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MEASUREMENTS OF STRONTIUM FERRITE HYBRID PERMANENT MAGNET QUADRUPOLES AFTER REMOVAL FOR THE FERMILAB NOVA UPGRADE IN 2012

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Abstract

During the 2012 NOvA upgrade forty strontium ferrite hybrid permanent magnet quadrupoles from the injection, extraction and electron cooling regions of the Recycler accelerator, which had been measured in 2000 and subsequently installed in the tunnel, were replaced. The basic design of the quadrupoles [1] and expected decay rate [2] are described in design documents. Nine of these magnets, of varying strength were measured in 2014. Measurements were made with a rotating coil in a fashion similar to their initial pre-installation measurements in 2000. The 2014 measurements are compared to the 2000 measurements and the expected decay.

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PERMANENT MAGNETS IN THE RECYCLER

The Fermilab Recycler contains approximately 500 permanent magnets [2] of several different types. These magnets use grade 8 Strontium Ferrite bricks to produce the magnetic field and machined steel poles to create the field shape [2]. Segments of a 4x6x1 bricks (cut to 2”x1” bricks of varying length) were used. To compensate for the change in magnetization as a function of temperature, 2”x1” thin pieces of 30% Ni 70% Fe alloy were interspersed among the ferrite segments [3].

During the initial years of the Recycler, measurements were made of several different magnets to understand the evolution of magnet strengths over time [2].

NOVA UPGRADE

For the 2012 NOvA upgrade, approximately forty 20” permanent quadrupole magnets (Figure 1) in the transfer lines and in the decommissioned electron cooling region of the Recycler needed to be modified or replaced because of new field strength requirements. The decision was made to replace them with new magnets [4]. This meant 40 magnets were uninstalled, allowing for the measurement of these magnets and the comparison of current measurement data with measurement data recorded prior to installation. Due to radiation these magnets remained an unused section of tunnel until 2014, at which time activation for nine magnets was low enough allowing for easier handling.

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ASSEMBLY AND INSTALLATION

Assembly

Assembly data was captured in “travelers” recorded during fabrication, and any modifications. Measurement data was captured in the Fermilab Magnet Test Facility system. The dates of measurements are correct, however dates of ferrite magnetization are approximate. The traveler records when the bricks were acquired from a pool of recently magnetized bricks. The time gap between magnetization and assembly is small (weeks to months range) compared to the time between these measurements. Initial strength specifications required the magnets to be within 5 units of grel [5].

Installation

Eight magnets listed were installed in the Recycler Ring and were in the proximity of Recycler Ring vacuum chamber "bake-outs". This typically involved baking sections of beam tubes in the range of 100^{o} C to 130^{o} C. Exact temperatures on the magnets were not measured. This is significant due to the potential effect of elevated temperature on the long-term decay of magnet strength [2]. RQMF009, however, was located in a transfer line so was not subjected to potential elevated temperatures.

ADDITIONAL STORED MAGNET MEASURED

PQP003

In addition to the removed quads, three additional magnets which had not been in the tunnel were measured. PQP003 was an early 20" permanent quadrupole prototype. Prior to 2009 there is uncertainty regarding modifications to this magnet. There are records of modifications as late as 1997. Because of the uncertainty, Measurements prior to 2009 were excluded. However, data from 1997 to 2009 would agree with the general trends in grel change since 2009. Since it is a form of 20” quad, PQP003 was included in Table 1.

RGF005

RGF005 is the first production gradient magnet which met Recycler specifications. It was kept as a standard magnet and was measured periodically since 1997 [2]. Continual measurements exist for this magnet. It was stored a temperature controlled building when not being measured.

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PDD002

PDD002. It is a dipole magnet [6] of the style used in the 8 GeV injection line from Booster to Main Injector/Recycler. It is a standard production magnet and was randomly chosen for measurement. It too was stored a temperature controlled buildings.

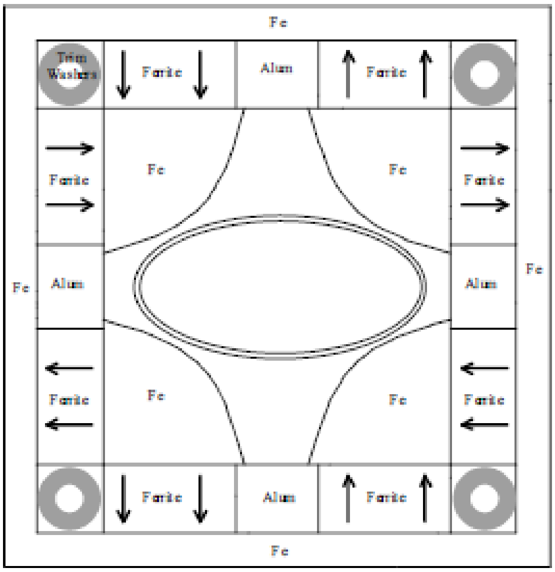

Figure 1: Cross section of 20” Permanent Quad [7]

MEASUREMENT TECHNIQUES

Measurements were made with a 4-meter Morgan coil [2]. Details of the quad measurements are displayed on Table 1. There is a small factor for temperature correction. For the temperature range over which measurements occur this corresponds to only ~ +/-2 grel unit. This is generally within the reproducibility of measurement data, but still was included. A Single Stretched wire method (SSW) [8] was periodically for cross reference. Details of some 2014 SSW to rotating coil measurements are in Table 2.

COMPARISIONS TO PREDICTED

The measurement data is compared to “expected” values of grel as calculated using the formula from the 2001 Volk paper.[2]

$$\Delta M/M_1 = -9 \times 10^{-4} \times \log(t_2/t_1)$$

The assembled magnets sat for a considerable time prior to the pre-installation measurement (typically over 2 years). Most of the predicted decay should have occurred over those first two years (typically ~26 units of grel). Measurements prior to the final pre-installation measurement cannot be used, since the magnets were adjusted up to that measurement. Table 1 does refer to a total expected change. This if based on a hypothetical predicted “original” strength which would have existed based on the pre-installation measurement.

Table 1 shows the value of grel is considerably lower than the expected value. This is true of all magnets regardless of lack of exposure to back-outs (RQMF009) or radiation (PQP003).

Single Stretched Wire (SSW) Measurements

An SSW method was used to cross reference to rotating coil measurements. The comparison shown on Table 3. These values are not temperature corrected.

Table 1: Measurement Comparisons

Magnet	Approx. Date magnetized	Pre-install measure date*	2014/15 measure date	Pre-install grel (Units)	"Recent" grel (Units)*	"Expected" 2014/15 grel	"Expected" total change (units) since magnetization
RQRE003	10/7/1998	8/31/2000	10/31/2014	-2.87	-53.85	-11.21	-33.97
RQMH006	7/2/1998	11/18/2000	10/27/2014	-0.26	-58.17	-7.78	-34.05
RQRD003	9/28/1998	11/18/2000	10/30/2014	-0.26	-37.93	-8.14	-33.99
RQRD002	9/28/1998	8/30/2000	10/28/2014	1.71	-40.36	-6.60	-33.99
RQMH002	6/28/1998	11/17/2000	5/4/2014	2.23	-54.56	-5.17	-33.94
RQRE007	11/11/1998	11/18/2000	4/17/2014	1.65	-41.77	-6.30	-33.83
RQMH004	7/6/1998	11/17/2000	10/31/2014	1.78	-60.09	-5.77	-34.05
RQMF009	8/14/1997	3/21/1998	10/27/2014	-4.89	-77.96	-18.00	-34.21
RQRE005	10/7/1998	9/6/2000	10/31/2014	-2.54	-56.76	-10.84	-33.97
PQP003*	10/2/1996	3/23/2009	4/18/2015	733.92	697.45	732.26	-37.12

*PQP003 was never installed

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Table 2: SSW to RC Comparison

Magnet	SSW Strength (T-m/m)	Rotating Coil (T-m/m)	SSW to RC (Units)
RQMF009	1.3245	1.3242	2.27
RQRE005	1.2409	1.2403	4.84
PQP003	1.585	1.5846	2.52

COMPARISONS TO OTHER STORED MAGNETS

RGF005

Measurements of RGF005 are shown in Figure 2. Field strength deviates from the original expected [2] logarithmic form. It can be seen that the relative field strength no longer shows a logarithmic time dependence.

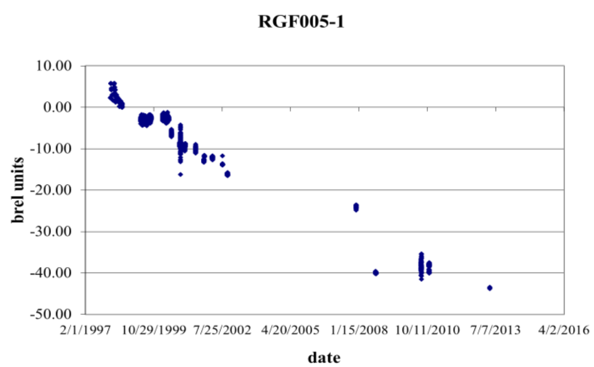

Figure 2: RGF005 Relative field strength vs date.

PDD002

No traveller exists for PDD002, however it was built and measured in 1996, and is a prototype PDD. The time between brick magnetization and fabrication was most likely small and will be treated as negligible. It was measured on 6/7/1996 with a grel of 435.19 units. It was measured again on 2/5/2015 and had a grel of -19.54 units. If it had been following the expected logarithmic dependence, the expected grel would be 399.19 units.

COMPARISION TO THE ACCELERATOR AND OTHER CROSS-REFERENCING

Recycler Ring Momentum [9]

Attempts to correlate the momentum in the Recycler Ring with changes to the field strength of permanent are inconclusive. Attempts to look at either the changes to the central frequency or the portion of the MI ramp used for transfers to the Recycler (the so-called "minidip") do seem to indicate a reduction in momentum, which may even appear logarithmic with time. However, different cases of attempting to correlate between the central frequency and the momentum yield inconclusive results (sometimes a faster change than the magnets, sometimes a POSITVE momentum change). Add to that complications due to lack of correlation with orbit, and there are just too many variables not controlled, recorded or understood to make this correlation.

Individual Ferrite Brick Measurements

As part of fabrication, individual bricks are measured after being magnetized [10]. This data is recorded. Most of the bricks for production were purchased at the same time, but are magnetized as needed. The data from bricks magnetized in the 90's could be compared with the modern data to see if bricks are starting out weaker. This could indicate some kind of chemical aging. Unfortunately, thought the mechanical elements of the system are the same, there are too many other variables that are not well accounted for. Also, the brick measurement system isn't nearly precise enough to measure this level of change [11].

CONCLUSION

All magnets measured seem to be losing field strength faster than expected. This is true regardless of exposure to heat and/or radiation. Though there are not enough measurements of quads to see the character of this change, the "standard" magnet (RGF005) hardly seems logarithmic. Though there are many possible theories, it is not understood why this might occur. The long term coactivity in the presence of fields inherent in shaped magnets (like quadrupoles) isn't understood.

Further measurements should be made of existing magnets. As part of the fabrication process, magnets are frozen and the quantity of compensator is adjusted to "flatten" the temperature response over projected tunnel temperatures [1]. This data is recorded, including a final "good" measurement. Magnets could be re-frozen and the temperature curve could be compared with the last good temperature cycle.

In addition, other magnets should be fabricated specifically for measurement purposes. These include some form of very simple dipole magnets, and magnets without any compensator material (all magnets measured did include compensator) as the long term effect of compensator on field strength is not understood.

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10,000 x (measured - design)/design

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