EFFECT OF MAGNETIC FIELD COUPLING ON INDUS-2 QUADRUPOLE MAGNETS

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Abstract

The distances between the magnets in the Indus-2, are small and as a result, the magnetic field of one magnet may affect the fields of the adjacent magnets. Therefore, it is important to find out the effect of mutual coupling between magnets in the actual condition in the ring and the ways to overcome this problem. In this paper, we will discuss how the field quality of quadrupole magnets (QP) in the ring is affected when accompanied by various corrector dipole magnets (CDP)(vertical and horizontal) and sextupole magnets (SP). Variations of integrated quadrupole field strength in presence of CDPs are measured at various field excitations and also by varying the distance between the magnets using a rotating coil. Experimental results are compared with the results obtained from 3D simulations. Possibilities of studying the interference effect by scanning the field by a Hall probe, is explored. Dependence of field interference on the distance between magnets, pole gap and the steel length are studied. Effects of the adjacent magnets on the higher order multipole of QP are also examined.

INTRODUCTION

Double Bend Achromat Indus-2 lattice consists of eight super periods each having two dipole bending magnets, four focusing and five defocusing QPs and four SPs and seven CDPs (used for closed orbit correction). There are total 72 QPs in the ring. These are divided in five different categories named as Q1, Q2, Q3, Q4 and Q5. All of these magnets have the same maximum gradient of 16 T/m. and same bore diameter of 85 mm and same cross section. Steel lengths of the Q1, Q2, Q3, Q4 and Q5 magnets are 262.5, 512.5, 362.5, 362.5 and 362.5 mm, respectively. There are two quadrupole triplets (Q1, Q2 and Q3) for the adjustment of beam sizes in the long straight section (LSS) and four CDPs are placed in between them (Figure 1). The achromat section consists of a triplet QP having two Q4s and one Q5 and four SPs and three CDPs. The distance (steel edge to steel edge) between a QP and a CDP vary from 176.25 mm to 383.75 mm in the LSS. In the achromat section, SP is placed as close as 195.75 mm from QP. It is clear that the fringe field of a QP is extended beyond the location of the adjacent magnets.

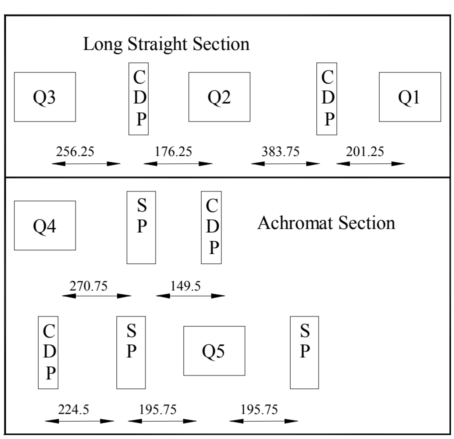

Figure 1: Block diagram of the portion of the unit cell where field interference between various magnets can occur. Distances are in mm.

EXPERIMENTAL RESULTS

Integrated QP field strength is measured at a reference radius of 32mm using a rotating coil system [1]. Around 150 A current in QP produces required maximum field gradient of 16 T/m. To find the effect of the adjacent CDP

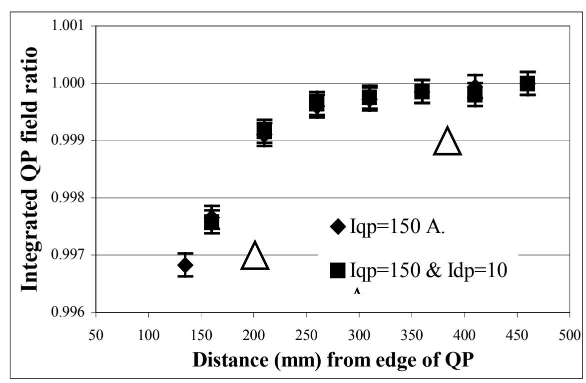

Figure 2: Variation of the ratio of the measured integrated quadrupole gradient, to the nominal gradient, with distance between the quadrupole (Q1) and the CDP. In one case current in QP is 150 A. and no current in CDP. Other case QP and CDP are having 150 A and 10 A currents, respectively. Open triangles indicate the minimum and the maximum distances in the ring.

on a QP, the current in Q1 is fixed at 150A and the distances between them are varied from 135 mm to 460 mm. In the first case there is no current in the CDP. Then the same experiment is repeated while the current in the CDP is set to 10 A to check whether the field interference depends on the field excitation of the CDP. The integrated quadrupole field strength (B_2.L) of Q1 (steel length is

262.5 mm) reduces by 0.18% and 0.0085% from its nominal value when the CDP is at a distance of 176 and 384 mm, respectively. Reduction of the field strength varies inversely with the third power of the distance between them (1/dist.^{3}). No additional change is observed when the CDP is powered by 10A within the experimental accuracy (Fig.2). Therefore, the reduction of B_2.L is independent of the field excitation of the CDP. This finding is in agreement with the simulation results obtained by others [2].

To check the variation of the field with the excitation current of the QP, position of the CDP is fixed at two different distances and the currents in QP are varied. Figure 3 shows that the reduction of B_2.L remains almost constant within the experimental accuracy, with the excitation of QP at two different distances.

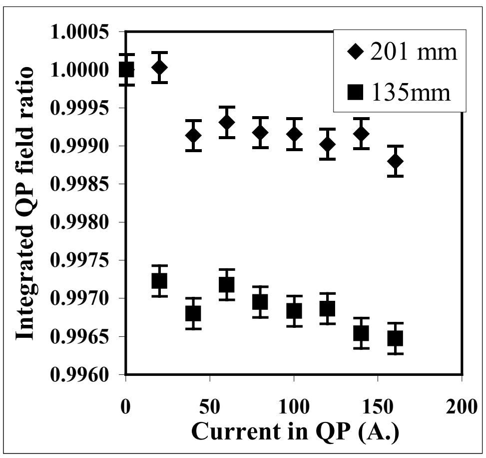

Figure 3: Variation of the ratio of the measured integrated quadrupole gradient to the nominal gradient with the quadrupole (Q1) current in presence of CDP at two different distances 201 and 135mm.

Therefore, the variation of the field also does not depend much on the excitation of the QP [3]. No significant

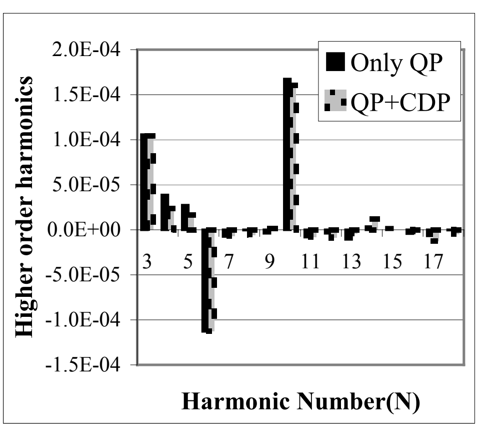

Figure 4: Higher order harmonics normalized with respect to the main quadrupole ($NB_nR^{n-2}/2B_2$) component. In one case CDP is placed at 201 mm away from the edge of the QP and the other with out CDP, i.e., QP stands alone.

effect on the higher order harmonics of QP from the magnetic field coupling is observed [3]. All the higher order harmonics are of the order of 10^{-4} or less (Figure 4).

Experiment is done by fixing the QP current at different values (30, 60, 100, 140 and 160 A) and then by varying the current in a SP. No significant change in B_2.L is observed in presence of SP at a distance of 265 mm and also with the excitation of SP. All the values are with in the experimental accuracy (± 3x 10^{-4}).

SIMULATION RESULTS

Simulation studies have been done using OPERA-3D[4] to understand the experimental results. Simulations have been done for a QP (Q1) alone and by placing a CDP at various distances 135, 201, 260 and 410 mm, respectively from the edge of the QP and then the difference of field from the nominal value was taken. Current in QP was set to 150 A, which produced integrated quadrupole field strength of 4.818 T.

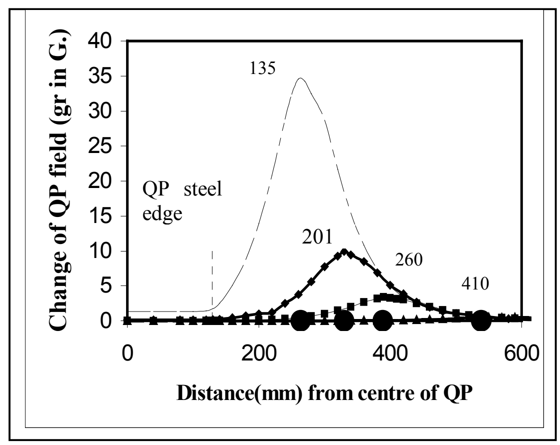

Figure 5: Plot of the difference of the simulated QP field component b_2 (gr) (between the case when QP stands alone and accompanied by CDP) against the distance from the center of QP. Dots on the X-axis indicate the position of the starting point of the CDP.

Magnetic field can be expressed as $B_y + iB_x = -\sum n(iA_n + B_n)(x+iy)^{n-1}$ where, A_n and B_n are the skew and normal components for 2n pole fields. Measuring the field on a circle of radius 0.032m and by doing FFT the QP field strength b_2 ($2B_2r$= gr) was found out. The differences of b_2, in Figure 5, starts' arising at the edge of the QP and become maximum near the point where the steel of the CDP starts (dots on the X-axis) and then it falls down symmetrically about the peak at all distances. Area under the curve, in each case, is the measure of the interference between the magnets. By knowing the total integrated quadrupole field strength in absence of nearby magnets and the difference in presence of CDP in each case, percentage changes are calculated which are in good agreement with the experimental results.

Figure 5 depicts an interesting point. When the distance of CDP is more than twice of the bore diameter (2d) of QP (for example at 201 mm) b_2 remains mostly constant throughout the steel length of the QP ($\Delta b_2=0$). It starts changing near the edge of the QP steel. However, if the distance is lower than 2d (at 135 mm) b_2 at the center also reduces. Δb_2 remains constant (not zero) throughout the length of QP and starts increasing near the edge, peaks near the starting point of CDP and then fall down as observed for larger distance. Therefore, if the adjacent magnet is placed closer to the QP it will affect the field even at the center of QP and the coupling will be stronger. In that case the change will also depend on the length of the QP. However, in Indus-2 ring magnet separations are more than twice of the bore diameter of QP. Therefore, in experimental data reduction of QP field strength is found independent of QP steel length (total change, not the percentage change). Experimental results on Q3 and Q1 showed same reduction of strength. So, the findings of Q1 have been used to calculate field reduction of other QPs.

A rotating coil measurement does not provide detailed of the field reduction because it provides an integrated value. Therefore, there is a need to do point by point measurement. It is possible to find the value of b_2 at different distances in case of simulation, which helps in better understanding the experimental results. b_2 can be obtained by taking Fourier transformation of the field measured on a circle at any distance. This is also found that the reduction QP field strength does not depend on the width of the CDP. This is because Δb_2 shows peak near the point where the steel of the CDP starts but not much variation through out the length of the CDP.

We tried to observe the variation of the vertical component of the field (B_y) at 32 mm distance from the center of QP along the length of the magnet from the simulation results. Figure 6 shows the difference of B_y

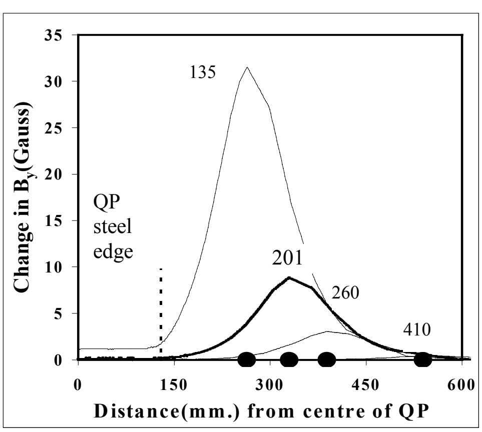

Figure 6: This is a similar plot as in figure 5. Here instead of Δb_2 the difference of the vertical component of the field (ΔB_y) at 32 mm, from the center of the QP, along the length of the magnet is plotted. This variation is very similar to that of Δb_2.

when a QP stands alone and accompanied by a CDP at various distances (135, 201, 260 and 410 mm from the edge of the QP). It also depicts the similar picture of the variation of Δb_2. This indicates that it is possible to understand qualitatively the coupling behaviour between magnets by scanning the magnetic field along the length using Hall probe. The percentage change of effective length of QP when the CDP placed at distances 135, 201, 260 and 410 mm from the edge of the QP are 0.27, 0.085, 0.032 and 0.004, respectively. Though the values of these changes are slightly less than that of b_2, it shows similar trend. Therefore, in some cases if the rotating coil measurement is not possible a simple Hall probe scanning can provide useful information about the magnetic field coupling.

CONCLUSION

In presence of the accompanying magnet in the ring the quadrupole field strength of Q1, Q2 and Q3 type of QPs are reduced by 0.098, 0.096 and 0.024 %, respectively. Proper excitation curve should be used for various QPs depending its position in the ring to overcome the field interference effect. The interference of the fields between a QP and a CDP does not depend on steel length of the QP and the excitations of both the magnets. Reduction of the field strength varies inversely with the third power of the distance between them ($1/\text{dist.}^3$). The presence of the steel block of the CDP distorts the fringe field of the QP and causes the reduction of quadrupole field strength. No significant effect on the higher order harmonics of QP from the magnetic field coupling is observed.

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