TEMPERATURE CONSIDERATIONS IN THE DESIGN OF A PERMANENT MAGNET STORAGE RING

K. Bertsche, J.-F. Ostiguy and W.B. Foster
Fermi National Accelerator Laboratory *, P.O. Box 500, Batavia, IL 60510

Abstract

To improve the luminosity of the Fermilab Tevatron proton-antiproton collider in the post Main-Injector era, the most straightforward approach is to increase the intensity of the antiproton beam. A number of schemes based on fixed energy storage rings have been suggested to accomplish this goal. A fixed energy ring can be used to accumulate freshly produced antiprotons and/or to recycle used antiprotons at the end a store. For reasons of cost and reliability, permanent magnets are strong contenders for the magnet assemblies, with ceramic ferrite the material of choice. Since ferrite magnetization has a relatively large temperature coefficient, temperature considerations are very important. In this paper, we investigate the expected temperature environment for a fixed energy ring at Fermilab, the required temperature stability and possible methods of compensating temperature dependent effects.

Introduction

To improve the antiproton intensity available in the Fermilab collider, a fixed energy storage ring is under serious consideration. Such a ring would be housed in the newly constructed main injector tunnel and would be used to accumulate freshly produced antiprotons and/or to recycle used antiprotons at the end of a store. The most attractive option appears to be a ring whose main bending magnets are low field (< 5 kG) based on permanent magnet technology. The modest field makes practical the utilization of inexpensive ferrite ceramic – of the same type used in large quantities by the automotive industry – rather than the considerably more costly rare earth samarium-cobalt or neodynium-boron magnets. At this point, a lattice based on combined function magnets of the hybrid "box" design [1] appears to be among the most interesting possibilities. Details are given in another paper presented at this conference [2]. Although ferrite is inexpensive the rather large dependence of its magnetization to temperature variations is a major source of concern.

Temperature Effects

Four classes of materials account for virtually all permanent magnets in use today.

- Alnico
- Hard Ferrites: $BaO{\cdot}6Fe_2O_3$, $SrO{\cdot}6Fe_2O_3$
- Rare Earth Cobalt (REC): $SmCO_5$, Sm_2CO_17
- Neodymium-iron-Boron (NEO): Nd_2Fe_14B

Some relevant properties of these materials are summarized in Table 1. The bulk magnetization of a permanent magnet is the result of the collective alignment of the atomic spins via the quantum

	Alnico	Ferrite	REC		NEO
Composition	Fe-alloy	$SrO{\cdot}6Fe_2O_3$	SmCo5	Sm2Co17	Nd2Fe14B
B_r	1.3	0.4	0.9	0.9	1.1
$d\log(B_r)/dT$	-0.02	-0.2	-0.06	-0.04	-0.12
H_C	150	320	2400	2000	1400
Curie T	800	450	750	800	300
Density (g/cm3)	7.2	5.0	8.2	8.4	7.4
Cost (rel)	10	1	80	80	70

Table I
Magnetic material properties.

exchange interaction. As temperature increases, thermal fluctuations induce more and more random variations in individual atomic spin orientations. Eventually, a phase transition occurs: all the spins are randomly oriented and the bulk magnetization abruptly dissapears. The transition temperature is known as the Curie temperature, T_C and can be considered as a measure of the magnitude of the exchange forces. For a simple element like Fe, the temperature dependence of the magnetization is well predicted by the classical Brillouin function. For ferrites and other alloys, the situation is much more complex and depends on the determination of specific forms of orbital overlap for three dimensional arrays of atoms of different types. Nevertheless, one still expects the magnetization to be a roughly decreasing exponential function of the ratio (T/T_C), so that $d\log M/dT$ is approximately constant over a wide temperature range. The maximum sensitivity obviously occurs when $T/T_C \simeq 1$. Referring to Table 1, one can indeed see that materials with similar Curie temperatures have similar temperature coefficients. Furthermore, ferrite and neodymium-boron have the lowest T_C and the highest temperature coefficients, as expected.

Temperature Environment

The temperature environement in an accelerator is composed of two distinct components:

- variations of the average temperature
- random temperature variations at different locations around the ring

Average temperature variations correspond to variations in the reference energy of the ring. Since no external adjustment is possible, a permanent magnet ring would have to be accommodated by other rings in the complex. Seasonal variations in temperature can be quite large in the Main Injector tunnel, on the order of 20 C between summer and winter. For ferrite magnets, this corresponds to a 4 % variation in ring energy.

More serious is the problem of random temperature fluctuations around the ring. These fluctuations have a time scale of hours. Typically, magnet to magnet variations in relative integrated strength larger than 0.001 must be corrected. To the extent that both dipole and quadrupole elements would be based on permanent magnet technology, correction would be required for both functions. Measurements made over a period of a month

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in the Main Ring tunnel indicate that rms temperature fluctuations on the order of 1 C around the ring can be expected. For ferrite magnet structures this results in dipole and quadrupole relative integrated strength fluctuations on the order of 0.002.

Compensation Schemes

Because of these expected temperature variations, a reduction of the temperature sensitivity by an order of magnitude or more is needed. An obvious possibility would be to utilize a permanent magnet material with a higher Curie temperature. REC and Neodymium-Boron are prohibitively expensive. The cost of Alnico may seem more reasonable but the active magnet volume needed to prevent the demagnetizing field from overcoming the coercivity would result in substantially larger overall dimensions.

Active correction of magnetic field, by adding windings to the permanent magnets or adding small outboard electromagnetic trim dipoles was discussed. This option was rejected because it would eliminate the possibility of keeping antiprotons in the ring during a short power outage without the added complexity of non interruptible power supplies. Quasi passive temperature control, by circulating water through the magnet structures and/or by coupling magnets through heat pipes was quickly dismissed because of added cost, complexity and potentially reduced reliability.

The scheme which we propose is purely passive. The field of each magnet structure is stabilized using one or more temperature sensitive flux shunts. These shunts are composed of alloys having permeability with high temperature coefficient. Binary alloys of Ni-Fe and Ni-Cu have been used for this purpose [3]. The alloy is placed in the magnet structure in such a position that it shunts some of the flux which would ordinarily appear across the magnet gap. As temperature increases, the ferrite supplies less flux to the magnet poles, but the flux shunt also shunts less flux. If the flux shunt has a higher temperature coefficient than that of the ferrite, it may be sized in such a way that the field in the gap is independent of temperature. A similar technique is routinely used in small structures, such as watt-hour meters and automobile speedometers. As far as we know, it has never been used for large scale accelerator magnets.

Temperature compensation alloys such as Fe-Ni have a Curie temperature close to the ambient temperature. Basically, the Curie temperature and the saturation magnetization of the Fe-Ni system change rapidly when the Ni fraction reaches 30%, due to a change in crystal structure. At the phase boundary, both T_C and the saturation magnetization vanish. By carefully controlling the composition and heat treatment of the material, the Curie temperature can be adjusted to be slightly above the ambient temperature, resulting in high temperature sensitivity of the saturation magnetization. By adjusting the thickness of a thin strip of compensating alloy, it is then possible to compensate the weaker temperature dependence of a larger volume of ferrite material.

A possible configuration for a box dipole magnet is shown in Figure 1. A strip of alloy is placed in the center of the magnet, between two ferrite blocks, in order to suppress odd multipoles. Fe-Ni has a temperature coefficient $d \log B_r 2/dT \simeq 2\%$/C. This is about an order magnitude higher than ferrite, so approximately 10% of the flux must be shunted. It should be noted that the temperature coefficient of compensating alloys generally depends on

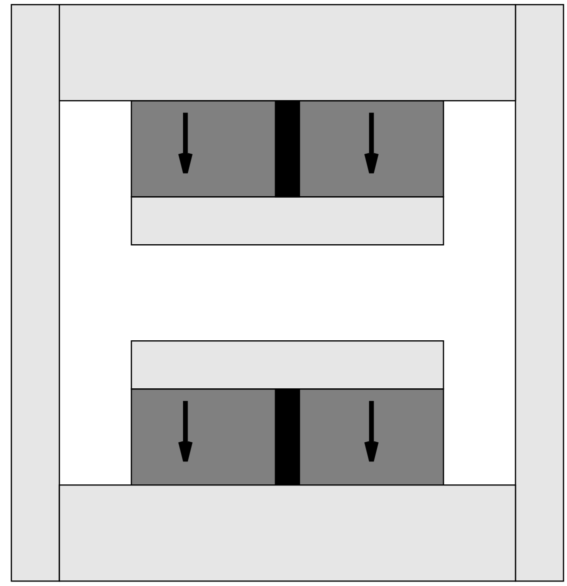

Figure. 1. Cross section of a dipole magnet. Temperature compensating strips are placed symmetrically between blocks of ferrite material.

magnetic field as well as temperature. In applications where the field is very weak it is necessary to take this into account. In the present case, the regime of operation is such that the compensating material is completely saturated. The strip behaves like a thin bar magnet of strength M_S polarized in the direction opposite to the ferrite blocks and M_S is essentially independent of H in the strip. As a result, the compensation effect is expected to scale linearly with the strip thickness.

Results

A 2 kG prototype dipole magnet was constructed both to understand basic assembly problems and to study temperature compensation. For the sake of this experiment, the thin strip of compensating alloy was placed on one side of the gap, though in practice this would affect field quality (Figure 1 is the preferred configuration). The result shown in Figure 2 is spectacularly better than anticipated; Line A represents the field in the center of the magnetic gap without the compensating strip. Line B represents a first iteration based on a rough estimate of the thickness. Line C represents the result obtained by linearly scaling the thickness on the basis of result B. $\frac{d \log B_0}{dT}$ was reduced by more than 2 orders of magnitude from the original 2000 ppm/C to less than 100 ppm/C between 25 and 30 deg C and below 10 ppm between 30 and 40 deg C.

Conclusion

We have demonstrated that the strength of a magnet built with ferrite material can be passively temperature stabilized at a level more than sufficient to build a storage ring without the need for expensive correctors. Work is in progress to build a larger model and a full scale prototype.

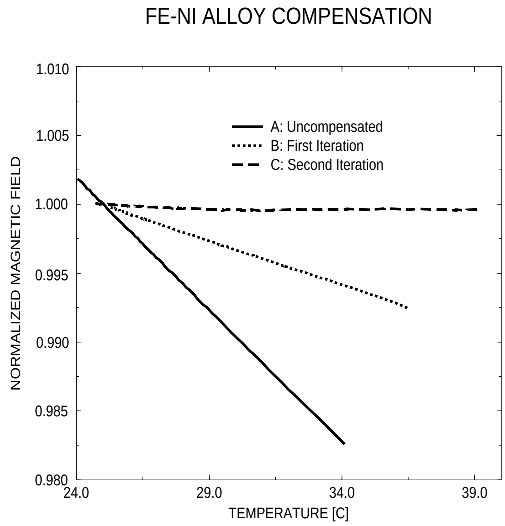

Figure. 2. Experimental results.

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