A Novel Method for Transport and Cooling of a Muon Beam Based on Magnetic Insulation

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Abstract. Unwanted field emission is a well known problem for high-gradient accelerating structures as it can cause damage and initiate breakdown. Recent experiments indicated that the deleterious effects of field-emission are greatly enhanced in the presence of external magnetic fields. In the context of designing a muon accelerator this imposes numerous constrains since rf cavities need to operate within strong magnetic fields in order to successfully transport the beam. Here, a novel design of a magnetically insulated cavity in which the walls are parallel to the magnetic field lines is presented. We show that with magnetic insulation, damage from field emission can be significantly suppressed. Effects of coil positioning errors on the cavity performance are discussed and the required magnetic field strength to achieve insulation is estimated. We present a conceptual design of a muon collider cooling lattice with magnetic insulated cavities and cross-check it's performance to the one with pillbox cavities. Finally an experiment to test magnetic insulation is described.

Keywords: muon accelerators, beam transport, field-emission, rf breakdown
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INTRODUCTION

Muon Collider [1, 2] lattices that have been designed and simulated provide the required cooling, but they require the rf cavity to operate in strong axial magnetic fields that focuses the muons. Typical rf frequencies on those lattices range from 201-805 MHz, with gradients from 12-25 MV/m, and the magnetic fields at the cavities ranges from 1.0 to 5 T. Any decrease in the rf gradient from its specified values proved deleterious, since it was accompanied by a drop in the transmission of muons due their fast decay.

Three experiments at the MuCool Test Area (MTA) explored the efficiency of pillbox rf cavities within magnetic fields: The first had a multi-cell 805 MHz cavity [3]; the second had a single 201 MHz one [4]; and, the third a single 805 MHz cavity [5]. All three trials showed that rf cavities did not operate well in external magnetic fields. In particular, the cavity windows in the first were punctured, and the second and third experiments revealed significant reductions in the maximum achievable rf gradients when the field was turned on; inspection of the cavities' surfaces noted severe damage also. According to a recent theory [6], this gradient-drop occurs after focused by the magnetic field electrons from a field-emission site damage a surface with high electric fields. Such surface damage would result by fatigue [7] from cyclical strains induced by local heating from the electrons. This theory agrees reasonable well with numerical simulations [8] and with the experimental data [5].

Cooling channels typically rely on rf cavities operating in high magnetic fields [9], so it is crucial to demonstrate that the technology is feasible and reliable. The intent of our present work is to design a "magnetically insulated" rf cavity, and study its application to muon ionization cooling lattices. The underlying principle is that a magnetic field can prevent an electrical breakdown by diverting the electron-flow generated and accelerated by a high-intensity electric field.

In this paper, we demonstrate that by designing a magnetically insulated cavity such that its walls are parallel to chosen magnetic-field contour lines, we can suppress damage from field emission. We then detail its application to cooling channels for a muon accelerator, and present a conceptual representation of a muon-transport lattice with magnetically insulated cavities. We demonstrate ionization cooling with such a lattice, and compare its performance against a conventional lattice with pillbox cavities.

THE PRINCIPLES OF MAGNETIC INSULATION

We could suppress the damage caused from field-emitted electrons by designing rf cavities such that all high gradient surfaces were parallel to the external magnetic field. Instead of focusing electrons, the field then would return them, with little energy, to near their points of origin. Fig. 1(a) illustrates our proposed magnetically insulated cavity. The cavity has two open irises, and its shape is constrained by the geometry of the two inner elliptical coils which, as we will show in the next section, will serve as to focus the muon beam. Note that the cavity's walls follow the magnetic-field lines that those coils generate. Note further that the outer bucking coils serve to modify the field lines so to improve the cavity's shape and performance.

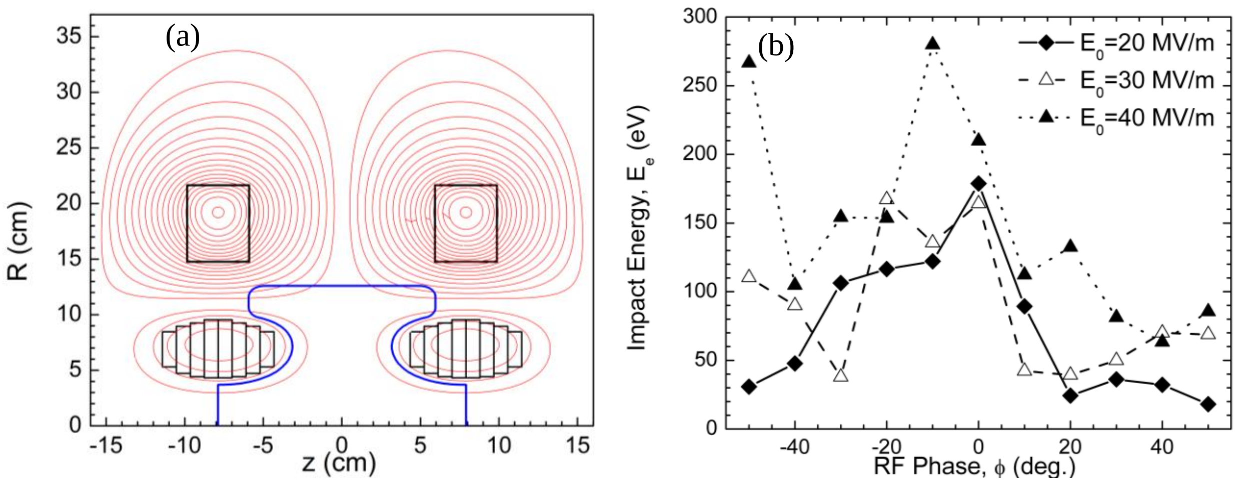

FIGURE 1. The principle of magnetic insulation: (a) Actual muon collider cavity; (b) incident energies of field emitted electrons.

Like in the pillbox rf case [10] we simulated field emissions within a magnetically insulated cavity via CAVEL; the results appear in Fig. 1(b). In the results shown herein the electrons are tracked from the location of the highest surface rf electric field [arrow in Fig. 1(a)]. We interpret the data as follows: Emitted electrons initially are accelerated by the electric field away from that surface. Then, as they attain significant momentum, the magnetic field deflects them and directs them back to the surface. Depending on their phase of emission, they may return to the surface after a single half-loop, or they may make several loops, but they always return to the surface. This is the standard font and layout for the individual paragraphs. Figure 1(b) shows their corresponding impact energies versus phase. We choose three different accelerating gradients, which are within the typical operating range for a muon accelerator. Interestingly, in all cases, the impact energy is lower by three orders-of-magnitude than that with the pillbox cavity (i.e $E_e < 1$ keV). One difficulty might arise due multipacting, since now, the energies with which electrons return to surfaces are in the range of a few hundred eV where secondary emissions are maximal. However, a simulation conducted at SLAC revealed no problems from multipacting inside this insulated cavity [11].

A lowest order estimate on the required energy to damage the cavity can be made. The induced surface temperature rise from the electron impact is given by [6] $\Delta T = W\tau S / E_e \rho C_s$ where C_s is the specific heat, ρ is the density, W is the power per unit area, E_e is the impact energy, τ is the rf pulse length, taken to be 20 µs at 805 MHz, and S is the energy deposition at the surface. Significant damage occurs when $\Delta T \approx 110\ ^0$C [12], which means that $E_e \approx 40$ keV is a enough to damage the cavity. Using this information we intend to estimate the strength of magnetic field required to successfully achieve magnetic insulation. Shown in Fig. 2(b) is a plot of the electron impact energy versus the strength of the surface magnetic field. As expected when we increase the strength of the coils the insulation becomes more effective, reducing both the electron "travel time" and their impact energies. It becomes apparent that when the magnetic field, B, is > 0.5 T the cavity is insulated.

Next, we explore the cavity's tolerances to misalignment errors by deliberately displacing the coils horizontally and vertically up to 5 mm. In all cases, both the cavity's position and the accelerating gradient remain fixed. The horizontan movement data are shown in Fig. 2(a). The data reveal that the cavity appears more sensitive to positional errors of the vertical coils. This fact may anticipated simply because the contour of the field lines along the emitter's vicinity in Fig. 1 change more abruptly in the vertical direction rather than the horizontal. Most importantly, 1-2 mm coil misalignments in both directions do not increase substantially the electron-impact energy; thus, operating the cavity under those conditions is likely to be safe.

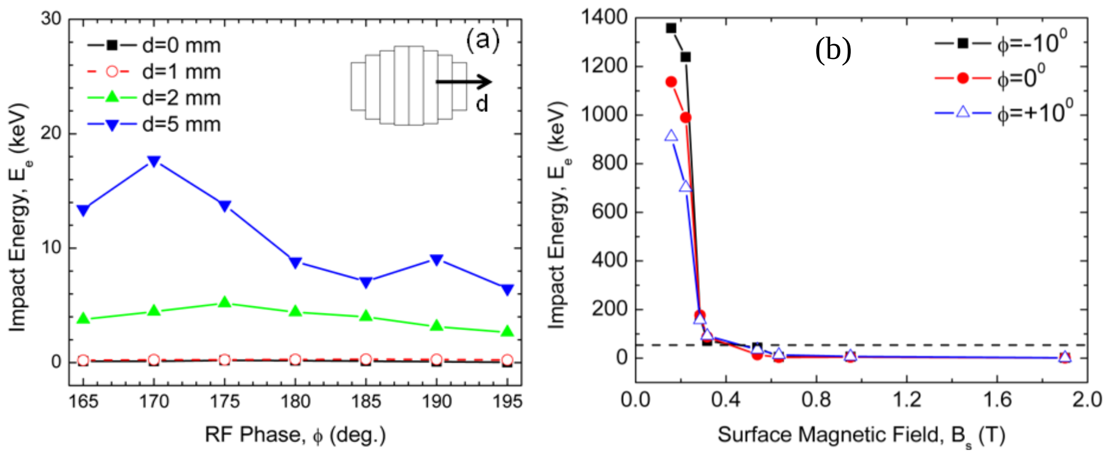

FIGURE 2. Investigation of the cavity tolerances by: (a) moving coils horizontally; (b) increasing the magnetic fields.

IONIZATION COOLING WITH MAGNETICALLY INSULATED CAVITIES

As we pointed out in the introduction, because of the way muons are produced, they inherently begin life in a beam with a very large phase-space volume. Ionization cooling therefore is necessary to transport the beam through a reasonable accelerator lattice. Typically, each cooling cell must have three components: An rf cavity, an absorber, and a solenoid magnet to focus the passing beam and thus eliminate scattering in the absorber. Absorbers with a high rate of energy loss are typically preferred, such as liquid hydrogen or lithium hydride (LiH). Even though cooling can take place at any momentum, it is better if it occurs at the momentum where the curve of the energy loss reaches its minimum so around 200 MeV/c.

Having described the basic configuration of a muon cooling lattice, it is important that we emphasize several details for achieving successful cooling. First, in order to eliminate scattering, the minimum value of the transverse beta function β_T, should be small over an axial region longer than the absorber. Second, the momentum acceptance of the lattice should overlap the reference momentum, and be larger than the momentum spread of the desired beam. Third, since the solenoid system will introduce angular momentum, altering polarity coils are preferred where the field reverses in alternate cells. We note that a more detailed description about the lattice design can be found in Ref. 13.

Figure 3(a) shows the design of a conventional lattice that has been studied [1, 14] for use in the final 6D cooling-state for a muon collider. The channel consists of a sequence of identical 80 cm cells, each containing three 8.1 cm-long 805 MHz pillbox cavities identical to that discussed in Ref. 10, with 1.9 cm spacing, and two 4 cm thick LiH absorbers to assure the energy loss. Moreover, each cell contains two solenoid coils of alternating sign, yielding an approximate sinusoidal variation of the magnetic field in the channel with a peak value of ~11.7 T, providing transverse focusing with low beta value of 4.8 cm. This low value of beta is required as the normalized rms emittance must be reduced < 0.4 mm when the beam exits the channel [2]. The axial length of the solenoids is 19 cm, with an inner radius of 8.1 cm, an outer radius of 13 cm, and a current density of 320 A/mm^2. Table 1 summarizes the main parameters of this lattice. A problem arises from the fact that, for successful beam transport, the cavities have to maintain a 25 MV/m gradient within a 5 T magnetic field.

Figure 3(b) illustrates our proposed alternative option for the same cooling lattice but with magnetic insulated cavities (MI lattice). Each cell contains now three 805 MHz magnetic insulated cavities, the geometry of each being identical to that shown in Fig. 1. The two full and two half elliptical coils on the cavity irises ensure that the magnetic field lines coincide with the cavity's surface. As also mentioned before, we incorporated the outer bucking coils (BC) to shape the field lines so that the form of the resulting cavity becomes more efficient in terms of engineering designs. The two orthogonal coils (FC) at the far left and right side serve as to focus the beam through the absorber. More specifics about the position of all coils as well as their corresponding current densities can be found in Ref. 12. Table 1 summarizes the main parameters of the MI lattice and compares them to the parameters of the aforementioned PB lattice.

TABLE 1: Overview of the parameters of the two lattices.

	PB Channel	**MI Channel**
Lattice period (cm)	80	80
RF frequency (MHz)	805	805
Peak rf gradient (MV/m)	25	25
RF phase at 0-crossing (deg.)	30	30
Max. axial magnetic field (T)	11.7	13.0
Average momentum (MeV/c)	0.199	0.199
Minimum transverse beta (cm)	4.8	4.7
Axial absorber length (cm)	8.0	10.0
Absorber material	LiH	LiH

The physical parameters of the MI lattice and PB lattice with the ICOOL codewere examined in detail in Ref. 8. The results highlight the following points: First, the MI lattice, like the PB lattice, has the same momentum acceptance with the desired central (reference) momentum ≈200 MeV/c. Second, the beta in both cases remains minimal for ≈4 cm, matching well with the absorber's axial length. Moreover, in both lattices, the minimum value of β at the center of the absorber at central momentum was ~4.7 cm, implying that they can cool up to the same equilibrium emittance. Third, in order to achieve the desired β the MI lattice requires a stronger magnetic-peak magnetic field (i.e. B=13.0 T), and has richer longitudinal harmonics of the axial fields; these harmonics initial were thought to entail considerable particle loss.

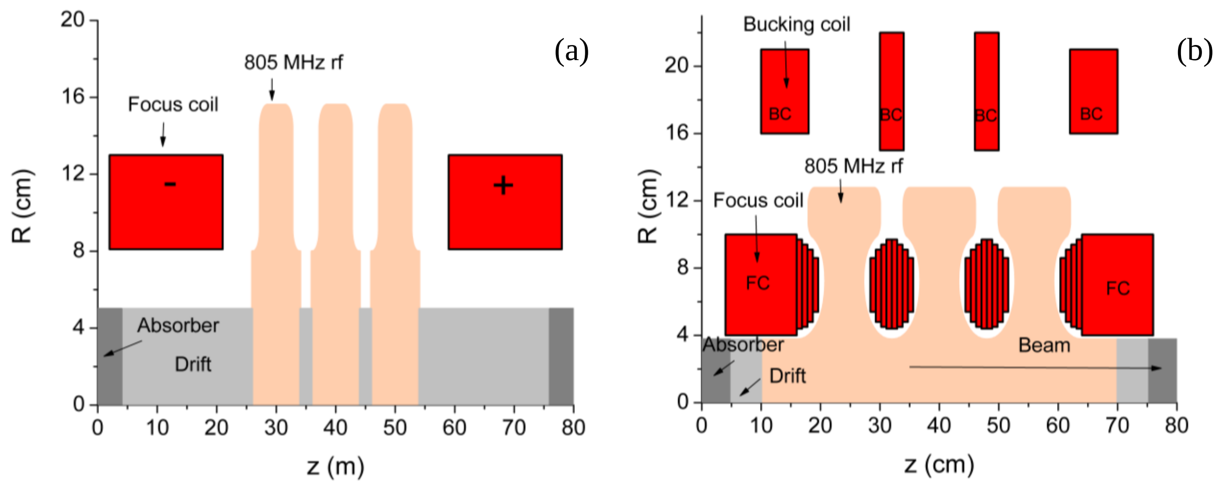

FIGURE 3. Two alternate cooling scenarios for the final 6D cooling stage of a muon collider: (a) Conventional lattice with pillbox cavities; (b) our proposed lattice with magnetically insulated cavities.

Quantitatively, two factors determine the performance of a cooling channel. First, is the lattice transmission T, a factor that quantifies the number of particles passing through the lattice. Second, is the ratio $\varepsilon_t(z)/\varepsilon_t(0)$, wherein $\varepsilon_t(z)$ is the transverse emittance at any point z, and $\varepsilon_t(0)$ is the starting emittance. Figure 4 illustrates the cooling performance of our magnetic insulated lattice (black line). These results have been obtained by post-processing the output of ICOOL with ECALC9 [12]. Figure 4(a) displays the ratio of the transverse emittance along the lattice to its initial value at z=0. After about 130 m, emittance has fallen by a factor of 3.5, with a transmission of 70% [see Fig. 4(b)]. There is no further cooling beyond that point. Interestingly, the MI lattice performs similarly to the PB lattice (dashed line) with transmission, and cooling factor that all meet the aforementioned specified requirements.

Figure 5 illustrates the cooling effect in the transverse direction, where we show the transverse trace space at different locations along the lattice. The reduction of the phase-space clearly is visible as the beam propagates through the lattice. So far, we assumed a linear transport-channel. We note that demonstrating 6D cooling is a more complex problem as it requires a bend magnet to introduce dispersion so that 6D cooling results from emittance exchange between the transverse- and longitudinal-directions.

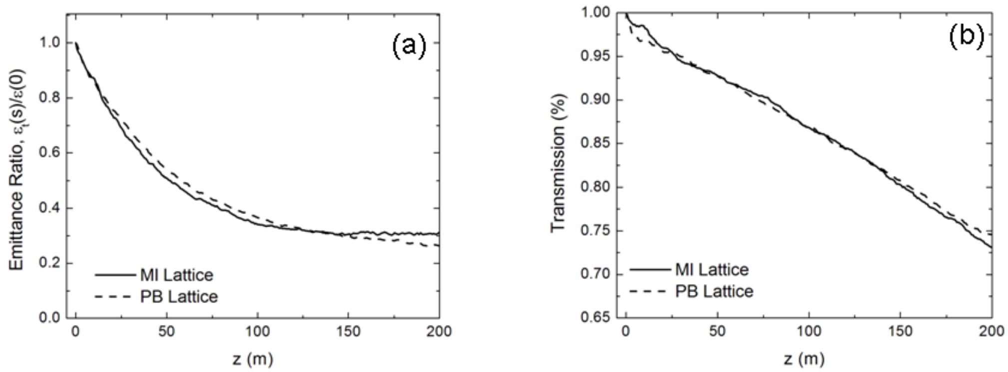

FIGURE 4. Performance of our proposed magnetic insulated lattice (solid line) vs. the conventional lattice with pillbox cavities (dashed line): (a) rms transverse emittance; (b) transmission.

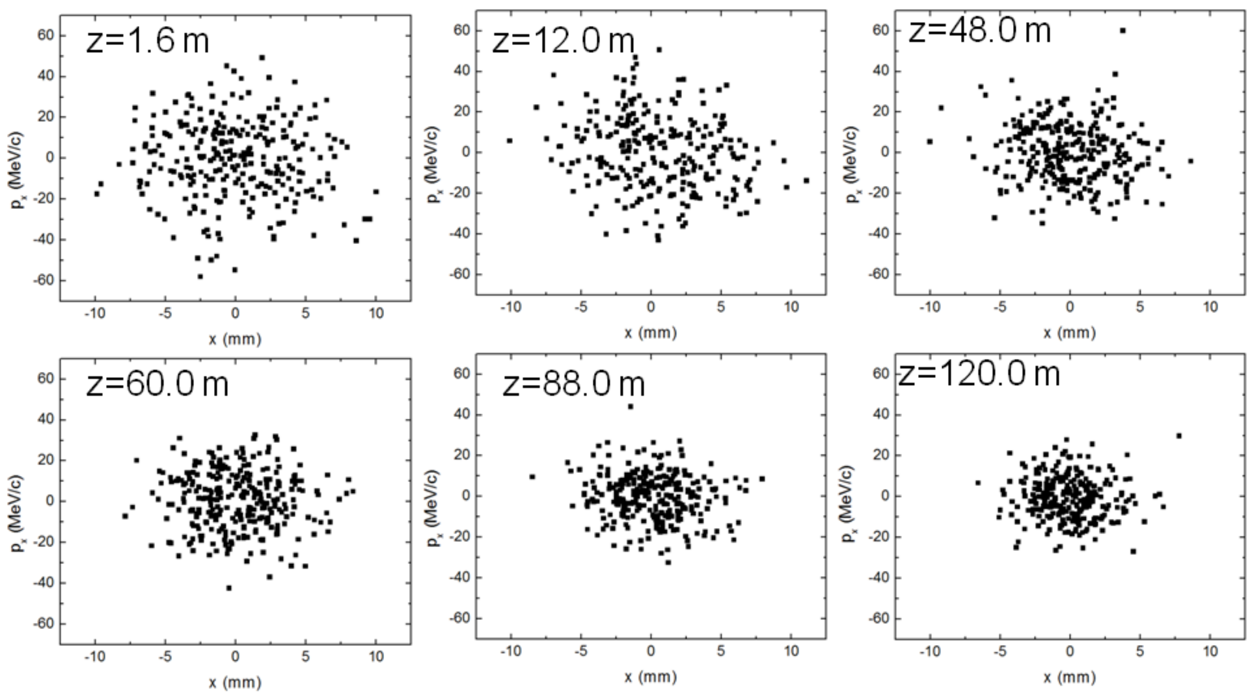

FIGURE 5. Reduction of the transverse phase-space volume by ionization cooling in a magnetically insulated lattice.

Before concluding let us make a few more comments about the practical aspects of our proposed magnetically insulated cavity. A proof-of-principle experiment [12] is underway to provide crucial information on the practical aspects of the concept i.e. power requirements, cavity performance and its tolerances to coil positional errors. In this experiment, the rf power will be generated by a FNAL 12 MW peak-power klystron [10]. The power from the klystron will be delivered through a standard WR 975 waveguide to the cavity by a slot either at its outer radius or from the cavity side. A preliminary simulation of this configuration with the CST Microwave Studio program showed no difficulties, and is illustrated in Fig. 6.

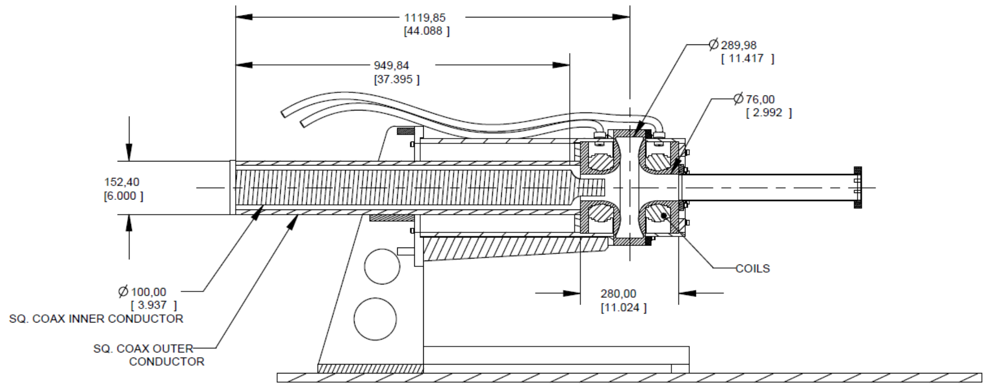

FIGURE 6. Design of a proof of principle experiment to test magnetic insulation.

SUMMARY

RF breakdown in magnetic fields is a continuing problem that limits the performance muon accelerators. It is believed that the cause of breakdown is the damage induced by the impact with the cavity's surface of a focused beam of field-emitted electrons. In this paper, we presented a novel design of a magnetically insulated cavity wherein the magnetic fields are parallel to its emitting surfaces. We showed that, with magnetic insulation, the field-emitted electrons impact the cavity surface with energies three orders-of-magnitude less than in conventional pillbox cavities; consequently, damage from field emission is suppressed significantly. We presented a conceptual design of a cooling lattice with magnetically insulated cavities and examined its performance. Similar to a conventional pillbox cavity lattice, it successfully transported and cooled the muon beam. Finally, an experiment to test magnetic insulation was described.

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