

Electron Beams in Capacitively Coupled Radio-Frequency Discharges

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Abstract—The generation of electron beams by the expanding sheath is observed experimentally in asymmetric single-frequency capacitively coupled radio-frequency discharges using phase-resolved optical-emission spectroscopy. Depending on the discharge geometry and conditions, such beams can propagate through the entire discharge and are reflected at the opposing plasma boundary. They are closely related to stochastic heating, and their generation is enhanced by the plasma-series-resonance effect. Confinement of these energetic electrons can lead to an effective heating of the plasma.

Index Terms—Capacitively coupled RF discharges, electron beams, phase resolved optical emission spectroscopy, plasma series resonance, stochastic heating.

CAPACITIVELY Coupled Radio-Frequency (CCRF) discharges are often used for etching and deposition processes in industry. However, fundamental mechanisms such as electron heating and plasma sustainment, particularly at low pressures, are not yet fully understood and are an important current research topic. In this paper, the spatio-temporal excitation caused by energetic electrons into a specifically chosen rare gas level (Ne 2p1, 19 eV) is investigated by phase-resolved optical-emission spectroscopy. Measurements are performed in a slightly modified GEC reference cell in an asymmetric CCRF discharge using different gases (neon, krypton) at low pressures (< 5 Pa) and 8 W (Fig. 1). The setup is a hybrid CCP/ICP discharge operated at 13.56 MHz. However, in the frame of this paper, it is operated exclusively in the capacitive mode. The modification is a replacement of the metal cylinder surrounding the ICP antenna by a monolithic quartz housing that acts as a floating surface in the plasma. The electrode radius and the gap between electrode and quartz are both 5 cm. The spatial and temporal resolution of the optical measurements is about 1 mm and 4 ns, respectively. Under the conditions investigated, the excitation rate can be easily calculated out of the measured emission [1], yielding spatio-temporal plots of the excitation caused by energetic electrons ($E > 19$ eV).

Figs. 2 and 3 show such spatio-temporal plots of the excitation within one RF cycle at various pressures and in different gas mixtures. At the beginning of each RF cycle, when the

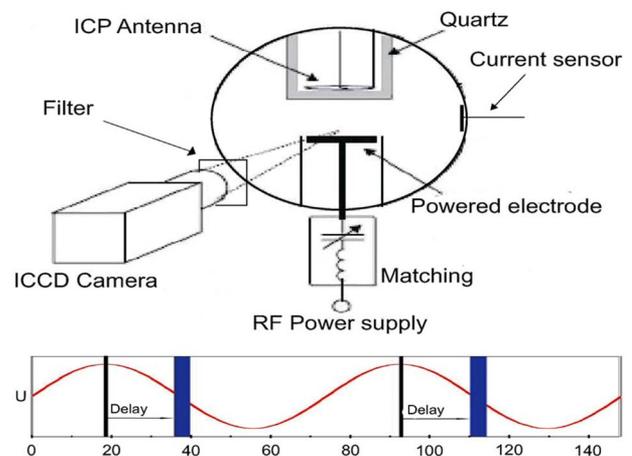


Fig. 1. Sketch of the experimental setup used for the investigations performed in an asymmetric single-frequency CCRF discharge.

sheath expands, the generation of a beam of energetic directed electrons is observed that penetrates into the plasma bulk. Its propagation velocity can be determined from the slope of the arrows shown in Figs. 2 and 3. However, the analysis involves an inherent uncertainty due to the relatively broad excitation pattern. At all pressures discussed here, the propagation velocities range around $2.5 \cdot 10^6$ m/s (17.8 eV) with a variation of $\pm 0.5 \cdot 10^6$ m/s being about equal to the uncertainty. This energy is substantially higher than the electron mean energy of about 5 eV under similar conditions [1]. Applying a simple analytical model [1], it is shown that such beams lead to an enhanced high-energy tail of the EEDF, resulting in bi-Maxwellian EEDFs. Therefore, stochastic heating is closely related to electron beams. Under the conditions discussed here, the plasma series resonance (PSR) plays an important role [1], [2]. It leads to nonsinusoidal RF currents. High-frequency oscillations of the measured current waveform on the order of 50 MHz are observed (Fig. 2, [1]). Consequently, the sheath expands more rapidly than in regimes of sinusoidal RF currents. The beam occurs exactly in the interval between the first two zeros of the current ($\Delta t = 14$ ns). This clearly indicates its generation by the fast sheath expansion caused by the PSR effect. Therefore, the PSR effect enhances the generation of such electron beams and leads to the observed spatio-temporal excitation [1], [3]. With decreasing pressure, the electron mean free path increases, and these energetic directed electrons can propagate further into the plasma until they hit the opposing quartz cylinder (bottom graph in Fig. 3). This cylinder acts as

Manuscript received December 1, 2007; revised March 19, 2008. This work was supported by the DFG under SFB 591 and GK 1051.

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Digital Object Identifier 10.1109/TPS.2008.924404

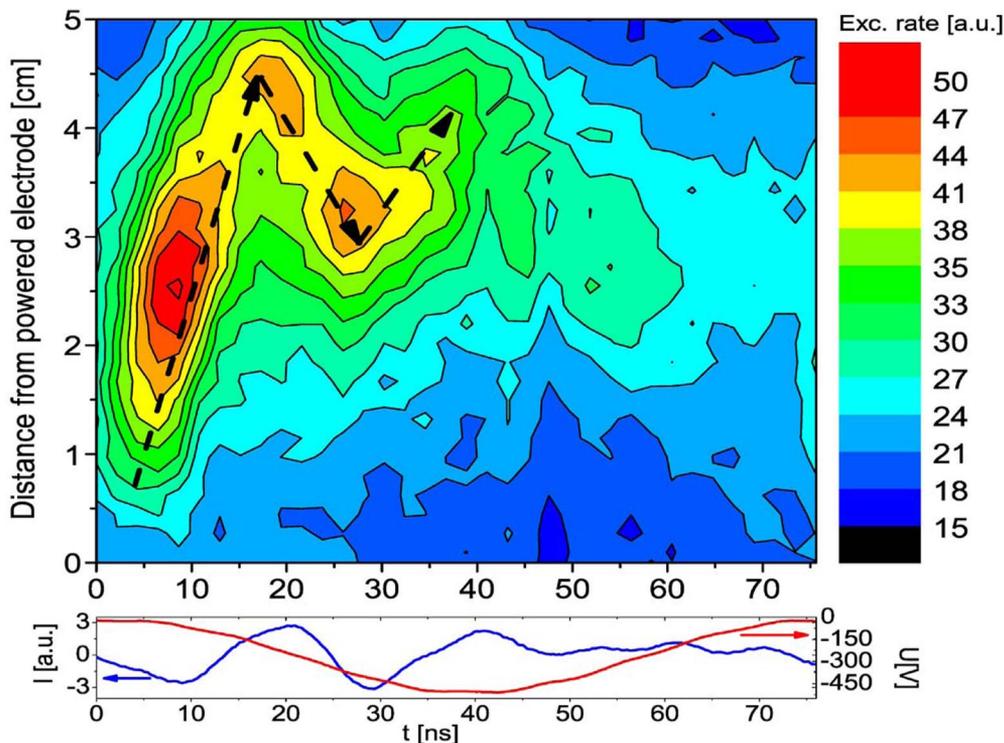


Fig. 2. Excitation into $\text{Ne}2p_1$ in an asymmetric CCRF discharge (0.2 Pa, 8 W, 90% krypton, 10% neon). The measured voltage at the powered electrode (high-voltage probe) and the measured RF current waveform at the discharge wall (current sensor) are also shown.

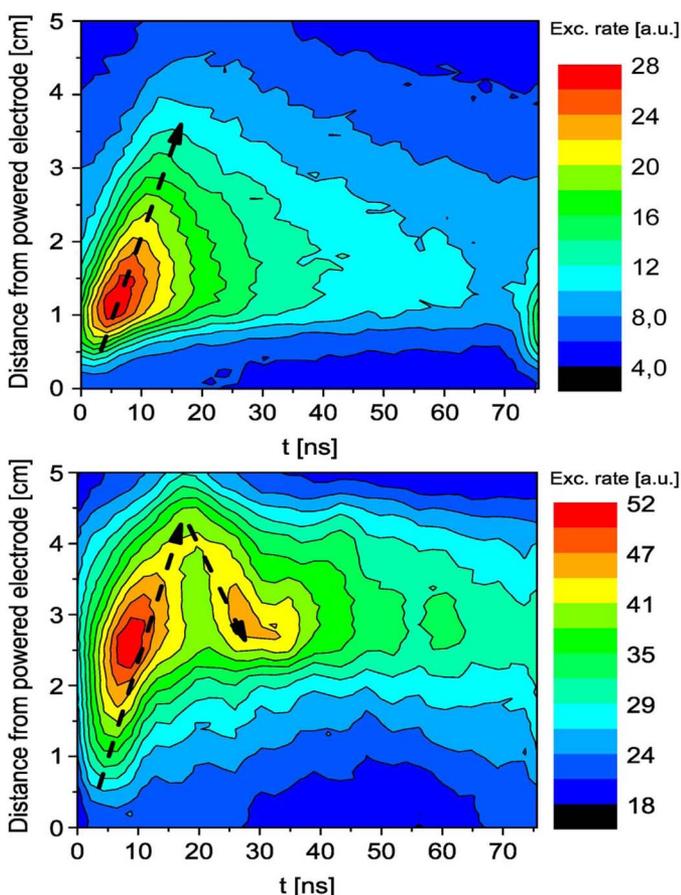


Fig. 3. Phase- and space-resolved excitation into $\text{Ne}2p_1$ in an asymmetric CCRF discharge operated at 8 W (current and voltage waveforms look similar as shown in Fig. 1). Top graph: Krypton with 10% neon admixture at 5 Pa. Bottom graph: Neon at 2 Pa.

a floating surface and charges up negatively, as it is bombarded by energetic electrons. Consequently, a sheath develops in front of the quartz that reflects following electrons back into the plasma. It should be noted that the floating potential at the quartz is high enough to reflect the energetic beam electrons ($E \geq 19$ eV). Assuming a Maxwellian EEDF, the static floating potential would already be higher than 20 eV. Here, the EEDF is strongly non-Maxwellian. Therefore, the floating potential is even higher. At very low pressures (Fig. 2), the reflected electrons hit the fully expanded sheath at the powered electrode, where they are reflected again back into the bulk. Such beams and their reflections have been observed theoretically before in PIC simulations [4], [5] but have never been detected experimentally until now. This “electron ping pong” effect is supposed to lead to an effective heating of the plasma at low pressures, since the high energy of the beam electrons is deposited in the plasma to a great extent.

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