ADVANCES IN ITER RELEVANT Nb-Ti AND Nb_3Sn STRANDS AND LOW-LOSS NbTi STRANDS IN RF

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Abstract

The review of the main results of R&D directed on the enhancement of ITER relevant NbTi and Nb_3Sn strands performance recently carried out in Russia (the Bochvar Institute) are presented.

For ITER PF type (NbTi) strands with Cu/non Cu ratio of 1.6 the attainment of ITER specified critical current density (J_c) ≥ 2900 A/mm^2 (5 T, 4.2 K) has been shown. For Toroidal Field (TF) strands (Nb_3Sn) the influence of doping and layout peculiarities of the wires produced by bronze method on their current-carrying ability has been investigated. It was shown that with non-doped matrix and doped filaments J_c exceeds 800 A/mm^2 (12 T, 4.2 K) while with the application of the doped bronze and non-doped filaments it exceeds 900 A/mm^2.

Internal-tin Nb_3Sn strand meeting the ITER TF specification requirements was also developed and fabricated. The results of testing of CICC samples in a SULTAN facility have shown that performance parameters are higher than ITER qualification requirements

Low loss model fine filament NbTi strands, intended for operating in fields with a ramp rate from 1 up to 4 T/s, has been developed and manufactured. The use of commercial MN-5 alloy (Cu-5wt.%Ni) and the Cu-0.5wt.%Mn alloy for matrix of strands are discussed. The critical current density higher than 2700 A/mm^2 (5 T, 4.2 K was shown to be attainable.

NB-TI STRANDS

In the Russia the development of Nb-Ti strands for ITER Project was based on the rich experience accumulated during almost 40 years of the development of the technical NbTi strands for different applications. Several typical examples of such strands that were produced commercially at the Ust-Kamenogorsk plant (established in 1970-s in the USSR) are presented in the Fig.1.

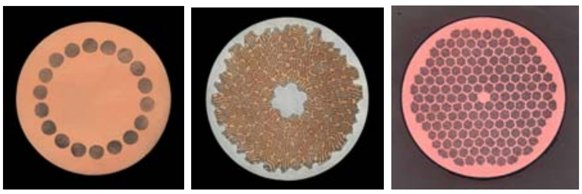

Figure 1: The Nb-Ti strands for different applications: a) for MRI tomographs, b) for AC electro technical devices, c) Strand for accelerator UNK (CKHT-8910-042).

The strand CKHT-8910-042 presented in the Fig.1c was designed for the accelerator UNK and produced commercially in amount of more than 100 tons. The strand of 0.85 mm in dia with the filaments diameter of 6 μm had the critical current density Jc (5T, 4.2K) - 2500 A/mm^2.

In the framework of ITER Project the RF Party has manufactured the Nb-Ti Cable (~0.5 ton), and shipped it to EFDA for further fabrication of the model Poloidal Field Coil Insert (PFCI). The testing of PFCI planned to be carried out in Japan (JAERI) in CSMC in June 2008. The cross section of this strand is presented in Fig. 2.

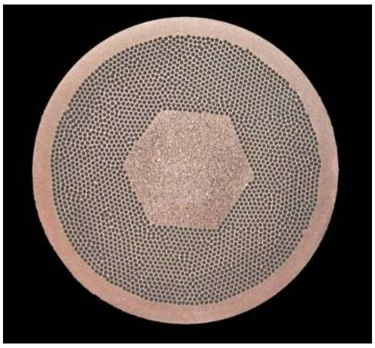

Figure 2: The Nb-Ti strand for ITER model coil PFCI. Strand diameter: 0.73 mm, number of filaments: 2346, filament diameter: 9.8 μm, Cu/non Cu ratio: 1.4, J_c > 2700 A/mm^2 (5T, 4.2K) (measured values: 2800-2900 A/mm^2).

In the frame of ITER Project the RF has to produce 40 t of Nb-Ti strands for PF 1&6 conductors and fabricate PF1 coil. The first model strands produced industrially from the billets 250 mm in diameter is presented in Fig. 3.

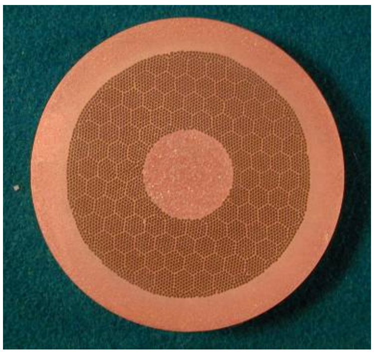

Figure 3: The Nb-Ti strand for ITER PF1&6 coils. Strand diameter: 0.73 mm, Cu/nonCu ratio: 1.6, filament diameter: 6.8 μm.

It was shown that the designed strands with Cu/non Cu ratio 1.6 met the requirements of ITER Specification for 4.2 K, 5T (J_c = 2900 A/mm^2), but at the high temperature (6.5 K) and in the high magnetic field of 6 T J_c was dropped to less than 100 A/mm^2.

For low loss Nb-Ti strands supposed to be used in the relatively high ramp rate magnetic field the specific specifications have to be met. Strands should be with small diameter filaments embedded in a resistive matrix and contain the resistive barriers. Minimum specification for J_c at 4.2 K and 5 T is 2500 A/mm^2; filament diameter reduction has to be attained with negligible coupling. Maximum effective filament diameter D_{eff} is 3 μm, with a target D_{eff} of 2 μm. An effective filament diameter of 3 μm corresponds to a hysteresis loss Q_h of 65 mJ/cm^3 of Nb-Ti for a bipolar field cycle +/- 3 T. An effective filament diameter of 2 μm corresponds to a Q_h of 48 mJ/cm^3 of Nb-Ti for a bipolar field cycle +/- 3 T.

Two types of resistive alloys were used as a matrix material – commercial available Cu-Ni alloys with Ni content from 5 to 10 wt%, and Cu-0.5%Mn alloy produced by induction vacuum melting. This alloy has RT resistivity of 3.41-3.42 μΩ·cm and resistivity in liquid helium – 1.70 μΩ·cm.

Fine filament (3.5 μm in diameter) NbTi strand for operating in fields with sweep rate up to 4 T/s was developed in Bochvar Institute (BI). The strand was fabricated by a single stacking method. Each of 10644 filaments was surrounded by a matrix of commercial MN-5 alloy (Cu-5wt.%Ni). The spacing was 0.5 μm. The central Cu core, tubes and the external sheath are fabricated from Cu with (R_{273}/R_{10}) > 250. RRR of the final strand is ~ 200. The cross section of this wire is shown in Fig. 4.

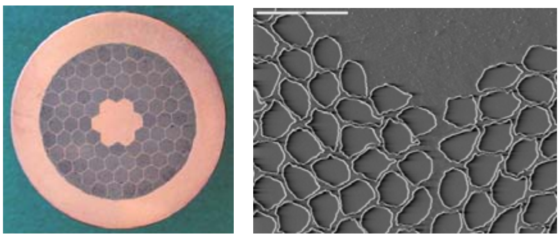

Figure 4: Low loss Nb-Ti strand 0.65 mm in diameter. Number of filaments: 10644; Cu/non Cu ratio: 1.8; combined matrix – Cu/ Cu-5wt.%Ni.

The properties of the wire were as follow: $J_c \geq 2900$ A/mm^2 (5 T, 4.2 K). The hysteresis losses = 51 kJ/m^3 per wire and 144 kJ/m^3 per superconducting volume.

Nb-Ti strands in resistive matrix for nuclotron type cable were designed for application in fast rate changing (up to 4T/s) magnetic field [1]. The design and cross section of trapezoidal cross section NbTi/Nb/Cu-5%Ni/Cu strand with 10374 filaments (6μm) fabricated by single stacking from billet 150 mm in diameter are presented in Fig. 5. Cu/non Cu ratio= 1.8. Nb-Ti, Nb, CuNi and Cu occupy 33.3%, 2.7%, 18.5% and 45.5% of the strands cross-section area respectively [2].

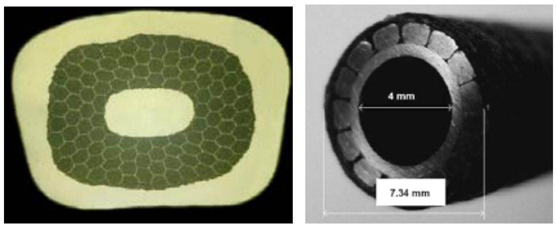

Fig.5. Low loss Nb-Ti strand designed for nuclotron magnets working at fast rate changing (up to 4T/s) magnetic field. Left: cross section of the strand. Right: cable for nuclotron magnet.

The AC losses were measured by calorimetric method at field amplitudes 1.05 T and 0.54 T. At nominal for SIS 100 dipole field rate of 4 T/s and field amplitude B=1.05 T the losses value normalized to overall strand volume are less than 30 mJ/cm^3 and 80 mJ/cm^3 for NbTi (see Fig. 6) [3].

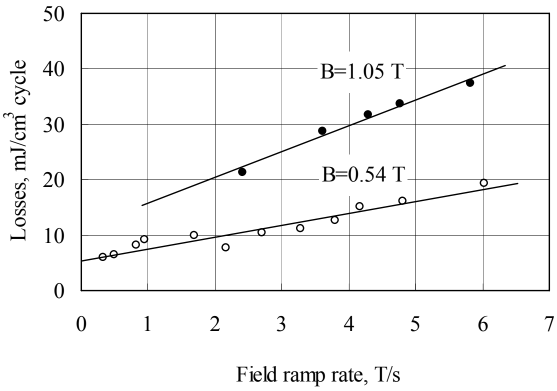

Figure 6: Hysteresis losses of the Nb-Ti trapezoidal cross section strand in different field ramp rates.

ITER-TYPE NB_3SN STRANDS

Starting from the middle of 1970-s both main types of Nb_3Sn multifilamentary strands (bronze and internal tin) were under the development. The typical cross sections of these early designed strands are shown in Fig. 7.

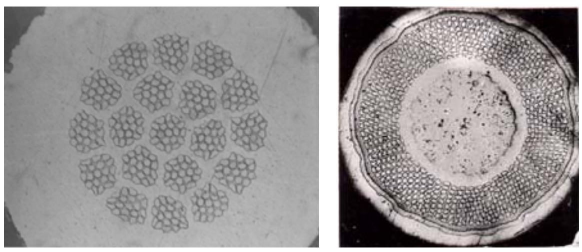

Figure 7: Cross sections of the Nb_3Sn strands; non stabilized bronze processed strand, 361 filaments (left); Cu stabilized Internal tin strand, 650 filaments (right).

For large magnet systems of fusion reactors the bronze processed strands were chosen to be used primarily because of simpler reaction heat treatment needed which assumed only solid state diffusion process for Nb_3Sn phase formation. Non-stabilized Nb_3Sn strand for Tokamak T-15 is presented in Fig. 8 altogether with the Rutherford type conductor, which was produced from these strands by applying the stabilizing copper after reaction heat treatment through the electrolysis process.

Figure 8: Left: Cross section of the Non stabilized bronze processed strand 1.5 mm in diameter; number of filaments: 14641; filaments diameter: 5 µm; J_c @ 8 T: 510 A/mm^2; average I_c: 900 A. Right: cross section of conductor for T-15; critical current @ 8 T is ~ 11.5 kA, i.e., ~ 110% of single strands current ability (11×900 A).

Approximately 90 tons of conductors were produced in an industrial way, which assumed production of more than 25 tons of strands.

In the frame of ITER Project the stabilized Nb_3Sn bronze processed strand (see Fig. 9, left) was developed and produced in amount of 1 ton. This strand was used for the fabrication of ITER TF Conductor (see Fig. 9, right) by cabling and jacketing in the Ti seamless tube.

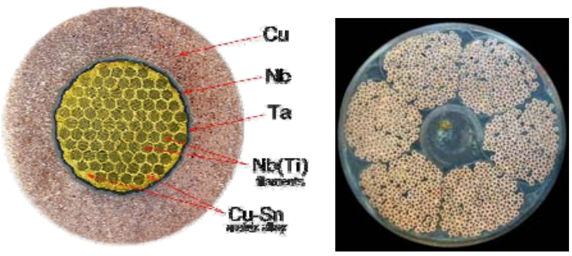

Figure 9: Left: cross section of stabilized bronze processed strand for ITER TFCI; diameter=0.81 mm, J_c @ 12T > 550 A/mm^2, hysteresis losses (+/-3T) < 200 mJ/cm^3, RRR > 100, Cu/(non Cu) = 1.5. Right: cross section of the cable in conduit conductor for TFCI.

The effect of degradation under mechanical loading was identified as an important issue for large magnet systems wound with CICC on the stage of ITER large model coils program. The strands with enhanced mechanical strength were developed (see Fig. 10). Mechanical strength was significantly (in a factor of 1.3-1.5) increased by replacing of certain part of stabilizing Cu on the nanostructured Cu-Nb layer. J_c of reinforced strands maintains at the same level.

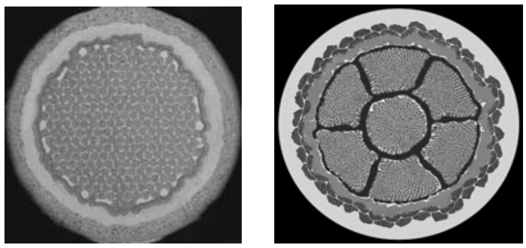

Figure 10: Strengthened by nanostructured CuNb alloy Nb_3Sn strands. Left: bronze processed strand with Cu-Nb layer replacing outer part of stabilizing Cu. Right: internal tin strand with Cu-Nb rods replacing the inner part of stabilizing Cu.

Due to overcome the consequences of the possible degradation of superconducting properties the new enhanced specification on the critical current density of TF strands (J_c >750 A/mm^2) was introduced by ITER. Development and fabrication of Nb_3Sn IT strand, meeting enhanced ITER TF specification for TF conductor's SULTAN sample testing has been performed (see Fig. 11 and Table 1). Fabricated strand total amount is ~110 kg (22.5 km).

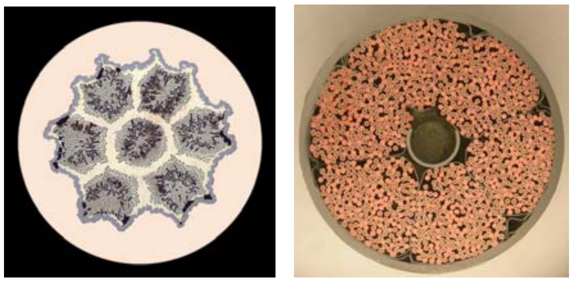

Figure 11: Cross sections of the internal tin Nb_3Sn strand, with J_c=830-950 A/mm^2, Non-Cu hysteresis losses (±3T; 4.2 K)=850-980 kJ/m^3 (left) and TF Conductor SULTAN sample, which met new ITER Specification Option 1 (right).

It is well known that in internal tin strand much higher J_c could be attained (up to 3000 A/mm^2 at 12 T, 4.2 K) due to the practical absence of limitation on the tin amount available for the Nb_3Sn phase formation. The comparison of the design features and properties of ITER type and so called high J_c internal tin strands is given in the Table 1. The quality of Nb_3Sn phase after heat treatment with last stage at 575° C 150 h + 650° C 200 h is essentially close to a quality observed in bronze processed strands (uniaxed grains and average grain size - approximately 90 nm).

The analysis of microstructure enables to suggest that large increase of J_c (not proportional to the increase of volume fraction of Nb_3Sn phase) is probably caused by the bridging of filaments. At the same time too strong bridging is negative for a stability of the strands.

Table 1. Properties of the ITER type and high J_c type internal tin Nb_3Sn strands

	ITER	High J_c
J(non Cu), [A/mm^2] (12 T, 4.2 K, 0.1 μV/cm, no external strain)	745	2070
Calculated volume fraction of Nb3Sn inside diffusion barrier, %	38.9	45.8
Qh, Hysteresis Loss [mJ/cm^3 non-Cu], @± 3T	~300	>1000
Calculated J_c(Nb_3Sn) [A/ mm^2] @12 T, 4.2 K	**2180**	**4850**

The practically attainable volume fraction of Nb_3Sn phase in bronze process strand is ~ 35% in the area inside the diffusion barrier. Therefore the requirement of J_{nc}= 800 A/mm^2 (12 T, 4.2 K) assumes the attaining of critical current density in Nb_3Sn phase equal to ~ 2700 A/mm^2.
Three main possible ways of J_c increase could be considered:

- increase of quantity of Nb_3Sn phase (increase of Sn in bronze matrix);
- increase of quality of Nb_3Sn phase (increase of pinning by modification of microstructure);
- controlled bridging (optimization of the strand's design).

In the Cu-Sn matrix alloys the Sn content gradually increased from 10wt.% up to the limit of 16wt.%. The artificial doping of the Nb filaments by Ti has been designed and proved to be effective for both types of Nb_3Sn strands (bronze processed and internal tin) improving the quality of the Nb_3Sn microstructure by diminishing of the average grain size and almost eliminating the nonuniformity in microstructure of the Nb_3Sn layer. The bronze processed Nb_3Sn strands with controlled bridging of filaments were designed (see Figs. 12-13).

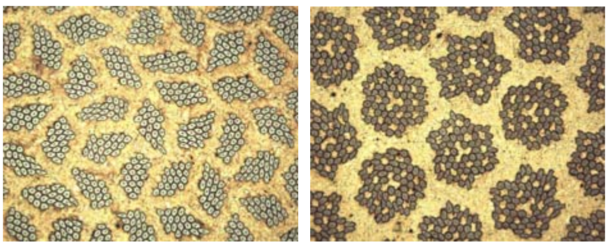

Figure 12: Bronze processed Nb_3Sn strands with controlled bridging of filaments.

As it was expected the J_c of the strands increased significantly to the values higher than 750 A/mm^2 (12 T, 4.2 K) in conditions of the same content of tin in bronze matrix. Also as expected the level of hysteresis losses increased proportionally to the diameter of the groups of filaments and attained the levels of 546 kJ/m^3 (for strand in Fig. 12, left) and 786 kJ/m^3 (for strand in Fig. 12, right) for standard ± 3T testing. The strands with controlled bridging and lower level of hysteresis losses (Q_h<350 kJ/m^3) were also designed (see Fig. 13, right).

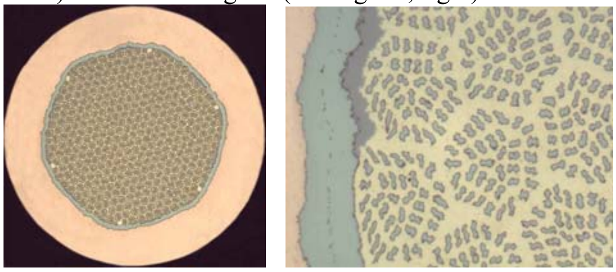

Figure 13: Bronze processed Nb_3Sn strands with controlled bridging of filaments and low hysteresis losses.
The critical current properties for the fields in the range of 8 T to 12 T are presented in Fig. 14. It was shown that for the diameter of the strand 0.82 mm (ITER specification) the values of J_c exceeded 900 A/mm^2.

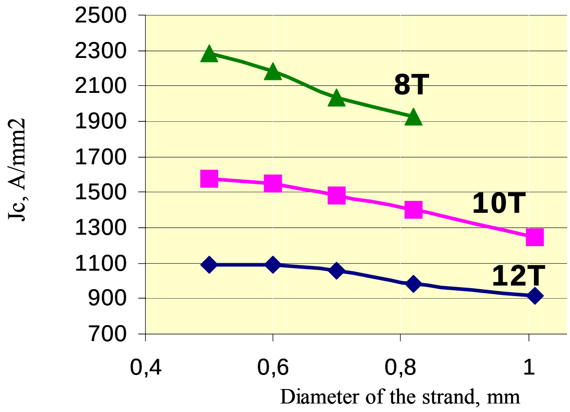

Figure 14: Dependence of J_c vs. strand diameter for the bronze processed strand with controlled bridging and low hysteresis losses.

CONCLUSIONS

Nb-Ti strands with Cu/non Cu ratio 1.4-1.6 designed for the use in ITER PF 1&6 coils have $J_c \geq 2900$ A/mm^2 (5 T, 4.2 K) and meet the ITER specification.

Nb-Ti strands with low-loss for application in Fast Cycled Superconducting Magnets made a good progress recently (strands with 3-4 μm filaments in resistive matrixes have been produced), and the work is ongoing. Still some R&D work has to be done to attain target value.

Bronze processed ITER type Nb_3Sn strands made a good progress in critical current density, attaining 800 A/mm^2 (non-Cu, 12 T, 4.2 K) in commercially produced wires. In laboratory scaled wires 900 A/mm^2 (non-Cu, 12 T, 4.2 K) has been attained. The internal tin technology has been successfully proved by testing a full scale TF conductor sample in SULTAN facility.

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