Nature of radiofrequency breakdown in argon viewed through electron energy distribution functions modeled by the Monte Carlo technique

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This paper investigates radiofrequency breakdown in argon by analyzing the electron energy distribution functions obtained from a Monte Carlo code. Energy gain is determined by the external AC field and applied frequency of 13.56 MHz while losses are due to many collisions between electrons and the background gas and electrons and infinite parallel electrodes. Two points on the breakdown voltage curve with the same breakdown pressure of 0.2 Torr and different voltages of 94 V and 447 V highlighted the need of increasing the number of electron – background gas collisions to maintain the discharge, which led to increase of pressure, hence the double valued nature of rf breakdown voltage curve. On the other hand, presence of Ramseur minimum in the cross section for elastic scattering is responsible for fast collapse of EEDF peak for some combinations of breakdown voltage and breakdown pressure.

Radiofrequency (RF) breakdown has been analyzed in our recent papers [1], [2] as well as the role of attachment process in oxygen gas on the breakdown curve as the loss mechanism in the gas volume between two electrodes [3]. Now we have employed Monte Carlo code to investigate electron energy distribution functions (EEDFs). Background gas is argon and the applied frequency is 13.56 MHz. Electron dynamics is defined only by the external AC field and electron-gas molecule collisions. When electron reaches one of the electrodes it is being deleted from the simulation.

In Fig. 1 we have presented EEDFs along the breakdown voltage curve. As expected, mean energies are higher at high voltages (left-hand side of the curve). Electrons can also gain more energy from the AC filed along their path uninterrupted with collisions, due to small pressures (background gas density). At the same time, there is a difference between EEDF sampled at different times in one period of AC field (lines in various colors in the same plot). When the AC field passes through zero, the EEDF has its maximum peak value because electrons gain small amounts of energy from the field and the low energy electrons are dominant. At the AC field maximum EEDF has the longest “tail”, electrons gain more energy, as expected. Right-hand side of the breakdown voltage curve has almost uniform EEDF over time period (from zero to 2π). Electrons mean energy has small deviation from the mean value. It is because the energy gain from the AC field gets “interrupted” by numerous collisions and EEDF doesn’t change much over one period.

Double valued nature of RF breakdown voltage curve [1] can be analyzed by focusing on the energy balance. Fig. 2 shows the differences between two breakdown points that have the same breakdown pressure of 0.2 Torr and different voltages of 94 V and 447 V (plots A and D from Fig. 1). In Fig. 2a there is comparison of mean energies. Minimum values of both energy plots are similar but maximum energies and means are quite different. Mean value for point A is around 20 eV while for D point is around 8 eV. We know that pressure is the same and it can be assumed that electrons experience the same number of collisions with background gas in both points (assuming that the collision frequency is not strongly dependent on the energy). Hence losses in the gas volume do not play a deciding role in energy balances for those two points. It is very likely that the high voltage in the second (‘upper’) curve is due to the high voltage that pushed electrons towards the electrode and thus increased the losses at same point allowed electron to gain enough energy to ionize before colliding with the electrode. That allowed for achieving selfsustained conditions again for the same pressure.

The main difference is in energy that electron can obtain from the field between two collisions, presented in Fig. 2b. At the higher voltage that energy is around 1.5 eV while at lower voltage that energy drops almost 100 times. It means that electron needs to experience 100 times more elastic collisions to acquire enough energy to perform ionization, compared to the electron at 447 V. As both points are in region of low pressures and small number of collisions with the background gas, we can conclude that higher voltage point has more efficient ionizations.

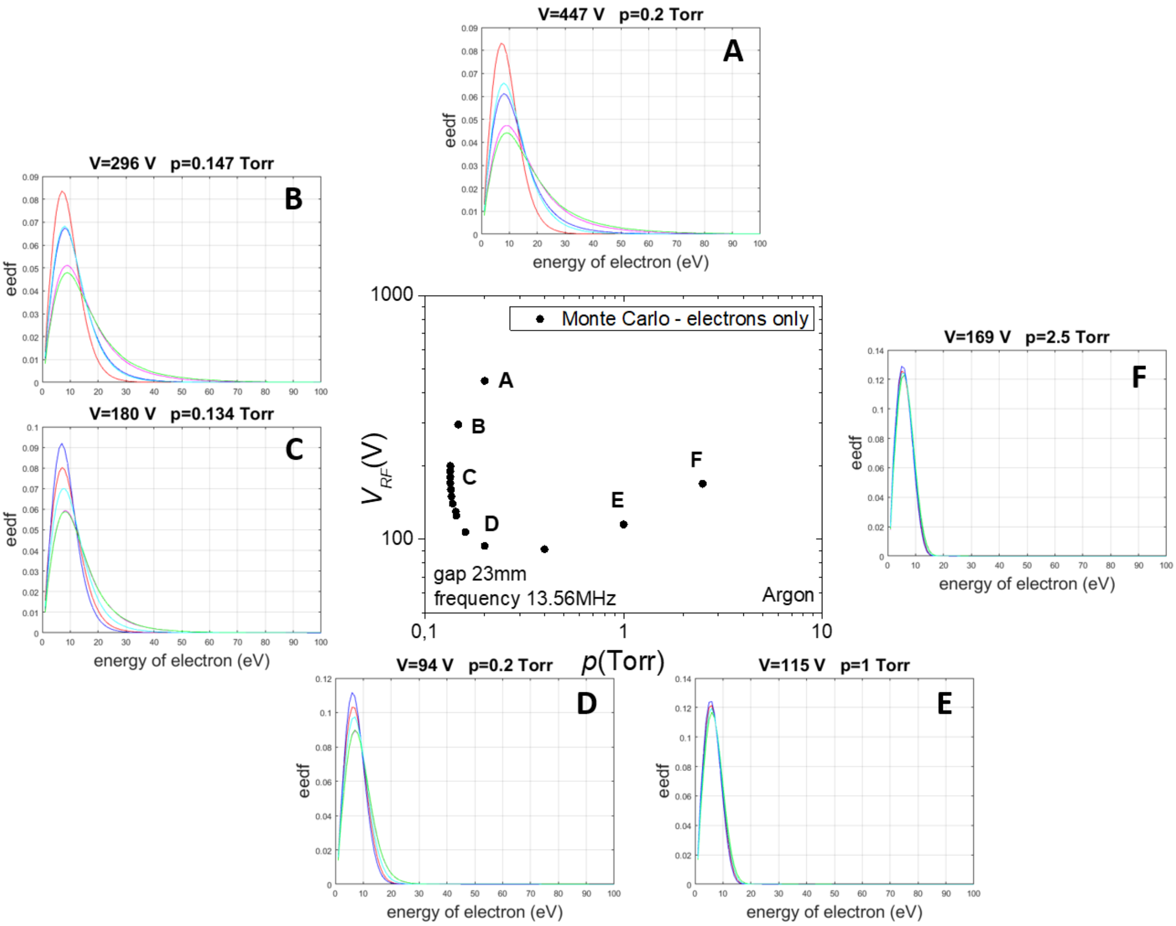

Fig. 1: Electron energy distribution functions (EEDFs) along breakdown voltage curve. Different lines at the same plot represent EEDF sampled at different times (from zero to 2 π). Background gas is argon, frequency is 13.56 MHz and gap is 23 mm.

How the EEDFs are linked to the number of collisions can be seen in Fig. 3. In Fig. 3a EEDFs in the volume of the gas over one half period of time for the already mentioned points A and D from Fig. 1 are presented. We can see that at higher voltage there is a narrow peak with long tail that indicates presence of high energy electrons. At lower voltage peak is wider and tail is much shorter than at 447 V. Both peaks are slightly delayed compared to the field minima at π/2 which is a consequence of the inability of energy to relax at applied frequency of 13.56 MHz. Also, the difference in time necessary for the peak to form and to diminish can be observed. To investigate this peak "cycle" we have presented relaxation of 95% EEDF peak value over half period of time in Fig. 3b with applied AC filed in light blue colored line. Value of 95% of the peak is chosen to avoid statistical fluctuations that the 100% of the peak has. Fig. 3c shows number of elastic collisions. As can be seen in Figure 3b, there is a steep slope that characterizes peak decline, which is more pronounced at the higher voltage. Decline in EEDF means that electrons obtain energy fast which is in a good agreement with the peak in number of elastic collisions. Peak in the number of collisions (Fig. 3c) has to be a consequence of the peak in argon cross section set. That leads to a conclusion that at point A after the EEDF peak, the majority of the electrons have the energy that corresponds to the energy of the Ramseur minimum and at the same time they gain energy fast.

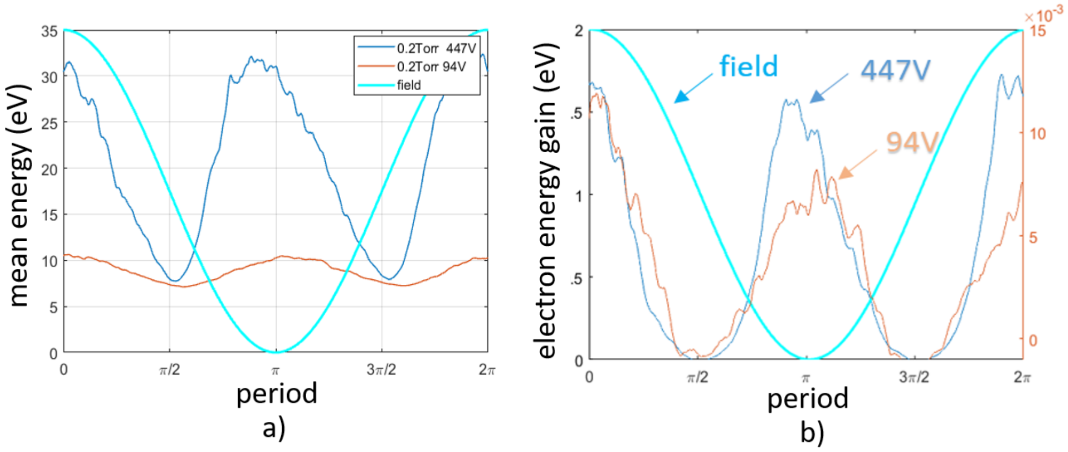

Fig. 2: a) mean energies for point A and D from Fig. 1, b) Gain of energy transferred from AC field to the electron between two collisions for points A and D (Fig. 1) with the same breakdown pressure of 0.2 Torr and different voltages: 447 V and 94 V. Background gas is argon, frequency is 13.56 MHz and gap is 23 mm.

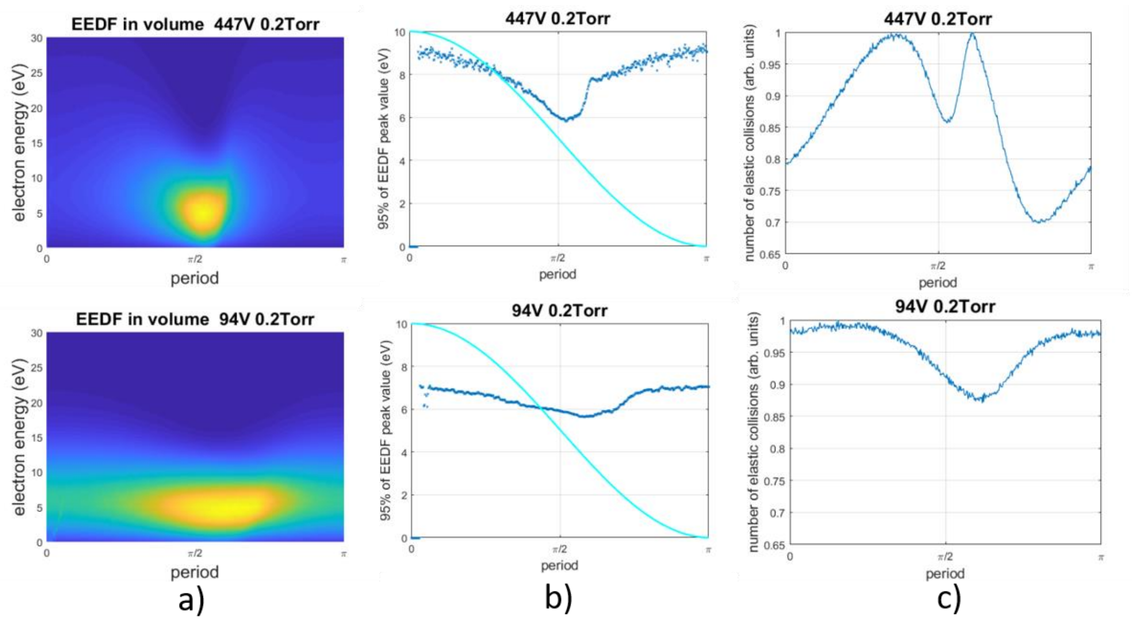

Fig. 3: a) EEDF over half period of time in 2D plots for points A and D (Fig. 1) with the same breakdown pressure of 0.2 Torr and different voltages: 447 V and 94 V. b) Relaxation of the 95% EEDF peak value over one half period for the same points as in Fig. 3a. Light blue line presenting applied AC filed. c) Number of elastic collisions over one half of the period. All features do not present values but only how their shape is changing over half period of time (all are normalized to have maximum at 1). Background gas is argon, frequency is 13.56 MHz and gap is 23 mm.

The moment when discharge induced by the applied AC field ignites, as we know, is a balance of electron production via ionization and losses at electrode surfaces by absorption. Behind rough counting of electron number over time [1, 2] there is a neat energy balance that needs to be fulfilled. When voltage breakdown curve moves towards high voltages and low pressures, number of collisions with the background gas decreases, breakdown voltage has a steep rise in its value and the amount of energy that electron can get from the AC field between two collisions has a steep growth as well. Rapid increase in electron energy is restricted by the point where electron crosses the gap between two electrodes too fast with insufficient number of collisions to perform ionization and they are being absorbed by the electrode, no matter how high their energy is. At that point, increase in number of collisions is required to randomize electron movement and to increase probability for them to experience ionization before they reach the electrode. Their portions of energy gained from the AC field between two collisions are being reduced but still big enough to overcome ionization threshold before they are lost at the electrode.

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