SIMULATIONS USING THE VORPAL CODE OF ELECTRON IMPACT IONIZATION EFFECTS IN WAVEGUIDE BREAKDOWN PROCESSES*

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Abstract

Waveguide breakdown and power absorption limit the performance of high-power microwave devices [1]. Researchers suspect gas ionization of playing an important role in these processes [2, 3]. We present a reduced model of the dynamics of waveguide breakdown, including ionization. We show results of this reduced model for numerical simulations using a voltage of 50V and a gas pressure of 200 Pa of argon. We find that if the rate of ionization is high enough, a two-stream instability develops in the 10-100 ns timescale, and we find that this can increase the electron current density by a factor of two. Also, due to the neutralizing ions, the current density in the simulations is more than an order of magnitude above the space-charge-limited threshold. Such increased electron current density could partially explain increased rf power absorption in a waveguide.

MOTIVATION AND APPROACH

Researchers suspect ionization effects of playing a main role in the breakdown of rf waveguides. Furthermore, breakdown of rf waveguides shares many features with breakdown in dc diodes [3]. To isolate the ionization effects in rf waveguide breakdown, therefore, we have adopted a simplified model of a dc diode, where researchers have developed analytic models to which one can compare simulation results [4].

For our diode model, we chose an argon gas fill of 200 Pa and a voltage of 50V in order to maximize the ionization effects at the anode (50V is near the peak of the electron impact ionization cross section of argon [5]). We use a diode spacing of 5 mm.

We used the VORPAL code for our simulations [6]. For the simulation parameters, we chose a 1D simulation region with 50-micron cells, an 11.8 ps time step, and roughly 100,000 particles toward the end of the simulations. We used a space-charge-limited emission algorithm to draw current from the cathode.

In Figs. 1-3 we show 1D simulation results at 5, 30, and 65 ns respectively. Each plot shows the phase space (upper right), voltage (lower left), and electric field (lower right). In the phase space plots, electrons are in red, and ions are in blue. For reference, we also show in each figure the time history of the anode current (upper left), with the relevant time indicated with a square.

Figure 1 shows the early time behavior of the diode, with ionization just beginning at the anode. In the phase space plot in Fig. 1, one can see the beam electrons and the ionized electrons as distinct populations. The field is nearly uniform and the voltage is nearly linear at this time. The anode current is a factor a few higher than the space charge limited current (roughly 33A for these parameters), due to the partial neutralization the ions provide.

Figure 2 shows an intermediate time, where ionization is developed enough to produce a region of voltage higher than 50V. The authors of ref. [4] predict such behavior. There is also a region of quasi-neutral plasma with near zero electric field.

Finally, in Fig. 3, the thermal background electrons and the beam electrons interact to form a two-stream instability. The two-stream instability was not predicted in ref. [4]. The anode current at this time is a factor of two higher than 5ns earlier. One explanation for this is that in the course of the beam-plasma interaction developing into an instability, the beam gives up energy to the plasma electrons. Thus, at the right phase in the phase space oscillations, the plasma electrons striking the anode have a higher energy than in the absence of the instability, which could account for the increased current. Also, this current is roughly 30-40 times higher than the space charge limited current. An increase of current beyond the space charge limit is one mechanism for explaining power absorption in high-power waveguides.

To isolate and understand the effects of ionization, we made approximations that limit the direct application of this work to waveguide breakdown. The timescale over which the instability develops (roughly 65 ns) is much longer than the period of a wave in a waveguide (for instance, the period of a wave in the X-band is 87 ps). Thus, our approximation of a dc voltage is not accurate. Further, we assumed an unphysically high pressure of 200 Pa (orders of magnitude too large for a real waveguide system).

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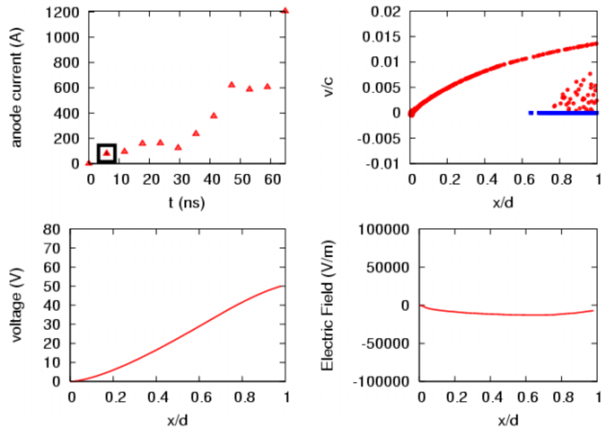

Figure 1: The phase space (upper right), voltage (lower left), and electric field (lower right) at 5ns after the start of electron flow. Ions are shown in blue. For reference, we also show the time history of the anode current (upper left), with the relevant time indicated with a square.

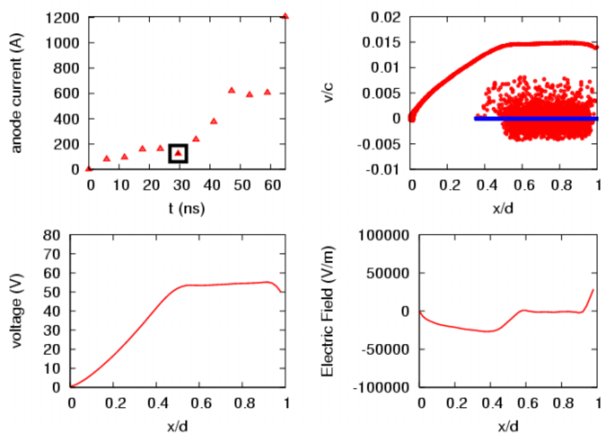

Figure 2: The phase space (upper right), voltage (lower left), and electric field (lower right) at 30ns after the start of electron flow. Ions are shown in blue. For reference, we also show the time history of the anode current (upper left), with the relevant time indicated with a square.

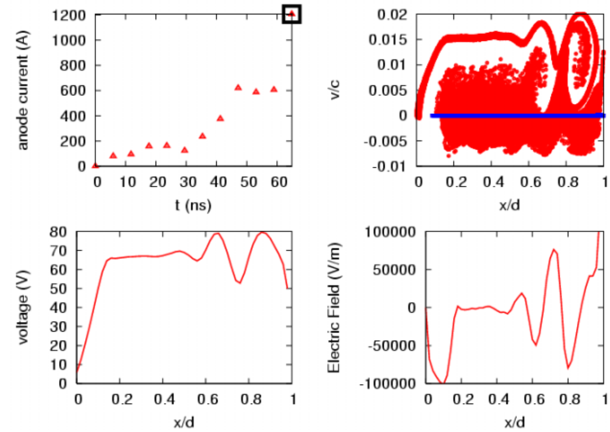

Figure 3 The phase space (upper right), voltage (lower left), and electric field (lower right) at 65ns after the start of electron flow. Ions are shown in blue. For reference, we also show the time history of the anode current (upper left), with the relevant time indicated with a square.

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