Advances in ITER relevant NbTi and Nb_3Sn strands and low-loss NbTi strands in RF.

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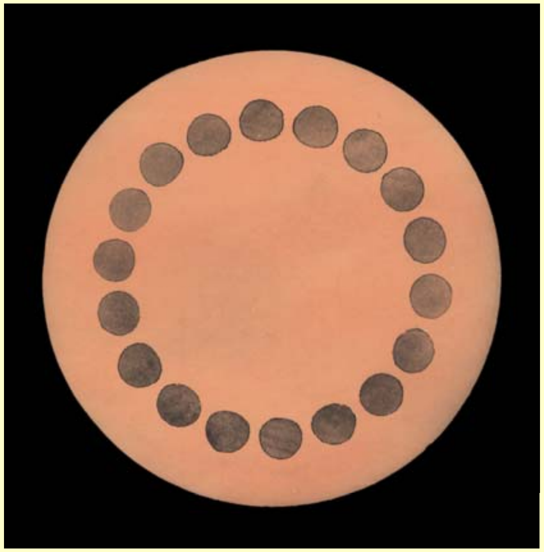
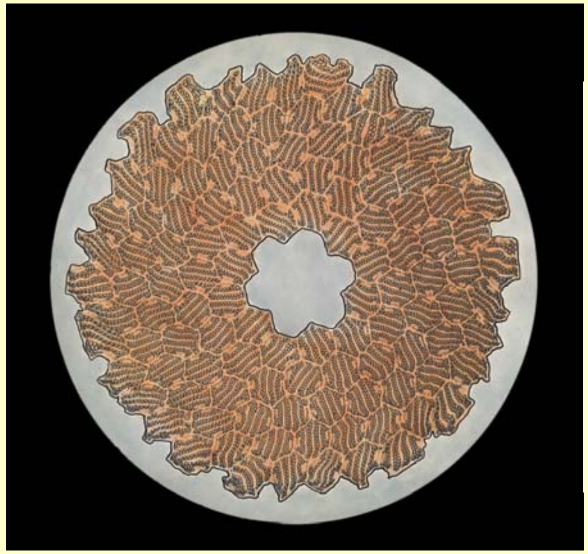
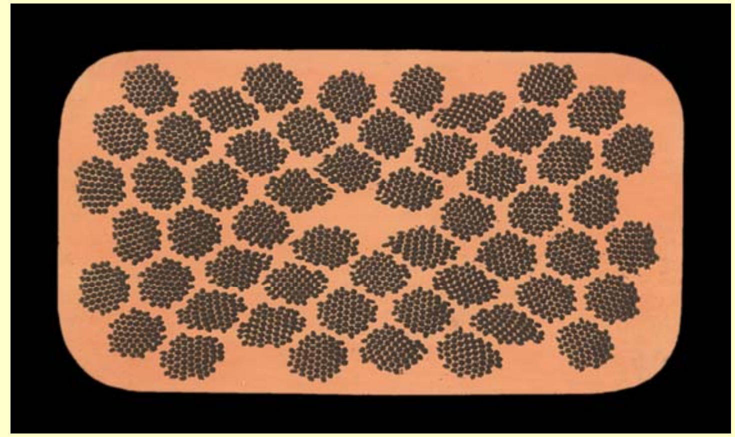
NbTi strands for different applications



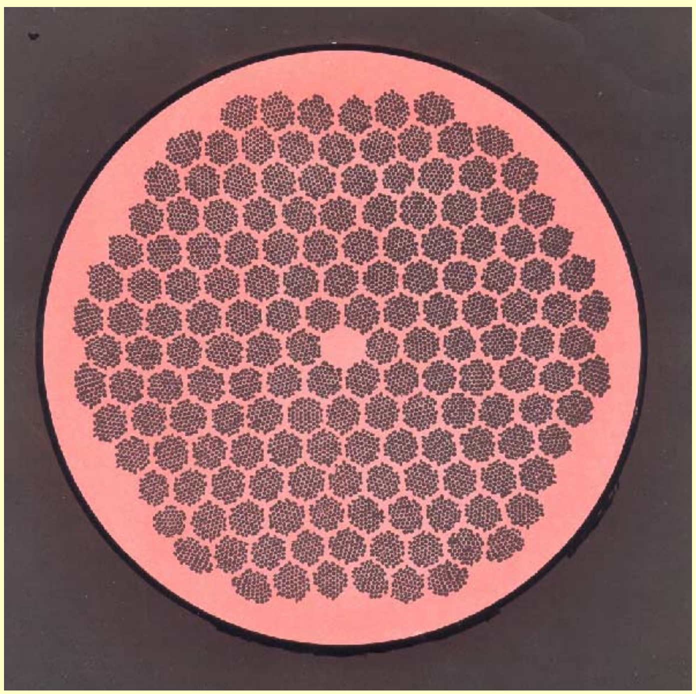




a) for MRI tomographs

b) for AC electro technical devices

c) for cryomotors



СКНТ-8910-042 Strand for accelerator UNK, **produced in amount of more than 100 tons**

Strand diameter – 0.85 mm

Filaments diameter – 6 μm

Jc (5T) - 2500 A/mm2

NbTi strands for ITER Project

In the framework of ITER Project the RF Party has manufactured the NbTi Cable (~0.5 ton), and shipped it to EFDA for further fabrication of PFCI. The testing of PFCI planned to be carried out in Japan in CSMC in June 2008.

Wire diameter – 0.73 mm

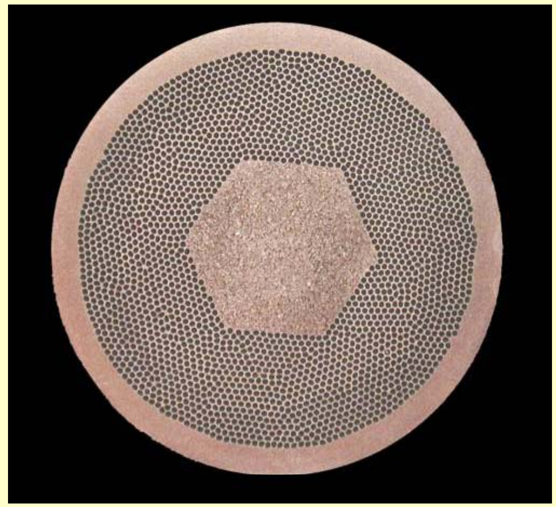
Number of filaments – 2346

Filament diameter – 9.8 mcm

Cu/non Cu Ratio - 1.4

Jc > **2700 A/mm^2 (5T, 4.2K)**

(2800-2900 A/mm^2 – measured values)



Current: **50 kA** (4.5 K, 6.3 T)

316LN stainless steel jacket

(51 × 51 mm^2)

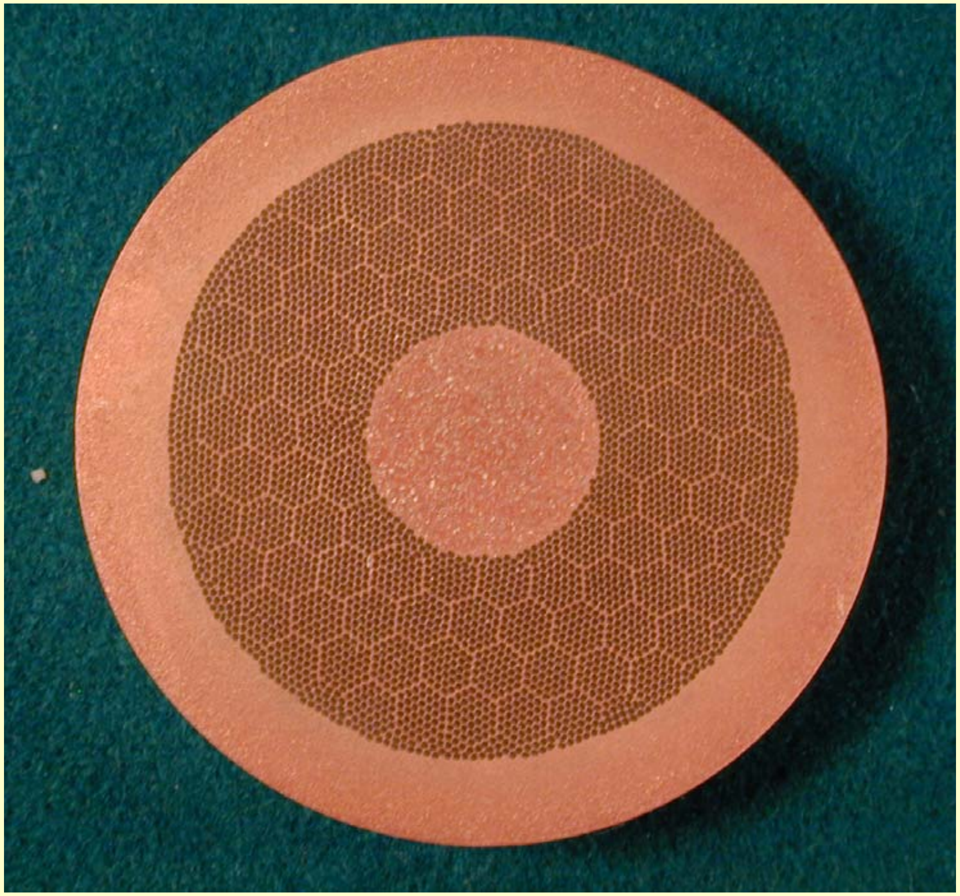
Cable Ø: 38.7 mm

1440 **NbTi** strands

NbTi strands for ITER Project

RF has to produce 40 t of NbTi strands for PF 1&6 conductors and fabricate PF1 coil

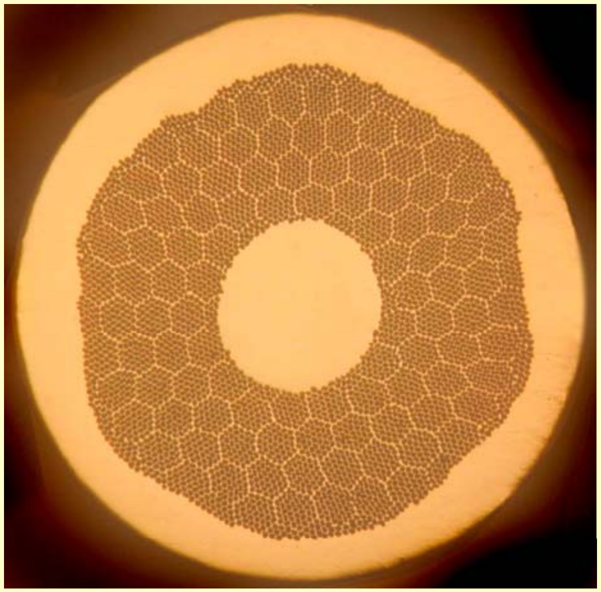
Strand	**PF1,6**
Diameter, mm	0.73
Cu/nonCu Ratio	1.6
Filament diameter, μm	6.8
Filament Number	4314



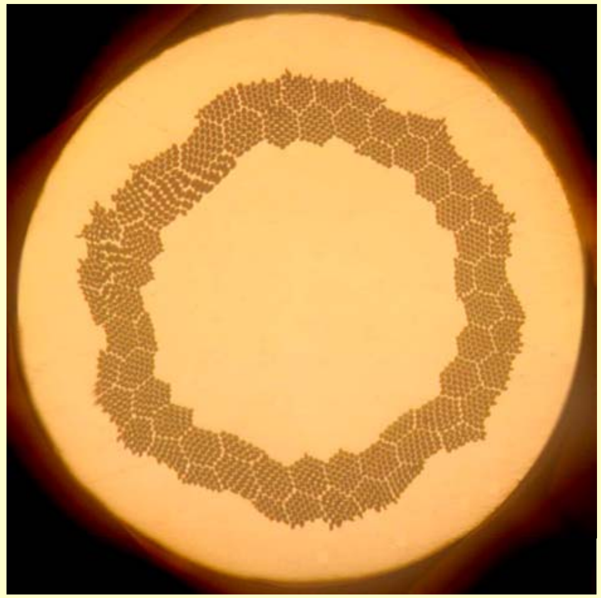
Extruded rod of PF1&6 experimental NbTi strand

Diameter of the billet 200 mm

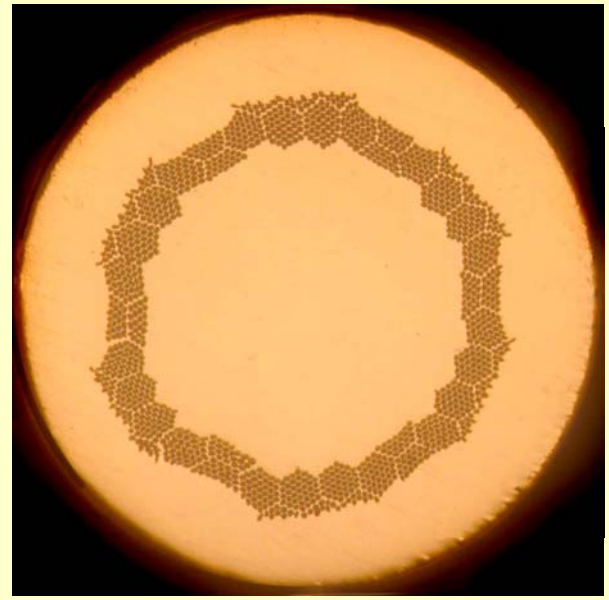
ITER type strands with Cu/non Cu ratios in the wide range of 1.6 to 6.9 (ITER PF conductors) produced from the same trimetal NbTi/Nb/Cu billets with Cu/non Cu ratio of 0.43



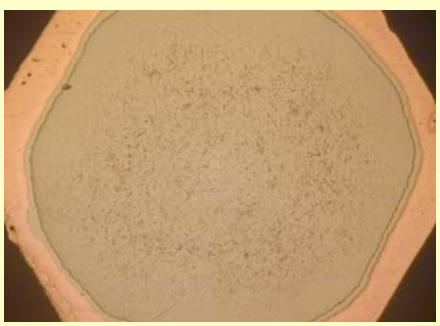
PF1&6 Cu/non Cu = 1.6



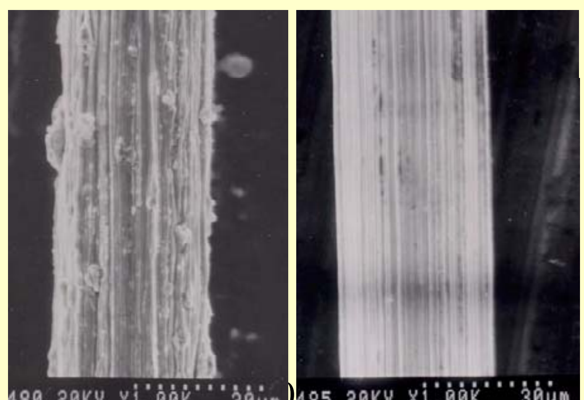
PF5 Cu/non Cu = 4.4



PF2,3&4 Cu/non Cu = 6.9



All Cu elements had RRR> 200



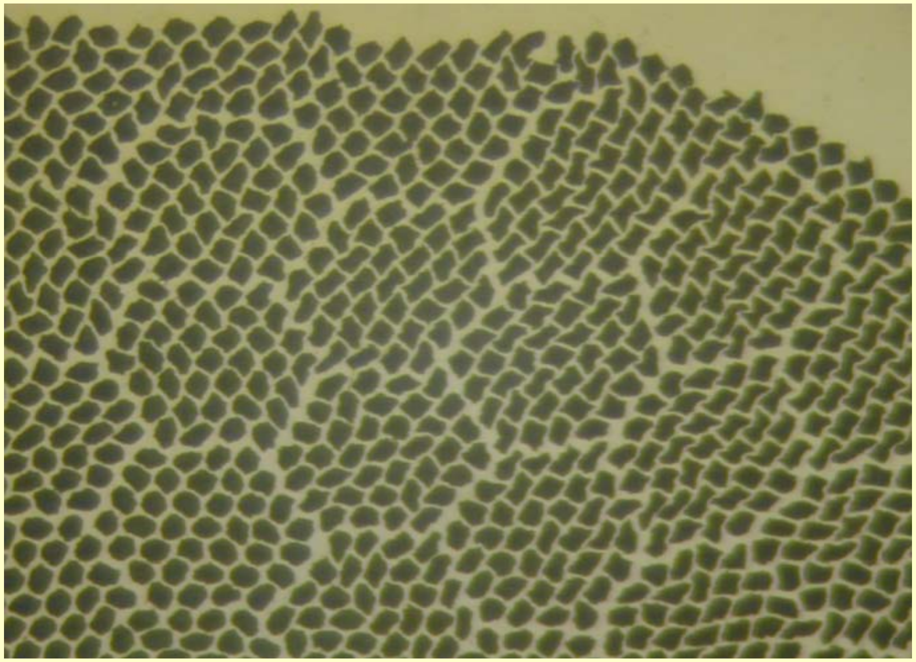
Nb diffusion barrier is necessary for avoiding the formation of brittle inclusions of Cu-Ti intermetallic compounds

Filament Distortions on the Boundary Between Filament Zone and a Bulk Cu

Strands with Cu/non Cu 1.6 met the requirements of ITER Specification for 4.2 K, 5T (Jc=2900A/mm^2)

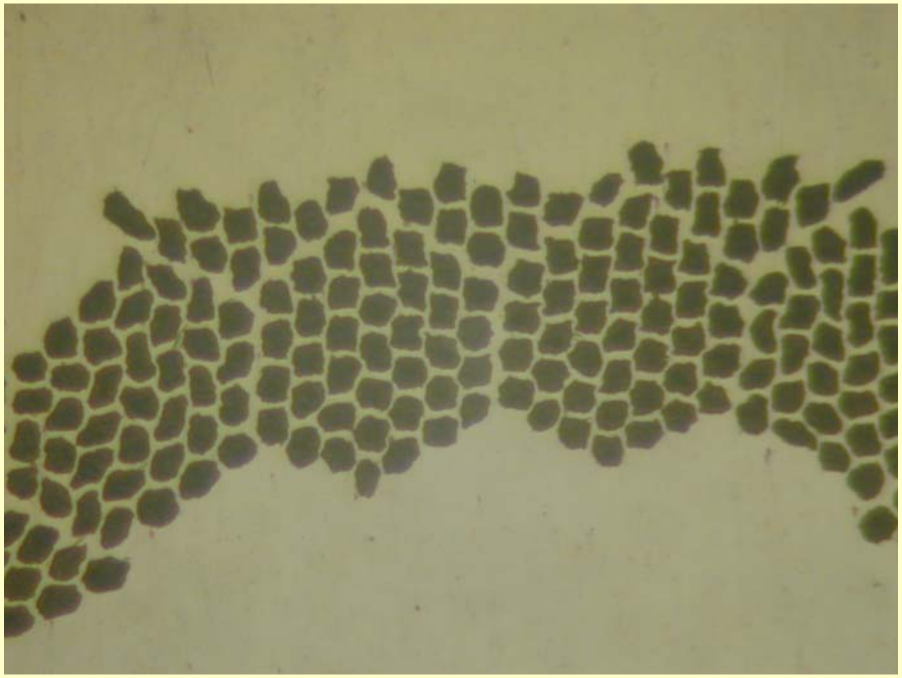
Jc (4.2 K, 5 T) = 2850-2900A/mm^2

"n" in the range of 50-60

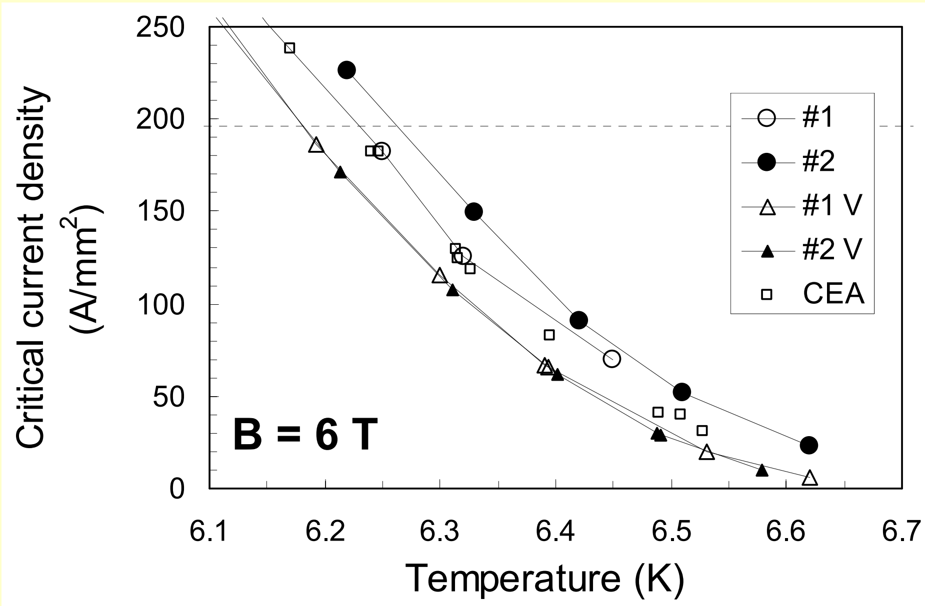


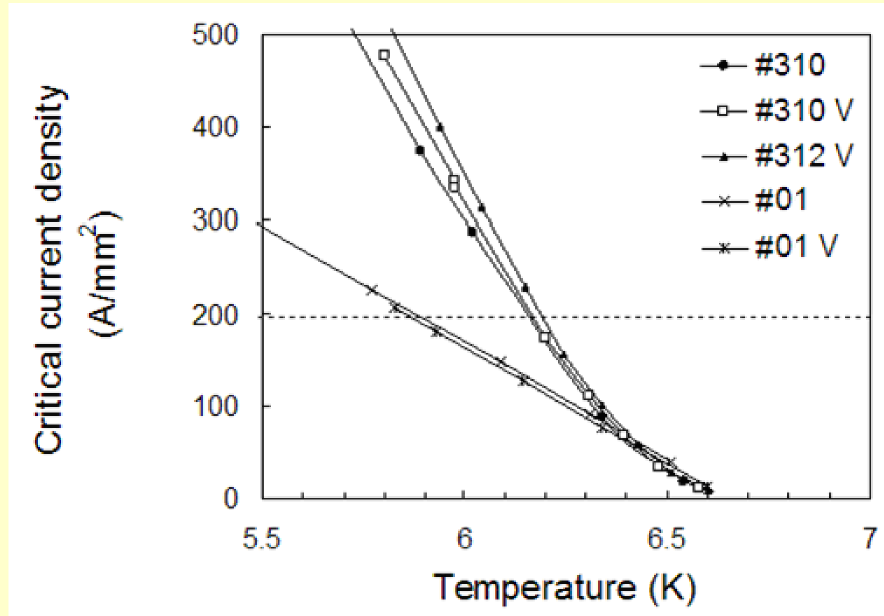
Jc (4.2 K, 5 T) = 2500-2600A/mm^2

"n" in the range of 25-35



ITER PF NbTi strands





Strands with Cu/non Cu 1.6 met the requirements of ITER Specification for 4.2 K, 5T (Jc = 2900 A/mm^2)

At high temperature (6.5 K) and in the field of 6 T Jc < 100 A/mm^2

Low-loss NbTi strands

Requirements for low-loss NbTi strands.

Strands - with small diameter filaments embedded in a resistive matrix and resistive barriers.

Minimum specification for J_C at 4.2 K and 5 T is **2500 A/mm²**, target value for for J_C at 4.2 K and 5 T is 2750 A/mm²;

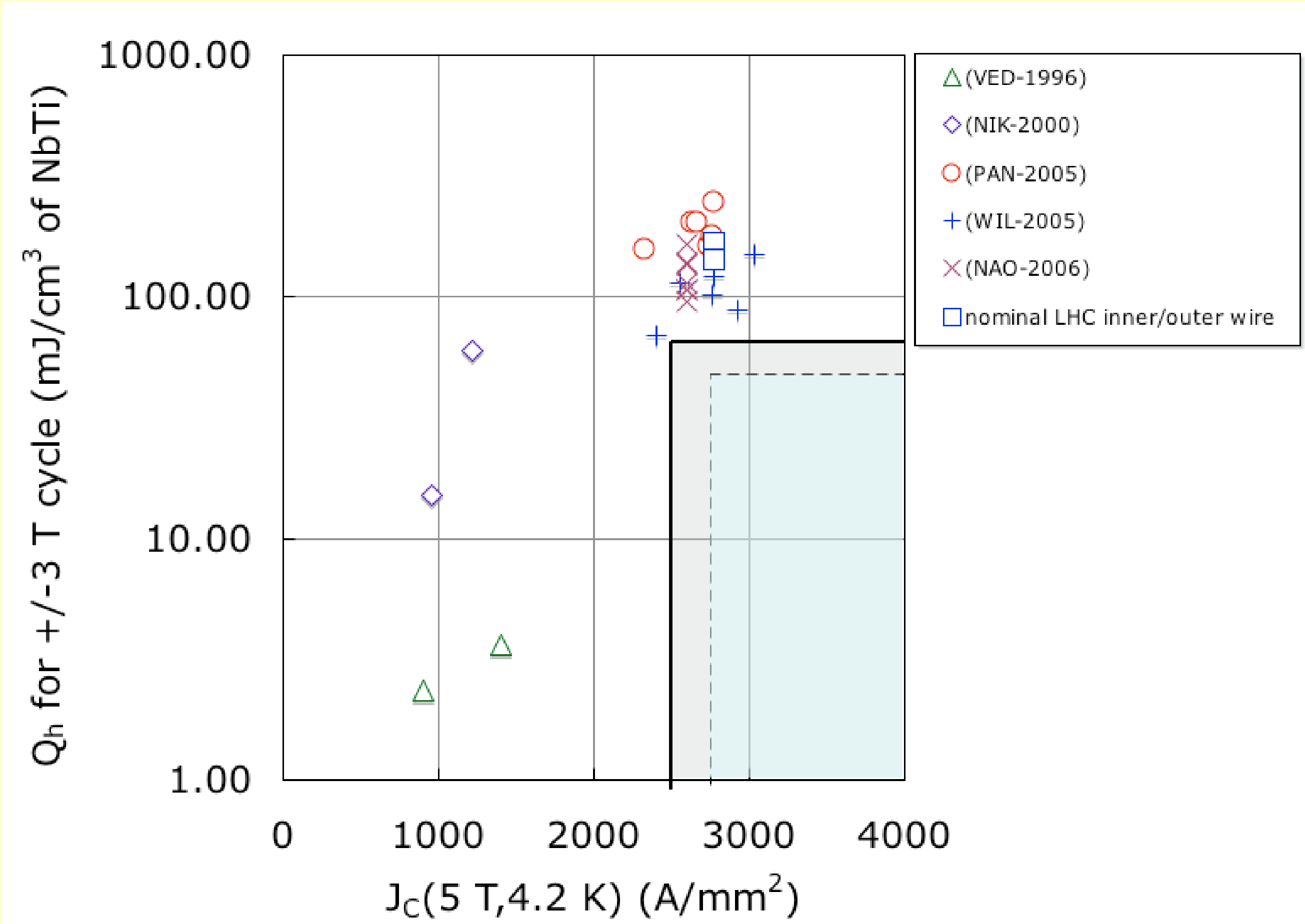
Filament diameter reduction with negligible coupling. Maximum effective filament diameter Deff is **3 μm**, with a target Deff of 2 μm.

The relevant value for the specification is the hysteresis loss Qh.

An effective filament diameter of 3 μm corresponds to a Qh of **65 mJ/cm³ 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/cm³ of Nb-Ti** for a bipolar field cycle +/- 3 T;

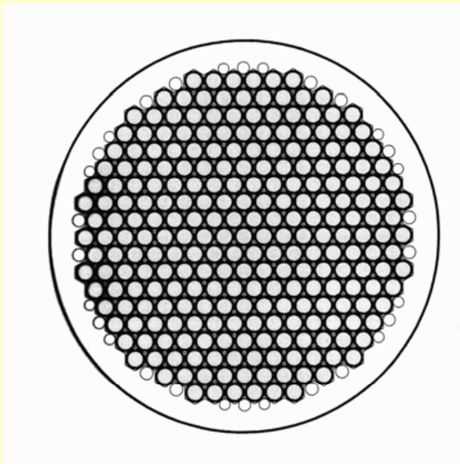
R&D Targets for Low-Loss Nb-Ti Strands and Cables for Fast Cycled Superconducting Magnets at CERN **(L.Bottura)**

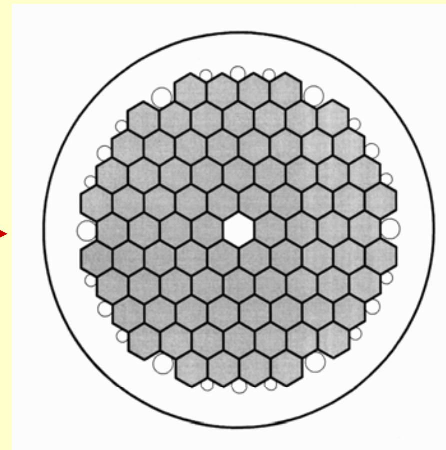


Survey of hysteresis loss and Jc in various Nb-Ti strands produced in the past 10 years. The data has been obtained from the references indicated in the legend. The rectangles represent the minimum specified performance (solid line) and the target performance (dashed line) of Nb-Ti strands suitable for fast cycled superconducting magnets.

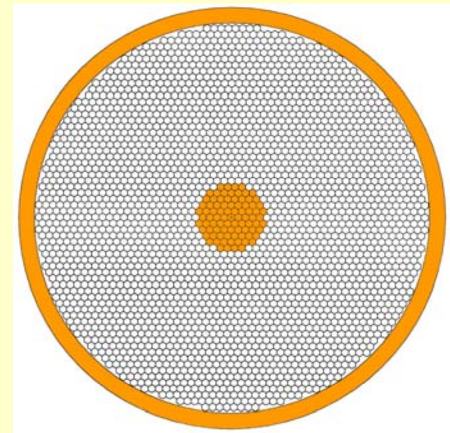
NbTi fine filaments strands designs (INTAS-GSI Project)

Ordinary hot double stacking (200-300 x85)

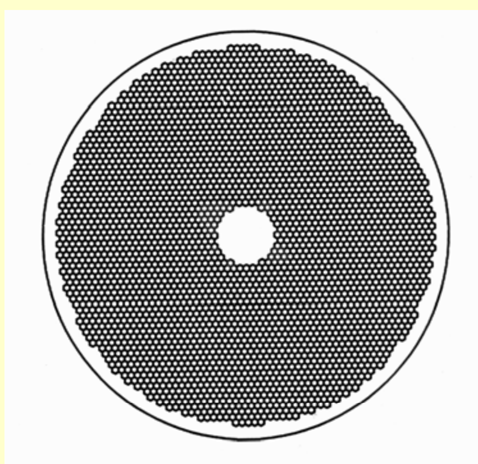


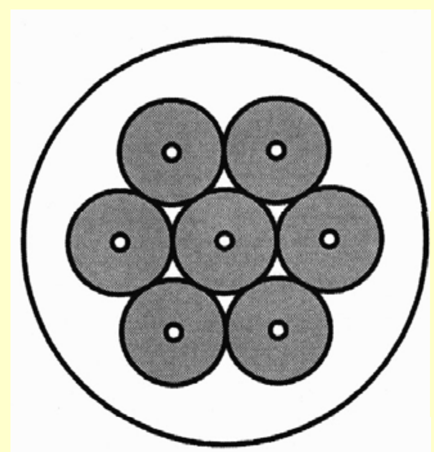


single stacking of (20000)



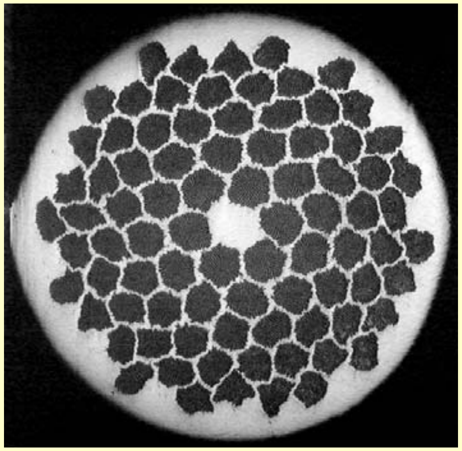
I – hot single stacking + II-cold bonding (3000 x7)





Ordinary hot double stacking (200-300 x85)



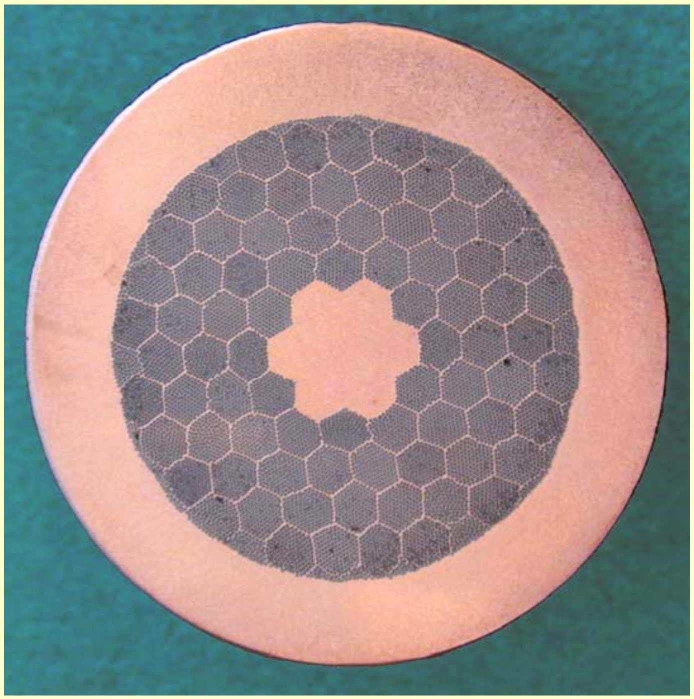


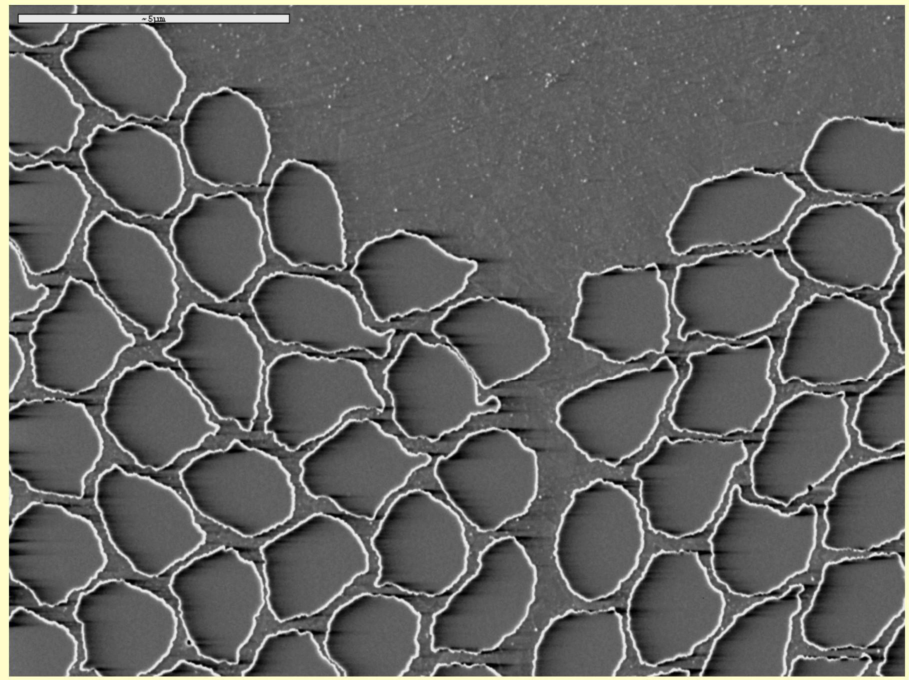
0.825 mm strand with filament diameter of 3.5 μm:
Ic = 553 A (5 T; 4.2 K); Cu/Sc = 1.415; Jc > **2500** A/мм^2 n = **56;** RRR $_{293/10}$ = **160**
0.46 mm strand with filament diameter of 1.9 μm:
Ic = 178 A (5 T; 4.2 K); Jc = **2400** A/mm2 n = **37** RRR 293K/ 10 K= 110

Resistive alloy Cu-0.5%Mn
(Annealed (500°C)
RT resistivity – **3.41-3.42 μΩ-cm**
Resistivity in liquid helium – **1.70 μΩ-cm**

NbTi fine filaments strands – design and properties

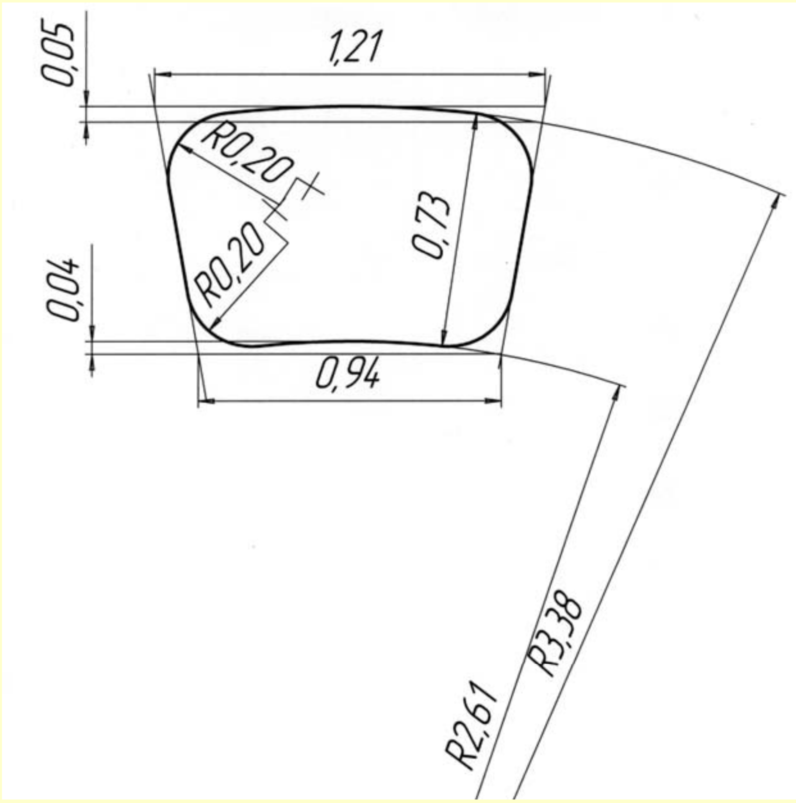
Fine filament (3.5 µm in dia) NbTi <u>0.65 mm</u> wire for operating in fields with sweep rate up to 4 T/s, was developed in BI. The wire was fabricated by a <u>single stacking</u> method. Each of 10644 filaments was surrounded by a matrix of commercial MN-5 alloy (Cu-5wt.%Ni). The spacing is 0.5 µm. Cu/non Cu = 1.8. The central Cu core, tubes and the external sheath are fabricated from Cu with (R^{273}/R^{10}) > 250. RRR of the strand ~200.

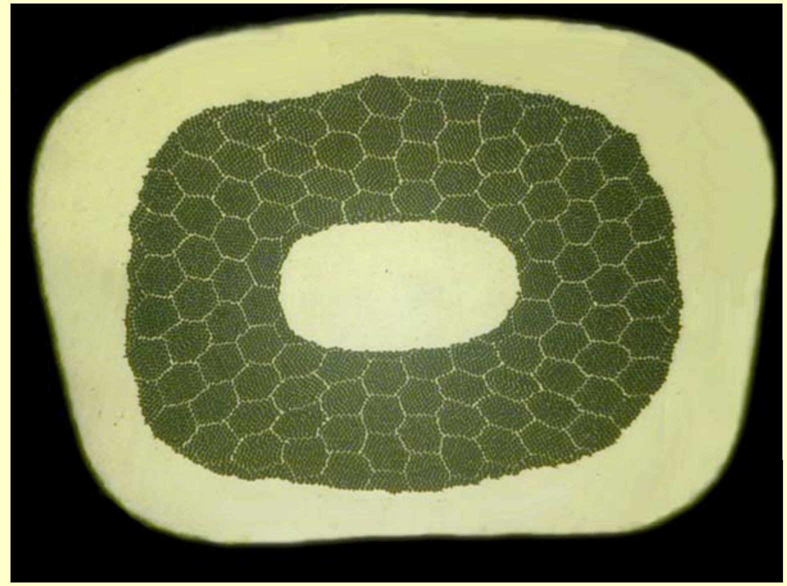




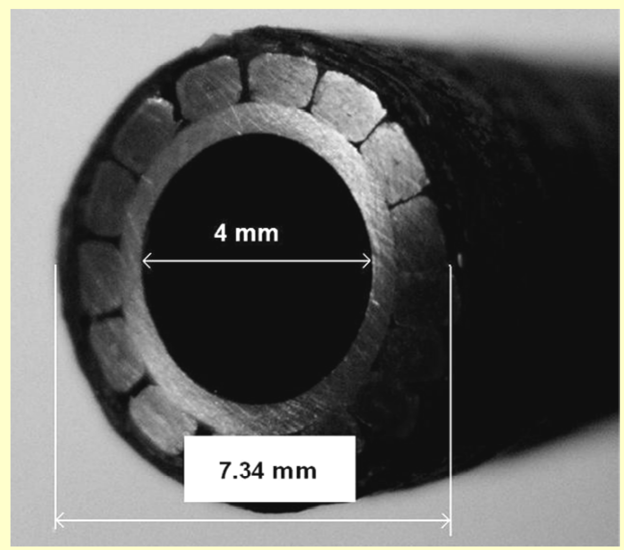
Jc ≥ <u>2900</u> A/mm^2 (5T, 4.2K). The hysteresis losses = 51 kJ/m^3 per wire and 144 kJ/m^3 per SC volume.

NbTi strands in resistive matrix for nuclotron type cable designed for application in fast rate changing (up to 4T/s) magnetic field



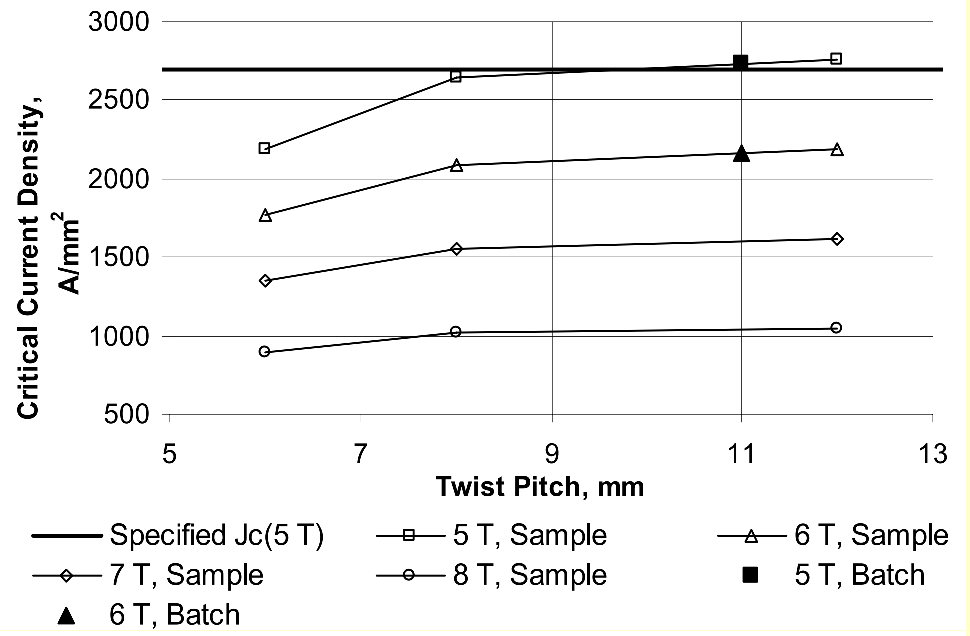


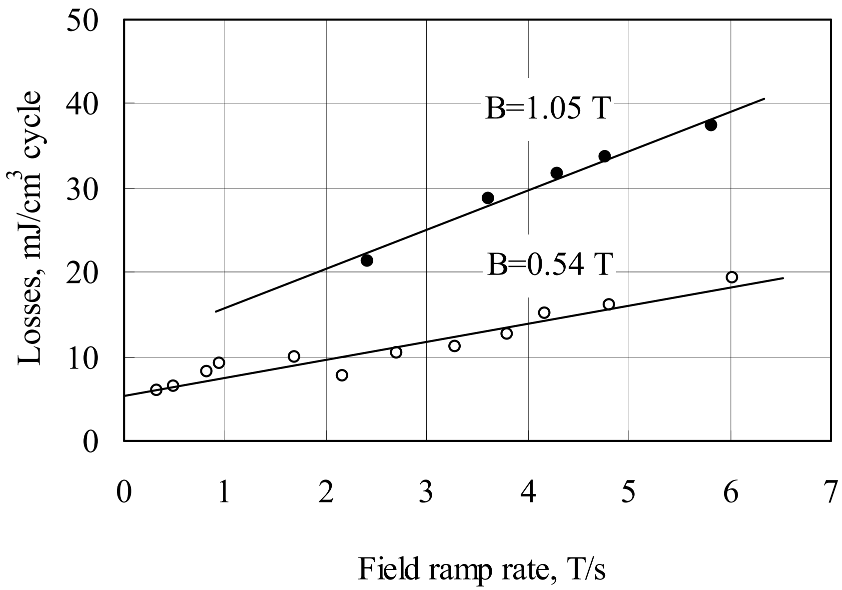
The design of trapezoidal cross section NbTi/Nb/Cu-5%Ni/Cu wire with 10374 filaments (6μm) fabricated by single stacking from billet 150 mm in dia. Cu/non Cu ratio= 1.8. NbTi, Nb, CuNi and Cu occupy 33.3; 2.7; 18.5 and 45.5 percent of a the strand's cross section area.



cable of SIS100 type

Properties of the trapezoidal cross section NbTi/Nb/Cu-5%Ni/Cu wire



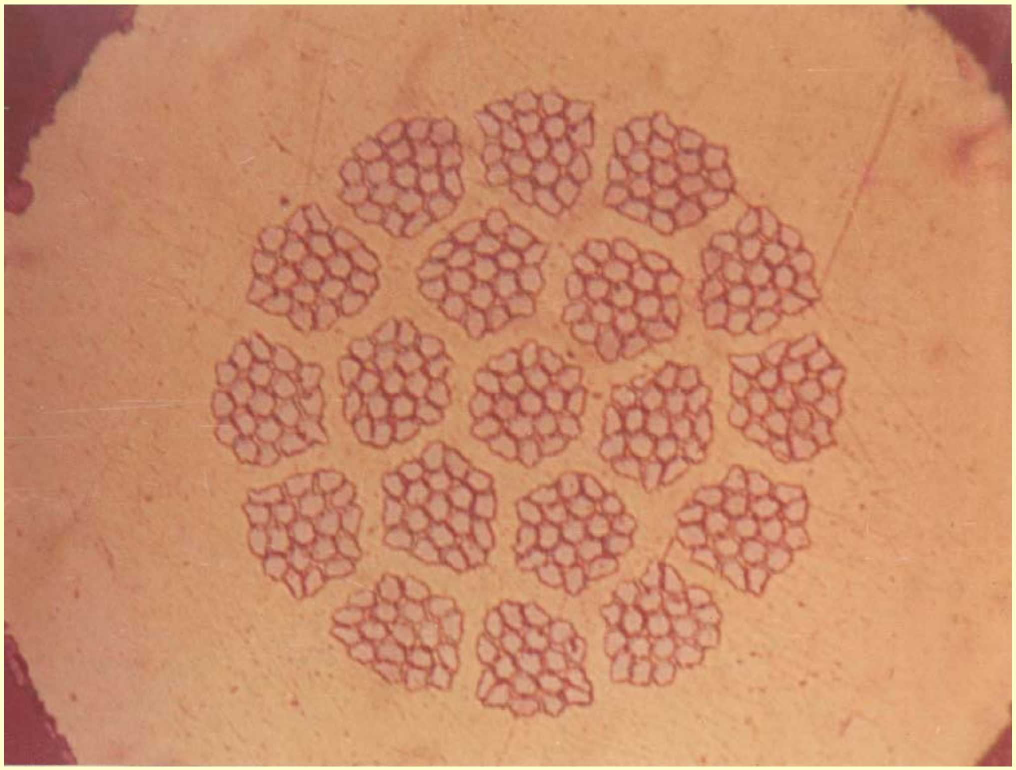


The dependences of J_c at fields of 5,6,7 and 8 T on twist pitch for the samples (hollow marks). J_c > 2700 A/mm^2 at 5 T until twist pitch is more than 10 mm (~3πd).

The AC losses were measured by calorimetric method at field amplitudes B=1.05T and B=0.54T. 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 wire volume is less than 30 mJ/cm^3 and 80 for NbTi.**

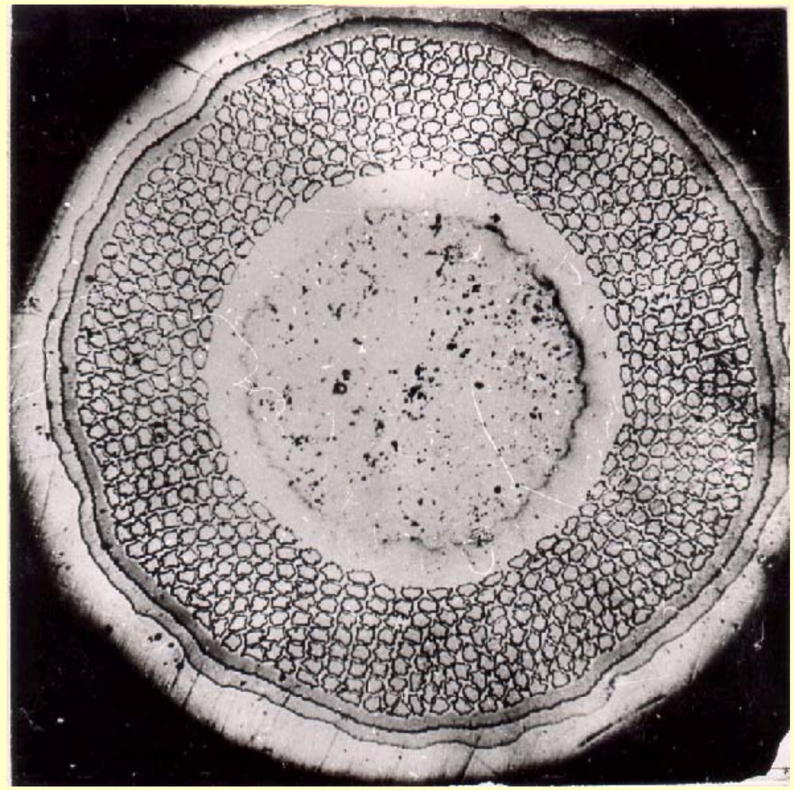
ITER type Nb_3Sn strands

Starting from the middle of 1970-s both main types of Nb_3Sn multifilamentary strands (bronze and internal tin) were under the development.



361 filaments

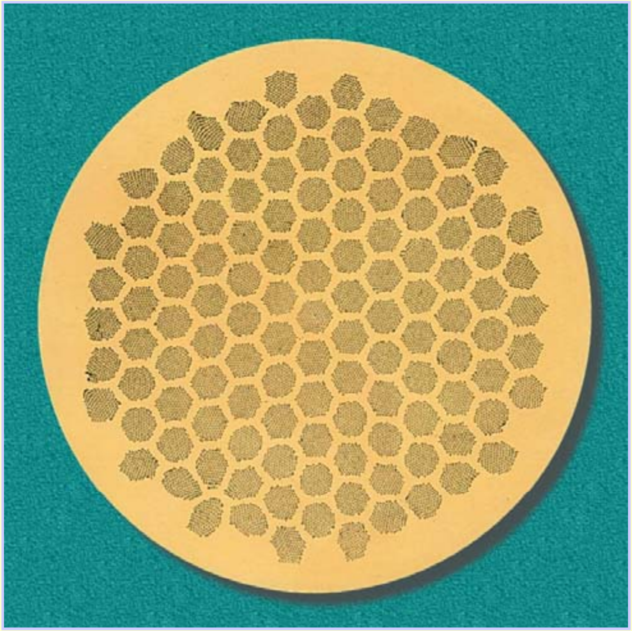
Non stabilized bronze processed strand



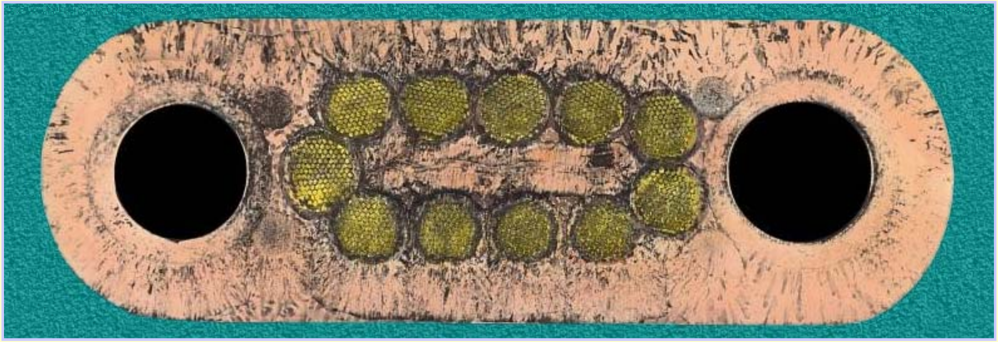
650 filaments

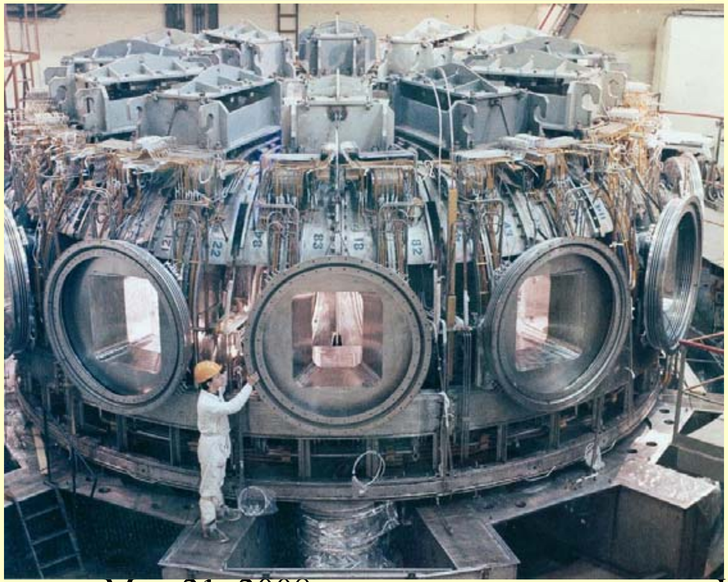
Cu stabilized Internal tin strand

Non stabilized Nb_3Sn strand for Tokamak T-15



Strand diameter – 1.5 mm
Number of filaments – 14641;
Filaments diameter - 5 μm;
<u>Jc (8 T)- 510 A/mm^2</u> Ic (average) –900 A



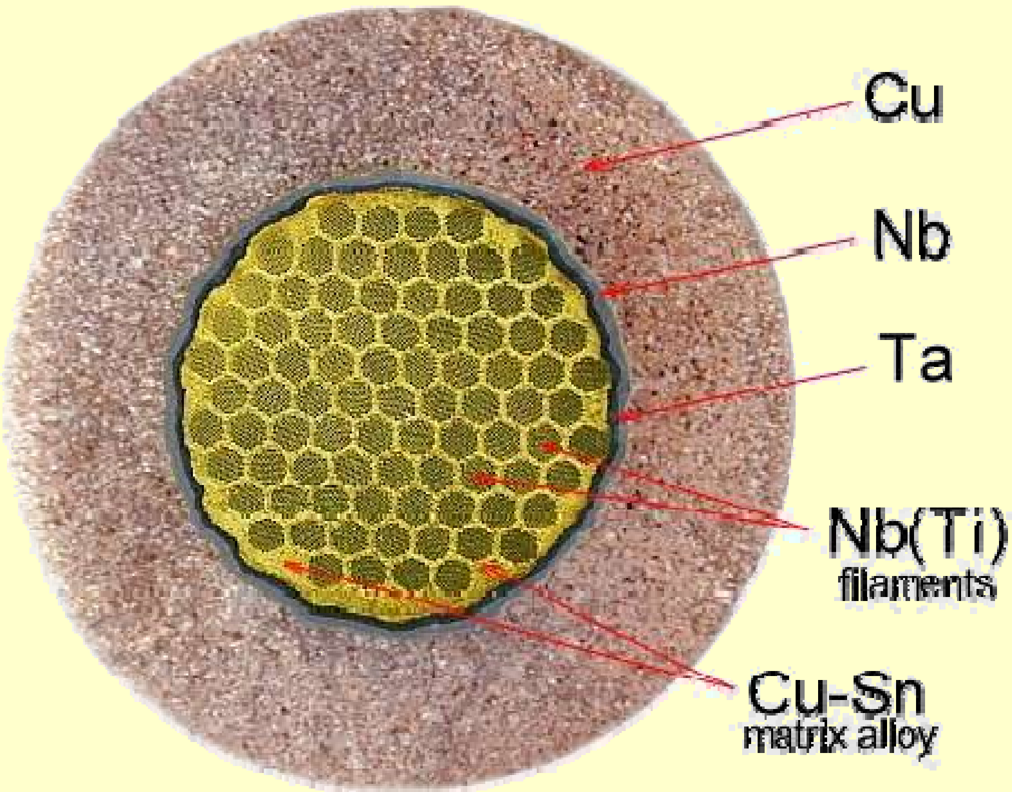


The critical current of T-15 conductor was ~ 11.5 kA in a field of 8 T or ~ 110% of single strands current ability (900A x 11).

Approximately <u>90 tons</u> of conductor were produced in an industrial way, which assumed production of more than <u>25 tons</u> of strands.

Nb_3Sn strand for model TFCI (ITER Model coils program)

(Designed and produced in amount of 1 ton)



Requirements:

<u>**Jc (12T) > 550 A/mm^2**</u>

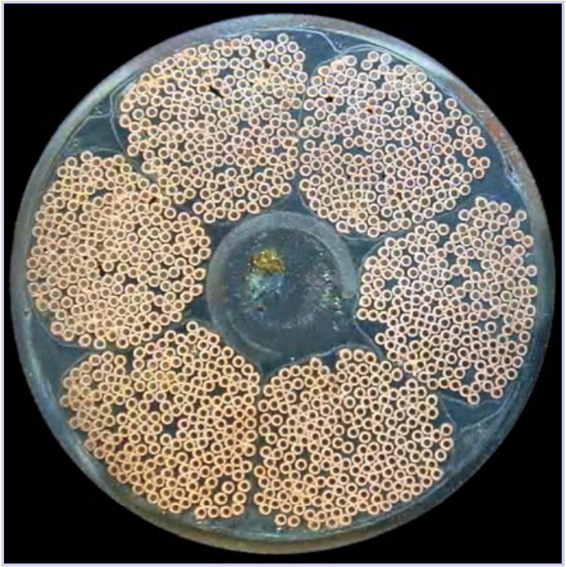
Hysteresis losses (+/-3T) < 200 mJ/cm^3

RRR > 100

Diameter = 0.81mm

Cu/(non Cu) = 1.5

In collaboration of VNIINM, VNIIKP and NIIEFA the TFCI has been produced as a part of ITER Model Coils Program



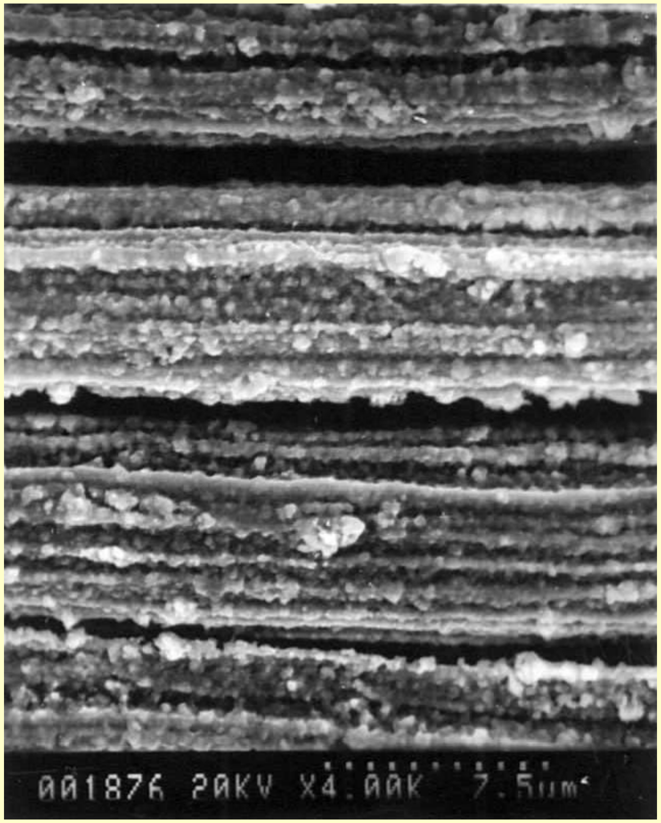
The coil reached the designed parameters:

Current – 46 kA at

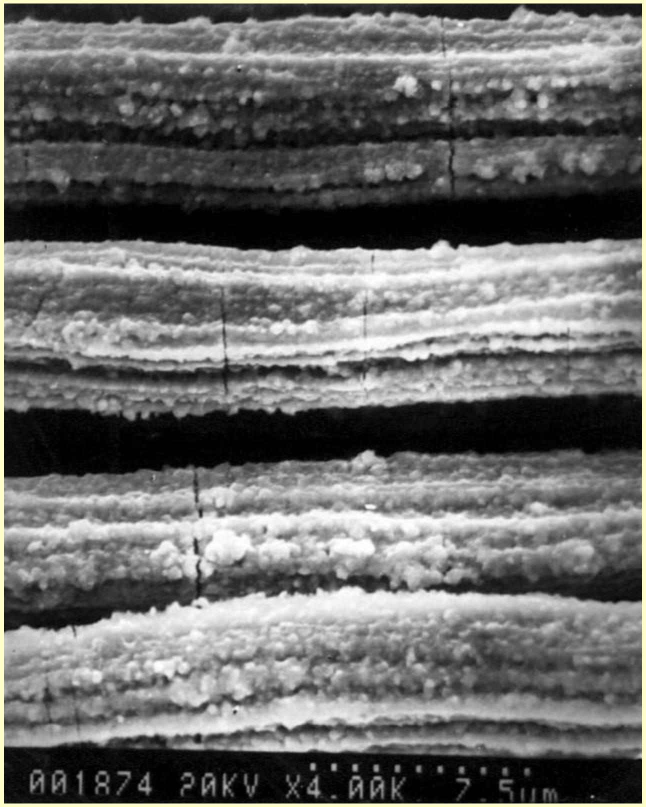
Magnetic field – 13 T

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

Tensile testing of bronze processed Nb3Sn strand 1.5 mm in dia with 14641 filaments

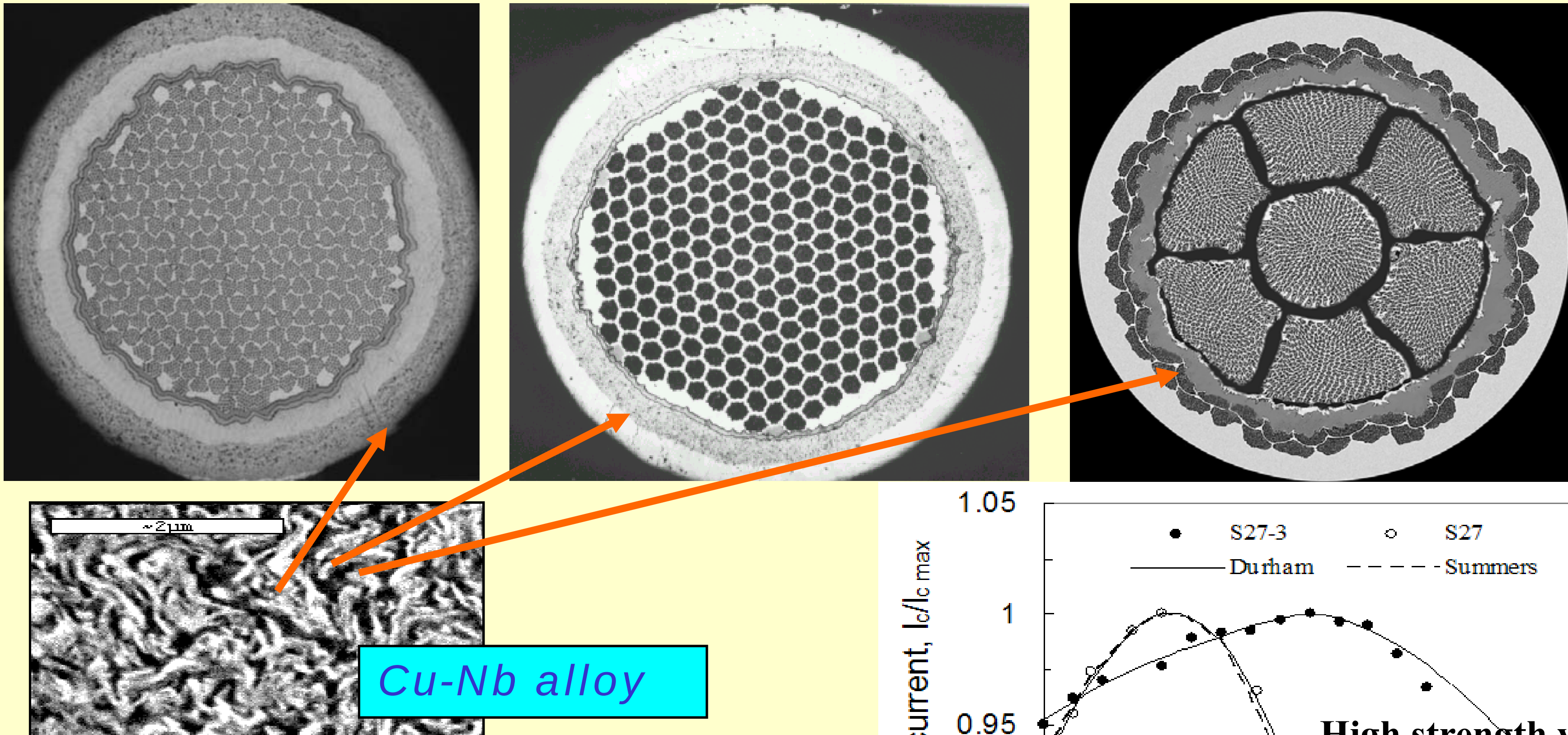


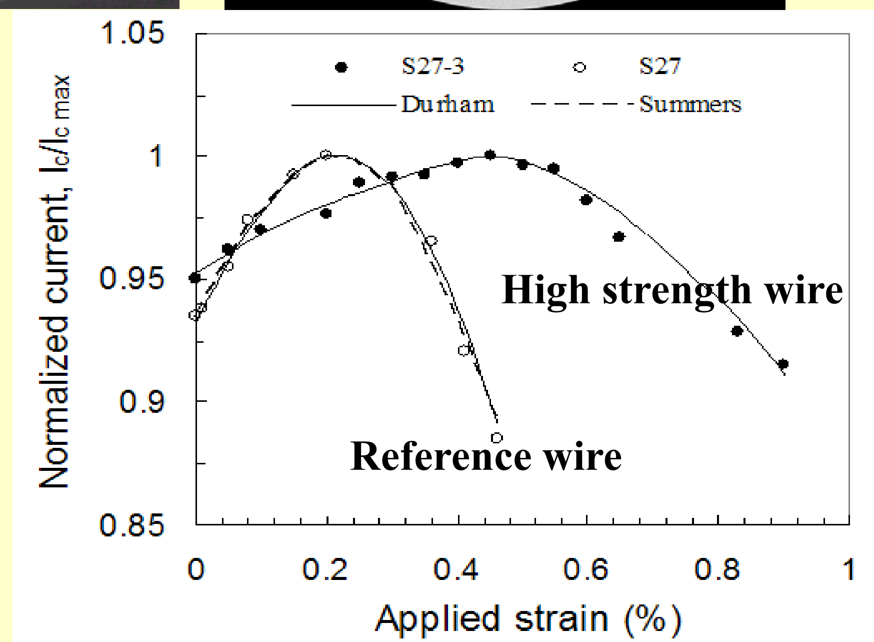
0%



1%

Nb_3Sn strands with enhanced mechanical strength

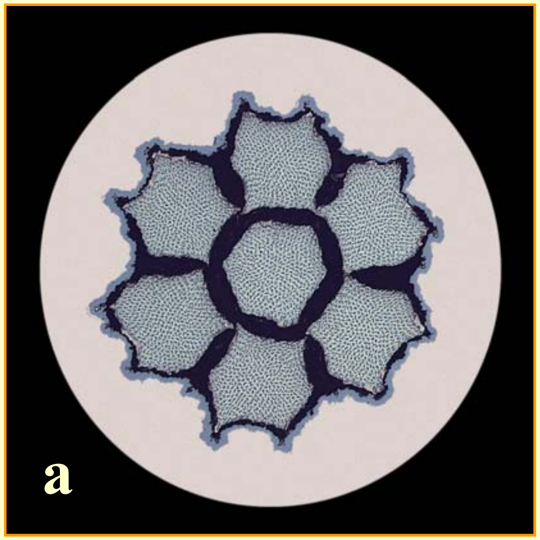


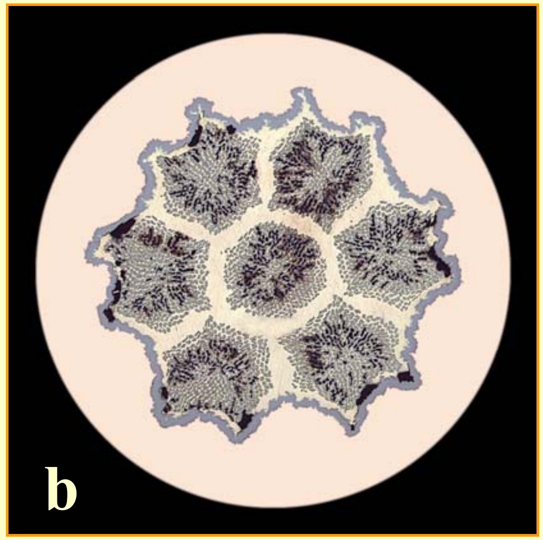


Mechanical strength was significantly (in a factor of 1.3-1.5) increased by replacing of part of stabilizing Cu on the nanostructured Cu-Nb layer. Jc of reinforced strands maintains at the same level.

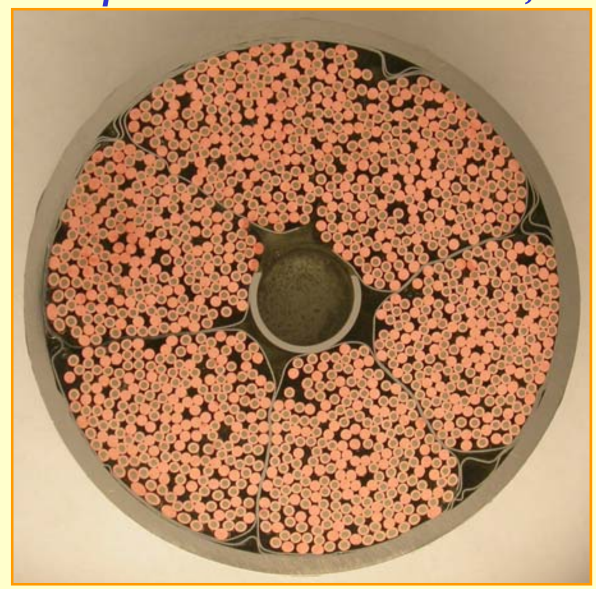
Nb_3Sn internal-tin strand for ITER TF conductor sample tested in SULTAN

Development and fabrication of Nb_3Sn internal-tin strand, meeting ITER TF specification for TF conductor's SULTAN sample testing. Fabricated strand total amount - 110 kg (22,5 km)





Cross-sections of internal-tin strand 0.82 mm in dia:
***a** – before reaction heat treatment;*
***b** – after reaction heat treatment;*



Conductor Cabling Layout [Option 1]
((2+1Cu)×3×5×5+core)×6
(Produced by VNIIKP)

T_{cs} > 6K

Parameters and properties	*ITER TF strand specification*	*Experimental results*
Outer diameter of the strand, mm	$0.82^{\pm 0.003}$	$0.82^{\pm 0.003}$
Cu:non-Cu ratio	$1.0^{\pm 0.05}$	$0.996^{\pm 0.03}$
Filament number	-	2947
Barrier material	-	Ta
Non-Cu critical current density (at 12 T, 4.2 K, 0.1 μV/cm)	> 800 A/mm²	830-950 A/mm²
Non-Cu hysteresis losses on ±3T field cycle at 4.2 K	< 1000 kJ/m³	850-980 kJ/m³
$RRR_{4.2\,K}$	> 100	102-110
"n"-value	> 20	30-45

Nb_3Sn internal-tin strands

	ITER type	High Jc type
J_{nc}, non-Cu critical current density [A/mm^2] @12 T, 4.2 K, 0.1 μV/cm, no external strain	745	2070
Calculated volume fraction of Nb_3Sn inside diffusion barrier, %	38.9	45.8
W_h, Hysteresis Loss [mJ/cm^3 non-Cu], @± 3T	~300	>1000
Calculated Jc(Nb3Sn) [A/ mm^2] @12 T, 4.2 K	2180	4850

The quality of Nb_3Sn phase after heat treatment with last stage at 575^{0}C 150h + 650^{0}C 200h 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 Jc (not proportional to the increase of volume fraction of Nb3Sn phase) is probably caused by the bridging of filaments. At the same time too strong bridging is negative for stability of the wires.

Perspectives of upgrading of bronze processed Nb_3Sn strands

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 (standard 12 T, 4.2K) assumes the attaining of critical current density in Nb_3Sn phase approximately **2700** A/mm^2.

Three main possible ways of Jc increase could be considered:

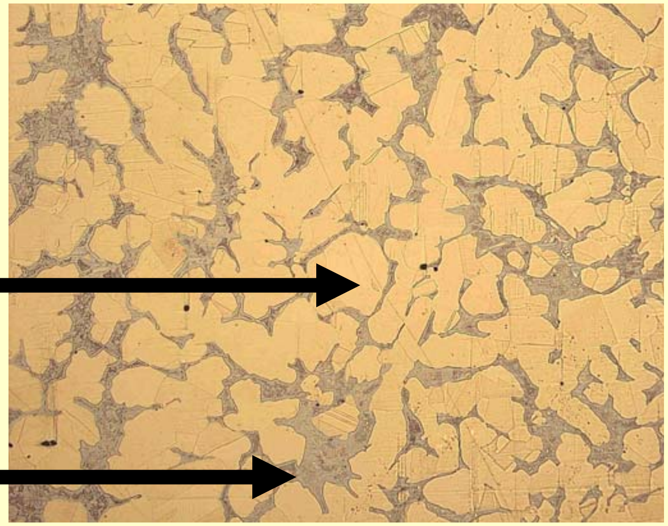
- **increase of quantity of Nb_3Sn phase (equal to increase of Sn in bronze matrix)**
- **increase of quality of Nb_3Sn phase (increase of pinning by modification of microstructure)**
- **controlled bridging (optimization of the strand's design)**

Increasing of tin content in Cu-Sn bronze

As cast

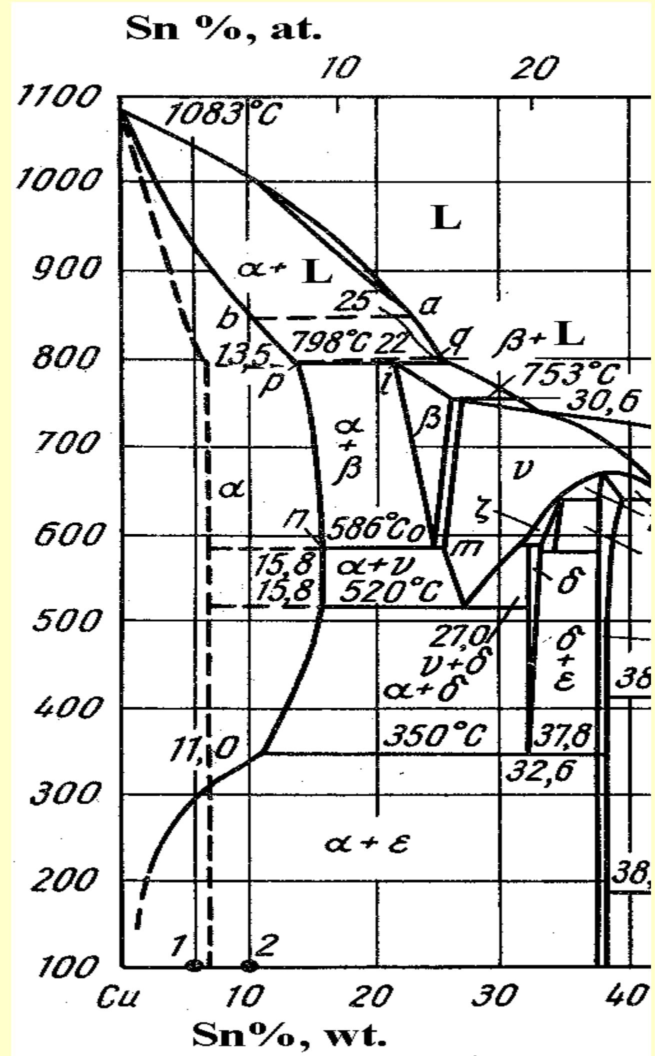
α

(α+δ)



$Cu_{31}Sn_8$

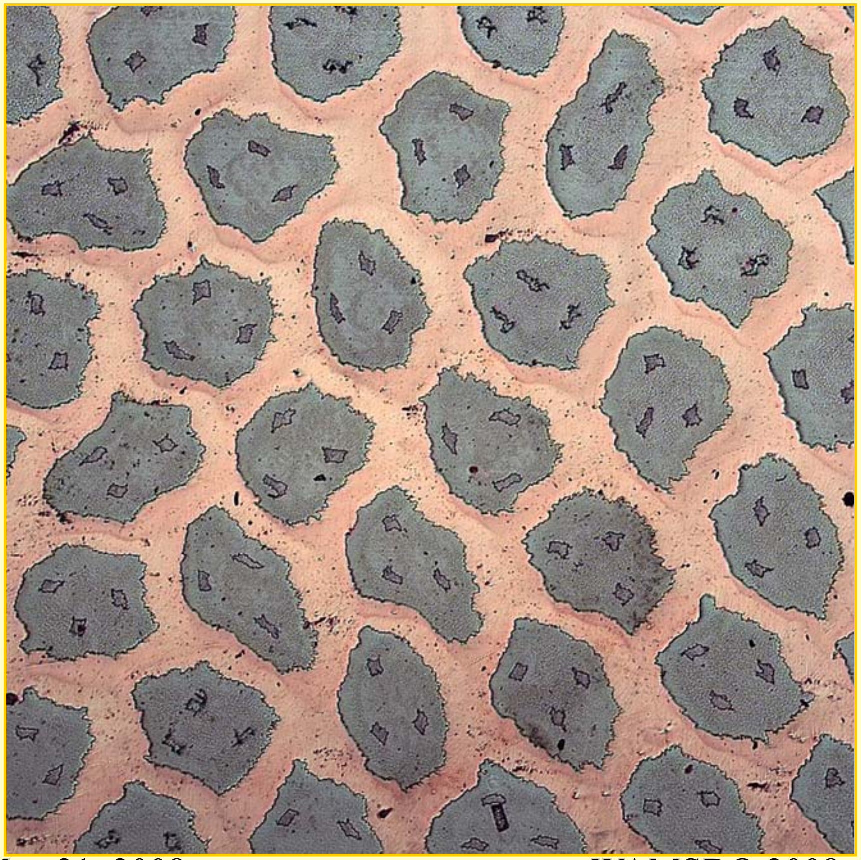
Homogenized

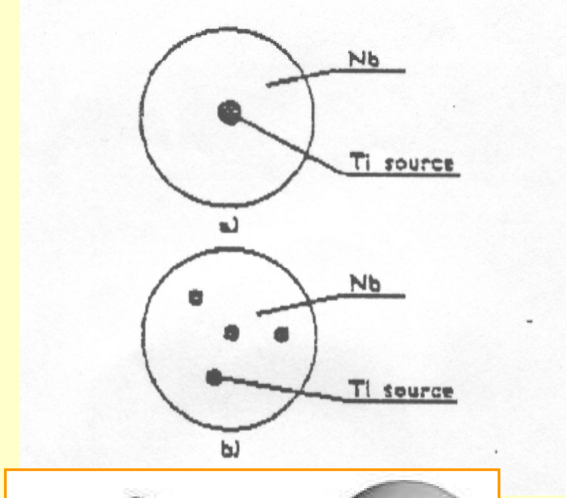


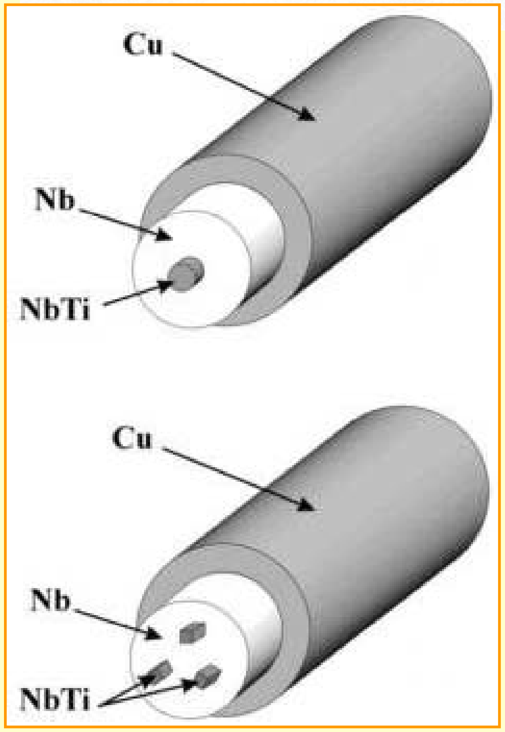
In the Cu-Sn matrix alloys the Sn content gradually increased from 10wt% up to 16wt%

Enhancement of Nb_3Sn strands properties

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)

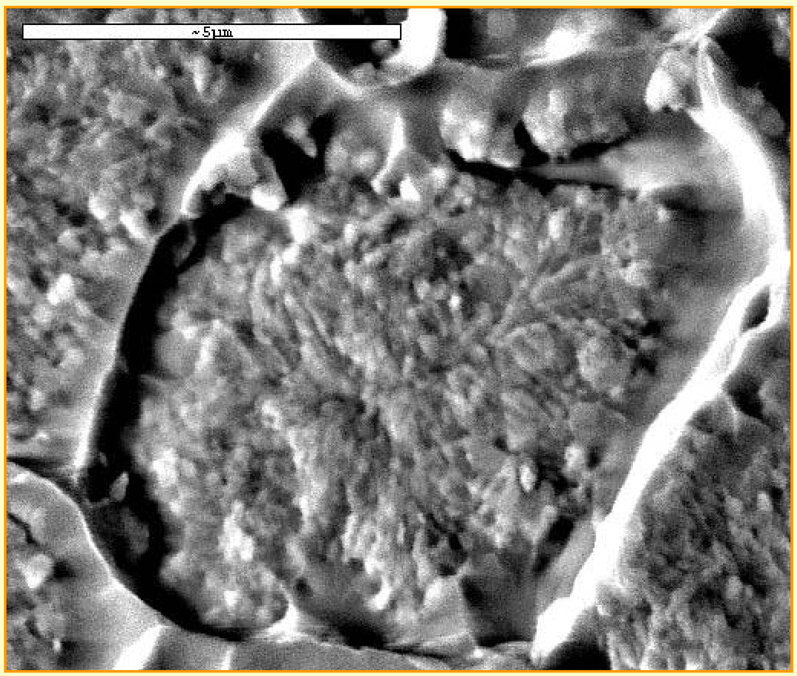


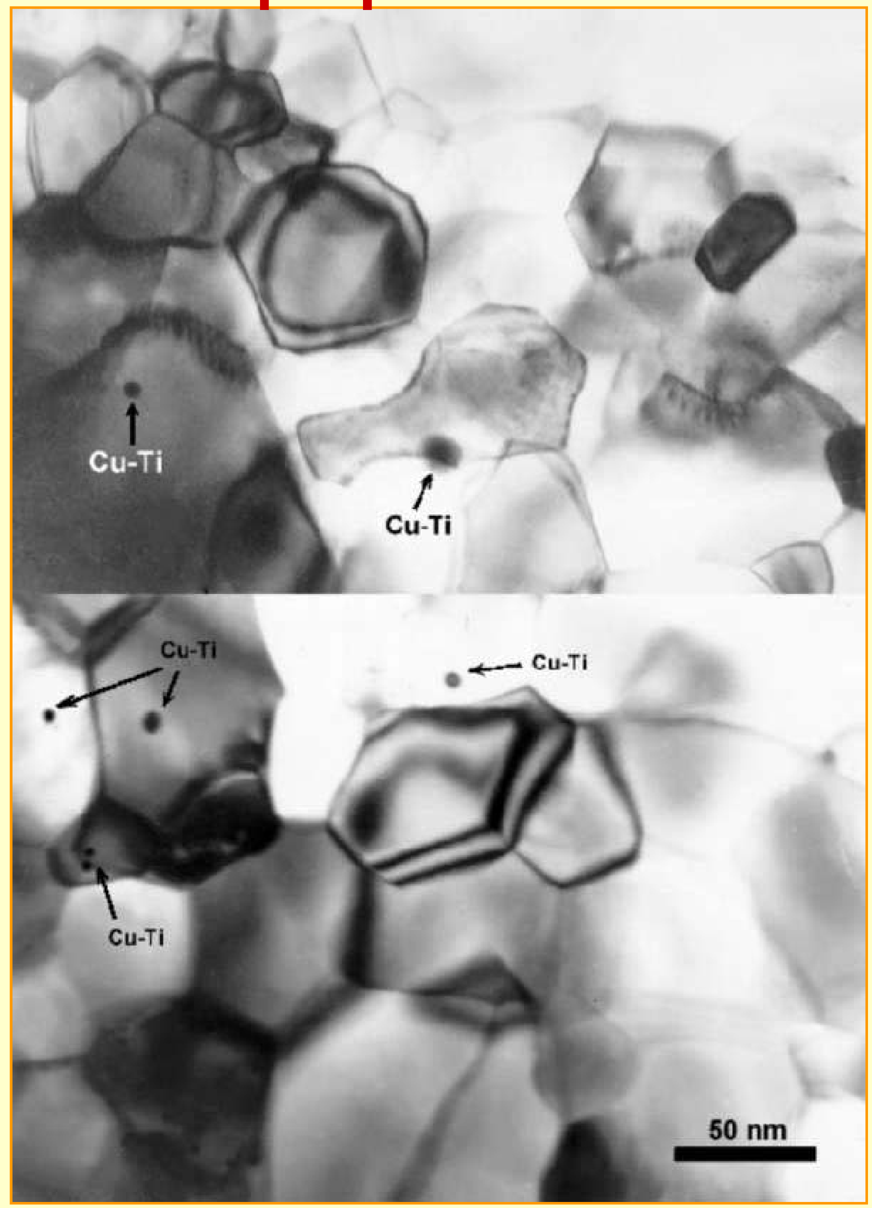




Enhancement of Nb_3Sn strands properties

Microstructure of Nb_3Sn layers with the use of artificially Ti doped Nb filaments (*introduction of new sources of pinning*)

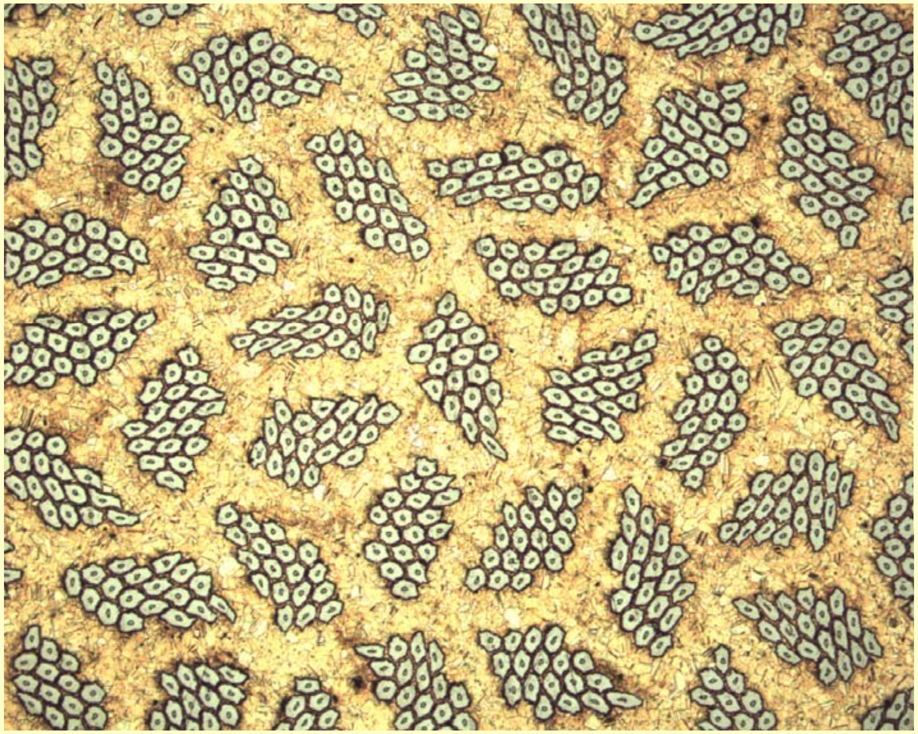




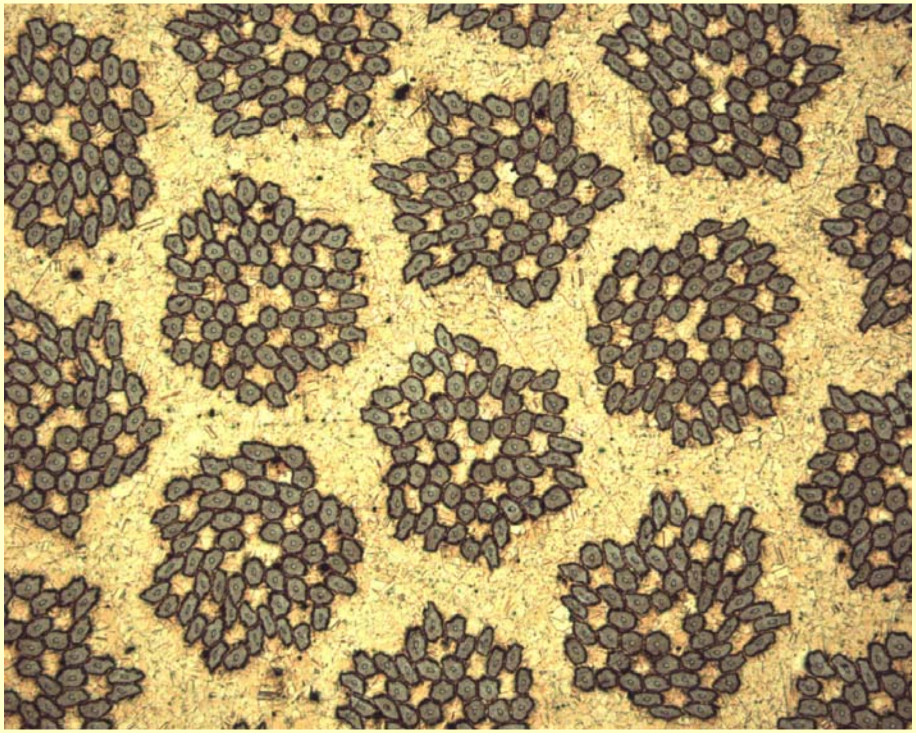
Enhancement of Nb_3Sn strands properties

Bronze processed Nb_3Sn strands

(with controlled bridging of filaments)



Qh (±3T) = 546 kJ/m^3

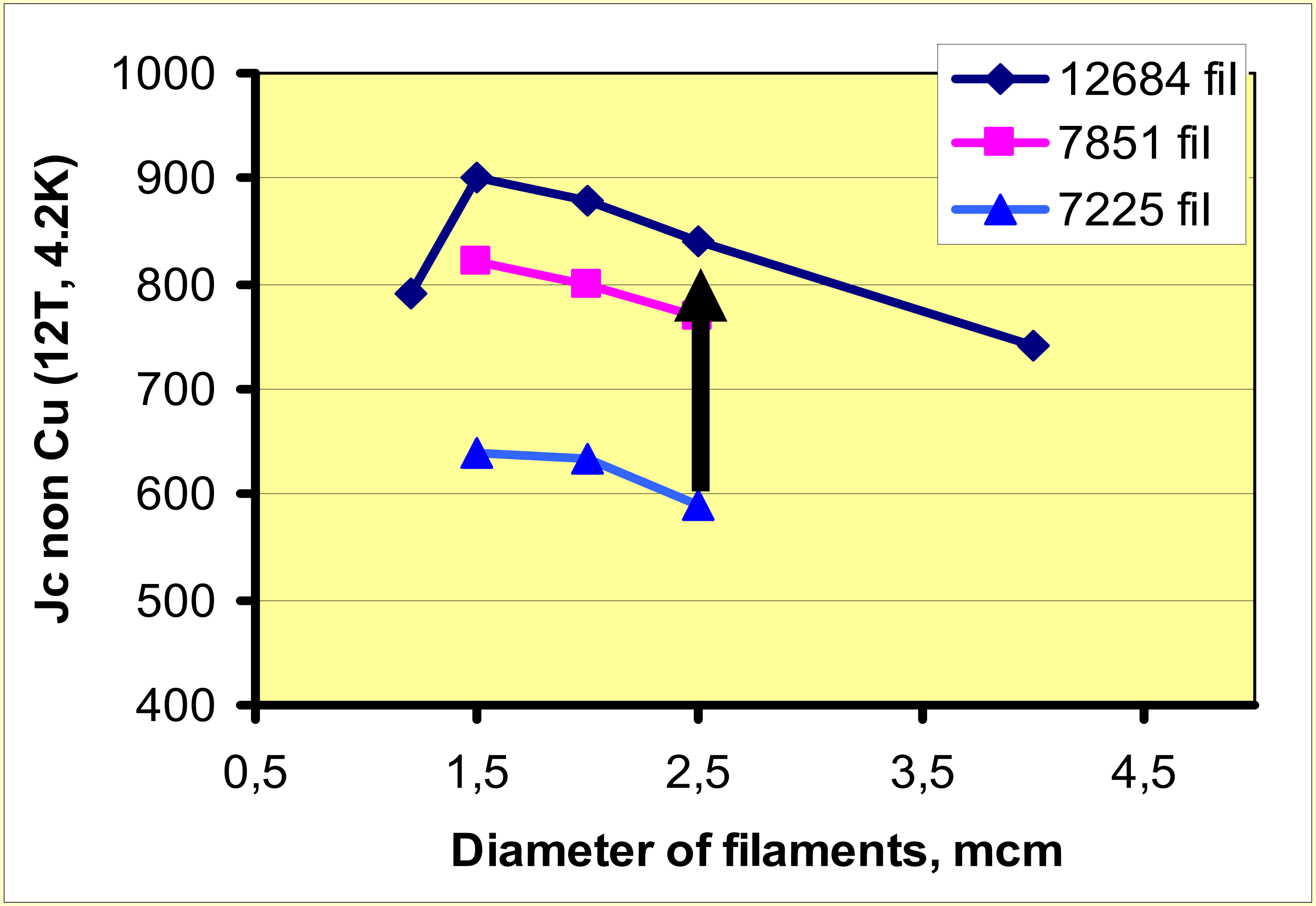


Qh (±3T) = 786 kJ/m^3

Diameter of filaments ~ 2.5 μm
Bronze matrix alloy – Cu-14wt.%Sn
Jc (12 T, 4.2 K, 0.1 μV/cm) > 750 A/mm^2

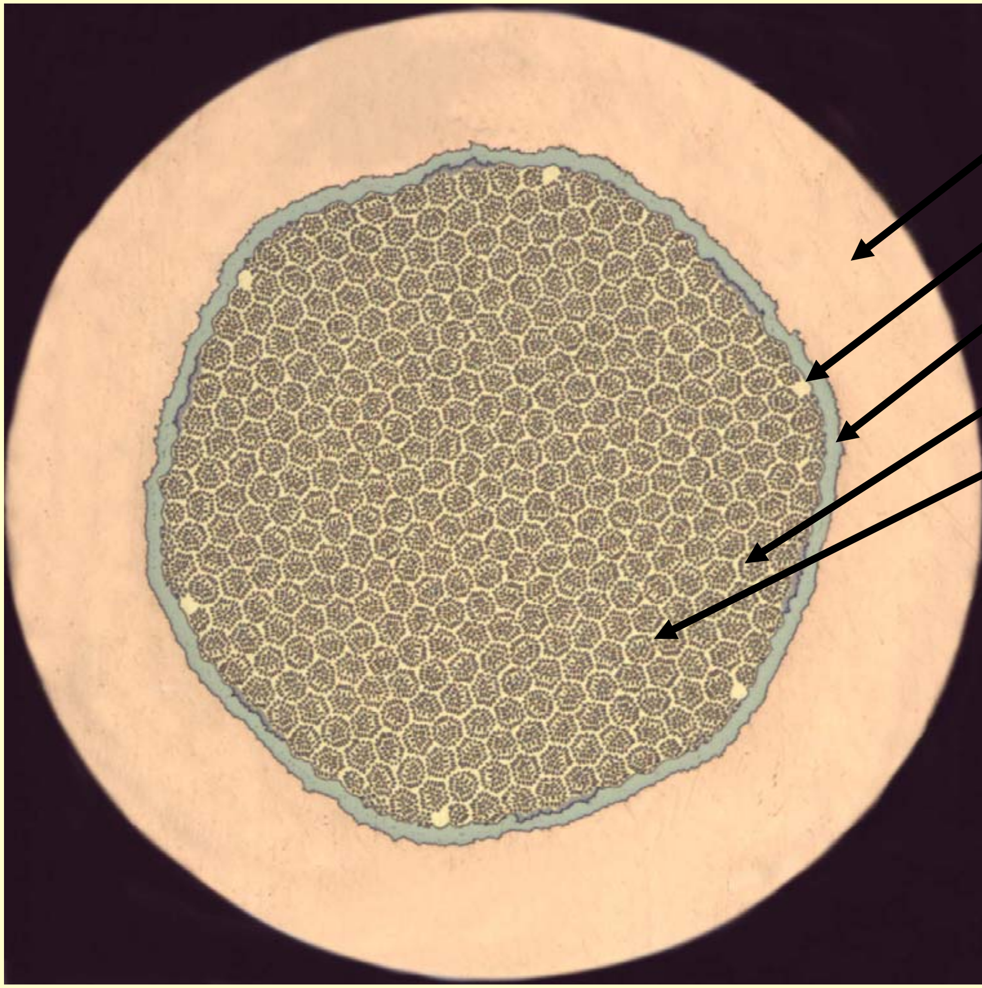
Bronze processed *Nb_3Sn* strands

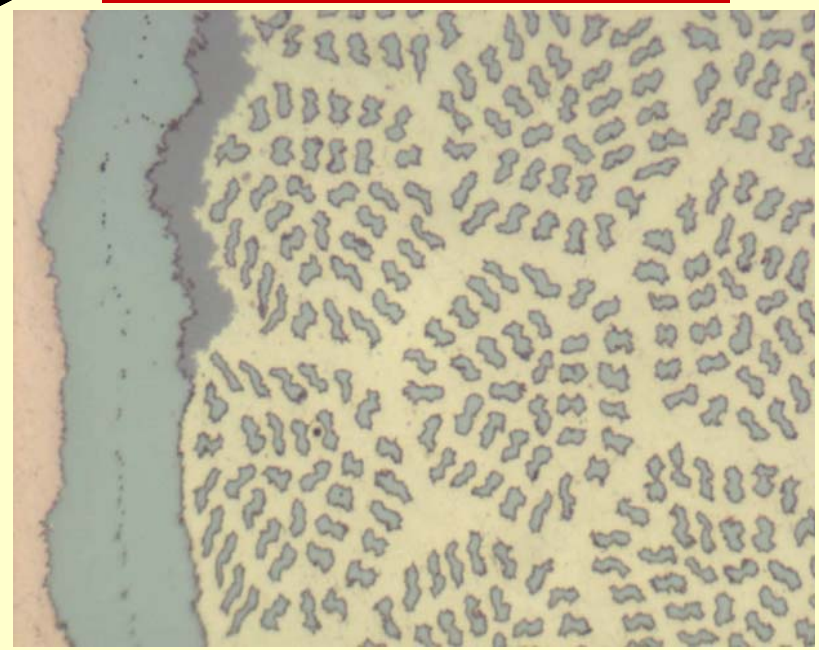
Bronze Nb_3Sn strand could be produced with Jc (12T) up to 800–900 A/mm^2



Cross-section of advanced ITER strand (0.82 mm)

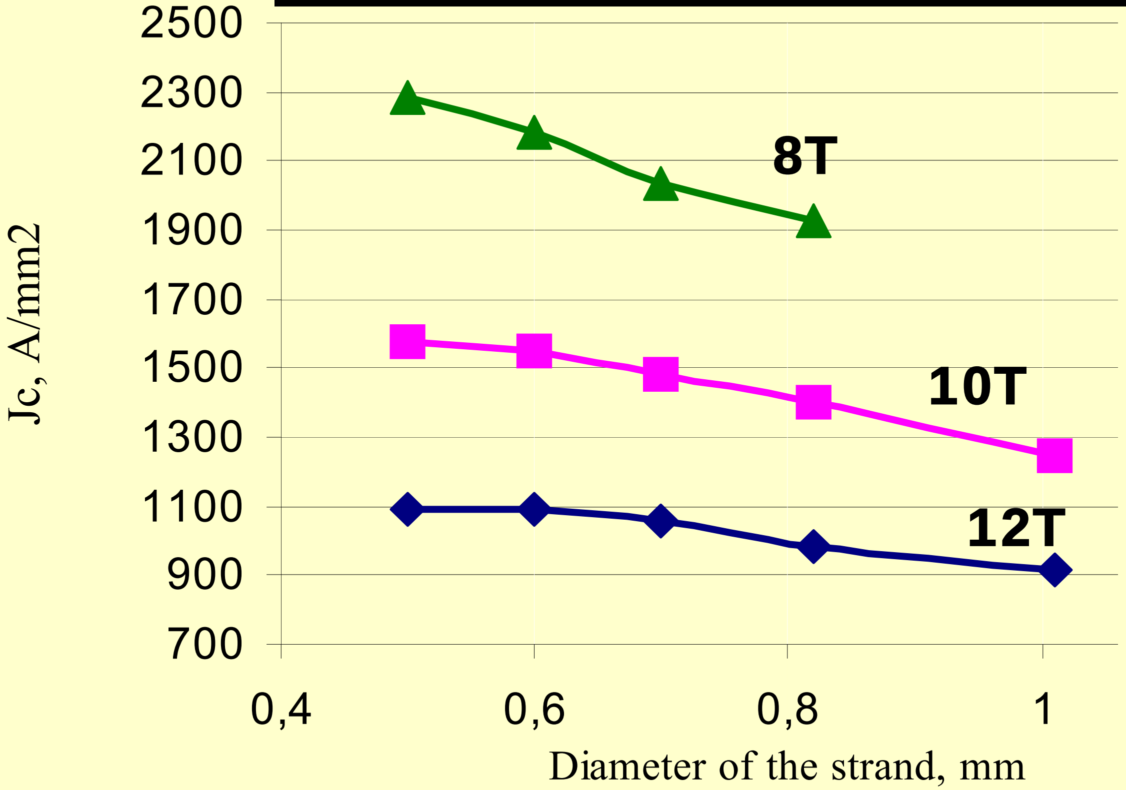
(To be produced in amount of 80 tons for ITER TF Conductor)

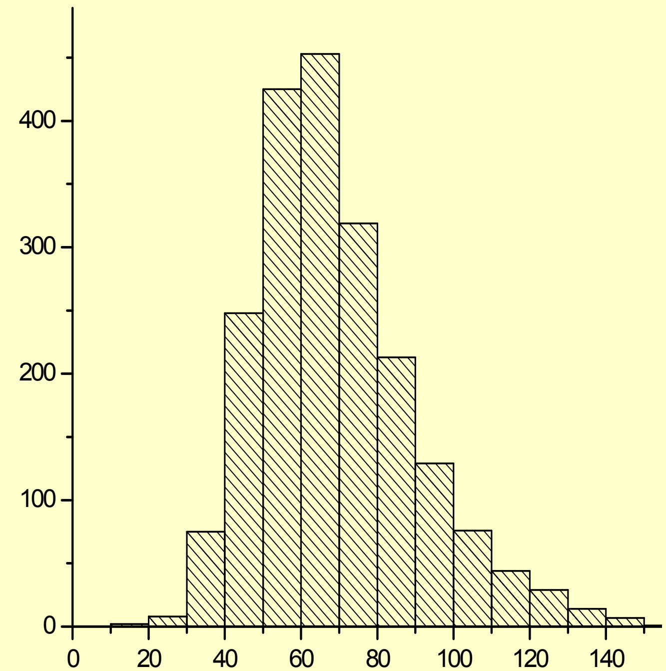




Advanced ITER strand for TF conductor

Hysteresis Loss, mJ/cm3	300-350
Jc (12T, 4.2K), A/mm2	➢900
«n»	> 30



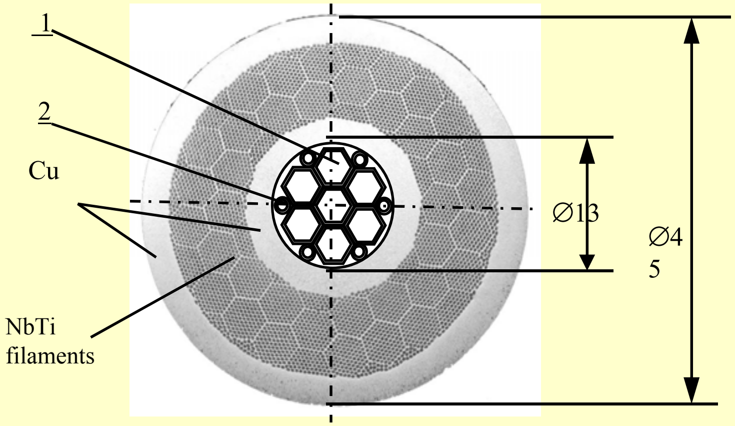


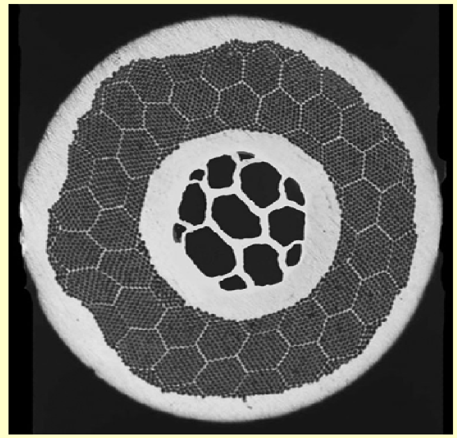
Nb_3Sn and NbTi strands with enhanced heat capacity

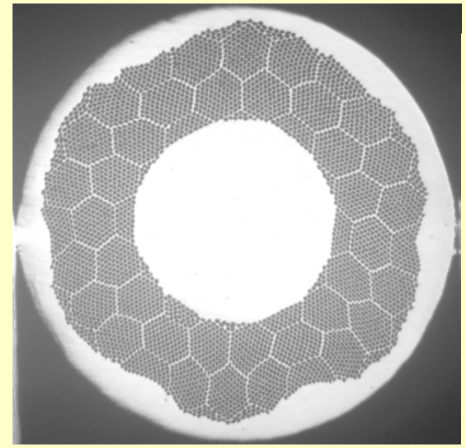
Material	Heat capacity at 4 -6 K, J/(cm^3*K)	Thermal conductivity at 4 - 9 K (mW/cm*K)	Density at RT, (g/cm^3)	Melting temperature, ^{o}C
Cu	0.002 ←	6000	8.94	1085
Nb_3Sn	0.008	3	~8.9	
NbTi	~ 0.002	1.5	6.1	~1920
$CeCu_6$	0.033	~10	8.262	~875
$HoCu_2$	0.300 ←	-	9.147	~900
PrB_6	0.2-0.15 ←	~80	4.85	~2500
$Ce(Al_{0.9}Cu_{0.1})_2$	0.064	~10	4.93	~1460
Gd_2O_2S	0.660 ←	~50	7.44	>1500

The traditional stabilization method of adding copper to the conductor cross section reduces the overall critical current density. Another approach to the stability increase - doping with some extremely large specific heat capacities substances at low temperature.

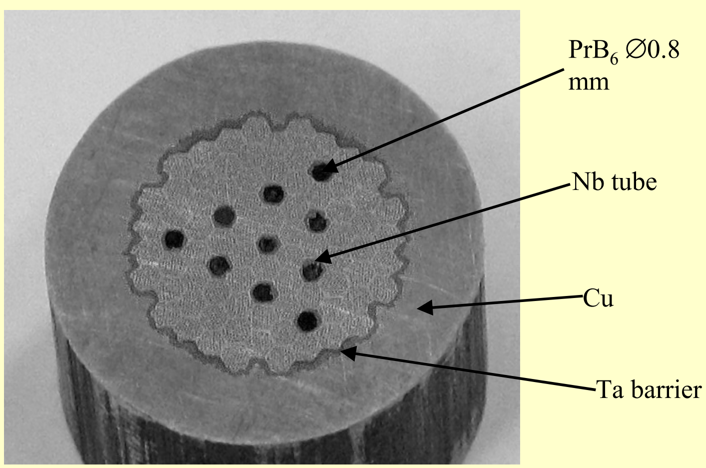
Nb_3Sn and NbTi strands with enhanced heat capacity

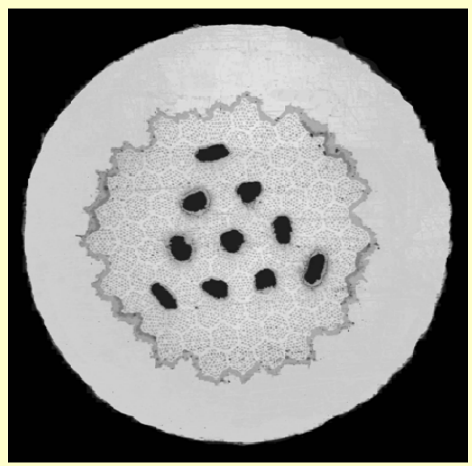


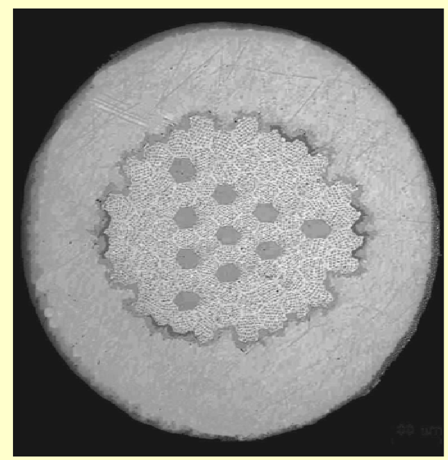




0.73 mm NbTi samples with/without Gd2O2S doping

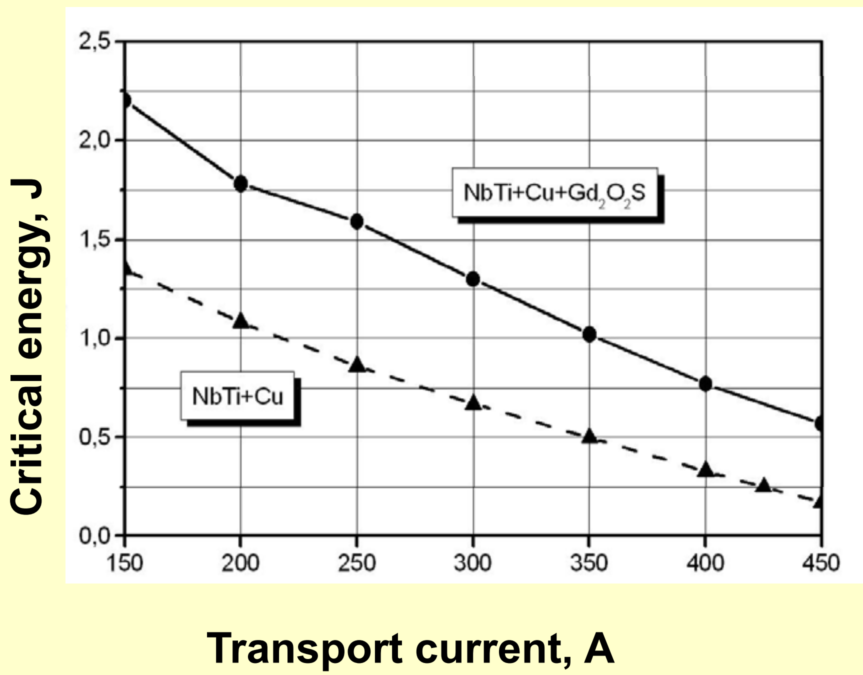




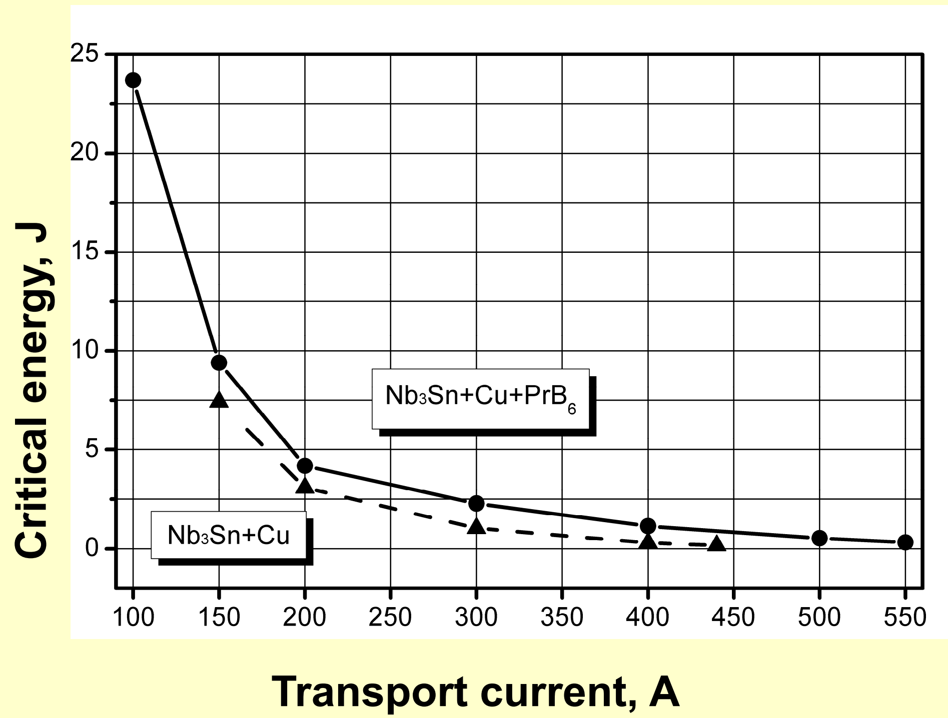


0.82 mm Nb3Sn samples with/without PrB6 doping

Nb_3Sn and NbTi strands with enhanced heat capacity



Critical energy versus transport current for 0.73 mm NbTi samples with/without Gd_2O_2S doping



Critical energy versus transport current for 0.82 mm Nb_3Sn samples with/without PrB_6 doping

summary

- NbTi strands with Cu/non Cu ratio 1.4-1.6 designed for the use in ITER PF 1&6 coils have Jc ≥ 2900 A/mm^2 (5 T, 4.2 K). Increase of Cu/non Cu ratio up to 6.9 in ITER type NbTi strands designed for the use in ITER PF 2-5 coils led to 10% drop in Jc values.
- NbTi 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), the work is in progress. Still some R&D work has to be done to attain target value.
- Bronze processed ITER type Nb3Sn strands have made a good progress in critical current density, attaining 800 A/mm2 (non-Cu, 12T, 4.2K) in commercially produced wires. In laboratory scaled wires 900 A/mm2 (non-Cu, 12T, 4.2K) has been attained.