Dynamics of the constricted mode of atmospheric pressure capacitively coupled radio-frequency driven plasma jets

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Abstract: Inside a capacitively coupled atmospheric pressure plasma jet, three fundamentally different types of discharges can be ignited; non-neutral discharges, quasi-neutral plasmas, and constricted discharges. This work applies a one-dimensional hybrid particle-in-cell/Monte Carlo collisions simulation to investigate the constricted discharge mode. By varying the driving frequency and/or voltage, the discharge dynamics become constricted to a tiny area in front of the electrodes. We aim for a fundamental understanding of the mode.

Keywords: Hybrid PIC/MCC simulation, atm. pressure plasma jet, CCPs, discharge modes

1. Introduction

Plasma discharges ignited at ambient pressure have various relevant applications and regained the attention of the scientific community. These applications range from biomedical treatments [1] to surface modifications [2]. The unique trait of atmospheric pressure discharges is that they can be applied directly without sophisticated vacuum systems.

The plasma jet is a commonly used realization of an atmospheric pressure plasma source. Plasma jets differ in their geometry and their power coupling. Thus, the COST plasma jet was introduced as a reference plasma source [3]. The COST jet is a capacitively driven plasma jet that consists of two parallel electrodes that guide a gas stream through a discharge channel (see Fig. 1).

Owing to the high pressure and small gap separation, the COST jet behaves differently than low-pressure plasma sources. In general, there are three discharge regimes. (I) non-neutral discharges. Here, a strongly modulated electron group is pushed in between the electrodes, and a quasi-neutral bulk region is missing at all [4]. (II) quasi-neutral discharges that have differentiable bulk and sheath regions. (III) the constricted mode. Tiny sheath regions shield a large bulk region, and most dynamics are constricted to these boundary regions. The order of these regimes as well as their transition basically scales with the plasma density. In general, and simplified, the non-neutral regime is found at low densities. Quasi-neutral plasmas ignite with intermediate densities. The constricted mode comes with very high plasma densities.

In this work, we focus on investigating the constricted mode of the COST jet by means of a hybrid particle-in-cell/Monte Carlo collisions (PIC/MCC) simulation. The general and unique structure of constricted discharges is introduced and discussed. Furthermore, the dynamics, especially the electron dynamics, are analyzed in detail, and the correlation to the other discharge regimes (i.e., non-neutral and quasi-neutral discharges) is shown. The transition between the discharge regimes is achieved by varying the discharge voltage and/or the driving frequency.

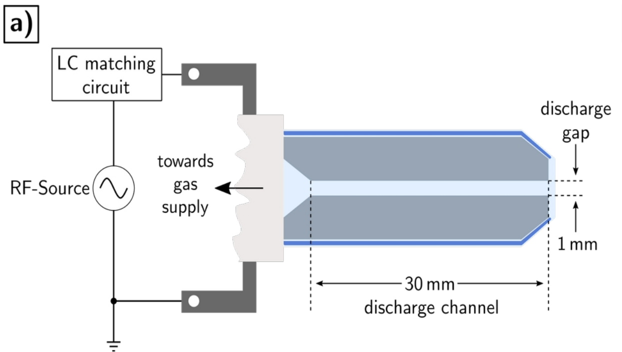

Fig. 1. Sketch of the COST plasma jet. Depiction published in [4].

2. Hybrid PIC/MCC simulation

For this work, we apply the self-developed simulation framework Eehric. The Eehric code is a hybrid PIC/MCC code that treats electrons kinetically within the classical PIC/MCC algorithm [5] while solving the continuity equation for each ion species. Thereby, the ion fluxes are calculated by applying drift-diffusion approximations.

$$\frac{\partial n_{i,s}}{\partial t}+\frac{\partial \Gamma_{i,s}}{\partial z}=S_{i,s} \tag{1}$$

$$\Gamma_{i,s}=\pm\mu_{i,s}E_z n_{i,s}-D_{i,s}\frac{\partial n_{i,s}}{\partial z} \tag{2}$$

Details of the implementation are given in [4].

Constant coefficients account for ion-induced secondary electron emission. The numerical values of the coefficients are based on an empical formula by Raizer [6]. Penning ionization is considered as described in [7],

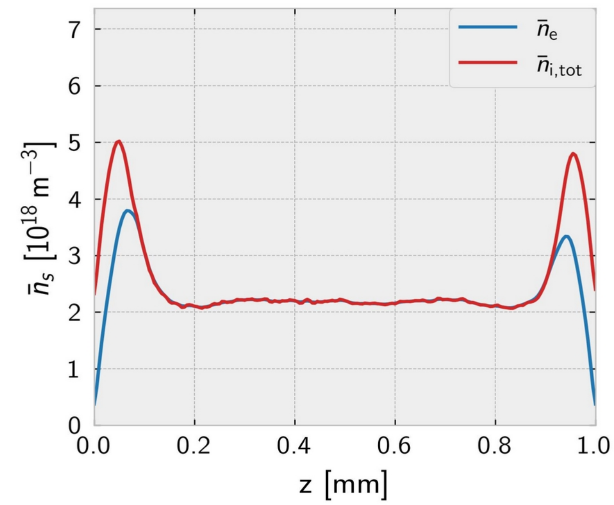

Fig. 2. Temporally averaged electron and total ion density profiles of a constricted discharge. V_{RF} = 340 V, f_{RF} = 18 MHz, x_{N2} = 0.1%.

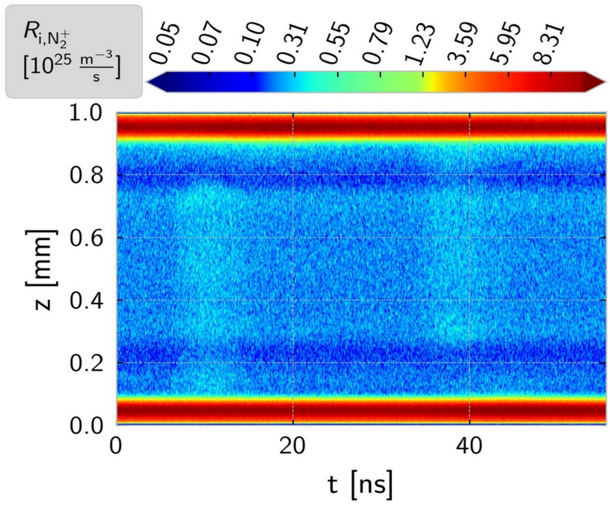

Fig. 3. Spatially and temporally resolved profile of the ionization of the nitrogen molecules. V_{RF} = 340 V, f_{RF} = 18 MHz, x_{N2} = 0.1%.

and electron-ion recombination is also included in the simulation.

3. Simulation setup

Previous work has shown that the geometrical features of the COST jet combined with the comparably inert chemistry of the helium/nitrogen gas mixture enables one-dimensional simulations to match experimental data [8]. Therefore, we conduct our simulation in a one-dimensional setup (i.e., between the electrodes) for a fixed nitrogen admixture of 0.1%. The chemistry set is based on previous work [4,6].

4. Results

Figure 2 shows the temporally averaged electron and total ion densities of a constricted discharge. It is visible that tiny sheath regions (<s> ~ 0.1 mm) shield a large quasi-neutral bulk region. However, the density profiles are uncommon for capacitively coupled plasmas. The maxima of the electron and ion density are positioned inside the boundary sheath resulting in a rather bi-modal profile (instead of the usual diffusion profile). Moreover, the densities are relatively high. All constricted discharges that we observed yield averaged densities in the order of 10^{18} m^{-3}.

These high densities are both the feature and the reason for the constricted character of the discharge. The simple formula for the sheath width s given by the matrix sheath model

$$s=\sqrt{\frac{2\varepsilon_0\phi}{e\,n_i}} \tag{3}$$

gives a viable estimate for s in the constricted mode. We present that high driving voltages are necessary for the discharge to induce the transition into the constricted mode. The combination of tiny sheaths and high voltages results in enormous local field (inside the sheath regions).

Due to the high collision frequency, secondary electrons cause ionization cascades within these boundary fields to build up the density maxima inside the sheaths. Figure 3 shows the resulting ionization dynamics for the N_2^+ ion in spatial and temporal resolution. The ionization structure vaguely resembles the structure of DC discharges. There is strong ionization in front of the electrodes, a small dark space at the sheath edge, and a large zone with weak ionization inside the bulk. The bulk ionization is about an order of magnitude weaker than the ionization inside the sheath regions. When the maximal current flows through the bulk area (t_1 ~ 10 ns and t_2 ~ 40 ns), bulk electrons ionize the background gas. The overall diffuse structure of the ionization profiles is caused by Penning ionization [4]. Because of Penning ionization, the sheath ionization structure is elongated over the whole period and not constricted to the moments of sheath expansion.

5. Conclusion

The constricted mode of the capacitively coupled atmospheric pressure plasma jets is a distinct discharge mode that can solely show up for atmospheric pressure discharges. A small free mean path and high field strength are necessary to achieve these discharges. The constricted discharge establishes an extraordinary, edge focussed density profile. However, the overall high densities and enormous local field strength result in an effective power coupling into both electrons and ions. In terms of plasma chemistry (e.g., CO_2 dissociation or NH_3 synthesis), the distribution of high powers is thrived for. The constricted mode of an capacitively coupled plasma jet might be the suitable operation mode for efficient plasma chemistry.

6. Acknowledgment

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7. References

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