DESIGN OF A DIPOLE MAGNET FOR THE 3-GEV PROTON SYNCHROTRON OF THE JAERI/KEK JOINT PROJECT

N. Tani, K. Kanazawa, T. Shimada, H. Suzuki, Y. Watanabe, JAERI, Tokai, Ibaraki 319-1195, Japan
T. Adachi, H. Someya, KEK, Tsukuba, Ibaraki 305-0801, Japan

Abstract

We have constructed a prototype dipole magnet. The field measurement has been performed. This paper reports the design concept and the results of the preliminary test about this magnet.

1 INTRODUCTION

The 3-GeV synchrotron proposed in the JAERI/KEK Joint Project is a rapid-cycling synchrotron (RCS), which accelerates a high-intensity proton beam from 400-MeV to 3-GeV at a repetition rate of 25 Hz. The 3-GeV synchrotron is used to produce pulsed spallation neutrons and muons [1]. It also works as an injector for a 50-GeV synchrotron. Since the magnets for the 3-GeV synchrotron are required to have a large aperture in order to realize the large beam power of 1 MW, there is a large leakage field at an end part than a usual synchrotron magnet. In addition, 25-Hz ac field induces an eddy current in magnet components: e.g. a coil, magnet end plates and etc. We intend to use a stranded conductor as a coil conductor so that the eddy current induced in the coil can be reduced. On the other hand, the eddy current induced in the end plates is expected to be large. Therefore, it is important to investigate effects of the large leakage field and the eddy field to the beam motion around the magnet end part.

In addition, the eddy loss and the eddy field at the edge of the magnet caused by the eddy current was measured and compared to a simple two-dimensional model. This model supposes that time dependent external field is expressed by:

$$\overrightarrow{H}_{ext} = \overrightarrow{\hat{H}}_{ext} e^{i\omega t} \qquad (1)$$

If the field component perpendicular to a plate, say z - component, is dominant, an eddy field can be treated two-dimensionally. Hence, supposing that the eddy field is sufficiently smaller than the external field $\overrightarrow{\hat{H}}_{ext}$, the following equation is obtained for the plate with electrical conductivity σ and magnetic permeability μ .

$$\frac{\partial^2 \upsilon}{\partial x^2} + \frac{\partial^2 \upsilon}{\partial y^2} = k\hat{H}_{ext} \qquad (2)$$

Here, υ is z component of vector potential that gives eddy current, and $k = i\omega\sigma\mu$. In order to solve the equation (2), the following boundary condition is required: $\upsilon = 0$ along the plate boundary. Eddy current that flows in the plate is given by the following formula.

$$\vec{j}_{eddy} = rot\vec{\upsilon} \qquad (3)$$

Eddy loss at the plate can be found from eddy current density j_{eddy} , and electrical conductivity.

2 DESIGN OF A DIPOLE MAGNET

2.1 Design

The magnet system comprises dipole magnets and quadrupole magnets, which are operated synchronously with each other. These magnets are characterized as follows:

- The magnets are excited with a repetition frequency of 25 Hz,
- The magnets has an aperture larger than a usual one,
- A saturation of the magnets has to be small in order to assure a close tracking between dipole and quadrupole magnets.

A large gap causes a large leakage field around a magnet edge. And rapid repetition of such a field induces a large eddy current in a magnet end plate. Therefore, the eddy loss of the magnet edge is a severe problem. RCS magnets are formed to some resonant networks and excited by a current with DC-biased sinusoidal waveform. Since it is very difficult to compensate a deformation of the waveform under a resonance condition, a magnet dimension is designed so as to keep the non-linearity between the inductance and the field less than 1 %. In addition, the maximum magnetic field in iron core is designed less than 1.6T. Taking these points into account, cross section of the dipole magnet is determined. The parameters of the dipole magnet are summarized in Table 1.

Table 1. Parameters of the dipole magnet

Field	0.27 T (for 400-MeV)
	1.1 T (for 3-GeV)
Useful Aperture (horizontal)	± 120 mm
Gap Height	210 mm
Core length	2770 mm
AC Current	970 A
DC Current	1600 A

2.2 A prototype dipole magnet

A prototype dipole magnet, whose useful aperture is ± 95mm and core length is 1000 mm, was constructed in order to investigate above-mentioned problems. The core material is 0.5 mm thick laminated silicon steel, 50BF470. Fig. 1 shows the cross section of a prototype dipole magnet.

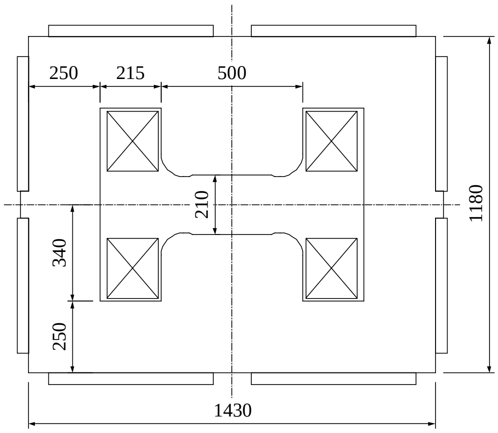

Figure 1: Cross section of a prototype dipole magnet.

The linearity between inductance and the field was estimated by POISSON. As shown in Fig. 2, the linearity between the field and inductance is expected to be within 1% in the necessary excitation region.

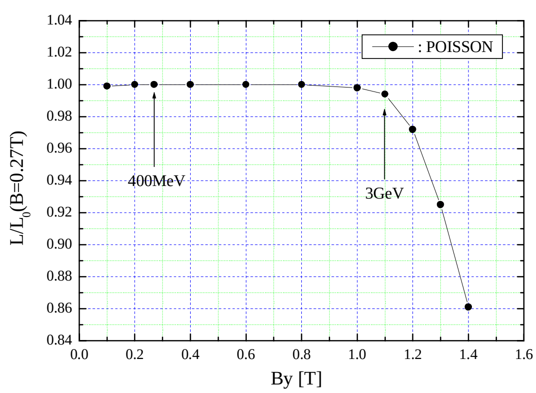

Figure 2: Linearity between the field and inductance.

2.3 Stranded conductor

A stranded conductor has been developed as a coil conductor for the magnet excited with a rapid repetition. In order to reduce an eddy current loss in the coil conductor, aluminium stranded wire is employed. An electric insulation between wires of the stranded conductor is expected to be performed by alumina (Al_2O_3) film formed on the wire surface by natural oxidation. Natural oxidation of aluminium reaches saturation at room temperature when the film thickness becomes approximately 2.5 nm. When a coil is impregnated with resin in vacuum, resin penetrates in a space between wires and it improves electric insulation and thermal conductivity. Fig. 3 shows the cross section of an aluminium stranded conductor used as a coil conductor of this magnet.

Figure 3: Cross section of an aluminium stranded conductor.

2.4 Preliminary result of field measurement.

The field measurement of the prototype dipole magnet has been performed within the field range of up to 0.342 T. The magnet was excited by an ac current with the repetition of 21.98 Hz. In this measurement, two search coils were used: one is a reference coil and the other is a measurement coil. The reference coil was fixed at the center of the magnet. The measurement coil was moved on the median plan. Signals of two search coils were sent to a 16bit-ADC with a sampling rate of 1 MHz, and amplitude and phase difference were measured. The latter gives an eddy field [2].

The field distribution in horizontal direction is shown in Fig. 4, together with the results calculated with TOSCA and POISSON. Black dots show the measurement result in the figure.

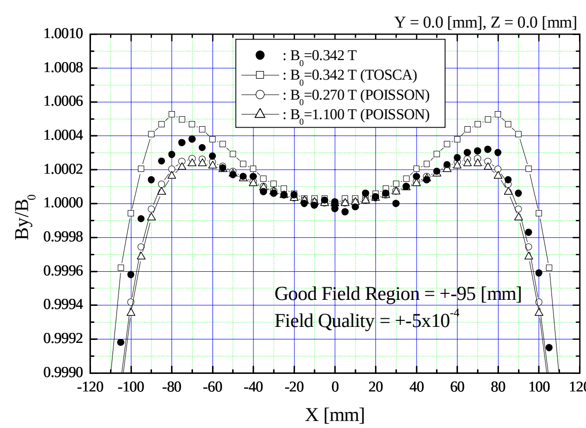

Figure 4: Field homogeneity.

As shown in the figures, field homogeneity fully satisfies required condition in the good field region.

The measured field distribution and eddy field along the beam axis are shown in Fig. 5. In the figure, black dots and triangles denote the main field and the eddy field, respectively. Broken line denotes the TOSCA result. As shown, the eddy field increases up to 0.45 % of the central field at 150 mm outside of the magnet edge.

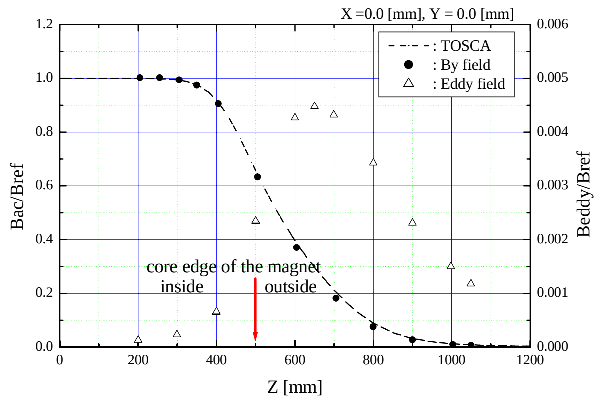

Figure 5: Field distribution in the longitudinal direction.

3 EDDY LOSS OF THE MAGNET END PLATE

3.1 Design of the end plate

The edge shape of a magnet core must be carefully designed so that the magnetic field component across the end plate does not become too large. Otherwise eddy current is induced by such a field. Thus, the fringe of the magnet core has a stairs shape, approximating to a Rogowski curve. And slits are put on the end plate of the magnet. The eddy loss of the magnet end plate was estimated by the simple two-dimensional model described above. The result was compared with the measurement. In case that thickness of a plate is sufficiently smaller than the plate size, it is unnecessary to use the three-dimensional model that requires great amount of time for calculation.

3.2 Measurement of the temperature of the end plate

In order to confirm adaptability of our model, a measurement was conducted with a prototype dipole magnet. For examination of eddy loss at the end plate, this magnet has five slits on one side of the end plate while there is not on the other side. Shape of the end plate is shown in Fig. 6. Material of the end plate is SUS316 and thickness is 40 mm.

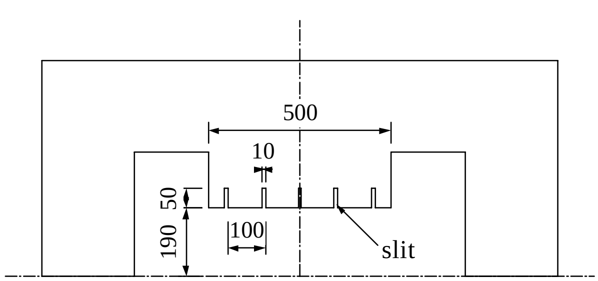

Figure 6: Shape of the end plate and a slit configuration.

The measurement has been performed by exciting the magnet with an alternate current, whose amplitude and repetition were 810 A and 21.98 Hz, respectively. Thermocouples were attached to each side of the magnet and temperature was monitored continuously. Temperature rise of the magnet end plate almost saturated after about 13-hours operation. The result is shown in Table 2. In the table, the temperature given by our model is also listed. Such a temperature was derived from the eddy loss by using Stefan-Boltzmann equation. The external field used in the model was calculated with the three-dimensional static field analysis program, TOSCA.

Table 2: Eddy loss and temperature of the end plate.

	Two-dimensional model		Measurement
	Eddy loss [kW]	Mean temp. [deg C]	Meas. Temp. [deg C]
Without slits	0.971	144	146
With slits	0.572	91	105

Considering roughness of the temperature estimation, this result is acceptable. Especially, when temperature difference is compared for the cases of with/without the slit, both show approximately 40 deg C. It is considered to be possible to employ our model as a rough standard for designing the slit configuration of the end plate. It was found that the eddy loss of the end plate of the dipole magnet was a severe problem. Configuration of the slit must be further studied in the future in order to reduce eddy loss of the end plate.

4 CONCLUSION

A prototype dipole magnet has been constructed successfully. The result of the field measurement agreed approximately with the calculated values. The temperature at the end plate was measured. The result implies that eddy loss evaluation using two-dimensional model is valuable for the design of the slit configuration of the end plate.

We intend to study the effect of edge field to a beam motion in the future.

REFERENCES

[1] Y. Yamazaki, Y. Mori et al, “High-Intensity Proton Accelerators for the JAERI/KEK Joint Project”, EPAC2000, Vienna, 2000, pp.286-288.
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