

Plasma density manipulation in staged discharge capillaries for plasma-based accelerators

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Plasma wakefield acceleration of charged particle beams relies on specialized devices for plasma generation and confinement. In both particle-driven wakefield acceleration and beam-focusing experiments, these devices are designed to precisely control plasma properties to optimize beam-plasma interactions. Recent studies employing centimeter-scale, gas-filled discharge plasma sources have demonstrated high accelerating and focusing gradients while preserving electron beam quality, motivating the extension of these techniques to larger structures to achieve higher beam energies. At the SPARC_LAB test facility, multistage accelerating modules based on plasma generation by electrical discharges have been developed to produce tailored longitudinal plasma profiles for simultaneous beam acceleration and focusing. The results presented here show that the longitudinal plasma density within each stage can be independently tuned by modifying the plasma generation conditions, including the applied voltage, current pulse parameters, discharge ignition timing, and plasma recombination dynamics.

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I. INTRODUCTION

In recent years, several experiments have been performed to achieve high accelerating and focusing gradients preserving the high quality of particle beams [1–3], in terms of emittance and energy spread, by means of the interaction with plasmas created in specific structures able to tune the electron density distribution according to the beam properties [4–9]. These results are leading towards a new generation of compact particle accelerators based on plasma technology and able to achieve accelerating gradients in the GVm^{-1} scale [10–12]. In this context, plasma sources consisting of gas-filled discharge capillaries, in which the plasma is created by using an electrical discharge, represent a very flexible solution for plasma-based accelerators since they can be designed to control plasma properties for focusing, acceleration, and bending of particle beams [13–15]. For these reasons, gas-filled discharge capillaries have been adopted at the SPARC_LAB test facility (INFN-LNF Frascati) and foreseen for the EuPRAXIA@SPARC_LAB project [16] for the plasma-based experimental campaign, where tailored plasma density profiles are needed to optimize the matching with particle beams. In these devices, plasma is generated by applying at the ends of the capillary a high-voltage (HV) pulse that ionizes the

neutral gas column contained within a narrow channel running along the longitudinal axes of the capillary [17–21]. However, such plasma formation process based on the use of HV discharges [22–24] is limited by length and pressure of the gas column itself, in terms of the minimum breakdown voltage, as shown by the Paschen curves [25,26]. To achieve the gas ionization needed for plasma sources in the meter scale (m-scale), voltage pulses of hundreds kV are typically required. The challenge will be to explore solutions that can extend these plasma sources to the m-scale while accelerating to GeV scale energies, which is needed for future applications. One potential solution is the development of long, staged, discharge-induced plasma sources, capable of producing tailored plasma profiles over extended lengths. By connecting multiple sections while keeping the voltage pulses applied to each element below a few kV, this approach offers an alternative method for ionizing long neutral gas columns. The breakdown voltage of a gas gap of length d at pressure p is given by Paschen's law, $V_b = Bpd / \{\ln(Apd) - \ln[\ln(1 + 1/\gamma_{se})]\}$, where the parameters A , B , and γ_{se} are constants that depend on the specific type of gas. For a single-section capillary that is 8 cm long and filled with hydrogen at a pressure of about 30 mbar, the breakdown voltage is approximately 4.5 kV. When the capillary length is increased to 16 cm under the same pressure conditions, the breakdown voltage rises to about 8.3 kV, whereas it could remain at 4.5 kV if two separate 8 cm segments were used instead. The advantage becomes even more pronounced when more than two sections are considered. For instance, at a total length of 24 cm, the breakdown voltage exceeds 11.5 kV, whereas in the segmented capillary configuration, it remains approximately 4.5 kV. In this study, we present the characterization of a gas-filled discharge

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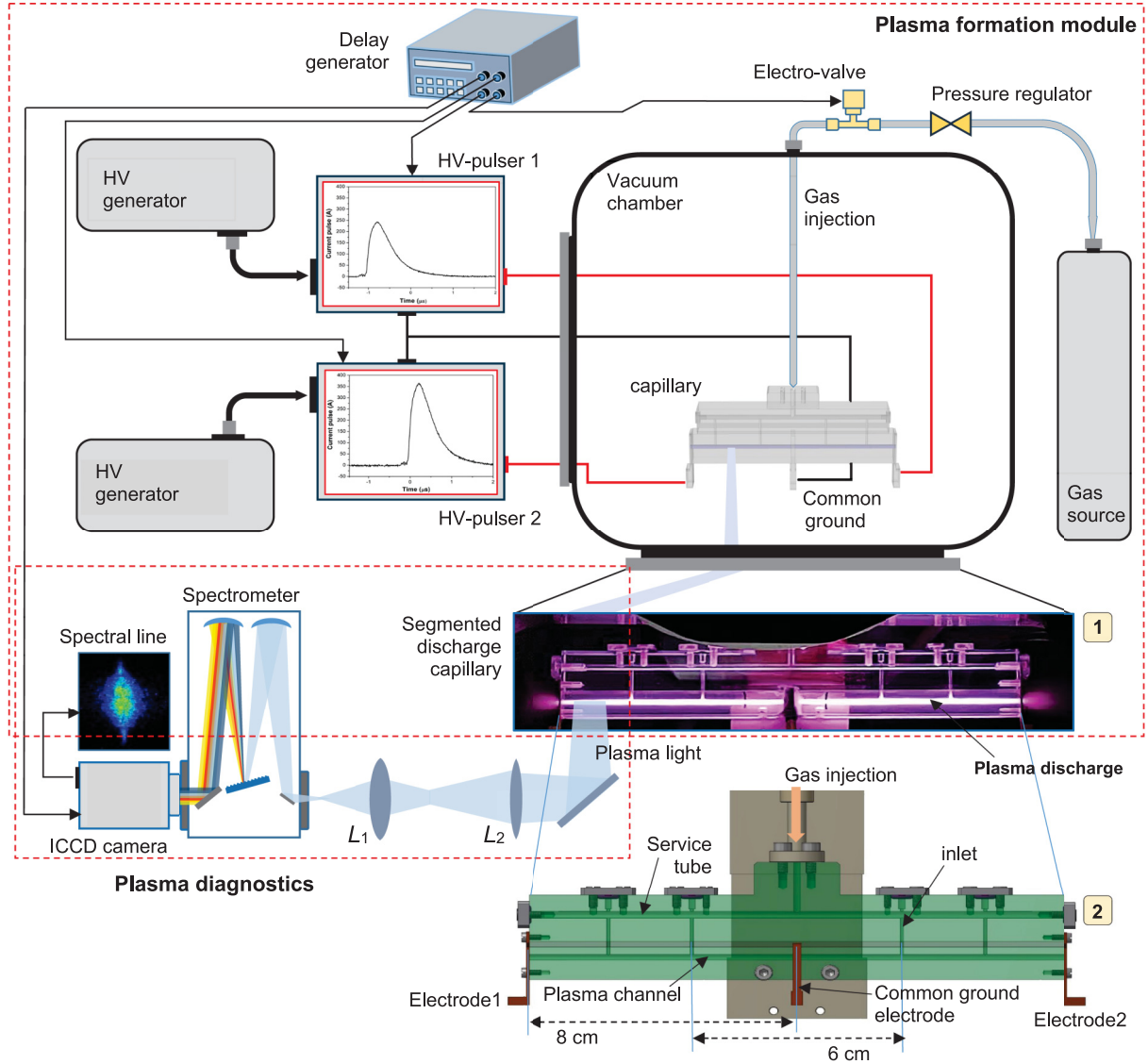


FIG. 1. Plasma module used at the SPARC_LAB test facility for creating and measuring plasmas inside a gas-filled discharge capillary composed of two sections that can be separately controlled by means of two different HV systems. Image of the capillary illustrating the plasma formation obtained by independently applying two different voltage pulses to the two stages (inset 1) and the final capillary design (inset 2), consisting of two sections, each 8 cm long, with a 2-mm-diameter plasma channel.

capillary consisting of two separate sections, serving as a proof of principle for a segmented discharge capillary. This design provides precise control over plasma formation in each section of the capillary, enabling the optimization and modulation of electron density profiles based on the specific requirements of each stage.

II. EXPERIMENTAL SETUP

The experimental apparatus implemented to produce and characterize plasmas inside a gas-filled discharge capillary is shown in Fig. 1. In particular, such plasma accelerating module has been designed to allow the formation and control of plasmas in staged plasma sources composed of different discharge sections, embedded in the same structure. The plasma module includes two main components: a subsystem responsible for generating and confining the plasma, and a

diagnostic unit designed to measure and monitor key plasma parameters [27]. The plasma formation setup includes a gas injection system, HV circuits for neutral gas ionization, and the capillary used for plasma confinement. The geometry of the capillary determines the resulting plasma density profile, which play a crucial role in controlling interactions with particle beams.

The inset 2 of Fig. 1 shows the design and the tested prototype of the segmented discharge capillary, composed of two independently controllable plasma sections and fabricated in plastic material by machining from the same block, ensuring a high degree of alignment among all horizontal channels. The central electrode acts as the common ground for the electrical circuits connected to the two sections. The neutral gas (hydrogen) distribution system includes a horizontal service pipe connected to the gas reservoir, which delivers gas into the plasma formation channel through four vertical

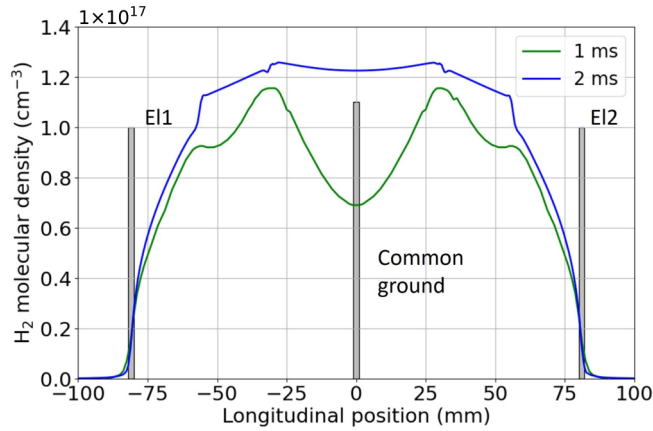


FIG. 2. Simulated distribution of neutral gas along the plasma formation channel of the segmented discharge capillary at two different propagation times, 1 and 2 ms, after the opening of the solenoid valve.

injectors—two for each segment. The gas injection system from the reservoir to the service pipe is controlled by a pressure regulator and a solenoid valve. The pressure within the plasma channel can be regulated in the range of 10–50 mbar by means of the first control element. Downstream of the pressure regulator, the solenoid valve is positioned 20 cm from the capillary to modulate the gas injection, adjustable between 1 and 10 Hz [28].

Figure 2 reports a simulation describing the propagation of neutral gas along the plasma channel before it is ionized by HV pulses. The simulation was performed using the OPENFOAM code [29,30]. The reported curves describe the longitudinal distribution of hydrogen gas at two different propagation times inside the plasma formation channel for both sections, namely, 1 and 2 ms, after the opening of the solenoid valve. It can be observed that after only 1 ms, the density profile is still not completely uniform due to the peaks located at the injector positions. These peaks progressively tend to smooth out along the channel when the delay increases to 2 ms. It should also be noted that a deeper density ramp appears at the exits, caused by the presence of the 2-mm-diameter holes that allow the electron beams to pass through.

HV circuits synchronized with the gas injection provide the energy required to ionize the gas within the horizontal plasma channel [31–33]. The synchronization system, which also handles plasma diagnostics, includes a delay generator (Stanford Research DG535). It is able to control the repetition rate and the opening time of the solenoid valve, in addition to the ignition of the voltage pulse at the electrodes of the capillary. Plasma is generated in pulsed mode to limit the amount of gas injected into the accelerator, thereby reducing the load on the vacuum pumping system. At present, acceleration experiments at the SPARC_LAB facility are performed with a maximum repetition rate of 10 Hz. As shown in Fig. 1, in order to achieve fully independent control of different elements of a segmented capillary—both in terms of amplitude and ionization discharge ignition—two separate HV systems have been implemented, each dedicated to a specific section of

the capillary. The measurement of plasma density profiles in the range 10^{15} – 10^{19} cm^{-3} can be performed through the spectroscopic analysis [34–36] of the plasma-emitted light, which is collected into an imaging spectrometer (SpectraPro 275) equipped with an intensified CCD camera (Andor Istar 320) by means of a dedicated optical beam line. The electron density distribution can be determined by analyzing the broadening of the spectral lines of the hydrogen Balmer series, for which the main transitions are centered at 656.3 nm (H_α) and 486.1 nm (H_β) [37]. The Stark effect is responsible for the spectral lines broadening due to the electric fields created between the charged particles in the plasma, which is proportional to the plasma electron density according to the equation $n_e = 8.02 \times 10^{12} (\Delta\lambda/\alpha)^{3/2} \text{ cm}^{-3}$ [20], where $\Delta\lambda$ is the full width at half maximum of the Stark broadened spectral line, expressed in angstroms, and α is a parameter, also expressed in angstroms, tabulated by Griem [34]. The characterization of the plasma produced in the segmented discharge capillary was carried out using the Stark broadening method.

III. RESULTS

A. Staged discharge capillary

The characterization of the staged gas-filled discharge capillary is carried out by measuring the plasma electron density distribution as a function of both the longitudinal position and the delay time relative to the discharge trigger, using the Stark broadening technique described in the previous section. Given the considerable longitudinal size of the capillary, images of the Balmer Beta spectral line, $H_\beta = 486.13$ nm, were acquired for three different longitudinal positions and then combined to cover both sections that make up the entire plasma source. The longitudinal plasma profiles show different behaviors of the electron distribution as a function of the voltage applied to each section and the resulting plasma current, thereby demonstrating the ability to modulate the plasma density. The time-resolved analysis of the densities provides a clearer description of the plasma formation and recombination phases within both sections, offering further insight into the capability to control the electron density of each element across the entire device [38].

Figure 3 shows the results obtained from the segmented capillary tests performed applying asymmetrical HV pulses to the two stages. Two independent voltage pulses with different amplitudes, 5 and 7.5 kV, have been applied according to the setup described in Fig. 1, where two independent HV sources are shown. Under these conditions, both the longitudinal plasma profiles and the temporal evolution of the formation and recombination phases have been investigated. Longitudinal profiles are shown for four time steps [Fig. 3(a)] with respect to the trigger of the HV pulse [zero x axis in Fig. 3(b)]. All measurements have been performed in a time range between 500 and 2200 ns, every 100 ns. Outside this range, the signal-to-noise ratio becomes too low and a meaningful measurement of density cannot be obtained. For each capillary section, the values of the time-dependent density curves are obtained by averaging the longitudinal spatial profiles within each electrode pair of that section. All measured values are reported in Fig. 3(b) (black and red squares) separately for

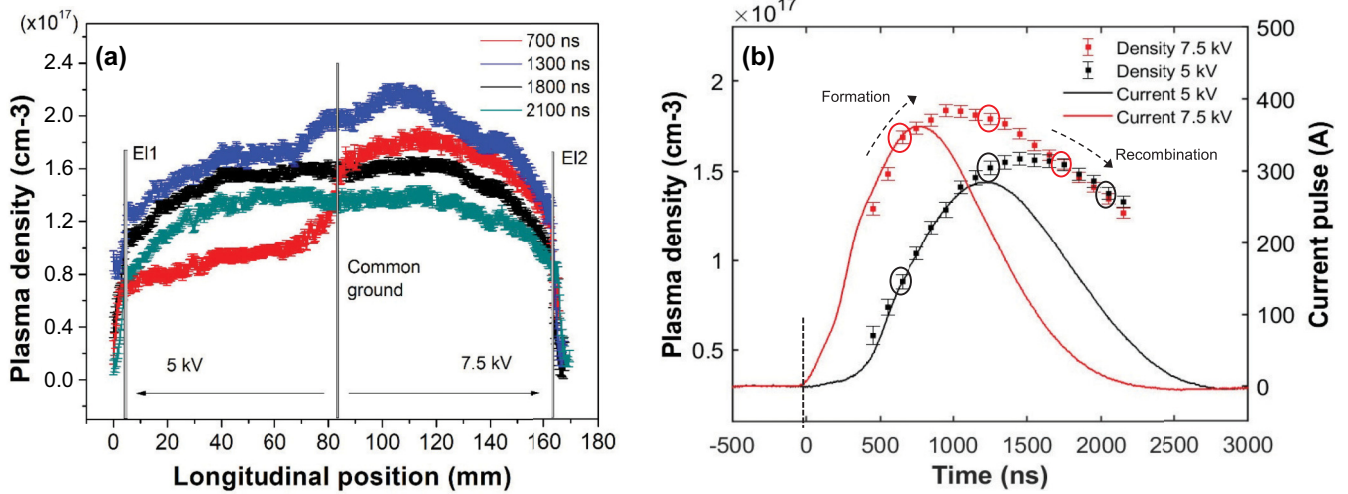


FIG. 3. Plasma density measurements in the segmented discharge capillary under conditions of asymmetrical HV pulses. (a) Longitudinal plasma profiles of the entire capillary for four different time steps. (b) Spatially averaged plasma density values for each section as a function of delay times. The elements El_1 and El_2 indicate the positions of the electrodes with respect to the longitudinal profiles.

each section of the staged capillary. The overlapping circles indicate the density values whose longitudinal density profiles are shown in Fig. 3(a). The solid-line curves represent plasma current pulses measured during the discharge at applied voltages of 5 and 7.5 kV.

Applying different voltages to the two sections initially produces, during the plasma formation phase, the creation of two distinct longitudinal distributions [700 and 1300 ns; red and blue curves of Fig. 3(a), respectively], with peak values of 1.8×10^{17} and $2.2 \times 10^{17} \text{ cm}^{-3}$ observed in the section powered at 7.5 kV, occurring at 700 and 1300 ns, respectively. Under this experimental condition, the two spatially averaged plasma density curves exhibit different behaviors, mainly during the initial plasma formation phase. In fact, in the section powered at 7.5 kV, the peak is reached between 1100 and 1300 ns, whereas in the 5 kV section, it appears later, between 1300 and 1500 ns. After these delays, the recombination phases set in, exhibiting similar trends [Fig. 3(b)]. During this stage, the longitudinal plasma profiles in the two sections gradually converge toward a uniform distribution. Indeed, after the density has exceeded its maximum value, electrons begin to diffuse through the two sections, from the denser to the less dense one, reaching an equilibrium phase in which the density of both sections becomes similar [≥ 1800 ns; black curve in Fig. 3(a)]. Even during the recombination phase, since there is still a residual current inside two sections, weak plasma formation occurs, which has significantly lower density than both the recombination and the electron diffusion processes, leading to a leveling of the density profile along the entire structure. Under the condition of asymmetric pulse application, it can be seen that the two current pulses start at the same time (red and black solid curves), but the one corresponding to the 7.5 kV voltage reaches nearly 380 A and also exhibits a faster rise time than the 5 kV case, for which the maximum current is about 300 A. The different current values flowing in the two sections determine the initial difference in plasma density during the formation phase.

The observed behavior of longitudinal plasma profiles shows the versatility of the staged plasma sources composed of two independent sections. Indeed, the asymmetric HV feeding shows the possibility of producing ramped and uniform plasma profiles, depending on whether the plasma is in the generation or recombination phase, respectively. In this way, the same plasma source can provide either uniform profiles, suitable for achieving high energies in m-scale devices by combining two or more sections, or tailored profiles to implement different functional elements within the same structure or to optimize particle beam matching. Furthermore, in the case of uniform profiles, the main advantage is offered by the possibility of sectioning the supply voltage, avoiding values of many tens or hundreds of kV, which would require the use of expensive and cumbersome HV generators.

There is a second way to use the segmented capillary, the one involving symmetrical voltage pulses applied to the two sections. Figure 4 describes this second case, where two voltage pulses equal to 5 kV have been applied to the capillary sections, showing the opposite behavior to the previous one. The initial longitudinal profiles are uniform between the two sections, around 0.6×10^{17} and $1.2 \times 10^{17} \text{ cm}^{-3}$ for 500 ns (black curve) and 800 ns (red curve) time steps, respectively [Fig. 4(a)]. This initial condition is maintained throughout the plasma formation phase, from 400 to 1000 ns. As the plasma enters the recombination phase, this initial state in the two sections evolves into two regions exhibiting a slight density difference (blue curve corresponding to a 1300 ns delay), which becomes increasingly pronounced as the recombination proceeds (green curve corresponding to a 2200 ns delay). The maximum difference is measured at the largest reported delay of 2200 ns, where average density values around 1.1×10^{17} and $1.3 \times 10^{17} \text{ cm}^{-3}$ are reached in the two sections, which means a difference of 20%. A confirmation of this behavior is shown in the evolution of plasma density and current pulses curves in time [Fig. 4(b)]. Indeed, although they start at the same time, they do not maintain exactly the same rise time (black and red continuous curves) and subtend a

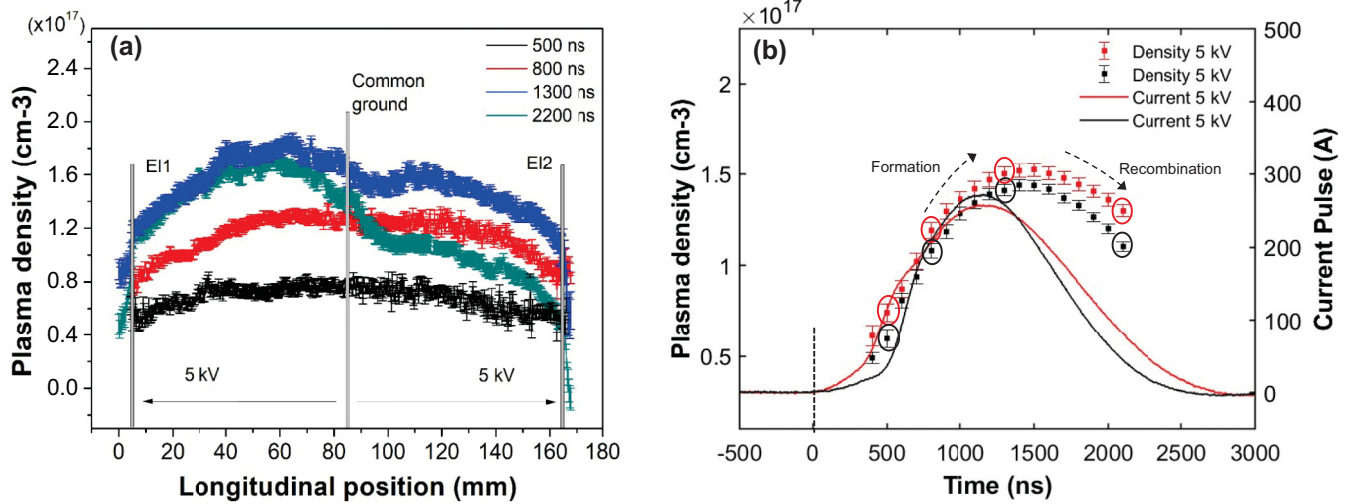


FIG. 4. Plasma density measurements in the segmented discharge capillary under conditions of symmetrical HV pulses. (a) Longitudinal plasma profiles of the entire capillary for four different time steps. (b) Spatially averaged plasma density values for each section as a function of delay times.

slightly different area, probably due to a small difference in the voltage supplied by the two HV generators or in the neutral gas pressures. These small differences in plasma current result in the creation of slightly different plasma densities in the two sections, small enough during the formation phase and more pronounced during the recombination phase (black and red squares). In fact, during plasma formation, despite the different currents, the densities in the two sections remain approximately equal (500 and 800 ns curves). A clear difference between the two curves, in Fig. 4(b), of the profiles is noticeable in the recombination phase, during which the formation of new free electrons is no longer negligible due to the different residual current in the two sections. Indeed, at a delay of 1300 ns, a slight difference in density is observed, which becomes more evident at 2200 ns, essentially because in the left section (red plasma current) the recombination is partly compensated by the creation of new electrons, while in the right section (black plasma current) this compensation is less strong. It should be noted that the maximum densities in this operating condition are lower than the previous one because a lower voltage has been applied. Figure 5 shows a three-dimensional representation of Figs. 3(a) and 4(a), highlighting the parametric evolution of the longitudinal plasma profiles over time, i.e., during the formation and recombination phases, both under symmetric and asymmetric applied voltage conditions. Under symmetrical power supply conditions, a predictable uniformity of the longitudinal plasma density is initially observed, which is maintained for approximately 500–600 ns, and it can be controlled and used to realize plasma sources in the m-scale, as in the case of asymmetrical power supply. Subsequently, due to a slight difference in the plasma currents, density growth occurs in the section where the current is higher.

Overall, the most effective operating mode of the segmented capillary is achieved with asymmetric application of the ionization voltage. Under these conditions, it is possible to obtain either a tailored longitudinal plasma-density profile during the plasma formation phase or a uniform plasma profile

during the recombination phase, with full control of the density levels through adjustment of the applied voltages. Both the plasma formation and recombination phases exhibit the same shot-to-shot fluctuations (around 2%), demonstrating that the plasma nevertheless maintains stable and reproducible behavior under both operating conditions. As expected, when the same voltage is applied to both sections, i.e., in the symmetric configuration, the same longitudinal plasma profile is established immediately during the plasma formation phase. During the recombination phase, a fluid-dynamic particle diffusion effect becomes dominant, which is likely triggered by a slight difference in the voltage pulse responsible for generating the plasma electrons. Although this condition is less intuitive than the previous one, it remains predictable and controllable for its use in plasma-acceleration experiments. Finally, it should be noted that the longitudinal plasma electron densities shown in Figs. 3 and 4 are consistent with the neutral gas profile prior to ionization presented in Fig. 2. In the latter, the neutral gas density drops sharply toward the outer electrodes due to the side orifices that accommodate the entrance and exit of the particle beams. A similar behavior is observed in the measured plasma electron densities, which show a steeper gradient toward the outer electrodes, independent of the operating conditions applied to the two sections.

B. Combined discharge capillary system

The results obtained from the studies on the segmented discharge capillaries, which have been presented in the previous section, were used to design a compact plasma source capable of combining three different plasma stages within the same device, consisting of a first active plasma lens (APL_{IN}) to perform electron beam-to-plasma matching, a subsequent plasma accelerating section (PWFA) and a second active plasma lens (APL_{OUT}) to capture the accelerated beams [Fig. 6(b)]. Plasma-based focusing and acceleration experiments have been performed at the SPARC_LAB facility with such integrated device [39]. Below we describe the design and

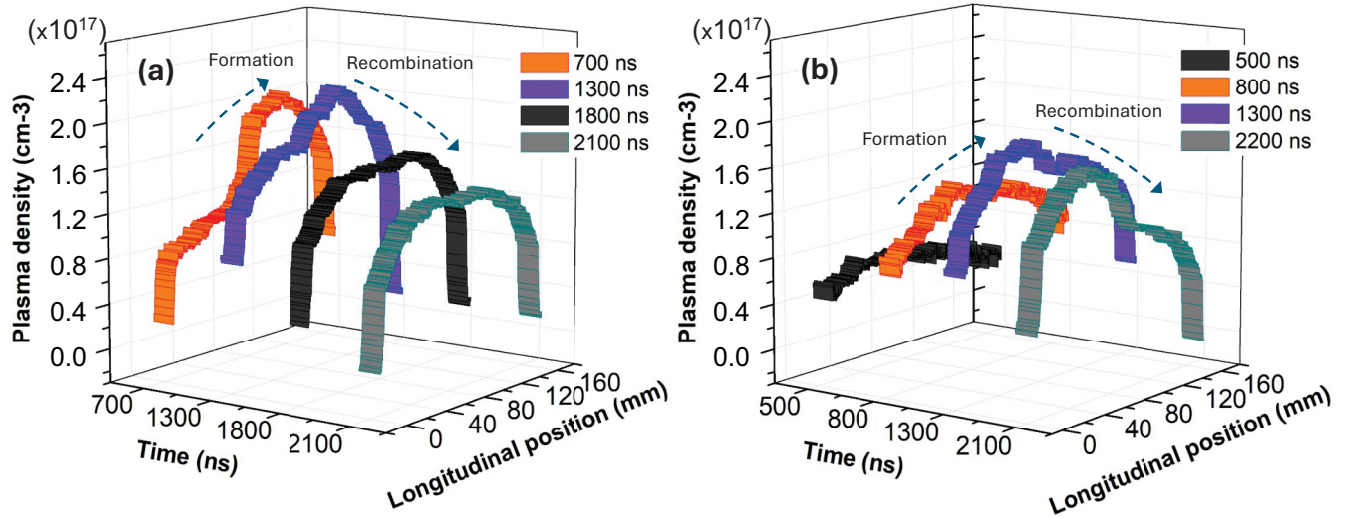


FIG. 5. Three-dimensional parametric representation as a function of plasma formation and recombination time. (a) Capillary under conditions of asymmetrical HV pulses. (b) Capillary under conditions of symmetrical HV pulses.

characterization of this device, carried out to optimize plasma properties for effective beam matching and, consequently, to improve the performance of plasma-based acceleration. Figure 6(b) shows the geometry of the combined capillary integrating the focusing and acceleration sections, also fabricated in plastic through machining. Each section includes a pair of copper-tungsten electrodes. The ground electrodes are positioned on the same side of each element so that the particle beams always experience a focusing magnetic field relative to their direction of propagation. Concerning the accelerat-

ing section, the electrodes polarity is not significant since the particle beams will pass through it several microseconds after the discharge current and the corresponding focusing magnetic field are over. Voltage pulses are applied to each stage to form the plasma independently. As for the segmented capillary, the gas injection system includes an upper horizontal service tube with 2 mm diameter and 19.5 cm length, from which three vertical inlets feed the three stages. The injector of the accelerating section has a diameter equal to half that of the injectors used for the two APLs, in order to reduce the

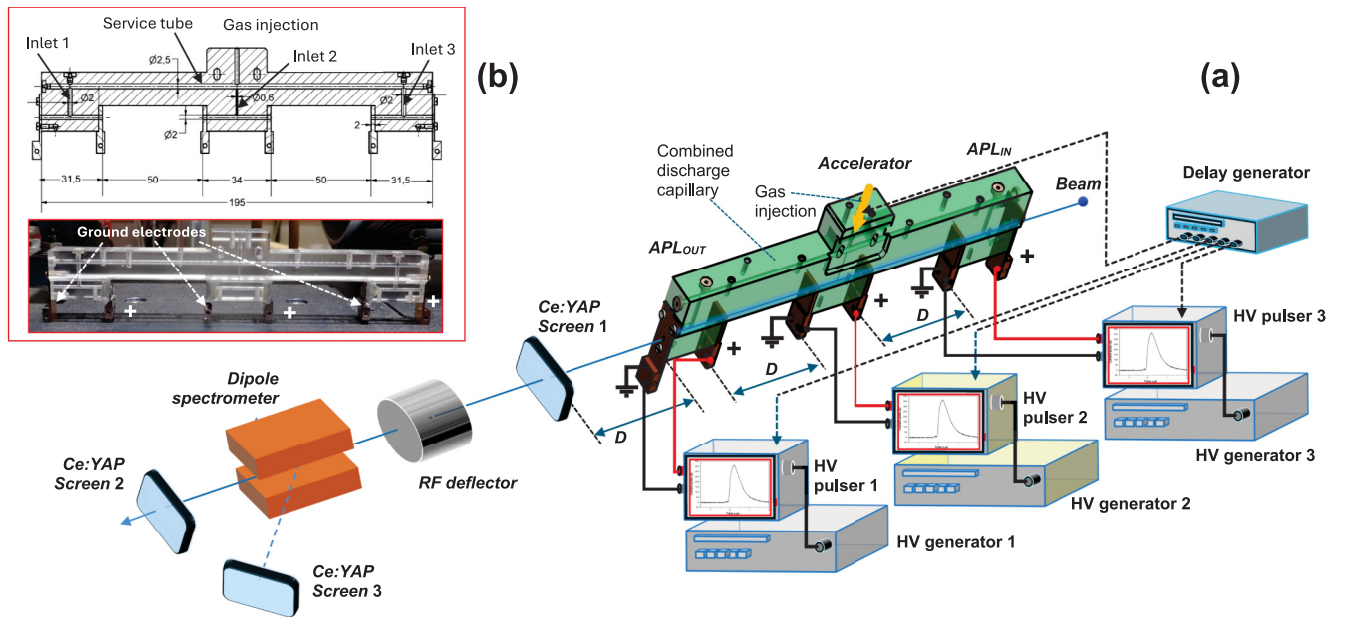


FIG. 6. Experimental setup used at the SPARC_LAB facility to perform acceleration experiments with the integrated capillary. (a) A plasma module enables the independent generation and control of plasma within structures composed of three distinct elements. A first Ce:YAP screen is employed to characterize the beam at the entrance of the accelerating section. Downstream, an RF deflector and a magnetic spectrometer enable complete characterization of the beam after acceleration. (b) Final design of the combined structure composed of three sections, two lenses, and a central accelerating unit, fabricated in plastic by machining, with the ground electrodes positioned on the same side of each element.

flow rate in the plasma channel and thereby achieve lower plasma densities than in the plasma lenses when the same voltage is applied to all three devices. The three sections are separated by drift regions to properly transport the particle beams between the APLs and the accelerating stage. The single-tube solution, which seeds all structural elements while synchronizing plasma channel filling and ensuring uniform gas injection, is optimal for controlling plasma properties and their impact on particle beams.

Figure 6(a) illustrates the HV system developed for plasma formation in the combined capillary, designed to independently control the plasma properties in each section. Each section is powered by a dedicated HV generator and pulse circuit system, with all three units synchronized through a delay generator. This configuration allows to deliver current pulses of the desired amplitude in each section, with tunable temporal offsets depending on the specific application. Gas injection, performed simultaneously in the three sections, is likewise synchronized with the onset of the voltage. Acceleration experiments, discussed in detail by Pompili *et al.* [39], have been performed placing a scintillating cerium-doped Yttrium aluminum perovskite (Ce:YAP) screen downstream of the integrated capillary, at a distance of $D = 5$ cm from the APL_{OUT} stage. Beam focusing with APLs—both for matching the input beam and for capturing the accelerated beam—is carried out using the same current, adjusted according to the beam energy and the required focal length. The beam waist of APL_{IN} must be located at the entrance of the accelerator stage, while the beam waist of APL_{OUT} must be positioned on the Ce:YAP screen 1 in order to measure the beam spot (see Fig. 6). These two positions are designed to have the same length in the experiments at the SPARC_LAB facility, allowing the current of APL_{IN} to be set by measuring it on APL_{OUT}. Specifically, with both the accelerator and the first lens switched off, the beam waist on screen 1 is obtained by varying the current of APL_{OUT}. The same current is then applied to APL_{IN} to reproduce the same beam waist at the entrance of the accelerator. A current pulse with lower intensity is applied to the accelerating stage and is triggered approximately a few microseconds in advance, depending on the desired plasma density. This procedure is implemented to ensure that the plasma density within the accelerating stage reaches the optimal value required for the specific particle-driven plasma acceleration scheme, which is approximately in the range 10^{15} – 10^{16} cm⁻³.

The temporal synchronization scheme employed in plasma-acceleration experiments based on the combined discharge capillary is illustrated in Fig. 7. This configuration is optimized according to the properties of the accelerated electron beams. The figure displays both the current pulses (solid lines) and the average plasma densities as a function of the relative delay (red, blue, and black circles). The accelerating section is ionized in advance with respect to the lenses by a time interval that depends on the target plasma density, about 3 μ s in this case. A larger delay corresponds to a lower plasma density experienced by the electron beams. Specifically, the beams are synchronized with the discharges in the two lenses, so as to undergo focusing during the current arc, while simultaneously propagating through an accelerating section where the plasma density has decreased to approximately

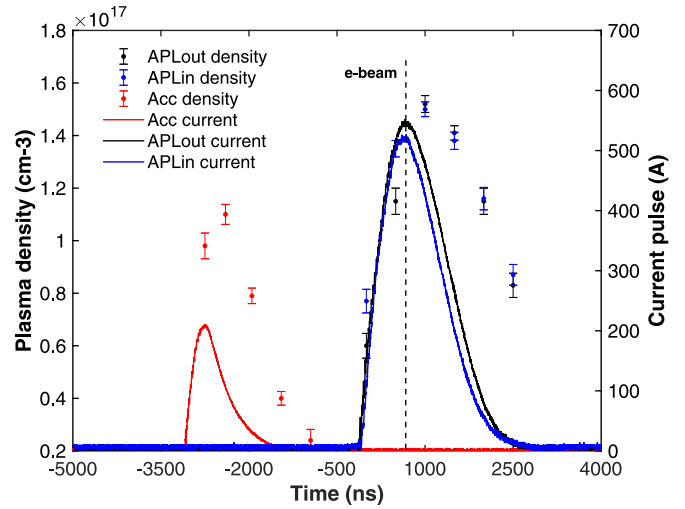


FIG. 7. HV pulse synchronization scheme for plasma formation. In the two lenses, plasma formation occurs simultaneously, while in the accelerating section, the plasma is formed a few microseconds earlier to allow it to reach the optimal density in relation to the properties of the beams to be accelerated. Superimposed on the current pulses are the time-dependent profiles of the average plasma densities.

3×10^{15} cm⁻³ due to recombination, starting from a maximum value of about 1.1×10^{17} cm⁻³ (red circles in Fig. 7). The dotted vertical black line placed at the peak of the plasma currents of the two APLs represents the arrival time of the electron beams, which experience a focusing magnetic field corresponding to plasma currents of approximately 550 A.

The plasma density evolution within each element of the combined discharge capillary was characterized using the Stark broadening technique, with the corresponding results reported in Fig. 8. The data indicate that the plasma evolves independently in each section: the longitudinal profiles display a pronounced peak in the central region of the capillary, resulting from the use of a single gas injector, and a significant decrease is observed along both lateral ramps outside the electrodes, in the accelerator as well as in the plasma lenses. For the latter, the same HV pulse of approximately 550 A–10 kV is applied. Both the temporal and spatial evolution of the density are observed to exhibit an almost identical behavior in the two plasma lenses. In contrast, the accelerating section, supplied with a voltage of about 5 kV and currents of 220 A, is found to display similar trends in shape, though with density values reduced by more than 30%. A rapid decrease in density is observed along the ramps outside the electrodes, in the free-propagation regions of the beam, where the density falls below measurable values (red dashed horizontal line). It should be noted that the HV pulse values used during the acceleration experiments at the SPARC_LAB facility can be varied according to the characteristics of the particle beams to be accelerated, thereby modifying both the magnetic field of the two lenses and the plasma density in the accelerating section.

The main advantages of a plasma device that integrates multiple functional elements within the same structure—for example, an accelerating section and two focusing lenses—lie

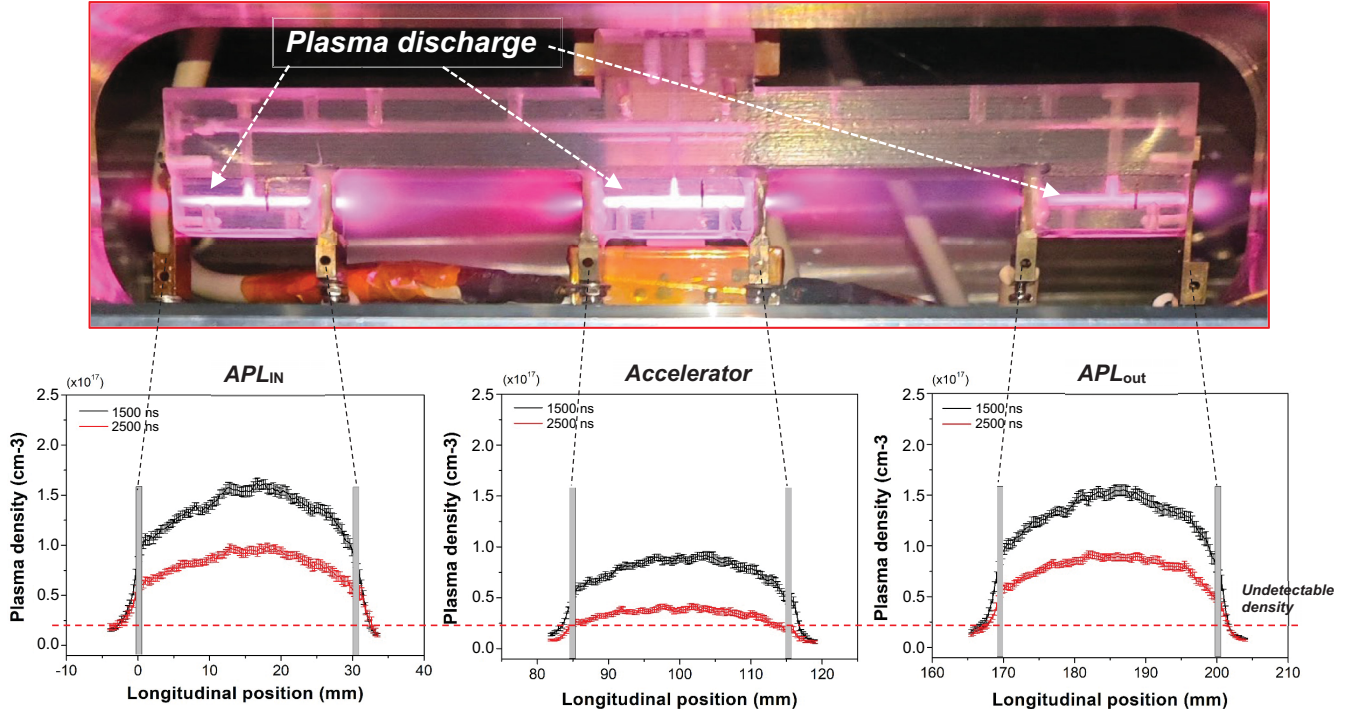


FIG. 8. Longitudinal plasma profiles measured via the Stark broadening technique in the three elements of the combined discharge capillary. For each element, two curves are shown, corresponding to measurements at delays of 1500 and 2500 ns: the first represents the peak plasma density, while the second reflects the region of plasma recombination.

in its compactness, the optimization of the neutral gas distribution and injection system, and the intrinsic mechanical alignment ensured by the joint fabrication of all components. In particular, the latter aspect reduces the complexity of alignment procedures: the movement of the device with respect to the particle beam can be achieved through a single automated motion, rather than requiring a separate adjustment for each element. With regard to the gas distribution and injection system, the implementation through a service tube that simultaneously seeds all elements of the structure ensures both efficient synchronization in the filling of all plasma channels and the injection of an identical amount of gas. This condition is crucial for controlling the properties of the generated plasma and its effects on the particle beams. On the other hand, this approach reduces the flexibility to independently adjust the position of each element, such as the longitudinal position of the two APLs, which could otherwise provide an additional degree of operational flexibility. In the proposed integrated architecture, however, the functionality associated with such longitudinal adjustments can be largely reproduced through electrical tuning of the plasma lenses, without introducing additional mechanical complexity. In the present configuration, the discharge current determines not only the generation of the focusing field, but also the effective focal length of each lens. As a result, the beam-matching conditions can be adjusted electrically while maintaining a fixed and integrated geometry. Therefore, the optimization that would normally be achieved through small longitudinal displacements can be largely reproduced through current tuning. This design choice was motivated not only by the need for compactness, but also by practical considerations related

to integration. All elements are realized on a single structure, eliminating relative alignment issues and enabling synchronized gas delivery through a common service line feeding both APLs and the accelerator stage.

IV. CONCLUSIONS

This work presents advancements in plasma sources based on discharge capillaries, aiming to identify viable strategies for developing large-scale structures capable of supporting high-energy operation using plasma-based technology. Within this framework, preliminary investigations have been conducted on the feasibility of modular capillary configurations, in which multiple sections can be independently controlled. This scheme is envisaged as a potential conceptual basis for the development of m3-scale plasma sources, offering the flexibility to generate either uniform or tailored plasma profiles, thereby addressing the different requirements of advanced beam-driven systems. Furthermore, a study is presented on a prototype of a multifunctional capillary that integrates three distinct elements—an accelerating stage and two lateral focusing sections—thus enabling the realization of a fully plasma-based compact structure. This prototype highlights the considerable potential of such configurations in terms of compactness and versatility, opening promising perspectives for the next generation of plasma-based accelerators.

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The authors declare no competing interests.

DATA AVAILABILITY

The data supporting the findings of this study are included in the figures. There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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