ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRO092

MAGNETIC-FIELD VARIABLE PERMANENT DIPOLE MAGNET FOR FUTURE LIGHT SOURCES

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Abstract

A permanent dipole magnet with variable magnetic field has been designed, fabricated, and tested at SPring-8. Permanent magnet can be advantageous over electromagnet in terms of power consumption, stability and reliability etc. One of critical issues to apply permanent magnets to future light sources and other accelerators is that the magnetic field should be somehow tuned. In designing future light sources, combined-function or longitudinal gradient magnet may play a key role in achieving extremely small emittance. Therefore, it may not be appropriate to change a gap for changing the field. We have proposed an alternative way to tune the magnetic field of permanent magnet by using outer plates, and the performance has been investigated.

INTRODUCTION

Future light sources have been discussed at many facilities, where main issues are smallest emittance that can be achieved with enough apertures, instabilities, compact but high field magnets that can fit in a high-packing-factor lattice, etc. Especially in Japan, and perhaps in other countries, a power consumption should also be taken into consideration, since a large accelerator facility consumes the power in the order of Megawatt. For the reason, permanent magnets have again attracted interests in designing new light sources [1, 2]. At SPring-8, we have studied a possibility of applying permanent magnets to our future light source.

In addition to the power consumption, permanent magnets may be beneficial to reliable and stable operations. Since no power supply is necessary for permanent magnets, no unexpected beam halt due to a power supply failure is supposed to happen. As far as no cooling water is supplied, there is no fluctuation of magnetic field coming from the water flow, nor beam halt due to troubles with cooling water system. These features can be important for future light sources, where very reliable and stable operation is mandatory.

Although one can readily change magnetic field of electromagnets, there is no straightforward way to do it for permanent magnets. It is important not only when an electron energy is changed in user operations or some specific studies, but also when magnets are first installed to an accelerator and the magnetic field is precisely adjusted to the nominal energy. Therefore, it is required to adjust magnetic field (i) in a small range for initial conditioning, and (ii) in relatively large range when the operating energy of an accelerator needs to be changed.

We have designed a dipole magnet that is embedded with outer plates. By this, magnetic field can be adjusted in relatively large range. The magnet has been manufactured and the performance has been investigated at SPring-8.

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PERMANENT DIPOLE MAGNET WITH VARIABLE FIELD

Generally, a magnet is designed so that as much magnetic flux as possible goes to a position where beam passes through. In our design, the flux is intentionally "leaked" to outer plates so that the magnetic field that beam experiences can be adjusted by moving the outer plates (see Fig. 1).

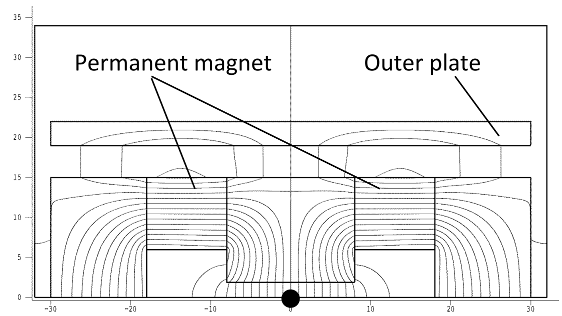

Figure 1: Cross sectional view (upper half) of a permanent dipole magnet with an outer plate. Black dot indicates the place where beam passes through.

The magnet is a hybrid type one, consisting of permanent magnet and irons. Such a structure is good at suppressing non-uniform magnetic field distribution due to inhomogeneous magnetization of permanent magnet pieces, and also protecting the permanent magnet from the radiation damage. Since only outer plates move and the pole face is fixed, the field distribution is invariable while the field strength is adjusted. It is effective when a magnet is combined functioned, or has longitudinal gradient field. In case that a gap is changed, on the contrary, the field distribution may be changed. Furthermore, as far as the outer plates extract a small fraction of total magnetic flux, it does not require a huge mechanical force to move the plates. Suppose the magnetic field is 1 T and the pole face is 1 m x 1 m wide, then the mechanical force to move a gap is estimated to be about 40 Ton, while that is necessary to move outer plates is 400 kg or less as far as less than 10 % of total flux is extracted by the outer plates;

$$F = S\frac{B^2}{2\mu_0}, \tag{1}$$

where F is the magnetic force, S is the area of pole surface, B is the magnetic field, and μ_0 is the permeability in the gap.

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Another advantage of using outer plates is relatively large tunable range of magnetic field. When the plates are placed close to the magnet, more than half of the total flux is extracted by the plates, thus the magnetic field on beam can be tuned by more than 50 % (see numerical and experimental results in Fig. 5). In such a case, however, the mechanical force to move the plates is evaluated to be a quarter of that is necessary to move a gap, though (see Eq.(1)).

FABRICATION AND MEASUREMENT

A H-shaped sector bending magnet was fabricated as shown in Fig. 2. The magnet is composed of Neodymium permanent magnet (NMX-44CH, Hitachi Metals Admet, Ltd.) and irons (SS400). The gap is 38 mm, and the longitudinal magnet length is 400 mm. The thickness of the outer plates is 30 mm, while the thickness of 50 mm or more is preferable if one wants to extract the maximum magnetic field to the plates. Although the nominal magnetic field of the dipole is 0.8 T, the magnetic field on the beam axis is designed to be slightly larger than 0.8 T without outer plates. By that, it can exactly be adjusted to 0.8 T by adding the pates. Thus, the initial magnetization does not ought to be precisely matched to the nominal value; it can be tuned by changing the outer plate position later.

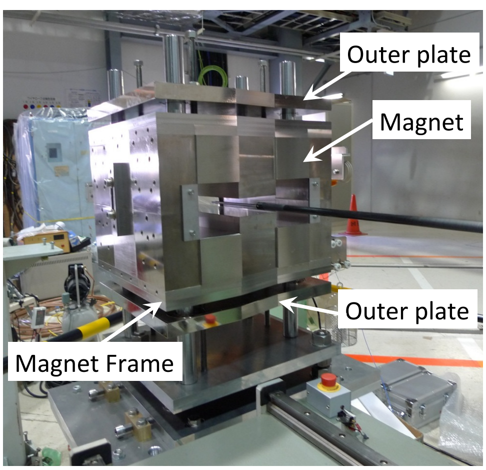

Figure 2: Permanent dipole magnet with outer plates.

First, the magnetic field was measured by scanning a hole probe and was mapped as shown in Fig. 3. The contour plot of the magnetic field in Fig. 3 verifies that the field distribution forms a sector magnet as desired. Detailed transverse and longitudinal magnetic field distributions at the center of magnet are plotted in Fig. 4 (a) and (b), respectively. In order to verify the reliability of the magnet itself, the measurement was first carried out with the outer plates removed. Because of this, the peak magnetic field exceeds 0.8 T.

Measured magnetic field distributions shown in Fig. 4(a)(b) agree well with 3-dimensional simulation except that there is unexpected field gradient in the longitudinal (z) axis; in Fig. 4(b), a flat-top distribution has a field gradient of 1 mT in 200 mm in z-axis. It was then found that the field gradient originated in a gradient of gap; the gap was found to be inclined from one side of the magnet to the other in longitudinal axis by 66 μm. Such an error likely occurred when the hybrid magnet was assembled in the factory. Even though the field gradient in z-axis does not significantly affect the lattice functions, precise measurements and the knowledge on the reliability of magnets are essential for reliable operations.

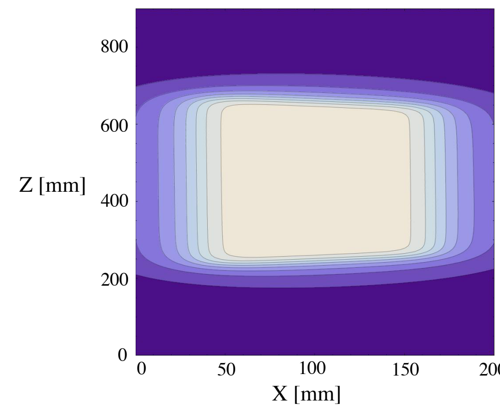

Figure 3: Contour plot of measured magnetic field for the sector magnet shown in Fig. 2. See Fig. 4 for detailed distributions and dimensions.

Next, the outer plates were attached to the magnet. The outer plates are supported by four shafts on each side, and are moved by rotating screws. As mentioned above, the magnetic force between the magnet and the outer plates is significantly smaller than that is needed to change a gap, so one can readily move the outer plates manually. Needless to say, it can be also driven by motor stages and remote system, if necessary.

In order to prove the principle, the magnetic field was measured while the outer plates were moved. In Fig. 5, the measured magnetic field as a function of outer plate positions is plotted in dots and the numerical result calculated by the 3-dimensional code CST STUDIO (CST Computer Simulation Technology AG.) is indicated in the solid line. The origin of the outer plate position is defined such that when the plates are attached to the magnet, the position is zero. Since the magnet has an outer frame with a thickness of 40 mm, the outer plates cannot be placed closer than 40 mm. Also note that the initial magnetization of the permanent magnet pieces was not precisely controlled at the factory, so the magnetization factor in the simulation was adjusted by 2 % from the nominal value so that the magnetic fields by the measurement and the simulation are consistent at the outer plate position of 150 mm. As a result, the measured magnetic field on the beam axis agrees well with the simulation. In Fig. 5, the magnetic field is varied by about 10 %, which is enough for the initial tuning of the magnet. The design value of 0.8 T is achieved by choosing the plate position of around 100 mm.

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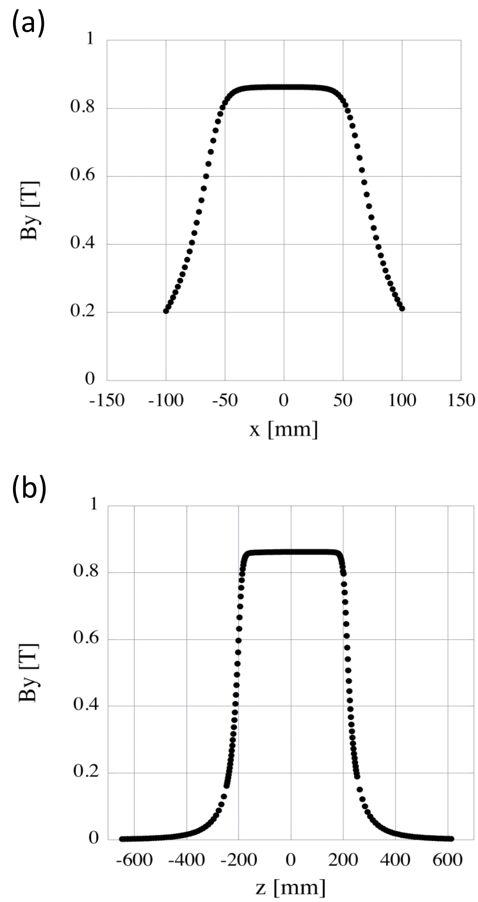

Figure 4: (a) Transverse and (b) longitudinal magnetic field distributions, By(x) and By(z), without outer plates. The origin, x=0 and z=0, is chosen as the center of magnet.

When the thickness of the outer plates is 50 mm or more, the field on beam can be less than 0.2 T by moving the outer plate until it attaches to the magnet. In principle, therefore, the tunable range of the scheme is supposed to be more than 50 %, or even 70 %. The feature of larger tuning range is beneficial when a operating energy of an accelerator needs to be changed a lot.

CONCLUSION AND FUTURE PERSPECTIVE

A hybrid-type dipole magnet consisting of permanent magnet and irons has been designed and fabricated, and the performance has been investigated at SPring-8. It is embedded with outer plates so that the magnetic field that electron beam experiences can be varied in a relatively wide range. It was experimentally verified that the magnetic field was generated and varied as expected except that slightly inclined magnetic field distribution along the longitudinal axis ($\Delta B_y/\Delta z \sim 1mT/200mm$) was found. We attribute it mainly to a tilt of the gap ($\Delta g/\Delta z \sim 66\mu m/400mm$) that occurred in the assembling process.

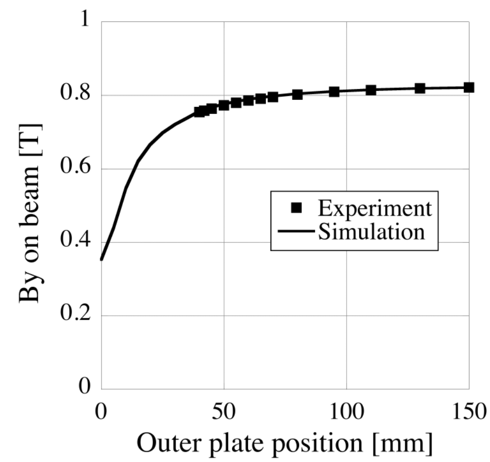

Figure 5: Magnetic field (By) on beam vs. outer plate position. Numerical result by CST studio (solid line) and experimental result (dots).

Upon applying the dipole magnet to future light sources, there are still a couple of critical issues to clear up. Since the temperature coefficient of remanence of Neodymium is -0.12 $\%/K$, the temperature shift of ambient air by couples of degree will affect on the lattice functions. In future light sources, such a closed orbit distortion will not be acceptable for sustaining extremely small emittance. Therefore, the ambient air temperature has to be kept constant within a fraction of degree, or magnet temperature has to be stabilized by cooling water, unless magnetic field is somehow feed-backed by outer plates or something else. In addition, the magnetic field may be gradually decreased by a radiation damage caused by stored electrons, or possibly a vibration of the magnet. These long-term degradation of magnets needs to be monitored, and corrected by outer plates or other mechanisms. Electromagnets have long been used in accelerators and the performances have been reliable. In order to replace it with permanent magnets, we ought to thoroughly investigate the characteristics and verify the reliability.

In the paper, only the dipole magnet is discussed. Obviously other magnets such as quadrupoles and sextuples may also be replaced with permanent magnets. These studies have been done at SPring-8 and other facilities [3].

ACKNOWLEDGMENT

The authors thank N. Kumagai for useful discussion and support.

REFERENCES

[1] e.g., G.Tosin, et al., Proc. of IPAC'10, Kyoto, Japan, p.3086.
[2] J. Chavanne, in the proceeding.
[3] e.g., Y. Iwashita, et al., NIM A 586 (2008) 73.