MAGNETIC FIELD MEASUREMENT OF THE J-PARC RCS STEERING MAGNETS AND SEXTUPOLE MAGNETS AND COMPARISON TO THE FIELD CALCULATION

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Abstract

The magnetic field of the steering magnets of the J-PARC rapid cycle synchrotron (RCS) has been measured using flip coils when the current pattern was a superposition of a direct current and an alternating current of 25 Hz. The integral of the magnetic field with respect to the beam direction, z, between –0.6 m and 0.6 m was four times as large as the requirement. The uniformity of the field integral was within ±1 % for the region of $|x| < 130$ mm. The measurement agreed with the results from the three-dimensional magnetic field calculation program OPERA3d/ELEKTRA that took eddy current effects into account. The magnetic field of the sextupole magnets has been measured using harmonic coils. The field strength was measured to have a margin of 30 % from the requirement. The relative amplitude of the 18-pole component to the sextupole component was observed to be 2×10^{-4} that was less than the requirement of 10^{-3}. The results were in a good agreement with the results from OPERA3d/ELEKTRA. The time shift of the 18-pole component with respect to the current pattern was observed with harmonic coils those covered the end region of the magnet. Eddy currents at the stainless steel end plate and end region of the iron were the cause.

INTRODUCTION

Schemes of the J-PARC RCS orbit correction and chromaticity correction requires 52 steering magnets and 18 sextupole magnets. The required specifications are listed in table 1 for the steering magnets and in table 2 for the sextupole magnets. Because the core lengths of the magnets were short, the three-dimensional effect at the magnet end had to be considered for designing the magnets. The magnetic fields were calculated and the pole shapes were decided with the three-dimensional magnetic field calculation program OPERA3d/TOSCA.

A typical current pattern is a superposition of a direct current and an alternating current of the frequency of 25 Hz. Eddy currents would cause undesirable temperature rises or deformation of the magnetic fields. The effects were estimated to be tolerable with the magnetic field calculation program OPERA3d/ELEKTRA for time varying current patterns.

The core of the magnet is made of lamination with 0.5 mm-thickness sheets. The electrical steel sheet 50BF470, a JFE Steel Corporation product, has high permeability and low coercive force. Hundreds of layers of steel sheets are sandwiched with end plates and fixed with tie rods and side plates. The end plates and tie rods are made of stainless steel. The tie rods are insulated from the end plates and core to cut a path of eddy currents. The side plates are made of stainless steel for the steering magnets and of high-tension iron for the sextupole magnets.

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Table 1: Required Specifications for the steering magnets.

Numbers of the magnets	21(CHN: Horizontal kick, Normal), 21(CVL: Vertical kick, Normal gap), 5 (CHL: Horizontal kick, Large gap), 5 (CVL: Vertical kick, Large gap)
Gap Height	340 mm (Normal), 420 mm (Large)
Core Length	100 mm
Peak Field	0.045 T
Field Uniformity	±0.01
Core Iron	Silicon steel, thickness 0.5 mm
Conductor	Insulated copper wire, 201 turns (N), 178 turns (L), Cross section 3 mm×10 mm (N), 3.5 mm×12 mm (L)
Maximum Current	61 A (Normal), 84 A (Large)

Table 2: Required Specifications for the sextupole magnets.

Numbers of the magnets	6 (SFX), 6 (SDA), 6 (SDB)
Bore	330 mm ϕ
Core Length	320 mm
Peak Field	18.6 T/m^2 (SFX), -17.4 T/m^2 (SDA), -14.8 T/m^2 (SDB)
Field Uniformity	±0.001
Core Iron	Silicon steel, thickness 0.5 mm
Conductor	Aluminum stranded wires 12 turns per pole, Cross section 18 mm×18 mm
Maximum Current	920 A (SFX), 863 A (SDA), 732 A (SDB)

Temperature rise due to eddy currents was concerned at the side plates of the steering magnets. The side plates for the steering magnets were specially machined and attached to the magnet core with minimum cross sections to minimize eddy currents and to avoid undesirable temperature rises.
Eddy currents in the magnet core near the end also had to be considered because the longitudinal component of the magnetic field near the end would be remarkably large for both the steering magnets and sextupole magnets. A disturbance in the field quality by the eddy currents was estimated to be within the tolerance.

STEERING MAGNETS

The magnetic field of the steering magnets was measured using ten flip coils those were aligned by a space of 20 mm in the z direction that was the beam direction. Each coil contained two kinds of windings. One was for the measurement of the x component of the field and the other was for the y component. The coils were set in a 3-D trasnlation stage and the field data were taken every 20 mm step. Figure 1 shows the y component of the field, By, of the horizontal N type magnet (CHN) along the z axis (top) and the integral of the field with respect to z from –0.6 m to 0.6 m, Byl, (bottom) at the peak current timing. The measurement results were compared with the results from the programs OPERA3d/TOSCA and ELEKTRA; TOSCA for the static field calculation and ELEKTRA for the field calculation for transition current patterns with the eddy current effects. The agreement was better with the ELEKTRA calculation.

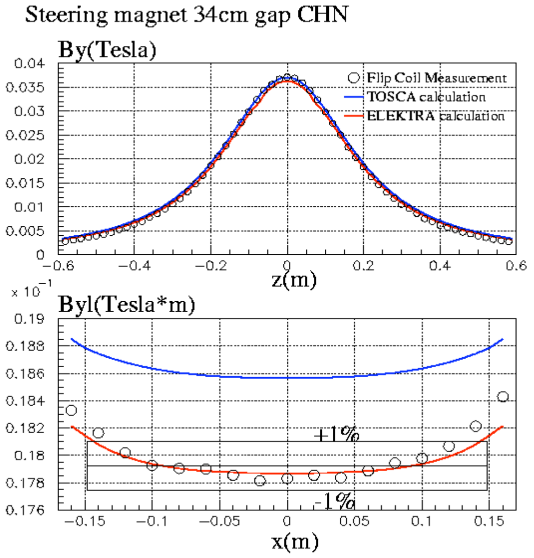

Figure 1: Top figure shows the y component of the magnetic field, By, by the steering magnet CHN along the z axis. The bottom figure shows the integral of the y component of the magnetic field, Byl, with respect to z between –0.6 m and 0.6 m as a function of x at y=0 m. Flip coil measurements are shown in open circles, TOSCA calculation in the blue line and ELEKTRA calculation in the red line.

The field integral Byl as a function of x and y are shown in figure 2 from the ELEKTRA calculation (top) and from the flip coil measurement (bottom). The agreement was good for the region of y＞-80 mm. The agreement, however, was not so good at y=-100 mm. This was most likely the effect of permeable iron in the bottom part of the magnet support.
The average power loss due to the eddy current was calculated to be 580 W. After a half day of operation the highest temperature was observed to be about 70 ℃ that was tolerable. Figure 3 shows the field integral Byl as a function of time. The field integral had a time delay of 0.7 ms from the current pattern. It may have to be considered when creating the current pattern for the operation.

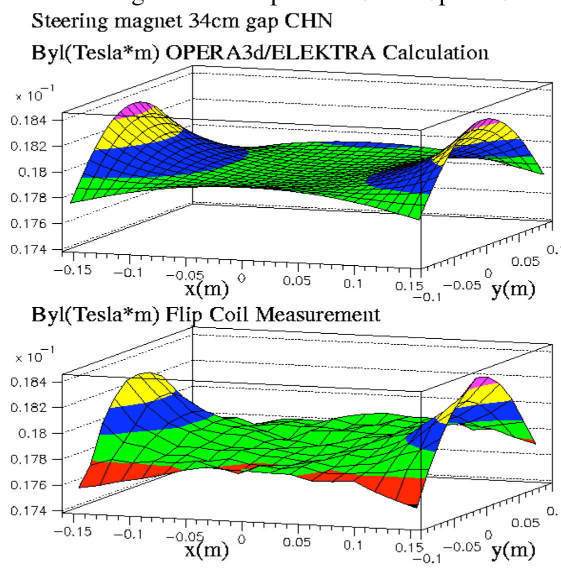

Figure 2: The top figure shows the ELEKTRA calculation of the integral of the y component of the magnetic field with respect to z between –0.6 m and 0.6 m, Byl, by the steering magnet CHN as a function of x and y. The bottom figure shows the flip coil measurement of the field integral Byl.

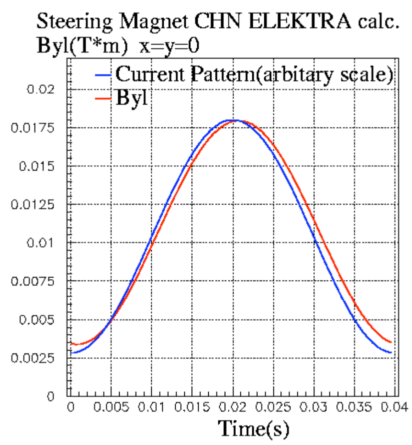

Figure 3: The field integral Byl as a function of time is shown in the red line and the arbitrary scaled current pattern is shown in the blue line. The field integral Byl delayed 0.7 ms from the current pattern.

SEXTUPOLE MAGNETS

The magnetic field of the sextupole magnets was measured using four harmonic coils; long coil, short coil and two medium coils. The long coil covered a region of r 0~135 mm and z –1000~+1000 mm. The short coil covered a region of r 5~135 mm and z –50~+50 mm. The medium coil 1 covered a region of r 5~135 mm and z +100 ~+700 mm. The medium coil 2 covered a region of r 5~135 mm and z –100~-700 mm. All four coils were fixed in one structure that was rotated by the speed of 0.13 turn/s. Details of the system are described in ref 1.

Figure 4 shows the amplitude of the harmonic components of the magnetic field flux in the long coil for six-time measurements of three sextupole magnets. Most of the harmonic components had large deviations and were not likely real signals. Only the sextupole component (3 in the figure) and 18-pole component (9) had small deviations and were most likely signals. The amplitude of the 18-pole component was 2×10^{-4} with respect to the sextupole component. The required field uniformity of $\pm 10^{-3}$ was thus achieved up to the radius of 135 mm.

From the results of the ELEKTRA calculation the eddy currents were observed mostly around the magnet ends and little at the central region, i.e. the small z region (figure 5). The effect of the eddy currents to the magnetic field was to shift the timing of field pattern from the current pattern. It was observed in the 18-pole component field pattern of the long coil measurement (figure 6).

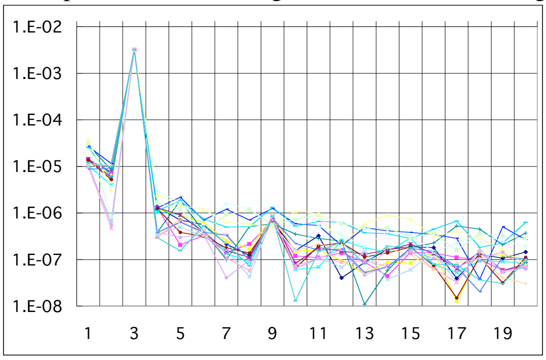

Figure 4: Amplitude of the harmonic components of the magnetic field flux in the long coil. Data were taken and shown for six times each for three sextupole magnets.

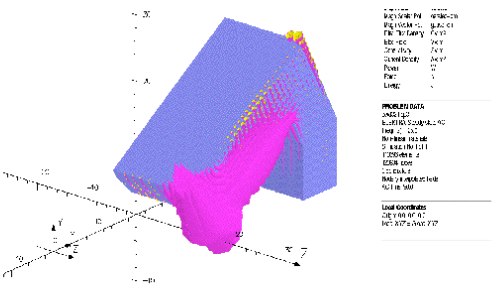

Figure 5: OPERA3d/ELEKTRA calculation result of the eddy current distribution in the iron of the sextupole magnet.

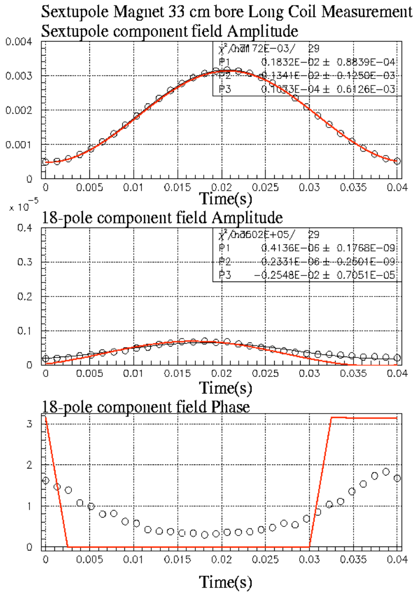

Figure 6: The sextupole component of the sextupole magnet in the long coil as a function of time from the current minimum timing (top figure). The 18-pole component in the long coil (center figure). The relative phase of the 18-pole component (bottom figure). Measurement results are shown in circles and the ELEKTRA calculation are shown in red lines.

The field pattern is 2 ms earlier than the current pattern. It was in a good agreement with the result of the ELEKTRA calculation. The agreement was also good for the sextupole component. The phase of the 18-pole component was measured to be about zero near the peak field when the noise was relatively small. It, however, became larger near the minimum field when the noise was relatively large.

SUMMARY

The results of the magnetic fields of the J-PARC RCS steering magnets and sextupole magnets satisfied the requirements of the orbit and chromaticity correction schemes and in a good agreement with the magnetic field calculation program OPERA3d. The temperature rise due to the eddy current effects was observed to be tolerable. The timing shift of the 18-pole component field pattern to the current pattern was observed in the long coil measurement. It was in a good agreement with the result of the OPERA3d/ELEKTRA calculation.

ACKNOWLEDGEMENTS

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REFERENCES

[1] T. Adachi et al, "Dynamic Field Measurement using a Harmonic Coil", Proceedings of the 3rd Accelerator Meeting in Japan, Sendai, Aug. 2-4 2006.