MEASUREMENTS OF MAGNETIC AXIS AND TWIST OF A LOW-β QUADRUPOLE MAGNET FOR LHC BY USING A MORGAN COIL

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Abstract

The magnetic center and twist angle of the quadrupole field along the superconducting quadrupole magnet MQXA for the low-β triplets of the Large Hadron Collider (LHC) were measured with a Morgan coil which consists of four 600 mm long windings. The MQXA was excited with the alternating current for this measurement at room temperature. A photo-sensitive device with laser and a tilt sensor are complement the Morgan coil for correction of its measuring position and roll.

1 INTRODUCTION

In the framework of the collaboration program between CERN and KEK for the LHC, KEK is responsible for production of eighteen quadrupole magnets (MQXA) including spares for the low-β triplets at the four beam interaction regions[1]. The field gradient of 215 T/m is induced by 7.15 kA at 1.9 K. The magnet is 6.37 m in effective length and 70 mm in aperture. After several years R&D with short models and prototype magnets, the production of the full scale magnets started in 2001. The field quality is checked with a rotating search coil, as a part of the acceptance tests at KEK[2]. It is also necessary to measure the magnetic center and twist angle. For this purpose a Morgan coil with a photo-sensitive device (PSD)/laser and a tilt sensor was prepared. This paper reports the measurement system and measured results on the magnetic center and twist angle for the production magnet.

2 MORGAN COIL

2.1 Configuration

A 60 mm diameter, 600 mm long Morgan coil[3][4] was made to precisely measure the magnetic center and twist angle along the magnet. It consists of four windings: two dipole windings and two quadrupole windings. The configuration of each normal winding is shown in Figure 1. The other windings are skew configurations.

The stationary use of the Morgan coil, i.e. by excitation of the magnet with the alternating current, was selected to measure the displacement of the magnetic center and twist angle without vibration of the Morgan coil and twisting of the shaft which will induce errors. When the Morgan coil with a normal quadrupole (dipole) winding having N turns, radius r_{q_n} (r_{d_n}) and length l is put in a pure quadrupole field with displacement $se^{\phi+\delta}$ in an r-ϕ plane as shown in Figure 2, the induced voltages on the Morgan coil V_{q_n} (V_{d_n}), excited with alternating current $I(t)$ in the magnet, are described as

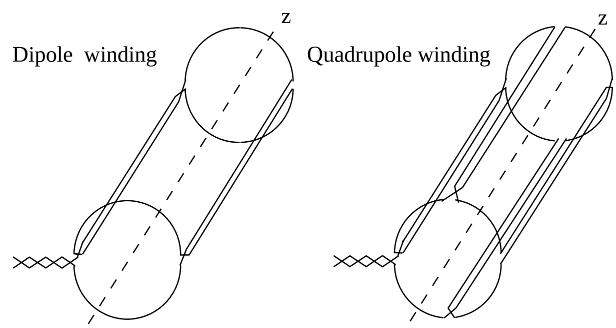

Figure 1: Single winding of the Morgan coil to measure the dipole field (left) and quadrupole field (right). The coils for normal and skew fields are wound on a same GFRP cylinder structure.

$$V_{q_n} = 4Nr_{q_n}{}^2 lT\frac{dI(t)}{dt}cos2\delta, \quad (1)$$

$$V_{d_n} = 4Nr_{d_n} slT\frac{dI(t)}{dt}cos(\delta+\phi), \quad (2)$$

where T is the transfer function of the magnet in T/m/A.

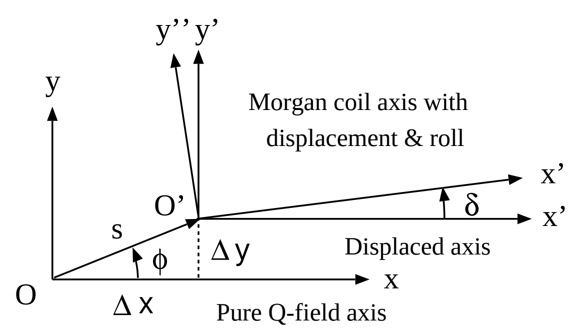

Figure 2: The definitions of the displacement and roll of the Morgan coil axis (x'', y'') from the pure quadrupole field axis (x, y).

The parameters δ, ϕ and s are calculated with the peak induced voltages on the normal and skew quadrupole or dipole windings as follows:

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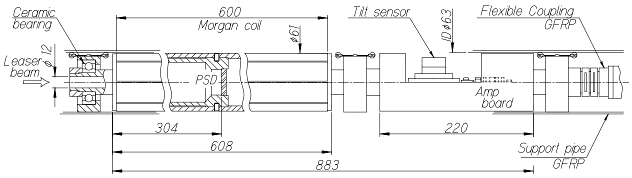

Figure 3: The measurement system of the magnetic center and twist angle along MQXA.

Table 1: Design of the Morgan coil windings.

ID	Radius(mm)	Length(mm)	Phase(rad)	Turns
D_n	30.00	600.00	0	3
D_s	30.00	600.00	$\pi/2$	3
Q_n	30.10	600.00	0	3
Q_s	30.00	600.00	$\pi/4$	3

$$\delta = \frac{1}{2} Arctan\left(-\frac{{r_{q_n}}^2}{r_{q_s}}\frac{V_{q_s}}{V_{q_n}}\right), \tag{3}$$

$$\phi = Arctan\left(-\frac{r_{d_n}}{r_{d_s}}\frac{V_{d_s}}{V_{d_n}}\right) - \delta, \tag{4}$$

$$s = \frac{{r_{q_s}}^2}{r_{d_s}}\frac{V_{d_n}}{V_{q_n}}\frac{cos2\delta}{cos(\delta+\phi)}. \tag{5}$$

From these parameters, the magnetic center and twist angle can be obtained when the position and roll angle of the Morgan coil are obtained by another measurement. The frequency of the induced voltages should have the same frequency of the magnet current, so the peak voltages of the signals can be extracted by FFT.

Each winding was wound with a 100 μm diameter copper wire on a glass fiber reinforced plastic (G-FRP) cylinder. Each coil has 3 turns. The design values of each winding are summarized in Table 1. The dimensions of the Morgan coil were checked in a conventional quadrupole magnet which provides 8.52 T/m at 500 A. The voltages induced by a constant ramp rate were compared with the expected values and matched within 1 %. This value was equivalent to the fabrication error of 50 μm in radius of the Morgan coil.

2.2 Calibration

Figure 3 shows the probe of the measurement system of the magnetic center and twist angle along the MQXA.

Both ends of the Morgan coil with a tilt sensor were supported by high quality ceramic ball bearings to fit on the inside of a support pipe which was prepared for the field measurements at room temperature and inserted into the magnet aperture. To obtain the corrected magnetic center and twist angle of the magnet for the beam axis, the corresponding radial position and roll of the Morgan coil should be measured.

A two-dimensional PSD (Hamamatsu photonics-S1880, detection area of 12×12 mm^2 and resolution <15 μm) was set on the central part of the Morgan coil cylinder. The position of the Morgan coil center was measured with a reference laser beam injected from one end of the magnet. The position of the laser beam axis was calibrated in advance using optical targets which were set to the center of the magnet aperture at the both ends.

The roll angle of the Morgan coil was measured with a tilt sensor (Nissho Kiki-Z-25 and LH200, detection angle range ±2.6 mrad, resolution <1.7×10^{-3} mrad) as reference.

Assuming the 50 μm fabrication error, the measurement accuracy of the displacement of the magnetic center is calculated using eq.(5) to be 0.95 %. This does not include the systematic offset which is measured by PSD. The measurement accuracy of the twist angle δ without correction by the tilt sensor is calculated using eq.(3) to be 0.45 % as well. The measurement accuracies for the displacement and twist angle including PSD and tilt sensor are within 1.25 % and 0.83 %, respectively.

3 MEASUREMENTS

The MQXA magnet was put on the two jacks which were fixed on a plate with 4200 mm span. The z position of the magnet was set with a telescope within 0.2 mm. The yaw, pitch and roll were aligned within 100 μm, 100 μm and 0.2 mrad, respectively.

The Morgan coil was connected to an 8-m long shaft made of carbon fiber reinforced plastic (C-FRP) via a coupling and supported via the bearings inside an 8-m long and 63 mm diameter C-FRP pipe. The other end of the shaft was connected to a stepping motor on a mover via a C-FRP coupling. The roll of the Morgan coil and the longitudinal position of the mover were controlled by stepping motors. The displacement of the mover was measured by a magnetic linear transducer.

A bipolar power supply provided a current of 0.6 A peak to peak at 160 Hz for the MQXA magnet. The peak induced voltage of the quadrupole winding was 56 mV. The effects of the frequency of the magnet current on the displacement s and twist angle δ were checked in advance, and were negligible; less than 0.02 μm and 0.9 μrad, respectively. The induced voltages on the Morgan coil windings were amplified by a DC amplifier (YOKOGAWA Type 3131) with gain=10^2. The voltages were digitized by a 16 bit ADC (HP 1342A) with a 10 V full scale. The PSD and tilt sensor output voltages were read with a digital multimeter (HP E1412A).

During these measurements, a laser beam was shot into the magnet aperture as a reference axis. The laser beam size along the full length of the magnet was tuned to less than 3 mm diameter. The tracking of the laser beam was done before the insertion of the Morgan coil into the magnet. The optical targets with PSDs were used to measure the position of the laser beam spot. The optical targets were calibrated with the telescope and the conventional magnet. The positioning error of the optical targets was less than 50 μm. The drift of the laser beam position was less than 24 μm/hour at a distance of 8 m far from the optical setup. It takes about 90 minutes for the measurement.

All the Morgan coils, sensors and other instruments were integrated with a personal computer and controlled by a program.

4 RESULTS AND DISCUSSIONS

The position of the magnetic center and twist angle measured by a longitudinal scan are plotted in Figures 4 and 5. In these figures, z=0 mm is defined as the mechanical center. The region where the Morgan coil is in the straight section of the MQXA is from z= -2700 to +2700 mm.

The displacement in x (y)-direction of the magnetic center for the straight section was within 0.2 (1.0) mm. The mechanical data obtained by the telescope with fiducial targets aligned with each 0.9 m span on the 490 mm diameter magnet-cylinder were plotted in each figure. The differences between the measurements with the Morgan coil and the mechanical fiducials were within 0.2 (0.2) mm.

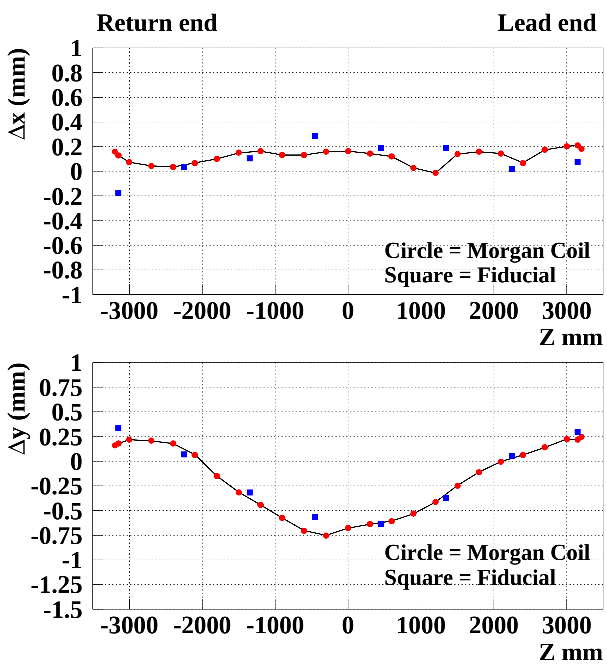

Figure 4: The magnetic center of the MQXA. The squared symbols are the mechanical fiducial positions measured by the telescope.

The twist angles of the magnetic axis along the longitudinal position are plotted in Figure 5. The twist of the magnetic axis was within 1.8 mrad for the straight section. The differences between the twist angle data obtained with the Morgan coil and those with the telescope were within 0.5 mrad for the straight section.

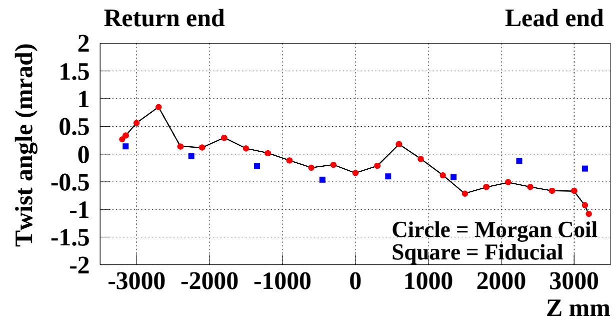

Figure 5: The twist angle of the quadrupole axis. The squared symbols are the mechanical fiducial positions measured with the telescope.

The requirements of the straightness, sag and twist angle for the MQXA is $<$100 μm/m, $<$100 μm/m and 1 mrad/5m, respectively[5]. The measured straightness and twist angle were within these requirements. The measured sag of 1.25 mm is due to the position of the support jacks. In practice, the MQXA will be assembled together with correction magnets at the ends, and this mechanical configuration will reduce the sag.

5 SUMMARY

The measurement system using a Morgan coil for measuring the magnetic center and twist angle along the magnet was constructed and tested with a LHC-MQXA full-scale magnet. The accuracy of the measurement system was 1.25 % for the displacement of the magnetic center and 0.83 % for the twist angle. The obtained data were consistent with the measurement with mechanical fiducials, and they were satisfactory to the required accuracy. The series of MQXA magnets will be measured by this system.

6 REFERENCES

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