**BNL-95361-2011-CP**

# *Enhancement of RF Breakdown Threshold of Microwave Cavities by Magnetic Insulation*

**D. Stratakis, Juan C. Gallardo and Robert B. Palmer**

*Presented at the 2011 Particle Accelerator Conference*
New York, New York
March 28-April 1, 2011

April 2011

**Physics Department**

**Brookhaven National Laboratory**

**U.S. Department of Energy**
**DOE Office of Science**
**Dept of High Energy and Nuclear Physics**

# DISCLAIMER

# ENHANCEMENT OF RF BREAKDOWN THRESHOLD OF MICROWAVE CAVITIES BY MAGNETIC INSULATION

D. Stratakis[#], University of California, Los Angeles, CA 90095, U.S.A
Juan C. Gallardo and Robert B. Palmer BNL, Upton, NY 11973, U.S.A.

### *Abstract*

Limitations on the maximum achievable accelerating gradient of microwave cavities can influence the performance, length, and cost of particle accelerators. Gradient limitations are believed to be initiated by electron emission from the cavity surfaces. Here, we show that field emission is effectively suppressed by applying a tangential magnetic field to the cavity walls, so higher gradients can be achieved. Numerical simulations indicate that the magnetic field prevents electrons leaving these surfaces and subsequently picking up energy from the electric field. Our results agree with current experimental data. Two specific examples illustrate the implementation of magnetic insulation into prospective particle accelerator applications.

## INTRODUCTION

The ultimate goal of several research efforts is to integrate high-gradient radio-frequency (rf) structures into next generation particle accelerators. For instance, the Muon Accelerator Program is looking at developing low-frequency cavities for muon cooling, and the International Linear Collider is optimizing the performance of 1.3 GHz rf structures aimed at designing a 1 TeV electron-positron collider. Furthermore, the High Gradient RF Collaboration is examining high frequency ($f$ >10 GHz) structures intended for an electron-positron collider operating at energies in the TeV range. In all this research, the accelerating gradient will be one of the crucial parameters affecting their design, construction, and cost.

Limitations from rf breakdown [1] strongly influence the development of accelerators since it limits the machine's maximum gradient. The emission of electrons from the cavity surfaces seemingly is a necessary stage in the breakdown process, acting either as a direct cause of breakdown or as precursor for other secondary effects [2]. Typically, electron currents arise from sharp edges or cracks on the cavities' surfaces, where the strength of the electric field is strongly enhanced compared to that of the nominal field when the surfaces of the cavity are perfect planes. Subsequently, a stream of emitted electrons can be accelerated by the rf electric field toward the opposing cavity walls [Fig. 1(a)]. Upon impact, they heat a localized region, resulting in the eventual breakdown by a variety of secondary mechanisms. Therefore, it is advantageous to develop techniques that could suppress field emission within rf cavities.

It has been proposed [3] that high voltages up to about a gigavolt range may be sustained in voltage transformers, by adopting the principle of magnetic insulation in ultrahigh vacuum. The basic idea is to suppress field emission by applying a suitably directed magnetic field of sufficient strength to force the electrons' orbits back on to the rf emitting surface. More recently, it was shown that magnetic insulation could be very effective in suppressing field emission and multipacting in rectangular coupler waveguides [4]. Hence, the question arises whether the same principle is applicable to rf accelerating structures. In this Letter, we shall consider application of the concept to low-frequency (201-805 MHz) muon accelerator cavities.

## MAGNETIC INSULATION

### *Numerical Studies*

The basic concept of magnetic insulation is to suppress surface-damage from field emission by applying a suitably directed magnetic field of sufficient strength to force the electrons' orbits back on to the rf emitting source. In order to design a magnetically insulated (MI) rf, the idea is to place the magnetic field coils in the irises of open multi-cell cavities, and shape their walls to follow the field lines. Figure 1(b) depicts an example of employing this principle in an 805 MHz rf cavity with two coils, one on each side of the cavity. Figure 1(c) shows the energy of field-emitted electrons on impact as a function of the insulation magnetic field. For the simulation, we used CAVEL, a code that tracks particles from arbitrary positions on the walls of a cavity until their final position on some other surface. Curves are shown for three different accelerating gradients. Clearly, larger magnetic field values constrain the electrons to move within shorter distances off the surfaces and gain less energy before striking the surface. Compared to the impact energies in a conventional 805 MHz pillbox cavity (PB) [Fig. 1(a)] the energies in a MI cavity are three orders-of-magnitude lower when $B_{ins} \geq 0.3\,\mathrm{T}$.

Next, we attempt to make a first-order estimate of the required electron energy at impact to damage the cavity surface. We shall assume that such damage arises from fatigue by pulse heating [5] from the electron's bombardment. Accordingly, this energy is [6] $E_e = \dfrac{\delta \pi q \rho \sigma_r^2 c_s}{I \tau} \Delta T$, where $c_s$ is the specific heat, $\delta$ is the thermal-diffusion length, $I$ is the current, q is the electron charge, $\rho$ the material density, $\sigma_r$ is the radius of the spot the electrons create on impact, and $\tau$ is the rf pulse length. $\Delta T$ is the threshold temperature rise over which the surface becomes prone to fatigue. Considering

---

*Work supported by US DOE contract DE-AC02-98CH10886.

[#] diktys@physics.ucla.edu

a copper 805 MHz cavity, we estimate that $E_e \approx 40$ keV using the following parameters: $c_s = 0.385$ J/g-$^0$C, $\rho = 8.96$ g/cm$^3$, $\sigma_r = 40$ µm, $I = 0.1\,\text{mA}$, $\tau = 20$ µs, and $\Delta T = 110\ ^0$C [7]. Thus, if $B_{ins}$ is about 0.3 T, damage from field emission is significantly diminished.

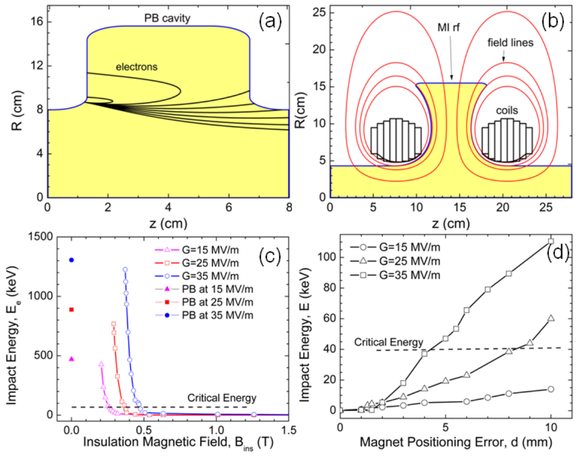
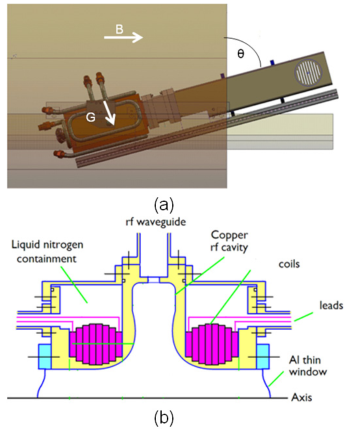


Figure 1: (a) Trajectories of electrons field-emitted in a conventional 805 MHz PB cavity; (b) A magnetic insulated 805 MHz cavity and two coils. (c) Plot of the energies of field-emitted electrons at impact versus the strength of the insulation field. The solid symbols indicate the impact energies for the PB cavity in Fig. 1(a). (d) Impact energies versus coil misalignments

Next, we explore the cavity's tolerances to misalignment errors by deliberately displacing the coils. In Fig. 1(d), we move the coils horizontally up to 5 mm while the cavity's position and the accelerating gradient remain fixed. The simulations suggest that up to a 5 mm misalignment of the horizontal coil is safe because the electrons strike with a impact energy less than the critical energy of 40 keV.

### *Experimental Studies*

It is critically important to the development of a magnetically insulated cavity that a well thought-out program be pursued. In collaboration with Fermilab, one experiment is already in progress and another one is under consideration. For the first experiment a box-shaped 805 MHz cavity has been designed and built so that it can be positioned in the center of an up to 4 T superconducting magnet and tested with the magnetic fields perpendicular to the rf electric field. The cavity was mounted on an adjustable support such that the angle between the rf electric field and the external magnetic field could be varied [Fig. 2(a)]. In the experiment, the maximum gradient was defined to be the limiting gradient above which the sparking rate was 1/20,000 pulses at 15 Hz. The cavity achieved only 24 MV/m and 31 MV/m, respectively, when the angle was $86^0$ and $88^0$. However, when the magnetic field was at right angles ($\theta = 90^0$) to the rf electric field, the maximum gradient was 36 MV/m. In this configuration, field emission seemingly was suppressed since no x-ray signal was detected. Although the first results are encouraging, the data are still preliminary and further tests are needed to fully verify the concept. In addition, it is crucial to test reproducibility of the aforementioned results and for this reason a second identical cavity is currently under construction.



(a)

(b)

Figure 2: Experimental verification of magnetic insulation showing the box cavity and the solenoid. B and G are, respectively, the magnetic field and the rf field. (b) Experiment to test magnetic insulation with a muon accelerator cavity.

Despite the fact that a rectangular cavity placed in a uniform field provides the simplest demonstration of the principle, a test of a cavity for a muon cooling lattice would need to place the primary focus coils in the irises of an open multi-cell structure and shape the walls of the cavity to follow the magnetic field lines[22] [see Fig. 2(b)]. In this experiment, superconducting coils would be mounted on either side of a cavity whose shape is such that the magnetic fields are parallel with the high gradient surfaces. Both coils and cavity could be operated at liquid nitrogen temperatures. Such cavity would form the basis of a demonstration experiment specifically for a muon accelerator application, and a preliminary experimental configuration can be found in Ref. 22. One thing to note is that it is likely that power demand may be a drawback of a MI rf cavity. Typical 805 MHz PB cavities have a quality factor, Q≈20,000 and a shunt impedance, $Z \approx 42\ \text{M}\Omega/\text{m}^{-1}$. While for an equivalent MI cavity [Fig. 1(b)], the quality factor is similar to the PB case, the shunt impedance is less by a factor of two[18]. Since the power scales as one over the shunt impendence, it is evident that MI cavities require at least twice the amount of power.

## MAGNETIC INSULATION

We shall now study the application of this magnetic insulation concept to the Muon Collider (MC) and Neutrino Factory (NF) lattices. A key challenge to realizing a muon accelerator lies in generating intense muon beams with small emittances via ionization cooling. Conventional cooling channels contain absorbers for reducing the momentum of the muon beam, PB rf cavities for restoring axial momentum, and multi-Tesla magnetic fields for focusing the beam through the absorbers.

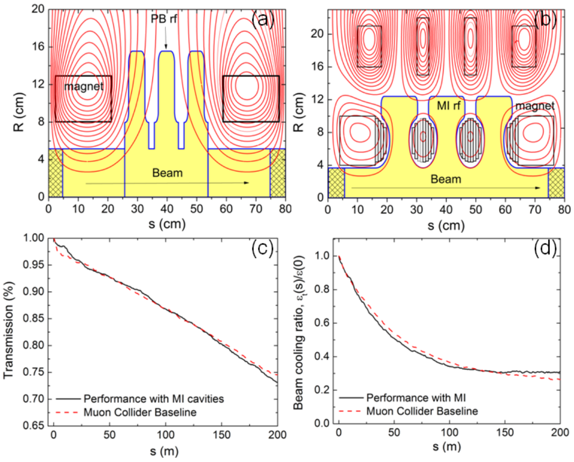


Figure 3: Layout of a NF cooling lattice with conventional PB cavities. Field lines crossing the cavity may trigger breakdown. (b) Scheme of the same lattice with MI cavities wherein the field lines now are parallel to the rf surfaces. The sparse pattern shows the absorber. (c) Lattice transmission vs. distance. (d) Transverse normalized emittance vs. distance. The solid line corresponds to a channel with magnetic insulated cavities; the dashed line represents the baseline parameters

Figure 3(a) shows a layout of a conventional channel that has been studied for use in the final 6D cooling-state for a muon collider. The lattice consists of a sequence of identical 80 cm cells, each containing three 8.1 cm-long 805 MHz PB cavities identical to that shown in Fig. 1(a) and two 4 cm thick LiH absorbers to provide the momentum loss. In addition, to ensure transverse focusing of the muon beam each cell contains two magnet coils of alternating sign, with a peak value of ~11 T. Clearly, under this configuration magnetic field lines are crossing the cavity. Electrons can ride along the magnetic field lines between the accelerating gap and can cause severe damage on the surface due to the focused current density. Figure 3(b) illustrates our proposed alternative option for the same cooling lattice but with MI cavities. Each cell contains now three 805 MHz MI cavities, the geometry of each being identical to that shown in Fig. 1(b). The two full and two half elliptical coils on the cavity irises ensure that the magnetic field lines coincide with the cavity's surface. The two orthogonal coils at the far left and right side serve as to focus the beam through the absorber. Figure 4(a) shows the equivalent magnetically insulated lattice for an NF with 201 MHz cavities. Note that in both cases [Fig. 3(b) and Fig. 4(a)] the field lines are parallel to the high-gradient surfaces and thus electrons are deflected before they can get accelerated by the electric field.

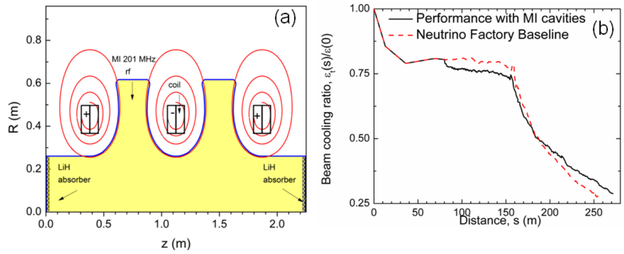


Figure 4: A Neutrino Factory front-end cooling lattice with magnetically insulated cavities.

Next, we use the simulation code ICOOL to compute the performance of a MI lattice. The lattice performance is quantitatively determined by two factors: The particle transmission T [Fig. 3(c)]; and, the cooling ratio $\varepsilon_t(s)/\varepsilon_t(0)$, wherein $\varepsilon_t(s)$ is the transverse emittance at point $s$, and $\varepsilon_t(0)$ is the starting emittance. Fig. 3 (d) and Fig. 4(b) plot the cooling rate for an MC and NF, respectively. As a baseline for the MC and NF we choose the numbers reported in Ref. 6 and 8. The data agree well with the baseline requirements suggesting that a magnetically insulated channel is likely a viable choice for a muon collider and a neutrino factory muon colliders.

## SUMMARY

In conclusion, applying a magnetic field tangential to the rf surfaces might well enhance the maximum achievable gradient for accelerating structures. Computations predict that this increase may occur because magnetic insulation suppresses field emission, and thus, no dark current can flow across the cavity. The good performance of the cavity in muon lattices indicates that this concept may prove a novel versatile tool for future particle accelerators, especially muon accelerators.

## REFERENCES

[1] H. Padamsee, J. Knobloch, and T. Hays, RF Superconductivity for Accelerators (Wiley, New York, 1998).
[2] R. B. Palmer et al. *Phys. Rev. ST Accel. Beams* **12**, 031002 (2009).
[3] F. Winterberg, *Rev. Sci. Instrum.* **41**, 1756 (1970).
[4] R. L. Geng et al., *Nucl. Instrum. Meth. A.* **508**, 227 (2003).
[5] D. P. Pritzkau and R. H. Siemann, *Phys. Rev. ST Accel. Beams* **5**, 112002 (2002).
[6] D. Stratakis, J. C. Gallardo, and R. B. Palmer, *J. Phys. G:Part. Nucl. Phys.* **37**, 105011 (2010).
[7] D. Stratakis, J. C. Gallardo, and R. B. Palmer, *Nucl. Instr. and Meth. A* **620**, p. 147 (2010).
[8] D. Stratakis et al., *Phys. Rev. ST Accel. Beams* **14**, 011001 (2011).