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Exploratory test of utility of magnetic insulation for electrostatic accelerators

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A recent paper [L. R. Grisham, Phys. Plasmas **16**, 043111 (2009)] proposed that a magnetic field which enveloped each of the electrodes in an electrostatic accelerator, along with their support structures, might suppress field emission of electrons and thus allows a higher electric field gradient to be applied between accelerator stages without the onset of vacuum electrical breakdown. Such a magnetic field configuration might be produced by flowing a substantial electric current through each accelerator grid and its support from high current low voltage supplies floated at each accelerator grid potential. This experimental note reports a preliminary exploratory test of whether this magnetic insulation approach might be of benefit at a modest magnetic field strength which could be suitable for practical accelerator applications. This experiment did not find evidence for an increase of the electrostatic potential gradient which could be sustained across a vacuum gap when the cathodic (electron-emitting) electrode was enveloped in a magnetic field of about 240 G. This note discusses a number of possible explanations for this observation as well as the inherent limitations of the experiment. © *2012 American Institute of Physics*. [doi:10.1063/1.3683554]

I. INTRODUCTION

The maximum electric field gradient which can be held reliably in an electrostatic accelerator is perhaps the most important determinant of the accelerator's performance, inasmuch as the sustainable electric gradient largely determines the length required to achieve the desired beam energy, and, in accelerators using lenses formed by planar apertures, it is the principal determinant of the strength of the lenses, and the amount of current which a channel can carry with good optics. Accordingly, the search for techniques to increase the electric field gradient which can be held without arcs between successive stages is probably as old as electrostatic acceleration. Among the methods used to improve voltage holding were surface treatments, insulator enhancements, and careful shaping of components and stress shields, along with accelerator conditioning procedures, to name a few.

Recently, a paper by Grisham[1] proposed that using a magnetic field which is everywhere parallel to the surfaces of each accelerator stage and its electrically conducting support structure to suppress field emission of electrons might allow higher electric field gradients with higher reliability. Such a magnetic field, the two-dimensional analogue of a magnetic monopole, can be produced by an electric current running through an electrode and its supports, and is topologically similar to the magnetic insulation of pulsed power lines[2] and the magnetically insulated transformer once proposed by Winterberg.[3] More recently, Stratkakis *et al*. have proposed enhancing voltage holding in radio frequency accelerator cavities by using external solenoids to produce a magnetic field parallel to the cavity surface.[4,5]

All of these magnetic insulation concepts depend, either explicitly or implicitly, upon inhibiting spontaneous field emission of electrons from the surfaces of electrodes. As discussed in Ref. 1, magnetic insulation could be expected to work for an adequately high enveloping magnetic field and adequate surface finish if field emission[6–10] is the dominant precursor to the development of electrical arcs across high voltage vacuum gaps. It might also have a chance of working if breakdowns are originated in accordance with the particle exchange model, which postulates negative ions, positive ions, and electrons all being accelerated across a gap as progenitors for breakdowns.[11–14] If other mechanisms of vacuum gap breakdown predominate, such as microparticle emission, sometimes called clump theory,[15] then magnetic insulation might still help but with less likelihood.

This paper describes a preliminary experiment to test the concept of magnetic insulation for electrostatic accelerators. Due to resource constraints, it was performed with materials and power supplies which were readily at hand but not necessarily ideal for the purpose.

II. EXPERIMENTAL ARRANGEMENT

The experiment was performed in the Princeton Ion Source Test Facility, an aluminum vacuum chamber with a volume of about 2 m^3, with primary pumping from a 5000 $l\ s^{-1}$ turbomolecular pump which could obtain a background pressure with the experimental apparatus in place of about $7–8 \times 10^{-7}$ Torr. The pressure remained stable during each experimental run.

The basic architecture of the experiment was defined by a vacuum gap between a copper busbar and a stainless steel probe. The copper busbar was at cathode potential (electron emitting), while the stainless steel probe was at anode potential, serving as the target for arcs. The test electrical potential

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(or bias Voltage) was produced by a standard Hipotronics$^{\text{TM}}$ hipotter device, mounted in a configuration such that the ground was at cathode potential (the electron source side of the supply). This was connected to the copper busbar, which was 4 in. wide, 1/4 in. thick, and 4 ft long, and was itself connected to building steel by a copper busbar of roughly similar dimensions. The busbar was mounted across the midplane of the vacuum chamber, with a clearance from the top and bottom of the vacuum chamber of about 30 cm and about the same clearance from the nearest end wall of the chamber, and these surfaces were likewise at ground potential. The busbar accessed the vacuum chamber through two double layered Lexan plates on either side of the chamber, each with a slit for the busbar. The vacuum seal was obtained via an O-ring seal between the matched Lexan plates and the busbar on each side of the vacuum vessel.

The current to produce the enveloping magnetic field came from a 4000 A 12 V DC supply. This was transmitted to the busbar through a large pair of cables connected to the side opposite the one with the connection to building steel. Two cables were used so as to spread the current across the copper busbar, and the distance from the end of the busbar where the current connections were made to the location where the probe was located was several times the width of the busbar, so the current should have been quite uniformly distributed through the busbar by that point, ensuring that there were no significant magnetic field components normal to the cathode busbar's surface, other than a portion of the earth's magnetic field, which would be several hundred times weaker than the roughly 240 G parallel to the busbar produced by the magnetizing current. This configuration resulted in no fringe magnetic fields at the electron emitting cathode surface. The sides of the stainless steel anode were intersected by magnetic field components orthogonal to these side surfaces. This should not have had any effect on the validity of the experiment, since, if the hypothesis is correct, field emission of electrons would not originate form the anode, so the magnetic field orientation there would be moot. In any event, no breakdowns or damage were observed on these side surfaces.

This experimental arrangement, which was greatly simplified by not needing to float the massive 4000 A DC supply at high voltage, was made possible by the decision to have the cathode (electron source) side of the high voltage supply at ground potential. Since the basic premise of the magnetic insulation idea is that it should impede spontaneous field emission of electrons, it is essential that the electron-emitting surface be the one which is enveloped in the applied magnetic field. If magnetic insulation were applied to a multistage electrostatic accelerator, or even to a single stage accelerator in the usual configuration where the source is at high voltage, the high current supply for each acceleration stage would have to be floated at the electrical potential of that stage, a substantial complication, but for the purposes of this preliminary test of the concept, enveloping only the cathodic electron-emitting electrode in the magnetic field should be adequate. The high voltage side of the hipotter was connected to the stainless steel probe plate through a porcelain electrical feedthrough. An external resistor or resistor chain could be connected in series with the high voltage feed to the probe. Since in the absence of current, there should be no voltage drop across the resistor, but a large voltage drop in the presence of current, such as in the event of an arc, the purpose of the resistor, which was chosen for low capacitive stored energy and low inductance, was to limit the energy available in a fault and thus prevent electrode damage. As will be mentioned below, this proved to be ineffective, despite trying a wide range of series resistor values from zero to many megohms. The reason for this was never clearly understood, although it might have been due to energy stored between the resistor and the experimental gap, primarily in the form of charging of the surfaces of insulators.

Two versions of the stainless steel probe were tested. One was a disk 0.25 in. thick by 1.88 in. diameter and the other a cylinder 1.0 in. long by 1.75 in. diameter. Both versions had smoothly radiused edges with a radius of curvature of about 0.18 in. The copper busbar also had smoothly curved edges, and both the busbar and the probes were polished with Noxon$^{\text{TM}}$, which did not leave apparent embedded particles, and then cleaned with ethyl alcohol. In the course of the experiment, whenever the anode probe or the cathode busbar was damaged by arcing, they were again polished and cleaned after the chamber was let up to air. Figure 1 shows the experimental layout and the circuit components.

The probe and busbar were located within the field of view of a window, so that sparks could be detected visually. The concept of the experiment was to start with a gap of about 5 mm between the stainless steel anode and copper busbar. Since the busbar was considerably wider than the flat anode, the edge effects from the busbar should be negligible, and the electric potential should be quite uniform and planar between the two electrodes. The magnetic field produced by the current flowing along the busbar cathode would be

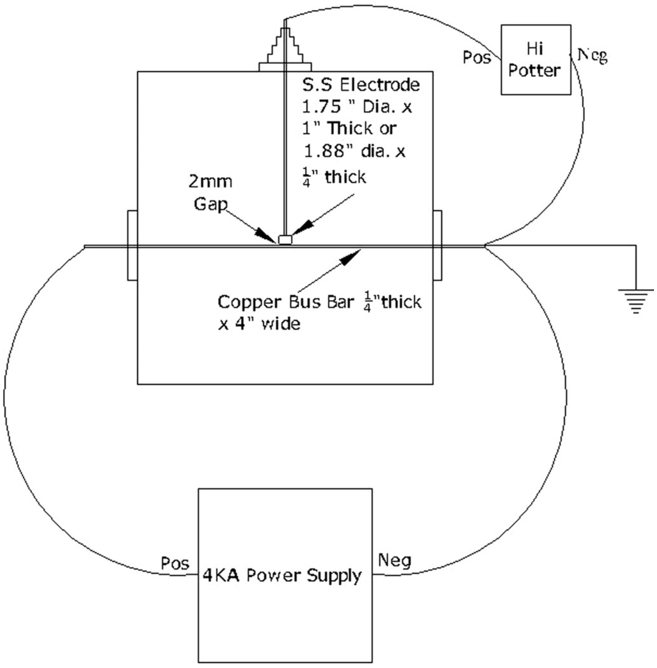

FIG. 1. Diagram of the experimental setup.

uniform, planar, and parallel to the surface of the cathode to impede spontaneous field emission of electrons. It would only be nearly parallel to the surface of the anode, and would in fact be normal to the edges of the anode probe. This should not matter for the purposes of this experiment, however, since the anode would not be the source of field emission electrons.

The plan was that the hipotter would be gradually turned up in voltage until a spark occurred between the cathode and the anode. It was expected that that crowbar circuit in the hipotter would trip when the spark occurred, limiting the available energy in the fault to at most a few tens of joules. In practice, we found that none of our available high voltage supplies had internal crowbar circuits, and none of them tripped when a spark occurred, so the high voltage supply had to be manually turned off. The experimental concept called for the spark to be sufficiently limited in energy and current so that no damage occurred to the electrodes.

After a number of shots had taken place so that the electrodes were conditioned to a reasonably well defined voltage at which breakdown occurred reliably, the magnetizing current would be turned on to produce an magnetic field enveloping the cathode busbar, and the breakdown process would be repeated with the high voltage supply to find the voltage at which breakdown occurred with the magnetic field inhibiting spontaneous field emission of electrons. The current would initially be the maximum available, as determined by the current limit of the magnetizing supply.

If the results appeared promising in the sense that the breakdown voltage with magnetic insulation inhibiting field emission of electrons was appreciably higher than without the magnetic field, then lower values of the magnetizing current and magnetic field would be tried, and the experiment would be repeated at a variety of smaller and larger gap lengths, including gaps of as much as 2–3 cm if the high voltage supply and the voltage integrity of the experimental setup allowed reproducible breakdown at these distances. For this reason, the anode probe was originally suspended from a linear translation probe mount. Even the largest of these gaps would still be small compared to the distance from the high voltage anode probe to the walls of the chamber, so it was expected that electrical breakdowns should be confined to the test gap between the stainless steel anode and the busbar cathode.

III. RESULTS AND DISCUSSION

In practice, the experiment encountered many difficulties, mostly related to the fact that it was done with available equipment and parts which, as it turned out, were not ideal for the experiment had there been more resources available. These problems did not become apparent until the experiment was under way. Initially, there were many difficulties with electrical breakdowns in the high voltage vacuum feedthrough, and along the insulators holding the anode probe, as well as charging of the insulator leading to surface discharges. Some insulators, once charged, also appeared to suffer coulomb explosions, resulting in tiny bits being ejected and ending up in the test gap where they stood erect and distorted the electric field.

These problems were eventually mostly solved by modifications to the experimental configuration and changes to the insulators, with the final, and most successful version simply consisting of a copper rod from the porcelain vacuum feedthrough supporting the anode probe at a fixed distance from the copper busbar. This configuration, while needed for voltage-holding, resulted in less than perfect alignment of the anode with respect to the copper busbar, simply because there was only a single, slightly flexible mounting point for the anode. This was unfortunate since the experiment ended up being done at much smaller gaps (1 and 2 mm) between the anode and cathode than originally intended, due to the fact that the gap between the carefully shaped and polished electrodes was much less prone to electrical breakdown than were the other much less optimized components in the balance of the experimental setup.

The alignment difficulties should not have affected the viability of the experiment, since, for any given voltage holding comparison, the alignment was the same for the conditions with no magnetic field and with magnetic field. If there was a slight tilt of the anode relative to the cathode, then the voltage breakdown began where the average electric field was highest. As a result of the careful, abrasive-free polishing technique, there were no visible occlusions on either electrode to initiate breakdowns. The vacuum pressure was unchanged by breakdowns across the test gap, indicating that no significant amount of volatiles was being released from the surfaces.

The most serious experimental problem, however, was the fact that the lack of a crowbar circuit and the apparent lack of fault energy amelioration by the series resistors resulted in damage to the electrodes whenever a spark occurred. It had been expected that even if there was damage, it would be confined to the anode, since that was where the electrons would have enough energy to do harm, but the narrow gaps of only 2 mm or so which were required for reliable breakdown across the test gap without breakdown or surface charging elsewhere meant that material eroded from the stainless steel anode was deposited on the copper cathode, resulting in projections on both electrodes which protruded from the flat surfaces of the electrodes.

This electrode damage, particularly to the electron-emitting cathode, was deleterious to the basic idea of the experiment, since the surface projections were not parallel to the enveloping magnetic field, and in fact were normal to the magnetic, in which case the magnetic field could enhance, rather than impede field emission of electrons. The electrode materials were chosen with this problem in mind. The cathode was copper so as to offer minimal electrical resistance to the large magnetizing current which would flow through it when the magnetic field was deployed, while the anode, which would be the target of the electrons which had been accelerated by the electric field and thus had some kinetic energy, was chosen to be stainless steel, which has significantly higher melting and vaporization temperatures than copper, and thus should be less susceptible to damage from sparks. The thermal conductivity of the stainless steel was much lower than that of copper, but on the short time scale of a spark the thermal conductivity should not matter,

TABLE I. Breakdown voltages across a 2 mm vacuum gap (4.2×10^{-7} Torr) and a 1 mm vacuum gap (2.8×10^{-7} Torr) with and without a magnetic field of about 240 G enveloping the grounded copper busbar at cathode (electron-emitting) potential.

Breakdown voltage across gap (kV)	(W) With magnetic field/(WO) without
2 mm vacuum gap (4.2×10^{-7} Torr)	
39	WO
40	WO
41	W
40	WO
40	WO
41	W
41	WO
42	W
1 mm vacuum gap (2.8×10^{-7} Torr)	
6	WO
10	WO
13	WO
14	WO
14.7	W
14.5	WO
14.4	W
14.4	WO
14.4	W
14.4	WO
14.4	W

since the time would be too short for heat conduction to remove appreciable energy from the impact zone of the spark. Tungsten or molybdenum would have been even better materials for the anode but would have been extremely difficult to machine and polish.

The net result of these experimental problems was that the experiment was less perfect than envisioned, but the preliminary observation was that under these imperfect conditions, no significant increase in the vacuum gap voltage holding was achieved when a current of approximately 4 kA, the maximum current capability of the power supply, was passed through the cathode busbar, resulting in a surface magnetic field of about 240 G. Table I shows a sample of results with the last two configurations tried. There was also no apparent increase in voltage holding across a larger gap in ambient air at one bar when the magnetic insulation was added, although the physical mechanisms involved in breakdowns in air gaps at one bar are in any case different from those in vacuum gaps. Due to the fact that there is more than one convention about what is meant by positive and negative terminals in physics and engineering, the experiment was also done with the polarity of the high voltage supply reversed, also with no apparent improvement in voltage holding due to the magnetic field.

IV. CONCLUSION

There are several possible explanations for the lack of any significant increase in the hold-off voltage in the vacuum gap when the electron-emitting electrode was enveloped in a magnetic field that was everywhere parallel to the electrode surface. One is that the persistent electrode damage impacted the efficacy of the magnetic field, since it would not be expected to inhibit electron emission if damaged or deposited material protrudes up from the surface so that the magnetic field lines strike it at a normal, rather than parallel, incidence. In any real accelerator, the crowbar and protection circuits would prevent this sort of damage from occurring, so the fact that the equipment at hand which was used in this experiment was not capable of preventing electrode damage means that this not a completely realistic simulation of how well magnetic insulation might work in an actual accelerator. As a consequence of the persistent electrode damage due to the lack of a crowbar circuit, only a few high voltage pulses were applied in each experimental test run. Thus, there was no opportunity to establish a stable operating voltage at which breakdown reliably occurred for comparison between the cases with and without the magnetic insulation.

Another possibility is that the magnetic field enveloping the electrode needs to be much stronger to impede field emission of electrons. This experiment was deliberately conceived as more of an engineering proof-of-concept rather than a physics proof-of concept, in that the field of 240 G corresponded to an electric current through the electrode which could be practical to apply in large accelerator systems where the power supplies would have to be floated at the potential of each acceleration stage. If this experiment were repeated by others, it might be better to start with a much higher magnetic field, such as could have been obtained in this example if the busbar were necked down to one tenth of the width used here and water-cooled, so that the magnetic field was about 2400 G. While the current density required for such a large enveloping magnetic field would be impractical for many applications, as would the magnetic force between adjacent acceleration stages, such an experiment would be better for testing whether spontaneous field emission electrons is the origin of most electrical breakdowns in electrostatic accelerators.

Field-emitted electrons are born with an energy of about the temperature of the electrode, which in this case was room temperature, so the birth energies would have a temperature distribution around 0.025 eV. For a 240 G magnetic field, this would give a Larmor radius of 2.2×10^{-3} cm to impede electrons from reaching and leaving the surface; increasing the current density and the magnetic field a factor of 10 would reduce the electron thermal energy Larmor radius to 2.2×10^{-4} cm.

Another possibility, and perhaps the most interesting from a physics point of view, is that the hypothesis that most electrical breakdowns in electrostatic accelerators are initiated by field emission of electrons, and which forms the physical basis of the magnetic insulation idea in its presenty form for electrostatic accelerators and earlier forms[2,3] for pulsed transmission lines and transformers, might not be appropriate, and that another model of electrical breakdown, such as emission of charged microclusters, sometimes referred to as clump theory,y might be a better description. Depending upon the size and charge of the microclusters or clumps, they would probably be less influenced by a magnetic field parallel to the surfaces of electrode material and thus might require much higher magnetic fields for any inhibition of electrical breakdown to become apparent.

The principal problems with the clump hypothesis are that it seems improbable that clumps of the electrode material could become sufficiently charged to break away from the surface and also the idea that the clumps vaporize the opposite electrode to start the discharge appears to run somewhat uphill against thermodynamics, requiring concentration of the energy of the many atoms in the cluster into a smaller number of atoms in the impacted electrode surface.

It has recently occurred to one of the authors (L. R. Grisham) that bacteria and their spores might be the "clumps" of the clump breakdown pathway. They have dimensions of a few microns, and while they have some water content even in a vacuum,[16,17] vacuum-dried bacteria and their spores should be sufficiently insulating to allow the accumulation of substantial electrical charge. Bacterial spores can survive for years in high vacuum,y although they would not need to be alive to cause voltage holding problems as charged projectiles They are only loosely attached to surfaces, so they should be much easier to dislodge in an electric field than pieces of the electrode. Moreover, it is likely that the bacteria or spores would break up into a cloud upon hitting the opposite electrode, obviating the need to vaporize the electrode in order to start a discharge. Thus, the clump hypothesis, if applied to bacteria, may be more physically plausible than it has seemed, and one of the outcomes of the present experiment is that it should be further explored. If correct, it would explain why even electropolished electrodes still require high voltage conditioning, since they would still carry bacteria or their spores.

This experiment appears to suggest that magnetic insulation is unlikely to be suitable for significantly increasing the electric gradient which can be held without breakdown in electrostatic accelerators, at least at magnetic field strengths which would be readily practical by flowing electric currents though the accelerator stages of large systems such as those used for heating of magnetically confined fusion plasmas. Nonetheless, it would be appropriate if the experiment could be repeated with better insulators and feedthroughs so that a larger gap could be tested and with a power supply with a crowbar and fault detector to prevent electrode damage. Also, going to a much higher magnetic field might help better elucidate the dominant physical mechanism initiating electrical breakdown in vacuum gaps, in particular, whether it is field emission of electrons from microprojections, emission of charged clumps, such as bacteria or their spores, or some combination of mechanisms.

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