Development of Nb_3Sn in Japan

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A. Vallarino, M. Benedict CERN,
K. Miyashita, Y. Suzuki SH Copper Products.,
K. Saito, S. Kawashima, Y. Fukumoto Kobe Steel and JASTEC
H. Sakamoto, T. Fukushima, H. Shimizu Furukawa Electric

Scope:

CERN, KEK and Tohoku university have jointly launched a R&D program

- The scope of the program is to develop, produce in representative lengths and characterize Nb_3Sn wire with enhanced characteristics.
- The final goal is to achieve in representative unit lengths of material the development targets defined, on the basis of magnets performance, for the FCC Nb_3Sn conductor:

Final Target Properties

- A non-copper critical current density at 4.2 K and 16 T (Jc(4.2 K, 16 T)) of at least 1500 A/mm^2;
- A wire diameter of not more than 1 mm;
- A fraction of stabilizer to superconductor in the wire of at least 1;
- An equivalent diameter of the superconducting Nb_3Sn filaments of less than 50 μm;
- A low electrical resistivity of the copper stabilizer of the wire, i.e. a Residual Resistivity Ratio (RRR) of the copper after wire reaction of above 150.

R&D Plan

4 Years Plan

Task1
Review past technologies and select.
First review meeting in Feb. 2016

Task2
Design wire layout and composition
Procure material (possible trial billets)

Task3
Production of R&D billets
L>3km * N>3

Task4
Select candidate
Produce 5km wire
Heat treatment study

Task5
Production of 20km wire with unit length > 100m

Workshop on High Jc Nb3Sn conductor development in Japan

Monday 22 February 2016 - Wednesday 24 February 2016

KEK, Tsukuba, Japan

Programme

Monday 22 February 2016

Registration - 102-1F, Ni-Go-Kan Bldg. (13:00-13:15)

time	[id] title	presenter
13:00	[12] Information	

Introduction - 102-1F, Ni-Go-Kan Bldg. (13:15-15:00)

time	[id] title	presenter
13:15	[1] Welcome and workshop scope	Prof. OGITSU, Toru
13:30	[2] FCC CERN-KEK development program	Dr. BALLARINO, Amalia
14:00	[3] Possible contribution from Tohoku-Univ.	Prof. AWAJI, Satoshi
14:30	[4] Test plan	Dr. SUGANO, Michinaka Dr. OGURO, Hidetoshi

Development status and plan at companies - 102-1F, Ni-Go-Kan Bldg. (15:15-16:50)

time	[id] title	presenter
15:15	[5] Development at SH-Copper	
15:40	[6] Development at Furukawa	
16:05	[7] Development at JASTEC/Kobelco	
16:30	[8] Discussion	

Closed session discussion with each company - 102-1F, Ni-Go-Kan Bldg. (17:00-18:00)

time	[id] title	presenter
17:00	[9] JASTEC/Kobelco	

Tuesday 23 February 2016

Tour to SH Copper Products (by KEK, CERN, and Tohoku Univ.) - (08:30-12:30)

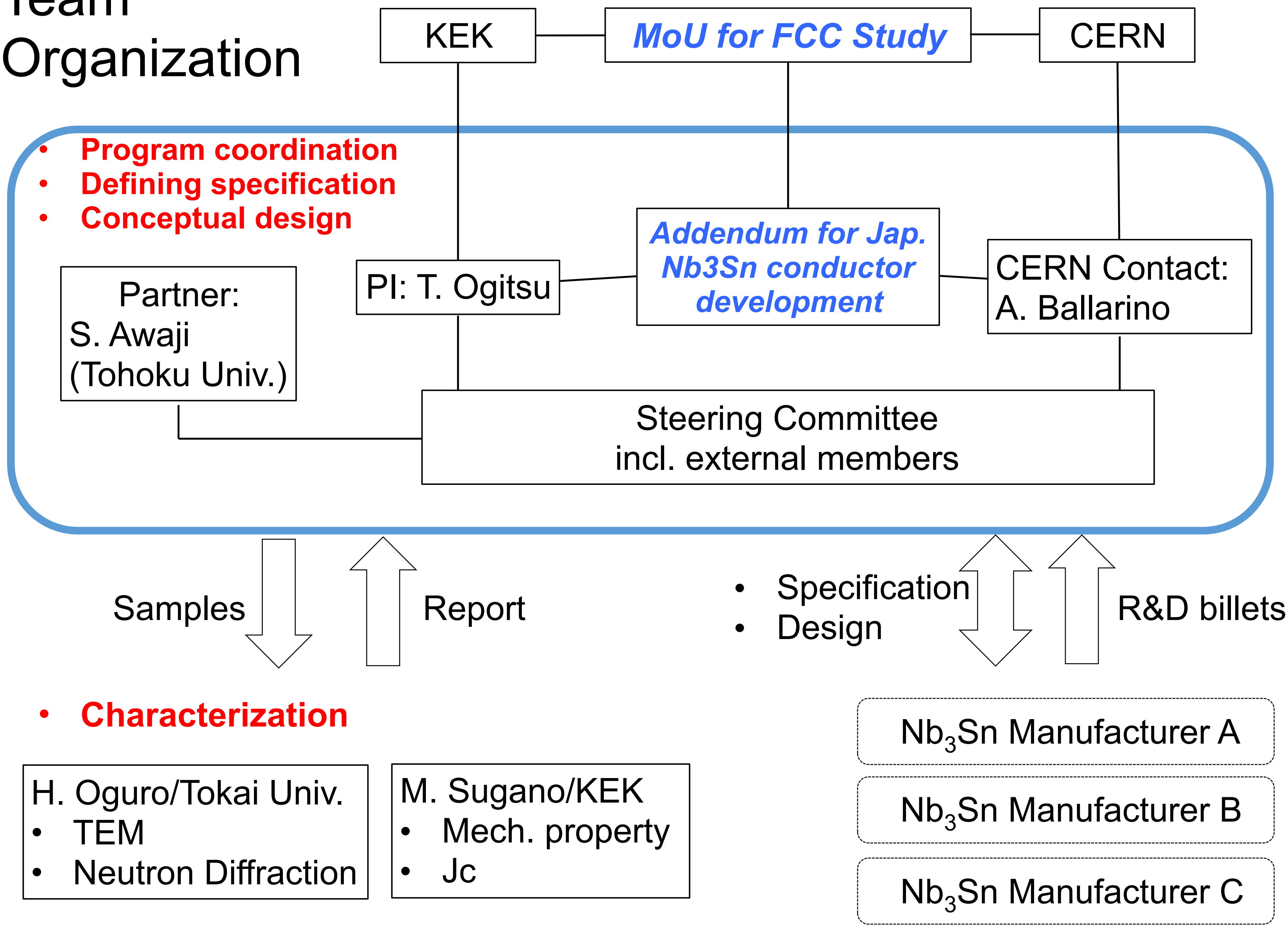
Closed session discussion with each company: Closed session discussion with each company - 102-1F, Ni-Go-Kan Bldg. (13:30-15:40)

time	[id] title	presenter
13:30	[10] SH Copper Products	
14:40	[11] Furukawa Electric	

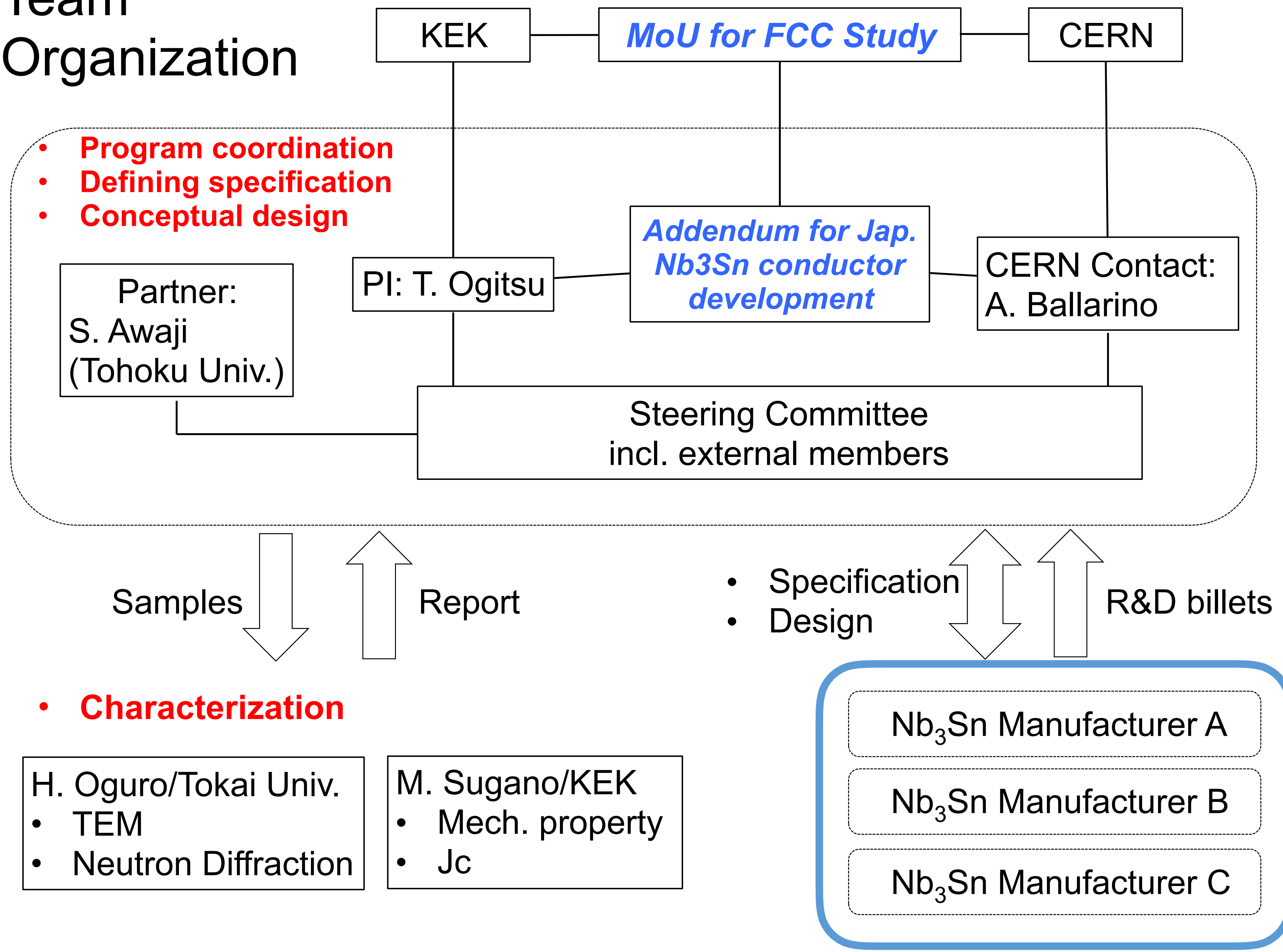
Discussion for Development Strategies - 102-1F, Ni-Go-Kan Bldg. (16:00-18:00)

Closing - 102-1F, Ni-Go-Kan Bldg. (18:00-18:10)

Team Organization



Team Organization

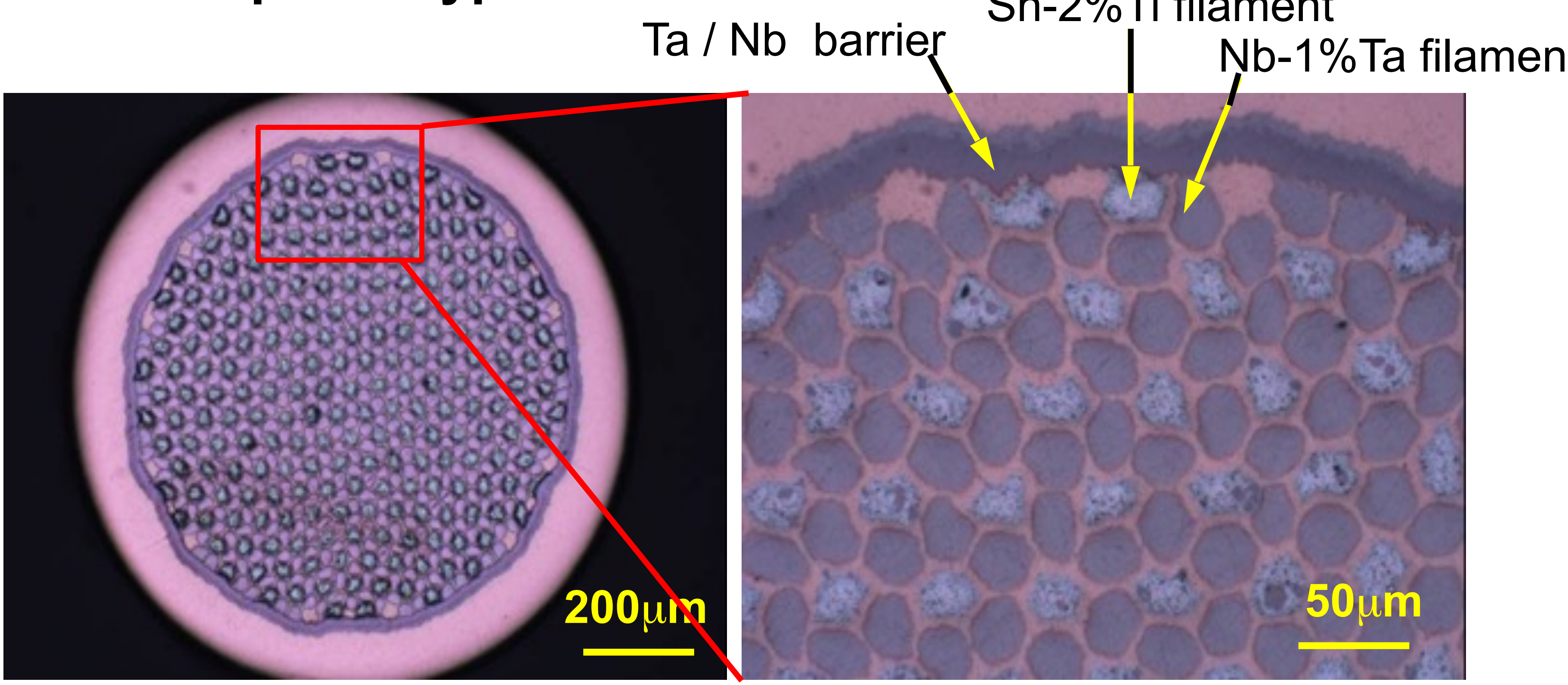


Development of high performance and low cost Nb3Sn wires at SH Copper Products

Internal Tin Nb_3Sn wire in SH Copper

SH Copper Products

For high field magnet application, since 2009, we started to develop new type internal tin wire



Sn Filament size is almost equal to Nb filament size.

Simple structure ⇒Low Cost

Corresponding to more than Cu-35wt%Sn bronze

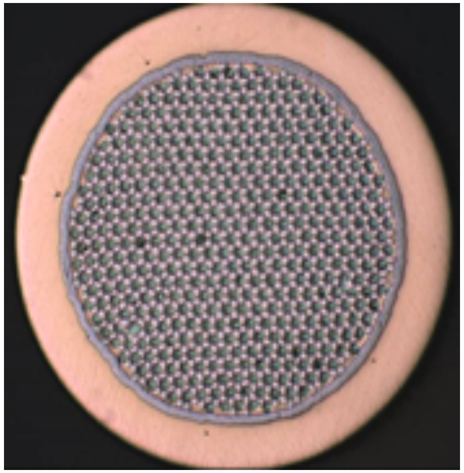
Manufacturing (L=14km class wire @ 1mm dia.)

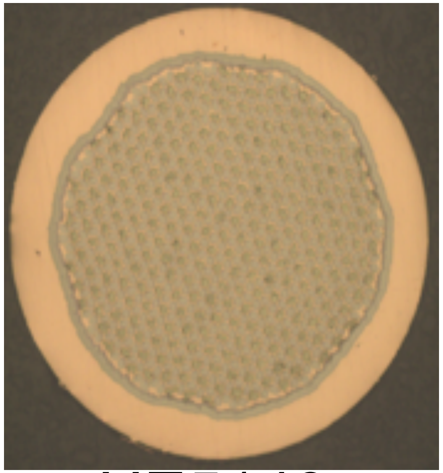
SH Copper Products

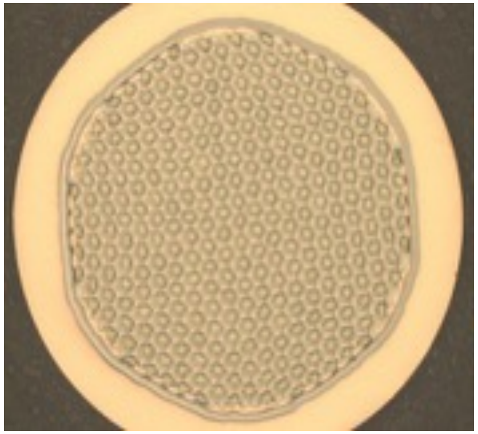
FCC Week 2016

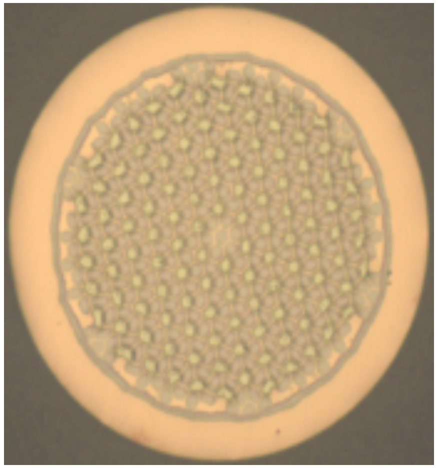
Four manufacturing size billets are successfully extruded and drawn.

Billet ID No.	**HE5000** **(2010)**	**HE5143** **(2011)**	**HE5542** **(2012)**	**HE6585** **(2014)**
Number of Nb filament	840	564	564	277
Number of Sn filament	421	283	295	120
Total number	1261	847	859	397
Filament dia. @φ1mm	15 μm	20 μm	20 μm	30 μm
Cu ratio	0.51	0.51	0.51	0.51
Mole ratio (**Nb**/Sn)	**2.53**	**2.72**	**2.40**	**2.89**


HE5000


HE5143

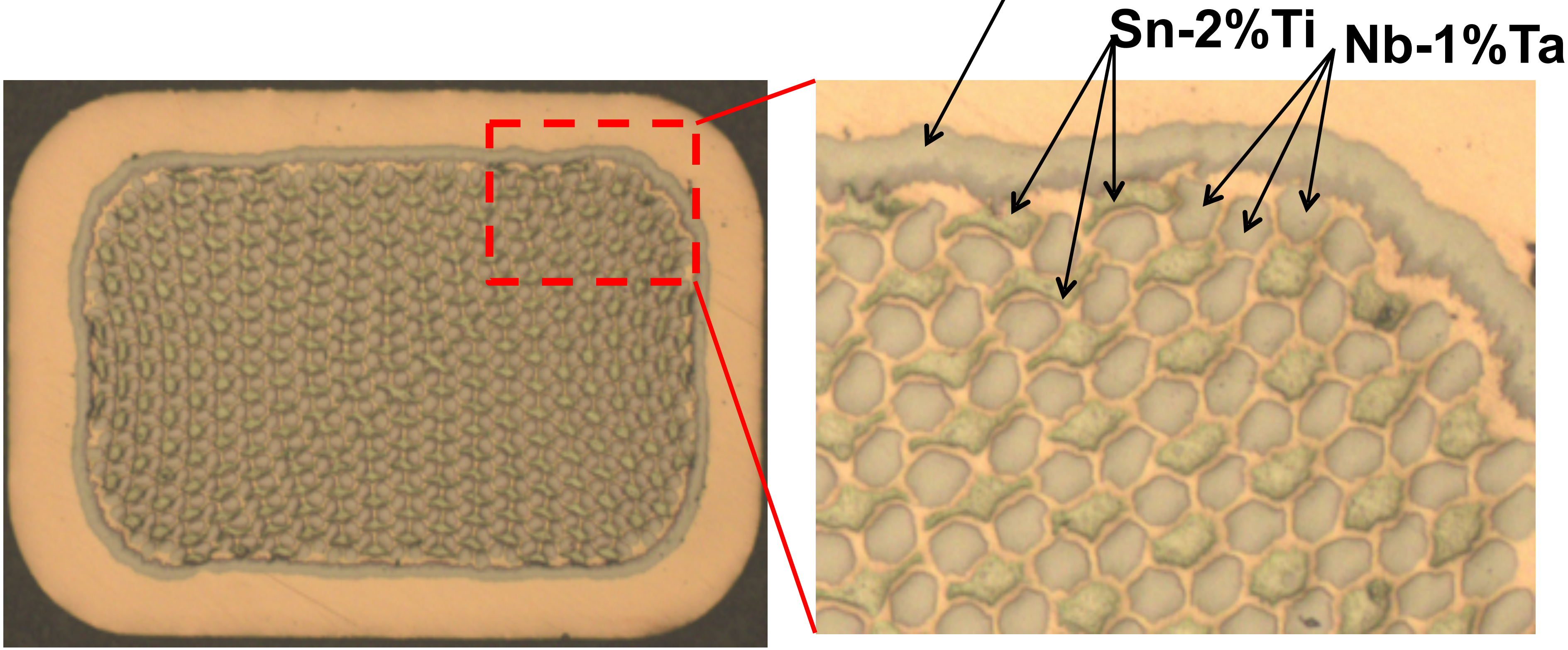

HE5542


HE6585

Rectangular Wire

Good barrier shape (no deformation)
High RRR ; ≧250

It is possible to work rectangular shape without Ic & RRR degradation.



ID No. HE5143, 1.14X1.72mm Ic=504A at 18T (Non-Cu Jc =403A/mm^2), RRR=254

Conclusion

Item	FCC final target	Status
Non Cu Jc at 16T (A/mm^2)	>1500	685
$\mu_0 \Delta M$ @ 1T, 4.2K (mT)	<150	233
Deff	<20	28～30
RRR*1	>150	>250
Unit Length (km)	>5	>20 (ϕ0.8mm)

***1 : After wire deformation, RRR is NOT degraded.**

Next stage (in 2016 ～ 2018)

SH Copper Products

FCC Week 2016

(1) High Jc (Non Cu > 1500A/mm^2 @16T)

(a) Optimization of ratio of Nb, Sn & Cu inside barrier

Mole ratio; Nb : Sn : Cu = 2.5～2.9 : 1 : 2.5～3.5 in the past

= 3.0～3.5 : 1 : 1.8～2.3 in the future

(Nb/Sn > 3.0 & Cu-45～58wt%Sn bronze)

(b) Nb-X filament (X ; 1～4wt% Ti or Ta)

(c) New cross section (For high Jc & low magnetization)

(d) Geometrical filament diameter ; < 20μm

(e) Optimization of heat treatment

(2) Low magnetization

(a) Prevent of completely proximity effect between each Nb_3Sn filament.

(3) Stability

(a) Prevent of completely proximity effect Jc

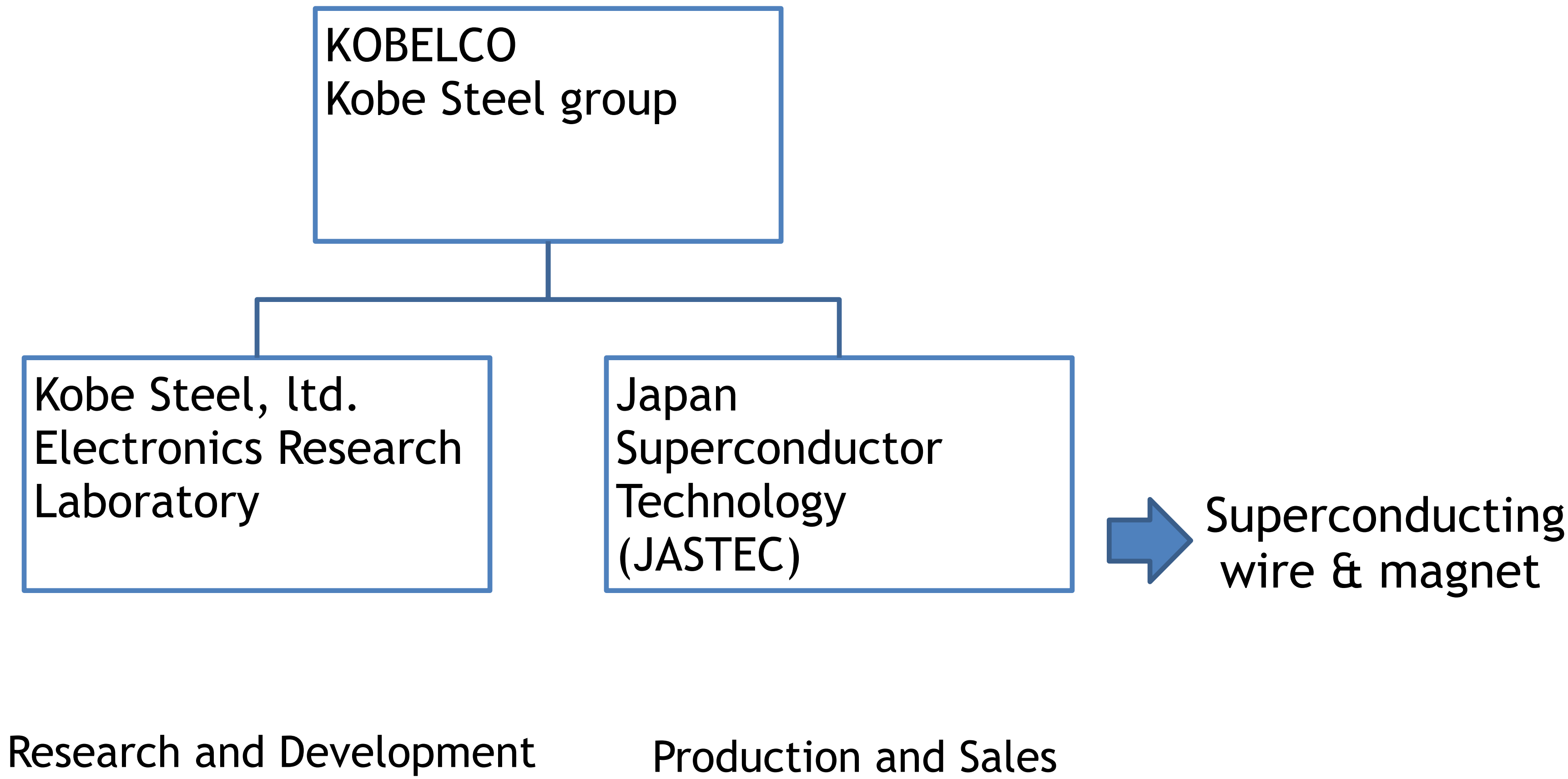
Development Status and plan at Kobe Steel/JASTEC

FCC Week 2016 High Jc Nb3Sn conductor development in Japan
2016/4/11

KOBELCO
KOBE STEEL GROUP

JASTEC
SUPERCONDUCTOR

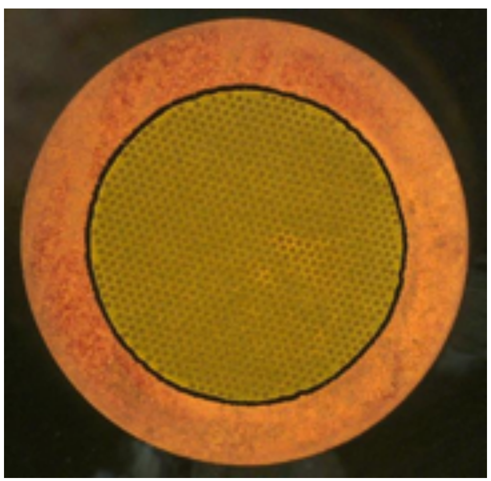
Kobe Steel and JASTEC



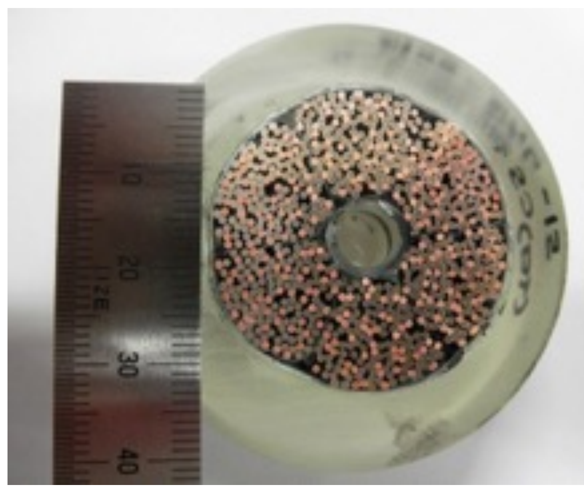
JASTEC/KSL Nb_3Sn Wire

JASTEC SUPERCONDUCTOR KOBELCO KOBE STEEL GROUP

- JASTEC is a world primary wire manufacturers, especially for Nb3Sn.
  - For NMR magnet : ~10 tons every year
  - For ITER: 100 tons in total
- JASTEC supplied TF & CS (Nb3Sn) wires for ITER.
  - 40 tons for TF conductor (~1/10 of total)
  - 60 tons for CS conductor (1/3 of total)
- R&D division in KSL works for JASTEC.

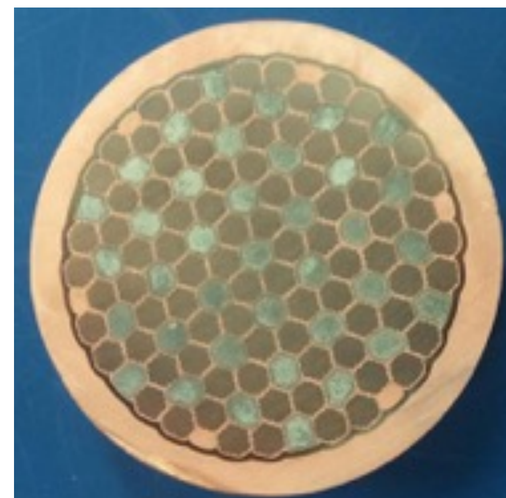


Strand (TF)



Cable (CS)

High-Jc Bronze wire/cable for ITER project



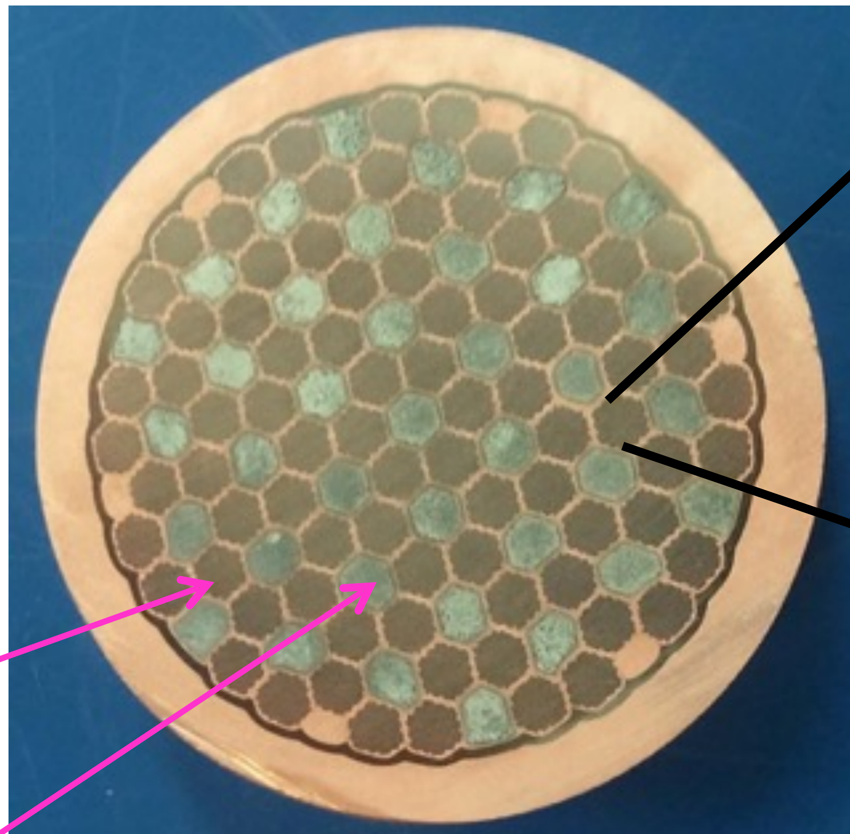
Distributed Tin (DT) wire with even higher Jc performance (under development)

Distributed Tin Nb_3Sn Wire (DT wi

Development target :

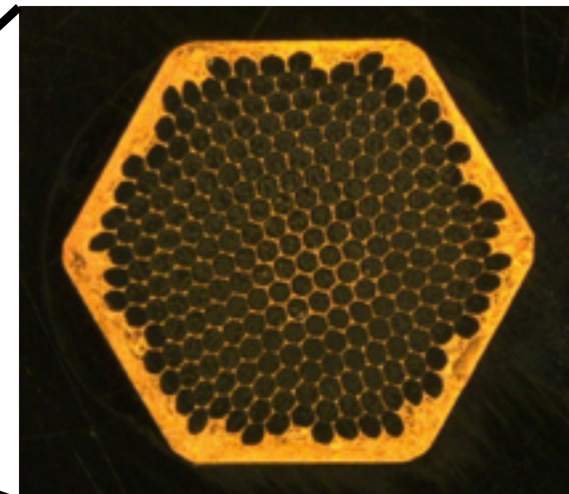
High Ic wire at high magnetic field（>18T) for NMR magnet

FCC ⇒ High Jc at 16T



Cu/Nb Multi fimament

Sn in Cu tube



192 filaments in a module

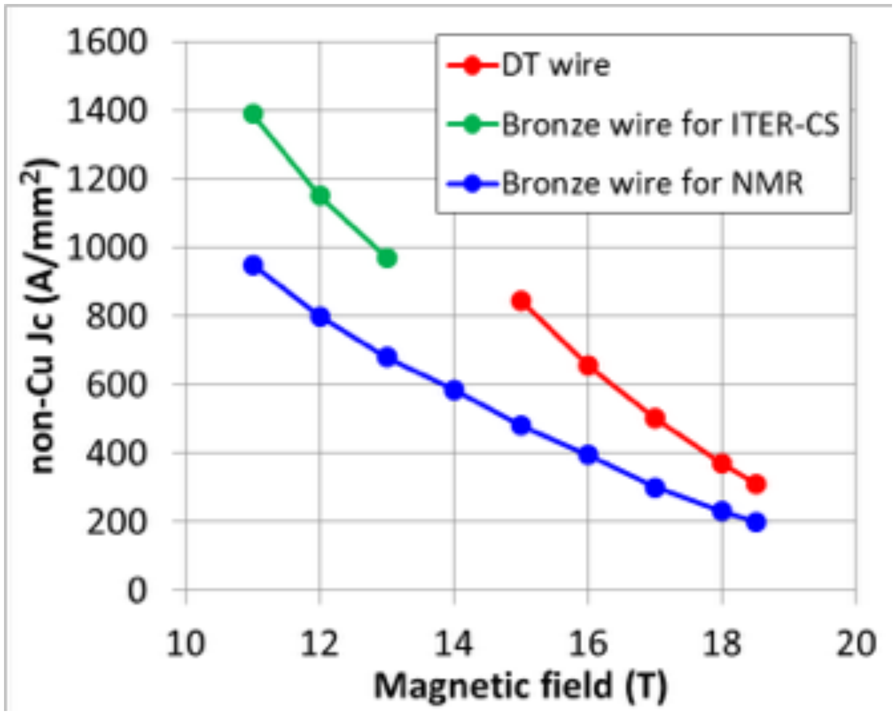
Wire diameter： φ1mm

Filament size ： ～3μm

Copper-Non Copper ratio: 0.3

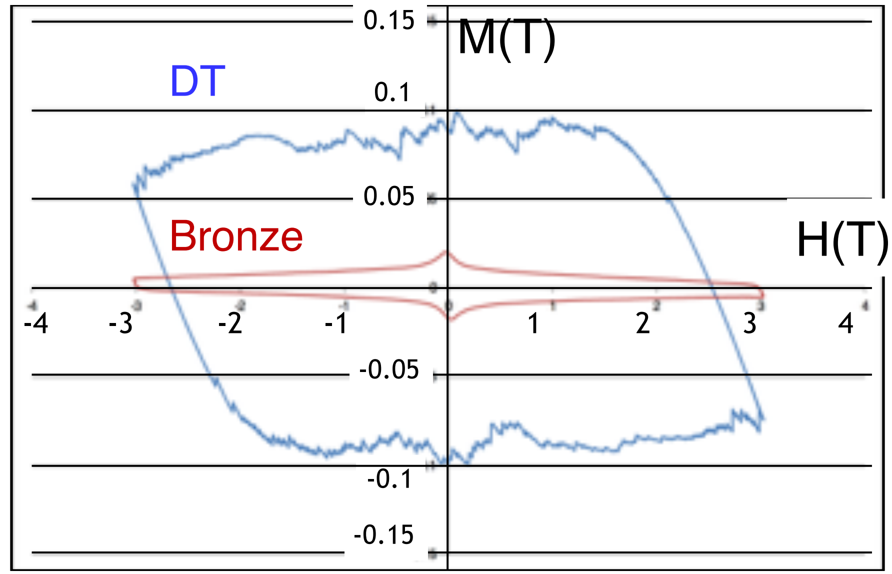
Performance of current DT-wire

Critical Current

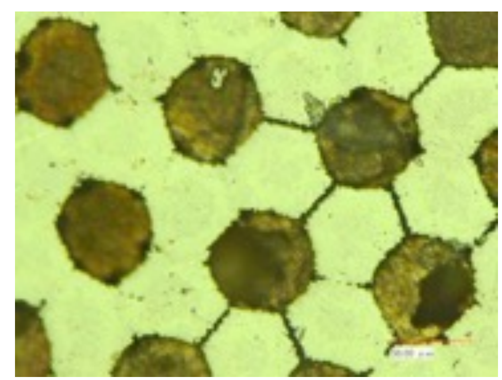


Non-Copper Jc : 650A/mm^2 at 16T

Magnetization



DT-wire has larger value comparing to Bronze wire ⇒ some filaments are bridged.



Future develop plan

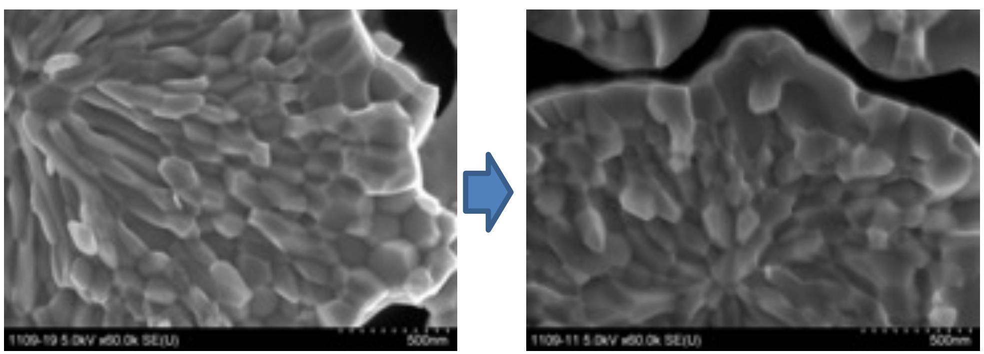
Step 1 for Jc enhancement

Intrinsic Jc (Nb_3Sn layer Jc) depends on the Nb_3Sn grain size, chemical composition and the Jc enhancing impurity (Ti, Ta). Controlling those factors could be applied for the development.

Also, artificial pinning technique are being considered

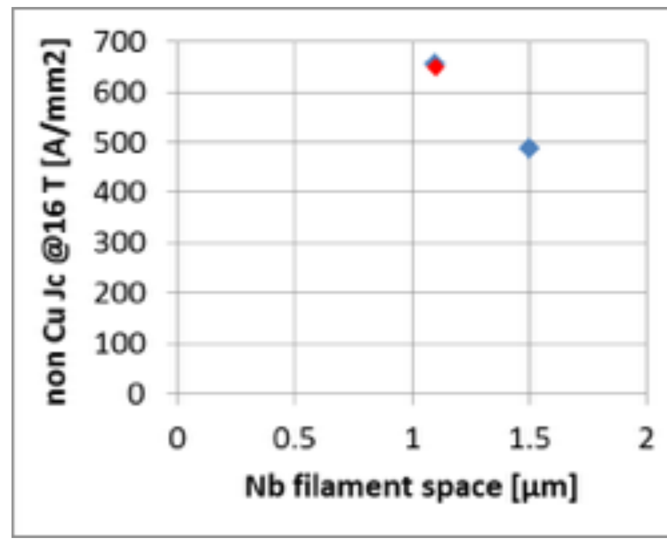
Non-Copper Jc : 540A/mm^2 at 16T

Non-Copper Jc : 650A/mm^2 at 16T



Refinement of grain size via adjustment o f heat treatment condition

Step 2 for decrease magnetizatio magnetization relate to the cros section design.



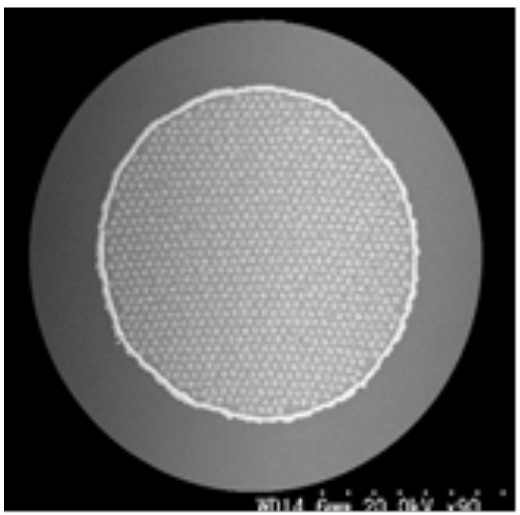
Trade-off relation between Jc and filament spacing

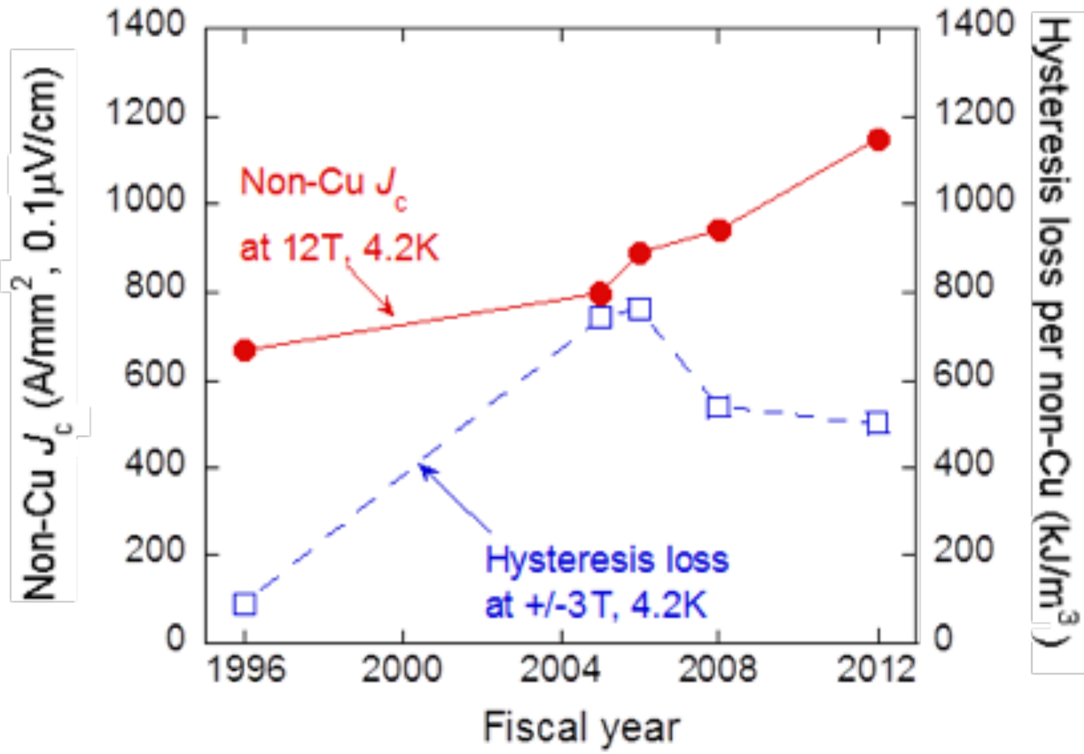
Development at Furukawa

March 31, 2016
Furukawa Electric Co., Ltd.

Increasing J_C of Bronze Method Nb_3Sn

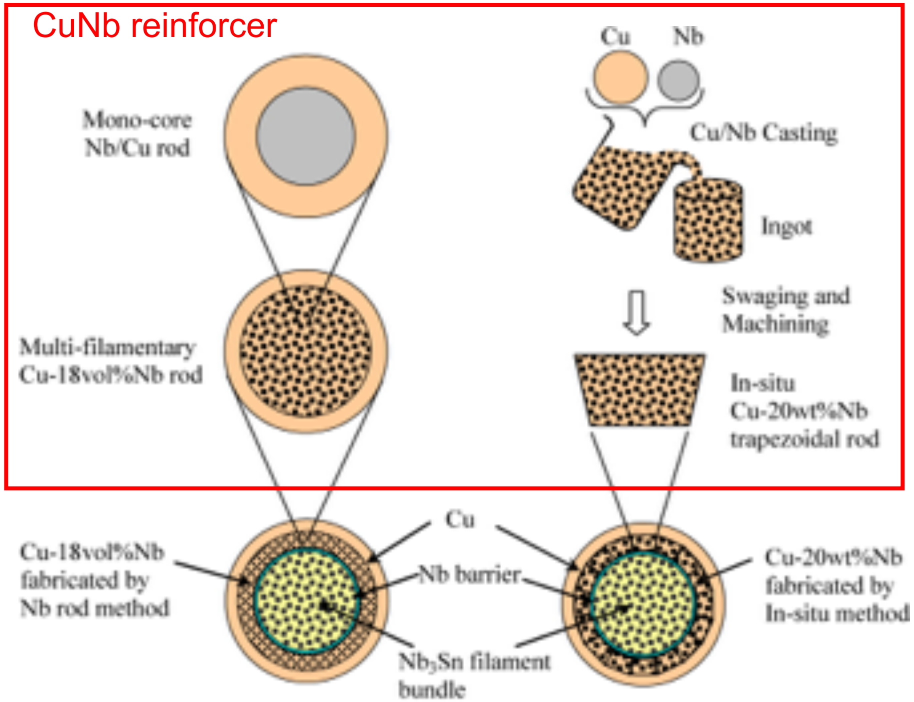
Items	2008 design	2012 design
Strand final diameter (mm)	0.83±0.005	0.83±0.005
Cu/Non-Cu ratio	1.0 ±0.1	1.0 ±0.1
Diffusion Barrier	Ta	Ta
Bronze composition (wt%)	16Sn-0.3Ti	15.7Sn-0.3Ti
Filament dia. (μm)	3.3 (nominal)	2.3 (nominal)

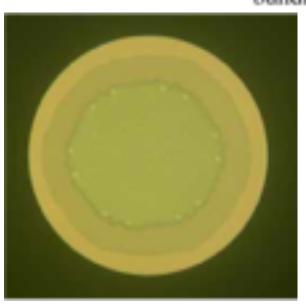




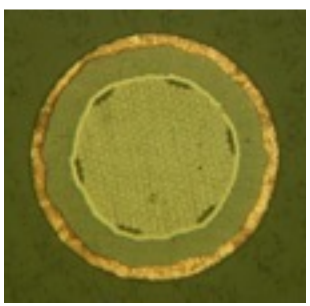
Cu-Nb reinforced Nb_3Sn wire

FURUKAWA ELECTRIC



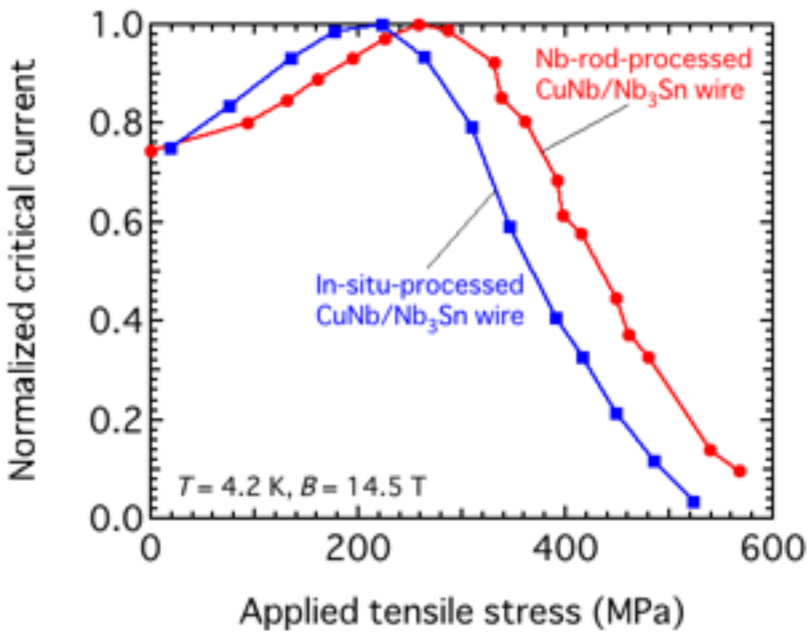


(a)Nb-rod method



(b)In-situ method

CuNb reinforced Nb_3Sn wires



Merit of Nb-rod method

- ➢Better Ic properties vs tensile stress
- ➢Larger RRR of wire （>100)
- ➢**Excel in productivity**

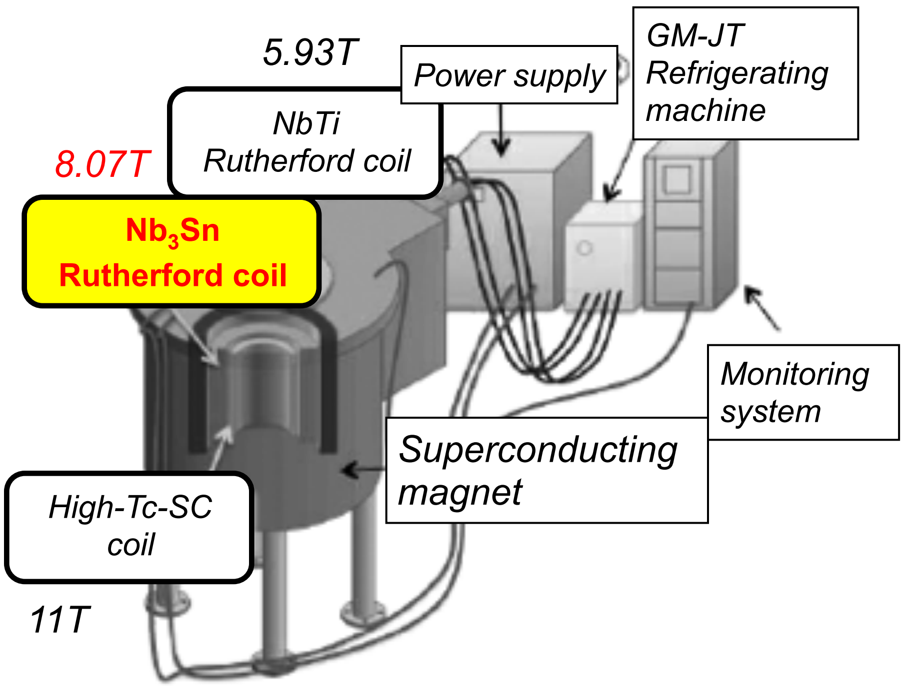
[5] H. Oguro, S, Awaji, K. Watanabe, M. Sugimoto, and H. Tsubouchi, *Supercond. Sci, Technol.*, vol. 26, no.9, p.094002, Sep. 2013.

[6] K. Watanabe, S.Awaji, Y. Hou, H. Oguro, T. Kiyoshi, H. Kumakura, S. Hanai, H. Tsubouchi, M. Sugimoto, and I. Inoue,” *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, p. 4300304, Jun. 2013.

Nb-rod method plays important role of R&W type Nb_3Sn wire

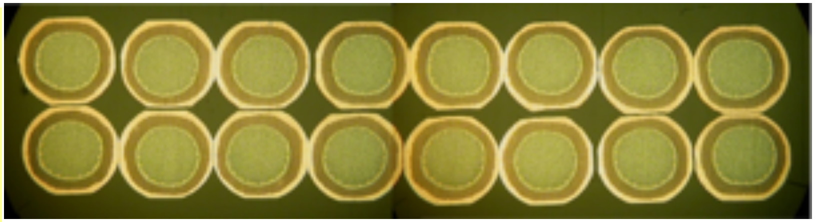
Applying to Superconducting Magnet

FURUKAWA ELECTRIC



25T CSM at Tohoku University

(a) Strand	
Superconductor	Bronze- processed Nb_3Sn
Reinforcement	Nb-rod-method Cu-20vol%Nb
Diameter	0.8mm
Cu/CuNb/non-Cu	20%/35%/45%
Filament diameter	3.3μm
Twist pitch (Direction)	24mm (S)
(b) Rutherford cable	
Number of strands	16
Heat treatment	670°C×96hr
Dimensions (After prevending)	6.5mm^{w}x1.55 mm^t
Cabling pitch (Direction)	65 mm (Z)



Cu-Nb/Nb_3Sn Rutherford cable

Requirements of Nb_3Sn Rutherford cables for the 25T-CSM

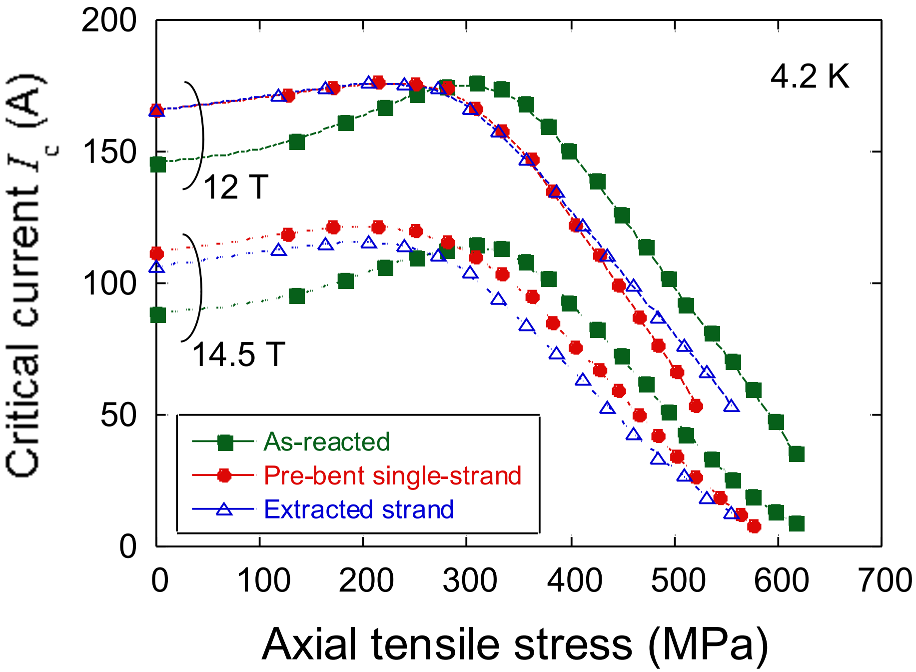
- ➢React-and-wind process
- ➢Applying Cu-Nb internal-reinforced Nb_3Sn strand with Ta barrier
- ➢Conductor critical current > 1,900 A @ 4.2 K, 12 T, 300 MPa
- ➢Irreversible tensile stress > 350 MPa @ 4.2 K, 14.5 T
- ➢I_c degradation rate at transverse compressive stress 60 MPa <5%
- ➢I_c improvement by pre-bending treatments
- ➢Excellent mass productivity for total length 7.8 km manufacturing

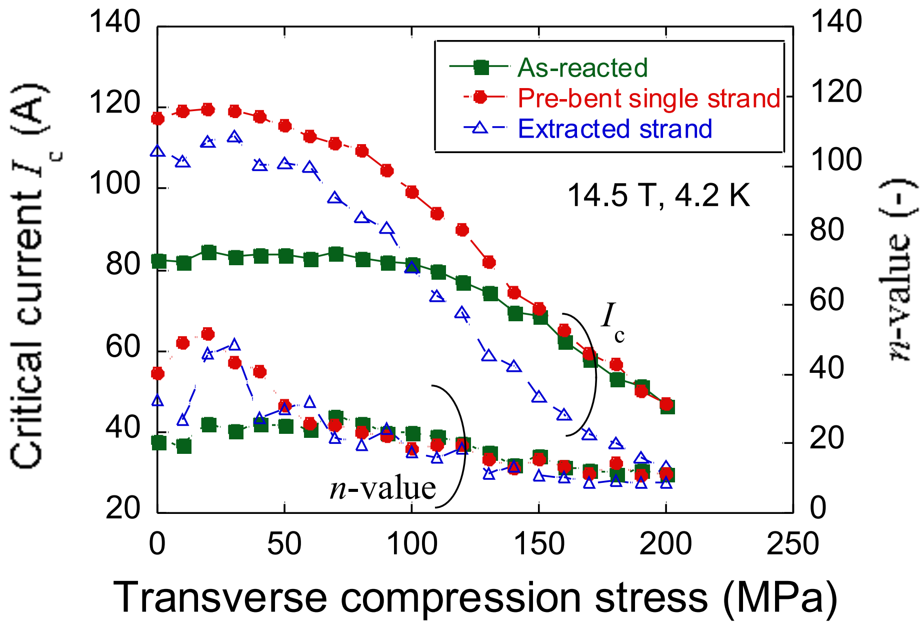
[7] K. Watanabe et al.: IEEE Trans. Appl. Supercond., Vol. 25 (2015) 4300504, [8] S.Awaji et al.: Abstracts of CSJ Conference, Vol.87 (2013) p.154,
[9] S.Awaji et al.: IEEE Trans. Appl. Supercond. Vol.24 (2014) 4302005, [10] M.Sugimoto et al., IEEE Trans. Appl. Super. – ASC 2014 Special Issue, accepted for publication.

I_C properties under stress

FURUKAWA ELECTRIC

[10] M.Sugimoto et al., IEEE Trans. Appl. Super. – ASC 2014 Special Issue, accepted for publication.





- **Ic enhancement range by pre-bending:**
  tensile≦ 250MPa, transverse≦100MPa
- **Optimum per-bending to be suitable for stress condition in operating magnet**
- **Pre-bending is useful for superconductor used under stressed winding.**

Plan for FCC

FURUKAWA ELECTRIC

- ✓ Furukawa has launched research study to come up with breakthrough idea for FCC target;

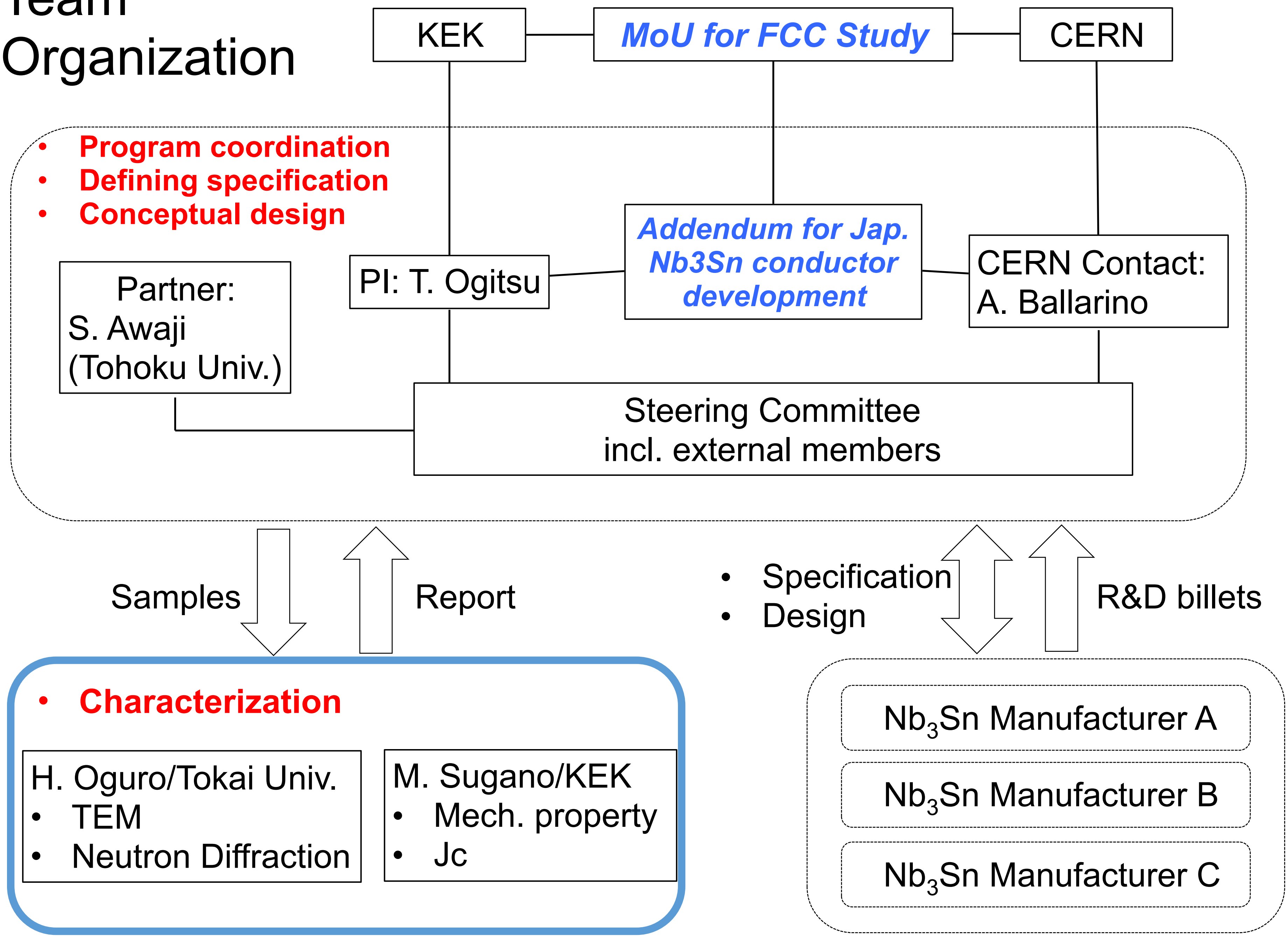
- ➢ Jc ≥1,500A/mm^2 at 4.2K, 16T
- ➢ Wire diameter ≤1mm
- ➢ Cu to non-Cu ≥1
- ➢ Nb_3Sn filament diameter <50μm
- ➢ RRR >150

- ✓ by modified Nb tube and/or modified internal tin (DT-like)

- ✓ under collaboration with CERN and KEK

- ✓ by Feb. 2020

Team Organization



Test items

Electro-magnetic performance

– Ic measurement at 4.2 K and B < 18 T
– RRR measurement (after rolling and HT)
– B-H measurement (VSM) → Magnetic stability

Microscopic observation

– Electron Backscatter Diffraction Analysis (EBSD) → Grain size
– Energy Dispersive Electron Spectroscopy (EDS) → Composition analysis
– SEM, TEM, …

Electro-mechanical performance

– Ic vs axial-tensile strain, compressive stress

Neutron diffraction at J-PARC

– Strain measurement at cryogenic temperature
– Observation of phase evolution during heat treatment

Ic measurements: mainly by KEK at Tohoku University
More detailed analysis: by Tokai University (Dr. Oguro's group)

Ic measurement

Required specifications

- Magnetic field: > 16 T
- Temperature: 4.2 K
- Current capacity

    non-Cu Jc = 1500 A/mm^2
    Wire diameter = 0.8 mm
    Cu/non-Cu ratio = 1

→ Ic ~ 380 A

18 T solenoid magnet
in Tohoku University

Assignment of measurements

A series of Ic measurements will be performed in Japan, and conductors with high Jc will be sent to CERN.

Ic measurements at B<12 T: Possible in all three conductor suppliers

Ic measurements at B>12 T: by KEK with Tohoku and Tokai University + each supplier

Standardization of measurement procedure

- Spiral sample for precise Ic determination
- Mandrel: ITER barrel
- Handling of samples

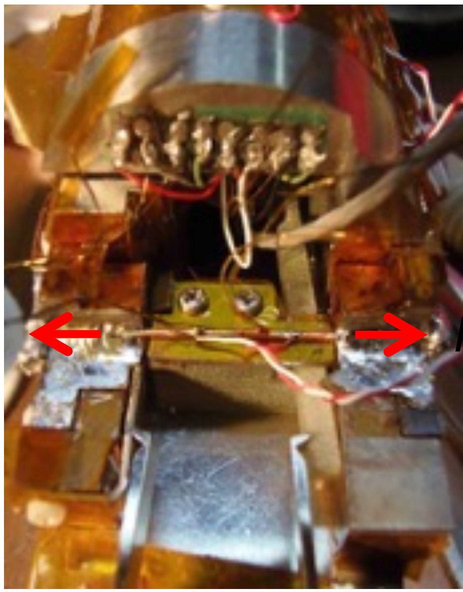
ITER barrel

Ghosh, IEEE TAS (2011)

Electro-mechanical tests

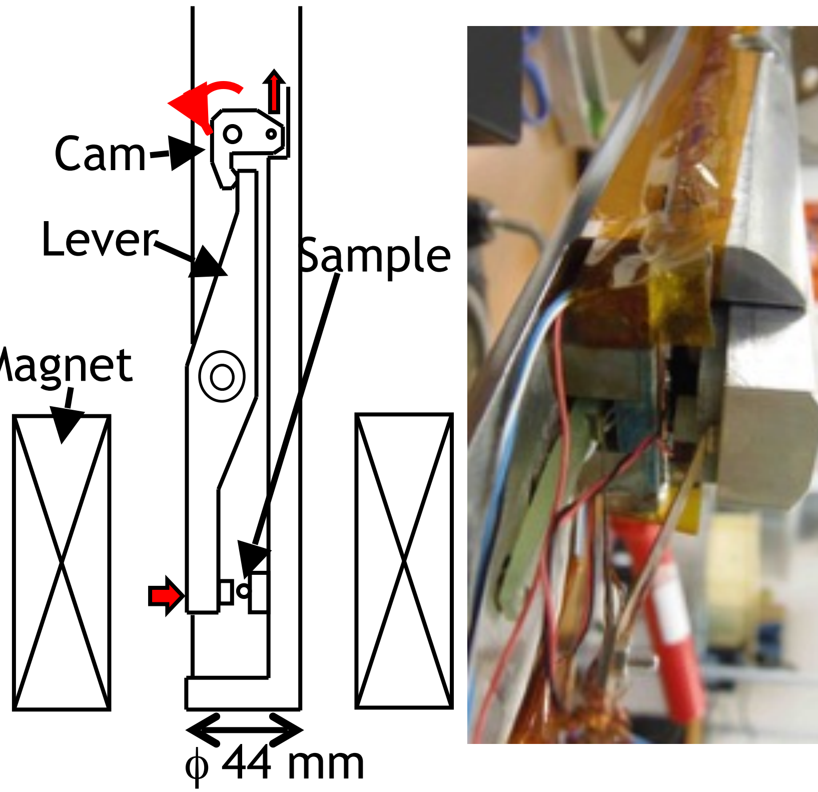
Various inserts for electro-mechanical tests for wires have been developed in Tohoku University.

Axial tensile strain



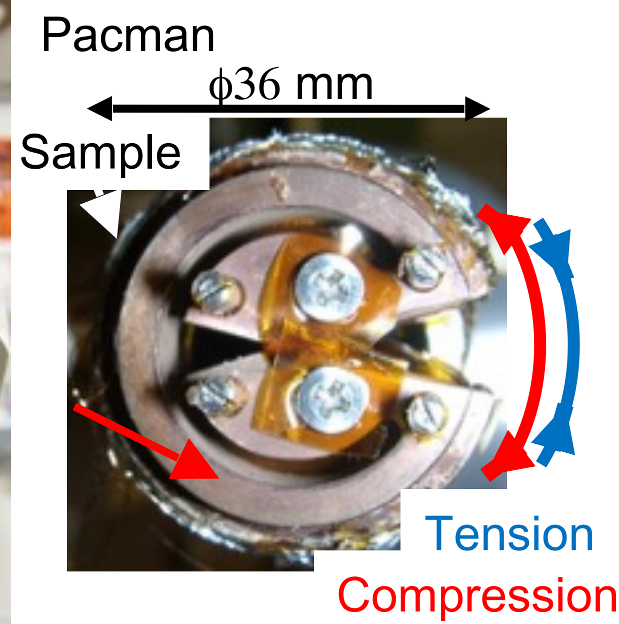
Field < 18 T
Temperature : 4.2 K
Load < 5 kN

Compressive stress



Field < 18 T
Temperature : 4.2 K
Load < 1 kN

Axial tensile/compressive strain

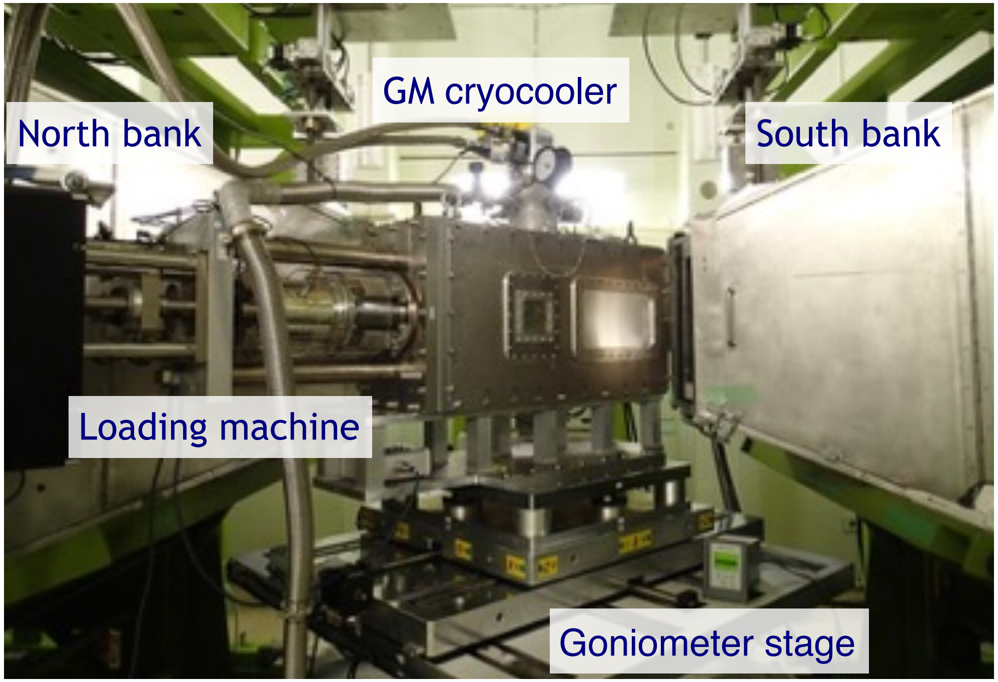


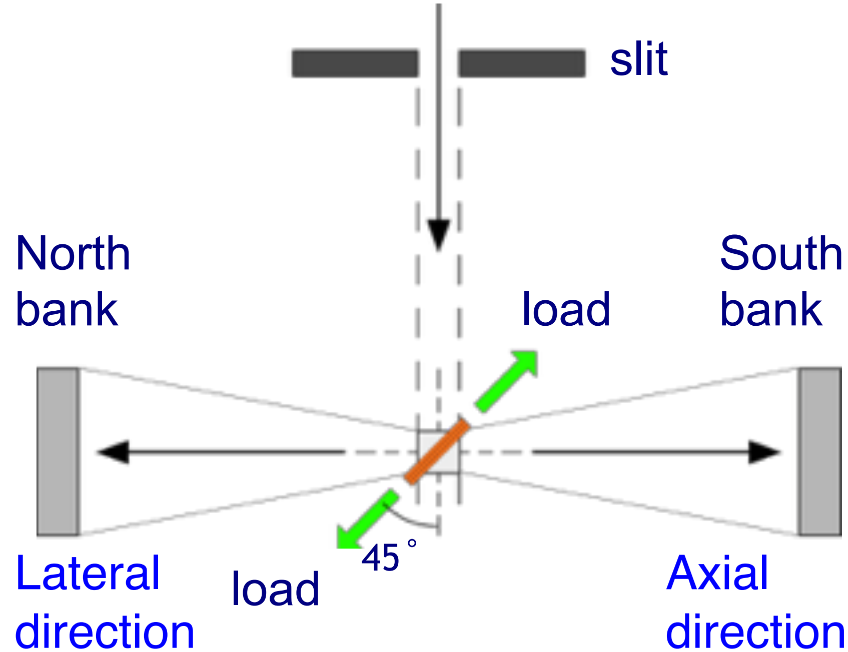
Field < 18 T
Temperature : 4.2 K
Strain -0.5 – 0.5%

Neutron diffraction technique at J-PARC

Engineering Materials Diffractometer (TAKUMI), J-PARC

Cryogenic tensile testing system





Temperature : 10 - 300 K
Load: < 50 kN

Residual strain of Nb_3Sn in composite conductors at cold can be evaluated.

Jc-strain performance for conductors with different cross-sections can be discussed.

Neutron diffraction technique will be also useful for observing phase evolution during heat treatment of Nb_3Sn wires.

Summary

- Joint R&D program: CERN, KEK and Tohoku university
  - 4 year program
- 3 Manufacturer will corporate
  - SH-Copper: DT (single stack)
  - JASTEC/KobeSteel:DT (Nb sub bundle)
  - Furukawa: Nb Tube (or DT)
- Characterization
  - KEK, Tohoku Univ., and Tokai Univ.