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Triggered breakdown in low-pressure hollow cathode (pseudospark) discharges

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Triggered breakdown in hollow cathode discharges in geometries similar to those used for pseudospark switches and pseudospark pulsed electron beams has been investigated experimentally and with a two-dimensional model previously developed. A systematic study of the influence of the discharge conditions (applied voltage and pressure), geometry, and trigger conditions (trigger intensity and position) on the time to breakdown in helium is presented, and some data are also shown for argon. Excellent qualitative agreement is found between the model predictions and the experimental results. The relation between the time to breakdown and the geometrical distribution of injected charge is discussed, and the understanding gained from these model results is used to suggest guidelines for trigger optimization. Conditions wherein significant oscillations in the current—a “current quenching” effect—are observed in the prebreakdown current wave form are discussed. © 1995 American Institute of Physics.

I. INTRODUCTION

Pseudospark discharges^{1,2} are transient hollow cathode discharges which, under proper conditions, display an abrupt transition to a highly conducting state a short time after application of a trigger. This type of discharge is particularly interesting for high power switching applications^{3,4} which require a rapid transition to a highly conductive state (1–100 kA) with a low jitter, a long life, and the possibility of high repetition rates. A high hold-off voltage (several tens of kilovolts) in simple geometries⁵ and more in multigap devices⁶ is achieved by operating the discharge at low pressure (such that a decreasing pressure leads to a higher hold-off voltage). Typical gas pressures are several 100 mTorr and the anode–cathode spacing is typically some millimeters. Triggering is accomplished by a variety of means for injecting charges into the hollow cathode backspace including electrical^{3,5,7,8} or optical^{9–11} schemes. Subnanosecond jitter and delays on the order of some tens of nanoseconds can be achieved under optimized conditions. When operated for tens of millions of shots, jitters of some 10–20 ns are typical, due to erosion of the electrodes. Although pseudospark switches have been developed to the point that they are now commercially available for certain applications,¹² work remains to be done to determine the best combination of physical and triggering conditions for minimizing the delay time and jitter. The pseudospark is also an attractive candidate for applications requiring an intense, pulsed, low emittance electron beam,¹³ and knowledge of the plasma processes leading to the formation and emission of the beam will contribute to a basis for optimal design for high brightness and low emittance.

Pseudospark switches are normally operated below their self-breakdown voltage, and in these switches as well as in other gas switches which operate below self-break, a trigger is needed to initiate the discharge. The trigger effectively “lowers the breakdown voltage” by changing the conditions in the discharge gap.^{14–16} In Ref. 17 it was shown that this can be achieved in pseudospark discharges by the introduction or cumulative generation of space charge in sufficient quantity to distort the applied field. Since the gas phase ionization rate is a very sensitive function of the field distribution in the gap (and especially, as we discuss below, in the hollow cathode geometries of interest in pseudospark discharges), slight distortions of the field due to space charge can significantly affect the voltage required for breakdown to occur. Choi *et al.*¹⁸ have also pointed out that the buildup of excited states in the discharge gap can also effectively lower the breakdown voltage in pseudospark switches.

The purpose of the work presented here is to identify the importance of the various parameters which can influence the time to breakdown in pseudospark discharges and to provide a physical basis for the observed effects. The eventual goal of this work is to determine the optimum triggering conditions for pseudospark switches and to understand and model the generation of the electron beam.¹⁹ We present below a combined experimental and modeling study of the time to breakdown in pseudospark switches as a function of the trigger conditions (intensity and spatial distribution) and physical conditions (electrode geometry, gas pressure, applied voltage, gas composition, and electrode material). Since the pseudospark discharge mode was first reported in 1979, a number of studies of the time to breakdown have been made,^{3,5,7–11,20–23} but no systematic parametric studies have previously been published. Our results are consistent with previous experimental results where available.

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The organization of this paper is as follows. We describe the model and the experimental setup in Secs. II and III, respectively. The nonmonotonic current wave forms observed experimentally and predicted by the model under conditions when the time to breakdown is long are discussed in Sec. IV. Results from a parametric study of the dependence of the time to breakdown and jitter on different trigger and physical conditions are presented in Secs. V and VI. A discussion of the results and a summary of optimum trigger conditions are presented in Secs. VII and VIII, respectively.

II. MODEL

A model of the transient evolution of pseudospark discharges must take into account self-consistently the space-charge distortion of the field and the transport and creation of the charged particles in the gap. The hybrid fluid-particle model reported in Ref. 17 was used in the calculations reported below. This model is a time dependent, two-dimensional (with cylindrical symmetry) hybrid fluid-particle description of the evolution of the charged particle densities and the electric field. This model yields a self-consistent description of the coupling between the charged particle transport and the electric-field distribution in the interelectrode gap and consists of Poisson's equation for the electric field and ion and electron fluid equations for the charged particle transport in addition to the appropriate boundary conditions. An essential feature of the model is that the ionization source term in the electron and ion fluid equations is determined through a "particle" or Monte Carlo simulation. This is especially important in the hollow cathode, pseudospark geometries where the ionization mean free path is large compared to the discharge dimensions and where the ionization produced by the pendulum electrons oscillating between the space-charge sheaths is not a simple function of the local value of the electric field to gas density ratio E/n .²⁴ The numerical results from this model are the space and time dependent electron and ion densities and the electric field, and from these quantities, the discharge current can be deduced. An implicit technique similar to that used in semiconductor device modeling²⁵ is used for the numerical integration of the fluid equations in order to minimize the computation time for conditions of high plasma density.

Since we are concerned here with the breakdown phase, effects of the external circuit are neglected and the applied voltage is supposed to be constant in time. The time to breakdown as predicted by the model is thus determined from the onset of the current and not by the drop in the voltage.

All electron emission processes from the cathode other than ion-induced secondary emission are neglected as is photoemission. Thermionic emission, field-enhanced thermionic emission or emission from microscopic structures on the cathode surface undoubtedly must be considered during the late stages of evolution of pseudospark discharges,²⁶⁻²⁸ but these effects can be safely ignored during the breakdown phase in single shot experiments of interest here. The neglect of photoemission is justified to some extent by the results of Pak and Kushner²³ who report only small effects of the inclusion of photoemission in their calculations.

Typical results of the evolution of the potential distribution in a pseudospark geometry and calculated from the hybrid fluid-particle model are shown in Fig. 1 for an applied voltage of 10 kV in helium at 0.67 mbar. The cross-section and transport data from Ref. 29 were used in these calculations, and the geometrical dimensions are given in the column labeled Geometry A in Table I. The trigger is assumed to have produced an equal density of electrons and ions ($5 \times 10^9 \text{ cm}^{-3}$, in this example) uniformly distributed through-out the hollow cathode volume, and these densities are used as the initial conditions in the calculation. At $t=0$, the potential distribution is determined by the geometry. The initial ions are drawn toward the cathode where they produce secondary electrons with a secondary electron emission coefficient of 0.3.³⁰ During their transit to the anode, the initial electrons and secondary electrons emitted from the cathode cause excitation and ionization in collisions with the neutral background gas in the main gap but with a small probability because the excitation and ionization mean free paths are comparable to or longer than the dimensions of the discharge. Ionization occurs in the main gap and also inside the hollow cathode where the initial and secondary electrons can attain energies greater than the ionization potential of the neutral gas before they exit the hollow cathode. The path length of the electrons inside the hollow cathode is enhanced by the fact that the electrons are trapped to some extent by the electric field and can make several oscillations before exiting through the aperture. Although for these conditions each individual electron produces less than one ionization event on the average during its transit to the anode, a positive ion space charge builds up because the total number of ionization events is large and the electrons exiting the ionization events are rapidly drawn to the anode, leaving the more massive ions behind. This is seen first as a space-charge distortion of the geometrical field inside the hollow cathode at 26 ns. As the positive ion space-charge density increases, the space-charge field acts to slow the electrons during their transit to the anode and a plasma forms. This occurs first near the axis in the main gap and is evident by the spreading apart of the potential contours on the axis in the main gap at 34 ns. The plasma "pushes" the higher potential contours toward the cathode (37 and 42 ns in Fig. 1). As the plasma continues to grow (we return to this point below in Sec. VII), the contour of maximum (anode) potential approaches the cathode and eventually penetrates into the aperture and hollow cathode backspace (at 50 ns in Fig. 1). The ionization rate increases dramatically from about 25 ns when the plasma formed in the main gap starts to penetrate the hollow cathode because the configuration of the electric field at that instant is an optimum for the hollow cathode effect. (Note that the hollow cathode is most efficient when the secondary electrons are born in ionization events in high-field regions. These secondaries are accelerated in the field and can themselves produce further ionization.³¹) An increasing ionization rate means that the plasma expands ever more rapidly into the hollow cathode, not because of transport of charged particles, but because of the generation of charged particles at the plasma boundaries. The current also increases rapidly

FIG. 1. Potential distribution during breakdown in triggered, undervolted hollow cathode discharge at six different times in helium at 0.67 mbar and for an applied voltage of 10 kV. The dimensions indicated on the figure are in centimeters and these correspond to geometry A in Table I. The contours are evenly spaced at 1 kV intervals between 1 and 9 kV contours at 0.2, 0.5, 9.5, and 9.8 kV are also shown.

when plasma enters the hollow cathode; the current at the cathode at that time is a displacement current due to the rapidly changing electric fields on the cathode surface.

In Fig. 2 the current wave form corresponding to the calculation of Fig. 1 is shown. The discharge current is shown in the upper half of the figure, and the electron multiplication (the number of ionization events in the volume normalized to the electron current leaving the cathode) is shown in the lower portion. The time to breakdown in the calculations is defined as the time of the maximum in the electron multiplication since this provides an easily identifiable

criterion. A large increase in the multiplication is seen at about 34 ns, the time that the plasma reaches and begins to enter the hollow cathode backspace, and correlated with the increase in the multiplication is an increase in the discharge current. As the plasma expands further into the hollow cathode volume, the electron multiplication decreases because the high-field sheath regions contract against the cathode surface. The discharge is then less efficient because the ionization events occur in low-field regions and the secondary elec-

TABLE I. Dimensions of the pseudospark geometry used in the calculations and in the experiment.

	Model geometries (cm)		Experimental geometry (cm)
	A	B	
Discharge radius	1.5	1.5	1.5
Total length	2.4	3.4	9.4
Cathode depth	0.77	0.78	3.8
Anode depth	0.62	0.87	3.8
Main gap spacing	0.58	0.39	0.4
Electrode plate thickness (anode and cathode)	0.19	0.68	0.7
Aperture radii (anode and cathode)	0.33	0.33	0.25

FIG. 2. Calculated current wave form and electron multiplication vs time for conditions of Fig. 1.

FIG. 3. Schematic of the experimental setup showing a typical pseudospark geometry.

trons born in ionization events gain little energy in the field and therefore produce little or no subsequent ionization. The time to breakdown, τ_b , can be identified as the time of the peak in the multiplication.

We will show below agreement between the trends observed in the experiments and those predicted by the model for the variation of the time to breakdown with different trigger and physical conditions. This provides some measure of validation of the model. Further validation has recently been provided by the experiments of Alberta and Derouard³² who have measured the transient electric-field distribution in hollow cathode discharges in a geometry typical of pseudospark discharges but at much lower voltages. Good agreement was found between the calculated and experimental transient electric fields, the current wave forms, and the transient emission intensity.

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III. EXPERIMENTAL SETUP

The pseudospark geometry used in the experiments is shown in Fig. 3 with the dimensions summarized in Table I. The pseudospark chamber consists of two cylindrical hollow electrodes with central apertures in the front faces which were aligned parallel to the opposite electrode. The main gap spacing (distance between the front faces of the electrodes) is 4 mm. The experiment was designed for easy changes in the discharges dimensions; the electrodes can easily be replaced

FIG. 4. Typical behavior of the time evolution of the laser trigger pulse and the experimental current wave form (for short time to breakdown).

to study the influence of diameter of the electrode aperture and the thickness of the cathode end plate on the breakdown delay time. In the present experiments, the aperture diameter was varied from 0.1 to 0.6 cm and the thickness of the cathode front plate from 0.1 to 0.7 cm. The experiments were carried out at gas pressures between 0.1 and 0.9 mbar in helium after pumping the system to a pressure lower than 5×10^{-5} mbar. The electrode end plates and cavities were made of brass in all the experiments reported here.

An optical trigger scheme (similar to that in back-lit thyratron devices)^{9,10} was used throughout this set of experiments. Thus, triggering was accomplished by illuminating the interior surface of the cathode front plate with light from a XeCl laser (308 nm). The output energy of the laser was variable up to 300 mJ, the rise time of the laser pulse is less than 10 ns, and the pulse length is about 30 ns. Without focusing the laser light onto the back of the cathode, triggering of the pseudospark was only possible for conditions near self-break, and the jitter and delay times were rather long in these cases, the latter being typically in the range of tens of microseconds. With focusing, a stable operating mode was obtained over a very large range of values of gas pressure, voltage, and electrode geometry, with small jitter and delay times on a submicrosecond scale. However, for given experimental conditions (geometry, pressure, gap voltage, and laser output power), the delay time is a sensitive function of the position of the laser spot on the cathode surface. The results presented here have been obtained by focusing the laser on the inside surface of the cathode a point 0.65 cm from the center of the cathode aperture.

The trigger laser pulse and the measured discharge current are shown in Fig. 4. The experimental time to breakdown (or delay time), τ_b , is defined experimentally as the time elapsed between the application of the laser pulse and the onset of the discharge current as measured by a current viewing resistor with a rise time of about 1 ns. Note that this is lower than the rise time of the current which is circuit limited at a value of 100 ns. Due to the short rise time of

FIG. 5. Typical current wave form observed experimentally for conditions where the time to breakdown is long.

both the laser pulse and the current signal, the breakdown delay times are measured with an estimated accuracy of 10 ns whenever the time to breakdown is less than 1 μ s or an accuracy of about 20 ns for the longer delay times.

IV. CURRENT WAVEFORMS

For experimental conditions which lead to rapid breakdown, the monotonic increase of the current during the discharge initiation, as shown Fig. 4, is observed. In contrast, for conditions where the time to breakdown is long, two or even three sharp consecutive maxima can be observed before the onset of the main current peak. An example of this behavior is shown in Fig. 5 where several sharp prepeaks appear in the current wave form before breakdown occurs at about 5 μ s. The same type of structure in the current wave forms is also predicted by the model under certain conditions (especially for small aperture diameters and high voltage). We show in Fig. 6 the calculated current wave form for conditions identical to those of Fig. 1 (10 kV, 0.67 mbar helium) except that the diameter of the cathode aperture was decreased from 0.65 (Fig. 1) to 0.4 cm. The calculated time to breakdown with the small aperture diameter is about 550

FIG. 6. Calculated current wave form for same conditions as in Fig. 2 except the cathode aperture diameter for decreased to 0.4 cm.

ns compared to some 50 ns for the larger aperture diameter, and several prepeaks in the current occur before the onset of the main current pulse.

Calculations of the evolution of the potential distribution in the gap (not shown here) were used to help interpret these results. We observed that up to the instant of the first current peak, the evolution is the same as described above with a plasma formation in the hollow cathode and in the main gap and expansion of the latter toward the cathode. When the aperture diameter is too small, however, the secondary electrons emitted from the cathode surface can multiply much faster inside the hollow cathode than they can be transported through the aperture. In this case, current continuity can only be accomplished by the rapid establishment of an axial field which extracts the electrons from the hollow cathode. The potential is thus expelled from the hollow cathode and the multiplication drops. The potential distribution in the gap essentially returns to the geometrical distribution of the potential which existed at $t=0$, but the charged particle density distributions in the gap are quite different from their initial conditions (the electron density is concentrated nearer the axis and there is a finite density in the main gap). The subsequent evolution of the discharge is then similar to that leading to the first peak, and after a sequence of several peaks in the current and the multiplication, breakdown finally occurs.

This type of current waveform is clearly undesirable. The experimental jitter for these conditions is large as might be expected since with very slight changes in the initial conditions, breakdown could occur at another one of the current prepeaks. The existence of prepeaks in the current wave form is expected to be favored at increasing voltage, decreasing aperture diameter, or decreasing aperture depth since the multiplication inside the hollow cathode is increased with these parameters. In a preliminary series of experiments, the parameter range for which the prepeaks occurred was indeed higher voltage and smaller aperture diameter and depth. We are also investigating the possibility that this same type of phenomenon may be responsible for certain types of quenching observed in pseudospark discharges.

V. EFFECT OF TRIGGER CONDITIONS ON TIME TO BREAKDOWN AND JITTER

We now turn to the results of our parametric studies on the dependence of the time to breakdown on the trigger conditions. In this section we present the results and a discussion is deferred until Sec. VII.

The various schemes used to trigger pseudospark discharges differ in the magnitude and spatial distribution of charges injected into the hollow cathode backspace.^{3,5,7-11} In this section, we show the effect of trigger intensity on the measured and calculated delay time in helium and of the position of the injected charge on the calculated delay time in helium. The discharge dimensions (geometry A) used in the calculations and in the experiments reported in this section are given in Table I.

FIG. 7. Calculated time to breakdown as a function of the initial charged particle densities in helium at 0.67 mbar and 2 kV for geometry A of Table I. The shaded areas in the inset indicate the cylindrically symmetrical volumes in the hollow cathode in which the initial charged particle densities were introduced. The lower curve corresponds to calculations where the initial densities were uniform throughout the hollow cathode volume, and in the upper curve, the initial densities were uniform throughout a cylindrical ring volume (equal to 6% of the total hollow cathode volume). The solid squares result from calculations with different cylindrical volumes adjacent to and centered about the aperture with a height of 0.3 cm and radii of 1.5, 0.76, and 0.4 cm.

A. Dependence of τ_b on trigger intensity

The dependence of the calculated time to breakdown on the initial charged particle density is shown in Fig. 7 for helium at 0.67 mbar and 2 kV in geometry A. The lower curve corresponds to the calculated breakdown delay time for initial charge densities uniformly distributed over the full volume of the hollow cathode, and for this case densities of less than $3 \times 10^9 \text{ cm}^{-3}$ are insufficient to lead to breakdown. Past this threshold, the time to breakdown decreases with a faster decrease near the triggering threshold. We will return to a discussion of the other data in this figure below where it is shown that triggering can be achieved with a smaller number of charged particles if they are suitably introduced near the aperture.

In the experiments, the initial charged particles are produced by focusing the laser on a small area on the cathode surface. We have not measured the number of initial electrons and/or ions, but it should vary with the incident laser power and we suppose here that the effect of the trigger intensity on the delay times and jitter can be studied by changing the laser intensity. Results are reported in Fig. 8 for two different diameters of the cathode hole. Starting from a critical value under which no triggering occurs, the time to breakdown dramatically decreases as the laser energy increases from threshold up to 50 mJ; above this τ_b continues to decrease but more gradually.

Experiments have been reported by Braun *et al.*¹⁰ in which initial electrons were produced by photoemission from a molybdenum electrode. Low jitter (a few nanoseconds) was obtained in hydrogen with either 1 mJ at 308 nm or 0.01 mJ at 222 nm. It was shown that efficient triggering is possible by coupling the radiation to the gap through an optical

FIG. 8. Experimental time to breakdown in helium as a function of the laser energy for two different values of the cathode hole diameter in helium at 0.41 mbar and 4 kV. The thickness of the cathode plate was 7 mm.

fiber. The number of electrons produced by the 308 nm photons were measured in Ref. 10 and it was determined that 10^9 electrons produced from a 1 cm^2 area (quantum efficiency $\approx 10^{-7}$) on the back of the cathode resulted in low jitter in hydrogen. The triggering threshold is higher in helium where the electron-impact cross sections are small, and smaller initial densities are needed to initiate the discharge in argon (see below) and hydrogen.

In spite of the differences in the trigger conditions between the model and the experiments (not measured directly) which preclude a direct quantitative comparison, the same qualitative behavior is seen in both the calculations and in the experiments. A distinct threshold in the trigger intensity is observed and τ_b rapidly decreases with increasing trigger intensity past the threshold until a saturation is reached.

There is also general agreement between the model predictions and the experiments measurements of the jitter. If we suppose that the jitter in the experimentally observed time to breakdown, given by the error bars in Fig. 8, is the result of small variations (on the order of 10%) in the trigger intensity from shot to shot, it is possible to calculate the jitter and its dependence on discharge conditions. The jitter so defined for initial densities of $5 \times 10^9 \text{ cm}^{-3} \pm 10\%$ is about 10 ns for helium at 2 kV in geometry A. The jitter decreases with increasing trigger intensity or increasing voltage. For an initial densities of $10^{10} \text{ cm}^{-3} \pm 10\%$, the calculated jitter is 4 ns, and for initial densities of $5 \times 10^9 \text{ cm}^{-3} \pm 10\%$, the jitter calculated at 4 kV is 6 ns. This assumed variation in the initial charged particle density is consistent with the approximately 10% variation in the intensity of the laser pulse used to trigger the pseudospark in the experiments.

B. Calculated dependence of τ_b on trigger position

Electrical triggering of pseudospark discharges is generally accomplished by the introduction of a plasma into the hollow cathode. Back-lit thyratrons are optically triggered

FIG. 9. Dependence of the calculated time to breakdown on the position of the initial trigger density. The shaded areas inside the hollow cathode indicate the volume in which the initial charged particles were introduced, and the time to breakdown, τ_b , is given below each diagram.

pseudospark discharges in which triggering can be caused by photoemission from the cathode surface (which can lead to a plasma inside the hollow cathode) or by the optical generation of a plasma near the metal surface. Thus, depending on the experimental arrangement, a plasma can be introduced at different positions inside the hollow cathode backspace.

Also shown in Fig. 7 are the calculated times to breakdown for different geometrical distributions of the initial density. The upper curve shows the calculated values of τ_b when the initial density is injected into a cylindrical ring volume (outer radius 0.76 cm, inner radius 0.4 cm) centered about the aperture and extending to a distance of 0.3 cm from the back of the cathode end plate. The same overall behavior is observed independently of the geometrical distribution of the initial charge—a decreasing value of τ_b past the threshold with a more rapid decrease nearer the threshold. For a constant initial density of $5 \times 10^9 \text{ cm}^{-3}$, the effect of a decreasing volume of injected charge is shown in the figure by the solid squares which correspond to cylindrical volumes of height 0.3 cm and radii of 1.5, 0.76, and 0.4 cm.

We also examined the effect of moving the trigger position further from the aperture by introducing an initial density of electrons and ions in three different elements of volume in the hollow cathode backspace. These positions are indicated by the shaded areas in Fig. 9. For the conditions chosen, i.e., helium at 0.67 mbar at an applied voltage of 2 kV in geometry A and for an initial charge density of $5 \times 10^9 \text{ cm}^{-3}$, the shortest time to breakdown (54 ns) occurred for the initial density closest to the cathode hole. When the density was introduced in the back of the hollow cathode, breakdown did not occur, and for an initial density in the middle third of the hollow cathode volume, the time to breakdown was 350 ns. The current wave form after breakdown is similar in the two cases when breakdown did occur. The addition of charged particles in the volume of the cathode hole to the trigger densities nearest the cathode hole does not change the time to breakdown.

VI. EFFECT OF PHYSICAL CONDITIONS ON TIME TO BREAKDOWN

In this section, we present results of the time to breakdown for variations in the pseudospark geometry, the gas

TABLE II. Calculated breakdown delay time τ_b for variations in the geometry about the standard (geometry A of Table I). The conditions of the calculations are helium at 0.67 mbar and an applied voltage of 2 kV. The values of τ_b given in the last column of this table are to be compared with 50 ns, the value calculated in geometry A of Table I for otherwise the same conditions.

	Change in dimension (cm)		Breakdown delay time (ns)
	from	to	
Cathode radius	1.5	1.8	44
Cathode depth	0.77	0.96	60
Cathode plate thickness	0.19	0.38	80
Cathode aperture radius	0.33	0.56	15
Anode aperture radius	0.33	0.56	52
	0.33	0.0	50

pressure, the applied voltage, the electrode composition, and for metallic and dielectric walls in the hollow cathode. A discussion of these results is given below in Sec. VII.

A. Pseudospark geometry

We report here a series of experiments and calculations designed to determine the influence of various of the discharge dimensions on the time to breakdown and jitter in triggered pseudospark discharges. In the calculations, we varied the geometry around the “standard” geometry (geometry A) to see on which of the dimensions the current wave form is most dependent. In the experiments the electrode thickness as well as the cathode and anode aperture diameters were changed while the depth and the diameter of the electrodes remained constant. For each geometry the measurements were performed as a function of gas pressure.

Table II summarizes the dependence of the calculated time to breakdown on certain of the pseudospark dimensions and shows that the most important dimensions for the range of conditions studied are the cathode aperture diameter and the cathode thickness. Dimensions which are not very important are the anode plate aperture and the dimensions of the hollow cathode. We performed another calculation with dielectric sidewalls in the hollow cathode for otherwise same conditions as in Table II, and, consistent with our conclusion that the cathode diameter is not an important parameter, we found that there is no effect of the dielectric sidewalls on the time to breakdown.

The experimental time to breakdown as a function of gas pressure is shown parametrically in Fig. 10 as a function of the cathode aperture diameter. As predicted by the model, τ_b decreases as the hole diameter increases up to a value of 5 mm which seems to correspond to the optimal value giving the lowest delay times and jitter (for clarity in the plotting the error bars have been omitted in Figs. 9 and 10). As the hole diameter is increased further to 6 mm, the delay time increases somewhat. This latter result may be affected by the fact that the laser is focused at a point 6.5 mm from the axis.

Figure 11 illustrates the measured dependence of τ_b on the cathode end plate thickness for an aperture diameter of 3 mm. Consistent with the calculations, we find that this is an important factor in determining the time to breakdown. A decrease in the thickness results in a decrease in τ_b , and the

FIG. 10. Experimental time to breakdown as a function of pressure for different diameters of the cathode hole in helium at 4 kV with a laser energy of 88 mJ. The thickness of the cathode plate was 7 mm.

delay time decreases an order of magnitude when the plate thickness is reduced from 7 to 1 mm. The jitter decreases correspondingly.

Our experiments have also confirmed the insensitivity of the time to breakdown on the anode aperture as predicted by the model.

B. Gas pressure

Figures 9 and 10 also show the effect of pressure variation on the experimental times to breakdown. For a given electrode geometry, an increase of helium pressure from 0.2 to 0.8 mbar leads to a decrease of τ_b by a factor of about 3. The trends in the model calculations with changing pressure are consistent with the experimental results.

FIG. 11. Experimental time to breakdown as a function of pressure for different thicknesses of the cathode plate in helium at 4 kV with a cathode aperture diameter of 3 mm and a laser energy of 90 mJ.

FIG. 12. Experimental and calculated dependence of time to breakdown on the applied voltage in helium. The experimental conditions were 0.4 mbar, 3 mm cathode aperture diameter, and 92 mJ laser energy. The calculations correspond to geometry B of Table I in helium at 0.67 mbar.

It should be emphasized that in pseudospark switches the gas pressure is chosen primarily to obtain the desired hold-off voltage rather than for ease or reliability of triggering.

C. Applied voltage

One of the most remarkable features of pseudospark discharges is that they can be easily triggered to breakdown at voltages less than 10% of the self-breakdown voltage. This feature is shown in Fig. 12 where the calculated and experimental τ_b is plotted as a function of the applied voltage. The experiments were performed with a laser energy of 92 mJ and at a pressure of 0.67 mbar. For comparison, the calculated values of τ_b as a function of applied voltage for geometry B (Table I) are shown for the same helium pressure and with an initial trigger density of $5 \times 10^9 \text{ cm}^{-3}$. Although, for the reasons previously discussed, a quantitative comparison is not possible, the same general trends appear: in both cases, τ_b rapidly decreases with increasing voltage and then saturates.

D. Electrode material

The electrode material enters into the calculation only through the value of γ , the secondary electron emission coefficient due to ion bombardment. The calculated time to breakdown in helium at 2 kV and 0.78 mbar is 50, 95, or 425 ns for $\gamma=0.3$, 0.15, or 0.08, respectively. These results are not surprising. With a larger value of γ , breakdown occurs earlier simply because of the higher efficiency of electron emission and consequently larger flux of electrons into the main gap from the hollow cathode. The variation in τ_b resulting from a small variation in γ is large; a 10% variation in the value of γ yields a larger change in τ_b than does a 10% variation in the initial densities.

FIG. 13. Comparison of the experimental time to breakdown as a function of gas pressure in argon and helium.

E. Gas composition

In this section a few results are presented for the time to breakdown in argon using the same experimental and calculational techniques as described above. The experimental and calculated times to breakdown in argon are considerably smaller than for helium for otherwise the same conditions. The cross sections for electron-impact ionization in argon (and in hydrogen) are considerably higher than in helium.³³ However, the secondary electron emission coefficient for argon-ion bombardment of metal surfaces is much lower than that for helium ions on the same surfaces. Typical values of γ for argon ions on metal surfaces range from 0.05 to 0.1,^{34,35} while for helium ions on metal surfaces, typical values are from 0.15 to 0.3.^{30,34,35} A comparison of the measured time to breakdown values in helium and argon is given in Fig. 13, for constant trigger intensity with the same electrode geometry and applied voltage, 2 kV. Self-breakdown occurs in argon under these conditions for pressures greater than 0.12 mbar, and the experimental time to breakdown in argon is a factor of about 6 lower than in helium at the same pressure. It can also be seen in Fig. 13 that the jitter is very low in argon; the error bars (jitter) are smaller than the symbols for argon.

VII. DISCUSSION

We showed in the example of Figs. 1 and 2 above that breakdown occurs in an undervolted pseudospark discharge as a result of plasma formation in the main gap and its consequent distortion of the geometrical field. Below the self-breakdown voltage and in the geometrical field, the rate of generation of electrons in volume ionization events is less than the rate of loss of electrons at the anode. However, even though the electron-loss rate exceeds the generation rate, a plasma can form if the density of the charged particles produced by the trigger is high enough. At each ionization event in the volume of the main gap, the electrons exiting the collision rapidly move toward the anode, and on time scales

short compared to the ion transit time, leave behind the heavier ions. If the trigger intensity is high enough and even though the electron multiplication (the number of ionization events in the volume per cathode emitted electron) is small, the positive ion space charge can increase to the point that there is a distortion of the field such as to impede the motion of the electrons toward the anode and a plasma forms. The electric field in the region of the plasma is reduced, and for a constant applied voltage, the field must increase in other regions of the gap. Note that in general the plasma formation will occur first in the main gap under these low-pressure conditions and the field will increase in the region of the cathode.

The plasma in the main gap will continue to expand and grow toward the cathode, increasing the space-charge field distortion of the geometrical field, as long as the number of charged particles in the main gap increases due to ionization. Once the plasma from the main gap reaches the hollow cathode, the multiplication increases dramatically and breakdown can occur. The multiplication is an extremely sensitive function of the field distribution within the gap as shown in Fig. 2 where the electron multiplication in the geometrical field is less than one, and it increases to about 50 within 30 ns when the plasma reaches the hollow cathode. (Recall that the multiplication shown in the figure is not the total number of ionization events due to the cathode emitted electrons during their lifetime in the gap, but rather the number of ionization events per cathode emitted electron per 2 ns interval. These quantities would be equal in a steady-state situation.) If, however, a plasma has not formed in the main gap and reached the cathode by the time the initial charged particles created by the trigger are collected at the electrodes, the charged particle densities in the main gap will decrease and breakdown will not occur.

For the same applied voltage, the electron multiplication in a nonuniform electric field is generally higher than in a uniform field if the field in the region of the cathode is higher. When there is plasma formation in the main gap, the field inside the hollow cathode increases and the electron multiplication increases. The reverse is true if there is plasma formation inside the hollow cathode before a plasma forms in the main gap. Then the field in the main gap increases and the electron multiplication (for electrons emitted from the interior surfaces of the cathode) decreases because electrons are accelerated further downstream and closer to the anode. Thus *plasma formation in the main gap outside the hollow cathode is necessary to increase the electron multiplication in pseudospark geometries above its value in the geometrical field distribution so that breakdown can occur.* This conclusion is consistent with the results of Penetrante and Bardsley³⁶ and with the observation of Pak and Kushner²² that “the virtual anode must be regenerated” in order for breakdown to occur. Note that in general there is plasma formation in both the hollow cathode and in the main gap before breakdown occurs, but it is the plasma in the main gap which dominates the field distribution.

It should be emphasized that the creation of a plasma inside the hollow cathode before the conductivity of the main gap increases favors the appearance of prepeaks in the cur-

rent wave form before breakdown and significantly increases the jitter. This “current quenching” phenomena prior to breakdown is accompanied by an expulsion of the potential from the hollow cathode as discussed above, and we are investigating the relation between this current quenching in the breakdown phase and that sometimes observed during later phases of pseudospark operation.³⁷

A. Effect of trigger conditions

The measured and calculated times to breakdown, τ_b , as a function of trigger intensity show that there is a minimum intensity below which breakdown does not occur and that τ_b decreases rapidly with increasing intensity near the minimum. Below the minimum trigger intensity, if a plasma does form in the main gap, it never grows to reach the cathode and the field distortion is always insufficient to increase the ionization rate above the electron-loss rate before the initial charged particles are collected at the electrodes. As the trigger intensity increases, the distortion of the field and the resulting increase in the ionization rate are larger and occur more rapidly, thereby decreasing τ_b for an increasing trigger intensity. The minimum or saturated value of τ_b is related to the number of electrons which can be extracted from the hollow cathode during an ion transit time in the main gap.

Results from model calculations presented above show that the efficiency of the trigger is highly dependent on the spatial distribution of the charged particles produced by the trigger pulse; triggering can be accomplished with fewer initial particles if the initial particles are introduced nearer the aperture. One reason for this is simply that the penetration of the geometrical field into the hollow cathode is small except in the region of the aperture. If the particles are introduced far from the aperture, the electrons can exit the hollow cathode only through diffusion, a process slow compared to the ion transit time in the main gap. Thus, in this case, ions produced by electron-impact ionization in the main gap never have time to accumulate in the main gap; they are pulled to the cathode as fast as they are created in volume ionization events.

Another reason for the strong dependence of τ_b on the trigger position is that the electron multiplication depends on the spatial distribution of the electron current emitted from cathode surface. In planar geometries when the radial electric field is uniform, electrons emitted from each cathode surface element are, on the average, equally efficient in producing ionization during their transit to the anode. By contrast, in nonplanar geometries, the average ionization produced per electron leaving the cathode depends on its point of emission from the cathode. In hollow cathode geometries where the electric-field distribution is highly nonuniform, electrons emitted from the interior of the hollow cathode near the aperture create more ionization during their transit to the anode than do electrons emitted from the front surface facing the anode. The calculated average electron multiplication per cathode emitted electron is shown in Fig. 14 for electrons emitted at different positions along the cathode surface in (a) the geometrical field and (b) in the field which exists at 31 ns for the conditions of Fig. 1 (10 kV, 0.67 mbar helium). In the geometrical field, the electrons emitted from points inside the

FIG. 14. Average multiplication in the electric-field distributions at $t=0$ and at $t=30$ ns for electrons emitted from different elements of surface area of the cathode and for conditions the same as in Fig. 1. The surface area elements are numbered from $S=0$ (on the axis on the back of the cathode surface) to $S=51$ (on the front cathode surface near the wall) as indicated in the inset. Note that because of the cylindrical symmetry, only half of the cathode need be considered.

cathode and off-axis contribute most to the total ionization but in any case the multiplication is small (less than 1.0) for all positions. After 31 ns (just before breakdown has occurred), the potential distribution is as shown in Fig. 1 and the electrons emitted from positions inside the hollow cathode off the axis (surface element numbers 14–26 in Fig. 14) are extremely efficient in producing further ionization because these electrons are trapped to a large extent between the sheaths in the hollow cathode and are forced to expend a large part of their energy in collisions with the gas atoms. Equally efficient in producing ionization are those electrons emitted from points just inside the aperture. Electrons emitted from the back surface on the axis are not at all efficient in producing ionization because they are accelerated in the field in front of the cathode to energies where collisions are infrequent and directly exit through the aperture experiencing very few collisions along the way.

It is clear from our calculations that triggering by the introduction of charged particles in and around the aperture should lead to more efficient triggering. This is indeed the empirical conclusion from several previous studies. Although we did not study experimentally the effect of varying the focal spot of the laser, we did note a strong dependence of the focal position on the delay time and the minimum jitter.

If breakdown is to occur, there must be not only a redistribution of the potential within the gap which enhances the multiplication, but there must also be electrons emitted from

points on the cathode surface for which the multiplication is high. Taking these two considerations together, we can conclude that triggering by introducing a plasma near the anode is not efficient (unless the trigger is arranged to also produce charges inside the hollow cathode). While the introduction of a plasma near the anode may lead immediately to a large field distortion and enhancement of the multiplication, there will be essentially no electrons emitted from interior points of the cathode surface to benefit from this favorable configuration of the field. As stated above, most of the ions from the trigger pulse near the anode will arrive on the front face of the anode and the average multiplication of the secondary electrons emitted from the front surface of the cathode due to this ion flux is always quite small and insufficient to lead to breakdown. In other of our calculations not shown here, breakdown did not occur for the conditions of Fig. 1 when the initial charged particles were introduced near the anode even when the number of initial charged particles far exceeded the number supposed for the calculation in Fig. 1.

B. Effect of physical conditions

The experiments and calculations above both show a strong dependence of the time to breakdown on the applied voltage and the gas pressure as well as on the cathode aperture diameter and depth. The dependence of the time to breakdown on the pressure is due primarily to the increased multiplication in the main gap due to an increasing number of ionization collisions in the main gap. Thus the plasma in the main gap forms and grows toward the anode faster at higher pressure. Increasing the gas pressure, however, is usually undesirable in pseudospark switches because of the consequent lowered breakdown voltage.

The aperture diameter and depth determine the geometrical field inside the hollow cathode and thus the rate at which electrons are pulled out of the hollow cathode and into the main gap. The applied voltage and the aperture dimensions also affect the prebreakdown multiplication of the initial electrons inside the hollow cathode. Since the plasma in the main gap is produced by the influx of electrons from the hollow cathode, multiplication of electrons inside the hollow cathode before breakdown (or plasma formation inside the hollow cathode) can serve the useful purpose of enhancing the electron flux leaving the hollow cathode and contributing to the plasma growth in the main gap. The prebreakdown multiplication of electrons inside the hollow cathode is larger for (a) higher applied voltages, (b) smaller aperture diameter, and to a lesser extent, (c) smaller cathode plate thickness. Therefore, it is not surprising that our measured and calculated τ_b 's decrease at increasing voltage, increasing aperture diameter, and decreasing cathode plate thickness.

It is important to recall the existence of prebreakdown current pulses (Figs. 4 and 5) when the multiplication inside the hollow cathode increases too fast relative to the current growth in the main gap. This suggests that there is an optimum aperture geometry for rapid breakdown at each voltage. As the voltage increases, the optimum aperture diameter increases.

Another effect of increasing the cathode aperture diameter is to reduce the range of undervoltages which can be

triggered to breakdown for otherwise similar conditions; that is, the applied voltage must be a larger fraction of the breakdown voltage in order for breakdown to occur for a larger aperture diameter. This is because the transit multiplication reaches a peak at a lower value for larger aperture diameters due to the diminished efficiency of the hollow cathode in confining the electrons.

Our experiments and calculations show that the anode aperture plays no role during breakdown. Unless ions accumulate in the main gap, there is no plasma formation, and ions created in the hollow anode cannot accumulate in the main gap since their transit time in the main gap is much faster than their transit time from inside the hollow anode (low-field region) to the main gap. Further, the ions which are created inside the hollow anode arrive, for the most part, on the front surface of the cathode plate. These ions are not very useful in leading to further ionization since the efficiency for secondary electron emission in helium for ions of energies up to 10 kV is less than unity and the multiplication of electrons leaving the front face of the cathode is quite small (see Fig. 14).

C. Jitter and time to breakdown

We have suggested above that one cause of jitter, e.g., the variation in the time to breakdown from shot to shot, in pseudospark discharges is small fluctuations in the trigger conditions. The jitter due to such fluctuations is thus expected to be larger for conditions where the time to breakdown is large, i.e., when the time to breakdown is rapidly varying with the trigger intensity, and this is the tendency observed experimentally.

Other factors can also contribute to the jitter. In particular, changing conditions of the cathode surfaces inside the hollow cathode and the aperture can also lead to variations in the time to breakdown and hence to an increasing jitter. Since the electron emission from the cathode during the discharge initiation is due to secondary emission (by ion, fast neutral, or photon bombardment of the surface), any variation in the dependence of the secondary electron emission with time can enhance the jitter. Because the secondary electron emission coefficient is known to be quite dependent on the surface conditions,³⁵ changing surface conditions will increase the jitter through to changes in the time to breakdown during the device lifetime. We showed above that the multiplication of electrons emitted from the cathode surfaces near the aperture is higher than for electrons emitted from other positions especially just preceding breakdown. Thus the jitter will be especially sensitive to surface conditions near the cathode aperture.

VIII. CONCLUSIONS

We have presented results from a combined experimental and modeling study of breakdown in hollow cathode geometries of the type used in pseudospark switches.

As in other low-pressure discharge devices, triggering of pseudospark discharges is achieved by the introduction of charged particles in the hollow cathode, and it is the cumulative generation of space charge within the gap which pro-

gressively distorts the geometrical field distribution and leads to breakdown. This effect is quantified in the calculations presented above which show that slight changes in the potential distribution in the gap (especially for this hollow cathode geometry) cause large changes in the number of ionization events occurring in the volume. Since the electron multiplication at the same applied voltage can vary orders of magnitude depending on the distribution of the potential within the gap, pseudospark switches can be easily triggered to breakdown at applied voltages much lower than the self-breakdown voltage. The hollow cathode geometry used in pseudospark switches is thus easy to trigger at low applied voltages. (In fact, by careful positioning of the triggering electrodes in an electrically triggered pseudospark, switching has been initiated with voltages as low as a few tens of volts, or $\approx 1/10$ th of 1% of the switched voltage.³⁸)

Work is underway to utilize the model to calculate the beam current, brightness, and emittance of the pseudospark electron beam.¹⁹ This is particularly attractive because beam currents as high as 1 kA³⁹ have been reported and the beam has recently been developed for broad-area high-resolution microlithography.⁴⁰ Using the model described above, it should be possible to calculate, from first principles, practical electron-beam properties and design parameters.

In the results presented above, we have shown that (1) the breakdown delay times and, hence, the jitter are strongly dependent on the spatial distribution of the initial charges produced by the trigger as well as on the magnitude of the initial charges, (2) the smallest values of the breakdown delay time and jitter are found when the initial charges exist near cathode aperture and for high initial charged particle densities, (3) the smallest delay times for constant trigger conditions are found for large cathode aperture radii, a small cathode end plate thicknesses, high voltages, large secondary electron emission coefficients from the cathode surface, and high pressures, and (4) prebreakdown peaks in the current wave form occur for certain combinations of voltage and aperture geometry. The trends in the calculated times to breakdown are consistent in every respect with the experimental results.

In addition to their effect on the breakdown delay time and jitter, variations in the trigger conditions or in the discharge conditions lead, of course, to changes in other of the pseudospark characteristics such as the breakdown voltage, lifetime, and rate of current rise. For example, while an increasing pressure may lead to a more rapid and reliable breakdown, the breakdown voltage will be correspondingly decreased. A trigger position near the cathode aperture can be expected to lead to changes in the breakdown characteristics over the switch lifetime because it is near the aperture that cathode erosion is most important. The choice of the cathode material (and hence the value of the secondary electron emission coefficient) is dictated by lifetime considerations, i.e., by which materials are most resistant to erosion. The applied voltage is determined by the application and the circuit, and we expect that the optimum geometry for rapid breakdown with low jitter will be different for each voltage with the optimum cathode aperture diameter and plate thickness increasing with increasing voltage in order to avoid the erratic

breakdown behavior associated with peaks in the prebreakdown current wave form. Thus consideration of the phases of pseudospark operation other than the breakdown phase will also influence the optimum switch design.

The breakdown phase of pseudospark discharge operation is now fairly well understood and the outstanding questions which now must be addressed in order to fully exploit this interesting discharge mode relate to the transition to the high current, "superemissive" phase.²⁶⁻²⁸

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