EXPERIENCE WITH MAGNETIC SHIELDING OF A LARGE SCALE ACCELERATOR

S. Nagaitsev†, C. Gattuso, S. Pruss, and J. Volk,
FNAL*, Batavia, IL 60510, USA

Abstract

It is not unusual to place multiple accelerators in a common enclosure to save on civil construction costs. This often complicates operations, especially if accelerators are affecting each other. At Fermilab, the influence of a rapidly cycling Main Injector (MI) synchrotron on an antiproton storage ring (Recycler), placed in a common tunnel, was initially found to be unacceptable for a reliable operation of the Recycler. Initial closed orbit excursions in the Recycler ring during the MI ramp were in excess of 5 mm (rms). This paper describes a shielding technique, used to reduce these orbit excursions by a factor of five.

1 INTRODUCTION

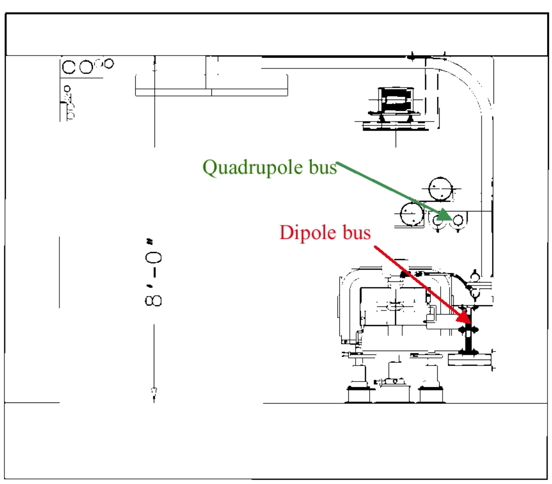

Figure 1: Tunnel cross-section in a standard arc cell showing a Main Injector dipole near the floor and a Recycler gradient magnet above it and near ceiling.

Figure 1 shows a cross-section of the Main Injector (MI)/Recycler tunnel. Stray magnetic fields originate from both the quadrupole and the dipole bus (supply and return) excitations during the MI ramp (8 to 150 GeV). At the top of the ramp the current in the quad and dipole buses are 3.5 kA and 9.2 kA correspondingly. Both buses contribute about equally to the transverse magnetic field at the Recycler beam location.

Figure 2 shows the measured transverse magnetic field in the Recycler beam pipe without a magnetic shield during the MI ramp.

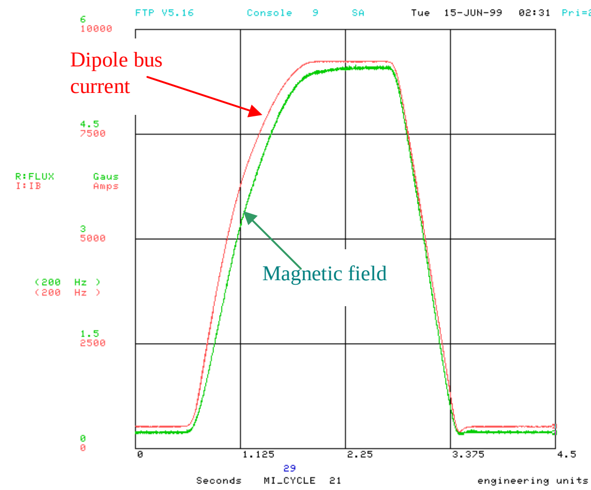

Figure 2: Dipole bus current (2.5 kA/div) and transverse magnetic field (1.5 G/div) as a function of time (4.5 s full scale) during the 150-GeV MI ramp. The quad bus was also energized.

The observed transverse fields were on average about 5 G but in some places as high as 10 G. These fields are distributed along the entire 3.3-km long Recycler circumference. It was estimated that if unshielded, these fields can move the closed orbit of an 8.9 GeV/c Recycler beam by as much as 30 mm. The problem of stray magnetic fields was recognized early on during the design stage of the Recycler ring [1]. The implemented shielding technique was to wrap the elliptic Recycler vacuum tube (48 mm x 100 mm) with two layers of high-permeability shielding material. For the inside layer Carpenter High Perm "49" alloy 12" wide, 0.004" thick foil was chosen. This foil material came as a coil, annealed (per manufacturer spec) and certified. According to the manufacturer's spec this material has an initial μ of about 8,000, a maximum μ of 150,000 and a saturation inductance of 13 kG. This foil was wrapped along the beam tube in pieces as long as one can handle and attached to the tube by Kapton tape. The circumference of the Recycler tube is about 9" so there was about 3" or less of overlap between two edges.

The outer layer was a silicone steel alloy AS-0 from Eagle Magnetic Co., Inc. It came as a coil 14.5" wide and 0.006" thick, certified per MIL-N-14411C specification. It was also wrapped along the beam tube in long pieces. The direction of wrapping was across the coil roll direction and it created a one turn with a small (about 1") overlap. The gap between the two layers (the "49" alloy and the "silicone alloy") was created by a fiberglass cloth of about 1/8" - 1/4" thick.

†nsergei@fnal.gov
*Operated by Universities Research Association, Inc., under Contract No. DE-AC02-76CH03000 with the U.S. Department of Energy

Figure 3 shows the measured transverse magnetic field inside the shielded (as specified above) Recycler beam tube at the same tunnel location as in Fig. 2. The measurements of the magnetic field were made with a Hall probe (zeroed prior to the MI ramp).

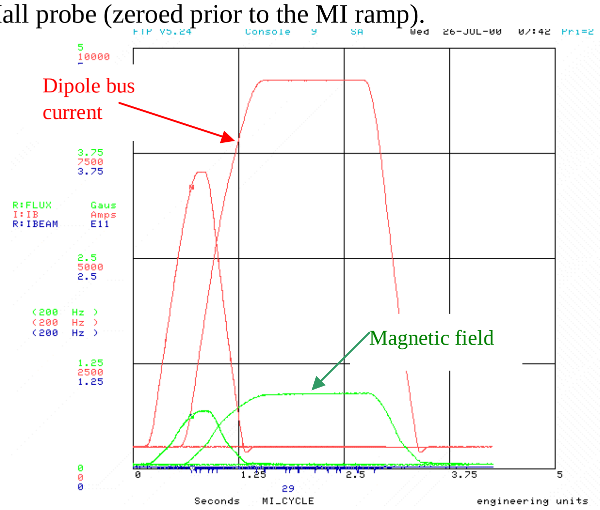

Figure 3: Dipole bus current (2.5 kA/div) and transverse magnetic field (1.25 G/div) as a function of time (5 s full scale) during the MI ramp. The quad bus was also energized.

The installed magnetic shielding reduced the transverse magnetic field on average by a factor of 6. The measured rms Recycler closed orbit excursion during the MI ramp with this shielding was 5 mm in both planes. This was determined to be inadequate and tests were initiated to design a shielding arrangement that would reduce the stray magnetic field by another factor of 10 or more. In addition, the field of 10 G should not saturate the shield.

2 SHIELDING COEFFICIENT

For an infinitely long cylinder with a wall thickness *t* and diameter *D* of a constant permeability μ in a uniform magnetic field the attenuation coefficient *k* is well approximated by the following expression:

$$k \approx 1 + \frac{\mu t}{D}. \qquad (1)$$

This formula is also valid for a finite length cylinder if its length is greater than 4*D*. For an ellipse one should probably use the larger of two sizes instead of the diameter for estimates. For multiple isolated layers the total coefficient is somewhere between the sum and the product of individual coefficients (depending on geometry). Since in most cases the permeability of the shield depends strongly on the flux density, the initial value of μ should be used for conservative estimates in low fields.

3 TEST RESULTS

To test various shielding arrangements and to measure the attenuation coefficient we have employed 20" diameter Helmholtz coils capable of producing fields of up to 10 G (dc or ac). The coils were large enough to simulate field at "infinity" for tube samples of up to 4" in diameter. The measurements were done by a 3-axis magnetic sensor [2] with a resolution of about 1 mG. Prior to measurements the probe was zeroed in a zero-field chamber. Measurements were performed with a 1-Hz ac magnetic field.

First, it was found that the silicone iron performs differently if wound in the roll direction (opposite to what was done initially). Figure 4 shows a comparison of two measurements performed with silicone iron only, wound on a 4" OD tube. The probe was placed in the center of the tube. The external field, generated by Helmholz coils, was calibrated without the tube.

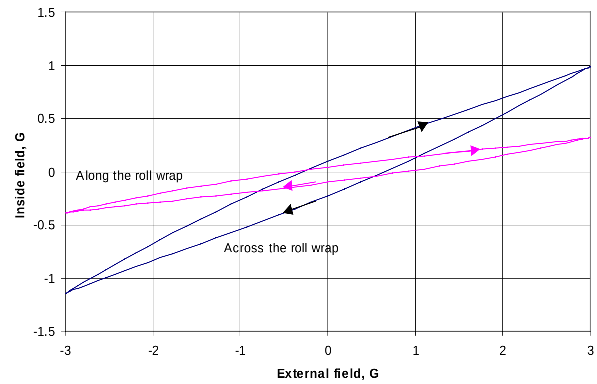

Figure 4: Comparison of two wrapping techniques for the silicone iron (outer shield layer). There is a factor of three difference between two wrapping styles.

The shielding coefficient is enhanced by a factor of three if the wrapping is done along the direction of the spool roll (as supplied from the factory). Along the beam tube the neighboring wraps were overlapped by 1".

For the inside layer a different (from the original Carpenter Alloy "49") was chosen. We compared several samples of a "μ-metal" alloy, supplied by various manufacturers. The tested materials had very similar manufacturer specifications and their shielding performance was identical with the uncertainty on the measurements. It was also found that all tested materials had a very isotropic nature: the direction of the roll did not affect the shielding performance. The material was then chosen on the cost basis. It was AD-MU-80 high nickel steel supplied by AD-VANCE Magnetics, Inc [3]. The material was delivered in 15" wide, 0.004" thick spools, annealed per manufacturer's specs and certified.

Three different wrapping techniques were tested. In all three the outer layer was the silicone iron, separated from the inside layer by a 1/8" gap and wound as described above. The inside layers were: (1) Alloy "49" and AD-MU-80 on top of it, (2) AD-MU-80, 1/8" gap, Alloy "49" and (3) AD-MU-80, 1/8" gap, AD-MU-80. Figure 5 shows a comparison of these three styles (three layers each) wound on a 4" OD tube. The external field was changed from -1 G to 9 G and back at 1 Hz. The performance was compared by comparing the total inside field swing when the external field changes by 10 G.

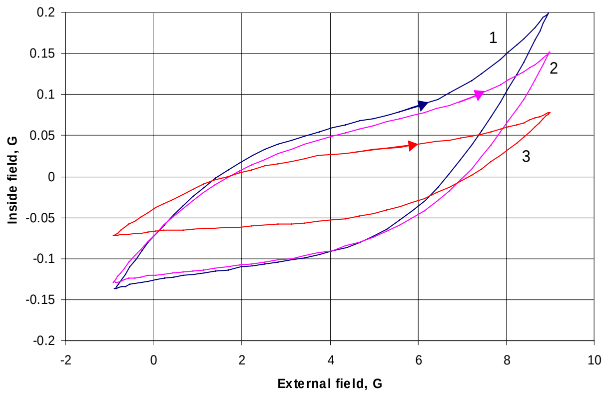

Figure 5: Comparison of three-layer wraps (see text for details).

Styles (1) and (2) had very similar results 0.34 G and 0.28 G field swings or the shielding coefficient of about 30. Moving the Alloy "49" to the outside of the AD-MU-80 resulted only in a small enhancement. One can gain another factor of two by adding one more layer of high nickel steel (3): 0.15 G field swing.

4 IMPLEMENTATION

For the final implementation we have chosen technique (1). It required several steps: (a) removing the outer silicone iron shield, (b) cutting it in shorter pieces, (c) removing the cloth spacer, (d) wrapping the tube with one layer of AD-MU-80 and the spacer, and (e) winding the silicone iron in its original roll direction. This was done for the entire Recycler ring. It resulted in a factor of 30 reduction of stray magnetic fields as compared with Fig. 2. The rms closed orbit excursions for both planes were measured to be about 1 mm.

5 DISCUSSION

Shielding the Recycler beam tube only eliminates the transverse fields at the orbit. It might not reduce the flux through the Recycler orbit. A 10 V per turn energy gain is needed to change the Recycler beam energy by 1 MeV during the MI ramp. This energy gain can exist if there is a 100 kG-m^2/s flux change through the orbit. If one divides this number by the Recycler circumference of 3.3 km it gives 30 G-m/s per meter of orbit length. This is not a very large number if one thinks of how much steel there is in the tunnel walls, magnets and shielding. Since the closed orbit variations were reduced to an acceptable limit we will be able separate the effect of energy change and the deflection. This betatron-style energy variation, if found, would require intercepting the flux before it reaches the Recycler orbit plane. Active devices are also not out of consideration. However, the beam energy deviation is equivalent to the change in the vertical field integral $B_y dl$. We have observed that the horizontal closed orbit moves to the inside of the ring in the areas of high dispersion. The measured move is equivalent to a change in the vertical field integral by 6×10^{-4} or to a presence of 0.34 G vertical magnetic field everywhere on the Recycler orbit, which is consistent with results in Fig. 5.

6 CONCLUSIONS

1. The effective μ calculated from Eq. (1) for the measured attenuation coefficents is an order of magnitude (or more) smaller than the lowest one provided in the material certificate.
2. Alloy "49" material had a very low attenuation coefficient. It did not perform as expected.
3. The attenuation coefficients for multiple layers of shielding material (if separated by a small gap) add rather than multiply.
4. It is important to keep in mind that some materials can be anisotropic and the roll direction can affect the shielding performance.

7 ACKNOWLEDGEMENTS

We are grateful to our colleagues B. Brown, A.C. Crawford, G.W. Foster, and J. Marriner for discussions. We would like to thank the entire staff of the mechanical support department of the Fermilab's Beams division for helping us to install the shielding in the tunnel.

8 REFERENCES

[1] G. Jackson, "The Fermilab Recycler Ring Technical Design Report", Fermilab preprint FERMILAB-TM-1991, Nov. 1996.

[2] Magnetoresistive sensor hybrid HMC2003, Honeywell sensor products.

[3] http://www.advancemag.com