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FACTORS DETERMINING THE CHOICE OF THE BEAM TUBE MATERIAL AND THE VACUUM CHAMBER DESIGN FOR A SUPERCONDUCTING HIGH ENERGY STORAGE ACCELERATOR

J. Aggus, D. Edwards, Jr., H.J. Halama, and J. Herrera

Abstract

The factors which determine the choice of the material and the basic design for the vacuum chamber of the ISABELLE Colliding Storage Accelerator are reviewed. When the physical, thermal, electrical, and mechanical properties of the bulk material, as well as the various surface characteristics, are considered, it appears that a stainless tube covered with a copper sleeve is the best choice for the chambers in the magnet lattice of the rings. Aluminum is probably the most desirable material for those chambers in the experimental straight sections.

I. Introduction

The choice of the beam tube material and the associated vacuum components to be used in a colliding beam storage accelerator is a difficult task, particularly when the colliding rings use superconducting magnets. ISABELLE, the colliding proton-proton facility under construction at BNL, will be one of the first of this class of accelerators and, therefore, we shall use the design of its vacuum system as a basis for discussing the factors which influenced our choice of materials and structures.

II. Material Selection

The characteristics of the ISABELLE vacuum system have been presented in Ref. (1). It will be noted that the vacuum chamber material considered there was Aluminum 6061T6. Basically this material, whose properties are listed in Table 1, is a good substance to use for an accelerator beam pipe, and it has been used in e^+e^- colliding rings. However, measurements performed by Gröbner at CERN[2] have shown that, for bunched proton beams, multipactoring can occur with aluminum chambers due to the relatively low secondary electron unit yield energy of aluminum oxide, which always covers aluminum surfaces. In addition, a recent study[3] indicates that a beam microwave instability may develop due to the good coupling provided by the high electrical conductivity of an aluminum tube joining the adjacent structures containing the pumping stations. On the basis of these possible problem areas, the ISABELLE design has switched to stainless steel. Consistent with the operational experience at CERN, this change represents a conservative approach. As can be seen from Table 1, the secondary electron unit yield energy[4] for stainless steel is greater than 400 eV, and its electrical resistivity is considerably greater than that of aluminum. It is interesting to note that Hoyt and Schultz[5] at SLAC have solved the multipactoring problem by coating the aluminum surfaces in rf cavities with titanium nitride. Subsequent measurements at BNL of the unit electron yield energy of titanium nitride surfaces have shown that its value is indeed comparable with that of a stainless surface.

III. ISABELLE Lattice Vacuum Chamber

With the basic choice of material completed, the further design of the vacuum chamber must satisfy the following requirements: (1) It must allow bakeout (in situ) to 300°C, and (2) It must prevent the heat induced by a bunched circulating beam from raising the temperature of the central portion of the beam tube above 50° C, in order to minimize the transmission of heat to the surrounding superconducting magnet. These two requirements are ideally met by cladding the 0.049" stainless pipe with 0.045" of copper and surrounding the assembly with 36 layers of crinkled, aluminumized Kapton. Such a copper shield will also confine the electrical fields which, at low frequency, would otherwise pass through the stainless envelope.

During the accelerating phase of the ISABELLE machine, the 8A average current in each ring will be bunched on the third harmonic of the revolution frequency with a bunching factor of approximately 3. Assuming a cosine square distribution of the azimuthal charge within a bunch, we can derive the average heating per unit length of the stainless chamber. It then follows that

$$\langle P \rangle = \frac{I^2\sqrt{\rho\mu_o f_o N_B}}{\sqrt{\pi}\, b} \sum_{n=1}^{\infty} n^{\frac{1}{2}} \left[\frac{B^3}{n\pi(n^2-B^2)} \sin\left(\frac{n\pi}{B}\right) \right]^2 , \qquad (1)$$

where

I = average beam current = 8A,

N_B = number of bunches = 3,

B = bunching factor = 3,

f_o = revolution frequency = 78.9 kHz,

ρ = chamber wall resistivity = $72 \times 10^{-8}\,\Omega$m.

b = chamber wires radius = 4.4×10^{-2}m,

μ_o = $4\pi \times 10^{-7}\,\mathrm{Hm}^{-1}$,

and the resulting average dissipation per unit length $\langle P \rangle$ is about 1 Wm^{-1}. In the case of a beam chamber within the ISABELLE dipole magnets, this heat not only flows along the length of the copper jacket, but also contributes to the heat entering the cold environment through the super insulation. A discussion of this aspect of the heat flow can be found in Ref. (6).

It is important to point out that continuous bunch beam operation would be impossible without the copper sleeve. For a machine with a cold bore, this added power would have to be entirely dissipated in the helium.

A cross sectional drawing of the bore tube and the surrounding super insulation is given in Fig. 1. An extensive series[7] of tests has been performed on such an arrangement in order to determine the effective thermal conductivity of the insulation as a function of temperature and the level of insulating vacuum. In addition, the heat flow into the superconducting dipoles and the beam tube temperature in the middle of the dipole were measured on the engineering full-scale test model (ETM). While the ends of the chamber were maintained at room temperature, the central portion of the chamber was lower by 8°C, and the accompanying heat flow into the 4K cold circuit was 1.7 W. During the 300°C bakeout of the assembled vacuum section the center of the chamber reached 205°C and 24 W of heat flowed into the 4°K cold magnet. This central temperature would appear, on the basis of our ion desorption measurements,[4] to be sufficient for bakeout. However, a small heater will be placed in the central region of the bore tube to bring the temperature to 300°C in case achieving this higher temperature becomes necessary.

The most stringent requirement on the mechanical properties of the copper clad vacuum chamber is imposed by the very fast collapse of the magnetic field

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Table 1. Properties of Commercial Grade Materials.

		Aluminum	Copper	Titanium	Stainless
Commercial Grade		6061T6	102 OFHC	RMI 6AL-4V	304 LN
Chemical Composition (Weight)		Al > 96% Si 0.4-0.8 Fe 0.7 Cu 0.15-0.40 Mn 0.15 Mg 0.8-1.2 Cr 0.15-0.35 Zn 0.25 Ti 0.15	Cu > 99.96% P < 0.0003% S < 0.004 Zn < 0.0003 Hg < 0.0001 Pb < 0.001 C < 0.0004	Ti > 90.3% Al 6% V 4% Fe < 0.3 O < 0.2 C < 0.1 N < 0.05 H < 0.015	Fe > 64.5% Cr 18/20 Ni 8/12 Mn < 2 Si < 1 C < 0.03 N 0.2/0.4 S < 0.03 P < 0.045
Condition		Hard	Annealed [Brazed]	Annealed	Annealed
Specific Gravity		2.7	8.92	4.43	7.8
Modulus of Elasticity (psi)		10×10^6	18.6×10^6	16.5×10^6	28×10^6
Modulus of Rigidity (psi)		3.75×10^6	6.4×10^6	6.2×10^6	10.5×10^6
Coefficient of Thermal Expansion ($^oC^{-1}$)		23.6×10^{-6}	16.7×10^{-6}	10.4×10^{-6}	17.3×10^{-6}
Melting Point (^oC)		615	1083	1638	1410
Yield Strength (psi)		40000	10000	126000	70000
Thermal Conductivity	20^oC	0.37	0.91	0.0162	0.036
($cal\ sec^{-1} cm^{-1}\ ^oC^{-1}$)	4K	0.086	0.6		0.6×10^{-3}
Heat Capacity	20^oC	0.21	0.093	0.136	0.12
($cal\ g^{-1}\ ^oC^{-1}$)	4K	62×10^{-6}	21×10^{-6}		
Electrical Resitivity	20^oC	4.3×10^{-8}	1.72×10^{-8}	171×10^{-8}	72×10^{-8}
(ohm m)	4K	1.4×10^{-8}	1.6×10^{-10}	136×10^{-8}	50×10^{-8}
Bakeout Temperature ^oC		200	300		300
Outgassing Rate ($Torr\ \ell\ sec^{-1} cm^{-2}$)		$\sim 1 \times 10^{-13}$			$\sim 1 \times 10^{-13}$
Ion Desorption Coefficient (200°C Bakeout)		H_2 1.3 CO 1.0 CO_2 0.3 CH_4 0.04			H_2 0.71 CO 1.64 CO_2 0.85 CH_4 0.03
Secondary Electron Unit Yield Energy		50 eV			> 400 eV
Machinability		Excellent	Poor	Poor	Fair
Weldability		Good	Fair	Good	Excellent
Magnetic Susceptibility ($\mu/\mu_o - 1$)		2.1×10^{-5}	-0.96×10^{-5}	7.1×10^{-5}	4×10^{-3}
Dominant Thermal Neutron Activation Cross Section, Isotope Produced, and Half Life		0.21 mb Al^{28} 2.3 min	4.5 mb Cu^{64} 12.8 h	0.14 mb Ti^{51} 5.8 min	2.8 mb Fe^{55} 2.6 y 15.6 mb Cr^{51} 27.7 d 1.5 mb Ni^{65} 2.6 h

(50 T sec^{-1} maximum) which could take place during a quench of a dipole. The eddy currents induced in the copper sleeve result in forces which tend to crush the vacuum chamber. This problem has been analyzed by Shutt[8] for a number of beam tube configurations. The maximum stress calculated for the present design of beam tube is about 30,000 psi. The yield point for stainless 304 LN is 70,000 psi, and, therefore, the selection of this material gives a safety factor of 2.

IV. Experimental Straight Sections

While the design of the vacuum chamber in the bending and special cells of the ISABELLE machine is essentially finalized, such is not the case for the experimental straight sections. Many possible variations of chamber designs have been considered in a number of summer studies.[9,10] Aluminum, with its low density and low residual radioactivity, appears to be the most desirable material. For structures of equal strength, an aluminum experimental chamber would be half as massive as a stainless chamber.

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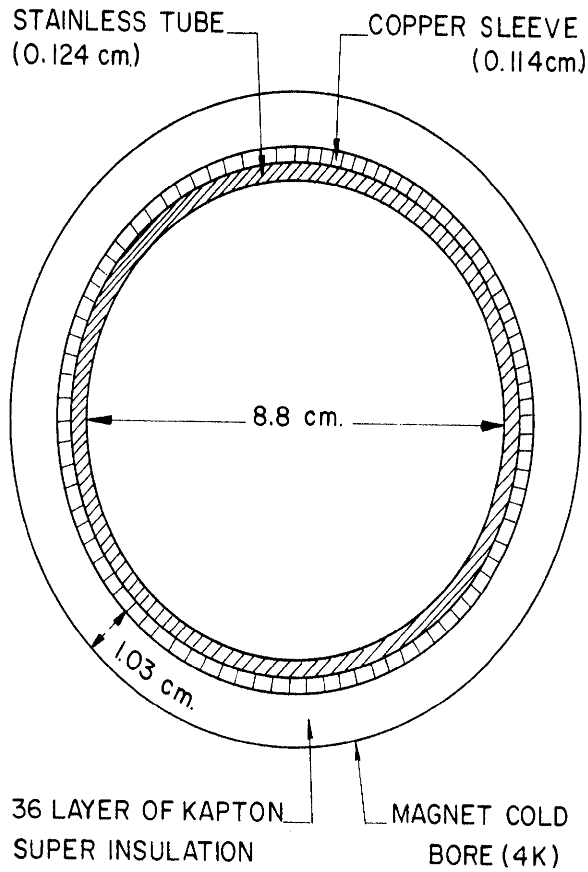

Fig. 1. Cross Section of Copper Clad Stainless Vacuum Envelope and Surrounding Superinsulation.