LNF Scientific Committee
Frascati

SPARC_LAB activity report

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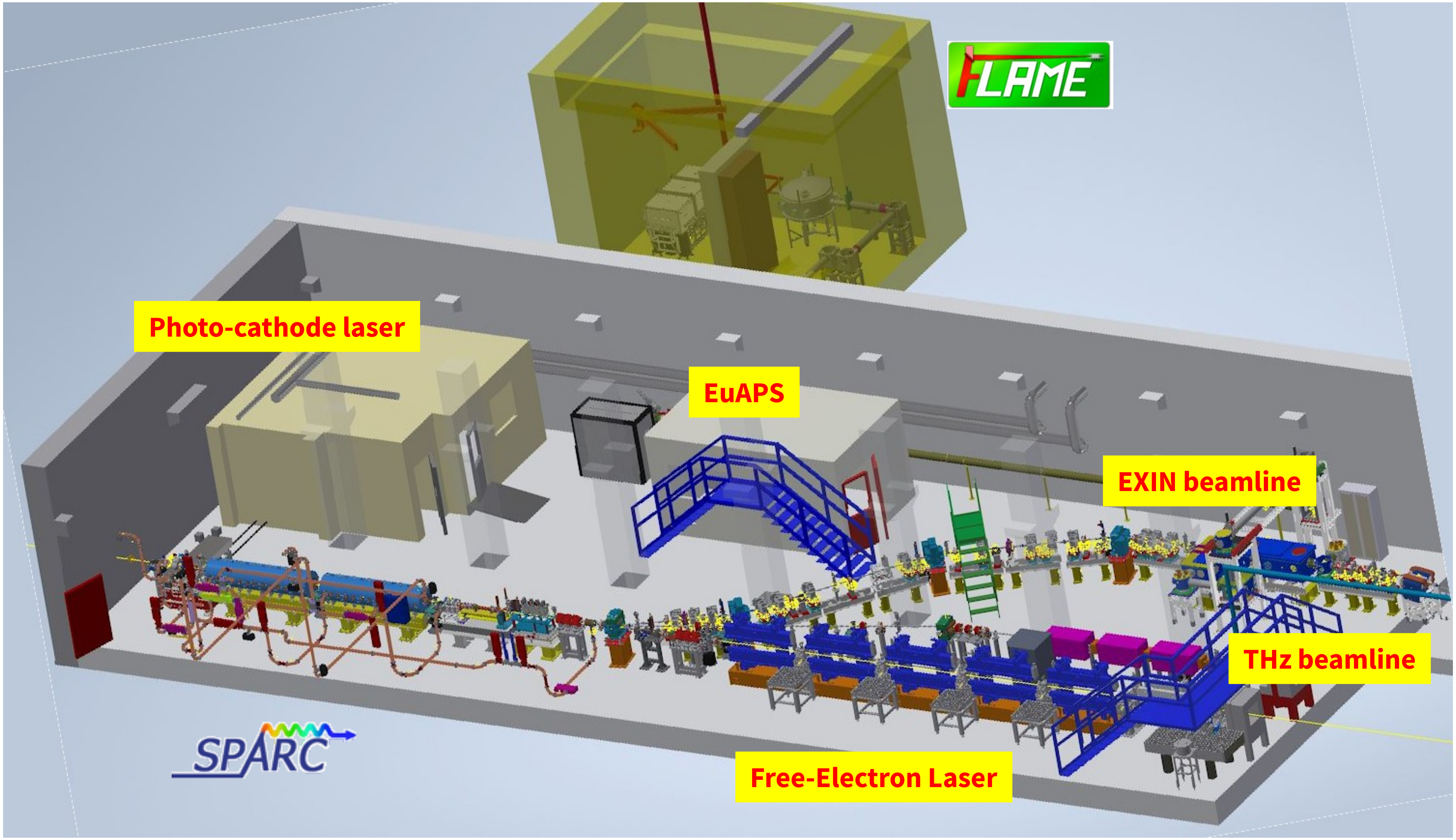
On behalf of the SPARC_LAB collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

SPARC_LAB facility



Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

Main considerations

After the last SciCom (November 2024), SPARC has been in operation till 21st March 2025. Several activities have performed

Beam-based alignment of the new solenoid coils. Spent several dedicated weeks on this topic. Now everything is aligned on the reference trajectory

Resonant plasma acceleration scheme. Test the plasma response using N drivers followed by a witness bunch. Interesting results obtained, paper prepared and submitted

Plasma acceleration using a laser-generated filament. It represents an alternative to the HV discharge. The Run-1 highlighted several issues that have to be fixed for the Run-2

EuPRAXIA-like working point. Test the SPARC injector to deliver the beam configuration as expected for the future EuPRAXIA facility. Some preliminary results obtained

SPARC is now shutdown to allow the EuAPS installations in the bunker. We expect to restart its operation by next September 2025.

The exact timeline of the experiments will be defined soon.

From previous SciCom

1. *The measured timing jitter in the Klystron LLRF control loops of less than 20 fs puts SPARC_LAB on equal footing with state-of-the-art FEL facilities. The SC would appreciate an overview of the achieved timing jitters not only for the RF but also for the cathode laser to RF stability in comparison with the EuPRAXIA requirements.*
2. *Studies of timing/bunching/energy stability with velocity bunching.*
    1. *Dedicated beam time has been proposed to estimate all the main jitter sources that would likely affect EuPRAXIA, too. In particular we should correlate the **energy-jitter** of the plasma-accelerated witness as a function of*
        1. *the **driver-witness distance** (RF+laser timing jitter) using the Electro-Optical Sampling diagnostics*
        2. *the **plasma density jitter** using a single-shot Stark-broadening diagnostics*
        3. *the **laser intensity jitter** on the cathode (**charge jitter**) using photodiode+BCM*
    2. *This measurement requires single-shot diagnostics that are already available at SPARC*

From previous SciCom

1. Assure that despite of EuAPS and SABINA activities sufficient effort and time is put on experiments relevant for finalizing EuPRAXIA@SPARC_LAB design.

1.The SABINA installations on the SPARC linac have been completed and a beam-based alignment has been performed to align the 24 coils on the beam trajectory. The SABINA installations to be completed are related on the transfer line (up to the THz undulators) and the radiation transport pipe (up to the user area).

2.The EuAPS installations are ongoing in both the SPARC and FLAME bunkers. So far no important delay is expected considering both the installations and the laser systems procurement

1. *Continue work on demonstration of robust plasma capillaries suitable for long term, high repetition rate operation*

    1. *This activity has been carried out at PLASMA_LAB that demonstrated the feasibility of working at large repetition rates (100-150 Hz) using a SHAPAL capillary. The tests included the evaluation of the thermal load on the plasma discharge pulser. Everything has been reported in the EuPRAXIA TDR, too*

From previous SciCom

1. *Comparison of PM magnet vs. plasma focusing*

   1. *The new set of PMQs have been employed for two experimental campaigns that ran from November up to March. The resulting focusing of the PMQs allowed to reach ~10 um spot sizes, that is still 2-3 times larger than expectations. Additional studies should be done.*

   2. *Regarding the plasma focusing, we are planning a new experiment that will involve 2 active-plasma lenses (APL). This will be an occasion to better quantify the focusing ability of the APL compared with PMQs*

From previous SciCom

1. Push procurement and installation of a solid-state klystron modulator for the velocity-bunching section of the injector despite of the administrative hurdles. A high stability RF power source at this position is imperative for demonstrating the stability of timing/bunching/energy.

   1. Due to several delays in the procurement process, the purchase of the solid-state modulators has been put on hold. Afterwards the EuPRAXIA TDR completion, we expect to continue with the procurement with the goal to upgrade the current SPARC modulators in the next years

Experimental results with the SPARC linac

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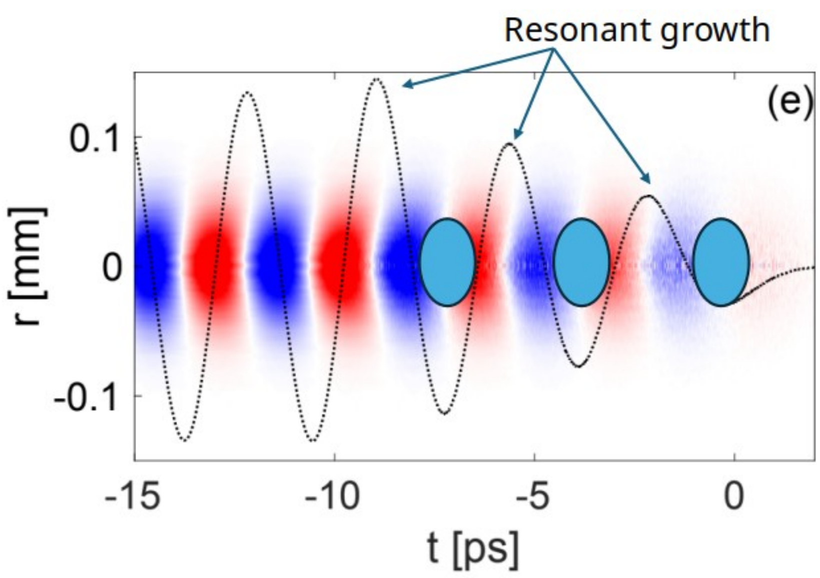
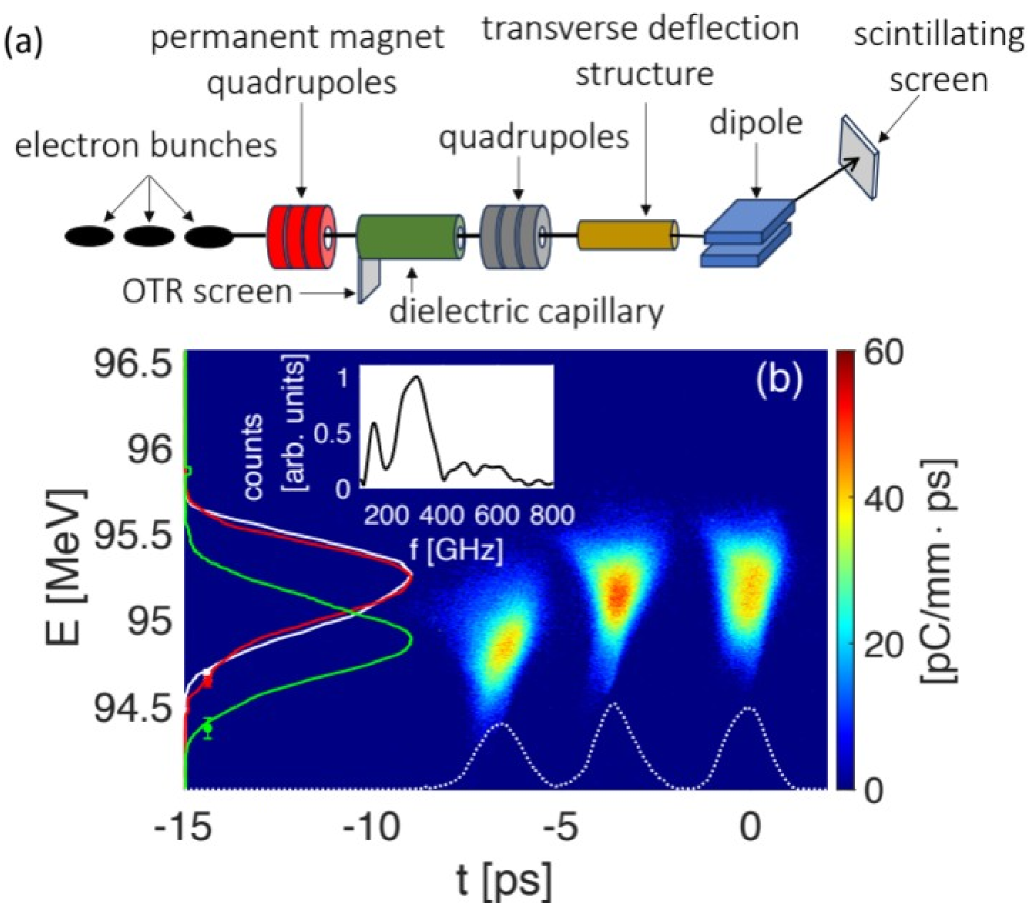
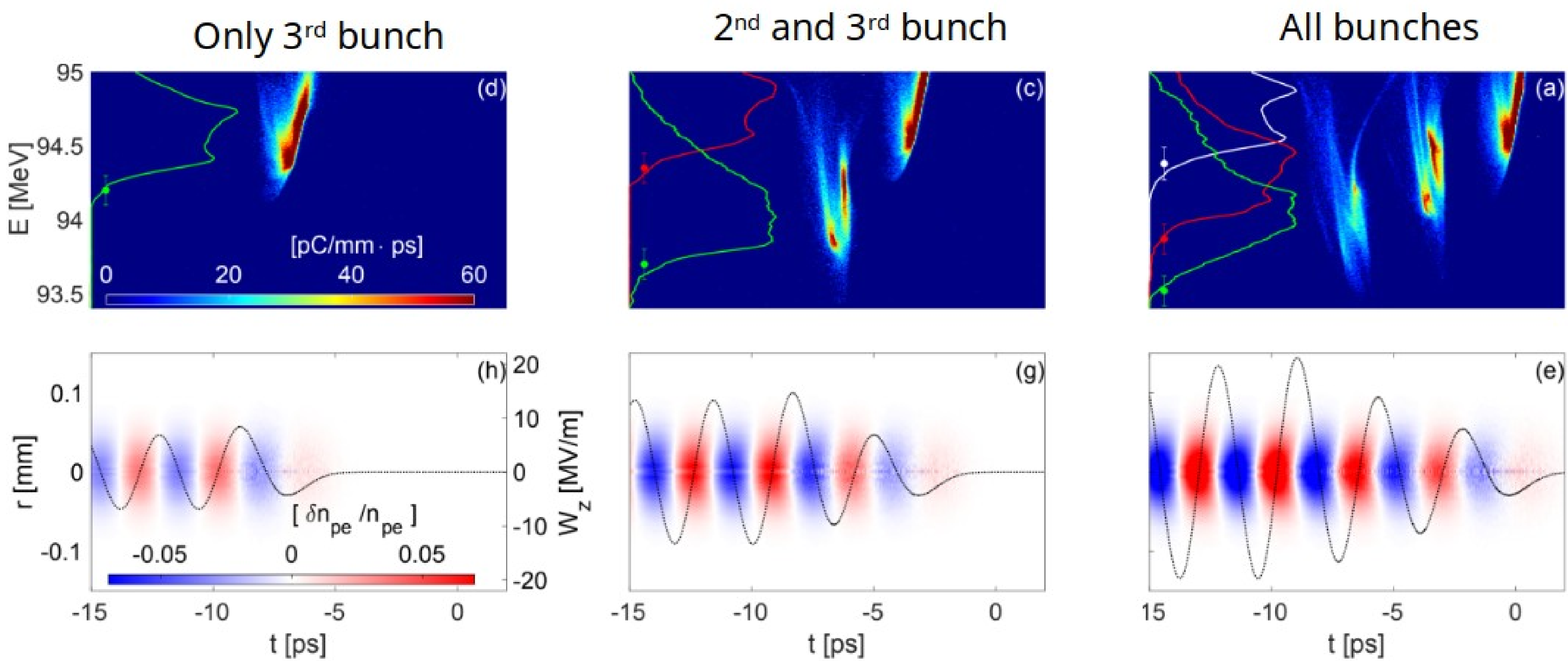


Train of equally spaced bunches
They drive wakefields resonantly when spacing equal to plasma wavelength



L. Verra, submitted

L. Verra et al., Excitation of Plasma Wakefields with a Train of Relativistic Particle Bunches, submitted, [https://doi.org/10.21203/rs.3.rs-6115160/v1]



Losses of third bunch increase when more bunches ahead are present

Larger amplitude of the wakefields → Resonant excitation

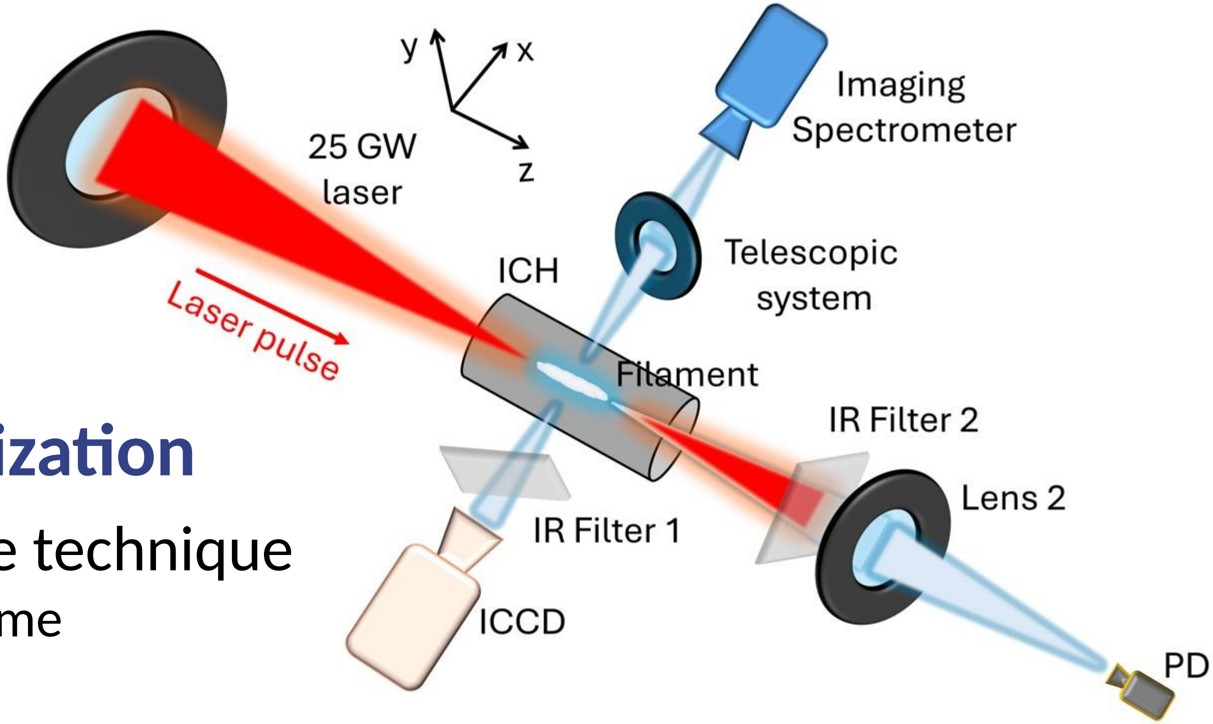
Linear regime wakefields driven by each bunch sum up linearly

L. Verra

Laser-induced plasma filaments

Experimental setup

- Ti:Sapphire laser system:
  - 10 mJ, 350 fs FWHM, 10 Hz
- 10 cm X 1 m gas cell
- 1 mbar N_2 95% - H_2 5%



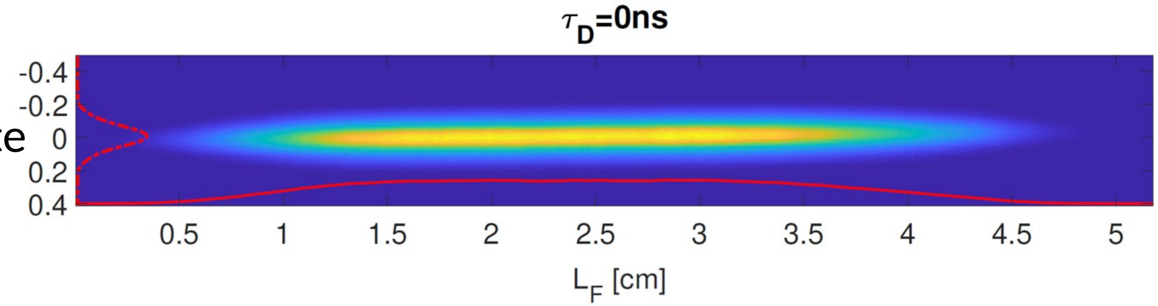
Experimental characterization

- Side imaging fluorescence technique
  - Filament size and decay time
- Spectral analysis
  - Plasma density and temperature distribution
- Photodiode
  - Decay time

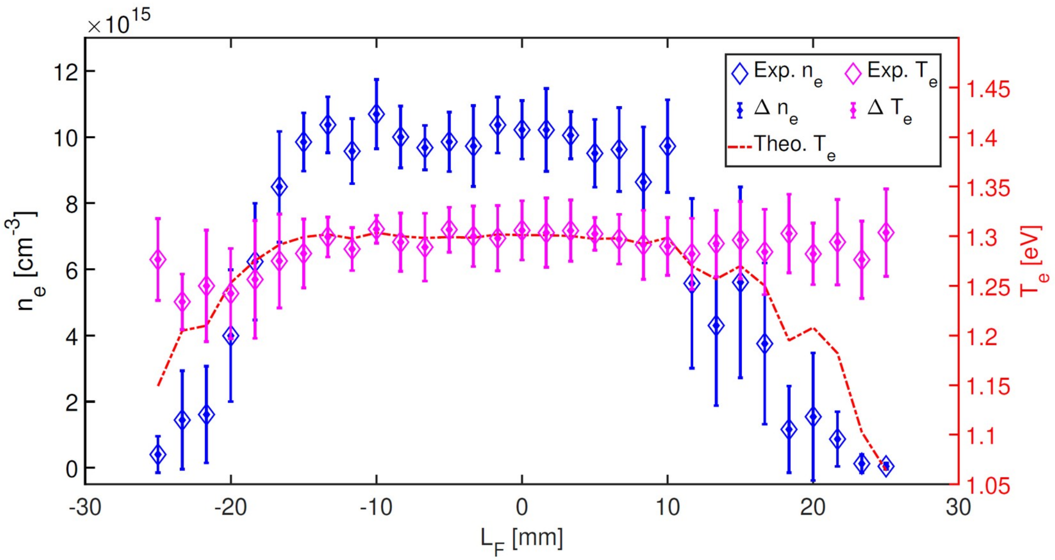
M. Galletti

Filament operation

1. **No need of** solid-state high repetition-rate discharge system
2. **No need of** high temperature-resistant materials capable of withstanding the plasma thermal load – **Low energy deposition**
3. **Low gas injection -** Vacuum systems suitable for continuous flow gas injection (turbo and primary pumps cooling system)
4. **Tunable dimensions and density** scanning gas pressure, laser energy and transverse dimensions.
5. **No time-jitter**
6. **High repetition rate – multi-kHz**



M. Galletti



Galletti, Mario, et al. "Femtosecond laser-induced plasma filaments for beam-driven plasma wakefield acceleration." Physical Review E 111.2 (2025): 025202.

Status of the filament experiment

Laser setup tested and properly working.

Laser synchronization with electron beam well under control

Additional diagnostics (intensified camera looking at the plasma filament) have been installed and tested

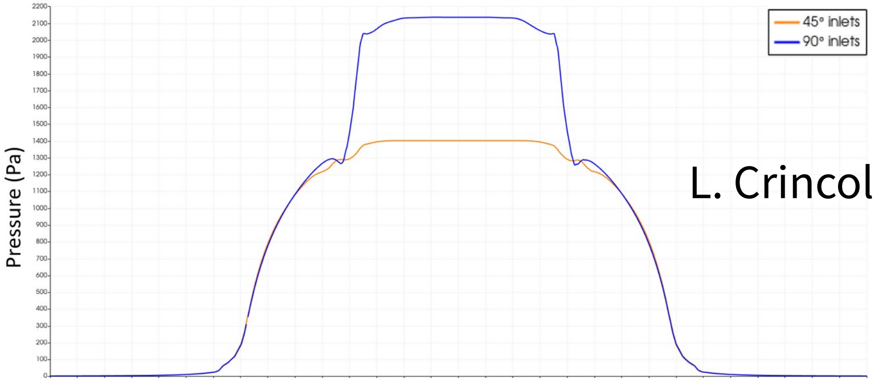
Problems

- *Non optimal gas injection (due to pulsed electro-valve) led to a non uniform gas profile along the capillary → not able to create a proper filament (few cm lengths)*
- *This has been cross-checked by gradually increasing the pressure in the experimental chamber (instead of using the electro-valve) → nice filaments created up to 10 cm*

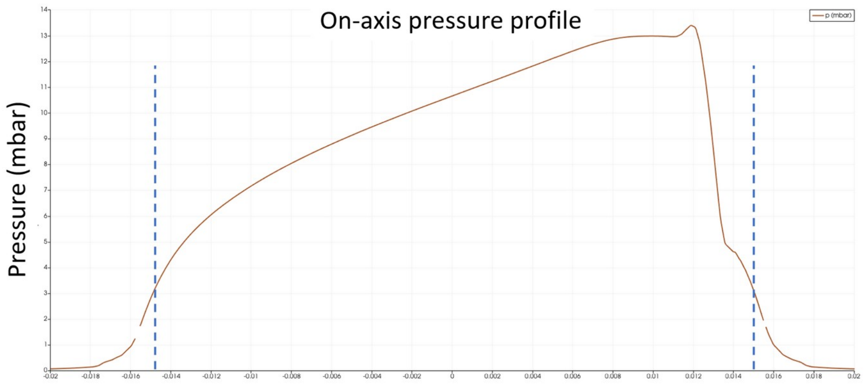
Ongoing improvements

- *3D printed capillaries with shaped inlets for better gas injection*

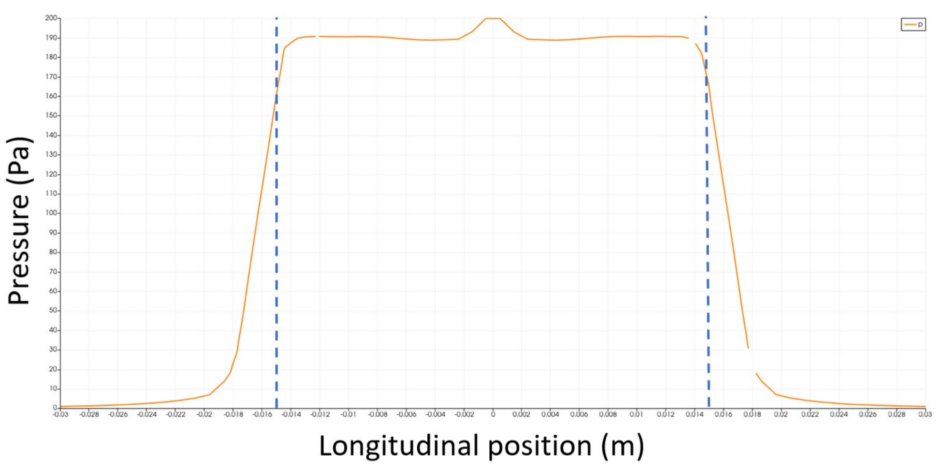
OpenFOAM simulations

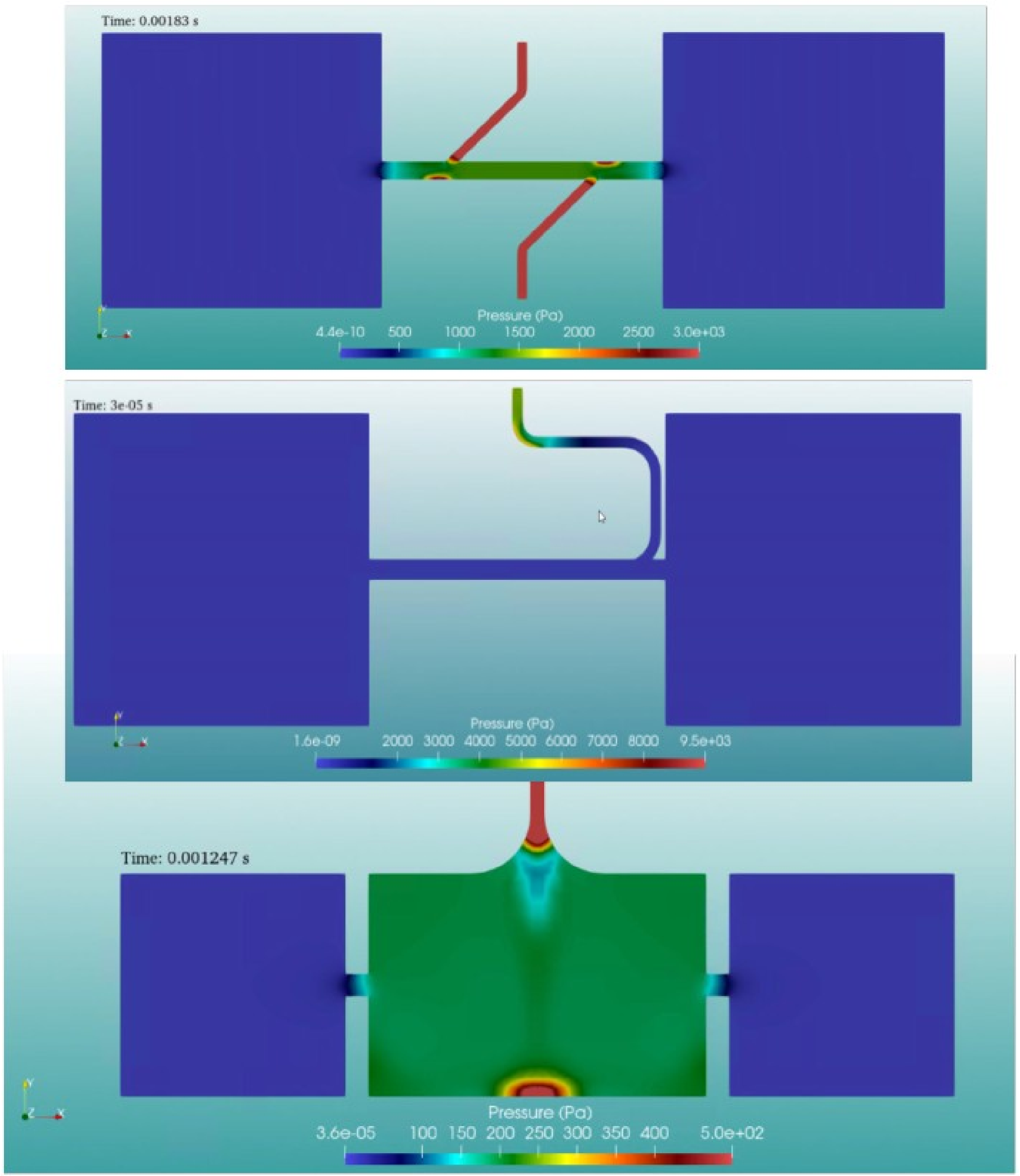


L. Crincoli



On-axis pressure profile





EuPRAXIA-like working point @ SPARC

- The **EuPRAXIA@SPARC_LAB** main operation foresees a **comb beam** with charges up to **450 pC**, generated through **RF compression** in the **first two S-band accelerating structures**.
- The proposed scheme is currently under investigation at SPARC_LAB through **experimental demonstration**.

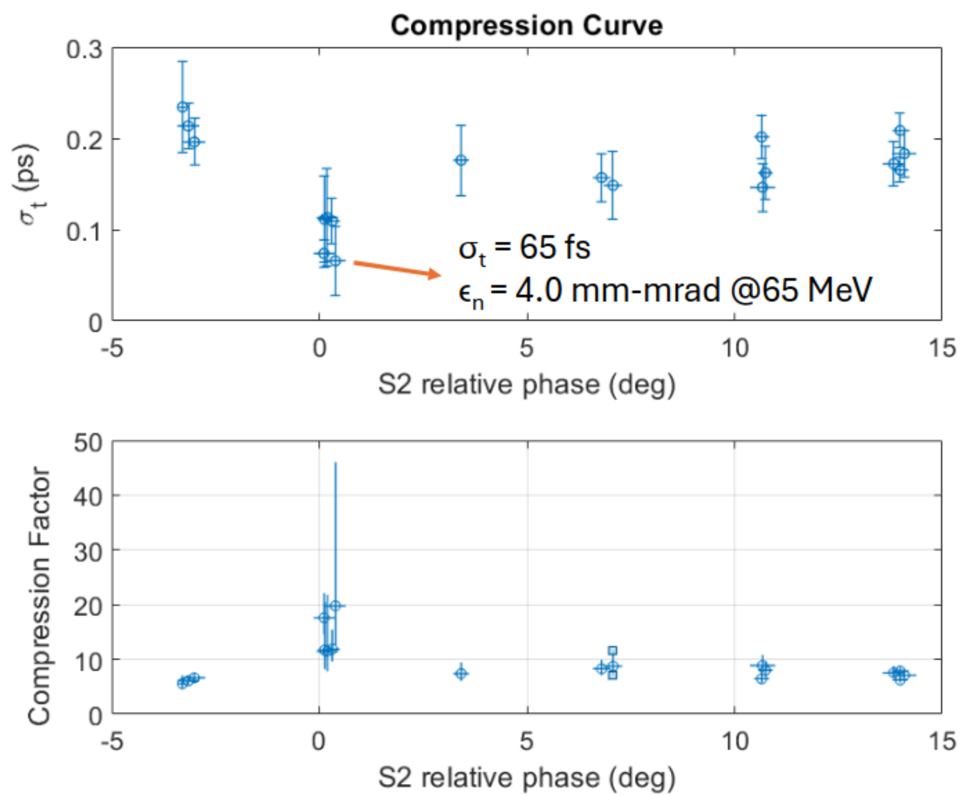
Recent Experimental Results (March 2025 – 2 weeks)

- Experiments performed in **single bunch mode**, with ~**300 pC** charge
- Achieved a **minimum bunch length** of **65 fs (rms)** with normalized emittance: **4 mm·mrad** at **65 MeV**

📌 Target beam parameters of the driver beam for EuPRAXIA@SPARC_LAB WP (@120 MeV)	
Charge	200-400 pC
Bunch length	**~ 160 fs (rms)**
Emittance	**≤4 mm·mrad**

Next Steps

- Further studies planned for Autumn 2025
  → Focus: Comb beam configuration
  → ⚠ Not tested in March due to laser system failure during the shift



Measured compression curve *as a function of the phase of the second accelerating cavity around the zero crossing*

A. Giribono

Possible next activities (tbc)

- High-gradient/high-quality PWFA beams
  - *Acceleration of a low energy spread/emittance witness beam with acceleration >1 GV/m*
- Filament experiment
  - *Demonstration of high-rep rates plasma columns for PWFA*
- Commissioning of the SABINA beamline
  - *Commissioning of the electron beamline, THz undulators and THz beamline*
- Test of the EuPRAXIA working point @ SPARC_LAB
  - *Demonstration of high-current low-emittance beam from an EuPRAXIA-like injector*
- Driver-Witness separation with APLs
  - *Compact plasma-based system with witness focusing/extraction and driver separation features*
- PWFA vs EOS (RF timing)-Plasma (density)-Laser (charge) jitter study
  - *Evaluation of the jitter sources (laser vs RF vs plasma) of the plasma-accelerated beam*
- Commissioning of the EXIN test-beamline
  - *This may be the new beamline dedicated to plasma tests and user experiments (more room available)*

SABINA installations

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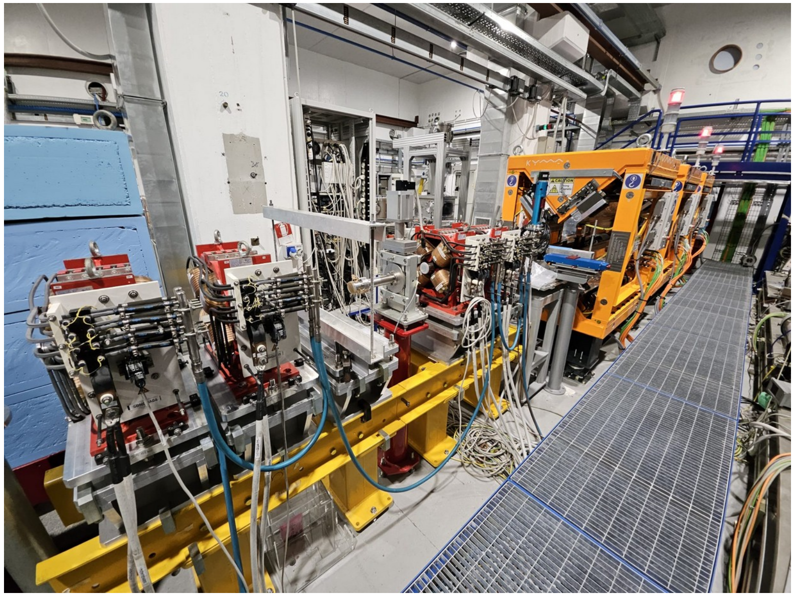
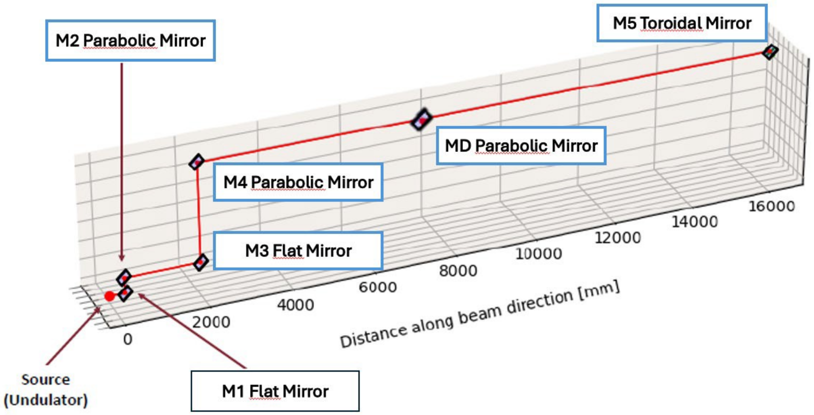
THz user beamline

SABINA project aim to develop a THz radiation production line at SPARC_LAB by means of a system of undulators, chosen to be APPLE-X profiting of their key properties (symmetric focusing properties, tunable polarization,..).



The facility will therefore enable the generation and control of intense pulses in a large spectral extension from 3 to 30 THz for advanced scientific applications.



L. Sabbatini, I. Balossino

Elements ready/delivered:

Almost all electron beamline elements in position

Intra-undulators beam pipe, beam diagnostics and magnetic elements ready for installation

First THz chamber and mirror delivered; final tests ongoing

All THz mirrors delivered to LNF, Vacuum Chamber M1 under testing and assembly

Ongoing activities/Next steps:

Extra-undulator beam pipe: design completed, purchase in progress

Vacuum Chambers: M2 delivery expected soon, M3 and M4 out for order, MD and M5 design ongoing

Control system implementation within the EPICS8 framework ongoing

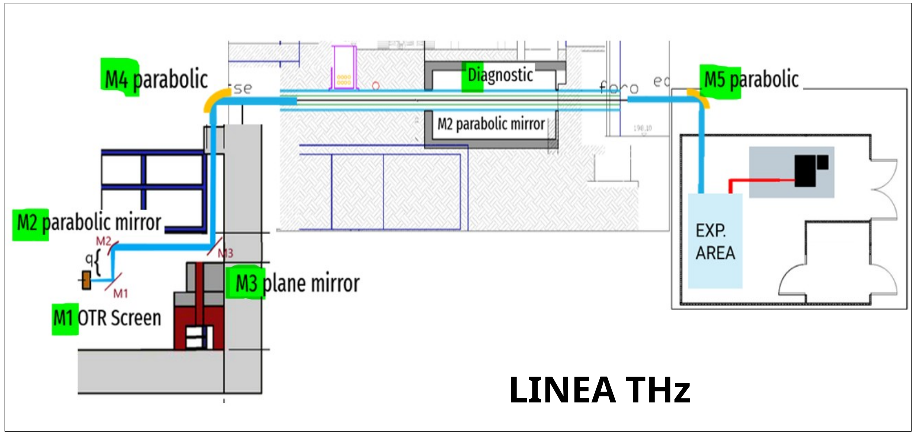
Safety measures (emergency exits, radiation protection) in preparation

Motion motors: purchase order ready

User facility: final design ongoing

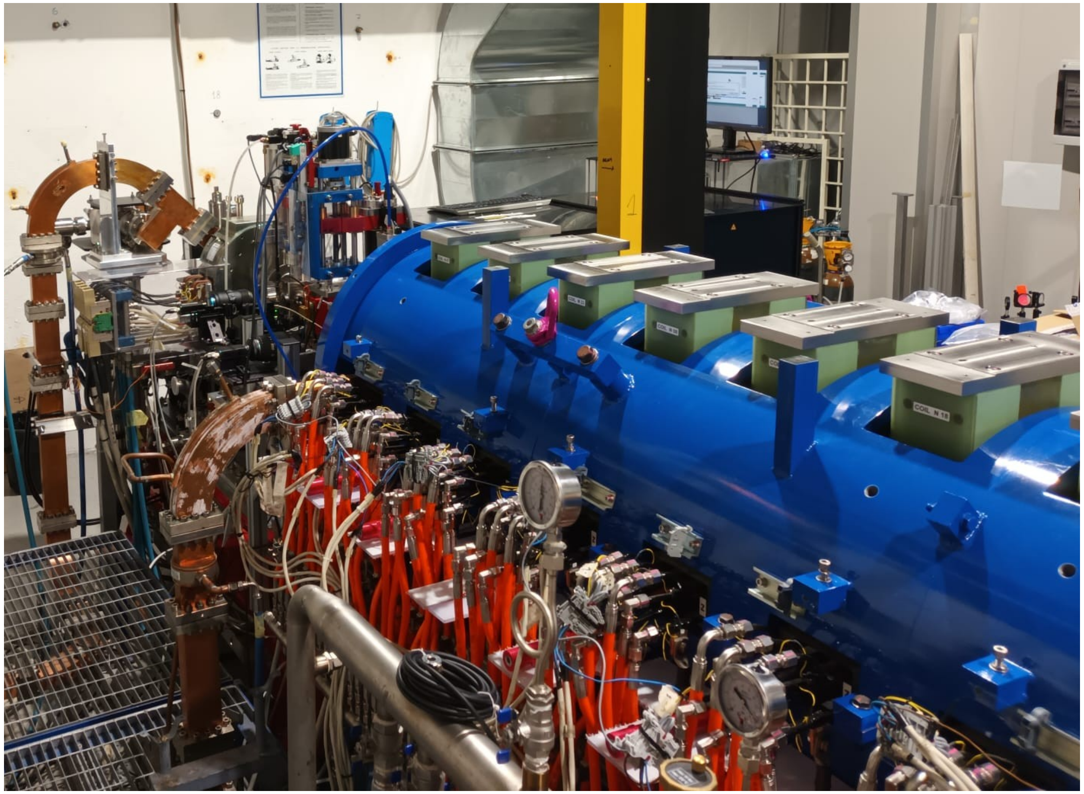
Mirrors' alignment procedure under finalization

Our goal:
TESTING **ELECTRON BEAM LINE BY SEPTEMBER**
TESTING **FIRST THz RADIATION BY EARLY 2026**



S1+S2 new solenoids

Solenoids aligned with beam-based measurements



FLAME - EuAPS

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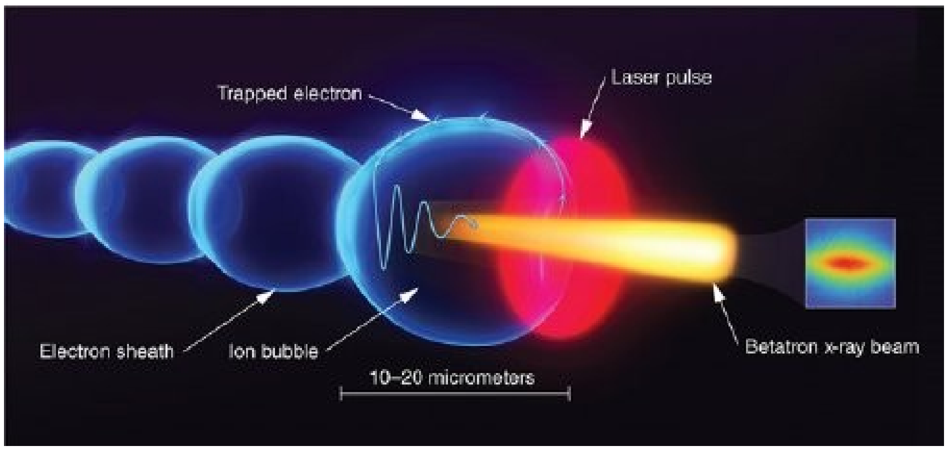
SPARC LAB

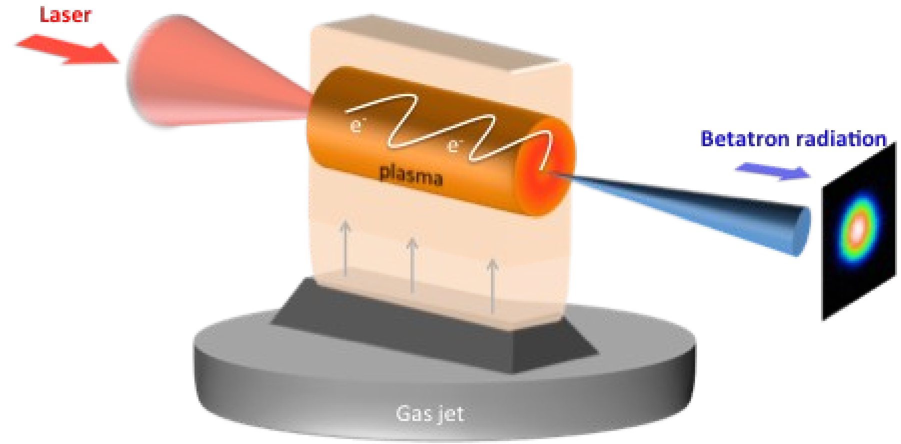
X-ray photon source parameters



A. Cianchi

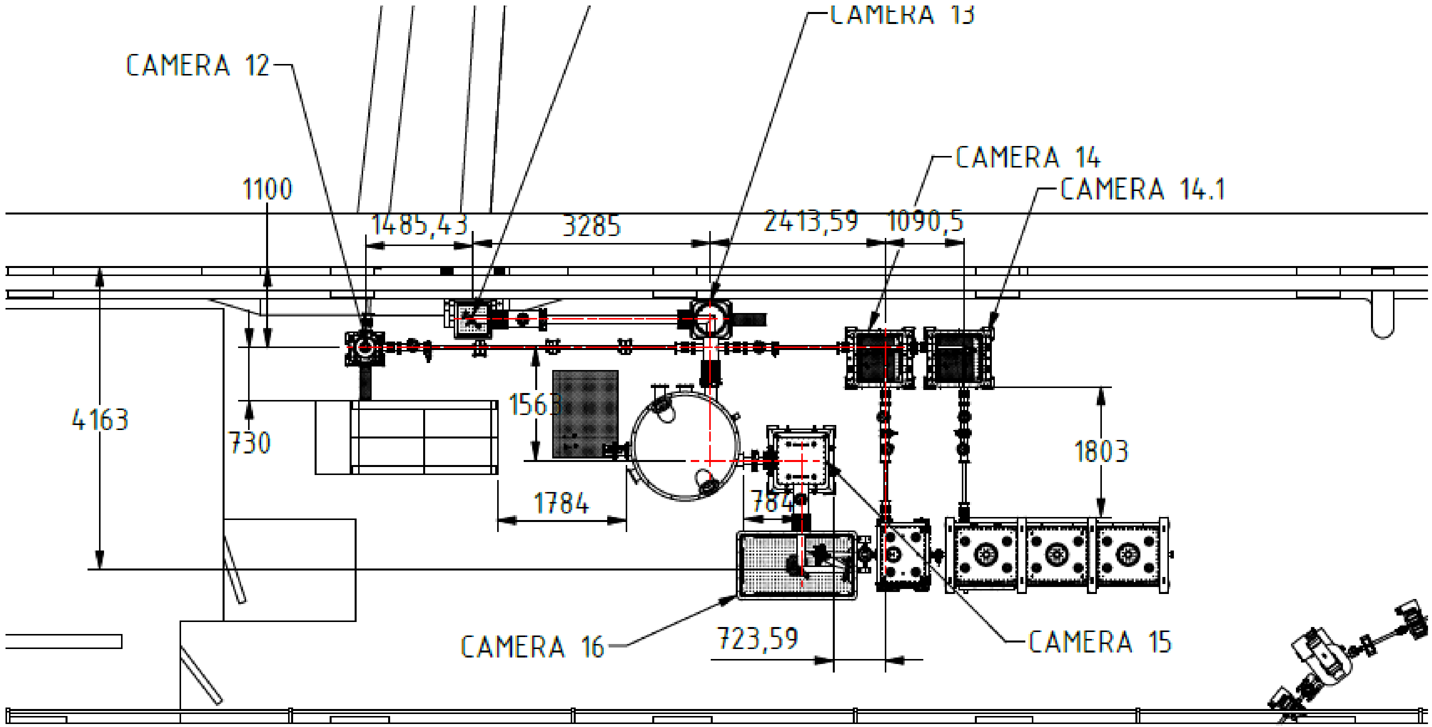
INFN

TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA



Parameter	Value	unit
Electron beam Energy	100-800	MeV
Plasma Density	10^{17}-10^{19}	cm^{-3}
Photon Critical Energy	1 -10 tunable	keV
Number of Photons/pulse	10^{6}-10^{9}	
Repetition rate	1-10	Hz
Beam divergence	3-20	mrad

EuAPS status



- Flame Laser upgrade and refurbishment are ongoing-> end in June
- Installation of transport lines in Flame bunker ongoing -> end in June
- Installation in SPARC bunker started -> end in mid July
- First shots expected before the summer vacation
- Source optimization and characterization -> September to mid October
- Pilot experiment -> before November 30th

Thanks!

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