DESIGN AND DEVELOPMENT OF AN ULTRA-THIN SOLENOID
FOR A HIGH ENERGY PHYSICS PARTICLE DETECTOR

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ABSTRACT

An enhanced-stability thin solenoid magnet design is presented. The details of the high purity aluminum stabilized conductor are discussed. The design details of a special cryostat constructed for conductor evaluation is presented, and the aluminum alloy NbTi superconductor under procurement is described.

INTRODUCTION

Currently, several thin radiation-transparent solenoid magnets ^{1,2,3} are under construction for use in particle detection systems at colliding-beam particle accelerators. Magnet thickness is denoted by radiation length λ , so that if a total thickness of 0.5λ were desired, then 0.7 cm of copper, or 0.9 cm of stainless steel, or 4.5 cm of aluminum could be used in the construction of the magnet coils and cryostat.

The required economy of materials necessitates the abandonment of conventional cryostable conductors with large Cu:NbTi ratios, and novel approaches to magnet stability and safety have been devised. Cryostat design and coil cooling have also been optimized for as thin a total package as possible.

At LBL¹, to protect the high current density conductor in the event of a quench, a low resistivity aluminum bobbin is inductively coupled to the coil so that at the onset of quench the current rapidly leaves the conductor and dissipates the magnet stored energy safely in the bobbin.

At Saclay², high purity aluminum directly cosoldered onto the superconducting composite provides a shunt to protect the superconductor in the event of a quench.

Cooling is achieved with a tube coiled (or applied serpentine fashion) onto the coil, filled with circulating helium at ~ 4.2 K.

CONDUCTOR DESIGN

The LBL approach precludes rapid charging of the magnet, due to the resulting massive heating of the high conductivity bobbin. Choosing a conductor directly stabilized with high-purity aluminum, we find the minimum amount of aluminum required for safety in the event of a quench from the general results of P. Eberhard, et al.⁴ They calculate

$$E_0 J^2 = V_0 I_0 F^* (\theta_{\max}) \frac{(r+1)^3}{r} \quad (1)$$

where E_0 = stored energy, J = matrix current density, V_0 = maximum external discharge voltage, I_0 = initial current, and r = metal/superconductor ratio.

$$F^* (\theta_{\max}) = \int_{\theta_{\text{bath}}}^{\theta_{\max}} C_p \delta/p d\theta \quad (2)$$

and the results give a worst-case estimate for $\theta_{\max}$.

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For a choice of $\theta_{\max} = 250$ K, and for aluminum with $RRR \sim 750$, $F^* (250 \text{ K}) = 5 \times 10^{16} \text{ A}^2 \text{m}^{-4} \text{s}$. Now $J = jc/r+1$ and for $B = 2\text{T}$, $jc (\text{NbTi}) = 3 \times 10^9 \text{ A/m}^2$. Choosing $V_0 = 2000 \text{ V}$ we have

$$\frac{(r+1)^3}{r} = E_0 J_c / V_0 I_0 F^* = 450, \quad (3)$$

so that $r = 20$.

In this case, the magnet has diameter 3 m, length 4 m, and generates 1.5 T central field. Since $A (\text{NbTi}) = 1.7 \times 10^{-6} \text{ m}^2$, we have $A (\text{aluminum}) = 3.4 \times 10^{-5} \text{ m}^2$. Since for 1.5 T central field, 12 kA/cm current per unit length of coil is required, a 5000 A conductor is 0.40 cm wide, allowing for 0.02 cm turn-to-turn insulation. Thus, the normal metal is 0.85 cm thick radially. Detailed calculations of a coil with these parameters, using the program QUENCH⁵ and the measured quench velocity from the Saclay test coil², show the ratio r to be very conservative with respect to $\theta_{\max}$. Expression (1) is retained so that scaling to other magnets is straightforward.

COIL SUPPORT

To safely maintain the aluminum resistivity as desired, the hoop stress should not cause the conductor strain to exceed 0.02%⁶.

The magnetic pressure at 1.5 T is 130 psi so the coil is supported with an aluminum alloy structure of thickness

$$t = \frac{pr}{\sigma} = \frac{pr}{\epsilon E} = 0.90 \text{ cm} \quad (4)$$

Since a hollow conductor is proposed, an equivalent amount of metal is formed into a jacket which clads the finished conductor. In Fig. 1 is a sketch of the proposed conductor. The superconducting wires are cabled around a tube of 1100 or EEE aluminum alloy ($RRR = 60$). A thick ribbon of high-purity aluminum is rolled around this and compacted on with a strip of high strength alloy rolled into place. The outer jacket is thick enough to bear the hoop load of the magnet.

COIL WINDING

The conductor is wound on a fiberglass-epoxy bobbin 0.5 cm thick, and a 0.5 cm thick layer of epoxy fiberglass is applied to the outside of the coil. The outer layer of fiberglass is applied with a wet layup process, and care is taken to squeeze out all excess epoxy as the conductors are locked into position. The filament winding technique can control thermal motion so that axial and radial shrinkage match the conductor upon cooldown.

This type of coil fabrication, without preload in the coil winding during construction, is seen to minimize the coil thickness since a thick metal bobbin is not required to support the winding preload. Such a winding concept will greatly benefit in stability if the coolant, instead of circulating in a tube outside the coil, circulates inside the conductor itself.

CRYOSTAT

An aluminum honeycomb-type vacuum vessel and a thin aluminum liquid nitrogen-cooled shield contribute 0.16 λ . This number increases if a more conservative vacuum vessel made of extruded aluminum panel is used.⁷

With careful design and construction, the cryostat can reduce the total heat load to the coil to ≈ 10 W. Use is made of epoxy-fiberglass support struts, multi-layer insulation, and an 80 K shield on both sides of the coil.

Figure 2 is a plot of overall magnet thickness, as a function of field and radius, for a coil and cryostat incorporating these concepts.

Fig. 1. Proposed Internally Cooled Conductor.

Fig. 2. Coil and Cryostat Thickness

CONDUCTOR STABILITY

This conductor can be made to appear locally cryostable, i.e., sufficient internal perimeter can be obtained so that for a choice of heat transfer coefficient (depending on the choice of helium coolant, e.g., supercritical, subcritical, or even superfluid) the ohmic heating in the composite is completely transferred to the coolant. However, it is easy to show that if sufficient coolant flow is provided for classic

cryogenic stability, then pumping losses, pressure drops, or pressure and flow instabilities, etc. become prohibitive. In fact, only enthalpy stabilization is truly obtained with this conductor. If, for example, subcritical liquid helium is considered, the available enthalpy of the conductor (if heated from 4 K to the critical temperature of the NbTi) is two orders of magnitude greater than without helium. The characteristic time thermal diffusivity of high-purity aluminum is

$$\tau(th) = 4 \frac{w^2}{\pi^2} \left(\frac{C \rho \delta}{K} \right) = 1.4 \times 10^{-5} \text{ sec} \quad (5)$$

so that a great deal of conductor enthalpy is available immediately to absorb a local disturbance. On this time scale the current never leaves the superconductor due to the extremely small magnetic diffusivity time constant of high-purity aluminum, e.g., ≈ 0.5 sec.

EXPERIMENTAL DEVELOPMENT

A special cryostat has been constructed to measure the stability properties of the proposed conductor (Fig. 3). Subcooled liquid helium (up to 4.0 gm/sec cm^2) can be continuously supplied to a test section of conductor or a model coil. Thermocouples and pressure taps are available to monitor local conditions in the conductor, and a capacitor technique is being considered to monitor fluid quality at the inlet to the test conductors. Since flow conditions in the conductor are to be nearly stagnant, it is desirable to study the transient response of a length of the conductor to a local heat pulse.

Fig. 3. Cryostat with Heat Exchanger and 5000 A Leads

Delivery of about 5000 m of 1100 aluminum alloy stabilized NbTi superconductor is expected in the near future. Short samples of such material exhibit good stability in contrast with 5056 alloy aluminum stabilized NbTi previously tested⁸ at ANL. The overall monolithic conductor is to have 1.4 mm diameter with NbTi filament diameter 25 μm . The critical current of the conductor is to be 1500 A at 4.2 K, 0.1% strain.

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