Permanent Magnet vs. Electromagnet Dipoles for Synchrotron Radiation

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Abstract

Permanent magnet (PM) dipoles for Synchrotron Radiation are configured in the paper. Analysis, design formulas and optimised design criteria of PM dipoles are deduced with a 1D magnetic circuit method. Finite element (FE) computation to one model with OPERA-3D electromagnetic software was used to check the 1D magnetic circuit method. Technical and economical comparisons with electromagnet dipoles are given.

1 INTRODUCTION

Synchrotron radiation is an outstanding tools in many branches of science. Presently, the Electromagnet (EM) Dipoles play a major role in bending electron beams of nearly all accelerators (including synchrotron radiation facilities). Temperature variations of coiling water in EM dipoles decrease the beam orbit stability of storage rings, which can not satisfy the stringent needs of evening increasing photo stability in some high level experiments [1]. Recent progress of decreasing the aperture (10mm vertical x 20mm horizontal) anticipated for the ring of next generation synchrotron radiation light source makes it worthy to explore the possibilities of PM dipoles [2]. Realizing storage ring dipole magnets with permanent magnets (PM) is a developing technology, which avoids power supplies and then freeing of operation cost [3,4,5,6]. It's main disadvantage is its high primary investment compared to normal electromagnet although it has merits of no operation costs. The paper gives one novel PM dipole configuration and the rule on how to decrease the investment on the PM dipole.

2 MAGNET CONFIGURATION AND ANALYSIS

2.1 Magnet Configuration

The novel PM dipole configuration is shown in figure 1. It uses a C-shaped iron yoke for emerging synchrotron radiation beams. The arrows indicate the directions of the easy axis in the PM material. The magnet is curved in an arc in the direction of the beam corresponding to the bending of the beam in the magnetic field. The PM magnets clipped between the poles and the iron yokes generate the required induction field in the air gap.

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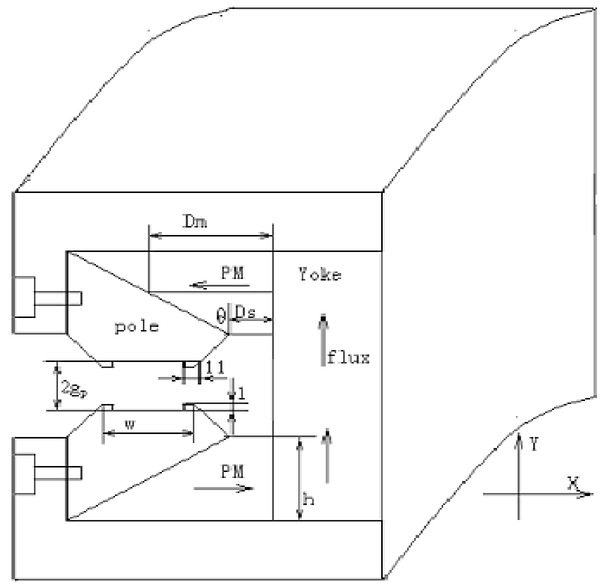

Figure 1. The Novel PM Dipole Configuration

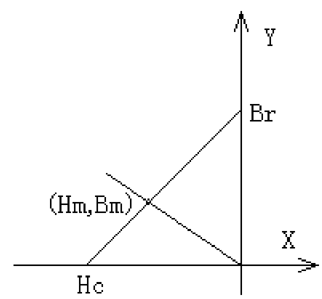

Figure 2. The $B_r - H_c$ curve of PM Material

2.2 Magnetic Field Computations

Because of the symmetry of the upper parts and the lower parts of above dipole magnet, we only study one half of the parts. Assuming that the magnetic induction factor of the pole is infinite, by Ampere's law, we can get:

$$g.\frac{B_y}{\mu_0} + H_m \cdot D_m = 0 \qquad (1)$$

Where, $2g = 2g_p$ is the total effective gap between the up and low poles; g_p is the half gap between the up and low poles; B_y is the magnetic induction field in the vertical direction; H_m and D_m are respectively the magnetic strength at the PM working point (including leakage magnetic field) and the length of permanent magnet.

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Defining η_m as the effective flux transfer factor from the flux of the permanent magnet to the flux in the gaps between the upper and lower poles, by flux constant law, we can get:

$$\frac{lhB_m\eta_m}{\cos\theta} = B_y lw \qquad (2)$$

Where, l is arc length of the dipole magnets; B_m, h and θ are respectively the average magnetic induction strength of the PM working point, the height and skew angle of permanent magnet. w is the width of the poles. These parameters are shown in figure 1.

In addition, by the $B_r - H_c$ curve of permanent magnets shown in figure 2, we can get the relations:

$$\frac{B_m}{B_r} = \frac{H_m}{H_c} + 1 \qquad (3)$$

Where, B_r and H_c are respectively the remanence and intrinsic coercive force of the used PM material.

Incorporating equation (1), (2) and (3), we can get the required average magnetic induction field:

$$B_y = \frac{B_r}{\frac{\cos\theta}{\eta_m}\cdot\frac{w}{h} + \frac{B_r}{\mu_0 H_c}\cdot\frac{g}{D_m}} \qquad (4)$$

2.3 Magnet Optimised Design

The parameter D_m can be deduced from equation (4) as follows:

$$D_m = \frac{\frac{B_r}{\mu_0 H_c}\cdot g}{\frac{B_r}{B_y} - \frac{\cos\theta}{\eta_m}\cdot\frac{w}{h}} \qquad (5)$$

In addition, D_m should satisfy the following condition:

$$D_m = D_s + \frac{h}{2}tg\theta \geq \frac{h}{2}tg\theta \Rightarrow D_m \geq \frac{h}{2}tg\theta \qquad (6)$$

Where, D_s is the short side of the used PM magnet.

Assuming that W_{PM} and ρ are respectively the weight and density of the used PM material, using the PM material property relation $\frac{B_r}{\mu_0 H_c} \cong 1$, W_{PM} can be expressed as:

$$W_{PM} = 2D_m\cdot h\cdot l\cdot\rho = 2l\rho g\frac{B_y}{B_r}\cdot\frac{h^2}{h - \frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w} \qquad (7)$$

Equation (7) can be rewritten as follows:

$$W_{PM} = 2l\rho g\frac{B_y}{B_r}\left[h + \frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w + \frac{\left(\frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w\right)^2}{h - \frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w}\right] \qquad (8)$$

In order to decrease the cost of PM raw material (the main raw material cost in making PM magnets), the weight of the designed dipole W_{PM} should be reduced as much as possible. Differentiating above equation two times, we can get:

$$\frac{d_{W_{PM}}}{d_h} = 2l\rho g\frac{B_y}{B_r}\left[1 - \frac{\left(\frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w\right)^2}{\left(h - \frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w\right)^2}\right] \qquad (9)$$

$$\frac{d^2{}_{W_{PM}}}{d^2{}_h} = 4l\rho g\frac{B_y}{B_r}\cdot\frac{\left(\frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w\right)^2}{\left(h - \frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w\right)^3}$$

By setting $\frac{d_{W_{PM}}}{d_\theta} = 0 \Rightarrow h = 2\frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w$, using $\frac{d^2{}_{W_{PM}}}{d^2{}_\theta} > 0$ at $h = 2\frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w$, we can get the criteria for getting lowest value of W_{PM} in designing this configuration of dipole:

$$h = 2\frac{B_y}{B_r}\cdot\frac{\cos\theta}{\eta_m}\cdot w \qquad (10)$$

Inserting equation (10) in equation (7) gives the minimum PM material in the dipole:

$$W_{PM} = \frac{8\rho}{\eta_m B_r^2}\cdot w\cdot l\cdot g\cdot B_y^2\cdot\cos\theta \qquad (11)$$

By Faraday law, we can get the attraction force between the up and low parts of the poles. It is:

$$F = \frac{B_y^{\ 2}}{2\mu_0}lw = \frac{(B_y l)^2 w}{2\mu_0 l} \qquad (12)$$

3 MAGNET DESIGN

3.1Typical Dipole Parameters

The designed parameters of PM dipoles are listed in table 1. In order to have the 60mm width of good field region, the pole width $w = 145mm$ is selected by engineering experience for this geometric dipole. $2g = 55mm$ is the minimum gap, which is determined by the storage ring vacuum.

Table 1: The typical parameters of the dipoles

Induction field B_y /T	1.04		
H_c /(kA/m)	1047	B_r /T	1.365
Gaps $2g$ /mm	55	r /m	2.2221
Good field width/mm	90	l /m	1.1634
PM height h /mm	314	θ	π/10
PM weight W_{PM} /kg	303.6	D_m	55.4
Flux transfer factor η_m	0.55	w /mm	145
Attraction force F /T	9.6	w_y /mm	145

3.2 3d Finite Element (FE) Computation to the Designed PM Dipole

Key parameters of above designed PM dipole are checked by 3d finite element method, Opera3d. The computed model of PM dipole and its field along horizontal direction are shown in fig. 3 and fig.4 respectively. Fig.4 shows that the good field region is larger than 90mm.

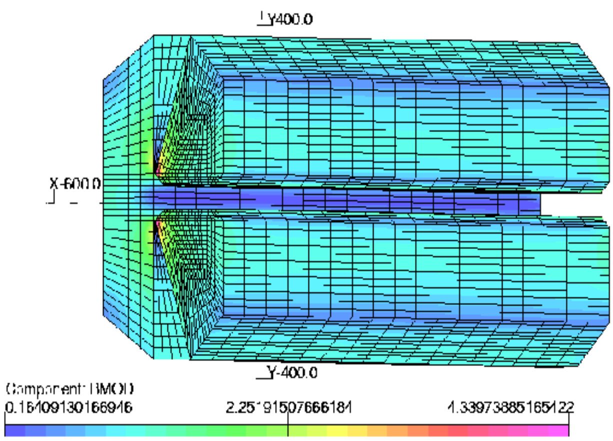

Fig. 3: FE Computed model of PM dipole

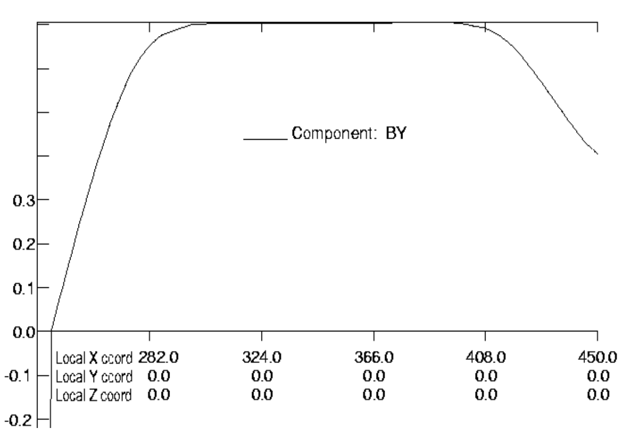

Fig.4: Vertical induction field along horizontal direction

In order to check the effective region of above analytic equations, above PM models in different air gaps is computed by Opera3d. The results by both methods are listed in table 2. It's shown that the analytic equation is more accurate when the gap becomes small.

Table 2: The Induction Field of PM dipoles

Gaps 2g/mm	Computed by OPERA3d By /T	Computed by analysis equation By /T
10	1.5317	1.53
20	1.2086	1.383
30	0.9946	1.264
55	0.7034	1.04

4 CONCLUSIONS

4.1 Although 1D equations gives concise relations between target field and geometry parameters of the PM dipole, the designed rough results with them needs to be checked and optimised by 3D FE methods, particularly in the case of large airgaps. The Effective flux transfer factor η_m of PM dipole is 0.55, i.e. about 45% flux can not be conducted to the working region. Effective means to enhance η_m still needs exploring.

4.2 Equation11 gives that the optimised PM material is ration to square of the dipole field By, Arc length l of the dipoles, the width of the poles w and Gap $2g$. Scaling above PM dipoles to that used in ALS-N, one 0.585T PM dipoles at 16mm vertical airgap, it only use 11.7kg PM materials. Such few PM magnets can be very easily implemented into the mounting system. So in this case, even the primary cost of the PM dipoles is less than that of EM dipoles.

5 REFERENCES

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