CHALLENGE TO A HIGH FIELD PERMANENT MAGNET OF VARIABLE FIELD STRENGTH

M.Kumada, T.Fujisawa, Y.Hirao, NIRS, Chiba, Japan
Y.Iwashita, NSRF, ICR, Kyoto, Japan
M.Endo, M.Aoki, T.Kohda, Sumitomo Special Metal Co.,Ltd., Osaka, Japan
I.Bolshakova, R.Holyaka, MSL, Lviv, Ukraine

Abstract

Permanent magnet is in general believed to be applicable to only weak magnet compared to electromagnet and superconducting magnet. It is possible, however to make a magnet much higher than the residual field of the material. We have demonstrated experimentally that the permanent dipole magnet exceeding more than by factor 3 is possible.. Challenge is to conceive such magnet for an accelerator application where variable field is often requested. We propose the methods by a mechanical rotation or with a combination of electro-magnet.

1 INTRODUCTION

Permanent magnet (PM) has been applied in an accelerator field mostly as undulator/wiggler in synchrotron radiation storage ring. There is a myth about PM. They are: The field strength is weak compared to electro-magnet and superconducting magnet. Working point of material in most of the cases is at half of a residual field B_r. PM is only good at small aperture magnet like undulator/wiggler. PM is unstable as magnetization strength depends upon temperature level of a few parts in thousand. Variation of strength of magnetization is a few percent and a high homogeneity required from accelerator performance is difficult.

Recently at Fermilab, large quantity of ferrite magnet was applied to an 8 GeV antiproton storage ring [1]. They made a remarkable progress in PM technology where they have almost solved temperature stability problem and homogeneity problem. The field strength of the Recycler PM is only 1.5 kG or so, which is about 1/3 of a ferrite material's B_r. Application to PM solenoid is also very attractive [2]. The strong PM magnet is challenged for Wiggler magnet. 3 Tesla Permanent magnets is so far the strongest [3]. The structure of this PM is the one proposed by K.Halbach where a combination of iron and PM magnet is placed periodically in a linear direction. This configuration can be extended to a circular type dipole magnet. We found out that when the iron pole is driven into a saturated level, the field strength inside the dipole gap is further enhanced [4].

It was found that lowering a temperature of the magnet has a great advantage in increasing the magnetization strength. DC PM can be used for cyclotron or FFAG (Fixed Field Alternating Gradient) accelerator for accelerating charged particle. There is an additional advantage if a PM magnet can be converted to variable field magnet. K.Halbach gave an idea of varying field magnet. It is a layered ring magnet where outer ring rotates around the centre of the ring. To avoid the inclination of a magnetic median plane, iron pole is used. One of the authors made a highest gradient (250T/m) Quadrupole in 1985[5]. Another method of varying field is to combine two PM located at axial positions, which was patented by R.F.Holsinger. There is a commercially available varying field dipole magnet on the market called MULTIMAG magnet (Magnetic Solutions Ltd). As the mechanism of it is not clearly described in a literature, we have developed our own way of two-layer ring magnet. Beside mechanical methods, we propose that a combination of PM magnet with electro-magnet or superconducting magnet is promising [9] when field level is around 3 Tesla. An example of this method is described in the present paper.

2 HIGH FIELD PERMANENT MAGNET

In most permanent magnet combined with iron pole and yoke, the field strength is several kG even when one uses strong NEOMAX whose B_r is 1.2 Tesla level. This is because the magnetic field strength B_g in a dipole gap is,

$$B_g = \frac{l_m}{d + l_m} \mu_0 H_c \approx \frac{l_m}{d + l_m} B_r \qquad (1)$$

where H_c is coercive field strength of the PM material, B_r is its residual field strength, l_m is its length and d is the gap length of the magnet. In most of the magnetic circuit, iron pole and iron yoke is designed so that they are not at a saturated level. Relative permeability of the iron is high and iron can be neglected to the contribution of the gap field strength. The maximum field strength is half of B_r in this conventional configuration. It is common that the field strength of the gap does not exceed B_r even at the limit of large l_m/d ratio. For a small l_m/d ratio, field strength of the gap is proportional to it.

K.Halbach invented an ingenious magnetic circuit [7]. In his configuration, pieces of REC (Rare Earth Cobalt) magnet material are placed on a ring where a direction of magnetization is rotated locally in a way so that resultant field forms a specified multipole field. See Figure 1. Iron pole or yoke are not used. For a dipole, he derived a simple formula for a gap field strength B_g,

$$B_g = B_r \ln(\frac{r_2}{r_1}) \qquad (2)$$

where r_1 and r_2 is an inner and outer radius of the magnet. This equation is quite challenging, as there is no theoretical upper limit. In fact there is a limit. To realize a high field as much as possible we started from this Halbach magnetic circuit. Permeability of the REC or NEOMAX or ferrite material is about 1.05, close to unity. Superposition holds. The field source located at long distance can contribute to the field at the centre accumulatively. Efficiency is poor from outer location.

To improve the efficiency, we introduced an iron pole to the Halbach REC configuration as in Figure 5. REC is replaced to NEOMAX. The field strength of the Extended Halbach magnet can be written as,

$$B_g \approx \frac{B_r l_m + \frac{l_i}{\mu^*} B_{s0}}{d + \frac{l_i}{\mu^*}\frac{S_g}{S_i} + l_m \frac{S_g}{S_m}} \qquad (3)$$

Parameter S_m, S_g, S_i respectively is cross sections of permanent magnet, gap, and iron. B_{s0} is a saturated induction of the iron pole and μ^* is a relative permeability of the iron. Eq. (3) indicates the saturated iron pole is effective to increase the field strength. A saturated permeability of the iron approaches unity. Note in general the saturated induction of the iron B_{s0} is greater than the residual field of the strongest permanent magnet material NEOMAX[4,6]!

The iron pole can be designed so that some part of it is not saturated and the other part is saturated. Thus, it is also possible to use the iron pole as a flux compressor where iron is not fully saturated. This effect is expressed as a ratio of cross section of the gap to PM and iron which is shown in the second and third term in the denominator.

At higher field level, we should take into account a demagnetisation effect of the PM material. This was not considered either in eq.(2) or eq.(3). Under a strong external magnetic field the magnetization strength is reduced. In either Halbach or Extended Halbach type of high field configuration, the outer part of the magnet produces strong magnetic field at some location of the inner part of the magnet. This problem could be coped with by selecting the material of high coercively. In a 4 Tesla model magnet, we have used two different kinds of materials, namely material of high B_r and high H_c [4,6]

3 VARIABLE FIELD MAGNET BY MECHANICAL ROTATON

If a field strength of PM magnet is variable, its application can be extended much more widespread. Furthermore, if its field strength is realized in a Tesla region, it could be used in a field where superconductor has been applied. PM of several Tesla is equivalent of room temperature superconducting magnet which people have long been dreamed. Variable field could be possible

either by a rotation of magnetization direction or with a combination of conventional electro-magnet or superconducting magnet [9]. In NIRS, a model magnet of moderate field strength of 1 T varying field magnet was designed and constructed and magnetic field is measured. In an accelerator magnet, a direction of magnetic plane in the gap has to be kept constant although direction of the magnetization varies in magnet material. In previous case of varying field gradient of 250 T/m Quadrupole magnet [5], this was done by a single layer rotation with iron pole. This time, the dipole field was varied with a rotation of two layers as shown in Figure 1. The outside view of the model magnet is in Figure 2. A mechanism to rotate each layer independently can be seen in the Figure.
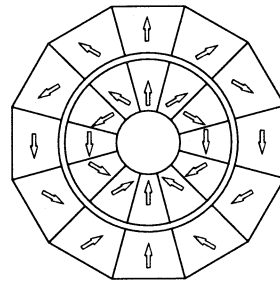

Figure 1. Cross-section of two layer variable field permanent magnet. Red arrows show a direction of magnetization.
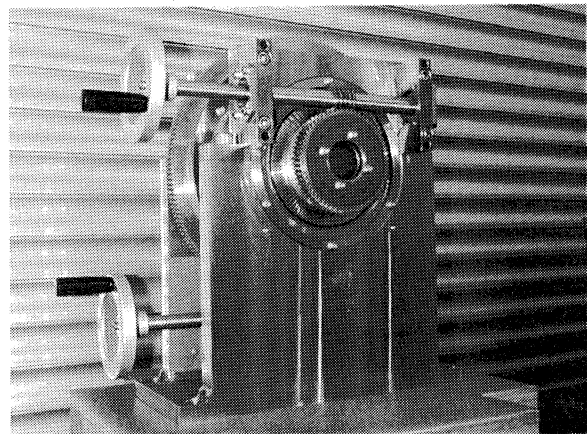

Figure 2. Outside views of two layers variable filed permanent magnet

4 VARIABLE FIELD MAGNET WITH ELECTRO-MAGNET

Field level of 3 Tesla is difficult by a conventional copper type magnet. 1.8 Tesla alternating field is not easy but possible while keeping field homogeneity within an acceptable tolerance level. In PM 1.5 Tesla is reasonable field strength and a required magnet size is moderate if one uses NEOMAX. Operation in liquid nitrogen makes it more feasible.

The first proposal is a longitudinally combined type and the second one is a transversely combined type magnet

system[8,9]. An example of longitudinal hybrid magnet is shown in Figure 3. In Figure 4, cross section of permanent magnet is superposed to copper coil electromagnet. Figure 5 shows an example of Extended Halbach 3 Tesla magnet with the saturated iron pole. Note that flux is compressed and concentrated at the saturated pole tip as expected. The effective field depend upon the ratio of both magnets.
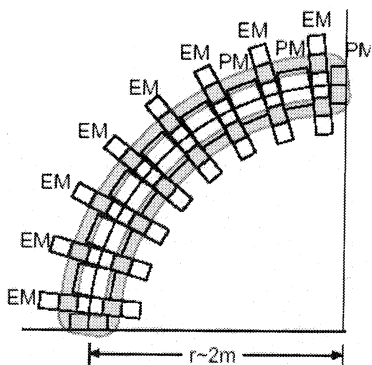

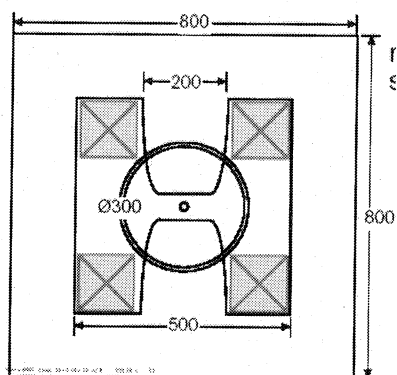Figure 3. Longitudinal variable field hybrid magnet.

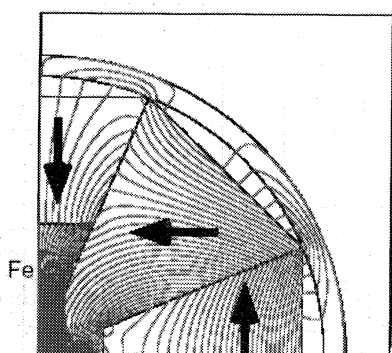Figure 4. Cross-section of longitudinal variable field hybrid magnet.

Figure5. ¼ cut view of Extended Halbach PM.

The 1.5 Tesla permanent magnet is moderate in size. To realize it, we need the ratio of outer and inner radius to be about 3.3, as a logarithm of 3.3 is 1.2 and one gets 1.6 Tesla for B_r=1.3 Tesla. For 40 mm bore diameter, the required outer diameter of the magnet is 132 mm. A gap size of 132 mm of a copper electro magnet is not a small magnet but within a tolerable range. If we provide a 1.5

Tesla electro-magnet, the field could be altered from zero to 3 Tesla. Choice of 1.5 Tesla in each magnet is adequate as a saturation of the electro-magnet is moderate and demagnetisation effect of the permanent magnet material is in a tolerable range.

For an application to a synchrotron magnet of a transverse hybrid magnet, there is a constraint that field gradient of each magnet has to satisfy the following equation,

$$\frac{B_{DC}}{B_{AC}} = \frac{\dfrac{dB_{DC}}{dx}}{\dfrac{dB_{AC}}{dx}} \tag{4}$$

where we have assumed that the alternating field is expressed as $B = B_{DC} - B_{AC} \cos(\omega t)$.

The necessary condition of eq. (4) is to keep a betatron tune constant as possible by keeping the effective field gradient constant with varying field strength. The time dependence is not necessary to be sinusoidal.
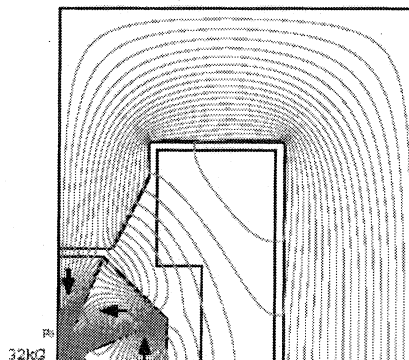

Figure 6. Cross-section of transverse varying field dipole magnet. PM is immersed in a gap of copper electro-magnet.

5 ACKNOWLEDGEMENT

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