POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Characterization of Plasma Sources for Plasma-based Accelerators

LAUREA MAGISTRALE IN NUCLEAR ENGINEERING - INGEGNERIA NUCLEARE

Author: CRISTINA MARIANI
Advisor: PROF. MATTEO PASSONI
Co-advisor: DR. ANGELO BIAGIONI AND LUCIO CRINCOLI, PHD
Academic year: 2021-2022

---

1. Introduction

Electron plasma acceleration technology is nowadays one of the main challenges in particle accelerator physics. Several achievements in many different fields can be reached through them, such as in medicine, industry and physics. Inside plasma accelerator technology, one of the most important components is the source in which the actual acceleration takes place, and where the plasma is generated.
This work, carried out entirely at SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Laser And Beam), part of the National Institute of Nuclear Physics (INFN-LNF) test facility, aims at characterization of the plasma source, in order to improve the interaction between plasma and electron bunches, in terms of maximum accelerating gradient and quality of the acceleration process. With this aim, several parameters have been investigated, as source geometry, plasma electron distribution and plasma formation process. The improvements on the original scheme of the plasma accelerator source are made to achieve new challenging results related to crucial topics for plasma-based accelerators and to be used in the EuPRAXIA European project. Furthermore, these analysis are made to ensure that future accelerators can become more compact and affordable, possibly becoming of aid in many aspects of everyday life.

2. Theory

The primary limit of the conventional acceleration technology is the small accelerating gradient, which means large dimensions of the accelerators and high cost to have more powerful machines. Plasma-based accelerators can overcome these problems with their compactness and their accelerating power, since they are able to accelerate the particles up to the order of GV/m, a gradient that conventional accelerators are not capable of reaching, since their order of acceleration is around few tens of MV/m.

2.1. Plasma electron acceleration

Plasma inside the accelerator acts as the medium in which the charged particles bunch passes and is accelerated. The mechanism is analogous to the wave created by a boat in the water, and a surfer behind it; the plasma acts as the water, the boat is the driver, that can be either a laser pulse or an electron bunch, and the surfer is the particles bunch, called also witness, who will be accelerated.
The driver will create a disturbance in the

plasma, generating a bubble in which only positive charges are present. If the witness is placed in the bubble, it can behaves, using the same analogy of the boat and the waves, as a surfer on the wave, who continues to move and accelerate.

The electrons oscillations in the plasma, also called plasma waves, have a range of wavelengths and so a range of velocities, called group velocities. The phase velocity associated to the drive will be really close to the speed of light c; the wavelength of the driver is so equal to:

$$\lambda_p = \frac{c}{\omega_p} \tag{1}$$

with ω_p the plasma frequency. This parameter is directly related to the plasma electron density by the following relation:

$$w_p = \sqrt{\frac{n_e q_e^2}{\epsilon_0 m_e}} \tag{2}$$

where q_e and m_e are the electron charge and mass, ϵ_0 is the dielectric constant.

The maximum electric field and maximum acceleration rate are determined by the maximum amplitude of oscillation supported by the plasma. When this boundary is reached, the plasma wave is said to break; this phenomenon is called the $cold\ wave - breaking\ limit$. The electric fields attainable by the plasma before the wave breaking phenomenon is:

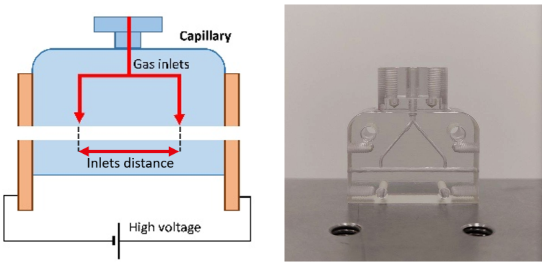
$$E \simeq 96\sqrt{n_e[cm^{-3}]} \quad [V/m] \tag{3}$$

Assuming a plasma with a density of $10^{18} cm^{-3}$, a wave with maximum electric field peaks in the order of $100 GV/m$ can be generated, being three orders of magnitude more intense than the accelerating gradient in a conventional accelerator powered by microwaves[3].

As it can be seen in equations 1 and 3, the wavelength of the driver, that will be the size of the bubble, is dependent on the plasma electron density, and so it should be constant inside the medium to optimize the acceleration process.

2.2. Plasma Source

Among the different sources that can be used for electron plasma acceleration, the one analysed and characterized in this work is the gas-filled discharge capillary. It consist in a tailored structure with a channel filled with gas via small holes, called gas inlets, located some millimetres from each end of the capillary. Two electrodes are placed at each end of the capillary, and when a discharge current pulse is driven inside the channel, the plasma is generated. Compared with other plasma sources, as plasma jets or plasma cells, gas filled capillaries allow to control the properties of the plasma channel locally by varying the geometrical characteristics or by timing the discharge with the beams to wait for the desired plasma profile during the interaction. The plasma electron density depends strictly on the capillary geometry, work conditions and gas distribution. A scheme of the capillary used at SPARC_LAB is shown in fig.1.



(a) Scheme of a generic capillary used at SPARC_LAB.

(b) Real photo of a capillary.

Figure 1

3. Experimental setup

All the analysis and measurements have been performed in the Plasma Diagnostic Lab at INFN-LNF. The overall diagnostic apparatus of the lab consist in a vacuum chamber, in which a gas discharge capillary is palced, and an apparatus needed in order to create and characterize plasmas for plasma-based accelerators. The capillary is connected at the extremities to two electrodes in order to generate the plasma through high voltage pulses able to ionize gases at pressures in the range 10-100 mbar. The two electrodes are connected outside the vacuum chamber with a high-voltage pulser circuit, a gas dispenser, with H_2 or another type of gas, and a vacuum pumping system to maintain 1x10^{-6} mbar inside the experimental chamber during operations.

The high-voltage source is composed of a switch circuit able to produce short electrical pulse of 1

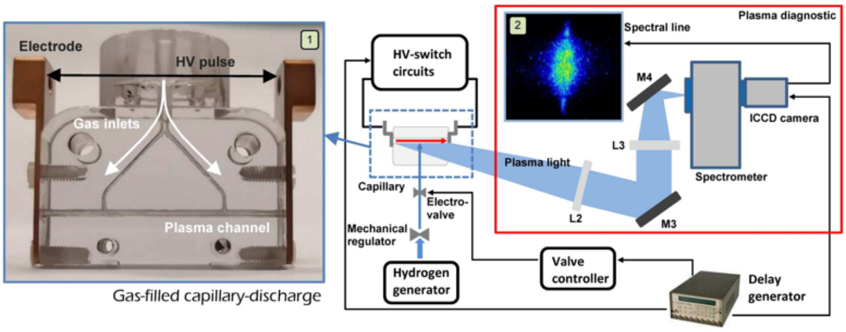


Figure 2: Scheme of the plasma module for plasma-based accelerators used at SPARC_LAB test-facility for which the plasma source is a gas-filled discharge capillary. (1) is an actual tested capillary, while (2) is the spectrum acquired through spectrometry; in (2) the longitudinal direction of the capillary is the vertical one[4].

μs duration and a high-voltage generator used as the power supply device of the first one. Voltage and current amplitude can be selected by using these circuits. For the gas discharge, it is possible to control the pressure at which the gas enter the inlets of the capillary. All the experimental apparatus is presented fig.2.

3.1. Diagnostic technique

To analyze the plasma inside the channel the Stark broadening technique is used. When the Hydrogen gas is ionized and generates a plasma, from the light emitted is possible to perform a spectrometry on the spectral lines of the Balmer series of H_2 (in our measurements Balmer β series is used). Stark effect is responsible for the broadening of spectral lines by charged particles in plasma due to the presence of an electric field created by the electrons themselves; the broadening of the spectral line is directly related to the electron density inside the plasma, through the relation present in eq.4.

$$n_e[cm^{-3}] = 8.02 \cdot 10^{12} \left(\frac{\Delta\lambda_{1/2}}{\alpha_{1/2}} \right)^{3/2} \tag{4}$$

where $\Delta\lambda_{1/2}$ is the full width at half maximum (FWHM) of the Stark-Broadening spectral width in angstroms, and $\alpha_{1/2}$ is a function of the electron density and the temperature, tabulated in [2].

By analyzing every horizontal line of the acquired spectrum (shown in fig.2) is possible to generate a distribution. Analyzing every line of the spectra is possible to reconstruct both the density along the channel axis and the temporal evolution of it, by finding an average value inside the capillary.

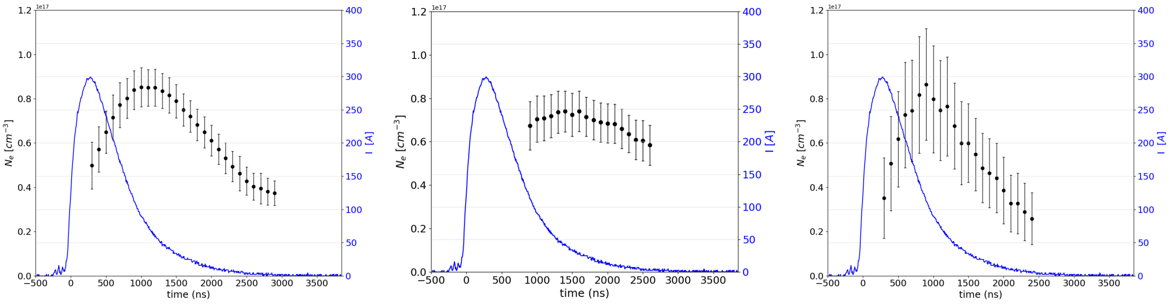
4. Results

Many analysis and measurements have been done to fully characterize the plasma source. First it has been analyzed the impact that the work conditions have on the plasma density. Then, since the geometry of the discharge capillary can modify the distribution, measurements and analysis on different channel geometries and inlets configurations have been performed. In the end, an actual and real application of the previous results has been analyzed; a segmented capillary with three electrodes (instead of the normal two) and four inlets has been characterized.

4.1. Parameters comparison

The work conditions investigated are the current, the pressure and the type of gas. The results obtained by tuning the current and the pressure are analogue: both parameters are directly proportional to the density inside the channel, but don't change the longitudinal distribution.

It has been also analysed the use of different gases, to understand how it could affect the plasma electron distribution inside the channel. Argon and Nitrogen have been investigated, using a mixture of 5% of Hydrogen and 95% of the gas at issue. The analysis is more difficult to be performed, because of the small quantity of Hydrogen present in the mixture. In terms of longitudinal distribution there are no change,



(a) H_2. (b) N_2. (c) Ar.

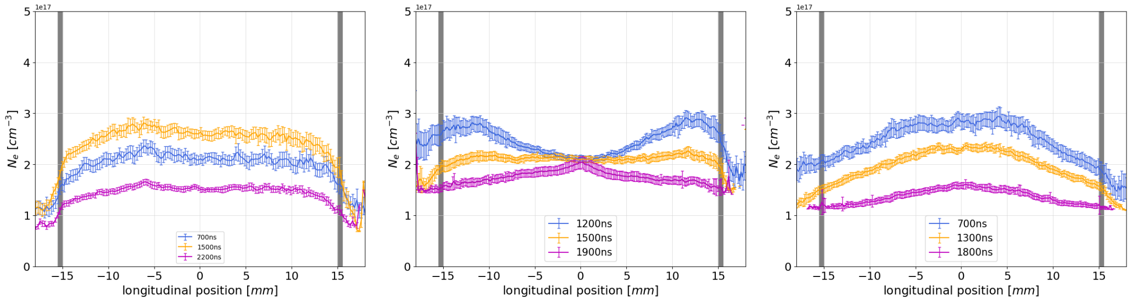
Figure 3: Temporal evolution of plasma density using different gases. The accuracy in case of N_2 and Ar is much lower than the case of H_2, due to the lower concentration of Hydrogen, element used to perform the diagnostic.

compared to the Hydrogen case, have been observed. The temporal profiles in figure 3 on the other hand show how,in case of Nitrogen, the recombination of atoms takes more time since the atomic number is higher, and so the slope after the peak is lower. In case of Argon, since the measurements are not precise due to equipment limits, the measurements taken are much less accurate; despite these limits, it has been seen a temporal profile similar to the H_2 one.

4.2. Geometries comparison

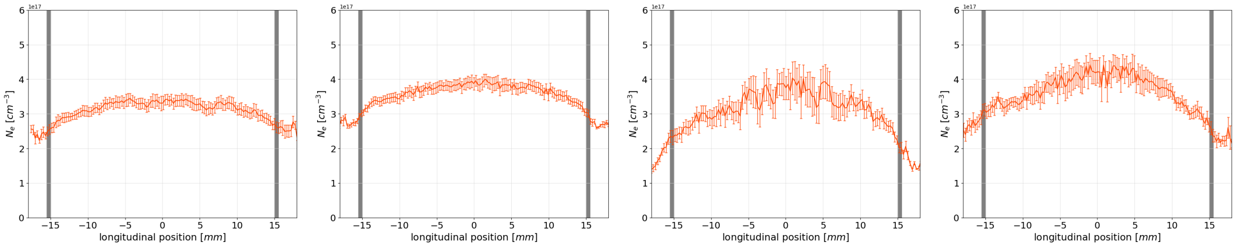
Different geometries have been investigated to understand the dependence of the plasma distribution with with respect to the capillary's design: starting from the capillary used in the accelerator as shown in fig.1, the diameter and the shape of the channel (with a variable diameter in some sections) and the configuration of the gas inlets have been modulated to study the effects on the density.

Using a smaller diameter causes an overall density increase, but doesn't affect neither the longitudinal profile of the density or the temporal evolution. From these results, different shapes of channel have been analysed; first, a capillary with one central inlet and cylindrical channel shape has been analyzed: graph 4a shows that the density distribution is quite uniform. After this analysis, it has been possible to modify the channel shape to evaluate different density distributions. In case of a bigger diameter in the central part (fig.4b), the density in the central part is lower than at the edges; this difference decreases during time, and the density uniforms itself. In case of flared edges(fig.4c) it can be noticed two ramps at the ends of the capillary, producing a density distribution with trapezoidal shape of the density distribution; also in this case the density uniforms with time. The results of this investigation are shown in figure 4.



(a) Cylindrical channel. (b) Bigger central diameter. (c) Channel with flared edges.

Figure 4: Longitudinal profiles in case of different channel configurations. Different delays for every configuration are showed, to display the development of the density distribution. The gray lines are the electrodes at the edges of the capillary.



(a) 9mm of distance. (b) 12mm of distance. (c) 15mm of distance. (d) 24mm of distance.

Figure 5: Longitudinal profiles at the same delay with the inlets at different distances from one another. It can be seen the more uniform profile in case (a) and (b) with respect with (c) and (d), where the distance between the gas inlets is higher. The gray lines are the electrodes at the edges of the capillary.

The last geometrical change applied on the initial configuration is the position of the inlets. Starting with two inlets, positioned at 15mm distance between one another, different distances (9, 12 and 24 mm) have been analysed, in addition to a change on the number of inlets itself. The best configuration is the one with two inlets at 9mm of distance from one another. This happens because, due to the close proximity between the inlets, the gas tends to spread quickly outside the capillary. Another thing that has been observed is that the configuration with lowest distance between the inlets is similar to that with a single inlet, as no difference was noted when switching between these two configurations; the comparison between the different configuration can be seen in figure 5, while the longitudinal profile of the of the single-inlet configuration is present in figure 4a.

In terms of temporal evolution, all configurations have shown similar behaviour, so the real change can be found in the longitudinal distribution.

4.3. Segmented capillary

All the analysis performed before can be used to modulate the density inside a capillary. A first experiment on this direction consisted on the use of a segmented 16cm long capillary. The innovation of this design is the fact that at the center of the capillary an electrode is placed. This permits to module the density inside the capillary, changing the current that passes in every region. A real picture of this prototype is shown in fig.6. This capillary needs two HV circuits that allow to have different currents and different delays inside the same structure. Measurements in case of same delay and same current, or in case of different currents but same delays have been performed.

The longitudinal profile, shown in graphs 7, show that an initial ramp is present at the center of the capillary; in time, the plasma electrons tend to spread in the region with less density,

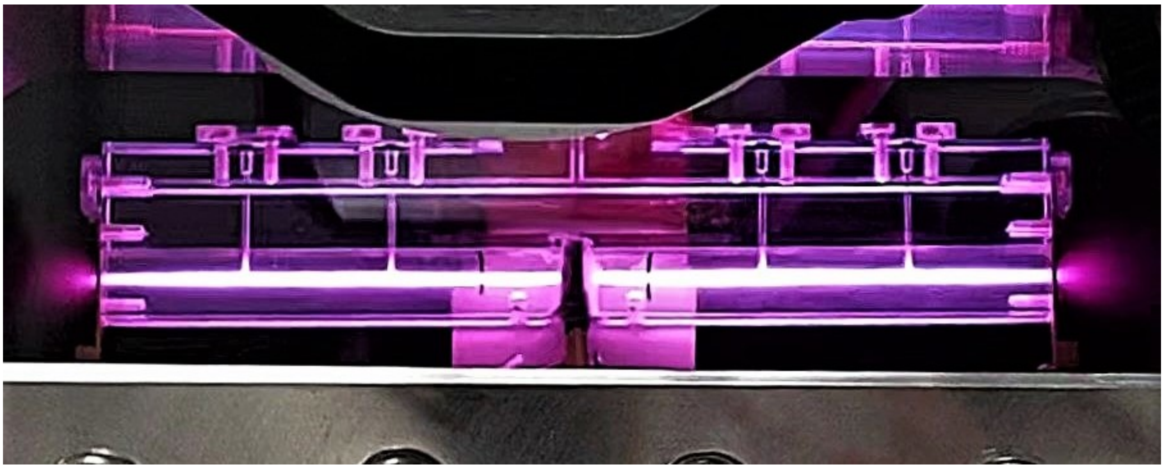


Figure 6: Segmented capillary with three electrodes, photographed during the diagnostic.

uniforming all the channel. In the end, the two regions will behave as one and the density decreases in a uniform way.

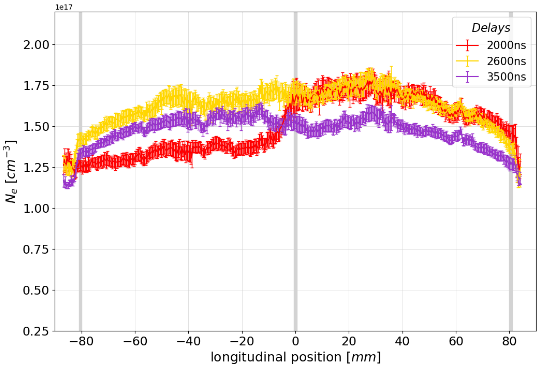


Figure 7: Segmented capillary longitudinal profile, in case of different current in the two regions. The right region has a current of ∼380 A, while the left region has a current almost of 300 A.

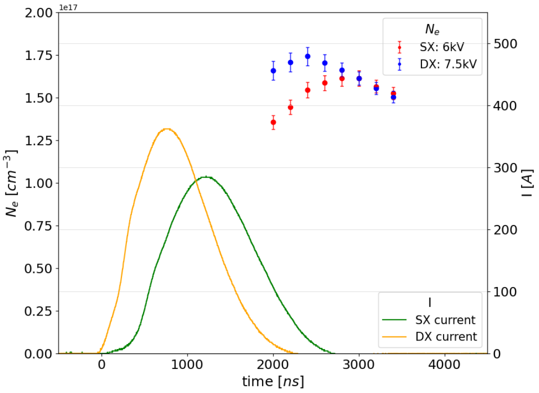


Figure 8: Segmented capillary temporal evolution. Also the current pulses are displayed, to underline the different current value and delay in the two regions.

Temporal behaviours in graph 8 show that the two pulses have a different time evolution, making it possible to tune the current pulse delays to increase or decrease the ramp created in the middle of the capillary. It can be noticed the point from when the regions start behaving as one, since the density will be the same.
Using these results, further improvements in the design and timing can be carried out.

5. Conclusions

Summing up, the thesis discusses the physics of electron plasma acceleration and the technology of many of the state-of-art configurations for the plasma discharge capillary used inside the accelerator t SPARC_LAB test facility.
It has been shown how important it is to find the right work conditions and geometrical design to obtain a better electron density distribution inside the plasma source, in order to optimize the acceleration process. Measurements and analysis showed how the density can be made more uniform using a configuration with a cylindrical channel and two inlets centered and placed at 9mm of distance. The possibility of tuning the density by changing some parameters or the geometry of the channel did permit to develop a longer capillary with tunable density and different currents through the channel.
Based on these ideas, the present work may represent a starting point for future experimental developments, such as the use of sections of a capillary as active plasma lenses and the possibility to reach m-scale long capillaries needed in the EuPRAXIA project[1].

References

[1] EuPRAXIA. Eupraxia design study project, 2020. `https://www.eupraxia-project.eu`.

[2] HANS R. GRIEM. *Spectral Line Broadening by Plasmas*. Academic Press, INC., 1974.

[3] Linbo Liang. *Beam-driven plasma wakefield acceleration in AWAKE*. PhD thesis, University of Manchester, 2022.

[4] INFN LNF. Particle-driven wakefield accelerators, 2019.