PROPERTIES OF NbTi AND Nb_3Sn FINE FILAMENT CONDUCTORS

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Abstract

Recent results on superconductors for accelerator dipoles and quadrupoles are described. These conductors consist of keystoned flat cables built up from between 20 to 40 multifilamentary strands. The most important parameters are the transport critical current density and the effective filament diameter, because they determine the maximum achievable field and the field homogeneity. Both, NbTi and Nb_3Sn conductors with fine filaments and high critical current density were developed. Conductor design, critical current values and magnetization characteristics are presented. Effective filament diameters of down to 5 μm were achieved for NbTi and to less than 10 μm for Nb_3Sn without sacrificing critical current density. At 4.2 K the wires exhibited more than 3000 A/mm^2 at 5 T and more than 800 A/mm^2 at 10 T for NbTi and Nb_3Sn, respectively.

Introduction

The next generation of hadron colliders like LHC at CERN, UNK in Soviet Union and SSC in United States calls for superconducting dipoles and quadrupoles with high magnetic fields and high field quality, i.e. low disturbance by higher multipole components. This requires superconductors with high transport critical current density at high fields and, simultaneously, with low magnetization by persistent currents at low field. The both requirements are contradictory in principle and can be accomodated only by using multifilamentary conductors with very fine filaments (typically 5 μm or below).

The wire fabrication process consists of a warm and cold working process from billet size (typically 250 mm diameter) to final dimensions (0.6 to 1.2 mm diameter). Typically the matrix (Cu) behaves softer than the superconductor. The geometry (e.g. filament separation) and the process parameters (e.g. processing temperatures) must be carefully adjusted to avoid an non-uniform deformation ("sausaging") of the filaments.

The composite consists virtually only of interfaces between different metals and alloys. Diffusion processes and formation of intermetallic compounds take place during each heat treatment, leading to a deterioration of the workability. On the other hand hot or warm working is necessary to allow bonding between the components. Intermediate heat treatments are necessary to optimize the current carrying capacity (NbTi) or for annealing purposes (Nb_3Sn bronze route). A careful adjustment of process temperatures and/or diffusion barriers are required.

The theoretical filament diameter and spacing are given by the billet design. Distortions can occur due to insufficient filling factor in the billet or non-uniform forming processes. Hot isostatic compaction and/or hydrostatic extrusion must be applied, especially in case of single stage bundling of many thousand elements. Too small spacing leads to magnetic filament coupling increasing the magnetization and the "effective" filament diameter to a multiple of the theoretical filament diameter. "Metallurgical" coupling may occur by touching of filaments due to uneven deformation and with Nb_3Sn by the growth of the filaments due to the 38 % volume increase during reaction from Nb to Nb_3Sn. Even in absence of touching filaments, the magnetization and the effective filament diameter can be enlarged in low fields by "proximity" coupling by tunneling of the superconducting carriers through the thin matrix especially with Cu as a matrix material.

Measurements and Evaluation

All measurements reported here were performed at 4.2 K. Critical current measurements were done on short samples and helix samples with the external field perpendicular to the conductors. As a rule, the selected I_c criterion was $10^{-14}\,\Omega$m for NbTi and 0.1 μV/cm for Nb_3Sn, respectively. Self field corrected j_c values were calculated by adding the self field of the transport current to the external field and by assuming that the critical current is reached when the filaments at the wire outer edge becomes resistive.

Magnetization measurements were performed independently in two different vibrating sample magnetometers with short pieces of conductors exposed to a field perpendicular to the wire axis.

The raw data of magnetic moments m were transfered into magnetization data by dividing through the wire volume V (wire magnetization M) or the volume $V_s = \lambda V$ of the filaments (superconductor magnetization M_s). Filament diameters were calculated from the full width of the magnetization curve $2\,\Delta M$ using the following relation:

(1) [illegible]

In this relation λ is the overall area fraction of superconducting filaments and j_c is the magnetization critical current density of the filaments which, for uniform filaments only, is equivalent to the self field corrected transport critical current density.

NbTi Conductors

NbTi fine filament conductors with filament numbers of 3500 up to 6000 were produced by single stacking of NbTi/Nb/Cu hexagons [1]. The thickness of the Nb diffusion barrier was optimized for 5 to 6 μm filament diameters.

Figure 1 shows a cross section of a strand with 6000 filaments and a Cu/NbTi ratio of 1.8 at a diameter of 0.65 mm.

This conductor was used for testing different optimization schedules using only technically relevant heat treatment numbers of 2 to 3. With filament diameters of 5 μm up to over 3000 A/mm^2 at 5 T and over 1100 A/mm^2 at 8 T were achieved. The measured n-values were of the order of 40 - 50 at 5T and 25 - 30 at 8 T. Filament sausaging was negligeable.

The same conductor was also used in optimization series for 2.6 μm filament size

(0.33 mm wire diameter). As expected, the Nb barrier was to thin to prevent formation of intermetallic particles such that the filament quality was degraded together with the superconducting properties [1].

Magnetization measurements were performed on both, the 2.5 μm and 5 μm type conductors. High field magnetization measurements were in good agreement with calculation according to equation (1). Low field magnetization curves were taken to detect possible proximity coupling effects. Two typical curves are shown for the 5 μm filament wire (Fig. 2) and the 2.6 μm filament wire (Fig. 3) with nominal filament spacings of 1 μm and 0.5 μm, respectively. The curve for 5 μm filaments shows no indication of coupling except of a very minute bumps in the magnetization curve (see arrows in Fig. 2). The low field magnetization data of this conductor were therefore taken to extrapolate j_c to zero field (see Fig. 6). The bump in the return paths increases markedly in the case of 2.6 μm filaments. In addition, the initial slope of the virgin curve is much steeper due to the filament bundle acting as a single filament in the very low field region.

These results indicate that in NbTi conductors with Cu matrix at 4.2 K coupling starts at filament separations below 1 μm but is significant only at low fields.

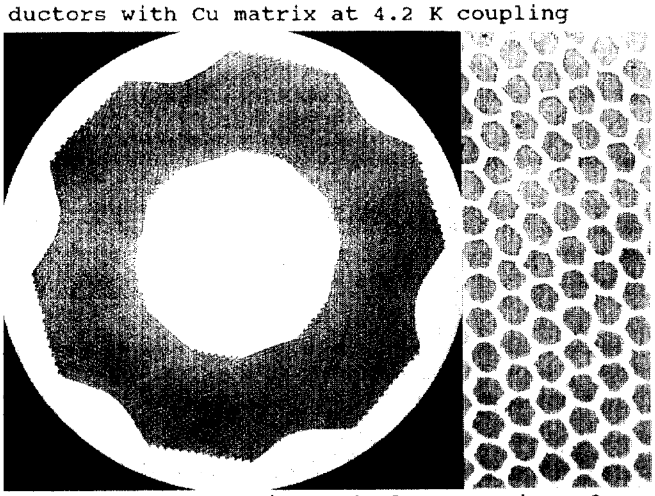

Fig. 1: Cross section and close-up view of a filamentary wire with 6000 filaments of 5 μm diameter (wire diameter 0.65 mm).

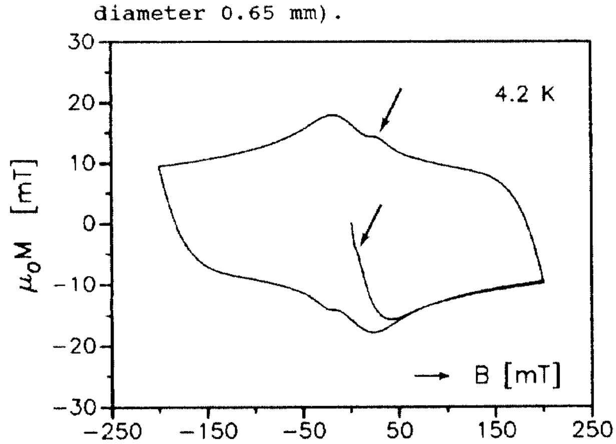

Fig. 2: Magnetization M (i.e. of NbTi+Cu volume) of the wire shown in Fig. 1 (nominal filament spacing 1 μm, $\lambda = 0.36$). The arrows indicate inception of filament coupling.

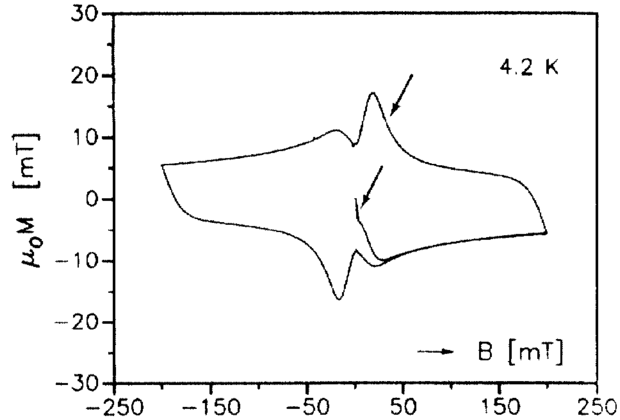

Fig. 3: Magnetization M of the wire shown in Fig. 1 processed to 0.33 m diameter, corresponding to 2.6 μm filament diameter and 0.5 μm spacing (λ = 0.36). Coupling effects are indicated by arrows.

Nb_3Sn Conductors

The task of reconciling the two requirements of having a high transport critical current density and having decoupled fine filaments is much more complex in Nb_3Sn than in NbTi. High j_c versions of Nb_3Sn conductors exhibit either large geometrical filaments (tube techniques) or densely packed filaments coupled together by intergrowth of the filament during reaction heat treatment. The best compromise seems to be possible by the bronze process with a geometry optimized for low magnetization [2].

The local ratio of bronze matrix to Nb filaments is typically chosen to be about 0.6 as for NbTi conductors in a Cu matrix. The additional bronze to get the needed overall ratio of 3:1 is added in a lumped way (e.g. in the outer shell of the billets). This design is adequate for pure DC applications. But due to the intergrowth of filaments the sub-bundles of the first stage extrusion tend to act magnetically as a single filament. There is, however, the possibility to redistribute the bronze into the filamentary area. By using of a much higher local ratio of 1.2 to 1.5 the intergrowth and the coupling can be prevented largely. In addition, the j_c values tend to increase with this arrangement of the tin sources close to the filaments.

Figure 4 shows an externally stabilized binary Nb_3Sn conductor with a Ta diffusion barrier and a local matrix to Nb ratio of 1.5:1.

The measured j_c values (Nb+CuSn area) for this type of conductors at 10 T and 4.2 K were between 800 to 850 A/mm^2 even with a non-negligeable amount of sausaging being visible in the micrographs. Enhancement of j_c to 1000 A/mm^2 and above seems therefore possible.

The degree of coupling was investigated by magnetization measurement. A high field magnetization curve is shown in Fig. 5. For this particular measurement an effective filament diameter d_{eff} of about 6 μm was calculated from equation (1). This is about a factor of 2 larger than the nominal diameter. Evaluation of the measurements on a series of

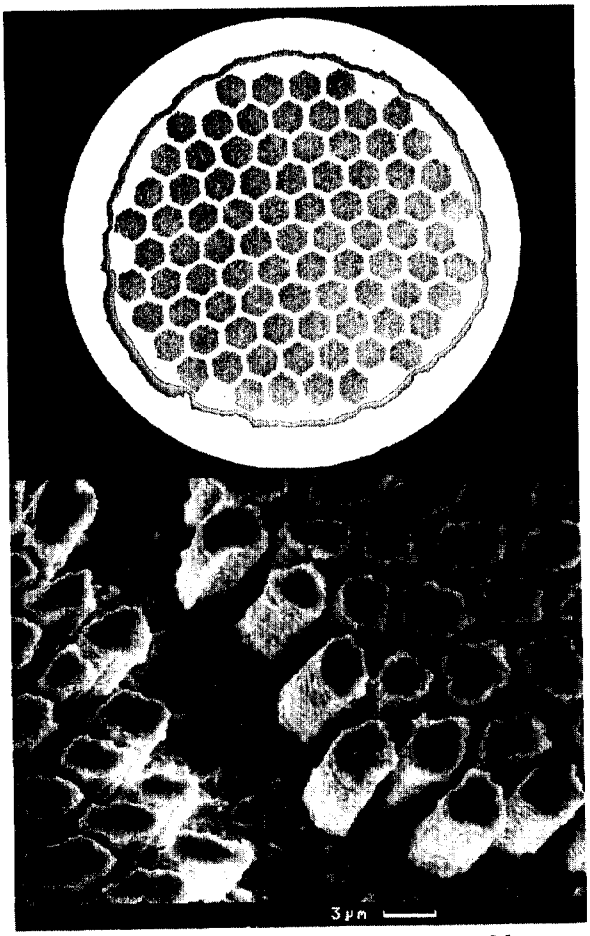

Fig. 4a) Cross section of an externally stabilized Nb_3Sn conductor with Ta barrier (0.92 mm diameter).
4b) Close-up view of the reacted filaments (3 μm nominal diameter).

samples yielded a relative large scatter of the magnetization width, but the calculated effective filament diameter was consistently below 10 μm. Low field magnetization measurements similar to those performed for NbTi revealed no sign for additional proximity coupling.

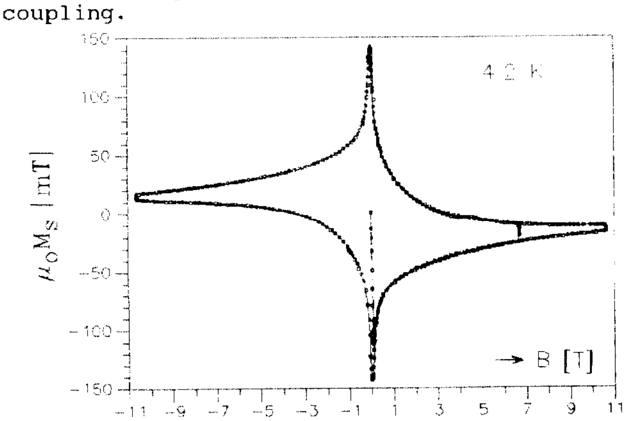

Fig. 5: Magnetization M_S (i.e. of filament volume) of the 20000 filament Nb_3Sn conductor shown in Fig. 4 (λ = 0.18). The (inverted) paramagnetic signal is due to the magnetization of the sample holder.

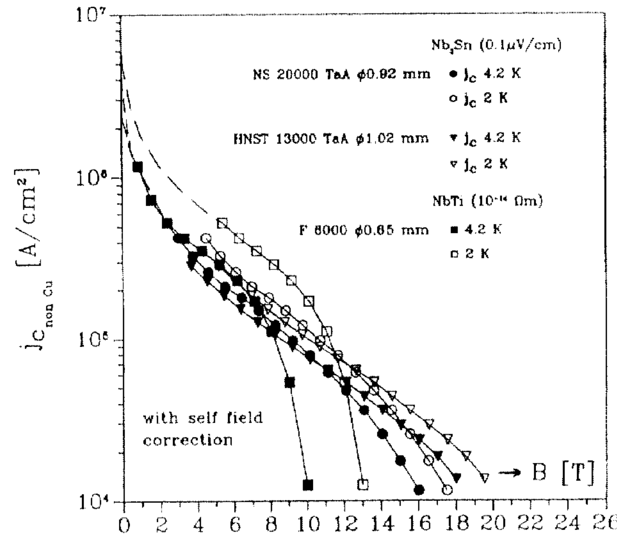

Fig. 6: Self field corrected non stabilizer critical current densities of NbTi, Nb_3Sn [NS], $(NbTa)_3Sn$ [HNST] fine filament conductors at 4.2 K and 2 K.

Comparison of NbTi and Nb_3Sn

The actual data of critical current densities of NbTi, Nb_3Sn and $(NbTa)_3Sn$ fine filament conductors with small effective filament diameters are summarized in Fig. 6. Self field corrected values are given to account for the significant contribution of the self field in an external field close to zero. The 4.2 K data are measured values and are extrapolated to zero by using the magnetization curves for calculating j_c from equation (1). Curves for j_c at 1.8 K are also given as a best possible estimation from previous measurements and theoretical considerations using the scaling behaviour of the flux pinning force.

Keystoned cables

Keystoned flat cables made from NbTi and Nb_3Sn fine filament conductors were described already elsewhere [1,3]. Successful dipoles and quadrupoles were made from these cables. In this context it should only be mentioned that degradation of conductor performance has to be taken into account. The degradation of j_c values is rather moderate in NbTi ($\leq$ 5 % typically) and virtually zero in Nb_3Sn.

Conclusions

Fine filament conductors were developed and produced on an industrial scale for both NbTi and Nb_3Sn. NbTi wires with effective filament diameters of about 5 μm with very high j_c values can be achieved. Similar effective filament diameters and relatively high current densities can be reached in bronze route processed Nb_3Sn conductors.

References

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