

# REVIEW OF SUPERCONDUCTORS FOR HFM

Emanuela Barzi

## Abstract:

A general review of commercial composite superconductors for application in high-field accelerator magnets is presented.

## 1. GENERAL REQUIREMENTS FOR STRANDS

The overall  $J_c$ , the effective filament diameter  $d$ , and the **strain sensitivity** are related to the intrinsic nature of the SC, while the **processing method**, the piece **length**, and the **cost** are related to fabrication and processing. These are non-independent criteria, since the manufacturing process influences both cost and properties, and so far increases in  $J_c$  have resulted in an increase in  $d$ .

The most important criterion is  $J_c$ . For an efficient magnet design  $J_c$  must be at least  $1000 \text{ A/mm}^2$  in the SC (i.e. non-copper), corresponding to an overall  $J_c$  of at least  $500 \text{ A/mm}^2$ . The overall  $J_c$  depends on the conductor composition (amount of SC, filament uniformity) and the intrinsic properties ( $H_{c2}$ , microstructure).

**Thus  $J_c$  can be increased by increasing the amount of SC in the cross section or by a stronger flux pinning (Artificial Pinning Center approach).**

A large  $d$  (large filament or filament bridging), which can be related to the processing method, produces large AC losses and magnetization (i.e. poor field quality).  $d$  must be in the range 5 to 10  $\mu\text{m}$  to minimize these effects.

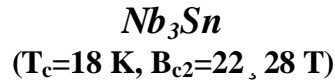
The  $J_c$  of both A15 compounds and HTS oxides exhibits sensitivity to stress. Strain sensitivity increases with the magnetic field. The goal for the material is to withstand a tensile strain of 0.5% without permanent degradation.

The use of wind-and-react coil fabrication requires an insulation that withstand the reaction cycle (several hours at  $650^\circ\text{C}$ ), like fiberglass or a ceramic.

Wire (as opposed to tape) is the preferred strand due to adaptability to various cable design. Moreover the co-winding of tape results in large inductances (poor field quality and AC losses). Nevertheless there might be no other fabrication routes for some materials.

**Above 10 T only the A15 compounds  $Nb_3Sn$  and  $Nb_3Al$ , and HTS oxides  $Bi_2Sr_2CaCu_2O_8$  (Bi2212) and  $Bi_2Sr_2Ca_2Cu_3O_{10}$  (Bi2223) approach the  $J_c$  criterion in long conductor length and multifilamentary form.**

## 2. COMPOSITE SUPERCONDUCTORS



Unlike *NbTi*, *Nb<sub>3</sub>Sn* is a brittle intermetallic compound having a well defined stoichiometry, which is obtained by long heat treatments at high temperature. In *Nb<sub>3</sub>Sn* flux pinning occurs by means of the **grain boundaries**, whose area increases with a small-grained structure (best if less than 40 nm). But heat treatments produce grain growth. In this regard the bronze process is helpful thanks to the copper that enables *Nb<sub>3</sub>Sn* to form at lower temperatures than with pure *Sn*.

The APC approach produces smaller grains by inhibiting grain growth or by increasing reaction rates.

The amount of *Nb<sub>3</sub>Sn* in the cross section is limited by the *Sn* content in the bronze, which above 15% creates brittle intermetallics.

### BRONZE PROCESS

*Nb<sub>3</sub>Sn* in 15% of wire area  
J<sub>c</sub> about 1000 A/mm<sup>2</sup> at 12T  
most developed

lowest cabling damage  
good for the APC approach  
lowest AC losses and d

### INTERNAL TIN PROCESS

*Nb<sub>3</sub>Sn* in 18% of wire area  
J<sub>c</sub> about 1500 A/mm<sup>2</sup> at 12T  
potential to increase the amount of SC

intermediate cabling damage  
cheaper

### POWDER-IN-TUBE (PIT)

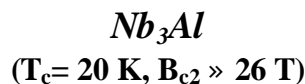
*Nb<sub>3</sub>Sn* in 33% of wire area  
J<sub>c</sub> about 1800 A/mm<sup>2</sup> at 12T  
most potential to increase  
the amount of SC  
good for the APC approach  
potentially cheaper

BUT

least achievable content of *Sn*  
expensive technology

filament bridging

limited filament size  
unreacted *Nb* excessive?  
*Nb* cost?



It withstands a strain as high as 1%. Unfortunately there appears to be no equivalent of the bronze process for *Nb<sub>3</sub>Al*, which means that the conflict between stoichiometry and grain size is severe. A way is to process elemental *Nb* and *Al* in finely subdivided form. At final size the wire is given a very rapid high temperature heat treatment followed by a quench at room temperature, which forms stoichiometric but amorphous *Nb<sub>3</sub>Al*. A subsequent heat treatment at lower temperatures is used to grow fine grains of the A15 phase.

Filament diameters are still greater than 50 μm and the high reaction temperatures (1900°C) place severe limitations on coil insulation.

Transverse loading studies on cables haven't yet been performed and although research has been done with powders, by June 1996 no company had yet commercialized a powder process.

### JELLY ROLL METHOD

J<sub>c</sub> of 750 A/mm<sup>2</sup> at 12 T

### QUENCHED JELLY ROLL

J<sub>c</sub> of 1800 A/mm<sup>2</sup> at 12 T

### TUBE METHOD

(*Nb* tube and *Al* rod)

J<sub>c</sub> of 750 A/mm<sup>2</sup> at 18 T

BUT

very expensive technologies

## *BSCCO's*

They have high upper critical fields although the field limit for a non-zero transport current in the SC is the so-called *irreversibility field*, which is much lower than  $B_{c2}$ .

The key limit to  $J_c$  is the connectivity of the grains. Weakly coupled grain boundaries, cracks and imperfect local composition make the current path through the material **percolative**.

$J_c$  is reduced with strain and the behavior is irreversible beyond  $0.0\% \leq \epsilon \leq 0.2\div 0.4\%$  (there is no compressive range). The upper limit depends on the state of the *Ag*, the amount of pre-compression, and the strength of the *Ag* (that can be strengthened by oxide inclusions).

Another drawback of HTS's is the anisotropy of  $J_c$  with respect to the field. In present BSCCO tapes, in a field perpendicular to the tape the  $J_c$  at 4.2 K is half than in a parallel field.

The effective filament diameter is large due to bridging during wire heat treatment or to large filaments from wire processing.

### ***BSCCO 2223 (PIT)***

only tape configuration (km)

### ***BSCCO 2212 (PIT)***

also round wires (170 m)

cheaper

higher  $J_c$

## **3. PRESENT MAGNET PERFORMANCE**

### • **Twente University Dipole Magnet**

- \* 1 meter long;
- \* 192 filament PIT  $Nb_3Sn$  conductor;
- \* 5 cm single aperture, 2 layer  $\cos(\theta)$ ;
- \* fully impregnated Rutherford cables, S-2 fiberglass insulation.

It reached 11 T central field (maximum transverse cable stress greater than 130 MPa) on its first quench at 4.2 K (transport current of 18.7 kA). After warm-up the quench field increased to 11.3 T in 4 quenches.

There were large field errors due to large effective filaments sizes (40  $\mu\text{m}$ ) and large interstrand cable coupling currents. The  $J_c$  degradation due to cabling has been about 25%.

From the detected voltages it appears that the limiting factor is not  $J_c$  or strain sensitivity, but the inability of the external support structure to maintain enough prestress in the coils.

### • **LBNL Dipole Magnet**

- \* 1 meter long;
- \* wind-and-react  $Nb_3Sn$ ;
- \* 5 cm single aperture, 2 double-layer;
- \* fully impregnated, S-2 fiberglass insulation.

It reached 13.5 T central field (peak stress of 140 MPa) at 1.8 K (operating current density of 290 A/mm<sup>2</sup>), and 12.8 T at 4.4 K. It demonstrated the flexibility and degree of control of the *tensioned wire winding* preloading technique.

Here too it seems that the performance limit was not  $J_c$  or strain sensitivity, but a portion of low-field coil not adequately supported.

## REFERENCES

- \* Proceedings of the Workshops on Superconducting Accelerator and Detector Magnets, Erice, 1995, '96, '97.
- \* Cern Accelerator School, Superconductivity in Particle Accelerators, 1995.
- \* T. Matsushita, P. J. Lee, S. Ochiai, *Composite Superconductors*, Kozo Osamura Ed., 1994.
- \* A. F. Greene, BNL, *Recent Status of Superconductors for Accelerator Magnets*, 1992.
- \* K.-H. Mess, P. Schmuser, S. Wolff, *Superconducting Accelerator Magnets*, World Scientific Ed., 1996.
- \* A. C. Rose-Innes, E. H. Rhoderick, *Introduction to Superconductivity*, Pergamon Ed., 1994.
- \* D. C. Larbalestier, P. J. Lee, ASC, UW-Madison, *New Developments in Niobium Titanium Superconductors*, 1996 IEEE.