Design features and microstructure of the commercially produced high Jc internal tin Nb_3Sn strands with one common diffusion barrier

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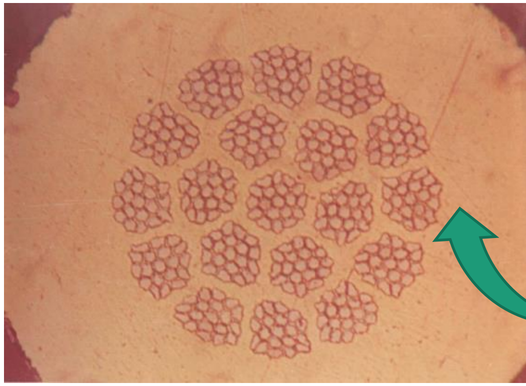
Nb_3Sn strands produced by bronze and internal tin methods

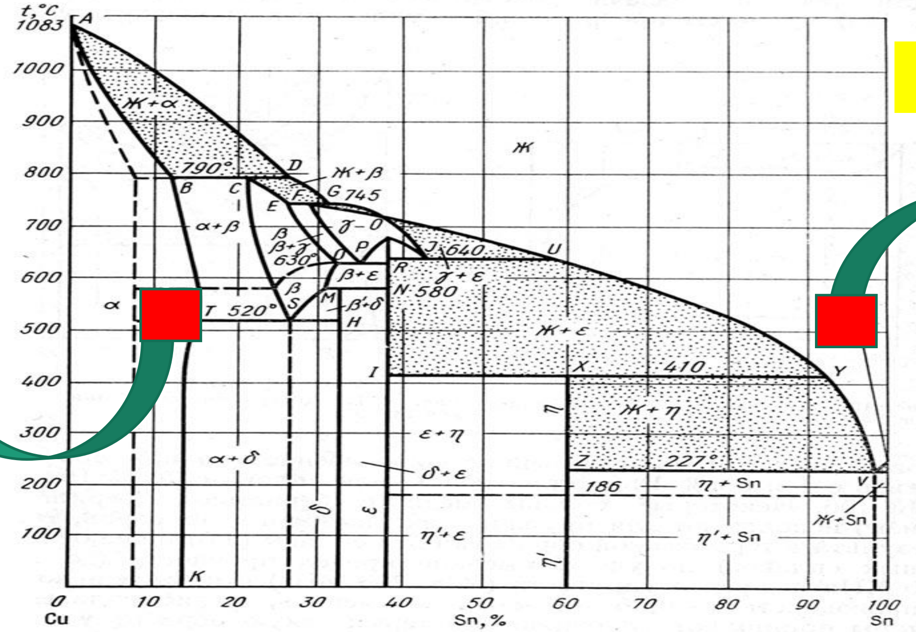
(In Russia: Development - Bochvar Institute; Production – [UMZ plant] - ChMZ plant)

1975 First bronze strands

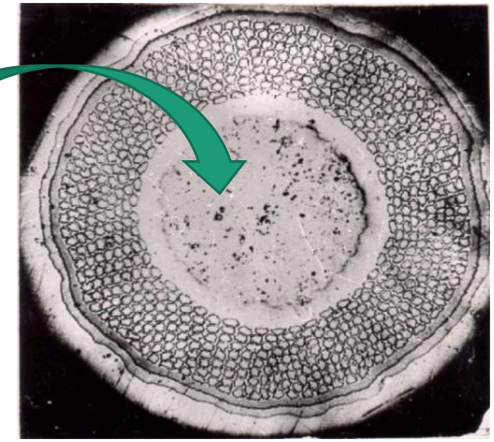


361 filaments

2 Components:
Nb + Bronze (Cu-Sn)



1975 First Internal Tin strands

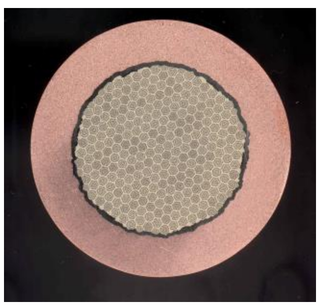


650 filaments

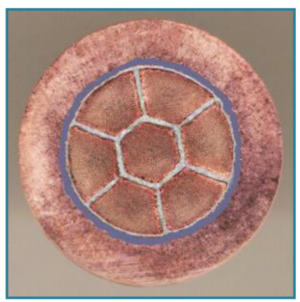
3 Components:
Nb + Cu + Sn

Commercially produced Nb_3Sn strands

ChMZ plant, Glazov, 2009-2015

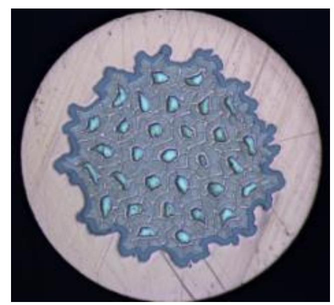


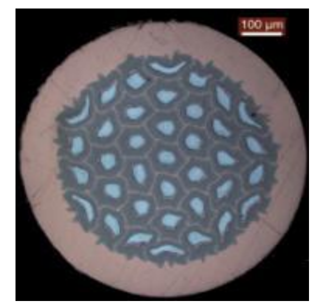
Bronze ITER type
Nb_3Sn wire Jc = 850 A/mm²



IT ITER type
Nb_3Sn wireJ c = 1000 A/mm²

ChMZ plant, Glazov, 2016-2017

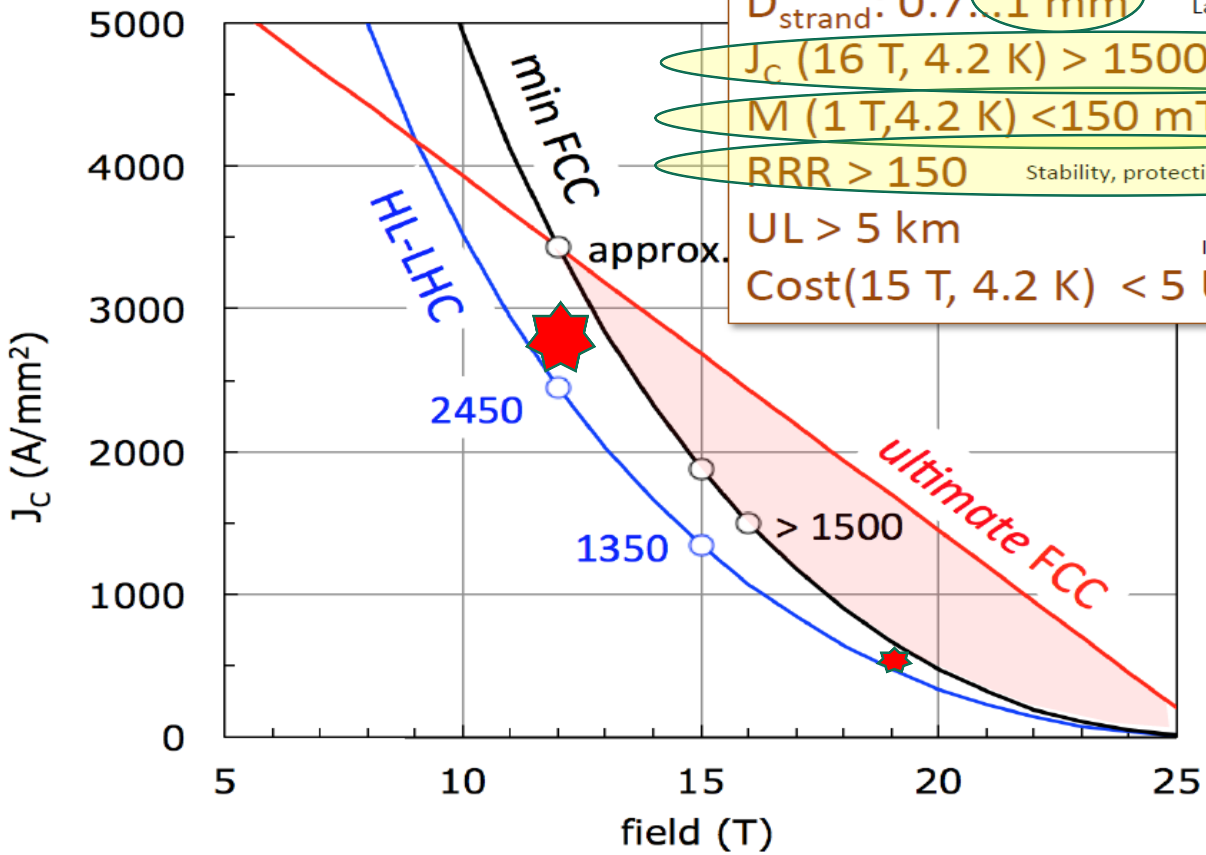




IT LHC-FCC type Nb_3Sn wires with common and separated barriers Jc (non Cu; 12 T) up to 2500 A/mm²

The FCC challenges for internal tin strands

FCC Nb_3Sn performance targets



D_{strand}: 0.7…1 mm — Large cables, **cabling !**

J_C (16 T, 4.2 K) > 1500 A/mm^2

M (1 T, 4.2 K) <150 mT (D_{fil} < 20 µm) — Field quality

RRR > 150 — Stability, protection

UL > 5 km

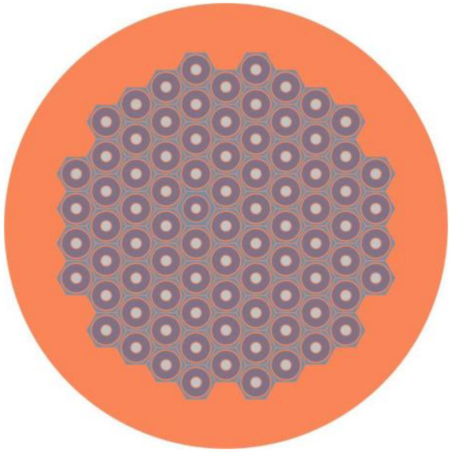
ITER material cost per kg

Cost(15 T, 4.2 K) < 5 USD/kA m

All single parameters are in reach, their combination is the challenge !

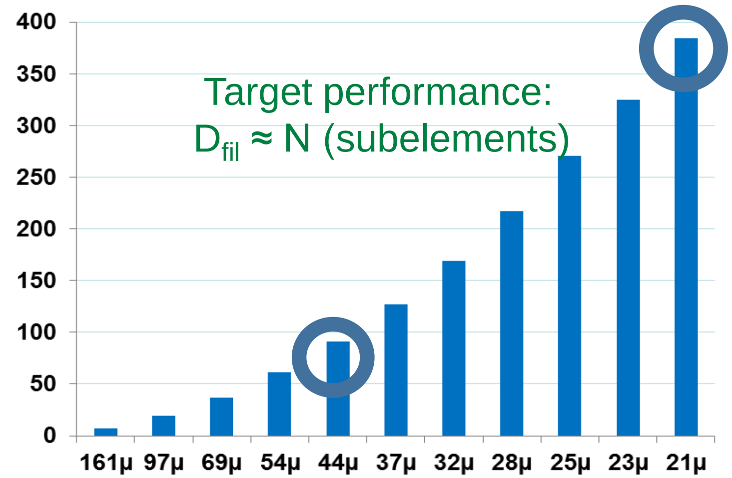
Experimentally attained Jc value in RF

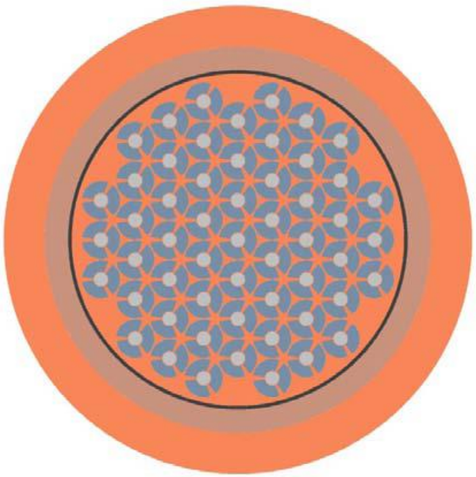
Design of Nb_3Sn High Jc Internal Tin strands for FCC



Separated diffusion barriers around each subelements

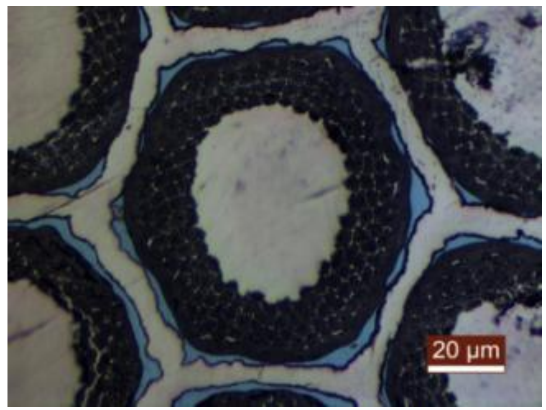
85 monoelements
Deff in the order of **50 µm**





Single common diffusion barrier

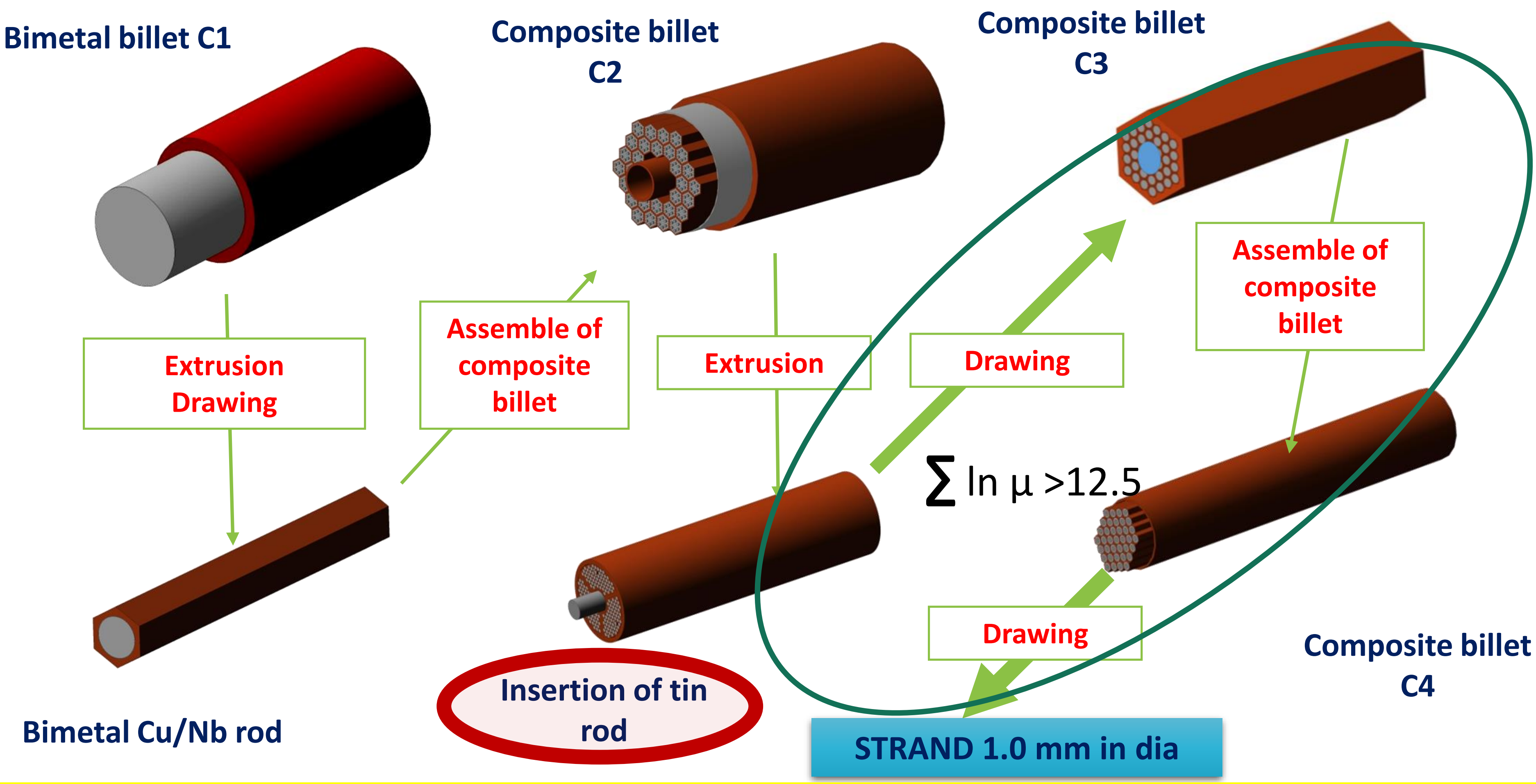
55 splitted sub-elements (equavalent to 270 effective filaments)
Deff in the order of **25 µm**



Up to 32% of non Cu area will be occupied by unreacted Nb for 20 µm subelements (assuming 4 µm average thickness)

- Increase of the number of subelements leads to the corresponding increase of the technological drawbacks connected with the large free surface between subelements enhancement and large preliminary plastic deformation before assembling of the final billet
- **Difficult to maintain initial RRR >150 for strands with separated diffusion barriers around each subelements**

Internal tin strand production scheme



Particular feature of IT strands – large cold plastic deformation by drawing without intermediate heat treatments (problems – formation of metallurgical bonding; texture formation)

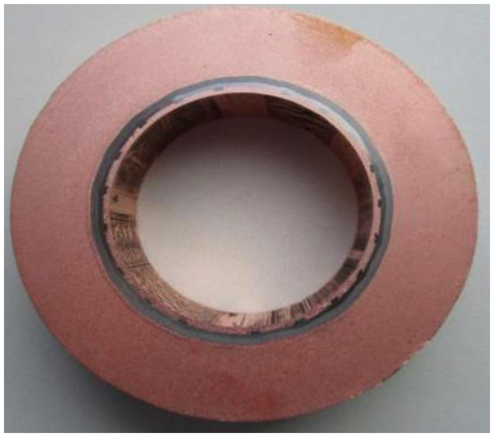
Basic design parameters of IT strands with one common diffusion barrier designed for HI-LU specifications

Parameter	Common Ta barrier
Strand diameter, mm	0.7
Cu/non Cu	1,20
Nb fraction within barrier, % vol.	≈41 %
Nb_3Sn fraction in non Cu area after HT, %vol.	46 %
D subelement, µm	70.5
Subelement spacing, µm	2.68
D filament, µm	2.7
Cu thickness between Nb filaments, µm	0.3
Ti doping (artificial; in Nb filaments), at%	1.74

The artificial doping by Ti has been done by insertion of the plurality of NbTi rods in the Nb filaments

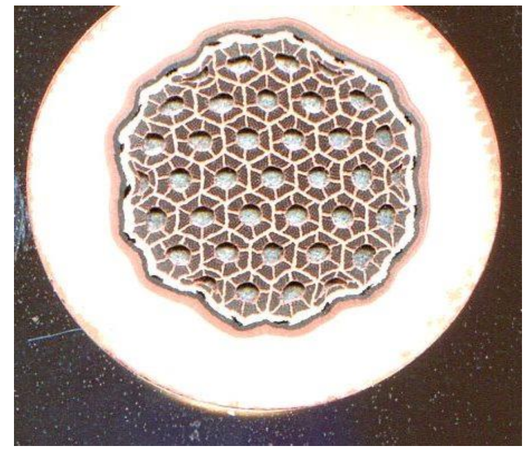
Deformation of IT strand's components without intermediate heat treatments

	Common barrier	Distributed barriers
Nb inside subelements	lnAo/A = 11-12	lnAo/A = 11-12
Nb (Ta) in diffusion barrier	lnAo/A = 8 - 9	lnAo/A = 11-12



60 mm in dia Composite outer tube consists of stabilizing Cu, strengthening Cu-Nb layer, Nb difusion barrier, Ta dividing inserts, technological Cu

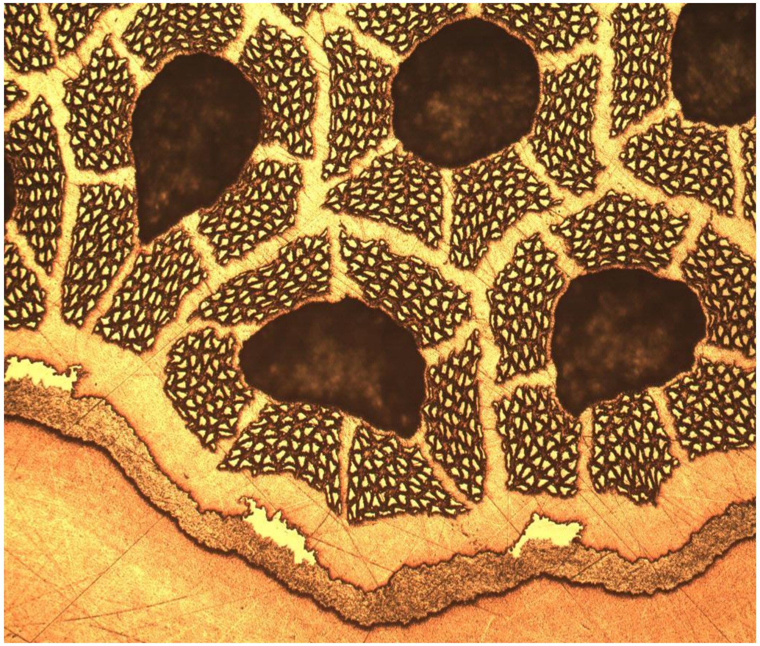
Hexagonal composite rod (subelement)consists of axial Sn alloy rod, 6 sectors composed by the Nb(Ti) doped filaments embedded into Cu matrix and separated by the Cu layers



2 mm in dia final design composite wire consists of 37 subelements 37 tin sources, 222 Cu-Nb sectors

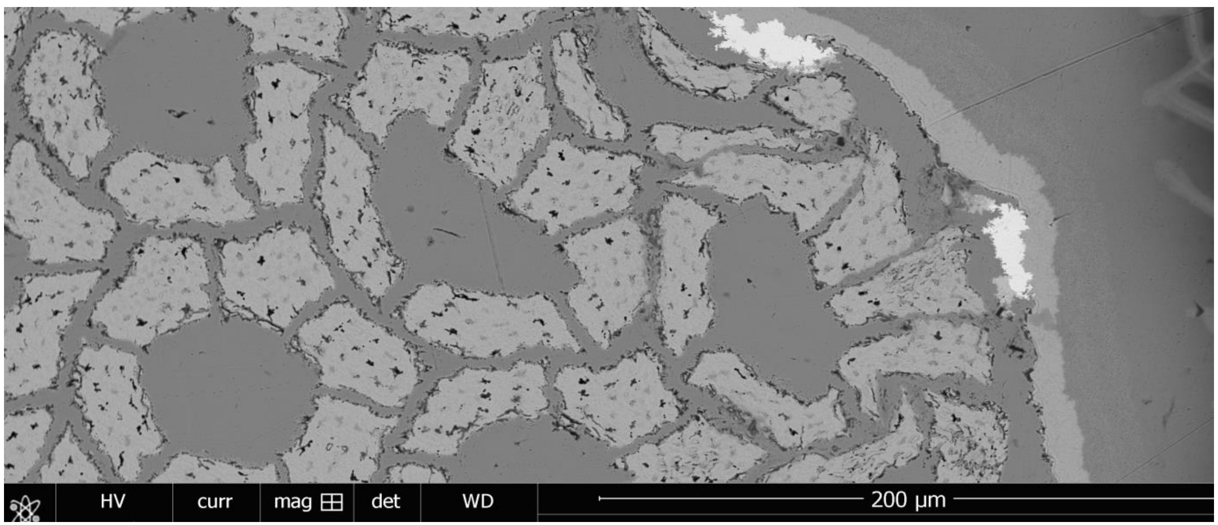
Different stages of IT strand manufacture

(Design of Diffusion barrier optimization)



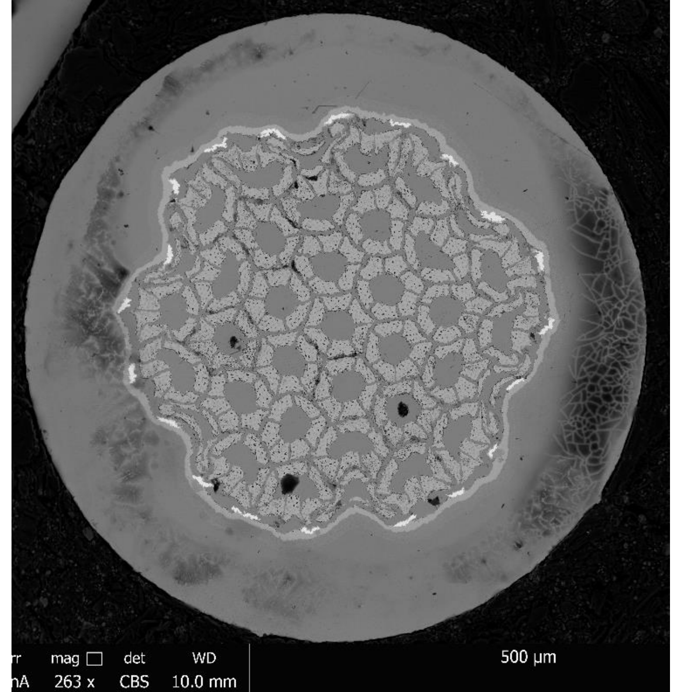
The Nb barrier should be optimized with 20 Ta rods for subdividing the circular Nb_3Sn layer. The thikness could be deminished due to positive role of Cu-Nb strengthening layer adjucent to Nb barrier.

The preliminary design assumes the thickness of Nb barrier around 8 µm
The 4-5 µm of Nb barrier should be reacted with the formation of the Nb3Sn phase. The vokume fraction of diffusion batrrier will be around 2,5% from non-Cu area.



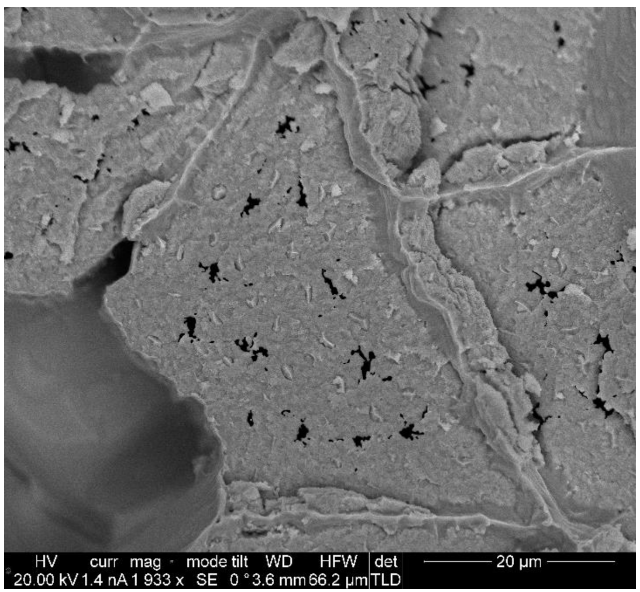
The strand after reaction heat treatment with several intermediate stages 220 C + 370 + 570 C + (660-700 C)

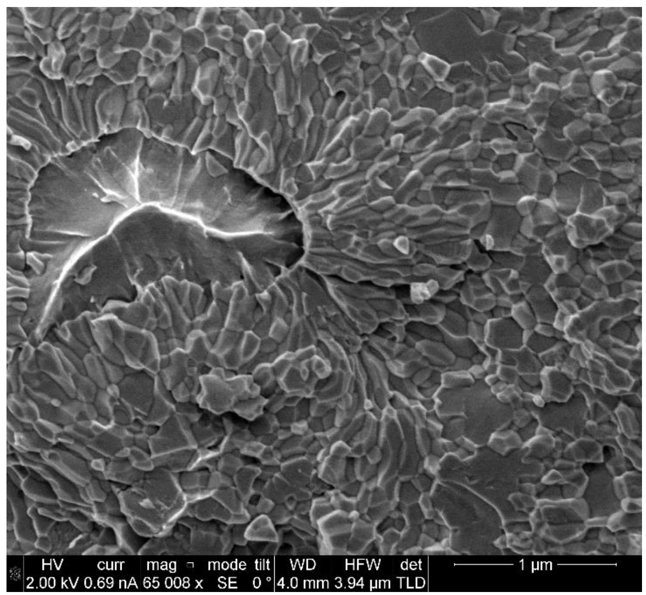
The microstructure of IT strands (common barrier)

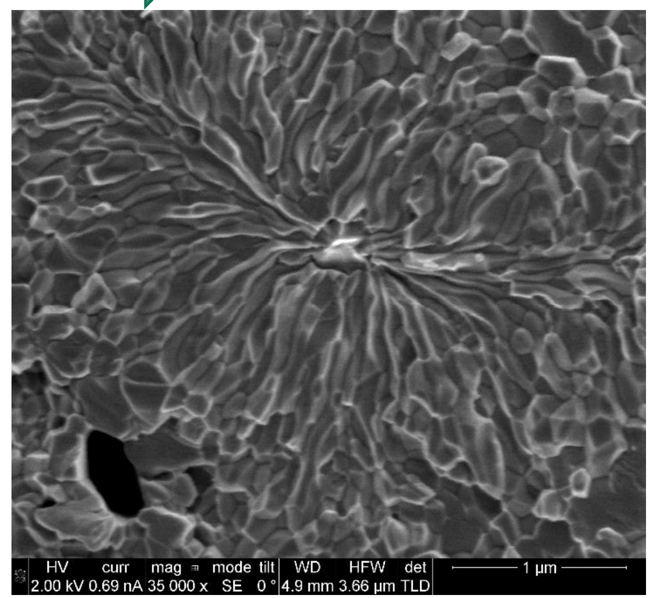


The microstructure of Nb3Sn layers in highly bridged macrofilaments has to be optimized in the futher R&D

Increase of last stage heat treatment's(660 C) duration акщь 25 р ещ 100 р

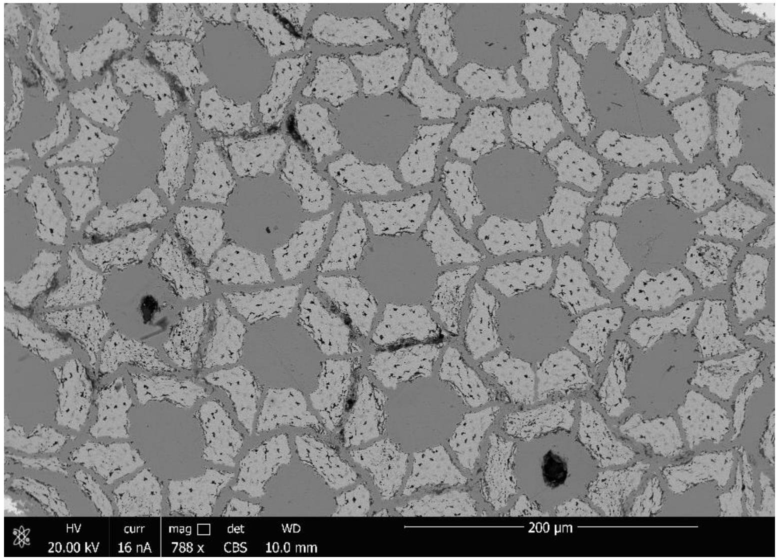


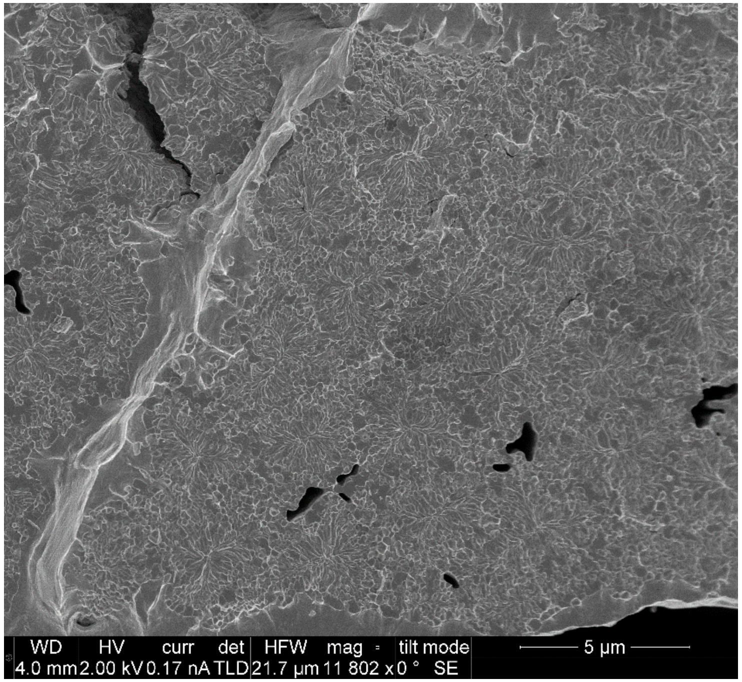


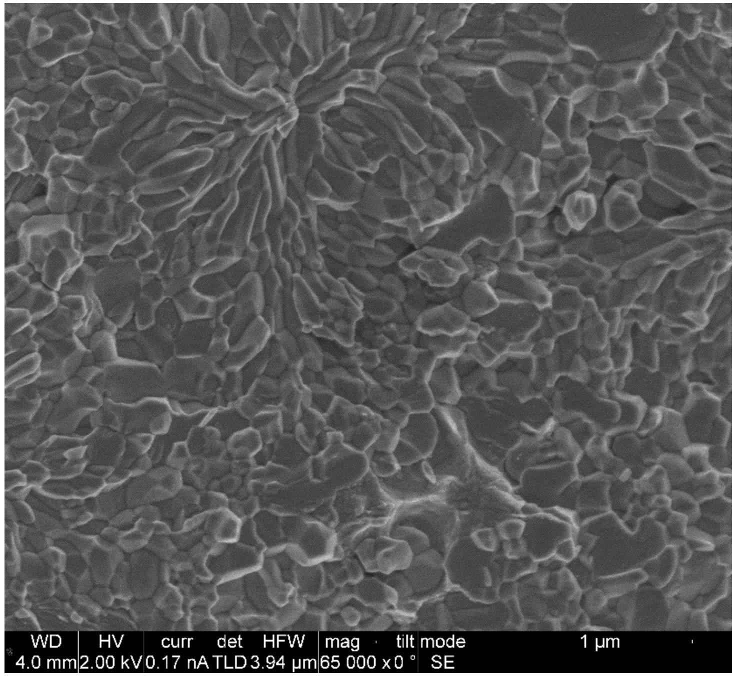


The microstructure of IT strands (common barrier)

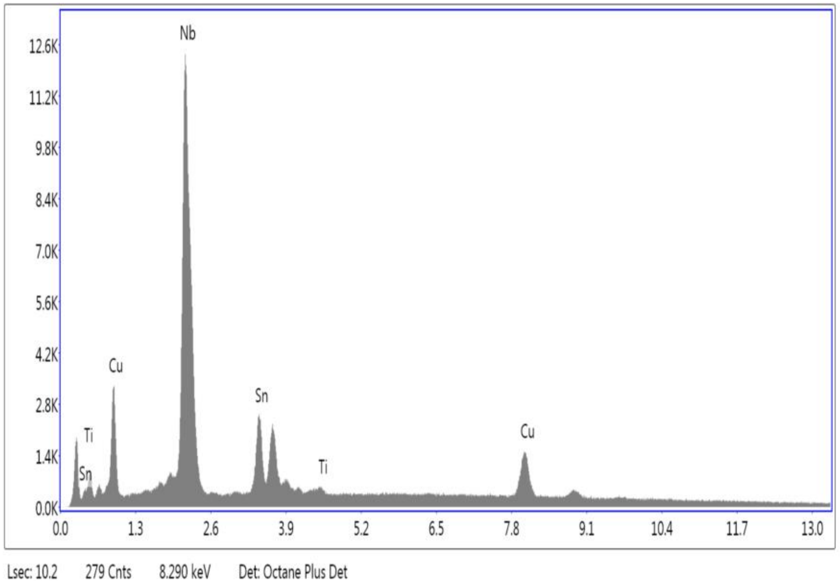
Each sector of Nb filaments forms a macrofilament as a result of reaction of Nb and Sn with formation of Nb3Sn phase (last stage heat treatment temperature – 700 C)

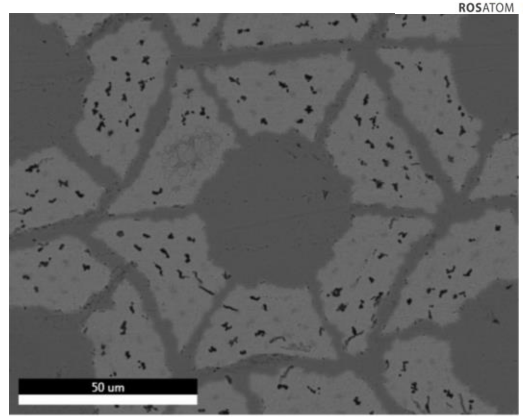


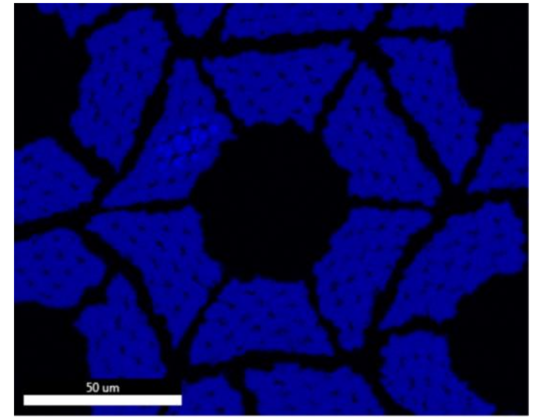




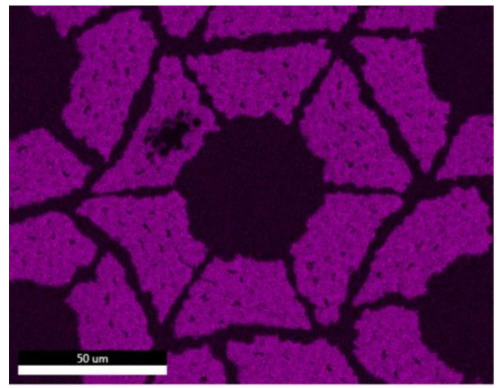
The microstructure of IT strands (common barrier)



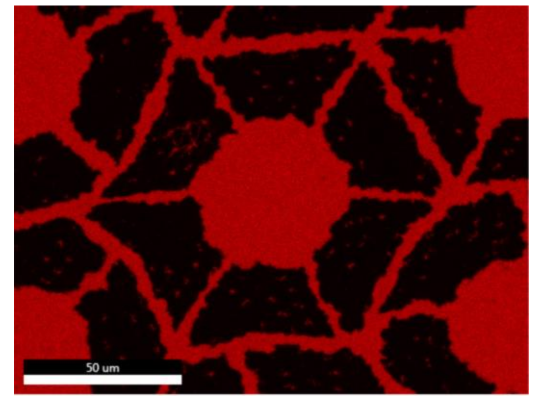




Nb



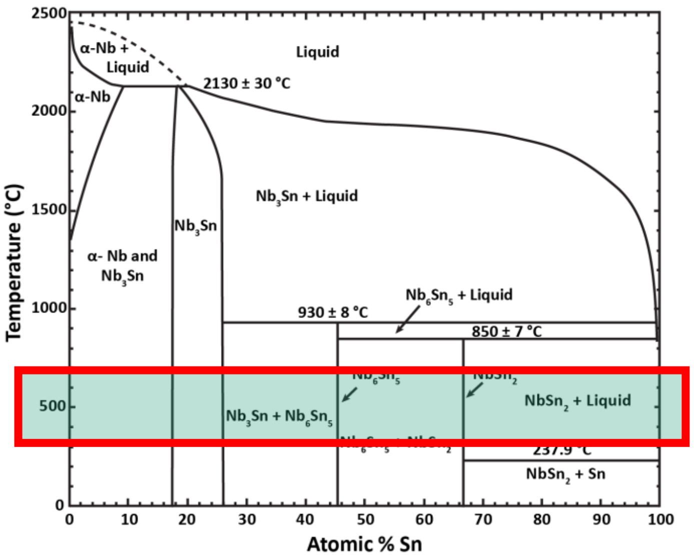
Sn

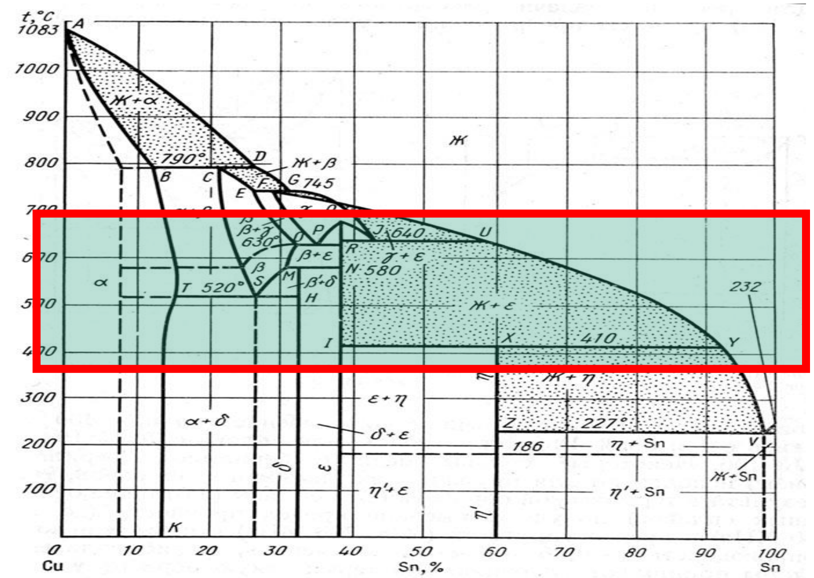


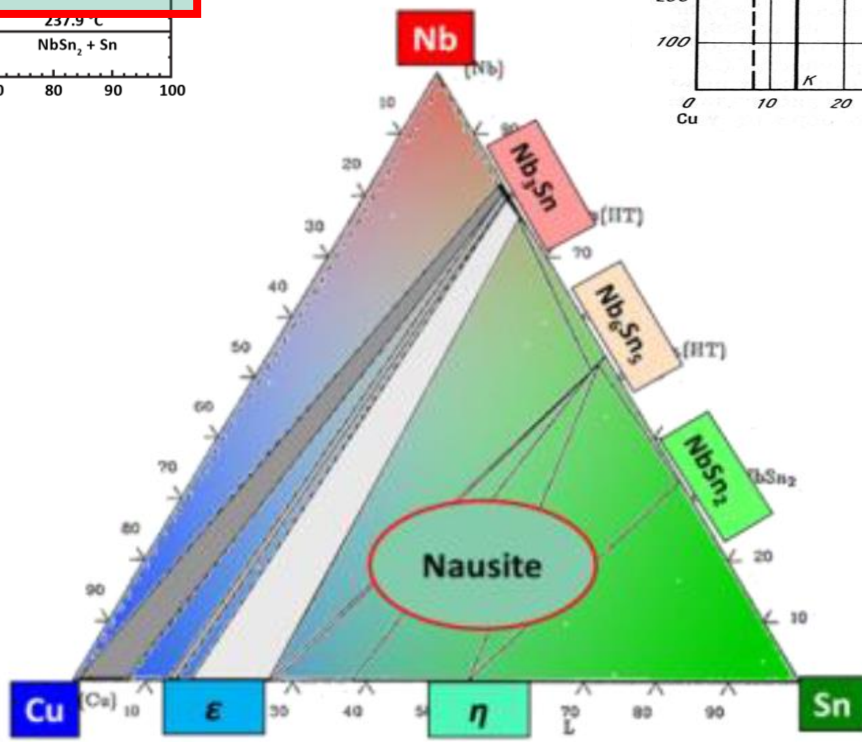
Cu

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	R	A	F
NbL	57.59	53.56	11448.70	2.98	0.4988	0.9949	1.0122	0.8614	1.0107
SnL	18.26	13.29	2223.70	5.05	0.1426	0.9315	1.0575	0.8216	1.0210
TiK	0.65	1.18	144.90	22.30	0.0059	1.1160	0.9083	0.7848	1.0297
CuK	23.50	31.96	2300.60	3.70	0.2644	1.0785	0.9587	0.9615	1.0848

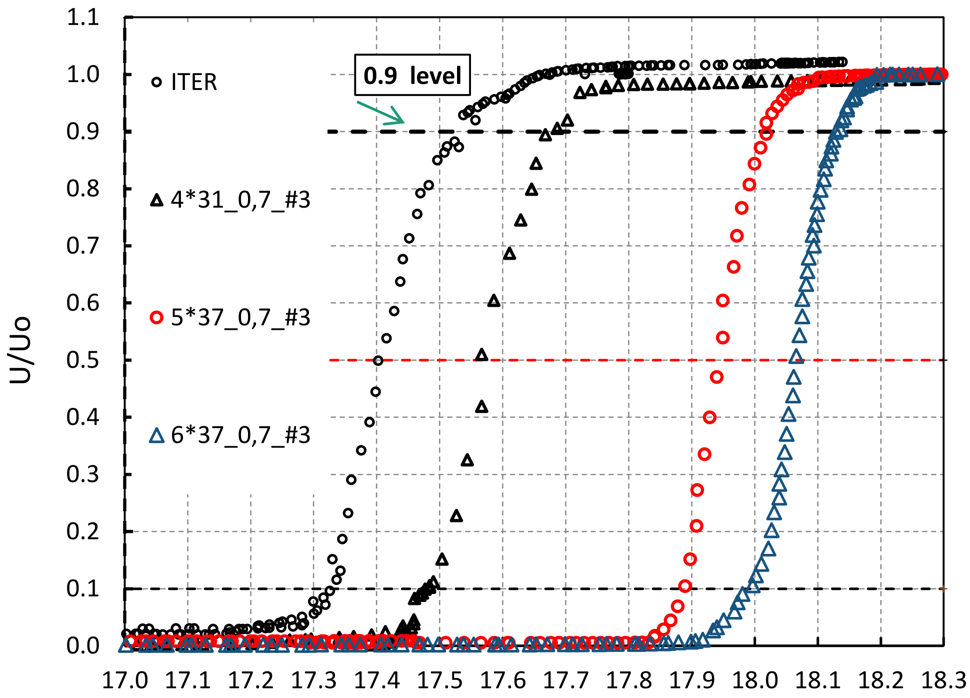
Heat treatment of Internal Tin Nb_3Sn Strands

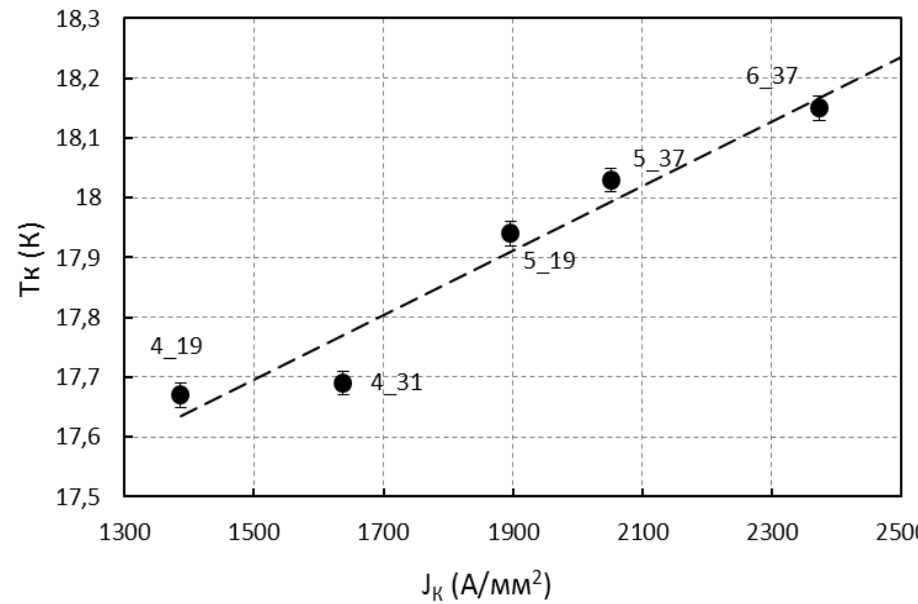






Superconducting properties of IT strands Tc - Jc

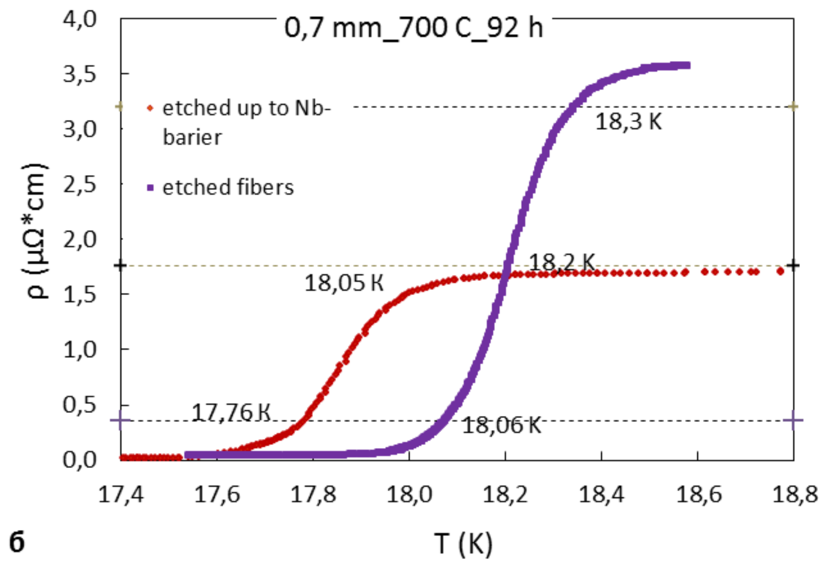


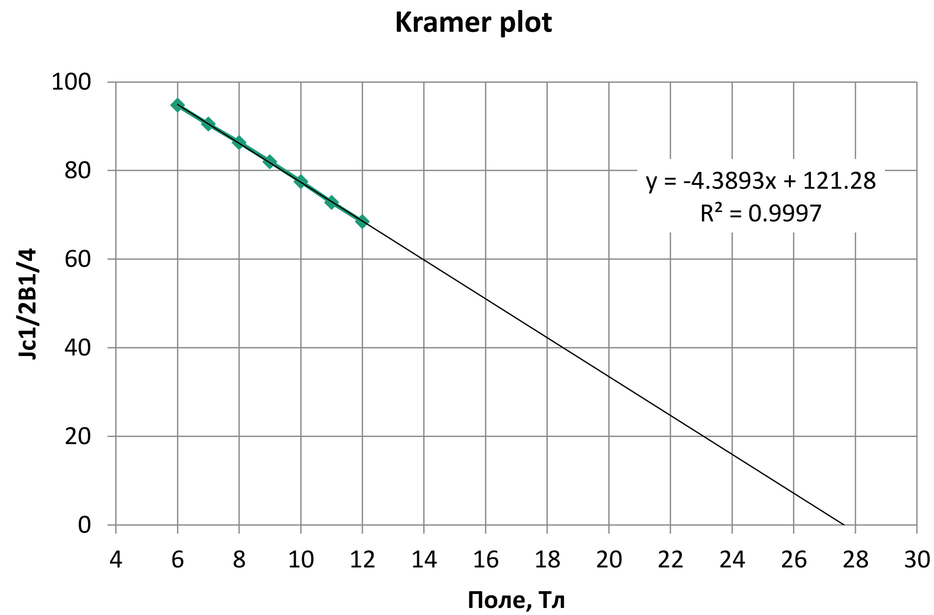


Voltage-temperature characteristics of the wires investigated after h.t .#3- 210 °C/50 h+400 °C/50 h_665 °C/100 h in comparison with ITER wire (bronze route, h.t. cycle B)

Critical temperature of IT strands are higher than of bronze processed

Superconducting properties of IT strands





Etching out outr Cu and outer diffusion barrier led to increase of the Tc caused by the relaxation of the internal stresses

SUMMARY

- The separation of the Nb filaments inside the subelements could be effectively realized by the introduction of the layers of copper based plates.
- The formation of Nb_3Sn “macrofilaments” with complete reaction of Nb filaments has been observed
- Nonuniformity of the grains microstructure in the Nb_3Sn “macrofilaments” has been found with columnar grains that is characteristic for solid state reaction altogether with the large equaxed grains in the boundaries regions between former Nb filaments
- The optimization of the heat treatment regimes with the accent on the intermediate 570 C stage is in progress.
- The attainment of the FCC strand’s specifications is challenging, still requires intensive R&D works but seems to be realistic