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PRACTICAL SUPERCONDUCTORS FOR HIGH ENERGY PHYSICS (HEP) MAGNETS

E. Adam, E. Gregory, D. Koop, and W. Marancik
Airco Superconductors
A Department of Airco, Inc.
600 Milik Street
Carteret, New Jersey, USA

Summary

The magnet designer has a large choice of materials and conductor configurations to choose from. His choice is based on electrical and magnetic performance, mechanical properties, ease in winding, reliability and cost.

This paper attempts to review and clarify standard NbTi and multifilament bronze Nb_3Sn configurations of interest to HEP magnet designers. Emerging variations of these basic materials, such as NbTiTa and in-situ Nb_3Sn are described and compared on a cost basis with each other. New techniques for manufacturing large quantities of high amperage conductors are described.

Introduction

Present day high energy physics accelerators place heavy demands upon the superconductor to satisfy all the various magnet operating conditions. The usual superconductor requirements include high critical currents (up to 10,000 amperes at 5 T, 4.2 K), fine filaments for low hysteresis losses, low coupling losses between filaments or adjacent strands in built up conductors such as cables or braids, mechanical strength, ease of winding, manufacturing reliability and reproducibility, and minimum cost. This paper summarizes the conductors which are available on a production basis for use in accelerator magnets, and the conductors being considered for the next generation of 10 T accelerator magnets.

NbTi HEP Conductors

Airco, where possible, uses a basic billet construction to fabricate a copper-stabilized NbTi conductor which can be utilized in a variety of conductors. The conductor can take the form of large current carrying monoliths or built up assemblies such as braids or cables. The use of a common "building block" conductor allows a great deal of manufacturing flexibility in that standard components can be inventoried in large quantity to facilitate short production lead times. The basic wire construction (Fig. 1) consists of 517 NbTi filaments uniformly distributed within a copper matrix (approximately 59 v.o).

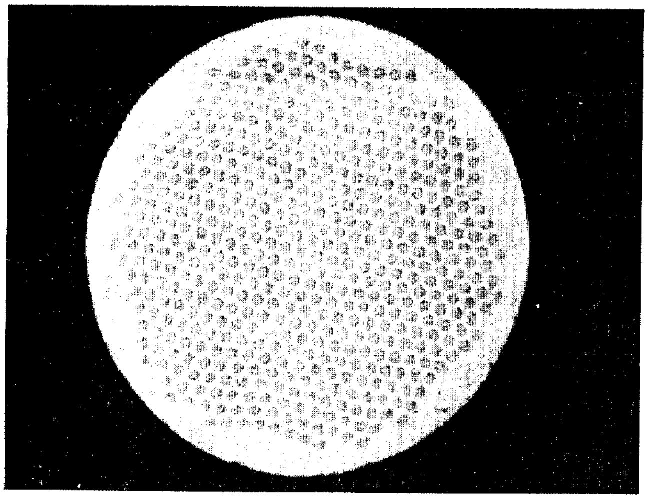
FIG. 1: 517 NbTi filaments in copper (59 v/o) matrix.

In order to reduce the coupling losses between adjacent strands, the wire exterier can be sheathed with a high purity Cu-10 Ni alloy, as in the BNL Isabelle braid of 97 - 0.3 mm diameter wires containing approximately 15 v/o Cu-10 Ni, 44 v/o copper, and 41 v/o NbTi. This braided conductor has been manufactured in thousands of pounds quantities in a production operation involving four braiding machines running around the clock. Each strand within the braid has 8 μm NbTi filaments and an outer Cu-10 Ni jacket approximately 10 μm thickness. Each wire strand has a critical current of 55 amperes at 5 T, 4.2 K, such that the resultant 97-strand braid (0.91 mm x 15.81 mm) has a critical current of 5200 amperes at 5 T, 4.2 K. This braid is normally manufactured in 0.9 km unit lengths (52.3 kg). An alternate thicker version of braid employs 59 - 0.56 mm diameter strands of the 517 filament wire to yield a conductor having a critical current (10^{-12} ohm-cm) of 10,620 amperes @ 5 T, 4.2 K.

The 517 filament wire has also been used by Brookhaven National Laboratory for the Isabelle trim coils (i.e. field correction coils). The conductor is a 7-strand cable filled with 95 Sn - 5 Ag solder and insulated with two layers of braided glass yarn insulation. An alternate insulation scheme utilizes a double wrap of 0.025 mm kapton overlaid with a single layer of braided glass yarn.

The 517 filament wire configuration is very desirable from a manufacturing point of view due to the mechanical stability of the billet during the extrusion process. Although it is sometimes desirable to insert as many as 2200 filaments into an extrusion billet, the accumulated tolerances between the hexagonal copper tubes result in a loose packing density. During the extrusion process, this looseness allows the motion of NbTi rods such that non-uniform mechanical metallurgical deformation (i.e. billet "upset") occurs. This phenomenon often results in wire drawing problems (e.g. short lengths due to breakage) and poor V-I take-off characteristics.

Occasionally the need for small filaments in fine wires is of overriding importance, as in the Fermilab Energy Doubler/Saver conductor. This need has resulted in a rather standard 0.7 mm diameter superconducting wire of 2160 filaments (8 μm diameter) contained within a cross-section of 64 v/o Cu (Fig. 2). This

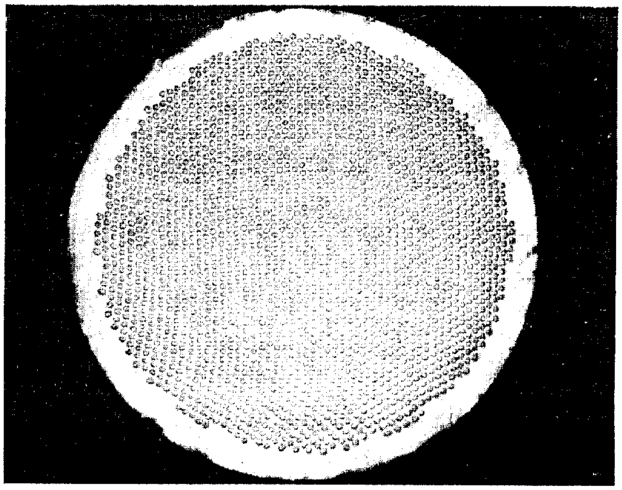
FIG. 2: 2160 NbTi filaments in copper (62 v/o) matrix.

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wire is typically formed into a 23-strand two-high (i.e. Rutherford) cable. In an effort to produce dipole magnets having higher current densities, Airco has manufactured Rutherford cables containing 27 - 0.81 mm wires having 2160 filaments.

It is also feasible to form a Rutherford cable from an array of subcables, each of which contains seven wires joined together with an ac impeding Pb-Sn solder (Fig. 3). This construction allows the building up to high critical currents but retains the stability advantages of fine wire strands and large numbers of fine filaments.

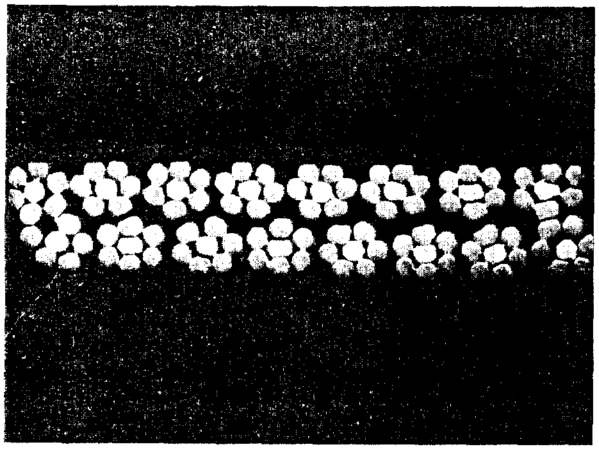

FIG. 3: Flat cable of 18 subcables (six 517 filament wires).

The 517 filament basic wire can also be used to manufacture larger monoliths having higher current densities and longer continuous lengths than are achievable by the usual production techniques (i.e. large extrusion billets) for large monolithic conductors. The current densities of conventional monoliths are typically lower than smaller wires due to the limited amount of mechanical cold work imposed upon the conductor. Therefore, higher currents can be obtained with maximum utilization of the costly superconductor alloy with a built up assembly of small wires, as in cables or braids. However, the mechanical properties and dimensional stability of built up conductors are often inferior to monolithic conductors. A novel monolithic fabrication process employed by Airco is to continuously sheath several (i.e. 8 to 37) multifilamentary wires (517 NbTi filaments, 59 v/o copper) with high conductivity copper strip in a tube mill. After sheathing, the conductor is drawn as a conventional monolith through wire drawing dies (Fig. 4) and then shaped to rectangular cross-sections with turkshead rolls and a final sizing die for close dimensional and corner radius control. This technique is applicable to many conductor designs. For example, high resistivity barriers can easily be incorporated within the monolith by copper sheathing of 517 filament wires which contain an outer layer of Cu - 10 Ni (Fig. 5). This construction provides an intrinsically stable conductor which provides high electrical resistance to eddy currents in pulsed field or ac environments. After twisting, this conductor has improved filament transposition compared to conventional monoliths.

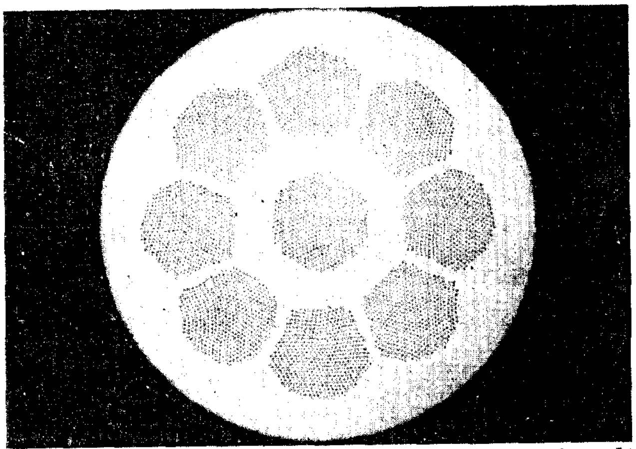

FIG. 4: Monolith of 4653 filaments fabricated from 517 filament wire.

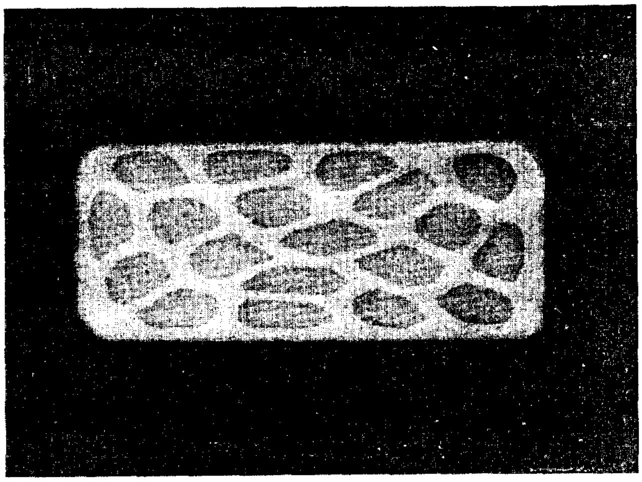

FIG. 5: Monolith of 9823 filaments with Cu-Ni barrier fabricated from 517 filament wire.

Next Generation 10 T Magnets

It has been suggested by several workers in the high energy physics community that future accelerators, beyond the BNL Isabelle and FNAL Energy Doubler/Saver, will require 10 T fields. These magnets will require superconductors having significantly higher current densities which cannot be provided by the usual NbTi alloys (e.g. Nb - 46.5 Ti) operating at 4.2 K. Although NbTi alloys subcooled to 2 K are a possibility, recent work has revealed that significantly higher current densities can be obtained in NbTiTa ternary alloys subcooled to 2 K. And finally, the high current densities and high critical temperatures afforded by Nb_3Sn are well known.

Although many considerations are involved in selecting a 10 T accelerator superconductor, Table 1 focuses on the rather high priority item of cost of the basic superconductor alloy, isolated from other material and labor costs, in relation to the current carrying capacity of the conductor. Based upon this criterion alone it is clear that Nb_3Sn operating at 4.2 K, offers a large economic advantage over the other listed candidate alloys. Although it is certainly recognized that the processing costs of Nb_3Sn are higher than NbTi and NbTiTa alloys, the significantly lower alloy cost per kA meter of Nb_3Sn ought to be carefully considered for 10 T dipoles. It is reasonable to expect that in a large accelerator construction project involving large quantities of conductors, the relative processing costs would be reduced such that the alloy cost per kA meter factor will assume overriding importance.

The experience in recent years in manufacturing large quantities of various Nb_3Sn conductors for fusion and high energy physics suggests that a sufficient technology base (5) exists in the manufacturing of Nb_3Sn conductors, as evidenced by Airco LCP (Fig. 6) HFTF, in-situ, and other development programs prinipally supported by BNL and LLNL, to assure a supply of Nb Nb_3Sn conductor for 10 T high energy physics applications.

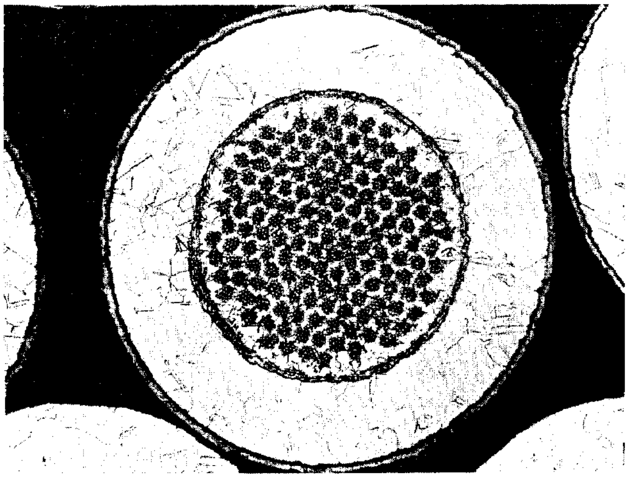

FIG. 6: Nb_3Sn wire strand (65 v/o copper) containing 2869 filaments in bronze matrix surrounded by tantalum diffusion barrier.

Acknowledgements

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TABLE 1

UTILIZATION OF SUPERCONDUCTING ALLOYS AT 10 TESLA

Wire Diameter : 1 mm
Copper Percentage: 66.7%

ALLOY	T	J_c@10 T (A/mm^2)	kA·m / km	kg Alloy / km	Alloy Density (g/cm^3)	Alloy Cost / kg	kA·m / kg Alloy	Alloy Cost / kA·m
Nb-46.5 Ti	2 K	1200(1)	314	1.57	6.0	$172	200	$0.86
Nb-44Ti-8Ta	2 K	1500(2)	392	1.76	6.7	$374(3)	223	$1.67
Nb-43Ti-25Ta	2 K	1600(2)	418	2.10	8.0	$517(3)	199	$2.59
Nb*in Nb_3Sn	4.2 K	589(+)	154	0.55	8.4	$127(4)	280	$0.45

* 25 v/0 Nb in bronze
\+ J_c in (Nb + bronze)

(1) D.C. Larbalestier, to appear in "Superconducting Materials", edited by S. Foner and B.B. Schwartz, Plenum Press, 1981.

(2) H.R. Segal et al., Trans IEEE, MAG-17, No. 1, Jan. 1981, 53.

(3) Per Teledyne Wah Chang Albany (3/10/81), base price for quantities in excess of 455 kg.

(4) Per Cabot Corp., KBI Division (3/9/81).