Field Measurement of Superconducting Quadrupole Magnets for TRISTAN Mini-beta Insertions

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Abstract

Eight superconducting quadrupole magnets for TRISTAN mini-beta insertions (QCS) have been measured by the rotating coil method before installation in the TRISTAN electron-positron colliding ring. Following the alignment of the magnet to the measuring system by use of a movable QCS-support, harmonics and field gradients were measured as functions of current and finally median plane was determined for each magnet. Details of the measuring system and results of the measurements are presented.

I. INTRODUCTION

Being commissioned in November 1986, the TRISTAN electron-positron colliding ring attained its highest energy 64 GeV in 1989. Now main efforts are being made to get higher luminosity. This luminosity upgrading is achieved by introducing eight high field gradient superconducting quadrupole magnets (QCS) as mini-beta insertions which must be positioned quite close to the interaction points. The QCS is an iron free quadrupole designed for a maximum operating field gradient of 70 T/m with a current of 3405 A and a maximum field on the conductor is 6 Tesla. The coil has 4 layers with inner and outer diameters of 140 mm and 217.7 mm, respectively. Details on the magnet construction, cryogenic system and overall QCS system can be found elsewhere [1],[2],[3].

II. MAGNETIC FIELD MEASUREMENT

A. System layout

The measurements were performed with a rotating coil system. A measuring cylinder made of a glass-epoxy tube contains a single turn 2.00 m long coil of radius 47.0 mm for measuring the integral field in the axial direction, a 6-turn 0.20 m-long center coil and two end coils of radius 42.1 mm for measuring the central part of the magnet straight section and the both end field, respectively. The measuring cylinder is supported at both ends by non-magnetic frictionless aerostatic bearings, which ensure a rotation concentricity of better than 0.02 mm. The rotation frequency (~10 Hz) was monitored by counting pulses of an angular encoder (10^4 pulses/revolution). Induced voltage in each coil was measured by a commercially available FFT (HP3562A) and a digital volt meter (DVM), (Fluke 2700A). A series of measurements started with alignment of a magnet to the measuring system by use of a computer-controlled movable QCS-support. Completing the alignment, harmonics and field gradient were measured and finally the median plane of each magnet was determined. The whole measurements were performed automatically with a NEC PC-9801 personal computer.

B. Field Gradient

Field gradients were measured with both DVM and FFT. The DVM with fixed range measured the total power of

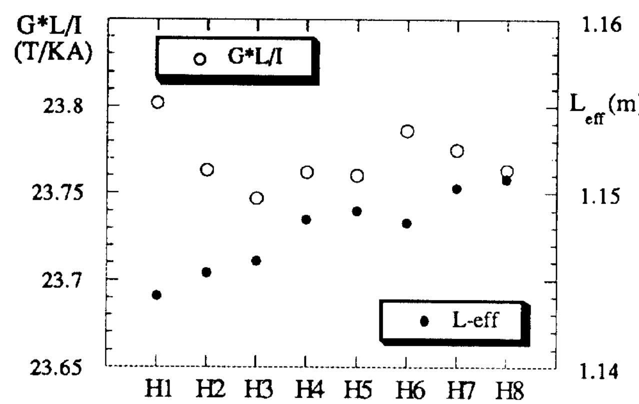

Fig. 1. ∫G.dl / I and effective length at 2540 A.

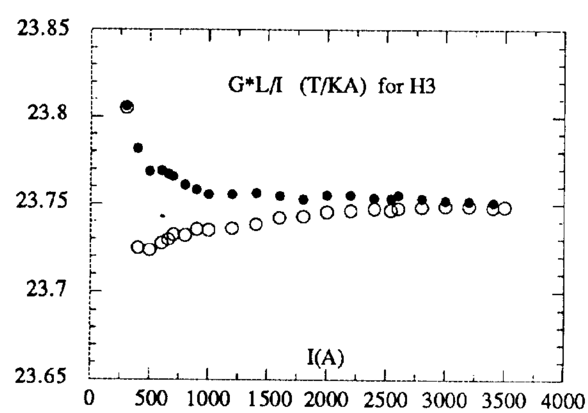

Fig. 2 ∫G.dl / I as a function of current. The white and black circles indicate the data obtained during ramp up and down of the current, respectively.

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induced voltage, which approximately represented the power of quadrupole term. On the other hand, the main purpose of FFT is to measure harmonics accurately so the suitable range is selected automatically at each current. The field gradients obtained by each method agreed with each other in a few 10^{-4}. The relative error of the field gradient is estimated less than 4 x 10^{-5}. The integrated field gradient ($\int G^*dl$) normalized to the excitation current in kA, referred as transfer function, and effective length of each magnet are shown in Fig. 1. The values are for measurements at 2540 A. These data show that the field gradient and effective length are controlled to about ± 0.001 and ± 0.003, respectively. The agreement between the calculated and measured values is fairly good.

Fig. 2 shows the transfer functions as a function of current, which show the effects of persistent currents in the superconductor at low currents. Although these values show a current dependence, the reproducibility is fairly good. No hysteresis effects except the persistent current were observed in following excitation cycles and the field gradients showed no change also in different excitation patterns with different maximum currents.

C. Multipole

The two-dimensional magnetic field can be expressed in a multipole expansion.

$$B_y+iB_x=B_{ref}\sum_{n=1}\left(\frac{r}{R}\right)^{n-1}(b_n+ia_n)e^{i(n-1)\theta}$$

Here R is the reference radius of the expansion and B_{ref} the amplitude of the main field component at the reference radius. The b_n and a_n are the normal and skew multipole coefficients. Each harmonics can be determined by Fast Fourier Transformation (FFT) of induced voltages. The allowed and unallowed harmonics were measured at various excitation levels. The integrated harmonic contents expressed as the ratio of the harmonic field strength to the quadrupole field at the radius 47 mm, which corresponds to 67 % of the coil inner radius, are given in Table 1. The values are for measurements at 2500 A. The reproducibility of the harmonic measurements was better than 2 x 10^{-5} at the radius of the measuring coil.

As can be seen in the table, major harmonics are sextupole and octupole, which are unallowed harmonics for quadrupoles. These might be coming from an asymmetry of assembled coils. In Fig. 3 we show the current dependence of the sextupole, octupole and dodecapole contents of a magnet H3. The current dependence of the multipoles except dodecapole is small. The normal dodecapole, b_6, displays the well known hysteresis effects caused by persistent currents at low excitation. Furthermore b_6 shows bigger current dependence than the sextupole and octupole, as can be seen clearly in the fine scale plot. This fact means that the magnet has almost no asymmetric deformation but a little symmetric deformation with excitation current.

Recently, time dependence of the multipole, generated by the persistent currents, has been observed in several superconducting magnets. Fig. 4 shows the 12-pole field decay at 350 A for an excitation ramp rate of 10 A/sec. The excitation cycle was from 0 to 3500 A, 3500 to 300 A , 300 to 350 A and then maintained for two hours. The decay of the 12-pole is less than 0.5 x 10^{-4} during an hour, which is the same order as the measurement accuracy.

D. Magnetic Axis and Orientation

Each quadrupole was aligned to the measurement system by minimizing dipole components of induced voltages in two end coils. The sensitivity of this magnetic center measurement is an order of 1 μm which is smaller by one order than displacement induced by temperature variation or other changes in environment. The axis shifts (Δx,Δy) with an excitation current were less than 50 μm for all the magnets.

Table 1. Harmonic content of the integrated magnetic field at 47 mm radius (B_n/B_2x10^{-4})

	H1	H2	H3	H4	H5	H6	H7	H8
3 N	1.1	0.7	1.3	-2.2	0.2	0.5	1.7	0.6
S	0.6	-5.4	-3.5	-2.1	-2.5	-10.0	-6.3	-6.0
4 N	-0.5	-0.7	0.1	-0.4	-0.3	-0.5	-1.0	-1.0
S	-5.9	-3.8	1.3	-0.5	-0.6	-0.8	0.9	-2.0
5 N	-0.1	-0.4	-0.3	-0.1	0.5	-0.1	-0.5	-0.3
S	0.8	1.1	-0.3	0.3	-0.1	-0.5	-0.2	0.2
6 N	-3.3	-2.7	-2.6	-3.4	-2.6	-2.8	-2.6	-2.0
S	-0.9	-0.6	0.4	0.1	0.1	0.1	-0.1	-0.2
7 N	0.3	-0.1	0.3	-0.2	0.2	-0.2	0.2	-0.2
S	-0.3	-0.4	0.0	-0.2	0.1	-0.3	-0.2	-0.1
8 N	-0.1	0.0	0.1	-0.1	-0.2	-0.0	-0.3	-0.3
S	-0.5	-0.1	0.1	0.0	-0.2	-0.3	0.2	-0.2
9 N	0.1	-0.1	-0.3	-0.2	-0.2	-0.0	0.1	-0.3
S	0.3	0.1	-0.1	0.1	0.2	-0.3	-0.1	-0.3
10N	-1.3	-1.3	-1.2	-1.4	-1.4	-1.2	-1.2	-1.4
S	-0.1	-0.1	-0.0	0.2	-0.2	0.2	0.1	0.1

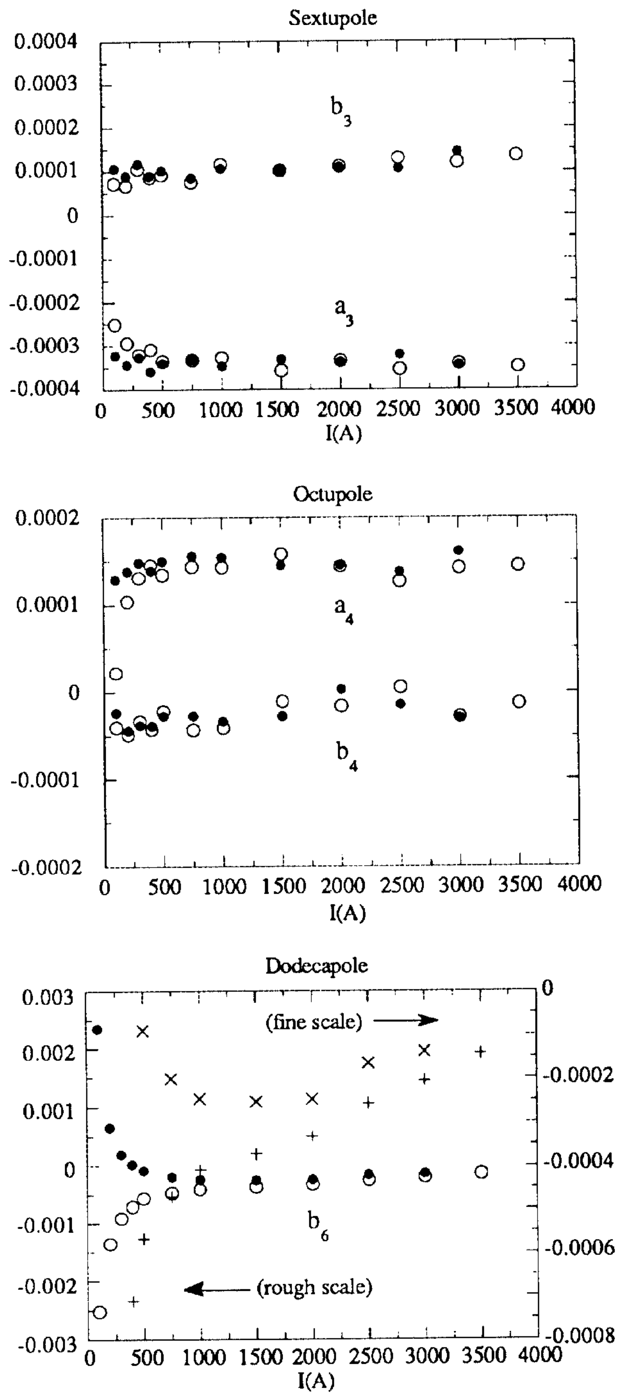

Fig. 3 Variation of the sextupole, octupole and dodecapole harmonics of H3 magnet. The white and black circles are the data during ramp up and down of the excitation current, respectively. Dodecapole components are also shown in fine scale. The plus and cross marks correspond to the data during ramp up and down, respectively.

The median plane of the quadrupole was obtained from a time interval between the encoder start pulse and the zero-crossing point of the induced voltage signal, which was measured by a digital storage oscilloscope (Tektronix 2430A).

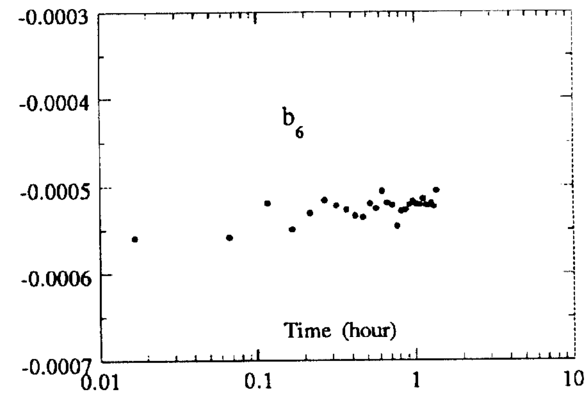

Fig. 4 Time evolution of the dodecapole at 350 A.

The resolution of this measurement is about 2 μsec in time, corresponding 0.13 mrad in angle. The total systematic error is estimated to be less than 0.2 mrad.

Besides the rotating coil measurements, the magnetic center of each quadrupole was determined by observing the scattering pattern of the plane-polarized light through the colloidal solution of Fe_3O_4 [4]. The accuracy is expected to be about 10 μm. This measurement showed that the magnetic axes of some magnets bent about 20 ~ 30 μm in both horizontal and vertical directions, which were also observed in the rotating coil measurements. The reference targets of the magnet, which are located around the surface of the cryostat, are then manually aligned with respect to the coordinates of the magnetic center and the median plane.

III. CONCLUSION

The results of the field measurements show that the relative errors of the integral field gradient can be kept within ± 0.001 for all the magnets and the higher multipole components are small enough for the tolerance required to the QCS.

IV. REFERENCES

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