International Journal of Scientific Engineering and Technology (ISSN : 2277-1581)
Volume No.2, Issue No.11, pp : 1152-1155 1 Nov. 2013

Indigenous Development of Close-Type Quadrupole Magnets for a 2.5 GeV Synchrotron Radiation Source

K.Sreeramulu, P.K.Kulshreshta, Vanshree Thakur, Kailash Ruwali, Lakshman Singh, Ashok Kumar, B. Srinivasan, Anil Kumar Mishra and R.S.Shinde
Raja Ramanna Centre for Advanced Technology, Indore -452013, India
Corresponding Email: sreeram@rrcat.gov.in

Abstract - ***Close type quadrupole magnets for Indus-2 require highly homogeneous magnetic field to focus electron beam. The field uniformity is governed by magnet geometry besides its steel quality. Magnets were developed with improved techniques and optimized for higher order multipole fields. This paper discusses development of magnets with magnetic measurement results.***

Keywords: close-type quadrupole, field gradient, multipole fields, harmonic bench.

I. Introduction

Indus-2 is a 2.5 GeV third generation synchrotron radiation (SR) source at RRCAT, Indore, India. The electron beam in Indus-2 is accelerated at 0.3 Hz from injection energy (550 MeV) to its operational energy (2.5 GeV) [i]. It employs various conventional magnets which include dipoles for bending, quadrupoles for focusing, sextupoles for chromaticity corrections and steering/corrector magnets for controlling close-orbit distortions of the circulating beam.

Total 72 quadrupole (QP) magnets are required in five groups; in which 40 are close types (Q_1, Q_2 & Q_5 groups) and 32 are open type (Q_3 & Q_4 groups) magnets. The design of open type QP is not fully symmetrical compared to close type and placed adjacent to dipole magnets for taking out the emerging SR beams. The magnet cross-section is same in all close type groups and differs only in their magnetic lengths (300, 550 & 400 mm for Q_1, Q_2 & Q_5 respectively) and magnets in each group need to be highly uniform as they are powered by single power supply.

Table 1 shows the important parameters of close type QP magnets. The magnet geometry (pole tip profile, pole width, coil geometry) was optimized using 2D POISSON code [ii]. The hyperbolic profile of tapered pole tip with end tangents is optimized to generate specified field gradient with minimized higher order multipole fields and to maintain field values below 1.4 Tesla anywhere in yoke in order to reduce saturation effect [iii, iv]. The magnet yoke is an assembly of four identical laminated quadrants with coils having specified turns. The high current density (6 A/mm^2) coils require cooling with low conductivity water and made from hollow copper conductor. The coil windings are subjected to thermal fatigue stresses during excitation and require bonding between them. Figure 1 shows the cross-sectional details of the magnet yoke quadrant and its magnetic flux distribution.

TABLE 1: Main parameters of the close-type QP magnets

S. No	Description	Unit	Values (Q_1, Q_2, Q_5)
1	Magnetic gradient (G)	T/m	16
2	Aperture diameter (D)	mm	85
3	Steel length (L)	mm	262.5, 512.5, 362.5
4	Total mass/magnet	kg	800, 1200, 1000
5	Number of turns/pole	No.	80
6	Ampere turns/pole	AT	13,000
7	Max. Power dissipation	kW	7, 9.7, 7.8
8	Good field region	mm	X=± 32, Z= ±17
9	Field errors $\Delta G/G_n$ on good field region.		$\pm 5 \times 10^{-4}$
10	Length variation ($\Delta L/L$)		$\pm 5 \times 10^{-4}$
11	Water flow/magnet	lpm	3.6, 5.4, 4.4
12	Temperature rise (ΔT)	° C	20

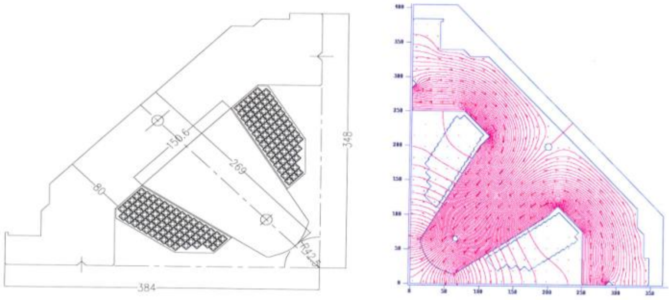

Figure1: 1/4th cross section of close-type quadrupole magnet and its magnetic field distribution.

The magnetic field distribution in conventional magnets is dominated by iron configuration, so the magnet fabrication and assembly errors introduce asymmetries [v] that cause undesirable multipole field harmonics. In order to meet the desired field uniformity, Indus-2 QP magnets need to be homogeneous, geometrically accurate and mechanically rigid in their construction.

Earlier laminated magnet yokes of Indus accelerators at RRCAT employed epoxy glued construction that has several limitations. The geometrical accuracy, rigidity, mechanical strength with aging is not good and also requires delicate handling. The magnet coils were insulated with self adhesive pre-impregnated tape and epoxy potted. The potted coils have voids and result to weak bonding between turns. Therefore, improved techniques for Indus-2 QP magnets are developed in order to achieve the (a) magnet geometrical accuracies, (b) desired magnetic field quality and (c) long term electrical & mechanical reliability. Initially, prototype magnets were developed and magnetically tested before their series production. All the 40 close type QP magnets are developed successfully and magnetically characterized. The details of indigenous development towards the completion of QP magnets are discussed in this paper.

II. Materials and Methodology

Materials: The materials chosen are : M36 CRNGO silicon steel (0.003 % carbon, 2.19 % silicon) of 0.50 mm thickness for magnet yokes, hollow copper square conductor of size 7×7x ∅5 mm for coil windings and AISI 316 grade stainless steel for magnet assembly parts.

Mechanical design: Design is done after estimating the forces, subsequent deformations, stresses on yoke & coils with ANSYS software [vi] by sequentially coupled magnetic and structural analysis using 2-D finite element model at 16 T/m field gradient. The analysis results (figures 2a, 2b) show that the vector sum of force between poles is 20282 N/m, across coils is 1712 N/m. The heat generated in magnet coils due to ohmic losses is estimated, cooling requirement is finalized with limits on coil temperature rise (ΔT) to $\leq$ 20°C, water flow velocity to $\leq$ 3 meters/sec, pressure drop (ΔP) to $\leq$ 6 bars and turbulent flow is considered for effective cooling.

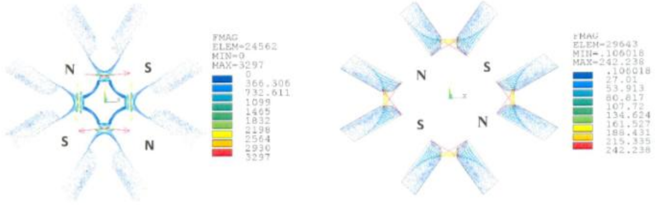

Figure 2a: Magnetic nodal forces on poles (left) and excitation coils in N/m.

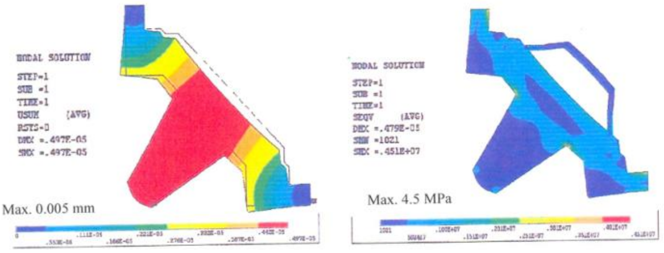

Figure 2b: 2-D Displacement (left) and stress (right) in a quadrant yoke.

Process development for magnet yokes: For joining yoke laminations, alternative techniques (bolting, welding and other combinations) were studied instead of gluing technique. Several welding trails were done (sequential intermittent, full welding using TIG, MIG and SMA welding) to achieve specified geometrical accuracy on sample quadrant yokes. Weld distortion on quadrants is controlled by good joint fit-up (gap ≤ 0.03 mm) and using low heat input while welding. Precision punching of laminations by standard press-tool, stacking & welding of quadrant yokes with high – precision rigid fixtures and tie-rods at the pole, bolting of quadrants′ assembly with uniform torque, tailor-made assembly and inspection gauges are some of the improved techniques. The stacked yoke quadrant laminations in fixture is joined outside by MIG welding with a rolled angle for reinforcement against weld deformations and clamped on pole-tip with a stud to limit its outward bulging as shown in figure 3. The overall geometrical accuracy (≤ 0.05 mm) is achieved without any further machining on welded quadrant.

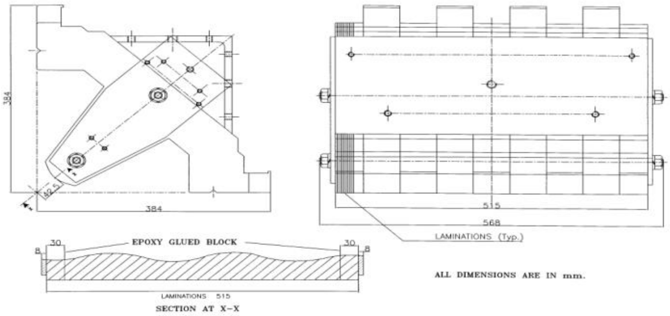

Figure 3: Details of sample welded laminated yoke quadrant.

Development of magnet coil insulation technique: The magnet coils in operation demand high fatigue strength in insulation to counteract alternating shear, compression stresses. Various coil insulation schemes viz. pre impregnated tape inter-turn insulation with vacuum epoxy-resin encapsulation, unvarnished glass fiber tape inter-turn insulation with vacuum pressure impregnation (VPI) or their combination were studied on prototype coils. The penetration of the epoxy resin and adhesion strength between coil turns is found better with glass fiber tape than pre-impregnated tape insulation. Figure 4 shows the shear and adhesive strengths of 50mm conductor joints wound with glass fiber and pre-impregnated tape inter-turn insulations. Therefore, plain glass fiber tape for coil inter-turn insulation, VPI with epoxy resin encapsulation for ground insulation of magnet coils is chosen.

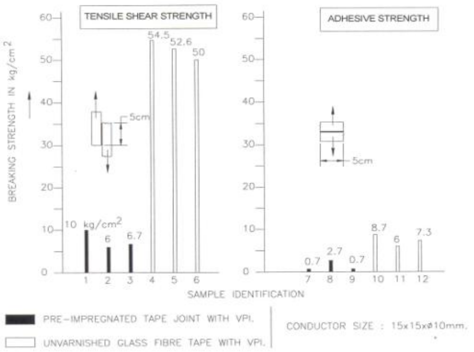

Figure 4: Strength of sample joints in shear and adhesion.

III. Development of magnets and Testing

Tested two prototype magnets with new techniques and the results found acceptable, but need the optimization of magnet pole end chamfers and reduction of yoke length w.r.t magnetic length. To minimize systematic higher order multipoles (12th, 20th poles …), optimization was done by varying the end chamfer lengths from 20 mm to 5 mm at a fix angle of 45° and tested. An end chamfer of 9 x 9 mm gave the acceptable level of systematic higher order multipoles. A systematic mixing of yoke laminations produced from various steel lots was done to average the magnetic properties in order to reduce magnet-to-magnet variations of series magnets. Figure 5 shows the series-produced Q_1 magnets. The geometrical accuracies on welded quadrants (refer table 2**)** are achieved within limits.

Figure 5: Series produced Q_1 group QP magnets.

Table 2: Mechanical inspection of welded quadrant yokes

Parameters	**Measured accuracy**
1. Pole profile accuracy with respect to references or matching surfaces	≤ 0.020 mm
2. Straightness of pole quadrants	≤ 0.030 mm
3. Flatness of the reference surfaces	≤ 0.050mm
4. Perpendicularity of reference surfaces	≤ 0.050mm
5. Packing factor	0.98

Four accepted quadrants with coils were used in each magnet assembly. Efforts were put on maintaining the specified accuracy on magnet pole symmetry and aperture diameter 'D' as shown in QP magnet cross-section (figure 6). The pole aperture (∅85 ± 0.05mm) was checked with GO & NO-GO gauges and the pole symmetry dimension (28.33± 0.04mm) was measured along the magnet length by precise plug gauges. The pole symmetry size variations of series Q_2 magnets are shown in figure 7. To achieve uniform electrical and mechanical parameters of magnet coils, a semi automatic coil-winding machine (figure 8) having a variable speed motorized winding head with layer pitch adjustment, coil formers, automatic insulation taping head, conductor straightening and tensioning unit, and de-realer unit has been developed. Series coils were wound on this machine and adopted the improved insulation techniques. Each completed coil was tested for dimensional inspection, water flow rate / leak test, electrical checks (coil resistance, inductance measurements, inter-turn and ground insulation checks at 1 kV DC). Figure 9 shows the series produced QP magnet coils.

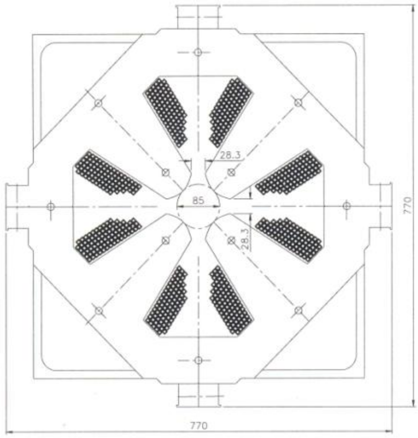

Figure 6: Cross-section of close-type QP magnet assembly.

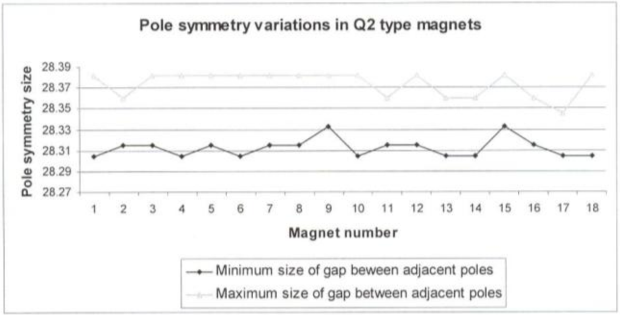

Figure7: Pole symmetry size variation of series Q_2 magnets.

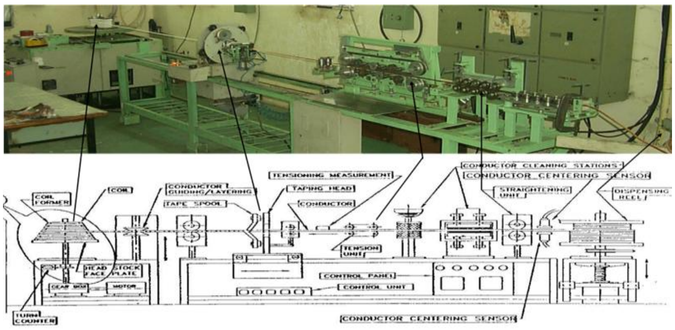

Figure 8: Details of semi automatic coil-winding machine.

Magnetic field measurements: Measurements were done on rotating coil based harmonic bench (Danfysik model 692). A coil rotates inside magnet aperture and induced voltage across coil is sampled and integrated over equal angular intervals for determination of integrated field, higher order multipole fields and magnetic axis. The relative measurement accuracy of bench is ±3x10^{-4} [vii] on determination of integrated main and higher order harmonics. Figure 10 shows the measurement of QP magnet on harmonic bench. Before taking measurements, each magnet was demagnetized completely by cycling 5 times that consists of ramping from zero to peak current in 30 seconds and stay for 10 seconds at peak and return to zero in 30 seconds.

Figure 9: Series produced close-type QP magnet coils.

Figure 11 shows the field gradient (G) plot of Q_2 magnet with excitation current. The current is 2.3 % higher than the required, mainly due to the finite magnet length and saturation in magnet yoke. Similarly, the observed non-linearity in Q_1 and Q_5 group magnets is 6.4% and 2.6% respectively [viii, ix, x]. This indicates the magnet gradient nonlinearity minimizes with increase in yoke length.

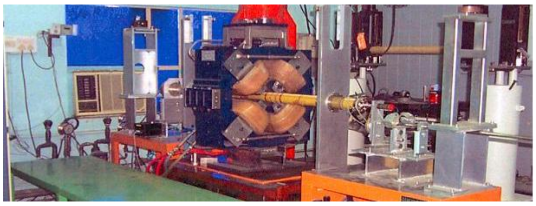

Figure 10: QP magnet Characterization on 'Harmonic bench'.

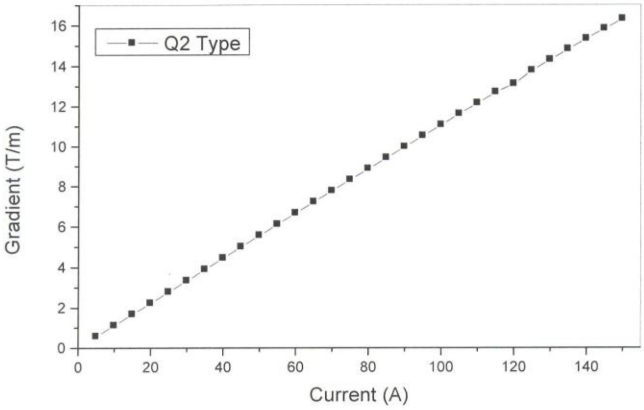

Figure 11: Measured field gradient of Q_2 magnet as a function of excitation current.

Figure 12 shows the higher order multipoles in Q_1, Q_2 & Q_5 group magnets. There is not much variation in their multipole levels and are not varying with the excitation current [viii, ix, x]. The magnetic centre shift with excitation in each group was within 0.03 mm and the reproducibility of measurements was within ± 2 x10^{-04}.

IV. Conclusions

Indigenous development of close-type QP magnets with improved technologies resulted in satisfying the high quality field requirements and measured higher order multipoles are comparable with the similar magnets of other SR machines [xi, xii]. The magnets are rigid enough for reproducibility on subsequent dismantling and re-assembly for placement of vacuum chambers of Indus-2 ring.

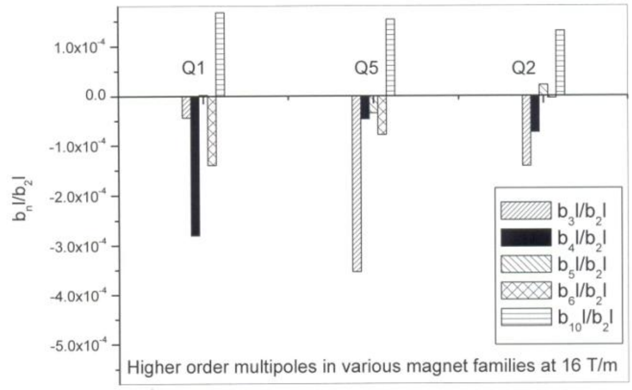

Figure 12: Measured higher order multipoles in Q_1, Q_2 & Q_5 magnets.

Acknowledgement

We are thankful to Mr. S.S.Prabhu, M.G.Karmarkar, Dr. S P Mhaskar for their valuable guidance. We acknowledge the contributions of Mr. S.K. Suhane, Mr. Jagadeesh during development of magnets. We acknowledge the support of magnet alignment group for fidusialization of these magnets. We also acknowledge the support of M/s. IGTR, Indore for making the series magnet yokes and M/s. D&S Electric works, Indore for series magnet coils as per quality requirements.

References

i. *Sahani V. C., "Commissioning of the Indus-2 storage ring" APAC 2007 RRCAT, Indore, Jan. 29 - 2 Feb. 2007, pp. 61-65.*

ii. *POISSON Group of Codes, Los Alamos National Laboratory, New Mexico, 86545.*

iii. *Vanshree Thakur, S.P.Mhaskar "Indus-2 Quadrupole magnet (Revised design)" CAT Internal document No: TN-G60 100010, dated August 22, 1995.*

iv. *Kailash Ruwali et.al, "Quadrupole magnets for Indus-2", IEEE Transactions on Applied super conductivity, volume 14, No.2, June 2004, page Nos. 406-408.*

v. *Halbach. K, "First order perturbation effects in iron-dominated two dimensional symmetrical multipoles", Nuclear Instruments and Methods 74 (1969), pp. 147-164.*

vi. *ANSYS Inc. ISO 9001:2000 group of codes.*

vii. *Danfysik Model 692, Danfysik A/S Denmark.*

viii. *Kailash Ruwali et al., "Results of magnetic measurements of* Q_1 *type quadrupole magnets for Indus-2", CAT Internal report CAT/2002-20.*

ix. *Kailash Ruwali et al., "Results of magnetic measurements of* Q_2 *type quadrupole magnets for Indus-2", CAT Internal report CAT/2003-7.*

x. *Kailash Ruwali et al., "Results of magnetic measurements of* Q_5 *type quadrupole magnets for Indus-2", CAT Internal report CAT/2003-8.*

xi. *Bessy Internal Report, BESSY TB 210/97.*

xii. *ESRF Internal Report, ESRF-SR/LAT-92-35.*