PERMANENT MAGNET DESIGN FOR THE FERMILAB MAIN INJECTOR RECYCLER RING

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ABSTRACT

The design of permanent magnets for use in the Fermilab Main Injector "Recycler" ring is described. The magnets are a hybrid design with the field shape determined from accurately machined pole tips and the field driven by strontium ferrite blocks. The choice of magnetic material is discussed. A temperature compensation scheme has been demonstrated which uses a low Curie-temperature alloy to null out the intrinsic temperature coefficient to the ferrite. 1.2m prototype magnets have been constructed which achieve the design goal of dB/B < 10-4 over an aperture of 3.5"(h) x 2"(v).

I. INTRODUCTION

Raising the luminosity of the Tevatron requires collecting and stacking more antiprotons. A key element in this is the "Recycler" ring [2], an 8 GeV storage ring located in the 3.3km Main Injector tunnel under construction at Fermilab [3] Permanent magnets are an attractive option because of the fixed energy and the 0.1T average guide field. Low cost and reliability are also important considerations in favor of permanent magnets. A workshop was held at LBL in November 1994. Since the successful outcome of that workshop, prototype work has begun with the goal of starting production in 1996 and commissioning the ring in 1998.

II. BASIC DIPOLE MAGNET DESIGN

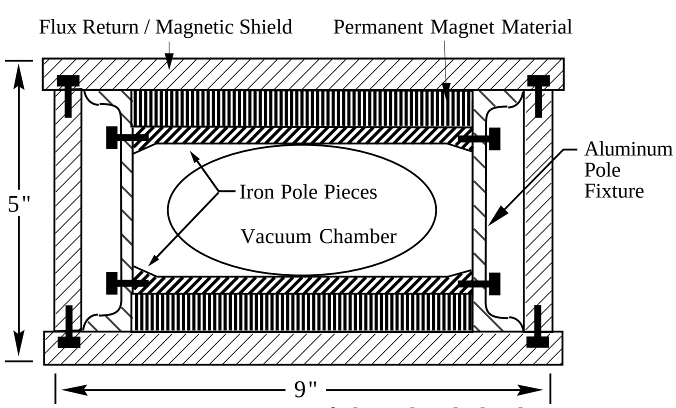

Figure 1: Cross-section of the 1 kG hybrid permanent magnet dipole. This design duplicates the Main Injector beam pipe dimensions and good field aperture (±1.75" at $\Delta B/B_o=10^{-4}$). The overall dimensions are 5"x9" and the weight of a 6 m section is approximately 2500 lbs. The field is driven by two permanent magnet blocks 3/4" thick by 6" wide.

In this "hybrid" design, the field quality is determined largely by the shape and placement of the iron pole tips located immediately above and below the beam pipe. The flux return is fabricated from 1/2" thick bar stock and provides a "box beam" structure which provides most of the mechanical rigidity. The peak field in the flux return is approximately 6 kG.

The assembly sequence used for the prototypes is to build the magnet from the inside out. First, the pole tip spacing is set by clamping them into position against a precisely machined 2.0000" thick bar of tool steel, then bolting or pinning them to side supports made from aluminum U-channel. This ensures the parallelism of the pole pieces which is essential to minimize gradient errors. Next, individual bricks are clamped or glued onto the pole tip/side support structure. Finally the entire assembly is slid into flux return and tested with a rotating coil harmonics probe.

The overall strength of the magnet can be controlled by any of the following: adjusting the amount of magnetic material included in each magnet, sorting the bricks by strength, using a commercially available fixture to perform a controlled demagnetization of the bricks to a standard level, or inserting small steel rods into the region alongside the bricks to help "steal" flux away from the pole tips and thereby trim the magnet strength. The gradient and sextupole can be controlled by means of wedge or parabolic end shims affixed to the ends of the pole tips. This procedure is straightforward because the shims need only function at one level of magnetic excitation. We plan to reserve one end of the magnet for production trims to ensure that all magnets have identical multipole content, and reserve the other end for "field modifications" to adjust e.g. the tune or chromaticity of the ring.

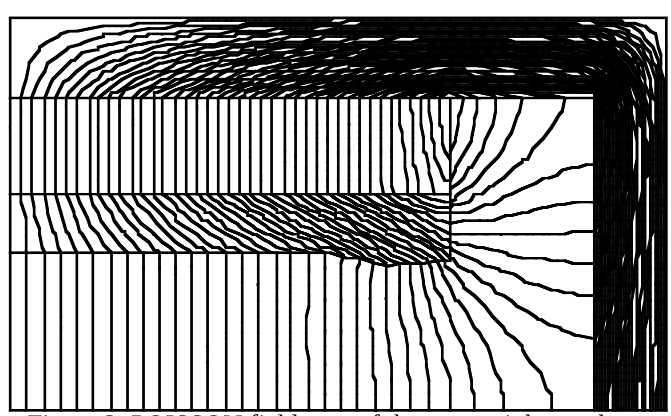

Figure 2: POISSON field map of the upper-right quadrant of the permanent magnet dipole shown in fig.1.

III. CHOICE OF MAGNETIC MATERIAL

Several magnetic materials were considered for the Recycler magnets, including Samarium Cobalt, Alnico, Neodymium-Iron-Boron, and Strontium or Barium Ferrite. Strontium Ferrite was selected on the basis of cost, ease of fabrication, radiation hardness, and stability over temperature and time. Samarium cobalt was roughly 30 times more expensive and has suspect radiation resistance [4]. Alnico was approximately 10x more expensive and an optimized Alnico design results in a tall, bulky magnet. Barium Ferrite is a largely obsolete material with no advantages over Strontium Ferrite and was not seriously considered.

IV. SAMPLE-TO-SAMPLE UNIFORMITY

Strontium Ferrite is the most commonly used permanent magnet material in automotive applications and can be obtained in standard sizes and strengths from a number of manufacturers [5]. We chose the standard 4"x 6"x 1" high "bricks" made of Type 8 strontium ferrite for the magnets in our prototype program. Samples of ~100 bricks were obtained from a number of foundries, and a single-brick testing device was made at the Magnet Test Facility at Fermilab. The design of our hybrid magnet makes the field quality insensitive to the details of the magnetization. of the material. Thus the magnetic strength of each brick could be adequately characterized by a test fixture which consisted of a magnetic circuit with approximately the same reluctance as the brick would see in the final magnet design. Individual bricks were inserted in the magnetic circuit and the resultant flux was recorded via a pickup coil and integrator. The distribution of brick strengths from samples one lot from one particular vendor is given in the figure below.

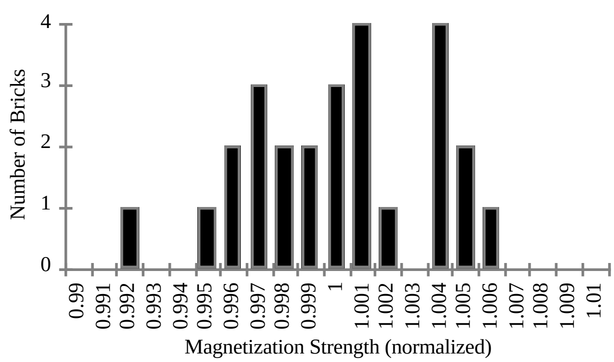

Figure 3: Histogram of the first 26 bricks tested with the MTF single brick field strength tester. The full spread of the bricks tested was 1.3% and the RMS spread was 0.3%. This measurement indicates that within a single lot of bricks we expect the variation to be less than the ±10% tolerance specified by the manufacturer.

V. TEMPERATURE COMPENSATION

One major drawback of strontium ferrite in accelerator applications is a reversible temperature coefficient of the residual field Br of -0.19%/°C. A technique has been proposed and tested [6] which uses an Iron-Nickel alloy with a Curie Temperature of ~55°C to shunt flux away from the pole tip in a temperature-dependent manner and thereby null out the temperature coefficient of the magnet. See fig. 4

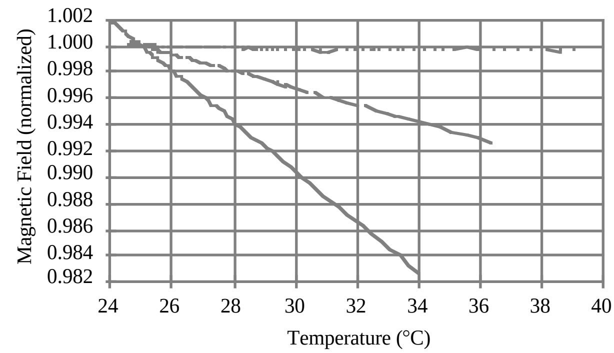

Figure 4 Cool-down curves showing variation of the magnetic field in a permanent magnet prototype with various size temperature compensation shunts. Bottom curve: uncompensated magnet showing the expected temperature coefficient of -0.19%/°C. Middle curve: first attempt at a temperature compensation shunt. Top curve: second attempt using a shunt of a larger size estimated from the performance of the first shunt. The temperature coefficient has been reduced by approximately two orders of magnitude, more than adequate for our application.

IV. LATTICE AND MAGNET OPTIONS

The lattice and permanent magnet design present a set of interrelated tradeoffs involving field strength vs. number of magnets, separated function vs. combined function magnets, laminated vs. "bar stock" construction, and sagitta'ed magnets vs straight magnets with a larger horizontal aperture. The four main lattice options under consideration are shown in fig. 5.

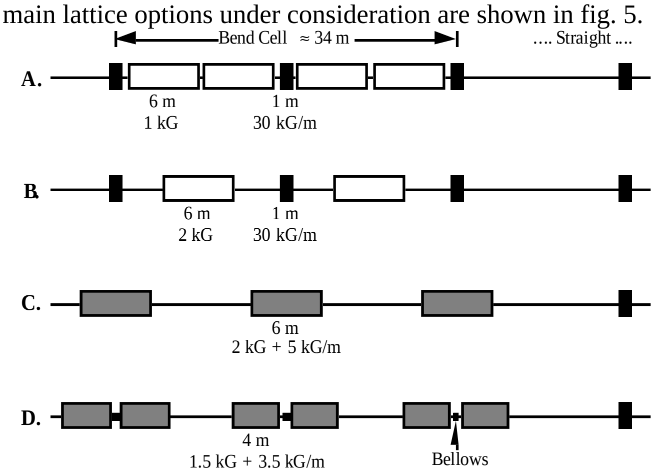

Figure 5: Sketch of the permanent magnet options under consideration in the magnet prototype program. Option A is a direct copy of the Main Injector lattice, while the 1.5 kG combined function option D is currently favored.

The "bar stock" magnet construction chosen argues in favor of straight magnets. Combined function magnets (fig. 6) reduce the number of quadrupoles from 208 to 36 at the cost of complicating the dipole pole tip machining and magnet measurements, and reducing the bend field by about 5%. A stronger field can be obtained by putting more bricks behind the pole tips, but one reaches a point of diminishing returns as the field asymptotically approaches the residual field Br of the driving material.. At the present stage in our prototype program we favor a 1.5kG combined-function, non-sagitta'ed magnet driven by a single 1" thick brick behind each pole tip.

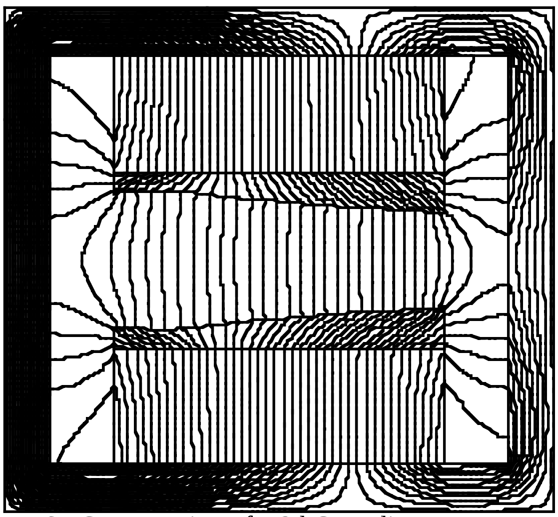

Figure 6: Cross section of a 2 kG gradient-sector magnet for lattice option C described in the text. The field is driven by two 1" high by 6" wide permanent magnet bricks at each pole tip. Overall dimensions are 8" x 12". The magnetic center of this dipole is 12" from the beam, so that its gradient is intermediate between that required for the arcs (17") and dispersion suppresser dipoles (8.6") needed for lattice option C.

VII QUADRUPOLE DESIGN

The quadrupole prototype currently under construction is shown in figure 7.

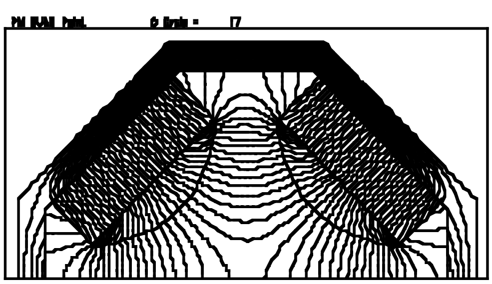

Figure 7: Magnetic field map for the upper half of the permanent magnet quadrupole magnet cross section used in all lattice options. Field shaping is provided by iron pole tips with circular inner surfaces. The field is driven by Ferrimag 8A material (B_R=3.9 kG) in blocks 1" x 3" in cross section. An iron flux return shell 1/2" thick surrounds the assembly.

The quadrupole magnet has the additional challenge that the strengths of the diagonally opposite poles must be matched in order to obtain a pure quadrupole field between the pole tips. Thus in production each pole tip must be individually trimmed to the specified strength., rather than trimming the overall strength as in the case of the dipole.

VIII. PROTOTYPE RESULTS AND STATUS

Following the temperature compensation test magnet, several 1.2m prototype magnets have been constructed. In general there have been no surprises in the construction of these magnets, with typical assembly times "from parts" of approximately an hour. The first prototype dipole had flat (non-shimmed) pole tips. The second had pole tips machined to the shape determined by POISSON. This 2nd prototype met the field quality specification (dB/B < +/-0.0001 over a 3.5" horizontal good-field region) with the help of a angled shim at the end of the pole tip to remove a minor gradient error. The first 1.2m combined-function prototype awaits test and a quadrupole is under construction. We expect to begin construction of 4-5m full length prototypes soon.

III. ACKNOWLEDGMENTS

It is a pleasure to recognize the contributions of all of the participants of the "Workshop on Issues Surrounding the Construction of Permanent Magnet Synchrotrons" and especially Klaus Halbach for his guidance in this project.

IV. REFERENCES

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