Magnetic Field Features of Various Magnetic Circuits on the Sextupole Magnet

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In this study, two adjacent sextants were partially cut from one side of a sextupole magnet in order to accommodate the electron beam bending chamber associated with a three x-ray beam line chamber. The yoke cutting of these two sextants creates a different magnetic circuit which induces several forbidden fields. Meanwhile, the fundamental strength of this magnetic circuit is less than that of the normal on cut sextupole magnets in the storage ring. An induced forbidden field and the lessened sextupole strength originated from the saturation effect occurring at the magnet's yoke cutting side. Therefore, an extra closed-loop magnetic circuit is added across the two adjacent sextants to compensate for the yoke's smaller core area. This extra magnetic circuit can eliminate the saturation effect which induces asymmetric field behavior. It can also compensate for the lessened sextupole strength. In this work, the field distribution for various excitation currents related to the three magnetic circuits were measured. The field measurement results with various excitation currents tell us that the field saturation phenomena create the asymmetry field, forbidden field, and the lessened sextupole strength of the yoke cut magnetic circuit.

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I. Introduction

Twenty-four sextupole magnets were installed in an electron storage ring for electron beam chromaticity correction. One sector of an electron bending chamber associated with three x-ray beam lines will be blocked by two adjacent sextants of the storage ring sextupole magnet. In order to remove the obstacle, the part of the yoke core at one side of the magnet's two adjacent sextants was cut [1]. Partial cutting of the yoke (shown in Fig. l(b)) accommodates the three-degree beam port of the bending vacuum chamber (Each bending chamber includes zero, three and six-degree beam ports). This yoke cutting method not only more easily facilitates the assembly and control of the mechanical accuracy than a total cutting of the two adjacent sextants, but also makes use of the remainder of the spare

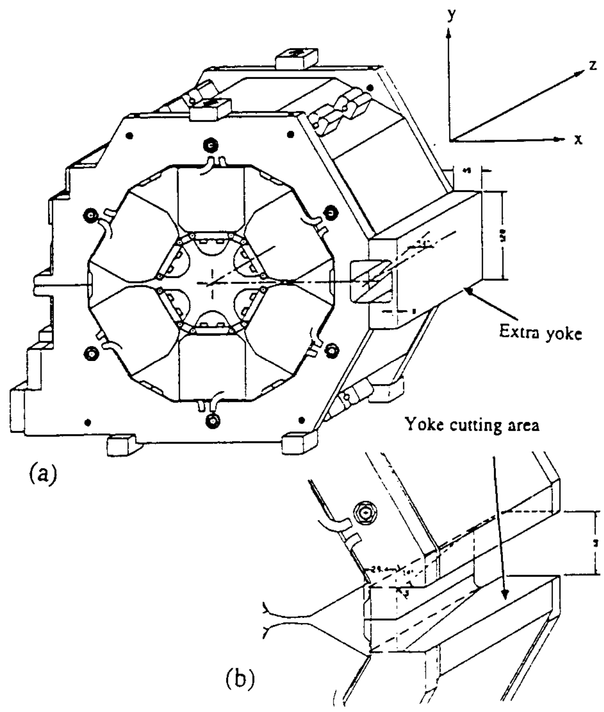


FIG. 1. (a) Structure of the sextupole magnet. An extra closed-loop yoke was added on the side of the magnet's yoke cut to compensate for the lesser yoke core area. The three-degree beam port of the bending vacuum chamber passes through the hole. (b) Magnification of the cut yoke configuration, the yoke cut direction begins from the edge along 14° tangential to the electron beam direction. (unit is mm).

part of the magnets so that designing and fabricating a new sextupole magnet becomes unnecessary. For this reason, a partially cut sextupole magnet yoke is selected to fulfill the location requirement for the bending vacuum chamber.

The yoke is cut at (see in Fig. 1(b)) 14° angle tangential to the electron beam direction (longitudinal z-axis). The magnet's core is constructed of six identical sextants. Laminations are glued and sextants are assembled by bolts through the end plate. The sextants are aligned by dowels. The core assembly consists of the magnet's upper and lower halves [2]. The yoke core is machined with an electric wire cutter to cut the edge along a 14° angle tangential to the electron beam direction, as shown in Fig. 1(b). Hence the amount of yoke cut area is a function of z. A partially cut yoke means that 80% of the horizontal surface cross section yoke area at the two adjacent sextants is cut. Thereafter, the mechanical accuracy and reproducibility of the magnet assembly remains unaffected because a larger yoke cross section between the two adjacent sextants remains on the mating surface. For the purposes of solving the magnetic field saturation, an extra closed-loop solid yoke extending in the longitudinal direction (z-axis) and across the vertical plane is added to compensate for the lessened yoke core area, as shown in Fig. 1(a). But because of space limitations, the cut area still has 20% which can not be compensated for. The extra solid yoke is designed not only to provide the same reluctance for the same flux passage through it, but also for easy assembly of the magnet.

Because an 80% yoke core area between the surface cross section of the two adjacent sextants is cut, at the cut side a stronger saturation field would be induced. The saturation field would create an asymmetric magnetic field distribution in the horizontal transverse direction (x-axis) of the sextupole magnet. Several forbidden harmonic fields also occur. To resolve the field saturation behavior at the yoke cut area, an extra closed-loop yoke is added on the cut side, across the two adjacent sextants. This extra closed-loop yoke fills an 80% yoke area to compensate the yoke cut area. Therefore, problems regarding the asymmetric magnetic field on the transverse x-axis and the lessened sextupole strength in the yoke cut magnetic circuit are resolved. The field can then once again achieve a good quality. In this work, we analyze the field behavior of the various magnetic circuits. Moreover, each harmonic field is measured to account for field asymmetry and field saturation phenomena.

II. Field measurement and discussion

A Hall probe was moved on a circular trajectory [3] of the transverse plane and along the longitudinal direction to map the vertical field $B_y(x,y,z)$ of the sextupole magnet. Harmonic field analysis can be obtained according to equations (1) and (2), individually representing the center field and the integral field [3], in which H_n^N is the normal term and H_n^S is the skew term.

$$B_y(x,y)=\sum_{n=1}^{n}\sum_{m=0}^{m} N_{nm}H_n^N(0)x^{n-2m-1}y^{2m}+\sum_{n=2}^{n}\sum_{m=0}^{m} S_{nm}H_n^S(0)x^{n-2m-2}y^{2m+1}, \quad (1)$$

$$\int B_y(x,y,z)dz=\sum_{n=1}^{n}\sum_{m=0}^{m} N_{nm}H_n^N x^{n-2m-1}y^{2m}+\sum_{n=2}^{n}\sum_{m=0}^{m} S_{nm}H_n^S x^{n-2m-2}y^{2m+1}. \quad (2)$$

The normal sextupole integral field deviation is calculated from Eq. (3) and the normal sextupole field deviation at the center is calculated from Eq. (4). Eq. (3) and Eq. (4) are used to determine whether the field quality is adequate or not.

$$\Delta H_3^N/H_3^N=\left(\frac{\partial_2}{\partial x^2}\left(\int B_y(x,0,z)dz\right)-H_3^N\right)/H_3^N, \quad (3)$$

$$\Delta H_3^N(0)/H_3^N(0)=\left(\frac{\partial_2}{\partial x^2}(B_y(x,0,0))-H_3^N(0)\right)/H_3^N(0). \quad (4)$$

For the original sextupole magnet [2] (before the magnet yoke is cut), Fig. 2 shows the features of the sextupole integral field deviation $\Delta H_3^N/H_3^N$ *as* a function of x, which is defined in Eq. (3). This figure demonstrates that the field behavior is symmetrical on the transverse x-axis. However, as indicated in this figure, the asymmetrical field behavior obviously occurs (see in Fig. 2) on the cut yoke of the original sextupole magnet. This

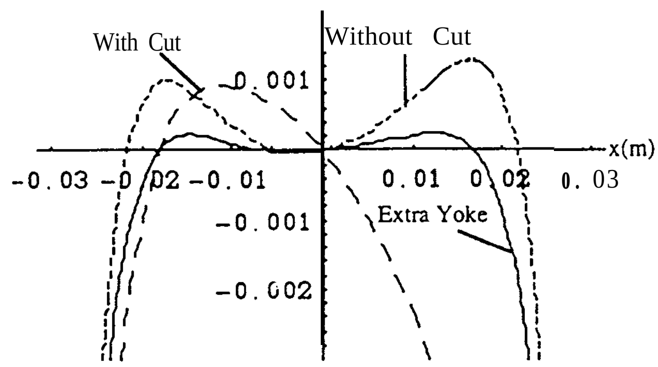


FIG. 2. Sextupole integral field deviation $\Delta H_3^N / H_3^N$ as a function of x with and without the yoke cut and with an extra magnetic circuit added to the cut side of the magnetic yoke.

TABLE I. Harmonic field strengths of the various magnetic circuit which are operated in the excitation current 170 amp., with and without yoke cutting and an extra yoke added to the cut yoke side.

Harmonic field	Without cut	With cut	Extra yoke	Tolerance*
H_1^N (T·m)	-0.00004	-0.00045	-0.00023	—
H_2^N (T)	-0.0002	-0.0015	-0.0004	
H_2^S (T)	-0.0001	-0.0002	-0.0002	—
H_3^N (T/m)	27.114	26.95	27.03	f0.05
H_3^S (T/m)	-0.057	-0.041	-0.018	—
H_4^N (T/m^2)	0.25	-1.41	0.11	±1.2
H_4^S (T/m^2)	0.03	-0.2	-0.2	f1.2
H_5^N (T/m^3)	24	-32.5	6.4	±36
H_5^S (T/m^3)	-1.2	4.5	-09	±36

*Tolerance is the criteria for whether the electron beam can survive in the dynamic aperture which can be simulated by accelerator physics codes such as PATRICIA. Tolerance can be found in the SRRC design handbook.

asymmetric factor derives from the strong octupole strength that is created due to field saturation behavior (the saturation phenomena is discussed later). After the extra yoke is added on the cut yoke magnet, the field behavior of $\Delta H_3^N / H_3^N$ once again becomes more symmetrical (see in Fig. 2). Hence, Fig. 2 shows that the extra closed-loop yoke added to the cut side of the magnet, has resolved the field asymmetry problem of the cut yoke magnet. Table I presents the field analysis results of the normal and skew harmonic strength the various magnetic circuits. The table also shows the tolerance values. If the harmonic field strength is beyond the tolerance (out side the tolerance region) then the electron beam may not survive in the dynamic aperture of the storage ring. The higher harmonic field between the field measurement results and the tolerance of the three magnetic circuits has been compared. The skew higher harmonic strength differences between the three magnetic circuits is found to be quite small, and all are within tolerance. The comparison also reveals that most of the normal harmonic strength of the cut yoke magnet is close to the limitation of the field tolerance. Moreover the normal octupole strength is much more out side of the tolerance. However, after the extra closed-loop yoke is added on the cut side of the magnet, the normal harmonic strength is all within the tolerance. Hence, the extra closed-loop yoke magnetic circuit has reduced the strong forbidden harmonic field strength.

Because of the characteristics of a sextupole magnet [4], the field asymmetry is derived primarily from the strong octupole field strength. Fig. 3 displays the octupole field distribution along the longitudinal direction with and without the yoke cut. As indicated in this figure, the extra close-loop yoke is added to the magnet's cut side. With yoke cutting, the octupole strength is a function of the longitudinal z-axis. This same figure verifies that the octupole field behavior has a strong relation with respect to the amount of the cut area, which is a function of the longitudinal z-axis (the maximum area cut is on the positive z-axis side and the minimum on the negative side. (see Fig. 1 (b)). Hence, from Fig. 3, we can conclude that a stronger octupole strength occurs when a larger area of the yoke core is cut. Fig. 4 shows the sextupole strength deviation $\Delta H_3^N(0)/H_3^N(0)$ at the center of the various magnetic circuits (as defined in Eq. (4)). This figure reveals that asymmetric field behavior of the cut yoke core exists; however, the field asymmetry of the cut magnet is markedly less than that for the integral sextupole strength deviation, $\Delta H_3^N/H_3^N$ (Fig. 2). Hence, comparing Figs. 2, 3 and 4 clearly indicates that the asymmetric field behavior is corrected after the extra closed-loop yoke is added to the cut side of the magnet. Meanwhile, the more yoke area that is cut implies that a stronger asymmetrical field is created. This observation would suggest that (a) the field problems are all derived from the field, saturated at the cut side, because there is too small an amount of yoke core so that the magnetic field will be saturated at the yoke cut area and (b) the saturation degree is as a function of the z-axis since the amount of cut area in the yoke core is a function of the z-axis.

In a good magnet operation field range, the ratio of higher harmonic strength normalizing to the fundamental harmonic strength is independent of the excitation current. However, if the ratios depend on the excitation current, magnet saturation must occur. Experimental results (Fig. 5) confirm that the strong forbidden field strength derives from field saturation. The forbidden field strength (e.g., the dipole, quadrupole, octupole, and decapole) of the cut yoke magnet becomes much larger than the original sextupole magnet. If the yoke core is cut partially along a 14° angle tangential to the electron beam direction, the magnetic circuit is still symmetrical; however, field saturation occurs in the cut region and then induces a forbidden multipole field. Meanwhile, the sextupole field deviation, $\Delta H_3^N/H_3^N$, becomes asymmetric as a function of x. Fig. 5 presents the normalization of the forbidden integral field strength with respect to the fundamental field strength (sextupole strength) on varied excitation currents. Fig. 5(a) shows that the dipole

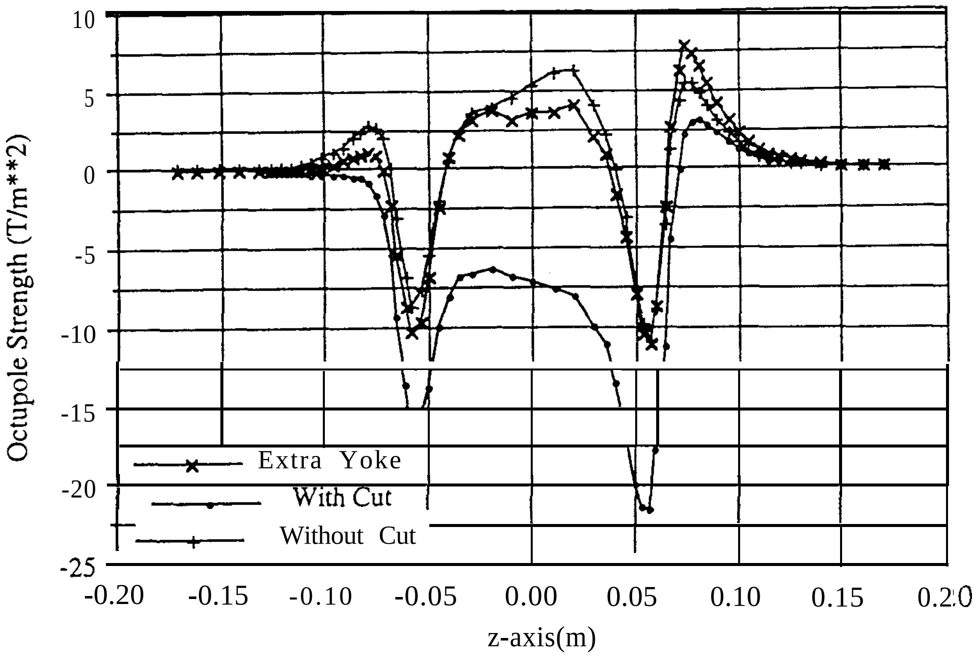


FIG. 3. Octupole field distribution along the longitudinal direction for varied magnetic circuits of the sextupole magnet.

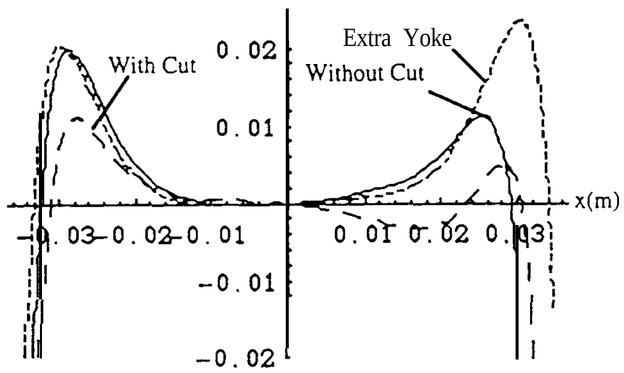
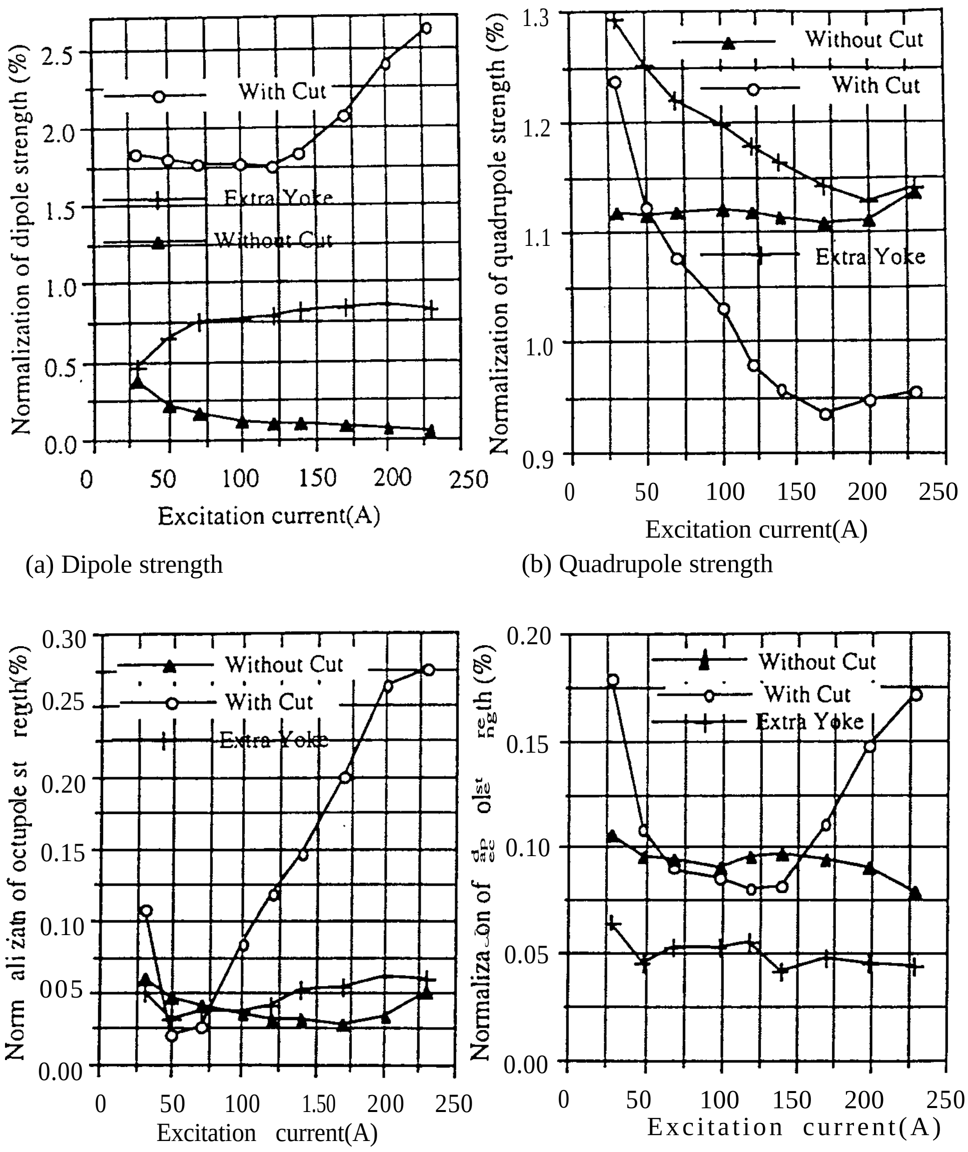


FIG. 4. Sextupole field deviation $\Delta H_3^N(0)/H_3^N(0)$ in the center region as a function of x with and without the yoke cut, and with an extra magnetic circuit added to the cut side of the magnet.

strength of the cut yoke magnet depends on the excitation current when it exceeds 100 amp.; however, for the uncut yoke or with the extra yoke installed to compensate the area part ofthe yoke cut, the dipole field behavior is almost independent of the excitation current. Fig. 5(b) displays the quadrupole field behavior related to the varied excitation currents,



(a) Dipole strength (b) Quadrupole strength

(c) Octupole strength (d) Decapole strength

FIG. 5. The individual normalization of each multipole field integral strength with respect to sextupole integral strength at various excitation currents.

For the varied excitation currents, the quadrupole strength of the uncut magnet yoke remains unchanged but there is large change for the cut magnet yoke. Because the quadrupole strength is changed, the magnetic field is center shifts and depends on the varied excitation current. The multipole field expansion of Eq. (2) defines the relationship, $2H_2^N = H_3^N \Delta x$, between the quadrupole and sextupole field strength, where Ax is the amount of field center shift, H_2^N is the quadrupole strength and H_3^N is the sextupole strength. The field center shift after the yoke cut is about -0.11 mm at 170 amp. (the harmonic strength is shown in Table I). However, with the extra closed-loop yoke installed in the cut yoke core area, the field center shift becomes -0.03 mm, i.e., close to the original sextupole magnet's center shift of -0.015 mm. Fig. 5(c) shows the octupole field related to the excitation current. The octupole strength, with the yoke cut, is a function of the excitation current and out of the tolerance (see in Table I), but remains constant on the other two magnetic circuits. Fig. 5(d) indicates that the decapole strength of the cut yoke magnet is also as a function of the excitation current; the other two magnetic circuits are not. According to the above discussion in Fig. 5, we can infer that the forbidden harmonic strengths of the cut yoke magnetic circuit are a function of the excitation current. This implies that the magnetic field should be saturated at the magnet yoke cut side [4]. However, the forbidden harmonic strengths in the other two magnetic circuits (without cutting or with the extra yoke compensation) do not depend on the excitation current, implying that saturation does not occur in the other two magnetic circuits. If the yoke core is fully cut at one side, the magnet becomes an asymmetric magnetic circuit and would induce a strong asymmetric sextupole field deviation $\Delta H_3^N / H_3^N$.

Why does the octupole strength change much more than the other forbidden fields under the same excitation current change? This is because the magnetic field at one side of the cut yoke magnet is saturated, but the other side of the magnet without the cut yoke is not. Therefore, the saturation degree is different at the two sids on the same magnet. Such a behavior creates a strong octupole field which will produce the asymmetry field [4]. This strong field saturation can be similarly explained [4] as an unequal distance of the adjacent sextants that belongs to the individual sides of the magnet. The above results suggest that the main problem of the asymmetry field is induced by the octupole field, which originates from the strong saturation on the cut yoke side of the two adjacent sextants.

These forbidden field strengths of the cut yoke magnet are a function of the excitation currents (Fig. 5); in addition the sextupole strength (see in Fig. 6) is smaller than for the original magnet. These harmonic field behaviors of the cut yoke magnet are due to field saturation happening at the cut side of the magnet yoke. Therefore, the saturation behavior can be eliminated by using a closed-loop magnetic circuit to cross past the cut side of the yoke, compensating for the lessened core area. After the extra closed-loop magnetic circuit is added,the asymmetric phenomenon disappears; meanwhile, the forbidden fields are independent of the excitation current and close to the results for the original sextupole magnet. In this work, we have eliminated the problems associated with the asymmetry and saturation behaviors. Moreover, the fundamental strength is 0.60% less than for the original magnet at an excitation current of 170 amp. (Fig. 6). However, after the extra magnetic circuit is installed across from the two adjacent sextants, the integral sextupole strength is compensated for and only 0.31% less (which is only slightly outside of the specification requirement) than that original sextupole magnet at an excitation current of 170 amp. (Fig. 6).

Why does the forbidden field of the yoke cut magnet gradually become flat (see Fig. 5) when the excitation current exceeds 200 amp.? This behavior is because the magnetic field saturation began to increase on the other (uncut) side of the magnet. herefore, the

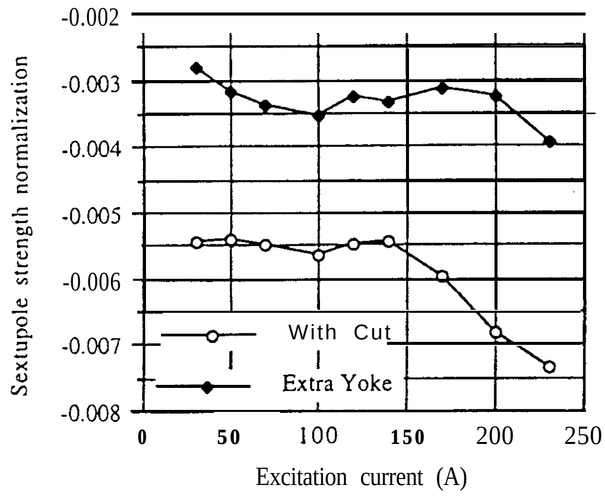


FIG. 6. Integral sextupole strength of the yoke cut and the extra magnetic circuit magnet individually normalized to the integral sextupole strength of the original sextupole magnet.

field saturation ratio between the two sides of the magnet (one side cut and the other side not) would become small.

III. Conclusion

In this work, the original sextupole magnet was partially cut at one side, as it is unnecessary to design and fabricate a new sextupole magnet to accommodate an electron bending chamber. This method also makes it more feasible to assemble the sextupole magnet and easier to control the mechanical accuracy than cutting the full yoke of a sextupole magnet.

After the yoke cutting, the forbidden field becomes stronger and the sextupole strength becomes much less than with the original magnet. These unreasonable field behaviors are induced from the field saturation. If the extra magnetic yoke is across from two adjacent sextants at one side of the magnet's cut yoke, the saturation behavior decreases much more than the magnetic circuit of the cut yoke magnet. However, the sextupole strength still remains 0.31% less than the original magnet at the excitation current 170 amp.. Because of limited space, the yoke cut area still has 20% that can not be compensated for, Hence, if a sufficient amount of space can accommodate for the extra yoke core area to fill the total area of the cut yoke, then the field features should be the same as for the original sextupole magnet.

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