

EDDY CURRENT AND QUENCH LOADS RESPONSE FOR THE SSC 4-K LINER AND BORE TUBE DURING COLLIDER 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.¹ The bimetallic liner tube is subjected to cooldown and eddy current loads.^{2,3} The square liner tube is a two-shell laminate.⁴ 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 dynamic helium loads in a quenching dipole magnet.

INTRODUCTION

The steel bore tube is subjected to external buckling pressure caused by liquid helium from the quenching dipole. 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 mid-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 is not seen in the liner system finite-element model. By designing the copper stress within the yield strength limit, the liner can be operated over many quench cycles in 25 years of operation.

LINER WITH BORE TUBE SYSTEM DESIGN

Figure 1 shows the proposed design of the SSC Collider dipole magnet liner and bore tube system⁴. The square liner tube with 30° round corners offers simplicity in production and satisfying the four-pole symmetry requirement for beam dynamic stability for the maximum pumping surfaces considering the vacuum preservation. The bore tube is designed with a bellow to eliminate the axial load. The failure of the bore tube is in a form the cylinder distorts into an elliptical shape similar to that of the long cylinder under external pressure. With the present of the helium pressure, the interaction between the axial compressive load and helium pressure is quite complex. Theory for axial tension with lateral external pressure for long cylinder has been developed^{11,15}. The accuracy of this theory applying to compressive axial load has not been tested and the end result is that the lateral buckling capacity of the bore tube is substantially reduced with the present of the axial load.

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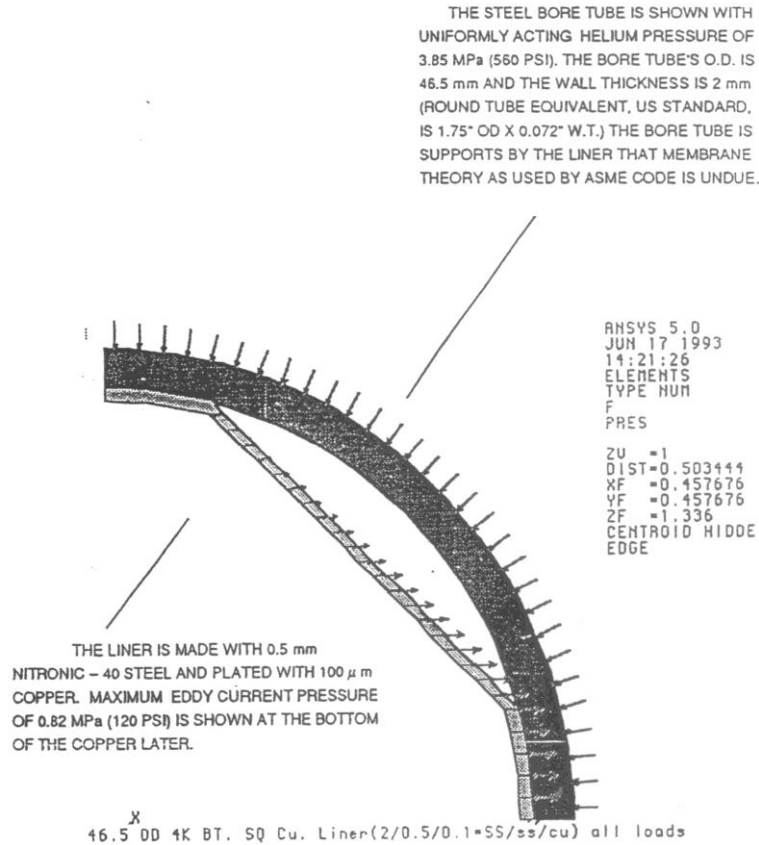


Figure 1. SSC Dipole 4 K Liner System.

EDDY CURRENT LOAD EVALUATION

The equation for equatorial eddy current pressure^{2,3} in a circular tube is :

$$PL_{\max} = B * (dB/dT) * b * t * \sigma, \quad (1)$$

where B (T) = dipole field strength⁴

$dB/dt(T/s)$ = rate of change during quench⁴

$b(m)$ = mean radius of the copper layer

$t(m)$ = thickness of the copper layer

$\sigma(\Omega^{-1} m^{-1})$ = copper conductivity at 4 K under magnetic field.

The liner eddy-current force at each of the 3° finite elements on the 30° round corners is calculated by Eq.

(1). The eddy current forces on the flat faces are evaluated by a scaling factor to account for the difference of the radial distance between the round corner and a flat face.

The Eddy current forces on the copper layer are shown in Figure 3.

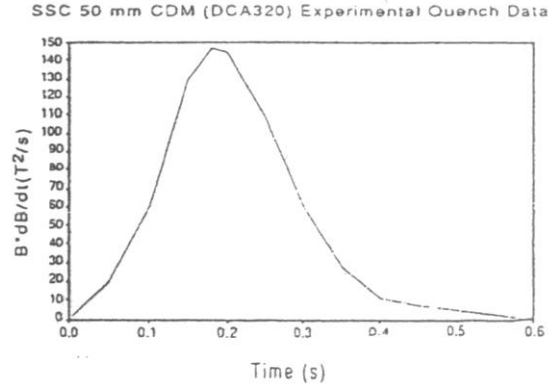


Figure 2. $B(t) \times [dB(t)/dt]$ as Function of Time⁴

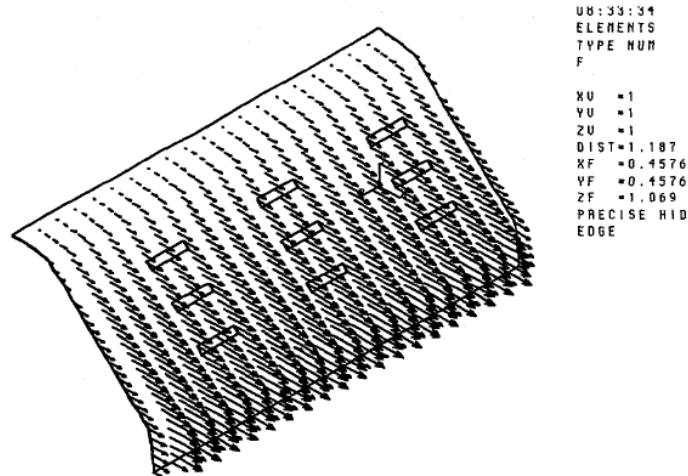


Figure 3. Eddy Current Pressure at the Copper Liner.

HELIUM PRESSURE EVALUATION

The bore tube external pressure (P_e) as obtained from the SSC ASST test data⁵ (DCA313) at the magnet end is 1.4 MPa (205 psi). The helium 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.⁶ The design helium external pressure used in the bore tube is shown as follows:

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

The 1.57 is a dynamic load factor estimated for the helium pressure.^{10,14} The ASME design rules¹⁹ are given in that the most severe condition of coincident pressure needs to be considered in determining the loading including water hammer and wund load, no design rules are given. Using the effect of asymmetry of triangular pulse on response of system with single degree of freedom, the line of constant from triangular pulse is about 0.1⁵ and the ration of the pulse peroid to the natural peroid of system for long cylinder, the dynamic factor is estimated as 1.57 for conservatism.

Applying Madhavan's procedure¹¹ for biaxial loading with modification for the bore tube loading from thermal strain developed by cool down, welding and quench heating condition,¹⁴ a bellowless bore tube is determined 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 99.99% reliability is only 8.0% 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 developed¹⁵ 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.

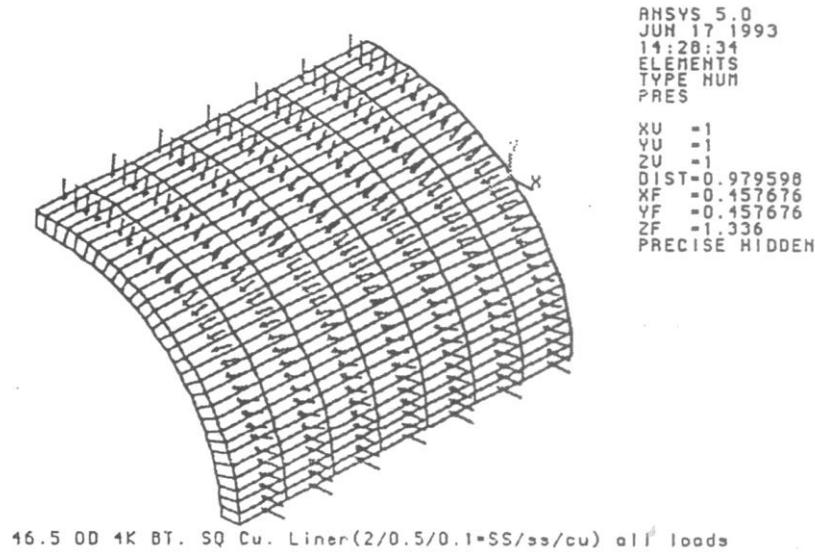


Figure 4. SSC Dipole Bore Tube FEM Model Shown With Helium Pressure.

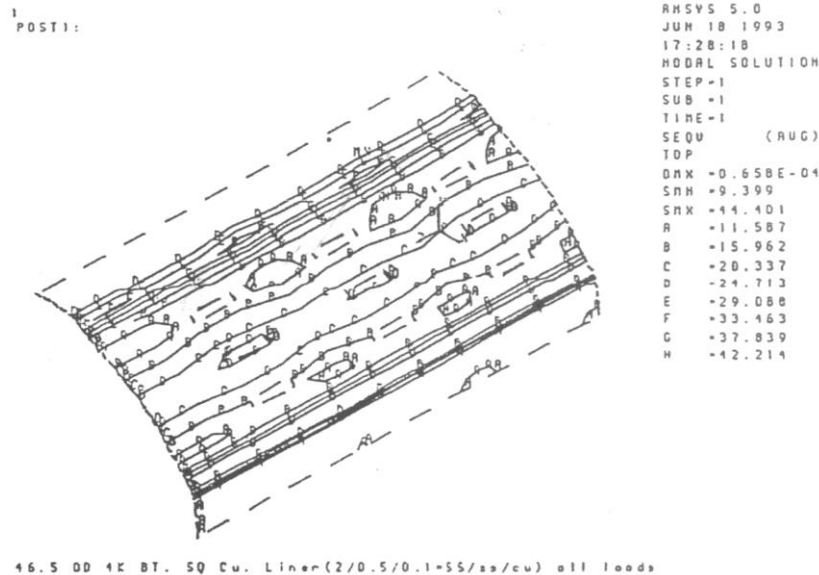


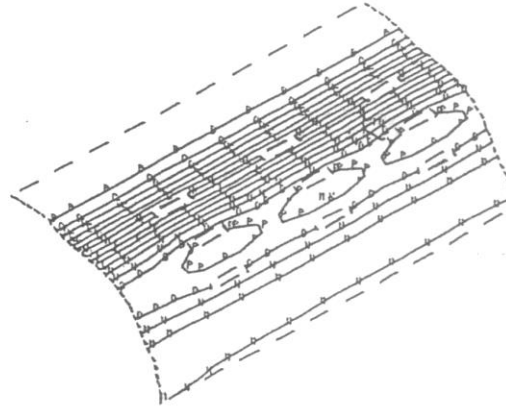
Figure 5. The Liner Copper Layer Combined Stress MPa Under Magnet Quench Condition.

RESULT OF ANALYSIS

Yield strength of the plated copper at 4 K is 45 MPa (6.5 ksi).⁹ 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)¹⁶, which is less than the Nitronic-40 yield strength of 1352 MPa¹⁶ (196 ksi). The bore tube stress is 703 MPa (102 ksi), which is less than the yield strength of 304 L, 1101 MPa¹⁶ (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. Results of analysis are shown in Figure 5, 6, 7, 8.

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.

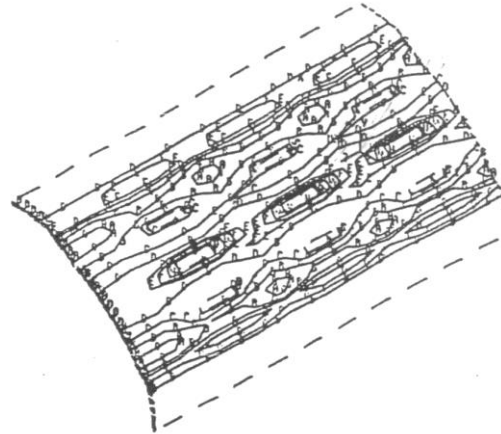
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E -0.105365
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Figure 6. The Liner Copper Layer Radial Deflection mm Under Magnet Quench Condition.

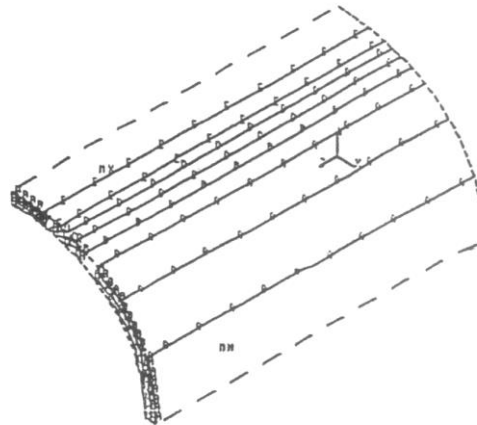


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D -258.183
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F -318.618
G -348.586
H -378.751
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Figure 7. The Liner Steel Layer Combined Stress MPa Under Magnet Quench Condition.

1
POST1:



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E -211.003
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G -296.919
H -339.877
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L -511.709
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O -640.583
P -683.541
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Figure 8. The Bore Tube Combined Stress MPa Under Magnet Quench Condition.

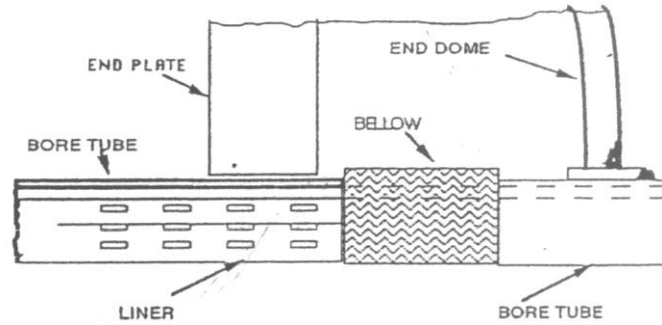


Figure 9. The Liner and Bore Tube with a bellow Combined to the End Dome.

DISCUSSIONS AND RECOMMENDATIONS

We have achieved in understanding the structural response on the liner and bore tube subjected to cool down, eddy current and helium loads. We believe that a 0.5 mm steel liner with 100 microns copper inside a 45 mm OD bore tube (designed with a bellow) with a 2.0 mm wall is sufficient in keeping the copper stress below the yield strength limit. Experimental study of the cryogenic properties of the copper after yield stress and near yield stress condition are recommended to evaluate the change of the photodesorbed gas production and conductivity. The increase of conductivity is known for copper under stressed condition. The conductivity and photodesorbed gas production needs to meet the SSC beam tube vacuum specification¹ and heat budget⁴ for the successful operation of the SSC Collider magnet system.

The collider dipole bore tube, under the bellow-less beam tube configuration, is subjected to axial compressive load from two sources: (1) The cool down stress due to the differential thermal expansion coefficients of the cold mass shell and the bore tube. (2) The heating by eddy current and other heat sources during the magnet quench adding axial stress besides the stress produced by the helium pressure rise. (3) The dimensional stability of the bore tube and the cold mass shell material that grows in different rate, typically ten to over hundred microns per year. (4) The residual-stress effect on axial load¹. The axial load and helium pressure present a biaxial instability problem that the reduction of hoop buckling strength as established by Madhavan^{11,15} needs to be considered in the bore tube design. The stress ratio method^{12,14} or interaction formula as employed by the civil/structural engineers¹¹ and aerospace stress engineers²⁰ may also be used to design the bore tube. The differential of thermal expansion coefficients of type 304 S.S. steel as reported¹⁶ gives $\Delta\alpha = 5.7 \times 10^{-6}/K^{-1}$. The axial stress is calculated as

$$\sigma_a = E \cdot \Delta\alpha \cdot \Delta T = 28 \times 10^{-6} \cdot 5.7 \times 10^{-6} \cdot (300 - 4.2) = 324 \text{ MPa (47000 psi.)}$$

For a 15 meter dipole bore tube, the critical buckling stress for a round tube as first established by Yang¹⁷ and recommended by the Column Research Council, USA is

$$\sigma_c = \pi^2 \cdot E \cdot (D_i/D_o)^4 / (KL/\gamma)^2 = \text{NEGLIGIBLE}$$

$$E = \text{Elastic Modulus} = 193 \cdot 10^3 \text{ MPa (26} \cdot 10^6 \text{)}$$

$$D_i = \text{Inside Diameter of the Bore Tube} = 40.5 \text{ mm (1.595")}$$

$$D_o = \text{Outside Diameter of the Bore Tube} = 44.5 \text{ mm (1.75")}$$

$$L = \text{Length of the Bore Tube} = 14600 \text{ mm (574")}$$

$$K = \text{End Condition Coefficient} = 0.6518$$

$$\gamma = \text{Radius of Gyration of the Bore Tube} = 17.2 \text{ mm (0.68")}$$

This study concludes that the SSC bore tube designed without a bellow, presents a serious risk to the SSC collider. There are hundreds of the bore tubes in a collider ring, this presents a major risk to the reliability. Incorporate a bellow with the bore tube can remove this risk by eliminating the axial load. Assuming a bore tube was designed with 100% of the ASME code¹⁹ standard of safety required SSC magnet design specification, if the 1000 bellow-less bore tubes in the collider magnet system have reduced the margin by 0.001%, The estimated percentage of reliability of the collider magnet under 25 magnet quench cycles is about 8%. $R_s(t) = e^{-1000 \cdot (1 - 99.99\%) \cdot 25} = 8\%$ of the ASME standard of safety. High yield stress of steel at cryogenic temperature and postbuckling "Euler" behavior on limited lateral deflection of the bore tube was proposed by some magnet scientists as the foundation for bellow-less bore tube or beam tube design. For the axially compressed long cylinders, besides the "Euler" behavior, it is necessary to account for the fact that the cylinder distorts into an

elliptical shape. This behavior is similar to that of the long cylinder under external pressure. The inward type of buckling for the axially compressed long cylinder was observed²¹. The use of bellows in superconducting magnet vessel were demonstrated to be safe and reliable from 1968 -1974 under extreme loads including parachute landing for the High Altitude Particles Physics Experiments in Berkeley²². We conclude that bore tube designed with bellows is a low risk design.

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