Permanent Magnets for the 500 MeV Accumulator Ring of the Intensity Doubler Project in KEK-PS.

E. Nakamura, K. Egawa, S. Igarashi and K. Takayama, KEK, Tsukuba, Japan
K. Ogata, Tokin Corporation, Sendai, Japan

Abstract

A 500 MeV accumulator ring (AR) is proposed as a part of the Intensity Doubler (ID) Project in KEK-PS [1, 2]. The AR will be installed in the same tunnel of the 12 GeV main ring. Its circumference will be 340 m. A total amount of 112 permanent magnets are required for the AR and beam transport lines from the booster ring and into the main ring; 88 gradient magnets, 12 quadruples, 8 bending magnets and 4 Lambertson magnets, with a wide mechanical aperture of a +/-50 mm transverse good field region and one or two meters long. The field is driven by strontium ferrite permanent magnets. The field is shaped by precision iron pole pieces. The temperature dependence of the ferrite is crucial to control the beam orbit in the actual tunnel environment with a variation of +/-3 degrees at least. The use of Ni(30%) Fe(70%) alloy operating near its Curie point is expected to compensate a gap field degradation due to the temperature variation. A prototype gradient permanent magnet 1 m long with a 70 mm center gap height is assembled to investigate its field performance and defects to be solved. In the paper, field measurement results will be presented and interested issues such as multipole components in field and a temperature compensation will be discussed.

1 INTRODUCTION

Permanent magnets have been chosen for the AR to save costs to make and operate power supplies for electromagnets. The remanent field of strontium ferrite is weak, $B_r \sim 0.39$ T, but it is cheap and sufficient to control 500 MeV proton beams. The main gradient (combined-function) dipole magnets 1.5 m long are required to have a flux density 0.1586 T and field gradient 0.3836 T/m for focusing or -0.3338 T/m for defocusing. In Fermilab, various types of similar gradient magnets have been developed for many years and almost characteristics of the ferrite, such as temperature stabilization and multipole correction, are reported precisely [3, 4]. The required field for gradient magnets of KEK-AR is close to type RGF of the recycler ring (RR) in Fermilab, but those aperture must be larger, a 70 mm gap at center, a 100 mm horizontal good field region. The beam pipe is supposed to be the same one used in the KEK 12GeV-PS with a diamond shape 68 mm vertically and 206 mm horizontally.

2 PERMANENT MAGNET

The basic design of the permanent magnet is shown in Fig. 1, with a 70 mm gap at center, a 230 mm horizontal aperture. This is a 1m long straight magnet and designed to give the center field of 0.13 T and the gradient of 0.31 T/m. Overall dimensions are 326 mm high by 450 mm wide by 1,160 mm long. The weight is about 660 kg. The field quality is required to be less than $1 \times 10^{-3}$ across the designed good field region. Figure 2 shows the 2-D calculation result with POISSON/PANDIRA. Three bricks of a ferrite, 100.6 mm $\times$ 222 mm $\times$ 25 mm, are stacked at both pole sides and drive flux vertically. The entire assembly is enclosed in a flux return shell 25 mm thick. Solid “bar stock” components are used throughout rather than laminations. The pole tip steel is SUYP1 low carbon steel and the flux return is construction grade (SS400) steel. The field of the magnet is terminated by flux clamp/end plates, which are magnetically connected to the flux return shell.

Figure 1: Cross-section of a prototype magnet.

Figure 2: Horizontal good field region in dB/dx calculated with POISSON/PANDIRA.
Type SR-2 Strontium Ferrite (Tokin Corp.) is chosen as the permanent magnet material because of its low cost and of availability. Ferrite bricks have been magnetized using three pulses of 1.7 T, produced with a spare bending magnet of KEK 12 GeV-PS. The products are not so even with +/-5 % difference, so those were shuffled and selected to be averaged in each unit, which is composed of three ferrite bricks. The difference in flux of each unit is within 0.02 %.

The intrinsic temperature coefficient of the ferrite material, -0.2 % / degree is canceled by interspersing “compensator alloy strip sheets” between the ferrite units above and below the pole tips. The compensator is an iron-nickel alloy with a low Curie temperature and therefore a permeability which depends strongly on temperature. The type MS-1A (SUMITOMO SPECIAL METALS Co., LTD) has been chosen because of larger temperature of dependence of –1.5 % / degree around 20 °C over 100 Oe. This shunts away flux in a temperature dependent manner which can be arranged to null out the temperature dependence of the ferrite. 12 strip sheets of MS-1A with 1.2 mm thick were inserted every 100.6 mm long brick and a 3 mm dead space.

3 FIELD MEASUREMENT RESULTS

All the data reported here were measured by a 2-D field mapping with flip coil system. The signal coil output determines a dipole component. A quadruple component is estimated from a difference in direct outputs from two coils, which are located 10 mm apart.

3.1 Dipole and Quadruple Fields

Figures 3 and 4 show the field measurement results of flux density and its gradient, that is dipole and quadruple components, respectively. The open circles fitted with solid lines indicate the flux density and gradient at the longitudinal center of the magnet. The closed circles fitted with dotted lines indicate longitudinal integrated values, $B_{\text{eff}}$ and $B'_{L_{\text{eff}}}$. Note that all the data about dipole and quadruple fields are given as absolute values in figures and sentences.

At center, the dipole field is 0.127 T and the quadruple field is 0.307 T/m. The measured ratio of dipole and quadruple field at the longitudinal center has a slightly difference 0.2 % from the designed value, and the ratio of integrated values at horizontal center has 0.15 % difference, those will be able to be corrected with end-shims. The error in quadruple field is kept within 1 % in required good field region +/-50 mm, but its integrated value of quadruple field has a larger gradient, sextuple component, 2.7 %. This is intrinsically caused by the difference in longitudinal leakage field at both ends due to the finite size of the pole tips. These errors are easily correctable by means of end shim correction technique.
3.2 Temperature dependence

The flux source, a ferrite SR2(TOKIN Corp.), has a weak temperature dependence of about -0.2 % / degree. In order to compensate it, a 14.4 mm temperature compensator material composed of 12 strips and several-mm non-magnetic spacers are inserted every 100.6 mm wide brick. Figure 5 shows the measured results of the temperature dependence of a gap flux density (a solid line), for comparison with an equivalent dependence of the ferrite (a dotted line). The variation against temperature is +0.022 % / degree and equivalent to 1/9 magnitude of a ferrite tendency. It is a little overcompensation, but is tolerable and can be adjusted by removing one or two sheets of temperature compensator strip.

![Figure 5: Measured temperature dependence of center field. The dotted line indicates -0.2 % / degree.](image)

3.3 Preliminary check of field correction

Unnecessary error fields must be corrected. A longitudinally integrated field correction is attempted by a traditional way using pole end shims. Figure 4(a) shows a strong sextupole dependence of integrated field (squared data), which is approximated by \( BL \sim BL_0 - BL_1 (1 + 0.135 x) \). To eliminate the sextupole component, each end-shim’s shape should be roughly represented by \( s(x) \sim 0.0675 L x^2 / \{ BL_0 / BL_1 - (x(1 + 0.15 x)) \} \); \( \sim 0.42 \times 50^2 \) in mm unit. Figure 6 shows results with and without simple parabolic concave end-shims, \( s(x) \sim 0.75 \times 50^2 \) in mm unit, which is foreseen overcompensation, for the purpose to find out enough effects of the applied end shims for correction. This curve is approximated with multi-layers of 0.5 mm thick iron sheets with 160 mm width, which is smaller than pole width, 230 mm, to make easily. The dotted line indicates the result with the end-shims. The sign of gradient, which means a sextupole component, changes to be inverse against the case without end-shims (a solid line) around center, as expected. More precise correction will be planned by using more proper and accurate end-shims cut by a numerical cutting machine.

![Figure 6: Measured quadruple integrated field. The dotted line indicates the field correction result with end-shims.](image)

4 SUMMARY

A prototype of permanent gradient magnet is assembled to establish a manufacturing process, to measure its magnetic flux density, its field gradient and to investigate multipole components and those correction. Dipole, quadruple fields and those integrated values at horizontal center are desirable. On the other hand, an end-effect appears evidently in the horizontal dependence of the integrated quadruple field. But it has been confirmed to be possible to correct such extent with end-shims.

This work is partly supported by the Grant-in-Aid for Scientific Research on Priority Areas "Neutrino Oscillation and Its Origin", No.12047228.

ACKNOWLEDGEMENTS

We are greatly indebted to James T. Volk and his staffs for their useful comments and showing their permanent magnets and marvelous techniques. We wish to thank Makoto Sakuda for his suggestions on the AR and supporting our work.

REFERENCES