

SPARC_LAB facility for advanced acceleration and radiation experiments

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The SPARC_LAB facility, operating at the LNF-INFN laboratories in Frascati, has been devoted over the past years to R&D related to accelerators, advanced diagnostics, and generation of radiation ranging from THz to extreme UV light. The facility has recently been significantly upgraded and moved toward user-oriented applications, especially after the approval of two additional projects with the goal to develop radiation sources up to the soft x-ray range and in view of the EuPRAXIA project, whose preparatory phase is ongoing with the support of the European Commission. This paper summarizes the electron beam and radiation parameters and describes the layout and main features of the upgraded facility in view of future user-oriented experimental activities and applications.

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I. INTRODUCTION

The SPARC_LAB [1] test facility operates at LNF-INFN laboratories in Frascati and is devoted to the generation of radiation over a broad range (from THz to the soft x-ray range) and to demonstrating innovative acceleration techniques based on plasma. Today, the research is mainly devoted to plasma-wakefield acceleration experiments with the aim of providing high accelerating fields, up to several GV/m, for high-quality electron beams with small energy spread and normalized emittance) [2]. Following the pioneering results obtained by Wang *et al.* [3] with a laser-driven plasma accelerator, the SPARC_LAB experience culminated with the first demonstration of a free-electron

laser from a beam-driven plasma accelerator [4] obtained both in SASE [5] and seeded [6] configurations. The R&D on plasma is also motivated, in the framework of the EuPRAXIA Preparatory Phase project [7], by the EuPRAXIA@SPARC_LAB user facility that foresees the realization at LNF-INFN of the first ever plasma-driven FEL [8]. At the same time, recent regional and national funding dedicated to the general improvement of the SPARC_LAB facility enabled the upgrading of both the accelerator and laser systems and the equipping of the experimental area with two additional radiation sources dedicated to external users: one employing undulators generating radiation in the THz range and the other based on a plasma stage producing soft x-rays from betatron radiation.

The manuscript is organized as follows. Section II describes the two facility key systems, namely the SPARC photoinjector and the FLAME laser. Section III presents the electron beams and laser pulses that can be generated by these two core systems, the diagnostics employed and the plasma stages used in the experiments

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and characterized in a dedicated laboratory. Section IV describes the three user beamlines dedicated to the generation of radiation based on FEL, THz, and betatron motion. Section V reports the subsystems and main equipment that allow the operation of the SPARC linac and FLAME laser. It also includes a description of the control system employed in both the facilities. Finally, Sec. VI describes the evolution and integration of SPARC_LAB within the EuPRAXIA@SPARC_LAB framework.

II. FACILITY CORE DRIVER SYSTEMS

This section describes the two main pillars of SPARC_LAB, namely the high-brightness ($\approx 10^{15} \text{ Am}^{-2} \text{ rad}^{-2}$) SPARC photoinjector [9] (see Sec. II A) and the high-intensity ($\approx 10^{19} \text{ W/cm}^2$) FLAME laser [10] (see Sec. II B). This unique combination has enabled extensive research into various plasma acceleration schemes including self- and external-injection, as well as laser- and beam-driven methods. Furthermore, the facility supports a broad spectrum of interdisciplinary research activities focused on novel radiation sources. These sources include free-electron lasers (FEL), using both self-amplified spontaneous emission (SASE) and seeded schemes, along with high peak power THz radiation in both broadband and narrow-band ranges. The facility's layout is depicted in Fig. 1. Recently, a third laboratory (PLASMA_LAB) was integrated into the SPARC_LAB framework (see Sec. III E). Its specific purpose is to develop and characterize the plasma stages to be used for the acceleration experiments. Additional details are provided in the subsequent sections.

A. High-brightness SPARC photoinjector

The SPARC photoinjector system utilizes a 1.6-cell S-band ($f_{\text{rf}} = 2.856 \text{ GHz}$) radio-frequency (rf) gun, which delivers robust 120 MV/m electric fields [11]. Electrons are emitted via a copper (Cu) cathode stimulated by a customizable UV laser ($\lambda_L = 266 \text{ nm}$). The shape and duration of this laser pulse (ranging from 0.1 to 10 ps) can be precisely adjusted to meet specific experimental needs. Electrons are accelerated to 6.1 MeV within the gun before injection into the linear accelerator (linac). This linac assembly includes two S-band traveling-wave (TW) structures and a C-band ($f_{\text{rf}} = 5.71 \text{ GHz}$) TW structure, resulting in a maximum achievable beam energy of approximately 180 MeV . The initial TW section also functions as an rf-compressor via the velocity-bunching (VB) technique [12]. Solenoid coils encircling the first two sections offer additional magnetic focusing during VB, allowing for precise control of emittance and envelope oscillations [13]. A specialized diagnostics transfer line, featuring a spectrometer and an rf-deflector (RFD), enables full 6D beam characterization by measuring the beam's longitudinal phase space (LPS), projected emittance, and slice emittance [14]. The SPARC photoinjector feeds three distinct beamlines located downstream of the main magnetic spectrometer. (i) The first beamline is dedicated to FEL research, incorporating six magnetic undulators (Sec. IV A). (ii) The second is a dogleg line [15] hosting three THz undulators designed for user applications (Sec. IV B). (iii) The third beamline is currently under development and is intended for the tests of new diagnostics as well external user experiments.

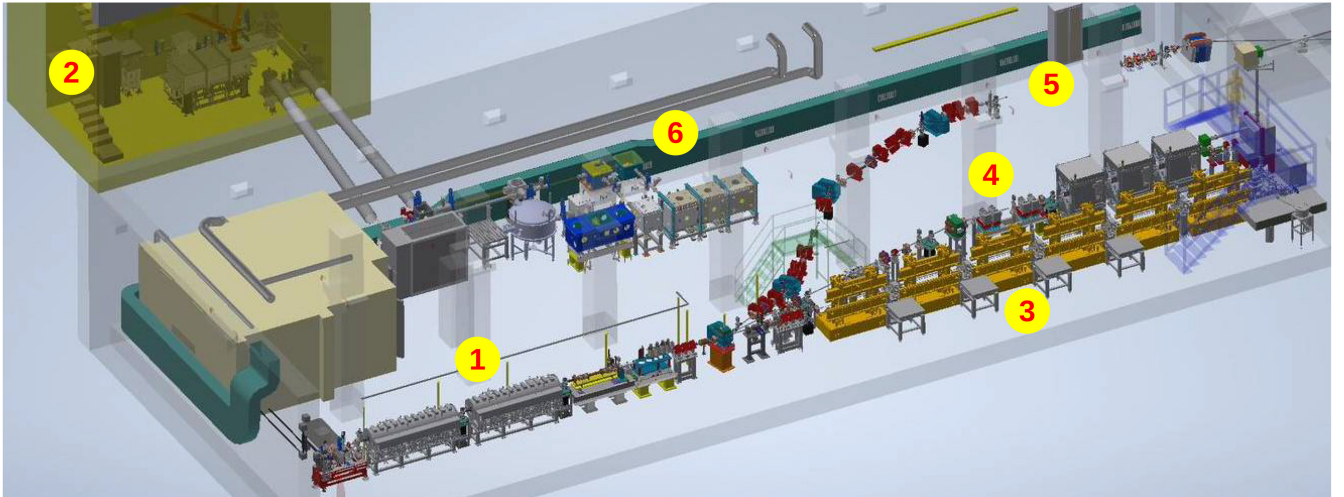


FIG. 1. Layout of the SPARC_LAB facility. The bunker hosts the SPARC photoinjector (1), its photocathode laser (2), and the three experimental beamlines: the FEL (3), the SABINA THz radiation source (4), and, finally, a test beamline (5) available for user experiments. The FLAME bunker (not shown here) is connected to the SPARC bunker by means of an in-vacuum laser transport line and drives the EuAPS betatron x-ray source (6).

TABLE I. Range of electron beam parameters that can be obtained with the SPARC photoinjector.

Parameter	Value
Number of bunches	1–5
Delay between bunches	0.5 ps–20 ns ^a
Charge	10 pC–2 nC
Duration	20 fs–10 ps
Energy	5–180 MeV
Energy spread	0.1–5 MeV
Normalized emittance	0.3–10 μm

^aDelays larger than ≈ 360 ps (i.e., one S-band rf period) are achieved by injecting the bunches in different rf buckets.

The nominal range of electron beam parameters that can be experimentally obtained is summarized in Table I.

B. High-intensity FLAME laser

The FLAME laser facility [16] aims to investigate processes associated with laser-matter interaction under extreme intensities (up to 10^{19} W/cm²). Within the scope of the EuPRAXIA project [7], FLAME is transitioning into an operational facility capable of delivering stable, laser-generated bunches consisting of ions, electrons, and x-rays from betatron radiation. The FLAME laser is a compact, femtosecond system that delivers compressed pulses with a maximum energy of 5 J and 10 Hz repetition rate. The pulses are temporally compressed down to 25 fs, achieving a peak power of 200 TW. The system is based on Amplitude Technology’s Pulsar design, augmented with a custom front-end and a modular configuration of pump lasers. As a titanium-sapphire laser, it operates on the principles of chirped pulse amplification [17]. Following the recent upgrades of the system, the FLAME laser is now used to directly drive the EuPRAXIA Advanced Photon Source (EuAPS) beamline [18] for the generation of soft x-rays (see Sec. IV C). The main parameters of the FLAME laser system are summarized in Table II.

TABLE II. The FLAME laser system parameters.

Parameter	Value
Laser wavelength	800 nm
Laser spectral bandwidth	80 nm
Main laser compressed energy	5 J
Main laser duration	>25 fs
Main contrast ratio	<10 ^{−9}
Main repetition rate	single shot −1 Hz
Probe laser energy	<40 mJ
Probe laser duration	~30 fs
Probe repetition rate	10 Hz

III. EXPERIMENTAL PLATFORMS AND METHODS

This section describes the main properties of (i) the electron beams that can be generated with the SPARC photoinjector and (ii) the laser pulses produced by the FLAME laser system. Particular emphasis is placed on the plasma acceleration schemes, which are able to extend the electron energy range beyond what is possible using only the rf linac.

A. Beams from SPARC photoinjector

The SPARC photoinjector has wide flexibility and is able to provide a wide range of working points for the electron beams in terms of charge and duration, and therefore peak current, with overall high quality in transverse phase space and relatively small projected emittances. The beam energy can be tuned over a wide range, from 5 to 180 MeV, by acting on the rf system of the accelerating sections. In addition, a slightly off-crest operation can be used to reduce the final energy spread or properly manipulate the beam LPS. The tunability in terms of beam duration is ensured thanks to the on-crest or rf compression operation of the first accelerating section. With the velocity-bunching (VB) configuration, longitudinal compression is achieved by slightly accelerating the tail of the electron beam while concurrently decelerating its head. This process results in a rotation of the beam’s longitudinal phase space, which becomes simultaneously chirped and compressed [19]. To prevent uncontrolled emittance growth, solenoids embedded in the linear accelerator are energized to provide the necessary additional focusing [13]. A key advantage of VB over alternative methods is that it does not necessitate the use of masks or scrapers in a dispersive section, which avoids charge loss and allows for a highly compact beamline design. The rf compression has been already exploited to compress bunches with few tens of pC charge down to tens of femtosecond durations and less than 10 μm normalized emittances. Similarly, higher charges up to 2 nC have been compressed to durations on the order of 200–300 fs. On the other hand, the on-crest operation can ensure the largest available energies (up to 180 MeV) with large charge, picosecond duration and, at the same time, less than 2 μm normalized emittances.

1. Multibunch configuration

The SPARC photoinjector can generate beams consisting of one to several bunches with typical separations on the order of 0.5–5 ps. When operating as an injector for the plasma acceleration stage, two bunches, hereinafter called *driver* and *witness*, are produced [19]. These bunches are directly generated on the photocathode by two UV laser pulses delayed by several ps [20,21]. Figure 2 shows the simulated LPS of the driver and witness bunches with charges of 500 and 50 pC, respectively. The temporal

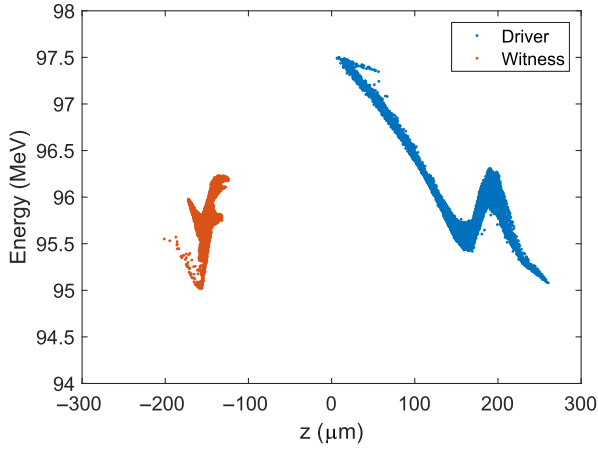


FIG. 2. Simulated longitudinal phase space of the 500 pC driver and 50 pC witness bunches.

separation between the bunch centroids is set to ≈ 1 ps. Their relative separation and durations are tuned with VB [12], which requires injection in the first TW section at the rf zero crossing. The energy chirp of the resulting bunches is made complementary by over-compressing the witness (the tail overcomes the head) while under-compressing the driver.

B. Beam-driven plasma acceleration

The energy of the witness bunch can be boosted over short distances in a plasma stage by the wakefields generated by the driver bunch. The plasma is generated in a few centimeter-long capillary installed in a vacuum chamber equipped with a windowless differential pumping system. The chamber can host capillaries as long as ≈ 20 cm consisting of a single or several shorter stages [22]. Previous results have demonstrated the ability to

accelerate ultrashort bunches with low energy spreads [2]. Figure 3 shows the resulting energy spectrum of an electron beam without and with a 3 cm-long plasma acceleration stage. The plasma was able to provide accelerating gradients as large as ≈ 1.2 GV/m with typical densities of $n_p \approx 4 \times 10^{15} \text{ cm}^{-3}$. Additionally, the interaction chamber can be used to investigate beam-plasma interactions. In this regard, experiments were performed to study the self-modulation and hosing instabilities [23], and the plasma screening of the space-charge field of the bunch [24]. A beam-based plasma density measurement technique was also tested [25], as well as the guiding of electron bunches in curved plasma channels [26]. Figure 4 shows the layout of the plasma interaction area consisting of the plasma stage and two triplets of permanent-magnet quadrupoles (PMQ) [27]. Capillaries as long as ≈ 15 cm can be installed in a vacuum chamber.

C. Electron beam diagnostics

This section presents an overview of the diagnostics devices and techniques currently employed in the facility. Apart from commercially available diagnostics commonly employed in any accelerator machine (e.g., beam position monitors, current monitors, etc.), several advanced diagnostics have been developed especially in view of plasma-based experiments [7,28]. In the following, a description of each setup is provided.

1. Transverse diagnostics

The beam transverse profile is measured by using scintillating crystals. YAG:Ce crystals with 100 μm thickness are commonly used. The diameter of the crystal is in the range 0.5–1 inches, depending on the position along the beamline. In total, nine transverse YAG:Ce screens are

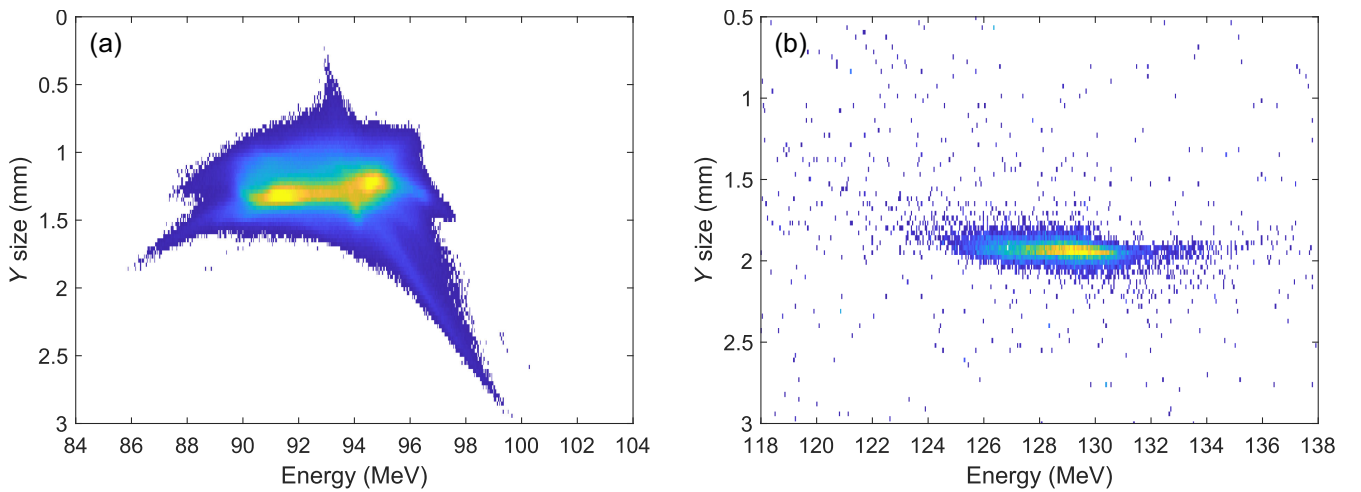


FIG. 3. Experimental results of plasma acceleration. The snapshots show energy spectrum images of (a) the driver and witness beams without plasma and (b) the plasma-accelerated witness bunch. The images are obtained by turning on the magnetic spectrometer and observing the deflected beam on a large acceptance.

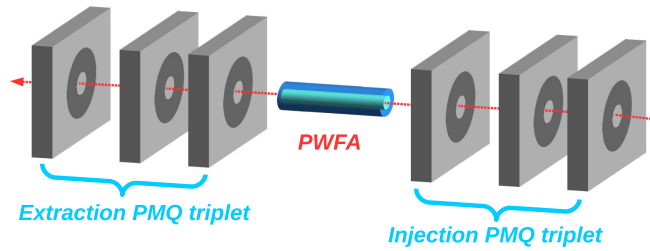


FIG. 4. Layout of the plasma interaction area. The PWFA module consists of a 3D-printed capillary containing plasma. The beam is focused into the plasma by the first PMQ triplet. Downstream of the capillary, a second triplet of PMQs is used to extract the plasma-accelerated beam.

installed along the linac, plus additional ones located along the three experimental beamlines. The transverse diagnostics located upstream of the plasma acceleration module has been extensively designed to measure very small transverse beam sizes. For PWFA experiments, the transverse matching in the plasma requires the electron beam to be focused down to $\approx 10 \mu\text{m}$ sizes. For this purpose a special diagnostics screen has been installed to avoid the saturation that can be reached using the YAG:Ce crystal. In this case an additional optical transition radiation (OTR) screen has been installed below the YAG:Ce crystal. The screen has a 100 nm-thick aluminum layer deposited on a silicon wafer. Such a screen is well suited to measure the beams with small transverse size, as OTR emission is not limited by saturation. At the same time, it is challenging to use with the unfocused beams due to the low photon yield, thus both OTR screen and YAG:Ce crystal are installed at this diagnostics station. The optical system at this location has a total point spread function $\approx 5 \mu\text{m}$, which allows us to measure the beams with transverse size less than $10 \mu\text{m}$.

The projected transverse emittance is measured using classical quadrupole scan. Figure 5 shows the diagnostics

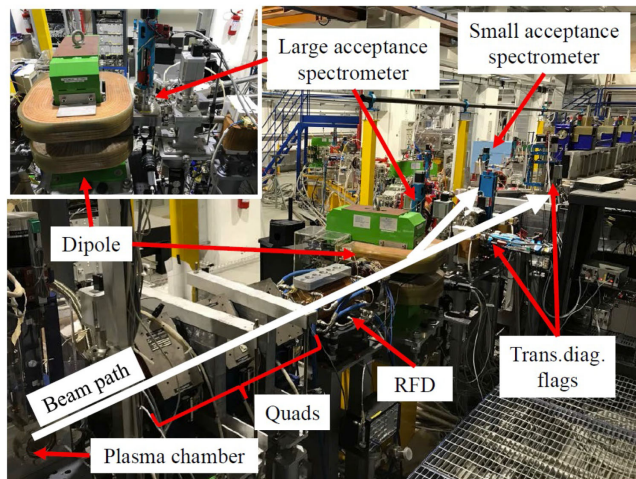


FIG. 5. Main diagnostics station used for the complete beam characterization (energy, duration, emittance).

station located downstream of the plasma chamber. It consists of a triplet of electromagnetic quadrupoles for beam focusing, a scintillating screen, a dipole, and the RFD. Considering the drifts, the station has a total length of ≈ 4.8 m. Figure 6 shows the resulting emittance obtained with the quadrupole-scan technique when the electron beam is generated by means of a UV and blue laser pulse. With blue, in particular, a larger intrinsic thermal emittance is expected due to the release of photoelectrons at larger energies: assuming $\Phi_w \approx 4.6$ eV for copper, the release energy is indeed ≈ 1.4 eV for blue (the overall photon energy is assumed to be $\approx 2 \times 3$ eV) and ≈ 0.06 eV for UV (≈ 4.66 equivalent photon energy).

2. Energy measurement

The main diagnostics station includes the magnetic spectrometer. The spectrometer beamline is deviated from straight propagation by 14° , coinciding with the second experimental line. The spectrometer screen is located 3.27 m downstream of the dipole with a resolution ≈ 0.1 MeV/mm for a typical electron beam with ≈ 100 MeV energy. The diagnostics uses a 1 inch Ce:YAG crystal and thus the spectrometer provides an energy acceptance on the order of 2.0–2.5 MeV. Such a spectrometer is fully sufficient for diagnosing the typical beams produced by the SPARC linac, which have relative energy spreads well below the percent level. The PWFA experiments, however, required several changes of the spectrometer in order to provide a larger energy acceptance. Indeed, the final energy of the accelerated beam (witness) can be much larger than the initial one by tens of MeV. In addition, the energy loss of the drive beam is a powerful

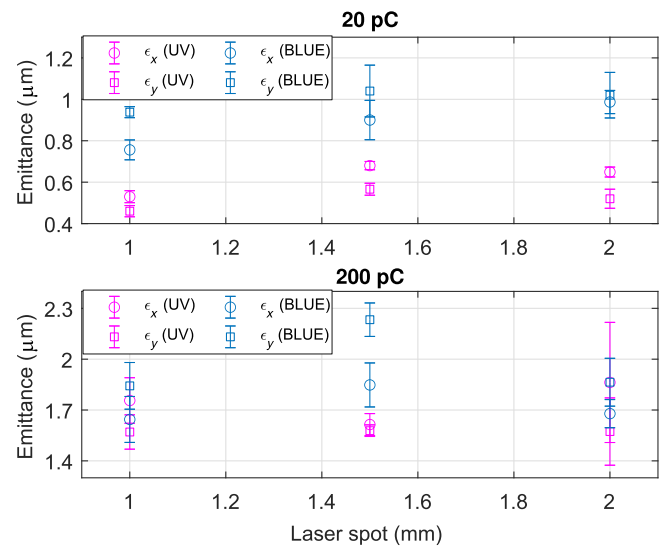


FIG. 6. Comparison of transverse emittance obtained with UV and blue laser pulses in the low-charge (20 pC, top) and high-charge (200 pC, bottom) regimes, as a function of the laser spot size on the cathode.

diagnostic [25] and should be measured as well, even if it may have energy spreads on the order of ≈ 10 MeV. This required the installation of an additional diagnostics screen, see Fig. 5 (inset). The new screen is a 50×20 mm, YAG:Ce crystal located 33 cm downstream of the spectrometer. Such screen provides full acceptance up to ≈ 50 MeV in a single frame. Significant contribution from the beam transverse size and, naturally, dropped energy resolution (≈ 1.0 MeV/mm) makes such a screen not suitable for normal operation (with small energy spreads) but it proved to be very helpful during the PWFA experiments.

3. rf-deflector

The characterization of the longitudinal and transverse phase space of the beam at the injector exit is crucial for the tuning and verification of all photoinjector performance parameters. In addition to the beam's energy spectrum, it is necessary to accurately measure its temporal profile. To achieve this, the facility is equipped with an rf deflector (RFD) [29] installed between the three electromagnetic quadrupoles and the magnetic spectrometer (see Fig. 5). The RFD temporally shears the beam, displacing its longitudinal slices proportionally to their relative positions. The applied rf voltage acts on the vertical plane, yielding a null effect at the bunch center and a linear transverse deflection for the head and tail. The SPARC RFD consists of a 5-cell standing-wave structure operating in the π -mode. This design allows for a maximum transverse deflecting voltage of more than 3 MV, using power directly split from the SPARC rf gun klystron waveguide by means of a 10 dB directional coupler. The drift distance between the RFD and the measurement screen is approximately 3.5 m, which provides a temporal calibration in the range of 0.8–5 ps/mm (depending on the mean beam energy), allowing us to measure beams as short as approximately 20 fs (rms).

The RFD and spectrometer can be used in combination to measure the emittance of the plasma accelerated beams [14]. The spectrometer allows to separate the bunches in the horizontal plane thanks to their energy difference. Therefore, on the spectrometer screen, it is possible to measure the bunches' vertical emittance. Similarly, for the horizontal emittance, the RFD is used to separate the bunches in time along the vertical plane on the located screen straightforward (while the spectrometer is turned off). Combining these two measurements, it is possible to fully characterize the emittance of the witness bunch [30] and to determine its optical parameters for matching into the FEL undulators [5,6].

4. Transition radiation

Transition radiation (TR) is additionally utilized for longitudinal diagnostics. A Michelson interferometer is employed to reconstruct the longitudinal charge profile of the electron bunches by measuring the coherent part of the TR spectrum (CTR). The setup consists of two highly

polished mirrors and a 12- μ m-thick Mylar layer that functions as a beam splitter. Only the backward radiation component is collected. This light is extracted from the vacuum chamber through a diamond window and collimated by a 90° off-axis parabolic mirror, which directs it toward a flat mirror that reflects the radiation into the interferometer. The light is then split into two beams: one is transmitted toward a fixed mirror, while the other is reflected in the direction of a movable mirror. The beams are subsequently recombined at the beam splitter and measured using a pyroelectric detector. Due to the limitations from the pyrodetector and Mylar beam splitter, the interferometer is most efficient in the spectral range ≈ 0.1 –30 THz, which allows us to measure the beams with rms duration down to ≈ 10 fs [31,32]. In addition to this, we use TR radiation also for user-oriented applications using the THz radiation in a pump-probe configuration [33].

5. Electro-optical sampling

Electro-optical sampling (EOS) provides a nonintercepting, single-shot diagnostic for measuring the bunch longitudinal profile and time-of-arrival. At SPARC_LAB, the EOS system employs both zinc telluride (ZnTe) and gallium phosphide (GaP) crystals, utilizing a portion of the infrared (IR) laser sourced from the main photocathode system. This setup yields a temporal resolution for the bunch duration on the order of 90 fs (rms). Because the probe laser is directly split from the photocathode laser system, it is inherently synchronized with the electron beam. This natural synchronization allows for the direct measurement of the relative timing jitter between the photocathode laser and the beam [15]. The encoding of the beam longitudinal profile is achieved using a spatial decoding setup, where the laser crosses the nonlinear crystal at an angle of 30° [34]. The configuration of the EOS diagnostics is detailed in Fig. 7. The EOS is installed upstream of the plasma acceleration stage, enabling the

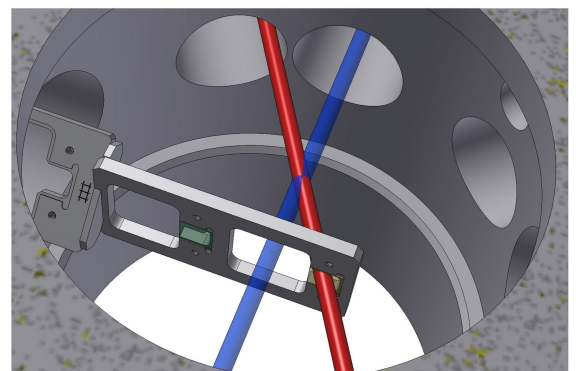


FIG. 7. Setup of the EOS diagnostics located downstream of the SPARC linac. The electron beam (blue line) passes near one of the two electro-optic crystals that is simultaneously crossed by the probe laser (red line).

monitoring of bunches immediately before they are injected into the plasma medium.

D. High-intensity laser pulses from FLAME

The FLAME laser system [16] is equipped with a cleanroom that hosts the front-end components, the high-power multipass amplifier, and a compact low-power laser compressor. Two experimental areas are available for research: the guiding experimental measurement (GEM) area and the TW experimental target (TET) area. The laser pulses generated by the front-end system are split into two beamlines operating at a 10 Hz repetition rate. The first line operates at low energy (≈ 40 mJ), is compressed within the cleanroom, and is delivered to the GEM area via an additional transport line (referred to as the “probe line”). The second line (the “main line”) undergoes further amplification within the multipass amplifier, reaching approximately 7 J, before it is compressed and delivered to the TET area.

1. Low-intensity target area

The low-intensity laser line in the FLAME laboratory is split from the main beam by means of a beam splitter placed at the exit of the second multipass amplifier. Subsequently, this beam is compressed to a duration down to ≈ 30 fs. A dedicated station is located in the FLAME bunker in order to carry out laser-plasma interaction tests between this low-intensity pulse and different types of targets. The maximum achievable intensity on the target can be as large as 10^{16} W/cm². The experimental station is set to drive different experimental campaigns, such as the guiding of a laser pulse by means of plasma or the ionization of gases by means of the laser pulse itself. For example, this kind of setup can be used to investigate the optimal matching conditions between the pulse and a plasma capillary discharge of a few centimeters in length and a few hundred microns in diameter. In this case, the goal is to be able to optically guide the laser pulse, over several Rayleigh lengths, by operating on the plasma refractive index. In general, it is possible to guide a Gaussian laser pulse if its waist size is matched to the transverse profile of the plasma density, i.e., if the transverse density within the plasma channel has a certain parabolic distribution.

It is possible to detect the transverse and longitudinal profiles of plasma density by exploiting the Stark broadening effect (see Sec. III E 1). The laser intensity is large enough to ionize the gas without the use of any discharge. For instance, by using hydrogen, plasma densities up to $\approx 10^{15}$ cm⁻³ can be achieved [35,36]. Such a low-intensity laser pulse is also used as a probe laser for laser-plasma interaction experiments in which the main pulse of the FLAME laser is used as a pump. For these pump-probe experiments, only a small portion of the beam is required.

The benefit of such a configuration is that the pump and probe laser pulses are inherently synchronized, being the laser front-end common to both the pulses.

2. High-intensity target area

The uncompressed pulse from the front-end (at an energy level of 600 mJ) is further amplified by a third high-energy multipass amplifier stage, consisting of a 4-pass amplifier pumped by 20 J of 532 nm light generated by ten Propulse+ Nd:YAG lasers from Amplitude Technologies. The amplifier features a water-cooled $50 \times 50 \times 20$ mm³ Ti:Sa crystal. The 800 nm output pulse reaches 7 J energy before compression at a 10 Hz repetition rate. When operating at full power, the amplified pulse is expanded to approximately 65 mm before entering an attenuator, which enables control of the output energy from 5% to 100% in 1% steps. Before entering the final compressor, the beam is expanded by an additional refractive telescope to approximately 100 mm diameter. An optical compressor, utilizing a four-passes scheme and installed in a vacuum chamber at 10^{-6} mbar, is able to recompress the pulse down to 25 fs without any residual spatial chirp.

Pulse optimization and metrology are conducted in the same room, utilizing a beam extracted via the insertion of a mirror along the transport line downstream of the compression stage. The compressor chamber itself hosts a gold-coated grating compressor arranged in a folded configuration that uses a retroreflector, ensuring a 75% efficiency. With an energy of ≈ 5.2 J after compression, a peak power on the order of 200 TW is achieved at the minimum pulse duration of 25 fs. Figure 8 shows a typical temporal measurement retrieved with the APE SPIDER. A series of remotely controlled mirrors are then used to transport the beam from the compressor up to the experimental area. Here, a dedicated vacuum chamber is installed. The laser is focused by means of a 15°, gold-coated, off-axis parabolic mirror, reaching a transverse size of about 5 μ m radius.

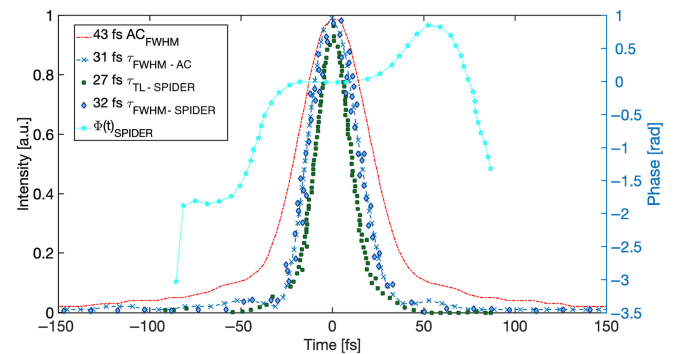


FIG. 8. Temporal measurement of the high-power beamline performed with a SPIDER diagnostics in the high-power compressor area. A simultaneous measurement was performed using an autocorrelator to cross-check the results.

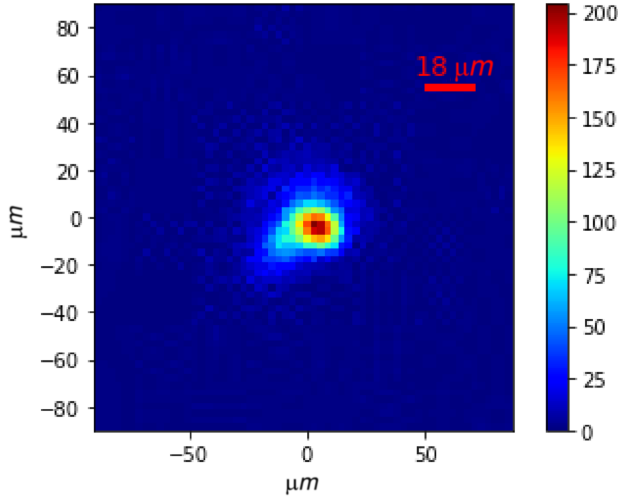


FIG. 9. Focal spot detected by a CCD camera placed in the laser focal plane.

Pulse optimization and metrology of the interacting laser are carried out in the same experimental area extracting part of it by means of a mirror. The extracted beam is delivered in a characterization station with temporal, spatial, and spatio-temporal coupling diagnostics. Figure 9 shows the laser spot transverse distribution. The TET area is dedicated to different experimental campaigns, among them gas-solid target interaction, high-power laser guiding for external injection experiments, and plasma characterization experiments [16]. Here several activities are carried out for user-oriented applications in view of EuPRAXIA, especially regarding laser-driven plasma acceleration experiments.

E. Plasma laboratory

The research on plasma sources is carried out in a dedicated laboratory called PLASMA_LAB. Here several capillary prototypes have been tested and completely characterized before the installation in the SPARC bunker, where the plasma acceleration experiments are performed. So far, capillaries as long as 50 cm have been tested by ionizing injected gas of different species (hydrogen, nitrogen, and argon). Ionization is obtained by applying a high-voltage discharge current through the two inlets at the capillary ends. Discharge currents as large as 4 kA have been successfully obtained. Once the plasma is generated, a spectroscopic diagnostics is used to probe its main properties [37]. Temperature, pressure and plasma electron density, in particular, represent the fundamental parameters that need to be investigated to optimize the plasma evolution and matching with the electron beam [38].

1. Plasma diagnostics

The setup available in PLASMA_LAB is shown in Fig. 10. The plasma source is represented by the gas-filled capillary. One or more gas inlets feed the capillary with

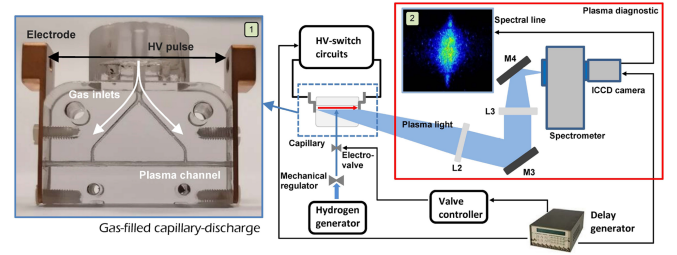


FIG. 10. A 3 cm long gas-filled capillary-discharge (1) with two symmetric inlets. (2) The plasma diagnostics based on the Stark broadening technique.

typical pressures on the order of 10–50 mbar by means of a high-speed electro-valve. This is placed 20 cm from the capillary and is used to control the gas filling time and repetition rate (1–100 Hz). A high-voltage pulser provides the discharge current that ionizes the gas. Its timing is controlled by means of a delay generator (Stanford Research DG535), also used to synchronize the gas injection with the plasma diagnostics.

The resulting plasma densities are usually in the range 10^{15} – 10^{19} cm $^{-3}$ and measured by a spectroscopic analysis of the plasma-emitted light [39], which is collected with an imaging spectrometer (SpectraPro 275) equipped with an intensified CCD camera (Andor Istar 320). The electron density distribution can be obtained by measuring the spectral line-width $\Delta\lambda$ of specific lines of the Balmer series centered at $H_\alpha \approx 656.3$ nm and $H_\beta \approx 486.1$ nm. The resulting plasma electron density is then estimated as $n_e \approx 8.02 \times 10^{12} (\Delta\lambda/\alpha)^{3/2}$ cm $^{-3}$, being α a normalization parameter associated with the chosen Balmer wavelength. The results for a 3 cm long capillary with 1 mm diameter and two symmetric inlets are presented in Fig. 11.

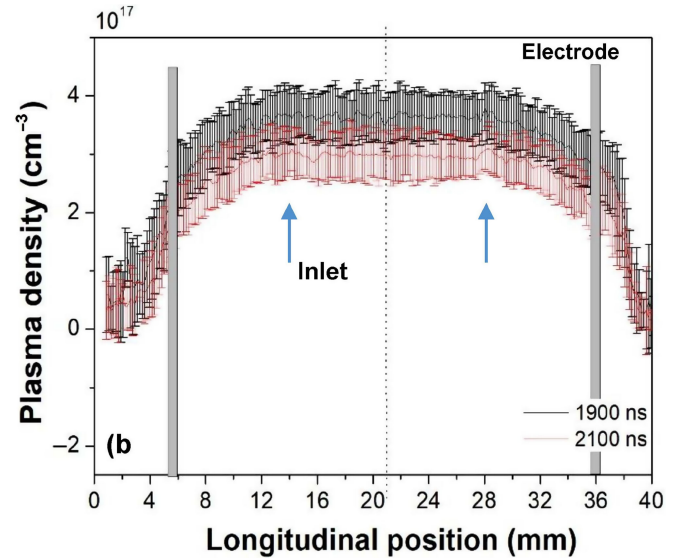


FIG. 11. Longitudinal plasma density profile obtained by measuring the H_β Balmer spectral line centered at 486.1 nm.

By using the intensified CCD camera mounted at the exit of the spectrometer, the spectral line width is obtained, with the x coordinate representing the wavelength of the spectral line. The y axis reproduces the longitudinal distribution of the plasma electrons along the source.

2. Plasma filaments

As an alternative to discharge-generated plasmas, we also adopt laser pulses to produce plasma filaments [40]. Laser-driven plasma-based sources operate in a markedly low-energy regime, requiring laser pulses with energies of only a few tens of mJ, in stark contrast to the joules typically needed in discharge-based systems or high-power laser platforms. This approach eliminates the need for high-voltage discharge infrastructures and significantly reduces energy deposition in the interaction region, thereby avoiding the use of high-temperature-resistant materials designed to withstand substantial thermal loads. The modest gas need to reach the desired plasma density enables operation with minimal gas injection, making the system compatible with vacuum environments suitable for continuous-flow gas operation. Furthermore, laser-based schemes support high repetition rate operation, extending up to the multi-kilohertz regime, while inherently eliminating time jitter since the same laser pulse simultaneously drives both electron injection and plasma formation. Finally, the characteristic dimensions and radiation properties of the source are readily tunable through straightforward adjustments of the laser parameters and/or gas target conditions, offering a high degree of flexibility for application-specific optimization.

In this case, the setup consists of a low-energy (~ 10 mJ) self-guided laser that can ensure high repetition rates (10 Hz) plasma channels, as shown in Fig. 12, with high stability and tunability by adjusting the laser parameters. Precise control of the plasma filament is crucial for plasma-based accelerators, so two different techniques, namely the side imaging and the Stark broadening techniques, have been implemented to precisely measure its density, temperature and dimensions. We obtained a stable generation of a 4 cm long channel with a $300\ \mu\text{m}$ diameter. The plasma

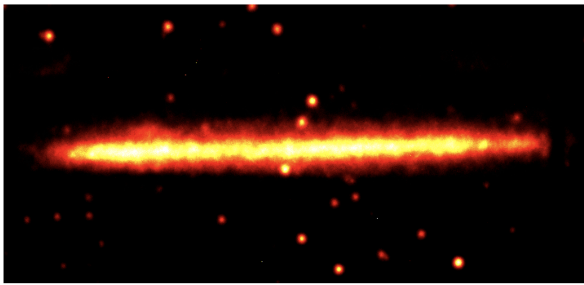


FIG. 12. Snapshot of a 4-cm-long, $300\ \mu\text{m}$ transverse size plasma filament generated by a low-power laser pulse taken via the side imaging technique.

density and temperature are $n_e = 10^{16}\ \text{cm}^{-3}$ and $T_e \approx 1.3\ \text{eV}$ with a decay time of about 8 ns. The typical transverse size of such plasma filaments is $\approx 100\text{--}400\ \mu\text{m}$ with lengths on the order of several centimeters when employing a few tens of mJ laser energies. The interaction length can be extended to several meters by employing higher laser energies [41] and by appropriately tuning the transverse beam dimensions, temporal length, and/or the gas type (hydrogen, nitrogen, and argon) and pressure, as inferred from the envelope equation presented in Ref. [40]. This model describes the nonlinear propagation of an ultrashort laser pulse by accounting for diffraction, group-velocity dispersion, Kerr self-focusing effect, plasma-induced absorption and defocusing, as well as energy losses associated with multiphoton and tunnel ionization.

IV. RADIATION SOURCES

The generation of electromagnetic radiation from ultra-relativistic electron beams has been one of the main purposes of SPARC_LAB from its origins. The goal has been to provide a wide and tunable radiation source with wavelengths spanning from the THz and far-infrared to the visible and extreme-UV and up to the soft x-ray range. The SPARC photoinjector successfully drove many FEL proof-of-principle experiments by using its high-brightness electron beams [42–47] and then by employing the plasma accelerator stage [5,6]. Similarly, a long R&D was carried out on coherent THz radiation [48,49]. The main purposes were its use as a diagnostics tool [50,51] and as a stable and tunable radiation for user experiments [33]. The successful operation of the SPARC_LAB THz source led to the design and realization of a user-dedicated beamline that generates SASE FEL in the THz range by using three undulators installed on the second beamline of the SPARC bunker. Similarly, the recent results achieved in the field of plasma acceleration pushed toward the development of a second user beamline delivering soft x-rays from the betatron radiation generated by laser-plasma accelerated electron beams. The details of the three radiation sources are provided in the following.

A. Free-electron laser

The first beamline downstream of the SPARC photoinjector hosts a FEL beamline consisting of six undulators that are commonly tuned to emit coherent light in a wide range centered at the fundamental wavelength $\lambda_{\text{FEL}} \approx 500\ \text{nm}$. The FEL is also equipped with an infrared (IR) seeding laser pulse directly split from the photocathode laser system [42,52]. Each undulator has a length of 2.15 m and comprises 77 periods, where each period length is $\lambda_u = 2.8\ \text{cm}$. Quadrupoles are installed between consecutive undulators to ensure proper beam transport. The undulator gap can be tuned to adjust the undulator parameter in the range $K_u \approx 0.4\text{--}3$. Downstream of each

undulator, an in-vacuum metallic mirror can be inserted to direct the generated FEL radiation toward a calibrated photodiode. The radiation spectrum exiting the final undulator is measured using an imaging spectrometer equipped with a diffraction grating and a cooled intensified camera (iCCD) [5,6].

B. THz radiation

High-intensity THz radiation represents a fundamental spectroscopic tool for probing and controlling advanced materials like graphene, topological insulators, and novel superconductors [33]. The Source of Advanced Beam Imaging for Novel Applications (SABINA) THz/infrared (IR) beamline at SPARC_LAB is based on the generation of SASE FEL, covering a broad spectral region from 3 to 30 THz, with picosecond duration pulses and energy per pulse of hundreds of μJ thanks to the tunable electron beam longitudinal phase space. Indeed, the emission of quasimonochromatic light, with subpicosecond duration and high energy (hundreds of μJ) in the 3–30 THz frequency range, is obtained by injecting a 30–100 MeV electron bunch coming from the SPARC photoinjector into the advanced Apple-X undulator (Advanced Planar Polarization Light Emitter) [53], placed on the second beamline. The undulator is divided in three modules of 1.3 m each, separated by about 20 cm drift spaces for beam diagnostics [54]. An additional feature of the SABINA THz/IR radiation source is the variable polarization, from linear to circular [55] thanks to the Apple-X undulator, being able to produce both vertically/horizontally linearly polarized radiation as well as left/right-handed elliptical polarizations [56]. The chosen Apple-X configuration provides inherent focusing properties in both the horizontal and vertical planes, a feature absent in conventional planar undulators. The radiation generated will be delivered from the SPARC_LAB bunker to a newly established user laboratory situated approximately 25 m away. The entire setup will be synchronized with a femtosecond (fs) laser system to enable sophisticated pump-probe experiments using THz/IR pump and VIS/UV probe schemes.

C. Betatron radiation

The EuPRAXIA Advanced Photon Sources (EuAPS) project complements the overall EuPRAXIA project by equipping the SPARC_LAB facility with a third photon source relying on the use of a plasma [18]. Betatron radiation, as shown in Fig. 13, is the characteristic emission of photons originating from relativistic electrons traveling along an oscillatory path, a phenomenon typical of plasma-based accelerators. This radiation exhibits a certain level of coherence [57], is emitted within a narrow forward cone, and possesses a source size typically on the order of a few microns. The photon pulse duration is comparable to that of the driver pulse, falling squarely within the femtosecond timescale [58]. In the strongly nonlinear regime, the

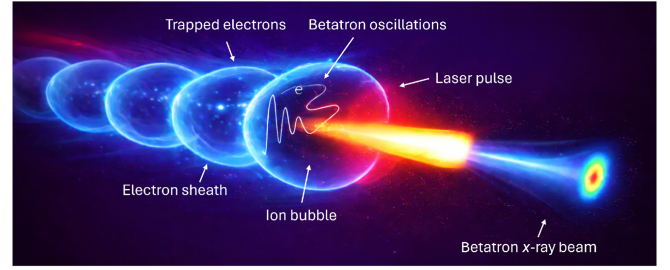


FIG. 13. Betatron radiation working mechanism. As electrons are trapped and accelerated within the plasma wake, they simultaneously experience a strong transverse restoring force due to the space-charge field of the ions. The combination of relativistic longitudinal motion and transverse acceleration leads to the emission of broadband, synchrotronlike x-ray radiation, referred to as betatron radiation.

wakefield accelerating structure for the electrons assumes a bubblelike shape. Electrons are self-injected from the rear of this bubble into the accelerating and focusing region, which has been completely depleted of electrons by the strong ponderomotive laser potential during its passage through the under-dense plasma [59].

The expected radiation features will enable the production of unique ultrashort particle and photon beams with applications spanning ultrafast science, including highly accurate medical imaging, materials characterization, and novel medical treatments. The EuAPS facility will establish a dedicated laser-driven x-ray source based on the utilization of betatron emission.

Table III reports the expected source parameters. The exceptionally short duration of these radiation pulses results in a peak brilliance that is comparable to that of synchrotron sources. This is achieved despite a significantly lower repetition rate, typically operating in the Hz range compared to the MHz rates common in synchrotrons. Betatron light pulses carry fewer photons than those produced by Free-Electron Lasers (FELs), but they possess a similar pulse duration and level of transverse coherence. Furthermore, the energy spectrum is broad, resembling that emitted from a wiggler, while maintaining a comparable peak brilliance. Betatron sources therefore serve to fill the operational gap between FEL and synchrotron radiation sources, uniquely combining the short pulse duration and

TABLE III. Expected betatron source parameters.

Parameter	Value
Laser energy	2.5 J
Plasma density	$1.7 \times 10^{18} \text{ cm}^{-3}$
Electron beam energy	395 MeV
Transverse beam size	1.5 μm
Charge	144 pC
Pulse duration	25 fs
Photons per pulse	1.7×10^9 (>1 keV)

coherence properties of FELs with the broad energy range characteristic of synchrotrons.

V. SUPPORT SYSTEMS

This section provides a technical description of the major equipment and systems that allow the operation of the SPARC photoinjector and FLAME laser. While the rf system is exclusively dedicated to SPARC, the control and vacuum systems have been implemented and are almost the same as those used for the FLAME laser. The section also includes a description of the laser system used for SPARC to generate the electron beam at the cathode.

A. Photocathode laser

The photocathode laser system is based on a Coherent Vitara Ti:Sa laser oscillator and a custom-made amplitude chirped pulsed amplifier, whose parameters are summarized in Table IV. Part of the laser is converted into blue (400 ± 6 nm) and UV (266 ± 3 nm) light by a harmonic generator based on nonlinear barium borate (BBO) crystals, with a maximum energy of a few (tens of) mJ for the UV (blue) wavelength. The laser pulse is then longitudinally shaped [60] to obtain up to 5 consecutive pulses with tunable delays (± 30 ps), energy per pulse and transverse size. The total available energy on the cathode is few mJ.

The laser pulse travels through a 13 m-long transfer line to reach the cathode. Several remotely controlled irises at the same longitudinal positions inside the split-and-delay system are used for the multibunch operation and are imaged on the cathode with a 1 m-long focal lens. This allows one to have a top-hat transverse spot at cathode location. The reflected light coming from the copper cathode ($\approx 30\%$ for UV and $\approx 50\%$ for blue wavelengths) is then collected downstream of the gun and used as an online shot-by-shot diagnostics of the size, position, and pulse energy using a CCD camera and a photodiode. The IR laser energy not used for the second and third harmonic generation (on the order of a few tens of mJ) is used for

TABLE IV. Parameters of the photocathode laser system.

Parameter	Value
Central wavelength	800 ± 10 nm
IR duration	40 fs FWHM
Repetition rate	10 Hz
IR energy per pulse	>100 mJ
IR energy fluctuations	<0.7% rms
1–10 ps contrast	1×10^{-4}
10–100 ps contrast	1×10^{-6}
100–300 ps contrast	1×10^{-7}
ns contrast	1×10^{-4}
Pointing stability	<10 μ rad
Peak-to-peak transverse uniformity	$\pm 15\%$

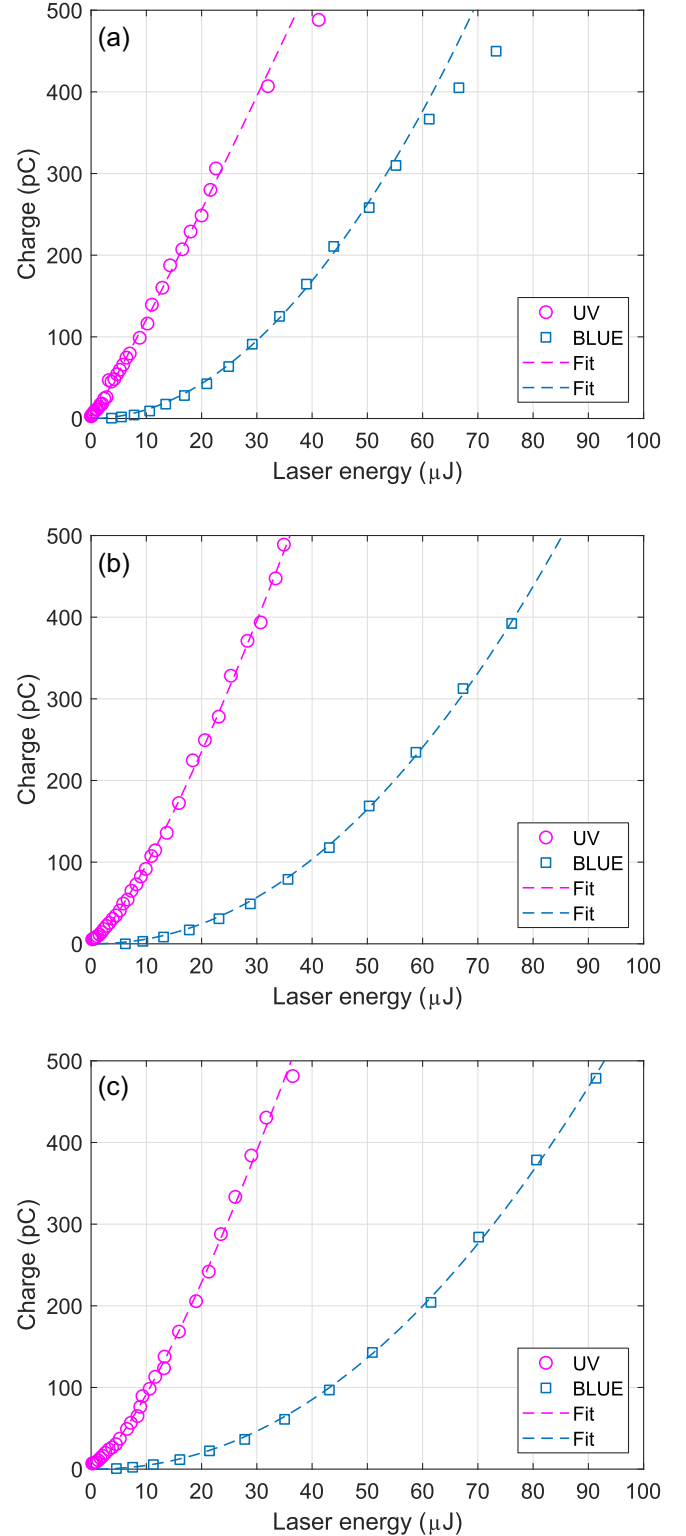


FIG. 14. Emitted charge measured as a function of the laser energy for UV and blue laser pulses with diameters of (a) 1 mm, (b) 1.5 mm, and (c) 2 mm. The reported values of the laser energy refer to the total one impinging on the cathode and do not take into account the losses due to its reflection (34% for UV and 47% for blue). The dashed lines report the computed numerical fits.

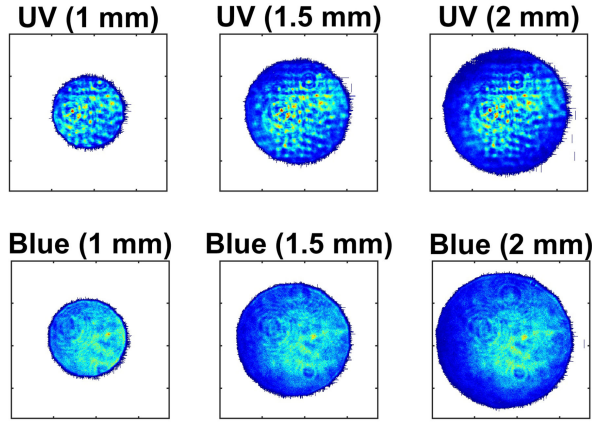


FIG. 15. Transverse spots of the UV (top) and blue (bottom) laser pulses for several apertures of the iris.

diagnostics purposes (on the laser and on the electron beam), for seeding the FEL in the IR range, and also for ionizing gas to generate plasma [40]. Considering the operation of the photocathode with such short laser pulses, photoemission process from copper is ensured even at longer wavelengths like blue [21]. Both UV and blue laser wavelengths can therefore be used to illuminate the cathode and generate the electron beams. Figure 14 shows the extracted charge amount as a function of the incident laser energy for both wavelengths. This, in turn, allows to estimate the cathode quantum efficiency that is expected to be nonlinear (quadratic) in case of the use of the blue laser pulse. The corresponding laser spots (tuned in the range 1–2 mm by means of remotely controlled irises) are reported in Fig. 15.

B. Low-level rf and power system

A sketch of the current SPARC_LAB rf system architecture is reported in Fig. 16. The system is anchored by the reference master oscillator, a custom ultralow phase noise oven-controlled crystal oscillator manufactured by Laurin

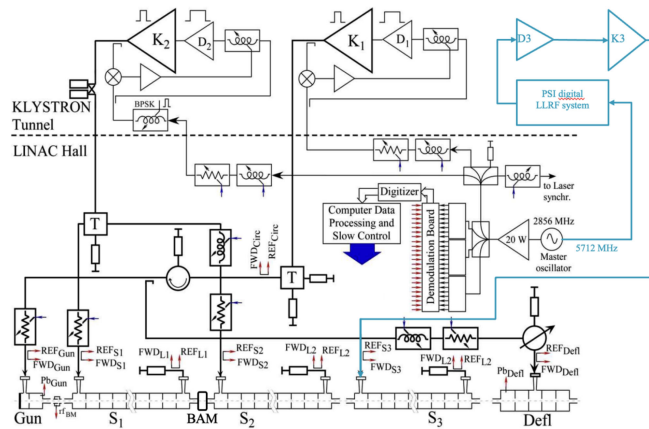


FIG. 16. The SPARC_LAB rf system layout.

AG, which provides coherent outputs at 2856, 5712, and 2142 MHz. Both the S-band and C-band references are amplified and distributed to the rf power plants and the low-level rf (LLRF) front- and back-end. The 2856 MHz signal is also used to phase lock the photocathode laser and the FLAME laser. The 2142 MHz frequency is employed to down-convert the signal from a beam arrival monitor cavity used for highly accurate beam timing measurements [61,62]. The two S-band rf power plants utilize PFN modulators (from Puls-PlasmaTechnik—PPT) and 45 MW pulsed klystrons from Thales (TH2128C), driven by 300 W solid-state amplifiers from microwave amplifiers. The C-band plant combines a solid-state modulator from ScandiNova and a 50 MW klystron from Canon (E37202) with a similar driver amplifier. The first S-band klystron drives both the rf gun and the rf Deflector (RFD) used for beam diagnostics. The associated waveguide network includes a circulator in the common path, and a variable attenuator, phase shifter, and rf switch within the deflector line; all these components are housed in an SF₆ atmosphere. The second S-band klystron serves the two SLAC-type traveling-wave accelerating structures, and its rf pulse is compressed using a SLED-type pulse compressor. The C-band plant is dedicated to powering the constant impedance high-gradient (35 MV/m) structure used as an energy booster. The low-level radio frequency (LLRF) system has recently been fully upgraded using digital systems provided by Instrumentation Technologies (Libera LLRF). These systems are temperature-stabilized, FPGA-based digital LLRFs equipped with a low-noise front-end that demodulates the rf signal down to 44.625 MHz prior to digital conversion (14-bit, 119 MHz, 5 MHz BW). The system possesses the capability to perform pulse-to-pulse amplitude and phase feedback on two independent channels. Additionally, the vector modulator can generate arbitrary pulse shapes from a user-defined mask (16-bit DAC, 15 MHz BW). This upgrade successfully overcame several known limitations of the previous system, primarily addressing the front-end noise floor, temperature stabilization (to minimize drifts), and the ability to produce arbitrary pulse shapes.

C. Vacuum

The vacuum system at SPARC_LAB is noncryogenic and consists of beam pipes and devices characterized by typical apertures of ≈ 4 cm diameter. The pumping devices are distributed along the entire photoinjector and experimental beamlines. In the injector, the pumps are positioned in correspondence of the beam diagnostic stations, while for the waveguides the pumping units are evenly positioned along the entire network. In particular, in the diagnostic chambers, several pressure readout systems and remotely-controlled valves are installed for pumping down and venting operations. The machine operating pressure is generally on the order of 10^{-9} mbar. Regarding the vacuum

chamber for the plasma experimental activities, the entire apparatus is directly connected with the last rf section through a windowless, three stage differential turbo-pumping system. Since the beam encounters no windows, its emittance is not degraded due to multiple scattering. In the experimental beamlines downstream of the linac the operating pressure is generally on the order of 10^{-8} mbar.

D. Control system

The control system of the SPARC_LAB facility is based on EPICS [63], a distributed control system framework based on client-server architecture. It uses an Ethernet network for communication via the channel access (CA) and process variable access (PVA) protocols. The EPICS server part runs on input/output controllers (IOCs) that communicate with hardware devices and expose their parameters through CA. Central services (archiver, logger, high level applications, machine protection tools, and alarm handler) and the graphical operator interfaces (OPIs) are EPICS clients that use CA to access device parameters. The IOC controllers are handled by a container orchestrator for all devices with Ethernet interface while dedicated control units on micro-TCA or industrial PC are interfaced for timing receivers or ADCs [64]. The graphical OPI framework is developed using CSS Phoebus [65], a Java-based graphical environment that is widely used for developing OPIs for large scale facilities employing EPICS-based control systems. Phoebus is the current implementation of CSS and features a scalable and modular architecture. It allows for the realization of OPIs for device control and monitoring by accessing the EPICS PVs from the IOCs database in read and/or write mode through CA and PVA protocols. A data-browser tool allows to display data trend over time, both for real-time data and for archived ones. EPICS also provides a nongraphical interface to access PVs. As previously mentioned, communication among IOCs occurs through CA and PVA protocols. This allows the communication with third-party software like MATLAB®.

VI. OUTLOOK IN THE CONTEXT OF EUPRAXIA@SPARC_LAB

The purpose of the EuPRAXIA@SPARC_LAB User Facility is to establish a research infrastructure that pioneers the use of plasma wakefield acceleration for driving a high-brightness FEL user facility in the soft x-ray regime [8]. As one of the two core pillars of the pan-European Plasma Research Accelerator with Excellence in Applications (EuPRAXIA) Research Infrastructure, EuPRAXIA@SPARC_LAB will be hosted at the INFN Frascati National Laboratory (LNF), serving both as a cutting-edge scientific facility for users and as a technological demonstrator. It will validate the integration of

high-gradient plasma acceleration and X-band rf technology within a compact FEL light source, laying the groundwork for future compact user facilities. This will improve their sustainability by significantly reducing the size, energy consumption, and operational costs typically associated with conventional accelerator-based FEL light sources, making advanced photon science more accessible and environmentally responsible in the long term. The user facility is expected to begin operations in 2031. Its first user beamline, AQUA, will deliver ultrashort femtosecond soft x-ray pulses within the biologically relevant *water-window* range, enabling real-time imaging, advanced materials development, and investigation of chemical processes with unprecedented spatial and temporal resolution.

A substantial part of the credibility and technical maturity of the EuPRAXIA research infrastructure is rooted in the long-standing experience of SPARC_LAB. For this reason, several major components that will equip EuPRAXIA will be very similar to the ones currently used at SPARC_LAB. The photoinjector layout (rf gun followed by two traveling-wave S-band structures) will be exactly the same and will operate again in the velocity-bunching configuration. Moreover, the SABINA THz FEL beamline, currently in the installation and commissioning phase, employs APPLE-X undulators of the same type foreseen for EuPRAXIA@SPARC_LAB. In addition to this, all the advanced plasma concepts developed at SPARC_LAB will be used as well. In this regard, the PLASMA_LAB laboratory will be used also to test the EuPRAXIA capillaries. In view of such a task, the laboratory has started the testing of longer plasma sources. A first prototype of a 40 cm-long plasma accelerating module has been successfully put in operation as shown in Fig. 17. By using a voltage pulse of 10 kV, a stable and reproducible plasma with an electron density on the order of 10^{17} cm⁻³ has been obtained along the entire capillary having a 2 mm diameter. It is expected that these tests will continue in the following years, during the realization of the EuPRAXIA@SPARC_LAB main building.

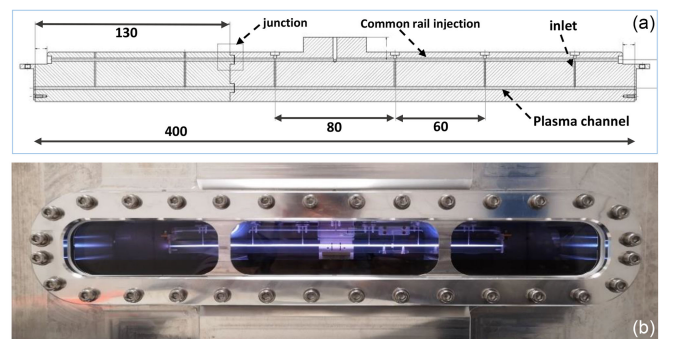


FIG. 17. EuPRAXIA plasma source consisting of a 40 cm-long gas-filled capillary-discharge. The gas is injected with 6 inlets, which are in turn fed by a common horizontal pipe.

VII. CONCLUSIONS

The SPARC_LAB facility at the LNF-INFN Laboratories in Frascati is now ready to support experimental programs that expand and improve upon the successful program conducted in the previous years. Two additional radiation beamlines are now available, extending the operating range from THz down to soft x-ray range. Starting in 2026, this will allow the hosting of user experiments, the resumption of electron beam-driven plasma acceleration research, new activities in view of EuPRAXIA, and tests on novel diagnostics.

ACKNOWLEDGMENTS

We also thank all the INFN technicians involved in the installations of the SPARC_LAB equipment and all the machine operators involved in the experimental runs.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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