SABINA: the THz-IR FEL beamline @SPARC

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on behalf of the SABINA team

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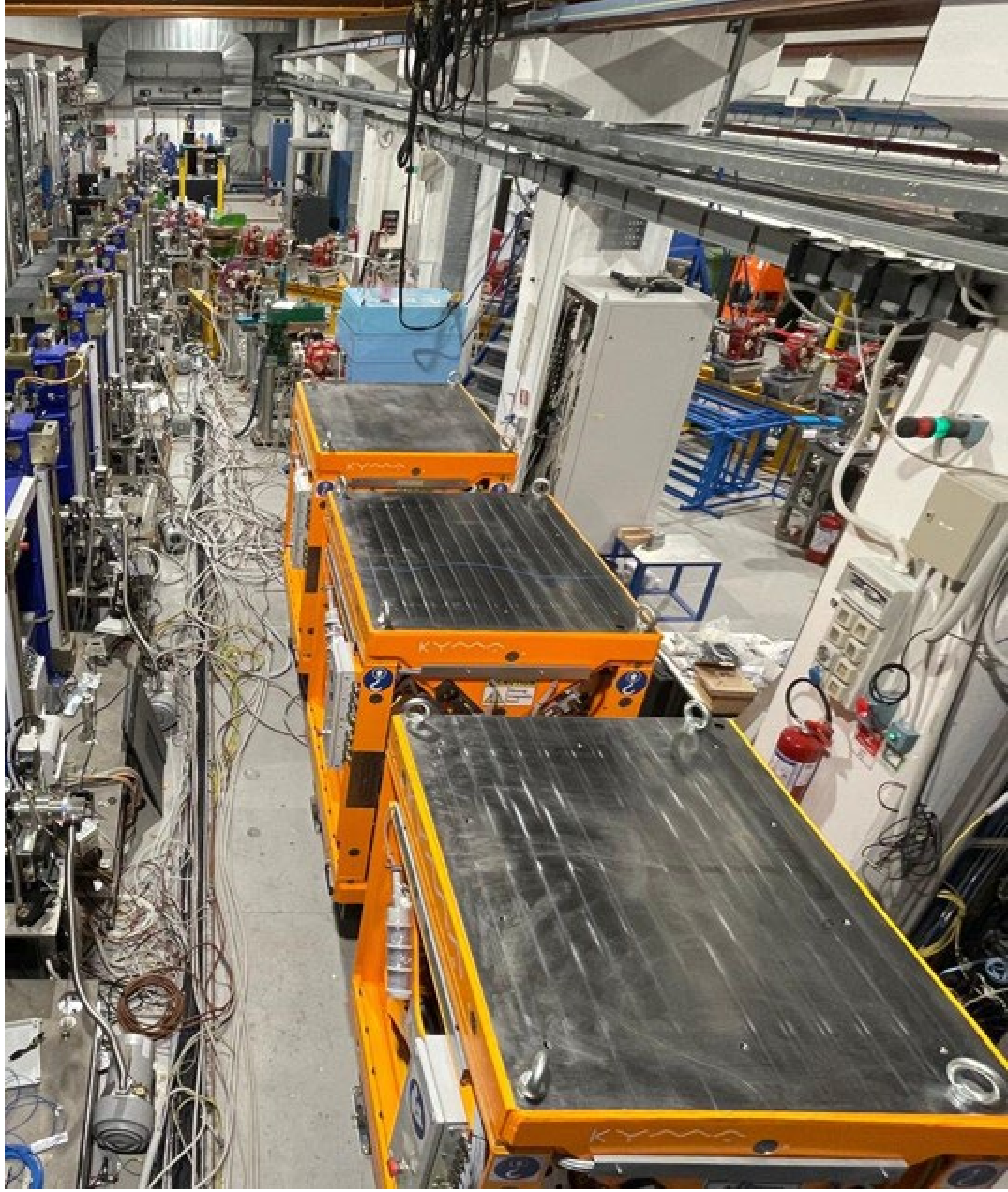


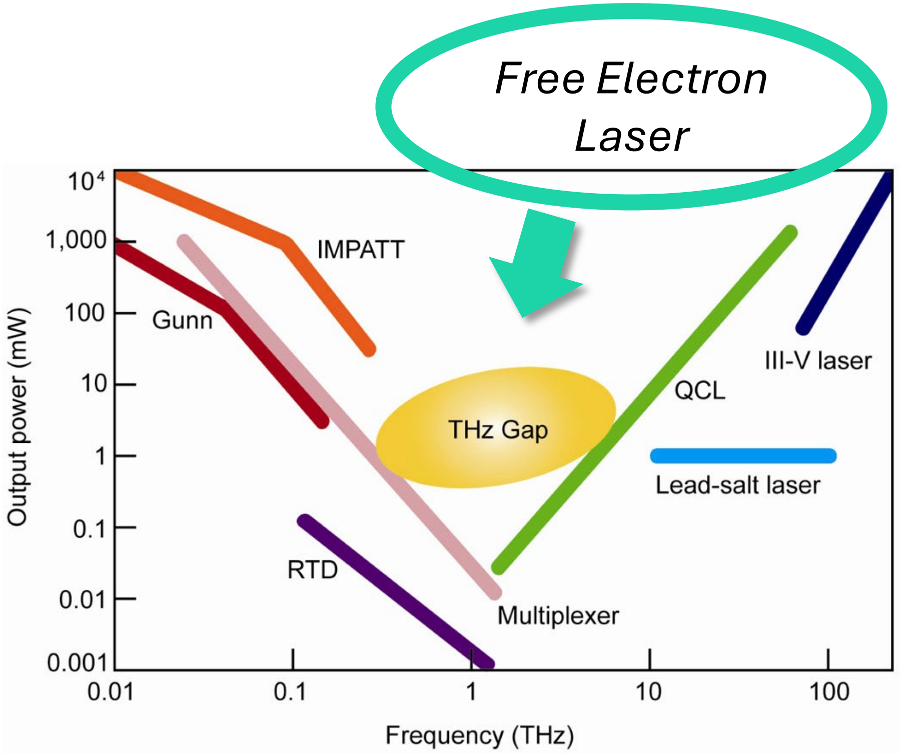
04.12.2024

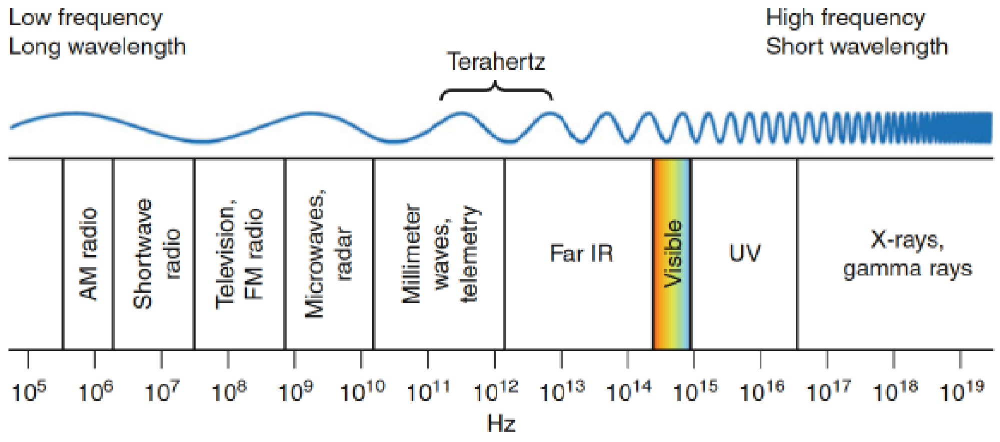
«Fundamental research and applications with the EuPRAXIA facility @ LNF»

Overview: THz radiation

THz Region in the EM Spectrum:

$0.1 - 10\ THz$ (with $1\ THz \sim 4\ meV\ \sim 300\ \mu m$)





'THz Gap': Challenges associated with the generation, manipulation and detection of THz radiation

THz Sources:

- **Quantum Cascade Lasers** (work mainly in CW, strict operational temperatures, small frequency tunability...)
- **Laser-based sources** (pulsed radiation, frequency range limited by the non-linear crystals, high energy pulses...)
- **Particle Accelerator-based sources** → they overcome the limitations of the previous sources

Why THz radiation?

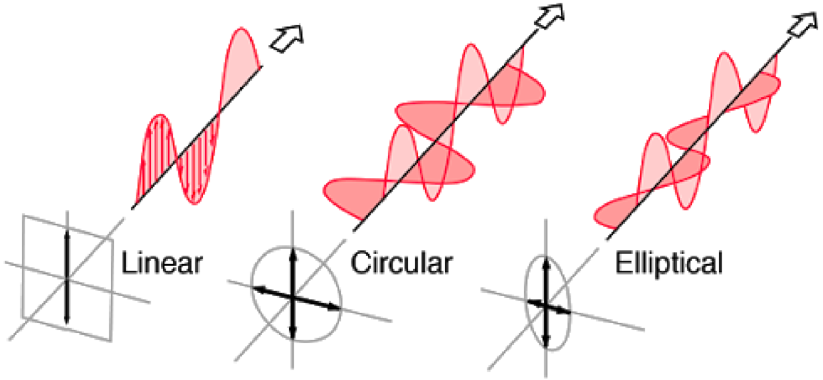
1. **Materials** | Characterization and control of quantum materials
2. **Biology** | Non-destructive, non-contact and label-free optical method for biological detection
3. **Medicine** | Imaging technique as a replacement for medical X-rays.
4. **Enviromental science** | Can be used for sensing and characterizing airborn pollution and VOCs
5. **Security** | Can penetrate fabrics and plastics, so it can be used in surveillance

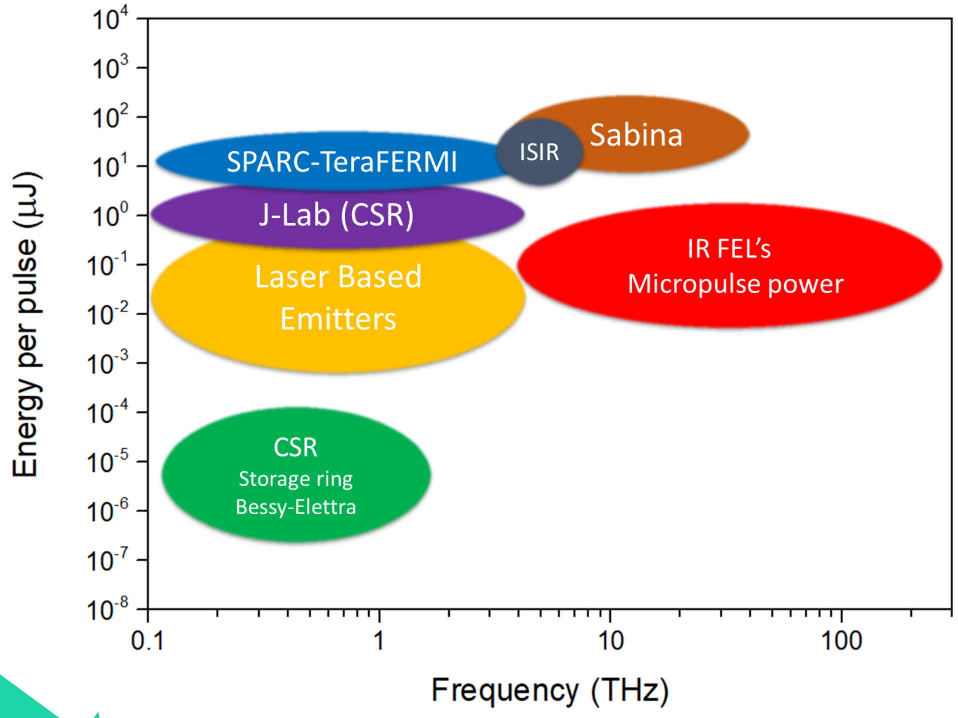
Dhillon et al. «The 2017 terahertz science and technology roadmap»
Leitenstorfer et al. «The 2023 terahertz science and technology roadmap»

The SABINA THz/IR FEL beamline

SABINA aims to develop a user facility based on a FEL delivering radiation with the following important properties:

- Quasi monochromatic light with short pulse duration ($\sim ps$/sub-ps)
- Tunable frequency in a large spectral range between 3 and 30 THz (by tuning the beam energy in the LINAC)
- High energy per pulse (up to $100\ \mu J/pulse$)
- Tunable polarization (from linear, to circular, to elliptical)

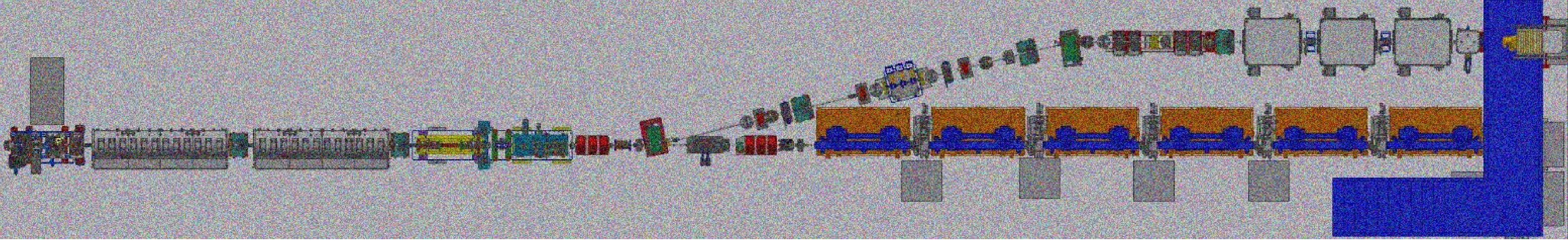




Accelerator-based THz sources embodies all the excellent qualities of conventional THz sources

Macis et al. "The SABINA TeraHertz/InfraRed beamline at SPARC_Lab facility", TERADAYS2022

FACILITY	STATE	SOURCE	SPECTRAL RANGE [THz]	ENERGY/PULSE [μJ]	PULSE DURATION	POLARIZATION	ELECTRON ENERGY
TERAFERMI@Elettra	ITALY	CTD/CDR	0.5-10	50	100 fs	linear	1 GeV
THz@ISIR	JAPAN	Ondulator THz laser	2-10	100	10 ps	linear	180 MeV
FELIX123 FELICE FLARE	NETHERLANDS	Ondulator THz laser	0.2-120	1-20	250 fs – 70 ps	linear	10 MeV
FELBE	GERMANY	Ondulator THz laser	1.5-80	few	1-25 ps	linear	5-40 MeV
TELBE	GERMANY	Ondulator THz laser + CTR	0.1-3	1-100	30 fs	linear	5-40 MeV
KAERI	KOREA	Ondulator THz laser	0.3-3	NaN	20 ps	NaN	NaN
THz@Novosibirsk	RUSSIA	Ondulator THz laser	1.5-3	40	10 ps	linear	12 MeV
THz@SABINA	ITALY	Ondulator THz laser	3-30	100	~ ps	linear elliptical circular	30-100MeV



SABINA:

SOURCE OF ADVANCED BEAM IMAGING FOR NOVEL APPLICATIONS

Founded by:

«Potenziamento delle Infrastrutture di Ricerca PNIR per elevare il tasso di innovazione del tessuto produttivo regionale» (*aka Infrastrutture per la Ricerca*)
http://www.lazioinnova.it/bandi-post/infrastrutture-la-ricerca/

POR-FESR 2014-2020

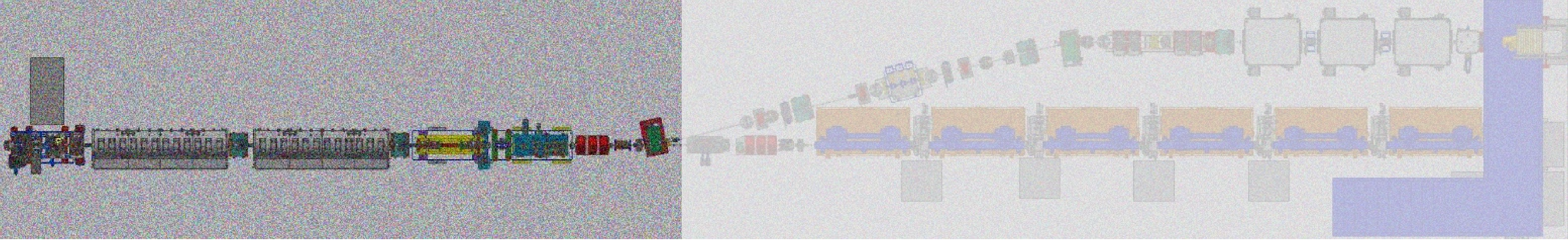
GOAL: Enhancement of the SPARC_LAB research facility to set up an infrastructure for users:

1. Increase of the uptime → Technological plant renewal
2. Improvement of the performance → update of systems and equipment
3. Commissioning of two users' facilities:

    FLAME: High power laser for solid target experiments

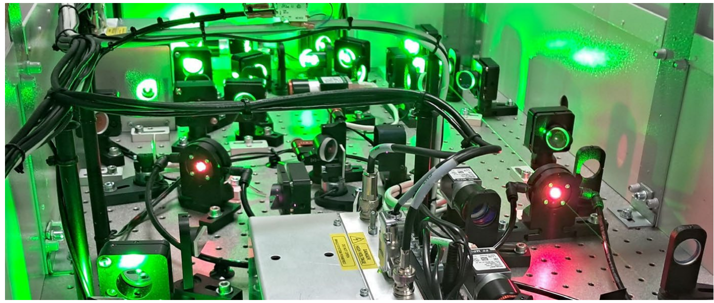
    THz/IR FEL: radiation source for optical spectroscopy (pump probe), also at cryogenic T

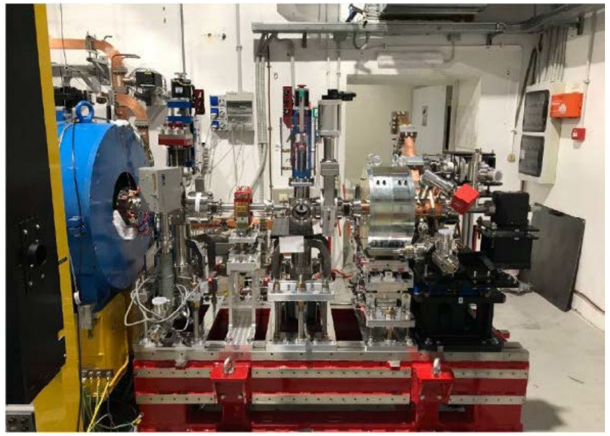
Sabbatini et al. "SABINA: A Research Infrastructure at LNF", IPAC2021

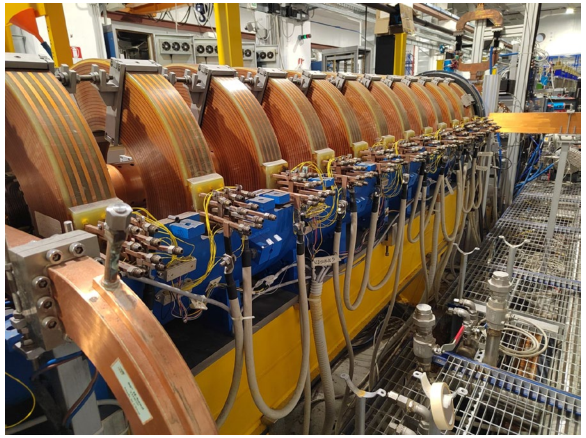


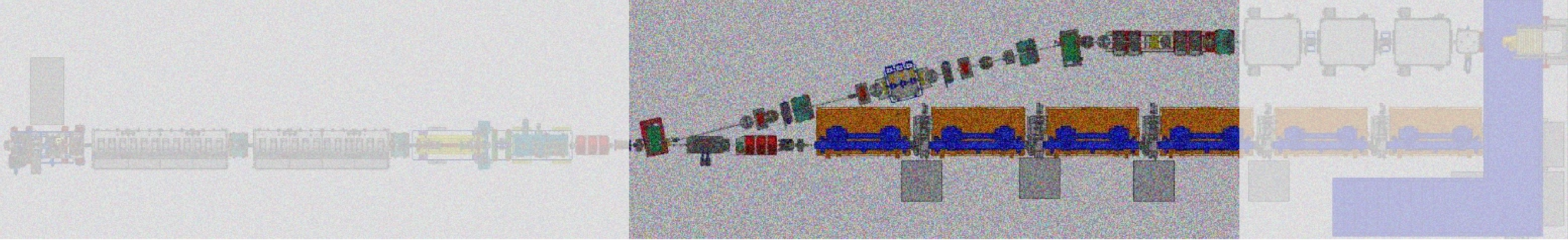
SPARC photoinjector is used to produce high quality and low energy electron beam:

- 2 mm-mrad emittance
- Few tenth per cent energy spread
- Tunable energy between 30 and 100 MeV
- High brillances are guaranteed by two main processes:
  - Velocity Bunching (compression in the longitudinal phase space)
  - Emittance compensation (minimum normalized emittance in the transverse dynamics)









The **Dogleg** is necessary due to limited space in the facility. It consists in:

- Two bending magnets
- Three Quadrupoles to close horizontal dispersion

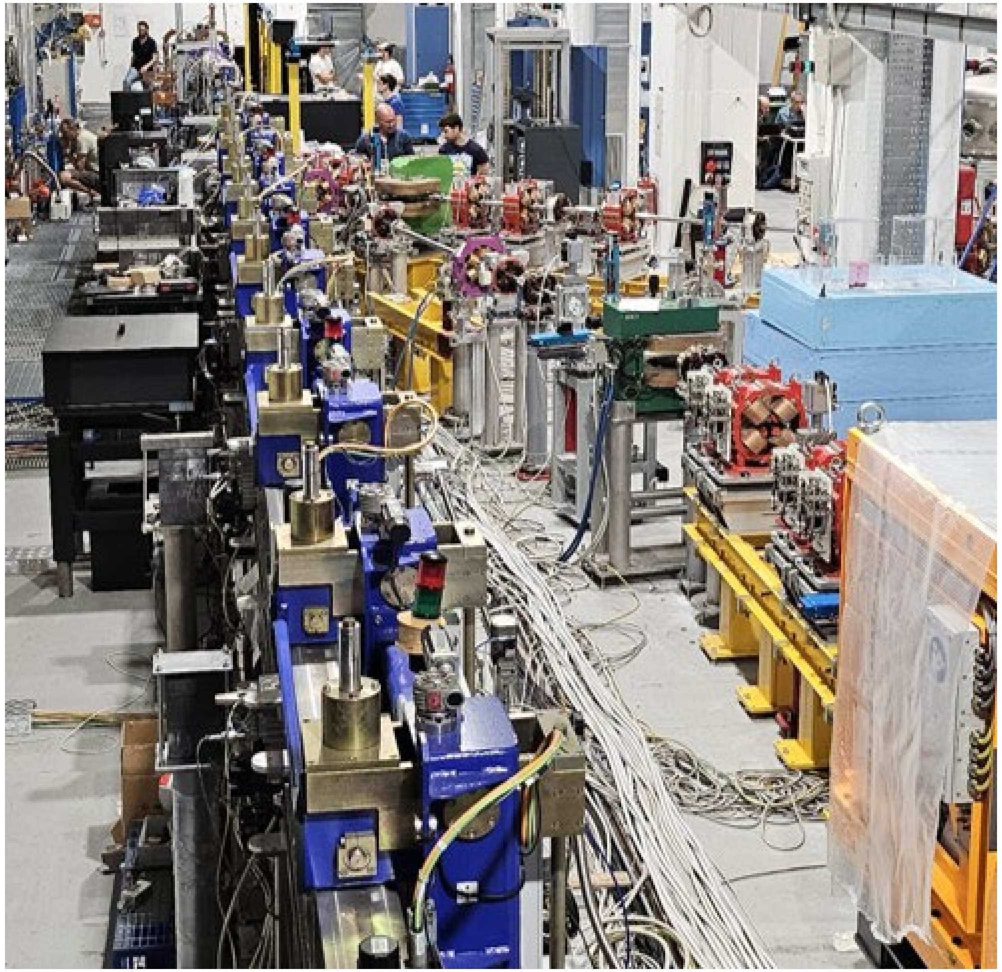
The last four Quadrupoles are set to fulfill the matching condition on the Twiss parameters:

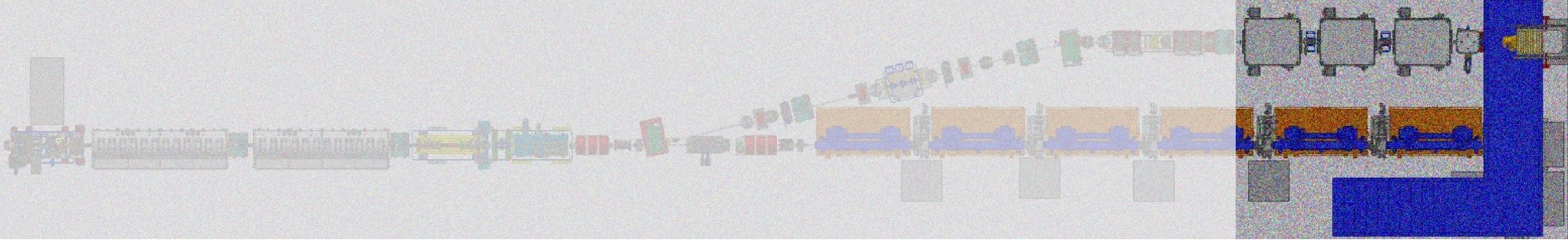
$$\alpha_{x,y} = 0$$

$$\beta_{x,y} = \frac{\gamma \lambda_u}{\pi K \sqrt{h_{x,y}}}$$

It should be $\beta_x = \beta_y = 0.15$ m

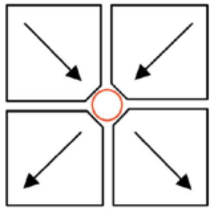
Study of beam stability in the dogleg area to verify space charge driven microbunching instabilities (MBI) that occurs at low energy

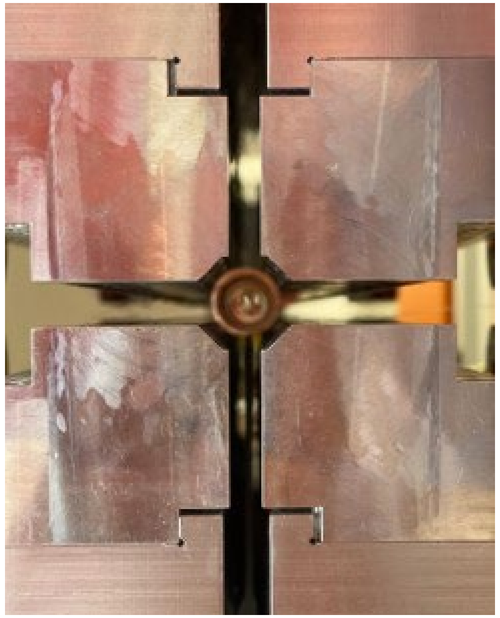




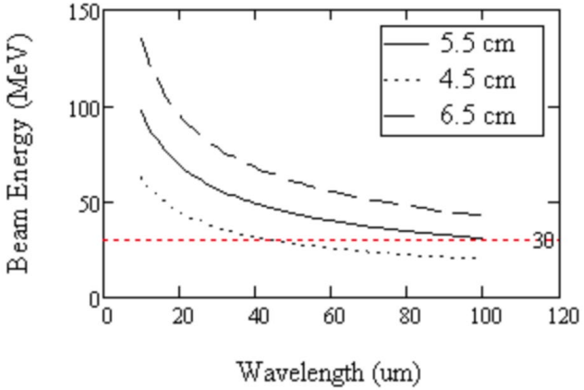
Magnetic simulations with RADIA [1] - FEL simulations for particles and radiation with GENESIS [2]

- Requirement for tunable polarization: undulator in the APPLE family, polarization can be tuned with longitudinal shifts of the magnetic array pairs
- Symmetric focalizing properties are needed due to the absence of quadrupoles between the undulator modules: **APPLE X** is the best choice
- The intensity of B along the undulator axis can be tuned by changing the gap
- Undulator length 4.5 m: 3 modules 1.3m each, separated by 40 cm for diagnostics, vacuum, HV steerer





Magnetic period λ_u	55 mm
Total length of the single module	1.35 m
Number of periods	24
Number of period full size	22
Minimum vertical magnetic gap	1.22 mm
Minimum horizontal magnetic gap	1.22 mm
Maximum vertical magnetic gap	60 mm
Maximum horizontal magnetic gap	200 mm
Magnetic material	NdFeB

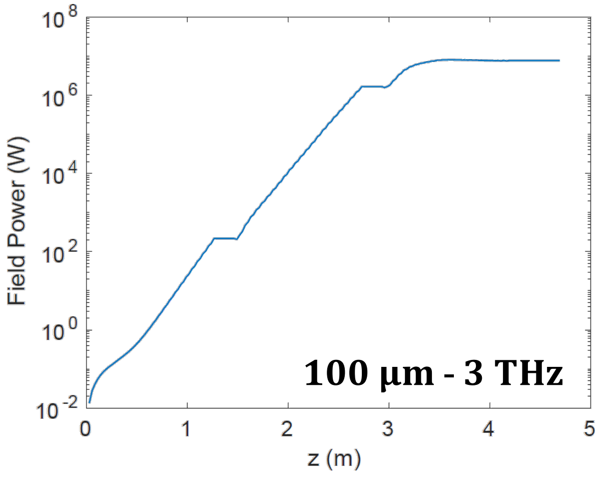


[1] Petralia et al. "Magnetic characterizations of the APPLE – X undulators for SABINA", FEL2024
[2] Dipace et al. «FEL design elements of SABINA», IPAC2021

GENESIS simulations at λ_r = 100-10 µm

Power Growth

Field Spectrum



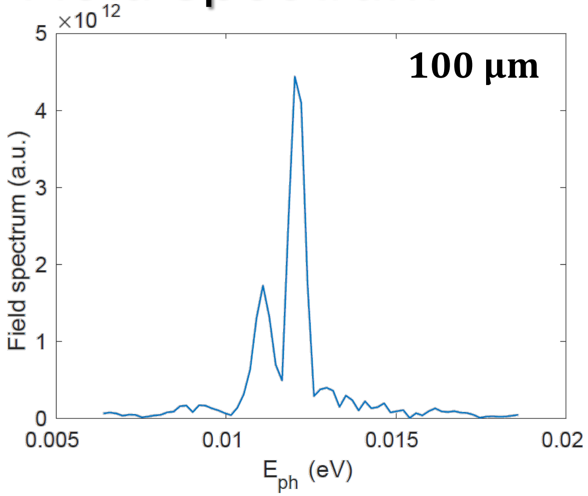
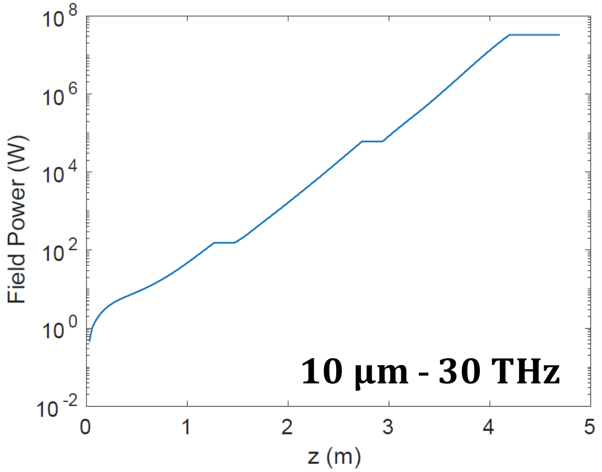


Figure of merit	Value
Energy per pulse	$(67 \pm 3)\ \mu J$
Pulse length	(6.2 ± 0.4) ps
w_0	(1.37 ± 0.05) mm
radiation divergence	(23 ± 1) mrad



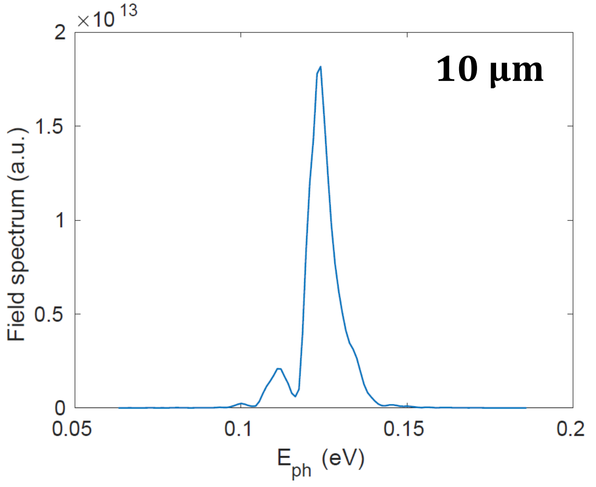
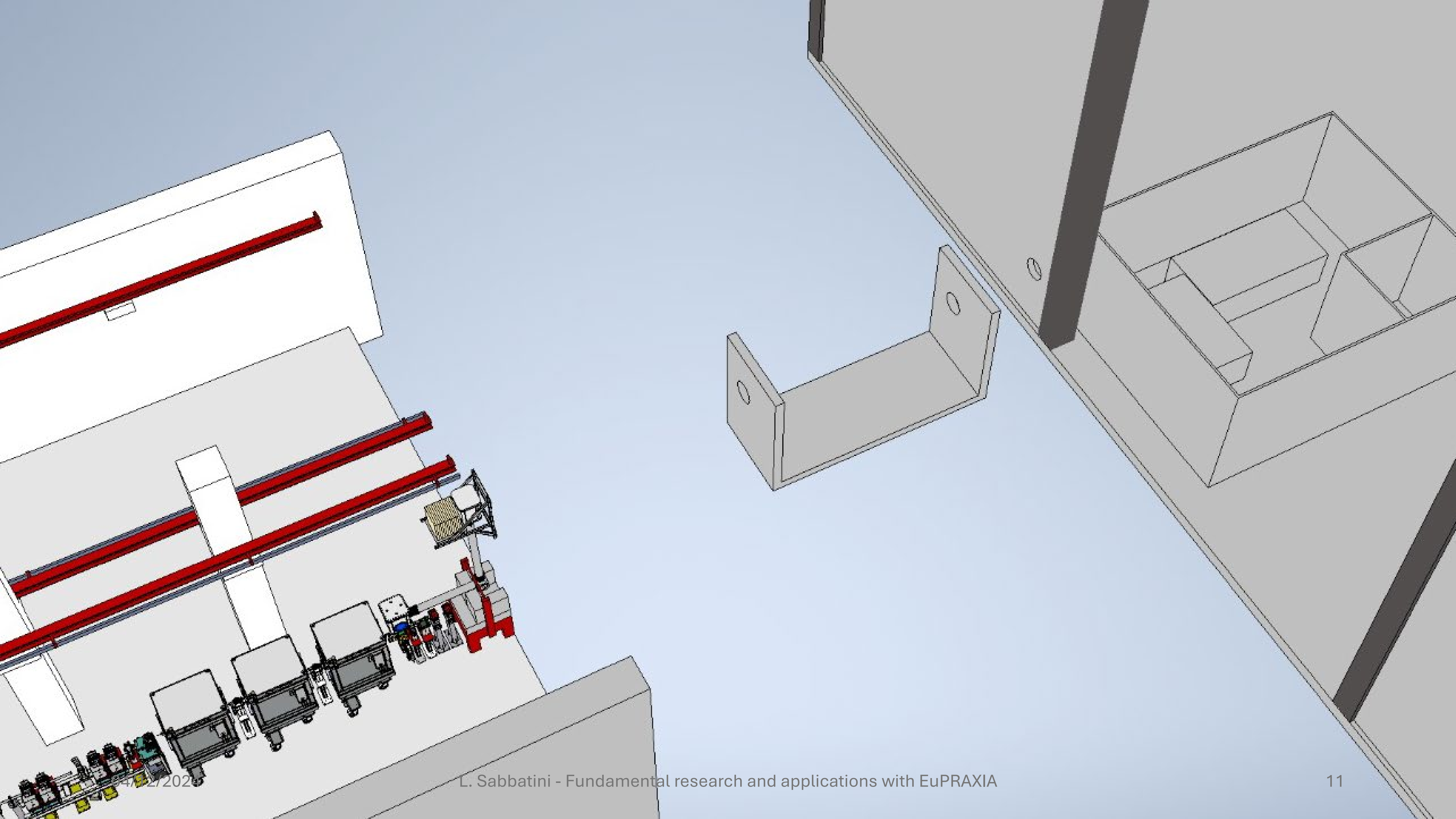
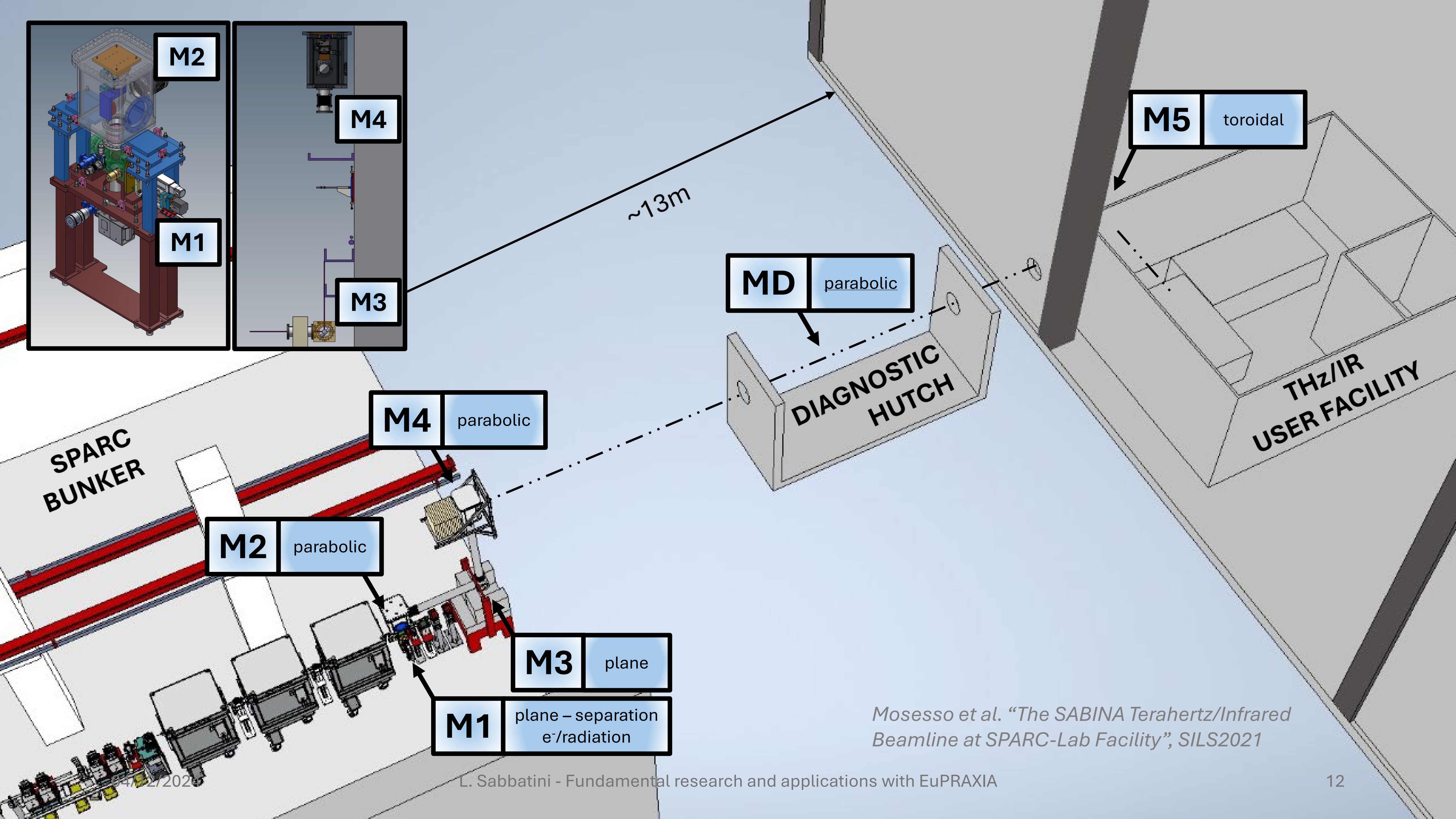


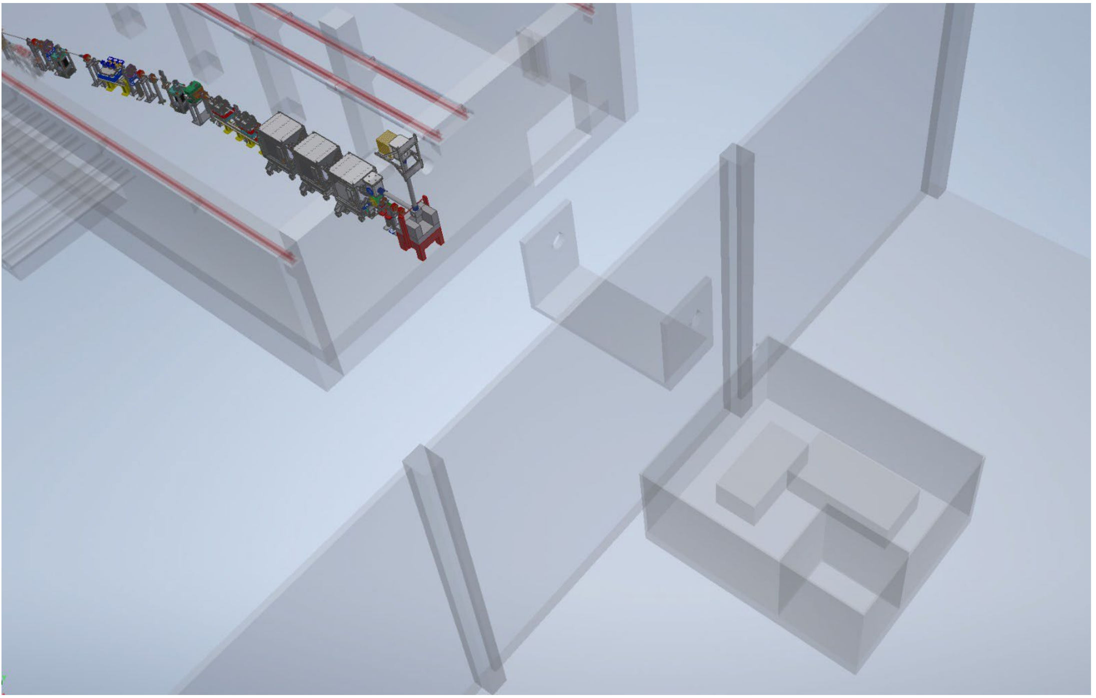
Figure of merit	Value
Energy per pulse	$(18 \pm 3)\ \mu J$
Pulse length	(300 ± 30) fs
w_0	$(680 \pm 60)\ \mu m$
radiation divergence	(4.7 ± 0.4) mrad





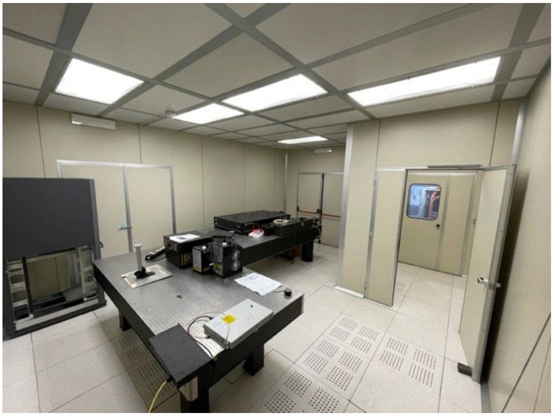
Mosesso et al. "The SABINA Terahertz/Infrared Beamline at SPARC-Lab Facility", SILS2021

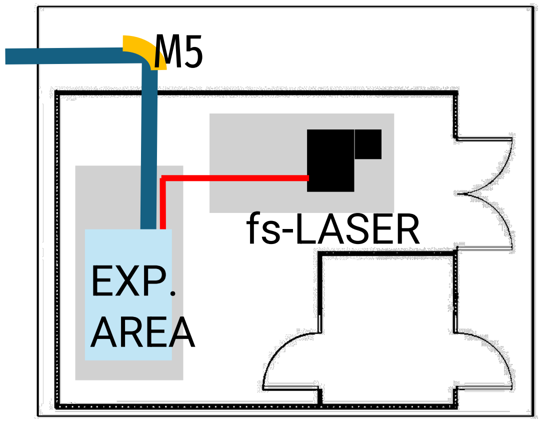
The experimental area



The experimental area is in a clean room equipped with:

- a 5 T magnetic liquid helium cryostat for temperature and magnetic field dependent measurements
- THz reflectance and transmittance setup for optical spectroscopy experiments
- A femtosecond laser ($50\ ps$ pulses) for synchronization & pump-probe experiments coupled with:
  - Optical Parametric Amplificator (OPA) + Difference Frequecy Generator (DFG) to tune radiation in the range 1.5 - $14\ \mu m$ by means of non-linear optical effects
  - High harmonic generation
  - Wide range pump probe setup





The availability of energetic THz/MIR source delivering short and variable polarization pulse allows to realize a wide variety of novel application:

- Chiral pump and probe spectroscopy on picosecond scale
- THz/MIR pump THz/MIR probe spectroscopy
- THz/MIR pump VIS/UV probe spectroscopy

2025											
JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
Completion electron beam line											
THz optical material **Procurement**											
			THz optical elements **Assembly** and **Installation** *								
								THz full line **Commissioning** *			

* to be coordinated with other activites @SPARC

SABINA will be opened to users at the beginning of 2026