Prototype Quadrupole Magnets for the PLS Storage Ring *

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May 13, 1993

Abstract

Two prototype quadrupole magnets for the 2.0 GeV PLS storage ring have been built and their magnetic properties have been measured. The prototype quadrupoles have a C-shaped core geometry to facilitate installation of the vacuum chambers and photon beam lines. Pole end chamfering experiments to reduce 12-pole and 20-pole errors, and core shimming experiments to compensate the effects of the core asymmetry, have been performed. After compensation, all multipole error levels are less than the tolerances set by the beam dynamics requirements.

Type of magnet	Q1	Q2
Max. field gradient [T/m]	18	18
Core length [mm]	204	204
Pole tip radius [mm]	36	36
Good field radius [mm]	30	30
Ampere-turns (efficiency=0.994)	9338	9338
Number of turns/pole	68	16
Current [A]	137.32	583.63
Voltage drop/magnet [V]	35.24	58.86
Current density [A/mm^2]	8.39	8.89
Power dissipation/magnet [kW]	4.84	8.08

Table 1. Major parameters of Q1 and Q2 type quadrupole magnets

I Introduction

The PLS storage Ring lattice is a Triple Bend Achromat structure with 12 superperiods and a 280.56 m circumference. Each superperiod has mirror symmetry about the central dipole. Each half superperiod contains six quadrupoles; three in the dispersive section and three in the non-dispersive straight section.

There are six different types of quadrupole magnets; Q1 through Q6. All types use same lamination. All SR quadrupole magnets are designed to have a C-shaped core geometry to facilitate installation of the vacuum chambers and photon beam lines. Core lengths are 204 mm for Q1 and Q6, 314 mm for Q3 and Q4, and 494 mm for Q2 and Q5. Magnet types which are the same length differ in their coils. Series powered magnets use a large cross section conductor, and individually powered magnets use a small cross section conductor. Both types of coils have the same exterior dimensions. The major parameters for Q1 and Q2 are shown in Table 1. The end view of the prototype Q2 magnet is shown in Fig. 1 Q1 and Q2 type prototype quadrupole magnets have been built, and the results of the magnetic measurements are summarized. Both prototypes use the smaller cross section conductor.

*This work supported by the Ministry of Science and Technology and Pohang Steel Co. Ltd.

II Manufacturing

The poles profile of these quadrupoles is designed by conformally mapping a pole profile from a dipole geometry which satisfies the required field quality.

The steel used is the same low carbon steel material used in our dipole magnet[1]. The bore diameter is 72 mm. Die clearance are kept to within 25 microns along the critical pole profiles. Sorting the laminations within a magnet type will be performed in the production phase. Since the lamination has no symmetry axis for flipping the lamination to remove material thickness variations, the material will be flipped *before* punching.

The core assembly is glued, using a full coverage epoxy film between each lamination. Each core is stacked using a fixture with precision reference surfaces. The epoxy is cured while the core is under compression in the precision fixture. After stacking, the core is compressed by fixture bars which go completely through the core.

The coils are constructed as an inclined pancake. A hollow copper conductor (4.6 mm-square with a 2.5 mm hole) is wound in four layers of 17 turns each. The conductor is insulated with 0.13 mm thick by 20 mm wide Dacron tape, half lapped, and coil pancakes are "ground wrapped" with 0.25 mm thick by 20 mm wide fiberglass tape, half lapped.

After the coil pancakes are installed on each half core, the top and bottom halves are joined with stiff tie bars as shown in Fig. 1. The two halves are aligned by means of steel dowel pins in two V grooves.

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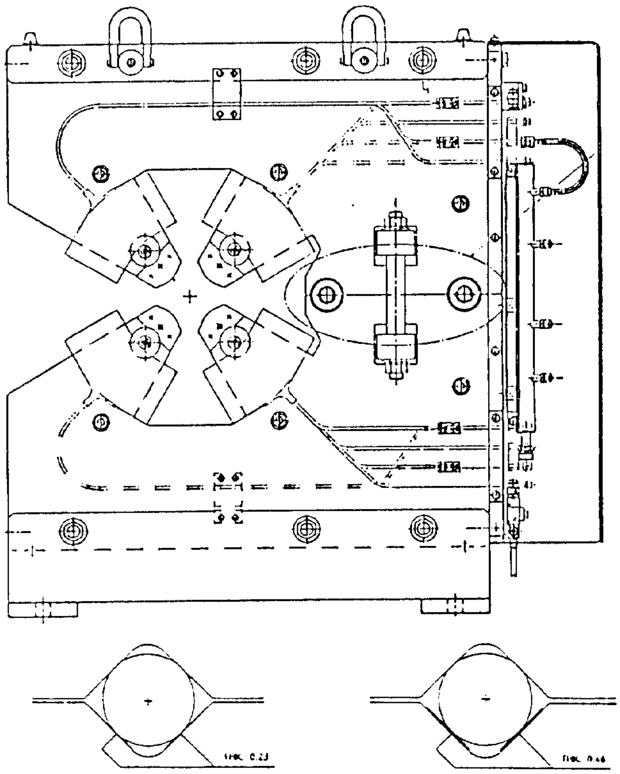

Figure 1: End view of prototype Q2 magnet

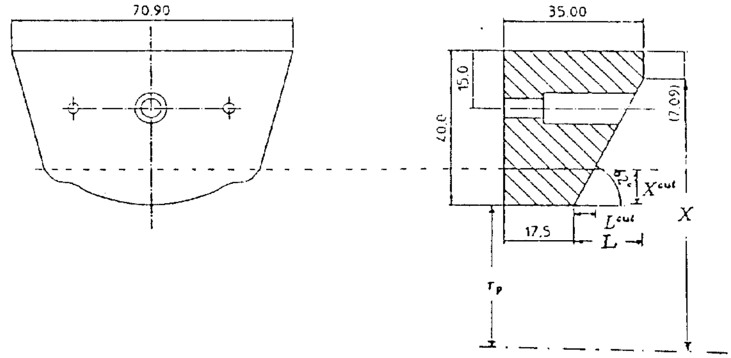

Figure 2: Profiles for pole-end chamfers

III Magnetic Measurements

III-A General

Magnetic measurements are made to investigate magnetic efficiencies at different excitations, to determine an acceptable pole-end profile for the production magnet design, to correct asymmetric core effects on multipole error fields, and to find an appropriate procedure for assembling magnets. A prototype quadrupole rotating coil is used to measure integrated field properties and multipole error levels. The rotating coil has two windings; an inner and an outer winding. The voltage response of each winding is the same for the fundamental field, and is different for multipole error fields. The fundamental field is measured with the outer winding. For the multipole error field measurement, a null measurement is used. The windings are connected in series, with opposing polarities, so that the response of the fundamental field is nulled, resulting in a better signal to noise ratio for the multipole error field measurements.

III-B Measurements and Compensations

For the as-assembled (unchamfered) Q2 magnet, the multipole error components are measured. All multipole errors, except n=3 and n=6 are below the tolerance level.

The n=3 multipole error originates from the asymmetric, C-shaped geometry and can be corrected by rotational motions of the poles. The n=6 multipole error is an allowed harmonic field on quadrupole magnets. Allowed multipole errors (n=6,10,14....) are induced either by imperfect pole shaping or by end fields, and can be corrected by choosing a proper profile on the pole-ends.

Pole rotation is achieved by placing shims in the "V"-grooves shown in Fig. 1. The effects of core motions on multipole error fields are given in K. Halbach's [2] perturbation table. For r_p = 36 mm, the optimum required shims for 90^o "V"-grooves are calculated to be 0.404 mm for groove 1 and 0.202 mm for groove 2. However, with the intention of slight overcompensation, we chose shims of 0.46 mm for groove 1 and 0.23 mm for groove 2. The expected sextupole error level with these shims is

$$-1.11 \times 10^{-3} + 0.1679\frac{0.23\sqrt{2}}{36}\frac{30}{36} = 1.54 \times 10^{-4}$$

which is well below the specified sextupole random tolerance of 9.9×10^{-4} for the Q2 magnet. The measured sextupole error level after shimming is 1.1357×10^{-4} which is close to the value predicted by the perturbation theory.

Next, the n=6 multipole error is reduced by pole-end chamfering. The measured normal n=6 component at $I = 100$ $[A]$ and a normalization radius of 30 mm is -1.779×10^{-3}, and the specified n=6 systematic and random tolerances for the Q2 magnet are 1.68×10^{-3} and 3.3×10^{-4}, respectively. The reason that pole-end chamfers reduce the n=6 multipole error can be understood by an analogy to the correction of n=3 multipole errors in a dipole magnet[3]. In a quadrupole magnet, the length of three dimensional fringe fields will be longest at the center of the pole and shortest at the pole edge where the gap is narrowest. The required cuts can be approximated with a straight chamfer as in Fig. 2. In Fig. 2, the additional iron at each of the pole edges provides a fringe field bump and introduces a n=6 multipole field in opposite polarity to that from the fringe fields of the original unchamfered magnet. The amount of n=6 multipole error compensation with a straight chamfer depends on the depth and the angle cut on the pole. To determine a proper chamfering profile, we test four different chamfer profiles. The optimum cutting depth and cutting angle is found to be L = 17.5 mm and 62^o. With this profile, the measured

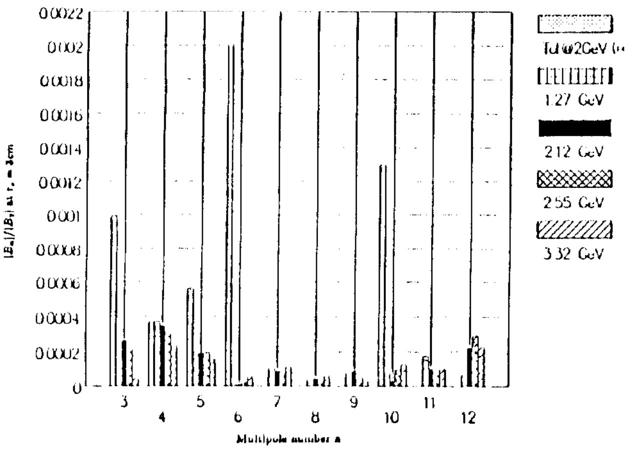
Figure 3: Normalized multipole error vs. multipole number for the shimmed and chamfered Q2 magnet

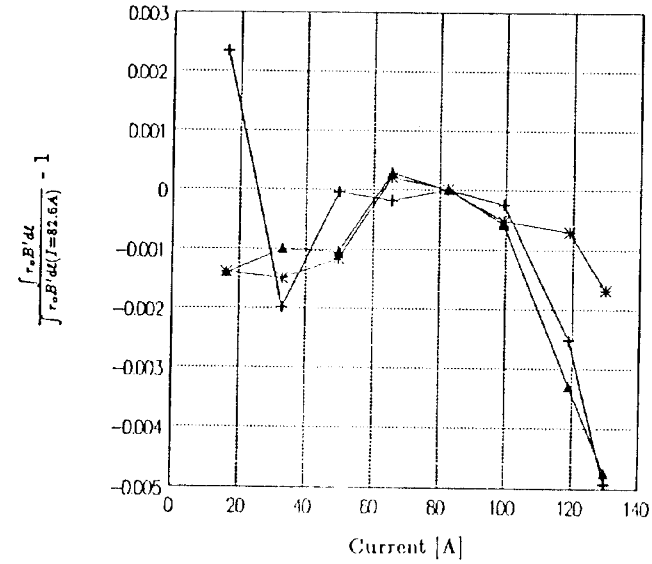
Figure 4: Difference in normalized $\int r_o B'dl$ versus current: Normalized at I=82.6 A. *; as assembled, Δ; chamfered and shimmed Q1, and +; chamfered and shimmed Q2.

n=6 error is -5.25×10^{-5}. By designing the pole profile well, so that the contribution of n=6 error in the central region of the magnet is small, the same pole end profile should work on any length quadrupole magnet.

After chamfering the pole-ends and shimming the core, all multipole error levels are measured over the full excitation range, and the results are given in Fig. 3. The results show that the described shims and pole-end profile are good enough to set all multipole error components below the specified criteria.

Quadrupole excitation properties are measured on the unchamfered Q2 magnet and the chamfered Q1 and Q2 magnets. The chamfer angle is 62^o with respect to the pole faces, and the depth of cut is 17.5 mm. Before taking data, the magnet current is cycled three times from 0 Amperes to 130 Amperes to condition any hysteresis effects. Then, the magnetic fields are measured at each excitation current. The current normalized quadrupole field $\int r_o B'dl/I$ is maximum at $I \simeq 82$ [A], and is 2.277×10^{-3} [T-m] for the unchamfered Q2, 2.062×10^{-3} [T-m] for the chamfered Q2, and 0.885×10^{-3} [T-m] for the unchamfered Q1. A plot of efficiency $\left(\frac{\int r_o B'(I)dl}{\int r_o B'(I=82.6)dl} - 1\right)$ versus current is shown in Fig. 4. Assuming that the contributions of fringe fields to the effective length are the same on both the chamfered Q1 and the chamfered Q2 magnets, and using $(L_{eff} = L_{core} + L_{fringe})$, and from the field integral measurement $\frac{L^{Q2}_{eff}}{L^{Q1}_{eff}} = \frac{0.17032}{0.07309} = 2.330$ at I=82.6 [A], we have $L_{fringe} = 49.0$ mm. Then, the effective length of the Q1 and Q2 magnets are $L^{Q1}_{eff} = 218$ mm, $L^{Q2}_{eff} = 508$ mm respectively. The field gradients calculated with these effective lengths compares well with the theoretically ($\mu = \infty$) calculated B'.

The measured magnet efficiencies are greater than 99.5% for all excitations, indicating that the levels of saturation are acceptable for both magnets.

IV Conclusion

Prototype quadrupole magnets for the PLS storage ring have been designed and built. They feature asymmetric iron cores to facilitate the installation of the vacuum chambers and photon beam lines. Results of magnetic measurements of the prototype quadrupole magnets are summarized. To meet the specifications set by the beam dynamics requirements, end chamfering and shimming experiments are performed on the Q2 magnet, which has eight removable pole-end pieces. The corrected magnet has an efficiency $\geq 99.5\%$ for magnetic field gradients $G \leq 17$ [T/m], and higher order multipole error levels are less than the specified tolerances for all excitations, indicating that the magnet has appropriate properties for the PLS Storage Ring quadrupole magnet.

References

[1] *Conceptual Design Report of Pohang Light Source*, Pohang, POSTECH Press, 1990.

[2] K. Halbach,"Tables and Graphs of First Order Perturbation Effects in Iron Dominated Two Dimensional Symmetrical Multipoles", UCRL-18916

[3] B. K. Kang et al., PLS-MN067, 1992