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One-dimensional time-dependent capacitor model of breakdown in DBDs at atmospheric pressure

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Abstract

Breakdown in a dielectric barrier discharge (DBD) at atmospheric pressure is shown computationally to closely resemble breakdown in a series of small capacitors, which can be described by simple analytic equations. The 'time-dependent capacitor model' captures the physics of breakdown and is an accurate and efficient simulation tool.

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1. Introduction

Breakdown of dielectric-barrier discharges (DBDs) [1–3] is in many cases the most critical aspect of the discharge, since essentially all the energy which is put into the plasma electrons is delivered in this phase. The electrons drive the plasma-related chemical processes, so breakdown is also the critical phase for determining what chemical reactions occur. This Letter sets out to establish a basis for understanding the breakdown, consisting of a very simple physical model which finds the available energy stored in the fields from a circuit model, and determines how that energy is shared between the various inelastic collision processes. The calculation of the energy is in fact very accurate indeed, the only real errors being the omission of sheath effects. The fractions of the energy going into each process are found from a detailed kinetic model and stored as functions of plasma parameters—again, the calculation suffers from rather little error. The purpose of developing such a model is, first, that it clearly elucidates the pertinent physics, and second, that it provides a very effective means of computing parameters in complex geometries. (We argue that standard approaches are unlikely to be ef-

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fective in this regard [16].) We apply the model to a one-dimensional plasma, and by comparing its results to accurate fluid models we show its applicability and examine the effects of including non-local processes. (Here we define 'local' as meaning that electrons in one 'capacitor' cannot travel into another 'capacitor' in the time available for breakdown.) We find that the breakdown is primarily local, but that in some cases non-locality is crucial to initiating breakdown.

In previous work [16] we examined kinetic [4–8] and fluid [9–14] modeling of breakdown. It was argued that the natural length and time scales of this problem are extremely short, which implies that kinetic or fluid models must both take very short time steps and employ very small spatial meshes. (We emphasize that this is not a feature of our models, but applies to any models in this class, of kinetic or fluid models.)

A semi-analytic approach to finding the plasma density after breakdown was also developed. In this Letter we extend this model to include time dependence. The original model treated the plasma as a number of small capacitors, which were allowed to breakdown sequentially—but only one at a time [15]. By including time-dependence in the description of breakdown, we obtain a considerably more accurate formulation which retains the simplicity of the previous capacitor model. The time-dependent capacitor model (TDCM) resembles a fluid model, but the level of description of the plasma which is employed in the TDCM is quite different from most fluid models. We use a small number of capacitors partly to bring out the physics of the locality of the breakdown. The small number of cells does speed up the run, but the method also has a relatively long time step compared to the fluid simulation. The time step τ_{cap} of the TDCM is set by the dielectric relaxation time, which is much longer than the required time step of the fluid model we compare to [15]. The spatial scale of the TDCM is the plasma dimension L divided by the number of capacitors N_c. This scale is also much larger than the scale permissible in a typical fluid model. The equations employed focus on the energy input to the plasma (which we have shown [15] can be found very accurately from a circuit model or equivalently from the electric field in each 'capacitor') and the fraction of that energy, α_j (expressed here as a function of the electric field), which is put into the jth inelastic process. (Clearly this method can be formulated as a fluid model, but a particular fluid model; one which conserves energy as indicated in Eq. (10) and uses α as in Eq. (11) to determine how much of the energy goes to ionization.)

2. Time-dependent capacitor model

The time-dependent capacitor model (TDCM) is based on the idea that, during breakdown of a dielectric barrier discharge, energy stored in the electric field is deposited locally, driving the breakdown. The one-dimensional discharge (higher dimensions will be examined in future) is divided into N_c small capacitors. (The capacitances do not have to be equal.) The energy stored in each capacitor, labeled i is

$$W_i = \frac{1}{2} D_i E_i \,\text{Vol}_i, \tag{1}$$

where D_i (E_i) is the electric displacement (field) in capacitor i (C_i) and Vol_i is the volume of capacitor C_i. The voltage across C_i is

$$V_i = -E_i d_i, \tag{2}$$

where d_i is the thickness of C_i. The density of electrons in C_i is n_i. In a time step, we consider each capacitor in turn, updating their densities one at a time and then updating all of the fields E_i after each n_i and Q_i is updated. For C_i, during a time step Δt the density is allowed to move, resulting in a charge

$$Q_i = \pm n_i \mu(E_i) E_i \Delta t \tag{3}$$

per unit area leaving Vol_i and moving to the 'plates' of C_i. This charge changes D_i by an amount equal to Q_i. However, the external voltage source is assumed to maintain a constant voltage V_a. A charge Q_{ext} flows in the external circuit, to maintain V_a. The external circuit thus does work

$$W_{\text{ext}} = Q_{\text{ext}} V_a. \tag{4}$$

The capacitance in series with C_i, consisting of other plasma capacitors and dielectrics, is C_i^s (which is calculated from $\frac{C_L C_R}{C_L + C_R}$—see Fig. 1). Since Q_{ext} appears on all the capacitor plates, the change in voltage due to Q_{ext} is

$$\Delta V = \frac{Q_{\text{ext}}}{C_{\text{TOT}}}, \tag{5}$$