EXPERIENCE WITH PERMANENT MAGNETS IN THE FERMILAB 8 GeV LINE AND RECYCLER RING

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Abstract

Fermilab is in the midst of constructing and commissioning the world's largest permanent magnet accelerator components, the 0.75km long "8 GeV Line" and the 3.3km "Recycler" storage ring. The magnets are a hybrid design with the field shape determined from accurately machined iron pole tips and the field driven by strontium ferrite blocks. The choice of magnetic material and the stability of the magnets over time and temperature are discussed. The automated trimming procedure used to null out multipole errors through decapole to the 10^{-5} level on Recycler magnets is described. Commissioning and initial experience with beam in the 8 GeV line is discussed. Future projects involving permanent magnets are mentioned.

1 INTRODUCTION

The permanent-magnet antiproton "Recycler" Ring [2] is a key component in the raising the luminosity of the Tevatron. Historically the Tevatron exceeded its design luminosity of 10^{30} in 1989 and has been increasing exponentially ever since, with a doubling time of ~1.5 years. Continuing this trend will require a continued expansion of the supply of antiprotons available at the beginning of collider stores. The Recycler ring, an 8 GeV antiproton storage ring located in the 3.3 km tunnel of the 150 GeV Fermilab Main Injector, will contribute to this by increasing the storage capability for antiprotons as well as providing the ability to recycle antiprotons left over from previous collider stores. When complete, the Recycler ring will be the world's ~5th largest synchrotron, completed at a cost of approximately $12M.

Permanent magnets are an attractive option for the Recycler because of the fixed energy and the 0.1T average guide field. They also provide the benefit of low system cost due to the lack of electrical, cooling water, and safety systems. These same considerations led to the adoption of permanent magnets for the 8 GeV proton transport line that connects the Fermilab Booster synchrotron to the Main Injector. This successfully commissioned project served as a "demonstration project" for the permanent magnets. Being a transfer line, the field quality requirements were significantly relaxed compared to the Recycler storage ring ($\delta B/B < 0.1\%$ instead of $\delta B/B < 0.01\%$ for the Recycler). The Recycler and 8 GeV line projects use approximately 580 permanent magnets, including dipoles, quadrupoles, gradient magnets, permanent magnet Lambertsons, and mirror magnets.

2 WHY PERMANENT MAGNETS?

Permanent magnets represent an attractive option for beam transport under the following conditions:

i) The energy must be fixed. This obvious requirement may be violated if one considers rotating permanent magnets. For example, the phase trombone insert of the Recycler Ring is composed of quadrupoles that can be mechanically rotated in phase or counterphase to adjust their effective strength in the lattice. Counterphasing works equally well for dipoles. One advantage of this technique is an immunity to power outages and supply failures. The fixed-energy requirement can also be violated by "mixed" systems in which relatively weak electromagnetic corrector magnets can be used to trim the energy of a permanent magnet bending arc. For example, each half-cell of the 8-GeV line contains free space to allow small air-cooled electromagnetic correctors to be installed. If all of these correctors were installed, the line would have an energy adjustability of ~4% while maintaining a much lower power dissipation (and no water cooling!) compared to a design based on electromagnets.

ii) The required bend field must be low. In the case of Strontium ferrite dipoles a comfortable field is 0.2-0.3 Tesla and the maximum practical field is 0.7 T. In the case of rare earth magnets (SmCo or NdFeB) the practical maximum is ~1.3 T. Obtaining these higher fields requires the use of the "Hybrid" permanent magnet technique pioneered by Halbach. This uses iron pole tips to concentrate the flux from a large volume of permanent magnet material into a much smaller magnet gap volume.

iii) The "tunnel costs" must be already be paid for, or at least be an unavoidable cost of the project. One example of this would be beam line that must connect points A to B. It would not make economic sense to build (for example) a new storage ring out of relatively weak 0.5 Tesla permanent magnets if one includes the increased costs of a larger radius beam line enclosure, vacuum system, etc.

iv) Reliability is important. Permanent magnets will not fail spontaneously, start to leak water or cryogens, or lose the stored beam in a power outage. Thus they could prove invaluable in areas such as high-radiation regions or remote beam line enclosures where service is difficult.

Transfer lines and low-energy storage rings often meet all of these requirements. Other applications which might benefit from permanent magnets include microtrons (which have a large number of low-energy bending arcs in the same enclosure as the higher-energy arcs), and injection accumulators (in which a low energy storage ring shares a tunnel with a ramped machine, and requires only an average bending field which matches the injection field of the main accelerator).

3 HYBRID PERMANENT MAGNETS

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 2cm thick bar stock and provides a "box beam" structure that provides most of the mechanical rigidity. The peak field in the flux return is approximately 6 kG.

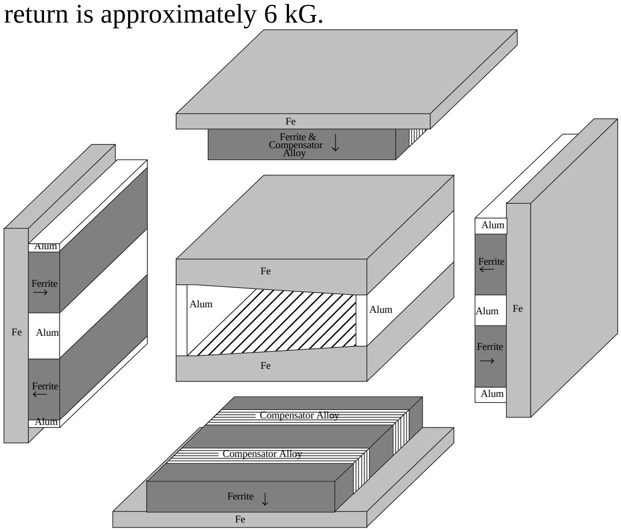

Figure 1: Cross-section of the 1.6 kG hybrid permanent magnet gradient dipole used in the 8 GeV line.

The field is driven by Strontium Ferrite permanent magnet material on the top and sides of the pole tips. A "compensator alloy" consisting of 29% Ni steel is interspersed between the ferrite bricks to null the temperature coefficient of the magnet. The magnet gap is 5cm and the good-field region is ~8cm wide. Overall dimensions are 17.5cm x25cm and the weight of a 4m section is 1 Tonne. Recycler magnets are similar except that the ferrite bricks on the side are absent (in order to better control field quality) and two layers of ferrite bricks are used above and below the pole tips.

3.1 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. 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.

An important option available to the designer is the choice of using "side bricks" shown in figure 1. These bricks significantly increase the strength of the magnet but make the field quality sensitive to the exact position and strength of the side bricks. By increasing the aspect ratio of the pole tip steel (i.e. making the pole tip higher than it is wide) the flux can be collected from a large volume of permanent magnet material and concentrated in the magnet gap. The strength of a magnet built in this way can therefore exceed the residual field (Br) of the permanent magnet material. Although in principle this method can be used to makes magnets up to the 2 Tesla saturation point of the iron pole tip, the practical limit is 2-3x the Br of the material or about 0.8T for Strontium Ferrite. Stronger magnets (in the 1.3-1.5T range) can be made with the more expensive SmCo and NdFeB material.

3.2 Strength Adjustment

During the R&D phase several methods were investigated to control the strength of the magnets: adjusting the amount of magnetic material included in each magnet, sorting the ferrite bricks by strength, performing a partial magnetization or a controlled demagnetization of the bricks to a standard level, and inserting small steel rods into the region alongside the bricks to help "short circuit" flux away from the pole tips and thereby trim the magnet strength. In production the first method was used exclusively to trim the strength of gradient magnets and dipoles

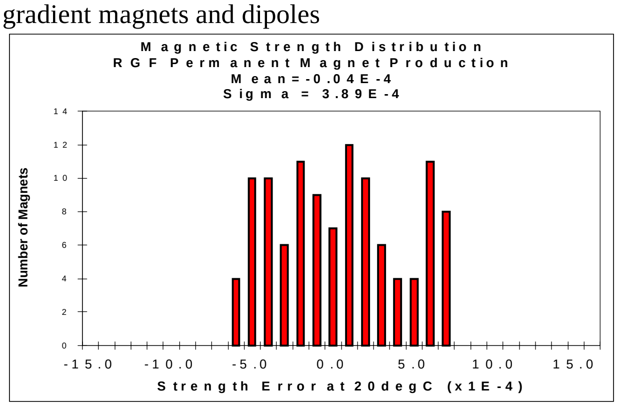

Figure 2: The strength distribution measured in production of Recycler RGF gradient dipoles. Magnets with strength errors outside of +/-6x10^{-4} were adjusted by adding or subtracting a small amount of ferrite at the ends of the magnets.

In the case of quadrupoles the magnetic strength of each pole had to be equalized no null out error multipoles. Threaded stainless steel rods with variable numbers of iron washers were placed behind each pole to perform the final trim of strength, normal and skew sextupole, and skew octupole.

3.3 Time Stability

One major concern about the use of permanent magnets in accelerator is the stability over time. An important part of the R&D program for the 8 GeV line and Recycler was to build and measure a series of test magnets to identify factors which might affect the time stability of the magnets. Factors such as temperature, degree of (de-)magnetization, etc. were not observed to be factors, and a nearly universal behavior was observed: the strength of the magnets decreased logarithmically with time, with a slope of approximately -0.02%/decade.

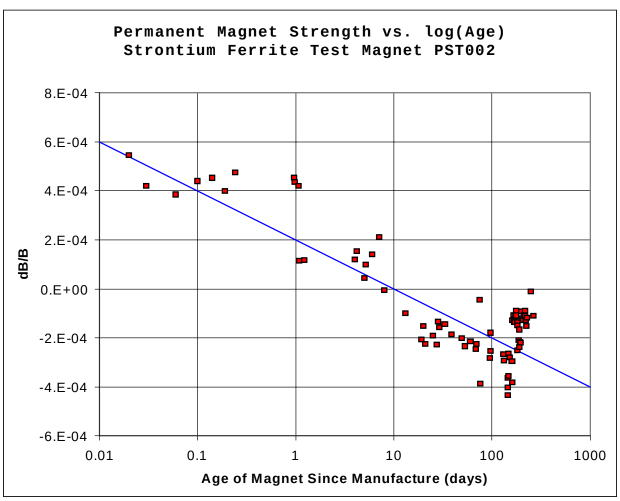

Figure 3: Time stability of a Strontium Ferrite test magnet measured for the Recycler Ring program. The magnet strength drops logarithmically with time, with a slope of ~$2x10^{-4}$ per decade.

Thus the magnets dropped in strength by 0.02% between 1 day and 10 days of age, then dropped by another 0.02% between 10 days and 100 days, and again between 100 days and 3 years, etc. Absent some breakthrough in cellular biology, we all expect to be dead by the time the cumulative ageing of the magnets has reached 0.1%. This is well within the energy acceptance of the lattice, our ability to tune the energy of the storage ring by moving the gradient magnets, and our ability to redefine what "8 GeV" means in the accelerator complex.

3.4 Temperature Compensation

One potential drawback of strontium ferrite in accelerator applications is a reversible temperature coefficient of the residual field Br of -0.19%/°C. A technique was proposed and tested [3] 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. The degree of temperature compensation was adjusted in production by varying the number of strips included between ferrite bricks. In practice it was not necessary to individually adjust the temperature compensation of each magnet, but only to reflect lot-to-lot variations in the properties of the ferrite and compensator alloy.

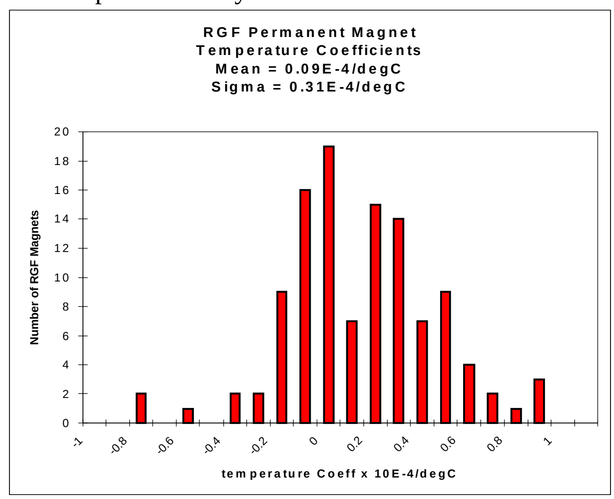

Figure 4: Temperature coefficients measured between 0°C and 20°C for Recycler RGF gradient dipoles.

The effects of temperature variations were further suppressed by magnet sorting, i.e. pairing magnets with opposite temperature coefficients into the same half-cell. In the case of the 8 GeV line, magnet sorting used a simulated-annealing technique that simultaneously minimized the orbit distortion at 25°C and 35°C, on the basis of both the measured strength defects and the temperature coefficients. This reduced the (calculated) temperature sensitivity of the orbit to the sub-1mm level over the operating temperature range.

In practice in the 8 GeV line no temperature or other drifts in the beam trajectory which could be attributed to the permanent magnets have been observed. Effects at the 1mm level cannot be excluded since they would potentially be masked by larger variations in the Booster extraction orbit, power supply fluctuations in the upstream electromagnets, etc. The stability of the closed orbit in the Recycler will be a much more sensitive test since it will be ~100% dependent on permanent magnets.

3.5 Field Quality and End Shims

The field quality in a hybrid permanent magnet is determined largely by the machining accuracy of the steel pole tip. We have successfully built pole tips using several methods, including form-grinding of solid steel pole tips, laminated and stacked iron pole tips, and an extrusion/cold drawn process. All have been successful, but in each case there is a residual field defect at the 10^{-4} level due to imperfections in the machining. This level of defect is at or near the maximum tolerable level for a storage ring magnet on the basis of computer tracking studies. Since only the defect in the field integrated over the length of the magnet is relevant to the accelerator performance, the defect can be cancelled with a specially sculpted "end shim" which is applied to the end of the pole tip.

Figure 5: Customized end shims produced on a N/C mill to null out error multipoles on Recycler magnets.

This procedure is straightforward because the shims need only function at one level of magnetic excitation. For example the gradient and sextupole defects can be cancelled by means of wedge or parabolic end shim. Higher polynomials in the shim shape can affect higher multipoles, but the correspondence is not exact and the polynomials have to be "re-orthogonalized" to produce the shape necessary for example, for a 14-pole shim.

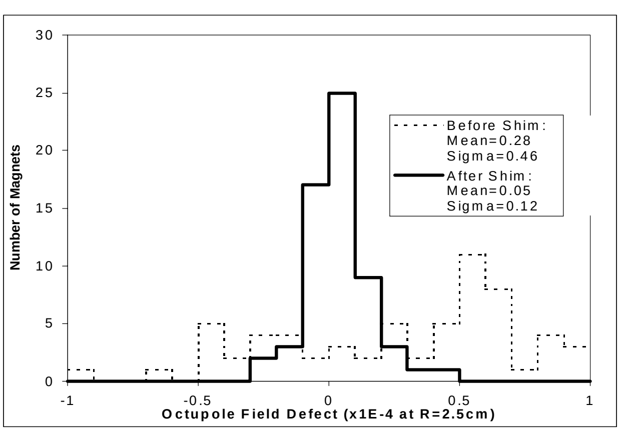

Fig. 6 - Effect of end shimming on the octupole error distribution for Recycler Gradient magnets. Random and systematic defects are at the 10^{-5} level (R=2.5cm) and are about 10x better than typical superconducting magnets.

The trimming sequence is: i) measure the harmonic content of the magnet using a rotating probe, ii) use the measured multipoles to define the shape of the required shim, iii) write out a tool path file for the numerically-controlled (N/C) mill which would cut the custom shim, and iv) apply the custom shim to the pole tip and re-measure to verify that the error harmonics had been eliminated. This calculation and the N/C tool path generation were initially done using a spreadsheet program running on the laptop used to write this talk.

We have reserved one end of the magnet for production trims to ensure that all magnets have nominal multipole content. The other end has a standard shim and is reserved for "field modifications" to adjust e.g. the tune or chromaticity of the ring.

4. 8 GeV LINE COMMISSIONING

The 8 GeV line consists of 120 permanent magnets including dipoles, quadrupoles, and gradient magnets. Most of the line consists of regular lattice cells containing dipoles and gradient magnets in a ~90° bending arc. The 8 GeV line also contains electromagnetic quads at the upstream and downstream ends for matching to the Booster and Main Injector.

Initial commissioning took place with a beam dump located midway along the line, in order to keep beam well away from ongoing construction activities in the Main Injector. Beam was established throughout the length of the line in the first two hours of commissioning. This time was spent mainly wrestling with the Booster extraction hardware and coaxing the beams through the upstream electromagnets. This area has complicated geometry arising from the connection between the existing Booster enclosure with the new civil construction for the Main Injector. When the beam was properly launched into the permanent magnet arcs, it was immediately observed at the beam dump at the end of the line. Initial orbit errors were ~1cm with no correctors energized in the permanent magnet section of the line, roughly what was expected from alignment and magnet strength specifications. Within a week the beam transmission was >95%, with the losses largely due to beam scraping during extraction from the Booster. Current status is that the beam transmission is >99% (due largely to upgrades of the Booster extraction hardware) and the orbit error sigma <0.3cm using only the handful of correctors in the line.

An amusing and illuminating occurrence was observed during the initial commissioning of the line. Due to a bureaucratic blunder [4], incorrect values were entered into the database of design strengths for several of the upstream quadrupoles. These were dutifully trimmed at the magnet factory to an accuracy of a few parts in 10^{-4} but to a value approximately 17% below design strength. This quadrupole strength error did not prevent getting good transmission through the permanent magnets. It however evidenced itself as incorrect beam sizes on the multi-wire monitors, inaccuracy of calculated 3-bumps for tuning the line, and incorrect phase advances when compared to the on-line computer model of the 8 GeV line. These magnets were pulled out and re-trimmed to the correct values in a week. This cured all anomalies in the permanent magnet section of the beam line. Agreement with the online computer model of the line is excellent (fig. 7) indicating that both the bend and focussing properties of the permanent magnets are fully understood.

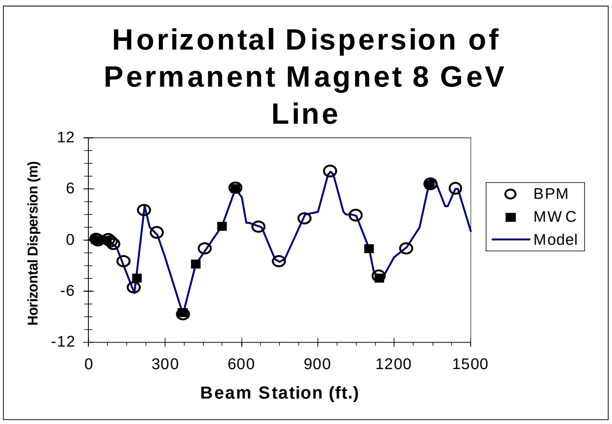

Fig. 7: comparison of the measured dispersion function of the 8 GeV line with the online computer model.

To date, no realignments of permanent magnets have been necessary in order to achieve essentially loss-free transmission in the arcs. Some magnet aperture upgrades are planned in the upstream section to minimize beam scraping coming out of the Booster, which might otherwise create a potential radiation limitation for high-intensity running due to the presence of nearby office buildings. The overall stability, predictability, and operational reliability of the permanent magnets have been excellent.

5 RECYCLER RING STATUS

The Recycler project requires approximately 460 permanent magnets including beam transfer magnets and spares. During the week of the conference the last of the arc gradient dipoles were completed. A production rate above 3/day was sustained during the peak of production using a crew of 12 people. Only a small number of specialty magnets, Lambertsons, mirror magnets, and quads remain to be built. The magnetic specifications on field quality, strength, and temperature compensation have been exceeded. The simplicity and low weight of the magnets allow them to be installed into the tunnel at a rate of up to 15/day when no tunnel-access scheduling problems occur. Current plans are for the entire ring to be under vacuum and by October 1998.

Figure 8: Recycler magnets stacked up and awaiting installation.

6 FUTURE PROJECTS WITH PERMANENT MAGNETS

Several new projects are currently projected. On the experimental side, the "Mini-BooNe" experiment has recently received Stage I approval. This is a neutrino-oscillation experiment using the beams from the Fermilab Booster. The beam line for this experiment will be built with permanent magnets to be constructed later this fall. On the machine side, permanent magnets are planned for beam line upgrades to allow more efficient transfers of antiprotons from the Accumulator to the Recycler. Also contemplated is a direct connection between the Booster and Recycler that would allow the Recycler to function as an injection accumulator for the Main Injector, and thereby increase the average intensity available in fixed-target made. Finally, prototype permanent magnets are being prototyped for the 150 GeV transfer lines into the 3 TeV Booster for the Very Large Hadron Collider (VLHC) project [5].

REFERENCES

[1] Operated by Universities Research Association Inc., under contract with the U.S. Department of Energy.

[2] "Storage Ring for Increased Antiproton Production at Fermilab", G.W. Foster and G. P. Jackson, PAC '95. "Recycler Design Report", FNAL-TM-1991, G. P. Jackson, ed.

[3] "Temperature Considerations in the Design of a Permanent Magnet Storage Ring", K. Bertsche, G.W.Foster, and J-F. Ostiguy, PAC '95.

[4] As project manager for the 8 GeV line the author takes full responsibility for not detecting this oversight. The author also wishes to correct a verbal slip-up in his talk which may have left the impression that G. P. Jackson had something to do with this. Dr. Jackson is the Recycler project manager and will have to make his own blunders.

[5] VLHC technical information can be obtained at: the web site www-ap.fnal.gov/VLHC.