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STUDIES OF COLLISION AND COMPRESSION OF PULSED PLASMAS GENERATED BY COAXIAL ACCELERATORS

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Abstract

This paper is about first studies of the collision and compression of plasma sheaths, generated by a coaxial plasma accelerator (CPA). A possible application could be the usage as a pulsed ion source producing high ion currents, coming along with high electron densities. To find the best electrode shape for an ion source, in a first setup, the charge and ion current has been measured.

In an optimized experiment with higher discharge energies and Helium as working gas, electron density, temperature and charge states could be estimated. To improve those parameters, the collision of two plasmas generated by two CPA's facing each other and, alternatively, the compression of a plasma by a glass cone have been investigated. To determine the electron density, the Stark broadening of the H_β line has been utilized at lower electron densities and the broadening of a copper line at higher values, respectively.

INTRODUCTION

Pulsed coaxial plasma accelerators are under investigation for many decades with applications, for instance, to space propulsion [1] and switching of high voltages and currents [2]. Another possible application for such a plasma gun not yet examined is the usage as a high current ion source. An advantage compared to other ion sources is, that the plasma is already bunched due to the pulsed discharge. Additionally, the ions are already propagating after ejection with velocities in the range of some 10 $\frac{\text{km}}{\text{s}}$ due to the Lorentz force between the electrodes.

The working principle of the plasma accelerator is depicted in Fig. 1. It is built up of an inner electrode connected to high voltage and a grounded outer electrode. Both electrodes are made of copper and separated by an L-shaped insulator made of PEEK. The inner electrode has a diameter of 9 mm, the outer electrode is 14 mm in diameter, respectively, resulting in a electrode gap of 2.5 mm. After applying a voltage above the self-breakdown voltage to the inner electrode, the electric field causes the ignition of a discharge near the insulator. The plasma dynamic inside the electrode gap can be described theoretically by the snowplow model [3]. In this model the plasma is considered as an infinite thin sheath, which is accelerated by the Lorentz force. This force works like a magnetic piston and is the result of the radial current flow and the induced azimuthal magnetic field around the inner electrode. The high sheet velocity of results in a shock wave that ionizes the residual gas, which also becomes part of the plasma sheath, increasing the number of ions further on.

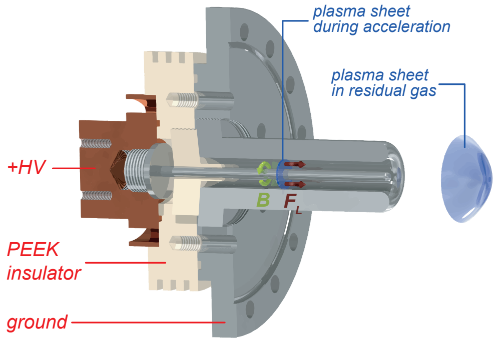

Figure 1: Working principle of a coaxial plasma accelerator.

This paper presents first measurements of ion current and charge generated by a CPA with several electrode configurations. Additionally, the results of an improved experiment are shown. This setup focuses on increasing the amount of charge carriers by accelerating the plasma into a glass cone and by the collision of two plasma sheaths in an angle of 180°.

FIRST SETUP AND ION CURRENT MEASUREMENTS

Experimental Setup

A first experiment was built up with a CPA powered by a pulse forming network with a total capacitance of 5.36 µF at maximum voltages of 12 kV leading to currents up to 40 kA. By using a differential pumping system, a pressure gradient could be established to perform the discharge at pressures in the 10^{-2} mbar range and the diagnostics at approximately 10^{-6} mbar to reduce interactions with the residual Nitrogen gas.

Ion Current

The current of the extracted ions has been determined via a Faraday cup in a distance of 100 mm to the electrode end. To prevent electrons to influence the currents signal, a negative bias voltage was applied to the cup.

The measurements presented in Fig. 2 have been performed in three different configurations of the inner electrode. The ion current has been determined with an accuracy of 5 % at a gas pressure of $1.2 \cdot 10^{-2}$ mbar inside the CPA. Initially, a solid inner electrode ending in parallel with the outer electrode (black square) was utilized. Hereby, a peak current of 275 mA has been achieved. To improve efficiency, the inner electrode was replaced by a hollow electrode (blue circle) leading to an increased ion current of 350 mA. For fur-

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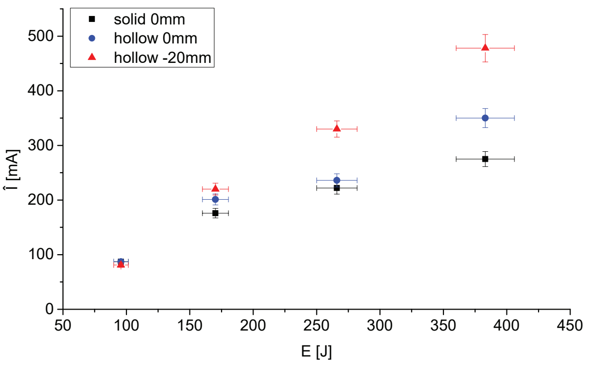

Figure 2: Measured ion current at the Faraday cup for different electrode configurations.

ther enhancement, the inner electrode was shortened 20 mm compared to the outer electrode to achieve a plasma focus (red triangle). In this configuration, a peak current of approximately 475 mA was measured.

Charge

The results of the charge for the three configurations are depicted in Fig. 3. With the solid inner electrode, a value of 303 nC could be achieved with an error of 5 %. Due to the usage of the inner hollow cathode , which is 20 mm shorter than the outer electrode, the measurements also show an enhanced charge value of 500 nC .

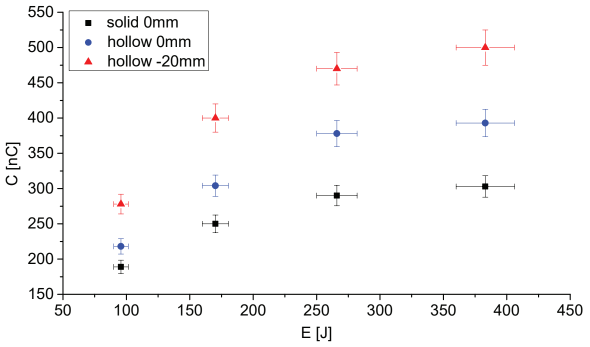

Figure 3: Measured charge at the Faraday cup for different electrode configurations.

While the ion current at lower energies it quite similar, it can be noticed, that the charge could be significantly increased due to the optimized setup. The signals have shown, that this is mainly due to longer Faraday cup pulse durations. It is assumed, that this behaviour is largely caused by the pinch effect of the plasma. Without pinch, the plasma cloud widens especially at lower discharge energies, whereby only a small amount of charge carriers pass the aperture of the differential pumping system. In case of the plasma pinch, in particular using the shorter hollow cathode, the plasma is mostly focused on the propagation axis. This results in longer pulse lengths and higher current at the Faraday cup.

IMPROVEMENT OF CHARGE CARRIERS BY COLLISION AND COMPRESSION

In an improved experiment, the focus is set on increasing the amount of charge carriers. Therefore, electron density, electron temperature and charge states have been estimated. This experiment is set up with a total capacitance of 27 µF at maximum voltages of 9 kV, which corresponds to a maximum stored energy of 1.35 kJ. Due to the low inductive design of the experiment, which is explained in detail in a prior publication [4], current rise rates in the range of $10^{11}\,\frac{\text{A}}{\text{s}}$ lead to currents up to 150 kA.

To determine electron density, the Stark broadening of emission lines could be used. For the electron density range from $10^{15}\,\text{cm}^{-3}$ to $10^{17}\,\text{cm}^{-3}$, the analization of the linear Stark broadening of the H_β line is very common and has a low error of 5 % [5]. Unfortunately, at higher electron densities, this line is broadened too widely to be utilized. Alternatively, the broadening according to the quadratic Stark effect of a Copper line at 479.40 nm was applied. By the cross-calibration with the H_β line, the half-width broadening of the Copper line $\Delta\lambda_S$ could be related to the electron density:

$$n_e\left[\text{cm}^{-3}\right] = (3.07 \pm 0.475) \cdot 10^{18} \cdot \Delta\lambda_S\,[\text{nm}] \qquad (1)$$

Results of Plasma Collision

The time and spatial integrated electron density of the plasma, generated by a single CPA is, depending on applied voltage and gas pressure, in the range of $10^{15}\,\text{cm}^{-3}$ with its maximum of $(6.38 \pm 0.83) \cdot 10^{15}\,\text{cm}^{-3}$ at $U = 9\,\text{kV}$ and $p = 70\,\text{mbar}$. These results are included in detail in the prior publication [4].

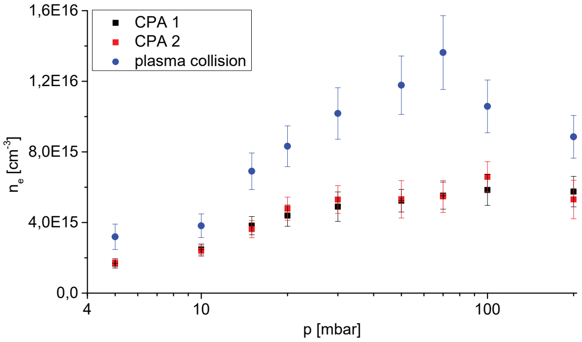

Figure 4: Electron densities of the two utilized CPAs and in case of plasma collision, respectively.

To increase the number of charge carriers, the plasma sheaths of two CPAs facing each other have been brought to collision. As shown in the graph in Fig. 4, the electron density could be increased by a factor of up to 2.48. Additionally, the average electron temperature increased from roughly 1 eV to 1.1 eV, determined by a Boltzmann plot of Copper lines. It should be noted that the collision zone has

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only a small temporal and spatial proportion of the full discharge, wherefore the peak temperature and the number of ions should be significantly higher.

Results of Plasma Compression

To compress the plasma volumetrically, a glass cone has been placed at the end of the electrodes (see Fig. 5). The cone tapers from 20 mm diameter to 0.5 mm at the tip with a tapering angle of 12°. All measurements presented have been performed at $U = 5\,\mathrm{kV}$ and $p = 5\,\mathrm{mbar}$. At higher voltages and pressures, the glass brakes due to the high mechanical stress.

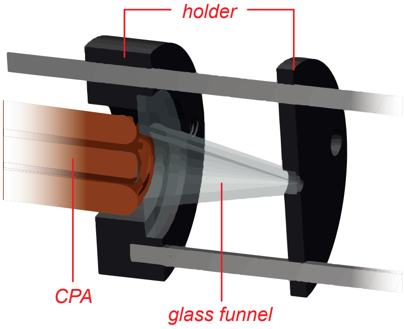

Figure 5: CAD cross section model showing the cone placed at the end of the electrodes.

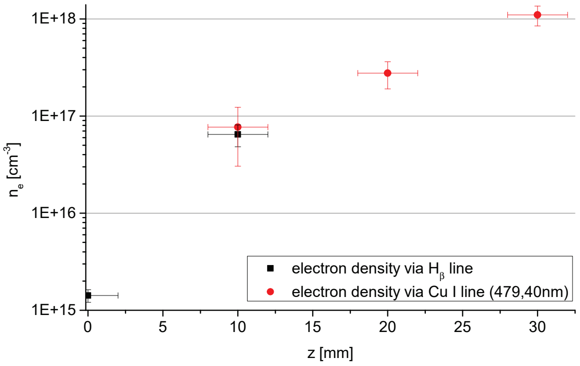

Figure 6: Spacially resolved electron density inside the cone.

For the determination of the electron density, the broadening of the Copper line had to be used, because the measured densities are above scope of the H_β line. The maximum achieved time and spatial averaged electron density is $(8.47 \pm 2.18) \cdot 10^{17}\,\mathrm{cm}^{-3}$ which is 632 times higher than without compression at 5 kV and 5 mbar. Additionally, the spatially resolved electron density has been measured. As can be seen in Fig. 6, the maximum values inside the cone are above $10^{18}\,\mathrm{cm}^{-3}$. According to the light emission of excited states of ions, which have been compared to FLYCHK simulations, the peak electron temperature is above 1.9 eV. According to simulations performed with the RALEF-2D code, electron density and temperature should be increasing with higher voltages and gas pressures. Therefore, in a next step, the glass cone will be replaced by another material to increase the values even further.

CONCLUSION

The aim of the presented project is the usage of a pulsed plasma accelerator as an ion source. Therefore, first measurements have been performed to investigate the proof of principle. An ion current in the range of up to roughly 475 mA and a emitted charge of 500 nC have been achieved at pulse durations of some µs. Theoretical simulations based on the plasma parameters indicate the ions to be single or double ionized. To determine the ratio of the charge states, spectroscopic measurements are going to follow. A second experiment at improved parameters has shown, that the initial density can be significantly increased by compressing the plasma by a tapering cone. Therefore, a calibration of the broadening of a copper line has been executed to be able to measure the achieved high electron densities.

As a next step, both experiments will be combined to increase the emitted amount of ions with the increased discharge energy of the improved experiment. Additionally, the electrodes will be designed with a tapering end to include the compression properties of the cone. To reduce the influence of the residual gas and the aperture of the differential pumping system, the experiment is planned to be performed in vacuum whereby the discharge gas will be pulsed injected by a fast valve. An expected problem of this type of a pulsed ion source is the energy distribution of the ions. Therefore, a Wien filter will be mounted to determine. An energy unsharpness probably will lead to high requirements for the extraction system, which is also currently studied. The current status of a pulsed ion source is in the very beginning, but the measurements are promising that the application as an ion source will be suitable.

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