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Rapid impedance change and electron power absorption mode transition during gas breakdown under radio-frequency excitation

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Gas breakdown——|when the medium changes from an insulating phase to a conducting phase —— is a spectacular phenomenon that takes place every time upon the initiation of any gas discharge [1, 2]. Contrary to this, breakdown is an unwanted phenomenon in electrical insulation, but in both cases the detailed understanding of the relevant physical effects is of utmost importance. Its simplest form, i.e., the Townsend breakdown in a dc electric field has been investigated for many decades. Whereas, the breakdown process under radio-frequency (rf) excitation exhibits its complexity, and most of relevant studies have been devoted to determination of a "breakdown curve", which describes the dependence of the breakdown voltage on the product of the gas pressure and the electrode gap. Details of the gas breakdown process, e.g., time evolution of electrical and plasma characteristics, under rf excitation are far from being well understood [2].

In this work, time evolution of the electrical and plasma characteristics since the beginning of the excitation pulse is studied on the nanosecond time scale by a synergistic combination of experiments (performed in a paralell-plate pulsed capacitively coupled rf discharge in Argon with the use of multifold diagnostics), kinetic simulations (based on the particle-in-cell approach coupled with Monte Carlo collision) and an analytical model.

During the breakdown process the system is found to undergo a sequence of distinct electron power absorption modes, i.e. "avalanche", "overshoot", "DA", and α modes, which were found to be highly correlated with the rapid changes of the system impedance as the plasma is building up. Figure 1 shows the time evolution of the voltage, V_{RF}, the current amplitudes: the total, conduction and displacement current, I_{RF}, I_c and I_d, respectively, the relative phase between V_{RF} and I_{RF}, φ_{vi}. I_c and I_d are provided in the center of the electrode gap.

The time axis is divided into three phases in Figure 1: (i) *pre-breakdown* ($t < t_1$), (ii) *breakdown* ($t_1 < t < t_2$), and (iii) *post-breakdown* ($t > t_2$). During the *pre-breakdown* phase, the system behaves like a gas-filled capacitor. The charge density is so low that I_c is negligible compared to I_d. φ_{vi} remains at 90 for dozens of rf cycles after an initial rise, and I_{rf} follows closely the increasing V_{rf}. This indicates a pure capacitive impedance, so that rf power is hardly deposited. During *breakdown* phase, I_c contributes increasingly to I_{rf}, while I_d decays, because the externally applied potential is gradually shielded by the formation of space charge regions adjacent to the electrodes. Shortly after t_1, I_{rf} increases quickly, due to the rapidly growing I_c, while V_{rf} drops slightly in the experiment. The opposite trends of I_c and I_d lead to a fast drop of φ_{vi} from 90 to a minimum of 62, corresponding to an increased resistance of the system. In the *post-breakdown* phase, the increase of I_{rf} slows down, and I_{rf} is now dominated by I_c, due to the attenuation of I_d.

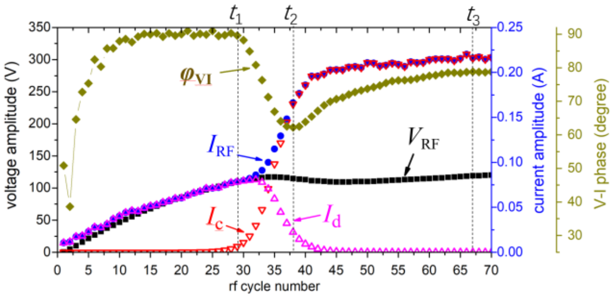

Figure 1 The evolution of the voltage amplitude (V_{RF}), current amplitudes [including total (I_{RF}), and conduction (I_c) and displacement (I_d) currents], and the relative phase angle (φ_{vi}) with the number of rf cycle.

Besides, the effects of changing the afterglow duration of a pulsed discharge on re-ignition process have also been studied. By decreasing the afterglow duration, it was found that the re-ignition process gradually deviates from the breakdown.

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References

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