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RF Cavity Breakdown in External Magnetic Field

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Neutrino Factories and Muon Colliders' cooling lattices require both high gradient rf and strong focusing solenoids. Experiments have shown that there may be serious problems operating rf in the required magnetic fields. It is proposed that electrons emitted from asperities on one side of a cavity are focused by the magnetic field to the other side where they damage the cavity surface in small spots. The theory is fitted to existing 805 MHz data and predictions are made for performance at 201 MHz. A possible solutions to these problems is *magnetically insulated rf* in which the cavity walls are designed to be parallel to a chosen magnetic field contour line and consequently damage from field emission is suppressed.

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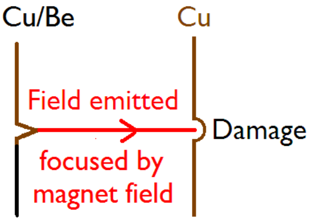

Figure 1: (Color) Proposed mechanism for breakdown with an external magnetic field.

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1. Requirements and Experimental Results

Low frequency (330-200 MHz) rf is needed for phase rotation and early cooling in the currently proposed Neutrino Factory and Muon Collider [1] designs. The magnitude of the required magnetic fields are of the order of 1.75 T for the phase rotation and around 3 T in the early cooling lattices. The rf gradients specified are between 12 and 15 MV/m. Higher frequencies (402 and 805 MHz) are needed for further cooling in a Muon Collider, and these would be operating in higher external magnetic fields of order 6 T.

Experimental results at both 805 and 201 MHz have shown damage and reductions of performance that suggest that neither the requirements for a Neutrino Factory, nor those for a Muon Collider are achievable with current cavity designs. These experiments include:

1) A multi-cell cavity with open irises [2] achieved accelerating gradients of the order of 50 MV/m with up to 3 T somewhat asymmetric fields. Damage was done to a vacuum window at a location that was on a field line that came from a high local gradient on an cavity iris.

2) A single 805 MHz ‘pillbox’ cavity with irises closed with Be windows[3] achieved gradients that fell to only about 12 MV/m at 4 T. Severe damage was subsequently observed on the high field locations on the cavity irises.

3) A single 201 MHz ’pillbox’ cavity was tested in the stray field at the end of the 4.5 T magnet used in the above experiments. After initial operation with 21 MV/m surface gradients, the maximum fields fell to approximately 10 MV/m with a magnetic field of only 0.6 T on the window facing the magnet.

Data on the rf operation of a test cavity in high pressure hydrogen gas showed no such magnetic field dependence [4]. However, there may be other problems using gas in the cavities arising when an ionizing beam passes through it. In addition, such gas filled cavities cannot be used in the later stages of cooling for a Muon Collider because the Coulomb scattering in the gas would cause too much emittance growth.

2. Proposed Mechanism of rf Breakdown with External Magnetic Fields

This mechanism is independent of the breakdown mechanism in the absence of magnetic fields (see Fig. 1). Breakdown occurs by this mechanism *only* if its breakdown gradient is lower than that from the case without a magnetic field. Its elements are:

- Electrons are emitted from an asperity, accelerated by the rf fields, and impact another location in the cavity. In the absence of a magnetic field these impacts are spread over large areas and do no harm.

- With sufficient magnetic field they are focused to small spots, where they can damage the surface. If such damage is at a low gradient location there is no immediate breakdown, but the damage can accumulate until, for instance, a hole is made in a window.

- If the electrons are focused onto a location with high surface rf gradient, then the damage can lead to breakdown.

Breakdown will be dependent on a) the Fowler-Nordheim field enhancement that determines the strength of the field emitted current, b) the local geometry of the asperity that will determine the initial particle distributions and effects of space charge, and c) on the geometry and magnetic fields that focus the electrons onto other locations.

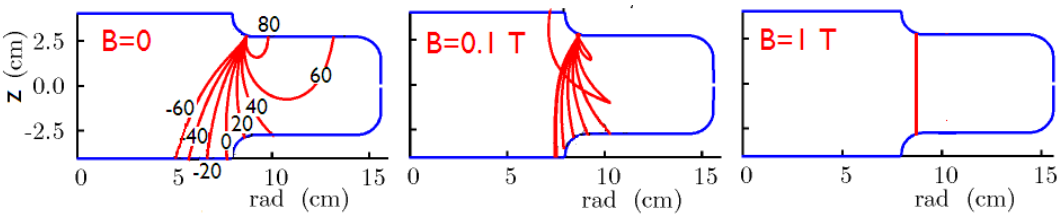

Figure 2: (Color) Trajectories of electrons field emitted at different phases from the highest surface field location in an 805 MHz pillbox cavity with a) no external magnetic field, b) an axial field of 0.1 T, and c) an axial field of 1 T. The axial electric field is 25 MV/m. Phases are in degrees relative to the maximum.

A program CAVEL tracks particles from arbitrary positions on the walls of a cavity until they end on some other surface. The program uses SUPERFISH to determine the rf electric and magnetic fields, and uses a map of external magnetic fields calculated for arbitrary coil dimensions and currents. Fig. 2 shows trajectories, for differing initial rf phases, starting from the highest field location on an iris. Without an external magnetic field, none of the trajectories from the high field location come back to their common origin. Tracks emitted at a phase of 20° do hit the opposing iris at a high gradient location, but they are not focused there and are spread out over a significant distance. But with a sufficient external axial magnetic field, the tracks are either focused to the high gradient location on the opposite iris or returned to their source.

The electron energies for the 805 MHz cavity with axial rf fields of 25 MV/m are approximately 1 MeV. For a 201 MHz cavity, and the same gradient, they are of the order of 4 MeV. At these energies, the electrons penetrate to significant depths in the Cu cavity walls. If Be is used, the penetration is even deeper. The relative surface heating and thus probability of melting and damage depends on the fraction of energy deposited in a surface layer, taking into account thermal conduction away from the deposition. Without an asperity and emission from a small area, the space charge forces give transverse momenta to emitted electrons causing the beamlet's radius to increase. As the beamlet increases in radius and the electrons are accelerated, the space charge forces drop. But if the electrons are emitted from the tip of an asperity then they will first be spread

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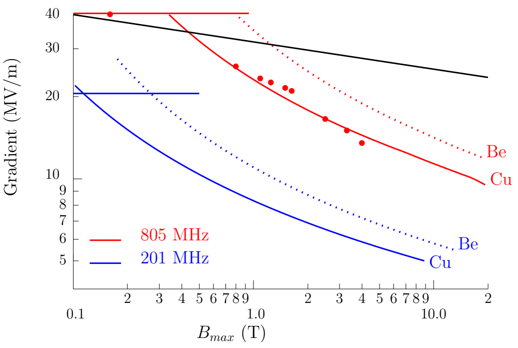

Figure 3: (Color) Breakdown gradients *vs* axial magnetic fields. Black line is dependency predicted by asperity twist model. Red lines are fit to the plotted Lab G [3] breakdown data. Blue lines are the calculated values for a 201 MHz cavity. Dotted lines are for Be surfaces.

by the approximately spherically symmetric local electric fields, and the effect of the space charge is consequently modified. The model is described in more detail in a recent preprint[6].

In Fig. 3 the observed pillbox cavity breakdowns are plotted as a function of the external average magnetic field. The points plotted are those where both superconducting coils were powered so that the magnetic fields were relatively uniform over the cavity. Without an external magnetic field, breakdown gradients have been observed to follow approximately a $\sqrt{f}$ behavior. Under the assumptions used here [5], the local field at breakdown is independent of the frequency; this implies that β_{FN} decreases approximately as $\frac{1}{\sqrt{f}}$. Using this assumption, and using the appropriately modified diffusion depth, the predicted breakdown limits at 201 MHz, for Cu (solid blue line) and Be (dashed blue line) are shown in Fig. 3.

3. Magnetic Insulation Solution to these Problems

Damage should be eliminated if cavities were designed such that all high electric gradient surfaces were parallel to the magnetic fields (Fig. 4). This idea of *magnetic insulation* [7] was suggested long ago for inhibiting breakdown in DC or pulsed voltage systems, but not, as far as we know, proposed for rf. Dark current, or otherwise emitted electrons would be constrained to move within short distances of the surfaces, would gain little energy, would cause no X-rays, and do no damage.

An example of a cavity demonstrating this idea is shown in Fig. 4. The cavity has to have open irises, and its shape is constrained by the geometry of the coils. The inner coils provide the muon beam focusing and provide most of the magnetic insulation. The outer *bucking coils* are used to modify the field lines so as to improve the cavity shape and performance.

Possible difficulties are: a) cavities so designed will not give optimum acceleration for given surface fields, and b) multipactoring might occur, now that the energies with which electrons do return to the surfaces are in the few hundred volt range where secondary emission is maximal. In addition, the use of open, instead of pillbox, cavities implies lower acceleration for given surface fields.

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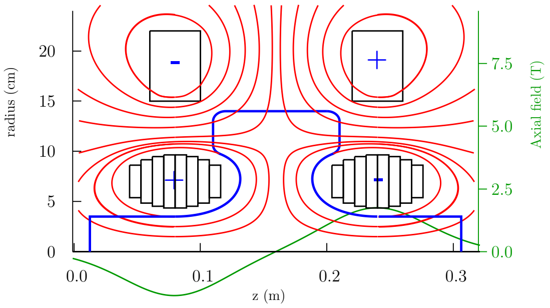

Figure 4: (Color) Magnetic field lines from coils in a cavity lattice, together with cavity shape that follows these field lines.

4. Conclusion

- Ionization cooling for Neutrino factories and Muon Colliders need rf acceleration in the presence of significant magnetic fields.
- Experiments have shown serious problems when operating in such fields
- Magnetic Insulation offers a possible solution to these problems

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