HYBRID PERMANENT QUADRUPOLES FOR THE 8 GEV TRANSFER LINE AT FERMILAB

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Abstract

Hybrid Permanent Magnet Quadrupoles for specialized portions of the 8 GeV transfer line from the Fermilab Booster to the new Main Injector have been built, tested and installed. These magnets use a 0.635 m long iron shell and provide an integrated gradient of 1.48 T-m/m with an iron pole tip radius of 0.0416 m. and pole length of 0.508 m. Bricks of 0.0254 m thick strontium ferrite supply the flux to the back of the pole to produce the desired 2.91 T/m gradient. For temperature compensation, Ni-Fe alloy strips are interspersed between ferrite bricks to subtract flux in a temperature dependent fashion. Adjustments of the permeance of each pole using iron between the pole and the flux return shell permits the matching of pole potentials. Magnetic potentials of the poles are measured with a Rogowski coil and adjusted to the desired value to achieve the prescribed strength and field uniformity. After these adjustments, the magnets are measured using a rotating coil to determine the integral gradient and the harmonics. These measurements are used to calibrate the production Rogowski coil measurements. Similar quadrupoles are included in the design of the Fermilab Recycler.

1 MAGNET DESIGN

These magnets serve both as necessary components of the 8 Gev transfer line and as production prototypes for the quadrupoles needed for the Fermilab Recycler. All the of Fermilab permanent magnets are of the "hybrid" type in which the field is driven by permanent magnet bricks and the field shape is determined mainly by iron pole pieces [1]. The advantage of this design is low cost due to the use of the same type of permanent magnet material (Type 8 Strontium Ferrite) as many automotive and other commercial applications. The magnets made in this way are also very stable over long time periods and are not affected by radiation. The disadvantage is the brick to brick strength variation which must be tuned out of each magnet based on measurements of assembled magnets. The intrinsic temperature coefficient of the Ferrite material (-0.18% / °C) is canceled by interspersing a "compensator alloy" between the ferrite bricks. In this application an amount of compensator about 14% of the brick in volume is required.

2 MAGNET ASSEMBLY

Assembly of these magnets from purchased parts is straightforward and requires two technicians for only two hours. The four precision pole pieces are assembled to two precision stainless steel end spacers and four aluminum spacer bars. The ferrite bricks and compensator strips are inserted along one side with one channel length having its field pointing into a pole and the other with its field pointing out of the adjecent pole. A steel flux return side is layed over the bricks and the assembly rolled 90°. This procedure is repeated for the remaining three sides, taking care to maintain the proper brick polarity. The four sides are bolted together but are not attached to the pole assembly. The flux return end pieces are installed and bolted to the sides, but again not to the pole assembly. The magnetic forces hold the pole assembly strongly to the flux return shell and prevent it from moving longitudinally. Nevertheless, we plan to have retainer spacers between the flux return end pieces and the pole assembly in the Recycler quadrupoles to prevent movement if the magnet is mishandled. A total of ten magnets were built, nine used in the beamline and one prototype/spare.

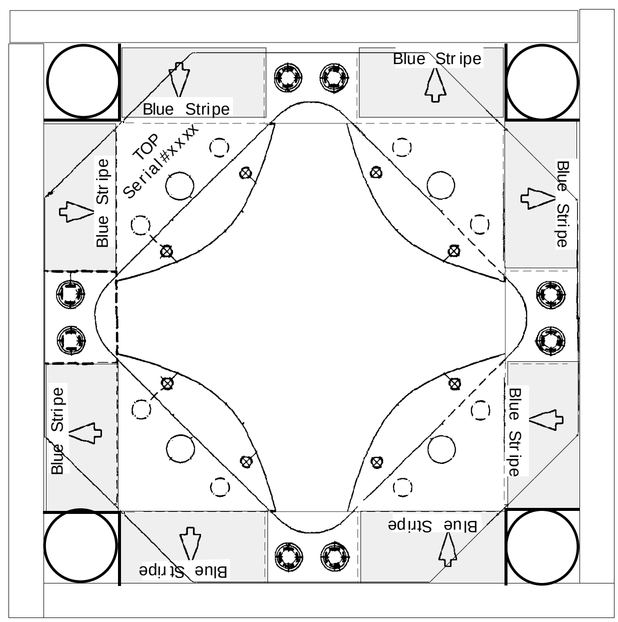

Figure 1 Magnet Cross Section, ferrite bricks are dotted.

3 ROGOWSKI MEASUREMENTS AND TRIMMING

After each magnet is assembled, the magnetic potential is measured at both ends of all four poles with a Rogowski coil [2,3]. The magnet is then put in a freezer overnight and cooled to 0° C. The magnet is removed from the freezer, wrapped in a thermal blanket in such a way that the ends are accessable, and the magnet temperature and the magnetic potential is quickly remeasured. After the magnet has completely returned to room temperature, the temperature and magnetic potential are remeasured. The freezing typically causes a very small increase in strength (~0.05%) in these magnets. While other types of hybrid permanent magnets have had seen variability of the temperature compensator material, because all the material for these magnets was from one lot, no variation was seen and all the magnets were stable over the temperature range.

In order to qualify the Rogowski measurement technique, a prototype magnet was measured 22 times over a one month period. The strength of the magnet, averaged over the eight points measured, had an RMS variation of 0.018% even though the RMS variation of the eight individual points was 0.18%. If this were a statistical error problem, one would expect the error of the average of eight measurements to be a factor of square root of 8 (= 2.8) smaller than the error of the individual measurements. The greater variation of the individual points suggests some slow variation with time in the distribution of flux lines within the magnet leaving the overall strength relatively more stable. However, this variation is small enought to allow use of this quick and simple measurement technique for trimming the individual pole variations. This was believed to be necessary to reduce the field errors which give higher order multipole components, especially sextupole and skew sextupole. The magnets were built with enought ferrite to give ~2.7% more integrated gradient than we calculated would be required to allow for brick variation. In fact, the brick variation was quite small and the actual magnet RMS variation before trimming was 0.17%. The trimming was done by loading steel washers onto stainless steel threaded rods and inserting these rods into the stainless steel tubes in the four corners of the magnet. Varying the number of washers changed the amount of flux shunted out the back corner of the pole into the flux return. One washer in one corner reduced the total magnet strength by about 0.007%, a quite reasonable least change. Of course the pole that the washer was behind was reduced more than four times that while adjacent poles were strengthened slightly. After a sufficient distribution of washers had been added to the magnets to produce the desired Rogowski readings, the magnet was shipped to the Fermilab Magnet Test Facility where a full length rotating harmonic coil was used to measure the integrated gradient and the higher order harmonics[4]. Only after this process had been performed on several prototype magnets did we determine the appropriate Rogowski readings to aim for. The average of the six magnets built to that aiming point were 0.1% stronger than desired as measured by the harmonic coil. They had an RMS variation of 0.06% in strength. The average sextupole component (normalized to the quad at 0.0254m) was 2e-5 for the normal component and 3.8e-4 for the skew with an RMS of 6e-4 for both normal and skew. Because the poles are cut off squarely at the ends with no chamfer, the magnets have an average 12-pole of -7.9e-4, again normalized to the quadrupole at 0.0254m. The RMS of this 12-pole is 2.7e-5. This can be fixed for the Recycler Ring magnets either by a small chamfer or by adding two small screws with a few washers to each pole.

REFERENCES

[1] 'Recycler and 8 GeV Line Permanent Magnets Reference Design & Performance Requirements', by G.W.Foster. FNAL Main Injector Note #150.

[2] 'A Modified Rogowski Coil for Measurements of Hybrid Permanent Magnets', by Kirk Bertsche. FERMILAB-Conf-95/190.

[3] 'Rogowski Coil Measurements of PQP003 and PQP004', by B.C.Brown, S.M.Pruss, FNAL Main Injector Note #193.

[4] 'Software for a Database Controlled Measurement System at the Fermilab Magnet Test Facility', by J.W.Sim, R.Baiod, B.C.Brown, E.Desavouret, H.D.Glass, P.J.Hall, D.J.Harding, C.S.Mishra, J.M.Nogiec, J.E.Pachnik, A.D.Russell, K.Trombley-Freytag, D.G.C.Walbridge. Proceedings of the 1995 IEEE Particle Accelerator Conference.