Conf-910505--133

SSCL-433

SSCL-433

Superconducting Super Collider Laboratory

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

S. A. Smith, C. Haddock, R. Jayakumar,
J. Turner, and J. Zbasnik

May 1991

To be published as a Conference Record, IEEE, New York

SSCL--433

DE91 013362

Mechanical Analysis of Beam Tube Assemblies for SSC Dipoles During A Quench*

S. A. Smith, C. Haddock, R. Jayakumar,
J. Turner, and J. Zbasnik

Magnet Systems Division
Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237

May 1991

---

*Presented at the 1991 IEEE Particle Accelerator Conference, San Francisco, CA, May 6–9, 1991.

†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC02-89ER40486.

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

S. A. Smith, C. Haddock, R. Jayakumar, J. Turner, and J. Zbasnik

Magnet Systems Division
Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue
Dallas, TX 75237

Abstract

An alternative beam tube/bore tube arrangement for the SSC consists of an elliptical beam tube mounted inside a circular bore tube to intercept the SR from the beam. The beam tube is operated at 80 K and is split at the vertex in order that it may be pumped by the 4.35 K surface of the bore tube. This paper presents the results of stress analysis of the beam tube due to 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. Currently three possible geometries for beam tube and bore tube assembly are being considered. These cases are designed to intercept the SR from the beam. During a magnet quench, eddy currents are induced in the beam tube; these interact with the rapidly decaying magnetic field to produce a Lorentz force on the tube. A force due to the external helium pressure, which may be as large as 20 atm during the quench, may also be exerted on the beam tube. It is essential that the beam tube assembly is not deformed 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 the FEM mechanical analysis package ANSYS to determine the stresses and deformations of the beam tube assembly.

II. Physical Description of the Beam Tube Assemblies

A. Copper Lined Bore Tube

The aperture of the magnet contains a stainless steel tube which fits closely to the bore of the magnet, the "bore tube" is itself copper plated to a thickness 't' in the first style of assembly considered. The copper lining thus forms the beam tube. The heat from the absorbed synchrotron radiation is dissipated directly to the cryogenic system cooling 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 external pressure due to expanding helium gas.

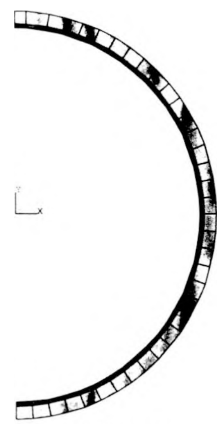

Figure 1.

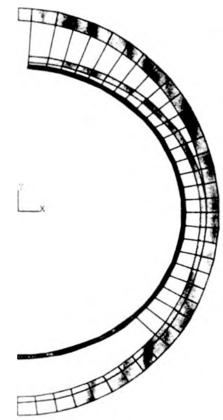

Figure 2.

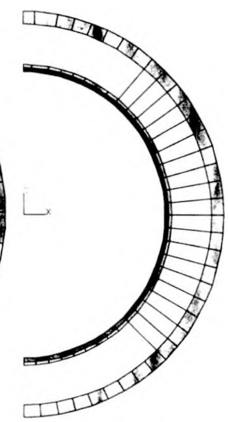

Figure 3.

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

It has also been proposed to place a copper beam tube within the bore tube and to physically separate the two. The copper surface may be operated at a temperature of 80 K. Access between the two tubes is required for pumping on any gas in the intercept. The first option is to use a slot along the entire length of the copper beam tube. Since the copper beam tube is operated at a higher temperature, with a concomitant increase in resistivity, the thickness of the tube needs to be larger to present the same impedance to the beam. With this design the beam tube is shielded from the external helium pressure which is supported by the bore tube alone. Further the Lorentz pressures on the bore tube are significantly reduced. The slotted beam tube must also be restrained during a quench, as it will tend to flex outwards under the Lorentz forces. It is proposed to study a stainless steel "slipper" structure, as shown in Figure 2, which supports the beam tube as it flexes outward.

C. Copper Lined Beam Tube with an Array of Holes

A second method of providing pumping access is to produce an array of holes in the copper tube. This arrangement of holes must be entirely random, since a regular array would produce instabilities in the beam. The structure is shown in Figure 3.

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.

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC02-89ER40486.

Since the 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 need to be 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 width $d\theta$, located at radius r. The force per unit length on this section [Ref. 3] is given by:

$$dF = J(t)\, B(t)\, ds \qquad (1)$$

The current density is given by:

$$dF = s(B,T)\, B(t)\, \dot{B}(t)\, r \cos q \qquad (2)$$

In polar coordinates one has:

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

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

$$F = F_m \cos\theta \qquad (4)$$

Where θ is measured from the horizontal median plane of the tube and F_m is the maximum force. In order to include these forces in a FEM code such as ANSYS, one can determine the Lorentz force on angular segments of the tube which are (for example) 10° in width. Integrating the above one obtains

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

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

Consider a copper lining on the stainless steel bore tube which has the following dimensions: ID = 43.0 mm and OD = 44.0 mm, as shown in the schematic in Figure 1. The temperature of the liner is 4 K and the conductivity of copper at this temperature (neglecting magnetoresistance effects) is $3.7 \times 10^9 \Omega\ m^{-1}$. Using Equation (5) above, the angular variation of the Lorentz force in units of N/m is given in Table 1. The table shows the forces at the time when they have the greatest magnitude during the quench, i.e., approximately 0.2 seconds after the quench starts.

Table 1
Lorentz forces on angular segments in the first quadrant for a copper beam tube OD = 44.0 mm and ID = 43.0 mm at 4 K during a quench.

Angle	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): A Copper Beam Tube Open at the Vertex

Consider a copper tube, elliptical in cross section, physically separated from the bore tube (See Figure 2.) An elliptical cross section is used in order to provide a greater bearing surface between the slipper support and the beam tube. In this case, the tube is operated at 80 K and its conductivity is $5 \times 10^8 \Omega m^{-1}$. Equation (5) may be used again since a single slit at the vertex of the tube will not affect the eddy current distribution or magnitude. The equation (5) is scaled to account for the elliptical cross section. The values of the forces are given in Table 2.

Table 2
Lorentz forces on angular segments in the first quadrant for an elliptical cross section copper beam tube open at the apex with major axis 39.2 mm (O.D) and minor axis 34.0 mm (O.D). The temperature of the tube is 80 K.

Angle	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): A Complete Copper Beam Tube with an Array of Holes

Consider a copper tube, physically separated from the bore tube, of circular cross section and with ID = 33.0 mm and OD = 34.0 mm. The number of holes required for pumping will occupy 5% of the surface area of the tube. This will not cause a large perturbation to the eddy current distribution. Equation (5) is used to calculate the forces in Table 3.

Table 3
Lorentz forces on angular segments in the first quadrant for a copper beam tube with OD = 34.0 mm and ID = 33.0 mm at 80 K during quench.

Angle	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 cross sections was performed to determine the peak stresses and deflections. Three different cases resulted in the study of the beam tube and beam tube liner. In Cases (b) and (c) the copper tube liner is supported by a slightly rigid body in both the right and left quadrant, although there has been no decision or analysis on the supports at this time. However, in order to complete the model, there was a requirement to support these tubes so the analysis would solve.

Consider option (a) of the beam tube design. The ANSYS model of this structure is shown in Figure 1. The forces used were from Table 1 in N/mm. The results ANSYS analysis are shown in Figure 4. The peak stress was found to be 509 MPa (72,000 psi) located at the midplane. The peak stress seen in the copper is 348–402 MPa (50,000–58,000 psi), which is beyond the yield stress for copper. Although this stress is beyond the yield stress for copper, the lining is still supported by the bore tube. The actual mechanism for this process will be further studied by experiment.

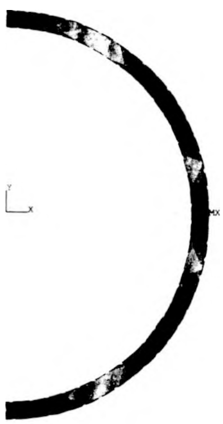

Figure 4.

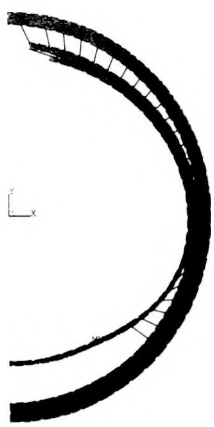

Figure 5.

Consider option (b) of the beam tube design. The ANSYS model of this structure is shown in Figure 2. The forces used were from Table 2 in N/mm. The peak stress was found to be 972–1011 MPa (138,000–144,000 psi). However, this is primarily located at the supports in the copper and in the midplane of the SST. Due to the rigid support, one would expect to see this, although this high value of stress is not real. The calculated stress in the copper varies between 491–613 MPa (70,000–87,000 psi). This is beyond the yield stress of copper and the model is being studied further to find a beam tube of sufficient rigidity which does not undergo plastic deformation during a quench. There was also a NIKE analysis done on this model for comparison due to the nonlinear and large deflection capabilities of the program. The comparison of analysis between the ANSYS and NIKE models are very similar, as seen in Figures 5 and 6. The forces used were from Table 2 in N/mm. The peak stress found in this analysis was 74,000 psi (518 MPa).

Consider option (c) of the beam tube design. The ANSYS model of this structure is shown in Figure 3. The forces used were from Table 3. The stress in the copper is calculated to be between 234 – 273 MPa (33,000 – 39,000 psi). This is acceptable for certain classes of copper. This analysis simulates a tube that is randomly perforated with small holes. The holes in this analysis were considered to be negligible. The results of the ANSYS analysis are show in Figure 7.

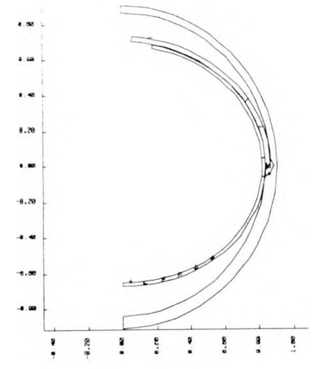

Figure 6.

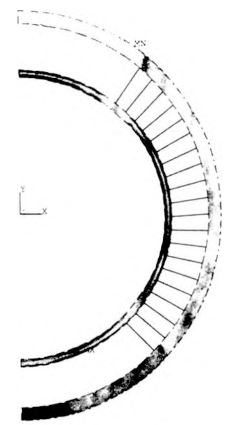

Figure 7.

V. Summary and Conclusions

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

Table 4
Three options for beam tube and beam tube liner.

Parameter	Inner Rad	Outer Rad
(a) Copper	21.50 mm	22.00 mm
SST	22.00 mm	23.50 mm
(b) Copper	maj. - 19.10 mm	19.60 mm
	min. - 16.50 mm	17.00 mm
Slipper Lower	21.30 mm	22.00 mm
Upper Ellip	maj. - 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 were reached:

1. For option (b) a more rigid support and different type of copper should be considered.
2. With option (c) variations in the type of copper, will make this design a contender.

VII. References

1. G.J. DeSalvo and R.W. Gorman, *ANSYS Engineering Analysis User's Manual*, Swanson Analysis Systems, Inc., May 1989.
2. ANSYS*, Trademark of Swanson Analysis, Inc., Houston, PA, USA.
3. C. Haddock, "Lorentz Pressure on a Copper Lined Beam Tube During a Quench for 50 mm SSC Dipole," SSC Laboratory Internal Report # MD-TA-165, August 1990.
4. NIKE2D*, *A Nonlinear, Implicit, Two-Dimensional Finite Element Code User Manual*, Trademark of Lawrence Livermore National Laboratory, by Bruce E. Engelmann and John O.. Hallquist, November 1990.
5. MAZE*, Trademark of Lawrence Livermore National Laboratory, by John O. Hallquist, June 1983.
6. ORION*, *An Interactive Color Post-Processor for Two Dimensional Finite Element Codes*, Trademark of Lawrence Livermore National Laboratory, by John O. Hallquist and Jo Anne L. Levatin, January 1982.