EFFECT OF AN EXTERNALLY APPLIED MAGNETIC FIELD ON THE BREAKDOWN RATE IN ULTRA-HIGH VACUUM MEASURED IN THE ‘LARGE ELECTRODE SYSTEM’ AT CERN

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Abstract

The influence of external magnetic fields of up to 0.5 T on the breakdown rate between copper electrodes, subjected to pulsed DC voltages in ultra-high vacuum, is investigated. Experiments were performed with the magnetic field oriented either parallel or perpendicular to the cathode surface. A better understanding of the effect the magnetic field has on the breakdown rate in ultra-high vacuum could help inform the geometric design of RF structures for projects such as CLIC, leading to higher accelerating gradients.
Effect of an externally applied magnetic field on the breakdown rate in ultra-high vacuum measured in the ‘Large Electrode System’ at CERN

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I. INTRODUCTION

CLIC requires accelerating structures which operate at an average loaded accelerating gradient of 100 MV/m and a breakdown rate of only $3 \cdot 10^{-7}$ breakdowns per pulse per meter. This is a challenging target which has necessitated a dedicated research program into breakdown in RF accelerating structures. However, RF accelerating structures are expensive and time consuming to build and test; a parallel research program which studies breakdowns in DC systems allows experiments to be performed quickly, cheaply and in a simpler environment than exists in an RF structure \cite{1} \cite{2}.

The DC systems used at CERN consist of an anode and cathode in ultra-high vacuum separated by a few tens of $\mu$m. To make sure the results obtained from the DC experiments are as applicable as possible to the RF case the electrodes are made from copper and undergo a similar heat treatment to the RF structures. The powering circuit is also designed such that the stored energy available during a breakdown is similar to that in a CLIC accelerating structure operating at the nominal CLIC gradient.

One of the major differences between breakdowns occurring in DC and RF systems is the magnetic fields which are present. Prior to breakdown, DC systems contain only negligibly small magnetic fields due to the Earth’s magnetic field and as a result of the field emission current. RF cavities however always contain a large RF magnetic field. The peak surface magnetic field in CLIC accelerating structures is $\approx 400$ kA/m \cite{3} \cite{4} or 0.5 T which is the same as the strength of the magnetic field used in the experiments described in this report.

The magnetic field which is present in RF structures is known to have a significant effect on the breakdown rate which can be obtained. For example, the field quantities $S_c$ and $P\lambda/C$ which depend on the magnetic field, have been shown to be more strongly correlated to the achievable accelerating gradient for a given breakdown rate than the peak surface electric field \cite{5}. As a consequence, the geometry of CLIC accelerating structures is now designed to keep these quantities to a minimum. Recent studies of the breakdown rate dependence on structure geometry have also shown evidence that an RF magnetic field has an effect on the breakdown rate \cite{6} \cite{7}.

This effect of the magnetic field on the breakdown rate is not peculiar to CLIC accelerating structures; for instance, in \cite{8} and \cite{9} an externally applied DC magnetic field was...
observed to effect the breakdown rate in RF accelerating structures operating at frequencies much lower than those used for CLIC.

Whilst the effect magnetic fields have on the breakdown rate can be studied in RF accelerating structures it is made more difficult by the complex time and spatial dependence of the RF magnetic field. By contrast, in a DC system no such RF fields exist and therefore the applied electric and magnetic fields can be varied independently of one another.

II. EXPERIMENTAL APPARATUS

In the experiments described in this report breakdowns occurred between two copper electrodes in ultra-high (≈ 10⁻⁹ mbar) vacuum. The electrodes were installed in the ‘Large Electrode System’ (LES) and were powered by the ‘High Rep Rate’ (HRR) Circuit. Detailed descriptions of this equipment can also be found in [10] and [11]. A high voltage probe and current transformer were used to detect breakdowns when they occurred.

A. Large Electrode System

The LES is a compact vacuum system containing two electrodes each with a high field surface area of 2800 mm². Figure 1 shows a 3D rendering of the LES (1a), a photograph of the LES (1b) and a photograph and optical microscope images of the electrode surface (1c). A ceramic ring is used to separate these electrodes by the desired distance. Since the gap between the electrodes is determined by the ceramic ring, three rings of different thickness are available so that the gap can be set to a nominal distance of either 20 µm, 40 µm or 60 µm. The exact distance between the electrodes may vary due to machining errors during the fabrication of the electrodes and the distance is therefore tested optically to determine the true gap distance and to ensure the electrodes are parallel to one another.

The LES was designed to enable the magnetic field experiments described in this report to be performed. It is compact enough to fit within the ≈ 30 cm aperture of the magnet. The LES can be stood either on its three legs or rested on its side, this allows the magnetic field to be oriented both perpendicular and parallel to the plane of the electrodes. The LES was made entirely from very weakly magnetic materials. The type of steel used was ‘316LN’ which has a very low magnetic permeability of ≈ 1.003 [12], this ensures the magnetisation of the materials does not significantly effect the strength of the magnetic field present at the surface and between the electrodes. With an approximate mass of only 30 kg the system could also be inserted and oriented in the magnet with relative ease.

B. High Rep Rate Circuit

The HRR circuit is used to provide high voltage pulses of up to 12 kV to the LES. It uses matched impedances throughout, stores the energy for breakdown on a 200 m long co-axial cable and uses a high power solid state MOS-FET switch to apply the pulses at up to 1 kHz. The voltage rise time of the pulse can be very fast at ≈ 10 ns although it is more of the order of ≈ 200 ns when electrodes with a very large capacitance are used as is the case in this paper. The applied voltage pulse then has a flat top for 3 µs before the switch is opened and the voltage will begin decaying towards zero with a time constant of between approximately 100 µs and 500 µs, depending on the gap size. As the time constant of the decay is much longer than 3 µs the 90% to 90% time is significantly longer than the 3 µs for which the switch is open.

The repetition rate which is achievable in practice is limited by the maximum power dissipation of certain components in the circuit. The power dissipation is influenced by the capacitance which is present after the switch and the voltage at which the circuit is operated. As the HRR circuit was not originally designed to be operated with the large capacitance presented by the LES it is usually necessary to run the HRR circuit at a repetition rate of less than 1 kHz.

The maximum allowed repetition rate is automatically calculated and set by the circuits control software. This results in experiments with different voltages or gap sizes being run with different repetition rates. However, it is not expected that the repetition rate will influence the breakdown rate and, indeed, experiments presented in [10] have found no correlation between them.

III. EXPERIMENTAL PROCEDURE

The effect of the magnetic field on the breakdown rate was tested in the LES with an electrode gap of 15 µm and 60 µm for a magnetic field both parallel and perpendicular to the surface of the electrodes. Rather than gradually varying the magnetic field between zero and the maximum possible field strength to study the effect on the breakdown
rate it was decided to first determine whether any effect on the breakdown rate at all could be detected by running the system either when the magnet was fully off or when it was set to the highest possible field permitted by the power supply of the magnet, which was approximately 0.54 T.

Ideally, in order to detect a potentially small change in the breakdown rate due to the magnetic field, the breakdown rate would be measured over a long period of time. However, the electrodes of the LES were known to condition over time.

Therefore, to prevent the conditioning of the electrodes from masking the effect of the magnetic field on the breakdown rate, the breakdown rate was measured over relatively brief periods of time before the field of the magnet was changed and a new breakdown rate measurement was started. The experimental procedure was as follows:

- The LES was first installed in the centre of the magnet.
- With the magnet initially off the electric field was varied until a breakdown rate of approximately $10^{-4}$ was obtained.
- A set number of breakdowns usually 20 or 30 were recorded and the breakdown rate calculated.
- After the set number of breakdowns had been reached the switch was stopped from pulsing.
- The magnet was then switched on and ramped up to full power over the course of a couple of minutes. A faster ramping time was not possible due to the limited current of the magnet power supply and the large inductance of the magnet.
- Once the magnet had reached the maximum field which could be obtained of 0.54 T, the switch was allowed to continue pulsing at the same voltage as previously.
- Once the set number of breakdowns had been recorded with the magnet switched on, so that the breakdown rate over this period could be calculated, the switch was again stopped.
- This process was then repeated as often as possible in the time available.

The main experimental conditions are summarised in tab. I. In order to gather data as fast as possible, the repetition rate was set to the maximum value allowed without exceeding the power limitations of the HRR circuit. This value depends on both the applied voltage and inter-electrode gap size.

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2Here conditioning refers to the breakdown phenomena where the breakdown rate between a pair of electrodes decreases with with successive pulses despite all the other conditions such as electric field and pulse length remaining unchanged.
### Table 1: Experimental conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure [mbar]</td>
<td>( \approx 10^{-9} )</td>
</tr>
<tr>
<td>Pulse Rep. Rate [Hz]</td>
<td>400 - 800</td>
</tr>
<tr>
<td>Electrode Material</td>
<td>Copper</td>
</tr>
</tbody>
</table>

#### IV. THEORETICAL BACKGROUND

Several models have been proposed to explain the increase in breakdown rate associated with the presence of a strong magnetic field. Here four such models are briefly reviewed and their applicability to the conditions of the experimental setup described in Sec. II is examined.

##### A. Heating of field emitting tips

In [5] the influence on the breakdown rate of the magnetic component of the RF field in accelerating structures was incorporated by considering the power-flow along the surface of the accelerating structure. It was argued that the power flow can provide energy to the field emission process at potential breakdown sites leading to increased heating and an increased likelihood of breakdown occurring. These considerations lead to the development of the ‘modified Poynting vector’:

\[
S_c = \Re(\vec{S}) + g_c \cdot \Im(\vec{S})
\]  

(1)

where \( \vec{S} \) is the Poynting vector and \( g_c \) is a weighting factor equal to \( \approx \frac{1}{3} \) introduced to account for the difference in efficiency between the active and reactive parts of the power flow in providing energy to the field emission process.

The square root of the ‘modified Poynting vector’ (which is a quantity linear in field) has a much smaller spread in value for different accelerating structures operating at the same breakdown rate and pulse length than does the peak surface field. This indicates it is a much better predictor of structure performance and goes some way towards validating the theory upon which it is based.

In the experiments described in Sec. II static homogeneous electric and magnetic fields exist over the area where breakdown can take place. With a static electric and magnetic fields, as there is no longer an imaginary component of \( \vec{S} \) the expression for \( S_c \) becomes simply:

\[
S_c = |\vec{S}|
\]  

(2)

However, considering the expression:

\[
P = \int_s \vec{S} \cdot d\vec{s}
\]  

(3)

shows there is no net power flow due to these fields into a volume surrounding a potential breakdown site. Therefore we do not expect the existence of a static magnetic field will effect the energy provided to the field emission process as described in [5] for RF fields. We believe therefore that any effect on the breakdown rate due to an applied static magnetic field will be due to other effects.

##### B. RF Pulsed Heating

When an RF pulse is passed through an accelerating cavity the changing magnetic fields induce a current in the structures surface leading to ohmic heating. This process is known as pulsed surface heating and the magnitude of the temperature change at the surface is given by eqn. 4:

\[
\Delta T = \left( \frac{R_s}{K} \right) \left( \frac{D T_p}{\pi} \right)^{1/2} \left( \frac{G}{Z_H} \right)^2
\]  

(4)

where \( \Delta T \) is the temperature change, \( R_s \) is the surface resistance, \( K \) is the thermal conductivity, \( D \) is the thermal diffusivity, \( T_p \) is the pulse length, \( G \) is the accelerating gradient and \( Z_H \) is an impedance defined as the ration between the accelerating gradient and the maximum surface magnetic field [13].

In [14] and [15] it is suggested that the principle cause of the increase in breakdown rate in the presence of RF magnetic fields is due to the fatigue caused by pulsed surface heating over many RF cycles. In [14] an RF pillbox cavity was designed in which two degenerate modes could be simultaneously excited allowing the ratio of peak surface electric and magnetic fields to be varied. This allowed the pulse surface heating to be increased whilst keeping the maximum surface electric field constant. Equation 5 is a proposed relationship between the average number of pulses between breakdowns and the magnitude of the pulse surface heating derived in [16] from thermodynamic considerations.

\[
N = \frac{C}{e^{kT^2} - 1}
\]  

(5)

\( N \) is the average number of pulses between breakdowns, \( T \) is the magnitude of the pulse surface temperature rise and \( C \) and \( k \) are unknown constants to be determined experimentally. Equation 5 fits the data obtained in [14].
although there were only four data points and two fitting parameters.

A correlation between breakdown rate and maximum pulsed surface heating has also been shown in [17] for several structures. In itself, this is unsurprising as from eqn. [4] it can be seen that the maximum pulsed surface heating is proportional to the square of the average accelerating gradient, and the accelerating gradient is well known to be correlated to the breakdown rate. However for the three structures tested in [17] the spread in the magnitude of the pulse surface heating for a given breakdown rate was smaller than the spread in the electric field, suggesting the breakdown rate is more strongly correlated to the magnitude of the pulsed surface heating.

With a static magnetic field there is no pulsed heating and therefore the experiments presented in this paper will be insensitive to this effect. Any increase in breakdown rate with magnetic field therefore must be due to another effect and therefore, should an increase in the breakdown rate comparable to that in [14] be observed, it would call into question whether it is possible that pulsed surface heating really does affect the breakdown rate as was proposed.

C. Torque on field emitting tips

It has previously been suggested [8] [9] that breakdowns between materials in vacuum occur when the intrinsic tensile strength of the material is exceeded by the force due to the electric field at field emitting tips.

This force is given as:

$$\frac{\varepsilon_0 (\beta E)^2}{2}$$

where $\beta$ is the geometric field enhancement factor of the tip and $E$ is the global surface electric field. The breakdown condition for a given field emitting tip without magnetic field would therefore be:

$$\frac{\varepsilon_0 (\beta E)^2}{2} > \sigma_{Cu}$$

where $\sigma_{Cu}$ is the tensile strength of copper.

Under the applied electric field electrons are emitted from the tip creating a field emission current. This current together with an applied magnetic field produces an additional torque $T$ on the field emitting tip due to the Hall effect equal to:

$$T = \vec{I} \cdot \vec{B} \sin(\theta)$$

where $\vec{I}$ is the field emission current $\vec{B}$ is the magnetic field and $\theta$ is the angle between them. The criteria for breakdown of a given field emitting tip then becomes:

$$\frac{\varepsilon_0 (\beta E)^2}{2} + \sigma_B > \sigma_{Cu}$$

where $\sigma_B$ is related to the additional perpendicular stress on the field emitting tip due to the torque from the magnetic field and field emission current.

All the same arguments used in [9] to explain the decrease in the maximum surface field due to an applied static magnetic field are also applicable to the experiments described in Sec. II. The experiments described in Sec. II investigated the effect of a magnetic field oriented parallel to the electrode surface as well as the effect of a magnetic field oriented perpendicular to the electrode surface as in the case considered explicitly in [9]. Even assuming a reasonably sharp cone angle for a field emitter (necessary for the high $\beta$ values on which this theory relies), one may reasonably expect the effect on the surface field to be greater with a magnetic field oriented parallel to the surface as the angle $\theta$ in eqn. [8] between the current and magnetic field will be larger.

In [9] an 805 MHz copper pill box cavity was operated at a maximum field of between 40 and 60 MV without breakdown. From fig. 2 in [9] we can see that an applied DC magnetic field of $\approx 0.44 T$ reduced the maximum achievable accelerating gradient to between $\approx 27$ and $\approx 33$ MV/m depending on the configuration of the magnet.

If this model is correct and given the results outlined in the paragraph above, the most conservative prediction of the maximum surface electric field achievable with a static magnetic field of $0.5 T$, $E_{Max}^{B=0.5}$, for the experiments described in Sec. II would be:

$$E_{Max}^{B=0.5} = r \cdot E_{Max}^{B=0}$$

where $E_{Max}^{B=0}$ is the maximum achievable surface electric field with no applied magnetic field and the ratio:

$$r \approx \frac{33}{40}$$

is the ratio for the smallest change in electric field observed in the experiments described in [9].

The dependency of the breakdown rate on the electric field has been explicitly measured in the LES [10] (the system used to make the experiments described in Sec. II) and found to be well fitted to the following law commonly used for accelerating structures [5] [18].
where \( n \) is an experimentally fitted parameter measured to be \( \approx 40 \) [10]. Therefore, given also that \( E_{\text{Max}}_{B=0} \) and \( E_{\text{Max}}_{B=0.5} \) are the smallest fields corresponding to a breakdown rate of \( \approx 1 \) with and without a 0.5 T respectively, eqn. [12] may be written as:

\[
BDR_{B=0} = \left( \frac{E}{E_{\text{Max}}_{B=0}} \right)^{40}
\]

(13)

in the absence of a magnetic field and:

\[
BDR_{B=0.5} = \left( \frac{E}{E_{\text{Max}}_{B=0.5}} \right)^{40}
\]

(14)

with a 0.5 T field present.

Combining eqns. [10][11][13] and [14] allows the following estimate of \( BDR_{B=0.5} \) to be made from \( BDR_{B=0} \) when both have been measured at the same electric field:

\[
BDR_{B=0.5} \approx \left( \frac{40}{33} \right)^{40} BDR_{B=0}
\]

(15)

\[
BDR_{B=0.5} \approx 2 \cdot 10^2 BDR_{B=0}
\]

(16)

This was the most conservative estimate possible and one would expect the actual difference to be greater than this especially for a magnetic field aligned parallel to the electrode surface.

D. Effect due to changes of field emitted electron trajectories

Table 2: Estimated electron deflections due to parallel B field in LES

<table>
<thead>
<tr>
<th>Gap (µm)</th>
<th>E Field (MV/m)</th>
<th>B Field (T)</th>
<th>Max. Deflection (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>144</td>
<td>0.5</td>
<td>0.48</td>
</tr>
<tr>
<td>60</td>
<td>88</td>
<td>0.5</td>
<td>4.9</td>
</tr>
</tbody>
</table>

In [19] an alternative to the ‘twist theory’ [8][9] outlined in the previous section was introduced to explain the effect of a static magnetic field on the breakdown rate in accelerating cavities.

In this theory magnetic field lines perpendicular to the surface cause electrons emitted from a field emission site to be focussed onto a smaller area than they would be in the absence of magnetic field. It is argued that the area impacted by these electrons can become damaged leading to sharp surface features with a high \( \beta \) and as such, when this damage occurs in areas with a high electric field strength breakdown can more readily occur.

It has also been suggested [20] that magnetic fields parallel to the surface on which the field emission sites are located could have the opposite effect and reduce the breakdown rate by returning the field emitted electrons to the surface from which they originated a process termed ‘Magnetic Insulation’.

It was reported in [21] that unlike the effect seen in evacuated accelerating cavities, the breakdown rate in gas filled rf accelerating structures does not depend on the applied magnetic field. A gas filled cavity would reduce the mean free path of electrons and counteract the focussing effect of the magnetic field. This is therefore consistent with the theory that the increase in breakdown rate with magnetic field in evacuated cavities is a result of electron focussing.

The geometry in the LES is different to that described in [19] and [21] but similar arguments apply; a magnetic field perpendicular to the surface will act to focus the field emitted electrons from the cathode onto a smaller area on the anode. The simulations necessary to estimate the extent of the change in the area of the anode bombarded by field emission electrons under the influence of a magnetic
field perpendicular to the surface have not been performed. Therefore whilst an observed increase in the breakdown rate with a magnetic field perpendicular to the surface would support the theory described in this section and an observed decrease would contradict the theory, it will not be possible to determine if the lack of an observed effect contradicts the theory or whether the change in surface area is simply too small to produce a noticeable change in the breakdown rate.

It is easier to provide an estimate for the effect on the electron trajectory of a magnetic field parallel to the surface as the effect of space charge and the distribution of initial emission angles can be neglected for a first order approximation. Figure 2 shows the expected trajectory of pre-breakdown field emitted electrons for two different electrode gap sizes and applied electric fields. Table 2 shows the estimated size of electron deflections under the influence of a magnetic field parallel to the cathode surface in the LES. It should be noted that in both cases the electrode gap is too small and the electric field is too high for the electrons to be returned to the cathode. However the position they impinge the anode is shifted and some defocusing could be expected due to the increase in path length and shallower angle of incidence. According to the theory this could lead to a decrease in the breakdown rate but no attempt has been made to estimate the expected size of this effect and whether it would be detectable.

V. RESULTS

Two types of results were obtained from these experiments. The first were measurements of the breakdown rate for different inter-electrode gap sizes and applied DC magnetic field. These were used to try and detect any changes in the breakdown rate caused by the magnetic field. The second type of results were electron microscope images of the electrodes after they had been tested.

Figure 3 shows a plot of the breakdown rate against the electric field measured in the LES with a gap size of 15 µm. All these measurements were made without a magnetic field. The order in which the measurements were made are the red points from right to left followed by the blue points from left to right. The fact that the measured breakdown rates shown in blue are all lower than those shown in red is evidence of ‘conditioning’, a phenomenon where the breakdown rate decreases over time. It was for this reason that the measured breakdown rates shown in figs. 4–7 were taken over only a relatively short period of time before the magnet was switched either on or off and another breakdown rate measurement was started. Without this methodology the conditioning effect would stand a greater chance of masking any effect due to the magnetic field.

It is important to note that estimating an error on the breakdown rate from some measure of the deviation in the number of pulses between successive breakdowns is not a straightforward problem. This is because the breakdowns are not independent and therefore the central limit theorem is not applicable. In addition, the degree of dependence one breakdown has on another is known to depend on the breakdown rate. In this paper no attempt is made to tackle this problem. The error bars shown on all plots are from the estimated maximum unwanted deviation of the inter-electrode gap size which was ≈ 1 µm. This uncertainty will cause an uncertainty in the electric field and it is this uncertainty which is shown in the error bars of the plots by making use of the measured breakdown rate dependence on the electric field.

A. Breakdown Rate Measurements

The breakdown rate was recorded with a gap size of either 15 µm or 60 µm and with the magnetic field oriented either perpendicular or parallel to the electrodes surfaces thus making four possible combinations to test. The parameters for each of these tests are summarised in tab. 3. For each test the electric field was chosen to give a breakdown rate of approximately $10^{-4}$ when no magnetic field was present. Once this had been accomplished a number of successive breakdown rate measurements were made.
with the magnet being either turned fully on or fully off between each of them.

Figure 4 shows the 20 breakdown rate measurements made with an electrode gap of 15 µm and a magnetic field oriented parallel to the electrode surface. Out of the first 10 measurements, those made with the magnetic on are higher than all but one of the measurements made with the magnetic off. However, there is not such an obvious correlation of breakdown rate with magnetic field in the second 10 measurements. Overall, the highest 50% of measured breakdown rates were made with the magnet on and half with the magnet off indicating no strong correlation between the presence of a perpendicular magnetic field and the measured breakdown rate at this gap size. It is worth noting however that the two highest measured breakdown rates were both made with the magnet on and these were much higher than average with a breakdown rate approaching 1.

Figure 5 shows 16 breakdown rate measurements made with a 15 µm gap between the electrodes and the magnetic field oriented perpendicular to their surface. Here, 6 of the 8 measurements made with the magnet on are higher than all but one of the measurements made with the magnet off. Overall, of the highest 50% of measurements, 75% were made with the magnet on compared to 25% made with the magnet off perhaps suggesting a correlation between the presence of a perpendicular magnetic field and measured breakdown rate. However, the differences between measured breakdown rates are still small compared to the error. It is noticeable that the later measurements shown in fig. 5 (the order in which the measurements were made is from left to right) have on average a lower value of breakdown rate, meaning that the electrodes are conditioning. This may partially explain why the first measurement made with the magnet off is unusually high and the last measurement made with the magnet on is unusually low compared to the others.

Figure 6 shows the 9 measurements made with a gap size of 60 µm and a magnetic field oriented parallel to the electrode surface. Of the highest 50% of measurements, half were made with the magnet on and half with the magnet off indicating no strong correlation between the presence of a parallel magnetic field and the measured breakdown rate at this gap distance.

Figure 7 shows 18 measurements made with an electrode gap size of 60 µm and a magnetic field oriented perpendicular to the electrode surface. Of the highest 50% of breakdown rate measurements, half are made with the magnet off and half with the magnet on indicating no strong correlation between the presence of a perpendicular magnetic field and the measured breakdown rate at this gap size. It is worth noting however that the two highest measured breakdown rates were both made with the magnet on and these were much higher than average with a breakdown rate approaching 1.

B. Microscopic observation of electrodes

After the first set of electrodes were tested in the LES (with an inter-electrode gap distance 15 µm) and subjected to several thousand breakdowns, the surfaces were imaged using both an optical and scanning electron microscope. These images are shown in fig. 8. Craters are clearly visible on both the anode and cathode surfaces surrounded by a larger damaged region. Table 4 shows the diameters of the craters and damaged surface areas on the cathode and anode as measured from the SEM images. For comparison, the estimated size of field emission sites is also included [22]. It can be seen that the estimated size of electron deflections shown in tab. 4 is large compared to the estimated size of field emission sites but small compared to the size of the craters and damaged surface areas.

As it is not known whether an individual crater was created when the magnetic field was on or when it was off, it is not possible to search directly for differences in the shape, size or structure of craters that may be caused by the presence of a magnetic field. However, when the breakdown craters were examined all the craters studied were similar in size and appearance. Two distinct populations of craters which differed in some aspect were not obvious. There is therefore no evidence to suggest that a static magnetic field of the size used in these experiments has a significant impact on the formation of breakdown craters. To investigate this further it would be necessary to subject two identical electrodes to multiple breakdowns, one with a static magnetic field present and one without, under otherwise identical conditions. The two populations of breakdown craters could then be examined with an electron microscope and compared directly.

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5Here the last measurement is excluded such that the measurements left are comprised of an equal number made with the magnet on as off, allowing a fair comparison.

6Here the first two measurements are excluded such that the measurements left are comprised of an equal number made with the magnet on as off, allowing a fair comparison.
Figure 4: 15 µm gap, magnetic field oriented parallel to electrode surface

Figure 5: 15 µm gap, magnetic field oriented perpendicular to electrode surface

Figure 6: 60 µm gap, magnetic field oriented parallel to electrode surface
Figure 7: 60 µm gap, magnetic field oriented perpendicular to electrode surface.

(a) Photograph of the LES anode showing marks left by breakdowns.
(b) SEM image of a crater left by breakdown on the anode after testing in the LES. The scale under the figure is 20 µm.
(c) SEM image of a crater left by breakdown on the anode after testing in the LES. The scale under the figure is 10 µm.
(d) Photograph of the LES cathode showing marks left by breakdowns.
(e) SEM image of a crater left by breakdown on the cathode after testing in the LES. The scale under the figure is 20 µm.
(f) SEM image of a crater left by breakdown on the cathode after testing in the LES. The scale under the figure is 10 µm.

Figure 8: Photographs and electron microscope images of the cathode and anode pair tested with an inter-electrode gap of 15 µm in the LES. The SEM images in figs. (b) and (c) are different zoom levels of the same location on the anode and figs. (e) and (f) are of the corresponding locations on the cathode.
Table 3: Table of the tests performed

<table>
<thead>
<tr>
<th>Test No.</th>
<th>B-field direction</th>
<th>Gap size µm</th>
<th>E field MV/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perpendicular</td>
<td>15</td>
<td>144</td>
</tr>
<tr>
<td>2</td>
<td>Parallel</td>
<td>15</td>
<td>144</td>
</tr>
<tr>
<td>3</td>
<td>Perpendicular</td>
<td>60</td>
<td>88.0</td>
</tr>
<tr>
<td>4</td>
<td>Parallel</td>
<td>60</td>
<td>91.3, 90.3, 89.5</td>
</tr>
</tbody>
</table>

Table 4: Size of craters and damaged surface areas on LES electrodes measured from SEM images taken after high power testing shown in fig. 8.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode Crater</td>
<td>71 µm</td>
</tr>
<tr>
<td>Cathode Crater</td>
<td>33 µm</td>
</tr>
<tr>
<td>Damaged Anode Area</td>
<td>191 µm</td>
</tr>
<tr>
<td>Damaged Cathode Area</td>
<td>182 µm</td>
</tr>
<tr>
<td>Field Emission Site¹</td>
<td>≈ 10 nm</td>
</tr>
</tbody>
</table>

¹ This is an estimation [22] and has not been measured.

VI. SUMMARY

No consistent effect on the breakdown rate due to an applied DC magnetic field was observed regardless of the gap size or orientation of the field relative to the electrode surface. This was despite using a magnetic field of a comparable size to that present in CLIC accelerating structures [3, 4] and to that used in experiments performed by the MuCool collaboration [9], both of which have been shown to influence the breakdown rate.

This lack of observation is still consistent with the theories described in sections II.A and II.B as a DC magnetic field would not result in either pulsed surface heating or an increased power flow to the field emission sites. However it is inconsistent with the ‘Torque on Field Emitting Tips’ theory described section II.C. If the additional torque due to the applied magnetic field had caused the effect on the breakdown rate witnessed in [9] it should also have been observed in these experiments.

For the Large Electrode System geometry, no estimates have been made for the reduction in area of the anode surface impinged by electrons emitted under the focussing influence of a magnetic field perpendicular to the electrode surface. It is possible therefore, that the lack of observed effect on the breakdown rate indicates too small a change in this area rather than a floor in the theory summarised in section II.D

However as the estimated deflection in electron trajectory was much greater than the estimated size of the field emission site [22] any neutrals or positive ions sputtered from the anode surface for instance would be much less likely to impinge the cathode near the original field emission site. As no effect on the breakdown rate was observed it would suggest that, even at these very small gap distances, any positive feedback effect due to anode processes must be very small and not play a significant role in the pre-breakdown process.

Larger gap sizes require smaller electric fields to achieve the same breakdown rates. To confirm the above results, it would be interesting to repeat this experiment with a gap size and electric field which would allow the electrons to return to the cathode surface, never having reached the anode.

REFERENCES


