APPENDIX V. SUPERCONDUCTING WIRE

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A. Introduction

Many of the operating characteristics of a superconducting magnet, as well as the cost, are strongly dependent on the specific design and construction of the superconducting wire. In this section we describe the choice of conductor and its construction, as well as some of the trade-offs that were made.

B. Superconductor Parameters

Superconductors can be characterized by their critical temperature, critical field, and critical current. High critical-current density is required in order to minimize the total amount of wire and cost. It is also required in order to stabilize the conductor for successful magnet operation. This stabilization is accomplished by providing a high-conductivity copper or aluminum matrix around the superconducting alloy. The stabilizing matrix serves two purposes. First, it provides a parallel conduction path shunting any excess current above the critical current of the superconductor. The criterion of stability is that the $I^2R$ losses in the matrix are less than the total capacity for local heat transfer to the helium bath. Second, high-conductivity metals such as copper have low magnetic diffusivities. This means that the movement of flux lines is slowed down, thus limiting the occurrence of flux jumps. A flux jump is a change in flux within the conductor that could cause a quench if the magnetic energy change exceeded a critical level.

By examining the physics of a single superconducting filament in a copper matrix, we can solve the diffusion equations for a finite local temperature rise at the surface of the superconducting alloy. This gives the following criterion for stability:

$$\frac{d}{D} < \frac{138 k_s}{\pi^2 \rho_{cu}} \frac{1}{J_c} \frac{J_c}{\alpha J_c^{3/2} T}$$

where $k_s$ is the thermal conductivity of the superconductor, $\rho_{cu}$ is the resistivity of the copper matrix, $d$ is the diameter of the filament, $D$ is the overall diameter of the strand, and $J_c$ is the critical current density. This criterion and the
adiabatic stability criterion of magnetic stored energy in an individual filament require that the individual filament size be smaller than 10 um. It should be noted that these models, as well as the ac loss models to be discussed later, require that the individual filaments be electrically decoupled from each other. Decoupling is accomplished by twisting the wire around its axis, thus forcing the individual filaments to assume a helical path within the stabilizing matrix. Thus, to attain stability, one must fabricate a conductor with small twisted filaments and one must provide a high-conductivity matrix.

C. Fabrication Techniques

With present technology, one is limited to niobium-titanium alloys in order to be able to fabricate conductors with all the above properties. Niobium-titanium has the ductility (as compared with, say, NbZr solid-solution) to permit the large-scale reductions necessary in production. For typical conductors, one starts by assembling alloy rods into hex-o.d., round-i.d. copper (ASTM Spe. B-170-1) tubes. These tubes are then stacked in a hexagonal array until the required number of filaments is reached. To attain the small filament sizes discussed above, more than 2000 composite rods are required. An extrusion can is then slipped over the stacked assembly and filler rods are inserted to help increase the packing density. The nose and tail pieces are then electron-beam welded into the can as it is pumped out.

The assembled can is then extruded at about a 16 to 1 reduction in area. Rod drawing then follows. In this process, the composite is reduced to approximately 0.30 in. diameter. Standard wire-drawing techniques are used to reduce the diameter of the wire further. At several points during this process, the wire is annealed to soften the copper.

D. Thermal and Mechanical Processing

In order to optimize the superconducting properties, the choice of alloy and the heat-treatment schedule during reduction are important. The critical temperature $T_c$ and upper critical field $H_{c2}$ are not very sensitive to composition, as shown in Fig. V-1. On the other hand, critical current is not an inherent property of the material and benefits from treatment. Microscopically, magnetic flux penetrates a type-II superconductor in the form of fluxons or quantized flux lines. These fluxons interact with the transport current by means of the Lorentz force, $J \times H$. During flux motion or change, voltages are induced by Faraday's Law and the superconductor becomes normal. Thus one must limit the motion of the flux lines by
Fig. V-1. $T_c$ and $H_{c2}$ as a function of composition.
"pinning" in order to optimize the critical current. Effective pinning sites are normal regions within the superconductor, which can be inhomogeneities, dislocations, precipitates or voids. In the following, the effects of mechanical and thermal processing are discussed.

For high-titanium alloys (those with greater than 50% Ti by weight), superconducting properties are optimized by a precipitation heat treatment (PHT) to form a fine distribution of normal flux-pinning particles. Figure V-2 shows parametric $J_c$ curves for several alloys as functions of time for fixed heat-treatment temperature. Here one can see typical effects that would be evident in plotting, say, mechanical properties in a PHT alloy. For example, the effects of over-aging are plainly evident. The amount of prior cold work also affects the current density, because dislocations usually provide nucleation centers for precipitation growth.

Figure V-3 is a plot of the critical temperature as a function of PHT. These data suggest that heat treatment may change the chemistry of the matrix phase because critical temperature is a function of composition.

For low-Ti alloys (Nb44-48Ti), cold work is the predominant factor in attaining high $H_c$. Figure V-4 shows the effect of heat treatment on a cold-worked Nb45Ti alloy. The ideal structure has the dislocation networks in a cellular structure with an average cell-wall separation of a few hundred Angstroms. In this work, the authors found that both the $J_c$ and the $\alpha$-phase precipitate increased with cold work.

Figures V-5 and V-6 are from work by Neal et al. Here one can see the effects of cold work and heat treatment on the Lorentz or pinning force. In Fig. V-5, one can see $J_c$ increasing with working and in fact there is a minimum amount of working at which the pinning force takes a large jump. In Fig. V-6, one sees the effect of heat-treatment time. Heat treatments in the range of 300°C for one hour produce a large increase in $J_c$. At higher temperatures, gain growth was obviously too high and properties began to fall. Heat treatment in the 350°C range for times exceeding one hour also improved the critical current capacity.

Intermediate Heat Treatments. The timing of the heat treatments can produce changes in $J_c$ for the equivalent amount of cold work. An intermediate heat treatment will result in recovery and cell-wall rearrangement and perhaps some precipitation within the highly deformed structure. Additional cold work after the heat treatment will produce new dislocations that tend to tangle around the precipitates and cell walls and result in more effective pinning centers. Figure V-7 illustrates...
Fig. V-2. $J_c$ (3T) as a function of heat treatment time for several alloys.
Fig. V-3. $T_c$ vs. heat treatment time.
Fig. V-4. Effect of increasing cold work on $J_c$. 

Cold work only  
Final size, mm  
- 0.50  
- 0.75  
- 1.50  
- 2.25  

Cold work + 375°C  
Final size, mm  
- 0.50  
- 2.25
Critical current density vs. cold work
Final heat treat = 1 hr / 585°C

Fig. V-5. Effect of increasing cold work on $J_c$. 
Critical current density vs. Heat treatment time
$T = 385^\circ C$
Area reduction $= 5 \times 10^4$

Fig. V-6. Effect of heat treatment time on $J_c$. 
Fig. V-7. The response of the pinning force \((J_cH)\) to an intermediate heat treatment.
the effects of increasing cold work after heat treatment at an intermediate state.

Pinning Force vs Cell-Wall Size. That the cell-wall size is an important parameter in determining $J_c$ is shown in Fig. V-8. A linear relationship exists between the critical current and the reciprocal of the cell size. There appear to be two processes occurring during heat treatment, first, dislocation, annihilation, and rearrangement, and second, sub-cell growth. Sub-cell growth is the slower process at lower temperatures. Heat treatment at about 375°C at times greater than one hour seems to provide an optimum balance between the cell-wall growth and the formation of effective pinning sites due to dislocation rearrangement. Nevertheless, once the effective pinning centers have formed, cell size controls $J_c$.

E. AC Losses

Having fabricated a superconducting composite that provides the required number of ampere turns, one must now engineer its final form to minimize ac losses. The dominant sources of conductor losses are hysteresis losses and eddy-current losses in the matrix. Hysteresis losses are caused by the fact that type-II superconductors in the flux-penetration region exhibit electrical "resistance" during field change. An estimate of this loss can be found by integrating the Poynting Vector over the superconductor during field change. Eddy-current losses are caused by changing magnetic field passing through the stabilizing matrix. These losses appear as ordinary Joule heating.

Hysteresis losses are independent of the rate of change of magnetic field $B$ and depend only on the peak magnetic field $B_{\text{max}}$, the critical current density $J_c$, the volume of superconductor $V_{\text{sc}}$, and the filament diameter $d_{\text{sc}}$. Thus the hysteresis energy loss is

$$W_h = 10^{-8} B_{\text{max}} J_c d_{\text{sc}} V_{\text{sc}} \text{ (Joules/cycle)}.$$ (2)

For a typical accelerator cycle, the losses can be approximated at one-half the above, which is given for a single-cycle sine wave.

Modeling the eddy-current losses on those in transverse laminae, we can formulate the losses for an accelerator pulse in the conductor as:

$$W_E = \frac{\pi^2}{4} B_{\text{max}}^2 d_{\text{cu}}^2 f V_{\text{cu}} K \rho^{-1},$$ (3)

where $W_E$ is the loss in Joules per cycle, $\rho$ is the matrix resistivity, $f$ is the equivalent accelerator-cycle frequency, $V_{\text{cu}}$ is the volume of copper, $K$ is an empirical coefficient (with $1 < K < 2$), and $d_{\text{cu}}$ is the diameter of the copper. It should be noted that the eddy-current losses are a function of the ramp rate and frequency.
Fig. V-8. The pinning force as a function of cell size.
as well as the physical size of the conductor. The eddy-current losses dominate at the higher ramp rates, but can be minimized more readily by specific conductor design. In particular, $d_{\text{Cu}}$ and $\rho$ can be changed easily.

**F. Present Doubler Conductor**

Based on the loss criteria, a requirement that total conductor losses be less than 1 W/m of magnet, the stability criteria and production limitations, we have chosen a Rutherford style of cable. Shown in Figs. V-9 and V-10, this cable is made with a Nb-46.5 wt/o Ti alloy and has a 1.8 to 1 copper to superconductor ratio. Each of the twenty-three strands of 0.027-in. diameter in the cable has 2100 filaments of 8 μm diameter. This filament size is small enough to insure stability, as well as low ac hysteresis loss, and represents somewhat of a lower limit on size. A coating of Sn-5wt/o Ag solder is used on each strand to provide a high resistivity layer in order to reduce the strand to strand coupling and hence reduce eddy-current losses.

Early in the program, the Laboratory purchased 300,000 lbs of copper. With this purchase we were able to bring up the average resistivity of the delivered material to better than 240:1. The resistivity ratio is a good measure of the impurity content of the copper and, in particular, the iron content. For stability reasons, it is necessary to have this ratio as high as possible. This copper has since been fabricated into enough copper hex tube and extrusion cans to produce 260 billets of material.

In placing large orders for the copper components and the NbTi parts described below, we have observed that the quality of the parts has shown significant improvement. Fabrication costs for the copper components have also dropped significantly.

Of the 15,000 lbs of NbTi purchased, most has been used in development programs and in the fabrication of production billets. Finished quality of the NbTi rods has improved over the past two years.

**G. Vendor Qualification**

By placing orders with domestic fabricators of superconductor, we have found that all are able to meet our specified electrical properties. There are differences in production rates, but these are not significant at present. We find that the differences in electrical properties vary more over a single billet than from fabricator to fabricator.

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Fig. V-9. Superconducting strand (2100 filaments).
Fig. V-10. Superconducting cable (23 strands).
Three firms have been able to provide us with 23-strand cable of varying quality. This process is rapidly attaining high quality levels overall and seems to depend strongly on technique.

In addition to the cabling, we are developing cleaning and taping capabilities in industry and hope to provide finished cable ready to wind in the magnets.

References


