Effective Stress of The SSC 80 K Synchrotron Radiation Liner in a Quenching Dipole Magnet*

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

Abstract

This paper describes the effective stress on a proposed SSC beam tube. The new issue for the Collider compared to earlier accelerators is the combination of synchrotron radiation with the 4.2-K bore tube of the superconducting magnets [1]. One design option is to use a liner within a bore tube to remove the radiated power and the accompanying photodesorbed gas that impair the beam tube vacuum. Design of the SSC 80-K synchrotron radiation liner requires vacuum luminosity lifetime =150 hours and liner electrical conductivity, $\sigma^*t > 2E5\ \Omega\text{-}1$. [1]. The bimetallic liner tube is subjected to cool down and eddy current loads [2,3]. The liner tube is a two-shell laminate [4] with Nitronic-40 steel for strength and a copper inner layer for low impedance to the image currents induced by the circulating protons. High electrical conductivity of the copper layer is essential for minimizing the power losses. Perforated holes are used to remove the photodesorbed gases for vacuum maintenance. The tube is cooled by 80-K lines. Structural design of the liner is not covered by the ASME code [5]. The life of the liner involves structural integrity and keeping the copper laminate within yield stress limits to maintain the high surface finish for minimizing the power losses. The copper layer stress governs the structural design of the liner. The liner tube analysis is a three dimensional non-linear stress problem. Thermal transient cool down stress [6] is not considered in this analysis because of the floating support design of the liner. This analysis will address the axial thermal stress, non-axisymmetrical eddy current loads, dynamic and non-linear material effect on the liner that have not been considered in publications on beam tube structural analyses

I. INTRODUCTION

The proposed SSC liner is a beam tube with two concentric tubes. A perforated liner tube inside a bore tube is designed to remove the photodesorbed gases and synchrotron radiation heat, and to withstand the eddy current and cool down load without stressing the copper beyond yield. The steel bore tube is subjected to external buckling pressure caused by vaporized liquid Helium from the quenching dipole [7]. The liner is designed to have the same reliability level as the ASME code [5]. The liner design can be predicted by nuclear quality code [8] employing adequate finite element modeling [9] to include eddy current load, bimetallic effect, and dynamic amplification.

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The effective stress analysis employs SSC 50-mm dipole test data to establish the eddy current loadings and response of the liner. By designing the copper stress within the yield strength limit, the liner can be operated over hundreds of quench cycles in 25 years of operation without increasing additional power loss.

II. LINER TUBE DESIGN

Figure 1 shows the proposed SSC dipole magnet liner system design [4].

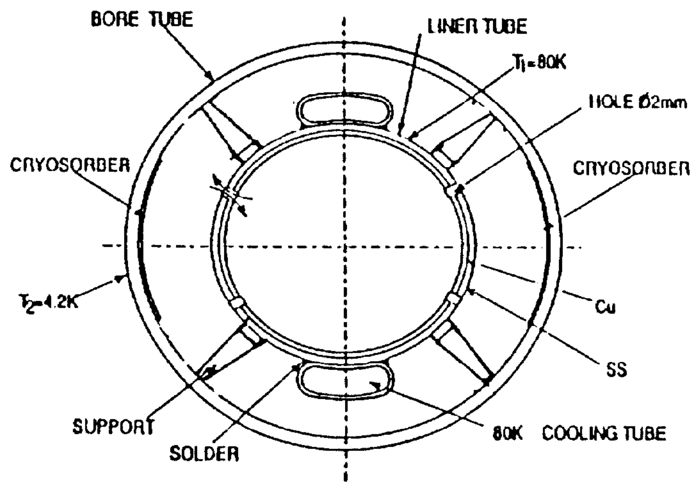

Figure 1. SSC Dipole Liner System.

The liner tube (25.3 mm I.D.) is a bimetallic lamination with a 0.5 mm copper bonded by a steel tube wall of 0.75 mm. Radial standoffs are used to support the liner tube from the bore tube. Torsional restrains are placed in some locations to avoid disturbing the dipole magnetic field. Bellows are used in the liner to reduce the axial load induced by the temperature rise of the tube from the heated coils during quench. Two 80-K cooling tubes are attached to the liner tube for removing synchrotron radiation heat rated as 0.14 watts per meter [4]. The holes are designed to maximize the luminosity lifetime of the liner system. The shape and the pattern of the holes have significant effect on the stress and impedance (<170 mohms/m) of the liner. The present design uses circular holes in a bend pattern with the cut-out area in a ratio of 2/9 along the axial direction. An intensive R and D study is underway to search for the hole shape and pattern.

III. EDDY CURRENT LOAD

(A) The equation of equatorial eddy current pressure (Maximum Lorentz pressure) [2] is:

$$P_{Lmax} = B * (dB / dT) * b * t * \sigma \text{ ....(a)}$$

B (tesla) = dipole field strength.[10]
dB/dt (tesla/sec) = rate of change during quench.[10] (also see Figure 2)
b (m) = mean radius of the copper layer.
t (m) = thickness of the copperlayer.
σ (Ω-1 m-1) = copper electrical conductivity at tempera ture, magnetic flux density and cold-worked condition

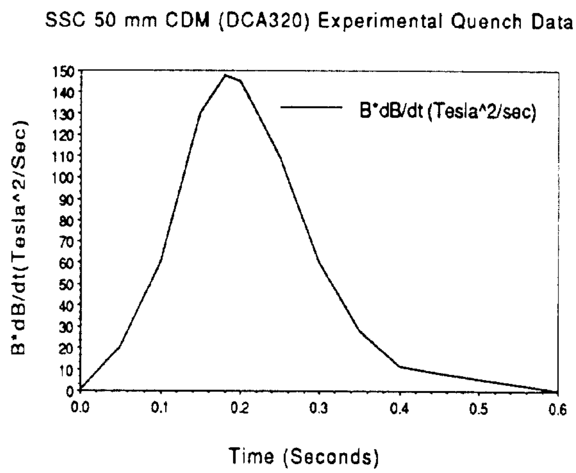

Figure 2. B(t)x[dB(t)/dt] as Function of Time.

From SSC dipole magnet test data and using equation (a) the eddy current pressure is calculated as 0.483 MPa (70 psi) including a dynamic factor of 1.25 as shown in Figure 3:

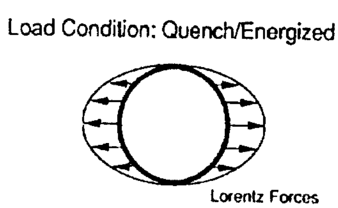

Figure 3. Eddy Current Pressure at Copper Liner.

Eddy current torque, or lateral [2,3,11] force are developed on the liner from geometrical tolerances in the tube forming and copper plating processes. Torque or lateral force induced stresses are used for bellow and torque restraints design to eliminate additional stress to the liner.

IV. FINITE ELEMENT MODEL

Three-dimensional finite element model (Figure 4) is employed to study the liner because the axial bimetallic effect combined with eddy current load which may collapse the tube, may develop bimetallic bond separation or produce stress beyond the copper yield limit,(Figure 5) that diminishes the thermal and electrical performance of the liner tube and produce unacceptable power loss.

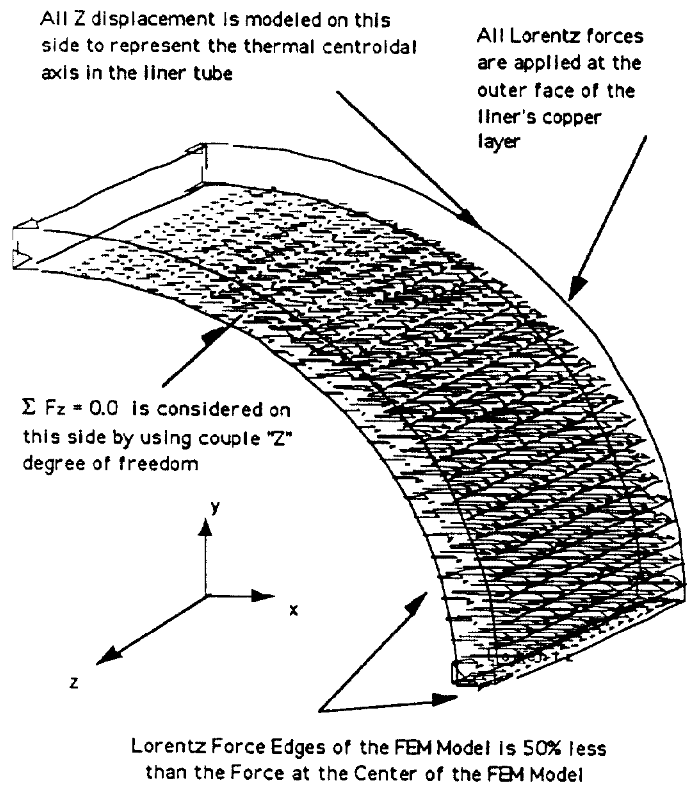

Figure 4. SSC Dipole Liner Tube FEM Model.

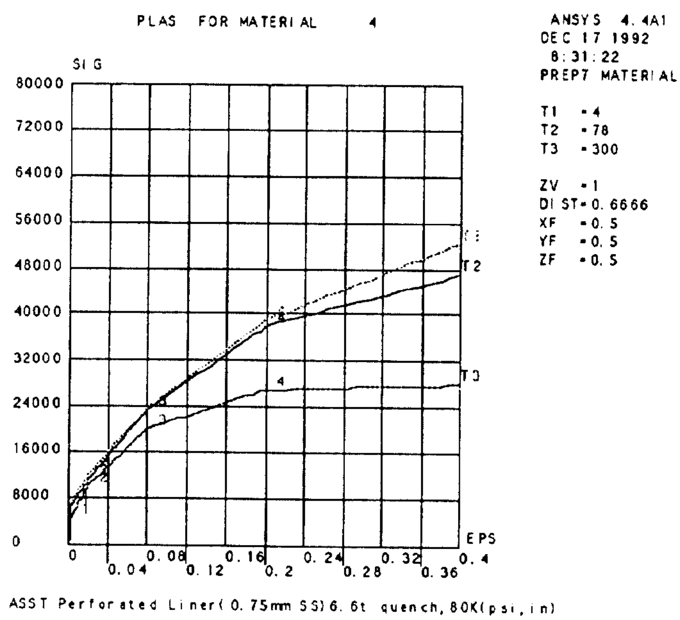

Figure 6. Non-Linear Copper Stress-Strain.

Effective stress analysis of the liner by the finite element method requires factors obtained from a test. (A) A carry-over factor is used to account for area reduced by the perforated holes. The factor is 1.286. (B) Dynamic factor based on the eddy current pulse shape is 1.25. (C) Stress concentration factor for circular hole is 2.0. The last factor is applied to the result of the finite element analysis is local effect on the overall effective stress.

V. RESULT OF ANALYSIS

The yield strength of annealed copper depends on grain size and purity. The average yield at 80 K is 44 MPa (6.4 ksi) [7]. The combined stresses for the liner at areas away from the holes are 53.8 MPa(7.8 ksi), see Figure 6, which is over the yield at 80 K [12] but within the ASME specified yield [5]. The stress around the hole will increase to 108 MPa (15.6 ksi) which is within the copper ultimate strength but its affect on the electrical performance of the liner requires additional investigation. The steel tube wall thickness may be increased to keep the copper stress within yield or eliding copper plating around holes. The steel wall stress of the liner is 289 MPa (42 ksi). The stress at the hole area in the steel wall will increase to 578 MPa (83.8 ksi) which is smaller than the 1034 MPa (150 ksi) of the Nitronic-40 steel's yield stress at 80 K.

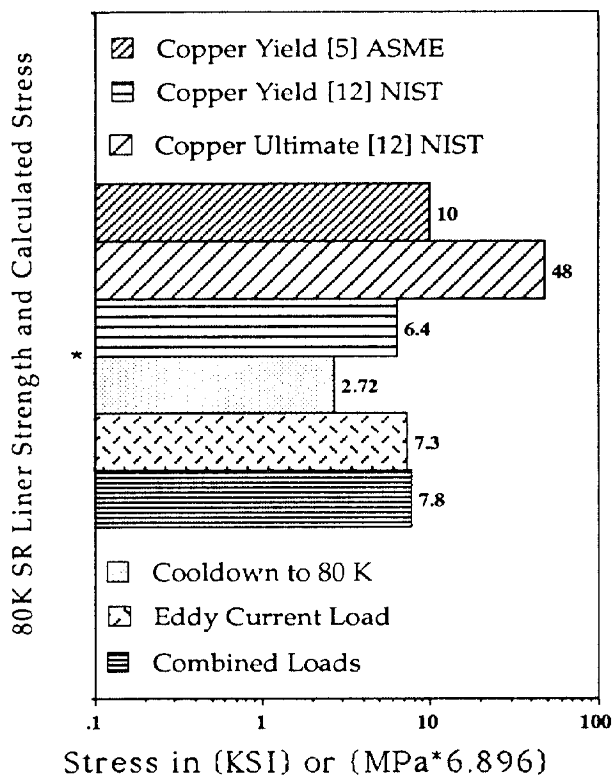

Figure 7. Result of Copper Layer Stress.

VI. CONCLUSIONS AND DISCUSSIONS

(A) High local stress on the copper layer reduces the level of confidence of the liner for multi-quench because micro-cracks may be developed in the copper surface and increase the power loss from the high frequency image current. Local steel wall may be increased to keep the copper within the yield stress limit.

(B) Analytical result is based on the shape and pattern of the perforated holes in the existing design [4] that induces low stress. Changing the existing circular hole shape to the shape of an ellipse or a square, and rearranging the hole in a random array will increase the copper layer stress. (C) A bellow and torque stoppers are required to reduce stress on the liner. The high slenderness ratio of the liner tubes (l/γ>200) practically deducts the liner to zero axial load capacity. The non-axisymmetrical eddy current Loads [5] will destroy the bellow and liner supports if torque stoppers are not used [3,11]. (D) This analysis is based on annealed copper properties. Cold work or residual stress will rise in post yield. The residual resistivity ratio (RRR) is a measure of the extent of physical defects such as lattice imperfections due to cold-working[12]. Additional analysis shows that stress at hole area is 414 MPa (60 ksi) for hard copper layer which has a yield stress of 207 MPa [30 ksi] and is not recommended to be used. Pure copper wire has an RRR of 50, but very high-purity copper, well annealed, could have an RRR of 2000 [12]. The liner fabrication technique by the electrode-posited method is preferable. It is possible to use high purity copper or gold for the liner using 0.25 mm for the conductive layer, and increasing the steel layer to 1.0 mm from the existing 0.75 mm. If the design guideline [1] for the copper conductivity as σ=4E8(Ωm)$^{-1}$ (80K in 6.1T. dipole field) is modified to =8E8(Ωm)$^{-1}$ with identical liner as specified by [4], the liner stress will be reduced to the comfortable level for a indefectible structural designed liner.

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