Experience with the SLC Permanent Magnet Multipoles*

G. Gross, J. Spencer and SLAC's MMG+
Stanford Linear Accelerator Center, Stanford University
Stanford, California 94309

Abstract: Permanent magnets have been used in the SLC Damping Rings and their injection and extraction lines since 1985. Recent upgrades of the DR vacuum chambers provided an opportunity to check DR magnets prior to higher beam current operation. Several PM sextupoles downstream of the injection kickers in the electron ring had exceeded their thermal stabilization values of 80° C and some showed serious mechanical deformations and radiation >1 R at contact. We discuss our observations, measurements and a few inexpensive modifications that should improve these magnets under such conditions. A new, block matching algorithm allowed us to use magnet blocks that had been considered unusable because of very different remanent field strengths and easy axis errors.

1. Introduction

Matching and timing errors, jitter and kicker problems can cause damage in the insertion regions of DRs that can result in serious downtime[1]. Small, strong PMs can be very useful in such regions if they can be made reasonably immune to the problems and easily removable so that they can be checked without breaking vacuum. One DR sextupole was remeasured after two years of SLC operation. No changes were observed in either the strength or harmonics to an accuracy of ±0.5%. However, the recent replacement of the vacuum chambers allowed both EMs as well as PMs to be checked. We discuss only the epoxy-filled, PM magnets that were replaced and the modifications based on the magnetic, mechanical and radiation measurements that were made on one of the worst looking PM sextupoles in both rings.

2. Studies of an Old Magnet

The SLC uses two DRs for its $e^{\pm}$ beams. The electron ring transfers more than twice the integrated current of the positron ring but the positrons have far greater input emittance. Chromatic corrections in the rings are done with the PM sextupoles. Prior to the vacuum chamber upgrade SD#32 downbeam of the injection kicker in the electron ring was removed. This split-ring sextupole was made with 12 $SmCo_5$ blocks contained by an Al ring at their OD and a brass collar for mounting to the beam pipe at their ID[2]. Despite the high initial level of radioactivity, measurements indicated the possibility of either restoring the magnets or recovering their PM blocks for reuse if the epoxy could be removed.

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2.1 Magnetic Measurements

The voids between PM blocks were filled with Al_2O_3 loaded epoxy for mechanical stability. If the magnets weren't moved, radiation damage would not cause deformations that would increase harmonics. However, to allow the magnets to be split, there was a small gap between magnet halves that did allow some distortion[3]. The epoxy had undergone differential heating from direct beam loss and conductive heating from the beam pipe which raised the temperature above the glass transition point causing considerable deformation in *some* magnets. The increases in harmonics in SD#32 are shown in Fig.1. Its strength was decreased by 2.5±0.25%.

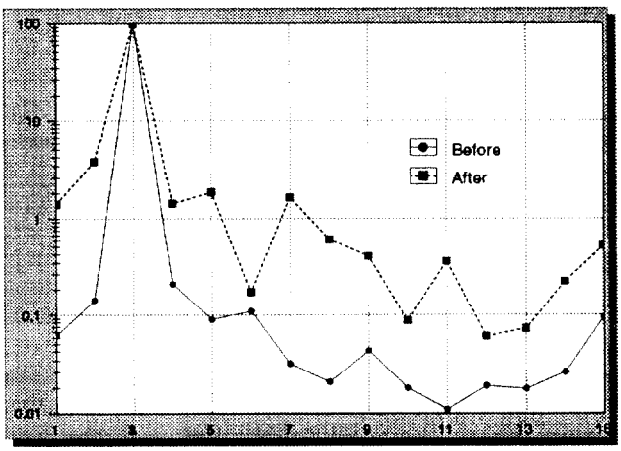

Fig. 1: PMSD#32 Harmonics 'Before' and 'After'.

2.2 Radiation Measurements

Because the $Co^{59}(\gamma,n)Co^{58}$ reaction dominates we give the residual radioactivity $\mathcal{R}$[4] relative to it:

Z	Co^{56}	Co^{57}	Co^{58}	Co^{60}	Zn^{65}	Mn^{54}
$\mathcal{R}$	0.91	1.2	100	0.56	5.5	0.80
$T_{1/2}$	78d	272d	71d	5.3yr	244d	312d

The Zn activity comes from naturally occurring $Zn^{64,66}$ in the brass collar via the (n,γ) and (γ,n) reactions. Because natural Co has a large n-capture cross section, the (γ,n) reaction must dominate for producing Zn^{65}. Also, even $Co^{57,56}$ were observed with comparable strength to Co^{60} as was Mn^{54}. The Al ring is only observed via Na^{22} with $\mathcal{R}$=0.085%. We estimate a neutron flux of 10^{12} neutrons per kJ of absorbed lepton energy in natural Co at 1.2 GeV.

2.3 Epoxy Removal Experiments

An attempt was made to remove the old epoxy to recover the PM blocks so they could be cleaned, tested and potted into new cases and collars. The epoxy showed considerable damage from heating and radiation and was bulging out from between the blocks in places with evidence of gas generation (foaming) within the epoxy. It also showed numerous cracks and was discolored from its pink color to brown and black. It was BONDMASTER M666, Parts A and B also known as "Pink Lady" at SLAC. It is a two-part, room-temperature-cure epoxy manufactured by NATIONAL STARCH & CHEMICAL, Bridgewater, New Jersey. About 50% powdered alumina (aluminum oxide) was blended with the resin prior to potting.

SD#32 was setup in a wire mesh, dip cage in a stainless steel tank with DYNASOLVE #210, a solvent made by DYNALLOY, Hanover, New Jersey. This solvent is a blend of methylene chloride (75% to 95%) and benzenesulfonic acid (5% to 25%) and is sold as an agent for the removal of silicone rubber. It is also used at SLAC to clean epoxy processing equipment. In this experiment, the solution was kept at room temperature.

After 24 hour immersion in the solvent, most but not all of the epoxy was dissolved. After 48 hours all of the epoxy appeared to have been removed. The magnet was allowed to remain in the solvent for an additional 5 days. The magnet was then removed, rinsed in trichlorethane, followed by a warm water rinse and then allowed to dry. On inspection, all epoxy had been removed and the individual magnet blocks were easily removed for testing.

2.4 Resulting Block Condition

An inspection of the blocks showed that the well defined, machined edges had been rounded over at the 90° corners. The cause is not fully understood but of concern because the missing material implies a reduced strength. It remains to test the effect of the benzenesulfonic acid on new blocks of VACOMAX 170 produced by Vacuumschmelze GMBH, Hanau, West Germany. The blocks were sintered without any binder material.

Photomicrographs of new blocks revealed some long fault lines. Because the result was not uniform among all blocks, it is possible that thermal cycling of the magnets allowed some intrusion of hydrocarbons into these faults so that after 8 years and the seven day immersion some erosion occurred. Some blocks were still usable but because of schedules, it was decided that attempts to recover and repot would be discontinued and instead, to manufacture new sextupole magnets from a stock of unused blocks that was available.

2.5 Recommendations for Future Work

Recovery of old magnet blocks in good condition from used sextupole magnets appears possible and is simplified by allowing the magnet's radioactivity to decay some more. Specifically, we should:

1) Continue to work with the DYNASOLVE #210. Minimize the block exposure time needed and determine if the blocks remain stable over time.

2) Use solvents such as DYNASOLVE #CU-5. This is a milder solvent with no acid and a neutral pH. It is usually heated to 150°F for dissolving epoxy but we could try it both heated and unheated. The magnet blocks are thermally stabilized at 176°F.

3) Replace the Zn component in the brass collar with a lighter element e.g. aluminum.

4) Replace the epoxy with Al. This is more expensive but could be especially useful in the insertions.

5) Replace the epoxy with a better one that is made to be free of any trapped gas (see below).

3. Production of New PMs

There are 72 PM sextupoles in each ring divided equally between different strength SD & SF types. 31 new sextupoles were made based on our discussion but using some available PM blocks with different easy axis angles that *had* been considered marginal before. For a variety of reasons, 13 new magnets were used in the electron ring.

3.1 Epoxy Potting of New PMs

A bisphenol, A type, room-temperature-cure, two part, filled epoxy was selected for new magnets. The materials were EPIC RESINS R1055 epoxy and EPIC RESINS H-5039 hardener made by General Fiberglass Supply, Waukesha, Wisconsin.

The R-1055 epoxy contains all the ingredients of the epoxy system with the exception of the hardener. It is a viscous liquid (75,000 centipoise) with approximately 50% silica filler. H-5039 is an amine type hardener with viscosity $\approx$ 200 centipoise. This system has a relatively long pot life at room temperature (4 hours) and the low mixed resin viscosity gives it high penetrating power into the small spaces in the magnet structure. Epoxy cure time at 70° F is 72 hours. This has been used at SLAC for two years in constructing damping ring kicker magnets and shown reasonably good resistance to radiation.

The mix ratio of the epoxy materials are 100 parts epoxy to 18 parts hardener by weight. Mixed resin viscosity is 2100 centipoise. The two components were mixed in four pound batches using a high speed mixer equipped with a 4" diameter "Boat Prop" style mixing impeller. After mixing, the epoxy

was vaccuum degassed for thirty five (35) minutes to a vacuum of 0.5 Torr. The vacuum degas step removed entrained and dissolved air from the epoxy that yielded void free castings.

Magnets to be potted were first assembled using 12 individually matched magnet blocks, a split brass collar, an aluminum case, an aluminum retaining ring and a stainless steel core mandrel. These parts were assembled in a precision alignment fixture which gave high mechanical placement accuracy to the magnet blocks along with precision control of the magnet's inside diameter.

Assembled magnets were installed in a special potting fixture that served to confine the magnet and define the geometry of the epoxy flow spaces during potting. The fixture surfaces which contacted epoxy were mold release coated to facilitate removal of the magnet after cure was complete. Epoxy was added to the magnets using 50 ml plastic syringes. After the addition of liquid epoxy, magnets were placed into a pressure curing tank and cured at 60 psig at room temperature for 72 hours. Pressure curing was utilized in order to compress and minimize the size of any air bubbles which may have been introduced into the magnet during injection.

In a typical magnet production cycle, five to six magnets were assembled, potted and cured at one time. One day was devoted to magnet assembly and installation into the potting fixture. On the second day, all magnets were potted and placed in the pressure tank for curing. On day five, the magnets were removed from the curing tank, the potting fixtures taken off and any flashing removed. The magnets were then cleaned, stamped with their respective serial numbers and taken to the MMG for testing.

3.2 Block Selection Algorithm and Results

The previous sextupoles were made with 3 types of blocks having easy axes of 0, 90 & 180°. The new magnets used only 2 block types (45 & 135°) based on an algorithm for combining blocks with large errors. In practice, it appears easier to produce blocks whose angles are at 90° increments to the axis of the large isostatically compressed, magnetized cylinders. Because we had made a number of 16-block quadrupoles using 5 easy axis orientations as well as the 12-block sextupoles using 3 easy axis angles we had a number of extra 45 & 135° block types. These had the advantages that there would be no PM material in the median plane of the magnet and the split could be oriented vertically for alignment use or horizontally where it could pass the radiation fan in the median plane more easily.

Using only 2 block types simplifies the algoritm e.g. if we had a sample of perfect blocks except for constant easy axis angle errors of $\pm\alpha$, we could make ideal magnets (a rotational error or skew component results *if* we don't rotationally align the magnet by the opposite amount $\mp\alpha$). Fig. 2 shows an example where we used two remanent field strengths B_r differing by 2% (SD#17) and compare it to a more ideal case with $\sigma(B_r)$=0.24% (SD#4) i.e. four times better. The symmetry allowed harmonics are N=6, 12 & 15 for SD#17. Thus one can loosen block tolerances and reduce costs.

Comparing to the results in Ref.[2]: $<SD>_{new}$= 108.92 ±0.72 versus $<SD>_{old}$=109.52 ±0.88 and $<SF>_{new}$= 76.61 ±0.55 versus $<SF>_{old}$ =77.87 ±0.54 T/m. The strengths were weaker and the harmonics not quite as good (Fig's. 1-2) but the uniformity is better. Errors in the η-function around the ring are much worse than these variations. There will also be some reduction in strength of the older magnets that reduces the overall spread in strengths.

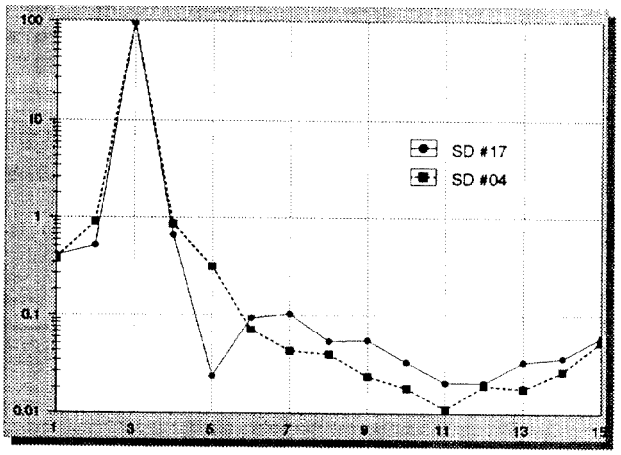

Fig. 2: Comparison of 'Good' and 'Bad' Magnets.

4. Acknowledgements

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5. References

[1] Transverse, nonlinear fields and chromaticity can produce decoherence of the CM motion for mismatched, off-axis injection. One strategy for optimal injection and extraction is discussed in IEEE PAC (1993)396.

[2] J.E. Spencer, "Some Uses of REPMMs in Storage Rings and Colliders", IEEE PAC (1985)3666. Also: "PM Protocol and Tolerances for the DRs", SLAC-CN-309(1985).

[3] Misassembly on the beam pipe by occasional over torquing the retaining screws was probably a worse problem.

[4] Kyle K. Millage, private communication, June 29, 1993.