Magnets with Full Apertures for Extracting Synchrotron Radiation at the Photon Factory Ring

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I. Introduction

For the next-generation synchrotron radiation (SR) sources, ring magnets should be designed to accommodate the vacuum chamber such as an antechamber, which lets intense synchrotron radiation from an insertion device to pass through and can reduce gas load produced by the photodesorption due to synchrotron radiation. Such kinds of magnets with iron yokes of largely deformed shape or with a missing part of yoke have been widely adopted in the SR rings planned or being constructed[1].

At the Photon Factory, we designed a set of magnets with apertures enough to extract almost all synchrotron radiation from the upstream bending magnet. These magnets are a quadrupole, a sextupole and a vertical steering. After the field measurement in the summer shutdown of 1990, they were positioned in the lump on a common magnet-base in the ring, taking the place of the then-existing magnets (see Fig. 1). On the restart of the ring operation in the following autumn, no harmful effect was observed on the circulating beam and since then the magnets are being operated without any trouble. In this paper, we will report the magnet designs, the field measurement and the effects of the magnets on the beam orbit.

II. Design Specifications

Before constructing the magnets, calculations of magnetic field were made using the program LINDA[2] for various types of the magnets, particularly, for those of the quadrupole, because it might have an effect on the beam more dangerous than the others; the sextupole and the vertical steering.

Quadrupole Magnet

For the quadrupole, we first investigated several types of magnet that simply had a deformed part of iron yoke not so as to interfere with SR being extracted. The field calculation showed that these types had quite the same field quality as usual types at a lower field, while at a higher field, i.e., when the iron yoke began to saturate, the quality got worse and the magnetic center moved sideways. Therefore, we next considered to attach correction coils wound on to the yoke, but found it complicated to make this method work well. Then we finally adopted a Collins' type, for which the magnetic center does not move because of its geometrical symmetry.

The designed magnet is shown in Fig. 2. Since it was planned to replace with a focusing magnet (called Type I) in a normal cell and to excite in series with several magnets of the same type, the thickness of the iron yoke was increased to 100 mm, two times thicker than that of Type I, in order to make the excitation curve at a higher field agree with each other as far as possible. In addition, two pairs of correction coils that can be excited by an independent small power supply were attached on the iron yoke to compensate for the difference in field excitation.

In order to study the structural strength under magnetic stress, a simple program using the method BEM (Boundary Element Method) was written to compute a magnetic field of the quadrupole with assuming μ infinite in iron and the structural distortion by induced magnetic stress. An example of the computed results is shown in Fig. 3. From such results, we adopted a structure of magnet with stainless steel sections in the yoke. With the magnet yoke having a protrudent portion of 100 mm-thick stainless steel, the magnetic center was expected to shift the order of a few tens μm at a current of 500 A. On the other hand, the thickness of the opposite portion made of stainless steel is constrained to allow the existing alignment instrument to use. The principal parameters of the quadrupole together with those of the sextupole and the vertical steering are listed in Table I.

Sextupole Magnet

For the sextupole, the magnetic field were also calculated by LINDA and the results showed that the whole yoke made only of iron has a relatively good field quality, though the horizontal field distribution is inclined at a high field and the sign of field within ± 5 mm around the center of magnet becomes opposite to that of the other region. This change of sign was estimated to give little effect on the beam orbit. Thus we adopted a simple structure for the sextupole as shown in Fig. 4.

Vertical Steering

In order to hold the symmetry of the magnetic structure, we

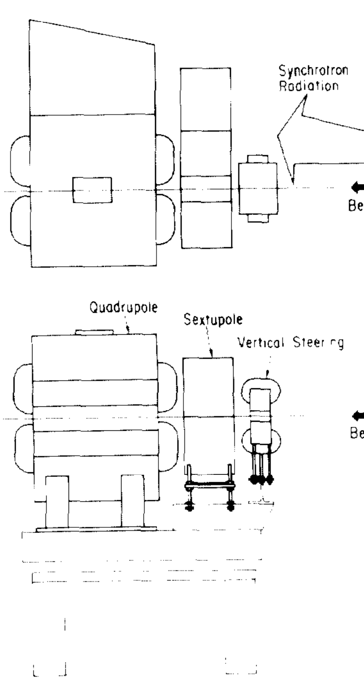

Fig. 1 Schematic view of the magnet arrangement in the ring.

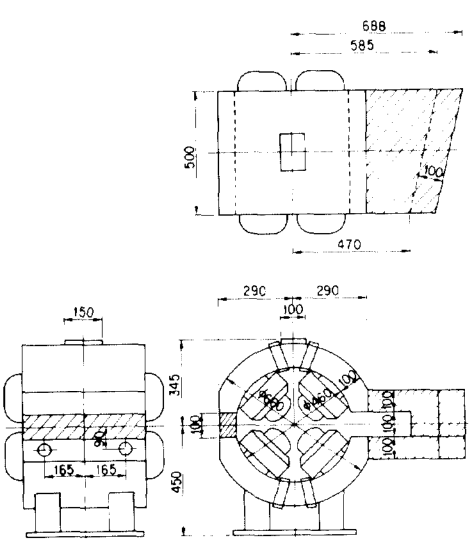

Fig. 2 Design sketch of the quadrupole. The shaded portions are made of stainless steel.

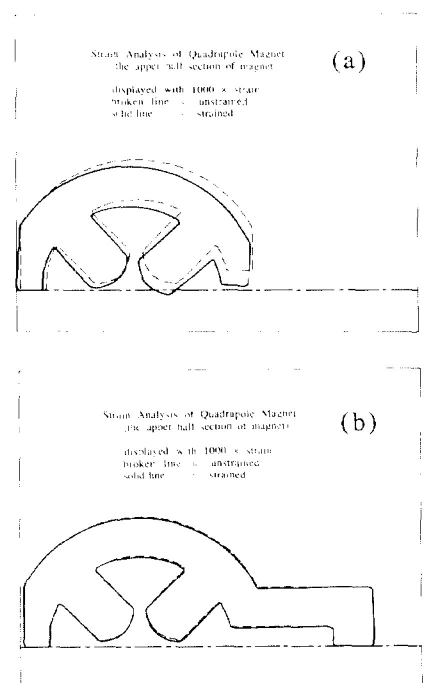

Fig. 3 Structural distortion of the quadrupole at a current of 500 A. (a): the case without stainless-steel yoke, (b): the case with a 100 mm-thick stainless-steel yoke. The minimum gap at right has a displacement about 30 μm in the case of (a) and about 4 μm in the case of (b).

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adopted a type of structure as shown in Fig. 5, much similar to the type adopted for the quadrupole. Differing from the quadrupole, however, the mechanical structure of the vertical steering is not necessarily so strong as the quadrupole is, so that one of the side yokes is made open to let SR pass through. Two-dimensional calculation of LINDA implied that the field degraded by splitting the side yokes could be restored by attaching four rectangular shims, each about 10 mm wide and 10 mm high, to the inside wall of the iron yokes. As the length of magnet is shorter than the transverse dimensions, however, various sizes of shims were prepared to choose an optimum size in the field measurement.

Table I. Principal parameters of the magnets

Qauadrupole	
gradient (B')	9.5 T/m
main coil current	500 A
turn number of coil	23 per pole
bore radius	55 mm
length of iron core	0.5 m
width of iron yoke	100 mm
electric resistance	32 mΩ
cooling water	5 *l*/min.
power dissipation	8 kW
correction coil current	4.5 A (max.)
number of correction coils	4
turn number of correction coil	100 per coil
Sextupole	
sextupole gradient (B")	29 T/m^2
current	3 A (max. 5 A)
turn number of coil	436 per pole
bore radius	70 mm
length of iron core	0.2 m
electric resistance	9.5 Ω
power dissipation	85 W (max. 240 W)
diameter of conductor	1.8 mmφ
Vertical steering	
field (B)	380 G
current	3 A
turn number of coil	2100 per pole
length of iron core	80 mm
electric resistance	14 Ω
power dissipation	127 W
diameter of conductor	1.6 mmφ

III. Field Measurement

The magnetic field measurements were carried out mainly using the following two methods; (1) a moving induction coil for the quadrupole and (2) harmonic coils for the sextupole and the vertical steering. Furthermore, a rotating coil was used for quadrupole and sextupole to check the reliability of measurement made by the above methods, and also used was a colloidal instrument to measure the magnetic centers[3]. In the method (1), at the same time that a horizontal position of the moving coil was measured with a precision of 50 μm by a Nikon position scale, the voltage induced by the quadrupole field was also measured with 1×10^{-4} accuracy by VFC (Voltage to Frequency Converter) connected to a CAMAC scaler system.

For the quadrupole, a good field region (about ±40 mm) of the integrated gradient distribution as shown in Fig. 6 was obtained by attaching a pair of end shims at each end of the pole pieces. The thickness of the end shims was chosen to be 4 mm. The excitation curve was measured up to 800 A (beyond a maximum-allowed current of 500 A), and compared with that of an existing quadrupole of Type I (see Fig. 7). The difference in excitation that became apparent above 300 A (0.7% at 300 A and 4.0% at 800 A) was compensated for by exciting the correction coil. The correction current required for compensation is plotted with respect to the main current in Fig. 8, and it is only 1.0 A at the ring energy of 2.5 GeV. The magnetic center was checked using a colloidal instrument[4] and agreed with a geometric center less than 50 μm below a current of 400A, though it was slightly deviated with the correction coil current as shown in Fig. 9. A large deviation seen in the figure at a high current that had also been observed for the existing Type I quadrupoles is due to the iron support legs, which give rise to an asymmetry in the magnetic circuit of the quadrupole.

The mechanical distortion due to magnetic stress was measured by strain gauges directly stuck on the magnet and by those stuck on pieces of aluminum that were in turn fixed between the minimum gaps in the magnet. The latter gauges had a better sensitivity and gave the same order of strain as predicted. Temperature rise and flow rate of the cooling water were measured simultaneously, and the flow rate was observed to increase with the current due to the

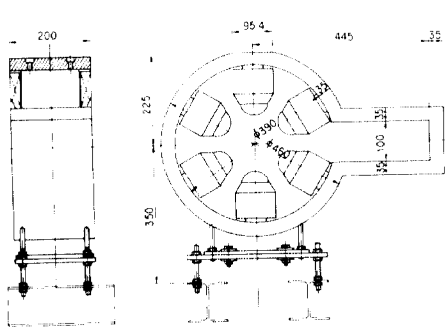

Fig. 4 Design sketch of the sextupole. The whole yoke is made of iron.

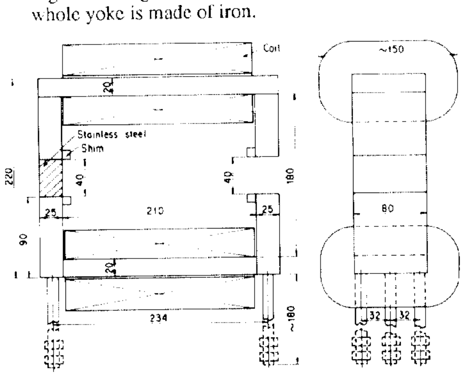

Fig. 5 Design sketch of the vertical steering. The shaded portion is made of stainless steel.

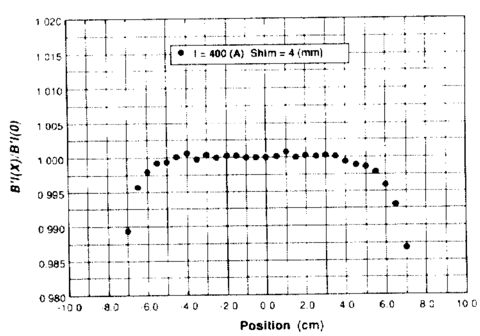

Fig. 6 Integrated gradient distribution ($B'l(x)/B'(0)$) versus the horizontal position (x) of the quadrupole at a current of 400 A with 4 mm-thick end shims.

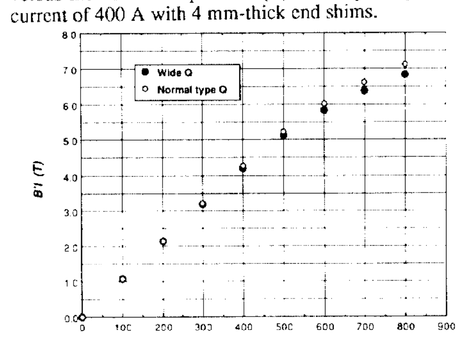

Fig. 7 Comparison of the excitation curves between the quadrupole and one of the existing quadrupoles (Type I). Wide Q and Normal type Q in the figure indicate the designed magnet and a magnet of Type I, respectively.

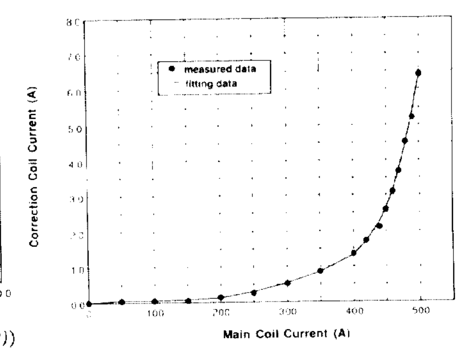

Fig. 8 Correction coil current required to compensate for the difference in excitation.

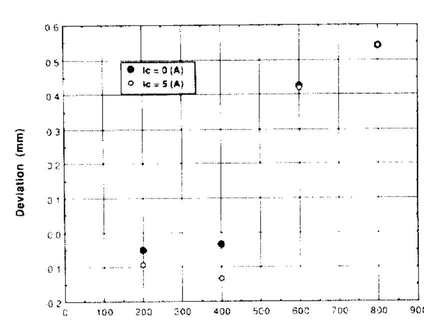

Fig. 9 Deviation of the magnetic center of the quadrupole versus the main coil current.

temperature dependence of the viscosity of water. The details of both strain and temperature measurements will be reported elsewhere.

The field strength of the sextupole measured by a harmonic coil is B''l = 10.13 T/m at 4.5 A, and the field distribution measured by a rotating coil is shown in Fig. 10. Further the field around the center of magnet was finely measured and found that the field has an opposite sign to that of the outer region, just as predicted by the field calculation.

For the vertical steering, the 10 mm-thick end shims were as optimum in the field measurement as in the two-dimensional calculation. The distribution of the integrated field is shown in Fig. 11 and the field strength is Bl = 73.4 G·m at a current of 3.0 A.

correction coil current (1.0, 2.5 and -4.5 A) and Fig. 13 shows the tune shifts with respect to the correction current. The method of measuring beta function is described in Ref. 4. At the nominal current of 1.0 A, both horizontal and vertical beta functions agreed well with the design values and any appreciable tune shifts were not observed. As shown in Fig. 14, the beta distortion measured at the other values of the correction coil current was also in good agreement with the distortion predicted from the data of field measurement.

The closed orbit distortion produced by the deviation of the magnetic centers in the quadrupole and in the sextupole was found to be negligibly small. The chromaticities were also measured and any appreciable change from the previous values was not found.

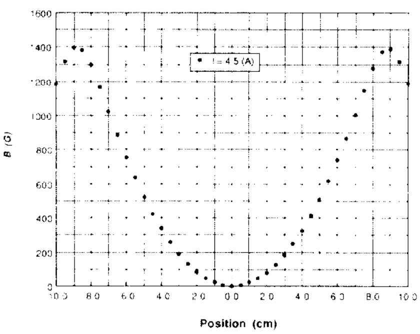

Fig. 10 Field distribution at the center of the sextupole measured by a rotating coil.

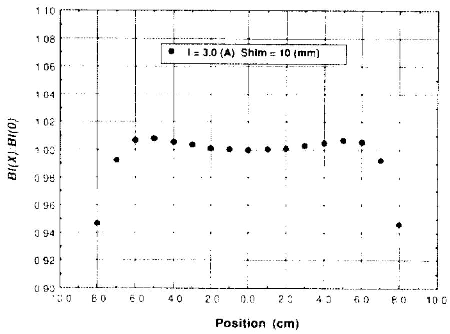

Fig. 11 Integrated field distribution of the vertical steering.

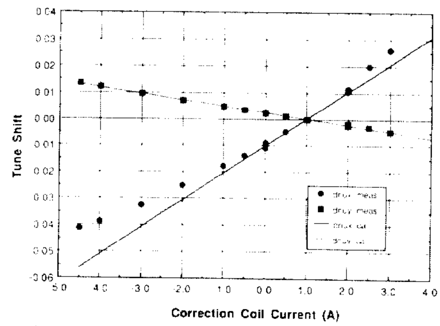

Fig. 13 Tune shift versus the correction coil current. Closed circles denote the measured values and solid line the expected value.

IV. Effects on Beam Orbit

The effects of the magnets on the beam orbit were studied after installing the magnets at the downstream of a bending magnet called B22, which was actually impossible to use for SR experiment because of the building structure. Since the quadrupole is a horizontally focusing magnet, the effects on the tune shift and the distortion of betatron function appeared more clearly in the horizontal direction than in the vertical direction, when the current of the correction coil in the quadrupole was set to a value different from the nominal one determined by the field measurement. Figure 12 shows the measured beta functions for three different values of the

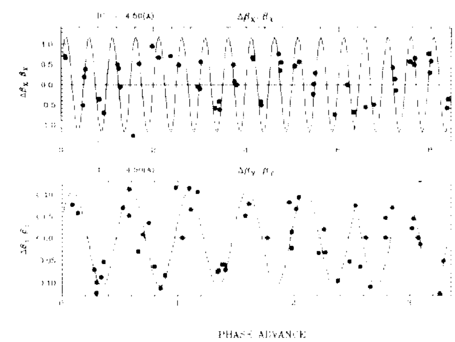

Fig. 14 Fractional changes of the beta functions at -4.5 A for the correction coil. Closed circles denote the measured values and solid lines the expected values.

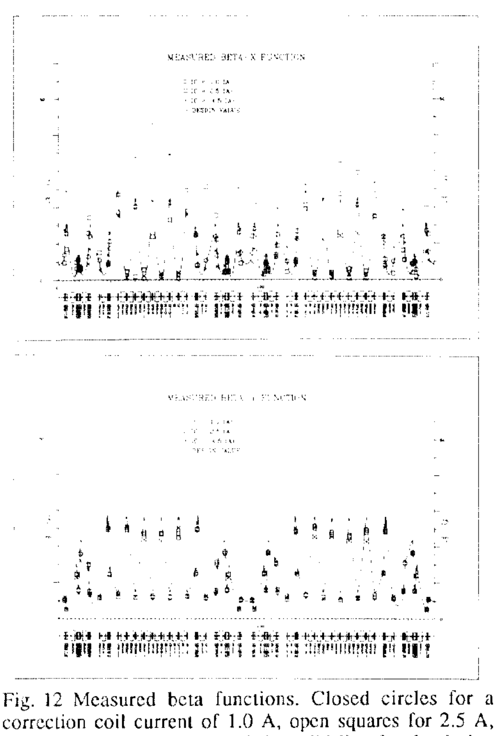

Fig. 12 Measured beta functions. Closed circles for a correction coil current of 1.0 A, open squares for 2.5 A, cross symbols for -4.5 A and the solid line for the design value.

V. Summary and Acknowledgements

The magnets described here are being operated without any trouble until now, while a kind of antechamber appropriate for the magnets will be installed within a few years [5]. If the magnets and vacuum chamber together achieve their design specifications, next step is probably "the full moon project" which will utilize the unused bending magnets in the injection region for supplying SR with extraction angles much wider than previously available.

We would like to thank all staff of the Light Source Division of the Photon Factory, in particular, Prof. M. Kobayashi and Dr. Y. Hori for their discussion about the vacuum chamber yet to be installed in the magnets. We also thank Prof. R. Sugahara of the Accelerator Department for kindly lending us his colloidal instrument.

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(1) for example see the ESRF Design Report "RED BOOK", January 1987, the ALS Conceptual Design Report, July 1986 and so on.
(2) KEK version of the program LINDA, and also see K. Endo and M. Kihara,"Manual of Magnetostatic program LINDA", KEK ACCELERATOR-1, 1972 (in Japanese).
(3) R. Sugahara, T. Kubo and Y. Oosawa, "A Colloidal Solution of Fe_3O_4 Crystallites to Optically Locate the Magnetic Center of Multipole Magnets", KEK Report 89-9, September 1989.
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(5) M. Kobayashi and Y. Hori, private communication.