COIL CENTERING OF THE KOLKATA SUPERCONDUCTING CYCLOTRON MAGNET

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Abstract

The superconducting Nb-Ti coil is wound on a stainless steel bobbin of about 1.5 m diameter and 1.2 m height. The bobbin acts as the liquid helium chamber inside which the coil is dipped. It is suspended with nine support links – six vertical and three horizontal, inside the iron vacuum chamber. These support links can be adjusted in length externally so that the coil can be moved inside the vacuum chamber. The annular cryostat, including the coil, is placed inside the pill box type iron yoke around the upper and lower poles. The cryostat is placed inside the yoke with two locating pins. A jig was made to measure the deviations of the vacuum chamber inner wall with respect to the magnet pole center and the locating pins were adjusted to place it accurately. The coil was then cooled to liquid helium temperature and energized. During energisation process, the coil was centered using the lowest force criterion. After the full current was achieved, the final centering was checked with the magnet field measurement data analysis. This paper summarizes the methodologies and procedures followed in this work.

INTRODUCTION

Positioning of the cryostat and the coil coaxially on the magnet yoke was of major concern during commissioning. Since both the cryostat and coil can be moved independently on yoke, introducing asymmetry in the magnetic field, which is quantified mainly by the first harmonic component of Fourier series expansion of median plane magnetic field. The magnitude of first harmonic is approximately equals to the centering error multiplied by the radial gradient of the average field produced by the component that is off-centered [1].

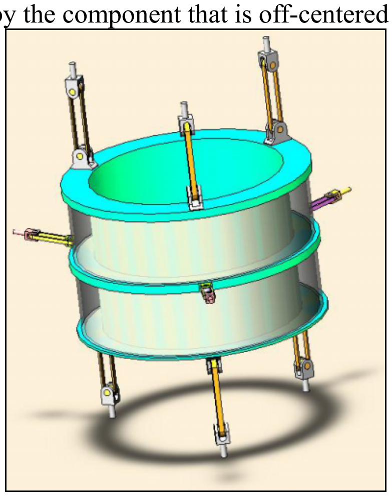

Figure 1: Bobbin hanging by nine support links.

The cryostat consists of three subassemblies – the liquid helium chamber (bobbin), liquid nitrogen cooled radiation shield and vacuum chamber (coil tank). The bobbin is an annular housing made of stainless steel (figure 1). The superconducting coil is wounded on its inner wall and the outer wall is welded to enclose the chamber. The bobbin is surrounded by another annular chamber, made of low carbon steel (AISI 1020), called coil tank. Coil-tank works as the vacuum enclosure for the bobbin. The copper (CDA 110) radiation shield is placed in between the bobbin and the coil-tank.

The magnetic field profile and its radial gradient due to coil and coil tank are shown in figure 2 and figure 3 respectively. The coil tank field gradient peaks near extraction radius, whereas that of coil is rather flat and peaks before extraction radius. At R=668 mm, $B_{coiltank}$ = 0.3352 T, $(dB/dr)_{coiltank}$ = 3.54 mT/mm, consequently even 1 mm shift in the coil tank may introduce 3.5 mT of first harmonic field. At R=560mm, (dB/dr)coil≈1.5mT/mm. So positioning the coil-tank and the coil coaxially with the pole-tips requires utmost accuracy.

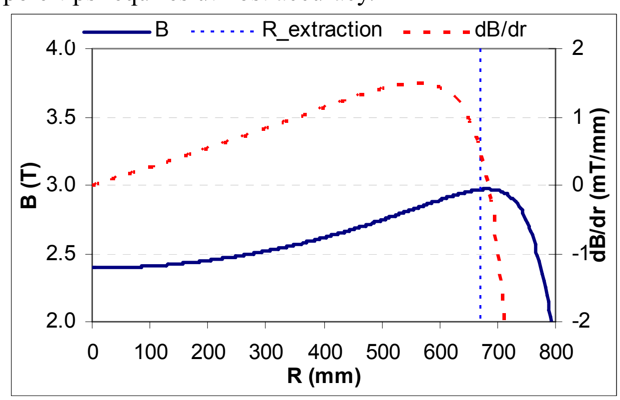

Figure 2: Coil field and its radial gradient.

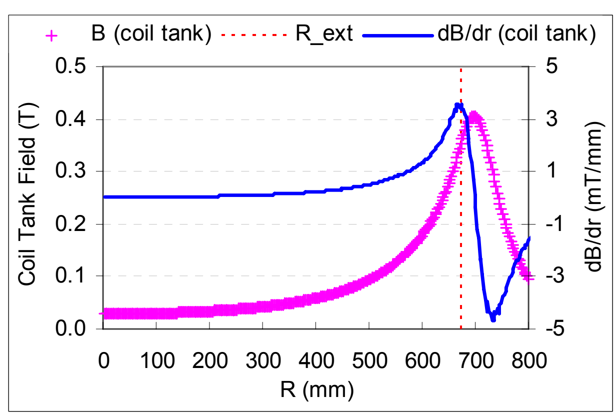

Figure 3: Coil-tank field and its radial gradient.

The bobbin, weighing about 7 ton, is hanging inside the coil tank, in an unstable equilibrium position, by nine support links made of glass epoxy material - three of these links pulling up, three pulling down and three pulling radially outward at the median plane, as shown in figure 1. Strain gauges, fitted at the room temperature end of the support links, are used to monitor the forces on the superconducting coil. As the temperature of the bobbin reduces the forces on the support links increases. The thermal stresses, developed in the links during the cooling process, were monitored continuously and those on the horizontal links were adjusted to keep within 3200 Kg [2]. The magnetic forces tending to pull the coil out of the position were observed as changes in link stresses with the increasing coil current. The pulling forces on radial support links were adjusted to move the coil within the coil-tank. Finally centering process was confirmed by magnetic field measurement. Following we describe the process of positioning the coil-tank and the coil so that they contribute minimum first harmonic field component.

CENTERING OF COIL-TANK

After installing the coil-tank on the pole-base, deviation of its inner diameter (ID) with respect to a central shaft held coaxially on the pole-tip central hole, was measured at different azimuthal angles. Figure 4 shows the deviation (y) of ID from its average value. The deviation y can be written in Fourier series,

$$y(\theta) = y_0 + \sum_{k=1}^{\infty} g_k \cos(k\theta) + \sum_{k=1}^{\infty} h_k \sin(k\theta)$$ Where, y_0=1.137 mm is the off-set due to choice of reference angle θ=0°. The first harmonic component $y_1 = \sqrt{g_1^2 + h_1^2}$ and $\phi_1 = \tan^{-1}(h_1 / g_1)$ gives the lateral shift and direction of shift. The second harmonic component $y_2 = \sqrt{g_2^2 + h_2^2}$ indicates the amount of distortion of the surface.

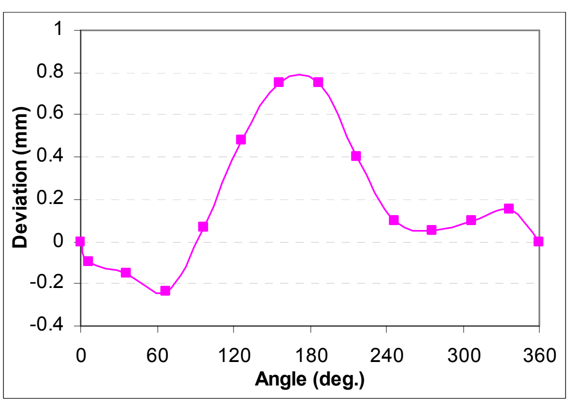

Figure 4: Deviation of the coil-tank ID at azimuths.

Initially we got y_1=1.42 mm and ϕ_1=36.5°, which would have caused ~5mT of first harmonic field. Then the coil tank was repositioned by off-set of dowelling pins and finally y_1 was brought down to 0.2mm, corresponding to 0.7 mT of first harmonic. The distortion y_2, appeared to be ~0.23 mm.

CENTERING OF COIL

During fabrication of the cryostat, proper placement of the coil inside coil tank was ensured with jigs and support links were held on the coil tank with nuts at the room temperature end. The radial position of the coil can be adjusted by turning the nuts on 3 radial links. 15° clockwise rotation of a nut along with 7.5° anti-clockwise rotation of other two gives about 0.1 mm movement along the first.

Ideally, if the coil can be positioned coaxially with a cylindrical symmetric yoke, then it would be in unstable equilibrium condition. A centering error of the coil produces a horizontal magnetic force, which must be balanced by the support links. Besides, due to expansion of the coil in response to the magnetic hoop stress, the forces on 3 radial support links would decrease with increasing current. The net magnetic forces are measured by the changes in strain gauge reading with increasing current.

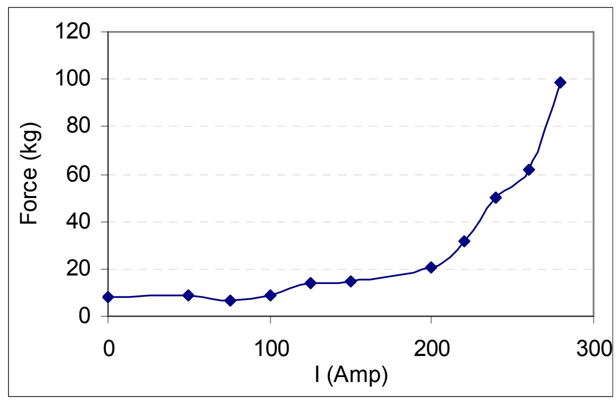

Figure 5: Resultant force on the coil.

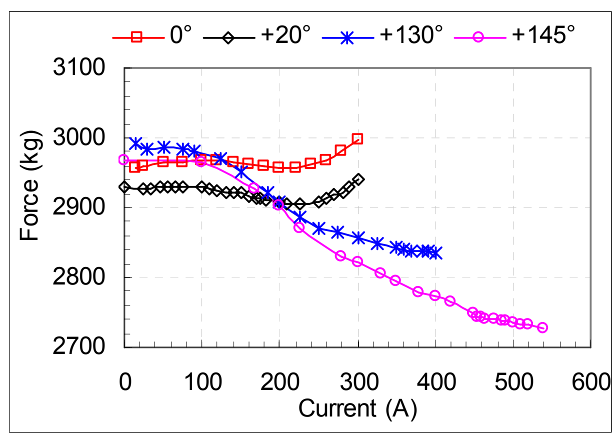

Figure 6: Force on E9 at different stages of adjustment.

The link forces were measured on line and the forces on the three radial support links (E7, E8 and E9) were plotted with current in the coils (I_α=I_β). The ideal profile of forces would be smoothly decreasing equally in all three links. The initial values, of course, would be different due to a result of various imperfections in the overall construction, small radial forces transmitted by the axial links, some radial forces transmitted by various lead connections and refrigeration connections etc. Practically, as the coil current increases a huge increase occurs in the spring constant associated with the decentering force, which may cause the stresses exceed the safety limit on very small adjustment of coil position, eventually breaking the bolt. [2]. Figure 5 shows the resultant force on the coil following a power-law-increase with current.

Figure 6 shows several iterations of rotation of the nut on link 9 and its effect on the trend of the force with increasing current. At the first iteration (labelled as 0º rotation) the force was rising rapidly at higher currents. After ramping down to zero current, a rotation of +20º (clockwise) was given to nut on link E9 along with rotation of -10º (anti-clockwise) to nuts on links E7 and E8, which hardly changed the trend. In third iteration, a rotation of +130º to E9, changed the trend and current could be ramped up to a higher value.

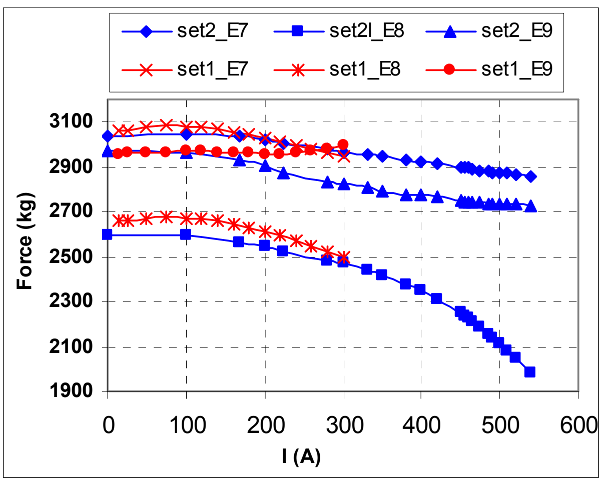

Figure 7: Forces on radial support links at two stages of adjustment of coil position.

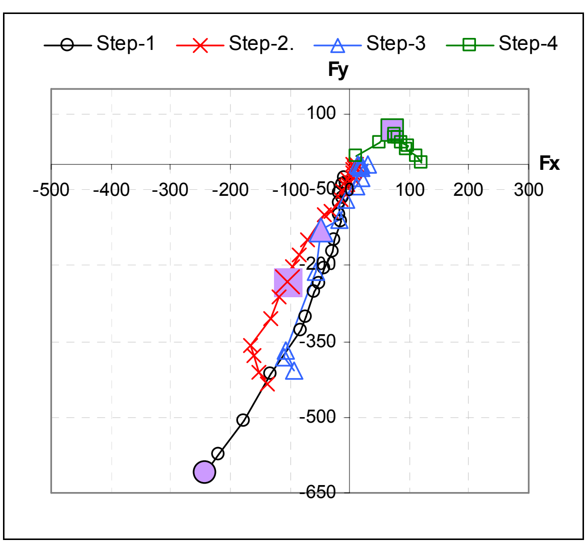

Figure 8: On line plot of magnitude of resultant force on coil at different stages of coil position adjustment. Link E7 is along 0º, E8 along 120º and E9 along 240º.

In figure 7 forces on all 3 radial support links are shown at two stages of coil position adjustment. Set-1 shows falling trend of force on E7 & E8, but rising trend of force on E9, the coil current reaching up to 300A maximum. After adjustment, Set-2 shows a changed trend, all three falling, up to a higher value of coil-current.

To have a quantitative idea of the net decentering force on the coil and its direction, resultant of three link forces were plotted on line (figure 8). The origin of plot is the position where the magnetic force is balanced in all direction. The individual points of a particular step are forces at different currents as the coil ramps up. The shaded points correspond to 300 A current. The first three steps show the direction of force along E9. When adjusted the position, force at 300A reduces (the shaded point moves close to origin). Step 4 is the best achieved position of coil, of course, a little over adjustment is done, so the force is now in the opposite direction.

After getting a minimum force position of the coil, magnetic field measurement was done and the first harmonic component was minimized by adjustment of coil position, keeping the forces under control (figure 9). It was seen, as expected from the coil field gradient, the reduction of first harmonic was at radius 400mm to 600 mm. The large first harmonic at centre, middle and extraction were due to iron assembly errors, which were subsequently reduced by adding iron-shims [3].

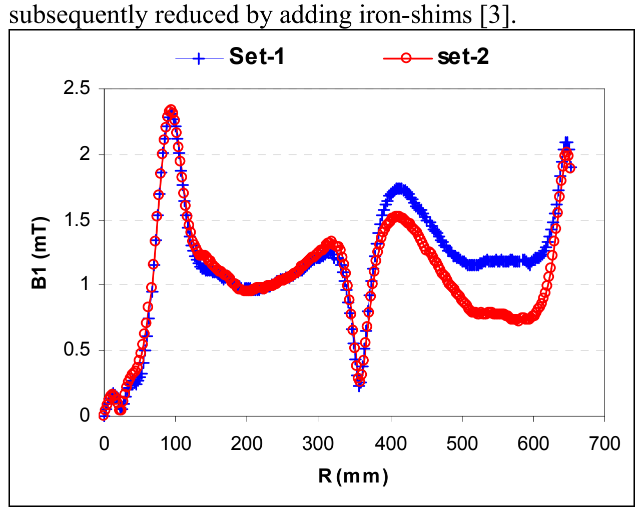

Figure 9: First harmonic component at two stages of coil position adjustment.

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