ 100 ps	$< 10^{10}$	
Repetition rate	10 Hz	
Proton ions	Max energy	4 MeV
	Particle per pulse (at 2 MeV)	10^{11} MeV^{-1} sr^{-1}
	Energy spread	100%
	Max beam divergency	± 20°
Electrons	Max energy	0.1 GeV
	Particle per pulse	10^9
	Max beam divergency	± 20 mrad
Neutrons	Max energy	TBD
Gamma beams	Synchrotron radiation of the e- inside the plasma or bremsstrahlung	
	Max energy	up to 20 MeV

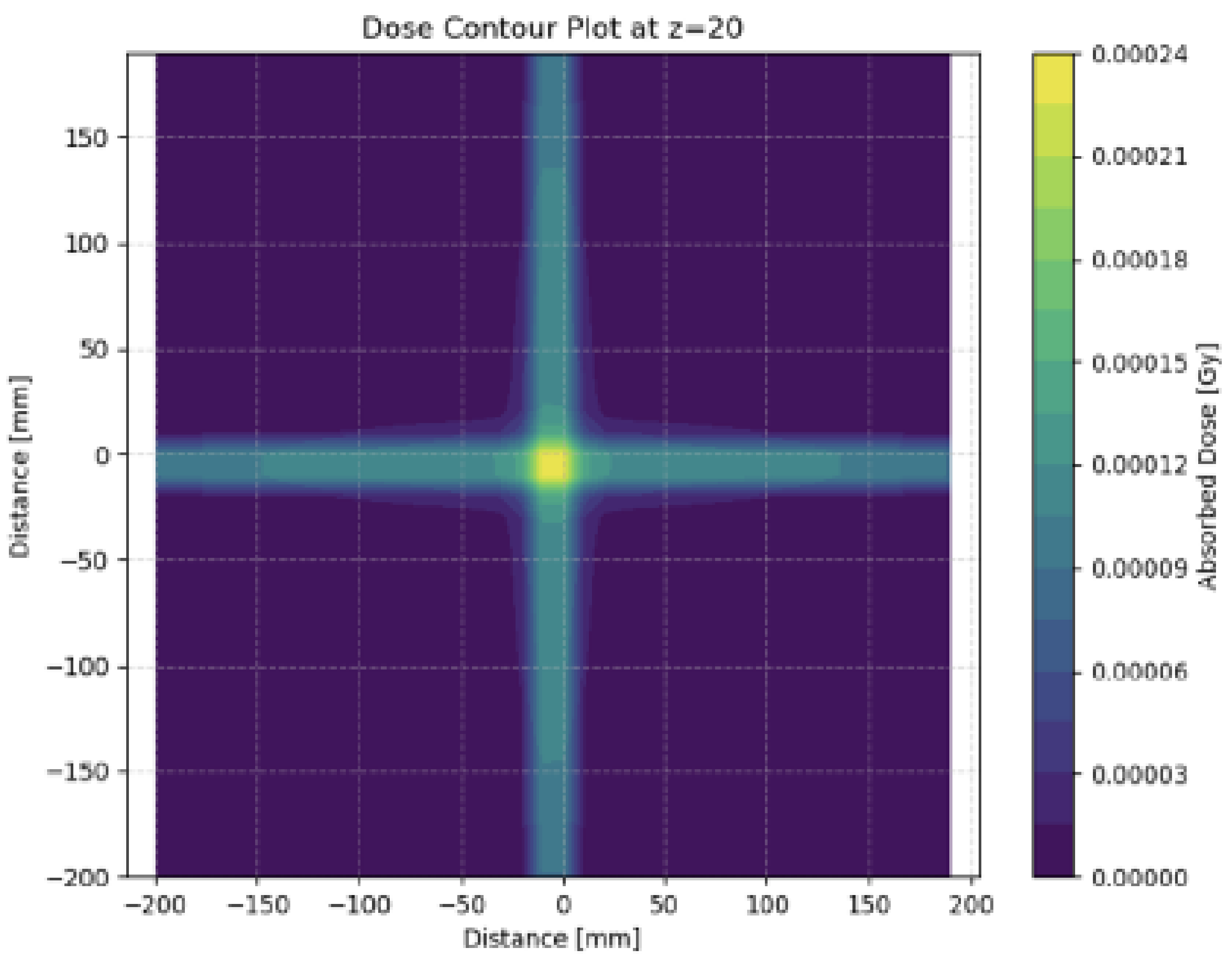
Laser Power	320 TW	
Energy per pulse	≥ 7 J	
Pulse Duration	≤ 23 fs	
Focusing surface	36 um^2	
Max power density (at the target)	8.82×10^{20}	
Contrast Ratio @ 100 ps	$< 10^{10}$	
Repetition rate	2.5 Hz	
Proton ions	Max energy	50 MeV
	Particle per pulse (at 2 MeV)	10^{11} MeV^{-1} sr^{-1}
	Energy spread	100%
	Max beam divergency	± 20°
Electrons	Max energy	3 GeV
	Particle per pulse	10^9
	Max beam divergency	± 20 mrad
Neutrons	Max energy	20
Gamma beams	Synchrotron radiation of the e- inside the plasma or bremsstrahlung	
	Max energy	up to 80 MeV

Istituto Nazionale di Fisica Nucleare

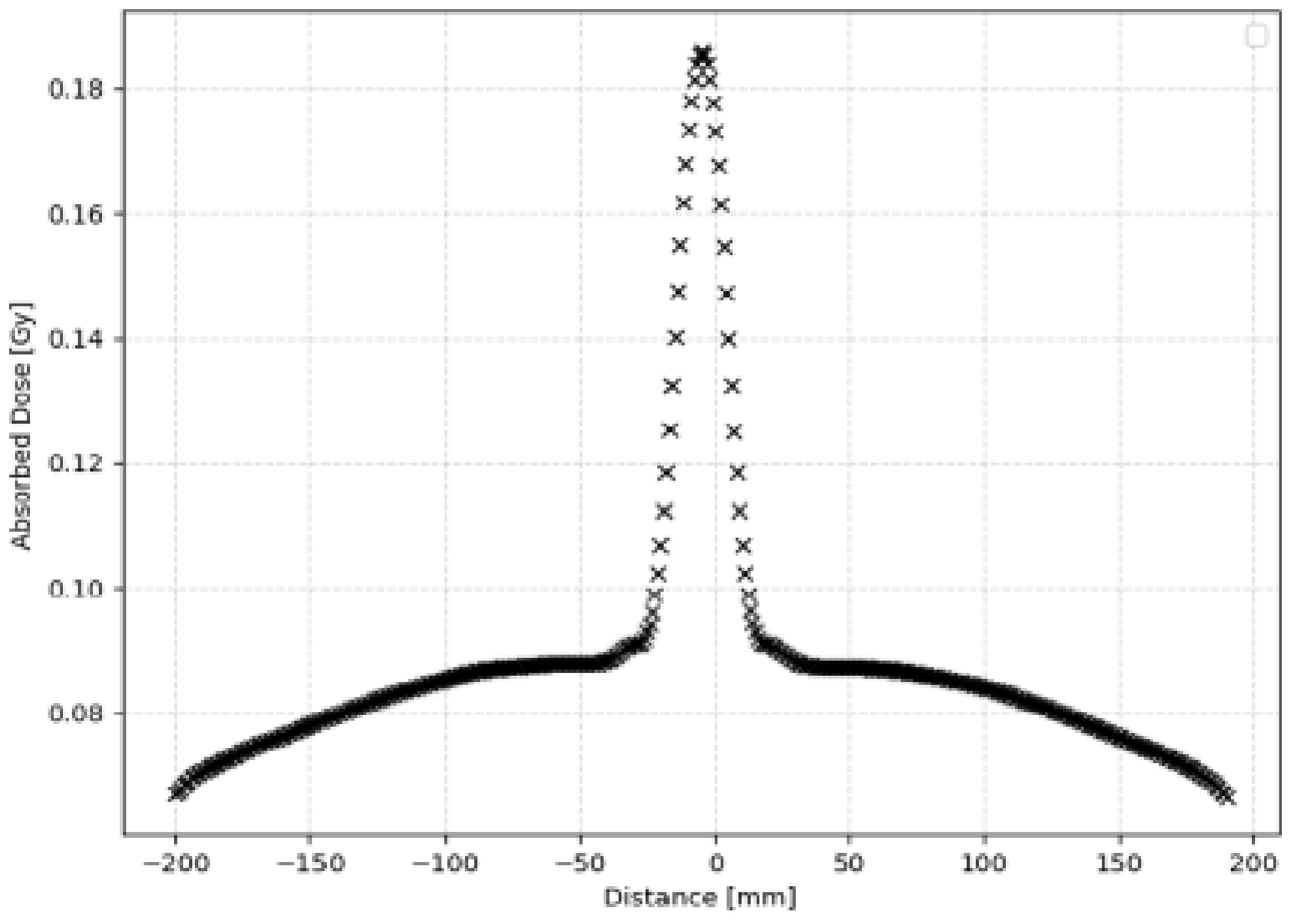
I-LUCE Laser parameters and expected beams (L2)

To perform dedicated dose studies, we developed a custom Geant4-based MC application that simulates dose deposition from laser-driven beams in complex geometries.

- The input beam parameters (220 MeV, 120 pC, few-fs duration) were based on measurements from a standard capillary setup.
- Four electron bunches were simulated entering a 400 × 400 × 400 mm^3 water tank from orthogonal directions, with a 40 × 40 × 40 mm^3 tumor located at the center.



2D dose map in the central plane of the water tank



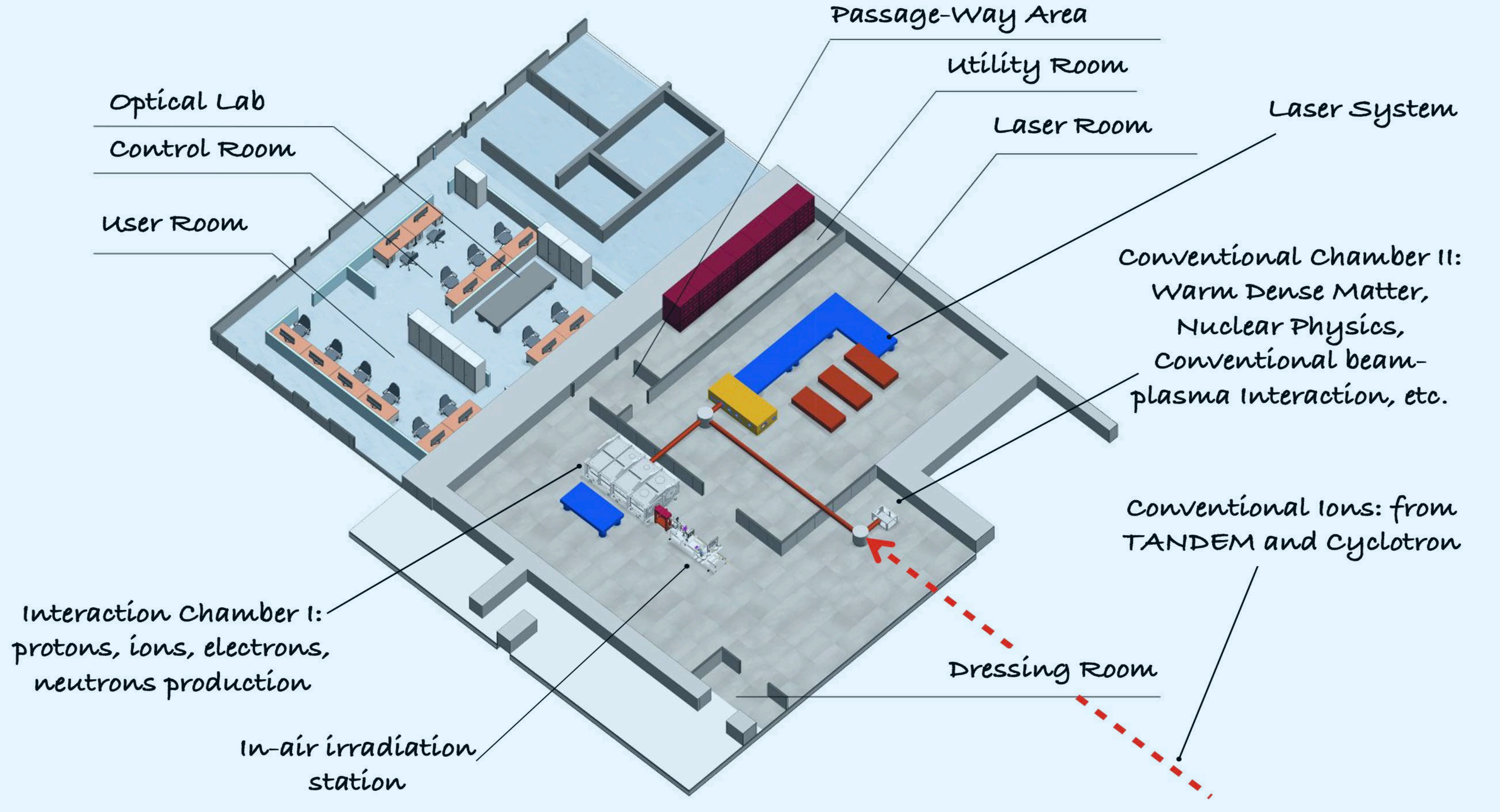
Absorbed dose profile

- The 4 beams converge to deliver a uniform 10 × 10 mm- dose profile at FWHM
- Geant4-based simulations, scaled to 120 pC per bunch, yield a deposited dose of 0.180 Gy per four bunches.
- With kHz-class lasers generating such beams dose rates could reach 42.5 Gy/s - enabling VHEET and FLASH-RT

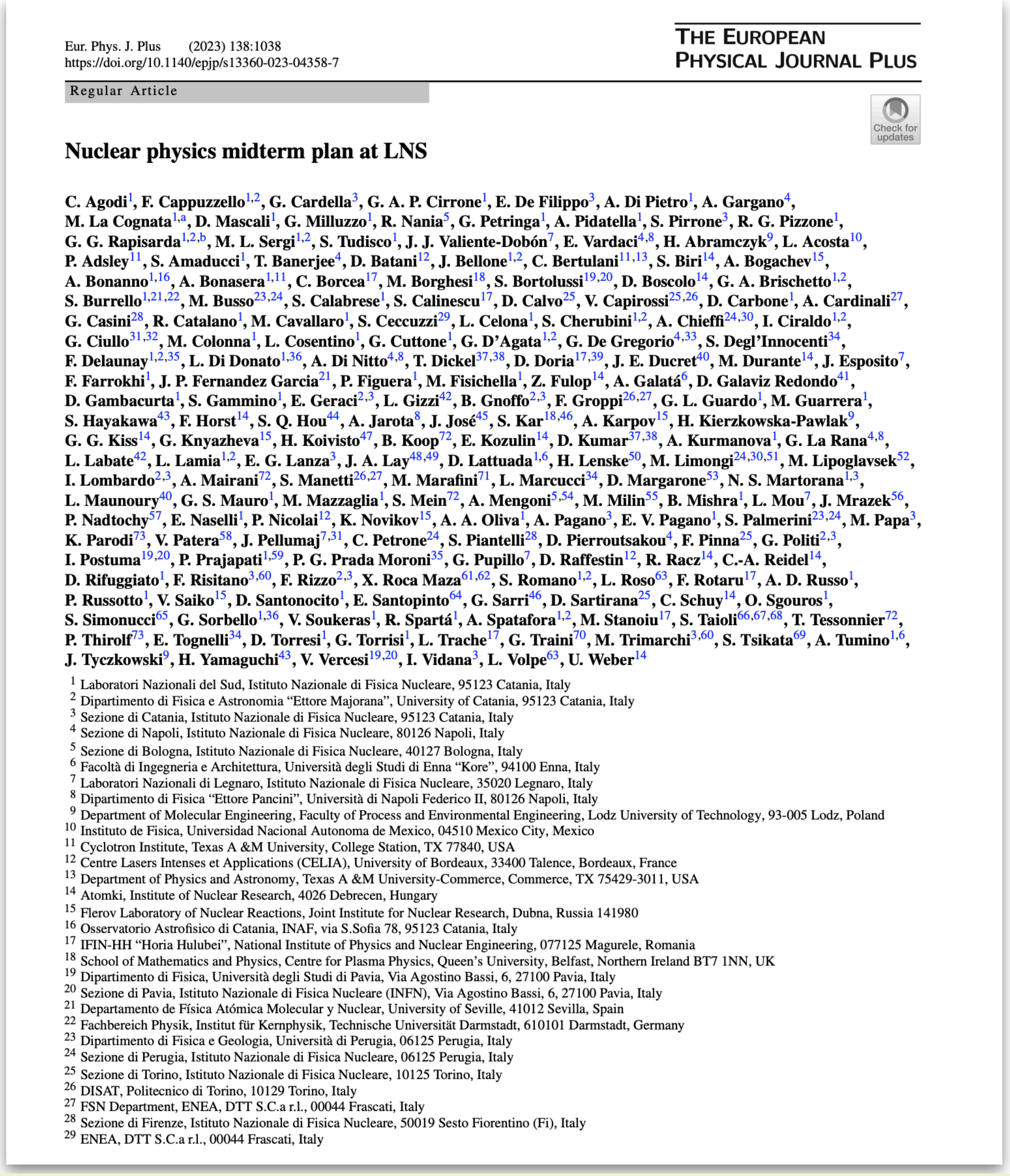
Other applications

- Stopping power in plasma
- Positrons generation
- Radioisotopes production
- Nuclear reaction schemes
- Hydrogen generation
- Conventional ions (4 AMeV – 80 AMeV) – plasma interaction
- From fs to ps plasmas
- Nuclear beta decay in plasmas of isomeric states on interest in nucleosyntesys
- Reaction of astrophysical interest
- Inertial fusion studies
- Warm Dense Matter studies

Nuclear and nuclear astrophysics station



Chapter 6.2 Laser applications



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Nuclear physics midterm plan at LNS

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Concluding remarks

- ❑ **Protons acceleration** up to 50 MeV with solid target
- ❑ **Electrons acceleration** up to 3 GeV with capillary and gas-jet system
- ❑ Neutron beam
- ❑ Irradiations stations for protons and electrons **for medical and multidisciplinary applications**
  - Radiobiology
  - VHEE and FLASH radiotherapy applications
  - Material science
- ❑ Interaction of conventional ion beams with laser-generated plasmas
- ❑ End of installation: Middle 2026
- ❑ End of commissioning: within 2027
- ❑ Opening of the facility to users: beginning 2028

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November 17-19, 2025

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- Laser-driven ion/proton acceleration
- Nuclear physics in plasma
- Neutron and gamma production
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- Electromagnetic pulse and its mitigation
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