ALUMINUM BEAM TUBE FOR SUPER COLLIDER: AN OPTION FOR NO-COATING & NO-LINER

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Abstract

This paper proposes to use a single-layer beam tube made of high strength, high resistivity aluminum alloy (such as 7039-T61 or A7N01) to replace the double-layer copper coated stainless steel tube in Super Collider. The merits, technical issues and possible implementation are briefly discussed. For details the readers are referred to Reference [1]. This work was originally done for the SSC. But it may also be useful to future colliders.

I. INTRODUCTION

The baseline design of the SSC Collider beam tube calls for a stainless steel (SST) pipe of about 2-mm thickness with a thin copper (Cu) layer (about 0.1-mm thick) coated on its inner surface. The purpose of the copper coating is to reduce the surface resistance, thus suppressing the possible beam instability caused by the resistive wall and reducing the beam-induced wall heating. This paper suggests a drastic change in the choice of the beam tube, namely, a single-layer aluminum (Al) alloy pipe without coating. The merits are as follows:

- There will be a potential saving of about $2300 per tube, as shown in Table 1, or $23M for a total of 10000 tubes.
- An extruded aluminum tube with a specially designed cross section (with antechambers or plate insertions) will more easily accommodate a distributed cryopump and, therefore, will eliminate the need for a separated liner addition to the tube.
- There is a concern about adhesion in the bi-layer Cu+SST tube over a 25-year lifetime. This will not be a problem for a single-layer aluminum tube.

Aluminum beam tubes have been used in many lepton storage rings. They were ruled out in the early SSC design mainly because of the concerns about eddy currents and mechanical stability during quench, and the technical difficulty of making leak-free joints between aluminum and stainless steel . However, we will show that the recent industrial development of some high strength, high resistivity aluminum alloys (e.g., 7039-T61 or A7N01) can meet performance requirements in a quench, and that the Al-SST joints have been successfully tested and employed in a cryogenic environment at DESY, KEK and LANL.

II. TECHNICAL ISSUES

A. Surface resistance

A.1 Low frequencies — Resistive wall instability problem:

In order to control the beam instability, the requirement on the surface resistance of the beam tube is:

$$\sigma_e \Delta \geq 1 \times 10^5 \quad \Omega^{-1} \tag{1}$$

in which σ_e is the electrical conductivity and Δ the thickness (which is assumed to be smaller than the skin depth δ) of the wall material. Table 2 shows that the product $\sigma_e \Delta$ of a 2.5-mm thick aluminum tube is comparable to that of a 0.1-mm thick copper layer (RRR = 30).

A.2 High frequencies — RF heating problem:

In calculating the parasitic heating due to the beam and wall resistance, the anomalous skin effect (which was overlooked in the early SSC design) plays an important role.[1] The surface resistance ratio $R_s(300\ \mathrm{K})/R_s(4\ \mathrm{K})$ of copper at high frequencies is significantly lower than the dc value.[2,3] The data measured by LANL using a copper coated stainless steel tube is listed in Table 3.[4] In order to have a realistic comparison between Cu and Al, more measurements are needed in the presence of cold temperature (4 K), high frequency (≥ 1 GHz) and strong magnetic field (6.8 T).

B. Quench problem

B.1 Eddy current:

The eddy current during quench is proportional to the product $\sigma_e \Delta$:

$$I = 2\dot{B} b^2 \cdot \sigma_e \Delta \tag{2}$$

in which $\dot{B}$ is the rate of decrease of the magnetic field B, and b is the beam tube radius. It is seen from Table 2 that the eddy current is comparable for the two tubes.

B.2 Quench stress and tube thickness requirement:

To analyze the stress during quench, three effects need to be taken into account: thermal contraction during the cool down from room temperature to 4 K, the vaporized helium pressure P_{He} (which is isotropic in the radial direction pointed inward) and the Lorentz pressure $P_{\max}$ (which is in the horizontal direction pointed outward, has a cos-θ distribution and peaks at the equator). For $P_{\mathrm{He}} = 488$ psi and $P_{\max} = 100$ psi, a stress analysis using the 3D code ANSYS for a 2.5-mm thick aluminum tube gives a maximum stress $\sigma_{\max} = 16.9$ ksi.[5] The critical buckling pressure P_c is 4.57 ksi. According to the American Society of Mechanical Engineers, the allowable stress for membrane loading is:

$$\sigma_{\mathrm{allow}} = 1.5 \times \min\{0.25\sigma_t^u,\ 0.67\sigma_t^y\} \tag{3}$$

in which σ_t^u is the ultimate tensile strength of the tube material, and σ_t^y is the yield tensile strength. For the aluminum alloy

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[1] When the frequency is high enough such that the mean free path of electrons becomes larger than the skin depth, the normal conduction theory based on electron collisions breaks down and the surface resistance becomes independent of the conductivity σ_e of the material. This is called the anomalous skin effect.

Table 1. Cost Comparison

Cu Coated SST Tube		*Al Tube*	
15-m 304LN tube	$930	15-m A7N01 tube, extruded	$240
Copper coating	$2000	Two Al-SST welding joints	$200
		Two Al-SST demountable joints	$156
TOTAL	$2930	TOTAL	$596

Table 2. Surface Resistance Comparison

Material	σ_e ($\Omega^{-1}\mathrm{m}^{-1}$)	δ (mm)	Δ (mm)	$\sigma_e\Delta$ (Ω^{-1})
Cu	1.8×10^9	0.6	0.1	1.8×10^5
Al	5.6×10^7	3.6	2.5	1.4×10^5

7039-T61 at 4 K, one has $\sigma_{\text{allow}} = 36.75 \quad \text{ksi}$. The allowable buckling pressure is:

$$P_{\text{c allow}} = \frac{P_{\text{c}}}{4} = 1.14 \quad \text{ksi} \tag{4}$$

To estimate the needed tube thickness, the stress ratio method is employed. The requirement is:

$$\frac{\sigma_{\max}}{\sigma_{\text{allow}}} + \frac{P_{\text{He}}}{P_{\text{c allow}}} < 1 \tag{5}$$

For a 2.5-mm thick aluminum tube, this ratio is 0.89. Therefore, it should be safe during quench.

B.3 Quench test:

A convincing evidence of the quench survivability of an aluminum tube comes from a preliminary quench test.[6] The sample is a 2-m A7N01 pipe (1.7-mm thick), which is co-extruded with an A1100 pipe (0.2-mm thick). The eddy current and Lorentz pressure of this clad pipe in a quench are comparable to what is calculated above. The test results showed that the elastic deformation was < 0.1 mm, and the plastic deformation < 0.01 mm.

C. Gas desorption problem

C.1 Photon induced gas desorption:

The main concern of the vacuum problem in the Collider is the photodesorption due to the synchrotron radiation of the protons. Previous measurements at NSLS and CERN showed that the initial photodesorption rate η of aluminum is higher than that of copper and stainless steel. But the rate of decrease is also greater. At sufficiently high photon dose, η for all the three metals tend to similar low values.[7]

C.2 Ion induced gas desorption:

The ionized molecules of the residual gas, which are accelerated by the potential field of the proton beam (about 400 V in the Collider), can desorb gas molecules from the accumulated layer on the tube surface. This effect is usually described by the quantity $\eta_i I$, the product of the ion desorption coefficient and the beam current. Thanks to the low beam current (0.07 A) in the Collider, this effect is small no matter what material (Al, Cu or SST) is used for the beam tube.

Table 3. Surface Resistance of a Copper Plated Tube

Frequency	Ratio R_s(300 K)/R_s(4 K)
dc	107
0.959 GHz	4
1.865 GHz	3.2
7 GHz	3.7

C.3 Electron multipactoring:

Because aluminum has a high secondary electron emission coefficient, the electron multipactoring could become a problem as has been observed in the ISR. However, the calculations using Gröbner's model show that this should not be a concern due to the low beam current and short bunch length in the SSC.[8]

D. Al-SST joint problem

The Al-SST joint presents a technical challenge in a cryogenic storage ring because of the possible leak of helium at the joint near the end of the coldmass. In recent years, however, it has been successfully used in a helium environment.

- The demountable joint:[9]
  It uses bolted aluminum and stainless steel flanges manufactured by Hakudo/SMC and is employed in a superconducting RFQ at LANL. The pipe contains helium gas at 450 psi. After 100 thermal cycles between room temperature and 22 K, there was no detectable helium leak. The cost is about $78 per joint.
- The explosion bonded Al-SST transition piece:
  This has been used in cryogenic and vacuum environments at KEK for years and proved reliable and leak-free.
- The friction welding method:
  In the dipoles of the HERA proton ring, the helium cooling tube of the 40 K shield is made of aluminum. It is connected to the stainless steel flanges and bellows by friction welding. The helium pressure is 300 psi. During the past several years of operation, no helium leak from these welds has been found.[10] These joints are manufactured by Thevenet Clerjounie Co. The price is about $100 apiece for a mass order.

III. IMPLEMENTATION

There are three possible ways to employ the aluminum beam tube in the Collider.

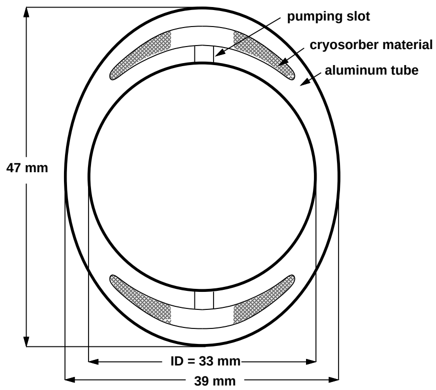

Figure 1. An aluminum tube with antechambers.

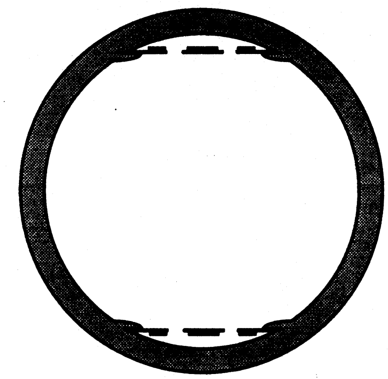
Figure 2. An aluminum tube with two plate insertions.

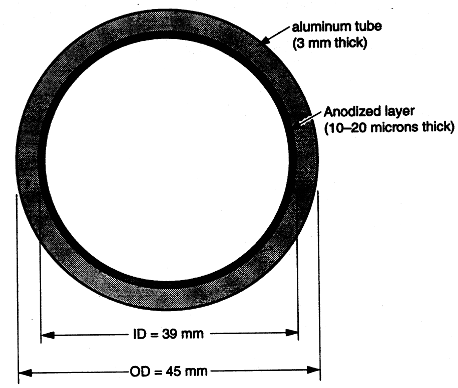

Figure 3. An aluminum tube with an anodized layer.

A. A beam chamber with antechambers

Because aluminum is easy to extrude, one may design a complex cross section to accommodate a cryosorber while eliminating the liner, such as the shape shown in Figure 1. It consists of a beam chamber and two "ears". The "ears" are the antechambers housing the cryosorber material such as coconut charcoal. The chamber and antechambers are connected by a series of pumping slots. The top-bottom symmetry is desirable for reducing the coupling impedance and the multipole magnetic field errors. The extrusion of a 15-m aluminum tube with such a cross section is feasible. There are, however, two potential problems: (1) Machining of the slots is not easy. (2) The two "ears" consume certain radial space that are precious to the magnet measurements.

B. A beam chamber with plate insertions

An alternative is to use a circular tube with two plate insertions as shown in Figure 2. The beam tube is extruded such that there is small bump on the inner surface that can support the plates. During magnet field measurements, the plates are not in place and, thus, a larger aperture is available. After the measurements, the two plates, which are perforated and have cryosorber material on one side, will be inserted into the beam tube for pumping purpose.

C. A beam chamber with an anodized layer

This is proposed in Ref. [11] and is illustrated in Figure 3. The anodized layer serves as a cryosorber. Therefore, no need for a liner. However, there are concerns about the impedance presented by this insulating layer and about the direct exposure of the layer to synchrotron radiation.

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