RESEARCH & PRODUCTION NANOELECTRO

Bochvar Institute
(VNIINM)

TVEL

Nb_3Sn Internal –Tin Strands for FCC (Dream wire). Approaches to Optimization
- Design, R&D,
- Commercial Production

V. Pantsyrny

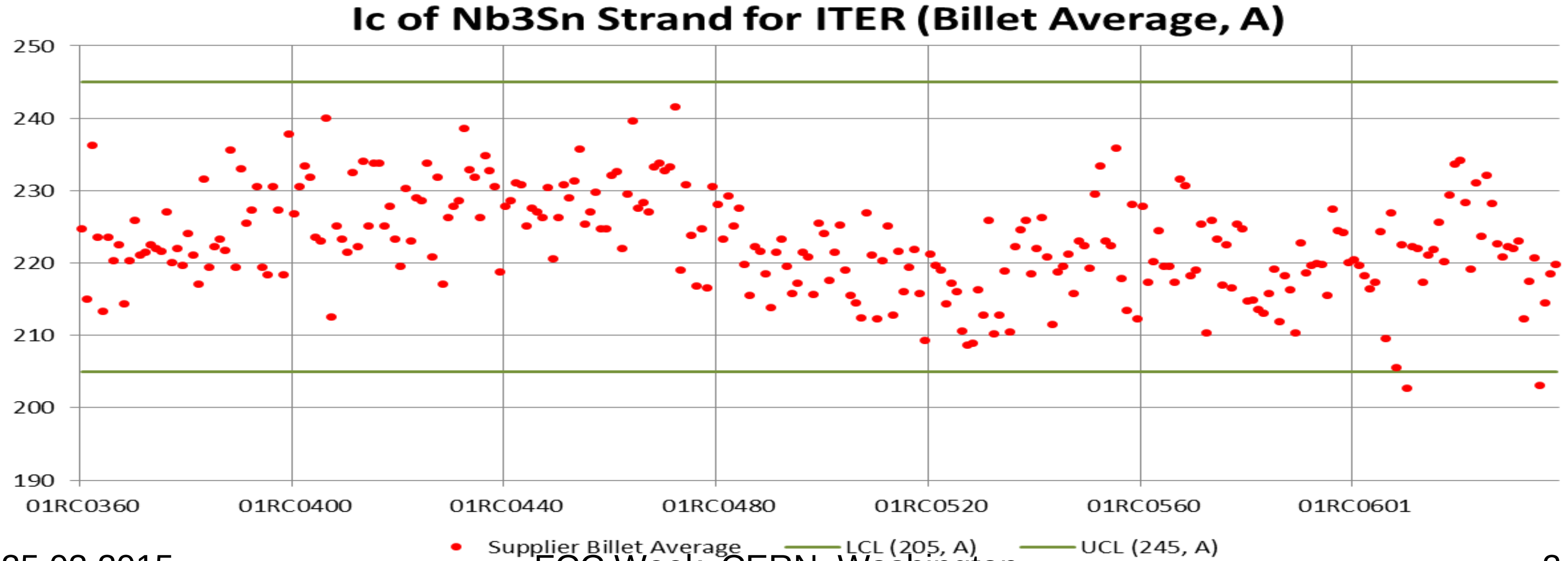
Chepetsky Mechanical Plant (Glazov) – Production of LTSC (NbTi and Nb_3Sn) - 60 ton/year

From - Melting of Nb, NbTi, Cu-Sn, Extrusion, Rolling, Drawing, Heat treatment
To - Superconducting properties testing

NbTi and Nb_3Sn strands production status for ITER (2010-2014)

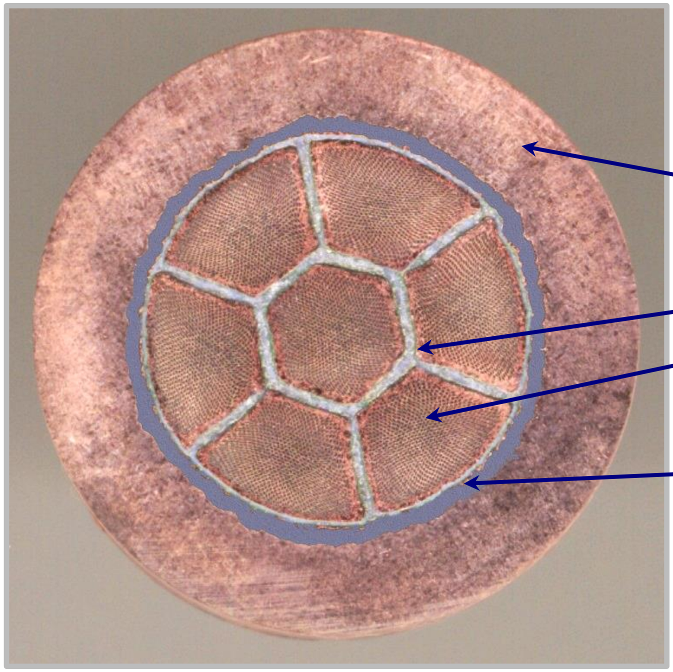
127.6t of NbTi strand produced. **Production has been completed.** Average yield is more than 90%. 798 billets have been produced:

More than 90t of bronze Nb_3Sn strand have been produced. **Production has been completed**; Average yield is 88%, (**UCL =245A, LCL =205A**)



RF produced Internal Tin Nb_3Sn strand for ITER tested in SULTAN facility in the scope of TF conductor (August 2007)

RFTF1 - showed Tcs = 6.25K
ITER Requirements: Tcs > 5.7K



Initial billet size 43.5 mm

Specification requirements

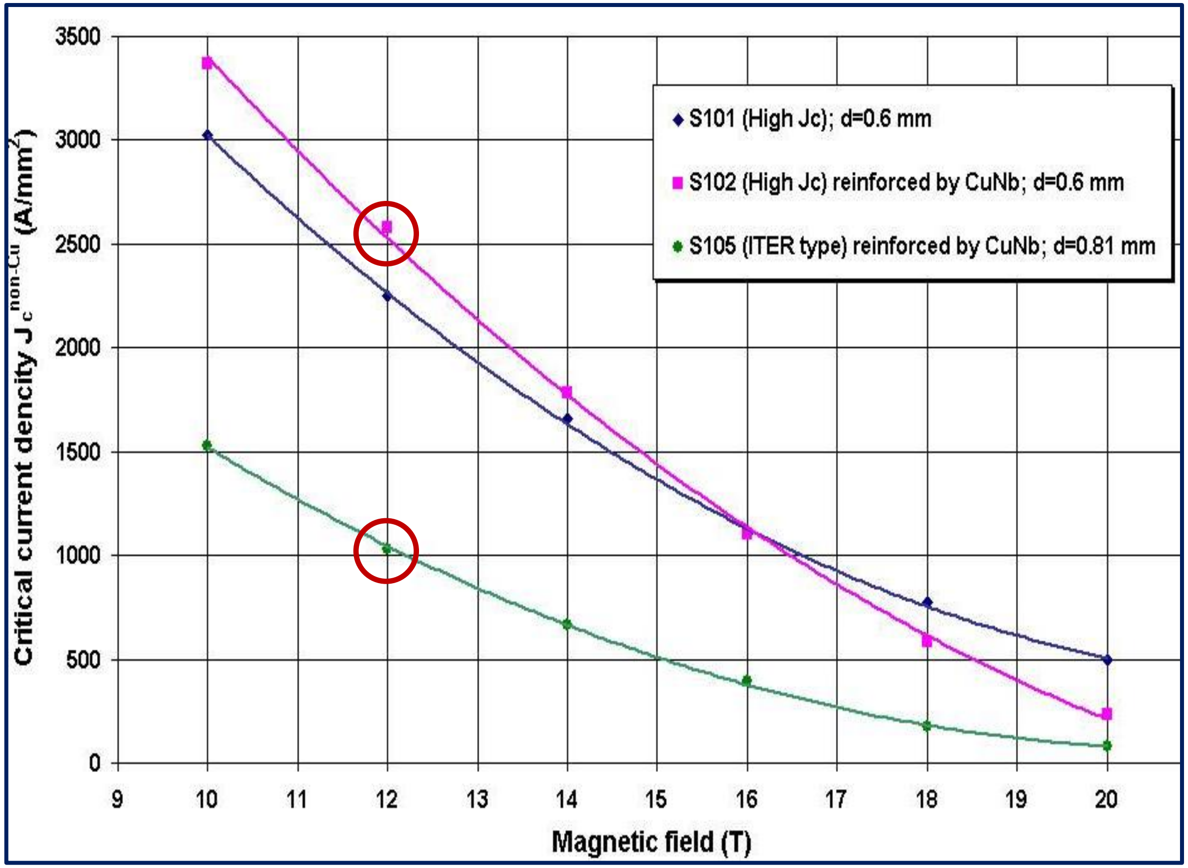
Non-Cu Jc (at 12 T,4.2K)	> 800 A/mm²
Non-Cu hysteresis losses on ± 3T field cycle at 4.2 K	<1000 kJ/m³
RRR after reaction heat treatment	>100

Design parameters

Diameter of the strand, mm	0,82
Cu stabilizer fraction, vol.%	50
Barrier	Ta
Nb fraction (inside barrier), vol.%	33,7
Diameter of Nb filament, µm	5,7
Spacing between Nb filaments, µm	2,4
Non-Cu Jc (at 12 T, 4.2 K), A/mm²	1000

Experimental data on ITER and HEP types Nb_3Sn strand

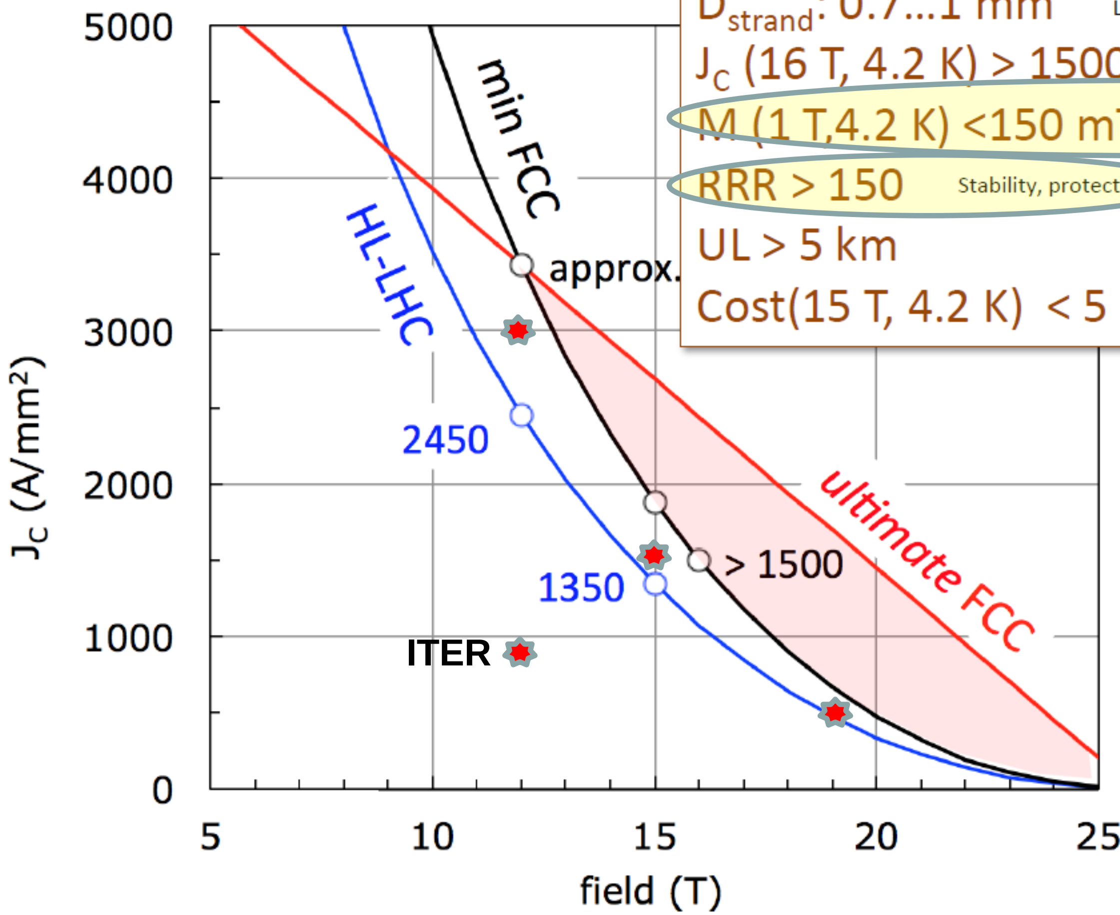
Strand diameter, mm	0,6
Number of fillaments	2947
Cu stabilization, vol. %	40
Critical current density (12 T, 4,2 K), A/mm²	2580
Critical current density (15 T, 4,2 K), A/mm²	1500
Hysteresis losses (±3 T, 4,2 K), mJ/cm³	~ 1200



Internal Tin (IT) Nb_3Sn strands are very flexible in attaining of wide range of different Jc levels (1000-3000 A/мм²).

The future 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

Cost(15 T, 4.2 K) < 5 USD/kA m — ITER material cost per kg

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

Experimentally attained Jc values

OPTIMIZATION – to find a balance
Quantity (amount of Nb_3Sn) – Quality (pinning in Nb_3Sn)

Increase of Nb_3Sn phase quantity

In bronze processed strands 15.0% of Sn in bronze matrix is available for transformation of Nb filaments to Nb_3Sn phase.

Attainable volume fraction of Nb_3Sn phase is around 30% in the non-Cu area.

For bronze processed strands non-Cu J_c ~ **900 A/mm²** assumes Jc in Nb_3Sn phase ~ **3000 A/mm²** .

(**In reality higher – due to non-uniformity of 3-4 μm in dia. Nb_3Sn filaments)**

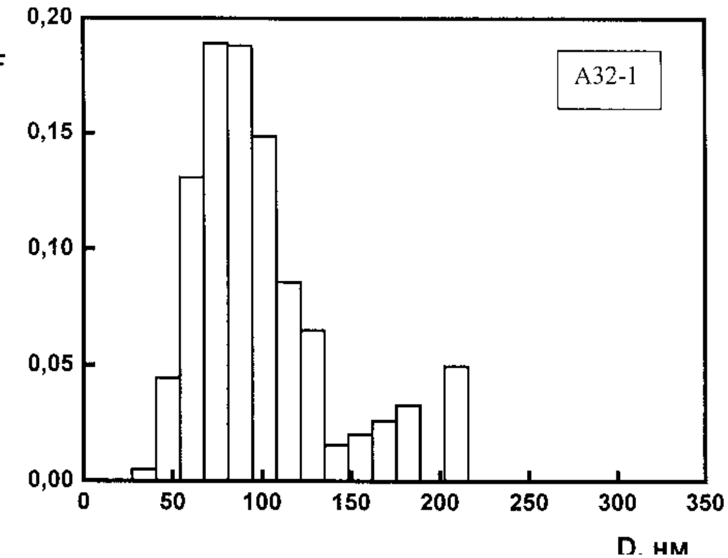
Unstabilized Nb_3Sn strands parameters and properties (Sn content in bronze – 13 %)

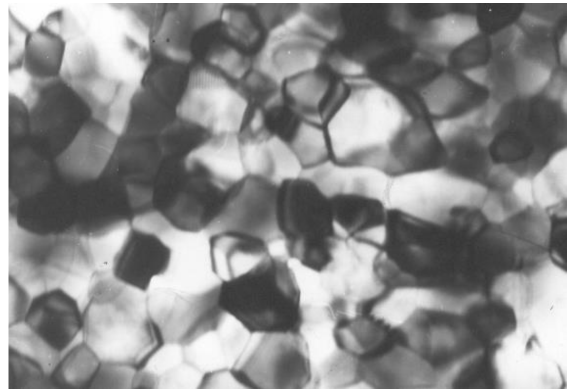
No	Fil. number	Fil.space, μm	Jc (12T), A/mm²	Wh (±3T) , mJ/cm³
1	44521	0.5	560	840
2	25531	**0.9**	**480**	**650**
4	7225	**1.3**	**420**	**110**

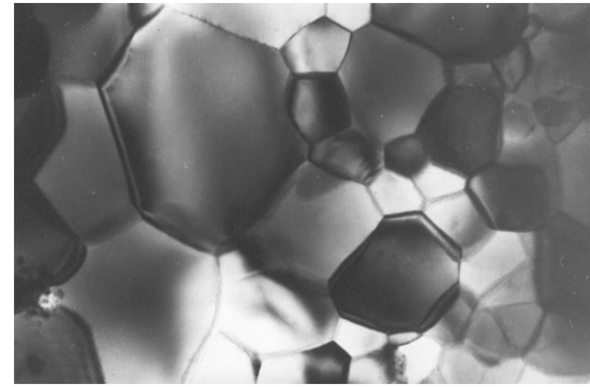
x 1.14 (Jc) — x 5.9 (Wh)

The critical Fil.spacing - > 1 μm – STRONG LIMITATION on volume fraction of Nb_3Sn phase in IT strands - R&D on strands design is required

Increase of Nb_3Sn phase quality (pinning in Nb_3Sn) by design and doping

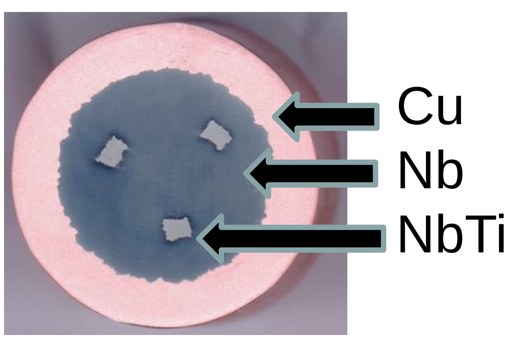


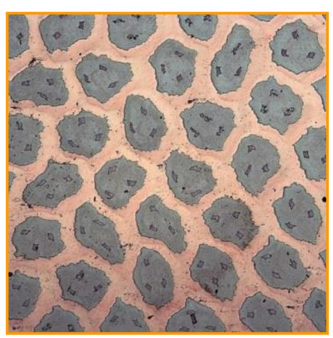


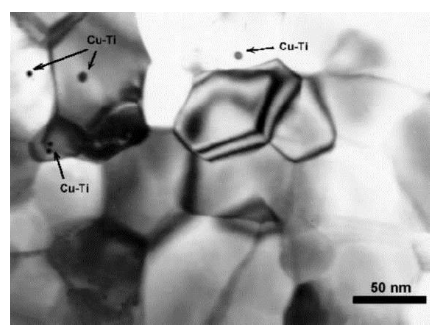


Distribution of the Nb_3Sn grain size in ITER type bronze processed strands (heat treatment 575^{0}C 150h + 650^{0}C 200h)

The internal oxidation method (doping by Zr) can significantly refine the grain size and improve the high-field Jc of Nb_3Sn strands.
The Nb_3Sn grain size could be reduced down to 20-50 nm,
XU X.; SUMPTION M.; Dr. PENG X.; Dr. COLLINGS, T.

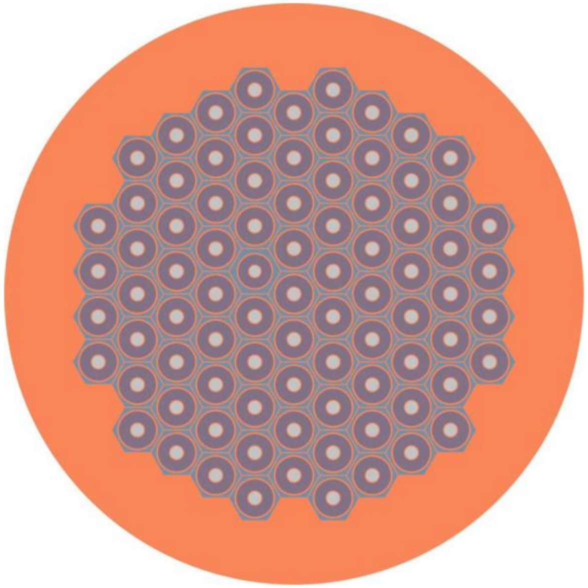






Doping by distributed NbTi - Internal precipitations of Cu-Ti intermetallic particles

Internal Tin Strands with tubular filaments

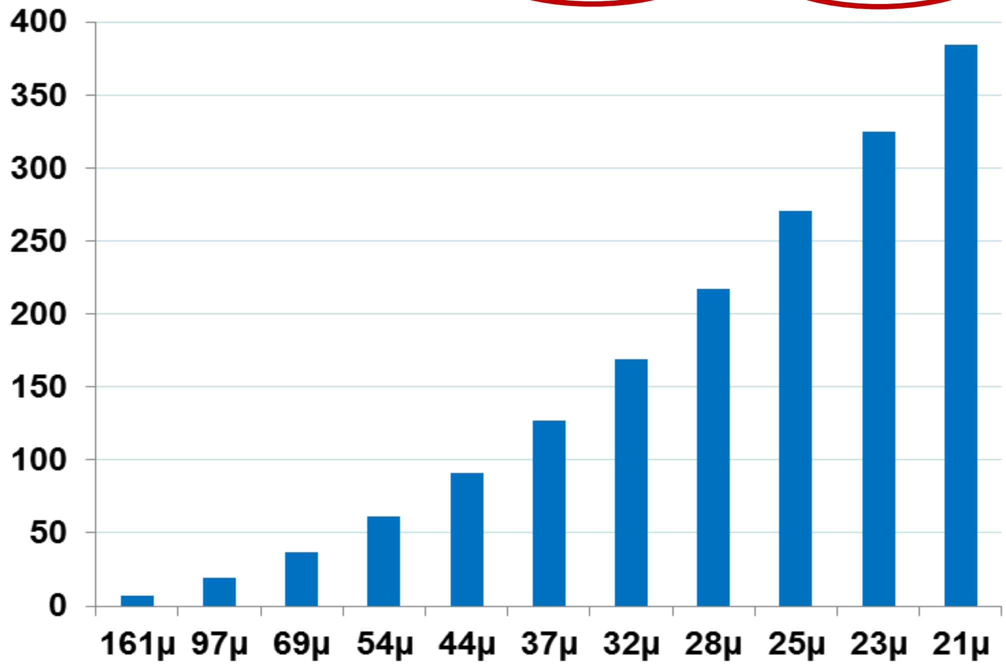


85 monoelements

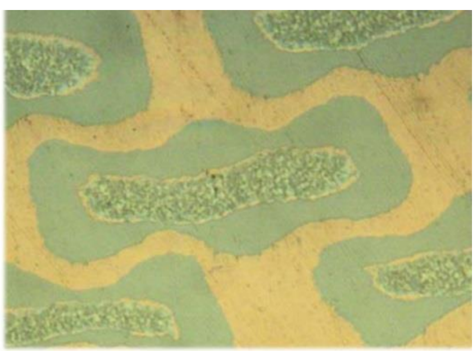
Deff in the order of **50 mkm**

Target performance:

Jc (12 T) > 3 kA/mm^2 ; D_{fil} < 20 μm; RRR > 150



Deff =20 mkm requires > 400 tubular filaments

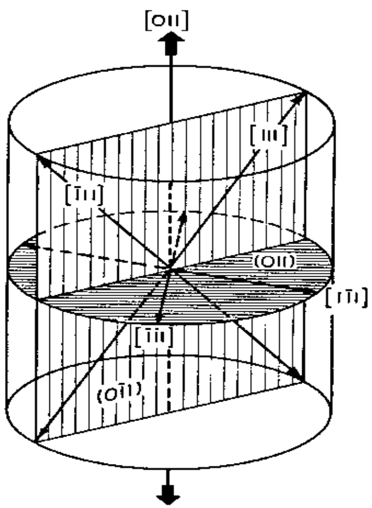


Thickness of Nb tubular filament should be less than 5 µ and due to nonuniformity and deformation of the strands during cabling operation the RRR >100 could not be attained

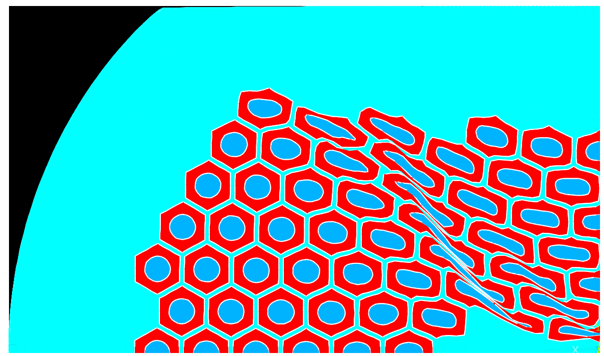
Trials to attain the Deff equal to 20 μm

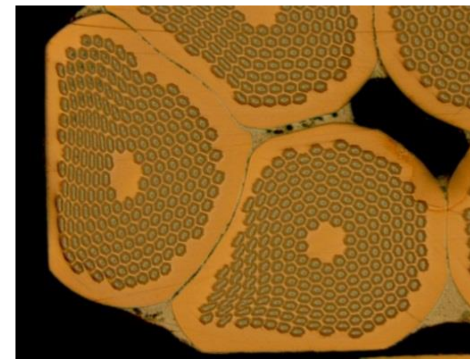
(Hi-Luminosity LHC Nb_3Sn wire)

The texture of drawing with direction of z = [011] is developing in Nb filaments. In BCC Nb the dislocations slipping system [111](011) is prevailing, therefore less than 5 active slipping systems remain. The uniform deformation is substituted by the plane deformation.



Deformed results: Hexagonal models experience sub-element merging

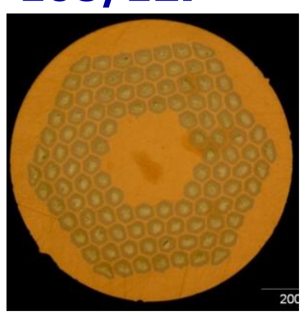




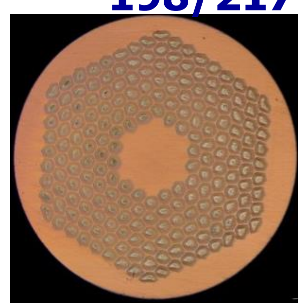
Smaller sub-element size

RRP®

108/127

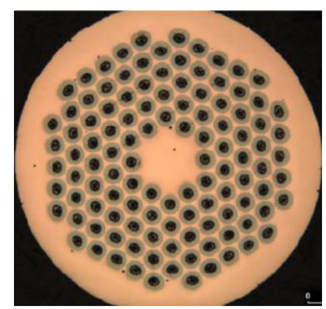


198/217

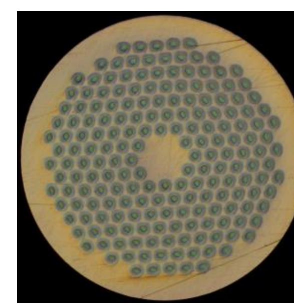


PIT

114



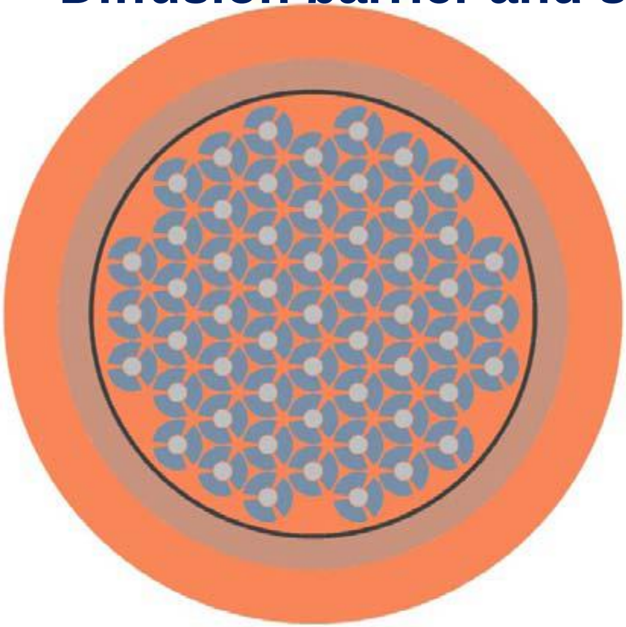
192



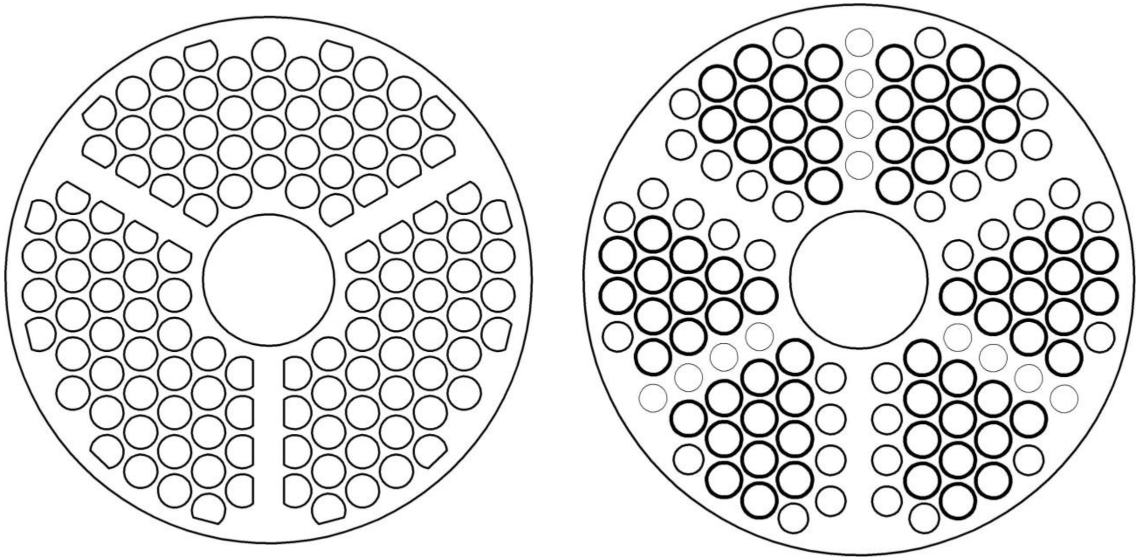
Still the amount of sub-elements have to be incteased in a factor of 2

Optimization of Deff – subdividing the sub-elements on the groups of Nb filaments

Internal Tin Strands made with sub-elements surrounded by one Diffusion barrier and strengthened by nanostructured Cu-Nb material



55 splitted sub-elements (equivalent to 330 effective filaments)

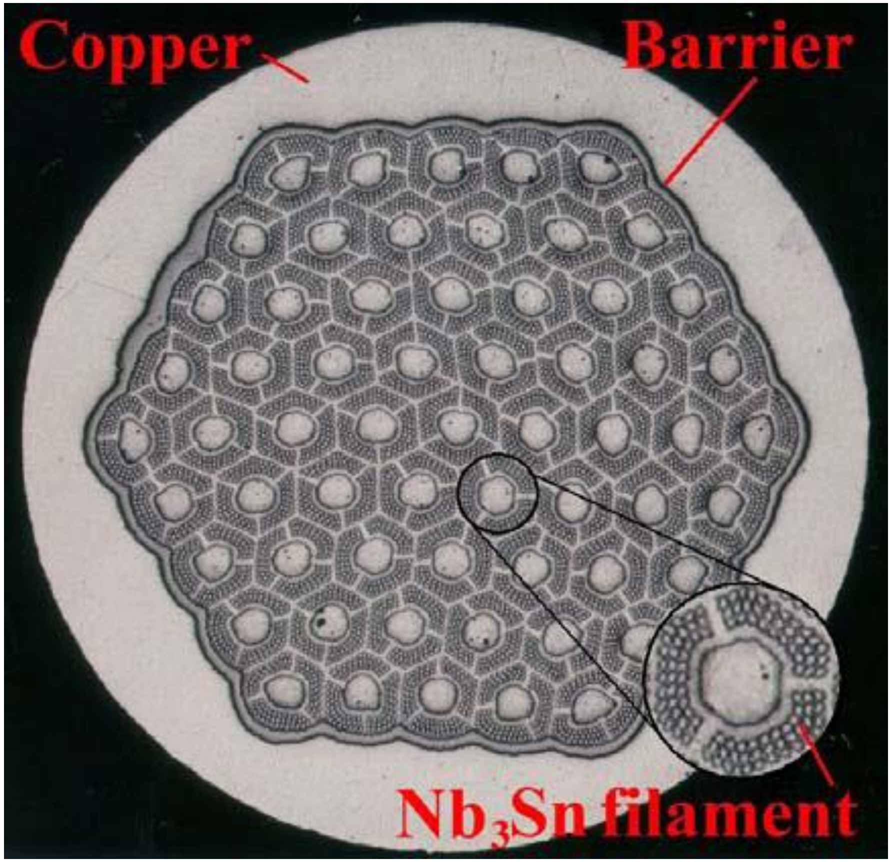


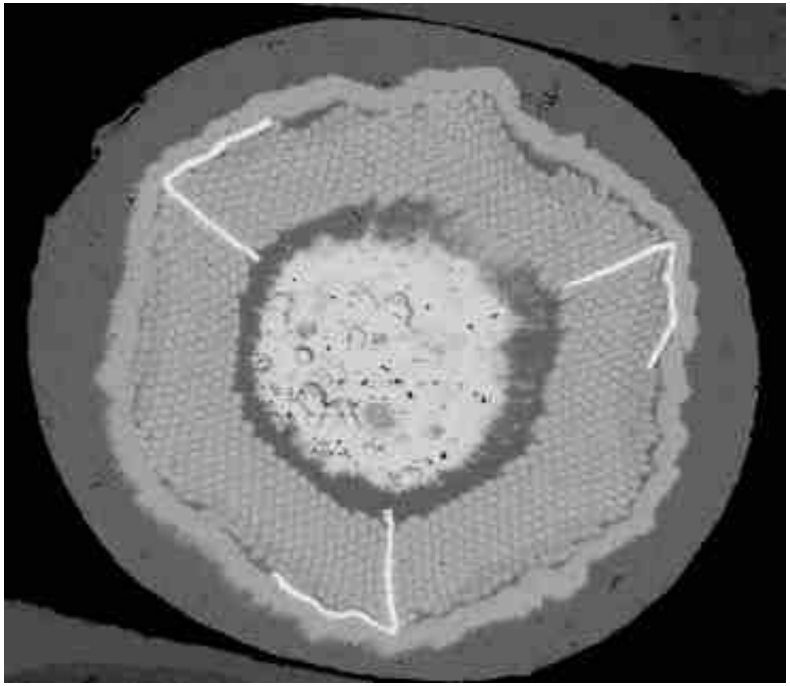
The strands assembled with subelements, containing 3-6 groups of Nb filaments (20 μm each), separated by the >1 μm spacings from each other could diminish the number of elements to be assembled in 6 times.

Similar approach for Internal tin strands design

(subdividing of the sub-elements)

Single and multiple diffusion barriers designs



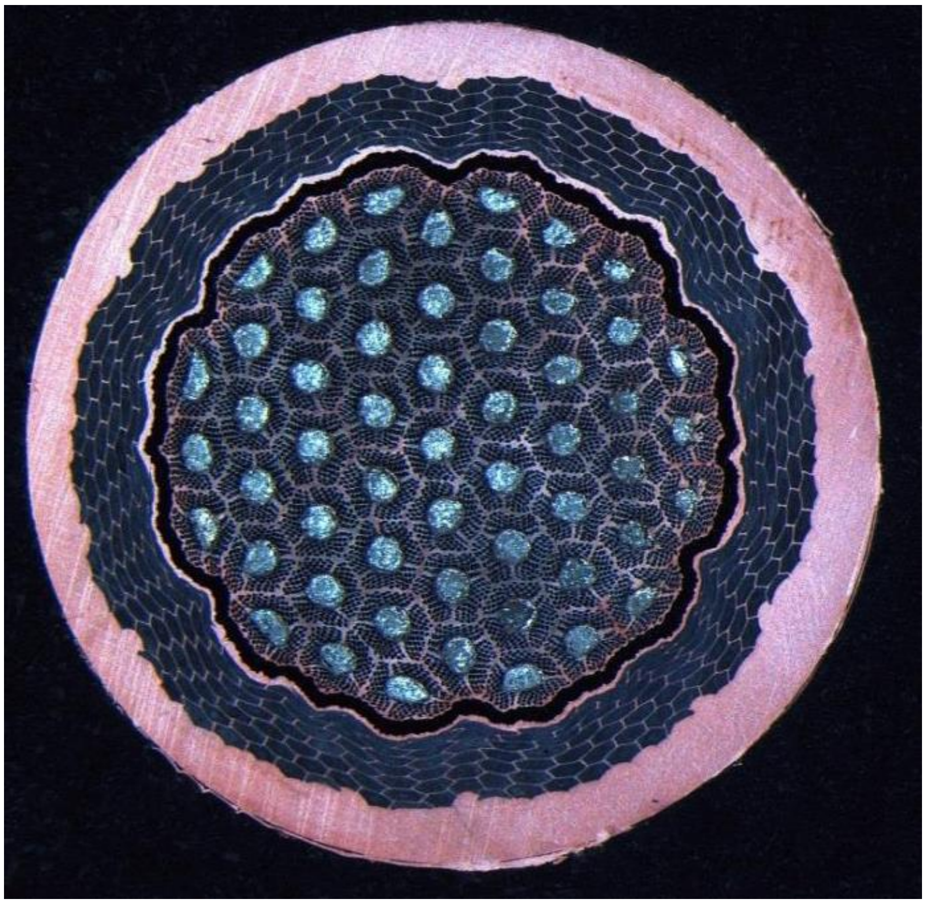


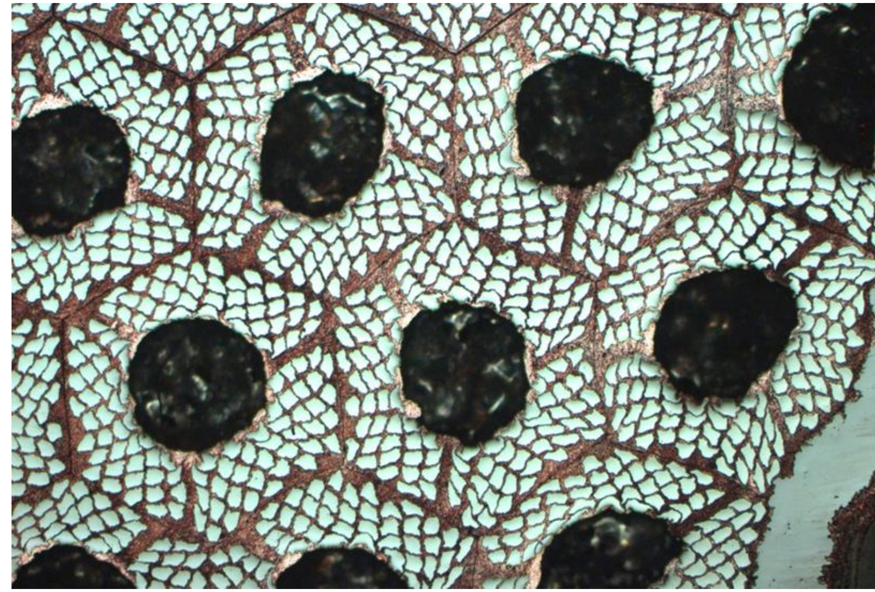
OKAS, Supergenics

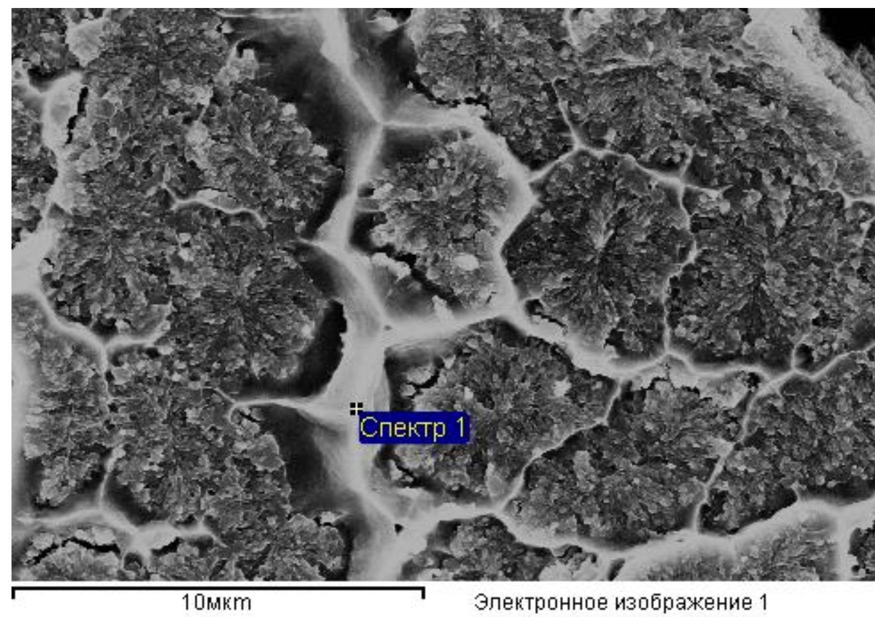
- **--three radial fins approachj**
- **--Ta 40 wt % Nb alloy to further subdivide Nb_3Sn**

R&D and Design of the FCC –type strand

New design of Nb_3Sn strand (55 sub-elements) with enhanced mechanical strength (Cu-Nb rods)



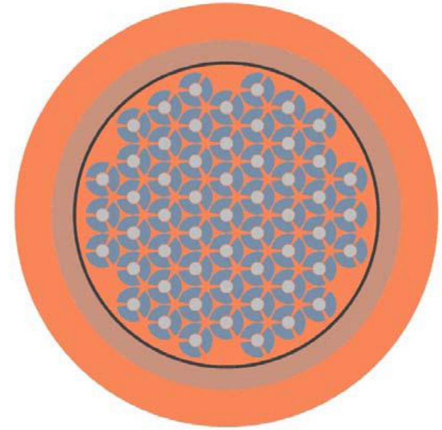




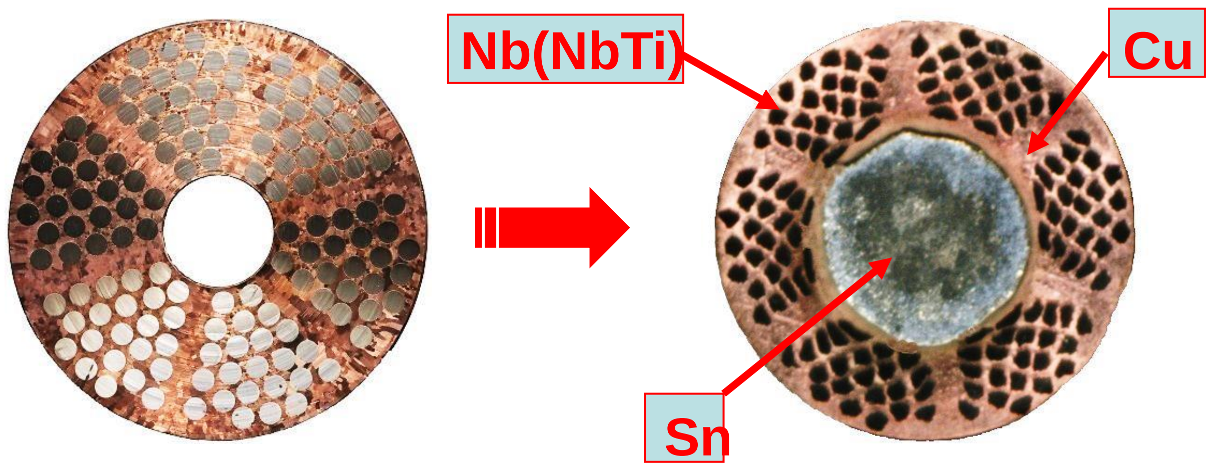
Commercial production – Reduction of cost

Cu-Nb subelements fabrication

The method of casting of Cu melt in Nb rods assemble for preparation of the Cu-Nb sub-elements billet has been developed



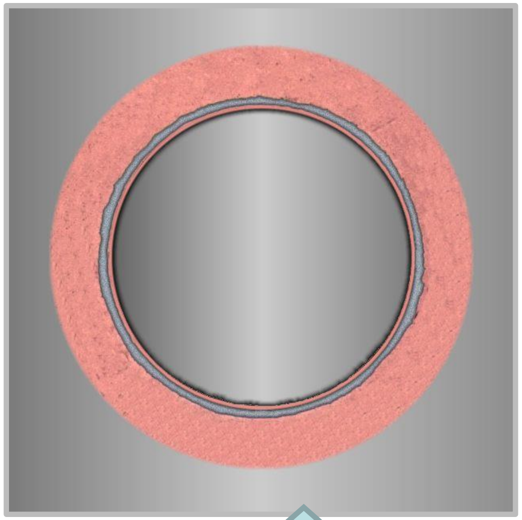
55 subelements

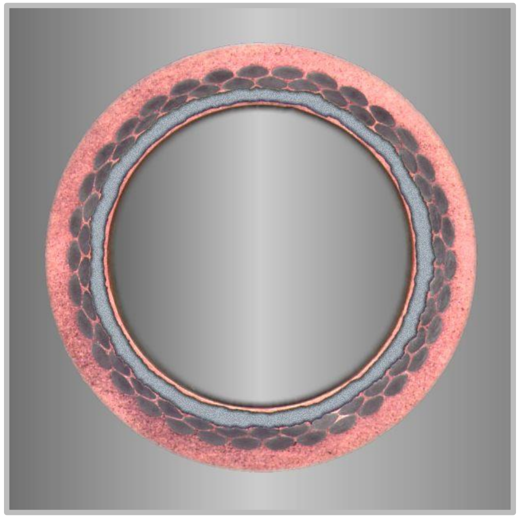


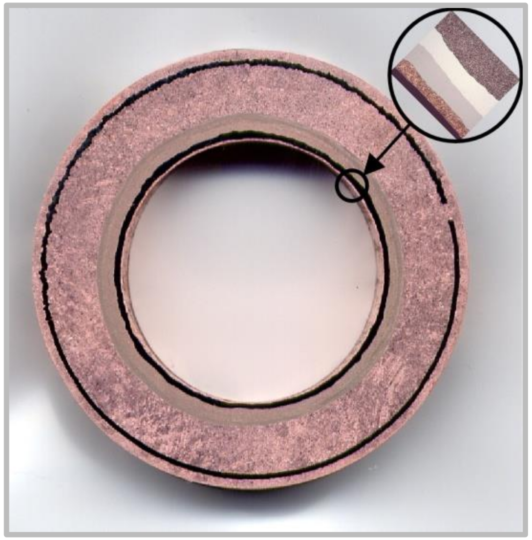
Diameter of Filaments bundle – (Deff) equal to approximately 0.3 x D subelement

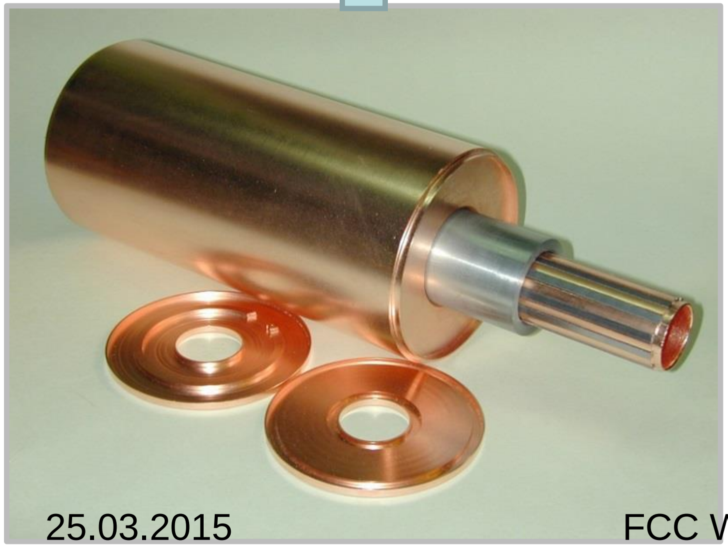
Commercial production – Reduction of cost

Diffusion barriers with Cu stabilization and Cu-Nb strengthening



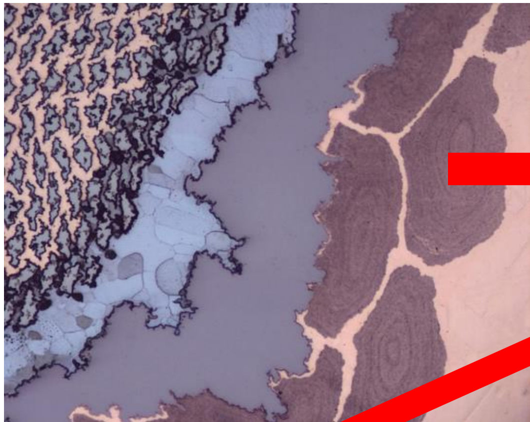


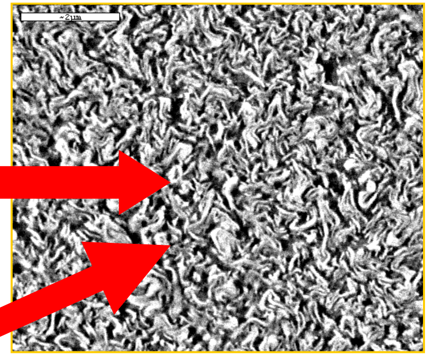




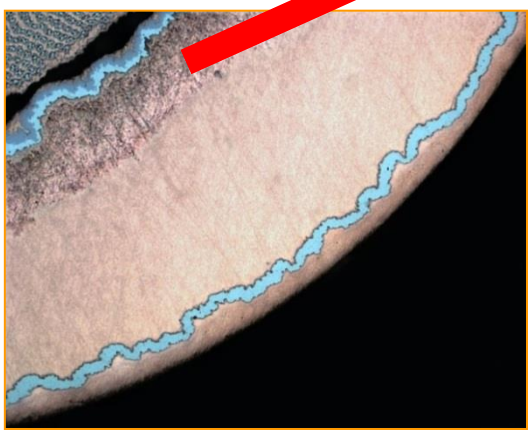
The technology of composite (Cu-CuNb-Ta-Cu) tubes with necessary diameters (25-50 mm) and lengths (up to 5 m) is developed

Mitigation of deformation induced degradation of Jc and RRR by introduction of Cu-Nb strengthening elements

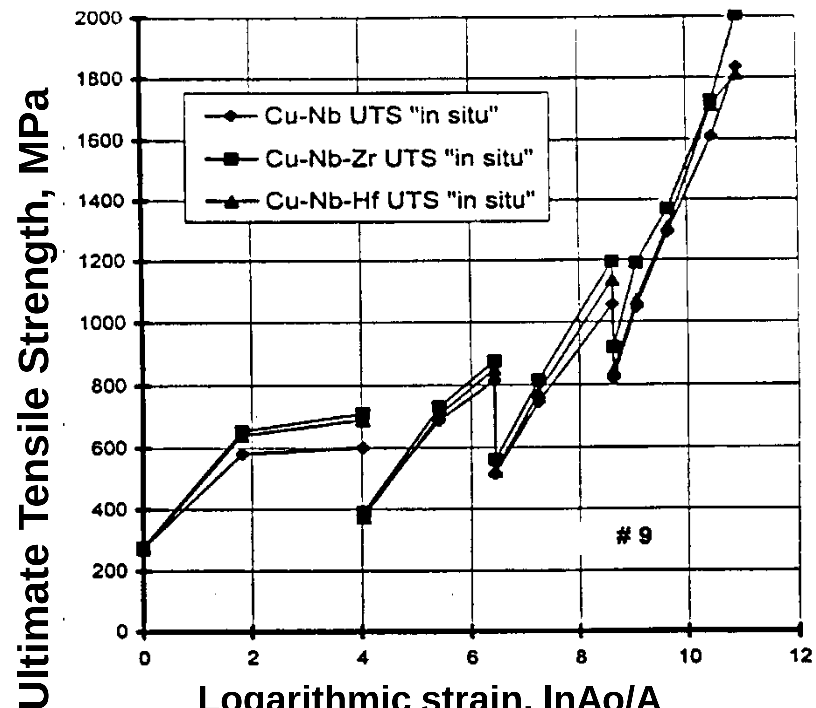




Cross section of Cu-Nb

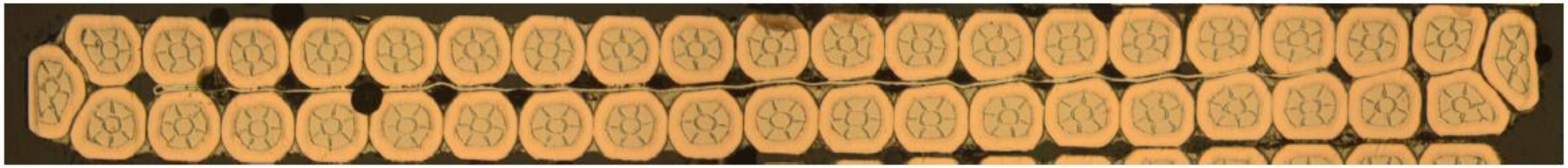


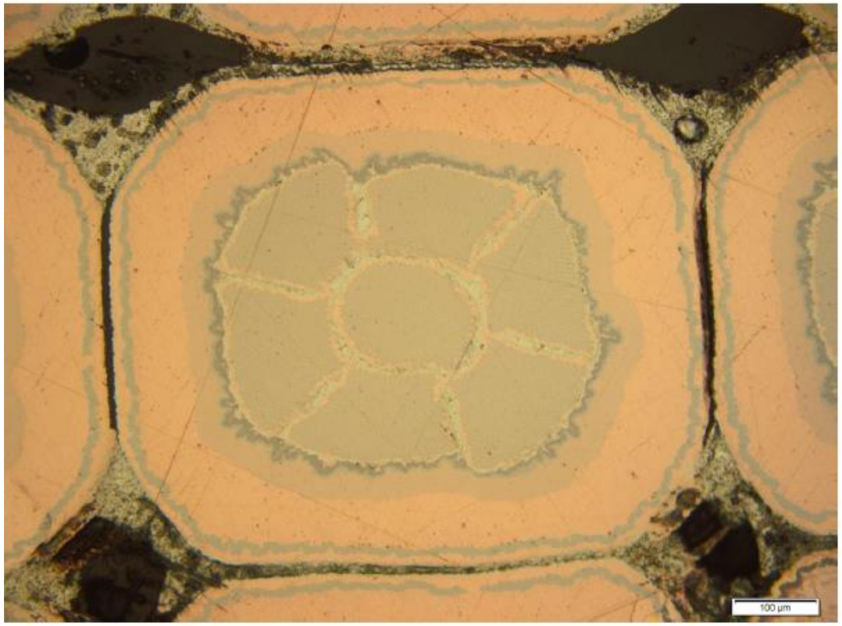
Two designs of nanostructured Cu-Nb elements – tube and rods.

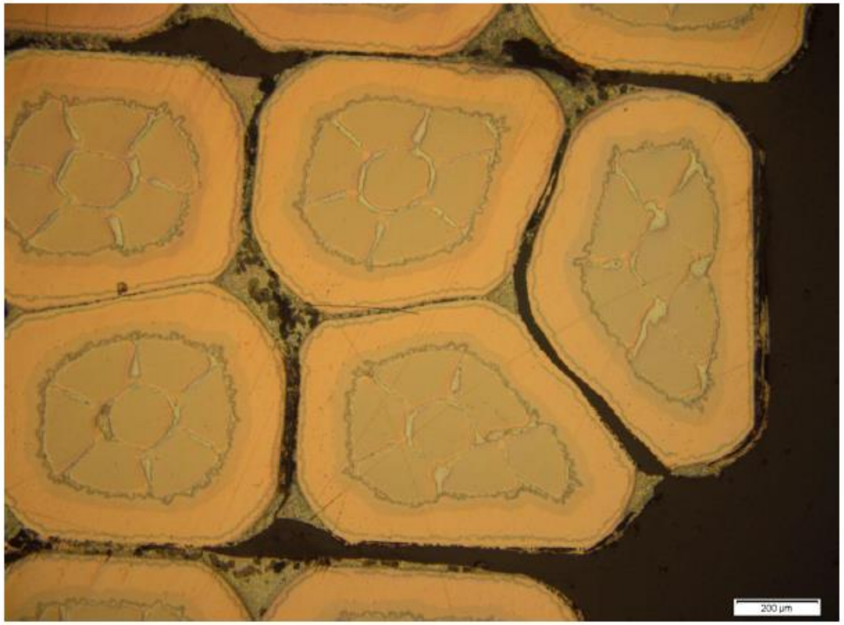


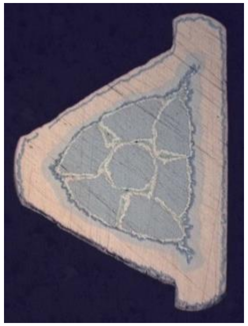
The logarithmic deformation (lnAo/A) of the wire should be around 7 for rods and up to 8.5 for Cu-Nb tube.

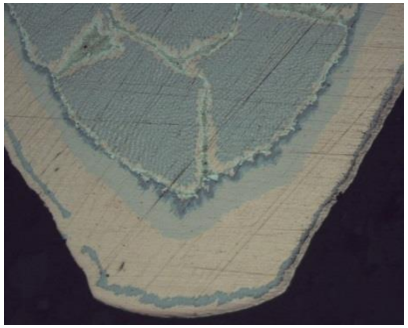
The Rutherford cable made from strengthened Nb_3Sn strands





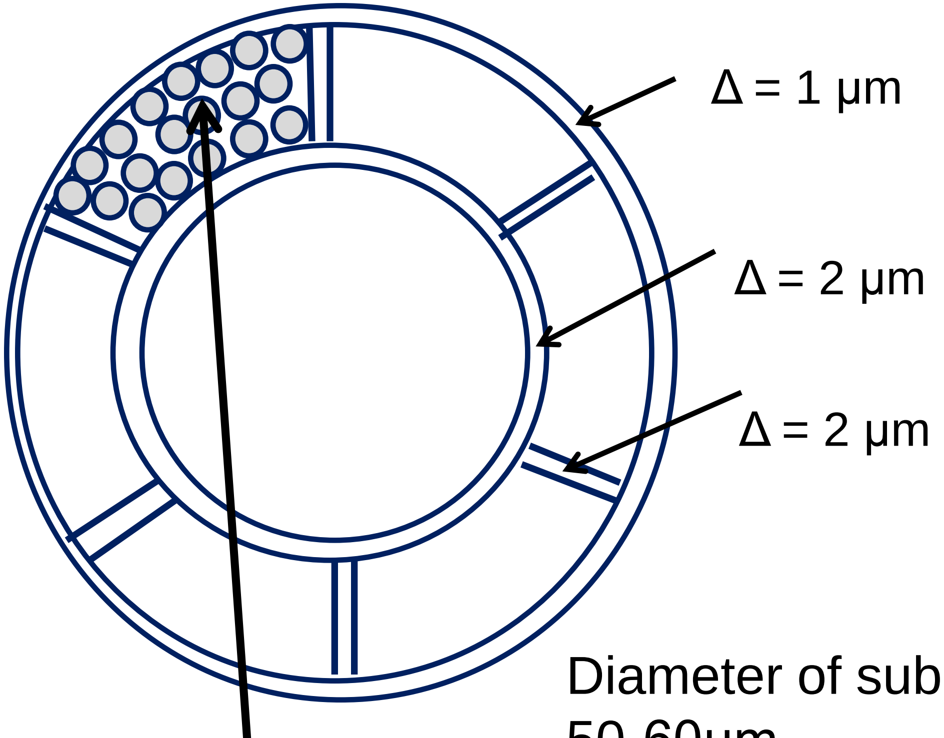






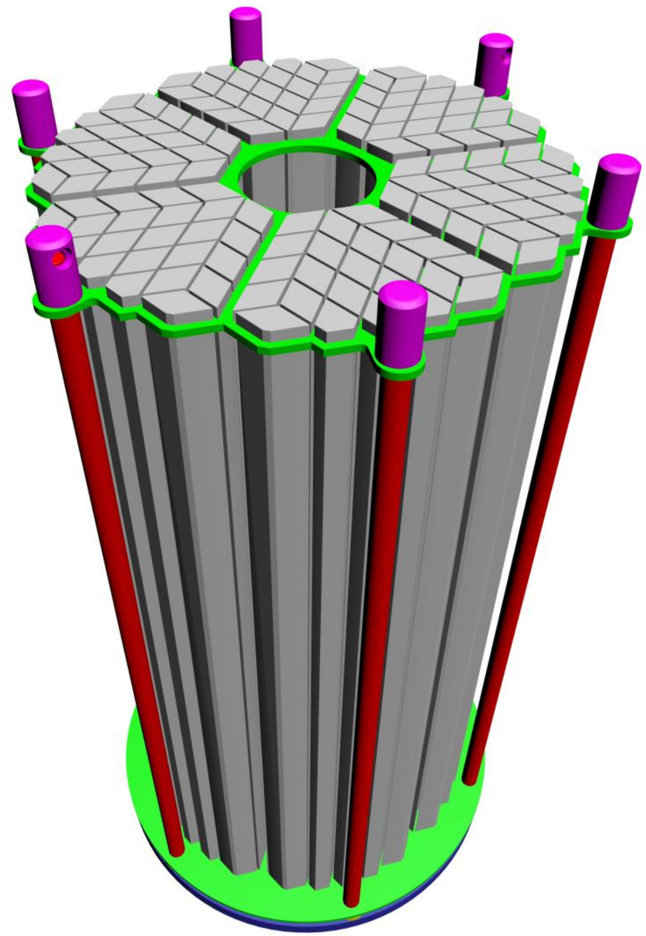
The replacement of the part of stabilizing Cu by nanostructured Cu-Nb tubular strengthening element leads to better geometry, better uniformity and survivability of Ta diffusion barrier and prevent the diffusion of Sn in case of leakage.

Preliminary design of the sub-element for “Dream” IT Nb_3Sn strand for FCC (Number of sub-elements 55-81)



Local volume fraction of Nb ~ 70%

Diameter of sub-element 50-60µm
Extensive bridging inside the sub-element



Jc = 3000 A/mm²	**Jc (Nb_3Sn) ~ 5000 A/mm²**

SUMMARY

Advanced Nb_3Sn IT strands with enhanced mechanical properties and high critical current density that meet the HL-LHC specifications could be produced on the base of existing technologies in RF in cooperation of Research centers (Bochvar Institute, Nanoelectro) and industrial plant (JSC ChMP).

Dream Nb_3Sn IT strands for FCC magnet system require R&D on design and technology in order to meet challenging not yet attained complex of properties (Jc + D eff + RRR + cost + Unit length + mechanical properties).

Combination of several local doping (tin source, copper matrix, filament materials) altogether with optimized arrangements of filaments groups in sub-elements and the introduction of nanostructured strengthening Cu-Nb elements in stabilized copper could lead to attaining of the FCC requirements in Nb_3Sn IT strands and have to be experimentally verified.