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KINETIC MODELING OF RF BREAKDOWN IN HIGH-PRESSURE GAS-FILLED CAVITIES *

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Abstract

Recent studies have shown that high field gradients can be achieved quickly in high-pressure gas-filled cavities without the need for long conditioning times, because the dense gas can dramatically reduce dark currents and multipacting. In this project we use this high pressure technique to suppress effects of residual vacuum and geometry found in evacuated cavities to isolate and study the role of the metallic surfaces in RF cavity breakdown as a function of operating frequency and surface preparation. A series of experiments at 805 MHz using hydrogen fill pressures up to 0.01 g/cm^3 of H_2 have demonstrated high electric field gradients and scaling with the DC Paschen law limit, up to ~30 MV/m, depending on the choice of electrode material. At higher pressures, the breakdown characteristics deviate from the Paschen law scaling. Fully-kinetic 0D collisional particle-in-cell (PIC) simulations give breakdown characteristics in H_2 and H_2/SF_6 mixtures in good agreement with the 805 MHz experimental results below this field stress threshold. At higher pressures the formation of streamers at operating parameters below the Paschen limit are examined using 2D simulations.

INTRODUCTION

Breakdown data obtained from the Muons Inc. test cell (TC), a high pressure RF cavity developed to support ionization cooling experiments for muon colliders [1, 2], is analyzed. These experiments exhibit Paschen-like breakdown characteristics for field gradients below a threshold value. At higher field gradients and gas pressures, deviations from the Paschen limit are found, and a nearly constant field gradient operating limit is established, dependent on the choice of electrode material. Fully-kinetic particle-in-cell (PIC) simulations are used to examine the initial breakdown phase in both the Paschen limit and the high-pressure, field-gradient threshold limit.

For the analysis of Paschen law characteristics, 0D simulations are carried out to establish the applied field required to initiate an electron avalanche for a given gas pressure. The results of these simulations are described in the next section. To analyze the breakdown characteristics above the threshold for deviations from the Paschen limit, 2D simulations are used. The conjecture explored in this limit is that at field gradients above the vacuum space-charge-limit (SCL) emission threshold for various materials, the formation of high-density localized plasmas at the electrode surface can lead to the formation of streamers. The local net fields at the tips of these streamers can exceed the average fields in the electrode gap and propagate into the gap. In the third section, we describe initial 2D simulations of streamer formation at different applied field levels. The results of these simulations are found to be in rough agreement with experimental measurements.

0D KINETIC MODEL ANALYSIS

A significant amount of data for high pressure H_2 has been collected on the Muons TC for a variety of electrodes materials. A subset of this data is shown in Fig. 1. The main features of the data are a nearly linear region at lower gas pressures where the maximum electric field gradient increases with pressure, transitioning to a region where the peak electric field gradient either increases slowly or is essentially constant. This behavior is characteristic of, and consistent with, other high pressure Paschen law deviations [3] reported in the literature (see, for example, Ref. [4]). This latter region is sometimes referred to as the electrode-dominated regime and is discussed further in the later sections.

Simulation Model and H_2 Analysis

The LSP PIC code [5] is used throughout for time-dependent 0D simulations. A Monte Carlo collision (MCC) package is used to treat the elastic and inelastic particle interactions within a computational cell. This model has been benchmarked against experimental data for RF breakdown in He [6], and steady-state breakdown of H_2 and SF_6 [7].

The 0D simulations apply a sinusoidally oscillating electric field as a function of time,

$$E(t) = E_0 \sin(2\pi f t), \quad (1)$$

where E_0 is amplitude of the RF field and f is the frequency. For all cases presented here, f = 805 MHz. The simulations are initialized with a low density "seed" population of electrons and ions (H_2^+), typically with initial number densities between 10^{10} and 10^{12} cm^{-3}. After 10-100 RF cycles, the presence of an electrode density growth (avalanche) indicates breakdown for a given value of E_0.

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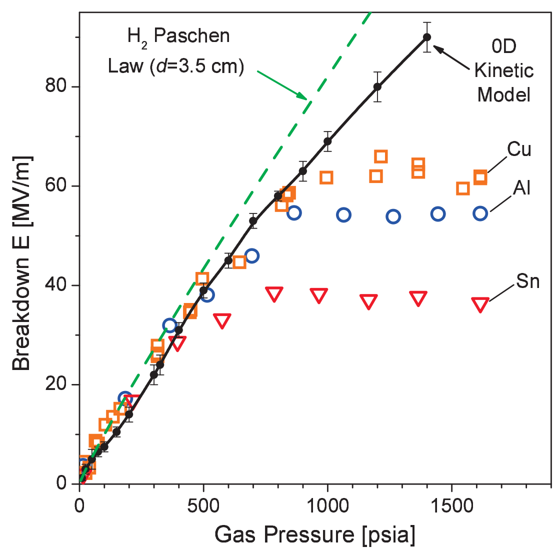

Figure 1: Breakdown curves as a function of H_2 gas pressure. The individual open points are different electrode materials from the 805 MHz RF test cell [1]. The solid black line is the result of 0D kinetic simulations that estimate the breakdown independent of electrode materials. For comparison, the dashed green line is the Paschen curve for H_2 for an electrode spacing of 3.5 cm.

The solid black lines joining the black circles in Fig. 1 represent the results of the 0D simulations identifying approximately the Paschen breakdown limit for H_2. The error bars shown with the individual data points indicate the approximate level of refinement in E_0 that was used to find the breakdown field value for a given gas pressure. As a check, several gas pressures were evaluated with a DC applied electric field. No significant difference in the breakdown value was found between the DC and RF simulations. This is due to the electron-neutral collision frequency ν_{en} being much larger than f for the parameters examined here, and assuming that no significant recombination takes place on the RF cycle timescale. Finally we note that the 0D simulations give an effective E/P for breakdown of roughly 40 Td for pressures above 100 psia.

Also shown in Fig. 1 is the Paschen Law for H_2, expressed as

$$V_B(\text{V}) = V_{\min}\frac{\delta}{1+\ln(\delta)}, \tag{2}$$

where $\delta = pd/(pd)_{\min}$, with d the electrode separation (cm), and p the pressure (Torr). For H_2, $V_{\min} \simeq 273$ V and $(pd)_{\min} \simeq 1.15$ Torr-cm. The value of $d = 3.5$ cm is larger than the 2.5-3 cm gap spacing in the experiment, but is used in the figure to illustrate the near linear scaling of Eq. (2) at these relatively high pressures.

H_2/SF_6 Mixture

In an effort to improve the breakdown characteristics of the high pressure RF cavity, small admixtures of electronegative gas have been explored [1]. Figure 2 plots the results of experiments with a 10^{-4} level addition of SF_6. A significant increase in the effective field gradient was achieved at lower total H_2 pressures.

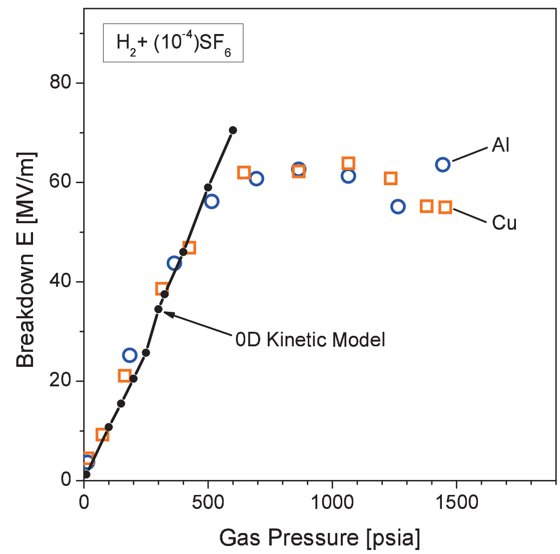

Figure 2: Breakdown curves for H_2 with 10^{-4} admixture of SF_6. The individual open points are different electrode materials from the 805 MHz RF test cell [1]. The solid black line is the result of 0D kinetic simulations that estimate the breakdown (independent of electrode materials).

The 0D simulation results (solid black circles connected by black line segments in Fig. 2) show an essentially linear rise with total gas pressure, as expected. The experimental data is in good agreement with the simulations, for both Cu and Al electrodes, for gas pressures up to about 500 psia. The 0D simulations give an effective E/P for breakdown of roughly 60 Td for pressures above 100 psia, a 50% increase over the case of pure H_2.

2D KINETIC SIMULATIONS OF STREAMER PROPAGATION

Typical metallic electrode surfaces are covered by microscopic whiskers, with scale sizes typically of a few micrometers and whisker densities between 1 and 10^4 cm^{-2} [8, 9]. Under high voltage, electric field enhancement at the whisker tips leads resistive heating of the whisker, and eventually these whiskers explosively vaporize, forming a high density, localized plasma. In vacuum these plasma flares merge, eventually covering the electrode surface. In a high pressure gas, it is postulated that the expansion velocities of the flares are moderated, potentially leading to the formation of individual streamers that propagate away from the electrode surface. As the streamers propagate, the will expand and merge, eventually crossing the entire electrode gap [10]. As the streamer body is comprised of a relatively dense plasma, the impact of field reversal under RF operating conditions is mitigated since the streamer can resume propagation once the RF cycle completes.

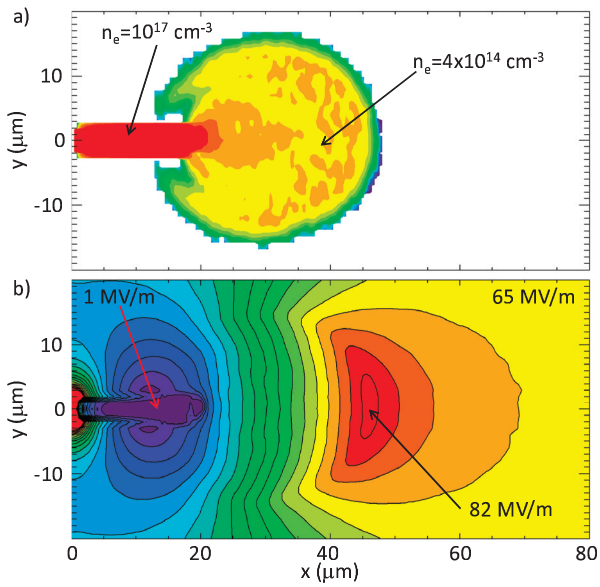

Figure 3: Electron number density (a) and electric field magnitude (b) from a 2D kinetic simulation at 65 MV/m and 1000 psia after 0.5 ns. The simulation is seeded with a 10^{17} cm^{-3} neutral plasma whisker 18 μm long and 2 μm thick.

To explore this possible breakdown mode, a series of 2D (x,y) simulations have been carried out. A constant value DC electric field $\vec{E} = -E_0\hat{x}$ is imposed on a gas-filled region. A relatively high-density plasma region, representing the exploded whisker, is placed in the neutral gas, on or near a conducting electrode surface. The simulated region is roughly 0.01 cm by 0.008 cm (x,y). The grid sizes are roughly 0.5 μm. A typical result is shown in Fig. 3. A 10^{17} cm^{-3} number density plasma whisker is initialized in contact with a conducting wall at $x = 0$. The whisker extends 18 μm from the electrode surface and is 2 μm wide. For this example the neutral gas is at 1000 psia and the applied electric field is 65 MV/m. After 0.5 ns, electric field enhancement at the whisker tip leads to the formation of a plasma density avalanche that in turn initiates streamer propagation. In this case, electric field enhancements at the whisker tip exceed 80 MV/m, well in excess of the Paschen limit ($\simeq$ 70 MV/m) at this pressure.

For an non-electronegative gas, diffusion modifies or limits the transition from an avalanche phase to streamer formation [11]. In the high pressure H_2 simulations carried out to date, streamer formation generally requires a relatively high field enhancement (or E/P value) in the vicinity of the streamer head, roughly 20% greater than the Paschen limit value, due in part to electron diffusion. For example in H_2, the transverse diffusion value is roughly a factor of 3 times the longitudinal value for E/P values greater than 20 Td [12].

DISCUSSION

The basic breakdown characteristics of the 805 MHz RF cavity are well-explained by the 0D kinetic simulation model in the Paschen limit. Examples for H_2 and H_2+SF_6 cases have been presented here. At higher field gradients, experimental measurements show deviations from the Paschen limit, suggesting a high-field-limit transition in behavior of the electrode materials. Previously, the different material melting temperatures has been examined as a signature of the high-field transition[13]. Here we have begun to explore the possibility that explosive electron emission is creating high-density plasma seeds leading to the formation of self-propagating streamers. The limited data available for explosive electron emission thresholds for different materials scales roughly with the maximum field gradients obtained in the RF cavity experiments. However, further modeling work is required to demonstrate that micrometer-scale streamers can efficiently propagating under these high-pressure RF conditions.

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