Hybrid Permanent Magnets for Accelerator Applications

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Abstract

To shape the precision field distribution in the magnet aperture, the hybrid permanent magnets can be used. The permanent magnets in the magnetic circuit provide the magnetomotive force instead of the excitation coil. If the pole pieces are made of iron which is shaped to give a desired field distribution and lined with the permanent bricks, the precise hybrid permanent magnet of the accelerator grade is obtained. The field strength dependence on the material and volume of the permanent magnet are investigated.

1 Introduction

Recent development of the high performance permanent magnet, high remanent field, large coercive force and high energy product, makes possible its application to the field of the high energy accelerators. Their magnets require the highly homogeneous magnetic field over the beam aperture to guide the beam without causing instabilities, otherwise the beam will be lost before reaching the maximum energy. In the accelerator application the deviation of the field distribution must stay within the limit imposed by the beam optics. In a circular accelerator such as a storage electron or (anti-) proton ring at the fixed energy the beam circulates many times in the same magnets, so the field quality is essentially important. This is the reason why the hybrid permanent magnet with machined iron poles is used.

There are many product series of permanent magnets ranging from alnico to rare-earth magnets and they have a wide range of applications such as motor, speaker, relay and so on in the industrial products. The first large scale application is embodied at the Recycler antiproton storage ring of Fermilab between Booster and Main Injector (MI) after an elaborate hybrid permanent magnet R&D program which include the counter measure against the temperature dependent field variation and the protection against the leakage field from the nearby pulse magnets. Recycler ring recycles the anti-proton beam at 8 GeV from the Tevatron through MI to get the luminosity gain of the Tevatron $p\bar{p}$ collider by a factor of two.

A small scale application is found at SLAC. In this case a part of the injection line magnets and the chromaticity correction magnets of the dumping ring use the permanent magnets [1]. Most recently PEP-II has adopted the high gradient permanent quadrupoles made of samarium cobalt (SmCo) at the interaction region [2] and CESR plans to replace the present SmCo magnets with ones made of neodymium iron boron (NdFeB) for the phase-III upgrade [3]. They are installed close to an interaction point in a detector symmetrically and suffer from the solenoidal field without disturbing it because they have a permeability close to unity. These magnets are not hybrid but composed of pure SmCo or NdFeB blocks ensuring a uniform high field gradient to converge both electron and positron beams at the crossing point.

In the present study we focus on the performance of the hybrid permanent magnets so as to apply them to the storage ring or beam transport line. The use of the permanent magnets benefits in the reduction of the fabrication and running costs. We select two kinds of permanent materials, Sr ferrite and SmCo, for the evaluation of the magnet performance.

2 Permanent Magnet Material and Properties

The basic properties of the permanent magnet is expressed by the demagnetization curve at the second quadrant which is obtained when its magnetic hyteresis curve is measured under the sinusoidal external magnetic field giving a saturation at the extreme fields. Most important properties are the residual induction and the coercive force. The larger both values, the higher the magnetic field available. An operating point of the permanent magnet is given by the point (H, B) on the demagnetization curve which is determined by the magnetic circuit. As an available energy is $HB/8\pi$, its maximum $(HB)_{\max}$ is given by the point where the demagnetizing curve and the hyperbola $HB = const$ are tangent. $(HB)_{\max}$ is the maximum energy product expressed by a unit of Mega-gauss Oersted (MG·Oe). Magnetic properties are summarized for typical permanent magnets in Table 1 [4].

Permanent magnet materials are grouped into three categories, metallic alloy, ferrite and rare earth. Alnico is the metallic alloy with 1.1~11 MG·Oe and has an excellent magnetic stability against temperature variation, but it is rather expensive because it contains Co.

Ferrite is a double oxide $MOFe_2O_3$, iron oxide Fe_2O_3 being a main component and M is Co (cobalt ferrite), Ba (barium ferrite), Sr (strontium ferrite), and etc. Among them Sr ferrite is most popular because it is cheep and chemically stable besides it has large coercive force and large resistivity. Its maximum energy product is 2.0~4.8 MG·Oe and magnetic properties suffer from the temperature variation.

$SmCo_5$ and Sm_2Co_7 have a vary large energy product (16~32 MG·Oe). As it is very expensive, about ten times more expensive than Sr ferrite, its application is limited to a small scale. Cheaper neodymium iron boron $Nd_2Fe_{14}B$ has the largest energy product (23~49 MG·Oe) at present and will find various applications including a high energy accelerator.

Irreversible and reversible thermal demagnetization of the permanent magnet are observed but the former is a one-time loss depending only on the lowest temperature for Sr ferrite or the highest temperature for SmCo to which the magnet has been exposed. Freezing Sr ferrite to condition can remove the irreversible demagnetization [5]. This kind of stabilization is called a thermal seasoning.

An intrinsic temperature coefficient of the residual inductance is -0.02~-0.03%/°C for alnico, -0.03~-0.05 for Fe-Cr-Co, -0.18~-0.20 for ferrite, -0.02~-0.043 for SmCo and -0.09~-0.13 for NdFeB. A large temperature effect on the field strength is expected for the Sr ferrite magnet, requiring a measure to compensate the temperature effect. At Fermilab several packages of 30%Ni-70%Fe alloy strips, having a low Curie temperature (~50-70°C) and permeability with a strong function of temperature, interspersed longitudinally between Sr ferrite bricks subtract flux in a fashion to null out the overall thermal dependence of the integrated field strength to less than 0.01%/°C [5,6].

Table 1
CHARACTERISTICS OF TYPICAL PERMANENT MAGNETS.

Material	Residual Induction (kG)	Coercive force (kOe)	Max. energy product (MG·Oe)	Curie temperature (°C)
alnico	5.0~14.0	0.5~1.6	1.1~11	850
Fe-Cr-Co	8.0~14.5	0.4~0.8	1.1~7.0	670
Sr ferrite	3.0~4.5	1.6~3.95	2.0~4.8	450~460
SmCo	8.0~12.0	4.0~10.7	16~32	710~820
NdFeB	9.8~14.5	9.0~14.1	23~49	310

3 Simple Formulae of Magnet Design

Assuming that the average half length of the iron yoke is L_i, the half length of the permanent magnet d, and the half gap height h as shown in Fig.1, the following relation is obtained according to the Ampere's law,

$$H_g h + H_i L_i + H_p d = 0, \qquad (1)$$

where H_g, H_i and H_p are the field strength of the pole gap, iron yoke and permanent magnet, respectively. Let B_p the flux density of the permanent magnet at its operating point,

$$B_p A_p = \mu_i H_i A_i = \mu_0 H_g A_g, \qquad (2)$$

where A_p, A_i and A_g are crosssections of the permanent magnet, yoke and pole gap, respectively. μ_i is the permeability of iron and μ_0 that of air (close to the permeability of vacuum).

From (1) and (2),

$$H_p B_p = -\frac{(B_g A_g)(B_g h)(1+\mu_0 L_i A_g / \mu_i h A_i)}{\mu_0 A_p d} \qquad (3)$$

is derived, where B_g is the flux density of the pole gap. The term $(1+\mu_0 L_i A_g / \mu_i h A_i)$ corresponds to the reluctance coefficient (ε>1) of the magnetomotive force (MMF) which is the correction factor corresponding to the MMF loss in the iron yoke. Another factor contributing to this loss is the flux leakage from the iron yoke given by β,

$$\varepsilon = H_p d / H_g h = 1 + \mu_0 L_i A_g / \mu_i h A_i + \beta. \qquad (4)$$

Usually $\varepsilon \approx 1.3$ in spite of $L_i / h \approx 10$ and $\mu_i / \mu_0 > 1000$ for accelerator magnets assuming $A_g = A_p$. The flux leakage inevitable in the pole gap is defined by the leakage factor (f>1) as follows,

$$f = B_p A_p / B_g A_g. \qquad (5)$$

Inserting (4) and (5) into (3), the slope (s) defining the operating point at the second quadrant of the permanent magnet is given by

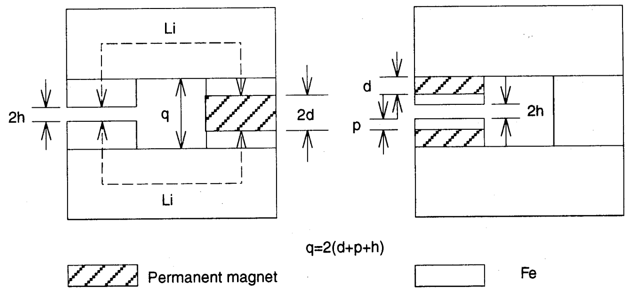

Fig.1 Geometry of the hybrid bending magnet.

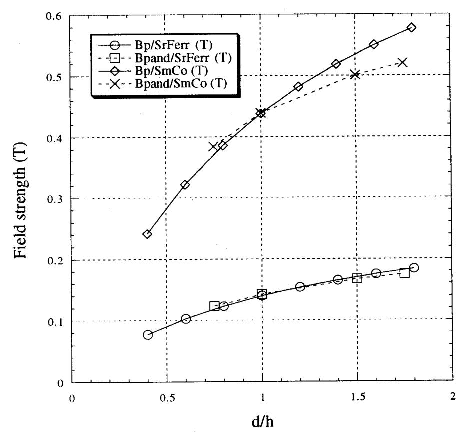

Fig.2 Field strength obtained by the simple formula and Pandira code. H_c=3.35kOe, B_r=0.35T for Sr ferrite and H_c=10.5kOe, B_r=11.0T for SmCo. Subscripts "pand" and "p" mean results by Pandira code and analytic formula, respectively.

$$s \equiv B_p / H_p = -\mu_0 A_g d f / A_p h \varepsilon. \qquad (6)$$

The permeance (P_g) of the rectangular pole gap is approximately defined as

$$P_g \approx \mu_0 [\ell w / 2h + 0.264(2\ell + 2w) + 4 \times 0.077 \times 2h],$$

where ℓ and w are the pole length and pole width ($A_g = \ell w$), respectively. Here we neglected contributions from other parts of the yoke. Then, the leakage coefficient is given by

$$f \approx 1 + 1.056(h/\ell + h/w) + 1.232 h^2 / \ell w.$$

Considering $h^2 / \ell w << 1$ and $h/\ell << 1$ for accelerator magnets, an approximate leakage coefficient is

$$f \approx 1 + 1.056 h / w.$$

Considering $0.1 < h/w < 0.2$ for accelerator magnets, $1.1 < f < 1.2$. If $A_g = A_p$, the operating point of the permanent magnet is given by

$$B_p / \mu_0 H_p = -0.885 d / h,$$

and the field strength by

$$B_g \cong B_p / f.$$

Detailed simulation was performed with the Pandira code and compared with the results obtained by above simple formula in Fig.2.

For an evaluation of the hybrid quadrupole magnet of Fig.3, the similar relations are obtained as follows. The 1/8 quad can be transformed into 1/4 dipole in new coordinates u, v as in Fig.4 through the conformal transformation [7],

$$w = z^2 / 2R, \qquad (7)$$

where R is a bore radius of the quadrupole magnet, $z = x + iy$ and $w = u + iv$.

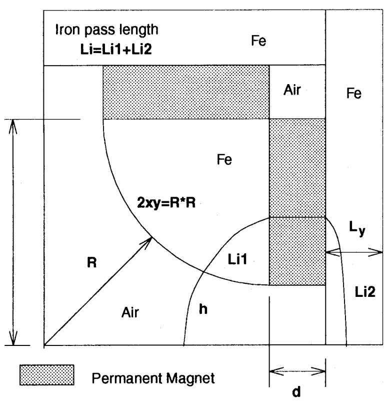

Fig.3 Geometry of 1/4 hybrid quadrupole magnet.

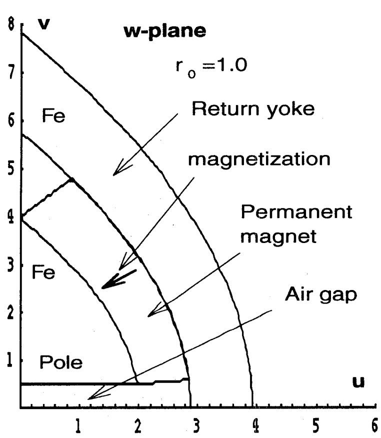

Fig.4 Transformed 1/8 quadrupole in the w-plane for the bore radius of $R = 1$, $d = 0.4$ and $L_y = 0.4$.

In the transformed geometry the half gap height of the dipole is $R/2$ and the Ampere's law for the closed integration loop in Fig.4 becomes

$$\oint H_z dz = \oint \gamma_w B_w w'^* dw / w' = \oint \gamma_w B_w z^* dw / z = 0, \qquad (8)$$

where $\gamma = 1/\mu$, $\gamma_z(x, y, |B_z|) = \gamma_w(u, v, |w'^*||B_w|)$ and $w' = dw / dz$. An asterisk means the complex conjugate and subscripts z and w stand for z- and w-plane, respectively. Taking the integration on the v-axis (u=0) in the gap, $w^* / w = -1$ without losing generality. Relation (8) is also expressed as

$$\oint H_z dz = \oint \gamma_w B_w z^* dw / z = \oint \gamma_w B_w \sqrt{w^* / w} dw = 0.$$

In the followings $\gamma_{zp} B_{zp} d \cong \gamma_{wp} B_{wp} d_w$ is assumed for the sake of simplicity. If there is no leakage flux,

$$B_{wg}(2 - 1/32)R = B_{zp}(2 - 1/4)R = 2GR^2,$$

where G is the field gradient in the z-plane.

The leakage factor is now defined as

$$f = B_{zp}(2 - 1/4)R / 2GR^2 = 7B_{zp} / 8GR, \qquad (9)$$

and the reluctance coefficient is

$$\varepsilon = 2H_{zp} d / \gamma_0 B_{wg} R. \qquad (10)$$

Assuming the same values for f and ε,

$$B_{zp} / H_{zp} = -9fd / 4\gamma_0 \varepsilon R = -1.99d / \gamma_0 R,$$

and

$$G = 7B_{zp} / 8fR. \qquad (11)$$

In Fig.5 the field gradient estimated from (11) is compared with the Pandira results.

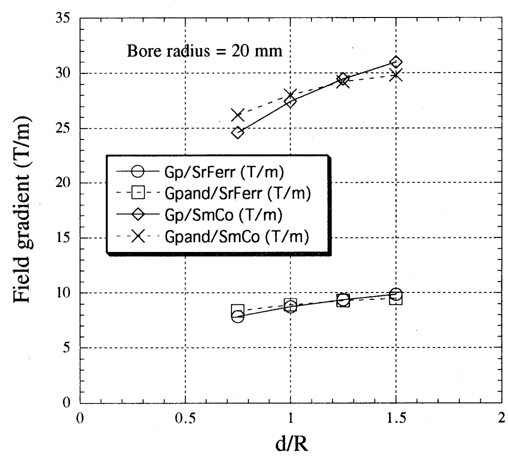

Fig.5 Comparison between the relation (11) and Pandira result. H_c=3.35kOe, B_r=0.35T for Sr ferrite and H_c=10.5kOe, B_r=11.0T for SmCo. Subscripts "pand" and "p" mean results by Pandira code and analytic formula, respectively.

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