RF Breakdown in Magnetic Fields: Previous work, recent theory and future plans

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Abstract. Recent experiments on the breakdown of rf cavities revealed severe surface damage and a reduction of the maximum accelerating gradient after applying an external magnetic field. This finding implies serious problems for cooling lattices in wherein rf cavities and external magnetic fields coexist, such as those of the proposed neutrino factory and muon collider. An experimental program that could study those problems and their possible solutions are discussed. Emphasis is given to a magnetically insulated cavity design in which the walls are parallel to the magnetic field lines and consequently damage from field emission is expected to be suppressed.

Keywords: rf breakdown, external magnetic fields, neutrino factory and muon collider.
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INTRODUCTION

Much effort is underway to explore the feasibility of designing and constructing a high-luminosity muon-collider and neutrino factory [1]. In these designs, ionization cooling [2] reduces the emittance of the muon beam as it passes through an absorber, thereby lowering the muons transverse- and longitudinal-momenta. Thereafter, longitudinal momentum is restored by accelerating the beam through an rf cavity (typically 201-805 MHz), leaving a net loss of the transverse momentum. The net effect of ionization cooling is more efficient when a solenoid strongly focuses the beam through the absorber. Because the field lines extend beyond the solenoid, the rf cavities contain significant magnetic fields. Thus, it is of fundamental importance that we understand thoroughly the operation of the rf cavities under external magnetic fields.

A novel theory for rf breakdown in magnetic fields is been presented. The theory is simple and intuitive, and agrees adequately with earlier experimental data. Additionally, possible solutions and suggestions are offered for future experiments to study those problems.

RF IN MAGNETIC FIELDS

Two recent major experiments at the MuCool Test Area (MTA) at Fermi National Laboratory tested the efficiency of the rf cavities within magnetic fields: One with a multi-cell 805 MHz cavity [3], and one with a “pillbox” 805 MHz [4]. Both revealed major problems. Particularly, in an early test of a multi-cell 805 MHz cavity, acceleration gradients seemed little effected by the field but damage was done to a titanium vacuum window and vacuum lost. The cause appeared to be electrons emitted at a high gradient location on an iris being focused by the magnetic field to the window. In fact, the electron current was measured and found to be 100mA [3]. A later test of a single ‘pill box’ cavity with beryllium or copper windows on both sides found a severe reduction in achievable surface gradients as a function of the strength of the magnetic field. The experimental data are plotted with black crosses in Fig. 1. Inspection showed considerable pitting on the copper iris surfaces. More recently, a test of a 201 MHz cavity without field achieved 21 MV/m, but in the 0.6 T fringe field of a 4.5 T magnet achieved only 10 MV/m, and when tested again without filed could not again achieve more than 18 MV/m. So in all cases, operation of the rf in magnetic fields equal to, or even less than, those specified, showed damage and most suffered serious loss of achievable gradient. Importantly, they suggested that the operational problems were associated with the combined effect of unwanted emission of electrons from locally enhanced field regions, and the presence of external magnetic fields.

The use of high pressure hydrogen in a Helical Cooling Channel has been also explored [5]. A simple test cavity has been operated with hydrogen at different pressures. No change in the breakdown was observed in the presence of an external magnetic field. However it is yet to be determined experimentally if the gas will not break down or become too resistive in the presence of the intense muon beams passing through them.

RF BREAKDOWN THEORY

A simple theory was developed to explain the rf breakdown in magnetic fields [6-8] for the pillbox cavity in Ref. 4. According to that theory the lessening of the gradient is related to the existence on the cavity's surface of microscopic roughnesses, or *asperities*, greatly enhancing the local electric field. In Ref. 7 that field emitted electrons were tracked by the PARMELA code. The code included the effect of space-charge as well as both the effect of field enhancement and RF fields. It was found that dark current electrons from the asperity are accelerated by the rf fields, and in the presence of a sufficiently strong magnetic field ($B \approx 0.5$ T), are focused into small spots at another location in the cavity where they heat the surface at about 50 ^{0}C.

A series of RF pulse heating experiments have been conducted at Stanford Linear Accelerator Center (SLAC) [9]. In those experiments a cavity surface free of electric fields was heated by the eddy currents due the high powered rf pulse [10]. The temperature rise induced mechanical stress into the metal resulting in microscopic damage on the surface. Because this damage was accumulated within each rf pulse, finally severe micro cracks and surface roughening was observed, a process known as *cyclic fatigue*. This phenomenon placed a limit on the maximum achievable gradient. Interestingly, the required temperature rise for such material deformation was close to 50 ^{0}C which is similar to the one predicted for our case.

It is likely the observed damage and breakdown observed in 805 and 201 MHz cavities, when operated in magnetic fields, may be caused by the impact of field emitted electrons focused by the magnetic fields onto copper surfaces in the cavity. As in the SLAC case, the heated volume will be constrained by the surrounding unheated bulk material and will thus also experience cyclical strain and fatigue. The geometry in our case is more complicated, and depends on the electron energies, focused dimensions, and angle of impact, but damage may reasonably be expected with similar cyclical heating close to 50^{0}C.

Shown in Fig. 1 are the predictions of our model [7] for the required magnetic fields to raise the surface temperature from 50-150 ^{0}C for a given surface gradient. The black crosses denote the maximum accelerating gradients for different magnetic fields in the pillbox experiment in Ref. 4. The fact that the MTA breakdown data lie much below the curves corresponding to the melting temperature of Cu (1085 ^{0}C) suggests to us that a different mechanism (other than melting) is responsible for the observed breakdown. However, even though our model does not predict melting, severe damage on the cavity's Cu surface was observed during the experiment, and this damage worsened as the strength of the magnetic field was increased. This could be due induced thermal fatigue.

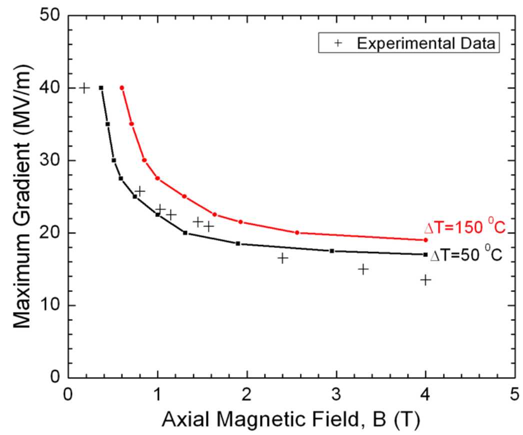

FIGURE 1. Solid lines are predictions of our model for a breakdown at 50-150^{0}C. The crosses are actual experimental data from Ref. 4. More details can be found in Ref. 7.

EXPERIMENTAL PLANS AND POSSIBLE SOLUTIONS

Three experimental studies are underway to study approaches to overcome rf breakdown in magnetic field for the muon collider and neutrino factory cooling lattices. Here we provide an overview of those.

Magnetic Insulated Cavity

It has been demonstrated in Refs. 6,7 that the observed damage and breakdown is due to electron beams emitted at asperities on one side of the cavity, being focused by the magnetic field to another surface. The solution proposed here is to employ 'magnetic insulation'. In this concept, an external magnetic field is introduced at right angles to the electric field. Magnetic fields have been tried to reduce rf breakdown, but those fields did not use the specific solution embodied in magnetic insulation. This is a concept has been long ago proposed for high voltage pulse applications, but never, to our knowledge, proposed for an rf application.

The novel idea is to employ externally applied magnetic fields with their direction parallel to any surface exposed to high rf electric field gradients. For a useful cooling lattice, the idea is to place the primary focus coils in the irises of open multi-cell cavities, and shape the walls of the cavity to follow the magnetic field lines. Figure 2 shows a simple example of this principle applied to a single rf cavity with just two coils, one on either side of the cavity. Recent studies show no multipacting activities inside the cavity [11]. Work is currently underway to study the efficiency of those cavities for 6D cooling into the muon collider lattices. Additionally, work is underway to explore the feasibility of a magnetic insulated lattice for the front of the neutrino factory.

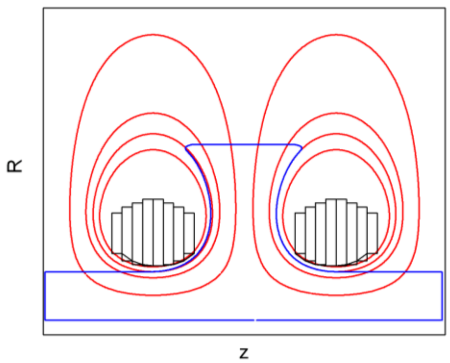

FIGURE 2. Schematic Illustration of a magnetic insulated cavity. Red lines are the field lines produced by the two coils. The blue line depicts the cavity. Frequency is 805 MHz.

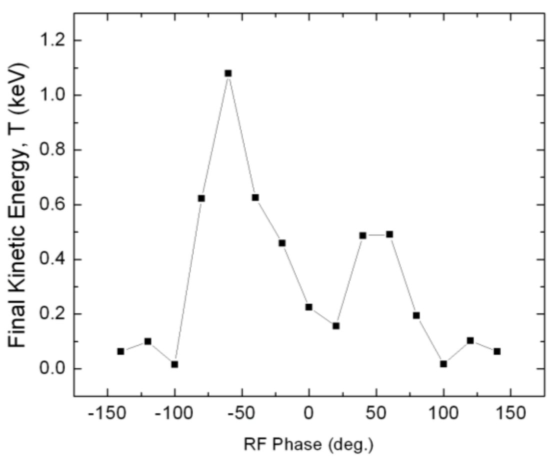

FIGURE 3. Energy of returning electrons as a function of their initial rf phase as obtained by CAVEL.

Simulations of an insulated cavity with the tracking program CAVEL [12], developed at Brookhaven National laboratory, indicated that electrons emitted from a surface, are initially accelerated by the electric field away from that surface. Then, as they attain significant momentum, they are deflected by the magnetic field and directed back to the surface. Depending on their phase of emission, they may after a single half loop, return to the surface, or, at early phases, they may make several loops but they always return to the surface with equal or less than a kilovolt so they don't induce damage. Figure 3 shows a typical plot of the impact energy of field emitted versus phase for a magnetic insulated cavity.

Box Cavity Experiment

The simulations discussed in the previous section showed that if the magnetic fields are perpendicular to the cavity surface exposed to an rf gradient, the emitted electrons do not move far away from the surface, but instead return with very low energies, and thus do not harm that surface. Work [13] is now underway at Fermi National Laboratory to design a box cavity which will be used to test the concept. Figure 4 is a schematic layout of this proposed 805 MHz cavity. Initially, the cavity will be placed inside the MTA's solenoid so that the RF field, E_{RF}, is perpendicular to the solenoid's axis ($\theta = 0^0$). Then, the cavity will be rotated ($\theta \geq 0^0$) and its performance will be crosschecked for different configurations of E_{RF} and B. Such cavity also is ideal for testing surface treatments, including atomic-layer deposition.

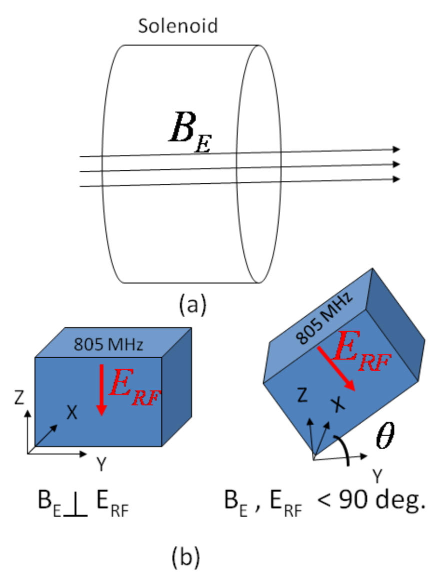

FIGURE 4. Basic principle of the box cavity experiment.

The RF cavity will operate at the lowest possible mode (TM_{110}) with maximum electric field at the center of the xy plane [see Fig. 4(b)]. The frequency will be 805 MHz. Once again, the code CAVEL is implemented to simulate field emission in the box cavity. Our results are shown in Fig. 5. The following conclusions can be made: Some portion of the field emitted electrons hits another side of the cavity while some electrons are coming back (close to the point they were emitted [Fig. 5(a)]. This implies that damage may occur at two different locations in the cavity. Note, however, that the returning electrons may hit a location with high gradient and thus it is likely that those electrons may initiate breakdown. Note further, that the impact energies [Fig. 5(b)]] are much lower that the pillbox cavity [6,7]. This could be due the shorter path the electrons travel. It is likely that rotating the cavity at 1-3^0 will be safe. At > 10^0 more damage is expected.

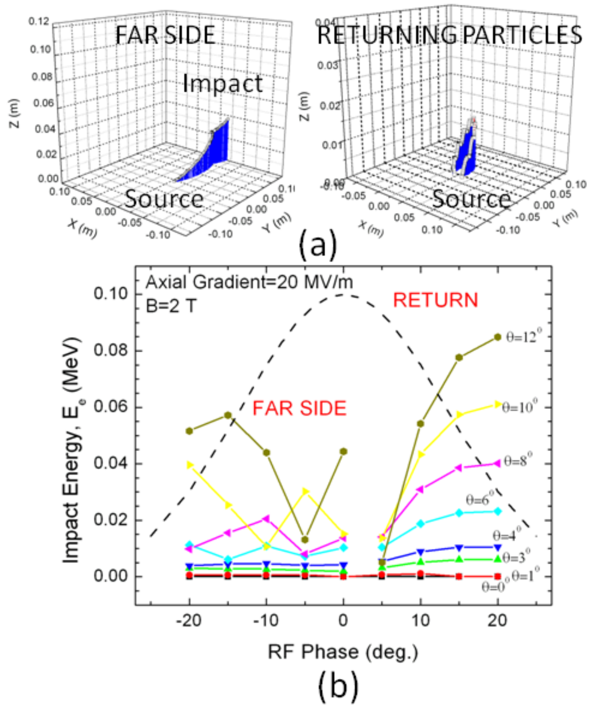

FIGURE 5. (a) Paths of field emitted electrons. Note that some particles are returning back to the source (right). (b) Electron impact energies versus rf phase. The term "far side" notes the electrons that do not return to the source.

Beryllium Button Cavity Experiment

It is known that breakdown depends on the material properties. Thus, another option would be to construct a cavity of materials that would be more resistant to damage from the impact of the focused dark current beams. The fact that no damage was observed on Beryllium (Be) windows in previous experiments [14] suggests that if a cavity would be made out of Be, the cavity could operate at higher gradients. This argument may be supported as follows. In Fig. 6(a) we compare the penetration of a 1 MeV electron beam in Cu and Be [15]. Clearly, in the Be case the electrons penetrate deeper so less energy is deposited on the cavity surface and consequently less damage may occur. It is likely then that the cavity may be operated at higher accelerating gradients before breakdown occurs. This fact is supported in Fig. 6(b) were by assuming that cyclic heating to 50 ^{0}C generates a critical strain threshold in a cavity we compare the breakdown gradients on axis for a Be and Cu made pillbox 805 MHz cavity.

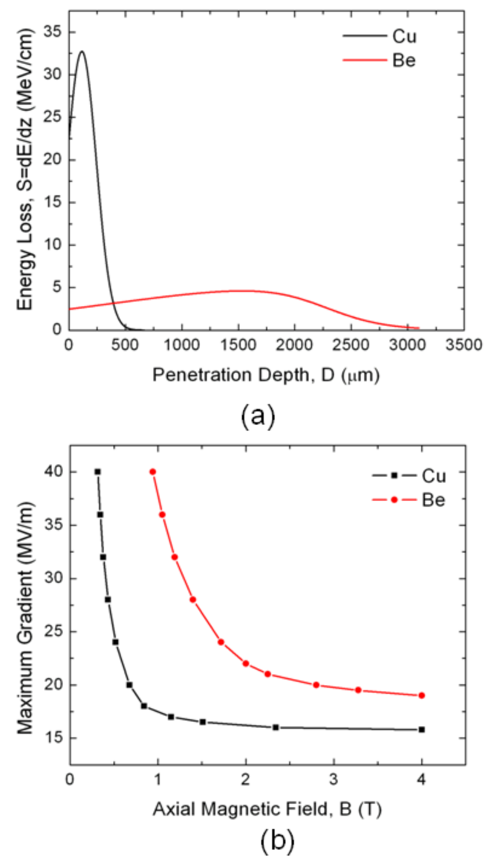

FIGURE 6. A comparison between Be and Cu made cavities: (a) Energy loss vs. penetration depth for 1 MeV electrons; (b) Expected breakdown gradients on axis for the 805 MHz cavity. Clearly, Be can sustain higher gradients.

Two sets of Beryllium buttons and two sets of Copper buttons will be made and each pair will be mounted on the axis of the 805 MHz pillbox cavity. The button dimensions will be such as to produce a tip enhancement that is 3 times bigger than that on the outer iris. The factor of 3 will make sure that the gradients on the iris will be significant smaller to avoid breakdown there. A schematic illustration of the button cavity is shown in Fig. 7. Note that to avoid a reduction of the RF frequency, 0.25 cm from the button holder will be taken out. Microwave studio [16] simulation suggested that the frequency of this cavity is 805.4 MHz as desired.

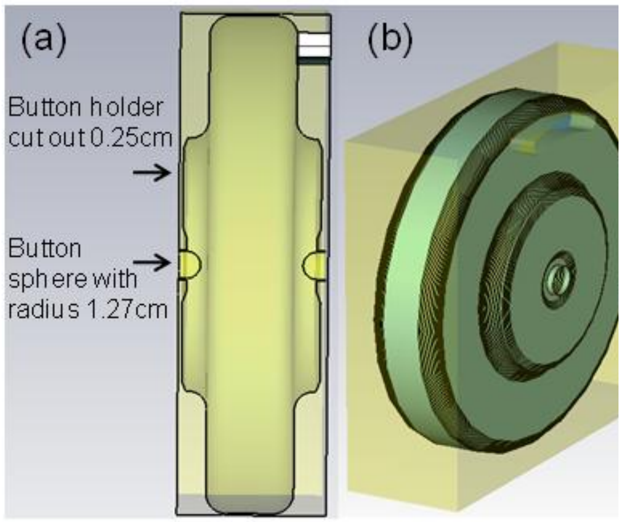

FIGURE 7. Schematic illustration of the pillbox cavity with the buttons on the center. The rf frequency with the coupler was 805.46 MHz. Note that the coupler is shown in Fig. 7(b).

SUMMARY

The observed damage and breakdown observed in 805 and 201 MHz cavities, when operated in magnetic fields, may be caused by the impact of field emitted electrons focused by the magnetic fields onto copper surfaces in the cavity. Such electrons would induce local cyclical heating of the copper. As in the SLAC case, the heated volume will be constrained by the surrounding unheated bulk material and will thus also experience cyclical strain and fatigue. Our simple model yields the following conclusions: (a) In the presence of asperities, “dark current” electrons are field emitted, accelerated by the rf fields, and impact another location of the rf cavity. With a sufficient magnetic field (B ~ 0.5 T), the emitted electrons are focused into small spots; (b) the cavity surface temperature rises from the impact. This increase is a function of the rf accelerating gradient, and also depends on the magnetic field’s strength and spots’ sizes; (c) in the presence of external magnetic fields, the surface material probably will be severely damaged by fatigue induced by the repeated deposition of local energy; and, (d) the relative amount of surface heating, and therefore, the probability of fatigue depends on the material’s properties. It is likely that if Beryllium could be used to construct a cavity little damage would occur.

Methods to address these problems were discussed, including the design of a magnetic insulated cavity. A possible experimental program to further study those concepts was outlined.

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