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Breakdown behavior in radio-frequency argon discharges

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The minimum voltage required to break down a discharge $V_{\text{brk}}$ has long been known to be a strong function of the product of the neutral gas pressure and the electrode separation ($pd$). This paper investigates the dependence of $V_{\text{brk}}$ on $pd$ in radio-frequency (rf) systems using experimental, computational and analytic techniques. Experimental measurements of $V_{\text{brk}}$ in an argon discharge are made for pressures in the range 1–500 mTorr and electrode separations of 2–20 cm. A particle-in-cell simulation is used to investigate a similar $pd$ range and examine the effect of the secondary emission coefficient on the rf breakdown curve, particularly at low $pd$ values. A zero-dimensional global (volume averaged) model is also developed to compare with experimental and simulated measurements of breakdown. © 2003 American Institute of Physics.

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I. INTRODUCTION

Low pressure, capacitively coupled radio-frequency (rf) discharges are widely used in research and commercial ventures. Understanding of the nonequilibrium processes which occur in these discharges during breakdown is of interest, both for industrial applications and for a deeper understanding of fundamental plasma behavior. In the 1890s Paschen determined that the minimum voltage required to break down a dc discharge is a strong function of the product of the neutral gas pressure and the electrode separation ($pd$), while similar measurements of breakdown in rf discharges were made in the 1920s. A brief review of previous experimental and theoretical work is given by Lisovskiy and Yegorenkov in Ref. 1. A theoretical description of breakdown in high frequency and dc discharges was initially developed in the 1940s and is described in a number of texts (see, for example, Refs. 2, 3, 20, and 21). Although in dc discharges breakdown is controlled by the flow of ions to the cathode and in high-frequency discharges it is controlled by electron diffusion, the characteristic shape of the breakdown curves is very similar. Typically Paschen curves are roughly “u”-shaped with a minimum breakdown voltage at a specific $pd$, and increasing voltages at both increasing and decreasing values of $pd$. The breakdown voltage generally forms a fairly smooth curve, with the left hand branch of the curve (decreasing $pd$) being markedly steeper than the right hand branch. Under certain circumstances inflection points and other changes in the slope of the breakdown curve have been measured (see Refs. 1, 4–6), some aspects of which we will discuss later.

In high-frequency (microwave) discharges the oscillation amplitude of the electrons due to the applied fields is small relative to the discharge dimensions. Consequently it is valid to apply a drift-diffusion model of electron behavior in this case, as explained in Refs. 2 and 7. This is also true for rf frequencies at high pressures, where the collision frequency is much larger than the source frequency. Thompson and Sawin in Ref. 8 model breakdown in a high pressure (>300 mTorr) rf discharge in SF$_6$ and found good agreement with experiment, and in Ref. 9 Sato and Shoji derive a two-dimensional (2D) theory for studying the right-hand branch of the Paschen curve for an argon discharge at 13.56 MHz. However, at lower pressures in rf fields the electron oscillation amplitude can approach the discharge length and electrons are lost to the electrodes at each half cycle. Consequently a diffusion model is not applicable and a different model must be used to predict the conditions for breakdown.

At high gas pressures and/or large electrode separations, when the collision frequency is greater than the source frequency, breakdown conditions are dominated by volume processes and are relatively independent of surface conditions. At low pressures and small electrode separations, the loss rate of electrons to the walls is large so surface effects, in particular electron induced secondary emission, plays an important role in determining breakdown. At very low pressures the breakdown is initiated by resonant production of secondary electrons and the dependence of the breakdown voltage on $pd$ has a very different shape from a traditional Paschen curve as shown in Refs. 6 and 10.

Breakdown is not an instantaneous phenomenon, it occurs over a finite period of time which is determined by the balance between creation of charged species by ionization and their losses via collisional processes and diffusion to the walls. We define the breakdown phase as commencing when electrons are hot enough to produce an ionization avalanche, and ending when sheaths are formed, which occurs when the density has increased sufficiently for the Debye length to become smaller than the system length. In both the experiment and the simulation the end of the breakdown phase is easy to detect, since the development of sheaths changes the impedance of the system, producing a noticeable discontinuity on the powered electrode voltage. This phenomenon is shown in a previous publication looking at breakdown in rf systems with asymmetric electrode areas, see Ref. 13.

This paper examines the breakdown behavior in an rf...
(13.56 MHz) argon discharge for a range of pressures and discharge lengths. We compare our experimental measurements with a planar 1D particle-in-cell (PIC) simulation. We then use the PIC simulation to investigate the effect of changing the secondary emission properties of the electrodes on the breakdown voltage, particularly at low $pd$ values. The experimental and simulation results have been used in the development of a global (volume averaged) model of rf breakdown which is valid for a wide range of pressures.

II. EXPERIMENTAL AND MODEL CONFIGURATIONS

A. Experiment

The reactor used to make the experimental measurements for this system has been detailed in a previous publication, Ref. 13, so only a brief description is presented here. It consists of a small parallel plate reactor with a 13.56 MHz radio-frequency power source (ENI), modified to obtain rise-times on the order of 100’s of nanoseconds, which is controlled by a pulse generator. Live and earthed electrodes are made of stainless steel with a diameter of 10 cm, and the grounded electrode could be moved to vary the inter-electrode distance, $d$. The electrodes are contained in a cylindrical, aluminum vacuum vessel 30 cm in diameter and 30 cm long and power from the rf generator is coupled to the live electrode via an L matching network with a 50 dB coupler inserted between the rf generator and the matching network. An rf probe on the powered electrode, connected to an oscilloscope, was used to measure the voltage waveform. The experimental system is shown schematically in Fig. 1, in comparison with the PIC simulation configuration.

The experimental measurements of the breakdown voltage were carried out by initially setting the pressure and coupling a continuous plasma in order to adjust the tuning of the matching box for that pressure. The plasma was then turned off, the pressure rechecked, and the voltage manually increased until breakdown occurred, indicated by the discontinuity on the voltage waveform, which was measured with an oscilloscope on roll mode. In this case the breakdown voltage was determined to be the peak value of the voltage at the discontinuity.

This system operated optimally at pressures in the range of a few tens to a few hundreds of millitorr. Outside this range it became harder to keep the pressure constant and the pressure measurements were much less accurate. This is particularly the case for very low pressures, where the gas pressure approached the minimum pressure obtainable in the system. Consequently the errors are much larger at very low and very high $pd$ values.

B. Particle-in-cell simulation

The 1D, electrostatic particle-in-cell code used in this work has also been previously described in Refs. 10 and 13; see also Ref. 17 for a description of PIC techniques. In this case parallel planar electrodes were used to represent the reactor, since during the breakdown phase asymmetry in the electrode geometry has little effect on the discharge profile. The simulation is voltage-driven with one electrode connected to the rf generator and the other electrode grounded. Since the external matching network is not modeled explicitly in the simulation the source voltage is given an exponential rise-time to approximate the same effect

$$V_{rf}(t) = V_{rf} \sin(2\pi f_{rf} t) e^{-t/\tau},$$

where $V_{rf}$ is the voltage amplitude, $f_{rf}$ the frequency and $\tau$ the exponential time constant. The rise-time used for the source voltage is explained later in this section.

The simulation models collisions between charged particles and neutral atoms realistically, using analytic fits to real argon cross sections. Electrons can make ionization, excitation and elastic collisions, and ions make charge exchange and elastic scattering collisions. At low values of $pd$ the secondary emission properties of the electrodes are very important in sustaining the discharge. We use an energy dependent model for the emission coefficient, taken from Ref. 10

$$\delta = \frac{\delta_m \epsilon}{\epsilon_n \exp \left( \frac{2\epsilon}{\epsilon_n} \right)},$$

where $\delta$ is the emission coefficient, $\epsilon$ is the impact energy of the electron, $\delta_m$ the peak emission value and $\epsilon_n$ the energy at that value. The form of this curve is characteristic of a wide variety of materials; $\delta_m$ and $\epsilon_n$ have been determined by fitting to experimental data and are available from a range of references, for example, Ref. 14. For comparison with the experiment we used $\epsilon_n = 300$ eV, which is characteristic for metals, and $\delta_m = 2.4$, which is higher than that of pure stainless steel ($\delta_m = 1.8$) but is applicable to a system with oxide or carbon layers on the electrodes. About 20% of the “secondary” electrons are actually reflected electrons, which can have relatively high energies, while the remainder are true secondaries and are emitted with a 1 eV temperature distribution, as described in Ref. 10.

A summary of conditions used in the simulation is given in Table I.

C. Global model

As previously mentioned, the diffusion model used for high frequency discharges is not valid for low pressures rf discharges. Consequently we wanted to develop a different
method for studying these discharges. Global models have successfully been used to study both steady-state and time-varying conditions in rf capacitive and inductive discharges (see, for example, Refs. 15 and 16). A global model, presented in Ref. 18, was previously developed by one of the authors for studying general discharge behavior during breakdown, approach to steady state and in the afterglow. We have improved the way wall losses are treated and included the effects of secondary emission, in order to obtain better agreement with the simulated and experimental results for a wider range of pressures.

The global model uses volume averaged equations for energy and particle balance to determine the time-variation of the average density and energy. The particle balance equation is given by

$$\frac{d\bar{n}}{dt} = \bar{n}(t) \nu_{iz} - \Gamma_w \bar{n}_w \frac{V}{V} (1 - \delta_s),$$

where $\bar{n}$ is the volume average electron density, $\nu_{iz}$ is the ionization frequency per electron, $\Gamma_w$ is the electron flux to the walls, $A_w$ is the wall area, $V$ the system volume, and $\delta_s$ the secondary emission coefficient. Note that only ionization and wall losses are considered in this case, since attachment and detachment processes do not need to be considered for argon.

The energy balance is given by

$$P_h - P_l = \frac{d(\bar{E} \bar{n})}{dt} = \frac{d\bar{n}}{dt} \epsilon + \bar{n} \frac{d\epsilon}{dt},$$

where $P_h$ is the power (per unit volume) supplied by the source to heat the electrons, $P_l$ is power loss from the plasma, and $\epsilon$ is the average electron energy. The product $E \bar{n}$ specifies the net energy stored in the plasma, assuming that almost all of it goes into the electrons rather than the ions. This is generally true for most rf discharges, and holds absolutely during breakdown when ions are virtually immobile since the voltage oscillations are occurring on too rapid a time scale for argon ions to respond.

During breakdown the fields in the center of the discharge region are very large, since the density of ions and electrons is too low to support sheaths to shield them out. Consequently electrons primarily gain energy through ohmic heating, rather than sheath heating, which usually dominates once the discharge is fully developed (as explained in Ref. 12). For ohmic heating the rate of energy gain per electron is given by (see Ref. 11)

$$\frac{d\epsilon_g}{dt} = \frac{e [E(t) \cos(\omega_{rf} t)]^2 \nu_m}{2m (\nu_{ex} + \nu_m)},$$

and the rate of electron heating is given by

$$P_h = \bar{n} \frac{d\epsilon_g}{dt}.$$  (6)

Electrons lose energy primarily through inelastic–neutral collisions and by impact with the walls.

$$P_l = \bar{n} (\nu_{iz} \epsilon_{iz} + \nu_{ex} \epsilon_{ex}) + \frac{\Gamma_w \bar{A}_w \epsilon}{V} (1 - \delta_s),$$  (7)

where $\epsilon_{iz}$ and $\epsilon_{ex}$ represent the energy losses per electron due to ionization and excitation collisions, respectively, and $\delta_s$ is the coefficient of elastically reflected electrons. Note that the last term, which represents energy loss when electrons impact the walls, is modified by the fraction of electrons which are elastically scattered from the wall back into the plasma. The coefficient of elastically reflected electrons is assumed to comprise $\sim 20\%$ of the total secondary emission rate $\delta_s$. True secondaries have an emission temperature of only 1 eV and are so ignored in this energy balance equation. For argon we use $\epsilon_{iz} = 15.6$ eV and $\epsilon_{ex} = 11.6$ eV (representing the first excitation level). Combining Eqs. (4)–(7) we get

$$\frac{d\epsilon}{dt} = \frac{d\epsilon_g}{dt} (\nu_{iz} \epsilon_{iz} + \nu_{ex} \epsilon_{ex}) - \epsilon \left[ \nu_{iz} A_w \frac{\epsilon}{V} (\delta_s - \delta_s) \right].$$  (8)

The flux of electrons to the wall is not straightforward to determine since it is governed by the spatial oscillation of the electrons in response to the rf fields. At low pressures and small electrode spacings in particular, this oscillation can be a substantial fraction of the system length. In order to calculate the flux we average the time the electron group spends at each electrode over the rf cycle to determine a period-averaged density at the wall, $n_w$, assuming that the density in the body of the plasma $\bar{n}$ is essentially uniform

$$\frac{n_w}{\bar{n}} = \frac{\Delta t}{T_{rf}},$$  (9)

where $T_{rf}$ is the rf period and $\Delta t$ is the average time the bunch of electrons spends at each electrode, which we approximate by

$$\Delta t = \frac{\alpha}{V},$$

where $\bar{V}$ the average electron velocity and $\alpha$ is the oscillation amplitude of the electrons. From Ref. 3, at sufficiently low electron density (pre-breakdown conditions) $\alpha$ is given by

$$\alpha = \frac{e V_0}{d m_e \omega_{rf} \sqrt{\omega_{rf}^2 + \omega_m^2}},$$  (10)

where $d$ is the electrode separation, $V_0$ the amplitude of the rf voltage, $m_e$ the electron mass and $w_{rf} = 2 \pi / T_{rf}$ is the driving frequency. Therefore, the flux to the wall is given by

$$\Gamma_w = n_w \bar{V} = \bar{n} \alpha \omega_{rf} / \pi.$$  (11)

At high pressures and large electrode spacings the electron oscillation amplitude is only a small fraction of the elec-
trode gap and Eq. (9) is not valid. Since electrons are lost primarily from the edges of the discharge we can no longer assume a flat density profile and in order to calculate the losses some approximation of the true profile is required. From the simulation we have developed an empirical expression of the form

$$\frac{n_w}{n} = 0.22/(1 + L/4\lambda_{iz})^{0.1},$$

where $L$ is the electrode spacing and $\delta_{iz}$ is the mean free path for ionization.

Since Eq. (3) depends on energy through the collision and loss terms, Eqs. (3) and (8) cannot be solved analytically and must be integrated numerically.

III. RESULTS

In a previous paper, Ref. 13, we examined the post-breakdown behavior of an asymmetric discharge, leading to the development of the self-bias voltage. Good qualitative agreement between the simulation and the experimental results was obtained for a range of parameters, such as ion and electron currents and the electrode voltage waveform, at a pressure of 50 mTorr. In this paper we investigate the breakdown characteristics of the discharge as a function of the pressure and the electrode separation, again comparing experimental and simulated measurements. The simulation was then used to further investigate the effect of the secondary emission coefficient on the breakdown.

A. RF breakdown voltage

Experimental measurements of the breakdown voltages were made using 3 electrode separations ($d=2, 5,$ and $10$ cm) and pressures in the range of a few millitorr to 1 Torr. When the breakdown voltage is plotted against the product of the pressure and electrode separation $pd$, the voltages all roughly lie on a single curve known as the Paschen curve. This is shown in Fig. 2. The minimum in this curve occurs at about $pd=0.3$ Torr.cm and $V_{brk}=70$ V. Note that capacitively coupled rf discharges are commonly operated at an electrode separation of 5 cm and a pressure of 50 mTorr, which is very close to the $pd$ value which we have determined gives the minimum breakdown voltage.

In Ref. 5 Lisovskiy and Yegorenkov extend a theory developed by Kihara, to determine scalings for the position and breakdown voltage of the minimum in the Paschen curve

$$(pd)_{min} = \frac{\xi}{A_1} e^{\xi},$$

$$(V_{brk})_{min} = \frac{B_0}{\sqrt{2} \xi},$$

$$\xi = 1 + \frac{\lambda_{rf}}{2C_2d},$$

where $\lambda_{rf}$ is the vacuum wavelength of the source voltage and $A_1$, $B_0$, and $C_2$ are molecular constants for the background gas, determined by curve fitting to experimental measurements. Although from this theory $pd_{min}$ and $V_{brk-min}$ are dependent on the system length through $\xi$, this dependence is small for $d=2–20$ cm. For argon they find $A_1=0$, $B_0 = 184$, and $C_2=7149$, which gives $pd_{min}=0.3$ Torr.cm and $V_{brk-min}=45$ V, which is in very good agreement with our measurements.

The PIC simulation was run using the same electrode separations, but a smaller range of pressures (15–500 millitorr) due to numerical limitations of the model. In the experiment the applied voltage is increased very slowly—with a rise-time on the order of seconds—so that the discharge conditions are always in equilibrium with the electrode voltage. In the PIC simulation it is not feasible to simulate time scales of seconds, and so voltage rise-times of the order of a few microseconds are used. Breakdown is not an instantaneous process—time is required for the ion and electron numbers to increase sufficiently for a plasma to form (see Ref. 18 for a detailed discussion of the breakdown process)—and typically the breakdown time is on the order of a microsecond. As this is the same as the rise-time used for the source voltage, care is required in defining exactly what value to use for the breakdown voltage measurement, since the voltage at the end of breakdown phase can be 50–100 V higher than at the start. We use the voltage at the commencement of the ionization avalanche as the breakdown voltage, rather than at the end of the breakdown period. This is because the breakdown would still continue, even if the source voltage was held at this value and we are interested here in the minimum voltage at which the system will break down. Indeed the results, plotted together with the experimental data in Fig. 2, show extremely close agreement between experiment and simulation for the range of $pd$ examined.

As far as the authors are aware only one other study of rf breakdown using PIC simulations has been published, see Ref. 19, also modeling an argon discharge, but at 10 MHz. Their results are very different from ours: They find $pd_{min} =2$ Torr.cm and $V_{brk-min}=300$ V and the shape of their Paschen curve is very different. As previously mentioned, it is very important to precisely define how the breakdown voltage is measured, particularly when using an increasing
source voltage. It appears that the criteria they have chosen produce results which do not agree well with experimental measurements, either ours or others.

In Refs. 1 and 5 Lisovskiy and Yegeorenkov present an experimental study of breakdown in various gases, including argon, in combined rf and dc fields. Our measurements at 2 cm electrode separation agree well with theirs at 2.3 cm for the magnitude and position of the minimum of the breakdown curve and the shape of the right-hand branch. However, the shape of the left-hand branch is quite different. According to their measurements, the 2.3 cm system will not breakdown below 80 mTorr, whereas we observe breakdown in the 2 cm system down to 5 mTorr. Their observations show a breakdown curve which does not go down to lower pressures, but doubles back producing multivalued breakdown voltages in a region just to the left of the minimum in the breakdown curve. They obtained these measurements by setting the voltage at a low pressure and then increasing the pressure until breakdown occurs. Since we do not vary the pressure during a measurement we could not observe this effect. However, our experience has been that the discharge will breakdown for any voltage larger than the minimum value for a given pd value not just particular voltages. Note that the shape of the left hand branch of the Paschen curve is strongly dependent on secondary emission characteristics of the electrodes and consequently on what material they are composed of and the surface conditions. The effect of the secondary emission coefficient on the Paschen curve is investigated further in a later section.

B. Comparison with dc breakdown

It is of interest to compare dc and rf breakdown characteristics in order to better understand the mechanisms dominating in each process. Figure 3 shows Paschen curves for breakdown in a dc argon discharge with four different electrode materials taken from Refs. 2, 20, and 21, in comparison with the rf results. This plot indicates that dc breakdown requires higher breakdown voltages in the same buffer gas than rf breakdown and that the minimum in the breakdown curve occurs at a higher pd value. It also shows that dc breakdown is strongly dependent on the electrode material. This is because dc breakdown is strongly influenced by the ion induced secondary electron emission characteristics of the electrode. Ions created in the discharge region are accelerated to the cathode and, if their impact energy is sufficient, produce secondary electrons which can be accelerated back into the discharge to further ionize the background gas. The threshold condition for dc breakdown requires that each ion impacting the electrode must produce enough secondary electrons for at least one gas atom to be ionized before the electrons are lost to the anode. Breakdown in dc discharges is, therefore, strongly dependent on both volume and surface processes.

The ion induced secondary emission coefficient, $\gamma$, is the average number of electrons emitted per ion impact and is typically given as a function of $E/p$. Gamma is strongly determined both by the electrode material, and any oxidation layers or adsorbed–absorbed gases on the surface of the electrode. Typically the minimum breakdown voltage is inversely dependent on the secondary emission coefficient. So iron, which has $\gamma=0.005$ at the breakdown conditions, has a minimum breakdown voltage of 265 V, while barium, with $\gamma\sim 0.05$, has a breakdown voltage of 94 V. However, breakdown does not always display a simple dependence on the secondary emission coefficient, since secondary emission can also be strongly influenced by impact of electrons, photons and metastable neutrals on the electrodes.

Conversely, for the rf system the voltage rise and fall occurs on too fast a time scale for ions to respond, so they remain essentially stationary and breakdown is governed mainly by electron processes. The electrons are accelerated back and forth between the electrodes under the influence of the oscillating voltage, which effectively increases the region of interaction with the background gas. The threshold condition for breakdown in the rf system also requires that each electron ionizes at least one gas atom before being lost to the walls. The minimum in the Paschen curve therefore occurs when the average mean free path for ionization is approximately equal to the electrode separation, and is a result of the optimization of the ionization rate as a function of the electric field. At higher values of pd the electron temperature is reduced by strong collisional losses and so larger applied fields are required to reach energies sufficient to initiate breakdown. In this case only a small fraction of the electrons interact with the discharge boundaries and breakdown is controlled by conditions in the volume of the discharge (i.e., the gas density). At lower pd values the ionization mean free path becomes substantially longer than the electrode gap and many electrons are lost to the walls before ionizing, consequently larger fields are required to balance the energy loss. In this case surface processes, such as electron impact induced secondary emission, are very important for determining the breakdown conditions. The next section examines the influence of secondary emission on plasma breakdown.

C. Secondary emission

We wanted to determine how the secondary emission properties influences breakdown in rf systems. Since it is not straightforward to vary the emission coefficient of the electrodes in the experimental system in a controlled manner, we...
used the simulation to study this. Two cases were run—one with \( \delta_m = 0 \) (no secondary emission) and the other with \( \delta_m = 4.8 \), doubling the maximum emission coefficient of the original case.

The results are shown in Fig. 4, and clearly shows that secondary emission is essentially unimportant in the right-hand branch of the breakdown curve, where breakdown is dominated by volume processes, but plays a large role at low \( pd \) values. With zero emission the left-hand curve rises much more steeply and cuts off at a higher pressure, while the larger emission coefficient strongly decreases the slope of the breakdown curve. The left-hand branch of the Paschen curve is strongly affected by the surface characteristics of the system boundaries since in this pressure regime the electron mean free path approaches, and can become larger than, the system length. Consequently electrons have a high probability of being accelerated across the plasma without making any collisions and lost at the electrodes. Higher voltages are, therefore, required to increase the electron temperature, thereby increasing the ionization rate to balance loss to the walls. For the two cases with \( \delta_m > 0 \), increasing the electron temperature will also increase the probability of reflection and/or producing a secondary electron when the primary electron impacts the electrode (at least for electrons with \( \epsilon < \epsilon_m \)), further reducing losses. Similarly, increasing the secondary emission coefficient reduces electron losses from the system at a lower electron temperature, allowing breakdown to occur at a lower applied voltage.

At very low \( pd \) values (<0.02 Torr.cm in the experiment), breakdown is not possible except under specific conditions. For these pressures a plasma can only be started by resonant production of secondary electrons, known as the multipactor effect (see, for example, Refs. 2 and 3). This occurs if an electron is accelerated across the plasma so that it impacts the electrode with enough energy to produce two secondary electrons, and at the correct phase for them both to be accelerated to the other electrode so that they can each produce two more secondaries and so on. The influence of multipacting electrons on initiating the discharge breakdown has been studied by simulation in a previous paper, Ref. 10. Hohn and collaborators studied the transition from a very low pressure electron multipactor \((10^{-5}–0.2 \text{ mTorr})\) to a plasma multipactor \((0.2–7 \text{ mTorr})\) to a traditional Paschen breakdown \((7 \text{ mTorr}–7 \text{ Torr})\) in a 5.5 cm 50 MHz argon discharge. Although we are working at a lower frequency the shape of our Paschen curve with \( pd \) in the range 0.01–10 Torr.cm (comparable to the portion of their curve in the 7 mTorr–7 Torr pressure region) agrees well with their results.

The results for the global model are plotted in comparison with the simulation in Fig. 4. The model shows very good agreement for the range of \( pd \) we used for the three different emission cases, particularly at low \( pd \) values. Note however that in the right-hand branch of the breakdown curve the results from the model for the three cases do not converge as one would expect, since secondary emission plays little part in this region. This is because the time-averaged method of determining the flux to the electrodes was derived for relatively large oscillation amplitudes and is not really valid here. Furthermore global modeling spatially averages the density profile and so assumptions about the profile influence the calculated flux to the electrodes. In the current model the electron losses to the walls are more strongly influenced by the secondary emission coefficient than is actually the case. A more accurate representation of the density profile and the emission probability might improve the behavior of the model at high \( pd \) values.

The benefits of using a global model are that it is very easy to implement and quick to run, unlike the PIC code, which is computationally very intensive. Developing the model also helped delineate the important physics of rf breakdown, in this regime of \( pd \). Agreement between the global model and the PIC simulation–experimental results is good enough to encourage confidence in using the model to predict breakdown characteristics for other rf systems, within the limitations of the model. Breakdown in other gases with different electrodes can easily be modeled by including the appropriate collision rates and secondary emission characteristics. However, care must always be taken, to include all the relevant physical processes—in other gases chemistry, negative ions and other interactions between charged and neutral species may play a large role in the breakdown, and thus must be included in the model.

**IV. CONCLUSION**

Experimental measurements of rf breakdown in argon gas have been performed and the shape of the Paschen curve was determined. The minimum in the Paschen curve is shown to occur at \( pd=0.3 \text{ mTorr.cm} \) and a voltage of 70 V. Breakdown in rf systems is shown to occur at much lower \( pd \) values than in dc systems, and typically requires significantly lower voltages. Furthermore, in dc discharges the whole Paschen curve, including the position and value of the minimum, is strongly influenced by the electrode material. In rf discharges the secondary emission characteristic of the electrodes has very little effect on the right-hand side of the Paschen curve or the position of the curve minimum, but strongly influences the slope of the left-hand side of the Paschen curve. PIC simulations of rf breakdown in argon have been performed and display excellent agreement with...
the experimental results. A global model developed to model breakdown in rf systems also shows very good agreement with the simulation and the experiment.

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