ANALYSIS OF EDDY CURRENT IN THE INDUS-2 DIPOLE VACUUM CHAMBER

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Abstract

Vacuum chambers, made of an aluminium alloy, have been used in Indus-2. An unwanted effect of the low electrical resistance of these chambers is that when the current of the magnets is varied to change the magnetic field, eddy current flows through the dipole vacuum chambers, which are placed within the pole gap of the dipole magnets. No detectable eddy current flows in the chamber in case of normal operating condition. In a (unusual) situation, when the dipole magnet power supply trips, the current of the magnets falls rapidly and the chambers are consequently subjected to a huge force. In Indus-2, the movement of the vacuum chambers caused by the force produced due to tripping of the power supply damaged some metallic bellows connecting the chambers with the adjacent straight sections. In this paper, we present the studies carried out to estimate the nature and magnitude of the eddy current and the amplitude of the resulting force. Here, we also propose some concepts to cancel the eddy current effects.

INTRODUCTION

2.5 GeV Indus-2 (SRS) lattice, a Double Bend Achromat, consists of eight super periods each having two dipole bending magnets, four focusing and five defocusing quadrupole and four sextupole and seven character magnets used for close orbit correction[1]. The maximum field and the magnetic arc length of the dipole are 1.5 Tesla and 2179.48 mm, respectively. The vacuum chambers of the Indus-2, made of aluminium alloy, are placed inside the 50 mm pole gap of the 'C' type dipole magnets. A large fraction of the total cross-section of the vacuum chamber (shown in Fig.1) lies outside the pole gap of the magnet to facilitate the paths for synchrotron radiation. During the commissioning phase it was noticed that some of the metallic bellows connecting the dipole chambers with the adjacent straight sections got damaged due to the movement of the dipole chambers. It was also noticed that the degradation of the vacuum coincide with the tripping of the dipole magnet power supply. Causes of such damage are investigated in details and reported in this article along with some solutions to prevent it.

RESULTS AND DISCUSSIONS

Consider a rectangular plate which is subjected to a transient field of magnetic induction $B_y(t)$ represented as

$$B_y(t) = B_0 e^{-\frac{t}{\tau}} \qquad (1)$$

where B_0 is the peak magnetic field and τ is the decay time constant. Our aim is to calculate the total current circulating in the plate using an equivalent electrical circuit of resistance R and inductance L. This can be describe as

$$L\frac{\partial I}{\partial t} + IR = E \qquad (2)$$

where E is the electromotive force induced by the flux variation. The Maxwell's equation (neglecting the field produce by eddy current) can be written as

$$\oiint E.\partial l = -\frac{\partial \Phi}{\partial t} \qquad (3)$$

where $E=\rho J$ when $I=I_{max}$ and j is current density. The value of j and hence, I can be found out by solving the Eqs. 1, 2, and 3 with proper boundary conditions. Standard solutions for regular geometry is available in the literature. However, in this case the geometry of the vacuum chamber is so complicated (Fig.1) that getting exact analytical solution is difficult. Therefore, we have used finite element code, ANSYS to find the solution [2].

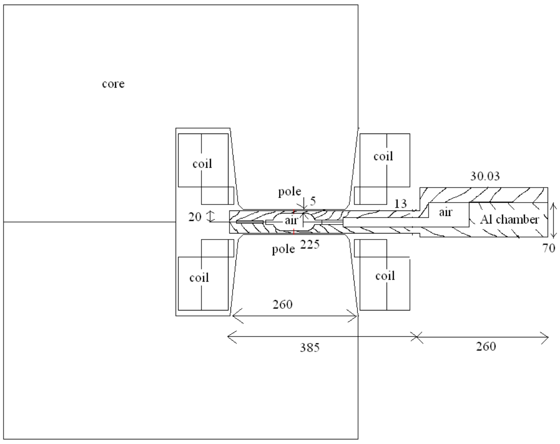

Figure 1: The geometry of the dipole magnet core and the vacuum chamber and its thickness.

Indus-2 consists of 17 dipole magnets which are connected to a power supply and the total inductance and resistance of the magnet assembly is 1.4 Henry and 1.0 ohm, respectively. This will dictate the rate of current reduction in case of power supply tripping (τ=1.4). In absence of eddy current field should follow the current decay. Simulated results show that the decay of field follow the exponential current decay in absence of any metallic vacuum chamber. However, the decay has slowed down in presence of eddy current in the chamber as expected. Figure 2 shows the simulation results of the decay of field for 2d as well as 3D cases.

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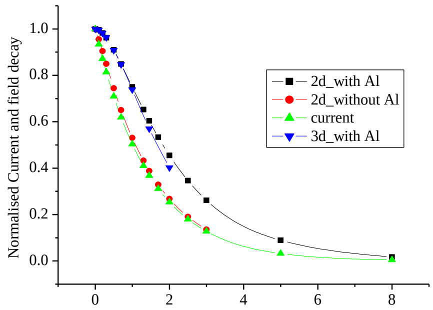

Figure 2: Decay of current and field with and without vacuum chamber obtained from 2d and 3D simulations. The presence of the vacuum chamber slow down the field decay as expected.

The existence of eddy current is established. Now, the contour of the eddy current that decide the net force on the chamber will be evaluated. If the eddy current flowing symmetrically with respect to the middle of the magnet pole then only the net force on the chamber will be zero.

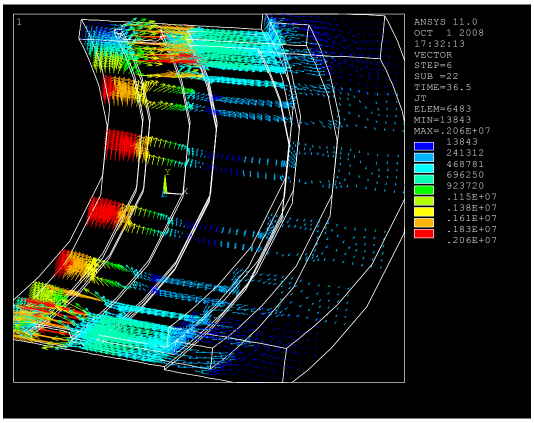

Figure 3: Contour of the eddy current loop in the vacuum chamber (current density).

But, 3d simulation indicates that the return loop of the eddy current is on the extreme right of the chamber where magnetic field is very low. This causes unbalanced force acting on the chamber [3]. Figure 3 shows the eddy current loop and figure 4 shows the field distribution in the vacuum chamber along with two schematic eddy current loops. Force would have been balanced if the loop follows the path A and C as the direction of eddy current is opposite in these two portions and field strength is also nearly equal. The resistance of the path A and B is lower than that of the path A and C because of the special geometry of the chamber. Hence, the eddy current prefers to flow the path A and B instead of A and C. At point A, field is very high and hence the force. This force is directed towards negative X direction. The lower field and hence the weak force at B is not able to counter balance the force at A.

The estimation of the average force, in a simplified manner, can be done as follows. In our case, the dipole magnet produces 1.5 T field for 760 A. current. So, at t=0, I=760 A. and B=1.5 T.

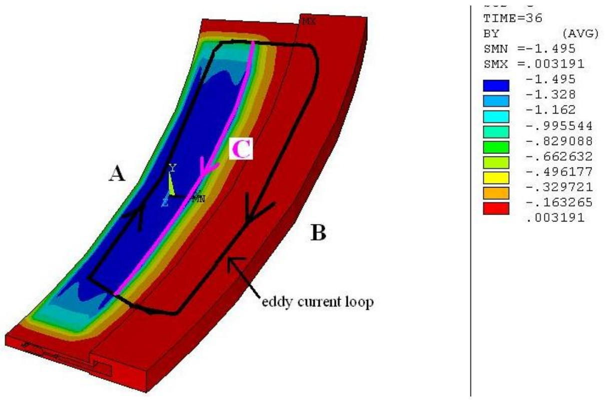

Figure 4: Magnetic field distribution on the vacuum chamber. The peak field on the chamber, near the pole, is 1.49 T and the field outside the pole is around 0.0031T. Because of this the amplitude of force due to eddy current at point B is very low to that of at point A.

We have observed from 3d simulation results that the force become maximum around t=0.5 Sec. So, the field at that instant can be calculated (neglecting the slow down for eddy current)

$$B = B_0 e^{-\frac{t}{\tau}} = 1.5 \times e^{-\frac{0.5}{1.4}} = 1.04 T and \frac{\partial B}{\partial t} = \frac{1}{\tau} B_0 e^{-\frac{t}{\tau}} = 1.04/1.4 = 0.74$$

Therefore, the potential difference is $\varepsilon = \frac{\partial (B.A)}{\partial t} = A \frac{\partial (B)}{\partial t} = 2.1 \times 0.325 \times 0.74 = 0.505 V \cdot$ If the average resistance of the chamber around the loop is 60μΩ them the maximum average eddy current is 8416 A. Force exerted on the left side of the chamber is F=I.dLxB=8416x2.1x1.04=18.38kNewton and the direction will be along negative X axis. This is close to the simulation results.

We proposed two concepts to cancel the eddy current effect based on simulation results. One, create another loop using the back leg of the magnet and feed the eddy current in opposite direction. However, the magnitude of the eddy current to match with the chamber the loop resistance should be of the order of the chamber which is micro-ohm. The second one is to have a power supply (capacitor bank) capable of delivering time dependent current, similar to the growth of eddy current, of peak amplitude of approximately 10 kA. Implementation of both the concepts is not possible in the present situation. Therefore, mechanical reinforcement is done to arrest the movement of the chambers in case of power supply fault. This is done by our vacuum group and also tested experimentally.

REFERENCES

[1] G. Sinha, A. Kumar, A.K. Mishra and Gurnam Singh, APAC07, Indore, India, Jan 2007, P 378-380.

[2] Multiphysics simulation software, ANSYS, Inc.

[3] C. Rathjen, EPAC, Paris, France, 2002, p. 2580.