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FUEL COMPANY OF ROSATOM
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BOCHVAR INSTITUTE OF
INORGANIC MATERIALS
JSC VNIINM

STATE ATOMIC ENERGY CORPORATION “ROSATOM”

Development of Internal Tin Strands for FCC Magnets in Russia

(TVEL, Bochvar Institute, ChMP)

V.Pantsyrny I. Abdyukhanov

Agreement on R&D CERN-TVEL

CERN proposed Main Objective of the Conductor Development Program in FCC Project

Provide feedback on possibility of **achieving <u>beyond state-of-the-art HL-LHC Nb_3Sn</u>** <u>high-field performance</u> (**Jc @ 16 T**) to enable design of compact and cost effective 16 T magnets;

Foster **Nb_3Sn conductor development in industry** and support the industrial development with academic **activities** (material studies and characterization) **in laboratories and institutes world-wide**;

Jc at 16 T *required to be up to ~* ***30% -50 % higher*** *than what achieved on the HL-LHC Nb_3Sn series production*

Present cost of high-performance (HL-LHC) Nb_3Sn is > 20 Euro/kA m (4.2 K, 16 T). ***FCC target is 5 Euro/kA m (4.2 K, 16 T)****.*

This Conference Presentations associated with the Development of Internal Tin Strands for FCC Magnets in Russia

Jc at 16 T *required to be up to* ***~30% -50 % higher***
than what achieved on the HL-LHC Nb_3Sn *series production*

Characterization of FCC conductors at TU Vienna

M. Eisterer, T. Baumgartner, M. Ortino, J. Bernardi, S. Pfeiffer, A. Moros, M. Stöger-Pollach, M. Sumption, X. Xu, X. Peng, M. Alekseev, A. Tsapleva, P. Lukyanov, I. Abdyukhanov, V. Pantsyrny, B. Bordini, S. Hopkins, A. Ballarino

FCC-hh Nb_3Sn wire development: superconducting and magnetic properties of prototype samples

Mattia Ortino[1], Alice Moros[2], Stefan Löffler[2], Maxim Alekseev[3], Anastasia Tsapleva[3], Pavel Lukyanov[3], Ildar M. Abdyukhanov[3], Victor Pantsyrny[3], Bernardo Bordini[4], Amalia Ballarino[4], Simon C. Hopkins[4], Michael Stöger-Pollach[2], Johannes Bernardi[2], Michael Eisterer[1].

AC magnetometry **-** in the range of temperature from 5 to 19 K;
Magnetic moment of wire sample as a function of temperature - M(T) curve for assessing T_c distribution.

Scanning Hall Probe Microscopy (SHPM) - in the range of temperature from 5 to 19 K;
Magnetization maps of individual sub-elements and clusters,

Development targets – Nb$_3$Sn

(starting with a 4 years program)

A. Ballarino, CERN

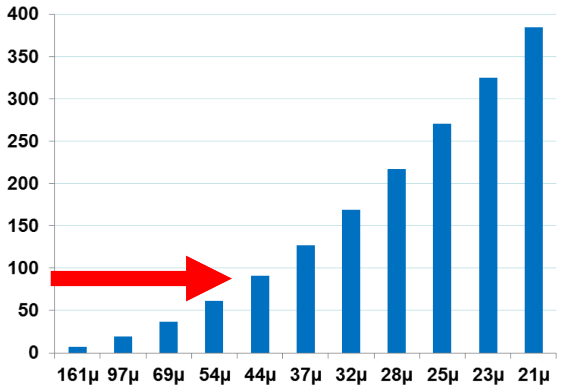
Wire diameter	mm	~ 1	
Non-Cu Jc (16 T, 4.2 K)*	A/mm^2	**≥ 1500**	
$\mu_0 \Delta M$(1 T, 4.2 K)	mT	**≤ 150**	
Deff	µm	**≤ 20**	**≤ 50**
RRR	-	**≥ 150**	
Unit length	km	**≥ 5**	**≥ 0.1**
Cost	Euro/kA m**	**≤ 5**	

Focus TODAY is on Jc

*Cu:non Cu ~ 1

** 16 T, 4.2 K

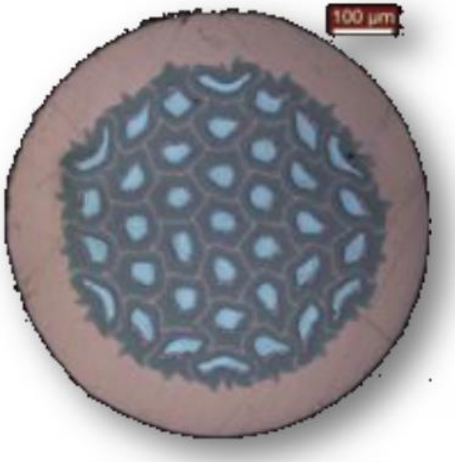
Deff ~ 50 µm could be Attained with 80-120 subelements

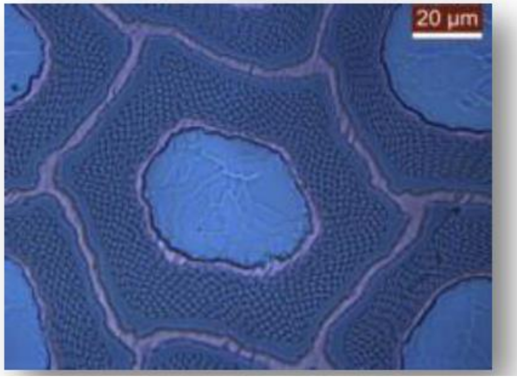


Process shall enable scalability and have potentially low cost for large production

Starting point - 2017 design of IT strand produced commercially

Distributed barrier

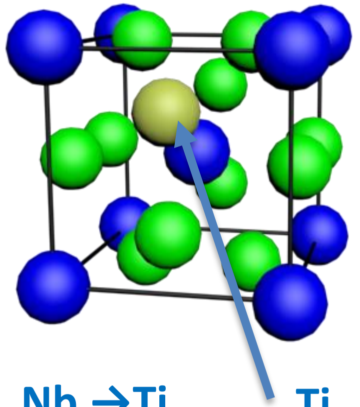




Parameter	
Strand diameter, mm	1,00
Cu/nonCu	1,20
Nb fraction within barrier, %vol	≈ 42%
Nb_3Sn fraction in non Cu area after HT, %. vol.	54%
D subelement, µm	113
Subelement spasing, µm	11
D filament, µm	4,9
Cu thinckness between Nb filaments, µm	0,6
Ti doping, at %	1,4
The last stage of HT	665°C/40h
J_c (12T; 4,2K) A/mm^2	2654
D eff (±3T), µm	134

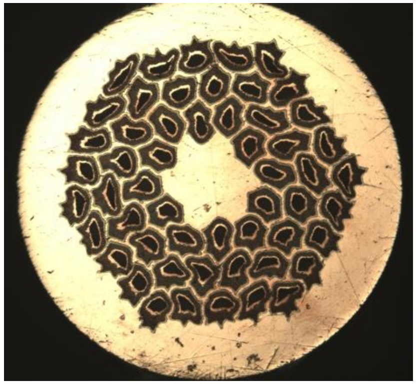
12 km of strands have been produced in industry ChMP Plant and supplied to CERN

Strands 2018 design with filaments doped by Ti, Ta



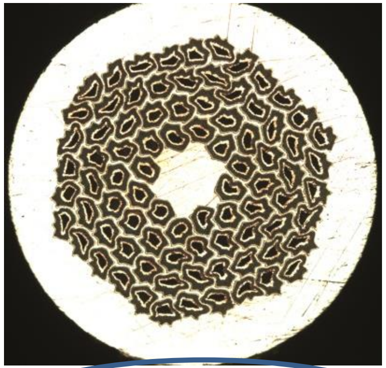
Nb →Ti

Ti

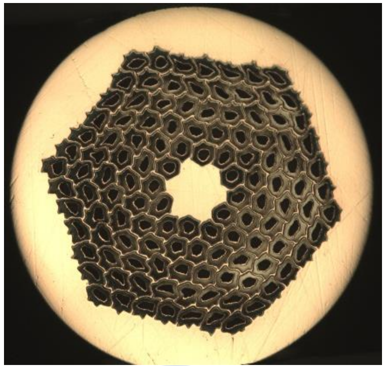


54 subelements

Strands 18 (Ti)

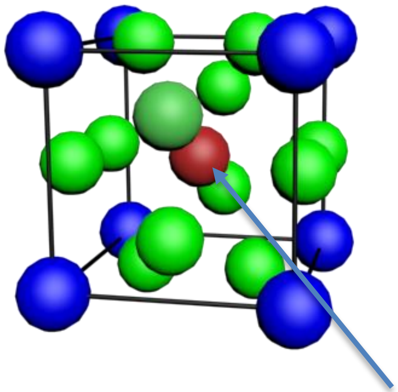


84 subelements

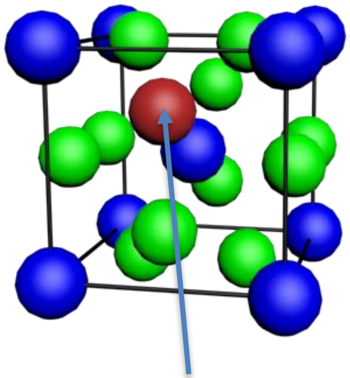


120 subelements

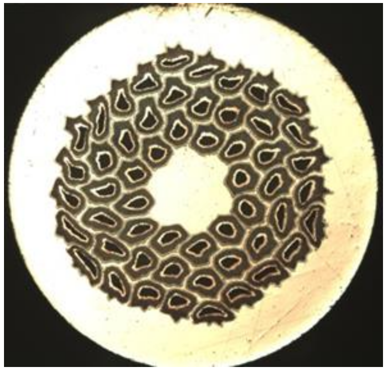
Strands 20 (Ti+Ta)



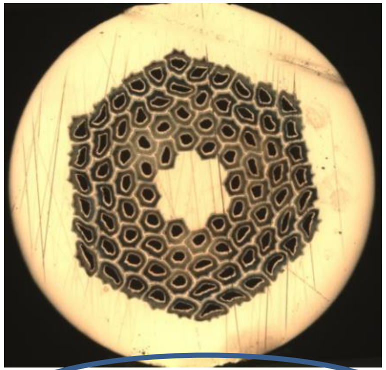
Sn →Ta



Nb →Ta



54 subelements



84 subelements

Ways to *target~30% -50 % higher Jc at 16 T*

1) Quantity of Nb_3Sn phase:
   - Barriers - number of subelements – thickness of the barriers – Nb_3Sn formation on the barrier – amount of deformation = variation in thickness of the barrier
   - Filaments - «monofilament» – or strongly bridged filament with inclusion of copper
2) Quality of Nb_3Sn phase:
   - Doping of the Nb filaments with objective to change the physical parameters of Nb_3Sn phase (Bc2 and Tc). Doping of the Cu matrix and Sn alloy
   - Composite filaments with possibility to change the mechanism of Nb_3Sn phase formation – not only changing the physical parameters of Nb_3Sn phase (Bc2 and Tc), but the morphology of the Nb_3Sn layer and size of grains
   - Heat Treatment Regimes (For IT strands much more influential than for Bronze strands). Have to be interrelated with the Doping.

First stage of Heat treatment in IT strands

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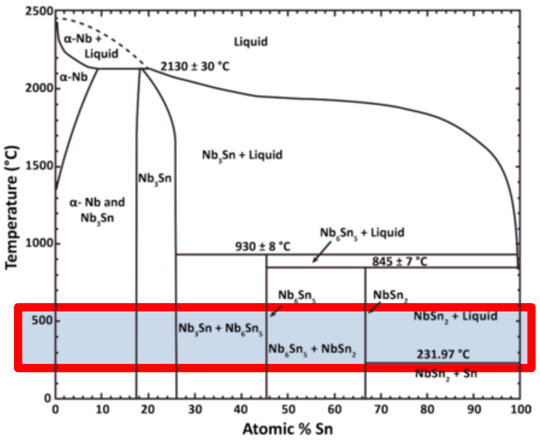
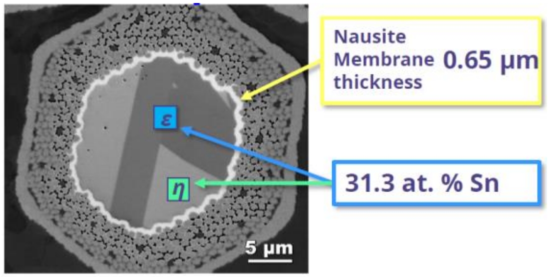
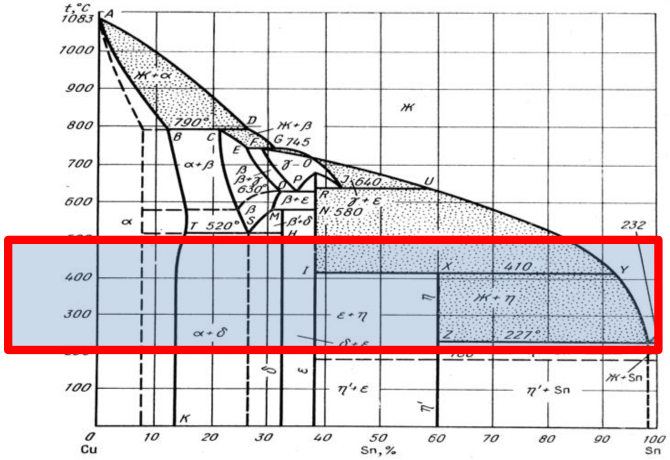
Heat Treatment in the presence of liquid phase on the first stage

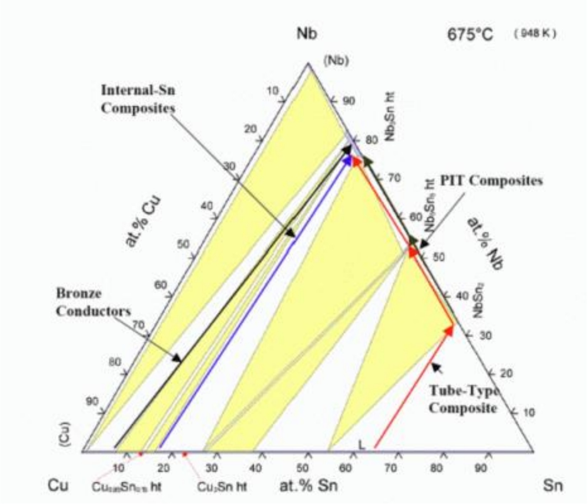


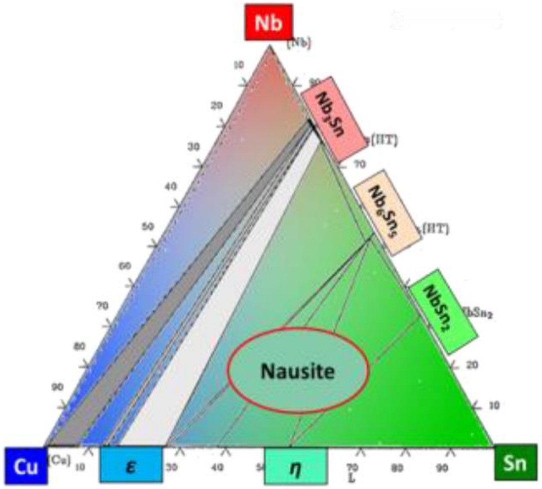


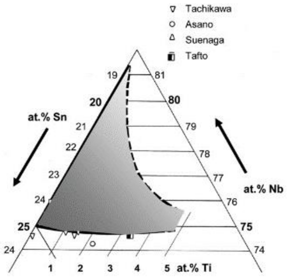
Nausite Membrane thickness 0.65 μm

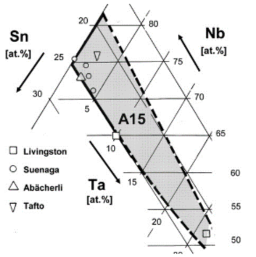
31.3 at. % Sn







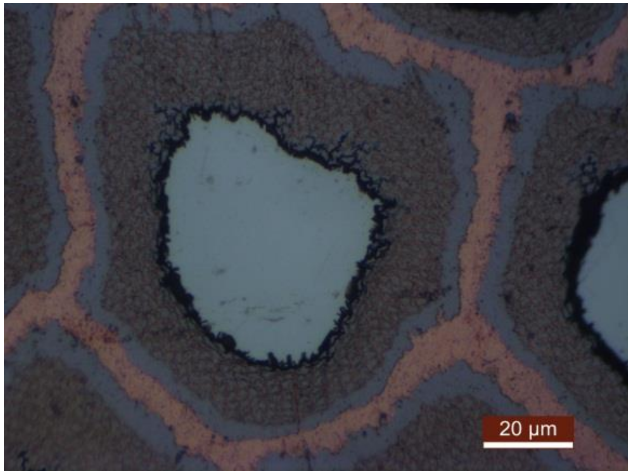




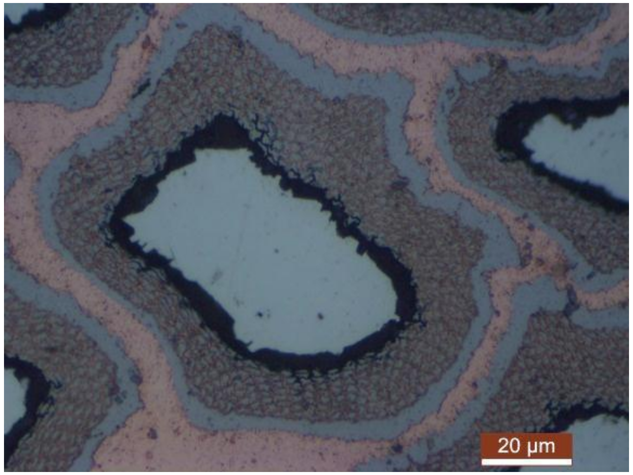
Cryogenics 48 (2008) 293–307

R. Flükiger

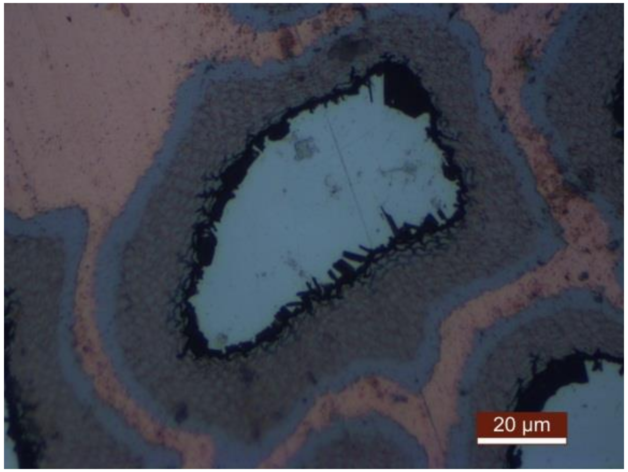
Microstructure of the subelements after the first stage (low temperature) annealing



330°C, 100 h



350°C, 100 h



410°C, 100 h

$$d = \sqrt{2D\tau}$$

Characteristic dimension (diffusion pass is 20-μ (20 *10 $^{-4}$ cm)

Characteristic time is 100-150 hours therefore equal to 5 * 10^{5} sec

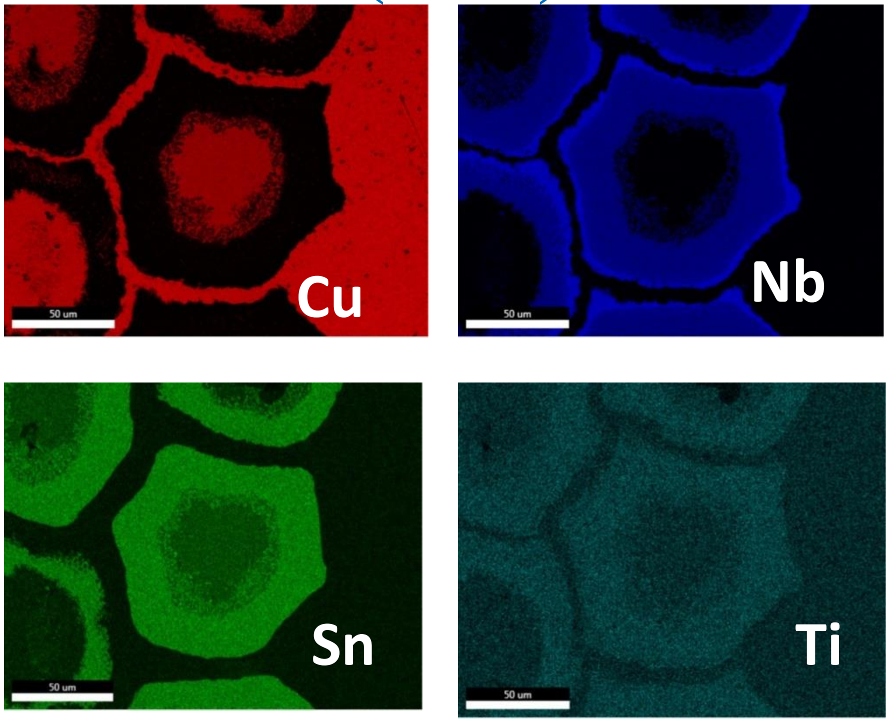
Therefore characteristic coefficient of diffusion reaction is equal to 4 * 10^{-12} cm^{2}/sec

Taking into account the presence of liquid phase – the process of homogeneization of Sn – Cu component of the strand on the first stage of Heat Treatment (before Nb3Sn formation) could not be limitation factor.

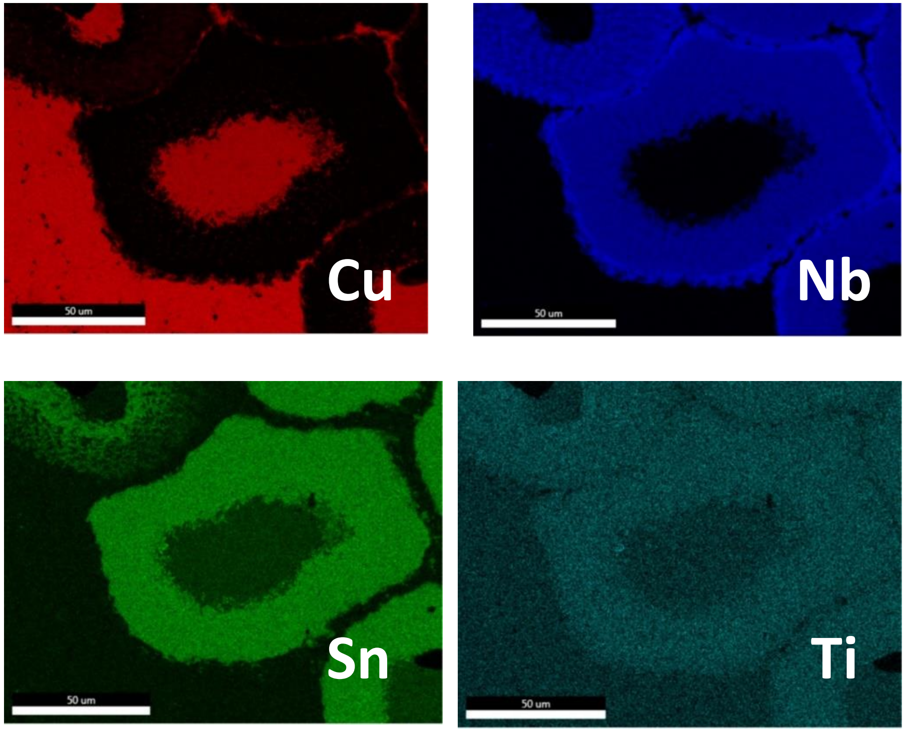
The reaction is started as a combination of the sold state diffusion in the central areas of filaments and reaction with prevailing of liquid phase presense in peripherical areas of macrofilaments.

Distribution of elements in Ti and Ti+Ta doped Nb_3Sn strands

(Ti+Ta)



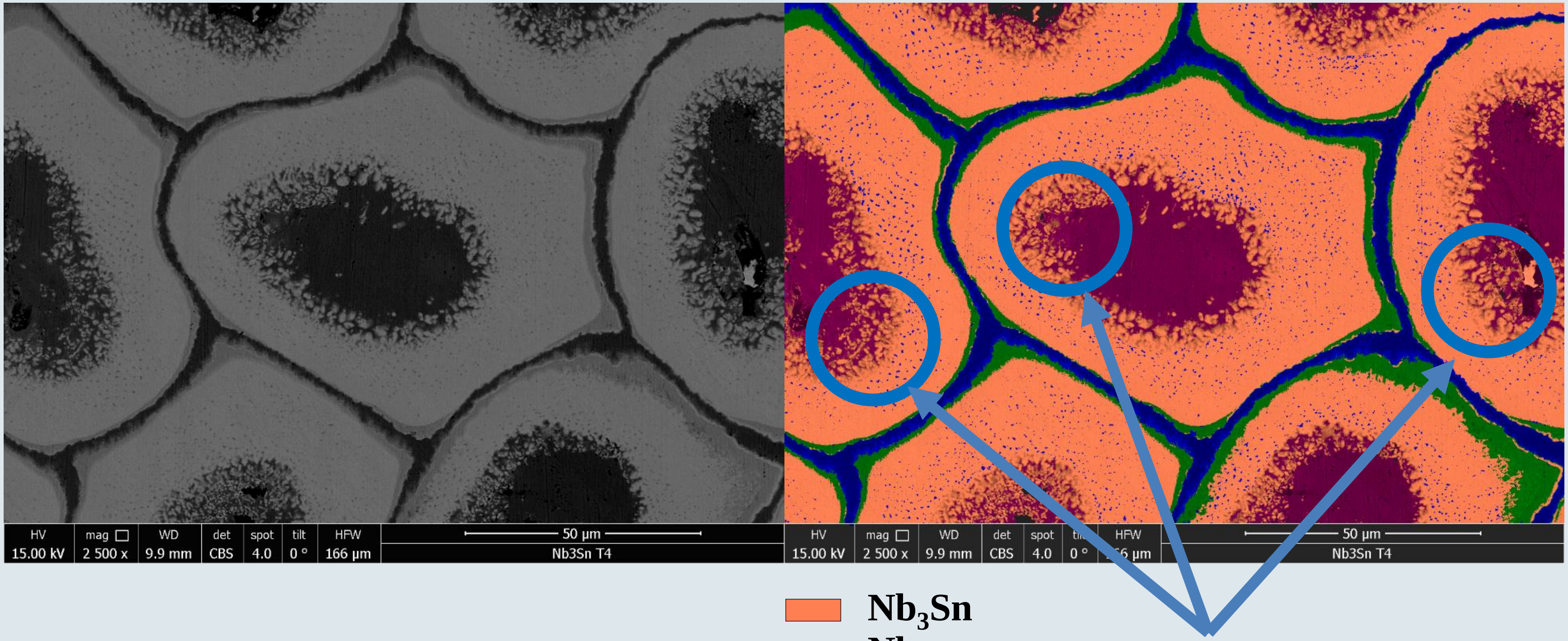
(Ti)



Uniform distribution of Sn, Ti and Ta in Nb_3Sn layers after reaction heat treatment

SEM investigation: distributed Nb

T4

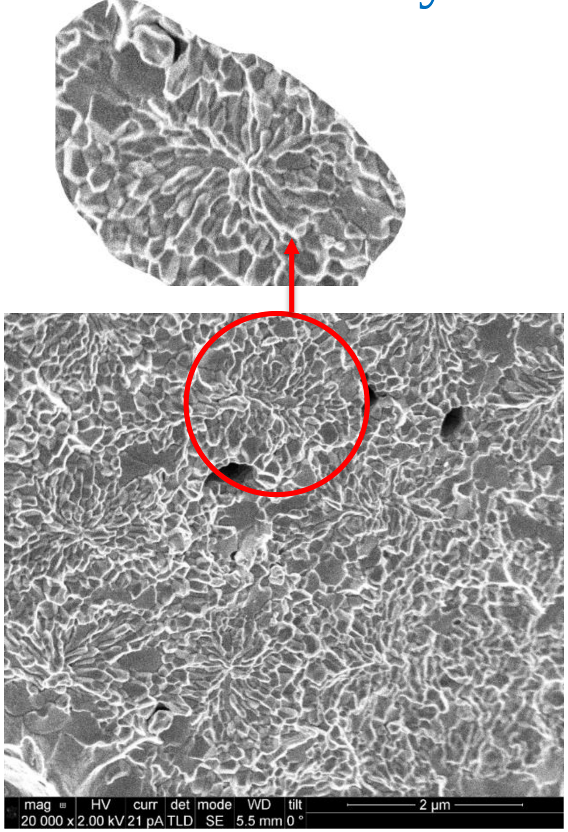


🟧 Nb_3Sn
🟩 Nb
🟦 Cu
🟪 Cu-Sn

Areas of Nb_3Sn phase with low current carrying ability. Here is the reserve for Jc increase

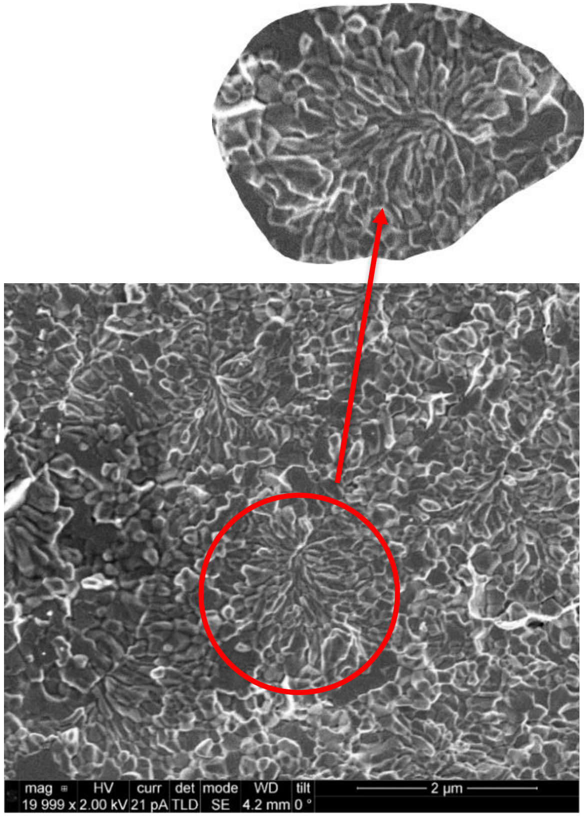
Microstructure of the Nb3Sn layer after heat treatment: 370°C, 100ч+665°C, 40ч

Doped by Ti



Average grain size 120 nm

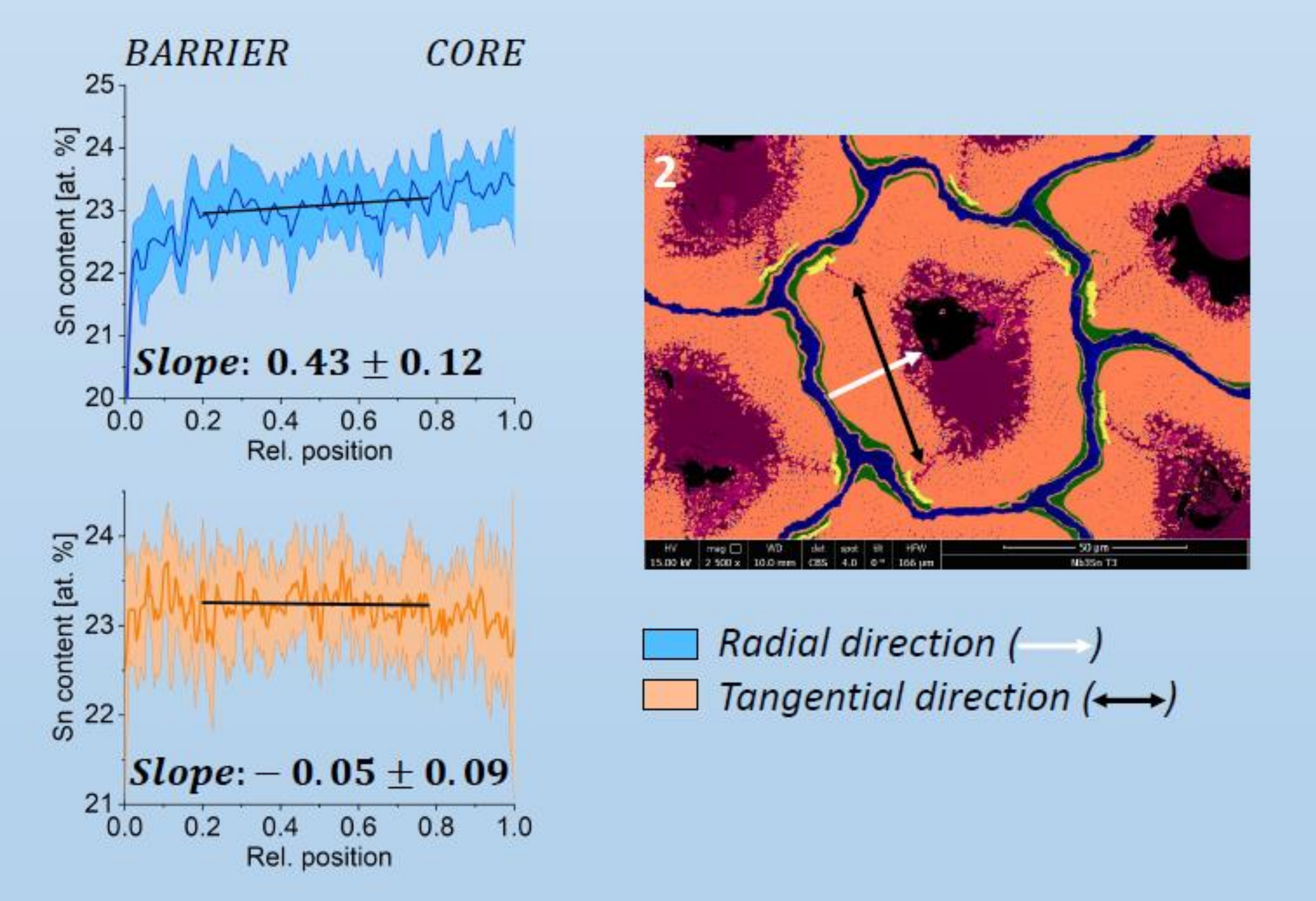
Doped by Ti+Ta



Average grain size 124 nm

Areas of Nb_3Sn phase with low current carrying ability. Here is the reserve for Jc increase

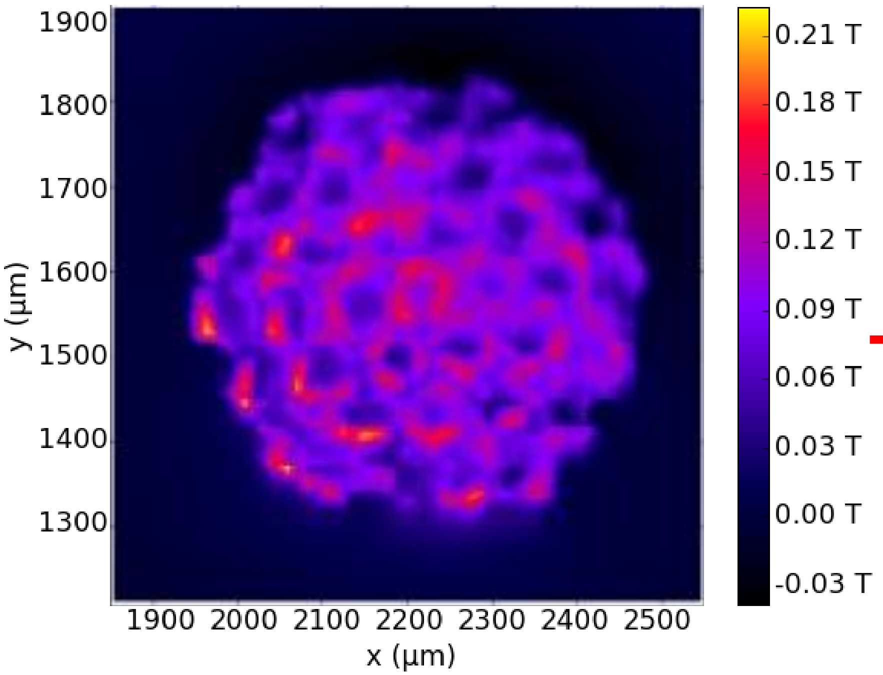
Homogeneity analysis: composition gradients

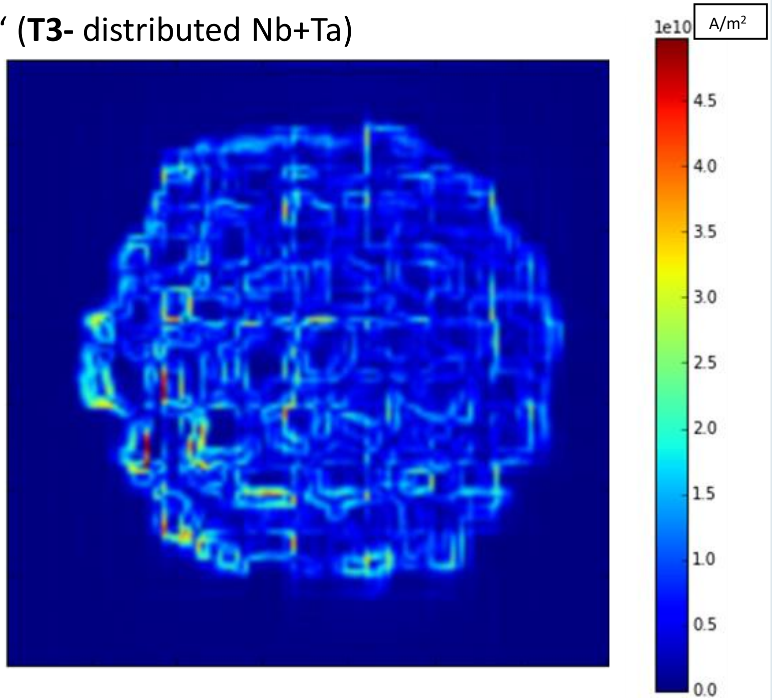


Nb_3Sn TVEL samples

Scanning Hall probe microscopy (SHPM)

Sample with „*clusters*“ (**T3-** distributed Nb+Ta)

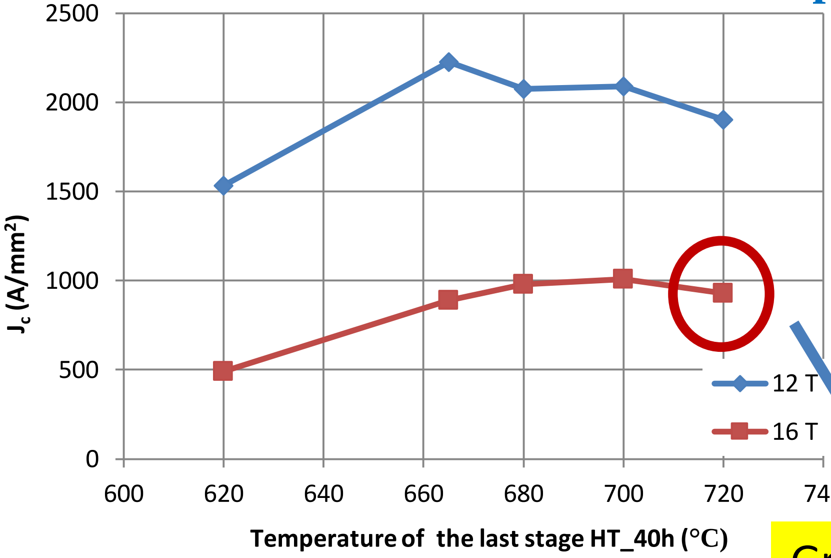




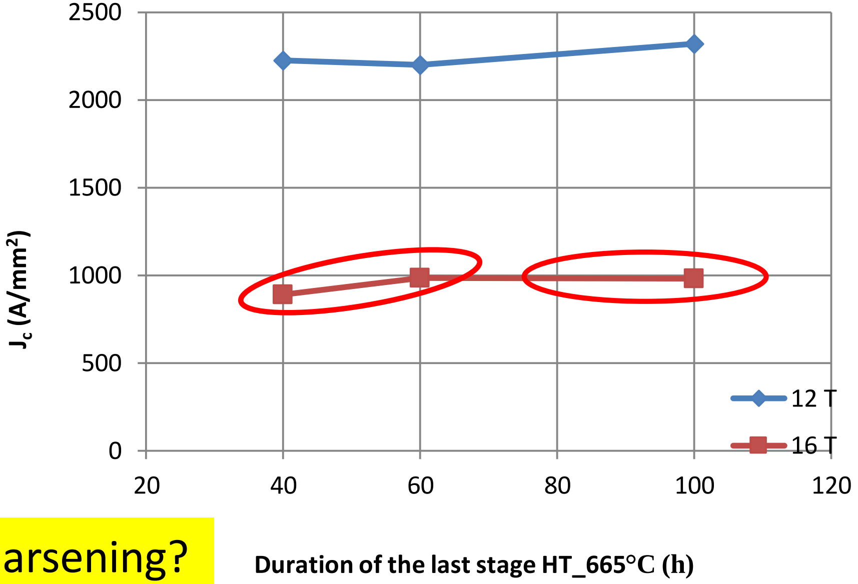
Remnant field scans used for local current evaluation → In line with the state-of-art RRP wires (@ 10K, 0 T)

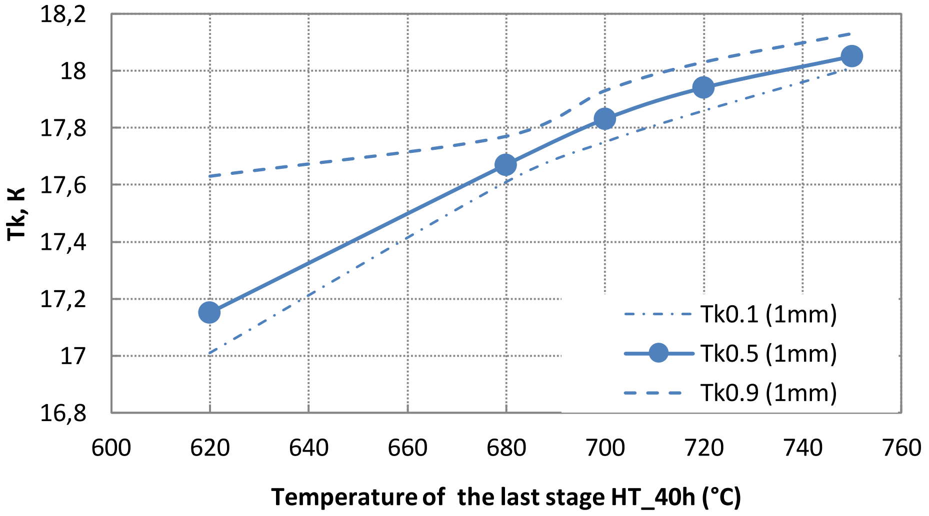
Superconducting properties of the strands

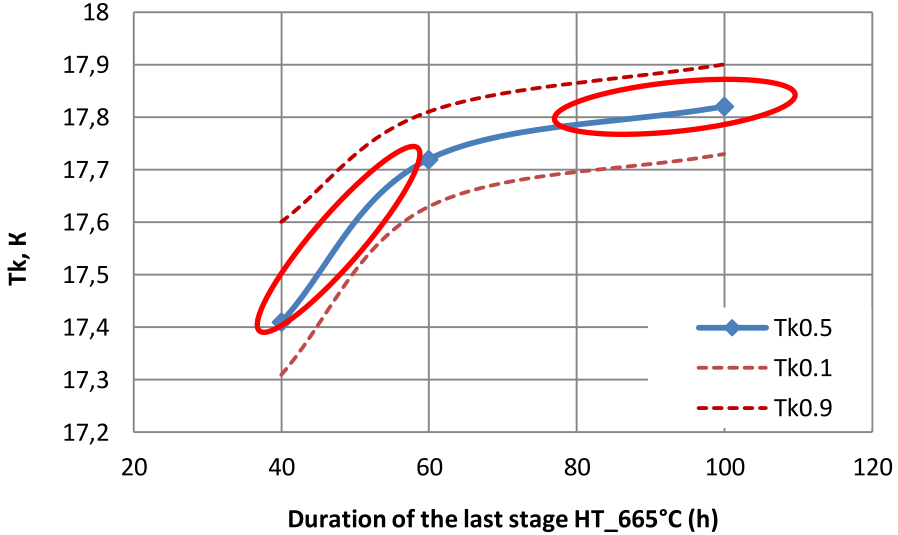
Doping by Ti+Ta



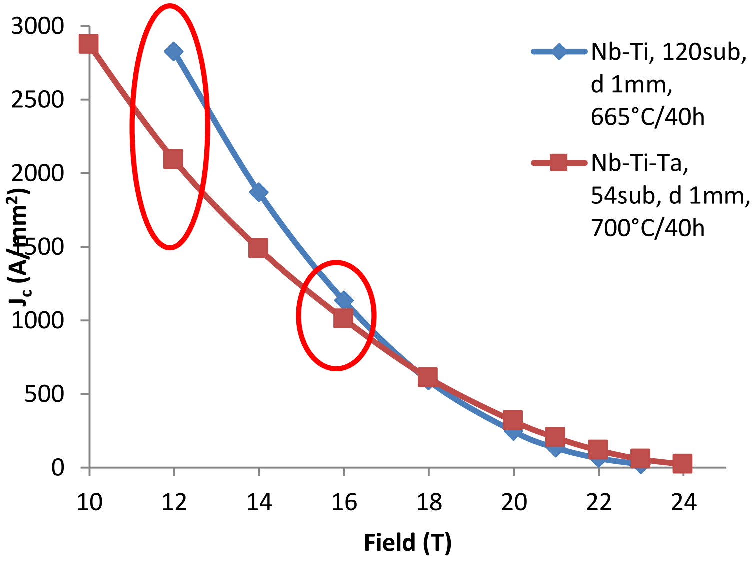
Grain coarsening?

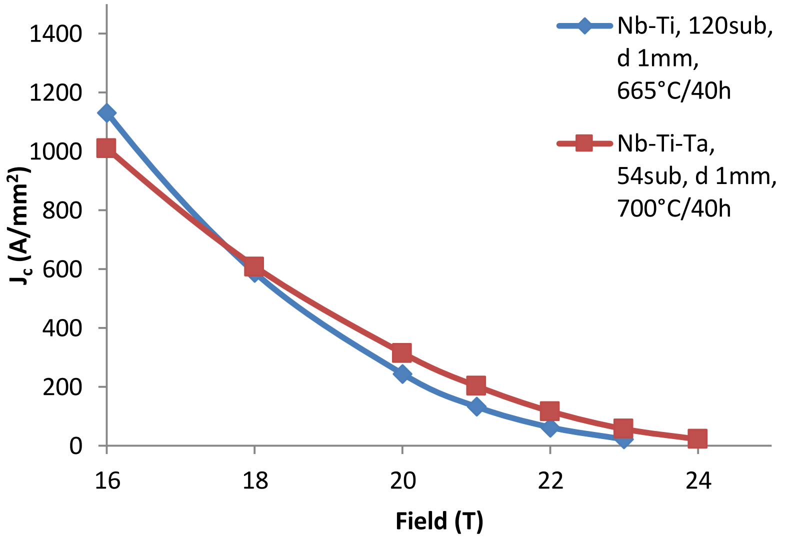






Superconducting properties of the strands





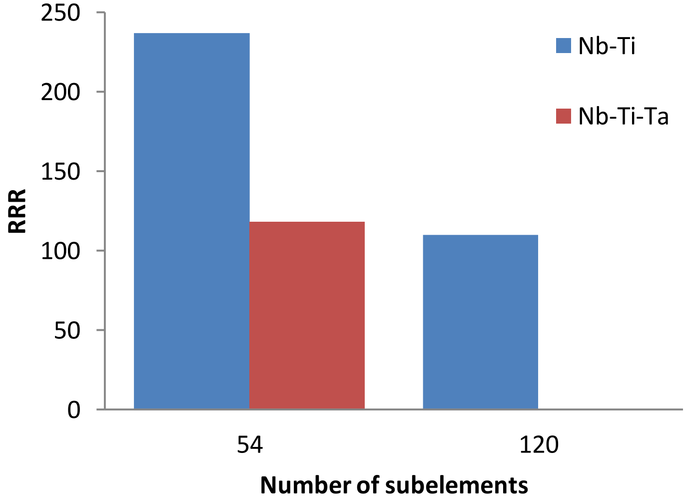
Пилот 20 (Ti+Ta)

РТО	B_{c2}, Тл	$B_{Fp\ max}$, Тл
Ø1 мм		
665°C, 100 ч	25,1	7
665°C, 60 ч	24,4	7
665°C, 40 ч	23,7	7
680°C, 40 ч	25,2	7
700°C, 40 ч	25,3	7
720°C, 40 ч	25,5	7

Пилот 18 (Ti)

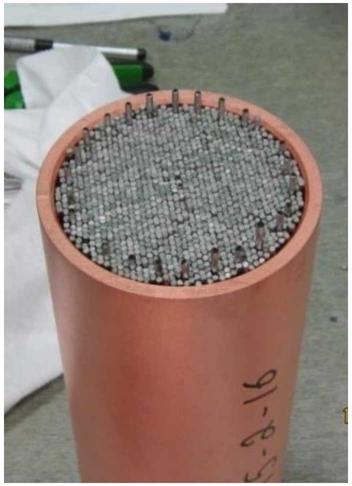
РТО	B_{c2}, Тл	$B_{Fp\ max}$, Тл
Ø1 мм		
665°C, 40 ч	24,1	5

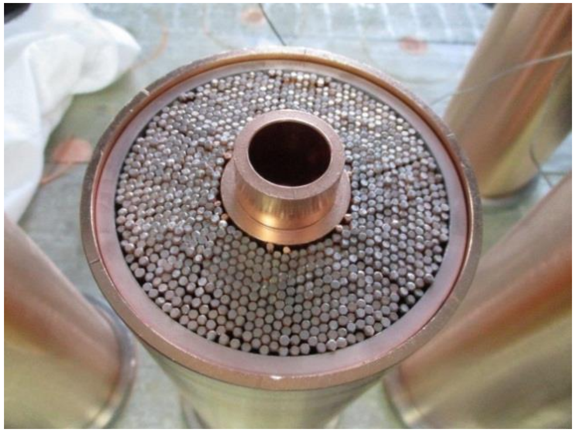
Deff - 75μm

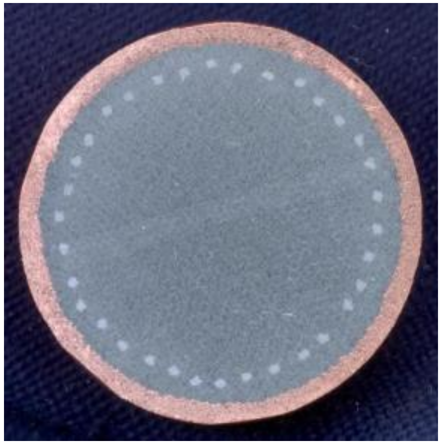


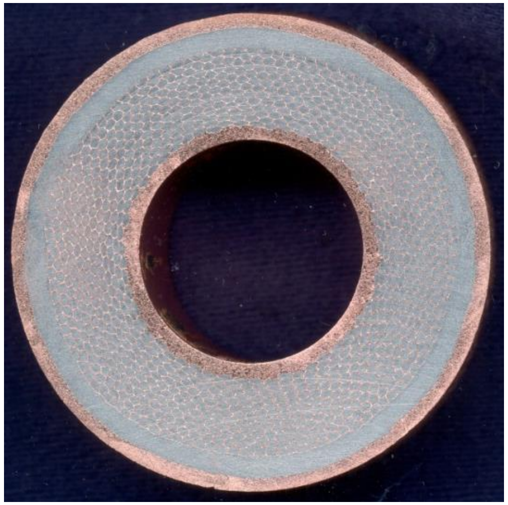
Industrial production of IT strands at ChMP

(*Capacity ≥ 60 tons per year*)









Industrial production of IT strands

(not only at ChMP)

Present cost of high-performance (HL-LHC) Nb_3Sn is > 20 Euro/kA m (4.2 K, 16 T). ***FCC target is 5 Euro/kA m (4.2 K, 16 T)***.

If the first objective is attained and the Jc non Cu (16 T 4.2K) = 1500 A/mm2 than the cost of production (5 Euro/kA m) should be diminished in a factor of 2.6
But technology of IT strands production has started in 1974 (Hashimoto – Japan and Bochvar Institute indendable) - 45 years ago. Therefore it is a challenging task for Industry.

SUMMARY

1) The last year progress on the road to the FCC target strand was associated mainly with the optimization of the design enabled to attain Jc (non Cu = 2850 A/mm^2 (12 T, 4.2K) and 1100 A/mm^2 (16 T, 4.2K)
2) The further increase of Jc is potentially possible by the eliminating of the Sn concentration gradient across the Nb_3Sn layers altogether with the approaching to the stoichiometry
3) Industrial production of the first batches confirms the scalability of the laboratory designed fabrication routes;
4) The way to all FCC targets (Jc, Deff, RRR, Cost) requires the necessity to handle the industrial scaled billets.