MONTE CARLO SIMULATIONS OF RADIO-FREQUENCY BREAKDOWN IN ARGON

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ABSTRACT

In this paper we employ Monte Carlo (MC) collision code to model radio-frequency (RF) breakdown. Electron dominated regime and conditions which lead to the breakdown were examined in an attempt to identify the most pertinent processes. We focus on scaling conditions based on breakdown voltage curves. Influence of surface effects on a breakdown voltage curve is also observed.

1. INTRODUCTION

Radio-frequency discharges have wide applications [1-3]. For every application it is important to establish operating conditions which can be determined from breakdown voltage curve that resembles the Paschen curve for DC discharges. In previous paper [4] we have examined double valued nature of breakdown (Paschen like) curve in RF discharges, in electron dominated regime. A necessary condition for a self sustained discharge is to have a feedback between electron growth towards the instantaneous anode and their production close to the instantaneous cathode.

The goal of this paper is to present features of a MC RF code and the results pointing out how one can scale between Paschen curves, which is in agreement with experiment [5].

MC code was developed within our group. It includes electrons only (at the moment) and was well tested for electron transport and gave accurate electron energy distribution functions (EEDF) and transport coefficients [6]. The background gas is argon, which is well covered with cross section data and other information [7]. Electrodes are plane-parallel with inter electrode distances of 23mm, 11.5mm and 2mm and with frequencies of 13.56MHz, 27.12MHz and 155.24MHz.

2. VOLTAGE BREAKDOWN CURVE DETERMINATION

When we talk about the process of a breakdown we must precisely define the point in which plasma ignites. Advantage of simulations is that the exact point can be determined with very high resolution, if necessary. The disadvantage of the RF breakdown is that it may not be simulated directly as in a direct-current DC case but has to be determined by trial and error. For every initial voltage and pressure we observe how electron numbers change over a period and with time. If it is ascending in some reasonable time interval, we can say that breakdown occurred.

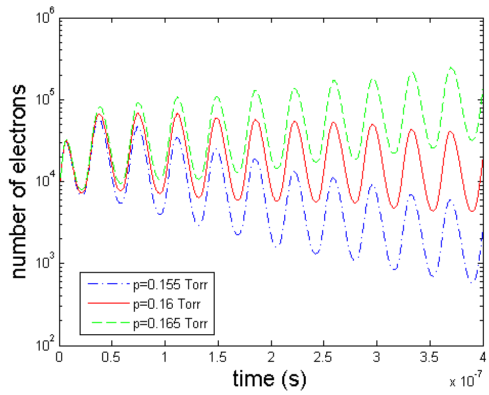

Fig. 1 Breakdown point determination. Conditions are U=400V, and pressures are: p_1=0.155Torr, p_2=0.16Torr and p_3=0.165Torr. Background gas is argon gap 23mm and frequency 13.56MHz.

Scanning through U-pd plane was done as follows. Left hand branch of the Paschen curve is obtained by fixing voltage point and scanning through different pressures in a similar fashion to experiments [8]. Right hand branch is obtained similarly, only this time the pressure is fixed and scanning was done through different voltages.

Figure 1 is a representation of this procedure. It shows electron numbers in time for a fixed voltage of 400V and three different pressures: 0.155Torr, 0.16Torr and 0.165Torr. In this example the resolution was 0.05Torr. One can conclude that breakdown point has voltage of 400V at pressure of 0.165Torr.

2. SCALING LAW

Any chosen property associated with the breakdown of a discharge, for example voltage U, depends uniquely on other properties, gas pressure, electrodes etc. One of the first authors who noticed significance of finding a law which is applicable to large sets of voltage breakdown curves was Francis [9]. Some authors have shown that scaling laws (or similarity law) for DC discharge cannot be used for RF discharge without some adjustment [5]. Condition that has to be fulfilled is that product of frequency and inter electrode gap has to be constant for every curve, thus U_{RF} is a function of *pd*, while *fd* is constant. Such curves are presented in Figure 2. Our MC simulations are supporting earlier experimental observations [5]. This scaling stems from the *pd* scaling and the scaling for RF fields well known in swarm transport theory ω/N (or f/N or f/p at a fixed temperature) which is associated with the number of collisions per period of the RF field.

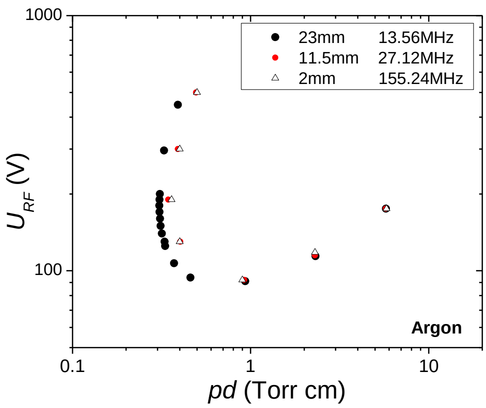

Fig. 2 Scaling law. Paschen curves for different gaps and frequencies supporting condition f·d-constant.

3. SURFACE EFFECTS

Surface effects at electrodes are the next step in development of a more comprehensive MC RF code. Many authors pointed out their importance [10]. When a particle, in this case electron, hits electrode there are several possible scenarios. It can be elastically reflected with the same energy, without any significant loss, referred as elastic reflection. Second, it can be reflected with some energy loss [11] due to inelastic losses that we label as inelastic reflection. During this process enough energy to release a secondary electron may be lost. Thus, we have a reflected electron, with a smaller energy than the incident energy and a secondary electron emission with some probability. Thirdly, incident electron may be absorbed and secondary electron be emitted. And finally, incident electron may be absorbed without any secondary electron emission. In either of the cases with secondary electron emission, the secondary electrons are released in our simulation with Maxwell distribution that has the mean energy of 2eV. As shown in Figure 3, a better agreement with experimental results [8] was obtained by including surface effects.

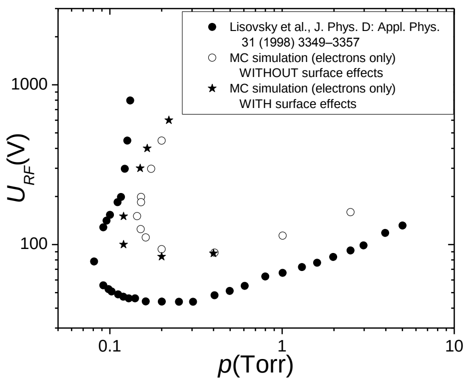

Fig. 3 Paschen curves obtained by MC code with and without surface effects included and comparison with experimental results [10]. Gap is 23mm and frequency 13.56MHz.

In Figure 4 spatial distributions of electron concentration, energy and the rate of ionization are presented. As expected, electrons are gaining energy from RF field, while field amplitude is rising, thus electrons with the highest energies are observed right after RF field reaches its peak (maximum). One can assume (and simulations confirm it) that ionizations are the most frequent in the region where the "hottest" electrons are. Most of the electrons are pushed near electrodes and after electrons reach electrode, their energy is declining due to inelastic reflection and secondary electrons which have considerably smaller energies. When field changes its direction, electrons are being pushed to the other electrode.

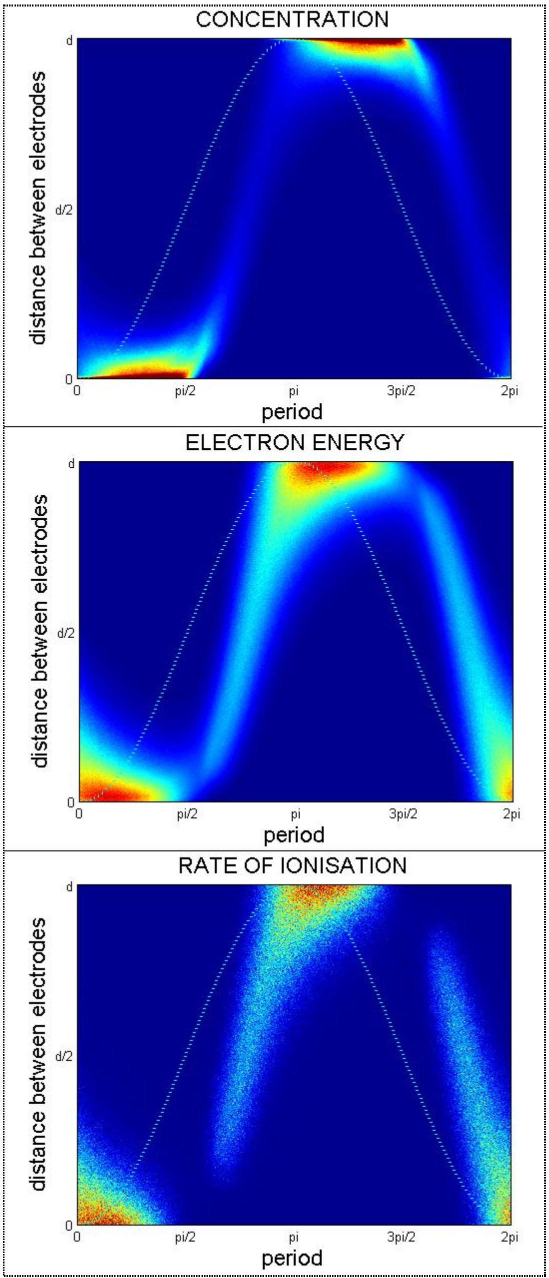

Fig. 4 Electron concentration, energy and rate of ionization. Initial conditions are U=450V, p=0.2Torr, f=13.56MHz, gap=23mm and surface effects are included. With dotted line is presented RF field with negative sign.

4. TIME DEPENDENCE OF THE ELECTRON ENERGY DISTRIBUTION FUNCTIONS

Electron energy distribution functions (EEDF) can help us better understand electron and discharge kinetics. Figure 5 is a comparison of EEDF in time in two cases: a) without and b) with surface effects included. In both cases mean energy is around 10eV. Electrons have the highest energies when RF field is at its peak, at 0, π and 2π and EEDF has a more populated tail, as expected. When field is at its minimum, electrons with lower energies are dominant. In Figure 5b there are very sharp peaks at smaller energies. These correspond to secondary electrons with mean energies of 2eV.

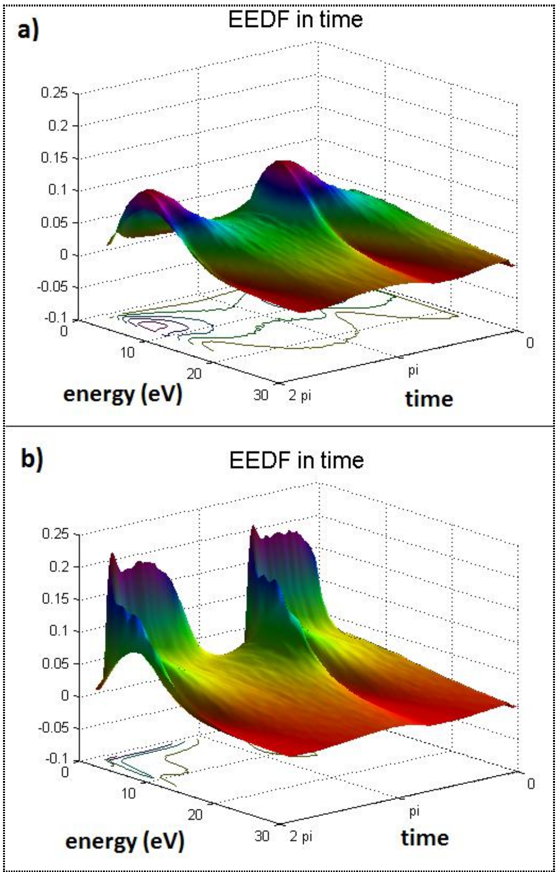

Fig. 5 3D plot of EEDF in time with a) and without b) surface effects included. Initial conditions are: U=450V and p=0.2Torr, frequency is 13.56MHz and gap=23mm.

5. CONCLUSION

We presented development and employment of a Monte Carlo collision code for radio-frequency breakdown. Code was tested in electron dominated regime and points in which breakdown occurs were examined. With certain condition (frequency times inter electrode distance being constant) we have demonstrated that scaling law, as observed in swarm physics and more specifically in RF breakdown, can be fulfilled and explained. By using 3D plots of electron concentration, energy and ionization rate we have explained particle behaviour between two plane-parallel electrodes. In addition, we presented 3D plots of electron energy distribution functions for the same initial conditions without and with included surface effects.

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