THE EFFECT OF EDDY CURRENTS ON THE HOMOGENEITY OF THE MAGNETIC FIELD OF A BOOSTER-RING SEXTUPOLE MAGNET

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Abstract

A 3-GeV electron-storage ring with tiny emittance has been designed for the Taiwan Photon Source (TPS) that will provide one of the world's brightest synchrotron x-ray sources. Sextupole magnets for the booster ring (BR) serve to correct the chromaticity of the beam particles. As an AC power supply is generally used in a booster ring to raise beam particles to a required energy, a power supply at 3 Hz AC is used to charge the sextupole magnet, which would induce eddy currents in the vacuum chamber resulting in a magnetic multipole field. As an aspect of the magnet design, decreasing the effect of an eddy current on the homogeneity of the magnetic field, the geometry and material of the chamber must be considered. We demonstrate the effects of an eddy current on the homogeneity of a magnetic field for a vacuum chamber of various types, and we discuss the magnetic circuit and the conductor design of the booster-ring sextupole. Analysis of the multipole field and eddy-current loss were included to assure the accuracy of the magnetic circuit design.

INTRODUCTION

In the accelerator of the Taiwan Photon Source (TPS) [1], sextupole magnets play important roles to compensate the chromaticity of charged particles. During acceleration of the particles, a temporally varying magnetic field in the TPS booster ring would induce a substantial eddy current on the surface of the magnets and in the vacuum chamber. Such a current generates a weak magnetic field that opposes the temporally varying magnetic-flux density and results in distortion of the magnetic field and power loss on the chamber walls [2]. OPERA 3d/2d ELEKTRA [3] software was used to investigate the effect of an eddy current on the central and integral magnetic fields. In numerical simulations we used an AC power frequency in a range 0 – 90 Hz, and aluminium 6061 T6 and stainless-steel 304 vacuum chambers.

The sextupole magnet designed for the 3.0-GeV booster ring and key specifications are listed in Table 1. The dimensions of the magnet are length 200 mm, width 260 mm and height 260 mm. The sextupole magnet has a bore radius 18mm, and the shape of the pole surface is described with an equation $3x^2y - y^3 = 18^3$. An edge shim (width 0.8 mm) was added at the edge of the poles to extend the x-axis region of good field. Cooper coils (height 3 mm and width 2 mm) were wound for conductors. Fig. 1 shows one quadrant of the designed sextupole magnet .

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HOMOGENEITY OF MAGNETIC FIELD

The magnetic field $B_y(x)$ was first calculated with Opera Tosca code [3]; the magnetic field was calculated in a steady-state, DC voltage case. The magnetic field $B_y(x)$ at the mid plane of the sextupole magnet was fitted with this polynomial equation,

$$B_x(x)+iB_y(x)= \Sigma_{n=1}(a_n/n!)x^n+i\,\Sigma_{n=1}(b_n/n!)x^n \qquad (1)$$

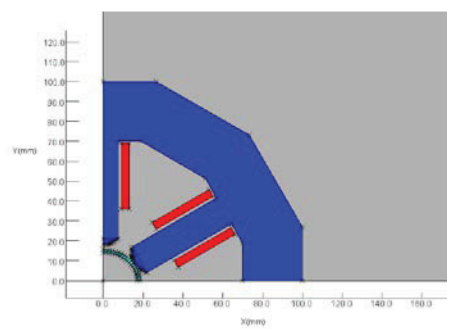

Figure 1: Designed pole shape of the sextupole magnet.

Table 1: Specification of sextupole magnet.

Type	Sextupole
Iron length (mm)	200
Bore Radius(mm)	18
Normal field(T/m^2)	200
Inductor dimension(mm^2)	3×2
Magnetic field at pole tip (T)	0.0324
Operation Current density(A/mm^2)	1.21
Current(A)	7.26
Resistance at 30℃(mΩ)	200.17
Inductance(mH)	2.71
Voltage drop(V) in AC ,3Hz, power supply	1.476
Power consumption(KW) in AC ,3Hz, power supply	0.0039

in which a_n and b_n denote skew and normal components, respectively. The magnetic field $B_y(x)$ is shown in figure 2 (red line). The field homogeneity was calculated according to a normalized equation $\Delta B/B_0=[B(x)-(b_0+b_1x+b_2x^2)]/B_y(x)$. The normalized variation of magnetic field, $\Delta B/B_0$, for $|x| < 15$ mm is also shown in figure 2 (black line). The variation of normalized field is less than 0.05 %, indicating that the designed sextupole magnetic field has satisfactory quality.

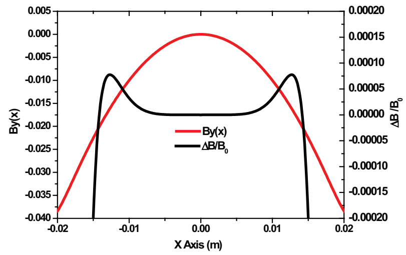

Figure 2: Distribution of magnetic flux density and field homogeneity in the traverse direction.

EFFECT OF AN EDDY CURRENT ON THE MAGNETIC FIELD

To examine the field distortion due to the effect of an eddy current, we calculated the temporally varying magnetic field with Opera 2D ELEKTRA code. In the absence of a vacuum chamber, the eddy current appears only on the magnet surfaces near the conductors. Fig. 3 demonstrates the magnetic homogeneity for AC input frequencies between 3 and 90 Hz. There is no significant change (less than 0.001%) in the field homogeneity within this frequency variation. The induced magnetic multipole fields strength are shown in figure 4. The maximum distribution field is about 0.12 G in the 18th multipole component (the first allowed term). Induced eddy currents on the magnet hence do not cause a major effect on the field homogeneity.

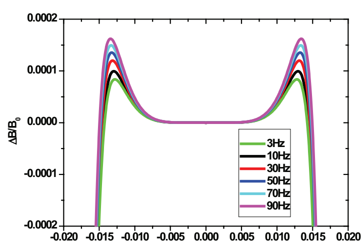

Figure 3: Variation of field homogeneity with AC frequency and without chamber material.

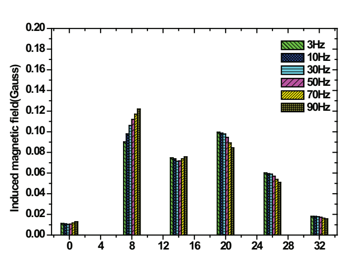

Figure 4: Variation of multipole field with AC frequency (magnet field strength measured at x=15mm).

The magnetic homogeneity inside a stainless-steel vacuum chamber (axis dimensions 17 and 21 mm) was calculated for varied AC frequency; the results are shown in fig. 5. A significant increase of $\Delta B/B_0$ near the chamber wall was observed when a high frequency was applied. The magnet field feature are no significant change between +5 mm from the centre of the magnet. The multipole field induced by the second and third allowed terms is shown in fig. 6. According to the results from the preceding discussion, the AC frequency variation would have only a weak influence on the field homogeneity; any field distortion would thus arise from eddy currents in the vacuum-chamber wall.

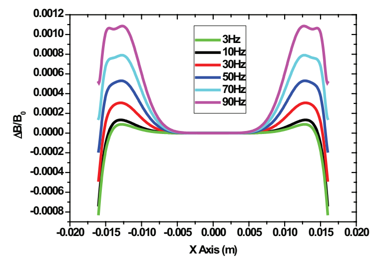

Figure 5: Variation of field homogeneity in a stainless steel vacuum chamber with AC frequency.

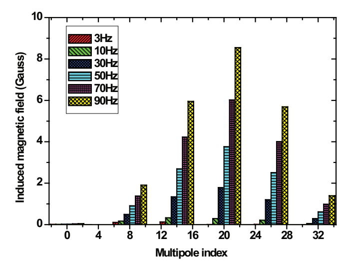

Figure 6:Variation of multipole field in a stainless steel vacuum chamber with AC frequency.

FIELD HOMOGENEITY IN VACUUM CHAMBERS

The field homogeneity was calculated for varied geometry of a stainless-steel or aluminium chamber. The size of the test chamber was modified from the designed dimensions – 34.6 and 21.4 mm for the long and short axes of an elliptic chamber, respectively. The half-width of the vacuum chamber was fixed at w = 17 mm and the half height (h) was varied as 14, 12, 10 and 8 mm. Vessel wall thicknesses 1.5, 1.0 and 0.5 mm were simulated. At AC frequency 3 Hz (Fig. 7d), little alteration of the multipole field was found for a stainless-steel chamber. Fig. 7(a)-(c) show a distribution $\Delta B/B_0$ along the transverse direction in an aluminium chamber for AC frequency 3 Hz. The field homogeneity depends strongly on the wall thickness and the eccentricity $((w^2-h^2)^{1/2}/w)$ of the elliptical chamber. A thicker wall and a greater eccentricity increases the eddy current on the surface and results in an inhomogeneous field.

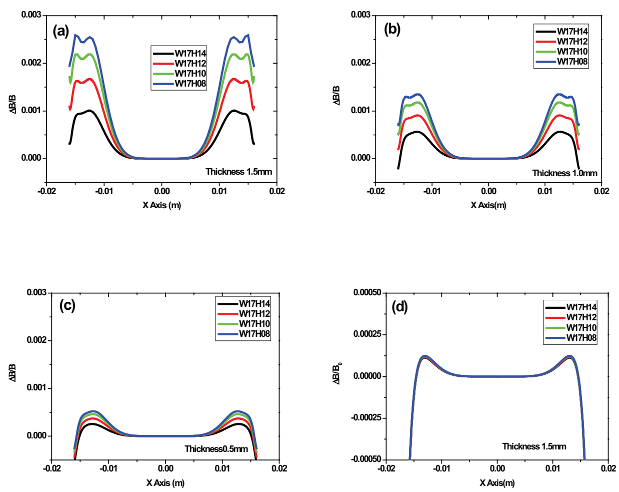

Figure 7: Field homogeneity at 3Hz for an aluminium chamber of wall thickness (a) 1.5 mm, (b) 1.0 mm, (c) 0.5 mm and (d) Field homogeneity for a stainless-steel chamber.

We calculated the eddy-current losses in vacuum chamber walls with three-dimensional models. Figure 8 shows that the temporally averaged eddy-current losses vary with AC frequency. An aluminium vacuum chamber has twice the energy loss of a stainless-steel chamber, but most eddy-current loss comes from the magnet iron that consumed about 6.2 W at AC frequency 90 Hz. The energy loss is expressible as a quadratic function of frequency. Fig. 9 shows the variation of energy loss with geometry of a stainless-steel vacuum chamber. A thicker chamber wall and greater eccentricity of the ellipse increase the eddy-current loss. Similar results are found in Lee's [4] estimate of power loss for a booster dipole magnet.

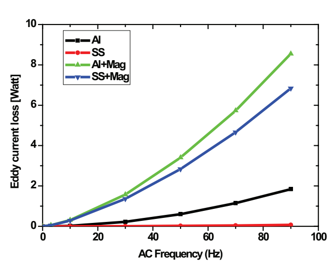

Figure 8: Eddy current loss in various materials.

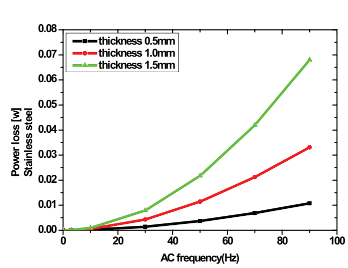

Figure 9: Eddy-current loss versus chamber thickness.

For a stainless-steel or aluminium chamber of wall thickness 0.7 mm, fig. 10 demonstrates the variation of sextupole gradient decay with frequency for various vessel materials. The decay of sextupole strength with frequency for an aluminium vessel is much more rapid than for a stainless-steel vessel. The rate of decay of the sextupole strength is insensitive to the vessel geometry. A stainless-steel chamber has a clear advantage over an aluminium chamber for the decay of magnetic field with AC frequency.

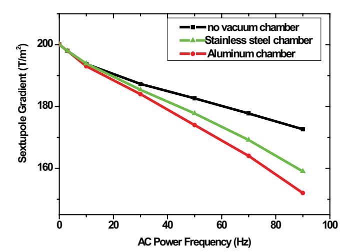

Figure 10**:** Sextupole strength versus AC frequency**.**

SUMMARY

The design of a booster-ring sextupole magnet is presented, and the effect of magnetic field in aluminium and stainless-steel vacuum chambers of varied geometry was investigated. Our main findings follow.

1. A temporally varying magnetic field induces a substantial eddy current in the vacuum chamber at high frequency and results in a distorted magnetic field near the vacuum chamber.
2. A stainless-steel chamber provides a clear advantage in relation to the generation of eddy currents, with a much smaller power loss than for an aluminium chamber.
3. The TPS booster is designed for frequency 3 Hz AC. The use of an aluminium chamber, a thicker wall and a greater eccentricity cause deteriorated field homogeneity near the chamber. A stainless-steel chamber does not affect the homogeneity of the magnetic field.
4. The sextupole strength decreases with AC frequency. A stainless-steel chamber maintains the sextupole strength better than an aluminium chamber.

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