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Nb_3Al PROTOTYPE CONDUCTOR FOR THE TRANSMISSION LINE MAGNET

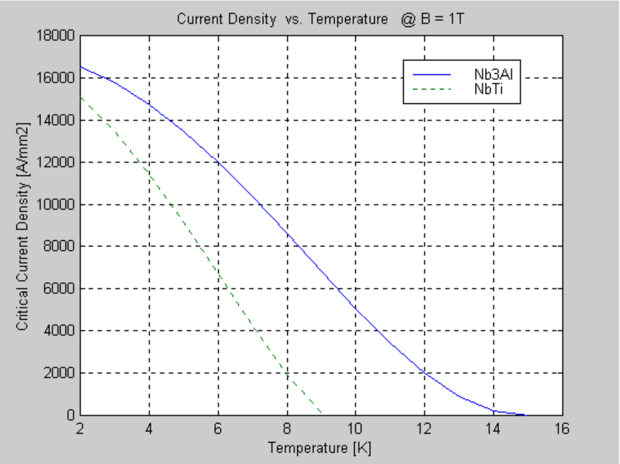
E. Barzi, G. W. Foster, E. Malamud[#], P. O. Mazur, H. Piekarz, Fermilab*, Batavia, IL
M. Wake, KEK, Tsukuba, Japan
K. Hayashi and M. Koganeya, Sumitomo Electric Industries, Ltd., Osaka, Japan

Abstract

The Very Large Hadron Collider (VLHC), under consideration for construction at Fermilab in the next 1-2 decades, is a 100 TeV cm pp collider [1]. A major cost driver is the magnet. R&D is underway on several possible magnet designs. A low-field (2T) superferric magnet, sometimes called a transmission line magnet [2], may be the most cost-effective route to the VLHC. Although NbTi is now the cheapest superconductor measured in cost/kA-meter, Nb_3Al has the potential advantage that it remains superconducting at higher temperature. It may be particularly suited to the single "turn" and long straight lengths of the transmission line design. The combination of the simple magnet design and the higher strain tolerance than e.g. Nb_3Sn allows a simple process of cable fabrication, reaction, and magnet assembly. This higher strain tolerance is an advantage for splicing in the field. Sumitomo Electric Industries is producing Nb_3Al conductor for the Fermilab low-field magnet program [3].

1 COMPARISON OF Nb_3Al AND NbTi

The graph compares the critical current density of the two materials at 1T, the field at the conductor in the transmission line magnet. We plan to operate the low field vlhc magnets at ~6K. One can see the increased current carrying capacity of Nb_3Al at this temperature.



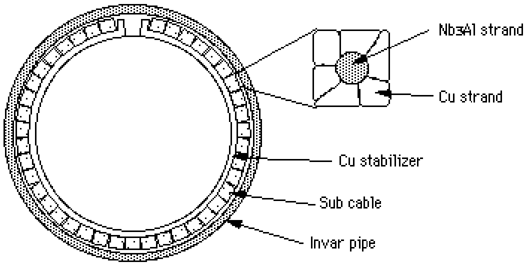
A higher operating temperature reduces the power required for the cryogenics system. The higher operating temperature also substantially reduces the size and complexity of the cryogenic distribution system. If one chooses to not increase T_{op}, Nb_3Al provides a higher enthalpy margin for beam-induced quenches.

2 CONDUCTOR SPECIFICATIONS

Sumitomo's wire is a Nb/Al composite assembled using a modified jellyroll process [4]. A thin Nb sheet, slit with controlled interconnection distances, is rolled up with an Al sheet, inserted in a copper container, and cold worked into a wire.

Diameter (one strand)	0.809 mm
Cu/non-Cu ratio	1.4
"Geometry"	"Jelly-roll"
Number of filaments	96
Filament Diameter	53 microns
Twist pitch	30 mm
Heat treatment (react)	$750 \pm 5\ ^{o}C$, 50 hours
Critical current (1 μV/cm)	133 A @ 12T, 4.2 K

3 CABLE SPECIFICATIONS



Number of sub-cables	41
Sub-cable dimensions	1.85 x 1.92 mm^2
Sub-cable topology	1 Nb_3Al, 6 Cu
Cabling pitch	~ 4 mm
OD of assembly (Invar ID)	35.7 mm
OD of Invar pipe	38.1 mm (1.5 in)
Thickness of invar	1.2 mm (0.047″)
Copper (OHFC) RRR	>100
Copper stabilizer width	85 mm
Copper stabilizer ID	29 mm
Copper stabilizer thickness	1 mm
Specified performance @ 1T, 6.5K	>75 kA

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* Operated by Universities Research Association under contract to the U.S. Department of Energy

[#] Email: malamud@fnal.gov

The figure shows how the Nb_3Al strand is enclosed with 6 copper strands to form one sub-cable. This configuration is to prevent contact between the Nb3Al and the Invar during reaction.

4 COPPER INVAR COMPATIBILITY TEST

A test was performed in order to observe the behavior of Invar in contact with copper during the high temperature reaction cycle for Nb_3Al conductor. As a control, a similar test was performed using 300-series stainless steel in place of the Invar.

Samples of stainless steel pipe 32-mm (1.25-inch) in diameter and Invar pipe 38-mm (1.5-inch) in diameter were cleaned. The pipes were wrapped in a spiral pattern with clean 0.25-mm thick copper foil. The typical thickness was 2-3 layers of foil. The copper foil was covered with stainless foil and stainless steel hose clamps in ~ six locations and the hose clamps tightened. The foil was held in close contact with the pipe in the areas under the clamps.

The prepared pipe/foil samples were placed in a furnace evacuated to 2×10^{-3} Torr and backfilled with argon. The furnace was heated to 800°C and held there for 15 hours. It was let cool to room temperature. An argon purge continued for the duration of the thermal cycle.

4.1 Results

The stainless steel foil was bonded to the copper foil, and the copper foil was bonded to itself. A slit was made along the length of the pipe, cutting through the foil to the underlying pipe. The foil was peeled back from the pipe.

The **stainless steel** pipe had discolored to a much darker gray than the original color. The copper foil was bonded to the pipe at only a few spots of area ~ one square mm. The copper peeled away from the pipe had a light discoloration where it had been held most tightly in contact with the pipe. The stainless was darkened in most areas although where the copper was most tightly clamped, the darkening was reduced. It seemed as if there was a fixed amount of darkening material and some was removed with the copper foil in the pattern of the hose clamps.

Unlike the stainless case the **Invar** pipe was not discolored. The copper foil was bonded much more solidly than in the stainless case. Areas of several square cm under the hose clamps were bonded between the Invar and the copper. No discoloration of the Invar or of the copper foil was seen in the areas where we peeled the copper away from the Invar.

4.2 Conclusion

Invar pipe does not contaminate the copper during the reaction process.

5 J_c MEASUREMENTS

A strand sample from Sumitomo was wound on a grooved cylindrical barrel made of a Ti-6Al-4V alloy, and fixed on two removable Ti-alloy end rings. This assembly was heat treated for 50 hours at 750°C in argon to form a wire having 96 filaments 53 μm in diameter, and a copper to non-copper ratio of 1.4.

I_c measurements were carried out at the Fermilab Short Sample Test Facility (SSTF) [5] [6]. The I_c dependence on field and temperature was measured with the 10^{-14} $\Omega\cdot$m resistivity criterion from 4T to 15T and temperatures of 3.5K, 4.2K and 4.5K. The measurements are shown in the table

B field [T]	I_c @ 4.5K [A]	I_c @ 4.2K [A]	I_c @3.5K [A]
4	1044		
5	793	830	923
6	602		
8	357		
10	210		
12	117	126	153
15	37	41	

Sumitomo's specification gives an I_c of 133A at 4.2K and 12T. This is defined at a critical field of 1 μV/cm. Our measurement with the more commonly used 10^{-14} $\Omega\cdot$m resistivity criterion gives an I_c of 126A at the same temperature and field.

5.1 Derivation of J_c at Higher Temperatures

The low-field vlhc magnets will operate at higher strand currents than can be measured at the SSTF. To infer J_c outside the field and temperature data ranges where measurements were done, data were fitted with parameterization by Summers et al [7] and Lubell [8].

$$J_c(B,T) = \frac{C_0}{\sqrt{B}}\left[1-\frac{B}{B_{c20}\left[1-\left(\frac{T}{T_{c0}}\right)^2\right]}\right]^2\left[1-\left(\frac{T}{T_{c0}}\right)^2\right]^2 \qquad (1)$$

$$\begin{cases} B_{c2}(T) = B_{c20}\left[1-\left(\dfrac{T}{T_{c0}}\right)^{1.7}\right] & (2) \\ T_c(B) = T_{c0}\left[1-\dfrac{B}{B_{c20}}\right]^{0.59} & (3) \end{cases}$$

Strain degradation was assumed to be zero. There are three parameters: B_{c20}, the upper critical field at zero temperature, T_{c0}, the critical temperature at zero field, and C_0, a normalization parameter expressed in $AT^{1/2}mm^{-2}$.

The best fit gives B_{c20} = 20T, T_{c0} = 15K, and C_0 =19003 $AT^{1/2}mm^{-2}$. The difference between parameterization and data is < 5% at 8T, and < 2% at 4T.

The parameterized J_c can now be used to obtain values at other temperatures.

J_c's inferred at 1T using these formulas are:

- 14,055 A/mm^2 at 4.5K (I_c = 3,010 A)
- 11,040 A/mm^2, at 6.5K (I_c = 2,364 A)
- 7,516 A/mm^2 at 8.5K (I_c = 1,610 A)

5.2 Conclusion

We therefore predict that the 41 sub-cable assembly will quench at 97 kA at 1T and 6.5 K. This exceeds the Sumitomo specification.

6 TEST PROGRAM

A test facility is being assembled in the MW9 building at Fermilab. A BM-105 analysis magnet and normal conducting primary excite a superconducting secondary turn.

Pressurized helium flow is established through the pumped loop. Pressure, temperature, and flow rate of helium can be controlled. The loop is appropriately instrumented with temperature sensors and voltage taps. Current is measured by an external Hall probe array.

A 4-m section of the loop can be removed and replaced with a test piece. This is where the Nb$_3$Al sections will be tested.

We will test the performance of the Nb$_3$Al transmission line at different currents and temperatures. By dividing the flow in the test region of the conductor and heating the helium in contact with the conductor under test, an elevated temperature region can be created [9]. Thus we will be able to test the middle of the Nb$_3$Al section at higher temperatures than either the rest of the loop which is made of NbTi or the NbTi-Nb$_3$Al splices.

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