PULSED VACUUM BREAKDOWN MEASUREMENTS WITH A 1-MV GENERATOR *

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Abstract

Measurements of the breakdown field of vacuum gaps have been made with a 1-MV, 50-ns test stand [1]. The first set of experiments was performed with planar, bare metal electrodes [2]. This geometry had an enhanced anode edge that affected measurements. Here, we report on a new set of measurements using anodes without field enhancement. Diagnostics include current and voltage probes, x-ray detector, x-ray pinhole camera and a fast framing camera. The results of these measurements give new insight into the cause of anode interactions that reduce the breakdown field with large gaps.

I. INTRODUCTION

There are several emission processes that we wish to study, but we are beginning with explosive electron emission. This is the mechanism usually responsible for cold cathode emission in high-power cross-field vacuum devices. Explosive electron emission has been studied for decades, especially for the case of DC. The original theory behind explosive electron emission is that emission begins at some threshold cathode field when Fowler-Nordheim tunneling of electrons from a field enhanced defect on the cathode surface into vacuum leads to heating and eventually vaporization and plasma formation. In the DC or long pulse case, this plasma can bridge the AK gap and result in gap closure with a very easily detected, low impedance state. However, with nanosecond pulses and AK gaps around a centimeter or more, gap closure is not possible. So, there is a difference in the way breakdown can be defined between the long pulse and short pulse cases, being much simpler in the long pulse case. Also, in the DC case conditioning can be used to remove defects in the cathode surface by limiting the current across the AK gap, thereby preventing damage while burning off the defect. But, conditioning is difficult and less used in high-power cross field devices.

For high-power, cross field devices we generally have areas of cathode surface that we want to emit uniformly and at a low threshold field and other areas where we do not want any emission. The general model for explosive emission consists of a threshold cathode field for the initial formation of plasma, then a turn on time for plasma to cover the surface enough to have space charge limited emission with essentially zero electric field at the cathode surface. This plasma then expands into the AK gap at approximately 2 cm/μs, gradually reducing the AK gap.

In the DC and long pulse case it is observed that, with AK gaps greater than ~1 mm, there are anode interactions that reduce the breakdown field. The general idea is that macroparticles are pulled from the anode and strike the cathode with enough energy to create a plasma. This mechanism is termed the "total voltage effect" because it seemed that it was mainly the voltage and not the electric field that caused breakdown [3]. The actual voltage dependence is found to fall with approximately the square root of the AK gap, explained by considering the area of the particle.

It was assumed that for fast pulses, ~50 ns, that anode particles would not have time to cross the AK gap and so the total voltage effect would not be observed. However, some of our observations combined with recent measurements by others bring this into question. Johnson, et al., has observed a breakdown dependence consistent with the total voltage effect with slightly longer, 160 ns pulses, and a similar experimental setup [4]. They also measured large breakdown fields at the smallest gaps, much larger than we usually assume in high-power cross-field devices, as shown in Fig. 1. The Pulse Power Formulary [5], for example, lists the breakdown field for 100 ns pulses as 290 kV/cm for aluminum (plotted in Fig.1) and 300 kV/cm for stainless steel. The formulary does mention that a voltage dependence has been observed, but states that it is "more pronounced" with DC breakdown.

The two plots in Fig. 1 appear as though they could be connected as one continuous curve, but the understanding

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behind them is very different. The understanding for the small gap case is that the breakdown field is being reduced with larger gaps due to particle bombardment. For the large gap case it is understood that only the field at the cathode causes breakdown. Also, it is unlikely that large particles could cross the AK gap in the 50-100 ns timescale. Another discrepancy in understanding is the low field for the large gap case. If there are truly no anode interactions, it seems that the field should be the same as it is for the smallest of the small gap cases, i.e., several times higher. With these and planned measurements, we aim to better our understanding of the role of anode interactions with larger gaps.

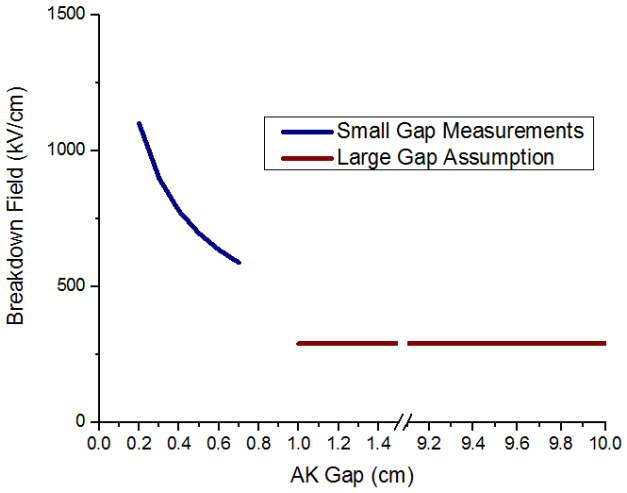


Figure 1. Breakdown field measurement trend for small gaps and 160 ns pulse (blue) and a constant value assumed ~290 kV/cm for large gaps and <100 ns pulse (red).

II. EXPERIMENTAL SETUP

These breakdown/turn-on measurements are being made with a modified 1-MV PulseRad flash x-ray source, as previously described [1]. There has been a change in the anode geometry for these most recent results. The original electrode geometry was a one inch diameter, flat anode disk facing a three inch diameter cathode disk (the largest size that easily fits in our SEM microscope). Breakdown measurements are usually made with specially shaped anodes and cathodes to reduce field enhancement at their edges. The special shapes are usually designed for a specific AK gap. But, our geometry allowed for low cost electrodes with cathode fields that didn't vary too much with AK gap. The flat cathode allowed clear x-ray pinhole images of the anode to be made, viewed through the cathode. It was originally believed that the highly enhanced edge of the anode would not affect turn on. However, the x-ray pinhole camera images of the flat anodes consistently showed the first x-ray emissions coming from the edge of the anode [2]. It appears that some anode particles are emitted from the enhanced anode edge. These particles then strike the cathode and release secondary electrons which then come back to the side of the anode. Rounding the edge of the anode with a one eighth inch radius so that the field enhancement at the edge was reduced to a factor of less than two times that of the center of the anode did seem to increase the field needed for this emission, however the breakdown locations on the cathode then preferred the radius of the anode, suggesting that anode particles were causing breakdown. To reduce the role of anode interactions, the anode geometry was changed to a uniform field, Chang profile [6]. This eliminated the low field emission from the edge of the anode and breakdowns no longer prefer the edge of the anode.

III. BREAKDOWN TEST RESULTS

Twenty cathodes have been tested so far, fourteen with the original, flat anodes and six with the Chang profile anodes. The AK gap was 8.8 mm for all results shown here. This paper will focus mostly on the results with the Chang profile anodes. The anodes and cathode materials were varied between different combinations of 6061 aluminum and 304 stainless steel. The cathode surface finish was varied between a #32 and a #64 machined finish. The actual finish was measured with a surface roughness tester. One cathode had a #12 mechanically polished surface.

The test procedure was to repeatedly pulse the AK gap with about 15 minutes between shots while raising the voltage. The test was usually ended when cathode damage was observed. The five machined cathodes all behaved in a similar way, with no obvious dependence on surface material or finish, consistent with earlier tests with the flat anodes. The typical progression for one anode and cathode set is shown in Fig. 2. Fig. 2a shows the typical trace before turn on where the cathode current is only due to capacitive displacement current between the electrodes. Fig. 2b shows the first sign of emission where the current starts slowly, after the peak voltage, and only reaches modest levels. As the voltage is further increased, a transition to a higher current occurs that starts early and is accompanied by visible damage to the cathode.

The gated optical imager was used to take 6-ns exposure time photos toward the middle and also the end of the pulse. The camera is at an angle to the cathode axis and so it appears as an oval in the pre-shot photo of Fig. 3a. Nearly the entire cathode surface is visible. These images show that the first sign of turn on is accompanied by a small number (between 1 and 4) of emission sites. Fig. 3b shows this case for the corresponding current and voltage traces of Fig. 2b with a single emission site. As the voltage is raised on successive shots there continues to be only a small number of emission sites until a sharp increase in current that begins earlier in the pulse is accompanied by an increased number of emission sites, as

shown in Fig. 3c, which corresponds to the current and voltage traces of Fig. 2c.

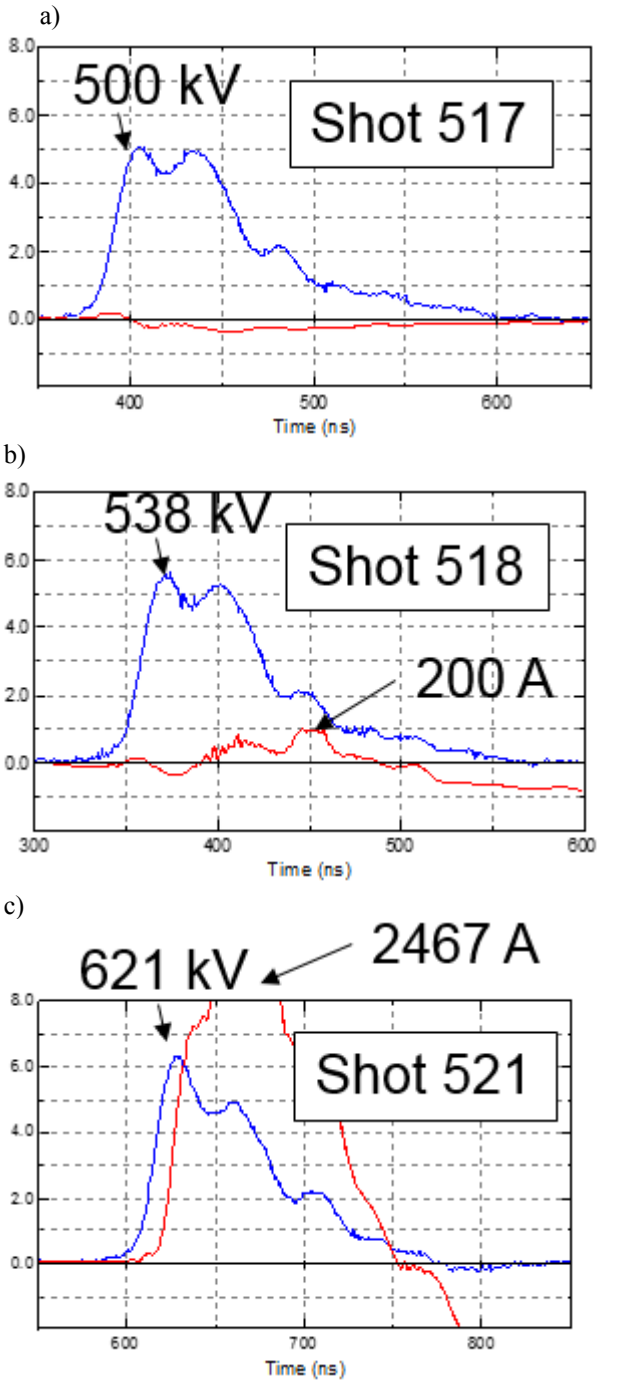


Figure 2. Example voltage (blue) and current (red) pulse traces (all with same scale) during a test for the case a) no emission, only displacement current; b) the first sign of emission; and c) after cathode damage

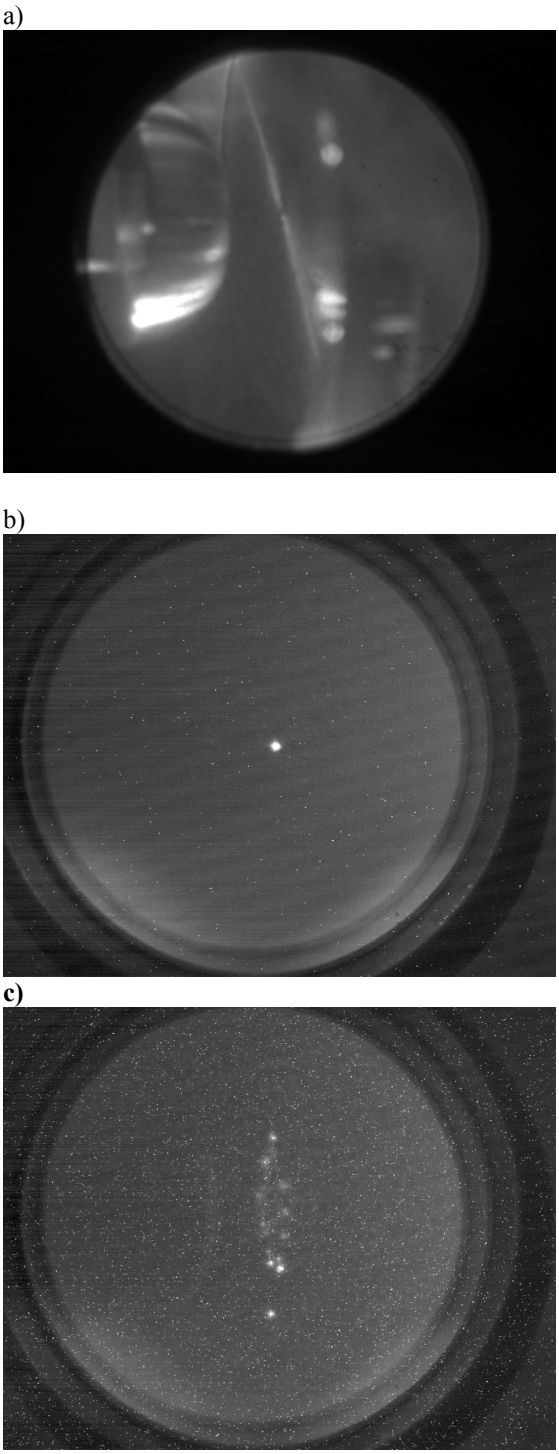


Figure 3. Gated optical imager photos of a) the setup with anode to the left and cathode appearing as an oval in center, b) a single emission site at initial turn on, c) the appearance of multiple cathode emission sites.

The actual cause for the initial turn on is not yet clear. The turn-on field appears to be the same for both the #32 and #64 finish cathodes, suggesting that field enhancement at the cathode surface is not the main contributor to the turn on field. The result with rounded flat anodes suggests that it may be due to bombardment of anode particles. This may also explain why this initial turn on occurs late in the pulse. Surprisingly, the one test with a #12, polished cathode surface showed low field turn on at multiple sites. These sites seem to condition themselves away as the voltage was increased until damage was finally observed. It is hypothesized that inclusions of the polishing material are responsible for this behavior. A summary of the first five tests with Chang profile anodes, cathodes #15 through #19, are shown in Fig. 4 where the peak electric field and peak currents are plotted for each shot. These tests were stopped when cathode damage was first observed, except in the case of cathode #17, where we kept firing at the same voltage for several shots and the current increased with each successive shot.

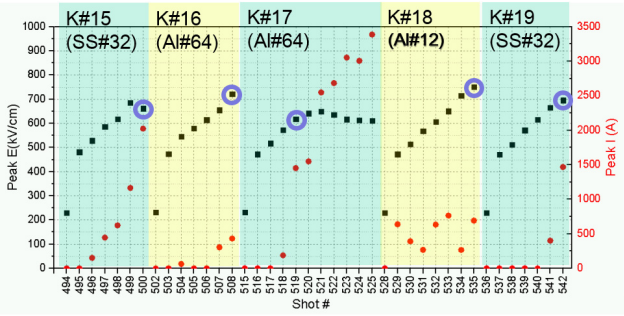
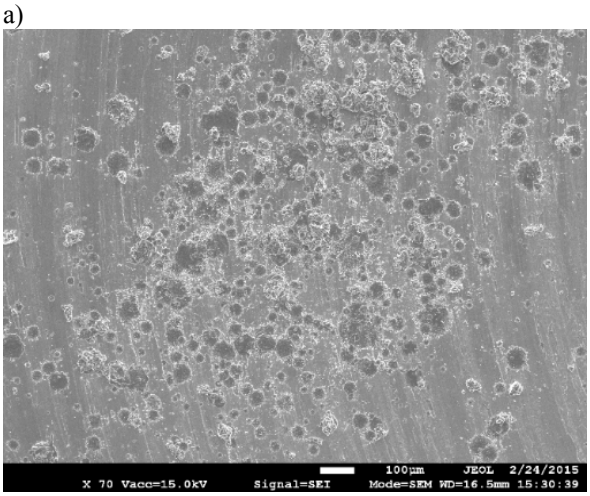


Figure 4. Test summary for first five Chang profile cathodes showing the peak electric field (black squares) increasing on each successive shot until damage occurs (indicated by purple circles). The peak current is also shown for each shot (red circles).

We have determined that anode melting is responsible for the sharp increase in current as the voltage is further raised. SEM images of anode and cathode surfaces clearly show erosion of material from the anode and the splatter of this material on the cathode. This is most apparent for stainless steel cathodes. An example of this is shown in Fig.5 where the test was stopped at the first sign of visible cathode damage on cathode #19 and the electrodes taken to the SEM. There is a gouge in the aluminum anode material with deep cracks inside the gouge. The cathode shows splatter patterns that look as though drops of liquid anode material were splattered across the surface. Since the cathodes were situated above the anodes, it seems that the electric field must have launched the liquid anode towards the cathode. This also shows that a much enhanced surface will turn on early in the pulse, at low field from multiple emission sites. Anode interactions probably do not play a role in this turn on. But, this surface is very much rougher than the underlying #32 finish.

a)



b)

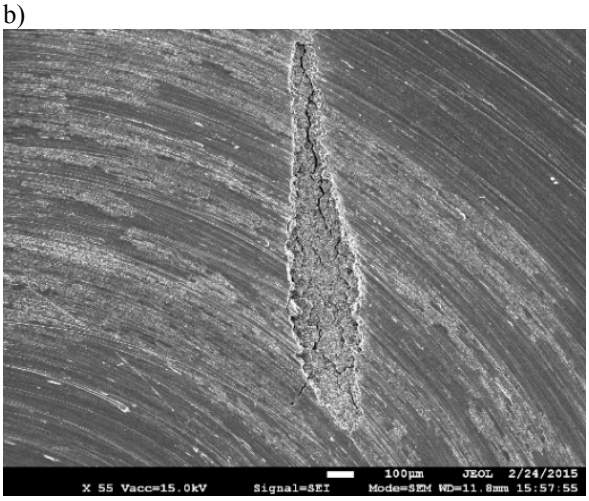


Figure 5. SEM images of a) the splatter on cathode surface and b) the gouge in the anode surface when breakdown test stopped at the first sign of cathode damage.

It is interesting to note that we did not observe a noticeable difference between aluminum and stainless steel anodes. Since the melting point of stainless steel is much higher, one might expect it to have a higher damage threshold, if surface melting is the responsible mechanism. However, a series of ITS (Integrated Tiger Series) calculations show almost no difference in the temperature rise, as a percentage of melting point, between stainless steel and aluminum, as shown in Fig. 6, for the case of a 20-ns, 250-A electron beam (0.5 µC) deposited over an area of 1 cm^2. This is due to stainless steel absorbing more of the electrons energy per unit depth. Tungsten and copper are also plotted for comparison and do not display much different results.

Another interesting feature of Fig. 6 is that lower energy electrons melt the anode surface more easily than

higher energy electrons. This, combined with the fact that the current is initially rising slowly during the current pulse at first (as in Fig.2b), suggests that melting is occurring at the very end of the voltage pulse. This also may imply some insensitivity to the width of the voltage pulse.

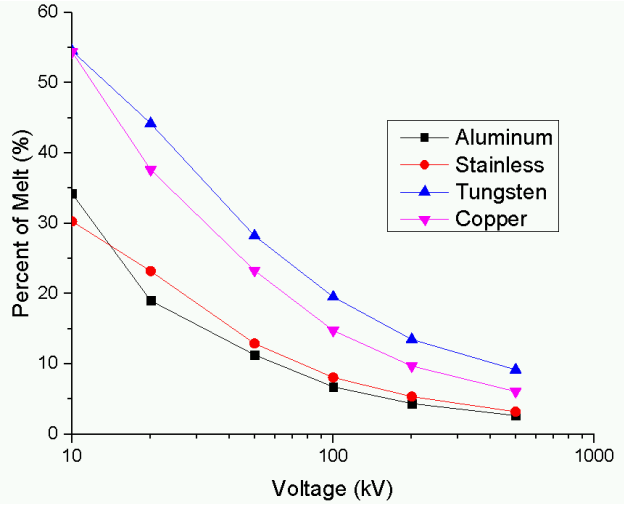


Figure 6. ITS calculated temperature rise, as a percentage of melting point, of various anode materials for 0.5 μC of charge deposited over 1 cm^2 as a function of applied voltage.

Measured current and voltage traces from a shot where there was a single emission site that caused the first cathode damage were used to calculate the temperature as a function of time during the pulse. The x-ray pinhole image of the anode showed the electron deposition from the single emission site was over an area of about 0.4 cm^2. However, it should be noted that this area may be a function of time and x-ray emission is stronger at higher voltage whereas temperature rise is higher at lower voltage. It is also possible that ion emission, which occurs before melting, may change the electron deposition profile. The current and voltage traces together with the area from the pinhole image and the calculation shown in Fig.6, show that anode melting is possible. This exercise did, however, highlight the need for a hardware integrated current monitor. The current signals used here were software integrated and have some uncertainty at the end of the pulse, where the most heating appears to be happening.

In Fig. 7, we show the average field for the first sign of turn on for the five Chang anodes tests described earlier as a red oval along with black oval showing the average field where damage is first observed overlaid with the shorter gap, longer pulse, measurements and larger gap assumptions from Fig. 1. It is not completely clear which of these points is best to use when comparing with the breakdown field with smaller gaps. It could be that the initial turn on, which is only from a small number of emission sites, does not create enough plasma soon enough to be counted as a breakdown. Regardless, there is not a large difference between the field required for first turn on and the field required for damage. Both of these fields could be considered consistent with the smaller gap breakdown measurements with 160-ns pulses where breakdown was attributed to anode interactions. It may be that this shorter, 50-ns pulse gives a slightly higher breakdown field. On the other hand, these fields are only about a factor of two higher than is often assumed for large gaps, without anode interactions.

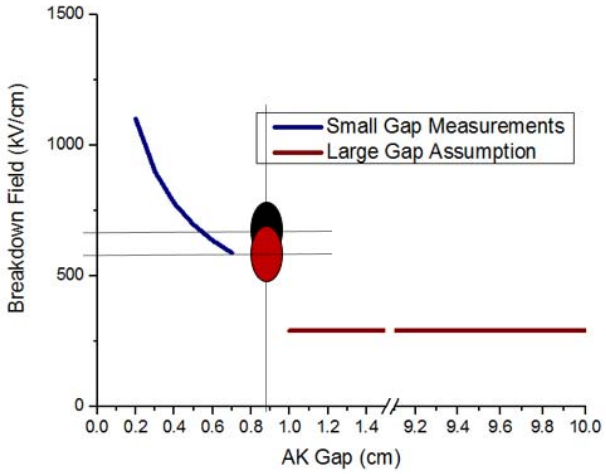


Figure 7. Overlay of average field for initial turn on (red oval) and first sign of damage (black oval) onto graph of Fig. 1.

IV. SUMMARY

We report on breakdown measurements with 8.8-mm AK gaps with a 50-ns pulse width. We see two different types of turn on, an initial turn on of a small number of sites with low current that begins after peak voltage and rises slowly and then a transition to a larger current from multiple sites that starts early in time. It appears possible that anode interactions are responsible for the initial turn on of machined surfaces given the results with anodes with a field enhanced edge and the seeming lack of dependence on finish roughness.

The transition to high current has been attributed to melting of the anode and subsequent spraying of anode material on the cathode, resulting in highly field enhanced sites on the cathode. ITS calculations show that melting is possible from the current and voltage traces of a shot where damage is first observed together with the deposition area from the x-ray pinhole image of the anode. The ITS calculations also show little dependence on anode material with respect to the current required to melt the surface, consistent with the measurements.

V. FUTURE WORK

The next step in this work is to repeat the measurements with 5.6 and 13.5 mm AK gaps to look for gap dependence of the initial turn field. This will help us determine if anode interactions are responsible for the initial turn on. Also, we will experiment with various anode and cathode coatings aimed to increase breakdown field or increase uniformity of emission. We will also integrate a 1-m spectrometer into the test setup for optical diagnostics.

VI. REFERENCES

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