



NATIONAL NUCLEAR CORPORATION "ROSATOM"



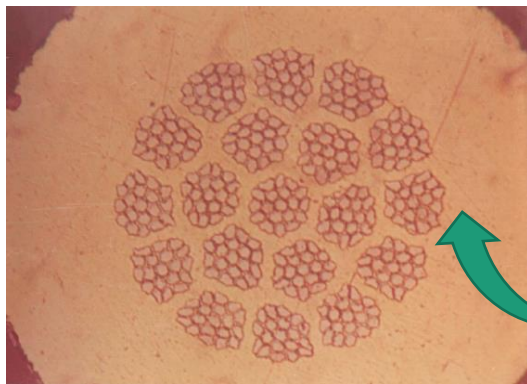
Design features and microstructure of the commercially produced high J_c internal tin Nb_3Sn strands with one common diffusion barrier

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Nb₃Sn strands produced by bronze and internal tin methods

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

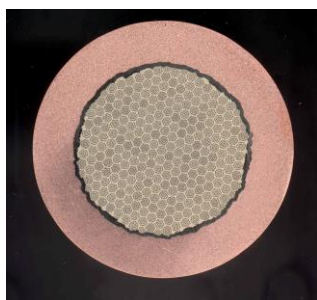
1975 First bronze strands



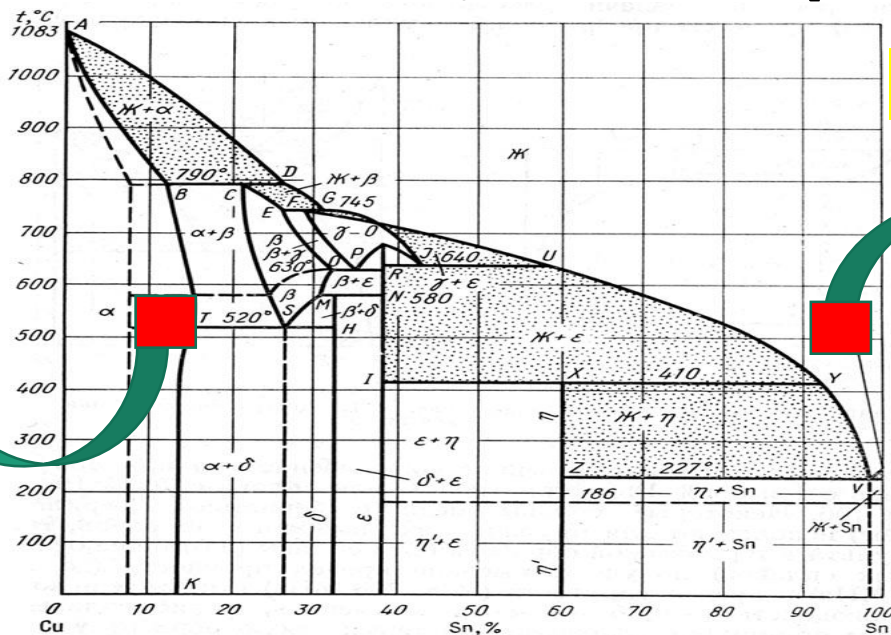
361 filaments

2 Components:
Nb + Bronze (Cu-Sn)

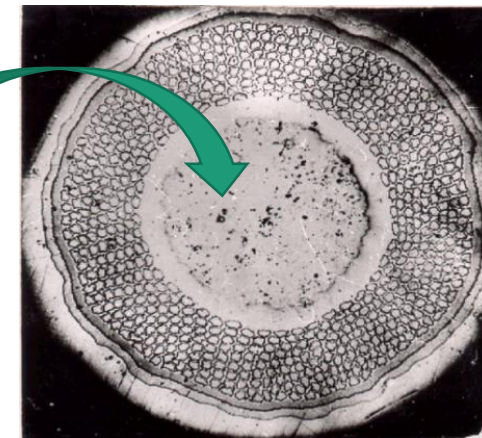
ChMZ plant, Glazov, 2009-2015



Bronze ITER type
Nb₃Sn wire J_c = 850 A/mm²



1975 First Internal Tin strands

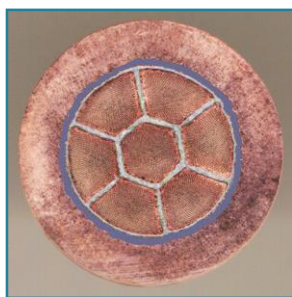


650 filaments

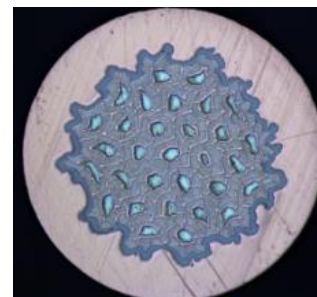
3 Components:
Nb + Cu + Sn

ChMZ plant, Glazov, 2016-2017

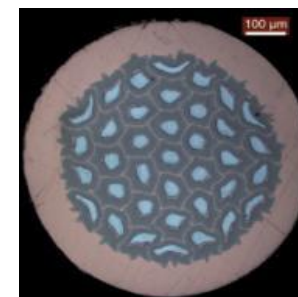
Commercially produced Nb₃Sn strands



IT ITER type
Nb₃Sn wire J_c = 1000 A/mm²

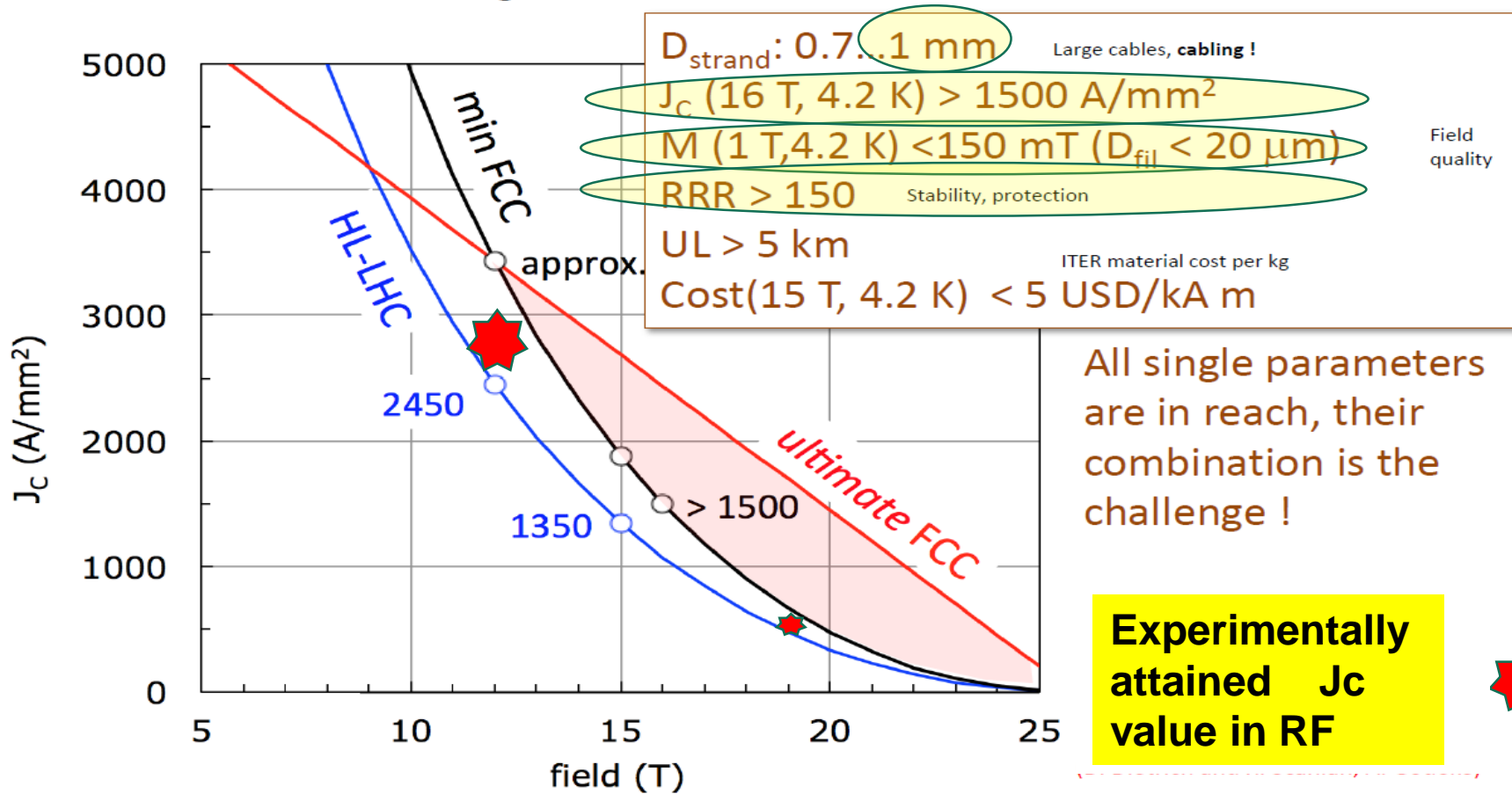


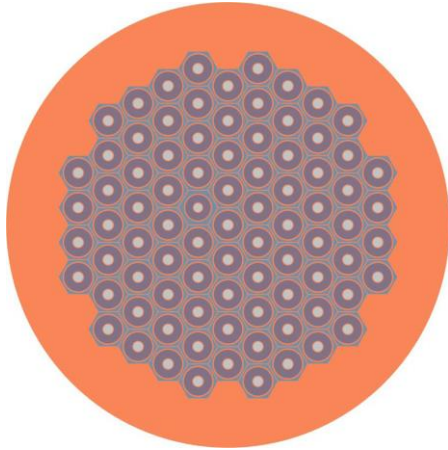
IT LHC-FCC type Nb₃Sn wires with common and separated barriers J_c (non Cu; 12 T) up to 2500 A/mm²



The FCC challenges for internal tin strands

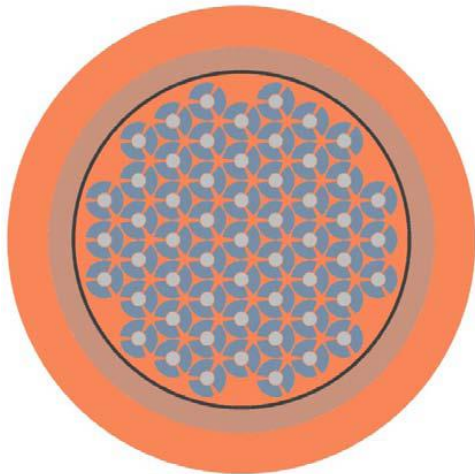
FCC Nb₃Sn performance targets





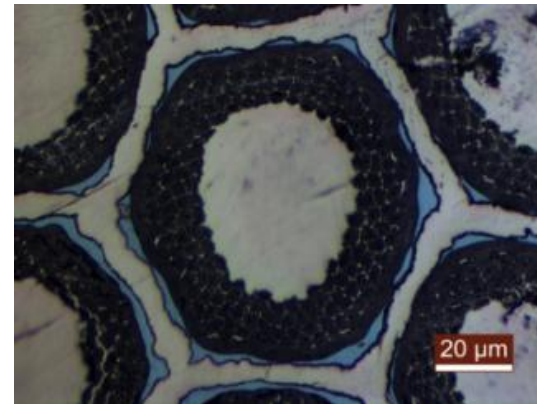
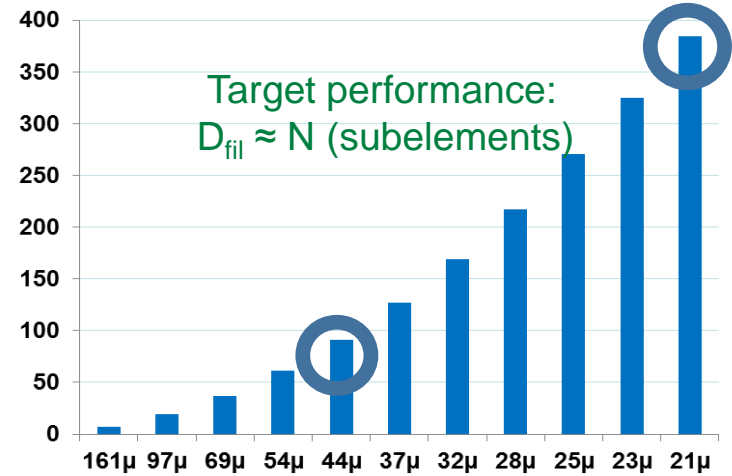
Separated diffusion barriers around each subelements

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



Single common diffusion barrier

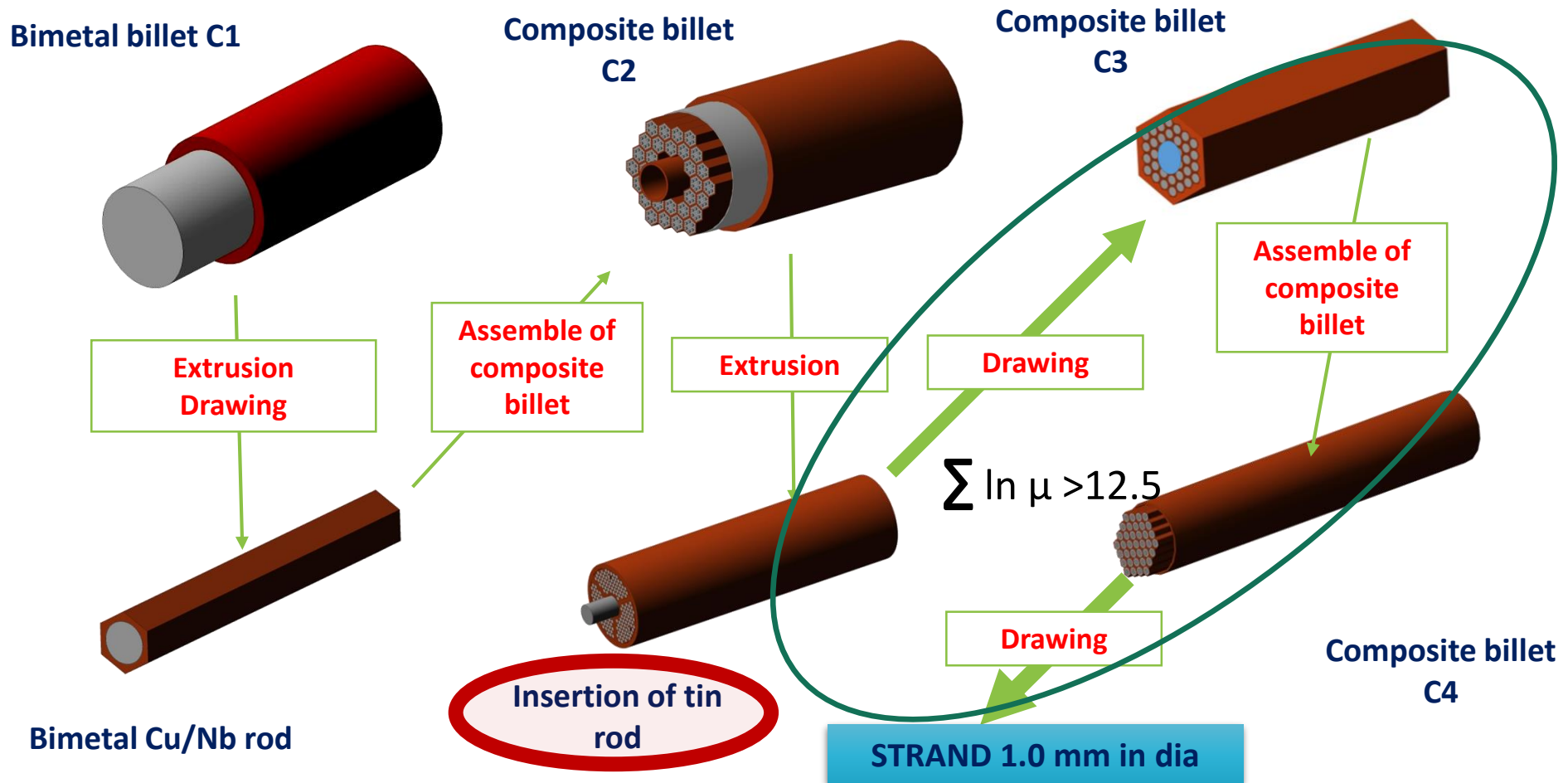
55 splitted sub-elements
(equivalent to 270 effective filaments)
Deff in the order of **25 μm**



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)

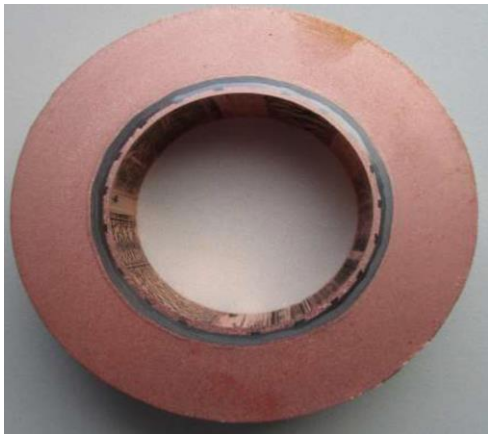
Basic design parameters of IT strands with one common diffusion barrier designed for HI-LU specifications

Parameter	Common Ta barrier
Strand diameter, mm	0.7
Cu/non Cu	1,20
Nb fraction within barrier, % vol.	≈41 %
Nb ₃ Sn 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

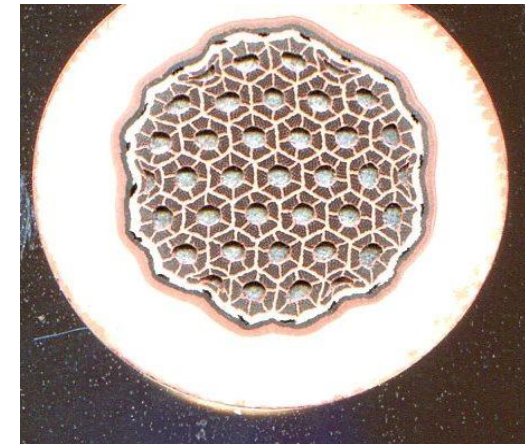
	Common barrier	Distributed barriers
Nb inside subelements	$\text{InAo/A} = 11-12$	$\text{InAo/A} = 11-12$
Nb (Ta) in diffusion barrier	$\text{InAo/A} = 8 - 9$	$\text{InAo/A} = 11-12$



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



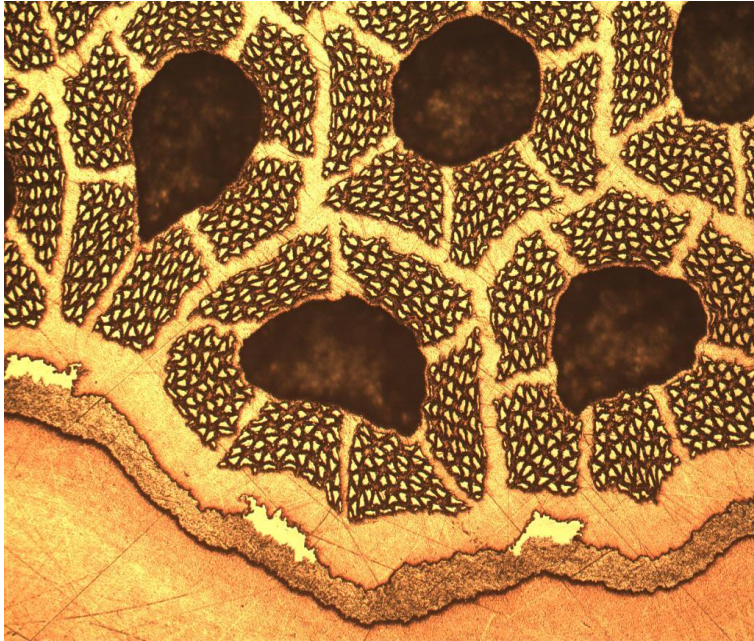
Hexagonal composite rod (subelement) consists of axial Sn alloy rod, 6 sectors composed by the Nb(Ti) doped filaments embedded into Cu matrix and separated by the Cu layers



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

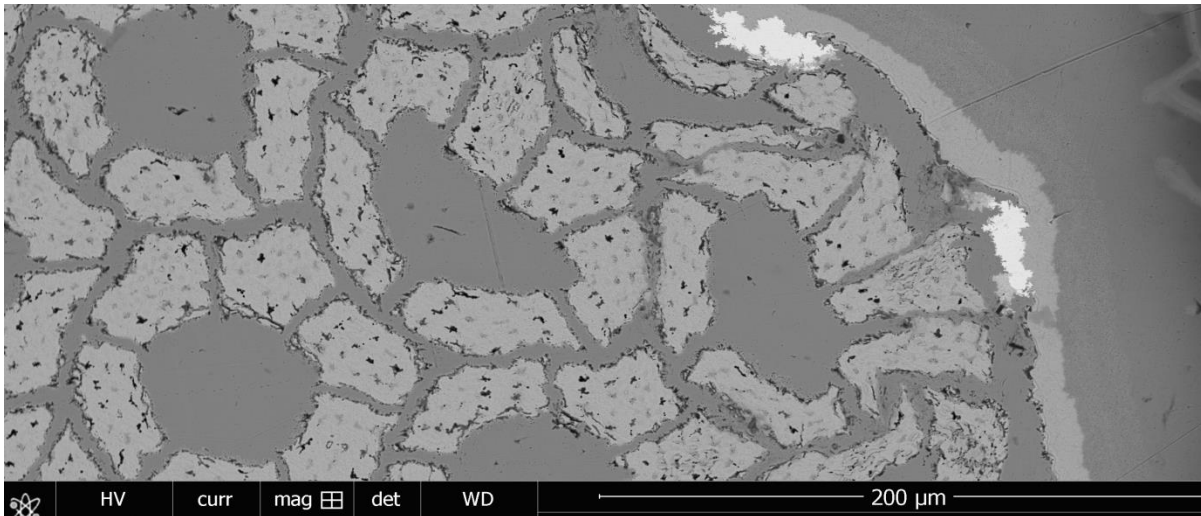
Different stages of IT strand manufacture

(Design of Diffusion barrier optimization)



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

The preliminary design assumes the thickness of Nb barrier around $8 \mu m$
 The $4-5 \mu m$ of Nb barrier should be reacted with the formation of the Nb_3Sn phase. The volume fraction of diffusion barrier will be around 2,5% from non-Cu area.

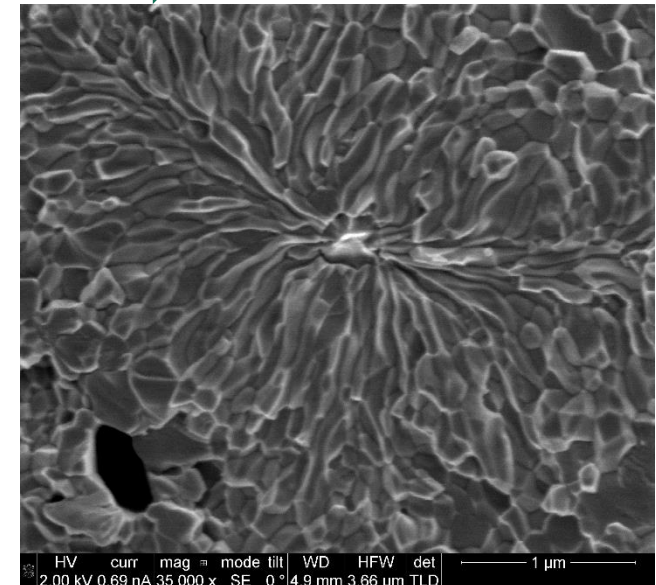
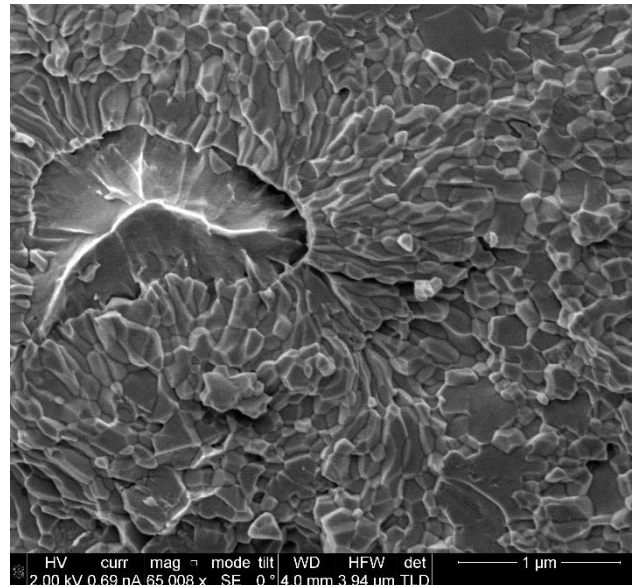
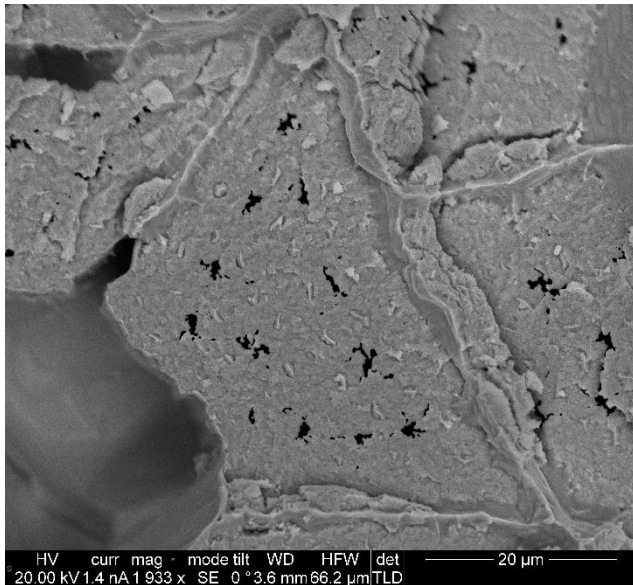
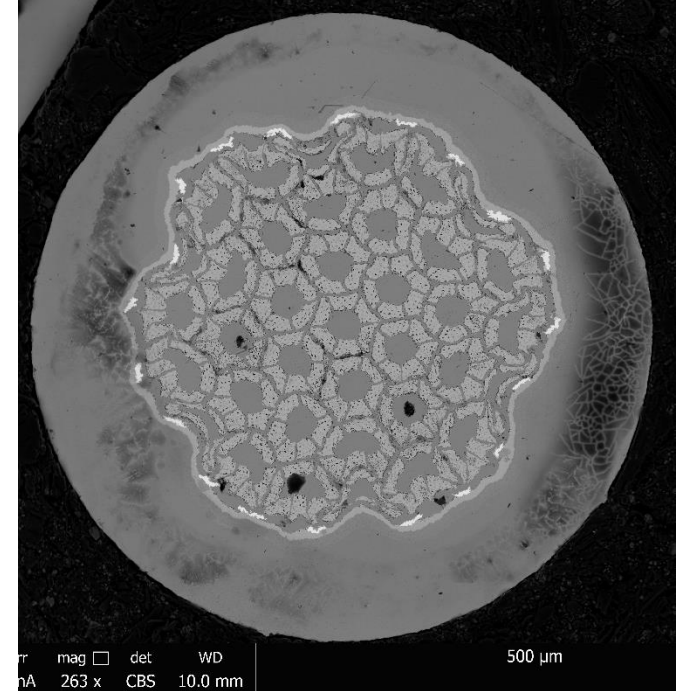


The strand after reaction heat treatment with several intermediate stages $220 C + 370 + 570 C + (660-700 C)$

The microstructure of IT strands (common barrier)

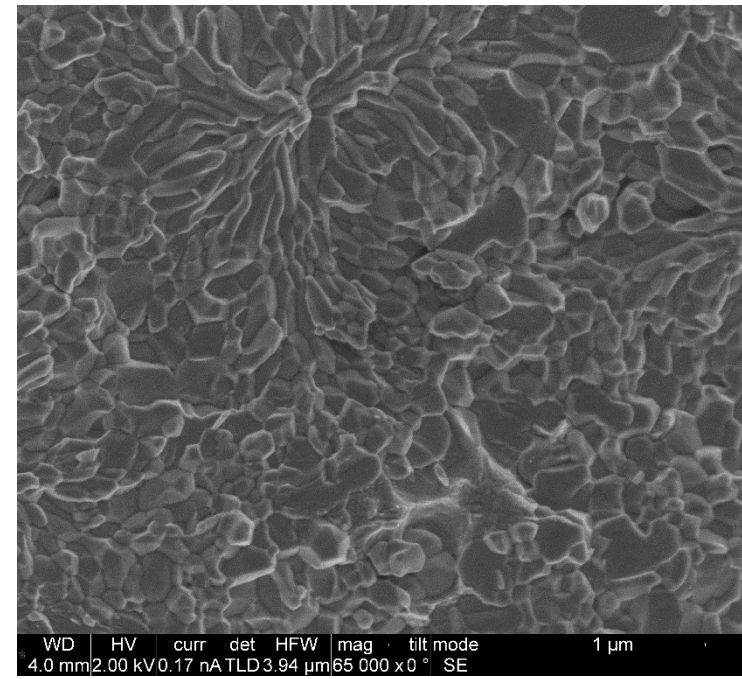
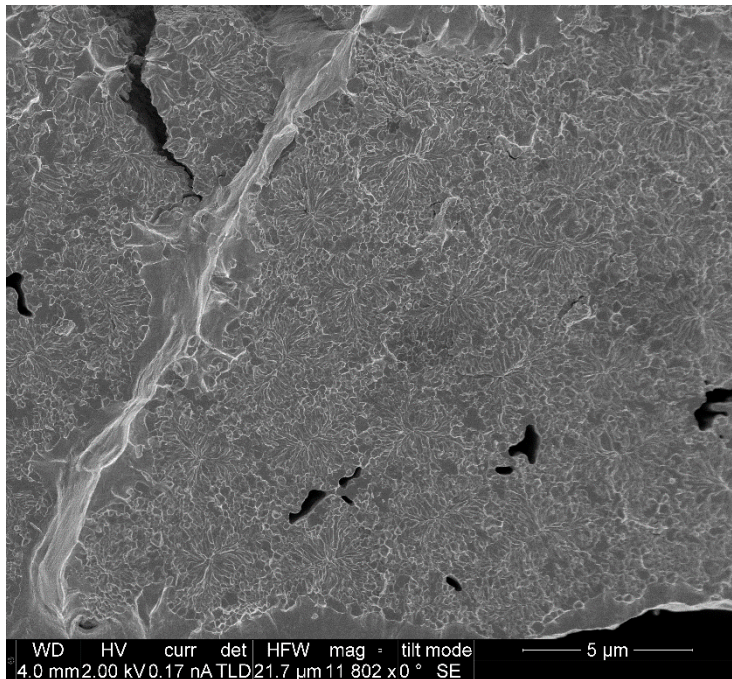
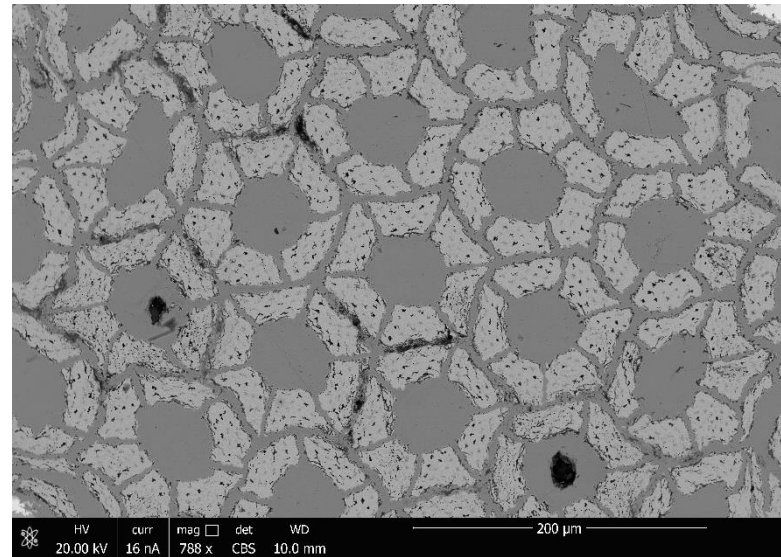
The microstructure of Nb₃Sn layers in highly bridged macrofilaments has to be optimized in the futher R&D

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

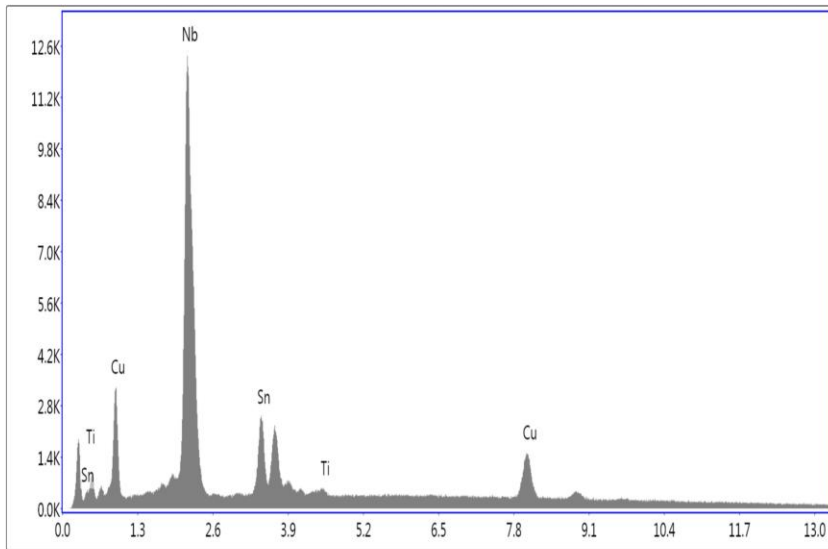


The microstructure of IT strands (common barrier)

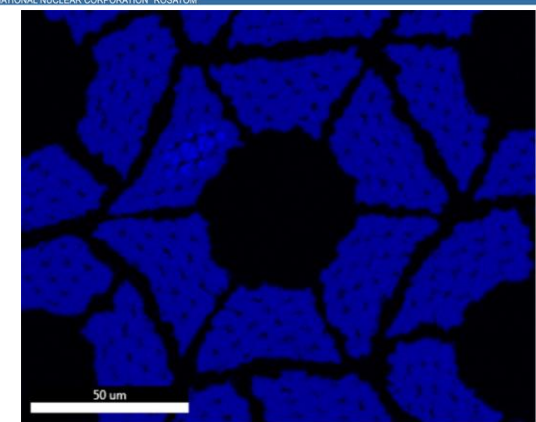
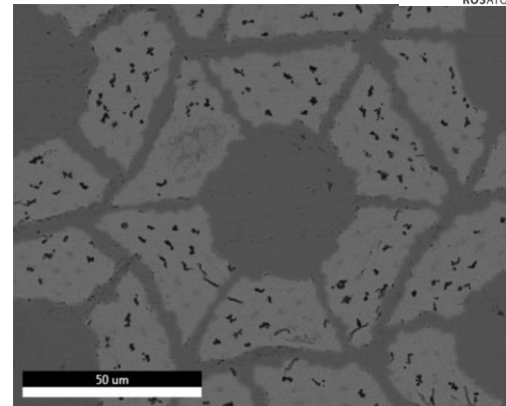
Each sector of Nb filaments forms a macrofilament as a result of reaction of Nb and Sn with formation of Nb₃Sn phase (last stage heat treatment temperature – 700 C)



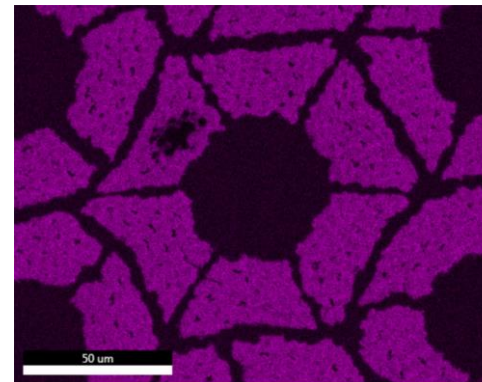
The microstructure of IT strands (common barrier)



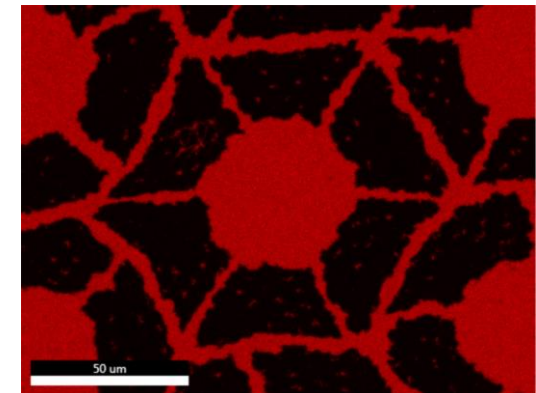
Lsec: 10.2 279 Cnts 8.290 keV Det: Octane Plus Det



Nb

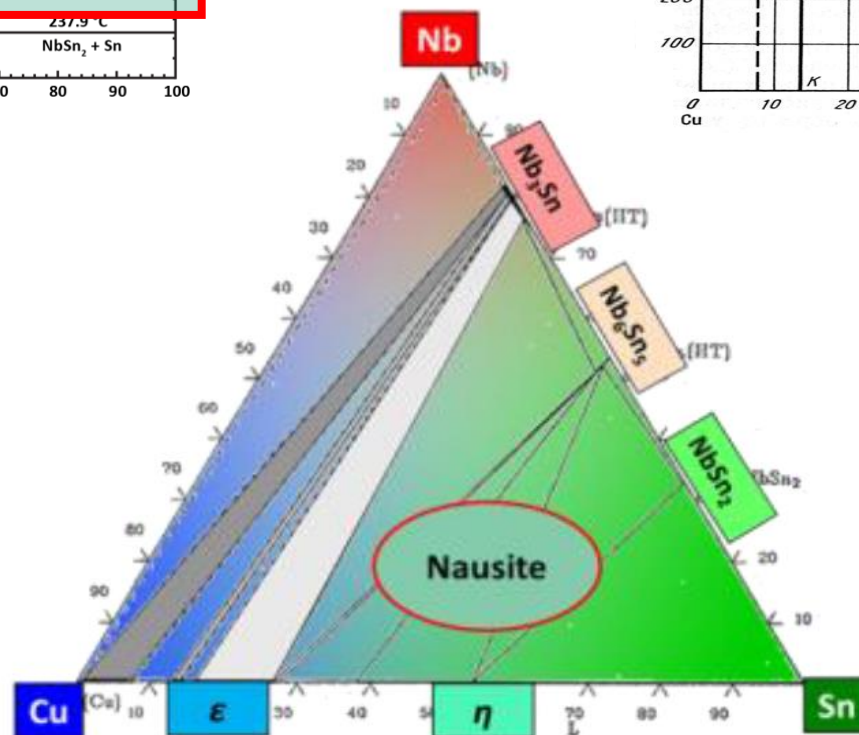
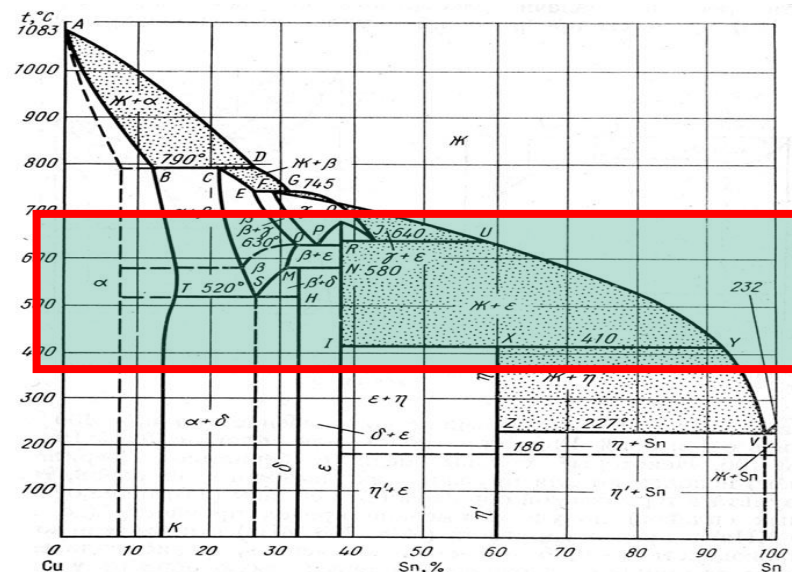
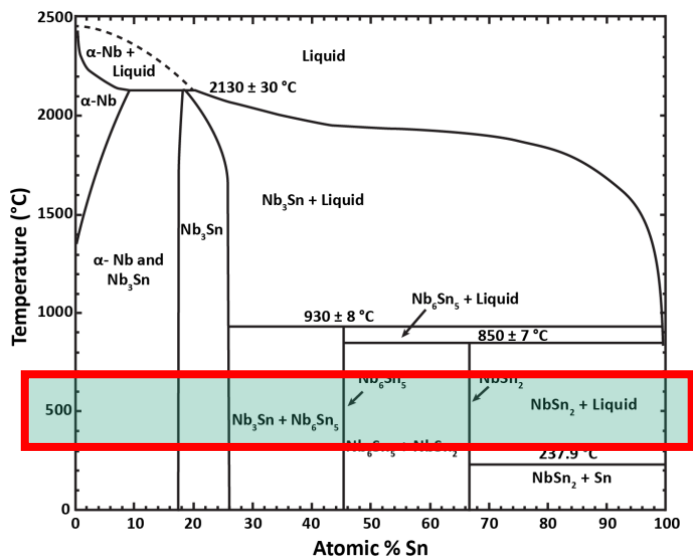


Sn

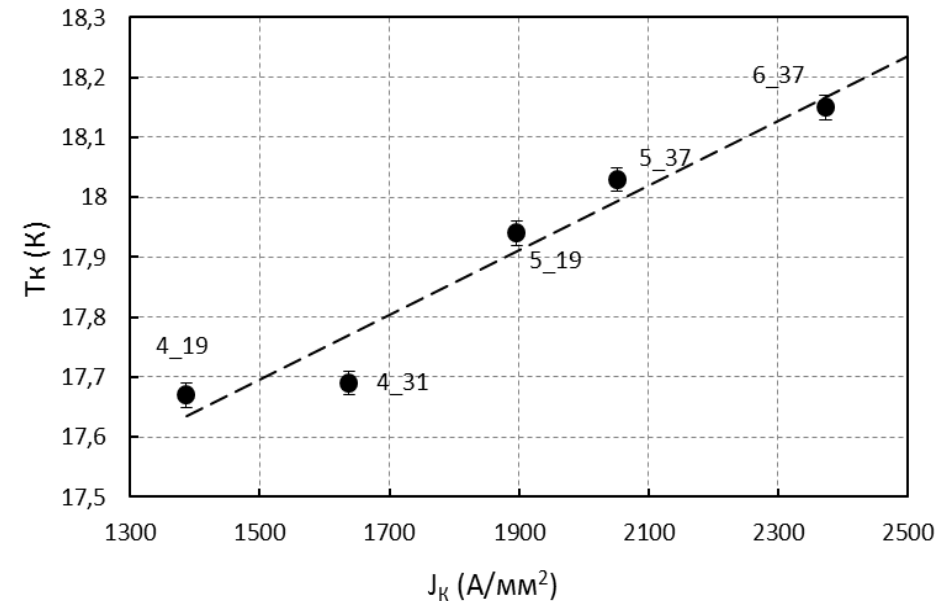
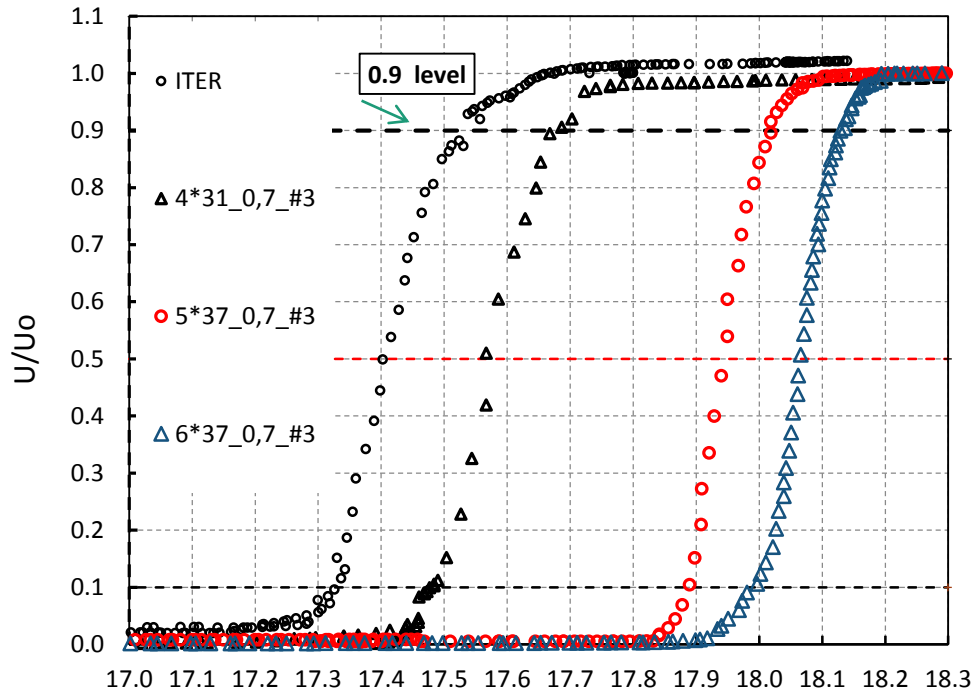


Cu

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



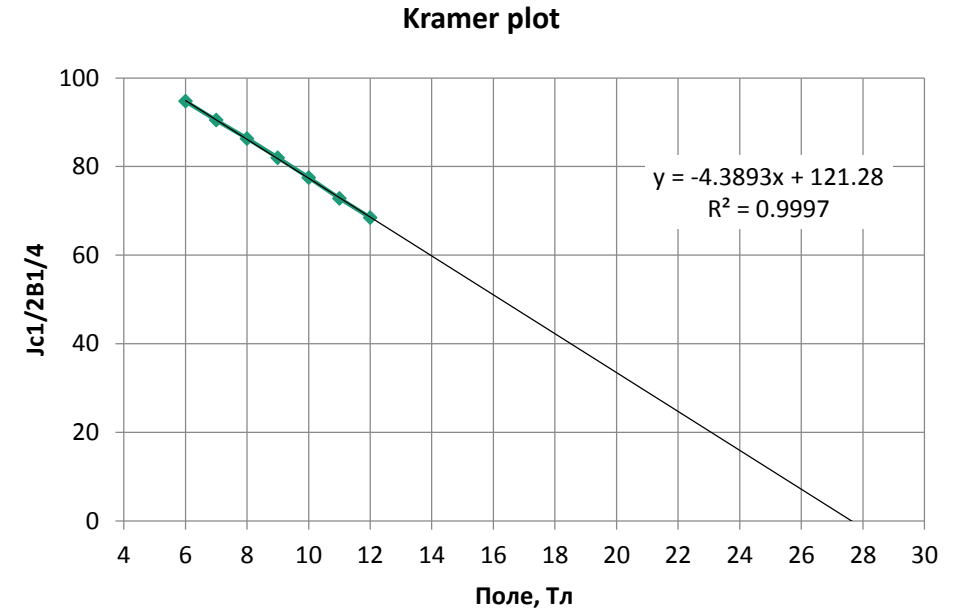
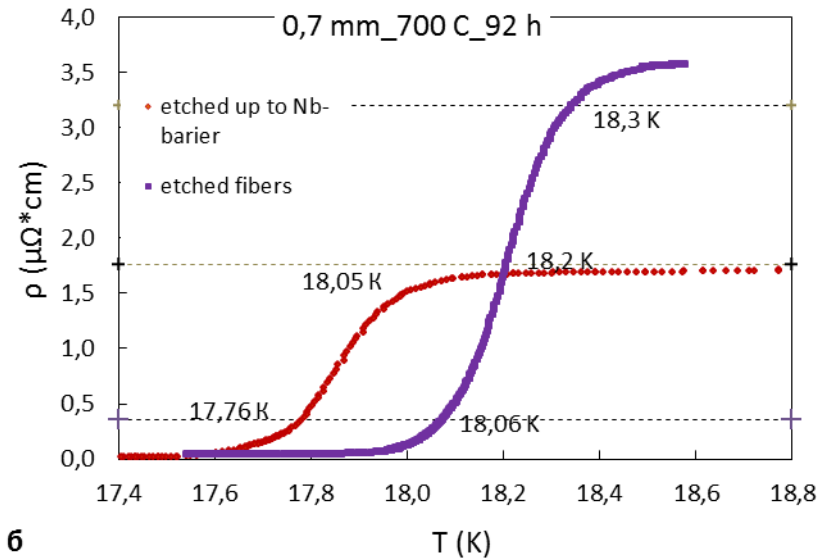
Superconducting properties of IT strands $T_c - J_c$



Voltage-temperature characteristics of the wires investigated after h.t
 T (K)
 #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 outer Cu and outer diffusion barrier led to increase of the T_c 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 Nb₃Sn “macrofilaments” with complete reaction of Nb filaments has been observed
- Nonuniformity of the grains microstructure in the Nb₃Sn “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