Ignition physics of a capacitively coupled RF discharge

Yong-Xin Liu, Xiang-Yu Wang, Quan-Zhi Zhang and You-Nian Wang

School of physics, Dalian University of Technology, China

Abstract: The temporal evolution of plasma ignition process under radio-frequency excitation is far from being well understood. During such an ignition process, it is found that the parallel-plate system undergoes a sequence of distinct electron power absorption modes, while its impedance changes rapidly. Extended study on the ignition process is also carried out under different gas pressures, voltage amplitudes, and initial charge densities.

Keywords: radio frequency, capacitively coupled plasma, ignition process.

Gas breakdown is a spectacular phenomenon that takes place every time upon the initiation of any gas discharge [1]. 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. However, under radio-frequency (RF) excitation the breakdown process exhibits its strongest complexity. Most existing studies of this topic have been devoted to the determination of a "breakdown curve", which describes the dependence of the breakdown voltage on the product of the gas pressure and the electrode gap [2]. Details of the gas breakdown or plasma ignition process, e.g., the time evolution of electrical and plasma characteristics, under RF excitation are far from being well understood.

In this work, time evolution of the electrical and plasma characteristics during the gas breakdown or plasma ignition is studied in a pulsed capacitively coupled RF (CCRF) plasma on the nanosecond time scale by a synergistic combination of experiments, kinetic simulations (based on the particle-in-cell approach coupled with Monte Carlo collision) and an analytical model. Note that our study shows that the ignition process of a pulsed CCRF plasma behaves quite like a gas breakdown when the power-off time is set to be sufficiently long.

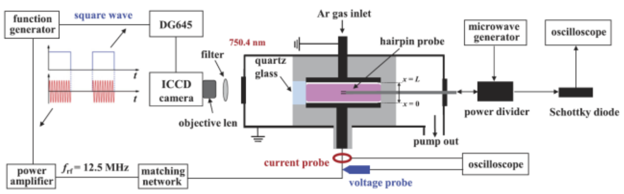

Fig.1 Schematic of the pulsed capacitively coupled RF plasma reactor, supplemented with a phase resolved optical emission spectroscopy, a time-resolved hairpin probe, and electrical measurement systems.

The experimental cell has two parallel 10 cm-diam. stainless-steel electrodes separated by 2.5 cm and surrounded by a Teflon liner, to minimize the dc self-bias (see Fig.1). A pulse-modulated sinusoidal 12.5 MHz RF voltage waveform of a function generator is amplified and applied to one of the electrodes via a fixed matching network. The electron density is measured by a hairpin probe, the spatiotemporal distribution of the electron impact excitation dynamics is determined by phase resolved optical emission spectroscopy, and the electrical parameters are obtained by analyzing the measured current and voltage waveforms at the power feeding point.

Fig. 2 shows the time evolution of the voltage amplitude (V_{RF}), the current amplitudes (I_{RF}), the conduction and displacement current amplitudes, and the relative phase between V_{RF} and I_{RF} (φ_{vi}). The conduction and displacement currents are provided in the center of the electrode gap. The time axis is divided into three phases in Fig.2: (i) *pre-breakdown* ($t < t_1$), (ii) *breakdown* ($t_1 < t < t_2$), and (iii) *post-breakdown* ($t > t_2$) [3]. During the *pre-breakdown* phase, the system behaves like a gas-filled capacitor. The charge density is so low that the conduction current is negligible compared to displacement current. 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 this phase, a low number of electrons are accelerated back and forth between the electrodes in the homogeneous RF electric field, generating the tilted excitation maxima. This observed electron power absorption mode can be termed as 'RF-avalanche' mode.

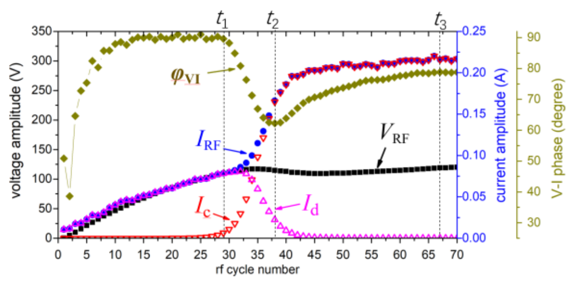

Fig. 2. The evolution of the voltage amplitude (V_{RF}), current amplitudes [including total (I_{RF}), and conduction (I_c) and displacement (I_d) currents], and the relative phase angle (φ_{vi}) with the number of RF cycle, T_N.

During *breakdown* phase, the conduction current contributes increasingly to I_{rf}, while the displacement current 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 conduction current, while V_{rf} drops slightly in the experiment. The opposite trends of the conduction and displacement currents lead to a fast drop of φ_{vi} from 90° to a minimum of 62°, corresponding to an increased resistance of the system. During this phase, the electric field distribution exhibits two significant changes: (i) its spatial gradient is enhanced locally near the electrodes, leading to the local excitation maxima near the edges of these space charge regions, (ii) the spatiotemporal distribution of the electric field is twisted and, consequently, a 'tailed' excitation pattern extending toward the electrodes is observed. The discharge is now operated in an 'overshoot' mode.

In the *post-breakdown* phase, the increase of I_{rf} slows down, and I_{rf} is now dominated by the conduction current, due to the attenuation of the displacement current. The excitation pattern exhibits features often seen in electronegative discharges, where both power absorption near the expanding sheath edges and within the plasma bulk are prominent (hybrid 'α–DA' mode).

The plasma ignition processes at different gas pressures and voltage amplitudes are investigated by multi-fold experimental diagnostics [4]. Based on the measured "V-shaped" RF breakdown curve, the gas pressures and voltage amplitudes of interest are selected, and then different characteristics of ignition processes are compared and discussed in detail. Particularly, the spatiotemporal pattern of the electron impact excitation rate obtained within the selected pressure range, as well as other results, aid the understanding of a typical "V-shaped" RF breakdown curve.

At lower pressures, the profile of electron density is strongly modulated by the RF electric field during the pre-ignition phase. Accordingly, a tilted region of the high excitation rate is enhanced toward the electrode, suggesting a large amount of electrons loss at the electrode. So, the breakdown voltage increases toward the low-pressure end of a breakdown curve to enhance ionization, bring about ignition. By increasing gas pressure, the electron drift velocity is reduced, and the profile of electron density becomes less modulated, manifesting a wider and less tilted region of spatially uniform strong excitation pattern during the pre-ignition and ignition phases. Due to smaller reduced electric field, at higher pressure, more electron energy is dissipated into the inelastic collisions of lower threshold energy, i.e., various types of excitation processes, so the overshoot of plasma emission intensity becomes more significant than that of RF power deposition. To fulfill ignition, as the pressure increases, a higher breakdown voltage is needed to enhance the reduced electric field, ensuring sufficient ionization.

By increasing the voltage amplitude, the ignition is advanced and becomes more significant, manifesting a faster increase in discharge current and a stronger overshoot of RF power deposition. Meanwhile, at high voltage amplitude, the excitation pattern exhibits complex spatiotemporal distribution due to enhanced local electric field when the plasma emission intensity overshoots.

In addition, it is found that the plasma and electrical parameters during the ignition process depend strongly on the power-off duration, T_{off}, primarily because of the dependence of the remaining charge density on this parameter [5]. The optical emission intensity is found to change with time in the same manner as the power deposition into the system at relative long T_{off}, suggesting that the power is primarily absorbed by the electrons, which dissipate their energy via inelastic collisions (see Fig.3). During the ignition phase, the system undergoes different electron power absorption modes depending on T_{off}. Specifically, for short T_{off} the α mode dominates during the entire ignition phase, while the ignition process behaves like a gas breakdown for longer T_{off} [3].

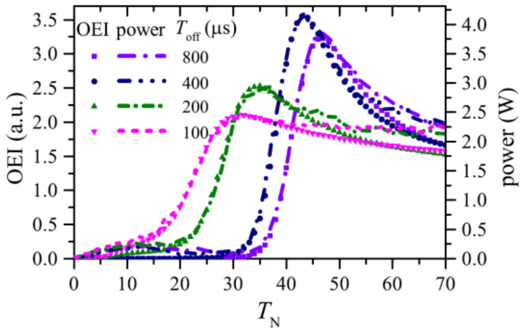

Fig. 3 Experimentally determined optical emission intensity (symbols) and deposited RF power (lines) as a function of the number of RF cycle, T_N, for relatively long T_{off} cases.

Conclusions

The time evolution of electrical and plasma parameters, and their intrinsic correlations during gas breakdown have been analyzed in a pulsed CCRF discharge in argon. We found that the system goes through different modes of electron power absorption i.e., 'RF-avalanche', 'overshoot', 'DA', and α modes, which were found to be highly correlated with the rapid changes of the system impedance. The plasma ignition processes are investigated at different gas pressures and voltage amplitudes, to aid understanding the "V-shaped" RF breakdown curve. Plasma ignition behaves differently for short and long power-off durations: 1) for short T_{off}, the plasma parameter evolves relatively smoothly, and α mode dominates; 2) for long T_{off}, plasma ignition behaves like gas breakdown.

Acknowledgements

The authors appreciate the contributions from Zoltan Donko from Wigner Research Centre for Physics, Hungary and Julian Schulze from Ruhr-University Bochum, Germany.

This work has been financially supported by the National Natural Science Foundation of China (NSFC) (Grants No. 11722541, No.11935005, and No. 12275043).

References

[1] J. M. Meek and J. D. Graggs, Electrical Breakdown of Gases (Oxford, Clarendon Press, 1953).

[2] V. A. Lisovskiy and V. D. Yegorenkov, J. Phys. D: Appl. Phys. **31**, 3349 (1998).

[3] Y. X. Liu, X. Y. Wang, Q. Z. Zhang, Z. Donko, K. Zhao, J. Schulze and Y. N. Wang, Plasma Sources Sci. Technol. **29**, 12LT03 (2020)
[4] X. Y. Wang, X. K. Wang, K. Zhao, Y. X. Liu, and Y. N. Wang, Phys. Plasmas **29**, 053501 (2022)
[5] X. Y. Wang, J. R. Liu, Y. X. Liu, Z. Donko, Q. Z. Zhang, K. Zhao, J. Schulze, and Y. N. Wang, Plasma Sources Sci. Technol. **30**, 075011 (2021)