Status of A15 Superconductor Developments in Japan

Tatsushi NAKAMOTO

KEK

Acknowledgement

- JASTEC: T. Miyatake, Y. Fukumoto
- Furukawa Electric: M. Sugimoto, H. Shimizu
- SH Copper Products: K. Miyashita, K. Nakagawa (formerly Hitachi Cable)
- NIMS: A. Kikuchi
- Tohoku Univ.: S. Awaji
- KEK: T. Ogitsu, M. Sugano

Contents

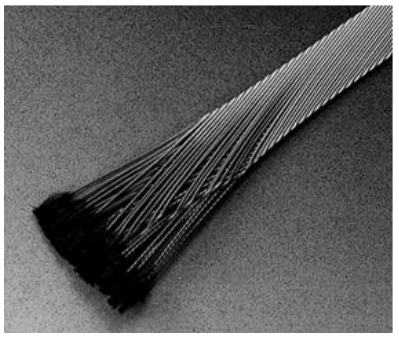
- **Nb_3Sn Manufacturers in Japan**
  - **Bronze wire for ITER, NMR…**
  - **Mechanically reinforced wire**
  - **Development of IT, DT wires**
- **Activity at NIMS for Nb_3Al and Nb_3Sn**
- **Stress/Strain Studies**
- **Cooperation for FCC and Support Needed**

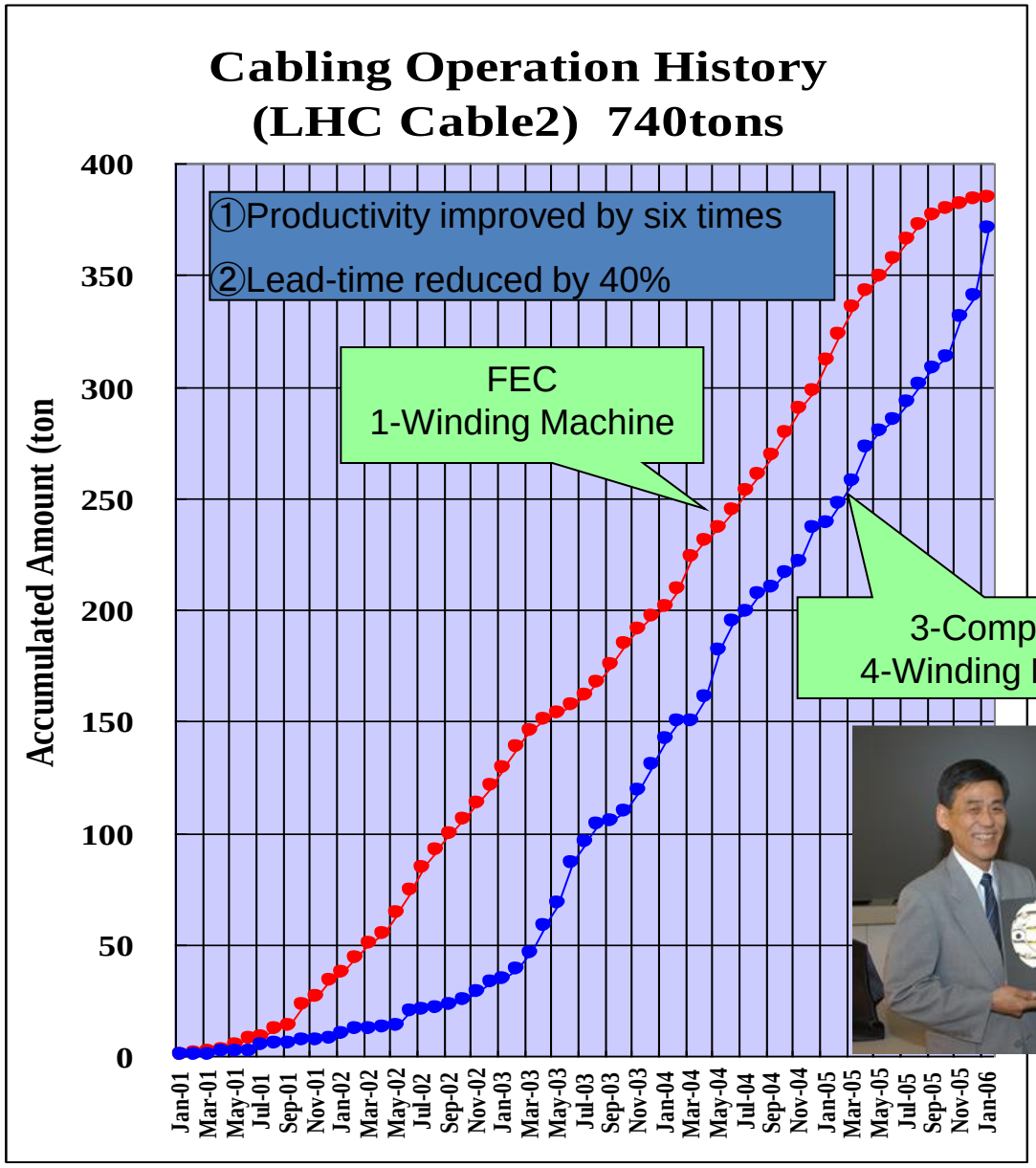

FURUKAWA
ELECTRIC

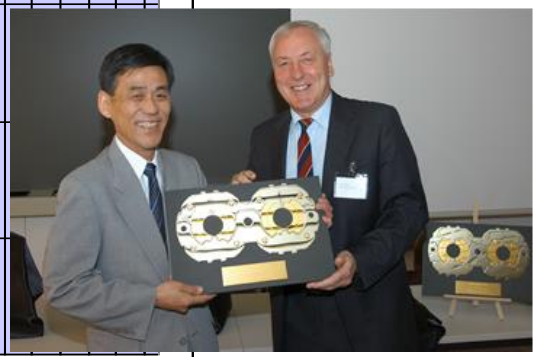
LHC Rutherford Cable Production

NbTi

FURUKAWA ELECTRIC



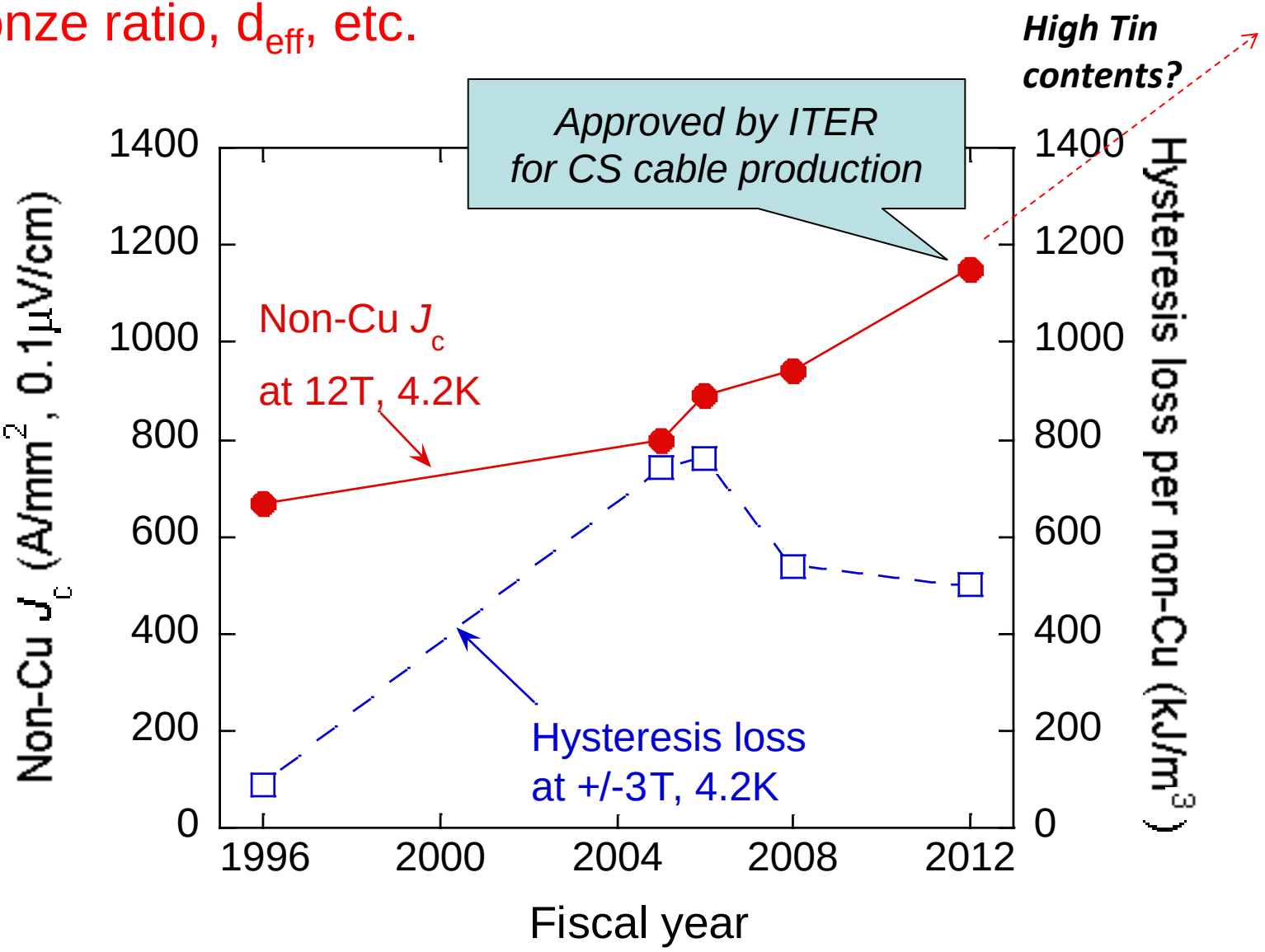




Increasing Jc of bronze-Nb_3Sn

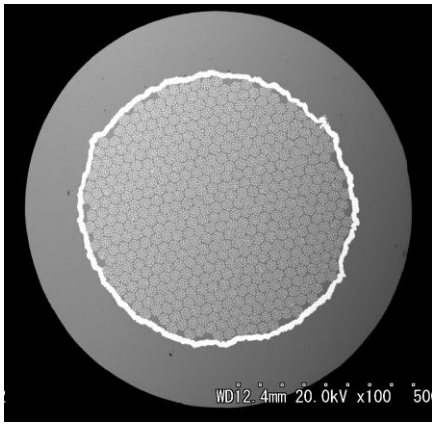
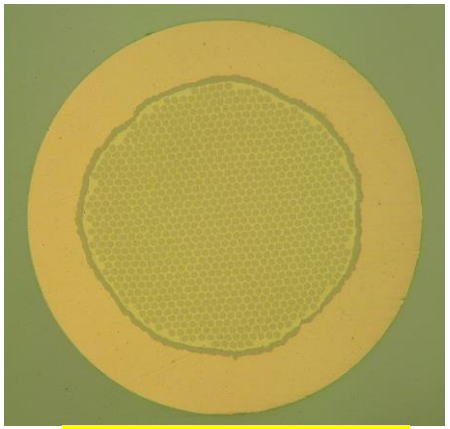
FURUKAWA ELECTRIC

Room for advancement by optimizing tin content in bronze, bronze ratio, d_{eff}, etc.



ITER-CS Wire -Design for higher Jc & lower Ph-

FURUKAWA ELECTRIC

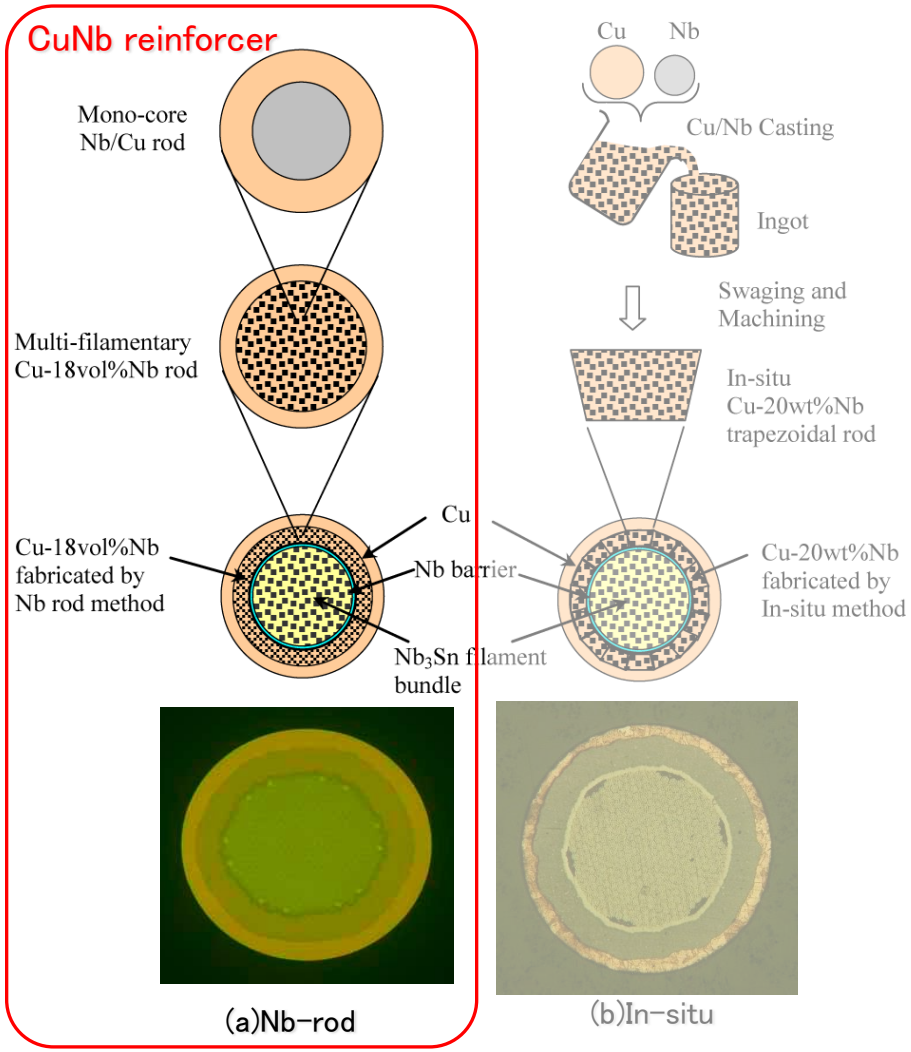
Items	2008 design	2012 design
Strand final diameter (mm)	0.83±0.005	0.83±0.005
Cr-plating thickness (μm)	2 +1/-0	2 +0/-1
Cu/Non-Cu ratio	1.0 ±0.1	1.0 ±0.1
Twist pitch (mm), direction	15 ± 2 (R.H.H)	15± 2 (R.H.H)
Diffusion Barrier	Ta	Ta
Bronze composition (wt%)	16Sn-0.3Ti	15.7Sn-0.3Ti
Filament dia. (μm)	3.3 (nominal)	2.3 (nominal)
Cross-section		

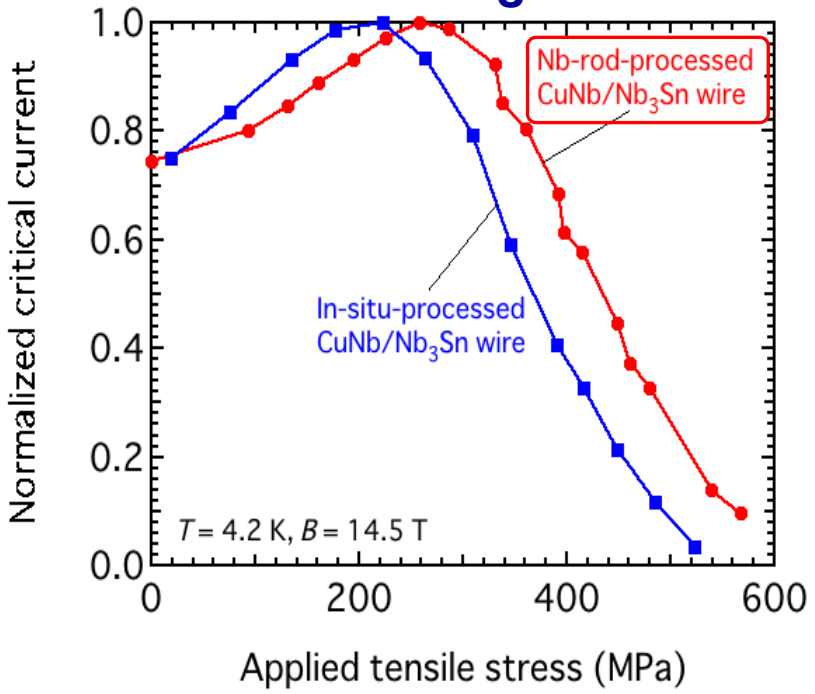
Optimized for ITER-CS

Mechanical Reinforcement

FURUKAWA ELECTRIC

Nb-rod-method CuNb reinforced Nb_3Sn





Feature of Nb-rod-method

- Excellent Ic vs stress performance
- Useful RRR larger than 100:
  count as stabilizer!!
- **Suitable for mass-production**

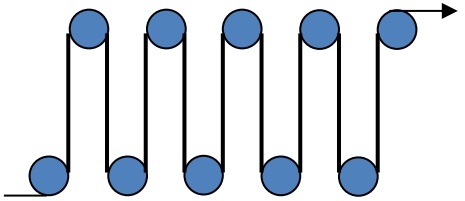
This work was performed under collaboration with HFLSM, IMR, Tohoku University.

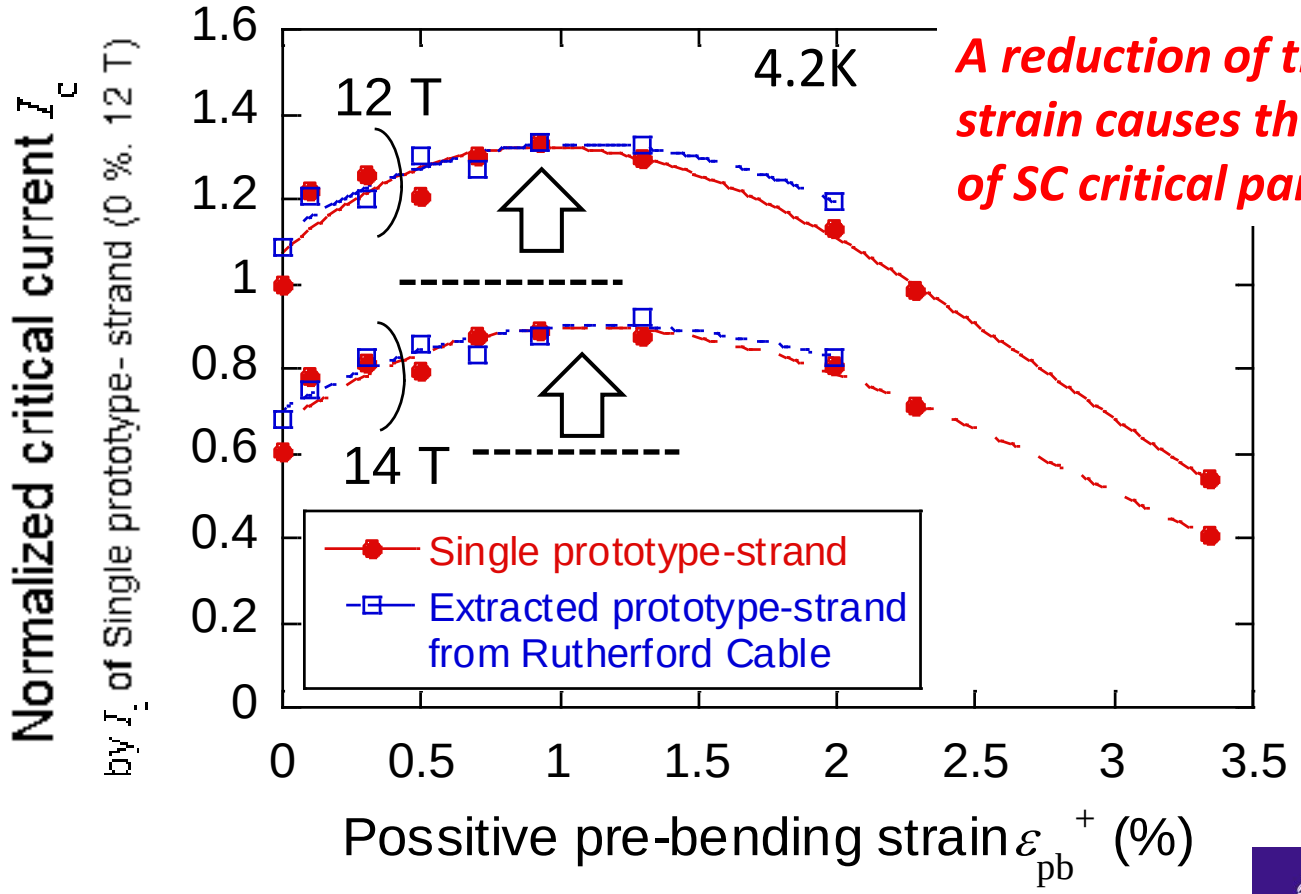
TOHOKU UNIVERSITY

Ic Improvement by Process

FURUKAWA ELECTRIC

Useful pre-bending (pre-strain) effect for enhancing Ic suggests a reality of ***React & Wind*** Nb_3Sn magnet.





A reduction of the residual strain causes the improvement of SC critical parameters!

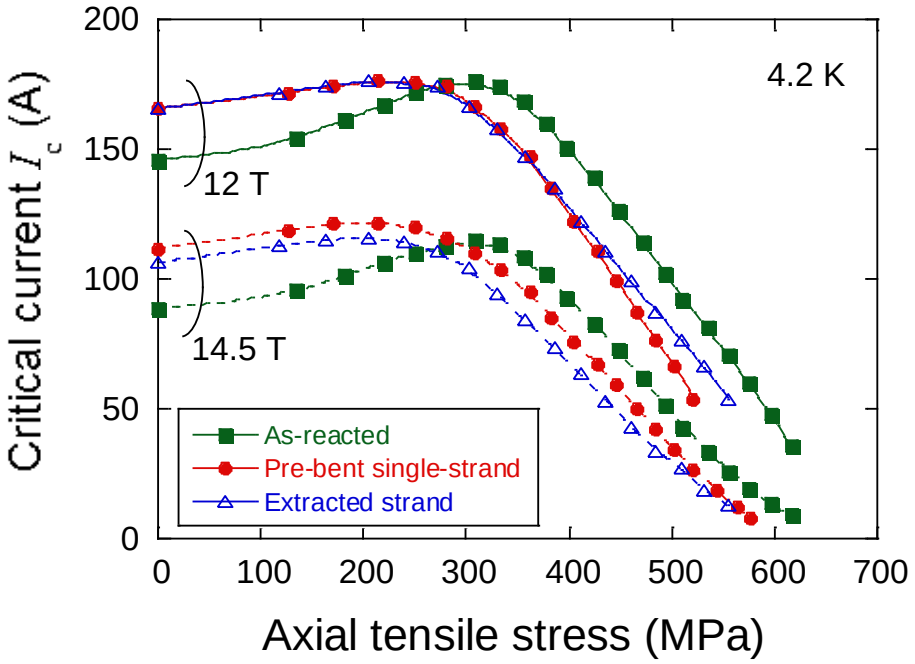
This work was performed under collaboration with HFLSM, IMR, Tohoku University.

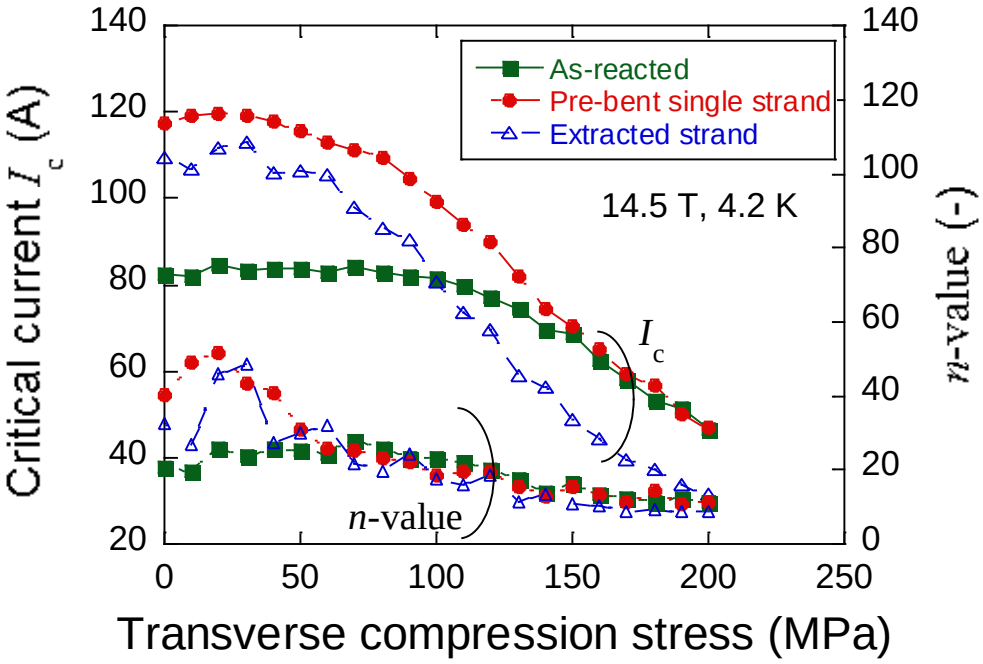
TOHOKU UNIVERSITY

Control of Stress Sensitivity of Ic

FURUKAWA ELECTRIC

"Pre-bending Process" & "Mechanical Reinforcement"





Pre-bended Cu-Nb/Nb_3Sn Rutherford cable (*React & Wind*)

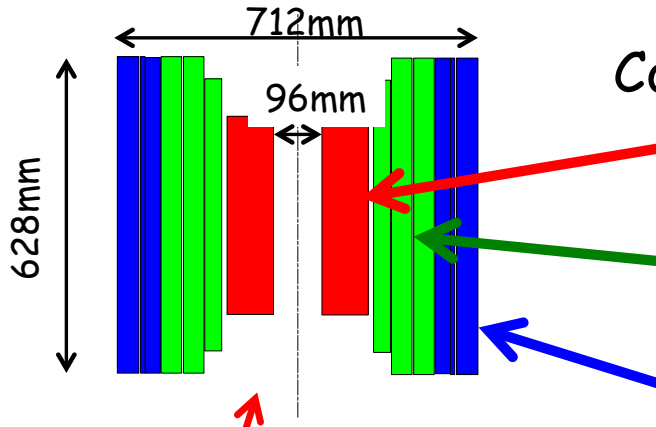
This work was performed under collaboration with HFLSM, IMR, Tohoku University.

TOHOKU UNIVERSITY

Application in HFM

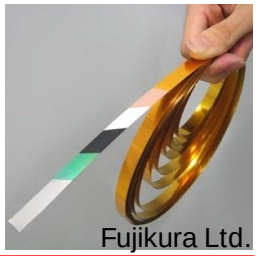
25T cryogen-free superconducting magnet with *high strength CuNb/Nb_3Sn Rutherford cables*

This work was performed under collaboration with HFLSM, IMR, Tohoku University.



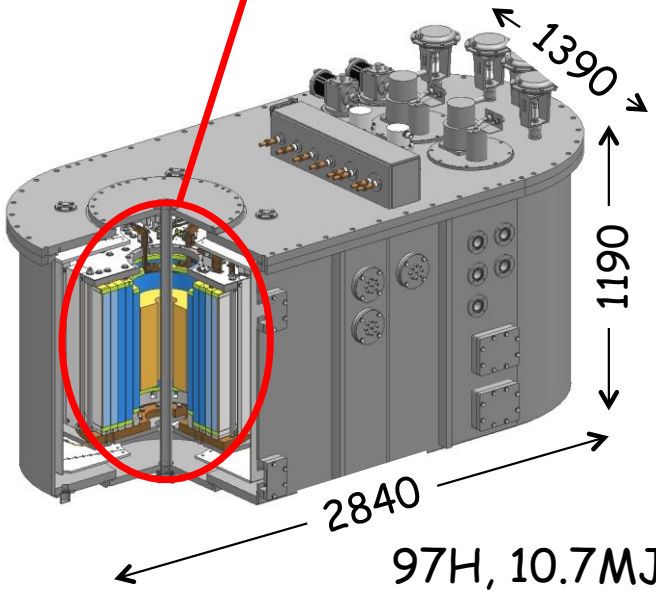
Coils

68 GdBCO single pancakes
(11.5T@140A, 417MPa)



3 CuNb/Nb_3Sn Rutherford solenoid
(14T@851A, 251MPa)

3 NbTi Rutherford solenoid



Cooling system

Conduction cooling using He circulation

Shield: 2 x 1 stg GM cryocooler

HTS: 2 x 4K-GM cryocooler
(3W@4.2K, 10W@8K)

LTS: 2 x GM/JT cryocooler (8.6W@4.3K)

ISS2014, S. Awaji SA-25-INV

Future at Furukawa

FURUKAWA ELECTRIC

- FCC target
  - Jc >3,000A/mm^2 at 12T
  - Df <20μm
  - RRR >150
- Future R&D at Furukawa
  - Rutherford cable with suitable Jc and Jc-σ properties by;
  - - improving Jc of bronze-method reinforced Nb_3Sn
  - - improving strength of internal-tin-method Nb_3Sn
  - roughly over 5 years from 2015
  - with potential customers and partners.
- Contribution to FCC project


JASTEC
SUPERCONDUCTOR


KOBELCO
KOBE STEEL GROUP

Introduction of JASTEC

JASTEC SUPERCONDUCTOR KOBELCO KOBE STEEL GROUP

Founded	:	Apr. 1st, 2002
Capital	:	400 mil JP Yen
Shareholder	:	Kobe Steel (100%)
Employee	:	147
President	:	Dr. Y.NISHIMOTO

Sales Office (Tokyo)

Wire Factory (Moji)

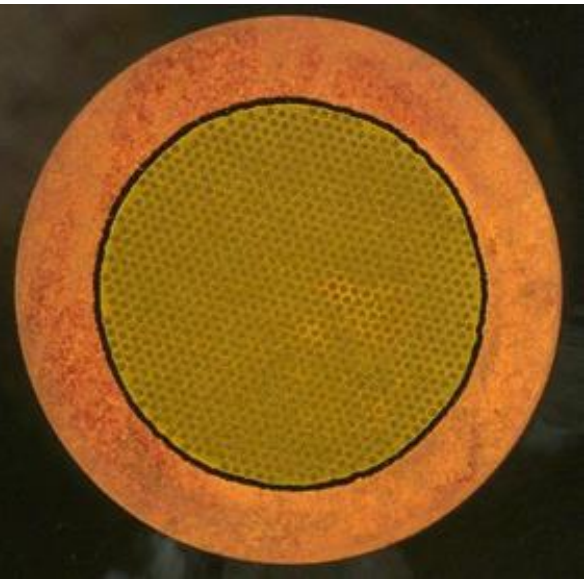
Head Office Magnet Factory (Kobe)

LLOYD'S REGISTER · LRQA ISO 9001 UKAS MANAGEMENT SYSTEMS 001

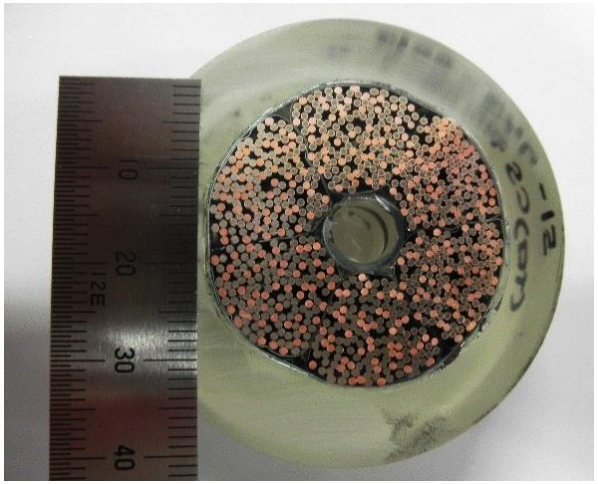
Eco-action 21

JASTEC Nb_3Sn Wire

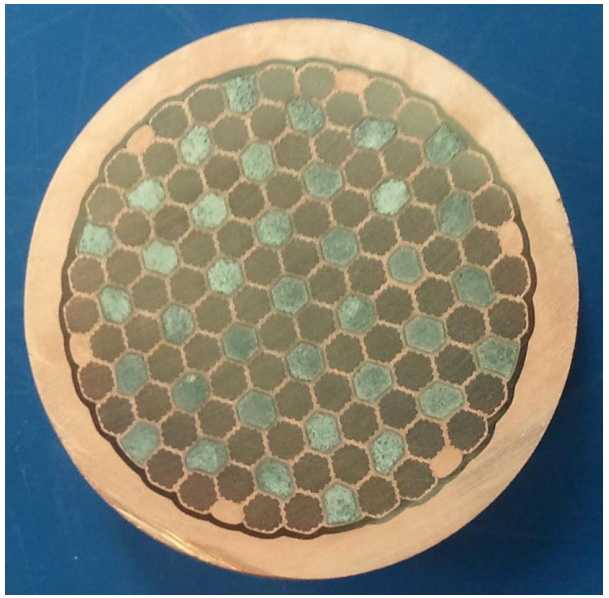
- **JASTEC is one of the world primary wire manufacturers, especially for Nb3Sn.**
  - **For NMR: ~10 tons every year**
  - **For ITER: 100 tons in total**
- **JASTEC supplies TF & CS (Nb3Sn) wires for ITER.**
  - **40 tons for TF conductor (~1/10 of total)**
  - **60 tons for CS conductor (1/3 of total)**



Strand (TF)



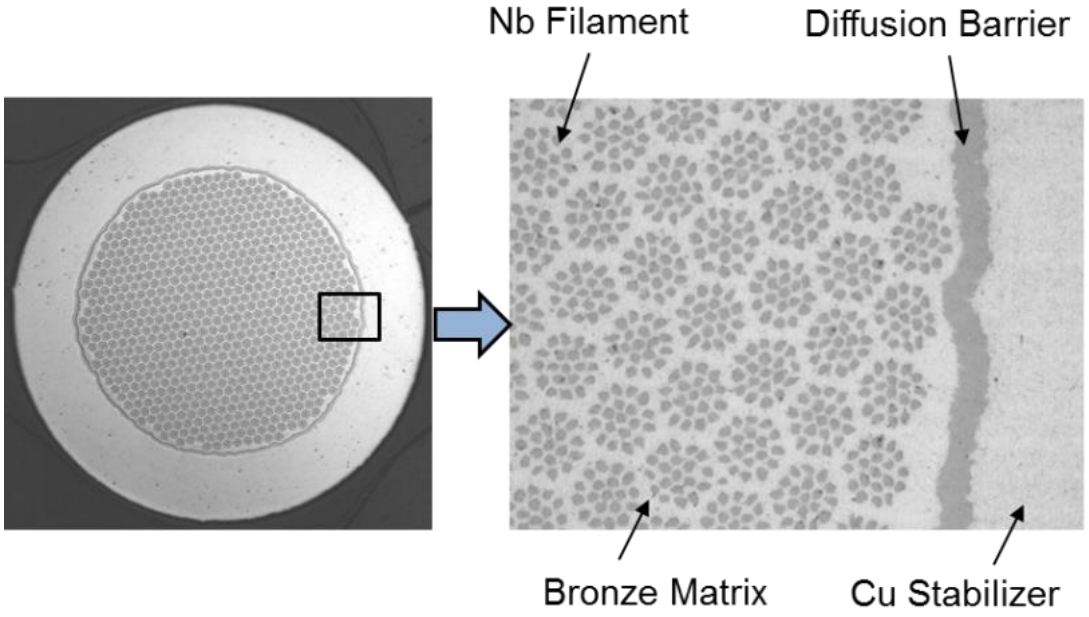
Cable (CS)

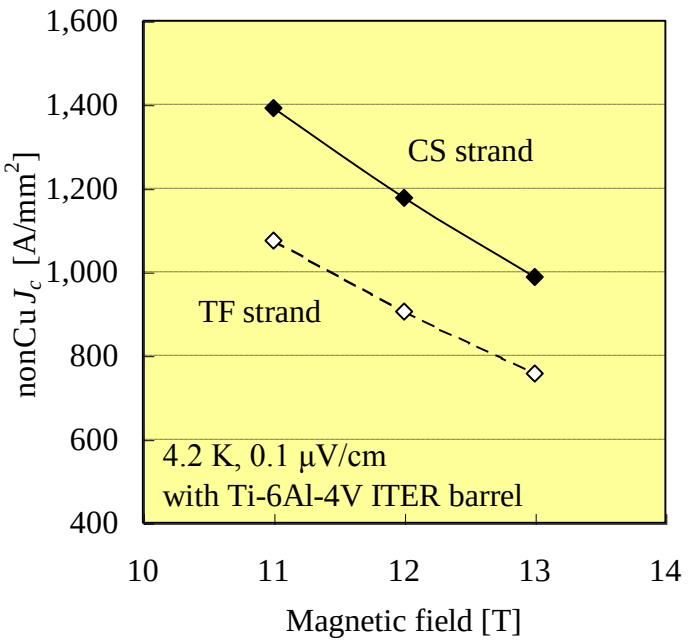


Distributed Tin (DT) wire with even higher Jc performance (under development)

High-Jc Bronze wire/cable for ITER

Bronze Wire for ITER

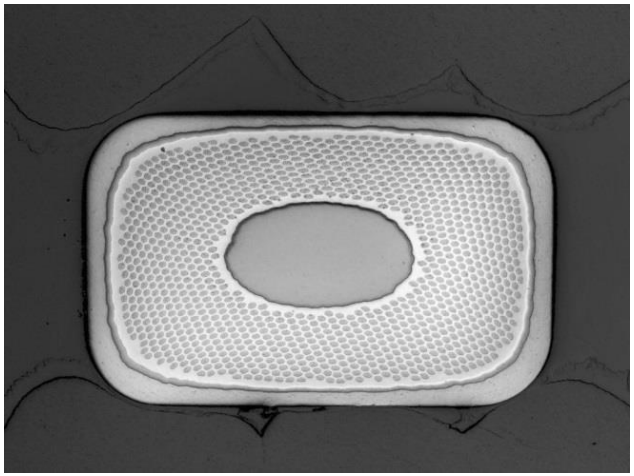




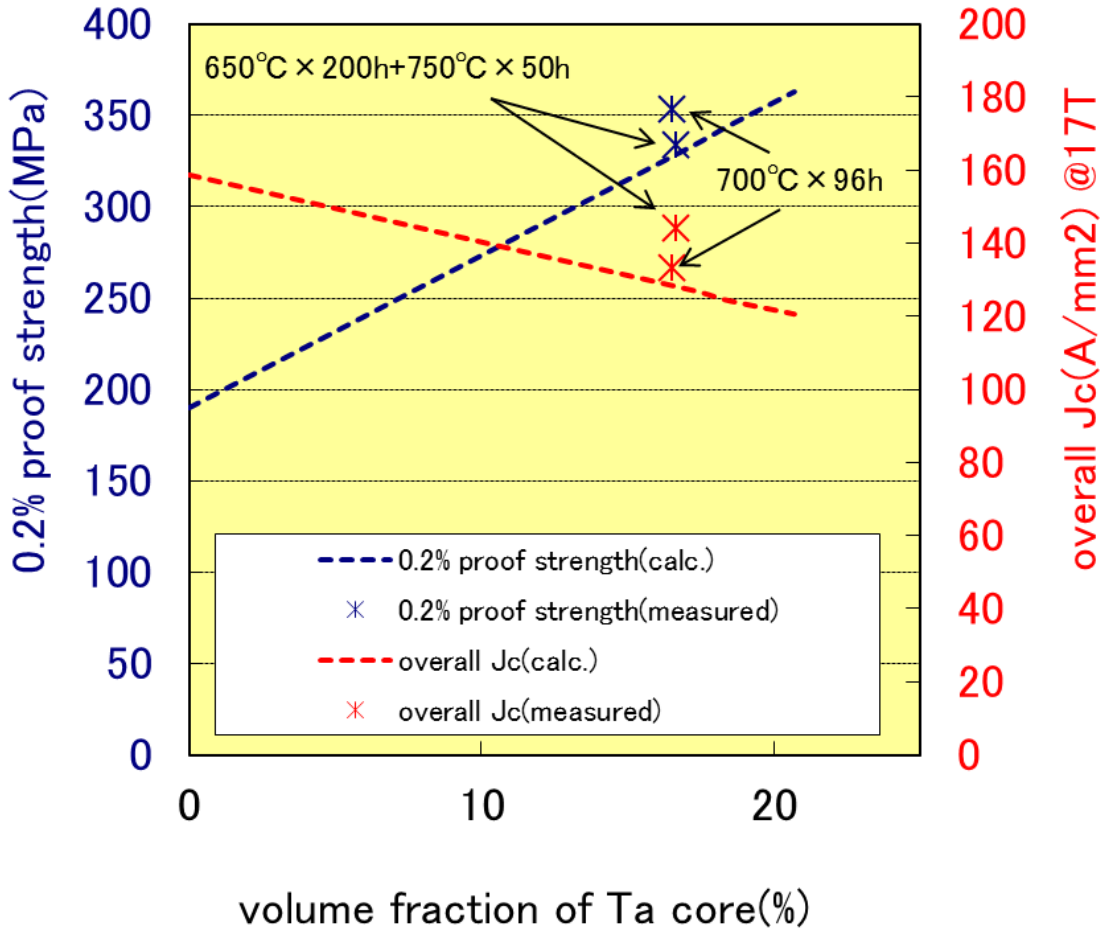
	TF	CS
Strand Diameter	0.82 mm	0.83mm
Stabilizer Material	Cupper	
Cu/Superconductor ratio	1.0	
Jc non-Cu @12T, 4.2K	800~950 A/mm2	1000~1150 A/mm2
Filament Diameter	2.8 μm	2.3μm
Barrier Material	Nb	Nb/Ta
Hysteresis Loss @ ± 3T	700~1000 mJ/cm3	400~600 mJ/cm3

Mechanical Reinforcement

Ta reinforced Bronze-Nb_3Sn



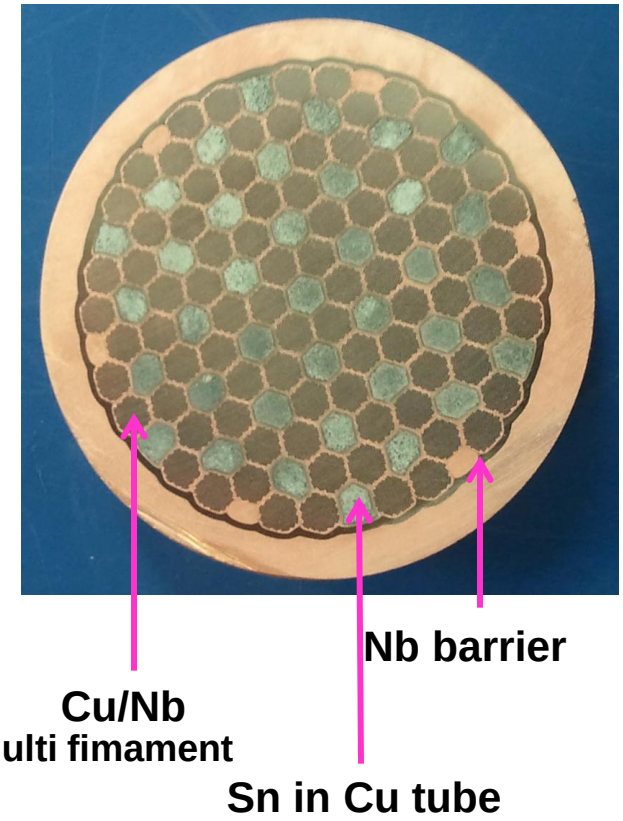
T20/0.5
Ta reinforced

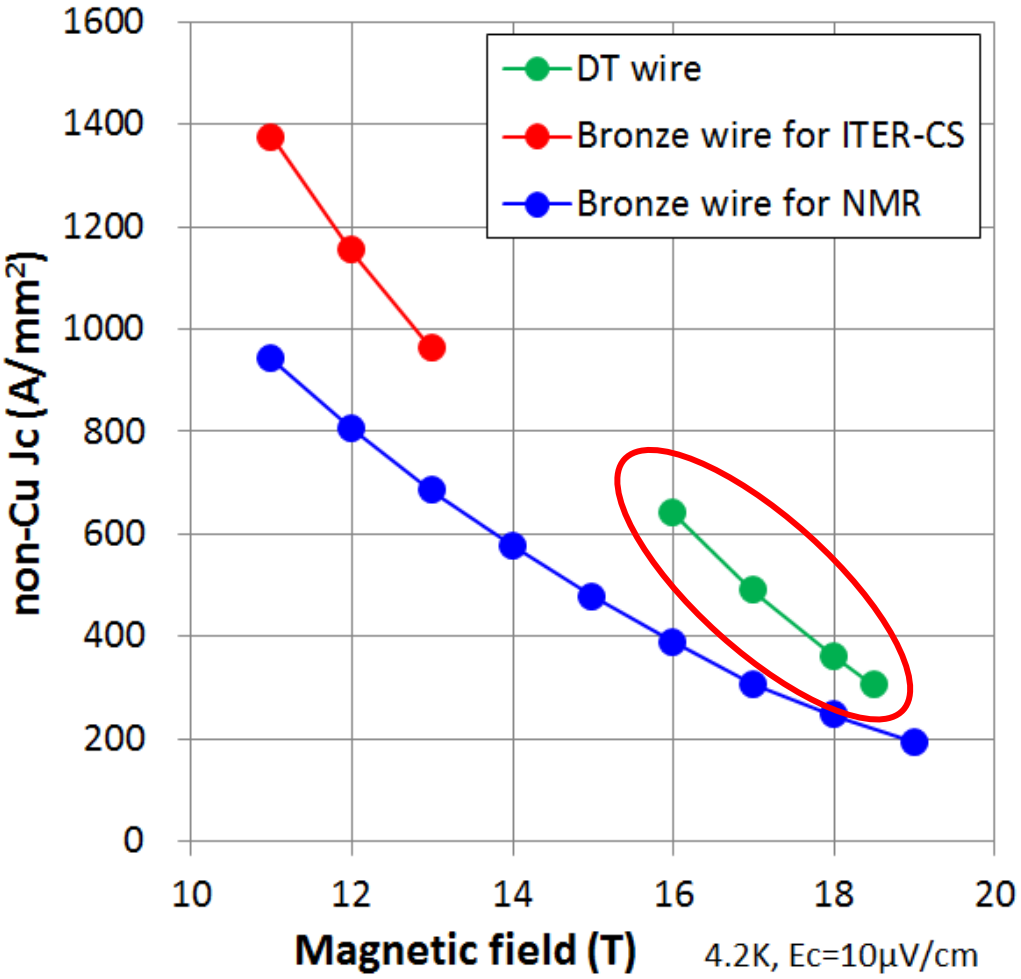


Development of DT Wire

New Process Nb_3Sn wire (DT: Distributed Tin)

>60% higher Jc than our H-type





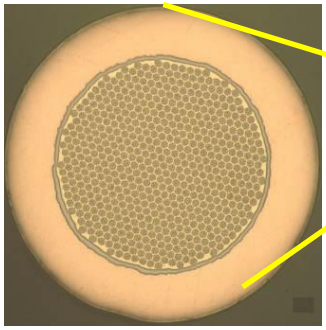
SH Copper Products

formerly Hitachi Cable

Bronze Nb_3Sn Wire & Cable in SH Copper Products

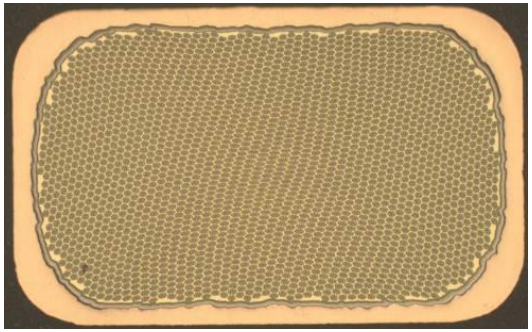
SH Copper Products

Since 1970's , SH copper manufactured Bz route Nb3Sn wires and cables for nuclear fusion, high field magnet, NMR etc. More than 70 ton Nb3Sn wires were manufactured for ITER project from 2009 to 2013.

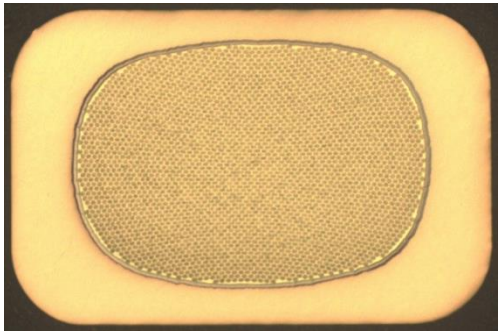


ITER Nb3Sn wire
ϕ0.82mm Cu ratio ;1

ITER conductor



For NMR Cu ratio ;0.3

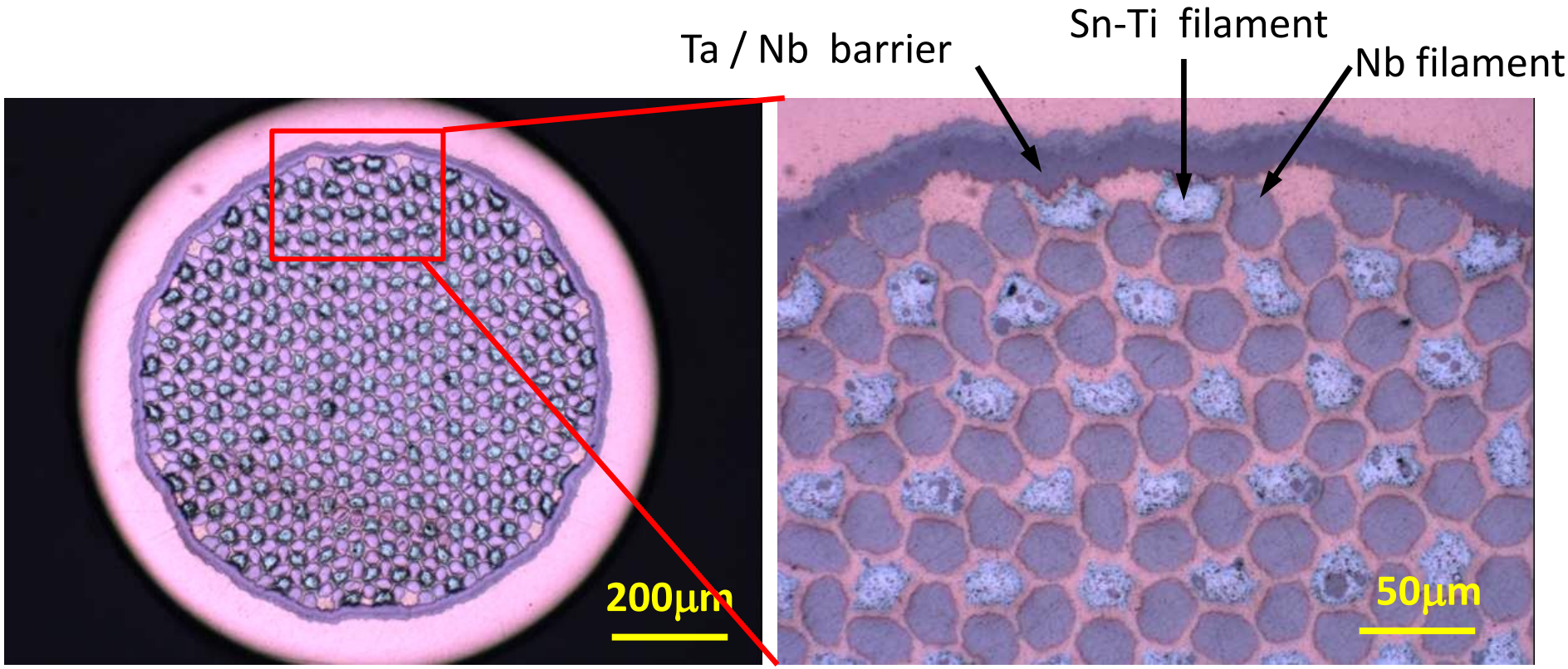


For High field magnet Cu ratio ;0.9

High Jc ⇒ High tin (Sn) bronze,
However, it is very difficult to draw bronze route Nb_3Sn wire with more than Cu-16wt%Sn bronze.

Internal Tin Nb_3Sn wire

SH Copper Products

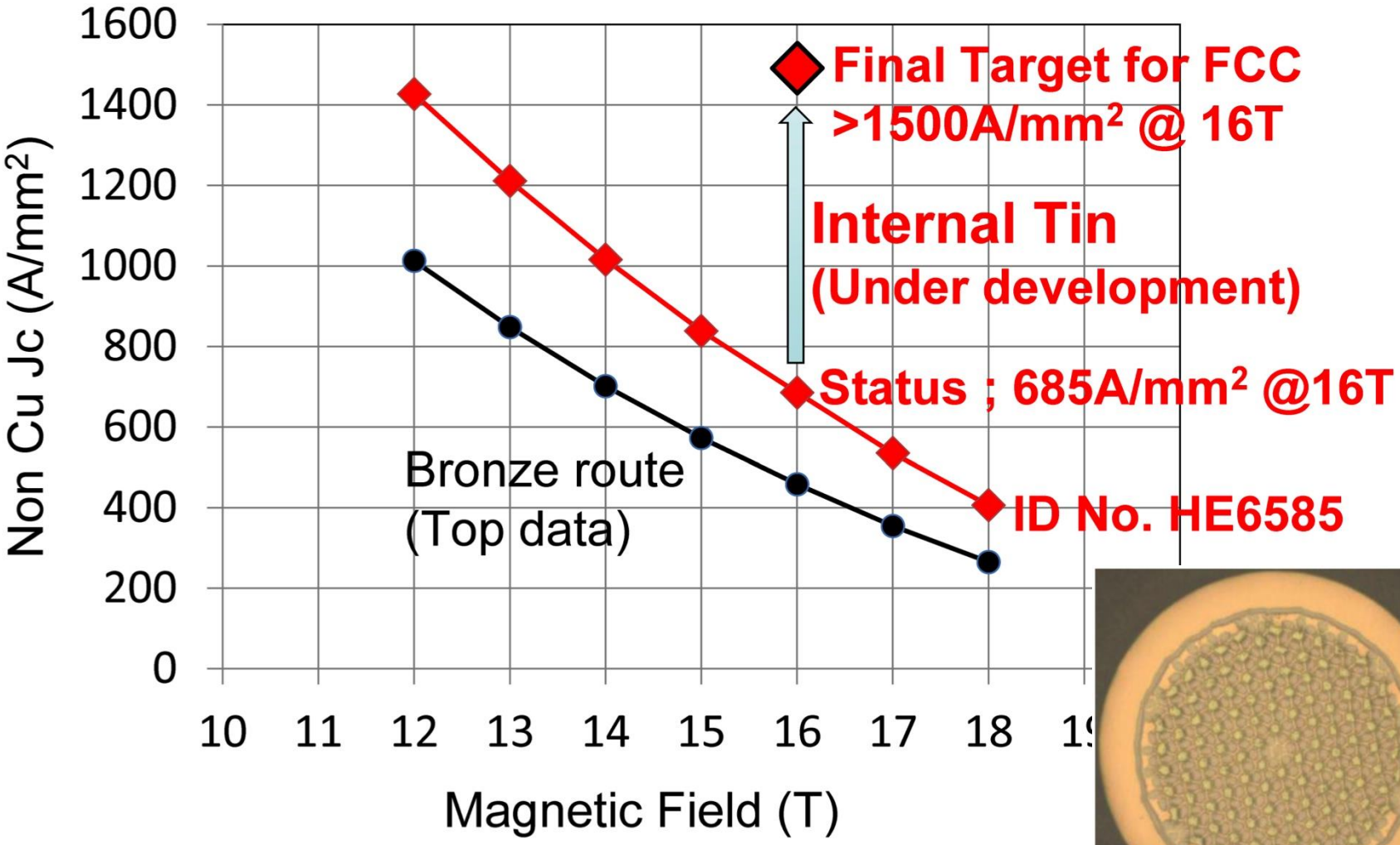


- Sn Filament is almost as large as Nb one.
- Simple structure ⇒Low Cost
- Equivalent to Cu-35wt%Sn bronze or higher.

- Good barrier shape (no deformation)
- High RRR ; ≧250
- Small effective mean ϕ_{fil}
- 20km / Billet (0.85mm diameter)

Internal Tin Nb_3Sn wire

SH Copper Products



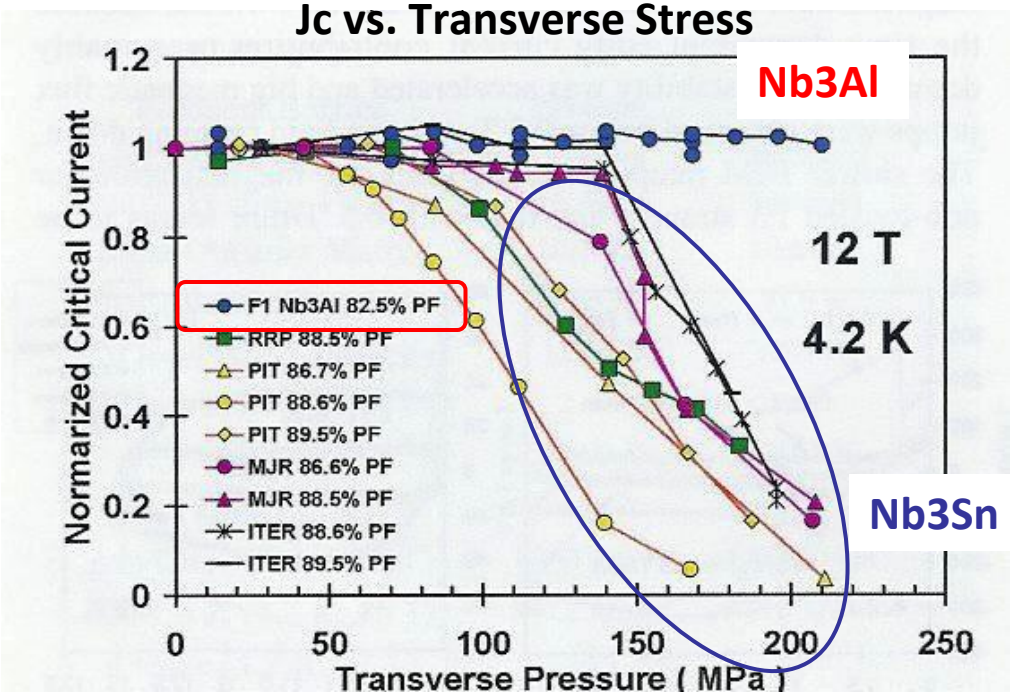
HE6585

Contents

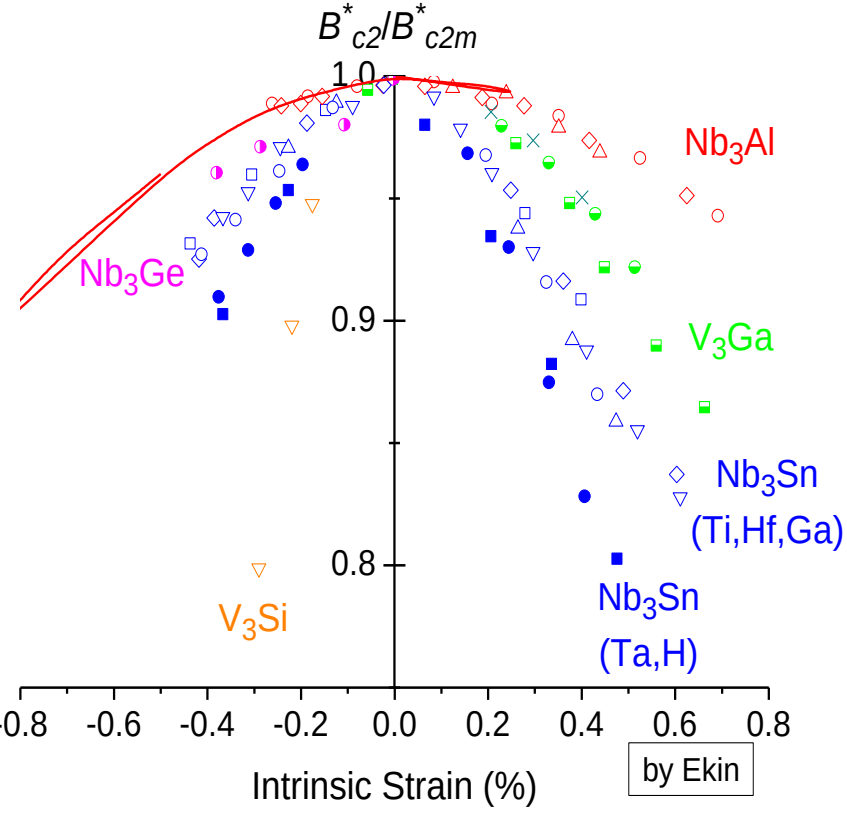
- Nb_3Sn Manufacturers in Japan
- Activity at NIMS for Nb_3Al and Nb_3Sn
- Stress/Strain Studies
- Cooperation for FCC and Support Needed

Property of Nb_3Al

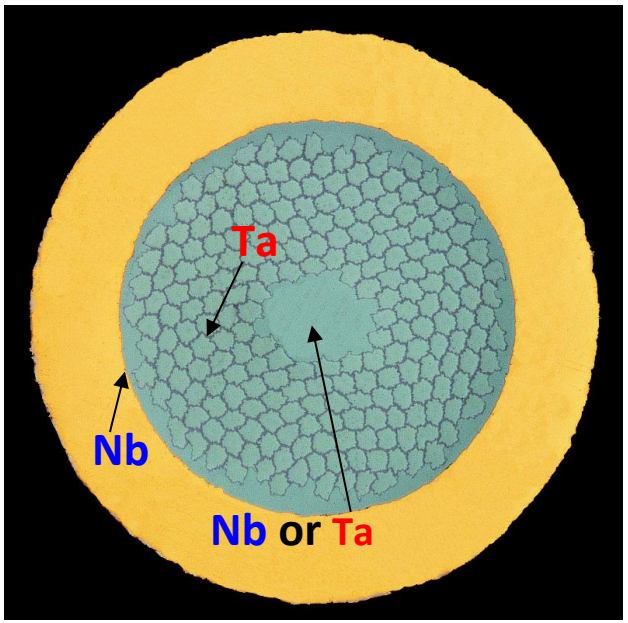
- Crystal structure: A15-type
- Al concentration: 18-25 at% (2000° C needed for stoichiometry)
- Lattice parameter: 0.5187 nm
- T_c: 15-19 K
- B_{c2}(4.2K): 19- 30 T
- Good strain tolerance

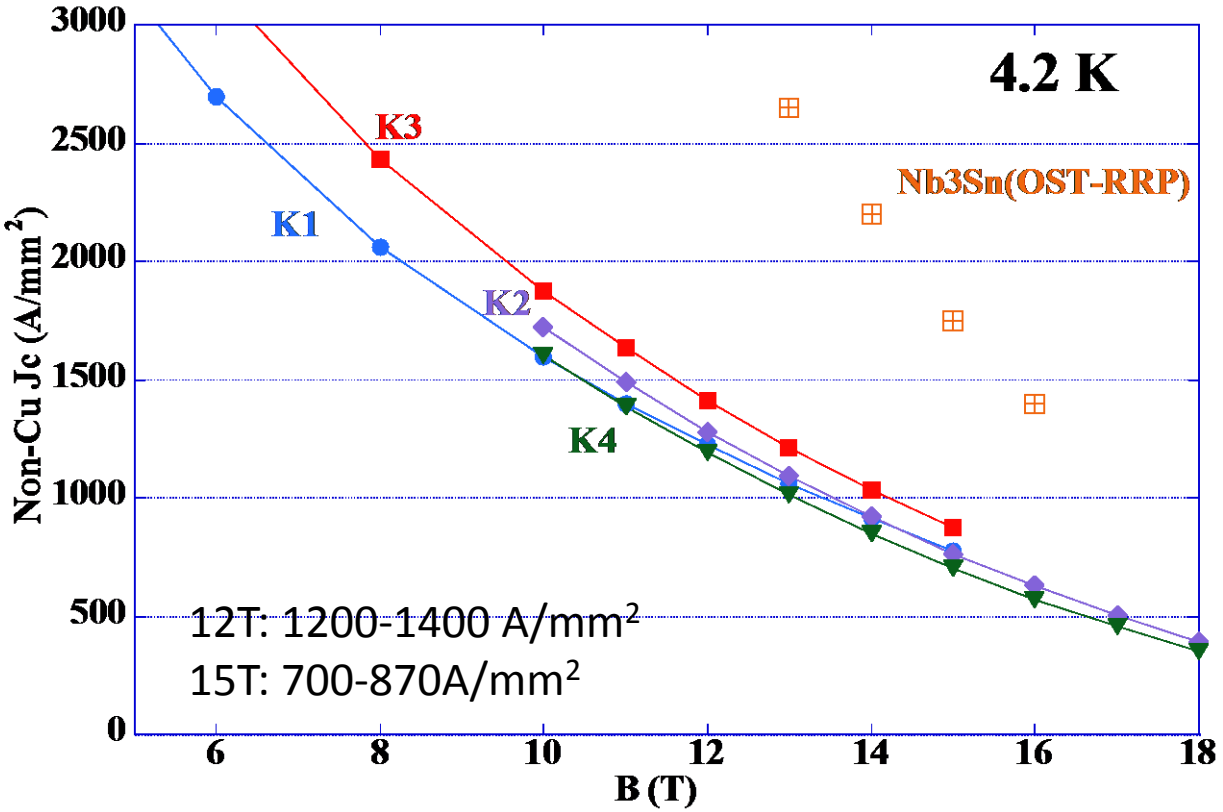


Presented at MT-20 by A. Kikuchi et al.



RHQ-Nb_3Al w/ Ta Barrier

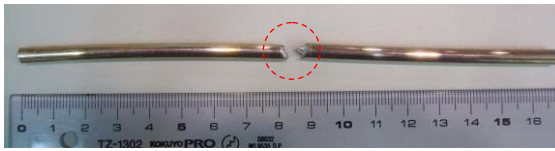




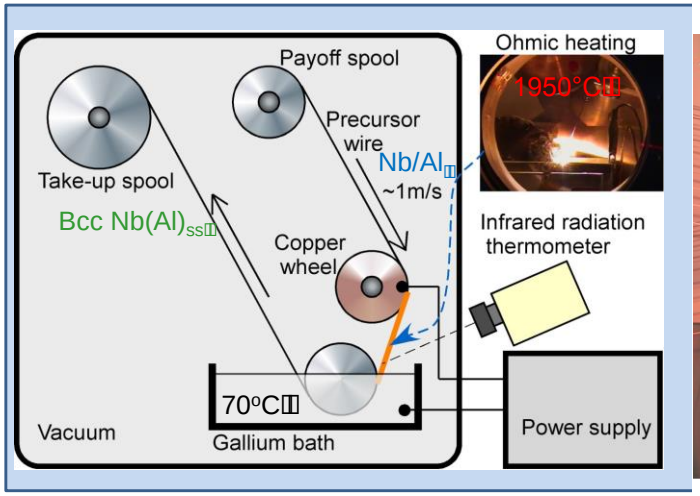
- Collaborative work between NIMS and KEK with a support from CERN (~2011)
- Development for high field accelerator magnet

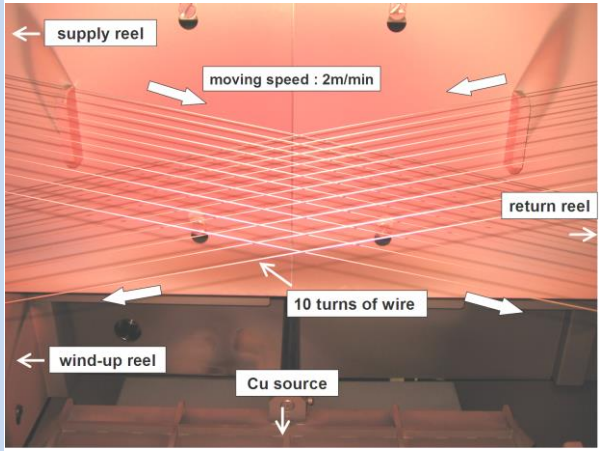
Issues for RHQ-Nb_3Al

- Many wire breakings with Ta matrix.



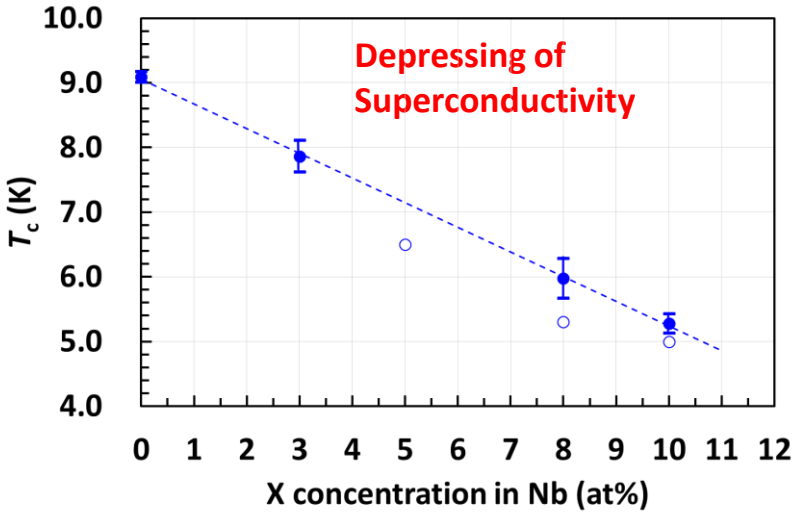
- RHQ process using Ga bath
  - Removal of Ga to clean wire surface
- Copper stabilization
  - Ion-plating
  - Copper electroplating

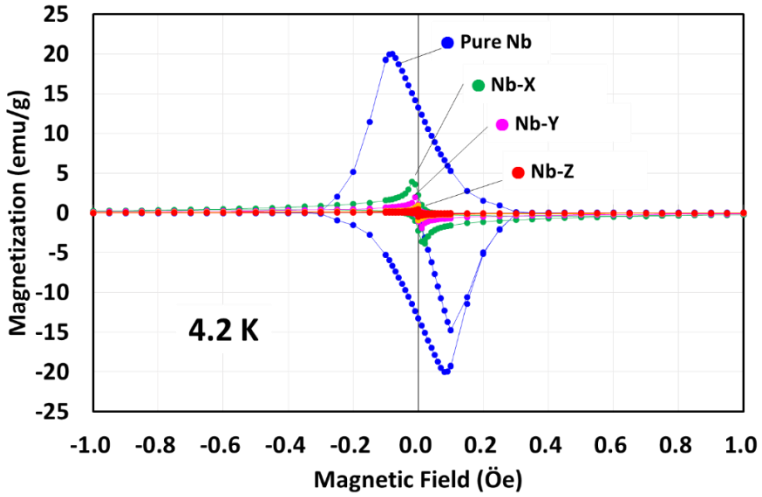




Nb Alloy Inter-filament Matrix

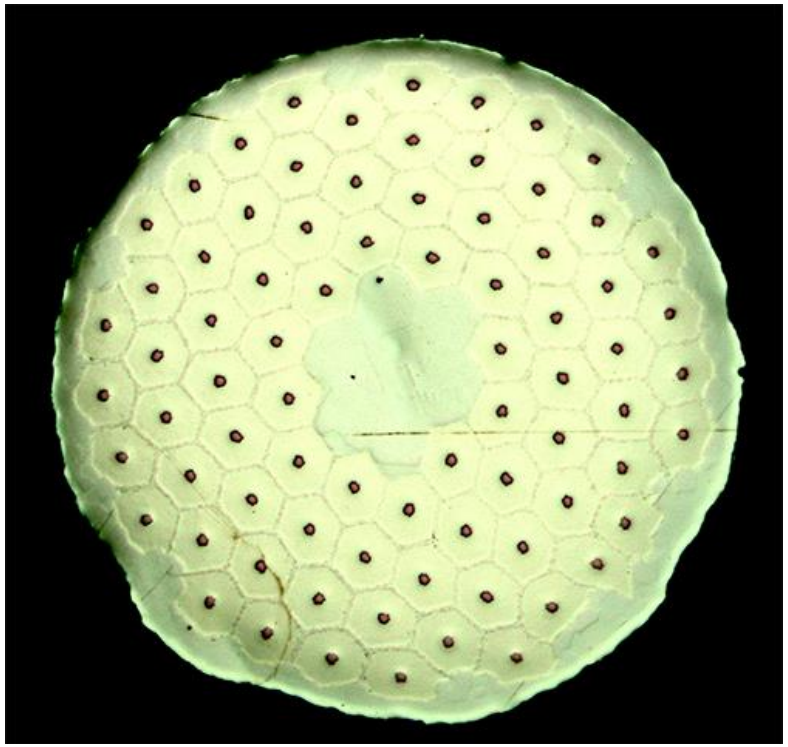
Much better workability than costly tantalum





Improvement of drawability with Nb Alloy

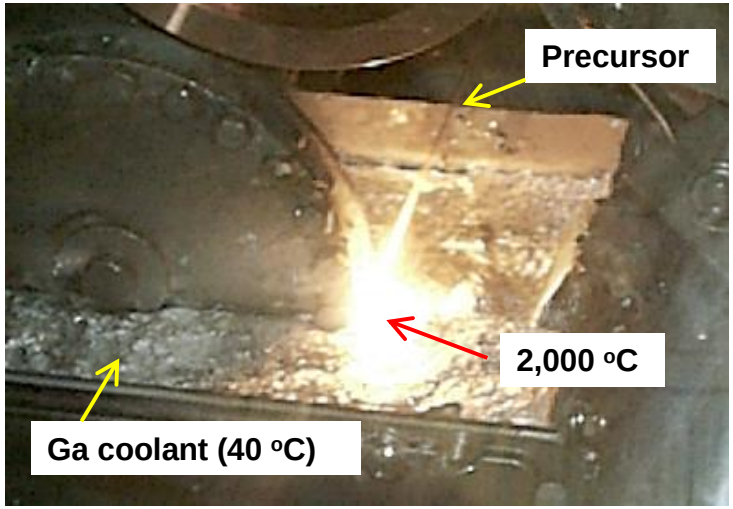
400 tonf Extrusion Billet
(1 km class)

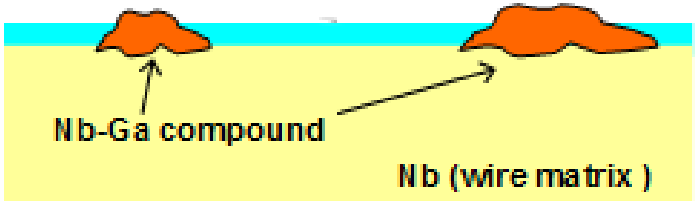


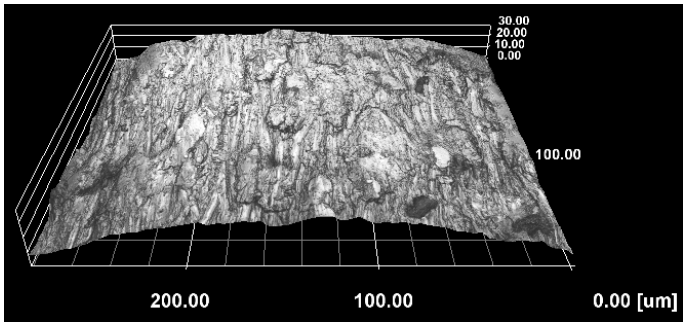
No Wire-Breakage
No Tantalum

Simplifying Nb_3Al Quenching Process

Dirty Ga Quenching at RHQ Process

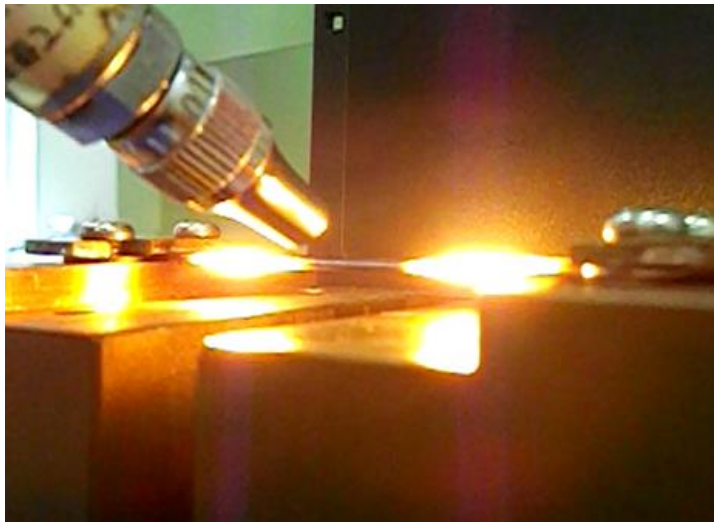


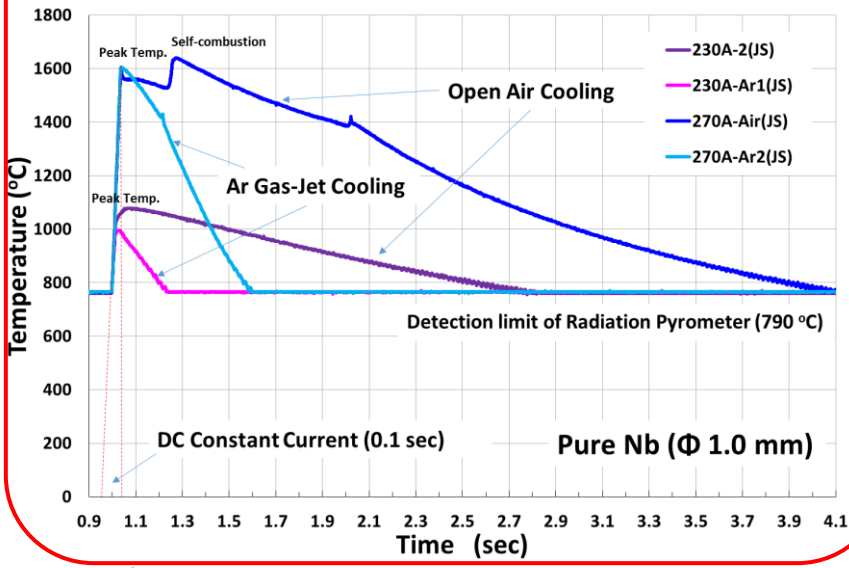




Ga removal process needed

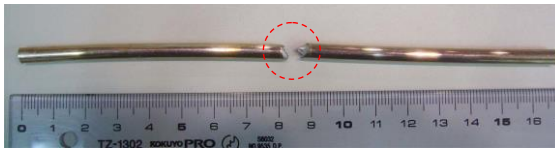
Clean "Gas Quenching": Low Cost

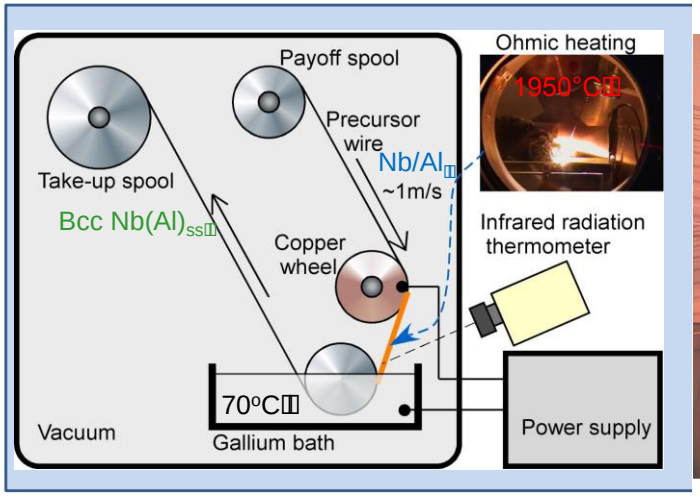


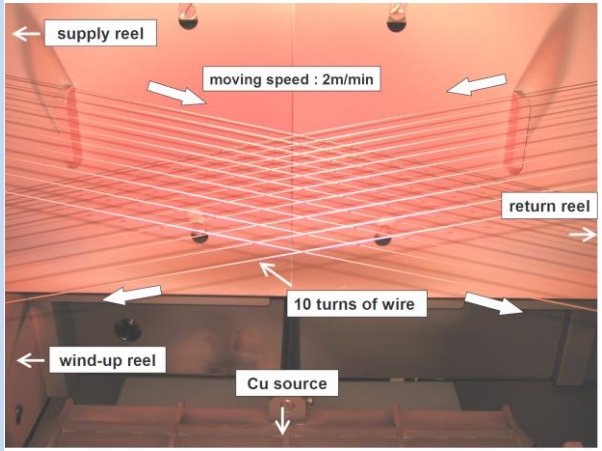


Issues for RHQ-Nb_3Al : Efforts for Improvement

- Many wire breakings with Ta matrix.
  >> Nb alloy matrix w/ good drawability
- RHQ process using Ga bath >> Gas quenching
  - ~~Removal of Ga to clean wire surface~~
- Copper stabilization
  - ~~Ion-plating~~
  - Copper electroplating >> speed-up



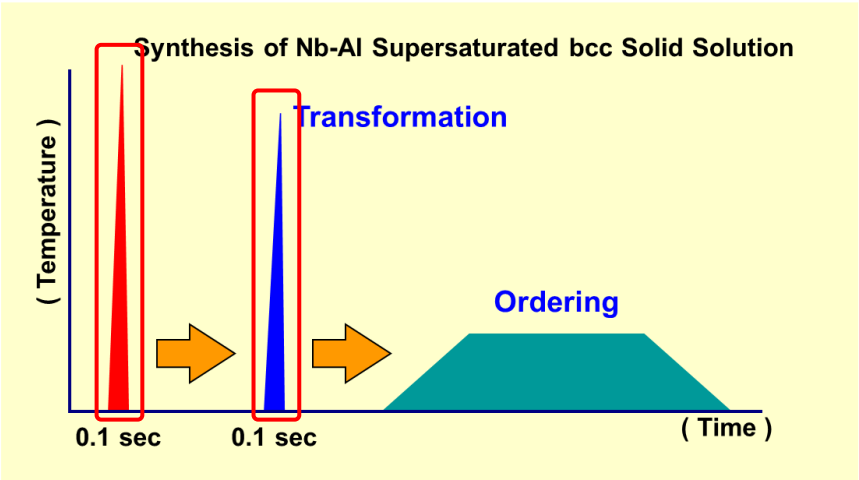




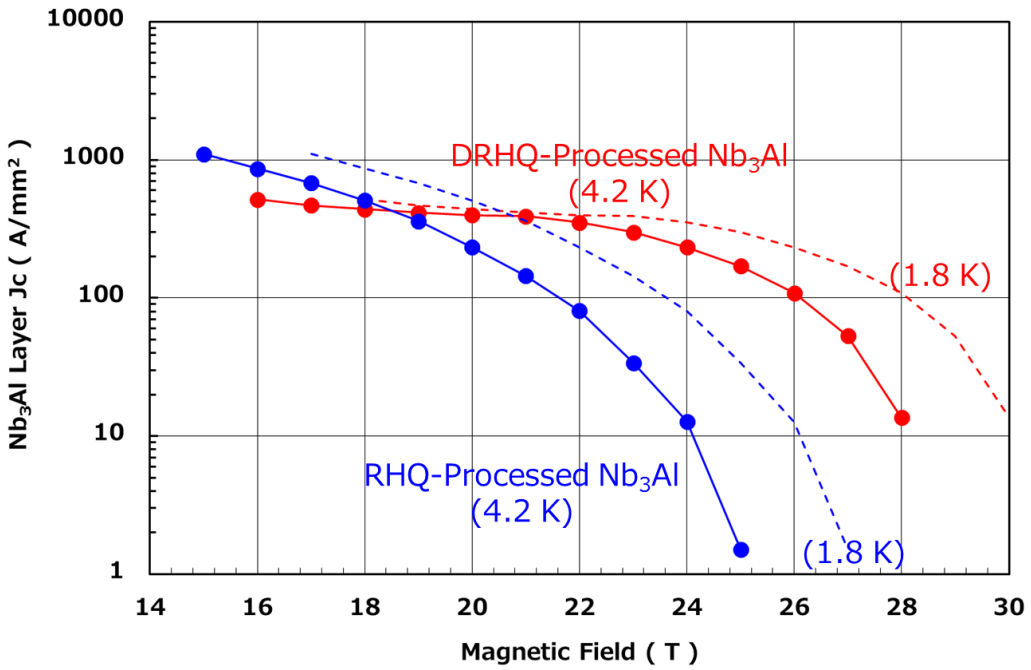
Double RHQ Processed Nb_3Al Conductor

DRHQ Process

(Double Rapidly-Heating/Quenching)



High Temperature Phase Transformation from bcc to A15

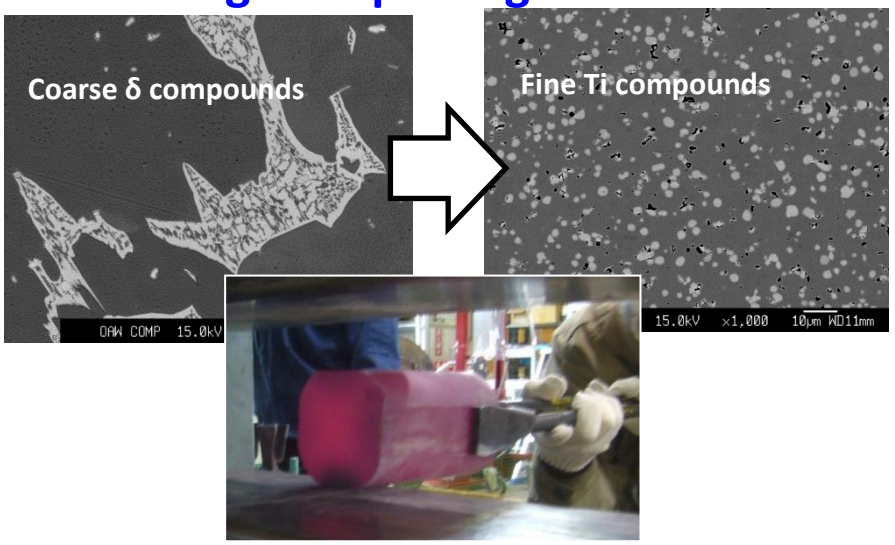


Higher Bc2

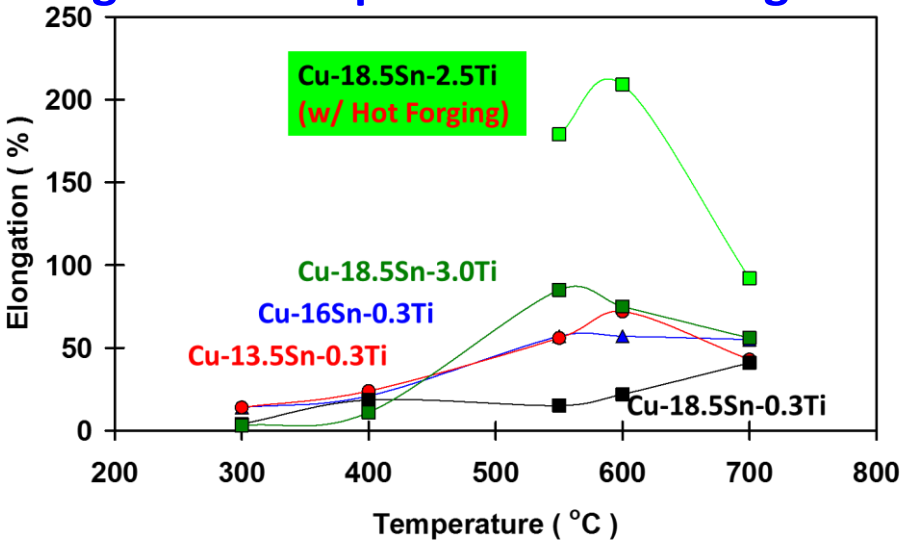
- Significant improvement of Jc beyond 20 T by DRHQ process
- Great potential for Inner coil of >20 T magnet
  - Coil winding would be challenging…

Super-High-Tin Bronze Nb_3Sn Wires

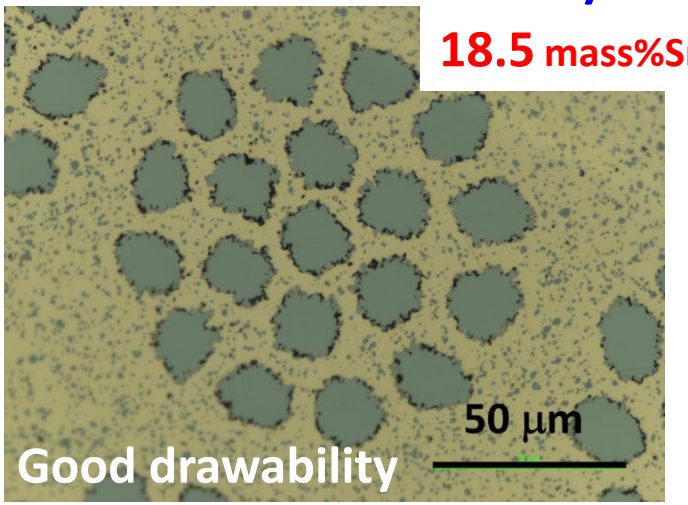
Hot Forged Super High Tin Bronze



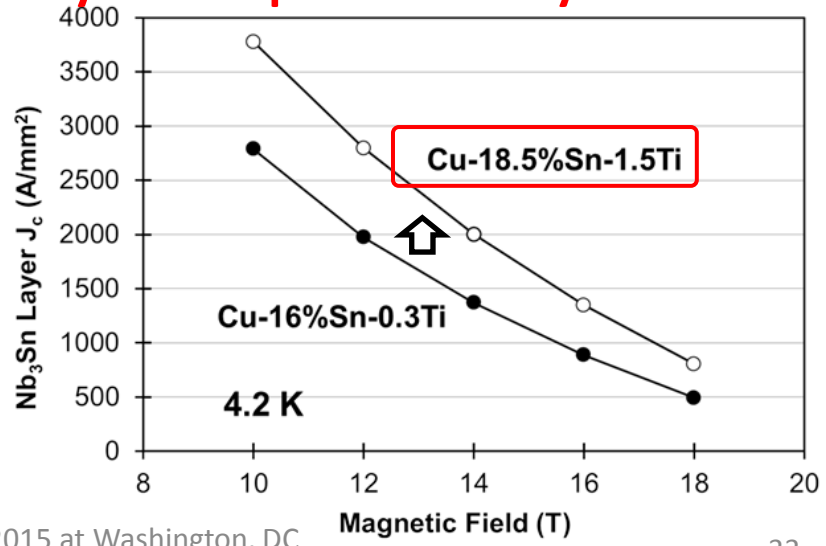
Significant Improvement of Elongation



Feasible Fine Multifilamentary Wires



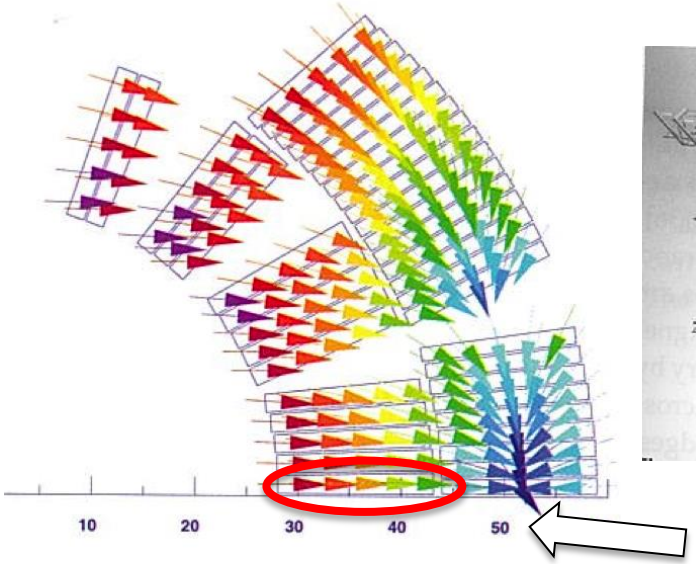
Layer-Jc Improvement by 40% or more

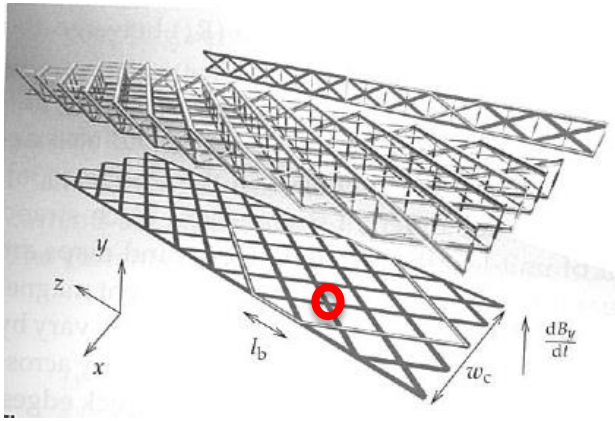


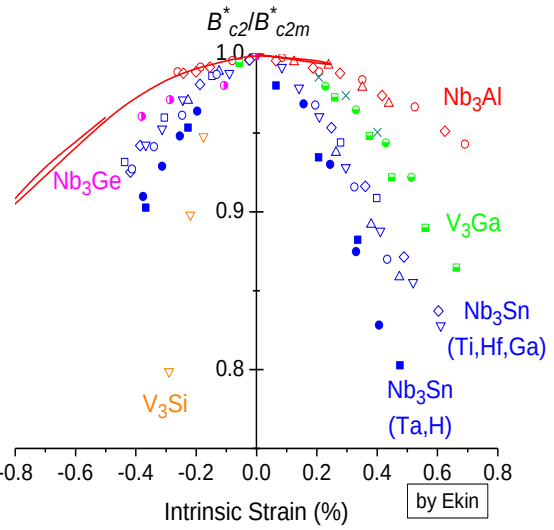
Contents

- Nb_3Sn Manufacturers in Japan
- Activity at NIMS for Nb_3Al and Nb_3Sn
- **Stress/Strain Studies**
- Cooperation for FCC and Support Needed

Stress/Strain Issues in High Field Magnet







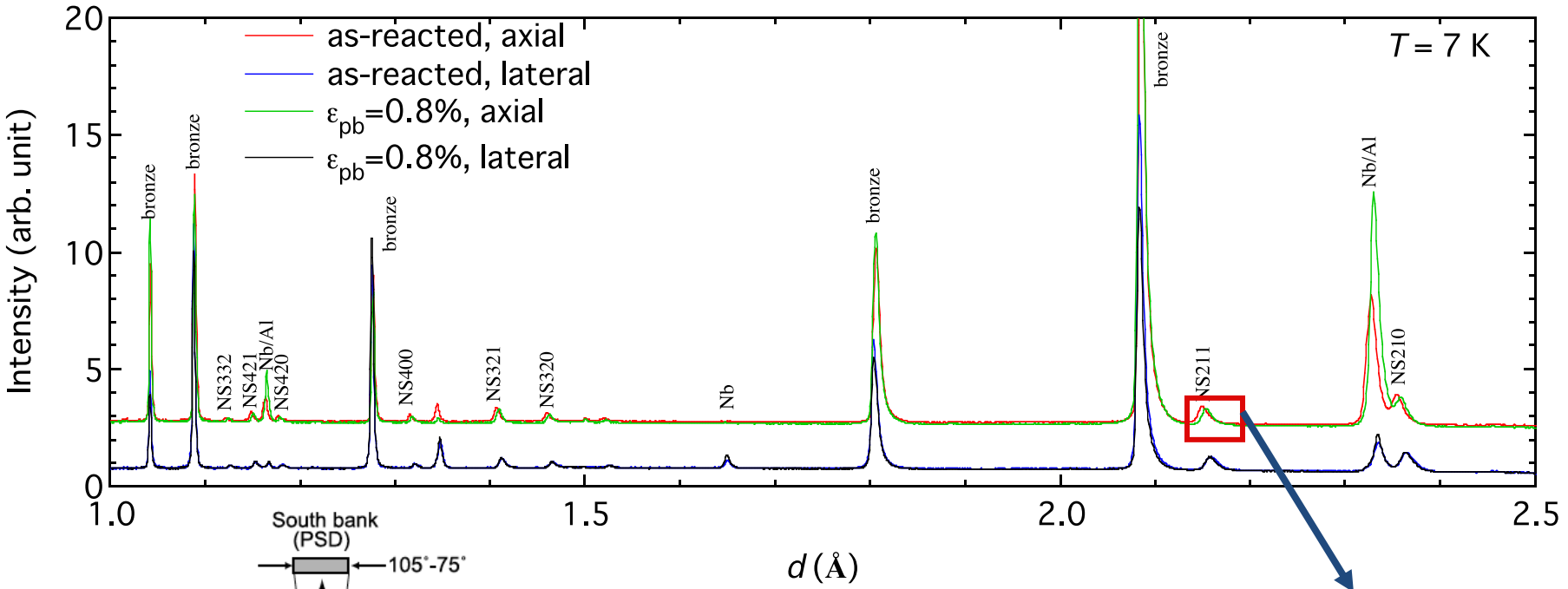
- **Actual "internal" strain of the SC strand at cross over of Rutherford-type cable in the magnet?**
- **Effect of mechanical reinforcement by resin impregnation?**
- **What is the "real" mechanical limit?**

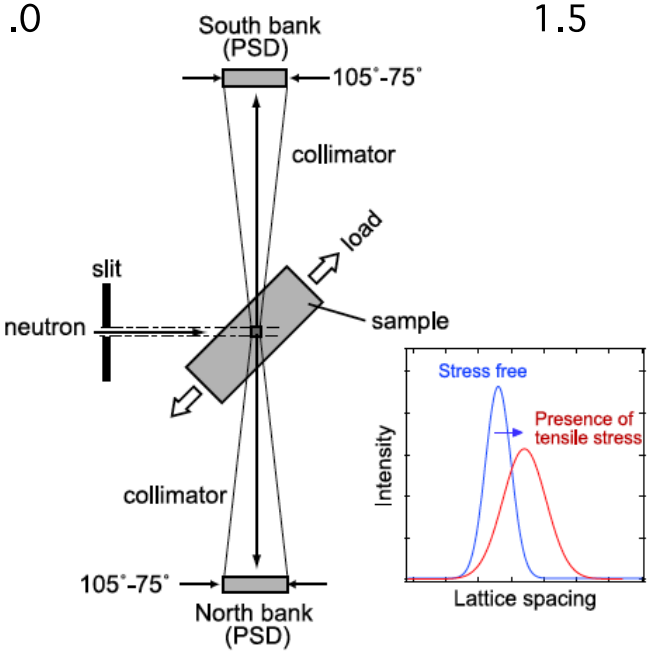
For HFM development, better understanding of

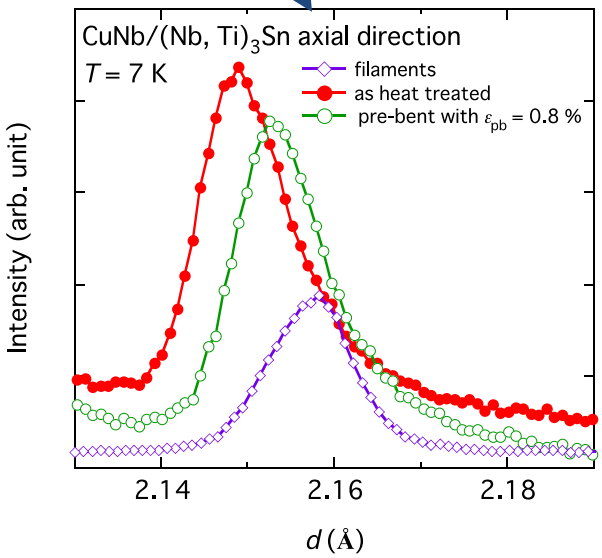
- ***the internal strain of the strand in the magnet,***
- ***SC critical parameters at various stress/strain,***

are crucial.

Internal Strain Evaluation by Quantum Beams





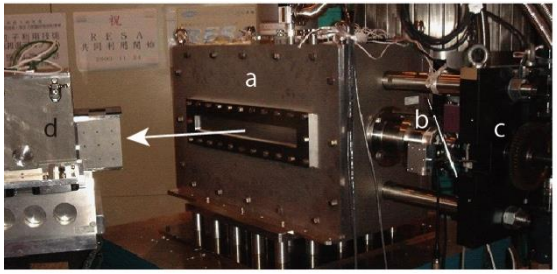


Various Load Frames for Q-beams

Load frames at Takumi@J-PARC (**Neutron**)

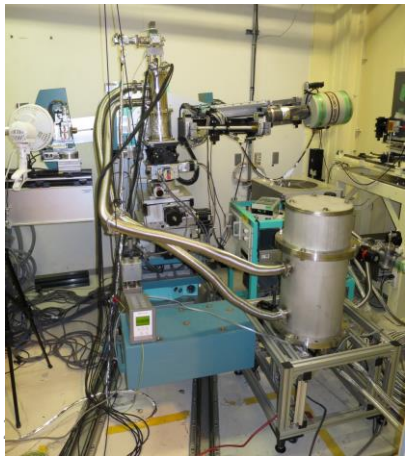
Flight time dispersion measurements.
Tensile load up to 50 kN at RT, HT(furnace) and LT (6K).
Compressive load jig also available.

Cryogenic load frame at RESA @JAEA (**Neutron**)



Angle dispersion measurements.
Tensile load up to 50kN at LT.

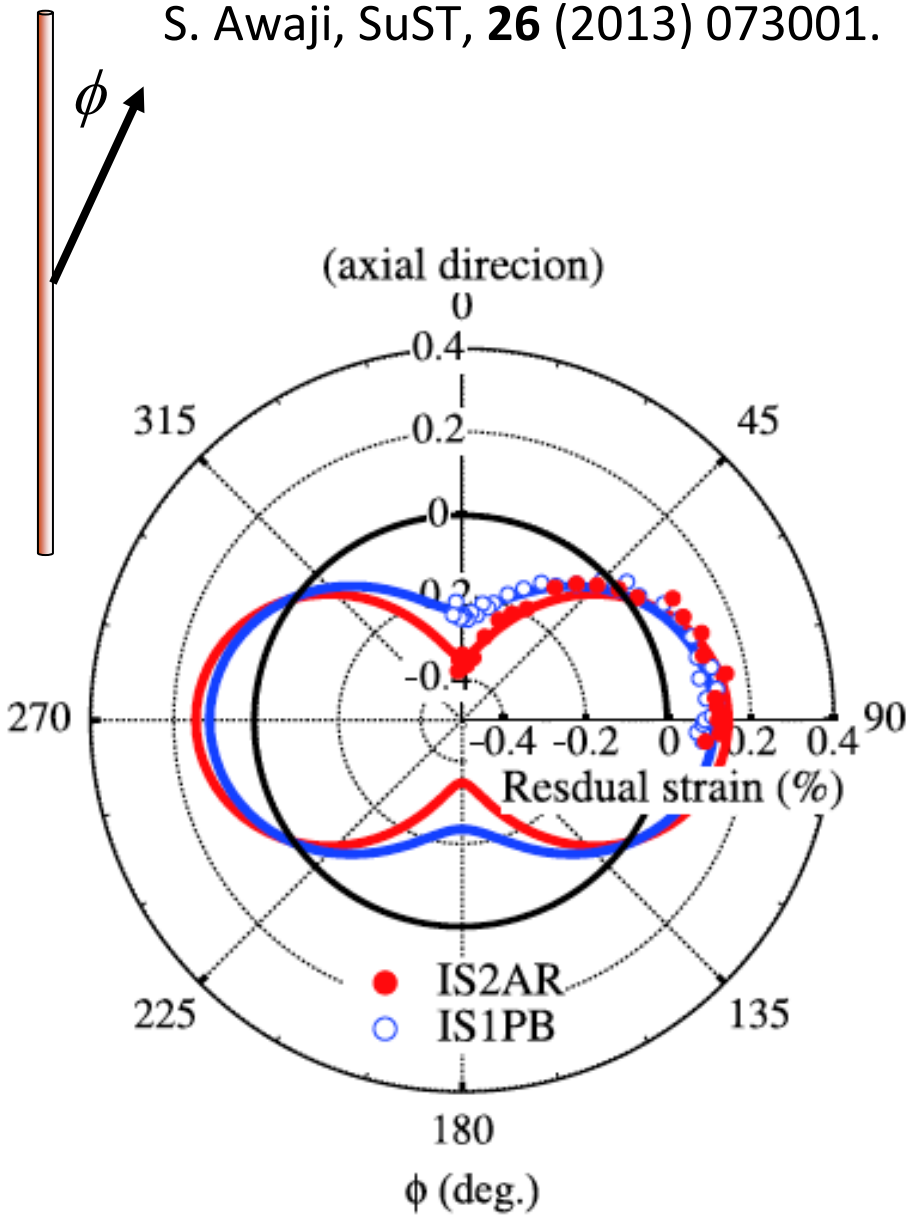
Load frame at SPring 8 (**X-ray**)

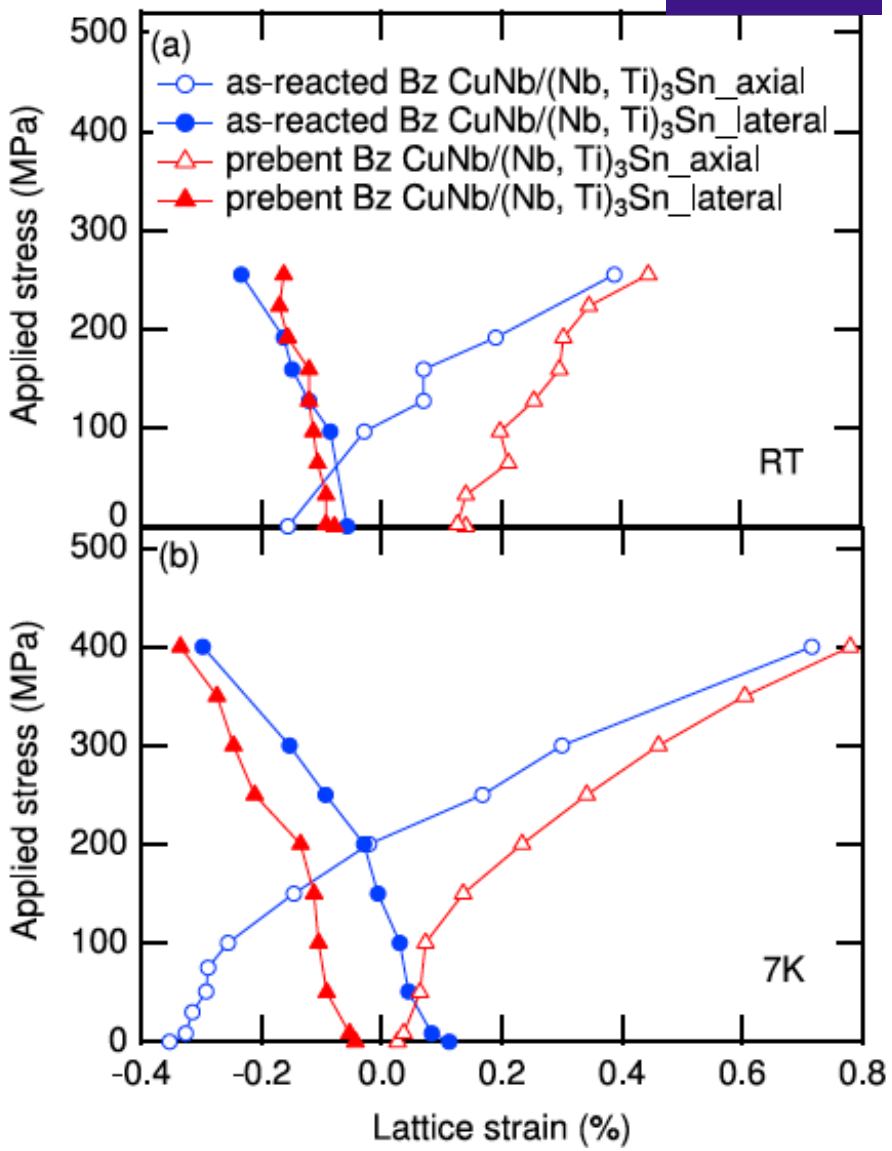


Angle dispersion measurements.
Tensile load up to 2kN at RT and LT (~25 K).

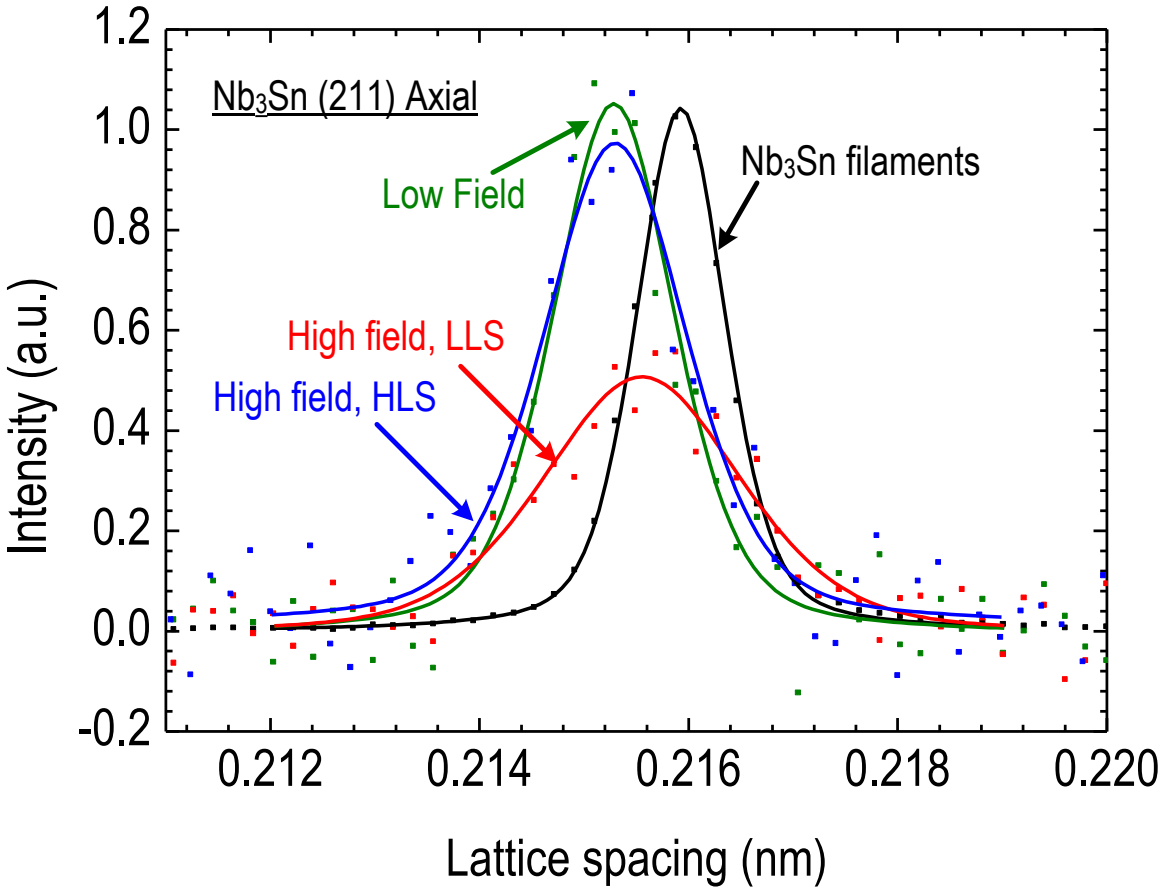
Internal strain in CuNb/Nb_3Sn

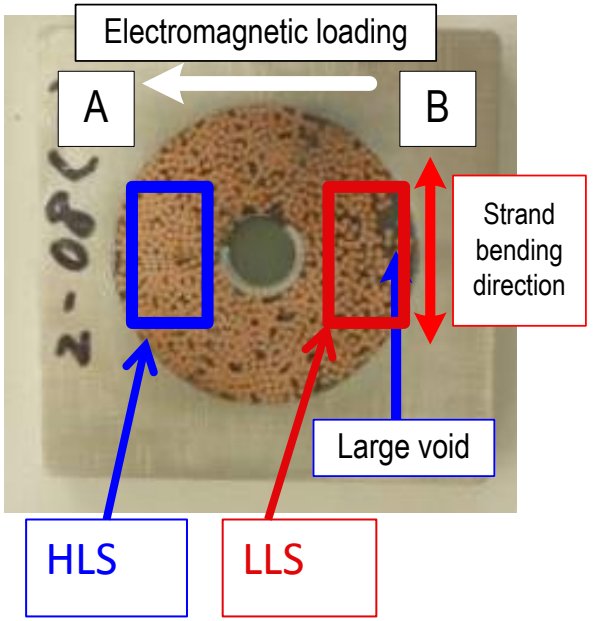
S. Awaji, SuST, **26** (2013) 073001.





Internal strain in CICC



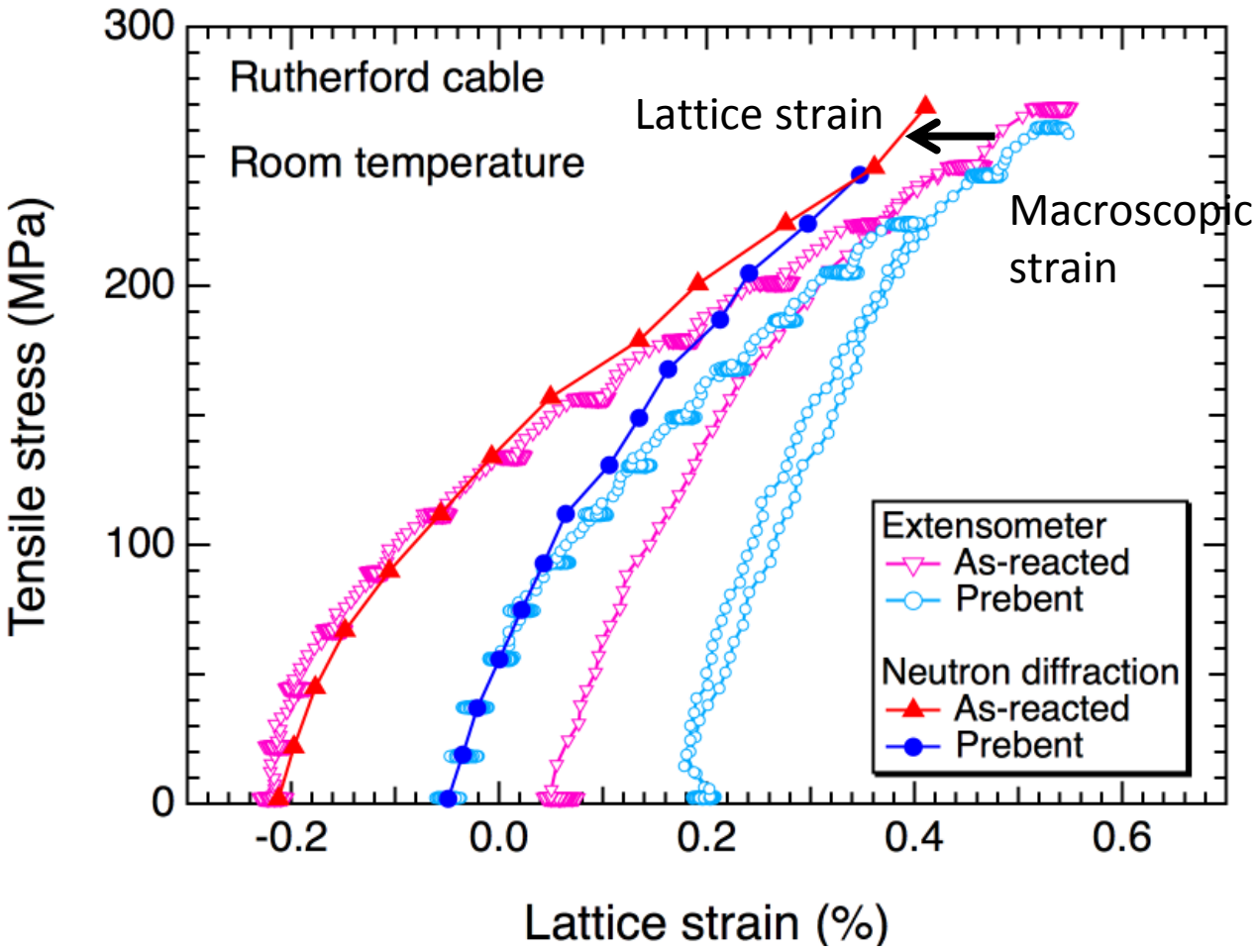


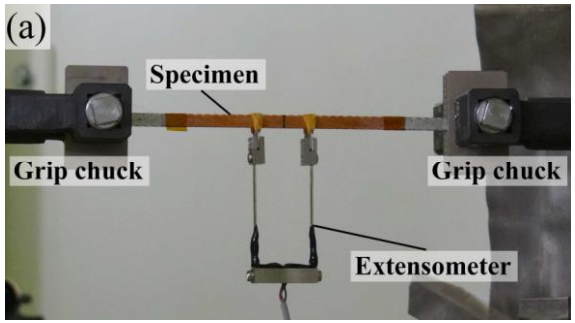
Nb_3Sn(211)	A	Ave. (%)	HWHM (%)	ΔHWHM (%)
Low field	1.00	-0.28±0.03	0.31±0.03	0.02±0.03
High field, LLS	0.80	-0.18±0.04	0.51±0.05	0.22±0.05
High field, HLS	1.09	-0.29±0.03	0.38±0.03	0.08±0.03

Hemmi et al., Abstract of the CSSJ conference 86 224. (In Japanese).

Lattice Strain & External Strain in CuNb/Nb_3Sn Rutherford cable

Measured by Neutron diffraction at the J-PARC, Japan





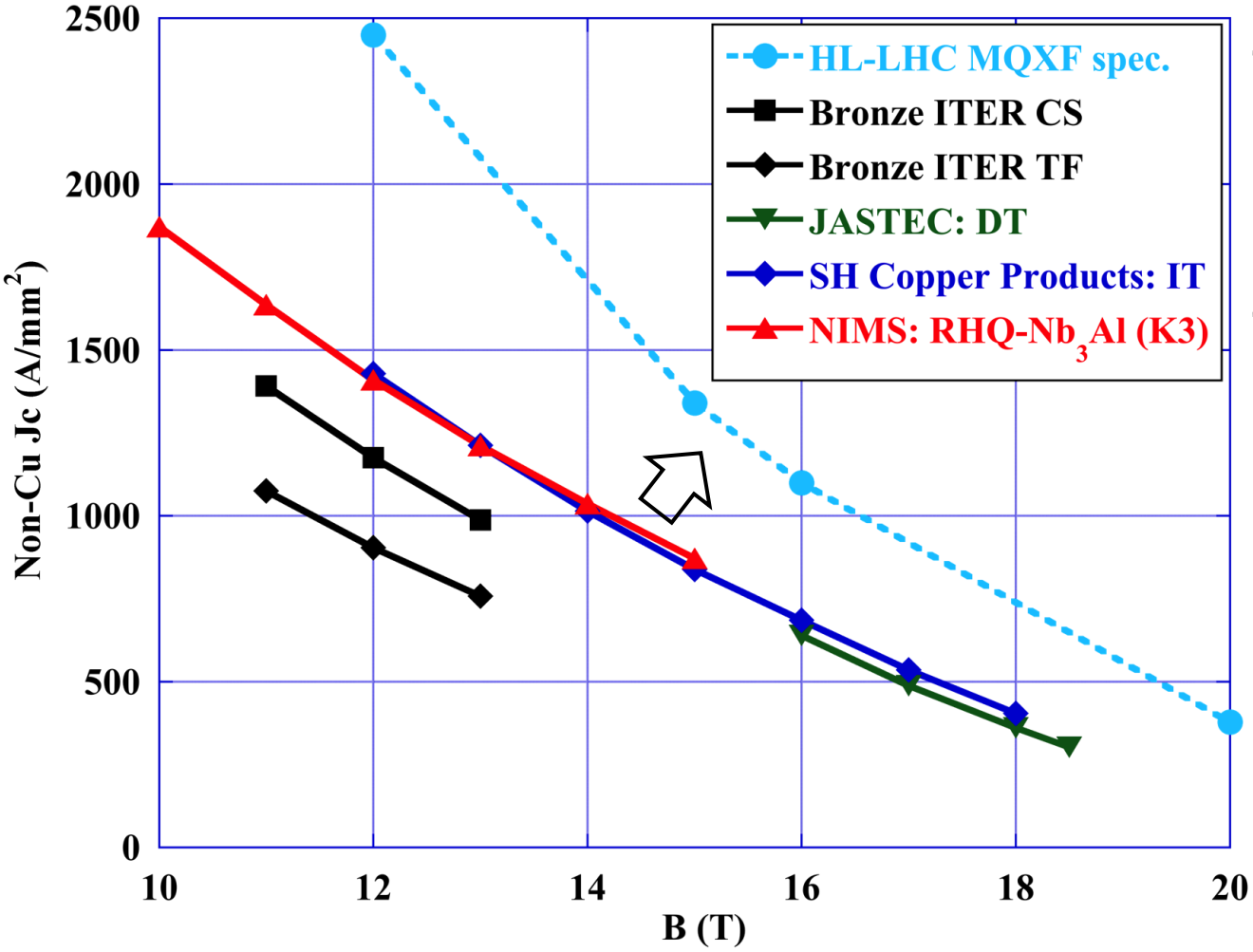
The strain in the strands is smaller than the macroscopic strain of cable.

Takahashi *et al.* IEEE TAS 25 (2015) 8400104

Contents

- Nb_3Sn Manufacturers in Japan
- Activity at NIMS for Nb_3Al and Nb_3Sn
- Stress/Strain Studies
- **Cooperation for FCC and Support Needed**

Jc of A15 Wires Developed in Japan



Jc-B is good enough?

Is it time to think about Jc-B-ε ?

Cooperation for FCC & Support Needed

- Proven Jap. manufacturers (with Bronze Nb_3Sn):

  JASTEC, Furukawa Electric, SH Copper Products.
- Development of Bronze Nb_3Sn
  - High mechanical strength with reinforcement
  - Improvement of Jc by high Sn contents
  - Small AC losses, high RRR.
- Development of IT/DT wire for higher Jc
  - w/ high strength (*in future*)
- Possibility of "*React & Wind*" approach
  - I_c improvement by the (internal) strain controlling by pre-bending
- Continuous efforts in RHQ-Nb3Al development by NIMS toward industrialization.
- Stress/strain study will become more important in HFM development for FCC. Japanese researchers have great interests in this field and will proactively work on the study with the advanced facilities.

Cooperation for FCC & Support Needed

- Serious situation of grant and funding for A15 development in Japan in comparison with HTS development...
- It will be quite nice if some small developments are directly supported by CERN.
- Following medium scale projects for further development to achieve the target specification would be much better.
  - Such a staging approach in development with “supports” would be truly preferred for the Japanese manufacturers…