Studies of Electrical Breakdown Processes Across Vacuum Gaps Between Metallic Electrodes

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Abstract

An experimental program to elucidate the physical causes of electrical breakdown across vacuum gaps, such as occur in charged particle accelerators, is discussed. Magnetic insulation is explored as a technique to differentiate between field emission of electrons and clump acceleration as possible causative mechanisms for the onset of breakdown. The results and limitations of an exploratory experiment are described, along with plans for more comprehensive experimental and theoretical campaign.

Keywords: magnetic insulation, vacuum electrical breakdown, bacterial-induced electrical breakdown, accelerator

Introduction

The magnitude of the voltage which can be reliably sustained across a gap between two conductors within a vacuum has long been one of the principal determinates of the design and performance of charged particle accelerators, since the magnitude of the electrical gradient constrains such parameters as the maximum strength of electrostatic lenses, the length required to achieve the desired increase in particle kinetic energy, and the current density which can be controlled within a given beam channel.

As a consequence, considerable effort has been expended over the past century or more in searching for techniques to improve voltage holding in vacuum. Among the standard practices which evolved were such techniques as polishing surfaces to reduce surface roughness that contributed to locally concentrated electrical fields, rounding all corners to reduce electrical field concentration, and reducing the use of materials in, for instance, accelerator insulator columns, which could outgas organic or other complex molecules which might coat electrodes. These techniques, all of which proved useful to some degree, had in common that they modified the local surface conditions or electric field. They also had in common that no matter which combination of techniques were used, new accelerators generally required conditioning (allowing sparks of limited energy to further alter surface conditions as the voltage is increased) if they were to be operated at anywhere near the generally accepted maximum gradients for their acceleration gaps.

The quest for improved (that is, higher and more predictable) voltage holding in vacuum has, however, always been impeded by a very imperfect understanding of the genesis of vacuum electrical breakdown and the dynamics which govern it, as discussed in such useful reviews of the field as references **[1,2,3]** and in many specific studies, of which a few examples are in references **[4,5,6]**. This situation is evidenced by the always-perplexing question of why one needs to condition electropolished electrodes if the conditioning process is simply smoothing the metallic surface to reduce local electric field strength. It is also apparent in the curious and non-intuitive scaling of the voltage difference that can be sustained in a vacuum between two electrodes without breakdown as a function of the distance between the electrodes. The aggregate of voltage-holding experience seems to show that the voltage which can be reliably held across a vacuum gap increases approximately linearly with the gap distance up to a gap separation of somewhere between a half centimeter and a centimeter, but that for larger gaps the reliably sustainable voltage increases as roughly the square root of the electrode separation.

If the initiation of electrical breakdown were solely the result of field emission from surface imperfections, then one would expect that a linear relationship between sustainable voltage and vacuum gap distance would hold for all gap lengths, since this could be construed to correspond to a constant electric field strength at the electrode surface. That this is not the case for gaps larger than something like 0.5 – 1 cm has led to other proposed mechanisms for breakdown initiation, of which the most widely invoked is the clump hypothesis, which is predicated upon the idea that charged clumps break away from the cathode surface, accelerate to the anode, and produce an ionized vapor cloud there. **[7]** While this mechanism seems to yield a scaling of voltage holding with distance similar to that which is commonly observed, the premise that pieces of an electrode or the fairly tightly bound oxides on its surface become charged and detach from the electrode seems somewhat implausible, as does the idea that the clump's energy would be concentrated into a sufficiently small number of atoms when impacting the opposing electrode to produce a vapor cloud.

Experimental Program

We have begun an experimental program to better understand the physical mechanisms which contribute to electrical breakdown in vacuum, and thereby to explore techniques to increase the electrical gradient which can be reliably maintained. A recent paper **[8]** postulated that if electron emission, **[9,10,11,12]** particularly field emission of electrons from the locally intensified electric field arising from microprojections on the electrode surfaces at cathode potential, is a dominant mechanism leading to electrical breakdown in vacuum, then it should be possible to improve voltage holding by producing an enveloping magnetic field which is everywhere parallel to the surface of the electron-emitting electrode, and which is topologically similar to the transient magnetic insulation produced around transmission lines in some pulsed power applications **[13]**. In the absence of magnetic monopoles, such a field cannot be produced in three dimensions, but it can be produced in two dimensions by running an electrical current of uniform current density through an electrode. A field with a fairly similar topology can also be produced for applications in RF accelerator cavities by using an external solenoid, and has been proposed by others for improving voltage holding in such devices **[14,15]**.

The magnitude of the field that would be required to produce an observable improvement in voltage holding characteristics if electron emission were the dominant mechanism for instigating breakdown is difficult to estimate, since it is likely a function of surface roughness and the degree to which the field also inhibits migration of electrons within surface imperfections, so the initial experiment **[16]** simply chose a magnetic field strength which was deemed to be practical for many applications, including for instance, large accelerator electrodes such as those planned for the neutral beam injectors of the ITER fusion experiment **[17]**. This magnetic field was about 240 gauss at the surface of the negative electrode, which would lead to a Larmor radius of 2.2 x 10^{-3} cm impeding the migration of room – temperature electrons in or leaving the electrode (field emission electrons are born at an energy of about the temperature of the material, and thus should be easier to suppress than electrons born from other mechanisms such as secondary emission or the photoelectric effect).

While there is a long history of using magnetic fields to impede electron flow in ion sources, as in magnetrons **[18]**, where it is sometimes chosen so as to produce an electron Larmor radius comparable to the gap between the cathode and the anode, the purpose of the magnetic field in the present study is to prevent electrons from ever leaving the immediate vicinity of the cathode surface. The likelihood of success probably depends in part upon how low the temperature of the cathode is, since the electrons are born at thermal energies, and upon the microstructure of the cathode surface, but these parameters were not explored in this limited study.

This magnetic field was produced by running a current of 4 kA through a polished copper bus-bar 4 inches wide and 0.25 inch thick which was also attached to the grounded negative output of a low current high voltage supply so that the high current supply would not need to be floated at high potential. A polished circular planar stainless steel electrode was employed as the electrode at anode potential, and both electrodes were mounted inside a vacuum enclosure (the Princeton 100 keV test stand) so that the voltage which could be held without breakdown across a variable vacuum gap could be measured with and without a magnetic field enveloping the negative (electron-emitting) electrode. This initial experiment did not find evidence that a higher electric gradient could be sustained across a vacuum gap with a magnetic field enveloping the electron-emitting electrode. With or without the enveloping magnetic field, the electric field which could be sustained across the nominally1 mm gap was 14 – 15 kV, and across the nominally 2 mm gap the sustainable voltage was 39 – 42 kV. Due to alignment difficulties related to the suspension of the stainless steel electrode, the gaps are approximate, and may not have differed by exactly a factor of two, so the salient feature of the results is the apparent lack of improvement with the enveloping magnetic field, rather than the absolute magnitude of the voltage. Due to limitations in this exploratory study, further work is needed to reach a conclusion about the primary mechanisms responsible for electrical breakdown between electrodes **[16].** The high voltage supply did not have a crowbar to allow the output current to be rapidly diverted when an electrical breakdown occurred, so it was found that breakdowns across the vacuum gap, which were essential to the execution of the experiment, produced electrode damage. As a consequence, it was not feasible to maintain similar electrode surface conditions when comparing voltage holding with and without an enveloping magnetic field. The magnetic field (240 gauss at the negative electrode surface) chosen for this scoping study was low enough that it could be practical to use in some applications with large accelerator electrodes; however, it may not have been high enough for a study of the fundamental mechanisms leading to vacuum electrical breakdown.

A second campaign is now being planned which will focus initially on understanding the physics of vacuum electrical breakdown, and then using the knowledge so obtained to enable techniques to improve voltage holding in accelerators. This will be accomplished by augmenting the magnitude of the magnetic field enveloping the negative electrode by an order of magnitude, using the same 4 kA supply, but reducing the width by a factor of ten of the portion of the copper bus-bar where the test high voltage gradient is applied. In addition, this campaign will employ a new high voltage supply with a fast crowbar circuit on the output to limit the number of joules dischargeable into a voltage breakdown, which should make it easier to maintain approximately constant electrode surface conditions through the course of the experiment, and it will also have a much larger vacuum electrical feed-through than was available for the first experiment.

With these improvements, it is anticipated that if electron field emission really is the dominant instigator of electrical breakdown across vacuum gaps, then some enhancement of voltage holding should be observable with a 2400 gauss magnetic field enveloping and everywhere parallel to the electron-emitting electrode. If no enhancement is observed, then this suggests that another physical mechanism is the dominant precursor of vacuum gap electrical breakdown.

Grisham recently suggested **[16]** that bacteria or bacterial spores could be plausible candidates for the "clumps" of clump theory, the principal alternative to electron field emission as a model for voltage holding limitations across vacuum gaps. Bacteria or their spores are ubiquitous on surfaces unless special precautions are taken, they are only loosely attached, and they can readily build up static electric charge. While a surface magnetic field strength of 2400 gauss would seriously impair the mobility of room temperature electrons with a Larmor radius of 2.2×10^{-4} cm, it should have little effect upon bacteria or bacterial spores (or clumps of other compositions, such as pieces of oxide), with typical dimensions of a few microns. Thus, testing whether a large magnetic field enveloping the negative (electron-emitting) electrode of a vacuum gap enhances the voltage gradient which can be reliably sustained should provide a method of discriminating between electron field emission and clump acceleration as principal instigators of vacuum gap electrical breakdown.

If the 2400 gauss magnetic field produces no improvement in voltage holding under these improved experimental conditions with better control of fault energy and electrode damage, then the experiments will be repeated under conditions as sterile as feasible to explore whether removing bacteria and bacterial spores from electrodes and their experimental environs leads to improved voltage holding in vacuum gaps, both with and without the magnetic field enveloping the negative electrode. The electrodes will be examined with an appropriate microscope after cleaning procedures to determine what fraction of bacteria and bacterial spores have been removed.

If the enveloping magnetic field by itself significantly improves voltage holding, then it suggests that field emission of electrons is the dominant instigator of electrical breakdown. If the magnetic field has no effect, but improvement is observed when the bacteria and their spores are removed, it suggests that they are the dominant determinant of voltage holding, and if the best voltage holding conditions are observed on surfaces largely free of bacteria and their spores, but also enveloped in a strong magnetic field parallel to the surface, then it will imply that both electron field emission and acceleration of bacteria and their spores are important channels in the onset of vacuum arcs. If removal of bacteria and their spores combined with the enveloping magnetic field produces no improvement in voltage holding, then it will suggest that either clumps of a different nature (such as pieces of electrode oxide) or another process is the principal causative mechanism for vacuum electrical breakdown.

It is expected that this experimental campaign will inform a theory counterpart to model these breakdown processes. Codes which are currently used to model intense beams as drivers for heavy ion fusion will be adapted to model the magnetic self-fields produced by the electron streams in field-emission and arc discharges to determine whether the focusing and kinks driven by the self-magnetic-fields can reproduce the non-linear scaling of voltage holding with gap distance commonly observed.

This integrated program should yield a better understanding of the physical causes of electrical breakdown across vacuum gaps, such as those in charged particle accelerators, and perhaps also one or more techniques for increasing the voltage gradients, improving reliability, or reducing accelerator conditioning time.

Acknowledgments

This research was supported by U. S. DOE Contract No. DE-AC02-09CH11466.

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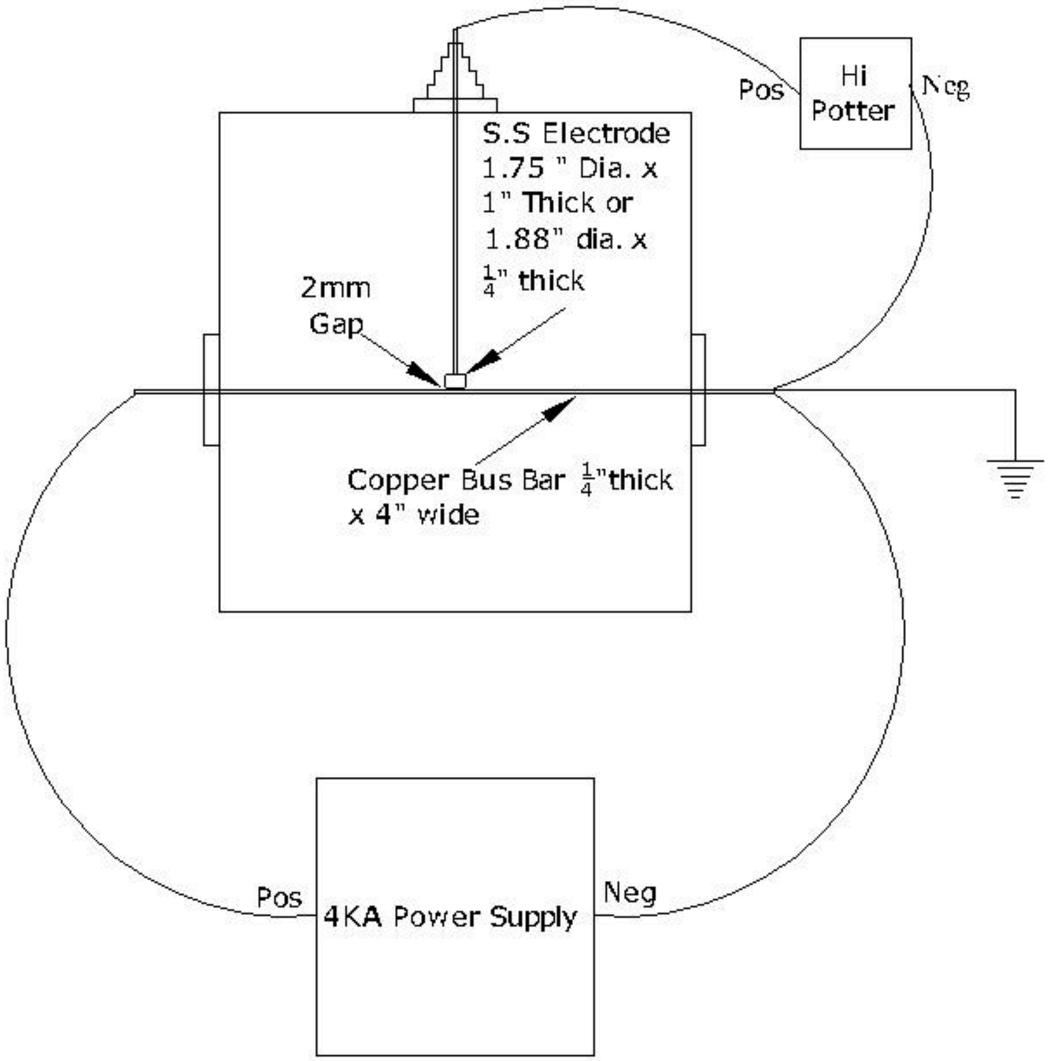
Figure Captions

[1] Diagram of the experimental setup.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4KA Power Supply
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Figure 1