Eddy Current and Quench Loads and Stress of SSC Collider 4-K Liner and the Bore Tube During Magnet Quench

Superconducting Super Collider Laboratory
Superconducting Super Collider Laboratory is an equal opportunity employer.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Eddy Current and Quench Loads and Stress of SSC Collider 4-K Liner and the Bore Tube During Magnet Quench*

K. Leung and Q. Shu

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

July 1993

*To be presented at the International Cryogenics Engineering Conference, July 12–14, Albuquerque, N.M.
†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER
EDDY CURRENT AND QUENCH LOADS AND STRESS OF SSC COLLIDER 4-K LINER AND THE BORE TUBE DURING MAGNET QUENCH

K. K. Leung and Q. S. Shu
Magnet Systems Division
Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave., Dallas, TX 75237 USA

ABSTRACT

This paper describes the response of the eddy current and quench loads on a proposed Superconducting Super Collider 4-K liner system. The liner within a bore tube is designed to remove the radiated power and the photodesorbed gas that impair the beam tube vacuum. The bimetallic liner tube is subjected to cooldown and eddy current. The square liner tube is a two-shell laminate. Nitronic-40 steel is used for strength and a copper inner layer for low impedance to the image currents. Perforated holes are used to remove the photodesorbed gases for vacuum maintenance. The holes are located in a low-stress area of the liner. Rectangular holes in a four-pole symmetry pattern are required for beam dynamic stability. The liner is conductivity cooled by the round steel bore tube with a 2-mm wall. The copper layer must not be stressed over the yield strength limit because copper properties such as conductivity are known to change when the copper is stressed over yield strength. This analysis will address liner system response under thermal, eddy current, and vaporized liquid helium loads in a quenching dipole magnet.

INTRODUCTION

The steel bore tube is subjected to external buckling pressure caused by vaporized liquid helium from the quenching dipole. The liner is designed to have a reliability level in stress limit equivalent to the liner’s impedance and heat load. The liner system design analysis is performed by the finite-element method in a 3-D model to include eddy-current load and cooling-induced axial bimetallic effect on the copper layer, helium pressure on the bore tube, and the interaction of the liner to bore tube in a quenching dipole at cryogenic temperature. Evaluation of the quenches’ survivability of the bore tube designed with or without a bellow is also included in this paper.

The present analysis employs data from the Superconducting Super Collider (SSC) 50-mm Collider dipole accelerator systems string test (ASST) to establish both the eddy current loading to the liner and the helium load to the bore tube. A critical assumption made for this analysis is that the liner and the bore tube are attached by the cold-welded effect. Bare metals contacted to each other in outer space environment that is similar to the SSC Collider dipole magnet are observed to be cold welded together. Therefore, the sliding effect beyond the frictional forces between the liner and the bore tube is not seen in the liner system finite-element model. By designing the copper stress to be within the yield strength limit, the liner can be operated over many quench cycles in 25 years of operation.

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contact No. DE-AC35-89ER40486.
LINER SYSTEM DESIGN

Figure 1 shows the proposed SSC Collider dipole magnet liner system design. The square liner tube with 30° round corners offers simplicity in production, satisfying the four-pole symmetry specification for beam dynamic stability and maximum pumping surfaces for the vacuum requirement.

Stainless steel bore tube under helium pressure = 3.85 MPa (560 PSI)
The o.d. of the bore tube is 46.5 mm with a wall thickness = 2 mm

Liner with 0.5 mm Nitronic 40 steel and plated with 100 μm copper under eddy current pressure 0.82 MPa (Max.)

Figure 1. SSC Dipole Liner System.
EDDY CURRENT LOADS EVALUATION

The equation for equatorial eddy current pressure$^{2,3}$ (also see Figure 2) in a circular tube is:

$$P_{\text{max}} = B \times (\frac{dB}{dT}) \times b \times t \times \sigma,$$

where $B$ (T) = dipole field strength$^4$
$\frac{dB}{dT}$ (T/s) = rate of change during quench$^4$
$b$ (m) = mean radius of the copper layer
$t$ (m) = thickness of the copper layer
$\sigma$ ($\Omega \cdot m^{-1}$) = copper conductivity at 4 K under magnetic field.

The liner eddy-current force at each of the $3^\circ$ finite elements on the $30^\circ$ round corners is calculated by Eq. (1). The eddy current forces induced by the finite elements on the flat faces is approximated by the scaling factor for the difference of the radial distance between a round tube and a square tube.

The Eddy current forces on the copper layer are shown in Figure 3.
VAPORIZED HELIUM PRESSURE EVALUATION

The bore tube external pressure ($P_e$) as obtained from the SSC ASST test data (DCA313) at the magnet end is 1.4 MPa (205 psi). The He pressure distributions along the beam tube channel at about 87% of the beam tube length, according to the SSC helium venting computer simulation, will be subjected to pressure of 1.67 times the magnet end pressure. The design liquid helium external pressure used in the bore tube finite-element analysis with material properties changed from 300 K to 4 K is shown as follows:

$$P_e = 1.57 \times 92.46 \text{ MPa} = 1.57 \times (342 \text{ psi} + 15 \text{ psi}) = 3.86 \text{ MPa (560 psi)}.$$

The 1.57 is a dynamic load factor for the Helium pressure.

Applying Madhavan’s procedure for biaxial loading with modification for the bore tube loading from thermal strain developed by welding and quench heating condition, a bellowless bore tube is calculated to be unacceptable. The bore tube needs to be designed with a bellow to eliminate the axial compression. The estimated reliability for a 1000-magnet system if built with a bellowless beam tube that gives a 99.99999% reliability is only 8.2% in 25 quenches, compared to the 100% ASME quality beam tube with a bellow. The conclusion is that biaxial buckling strength data and stress theory have not been developed to predict the safety of the bellowless beam tube or bore tube. Thus we must employ a bellow to eliminate the axial compressive load.

The peak external helium pressure at magnet quench condition $P_e$ is used to design the bore tube. The $P_e$ is shown in Figure 4.

Figure 4. SSC Dipole Bore Tube FEM Model Shown With Helium Pressure.
RESULT OF ANALYSIS

Figures 5, 6, 7, and 8 show the results of the analysis. Yield strength of the plated copper at 4 K is 45 MPa (6.5 ksi). That is higher than the calculated 42 Mpa (6.2 ksi), as shown in Figure 5. The steel layer stress is 393 MPa (57 ksi), which is less than the Nitronic-40 yield strength of 1352 MPa (196 ksi). The bore tube stress is 703 MPa (102 ksi), which is less than the yield strength of 304 L, 1101 MPa (159 ksi). We conclude that the proposed liner system structural design is acceptable. Figure 5 shows the distribution of the combined stress on the copper layer of the liner. The stress is given in MPa, and the radial deflection in the radius direction is given in mm.

Figure 5. The Liner Copper Layer Combined Stress Under Magnet Quench Condition.

Figure 6. The Liner Copper Layer Radial Deflection Under Magnet Quench Condition.
Figure 7 shows the distribution of the combined stress on the steel layer of the liner. The stress is given in MPa. Figure 8 shows the distribution of the combined stress on the steel bore tube of the liner system. The stress is given in MPa.

Figure 7. The Liner Steel Layer Combined Stress Under Magnet Quench Condition.

Figure 8. The Bore Tube Combined Stress Under Magnet Quench Condition.
DISCUSSIONS AND RECOMMENDATIONS

We have achieved an understanding of the structural response on the copper layer of the liner subjected to cooldown, eddy current, and helium loads on the bore tube and liner system. It appears that 0.5-mm steel lamination to the 100-μm copper is sufficient to keep the copper stress below the yield strength limit. We recommend experimental study of the cryogenic properties of the copper under repetition of near yield stress condition. The increase of conductivity is known for copper under high-stress conditions. The conductivity needs to be within the SSC liner specification for the successful operation of the SSC Collider magnet system.

REFERENCES