RESEARCH AND DEVELOPMENT OF AN ELECTRIC/PERMANENT HYBRID MAGNET

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Abstract

Permanent magnet is a reasonable option to replace electromagnet in accelerator systems to save power consumption of accelerator facility. However, the usage of permanent magnet is still very limited until now. One of the reasons is the temperature dependence of permanent magnet properties. We are designing electric/permanent hybrid magnet for future synchrotron light sources, which would be capable of field adjustability for flexible accelerator operation. A model permanent dipole magnet developed at Nagoya University is used to investigate the thermal effect generated by the coils in the magnet operation. Through the research, an active feedback system uses the real-time temperature of the permanent magnet to adjust the coil current for precise control of the magnetic field strength. A design for an electric/permanent magnet is also in progress. The experimental result and design will be presented.

INTRODUCTION

The use of Permanent Magnet Material (PMM) is a trend in accelerator facilities, which can save power consumption [1]. For the future plan of Hiroshima Synchrotron Radiation Institute at hiroshima University, a new low-energy storage ring HiSOR-II is under designing for the increasing demand of high-brilliance radiation. The usage of PMM is taken into consideration for magnet. However, the temperature dependence is a negative effect to use PMM in accelerator operation. The magnetic field of a PMM will change with temperature according to the temperature dependence of the remanence. In stead of a passive compensation method using Fe-Ni alloys, we are designing electric/permanent hybrid magnet to pursue flexibility of magnetic field and explore an active compensation method by adjusting the current of coil.

The concept of such a magnet is that the magnetomotive force is mainly generated by the Permanent Magnet (PM), and excitation coils are assembled to ensure adjustability of the magnetic field. The coils do not require water-cooling, which would contribute saving the operation cost but would cause temperature change of the magnet. Researchers at Sirius Light Source fabricated a hybrid quadrupole magnet but did not investigate the compensation of thermal effect [2]. An active compensation method is expected to stabilize the

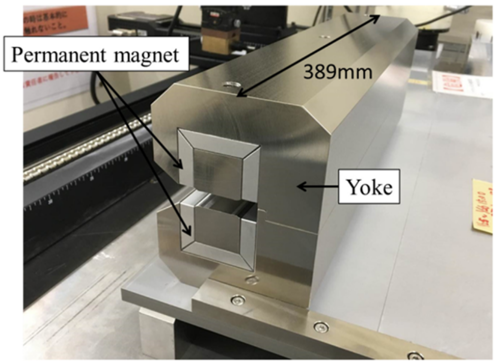

Figure 1: A reduced-scale permanent magnet-based dipole magnet.

magnetic field by adjusting the current of coil, and the magnet will finally reach a thermal equilibrium state.

PRE-RESEARCH USING A PERMANENT MAGNET-BASED DIPOLE MAGNET

Experiment System

The thermal effect compensation scheme is studied by using a permanent magnet-based dipole magnet developed at Nagoya University [3]. As shown in Fig. 1, the magnet is a reduced-scale model magnet, and the length is 389 mm. The PM is made of Neodymium-Iron-Boron (NdFeB) magnet (NMX-46CH). The remanence B_r and the coercivity H_{cb} of the NdFeB magnet are 1.37 T and 1040 kA/m, respectively. The magnetic flux density in the gap is almost 1.4 T.

The magnet was assembled with the coil to provide additional magnetomotive force. The coil is made of enameled

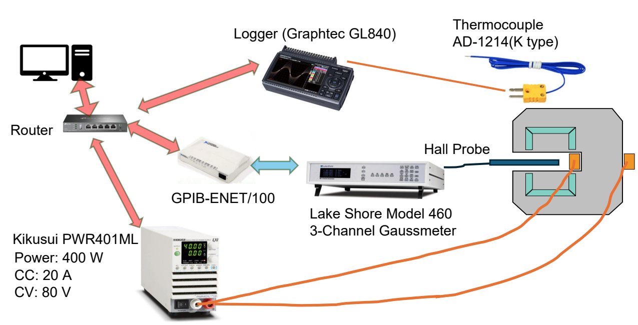

Figure 2: Schematic view of the experiment system.

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wire (PEW-1.6 mm), and the turn number is 20. An experiment system has been constructed, which is shown in Fig. 2. The thermocouple is used to measure the temperature of the PM, and the data is saved in the logger. The magnetic field in the gap is measured with a Hall probe.

Experimental Results

One experiment is getting the proportional relationship between the current and magnetic field. The current is adjusted in a short time, and the thermal effect is negligible. The result is shown in Fig. 3. The variation of By is proportional to the current as expected. The gradient is 0.001275 T/A. The effectivity of the coil's magnetomotive force is low. Because the dipole magnet is not designed for an electric/permanent hybrid magnet.

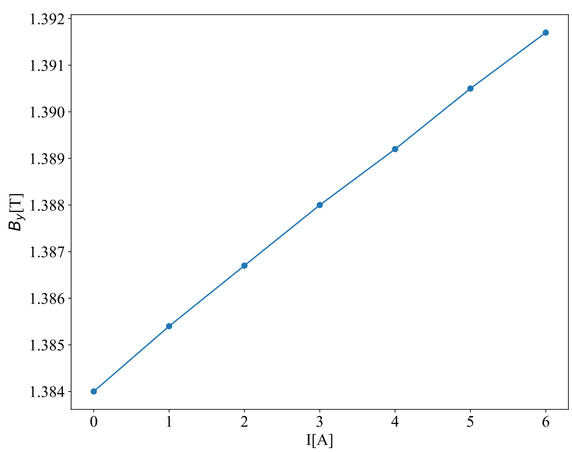

Figure 3: Relationship between magnetic flux density and current.

The other experiment is examining the thermal effect of the coil. In the experiment, the current was 6 A. The magnetic field and temperature results were read simultaneously in every 5 seconds. As shown in Fig. 4, the magnetic flux density gradually decreases when the temperature of the PM increases. It is known that PMM has a linear thermal coefficient for the remanence. However, it cannot be clearly

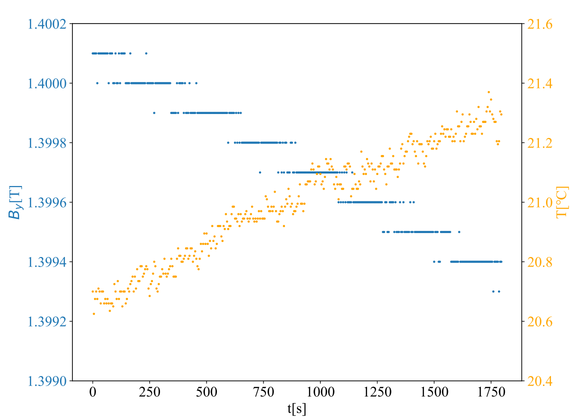

Figure 4: Measurement of the magnetic flux density and PM's temperature.

distinguished from the result due to the measurement precision. The Lake Shore Model 460 has a minimum scale of 0.0001 T, and the measurement precision of the PM's temperature is about 0.1 ℃.

The linear coefficient should be measured as precise as possible, otherwise the magnetic field cannot be adjusted correctly by the current of the coil. To improve the measurement precision, a filter algorithm was applied to get a smooth response. The number of filter point is 8. A linear average is used, and the data updates at 4 readings per second, the filter will settle in 2 seconds. Then the minimum scale becomes 0.1 Gauss. Similarly, the linear average method is used in the temperature measurement. An updated result is shown in Fig. 5. The measurement precision of the PM's temperature is reduced to about 0.03 ℃. In the experiment, the linear coefficient is -0.00126 T/℃, corresponding to -0.09%/℃.

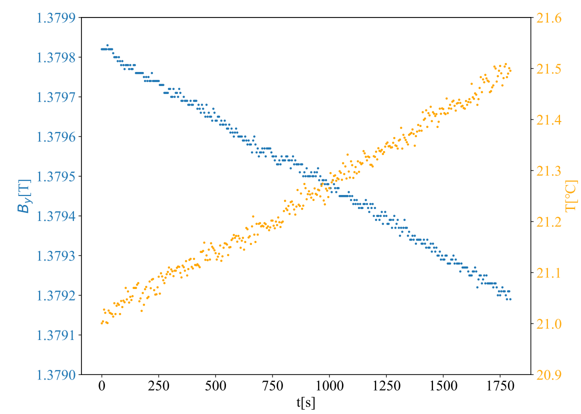

Figure 5: Measurement of the magnetic flux density and PM's temperature after a linear average.

Active Feedback Control

A feedback control by monitoring the temperature of the PM was developed to stabilize the magnetic field. The variation of the current is calculated as:

$$\triangle I = \triangle T/(g * k) \tag{1}$$

where $\triangle T$ is the variation of the PM temperature, g is the gradient between the current and magnetic flux density, and k is the linear coefficient of the PM.

The feedback control was tested when the initial current was 4 A. As shown in Fig. 6, the drift of the B field is less than 0.00015 T in 45 min. Although the magnetic field kept stable after applying the feedback control. It cannot reach a thermal equilibrium state in a long time. The current gradually increased. Because the reduction of magnetic field caused by the temperature is larger than the growth resulted from the current. It should be noted that the magnetic field variation is proportional to the current, but the thermal effect is proportional to the square of the current. This issue should be treated carefully in an electric/permanent hybrid magnet design.

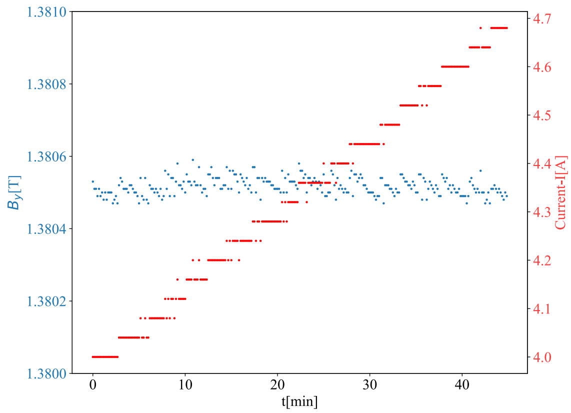

Figure 6: Change of the magnetic flux density and the current.

PRELIMINARY DESIGN OF AN ELECTRIC/PERMANENT HYBRID MAGNET

From the pre-research using a dipole magnet, an electric/permanent hybrid magnet must meet a requirement that the magnetic flux generated by the coil should be much larger than the reducing effect caused by the temperature dependence. However, because of the usage of PM, the magnetic resistance increases in magnetic circuit. If the magnetic resistance cannot be reduced, an electric/permanent hybrid magnet will require a large current to generate the magnetic field, and it will also not be energy-saving.

To investigate whether an electric/permanent hybrid magnet can be used, a C-shaped dipole magnet will be designed. As for the parameters, it is assumed that the magnetic flux density is 1 T, and 30% of the value is variable. That is to say, the magnetic flux densities generated by the PM and the coil are 0.7 T and 0.3 T, respectively.

Magnetic Field Calculation

To start a 2D analysis for the magnetic field calculation, a magnetic circuit of a C-shaped magnet is constructed, which is shown in Fig. 7. The width and thickness of the PM are w and t, respectively. The arrow shows the direction of easy axis. For the convenience of calculation, it is assumed that the gap ($2h$) is 30 mm with a pole width (g) of 80 mm, and the PM material is NMX-46CH.

The integration of magnetic field strength in the circuit is given by

$$\frac{1}{\mu_0}\int_0^h B\mathrm{d}l + \frac{1}{\mu}\int_{core} B\mathrm{d}l + \frac{1}{\mu_0}\int_0^t (B - B_r)\mathrm{d}l = NI \quad (2)$$

If the integral of magnetic field strength in the core is ignored, the equation is simplified as

$$B_0 h + B_p t = \mu_0 NI + B_r t \quad (3)$$

where B_0 is magnetic flux density in the gap, B_p is an average magnetic flux density inside the PM, and B_r is the remanence.

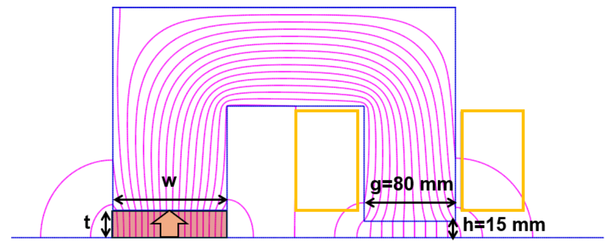

Figure 7: A magnetic circuit of a C-shaped magnet.

Because the magnetic flux is conserved in the circuit, the following equation is obtained.

$$B_p w = f B_0 g \quad (4)$$

where f is a leakage factor of the rectangular pole gap [4], and it is approximately calculated as

$$f \approx 1 + 1.056\frac{h}{g} \quad (5)$$

Therefore, the magnetic flux density in the gap is given by

$$B_0 = \frac{\mu_0 NI + B_r t}{h + \frac{fgt}{w}} \quad (6)$$

It is noted that the magnetic flux loss of the PM caused by the flux return is ignored in the calculation. Therefore, the calculated magnetic flux density is larger than a result in numerical simulation.

When the current is zero, the magnetic flux density in the gap is calculated by the PM with different width and thickness. As shown in Fig. 8, if B_0>0.7 T, the thickness had better be larger than 10 mm.

Then the magnetic field generated by the coil is discussed. If the geometry of the PM is different, the necessary current will also be different to generate a B_y of 0.3 T. As shown in Fig. 9, if the thickness is zero, there is no PM, and the total current NI is 3580 A. After inserting a PM, the NI will

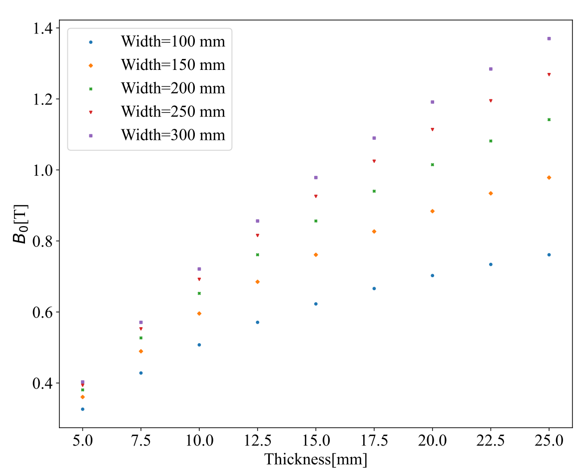

Figure 8: Magnetic field generated by the PM with different width and thickness.

increase. A desirable NI should not be more than 6000 A. Considering the precious condition that $t >$ 10 mm, the width of the PM should be larger than 200 mm.

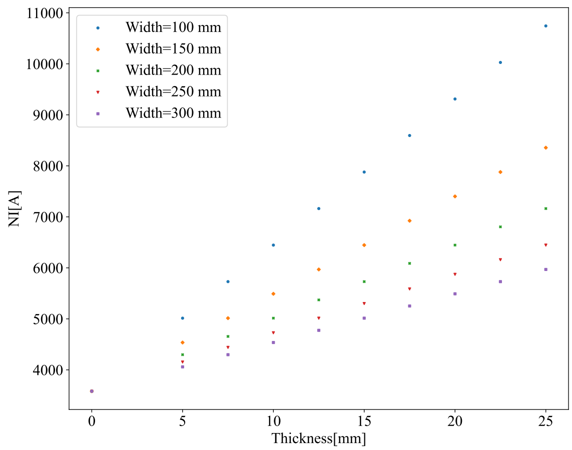

Figure 9: Necessary current for using PM with different width and thickness.

Proposed Dipole Magnet

From the previous calculation, the PM should have a wide width and a small thickness to generate enough magnetomotive force and reach a small magnetic resistance. To save the electric power, the width should be larger than 200 mm, which is much larger than the pole width. If a rectangular PM is used directly, the volume of iron will increase much more.

To save the construction cost and achieve a good performance of the B field, one proposed design is shown in Fig. 10. Such a structure of PM can generate enough magnetomotive force and reach a small magnetic resistance. The total width of the PM is 280 mm. The thickness of two PM blocks is 10 mm, and another one's thickness is 14 mm. We chose such a design to reduce the magnetic resistance. As shown in Fig. 11, the B field result of a 2D model is calculated using Radia [5]. The magnet that has a constant field (0.7 T) generated by the PM. If the total current is 5000 A, an additional field (0.3 T) can be generated by coil. For an electromagnet that has same geometry, the total current will be 13000 A to generate a B field of 1 T. The electric power will be 1/7 of the power consumed by the electrical magnet when B_0=1.0 T. We will continue careful design study on the magnet configuration later.

CONCLUSION

To develop an electric/permanent hybrid magnet, a permanent magnet-based dipole magnet was used to investigate the operation scheme to suppress the thermal effect of coil. An active feedback system using the real-time temperature of the PM to adjust the coil current has been developed, the drift of magnetic field is less than 1.5 Gauss. The pre-research also shows that the magnetic resistance generated by the PM is significant in a model magnet design. An analytical calculation for the magnetic performance of an electric/permanent hybrid dipole magnet was performed, and a feasible design of a model dipole magnet was proposed.

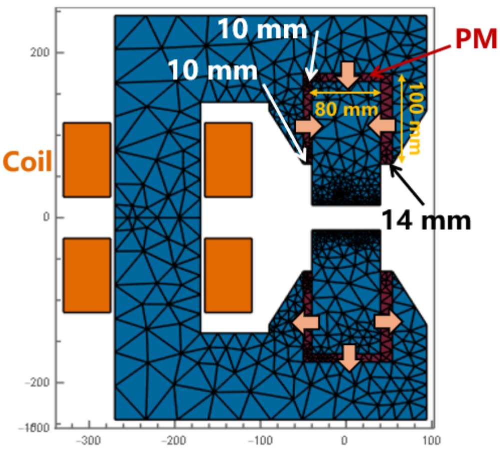

Figure 10: 2D Design of an electric/permanent hybrid dipole magnet.

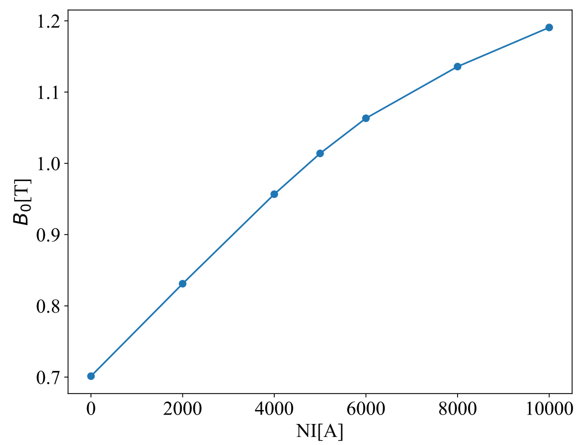

Figure 11: The magnetic flux density corresponding to different current.

ACKNOWLEDGEMENTS

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