Mechanical Analysis of Beam Tube Assemblies for SSC Dipoles During a Quench

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Abstract

An alternative beam tube/bore tube arrangement for the Superconducting Super Collider (SSC) consists of an elliptical beam tube mounted inside a circular bore tube to intercept the synchrotron radiation from the beam. The beam tube is operated at 80 K and has a slot with a width of 2 mm along the length in order that it may be pumped by the 4 K surface of the bore tube. This paper presents the results of stress analysis of the beam tube under the action of the Lorentz forces during a quench. A stainless steel elliptical support, which supports the beam tube during the quench, is described.

I. INTRODUCTION

The beam tube of the collider ring must be copper-lined in order to present a low impedance to the image currents produced by the circulating beam. During a magnet quench, eddy currents induced in the beam tube, interact with the rapidly decaying magnetic field to produce a Lorentz force on the tube. Currently three possible designs for beam tube and bore tube assembly are being considered. In all the beam tube designs, a force due to the external helium pressure, which may be as large as 2 MPa during the quench, is exerted on the beam tube in addition to the Lorentz forces. It is essential that the beam tube assembly not undergo plastic deformation by these forces. This paper presents electromagnetic analysis which calculates the Lorentz forces during the quench and their azimuthal distribution around the beam tube. The values of these forces are then used in an FEM structural analysis to determine the stresses and deformations of the beam tube assembly.

II. PHYSICAL DESCRIPTION OF THE BEAM TUBE ASSEMBLIES

A. Copper-Lined Bore Tube

In the first case of assemblies considered, the aperture of the magnet contains a stainless steel tube which fits closely to the bore of the magnet; the "bore tube" is copper-plated. The heat due to the synchrotron radiation is dissipated directly into the cryogenic system, which cools the magnet. The bore tube and its copper liner are at a temperature of 4 K. During the quench, this structure (see Figure 1) is subjected to Lorentz forces and also to an external pressure due to the expanding helium gas.

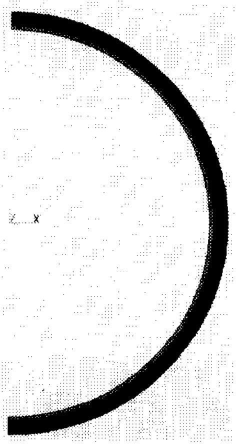

Figure 1.

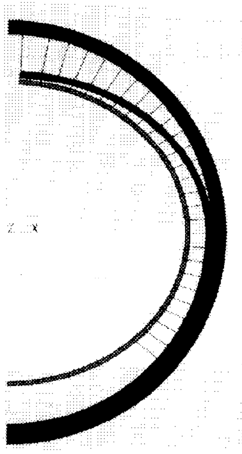

Figure 2.

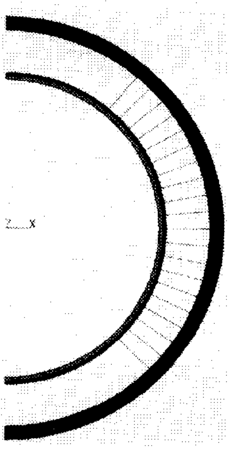

Figure 3.

B. Slotted Copper Beam Tube and Supporting Structure Inside the Bore Tube

In order to intercept the synchrotron radiation from the beam, consider a copper beam tube within but physically separated from the bore tube. The beam tube intercept may be operated at a temperature of 80 K. The space between the two tubes is required for pumping out any gas in the intercept. In this case, the copper beam tube is slotted along the entire length. The slotted beam tube is restrained during a quench by a stainless steel "slipper" structure, as shown in Figure 2, which supports the beam tube as it flexes outward under the Lorentz forces. In this design the beam tube is shielded from the external helium pressure, which is supported by the bore tube, during a quench. If the beam tube operates at a higher temperature, with a concomitant increase in resistivity, the thickness of the tube needs to be increased in order to provide the same impedance to the beam. The eddy currents induced in the bore tube are negligible due to the larger resistivity of the stainless steel bore tube.

C. Copper-Lined Beam Tube with an Array of Holes

A second method of providing pumping access to the volume inside an intercept beam tube is to distribute a random pattern of holes in copper and stainless steel beam tube. This configuration does not produce instabilities in the beam. The structure is shown in Figure 3. Once again, such an intercept beam tube would be placed inside a 4 K bore tube, and may be at 80 K.

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III. LORENTZ FORCE CALCULATIONS

In order to minimize transverse resistive wall instability, either the Nitronic 40 bore tube is copper-lined on the inside, or a copper beam tube is physically separated from the bore. Since the electrical conductivity of copper at 4 K-80 K is several thousand to several hundred times greater than that of Nitronic 40, almost all of the eddy currents flow in the copper. For the purposes of calculating Lorentz forces on the beam tube and bore tube assembly, only the forces on the copper are calculated, since the additional force due to eddy currents induced in the bore tube is negligible. Consider a section of the beam tube of thickness dr, and azimuthal angular width $d\theta$, located at radius r. The force per unit length on this section (1) is given by:

$$dF = J(t)\,B(t)\,r\,dr\,d\theta \tag{1}$$

Where $J(t)$ is the current density.

The current density is given by:

$$J(t) = \sigma(B,T)\,\dot{B}(t)\,r\cos\theta \tag{2}$$

Where $\sigma(B,T)$ is the electrical conductivity as a function of magnetic field and temperature, $B(t)$ is the magnetic field during a quench and $\dot{B}(t)$ is it's time derivative.

Therefore:

$$dF = \sigma(B,T)\,B(t)\,\dot{B}(t)\,r\cos\theta\,r\,dr\,d\theta \tag{3}$$

Thus, during a magnet quench, eddy currents induced in the beam tube result in a Lorentz force which is distributed according to:

$$F = F_m\cos\theta \tag{4}$$

Where θ is measured from the horizontal median plane of the tube and F_m is the maximum force. For an FEM calculation, we assumed the Lorentz forces were applied at 10° increments on the beam tube. Integrating equation (3) for each increment, the resulting equation is as follows:

$$F_{segment} = \sigma(B,T)\,B(t)\,\dot{B}(t)\left[\sin\theta\right]_{\theta_2}^{\theta_1}\left[\frac{r^3}{3}\right]_{r_i}^{r_o} \tag{5}$$

Where r_i and r_o are the inner and outer radii of the copper, and θ_1 and θ_2 are the angles.

A. Case (A): Copper-Lined Bore Tube

A stainless steel bore tube lined with 1 mm thick copper, shown in Figure 1, was considered in this case. The temperature of the copper at 4 K and the electrical conductivity of copper at this temperature (not including magnetoresistance effects) is 3.7×10^9 $(\Omega m)^{-1}$ (RRR~60). Using Equation (5) the angular variation of the Lorentz force is given in Table 1. The forces on the lining have been evaluated as a function of time during a quench (1). Table 1 shows the forces at approximately 0.2 seconds after the quench starts, which corresponds to the peak force.

Table 1

Lorentz forces on angular segments in the first quadrant for a copper beam tube at 4 K during a quench. (See Table 4.)

Angle (degree)	F (N/m)
0-10	23449.96
10-20	22737.45
20-30	21334.07
30-40	19282.46
40-50	16644.97
50-60	13501.73
60-70	9948.247
70-80	6092.491
80-90	2051.618

B. Case (B): Copper Beam Tube Open at the Vertex

An elliptical copper liner beam tube, separated from the bore tube (See Figure 2.) and supported by a stainless steel slipper was considered. The elliptical cross section is used to provide a greater bearing surface between the slipper and the beam tube. In this case, the tube operates at 80 K and it's electrical conductivity is 5×10^8 $(\Omega m)^{-1}$. Equation (5) may be used again since a single slot will not affect the eddy current distribution or magnitude. Equation (5) is scaled to account for the elliptical cross section. The values of the forces are given in Table 2. The forces are considerably less due to the lower conductivity of the copper at 80 K.

Table 2

Lorentz forces on angular segments in the first quadrant for an elliptical cross section copper beam tube open at 80 K during a quench. (See Table 4.)

Angle (degree)	F (N/m)
0-10	2505.140
10-20	2406.265
20-30	2219.189
30-40	1961.530
40-50	1652.721
50-60	1310.013
60-70	946.6287
70-80	571.6892
80-90	191.1176

C. Case (C): Complete Copper Beam Tube with a Random Pattern of Holes

In this case, the beam tube is a circular copper tube with stainless steel sleeve of .35 mm thick, randomly perforated with holes. The beam tube does not contact the bore tube. The number of holes required for pumping will comprise only 5% or less of the surface area of the tube. This will not cause a large perturbation to the eddy current distribution. Equation (5) is used again to calculate the forces in Table 3.

Table 3

Lorentz forces on angular segments in the first quadrant for a copper beam tube at 80 K during quench. (See Table 4.)

Angle (degree)	F (N/m)
0-10	1879.394
10-20	1822.289
20-30	1709.816
30-40	1545.390
40-50	1334.009
50-60	1082.094
60-70	797.3007
70-80	488.2818
80-90	164.4266

IV. MECHANICAL ANALYSIS OF STRUCTURES

Finite element analysis of 2-D (plane stress) cross sections was performed to determine the peak stresses and deflections. In cases (b) and (c) the copper tube liner is supported by rigid supports in both the right and left lower quadrants.

For option (a) of the beam tube design, an ANSYS® (2) model which is shown in Figure 1.(The forces are in Table 1.. The results of the ANSYS® analysis are presented as an equivalent stress contour plot in Figure 4. The peak stress seen in the copper is 348–402 MPa, which is beyond it's yield stress.

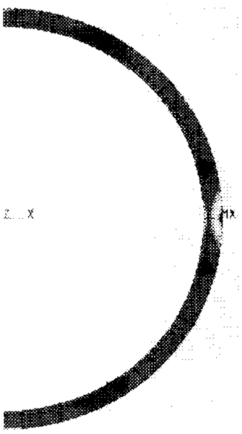

Figure 4.

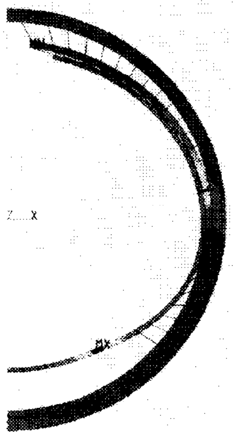

Figure 5.

For option (b) of the beam tube design, an ANSYS® model which is shown in Figure 2.(The forces are in Table 2.) The calculated stress in the copper varies from 491 to 613 MPa. This is again beyond the yield stress of copper. NIKE (3), which has very good non-linear and large deflection capabilities, is used to verify the ANSYS® calculations. The results of this analysis for ANSYS® and NIKE agree and are shown in Figures 5 and 6. These results show the beam tube undergoes plastic deformation, forcing the copper tube against the SST slipper. It may be possible to find a material and design that will be elastic in deformation when it makes contact with the slipper; this is under investigation. The peak stress found with NIKE is 518 MPa.

For option (c) of the beam tube design. The ANSYS® model which is shown in Figure 3.(The forces are in Table 3.) The stress in the copper is calculated to be between 234 and 273 MPa. This is acceptable for certain classes of copper. This analysis simulates a tube that is randomly perforated with small holes. In the analysis, the structure was modeled as a solid tube. The results of the ANSYS® analysis are shown in Figure 7.

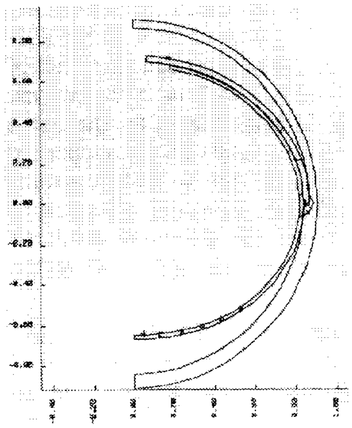

Figure 6.

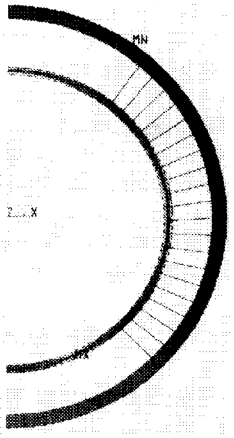

Figure 7.

V. SUMMARY AND CONCLUSIONS

A summary of the cases studied is presented in Table 4.

Table 4

Parameters for the beam tube, support and bore tube.

Case	Inner Rad	Outer Rad
(a) Copper	21.50 mm	22.00 mm
SST	22.00 mm	23.50 mm
(b) Copper major	19.10 mm	19.60 mm
minor	16.50 mm	17.00 mm
Slipper Lower	21.30 mm	22.00 mm
Upper Ellip major	21.30 mm	22.00 mm
Bore Tube	22.00 mm	23.50 mm
(c) Copper	16.50 mm	17.00 mm
Beam Tube SST	17.00 mm	17.35 mm
Bore Tube SST	22.00 mm	23.50 mm

SST = Stainless steel

Many iterations of the above designs have been analyzed, and the following conclusions can be drawn:

Electromagnetic and mechanical analyses of possible beam tube designs for the SSC have been studied. The results show that a perforated beam tube has the most attractive features. Studies of the slotted beam tube with a SST support tube are continuing.

VI. REFERENCES

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