

STABILITY TESTS OF PERMANENT MAGNETS BUILT WITH STRONTIUM FERRITE

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Abstract

Permanent magnets built using strontium ferrite bricks have been tested for stability against demagnetization. Ten test dipoles were built to monitor ferrite behavior under a variety of stressing conditions, including irradiation, mechanical shock, extreme thermal excursions, and long term magnetization stability. The test magnets were geometrically similar to, but much shorter than, the magnets built for the 8 GeV transfer line at FNAL. No loss of magnetization was observed for bricks exposed to a proton beam, and a magnet exposed to several Gigrads of Co^{60} gamma radiation suffered no measurable demagnetization. The magnet strength was observed to decrease logarithmically with time, consistent with the expected effect of thermal fluctuations. Irreversible demagnetization of $\sim 0.1\%$ was seen in cooling magnets to 0°C , and the loss was $\sim 0.2\%$ for magnets cooled to -20°C . No additional demagnetization was seen on subsequent cycling to 0°C . Finally, one of the long dipoles built for the 8 GeV line was periodically tested over the course of 3 months, and showed no measurable demagnetization.

1 MAGNETS FOR THE 8 GEV LINE

The new Fermilab 8 GeV transfer line connecting the Booster to the Main Injector has been built using hybrid permanent magnets [1,2]. This beamline is designed to have an operating lifetime of 30 years. The magnets will be operated at an ambient tunnel temperature between 20°C and 35°C . They must also be capable of storage between 5°C and 50°C . We also require that the magnets be resistant ($\Delta B/B < 0.05\%$) to shock and vibration under normal handling. We also impose a reasonable requirement for radiation resistance, demanding that $\Delta B/B < 1\%$ for an exposure of 1 GigaRad. Finally, a long operational lifetime imposes a temporal stability requirement of $\Delta B/B < 0.02\%$ per year, measured from the first month after initial magnetization.

1.1 Permanent magnet material

We chose Type 8 Strontium Ferrite as the material to be used for making our permanent magnets [3]. This choice was driven by low cost, consideration of stability over time, temperature, and radiation. Strontium ferrite is the material of choice in automotive and other industrial applications, and is available from vendors in standard grades and sizes.

2 THEORY

The phenomenon of decrease in magnetization with time, often and incorrectly referred to as aging (it has nothing to do with long term chemical or structural changes in the material) is qualitatively well understood. The theory was developed by Louis Néel [4] and by Street and Wooley [5]. It was initially applied to Alnico magnets, but was later shown to apply to ferrites as well [6].

Hard ferrites are composed of small ferromagnetic regions or "grains" generally about $1\ \mu\text{m}$ in size, closely packed and separated by non-ferromagnetic media. Each grain is constituted at most of a few domains whose walls are pinned by various imperfections. Thermal fluctuations induce local strain variations and changes in the magnetic anisotropy constant resulting in wall nucleation and changes in the net magnetization of the grains. Regardless of the exact nature of the mechanism, the energy required to irreversibly change the magnetization can be seen as the activation energy for the grain.

It is supposed that at some time $t = t_0$, a certain number of grains have their net magnetization vector in metastable orientations and fluctuations in thermal energy induce irreversible magnetization rotation in small volumes of the material.

Consider the number N of domains characterized by activation energies between E and $E+dE$ at the time t

$$N(E,t) = f(E,t)dE \quad (1)$$

The rate of change of N due to thermal activation at a temperature T is

$$\frac{dN}{dt} = -Cf(E,t)e^{-E/kT}dE \quad (2)$$

where C is a constant which depends on the material and f is a distribution function. Equation 2 is satisfied by

$$\begin{aligned} N(t) &= f(E,t_0)e^{-\lambda(E)t}dE \\ &= f_0(E)e^{-\lambda(E)t}dE \end{aligned} \quad (3)$$

where

$$\lambda(E) \equiv Ce^{-E/kT} \quad (4)$$

If each activation contributes an average amount m to the magnetization, then the activation of dN regions results in a mean decrease of the magnetization M

$$dM = -mCf_0(E)e^{-\lambda t} e^{-E/kT} dE dt \quad (5)$$

Integrating over all values of the activation energy

$$\frac{dM}{dt} = -mC \int_{E_0}^{E_m} f_0(E) e^{-\lambda t} e^{-E/kT} dE \quad (6)$$

In practice, the detail of the distribution $f_0(E)$ and the limits E_0 and E_m are not known, but it is reasonable to assume that $f_0(E)$ should vanish beyond a maximum energy E_m .

For a simple impulse distribution at $E=E_m$ one obtains after integrating,

$$\Delta M = -mN_0 \left[1 - e^{-\lambda_m t} \right] \quad (7)$$

where

$$\lambda_m = e^{-E_m/kT} / t \quad (8)$$

For a more realistic rectangular distribution where all activation energies are between E_0 and E_m

$$\Delta M \cong -mN_0 \frac{kT}{(E_m - E_0)} \left[\log \frac{t}{t_0} - \lambda_0 (t - t_0) \right], \quad \text{for } \lambda_0 (t - t_0) \ll 1 \quad (9)$$

$$\cong -mN_0 \frac{kT}{(E_m - E_0)} \left[\log \frac{t}{t_0} \right], \quad \text{for } \lambda_0 (t - t_0) \gg 1 \quad (10)$$

Thus, the theory predicts that after a brief more or less linear drop, the magnetization decays logarithmically with time.

3 STABILITY TEST MAGNETS

To study the long term behavior of magnets built with strontium ferrite, we built a set of 0.5 m long dipoles having a cross section similar to the design used for the production 8 GeV magnets. In Table 1 we list a description of the properties and testing history of each magnet. Magnets were built from strontium ferrite bricks supplied by several vendors, including Hitachi and Crucible. The magnets were thermally compensated using NiFe alloys obtained from vendors Telcon and Carpenter. All magnets listed in the table were made using Hitachi bricks and Carpenter compensator, unless otherwise noted. The bricks were fully magnetized (100% saturation), except for magnet 5.

<i>magnet</i>	<i>description</i>
1	standard reference
2	same as #1
3	Crucible bricks
4	Telcon compensator
5	bricks @ 95% saturation
6	cooled to -20°C
7	heated to 45°C
8	Co-60 irradiation
9	identical to #1
10	no side bricks

Table 1. Properties of the 10 stability test magnets.

All of magnets were built using a single layer of full-size bricks (4" x 6") on the top and bottom poles, and using half-size bricks (4" x 3") on the sides, with the exception of magnet #10. For this magnet, we left out the side bricks in order to study whether these bricks aged at a different rate than the top/bottom bricks.

4 AGING RESULTS

All of the magnets showed a slight degree of aging consistent with the logarithmic model discussed above. The main loss of magnetization, generally around the level of 0.1%, occurred within the first few weeks after magnetization. After that period of time, very little additional loss was observed. Some examples of the decrease in magnet strength vs time are shown in the accompanying figures. All of the observations are within the allowable limits for operation of the 8 GeV beamline and Recycler. No significant differences were seen in the behavior of ferrite or compensator from different vendors.

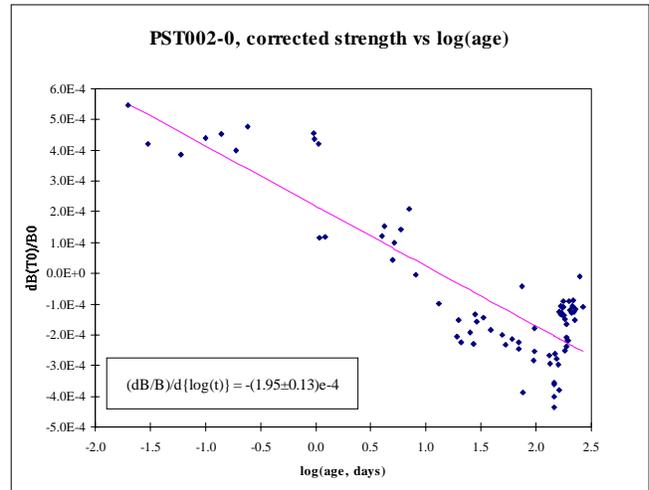


Figure 1. Stability of test magnet #2 as a function of the log of its age. The magnetic strength loss is 0.02% per "decade".

In Fig. 1, a fit is shown for $(dB/B)/d(\log t)$ vs $\log(t)$, where time is measured in days. The interpretation of the result is that the magnet is observed to lose 0.02% in strength after its first 10 days of existence (after magnetization); a subsequent loss of 0.02% after the next 100 days; and an extrapolation that over the next 1000 days, the loss will be an estimated 0.02% additional loss.

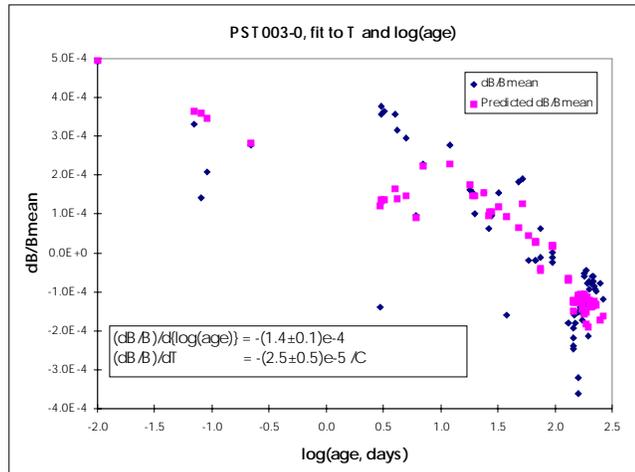


Figure 2. Stability of test magnet #3 as a function of both temperature and time. This fitting accounts for thermal effects due to imperfect temperature compensation.

A slight complication in the analysis of the aging of the magnets was to properly account for temperature effects. In constructing these magnets, we attempted to correctly balance the compensator to ferrite ratio so that there was a minimal temperature dependence to the magnet strength. Compensation was not perfect (although generally less than 0.01%/C), and could provide an important source of systematic error in the measurement of aging. Figure 3 shows the result of fitting the magnetic strength to a functional form $dB/B = k_1 * T + k_2 * \log(t)$. The fitting for temperature and temporal effects simultaneously are shown in the figure.

4.1 Other stability results

Magnet #8 was exposed to several gigarads of gamma radiation from a Cobalt-60 source. The magnet strength was monitored with an NMR probe over the course of the exposure, which lasted several months. There was no observed loss of strength that could have been attributed to radiation damage; i.e., the observed losses were consistent with aging with $\log(t)$.

Magnet #7 was heated to 45 C. As with other magnets which we have heated, only reversible changes in strength with temperature are observed. Magnet #6, on the other hand, was cooled first to 0 C, and we observed a strength loss of 0.1%. A second cycle down to 0 C saw no additional loss. This was followed by a cooling down to a temperature of 20 C, and the loss was 0.2% from the

original strength. A second cooldown to 20 C saw no further loss. This series of tests led us to cool all our production magnets for the 8 GeV line to 0 C as a conditioning against thermal losses.

CONCLUSION

We have studied the temporal stability of a number of model magnets over an 8 month period. These data are consistent with logarithmic aging at a level of 2×10^{-4} / decade. This corresponds to a field degradation of 0.06% between 10 days and 30 years after initial magnetization. Aging at this level can be easily accommodated by occasional recentering of the gradient magnets over the lifetime of the 8 GeV line.

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