Development of Nb_3Sn wire and high field superconducting magnet in JASTEC

23 January 2019

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Japan Superconductor Technology, Inc.

Workshop on advanced superconducting materials and magnet
@ KEK, Japan 23rd Jan. 2019

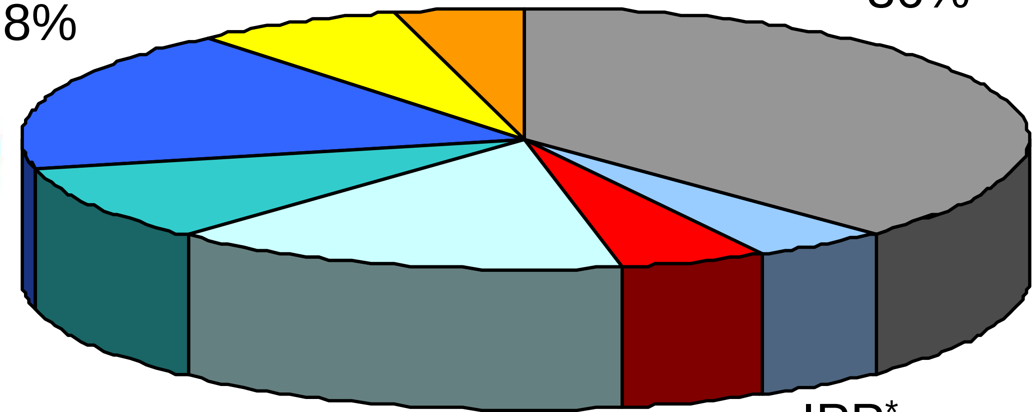
Today’s OUTLINE

1) About JASTEC
2) Nb3Sn wire for NMR magnet
3) Nb3Sn wire for ITER
4) Nb3Sn wire for FCC

About JASTEC

Outline of Kobe Steel Group (FY 2017)

Consolidated Net Sales : US$ 17.1 billion



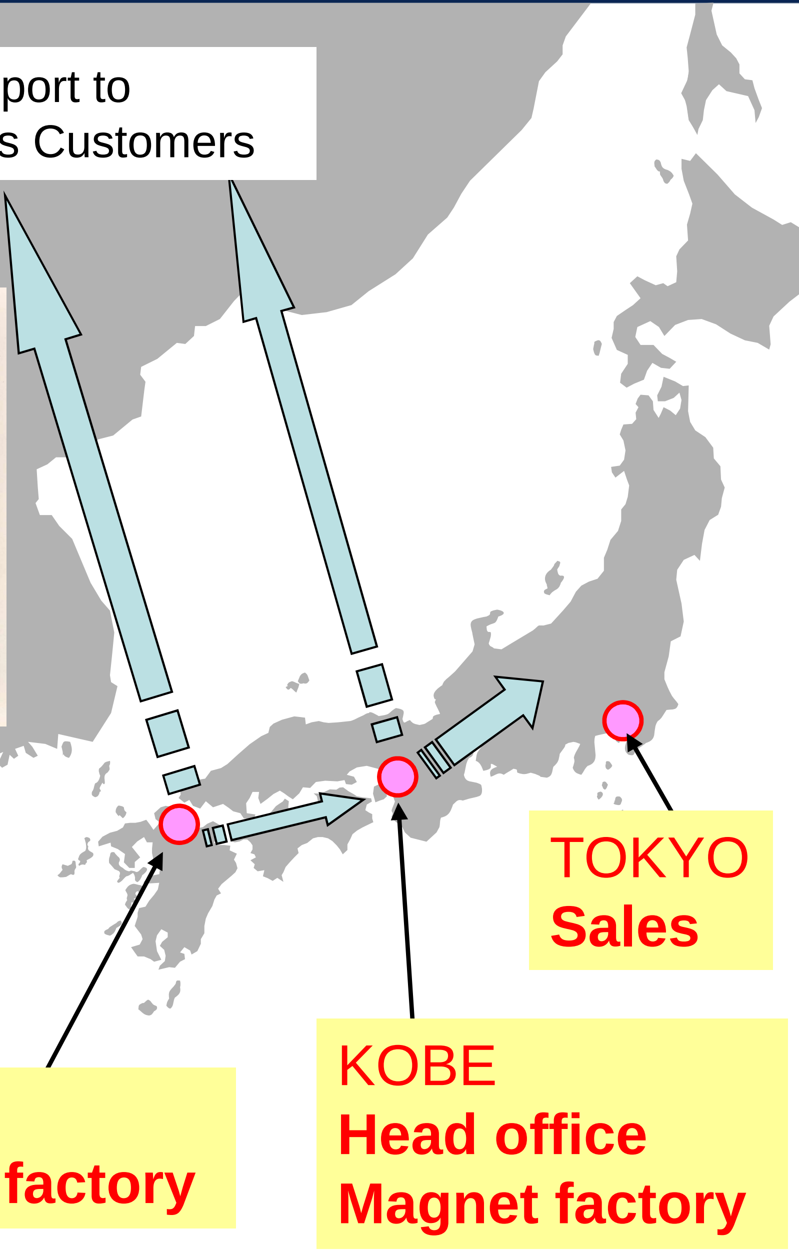
IPP : Independent Power Producer

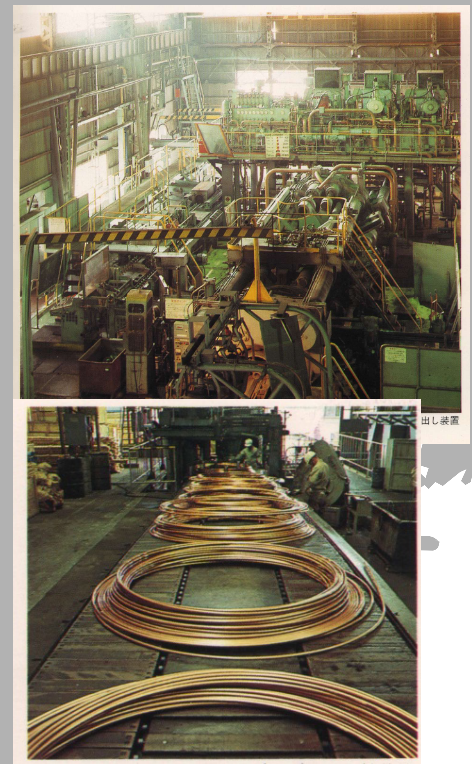
KOBELCO KOBE STEEL GROUP

JASTEC SUPERCONDUCTOR

Company Profile

Founded	**:**	**Apr. 1st, 2002**
Capital	**:**	**400 mil JP Yen**
Shareholder	**:**	**Kobe Steel (100%)**
Employee	**:**	**169 (Dec. 2018)**
President	**:**	**Dr. T. Miyatake**





ISO 9001 001

ISO 9001・ISO 13485 001

エコアクション21

Eco-action 21

Company history

1964 Asada Fundamental Research Lab @Kobe Steel

KSL Started Superconductor R&D

1980 Wire Business @Kobe Steel

NbTi Wire:1980～
Nb3Sn Wire: 1983～

1989 Magnet Business @JMT

Kobe Steel	60%
Magnex	20%
Otsuka Elec.	20%

Magnex T/T:1989～1994
MIT Collab (750MHz-NMR): 1990
NMR Magnet Ship:1990～
Cryogen-free Magnet Ship:1996～

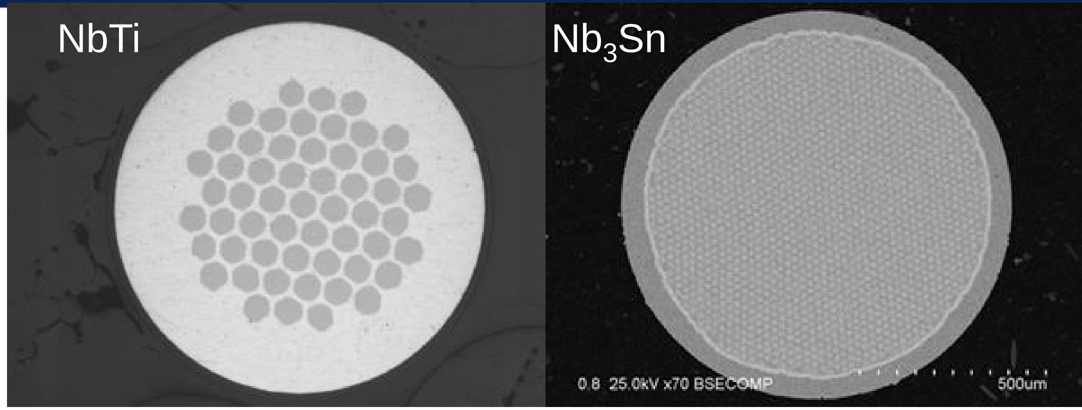
920-930MHz NMR: 2001,2004
Pre-clinical MRI 7T400:2004

2002 Integrated Superconductor Business @JASTEC

ITER-TF:2008～
ITER-CS:2012～

Extremity MRI 1.5T to GE:2008～
Therapy MRI to ViewRay:2014～

Current products lineup in JASTEC



Superconducting wire

- ✓ NbTi⇒ low magnetic field
- ✓ Nb_3Sn⇒high magnetic field

Superconducting magnet

- ✓ Biology/Chemical Analysis : NMR
- ✓ Medical Imaging：MRI
- ✓ Silicon Crystal Growth：MCZ
- ✓ Gyrotron: High power Microwave radiation

High performance Nb_3Sn wire development in JASTEC/KSL

◆NMR magnet

Filed :18T

200-300A/mm²

◆ITER coils

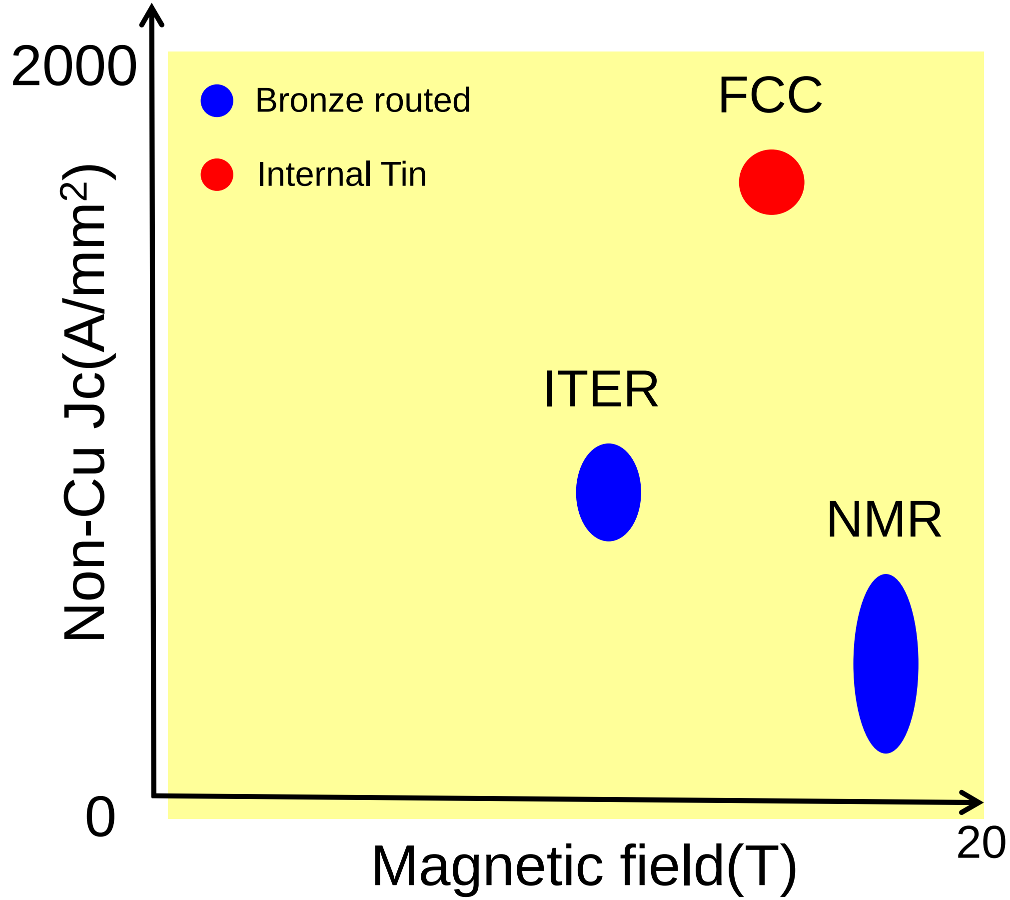
Field :12T-13T

700（TF)～1,100（CS) A/mm²

◆FCC(Accelerator)

Field: 16T

Non Cu Jc: Target 1,500A/mm²



" application driven development"

Nb_3Sn wire for NMR magnet

NMR magnet

400MHz(9.4T)

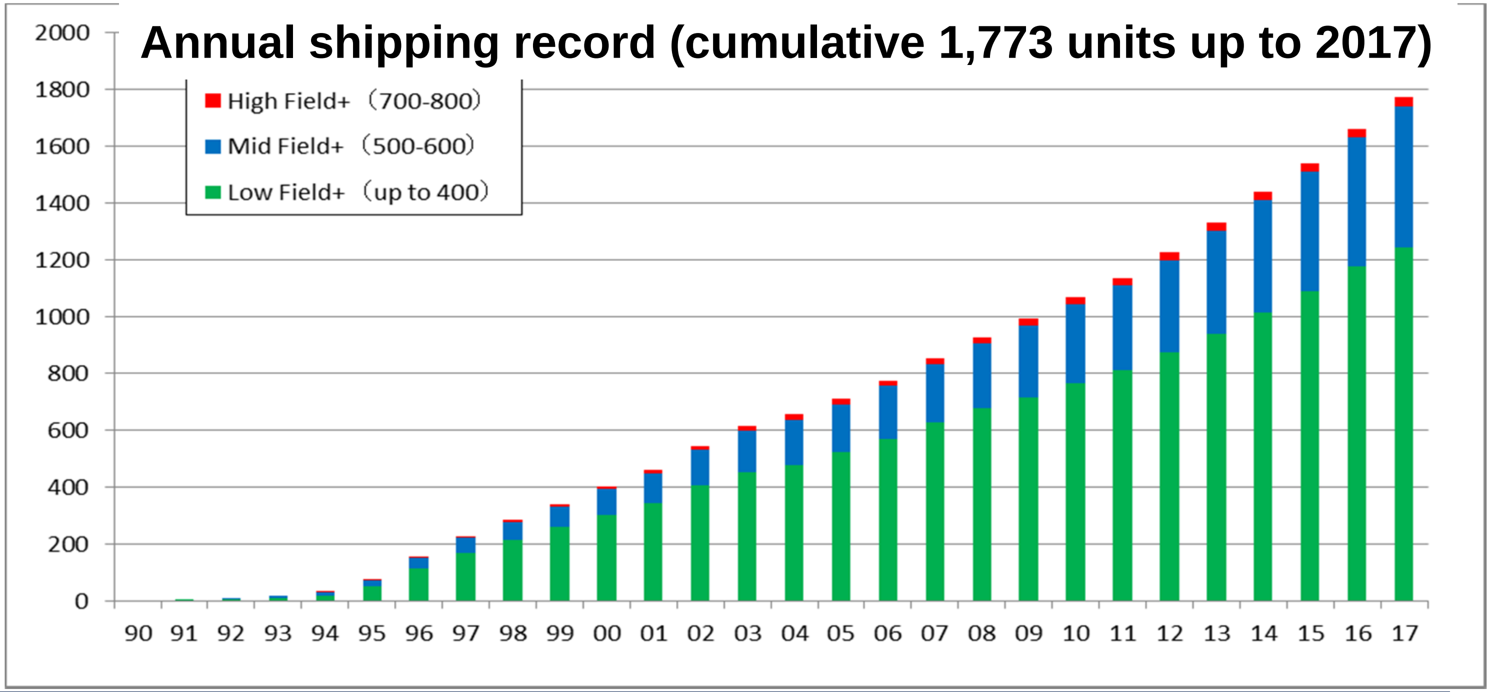
500MHz(11.7T)

600MHz(14.1T)

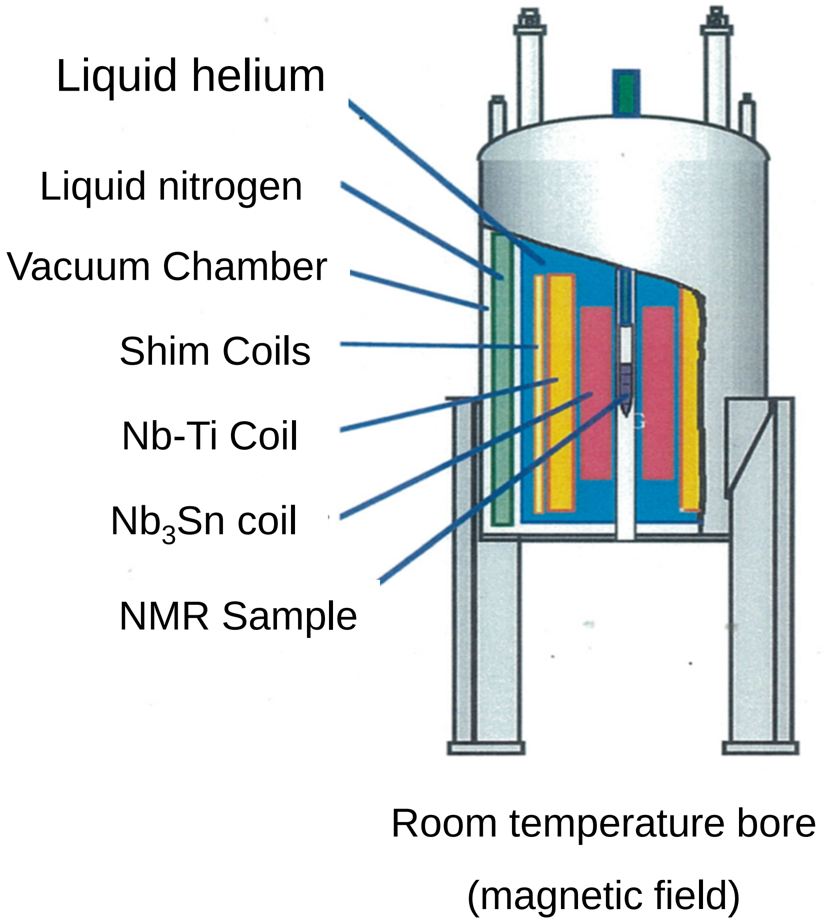
700MHz(16.4T)

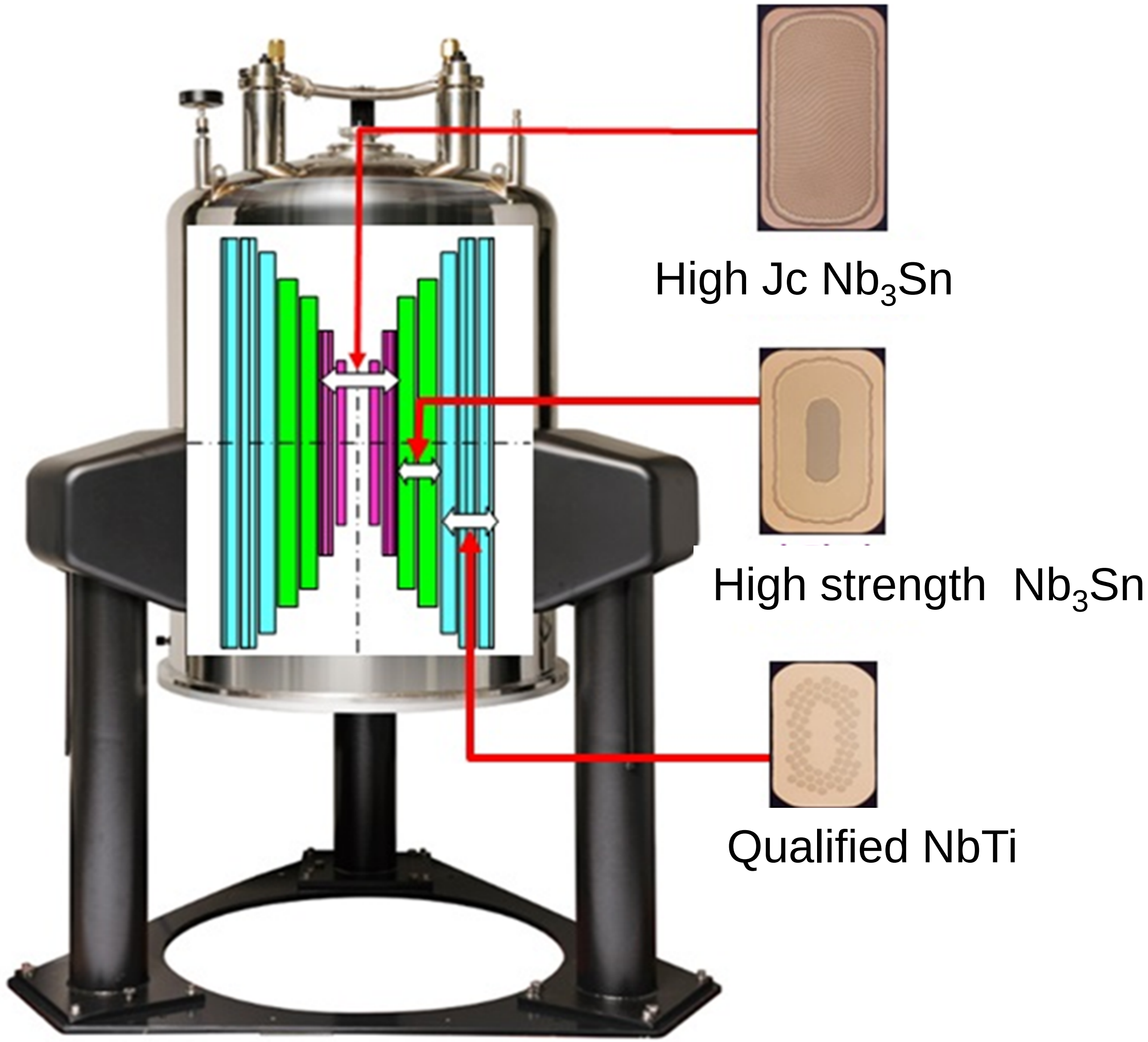
800MHz(18.8T)

1020MHz(24T)

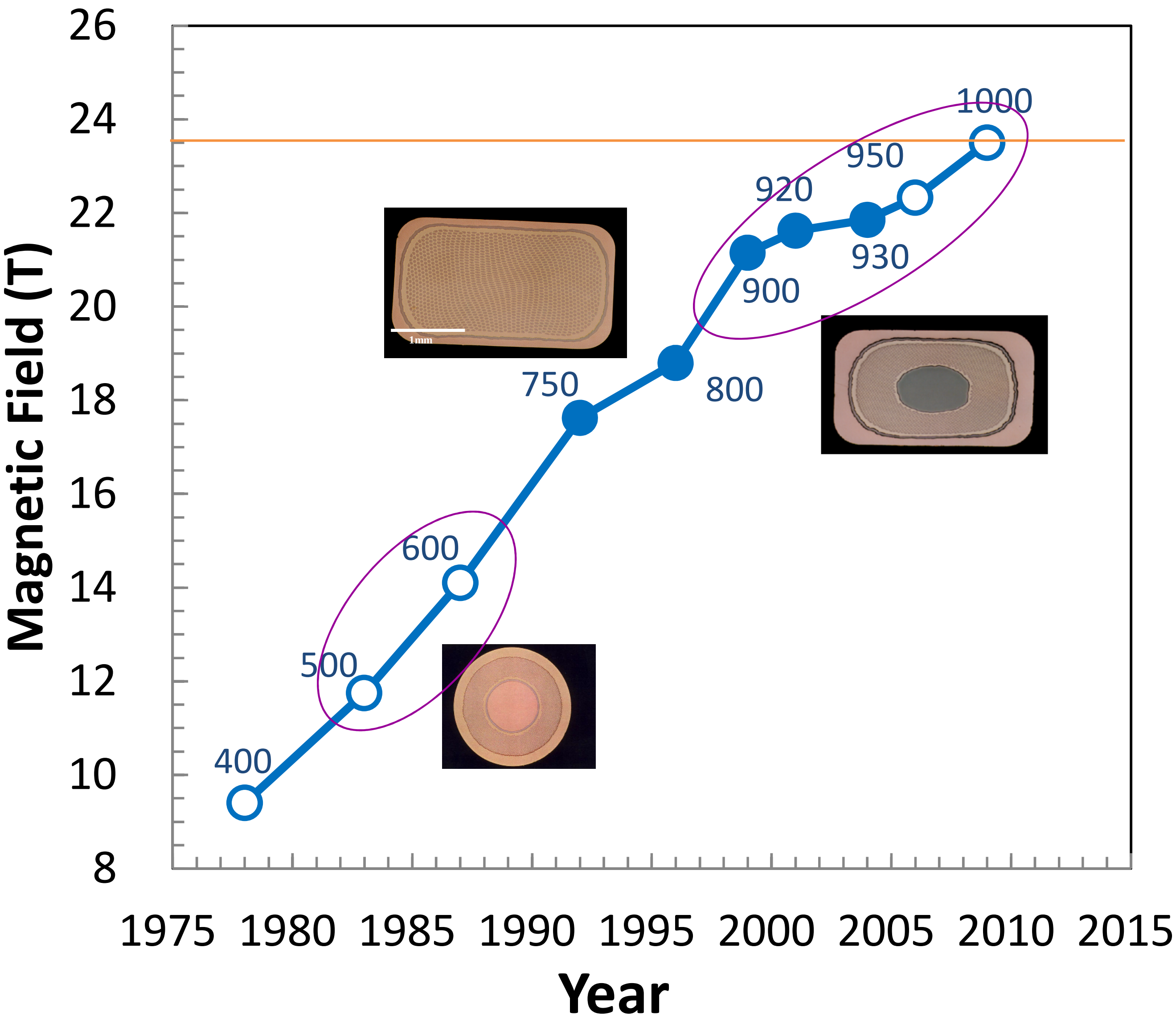


high field NMR magnet





Development of Nb_3Sn wires of Bronze routed type



- **500/600MHz magnet:**
  Internal stabilized wire
- **750MHz magnet:**
  Rectangular wire
- **900MHz magnet:**
  High J_c wire
  High strength wire
- **950-1,000 MHz magnet:**
  High Sn wire
- **Improvement in *n*-value**

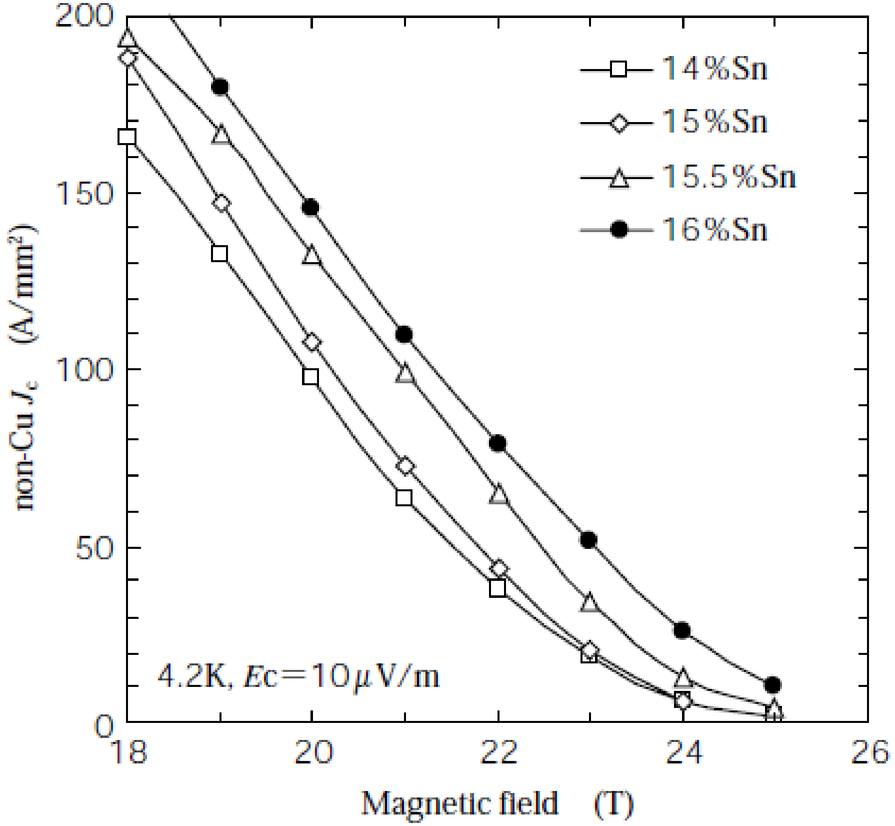
Jc increase by using high Sn contents Cu-Sn Alloy

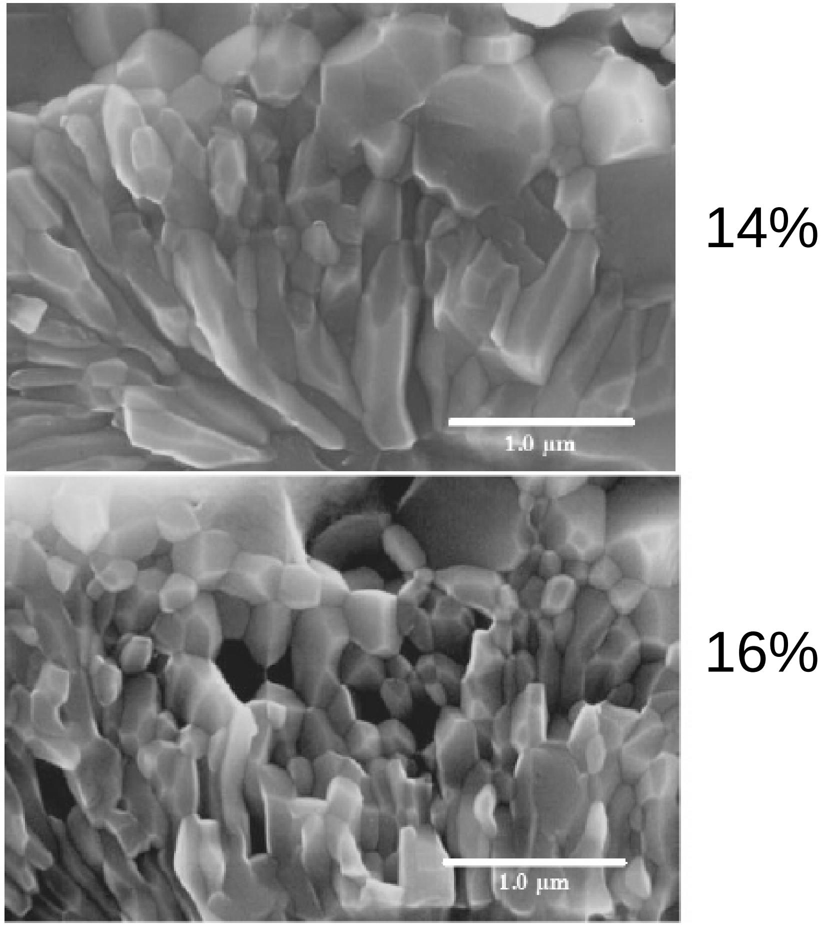
Effect of higher Sn content in Cu-Sn alloy

Increasing Nb_3Sn volume fraction,

better stoichiometry

decrease grain size



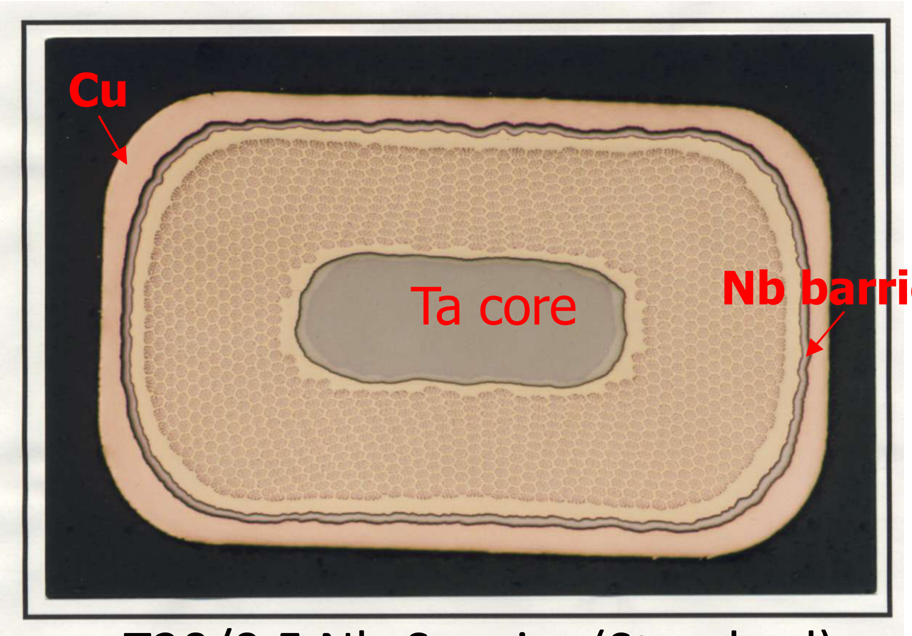


Fracture cross section of

Nb_3Sn filament

Higher strength Nb_3Sn wire (1)

- High strength wires with reinforced materials have been developed by several companies/institutes.
- JASTEC has developed a Ta reinforced Nb_3Sn wire with yield strength (YS) beyond 300MPa at 4.2K. (YS of Ordinary Nb_3Sn wire: 180MPa at 4K)



T20/0.5 Nb_3Sn wire (Standard)

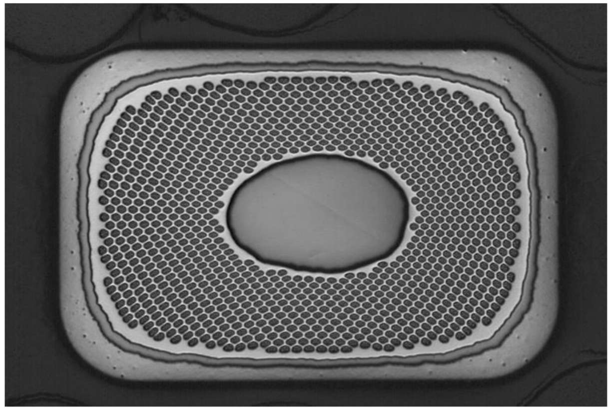
- (Cu+Ta)/SC ratio : 0.5
- Number of filament : 20,292
- 0.2% proof strength : >280MPa

Ta as a reinforcement material has :

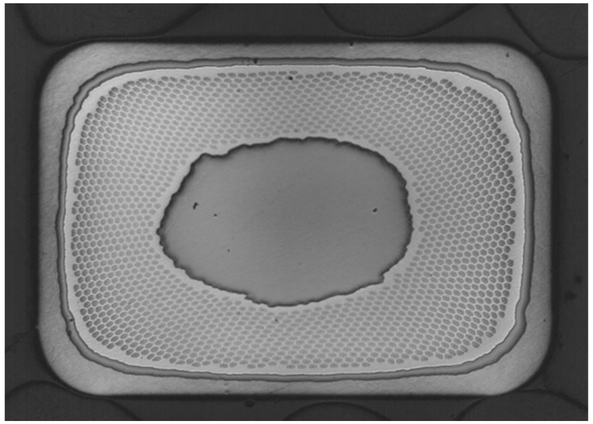
- Good workability in cold drawing
- High YS at cryogenic temperatures
- High YS even after Nb3Sn formation heat treatment

Higher strength Nb_3Sn wire (2)

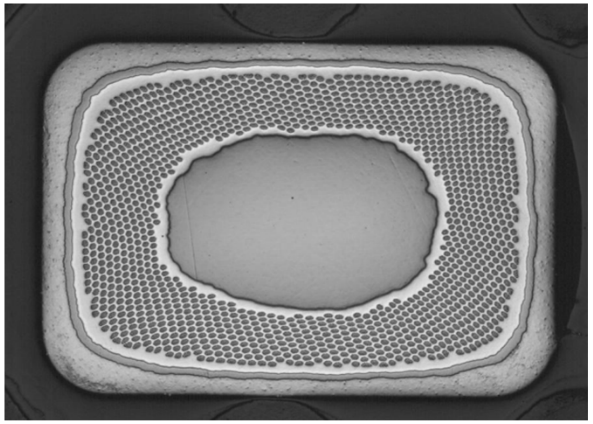
- The YS of Ta reinforced Nb_3Sn wire can be controlled by a volume fraction of Ta.



T20/0.5



T30/0.6



T26/0.8

	T20/0.5	T30/0.6	T26/0.8
Volume fraction of Ta core	～11%	～17%	～24%
Yield strength (MPa) @4.2K	～300	～340	～400

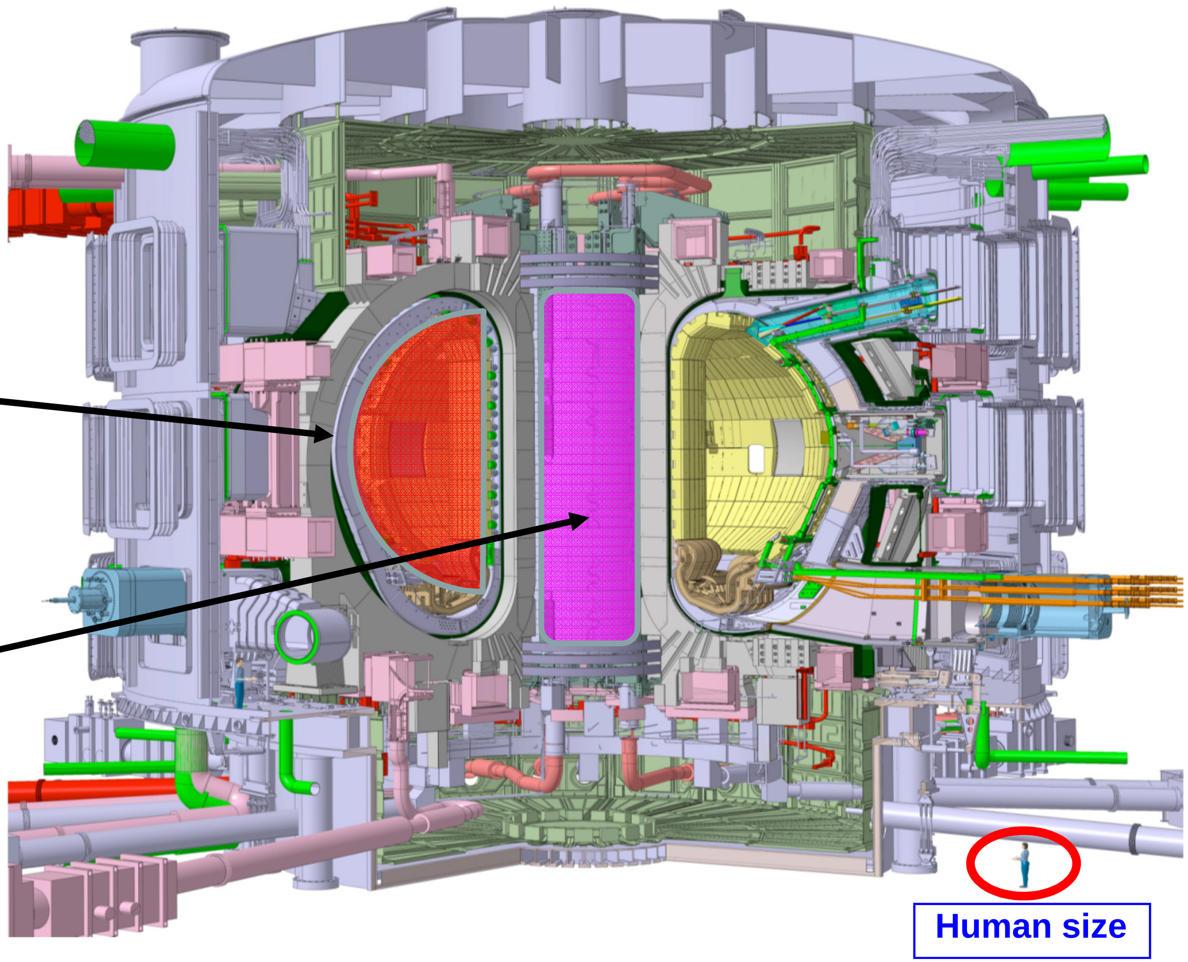
Nb_3Sn wire for ITER coils

ITER (International Thermal nuclear fusion Experimental Reactor)

- Japan, EU, US, Russia, China, South Korea, India
- Site：Cadarache, France
- 2007-2024 Construction
  2025 First plasma
  2025-2042 Operation

- TF coil：420 ton（Japan 105 ton）
  (to confine tokamak plasma)
  wire procurement：2009～2012
  #2,3 = 40tons: JASTEC #1,4,5:Hitachi

- CS coil：120 ton（Japan 120 ton）
  (to induce plasma current)
  wire procurement：2012～2016）
  #1,2,6 = 60tons : JASTEC
  #3,7:Furukawa #4,5:KAT (South Korea)



JASTEC, having share of 41% in Japan,
is one of the leading suppliers of Nb_3Sn conductor to ITER.

Nb_3Sn wire development for CS coil

Parameters for TF coil and CS coil

Parameters	TF	CS
Nominal Peak field (kA)	68	45
Maximum Operating Current (T)	11.8	13

N. Mitchell *et al; IEEE Trans. Appl. Supercond. 22(2012), 4200809*

Table 1 Required specifications of Nb_3Sn strand for ITER

Item	Strand for TF coils	Strand for CS coils	Remarks
Strand diameter	0.820±0.006mm	0.830±0.005mm	After Cr plating
Cu to nonCu ratio	1.0±0.1		
RRR	>100		
nonCu J_c	>700 A/mm²	>750 A/mm²	at 4.2K, 12T
n-value	>20		at 4.2K, 12T
nonCu hysteresis loss	<1,000 mJ/cm³		at 4.2K, ±3T cycle

N. Murakami et al; *Kobe Steel Engineering Reports, 59(1),36(2009)*

Comparing with TF coil, CS coil required higher Jc to Nb_3Sn wire (strand)

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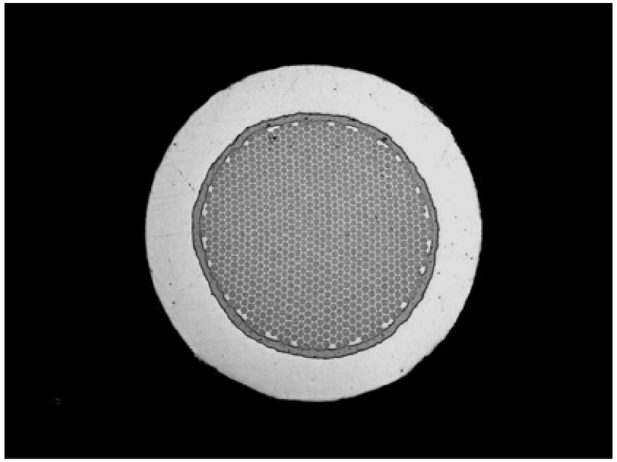
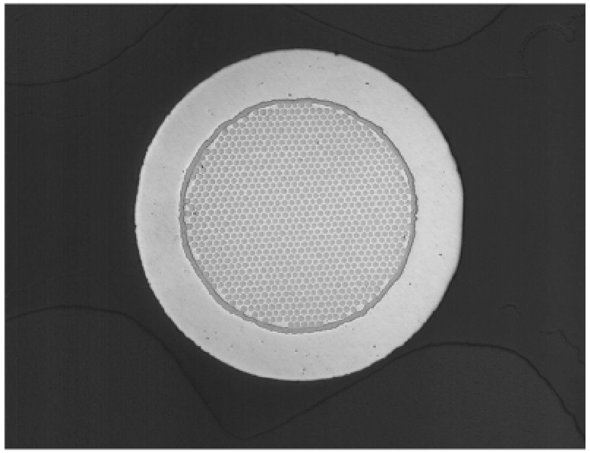
Nb_3Sn wire development for CS coil



(a) GNS-J with barrier thickness of 15μm



(b) GTSM-I with barrier thickness of 9μm

WIRE PARAMETERS OF SAMPLES

Sample	GTS-I	GTS-J	GNS-J	GNB-J	G-TF-I	GTSM-I	GNSM-J
Wire diameter (mm)	0.818	0.818	0.818	0.818	0.826	0.826	0.815
Cu ratio	0.96	0.96	0.94	0.91	0.91	0.93	0.93
Filament number	16,891	16,891	16,891	7,999	12,787	17,347	16,891
Filament diameter (μm)	2.3	2.3	2.3	3.4	2.7	2.3	2.3
Barrier material	Ta/Nb	Ta/Nb	Nb	Nb	Nb	Ta/Nb	Nb
Barrier thckness (μm)	15	15	15	15	7	9	7
Heat-tratment pattern	Type-I	Type-J	Type-J	Type-J	Type-I	Type-I	Type-J

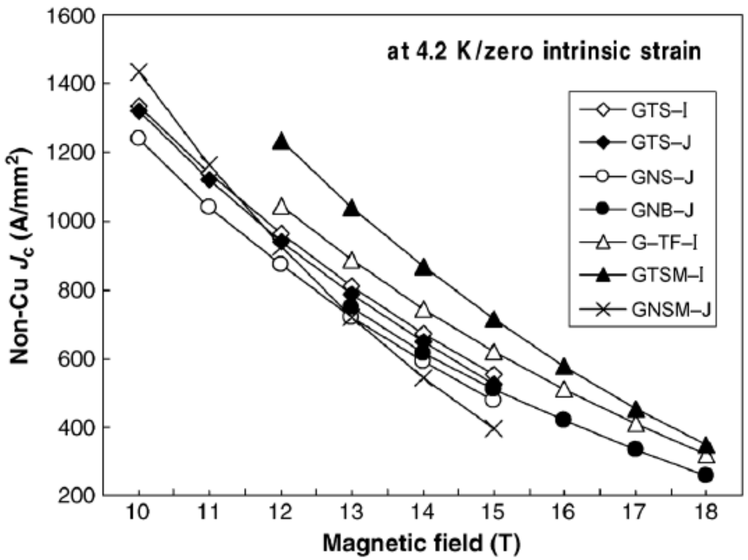


Fig. 3. Magnetic field dependence on non-Cu critical current density at 4.2 K and zero intrinsic strain for all samples.

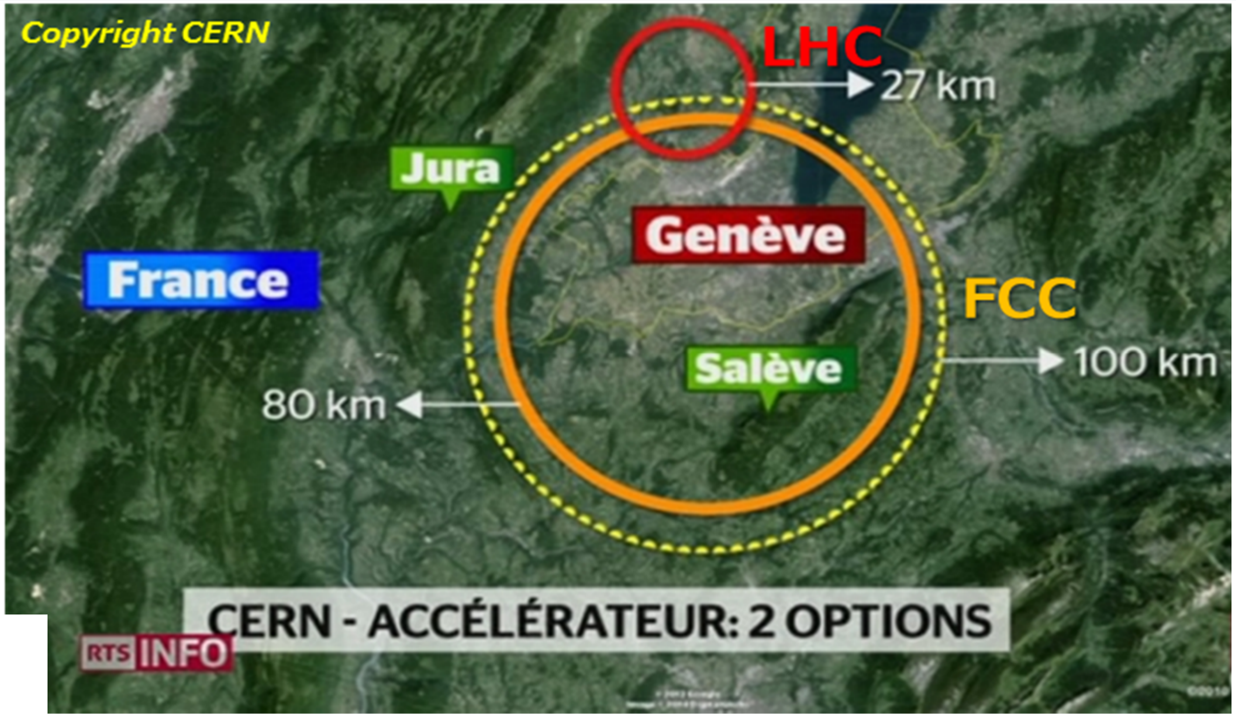
Key Factors

- ✓ Filament diameter
- ✓ Heat treatment
- ✓ Barrier thickness
- ✓ Barrier material

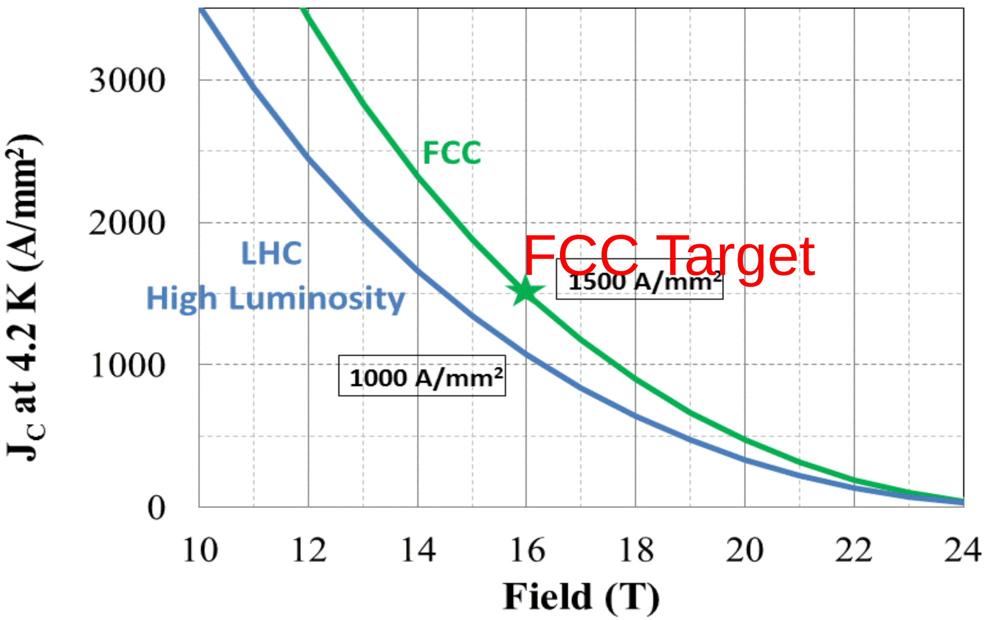
Non-Copper Jc>1100A/mm2@12T

T. Miyatake et all; IEEE Trans. Appl. Supercond. 22(2012), 4805005

Nb_3Sn wire for FCC



High J_c Nb3Sn for FCC

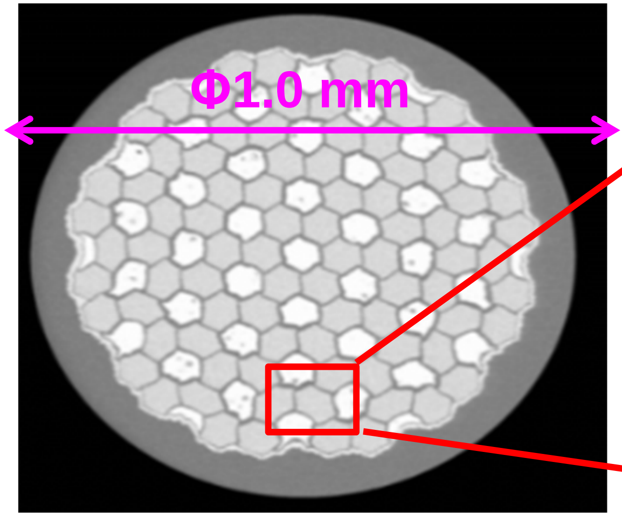


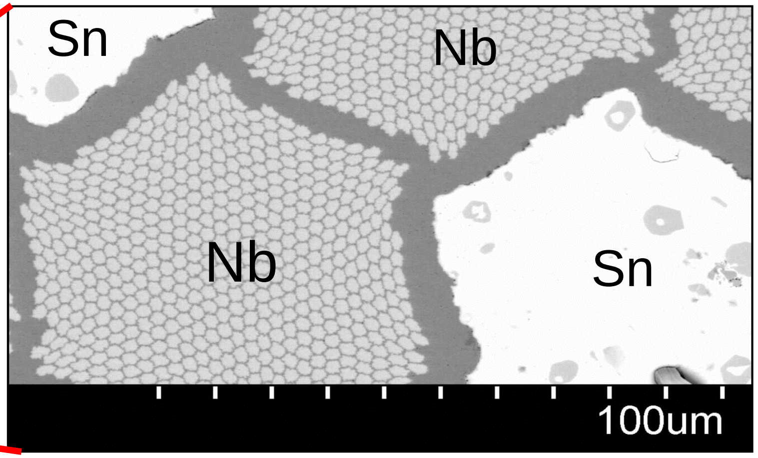
The target value: non Cu J_c : 1500 A/mm^2 at 4.2 K, 16 T. It needs 50 % increase than that for HL-LHC.

Key factors for higher J_c Nb_3Sn

For FCC, Distributed Tin (DT) method with higher Sn concentration is under development.

Cross-section of DT wire (before Heat treatment)





- Nb sub-element
- Monocore Sn
- Nb common barrier
- Stabilized Cu outside barrier

For higher *Jc*…

(1) Improvement in Sn diffusion：Reduction of Sn diffusion distance

(2) Increase in Nb volume fraction：Reduction of useless volume

(3) Ternary additive elements ：Control of B_{C2}

(4) Optimization of heat treatment ：Stoichiometry, Refinement

Experiment

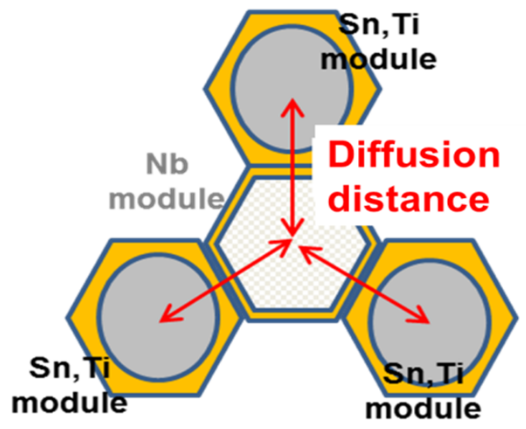
Sample parameters

	1A	1B	1C	2A	2B
Wire Dia. (mm)	0.80	0.75	0.64	0.80	0.80
Nb ratio (%)	47.1	47.1	47.1	48.0	48.0
Dia. Nb Fila. (μm)	2.0	1.8	1.6	1.2	1.2
Dia. Nb module (μm)	60	56	48	32	32
Sn diffusion distance (μm)	60	56	48	32	32
Ti ratio (%)	0.55	0.55	0.55	0.48	0.35
Cu/non-Cu ratio	0.34	0.34	0.34	1.0	1.0

・We prepared 5 samples focusing on Sn diffusion distance and Ti contents.

・1A, 1B and 1C have the same design excepting Sn diffusion distance.

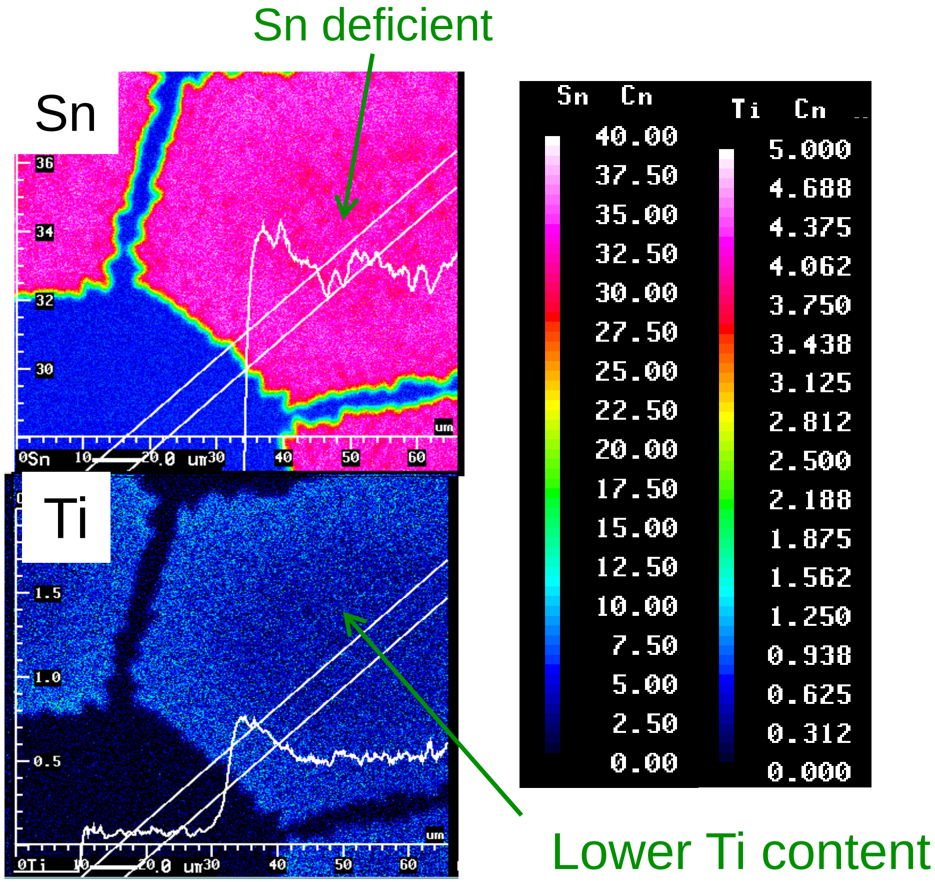
・2A and 2B were reduced the Ti content compared to 1C.



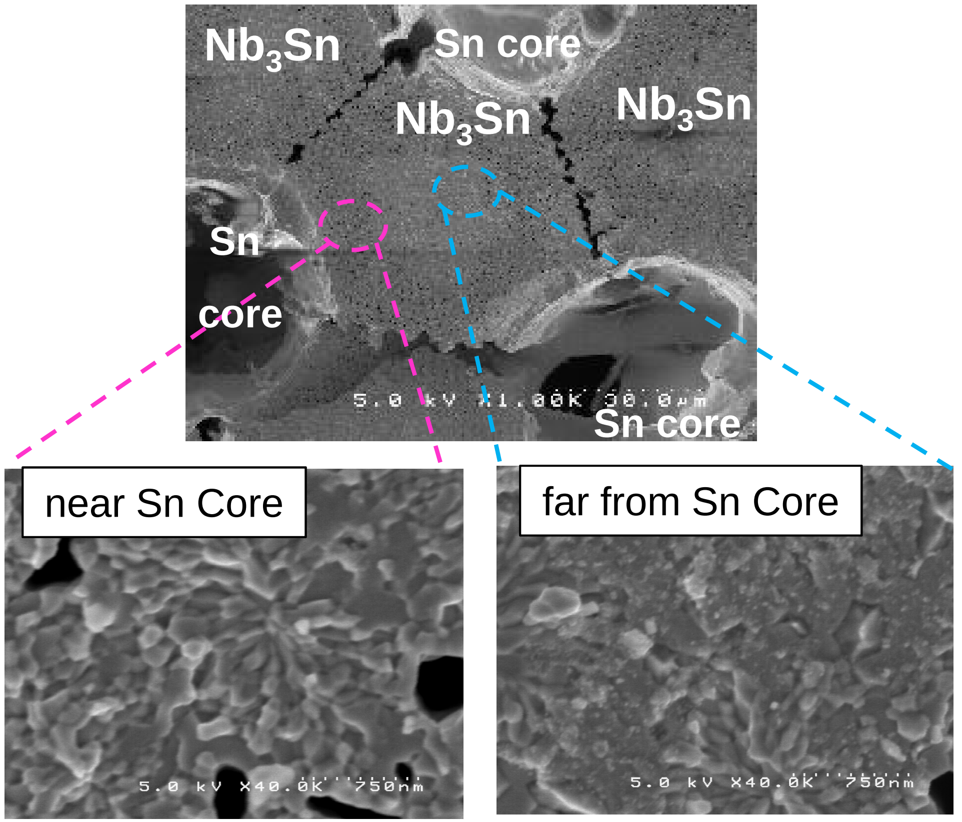
【Definition of Sn diffusion distance】

Improvement in Sn diffusion

Sn diffusion is one of key factors to achieve higher J_c



Sn and Ti EPMA map of 1A
(after HT at 650°C, 200h)

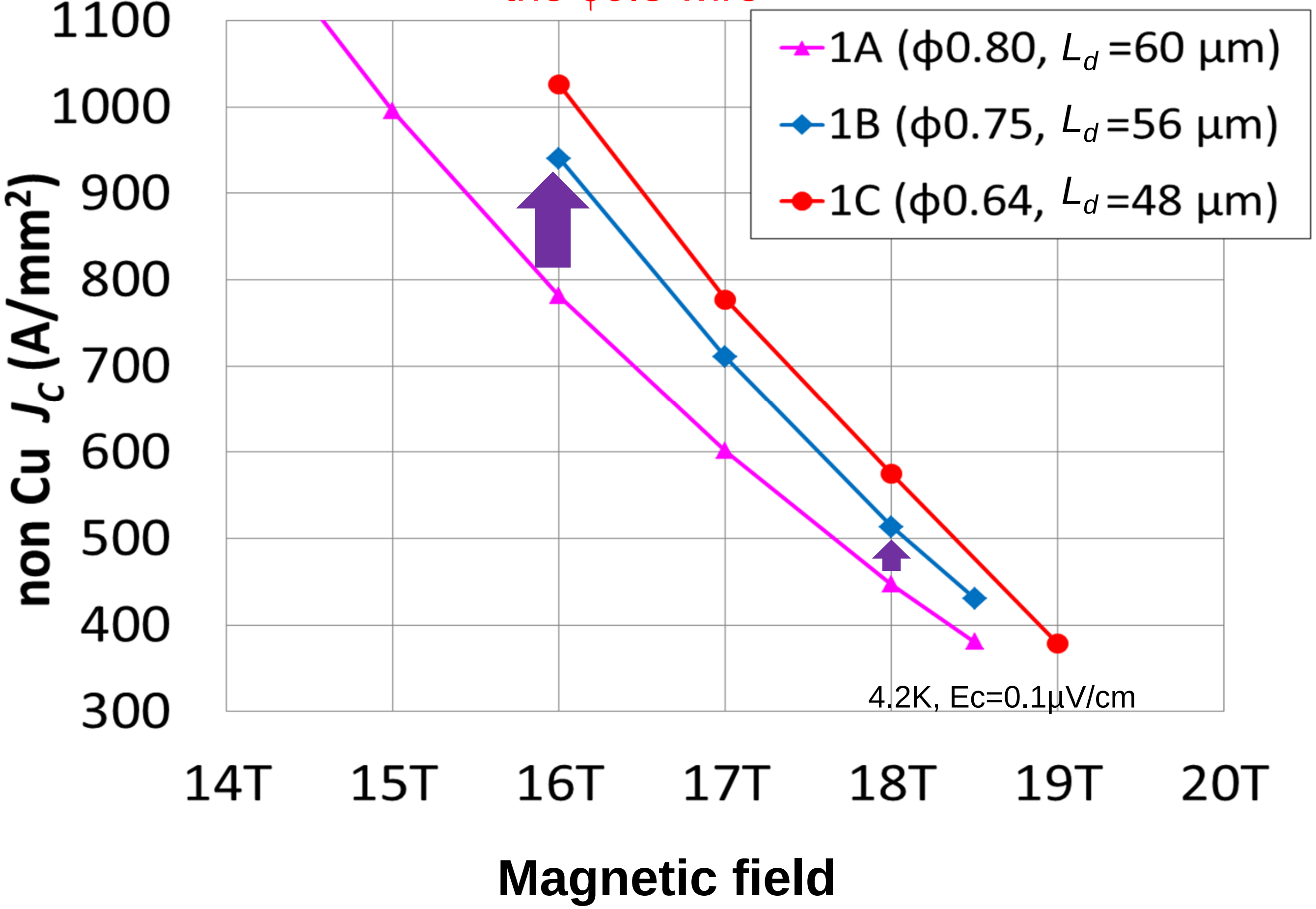


SEM image of 1A
(after Heat treatment)

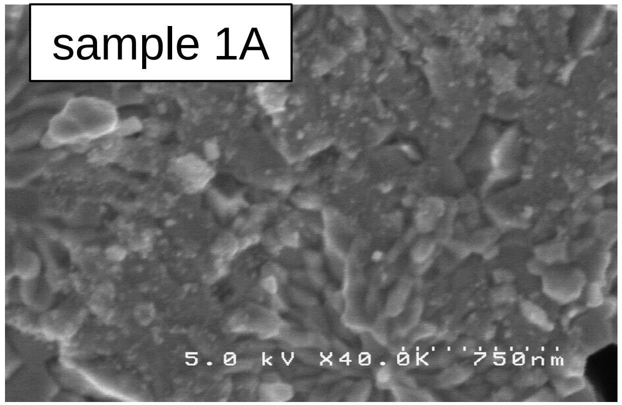
Long diffusion distance of Sn ⇒lack of Sn and Ti in Nb module
⇒larger grain size at the center.

Improvement in Sn diffusion

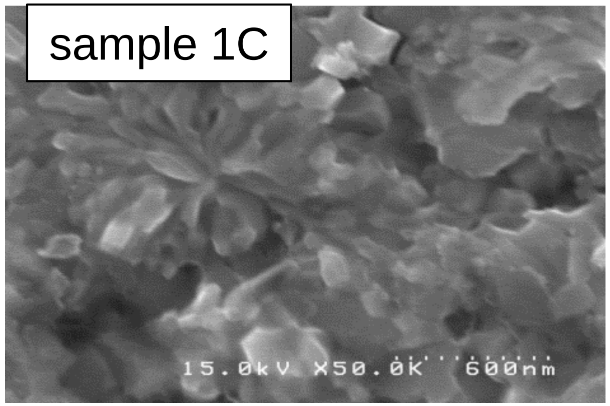
Sn diffusion distance (L_d) was reduced by drawing down the ϕ0.8 wire



Before Sn diffusion improvement



After Sn diffusion improvement



SEM image of A15 area far from Sn core before/after Sn diffusion improvement

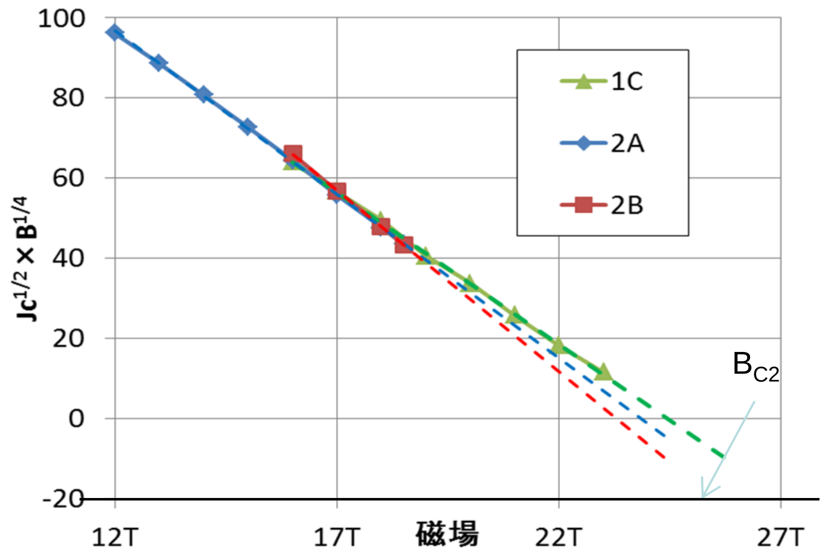
Reduction in Sn diffusion distance can improve J_c by 28%.

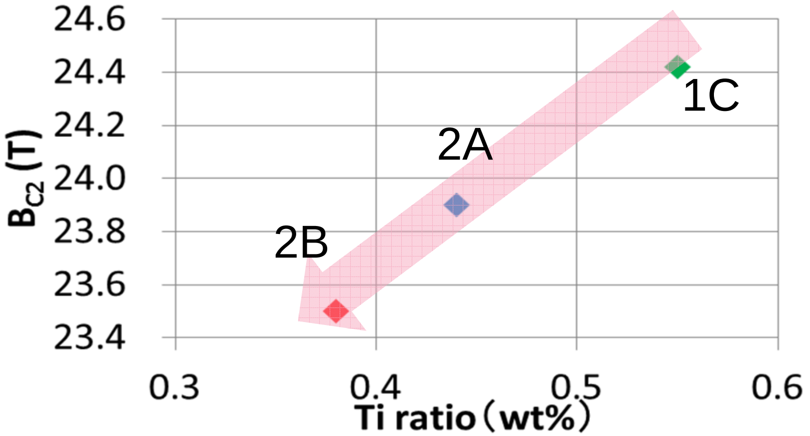
non Cu J_c = 1025 A/mm² @ 16 T.

Ternary additive elements

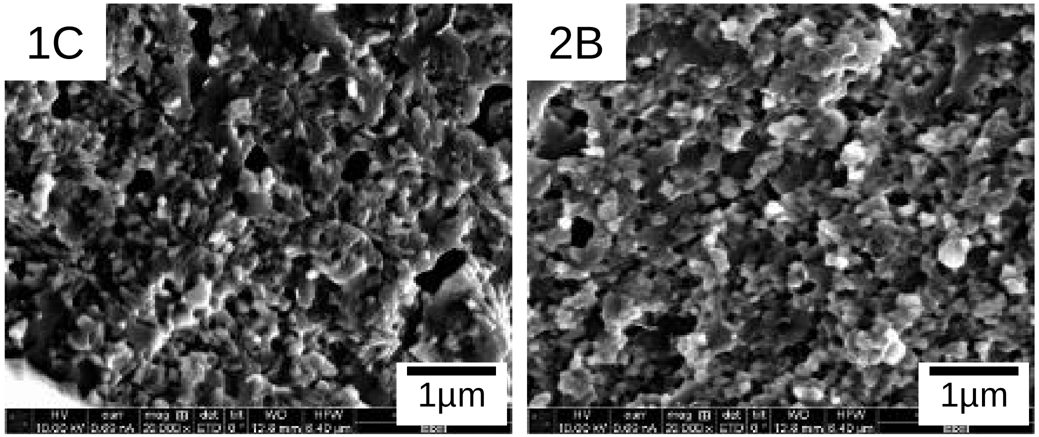
① Control of B_{C2}

Kramer Plot





② Nb_3Sn grains



	Aspect ratio * of Nb_3Sn	Average grain size of Nb_3Sn
1C	2.1	181nm
2A	1.7	188nm
2B	1.7	200nm

* Aspect ratio≒1 → Equaxed grains → High *Jc*

・There is no negative influence such as coarsening of Nb_3Sn grains due to Ti reduction

・By decreasing Ti contents, we suppress B_{C2} .(In descending order of Ti amount: 1C > 2A > 2B).

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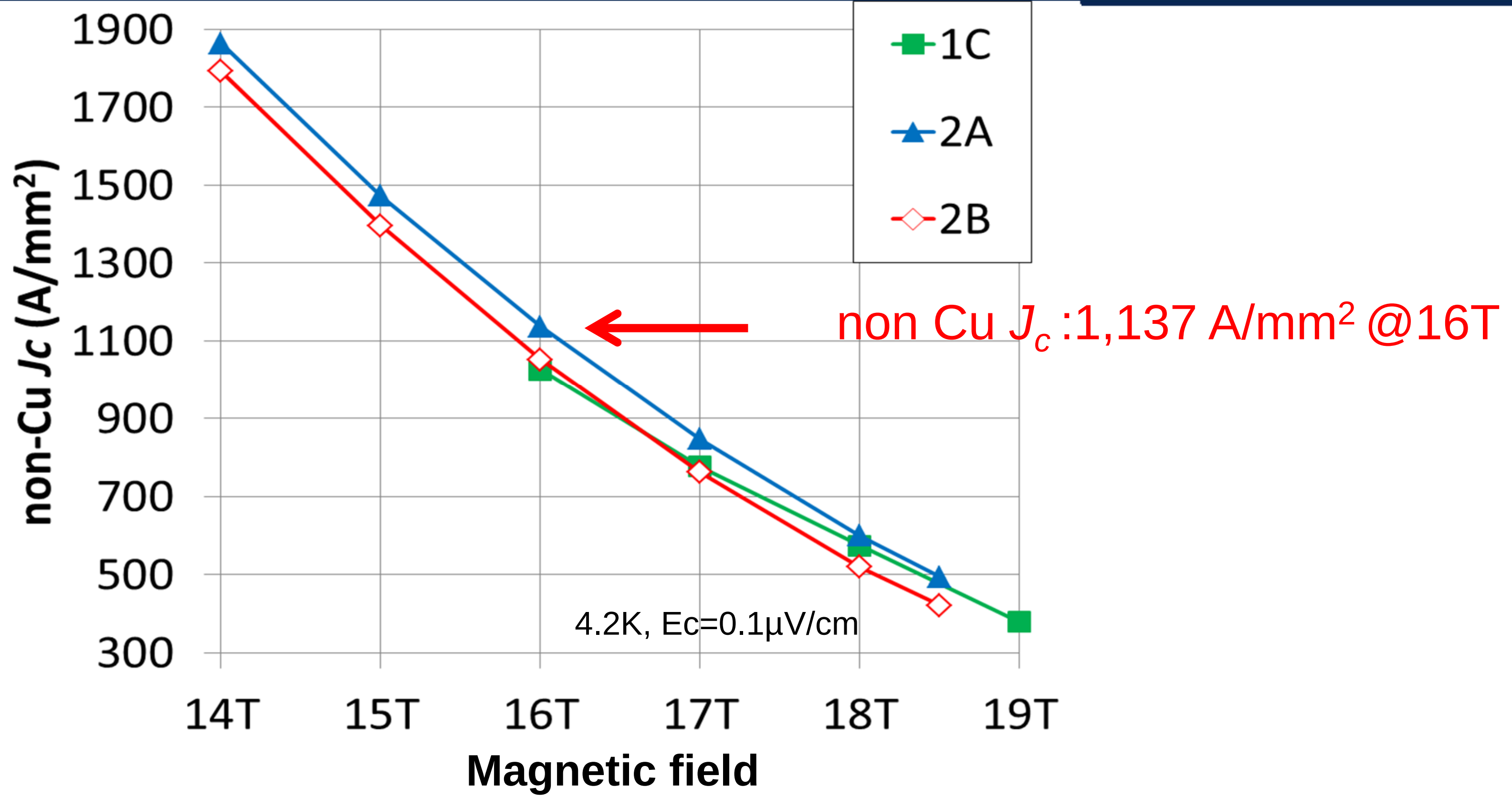
Ternary additive elements



	1C	2A	2B
Wire Dia. (mm)	0.64	0.80	0.80
Sn diffusion distance (μm)	48	32	32
Ti ratio (%)	0.55	0.48	0.35
non Cu J_C (A/mm^2)@16T	1025	1137	1032

Lower Ti content is not necessarily harmful when Sn diffusion distance is short enough.

Short summary

- We have achieved non Cu J_c @16T up to 1,137A/mm^2, by improving Sn diffusion and controlling Ti content. J_c value is approaching to the target for 16T magnets for FCC.

- The following items will be addressed to attain the provisional J_c target of 1,200A/mm^2:

(1) Control ternary additive element (further reduction of Ti, Ti doping method)
(2) Increase in Nb area ratio (by decreasing Cu inside barrier)
(3) Further refinement of Nb_3Sn grains by controlling heat-treatment condition

Thank you for your attention！