ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST035

SPECTROSCOPIC MEASUREMENTS AS DIAGNOSTIC TOOL FOR PLASMA-FILLED CAPILLARIES*

S. Arjmand†,1, University of Sapienza, Rome, Italy
[2]also at INFN, Laboratori Nazionali di Frascati, Frascati, Italy
M. P. Anania[2], A. Biagioni[2], G. Costa[2], L. Crincoli[2],
M. Ferrario[2], M. Del Franco[2], M. Galletti[2], V. Lollo[2], D. Pellegrini[2], R. Pompili[2]
D. Giulietti[3], Physics Department, University of Pisa, Pisa, Italy
A. Zigler[4], Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem, Israel

Abstract

The research concerns the study of the plasma sources for plasma-based accelerators (PBAs) at the SPARC_LAB test-facility (LNF-INFN). The interest in compact accelerators, overcoming the gigantism of the conventional radio-frequency (RF) accelerators, is growing in High Energy Physics. The plasma-based accelerating gradients can attain the GV/m scale. At the SPARC_LAB test-facility, a plasma device is under development. It consists of a capillary in which one or more inlets inject neutral gas (Hydrogen), ionized by a high-voltage (HV) discharge. Electron density has been measured as a function of time through the Stark broadening profiles of the Balmer line.

INTRODUCTION

The cutting-edge generation of accelerators based on plasma technology can force electron bunches to GeV energies within centimeter lengths [1,2]. Such high accelerating gradients are produced by electron density modulations induced in the plasma by an intense and ultra-short laser pulse (Laser Wakefield Acceleration, LWFA) or a relativistic electron bunch (Particle Wakefile Acceleration, PWFA) [3–6]. The innovative acceleration technique proposed by Tajima and Dawson [7] in 1979 has prompted an expansive and rapidly extending field of research desiring to decrease the typical dimensions of the accelerating frames to the small-scale and invent futuristic miniaturized devices. This technique attains huge accelerating fields up to GV/m compared to the conventional radio-frequency (RF) technology limited to MV/m. The particle wakefield acceleration exploits the electric fields of a plasma wave compelled by a relativistic electron bunch used as a driver [8]. Such fields can be efficiently applied to a trailing bunch, the witness, which accumulates a part of the energy deposited by the driver. The experiment at the SPARC_LAB test-facility has been performed within the EuPRAXIA framework [9] by employing two bunches, a driver tracked by a witness (accelerated beam), propagating in a plasma confined in a 3 cm/long discharge capillary. Various methods are employed to generate the plasma from a neutral gas, such as Hydrogen, using a high-voltage (HV) discharge [2] or an ionizing laser pulse [10]. The plasma is dynamically formed shot-by-shot with a typical lifetime of a few tens of microseconds, its stability and reproducibility are essential features for the quality of the accelerated electron bunch. The plasma characteristics inside the gas-filled capillary depend on several parameters like its pressure and temperature, the applied voltage, the geometric of the capillary itself. The shape and the position of the gas injectors can influence the shot-to-shot stability and uniformity of the plasma. The features of the plasma inside and just outside the capillary are fundamental for preserving the electron bunch quality during the acceleration.

* Work supported by EU Commission in the Seventh Framework Program, Grant Agreement 312453-EuCARD-2, the European Union Horizon 2020 research, innovation program with the Grant Agreement No. 653782 (EuPRAXIA), and INFN with the GRANT73/PLADIP grant.
† sahar.arjmand@lnf.infn.it

EXPERIMENTAL APPARATUS

The overall setup used to form and characterize the plasma behavior has shown in Fig. 1. The main component for plasma-based accelerators is a plasma-discharge capillary. It is a 3D-printed capillary tube, filled with Hydrogen by means of two injectors. Different diameters (1 and 2 mm) were tested.

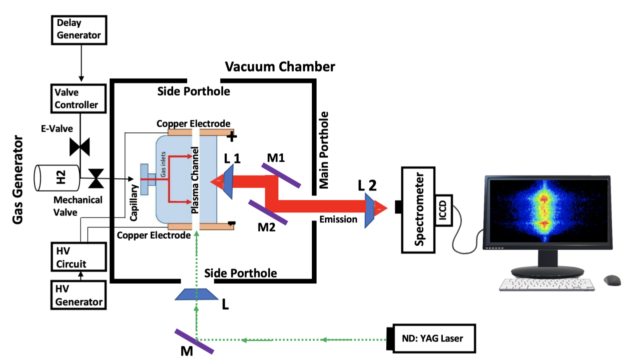

Figure 1: Scheme of the experimental set-up used at the SPARC_LAB test-facility to form and characterize plasma in a gas-filled capillary. An optical path is designed for guiding the plasma light into the spectrometer. L1, L2, represent lenses and M1, M2 indicate mirrors. The Copper electrodes have mounted on the capillary extremities. An Nd: YAG laser probe of 532 nm is used for the optical alignment.

We used capillaries with different geometries to oversee how the geometry can affect the plasma density distribution. Two gas inlets inject the Hydrogen gas inside the channel by

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST035

a gas generator. A high-voltage source [11] supplies power to produce the current discharge along the capillary through two Copper electrodes mounted on the capillary extremities. The gas flows inside the channel and is controlled by an electro-mechanical valve. The gas injection frequency is set to 1 Hz using a valve aperture time of 3 ms to preserve the vacuum ($\approx 10^{-7}$ mbar) inside the chamber shot-by-shot. A pressure regulator controls the inlet pressure from 10 - 15 mbar. The plasma diagnostic system consists of an imaging spectrometer (iHR Fully Automated Imaging Spectrometer iHR320), an optical path to transfer the plasma light into the spectrometer, and an intensified camera (Andor iSTAR 20) to record images. The 600 g/mm grating allows a resolution of $\approx$ 0.06 nm in the considered spectral range. The focal length of the spectrometer grating is 320 mm, and its aperture ratio is f/4.1. An intensified camera is connected to the spectrometer and acts as a detector. Ultimately, a delay generator (Stanford Research DG535) synchronizes all individual events such as the gas injection, the voltage pulse, the valve opening time, the triggering of the camera, and the plasma density measurements. Consequently, by delaying the camera trigger, snapshots at different times are detectable. Such a diagnostic system allows a time-resolved measurements of the electron density in the capillary.

SPECTROSCOPIC PLASMA DIAGNOSTICS

The particle wakefield acceleration (PWFA) is bottomed on the interaction between plasma and electron bunches, depending on the longitudinal and transverse plasma electron density distribution inside the capillary [7, 12, 13]. The plasma density modulation generated by a driver bunch leads to the formation of strong electric fields that provide accelerating gradients in the GV/m scale, proportional to the square root of the plasma electron density n_e [14]. The so-called Dawson limit represents the maximum longitudinal electric field E0 associated with an electron plasma wave. It depends precisely on the square root of the electron density n_e of the considered plasma [15]:

$$E_0\ [\frac{V}{m}] = \frac{\omega_p\, m_e\, c}{e} \simeq 96\ \sqrt{n_e\ [\mathrm{cm}^{-3}]}; \qquad (1)$$

e and m_e being the charge and the mass of the electron respectively, c the speed of light in vacuum, and ω_p the electron plasma frequency. At a given plasma density, the Langmuir wavelength $\lambda_p = \frac{2\pi c}{\omega_p}$ conditions the transverse and longitudinal dimensions of bunches that contribute to the plasma acceleration, either for the driver or the witness. Since the plasma wavelength sets the length of the plasma bubbles, where is the accelerating electric field, the witness bunch must be injected at the accurate time [7, 16]. Hence, a spectroscopic technique based on the Stark-broadening effect is employed to detect the plasma electron density during the gas ionization within the capillary [17, 18]. In plasma the Stark effect produces the broadening of spectral lines due to the electric field of the charged particles. The dependence of the Stark broadening on the density of the plasma can be exploited to determine the density itself [19]:

$$n_e\ [\mathrm{cm}^{-3}] = 8.02 \times 10^{12} \left(\frac{\Delta\lambda_S}{\alpha_{\frac{1}{2}}}\right)^{\frac{3}{2}}, \qquad (2)$$

where the parameter $\Delta\lambda_S$ is the full width at half maximum (FWHM) of the Stark-broadened spectral line in nm fitted by a Cauchy distribution. The parameter $\alpha_{\frac{1}{2}}$ is a function of the electron density and the temperature, that can be considered almost constant within our typical electron temperature range of 1 – 4 eV and plasma density of 10^{16}-10^{17} cm^{-3} [17]. The light radiated by excited Hydrogen atoms at different wavelengths in the visible spectrum refers to the Balmer spectral lines (H_α, H_β, H_γ, and H_δ at 656.2 nm, 486.1 nm, 434 nm, and 410.1 nm, respectively). Indeed, to retrieve the plasma density, the Balmer H_β line is considered. By measuring the FWHM of the H_β line, we can obtain the plasma electron density. The parameter $\alpha_{\frac{1}{2}}$ for H_β line for the density of the order of 10^{17} cm^{-3} is 0.919 nm [17]. There are numerous physical mechanisms that can produce the line spectral broadening. These include Natural broadening, the Doppler broadening due to the thermal motion of the particles, and the Stark broadening related to the electric fields produced by charged particles in the plasma. The transverse profile of the Balmer beta line fitted with a Lorentzian (Stark effect) in Fig. 2 is illustrated.

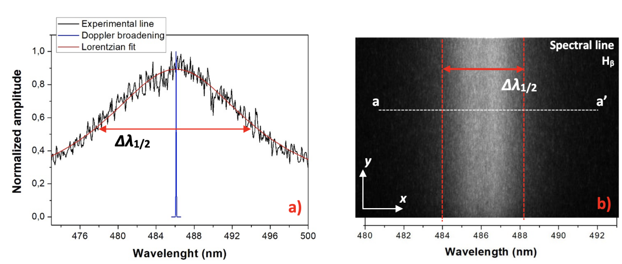

Figure 2: Balmer beta line measurements: a) transverse profile of the Balmer beta line corresponding to the cut aa' with the overlapped Lorentzian fit (Stark effect) and the contribution of the Doppler effect calculated for a plasma temperature of 2 eV, and b) image of the spectral line acquired via the ICCD camera.

Compared to a 16 nm Stark broadening, the Natural (0.3 nm) and the Doppler ones (0.06 nm) are absolutely negligible in our case. The goal of this research activity is to produce a variable electron density relative to 10^{16}-10^{17} cm^{-3} for the corresponding plasma wavelength, λ_p, in the range of 300-100 μm [20–22]. The time dependence of the plasma density is obtainable by scanning the relative delay between the discharge trigger (the starting point of the current profile) and the acquisition time on the camera. Thus, it is feasible to characterize the plasma evolution as a function of the plasma recombination time. According to Paschen's law (used to evaluate the breakdown voltage), the ionization mechanism of a gas column depends on both the neutral gas pressure

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST035

and the applied voltage at the capillary ends [23]. Therefore, for a plasma density of the order of 10^{17} cm^{-3} the pressure inside the capillary is set in the range of 10 - 20 mbar. During the operations, a voltage of 12 kV is applied and the plasma current of 400 A is measured. The electron temperature, T_e, is a valid indicator of the quality of the plasma produced in the capillary [24]. Indeed, the plasma density distribution, the capillary's walls deformations, the radial uniformity of the plasma, the ionization degree [11, 25], and preserving the bunch quality are strongly dependent on the axial plasma temperature. Assuming a quasi-static model (QSM), an estimation of the temperature on the axis of the capillary is [26]:

$$T_e\ [\text{eV}] \approx 5.7\left(\frac{I\ [\text{kA}]}{r_{\text{cap [mm]}}}\right)^{\frac{2}{5}}, \quad (3)$$

where I is the pulse peak current in kA, r_{cap} the capillary radius in mm, and T_e the on-axis electron temperature. For a 3 cm/long capillary with a peak current of 400 A, 1 mm, or 2 mm/diameter, an on-axis temperature of 5.2 eV and 3.2 eV, respectively, is expected. Although this estimation does not include the temporal evolution of the plasma it is sufficient to know if the plasma that will be produced is completely ionized.

RESULTS

Through Eq. 2, the plasma density is retrieved as a function of plasma recombination time and illustrated in Fig. 3. Therefore, by varying the relative delay time, the temporal evolution of the plasma density is achievable as a function of plasma recombination time. Moreover, by acquiring several more than one shot with the same delay time, it is feasible to study the shot-to-shot variation of the plasma density at the various instants of the discharge. Thus, we have studied the time dependence of the shot-to-shot variation of the plasma density. The mean density profile for every delay time is evaluated along the capillary longitudinally averaged over 50 independent shots. The time-resolved (from 900 to 2100 ns) spectroscopic density measurements using these two capillaries reveal that the density expands gradually after gas breakdown, arrives at its peak around 10^{17} cm^{-3}, then diminishes over time. Moreover, we observed that expanding the capillary diameter leads to a reduction of the plasma density distribution. The maximum plasma density for a capillary in 1 mm/diameter starts from 1.3×10^{17} cm^{-3} and reaches a maximum of 7.3×10^{17} cm^{-3}, while in 2 mm/diameter, it varies between 0.5×10^{17} cm^{-3} and 1.37×10^{17} cm^{-3}. For both capillaries, the electron density has a parabolic trend starting from 900 to 2100 ns after the formation of the plasma current. To understand many of the effects that occur during the ionization of the plasma inside the capillary, it is essential to consider the electron-ion collision frequency [27]:

$$\nu_{ei}\ [\text{sec}^{-1}] = 3 \times 10^{-6}\ Z\, n_e\ \ln \Lambda (T_e)^{-\frac{3}{2}}, \quad (4)$$

where n_e is the electron density, T_e the electron temperature, $\ln \Lambda$ the Coulomb logarithm, and Z the ion charge in units of the elementary charge (e).

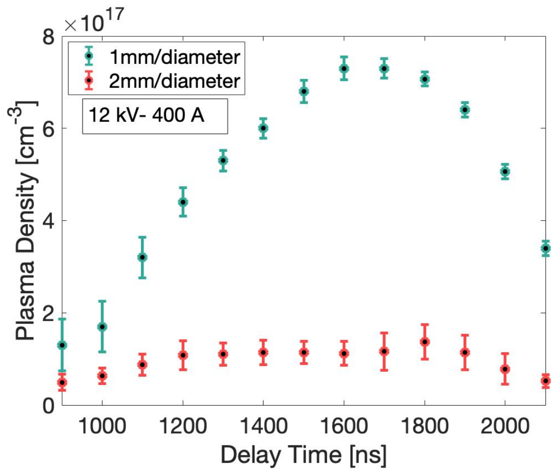

Figure 3: The variation of averaged electron density as a function of delay time after the discharge trigger in the targeted capillaries of 3 cm/long-1 mm/diameter and 3 cm/long-2 mm/diameter with a double-inlet system. The reported error bars represent the standard deviation calculated by 50 independent plasma density profiles (in a duration of 100 ns gate width).

The plasma density in the capillary with a larger diameter (2 mm/diameter) is lower than the device with a 1 mm/diameter (see Fig. 3). This density reduction depends on the time of the heating produced by the electric discharge since, during the triggering of the electric discharge, there is less containment of the plasma. Since the plasma is less dense, the electron-ion collisions that determine the heating of the gas-plasma decrease.

CONCLUSION

A spectroscopic technique has been used based on the Stark effect for plasma density characterization inside the gas-filled plasma-discharge capillary. One of the main objectives of the new acceleration techniques is to preserve the quality of the electron bunch injected into the plasma section with a high (GV/m) field gradient. Therefore, by studying the shot-to-shot variation of the plasma density evolution as a function of time, the effects of the plasma behavior on the electron bunch passing within the capillary can be controlled. Moreover, we studied how the geometry of the capillary itself can affect and rule the plasma density behavior. We have observed that the capillary geometry modifies the electron distribution, which can be effective for attaining the required properties of the electron bunches used for particle acceleration.

REFERENCES

[1] J. Faure, "Controlled injection and acceleration of electrons in plasma wakefields by colliding laser pulses", *Nature*, vol. 444,

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST035

pp. 737–739, 2006. doi:10.1038/nature05393

[2] A. J. Gonsalves, "Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide", *Phys. Rev. Lett.*, vol. 122, p. 084801, 2019. doi:10.1103/PhysRevLett.122.084801

[3] I. Blumenfeld, C. E. Clayton, F. J. Decker, M. J. Hogan, C. Huang, R. Ischebeck, R. Iverson, C. Joshi, T. Katsouleas, N. Kirby, W. Lu, K. A. Marsh, W. B. Mori, P. Muggli, E. Oz, R. H. Siemann, D. Walz, and M. Zhou, "Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator", *Nature*, vol. 445, p. 741, 2007. doi:10.1038/nature05538

[4] M. Litos, E. Adli, W. An, C. Clarke, C. Clayton, S. Corde, J. Delahaye, R. England, A. Fisher, J. Frederico *et al.*, "High-efficiency acceleration of an electron beam in a plasma wakefield accelerator", *Nature*, vol. 515, p. 92, 2014. doi:10.1038/nature13882

[5] S. Lee, "Energy doubler for a linear collider", *Phys. Rev. ST Accel. Beams*, vol. 5, p. 011001, 2002. doi:10.1103/PhysRevSTAB.5.011001

[6] K. Nakajima, "Towards a table-top free-electron laser", *Nat. Phys.*, vol. 4, pp. 92–93, 2008. doi:10.1038/nphys846

[7] T. Tajima and J. M. Dawson, "Laser Electron Accelerator", *Phys. Rev. Lett.*, vol. 43, no. 4, pp. 267-270, 1979. doi:10.1103/PhysRevLett.43.267

[8] P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, "Acceleration of electrons by the interaction of a bunched electron beam with a plasma", *Phys. Rev. Lett.*, vol. 54, pp. 693–696, 1985. doi:10.1103/PhysRevLett.54.693

[9] M. Ferrario *et al.*, "EuPRAXIA@SPARC_LAB Design study towards a compact FEL facility at LNF", *Nuclear Inst. and Methods in Physics Research, A.*, vol. 909, p. 134, 2018. doi:10.1016/j.nima.2018.01.094

[10] J. J. Rocca, D. Clark, J. Chilla, and V. Shlyaptsev, "Energy Extraction and Achievement of the Saturation Limit in a Discharge-Pumped Table-Top Soft X-Ray Amplifier", *Physical review letters*, vol. 77, p. 1476, 1996. doi:10.1103/PhysRevLett.77.1476

[11] M. P. Anania *et al.*, "Plasma production for electron acceleration by resonant plasma wave", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 829, p. 254, 2016. doi:10.1016/j.nima.2016.02.029

[12] T. Hosokai, M. Kando, H. Dewa, H. Kotaki, S. Kondo, N. Hasegawa *et al.*, "Optical guidance of terrawatt laser pulses by the implosion phase of a fast z-pinch discharge in a gas-filled capillary", *Opt. Lett.*, vol. 25, p. 10, 2000. doi:10.1364/ol.25.000010

[13] W. P. Leemans, B. Nagler, A. J. Gonsalves, C. Tóth, K. Nakamura, C. G. R. Geddes *et al.*, "GeV electron beams from a centimetre-scale accelerator", *Nat. Phys.*, vol. 2, p. 696, 2006. doi:10.1038/nphys418

[14] D. J. Spence, A. Butler and S. M. Hooker, "Gas-filled capillary discharge waveguides", *J. Opt. Soc. Am. B*, vol. 20, p. 138, 2003. doi:10.1364/JOSAB.20.000138

[15] J. M. Dawson, "Nonlinear electron oscillations in a cold plasma", *Physical Review*, vol. 113(2), p. 383, 1959. doi:10.1103/PhysRev.113.383

[16] A. Martinez de la Ossa, Z. Hu, M. J. V. Streeter, T. J. Mehrling, O. Kononenko, B. Sheeran et al., "Optimizing density down-ramp injection for beam-driven plasma wakefield accelerators", *Phys. Rev. Accel. Beams*, vol. 20, p. 091301, 2017. doi:10.1103/PhysRevAccelBeams.20.091301

[17] H. R. Griem, *Spectral line broadening by plasmas*, Academic Press, New York and London, 1974.

[18] H. R. Griem, A. C. Kolb, and K. Shen, "Stark Broadening of Hydrogen Lines in a Plasma", *Physical Review*, vol. 116, p. 4, 1959. doi:10.1103/PhysRev.116.4

[19] D. G. Jang, M. S. Kim, I. H. Nam, H. S. Uhm and H. Suk, "Density evolution measurement of hydrogen plasma in capillary discharge by spectroscopy and interferometry method", *Appl. Phys. Lett.*, vol. 99, p. 141502, 2011. doi:10.1063/1.3643134

[20] A. Biagioni *et al.*, "Gas-filled capillary-discharge stabilization for plasma-based accelerators by means of a laser pulse", *Plasma Phys. Control. Fusion*, vol. 63, p. 115013, 2021. doi:10.1088/1361-6587/ac1f68

[21] F. Filippi *et al.*, "Spectroscopic measurements of plasma emission light for plasma-based acceleration experiments", *Journal of Instrumentation*, vol. 11, no. .09, p. C09015, 2016. doi:10.1088/1748-0221/11/09/C09015

[22] S. Arjmand *et al.*, "Characterization of plasma sources for plasma-based accelerators", *Journal of Instrumentation*, vol. 15, p. C09055, 2020. doi:10.1088/1748-0221/15/09/C09055

[23] A. M. Loveless and A. L. Garner, "A universal theory for gas breakdown from microscale to the classical Paschen law", *Physics of Plasmas*, vol. 24, p. 113522, 2017. doi:10.1063/1.5004654

[24] N. A. Bobrova, A. A. Esaulov, J. Sakai, P. V. Sasorov, D. J. Spence, A. Butler, S. M. Hooker, and S. V. Bulanov, "Simulations of a hydrogen-filled capillary discharge waveguide", *Phys. Rev, E*, vol. 65, p. 016407, 2002. doi:10.1103/PhysRevE.65.016407

[25] F. Chen, *Introduction to Plasma Physics and Controlled Fusion*, Springer, Volume 1: Plasma Physics, 2nd edition, 1984. doi:10.1007/978-3-319-22309-4

[26] A. J. Gonsalves *et al.*, "Demonstration of a high repetition rate capillary discharge waveguide", *J. Appl. Phys*, vol. 119, p. 033302, 2016. doi:10.1063/1.4940121

[27] D. Giulietti, L. A. Gizzi, "X-ray emission from laser-produced plasmas", *La Rivista del Nuovo Cimento*, vol. 21(10), pp. 1-93, 1998. doi:10.1007/BF02874624