MECHANICAL STABILITY OF OPEN-TYPE QUADRUPOLE MAGNETS FOR A 2.5 GeV SRS (INDUS-2)*

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Abstract

The open type Quadrupole magnets (max. gradient: 16 T/m) for 2.5 GeV Indus-2 are made in C-configuration in which both of outer vertical sections of the steel are removed to take out the emerging synchrotron beam (SR) lines, in the region immediately adjacent to main dipole magnets of the ring. This induces engineering complexity relating to mechanical stability that critically controls the deviations in magnetic centre and field quality. To meet the stringent field quality requirements, the mechanical structure, which is precisely holding the magnet poles, is designed for minimum deflection at maximum gradient. The magnet is simulated with coupled magneto-structural analysis, using ANSYS. The measurement of deformation in prototype magnet assemblies with maximum excitation current is carried out and found within the acceptable limit. Measured magnetic centre shift with excitation is within 0.02mm. The magnetic measurement results show that the higher order multipoles are low and not changing with excitation current. The optimised open-type Quadrupole magnet design is implemented in series production of all 32 magnets for Indus-2. The mechanical assembly accuracies and stability of magnets with measurement results are discussed in this paper.

INTRODUCTION

The quadrupole magnets for Indus-2 are slowly ramped magnets (from 3.84 T/m to 16 T/m in 300 seconds). The main magnet design parameters are shown in Table 1. There are five families (Figure 1) in which Q1, Q2, Q5 families are of close type and Q3 (defocusing), Q4 (focusing) are of open type. The physical design of Indus-2 open-type quadrupole magnet is done using 2D POISSON group of magnet design codes [1]. Figure 2 shows 1/4th cross-section of the open type quadrupole

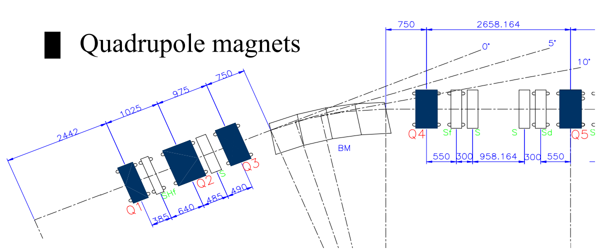

Figure 1: Half unit cell of Indus-2.

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magnet. The design of Q4 magnet is a non-conventional 'open-sided' design, with upper and lower pole pairs not connected magnetically to take-out the emerging SR beam lines, which are located in the main dipole magnets of the ring and also to maintain symmetry. The design of

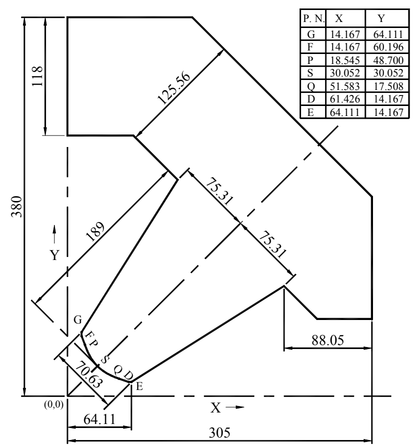

Figure.2: Magnet lamination (1/4th).

Q3 magnet is also kept same except supports at RHS (figures 4) to have symmetry in ring.

Table 1: Magnet Design Parameters.

Description	**Unit**	**Values**			
Pole aperture diameter	mm	85			
Steel & magnetic lengths	mm	362.50&400			
Ampere turns/pole	AT	13,000			
Good field region	mm	X=± 32, Z= ±17			
Good field region field errors	Δk/k	$\pm 1 \times 10^{-4}$			
Allowed centre shift	mm	$\delta X = \delta Y \leq 0.03$			
Allowed gradient errors over good field region					
$c_1 l/c_2 l$	$c_3 l/c_2 l$	$c_4 l/c_2 l$	$c_5 l/c_2 l$	$c_6 l/c_2 l$	$c_7 l/c_2 l$
2.35E-4	8.59E-4	1.33E-3	5.34 E-4	5.07 E-4	1.65 E-3

Where $c_n = \sqrt{(a_n^2 + b_n^2)}$ and a_n, b_n are skew and normal components for 2n-pole fields.

MECHANICAL DESIGN OF MAGNET

The magnet is an assembly of four laminated stacks in order to accommodate the required number of excitation coil turns in each pole. The design of mechanical assembly structure for holding four laminated poles is done after estimating the amount of magnetic forces from

2-D electromagnetic static analysis with magnetic vector potential (MVP) formulation using ANSYS1[2] and also consideration of gravity load of the magnet.

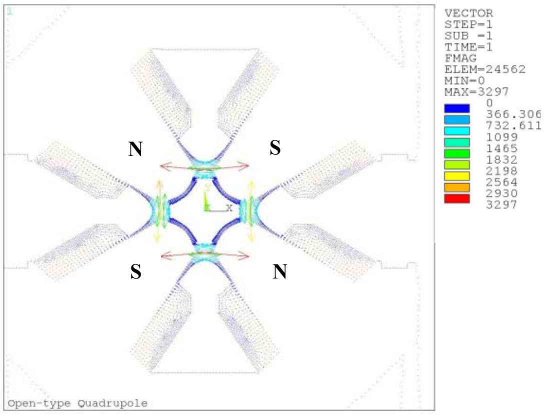

Figure 3: 2D-Magnetic nodal forces on poles in N/m.

The pulling force between top and bottom poles found from 2-D analysis is 39315 N/m. Considering the magnetic length of 0.4 m, the attractive force between the poles is 15726 N and the estimated weight of the magnet as 12,000 N. As the field uniformity of magnet is very much dependent on its geometry (pole geometry imperfection must be kept < 0.1mm from its ideal geometry), the sizing of various components for initial design of magnet assembly structure is done by considering the above mentioned forces and limiting the allowed deformation (0.01 – 0.02 mm) on critical magnet assembly components as per their functional importance. Therefore, the permissible stress level in various magnet components would be much below the proof stress of the material. The material for main assembly structural components is taken as nonmagnetic. The initial mechanical design of magnet assembly structure is further simulated with 3D magneto-structural analysis.

3-D magneto-structural analysis

The mechanical support structure of Q4 magnet is slightly weak (figure 5 - a C-clamp is asymmetrically placed on RH side due to space constraints) as compared to Q3 magnet. Therefore, Q4 magnet is taken for analysis and a 3D finite element model is made for sequentially coupled field static magneto-structural analysis using SOLID5 brick (eight nodded) elements. Scalar potential formulation is used for static magnetic analysis. SOURC36 elements are used to model racetrack coils. The vertical pulling force acting on the poles found from 3D- magnetic analysis is 15340 N. After the static magnetic analysis, structural analysis is carried out by directly imposing the magnetic forces from the static magnetic analysis. The gravity load is also applied at the centre of the FE modal during structural analysis. The $E_{lamination}$ (along magnet length) is taken as $E_{steel}/60$ [3] i.e. the properties on the magnet core is considered as orthotropic.

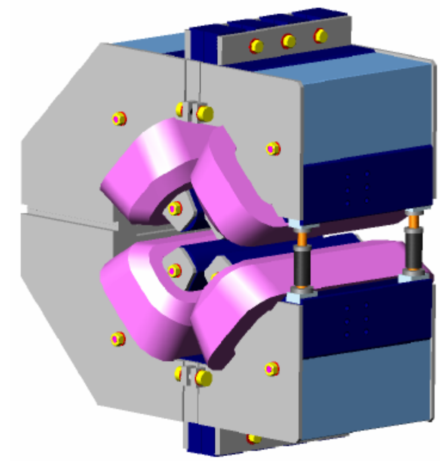

Figure 4: Open-type quadrupole (Q3) magnet.

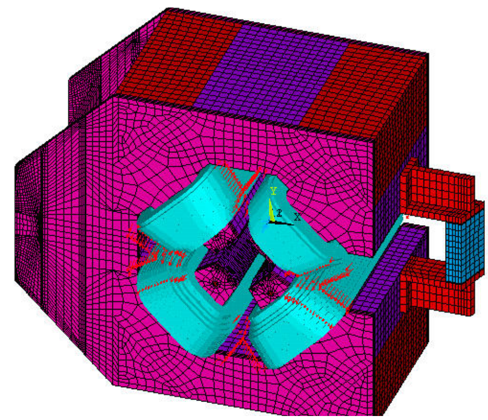

Figure 5: FE model of Q4 magnet (air region not shown).

The analysis shows that without any C-clamp or spacers at RH side of the magnet, under load, the top pole (in 1st quadrant of figure 5) displaced vertically downwards by ~ 0.1mm and horizontally by ~ 0.04 mm, which is not acceptable. The structural analysis with C-clamp shows (figure 6) the vertical displacement of 1st quadrant pole tip under load in the range of 0.020-0.025mm, which is quite acceptable. The horizontal displacement is found negligible (not shown).

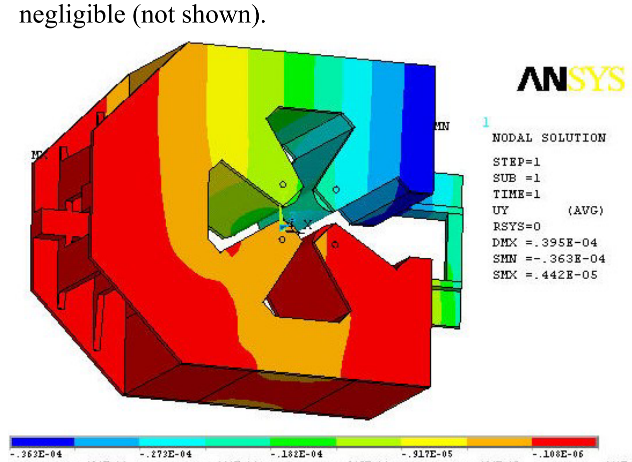

Figure 6: Vertical displacement plot of Q4 magnet.

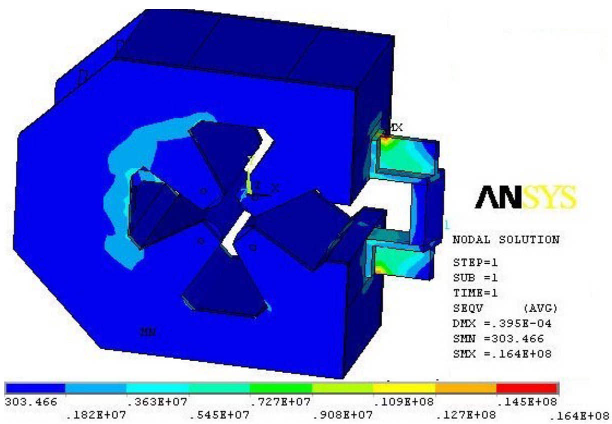

Figure 7: Stress plot of Q4 magnet.

Figure 7 shows the stress level in the structure which is found max. 16.4 MPa on C -clamp.

PROTOTYPES & CHARACTERISATION

Two prototype laminated cores (Q3 and Q4 types) are made by hybrid methods of laser cutting / wire-EDM and excitation coils from 7 x 7 x ϕ5 mm OFHC copper conductor [4]. The magnet assembly tolerances (on pole aperture diameter, angular spacing of poles) are maintained within in ± 0.05mm. The magnets are initially powered at rated excitation currents and measured the vertical displacement of core with precise mechanical dial gauges by placing them on outer surfaces of magnet core. The measured vertical displacement is found 0.04mm in the outer location (top edge), which is in good agreement with the 3D-ANSYS result (0.036 mm as shown in figure 6). The prototype magnets are tested using a rotating coil harmonic bench model 692 (Danfysik). The magnet is initially aligned with the magnetic centre at the operating gradient (16 T/m) and measured the changes in magnetic centre at injection to maximum operating currents (beam energies). Figure 8 shows the higher order harmonics present in Q3 and Q4 type magnets at 0.6 GeV and $c_n l/c_2 l$ does not change with various beam energies.

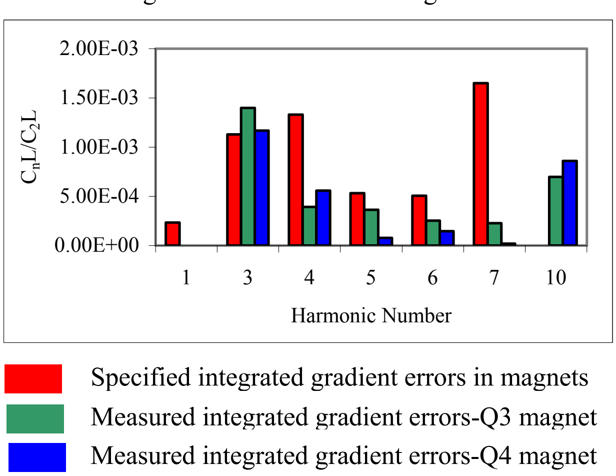

Figure 8: Higher order multipoles in Q3 and Q4 magnets.

Figure 9 and 10 show the magnetic centre shift of Q3 and Q4 types at various beam energies. Also, the opening and closing exercise on prototype magnets has been done few times for assembly of vacuum chambers and retested the magnets. We found that the magnetic centre is repeated within 0.02mm and also the multipole pattern does not change with opening and closing of magnets.

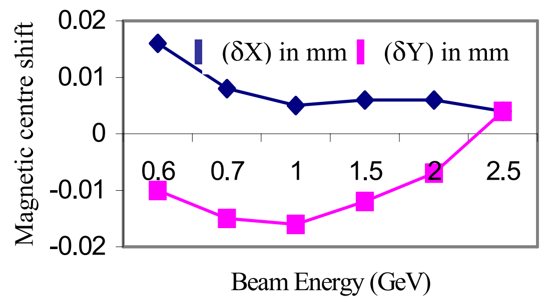

Figure 9: Magnetic centre shift of Q3 magnet.

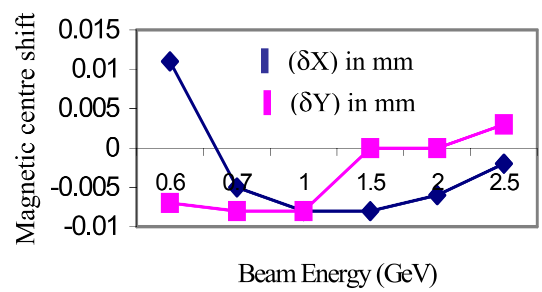

Figure 10: Magnetic centre shift of Q4 magnet.

Therefore, the same mechanical design is implemented in all series production of 32 units of magnets. We have magnetically characterized all the magnets after fabrication and are found acceptable.

CONCLUSIONS

The mechanical design of the assembly structure is rigid enough to satisfy the magnet design requirements. Repeatability of magnet is achieved during opening and closing of magnets for installation of vacuum chambers.

ACKNOWLEDGMENT

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