Status and perspective of the Nb_3Al development in Japan

T. Takeuchi

Nat. Inst. Materials Sci. (NIMS)

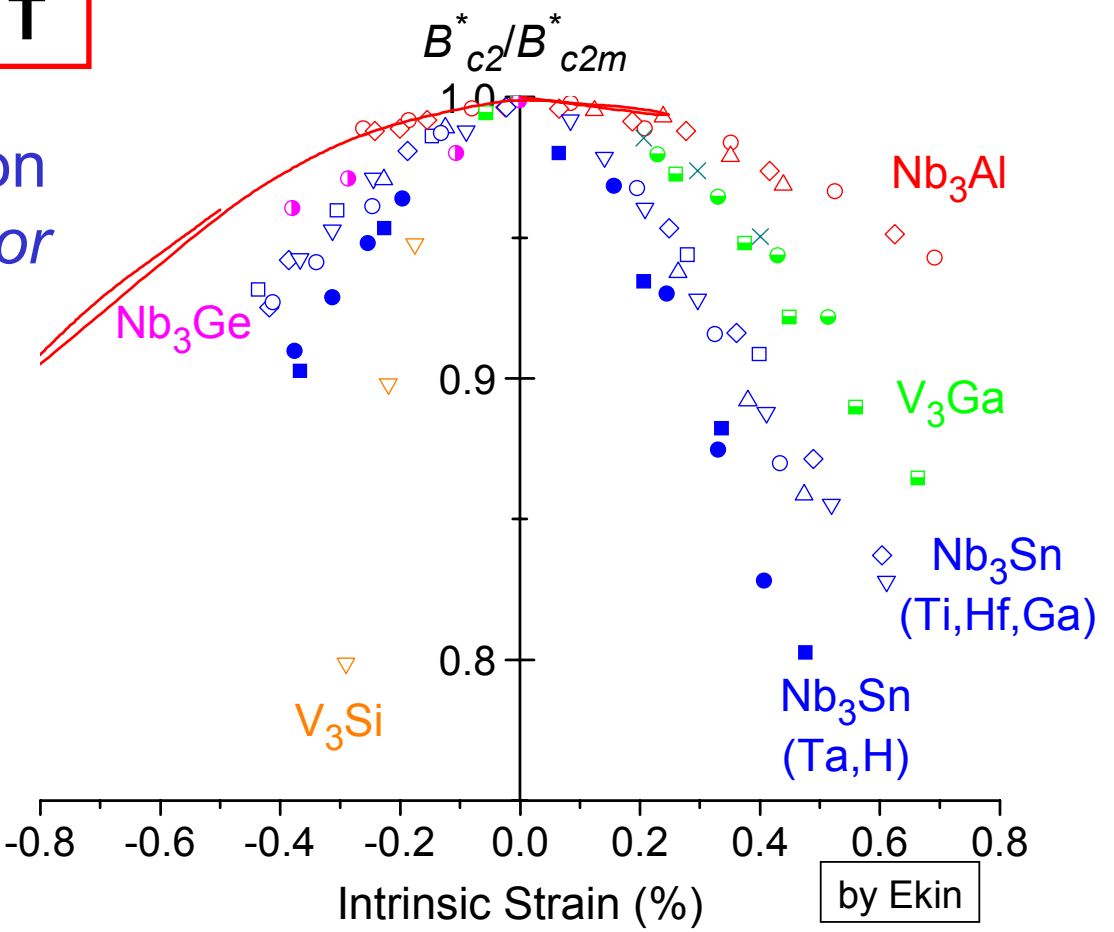
K. Tsuchiya

High Energy Accel. Res. Organ. (KEK)

Advantages of RHQT Nb_3Al over Nb_3Sn

better strain tolerance
higher B_{c2}(4.2K): 30 T

Large scale application
Fusion, Accelerator



Advantages of RHQT Nb_3Al over HTS

- Easy superconducting joint
- Large *n*-value
- Tolerance to stress and strain

Application

- High-field NMR spectroscopy

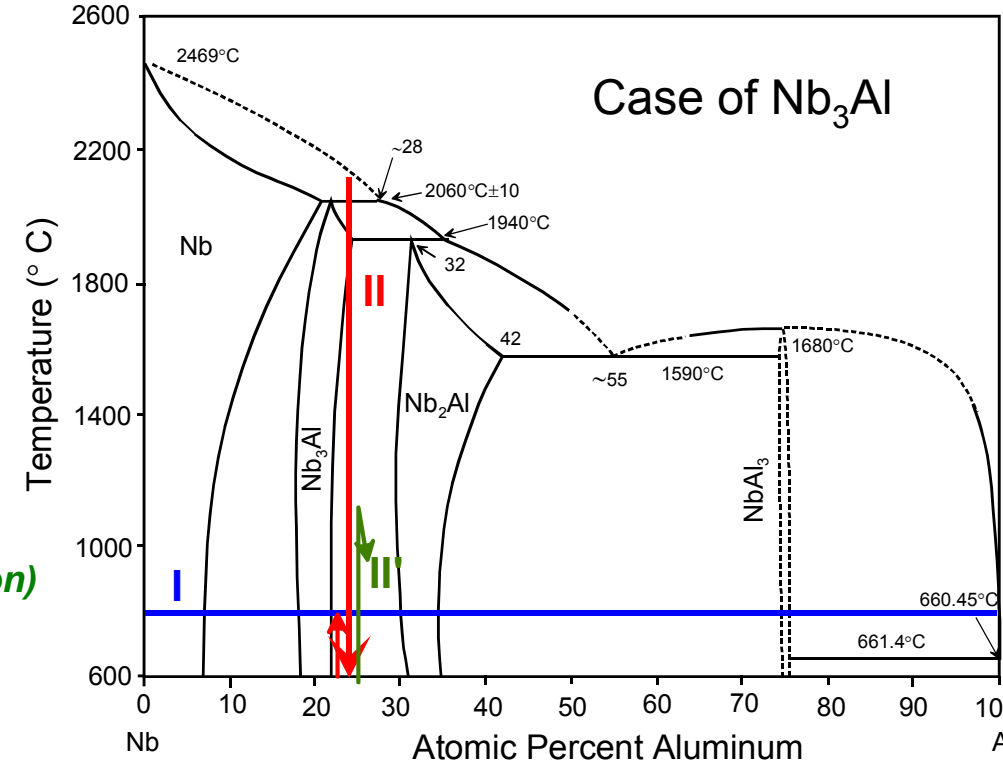
Specification of Nb_3Al conductor for NMR uses

- Rectangular
- Stabilizer (Cu clad)
- Nb matrix (superconducting)
- DC (filament diameter, spacing)
- Optimization of Jc (4.2K) at 21 T

Advanced A15 Compounds

- Nb_3Al
- Nb_3Ga
- $Nb_3(Al,Ge)$

Explored processes to achieve stoichiometry without grain coarsening



Off-stoichiometry at LT

New approach

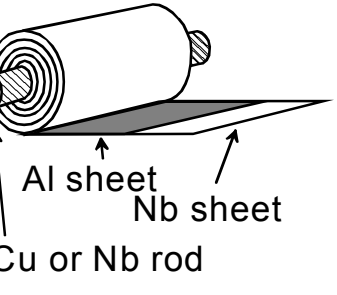
RHQT technique

(rapid-heating, quenching and transformation)

stoichiometry

without grain growth

Manufacture: binary reaction, Al dimension: < 100nm



Diffusion process (750°C x 50h)

11-14 T, off-stoichiometry

Cu-matrix JR

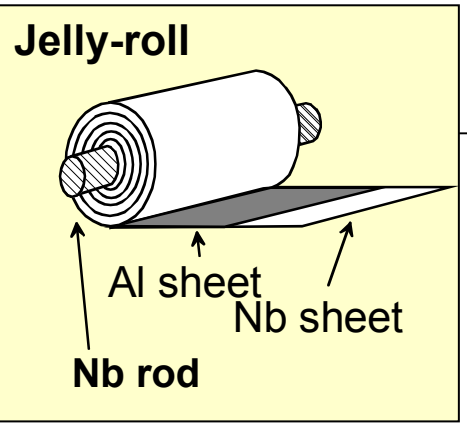
RHQT process (1900°C + 800°Cx10h) → **New process (TRUQ, DRHQ**

12-23 T, stacking faults

Nb-matrix JR

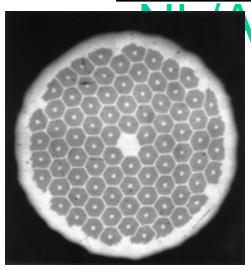
21-25 T

Rapid Heating, Quenching and Transformation process



Precursor : Nb/JR

Extrusion + Drawing



Joule Heating
+
Quenching

Nb/Nb(Al)$_{ss}$

bcc supersaturated solid solution

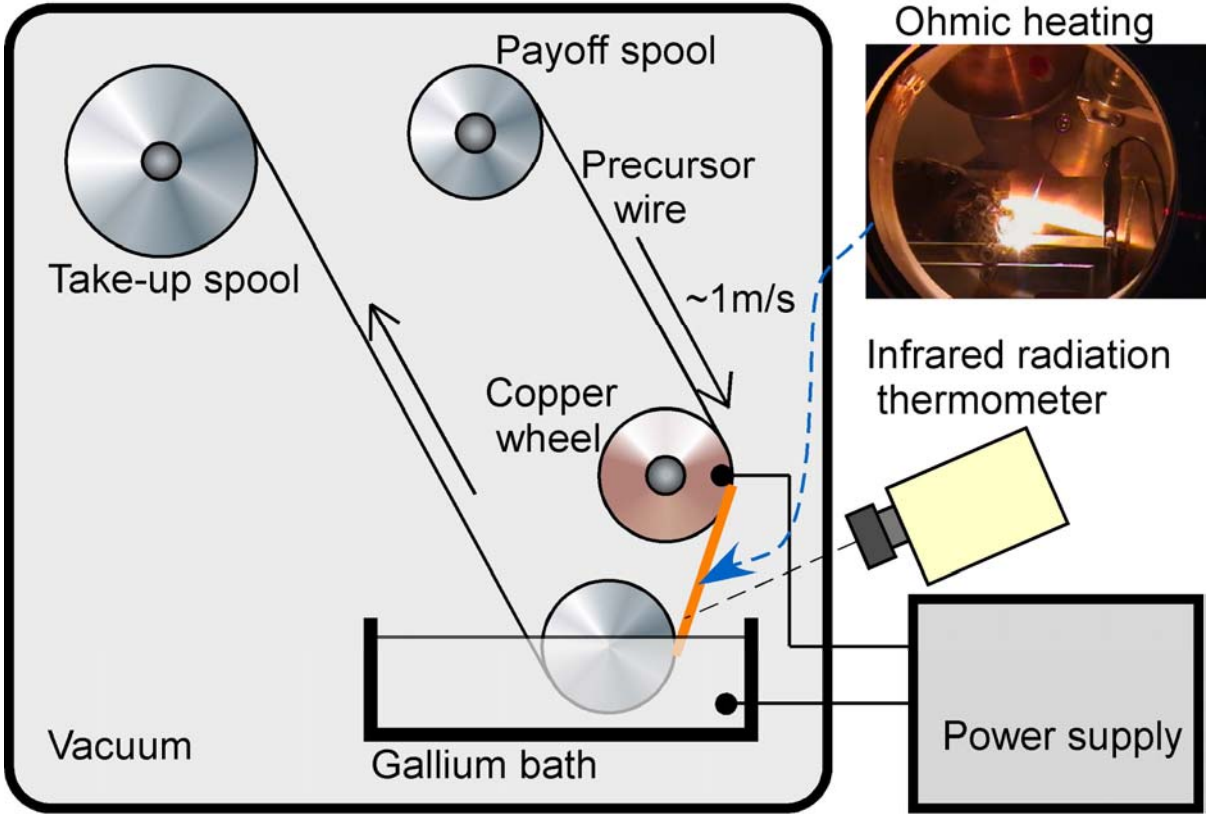
Cu cladding

Cu/Nb/Nb(Al)$_{ss}$

Winding
+
Transformation

Cu/Nb/Nb_3Al

stoichiometry
fine grain



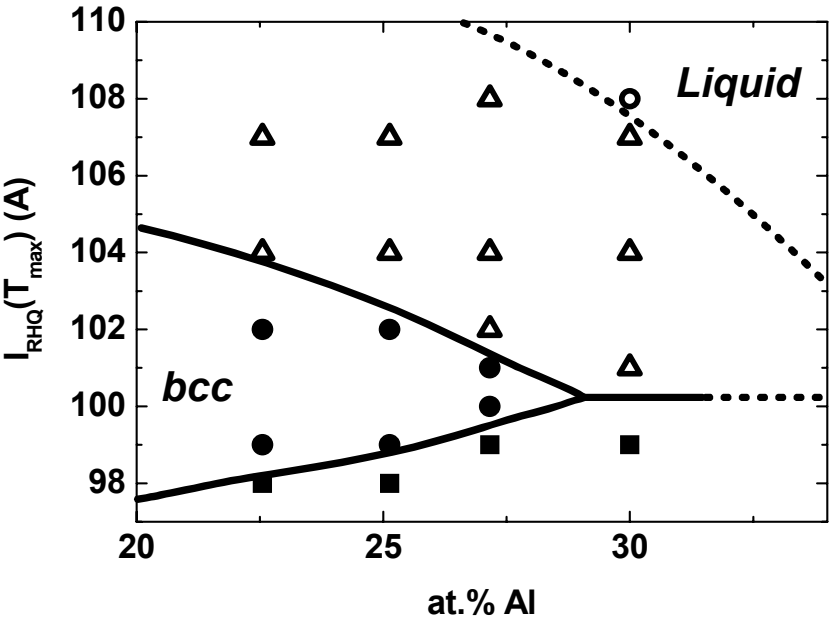
Ohmic heating

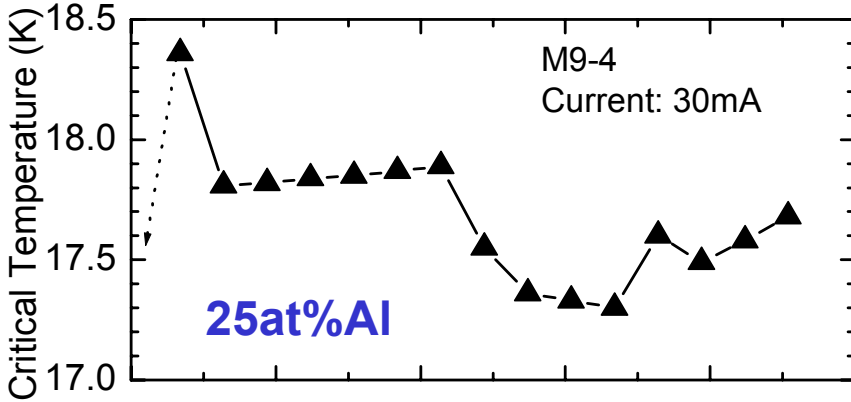
Infrared radiation thermometer

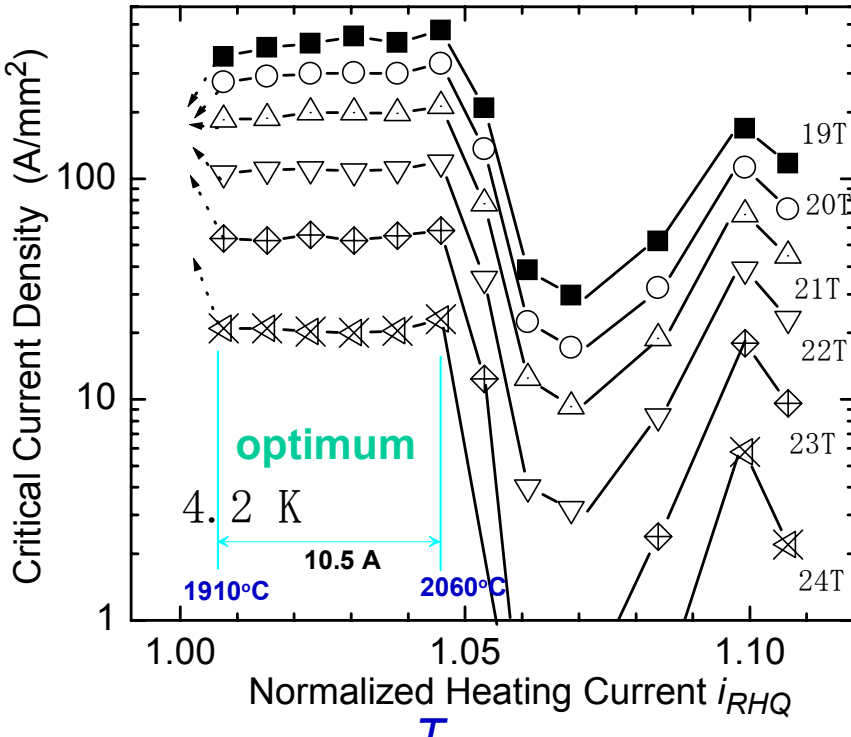
Long-length of RHQ processing

	solid solution	melting	melting
A15+σ brittle	bcc ductile	Al-poor bcc + liquid (not brittle)	bcc ductil

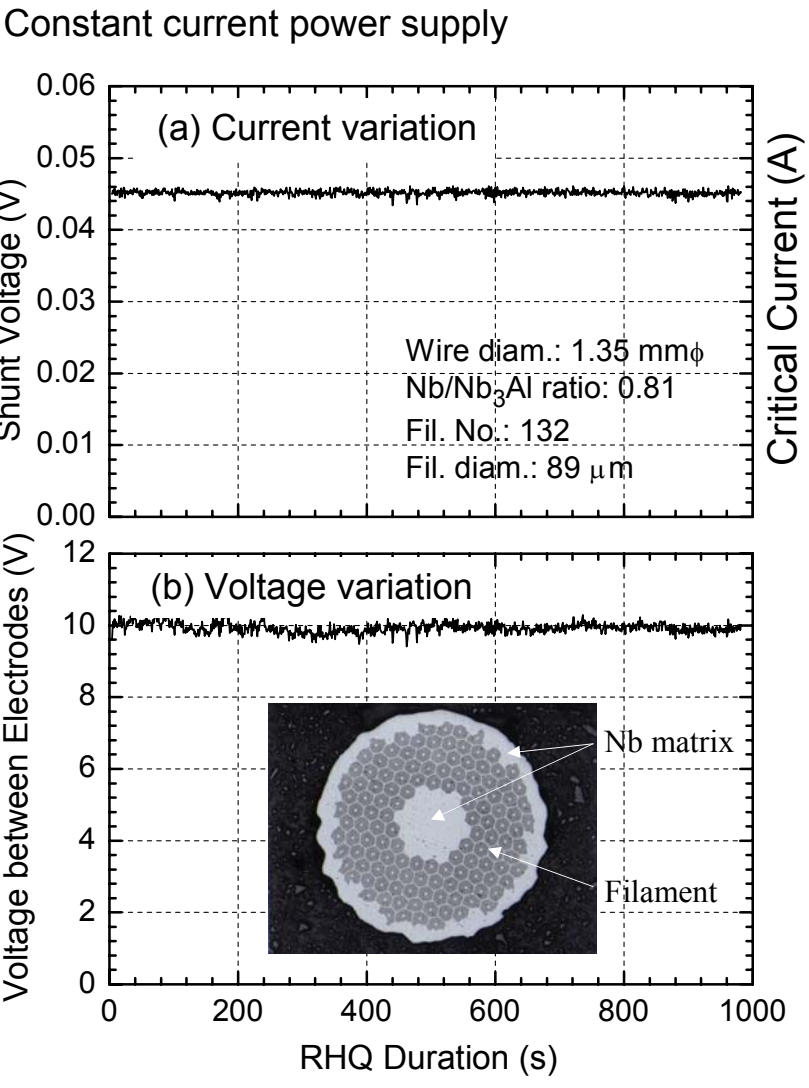
- Plateau region (150°C): optimum
- Insensitivity to unwanted temperature scatter
- Uniformity of SC properties along a long-length of wire

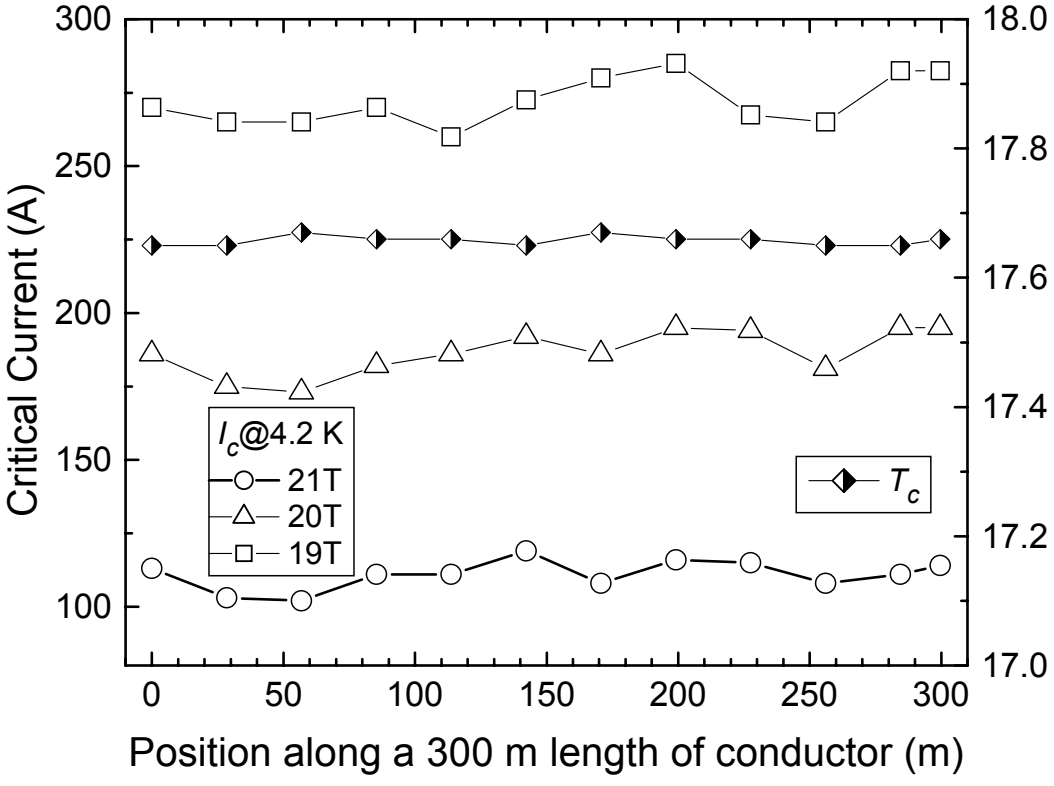






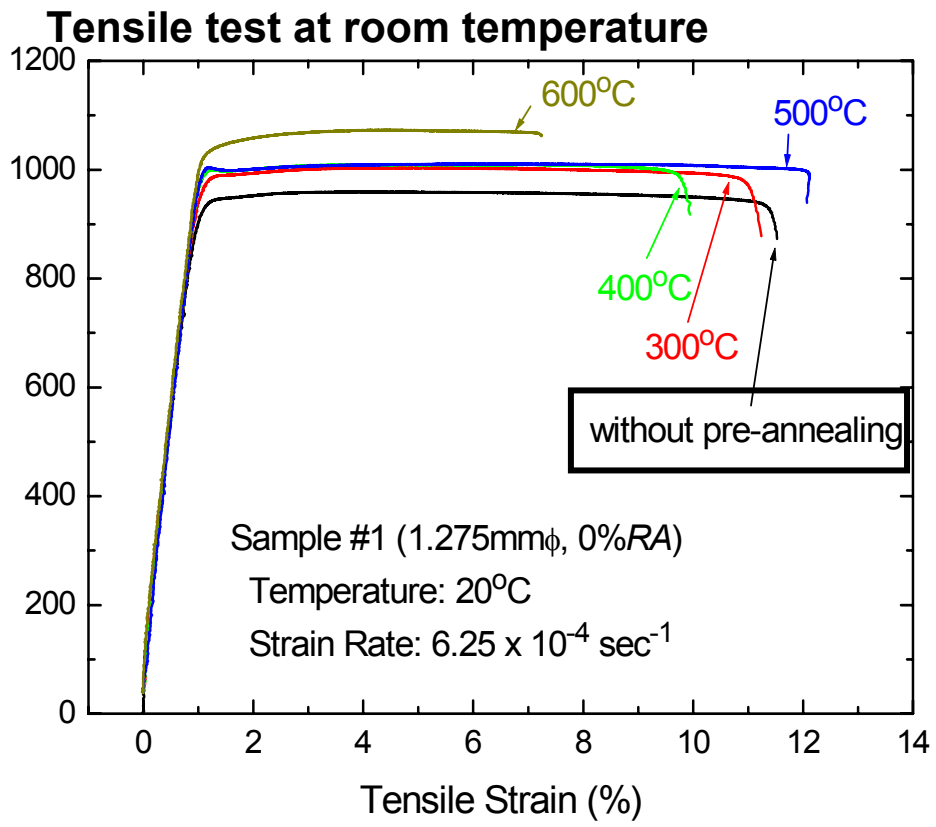
Distributions of T_c and J_c along a 300 m length of wire





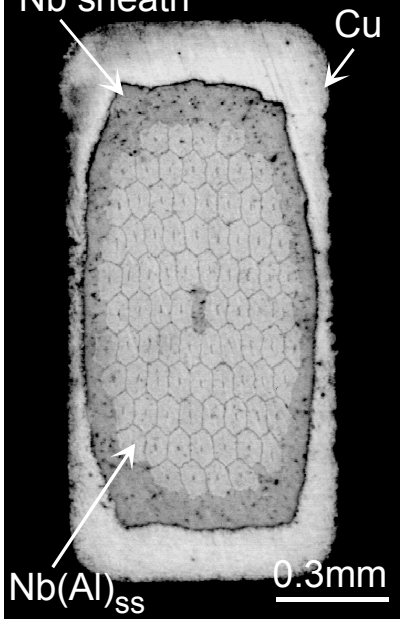
Standard deviation of J_c (4.2K&21T) : 5 %

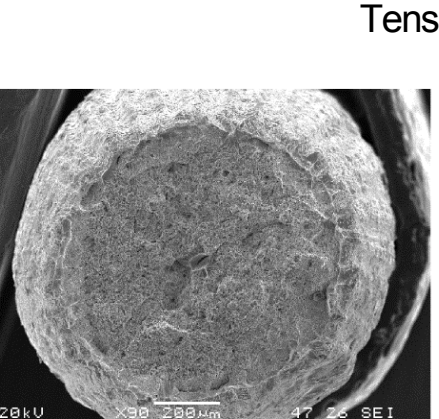
Deformability of $Nb(Al)_{ss}$ at RT

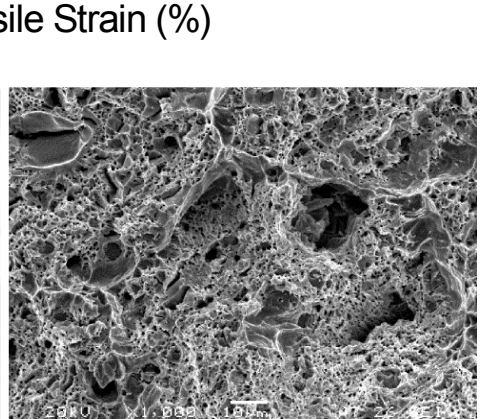


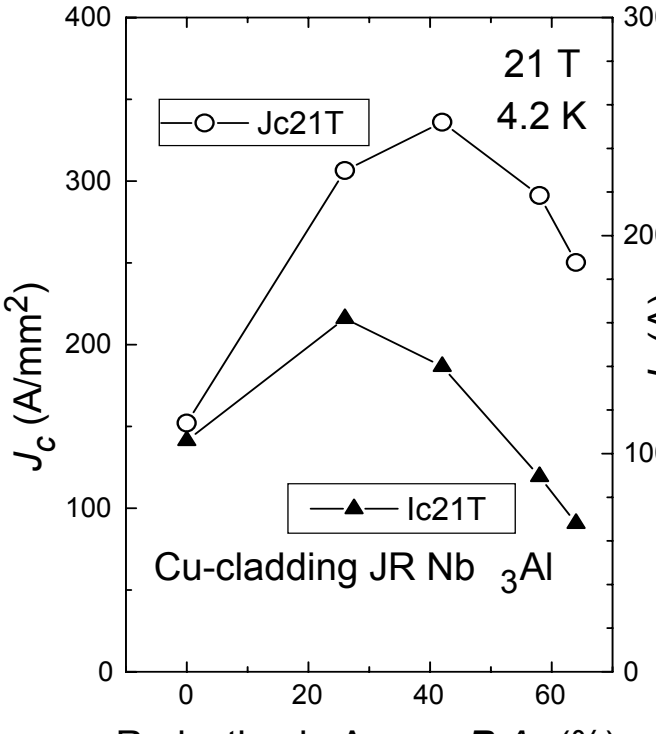
Incorporation of Cu stabilizer by mechanical cladding

J_c improvement

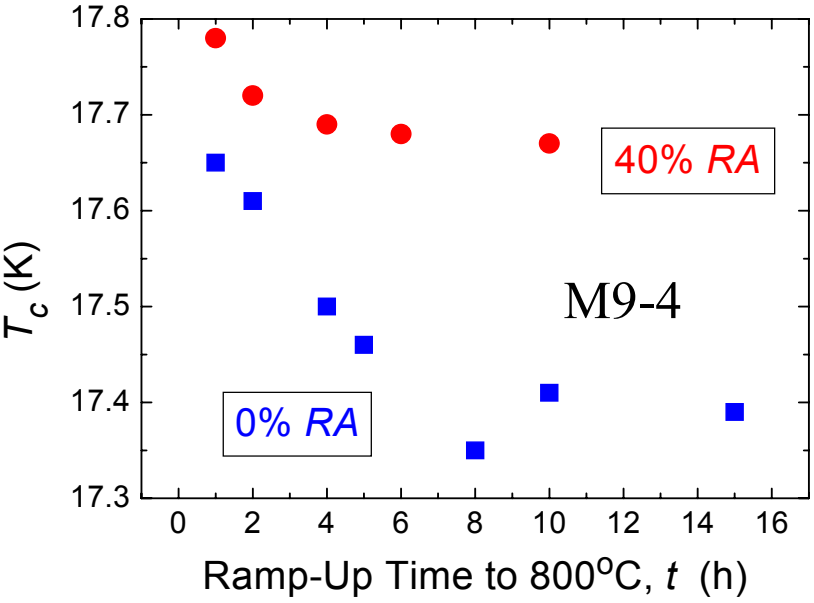


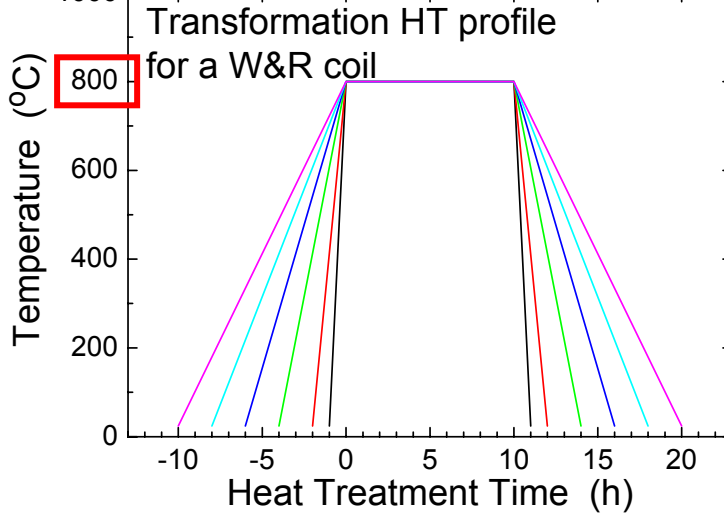


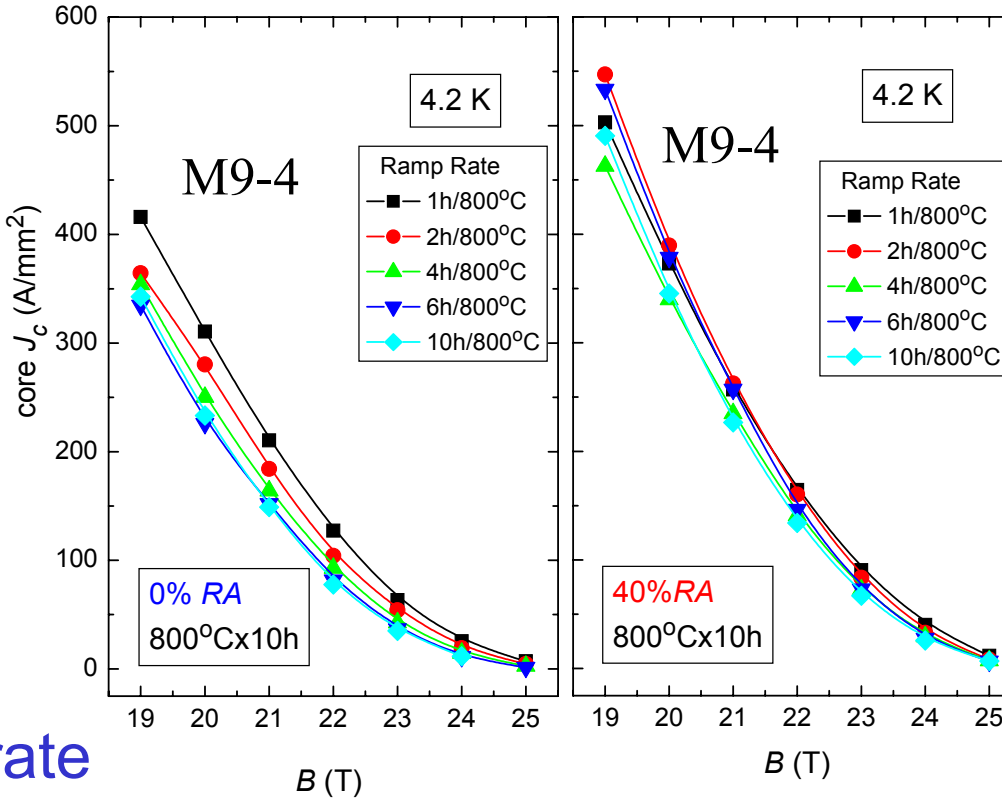




Temperature ramp-up rate at transformation annealing







Deformation

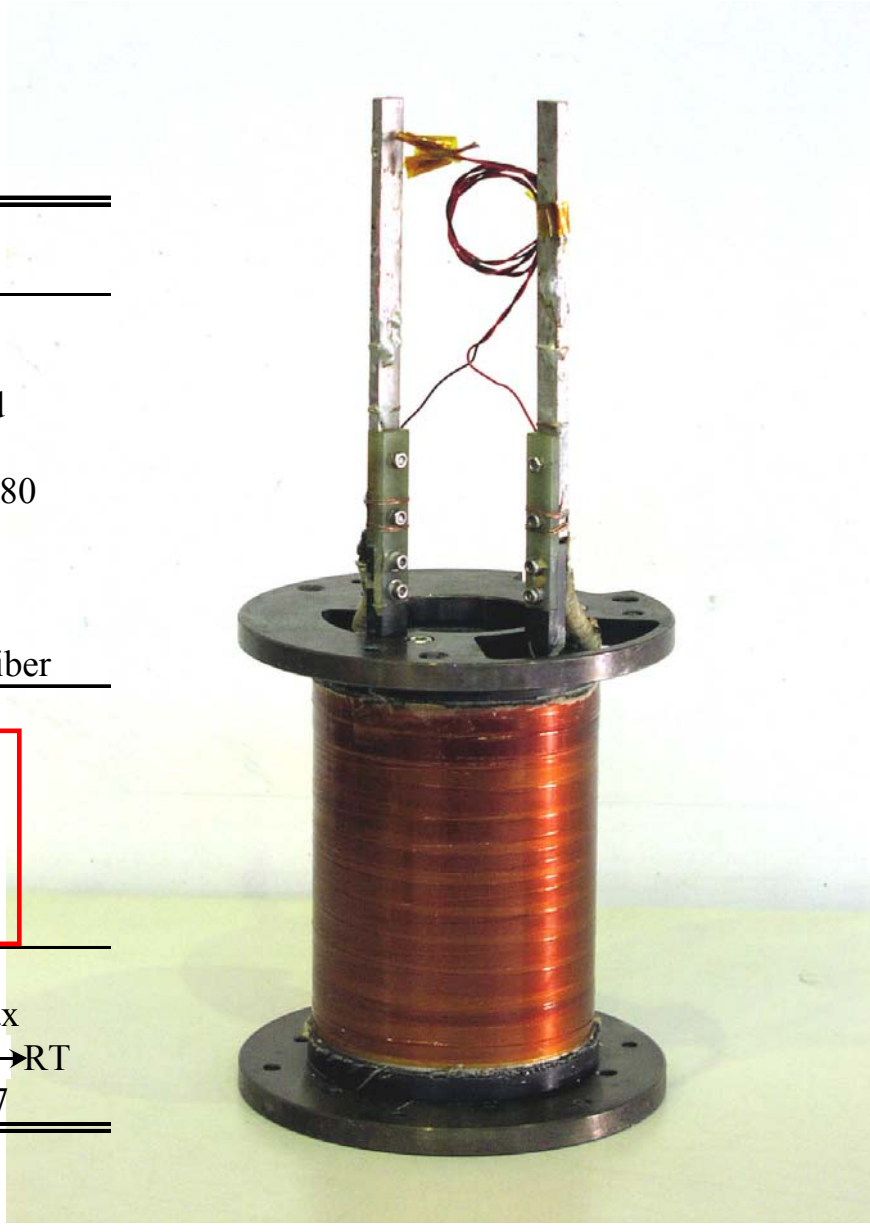
J_c enhancement

Less sensitive to ramp rate

Coil specifications

TABLE I
SPECIFICATIONS OF WIND & REACT Nb_3Al SOLENOID COILS

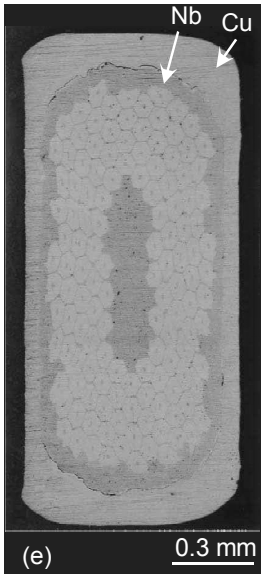
	Previous M11-1	Present ME332	Present ME356
HQT JR Nb_3Al con-ctor			
Stabilizer	Cu-clad	Cu-clad	Cu-clad
Piece length (m)	35	370	370
Cross section (mm^2)	1.61x0.71	1.82x0.84	1.81x0.80
Filament diameter	70	74	75.5
Number of filaments	84	132	132
Cu/non-Cu ratio	0.45	0.38	0.39
Insulator	Al_2O_3 fiber	Al_2O_3 fiber	Al_2O_3 fiber
Winding			
Inner diameter (mm)	19.7	90.2	64.6
Outer diameter (mm)	40.8	111.8	99.3
Height (mm)	49.7	200	132.4
Number of turns	311	949	988
Total length of wire	30	300.5	254
Coil			
Impregnation	Beeswax	Beeswax	Beeswax
Transformation	RT→(5h)→800°C→(10h)→800°C→RT		
Coil constant (T/A)	0.00106	0.00562	0.00797

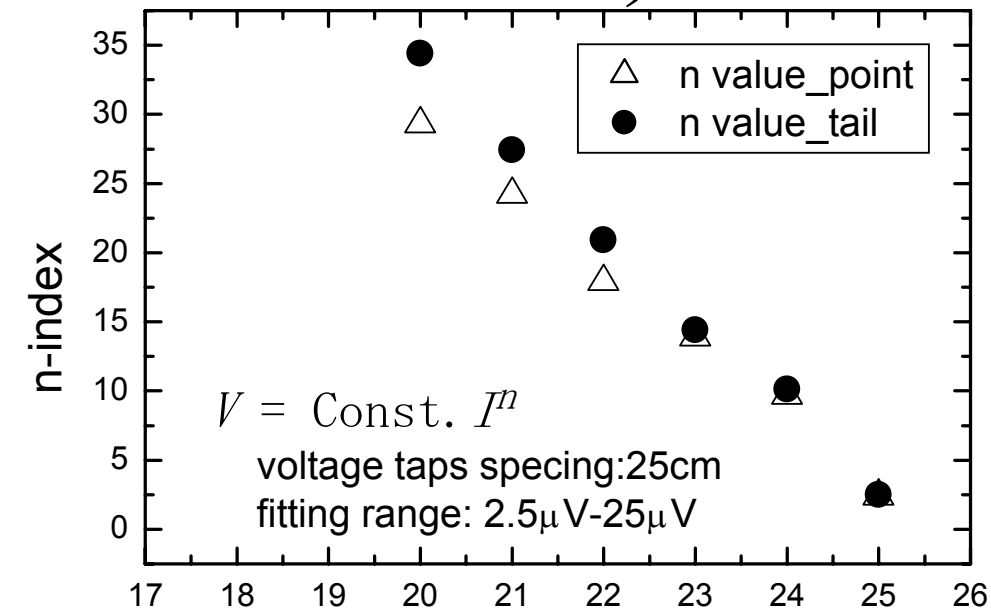


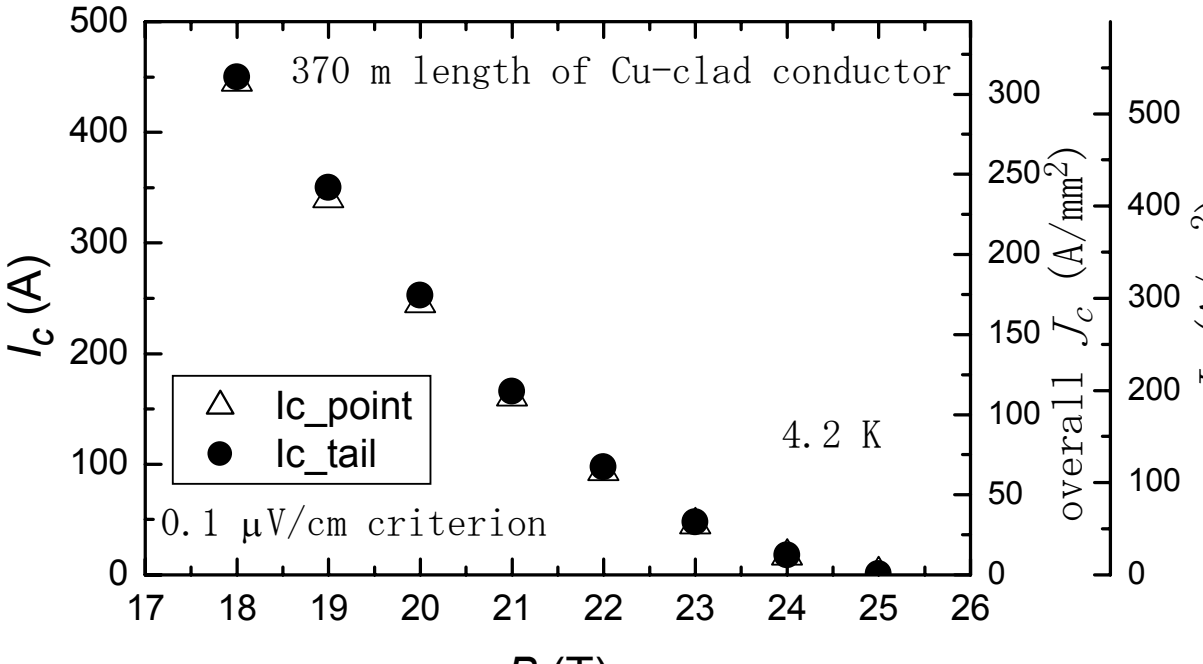
n-value (10^{-5} – 10^{-4} V/m)

Consistency of I_c point, tail of 370 m *n*-value

25@21T,4.2K





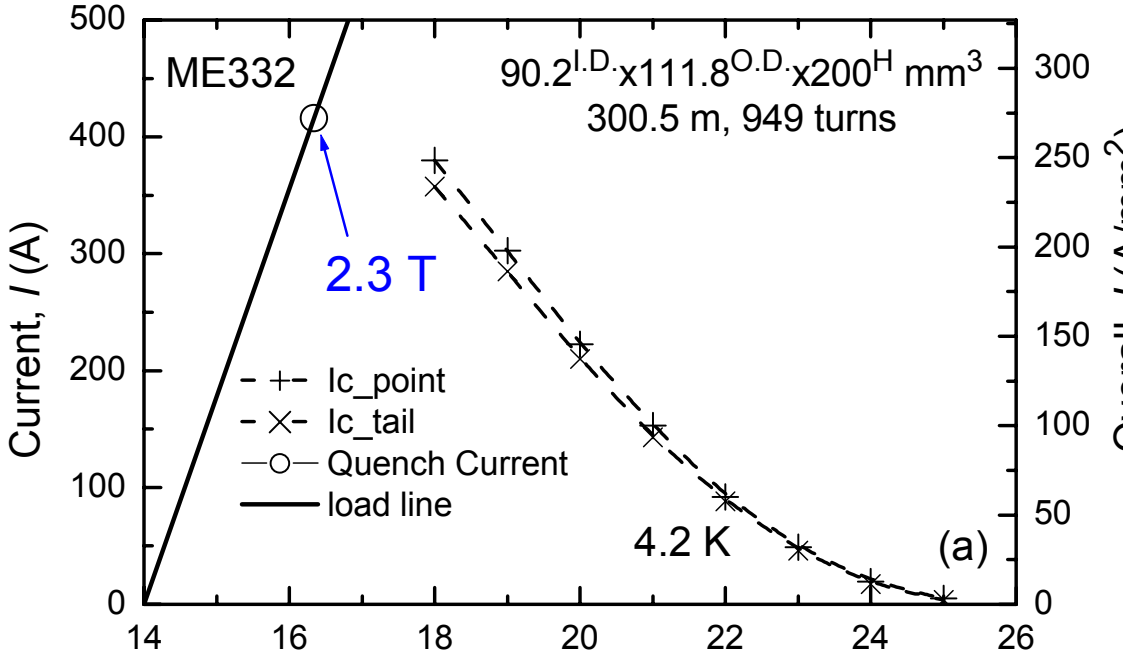


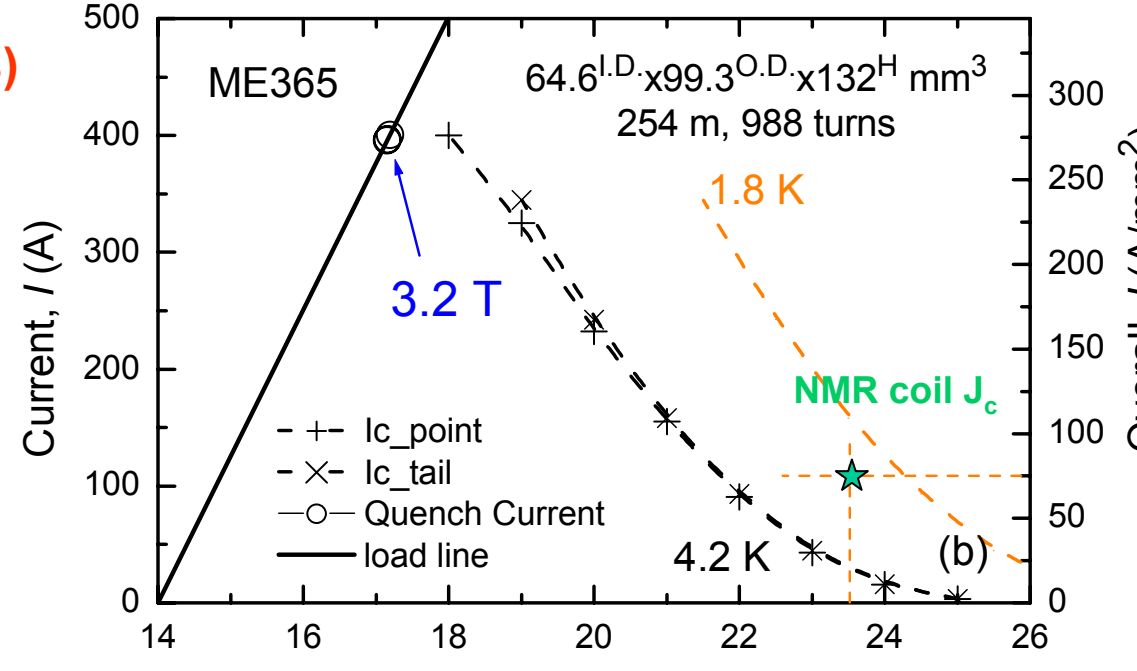
· Loading test

I_q (coil) > 0.9 I_c (short samples)

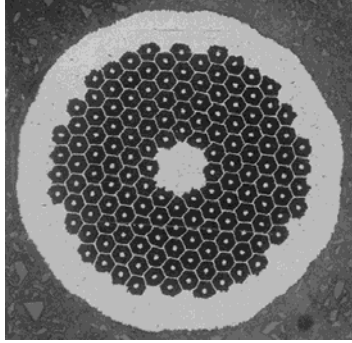
Uniformity of a long-length of RHQ operation over 300 m

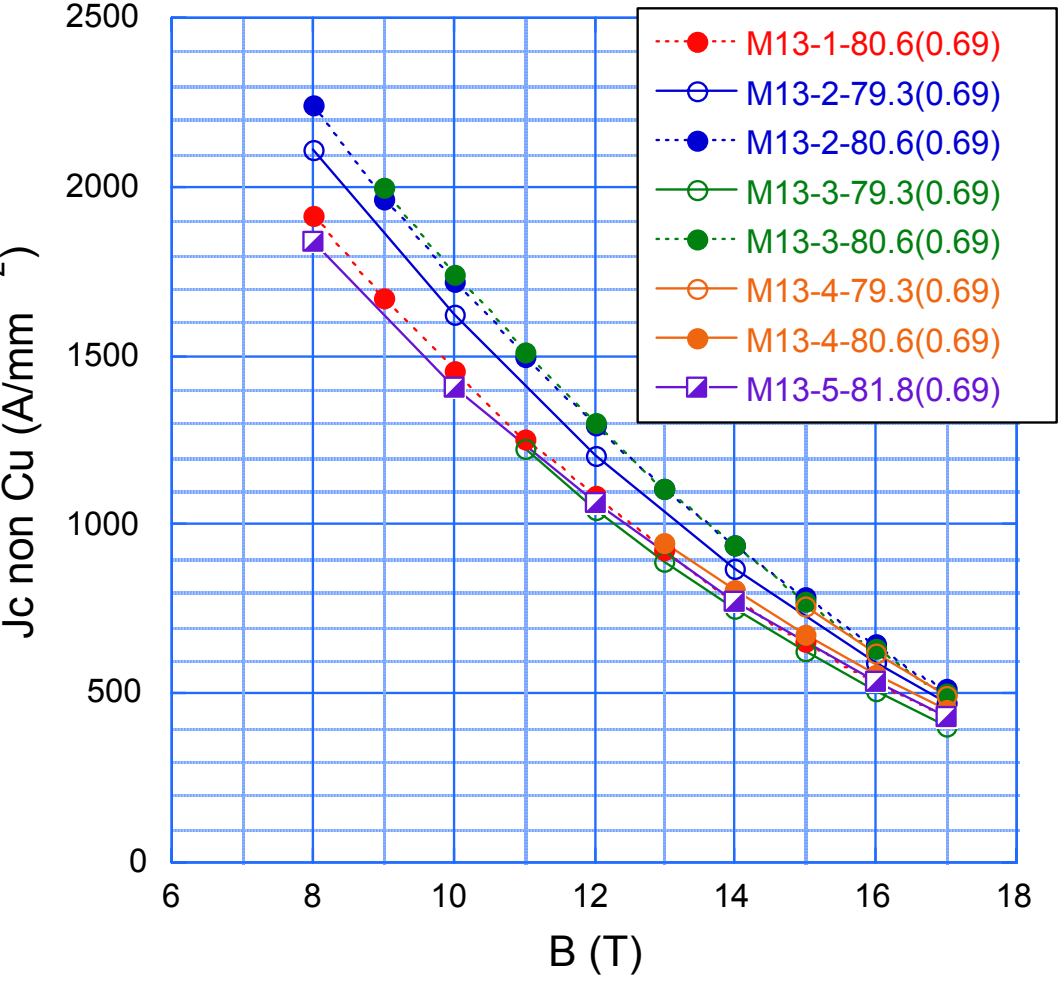
· **RHQT Nb_3Al is really reliable for practical coil application.**



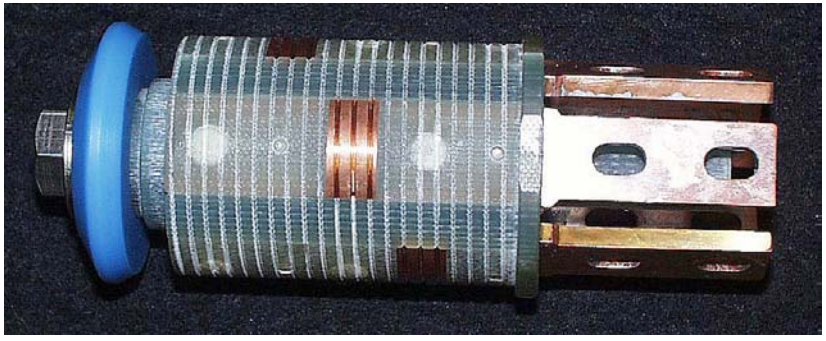


KEK





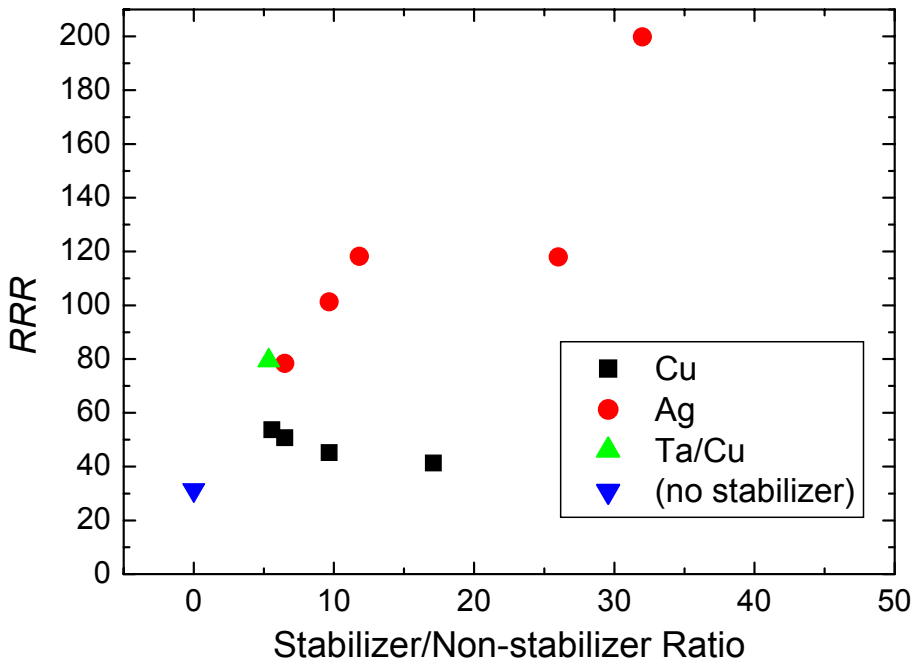
- 1 kA I_c probe
- Measurement of J_c of round wire
  electroplated with Cu
  in fields from 8 to 17 T
- Optimization
  wire diameter: 0.8→0.69 mm
  RA: 20% (< 40% for 21T)
  transformation HT: 775°C15
- Highest J_c:1730 A/mm^2 at 10 T

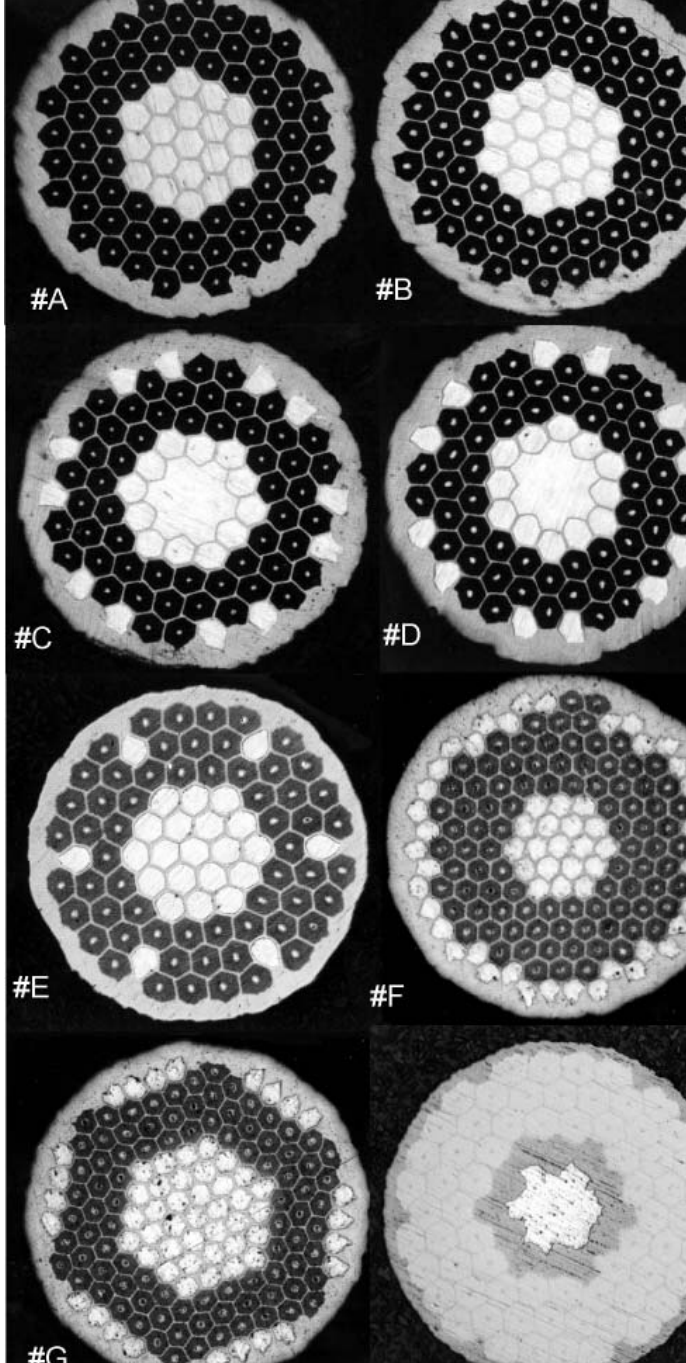


Sample length: 300 mm
Large cross section of Cu: 72 mm^2
Heating at 1000 A: < 80 mW/lead
(ΔT < 10 mK)

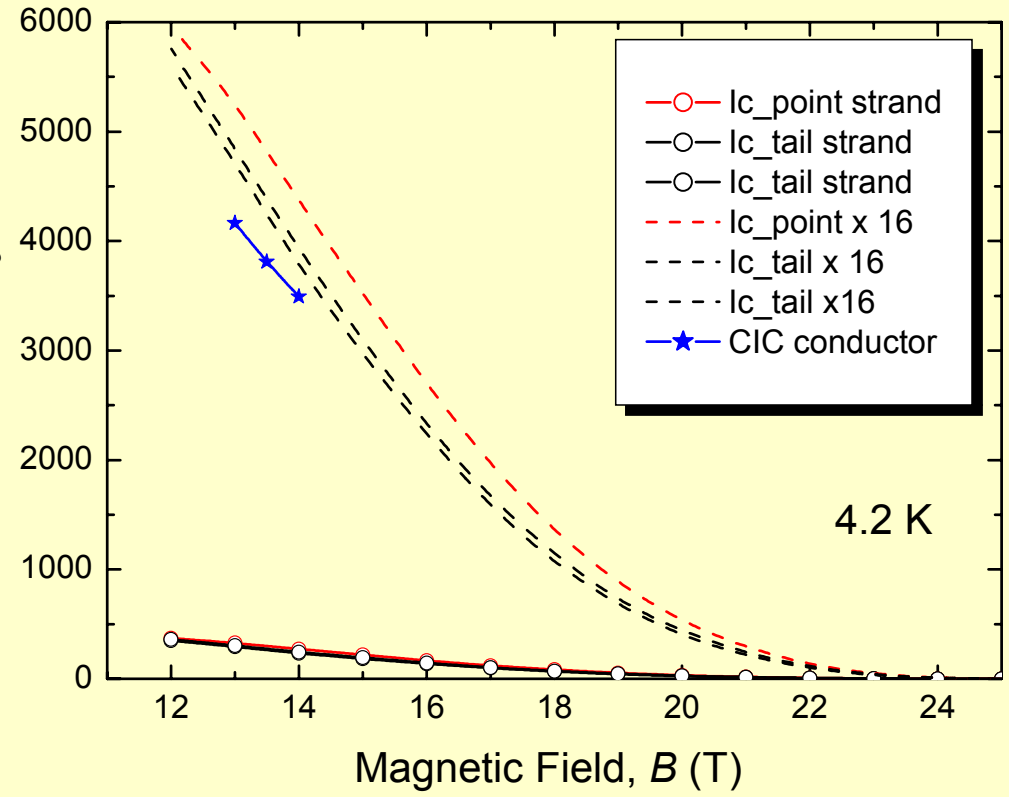
Internal Stabilization

- Less expensive
- Round cross section of wire
- Possible high current conductors (CICC, Rutherford cables, etc)
- No contamination of Ag with Ga
- Large RRR (200)
- Applicability to high temperature transformation (TRUQ, DRHQ)





Trial Manufacture of High-Current RHQT Nb_3Al Conductors



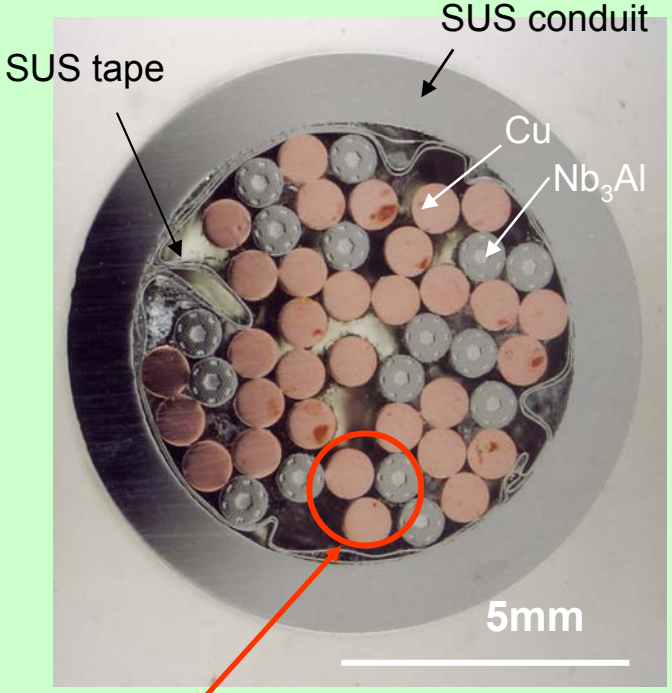
I_c at 14 T

Measure: 3.49 kA

Design ($I_{c,\ strand}$ x 16): 3.7 – 4.3 kA

7% degradation

Cable-in-Conduit Conductor for Fusion Uses



The 1st triplet: a Nb_3Al, two Cu

The third stage cable: 3 x 4 x 4

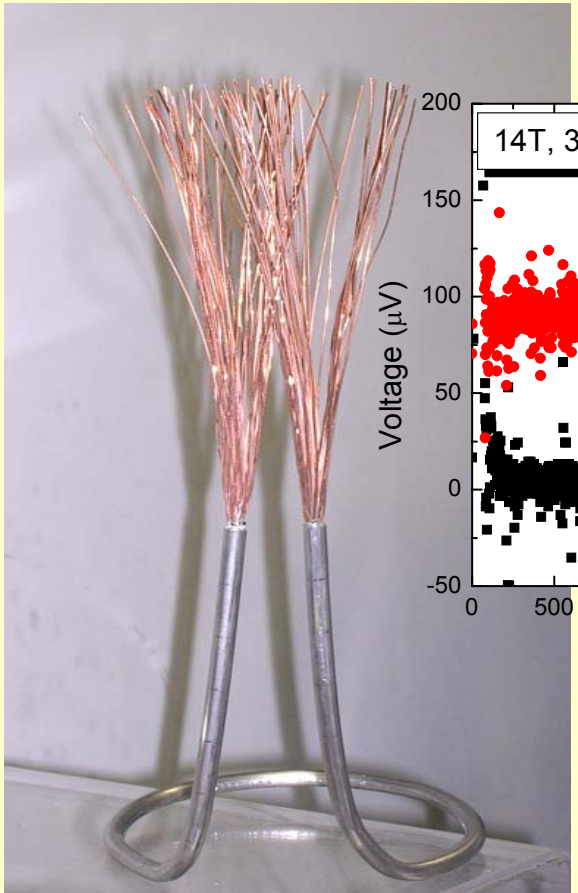
Internally stabilized Nb_3Al strand

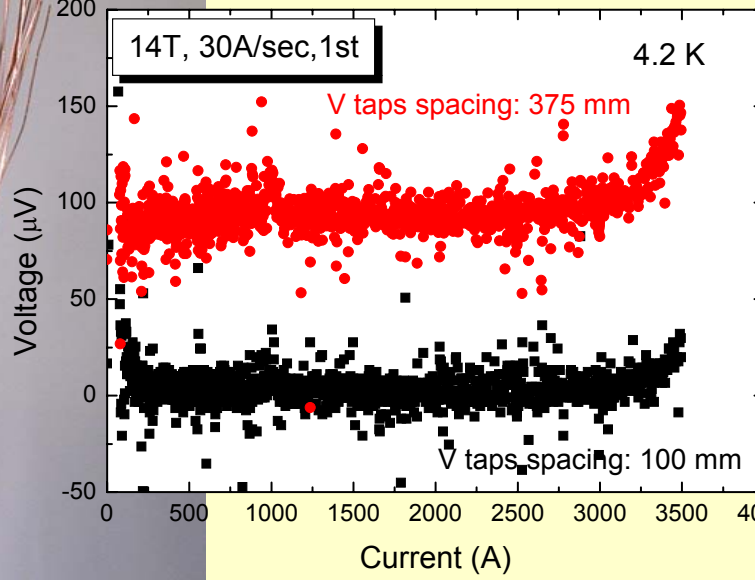
0.8 mm Φ

Measurement_1

V taps spacing: 100 mm, 375 mm

Current ramp rate: 30A/sec, 60A/sec





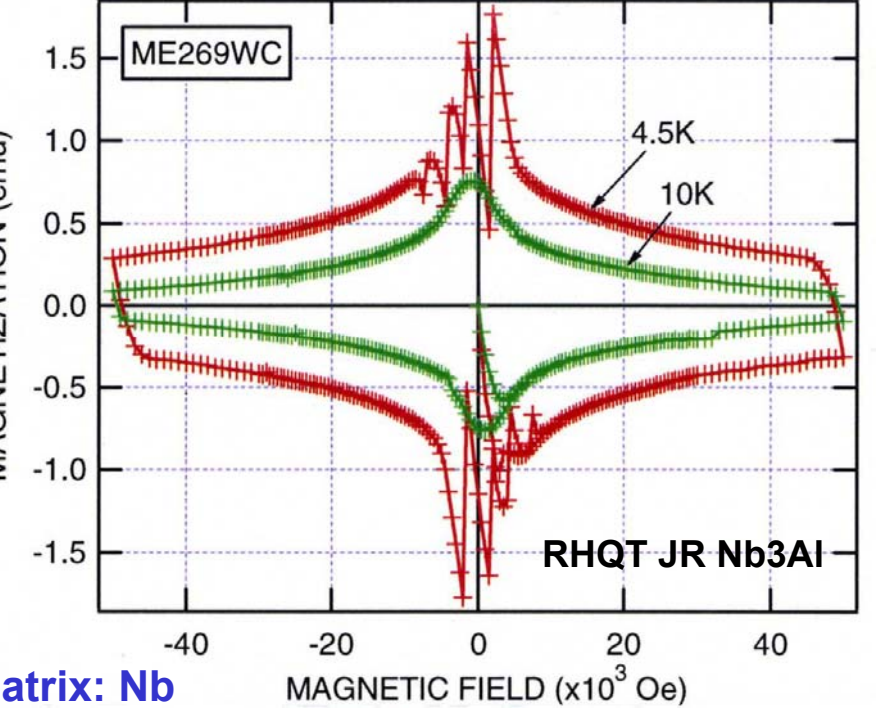
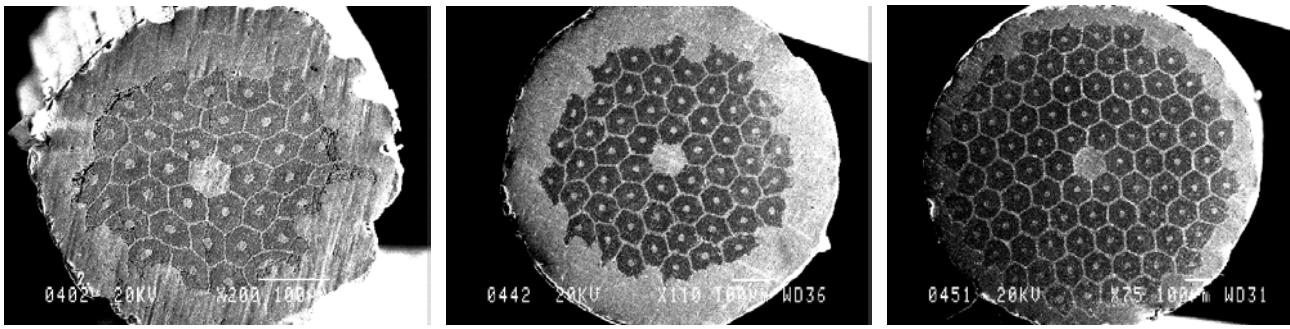


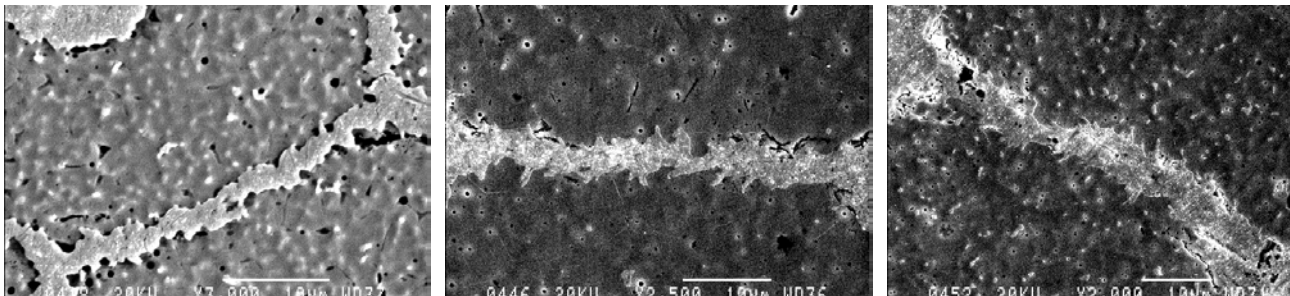
Table 1 Specifications of measured JR Nb_3Al wires.

Sample	#1	#2	#3
Diameter of wire (mm)	0.507	0.89	1.275
Number of filaments	36	84	84
Diameter of filament (μm)	55	76	108
Average thickness between filaments (μm)	2.8	6	9.4
Nb/Non-Nb ratio	1.5	1.39	0.59

atrix: Nb
lux jump

Not desirable for fusion and accelerator magnets



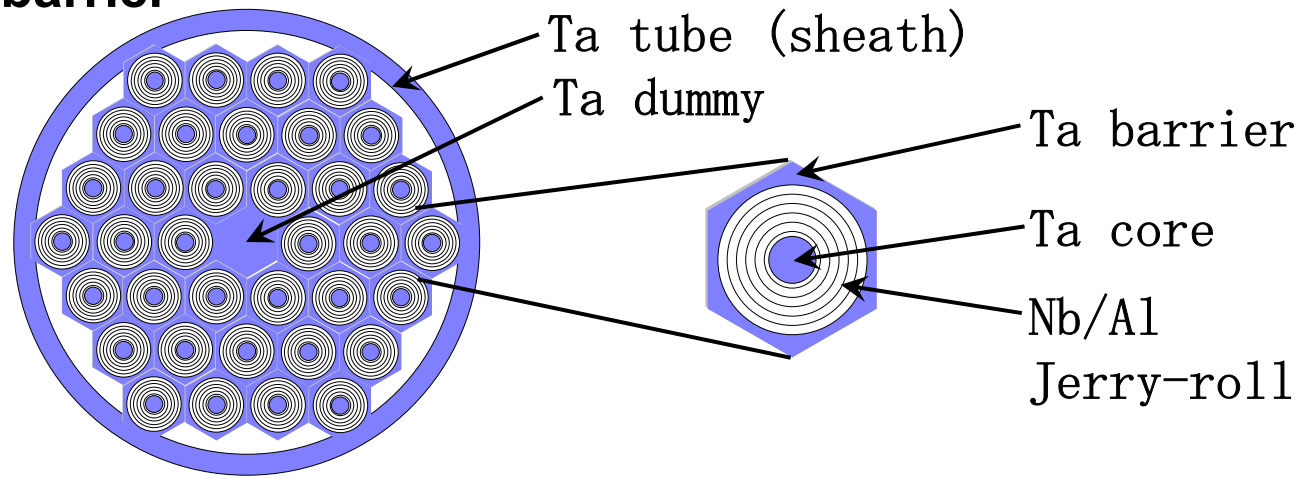


AC Loss

- **bridging**
- **proximity effect**

Manufacture of Ta matrix JR Nb_3Al wire

Ta core-Ta barrier



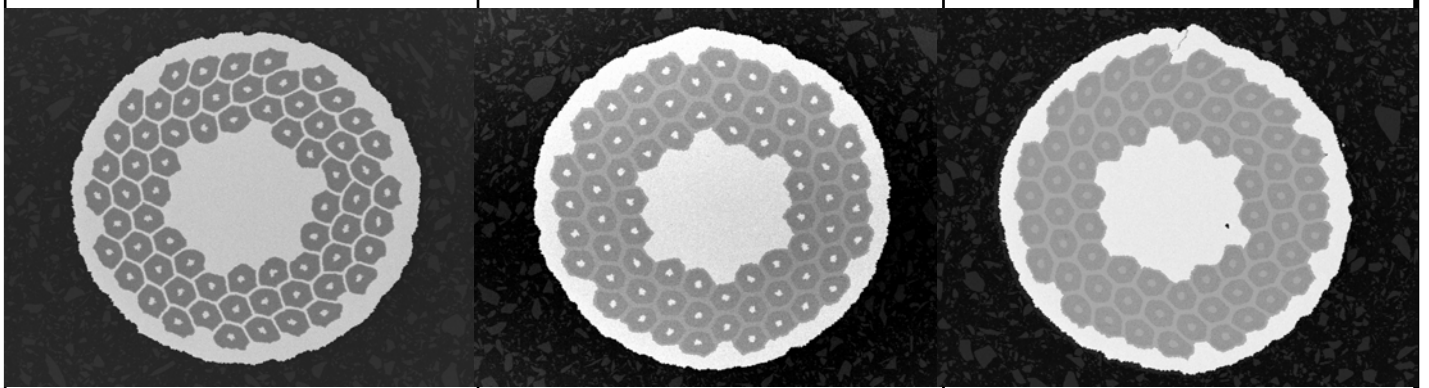
2 other filament structures

Ta core-Nb barrier

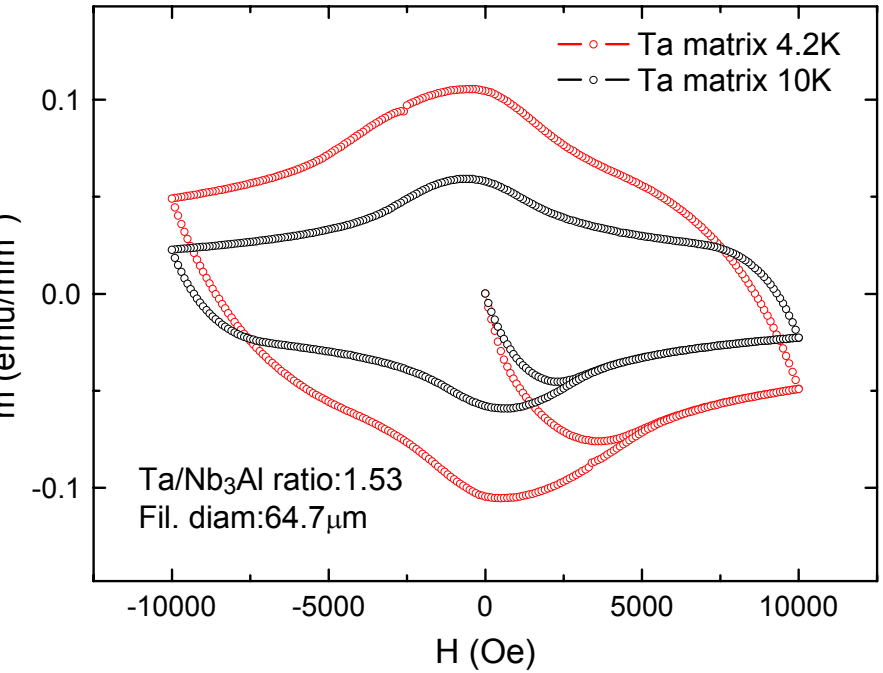
Nb core-Nb barrier (conventional)

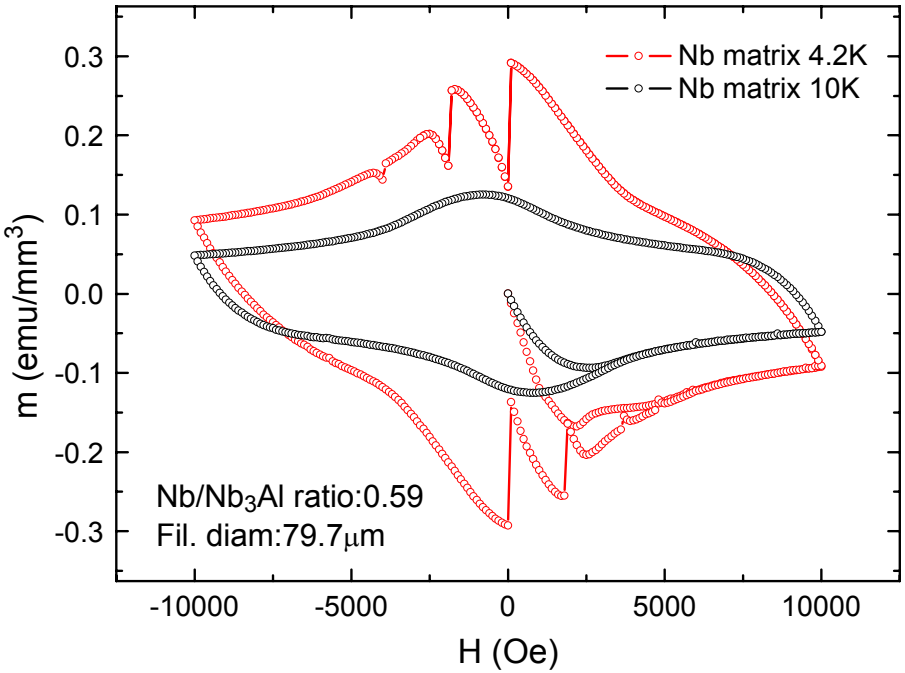
Workability

Wire Diameter	No of filaments	Filament diameter	Matrix ratio (non JR / JR)
Φ0.8mm	66	ϕ 65 μ m	1.5

Structure	Ta core-Ta barrier (ﾌｨﾗﾒﾝﾄ間:Ta JRｺｱ:Ta)	Ta core-Nb barrier (ﾌｨﾗﾒﾝﾄ間:Nb JRｺｱ:Ta)	Nb core-Nb barrier (ﾌｨﾗﾒﾝﾄ間:Nb JRｺｱ:Nb)
Cross section			
Workability	Very Good (no breakage until ϕ 0.5mm)	Good (no breakage)	Good (no breakage)

Magnetization curve





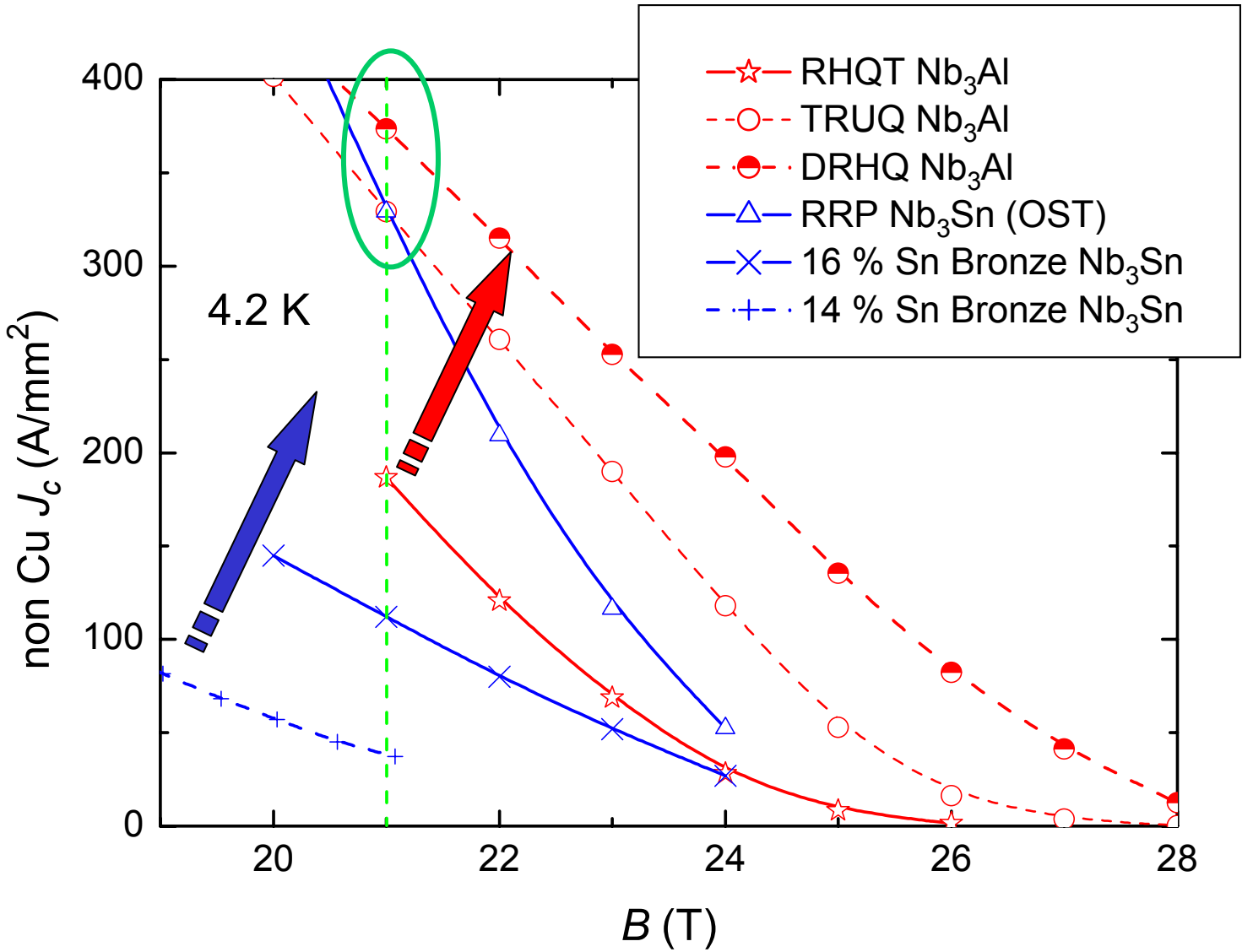
Ta matrix

⟶ suppression of flux jump

Other advantages

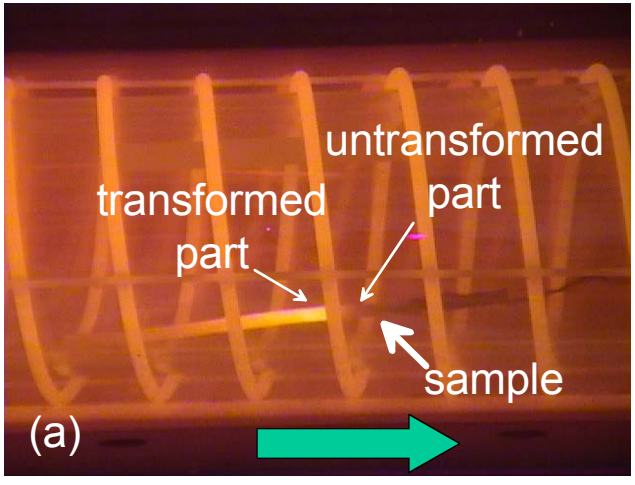
- **high strength at high temperature**
- **no formation of Ga-rich compound on a surface**
- **less induced-radioactivity**

Potential of RHQT Nb_3Al

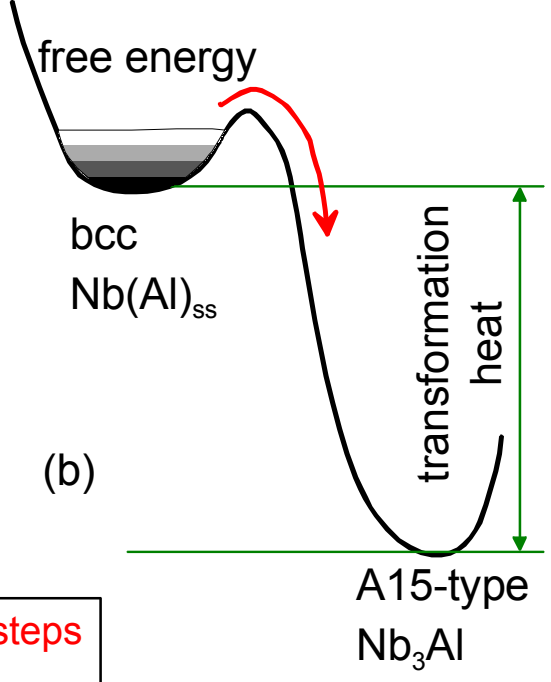


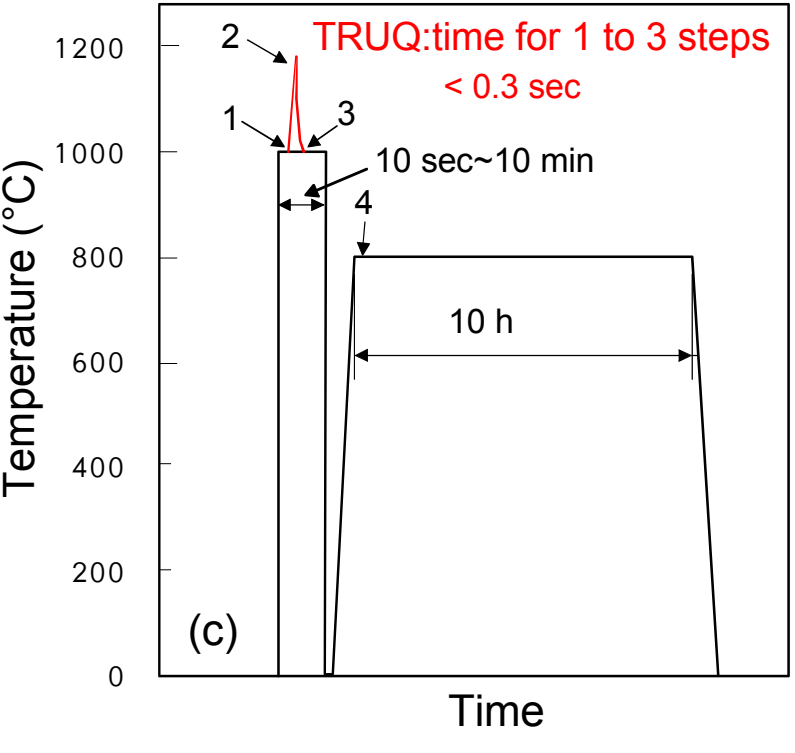
TRUQ

similar to a combustion synthesis



propagation of heat

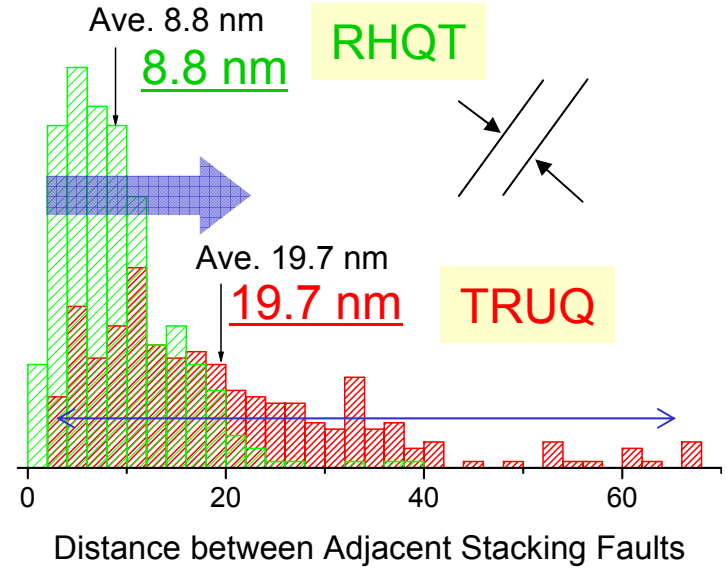


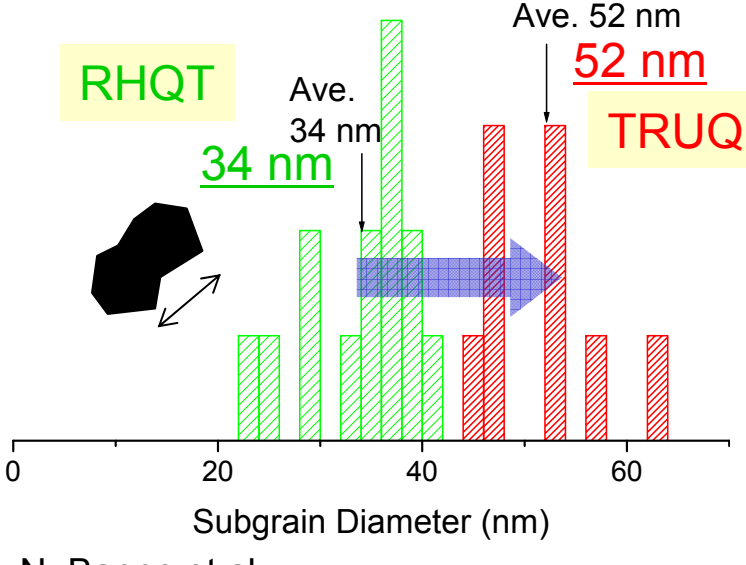


TRUQ *(**TR**ansformation-heat-based **U**p-**Q**uenching)*

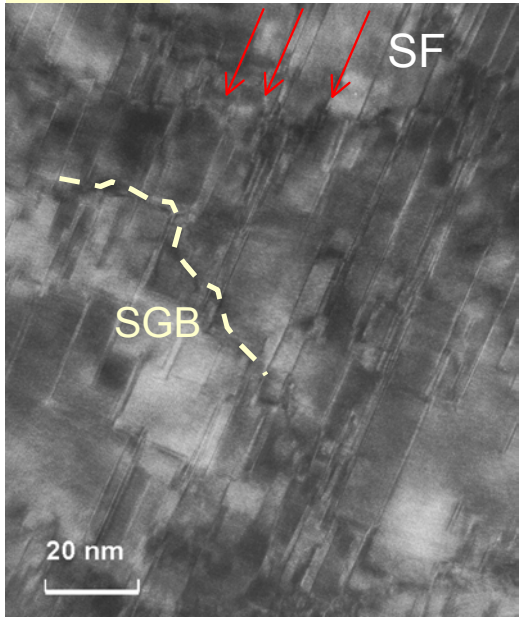
1. ignition (nucleation of transformation)
2. thermal explosion
   - ·propagation of the transformation interface
   - ·trasform to A15 via highly disordered bcc phase
     - low long-range order
     - free from stacking faults
3. self-turn down to ambient temperature
4. annealing for long-range order

Microstructure

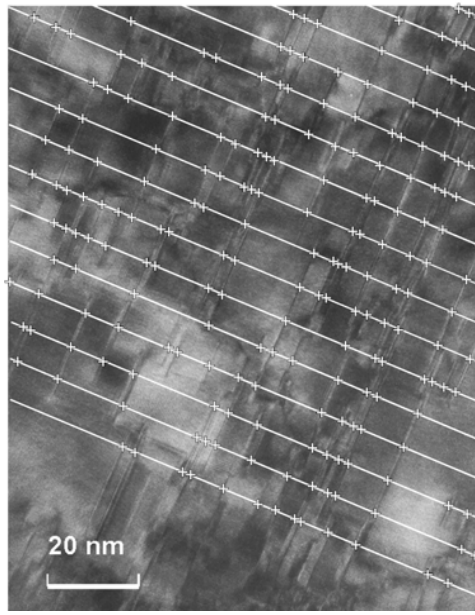




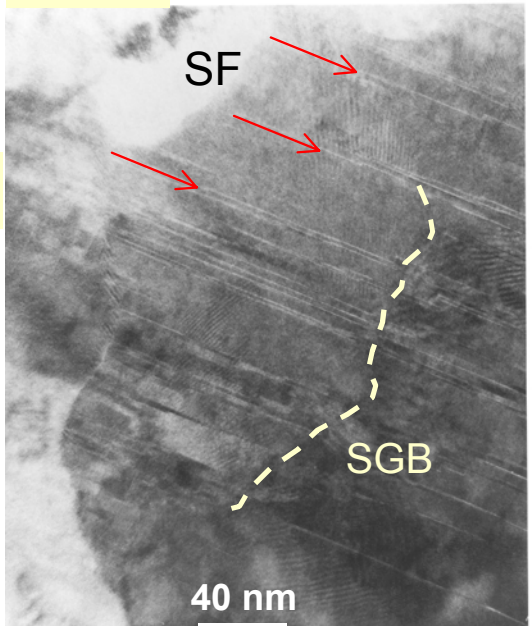
RHQT

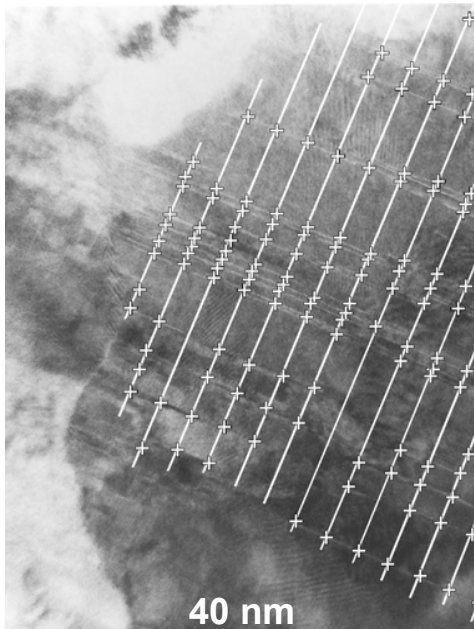


TEM像



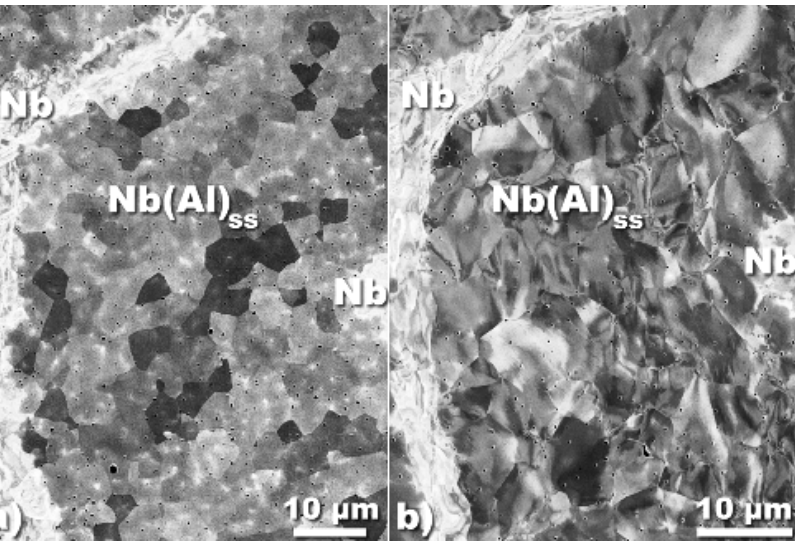
TRUQ





Non-uniformity

Microstructure by FESEM by P. Lee



a) as-quenched wire at 1.27 mm and b) after Cu-cladding and forming into tape.

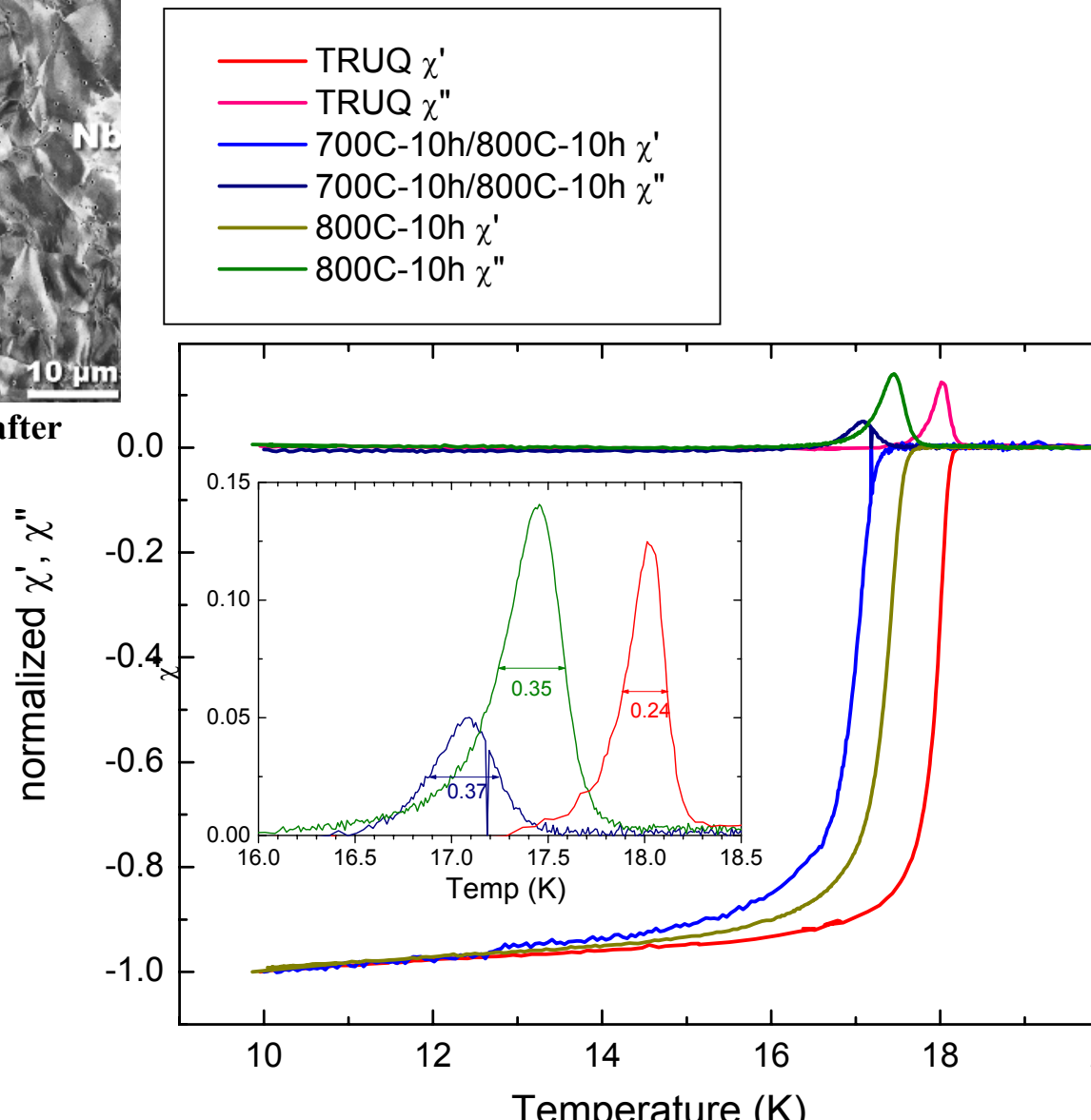
Microchemical homogeneity in filaments

↓

Sharp transition

↓

Enhancement in Jc



Optimization for Jc

under the condition of ordinary transformation
that enables W&R coil (～800°C, ramp rate of 1-5 h/800°C

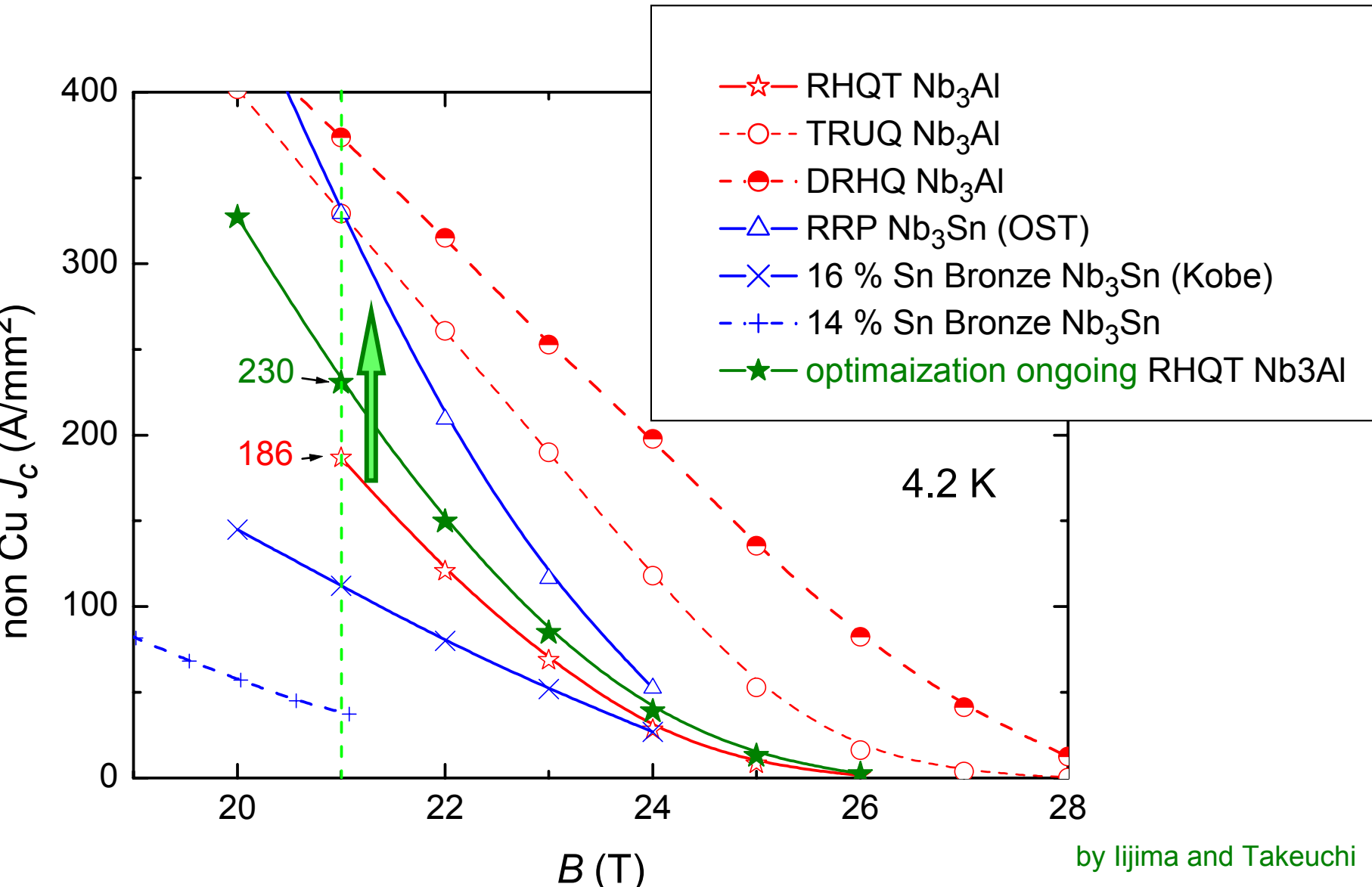
Parameters

- Wire diameter
- Nb matrix ratio
- No. of JR filaments
- Filament diameter
- Inter-filament spacing
- Nb/Al ratio
- layer thickness
- Alloying

- Joule heating current density
- Heating distance
- Wire speed at RHQ
- R.A. after RHQ
- Transformation HT

Microchemistry
Crystal imperfection
bcc grain, ordering
A15 grain
Stacking faults

Ongoing improvement of JR Nb_3Al



by Iijima and Takeuchi

Development Schedule

- Long-length of precursor (>2km)

  large billet
- Long-length of RHQ processing (>2km)

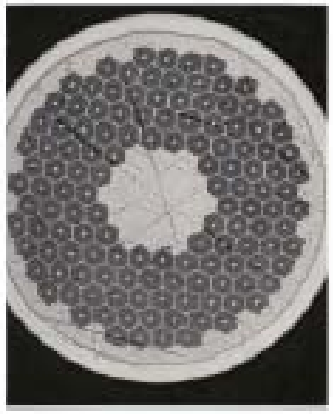
  large-scale RHQ apparatus: under construction
- Reel-to-reel Cu ion plating

  installation, trial operation

Target: piece length of more than 2 km for 1.35 mmϕ wire

Multifilament billet (50kg)

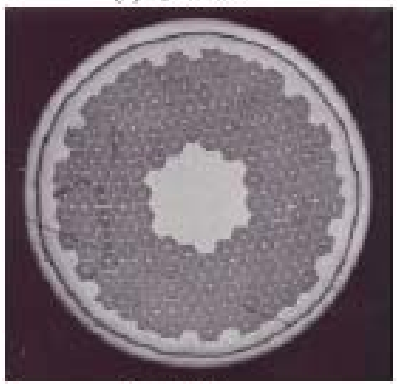
(a) φ8.40mm



(b) φ5.90mm

(c) φ2.90mm

Φ 2. 9 mm



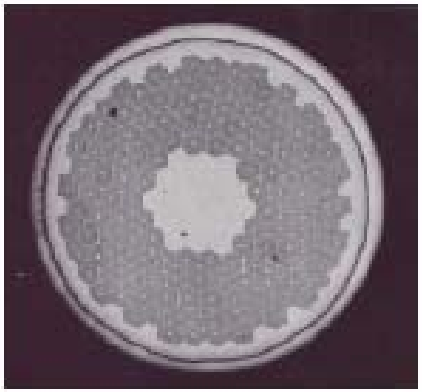
(d) φ1.75mm

Φ 1. 75 mm

No breaking during drawing of wire

Piece-length: 2.6 km for Φ 1.35 mm wire

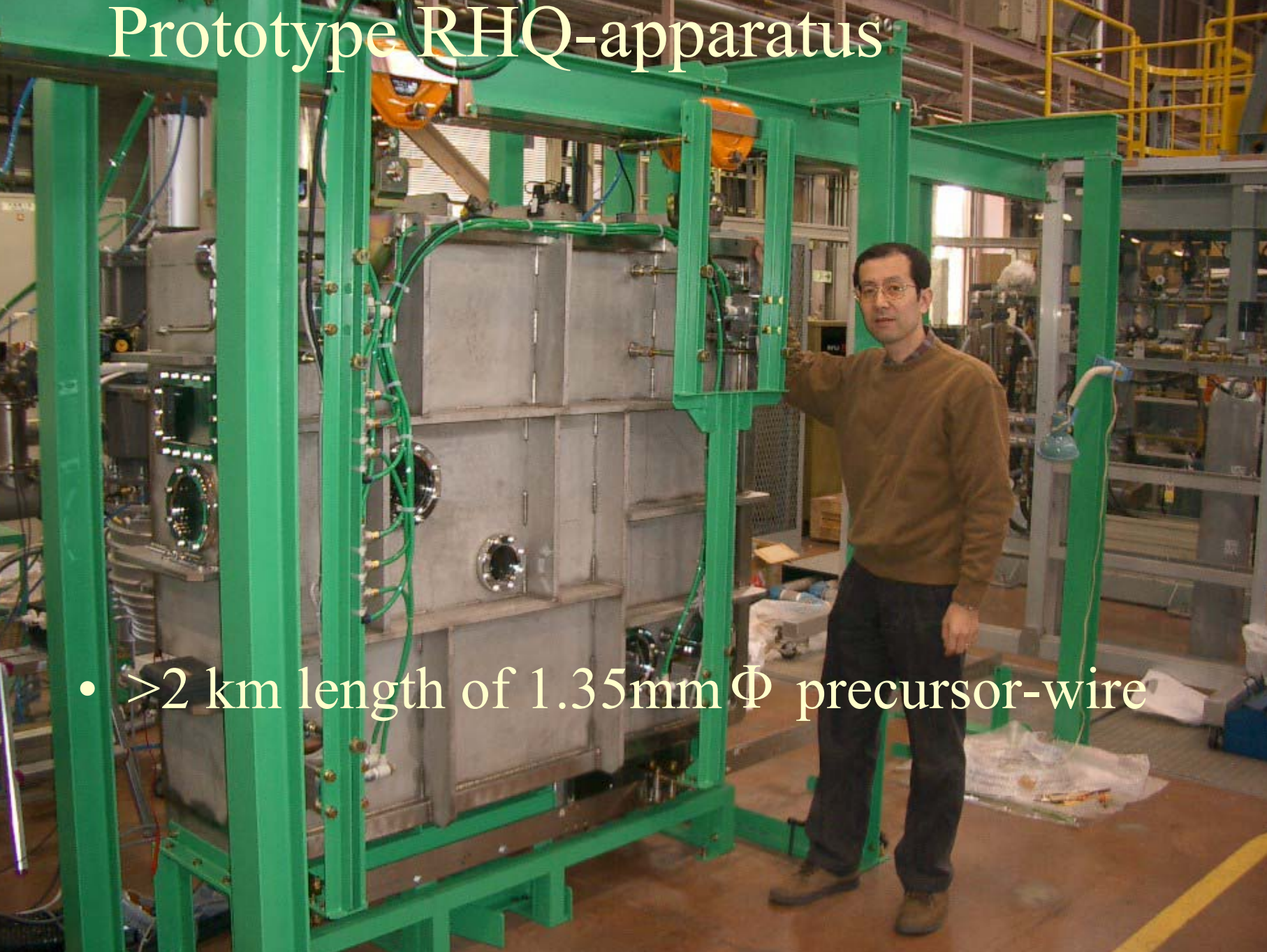
(corresponding to 9.7 km for Φ 0.7 mm wire)



(e) φ1.50mm(最终拔丝)

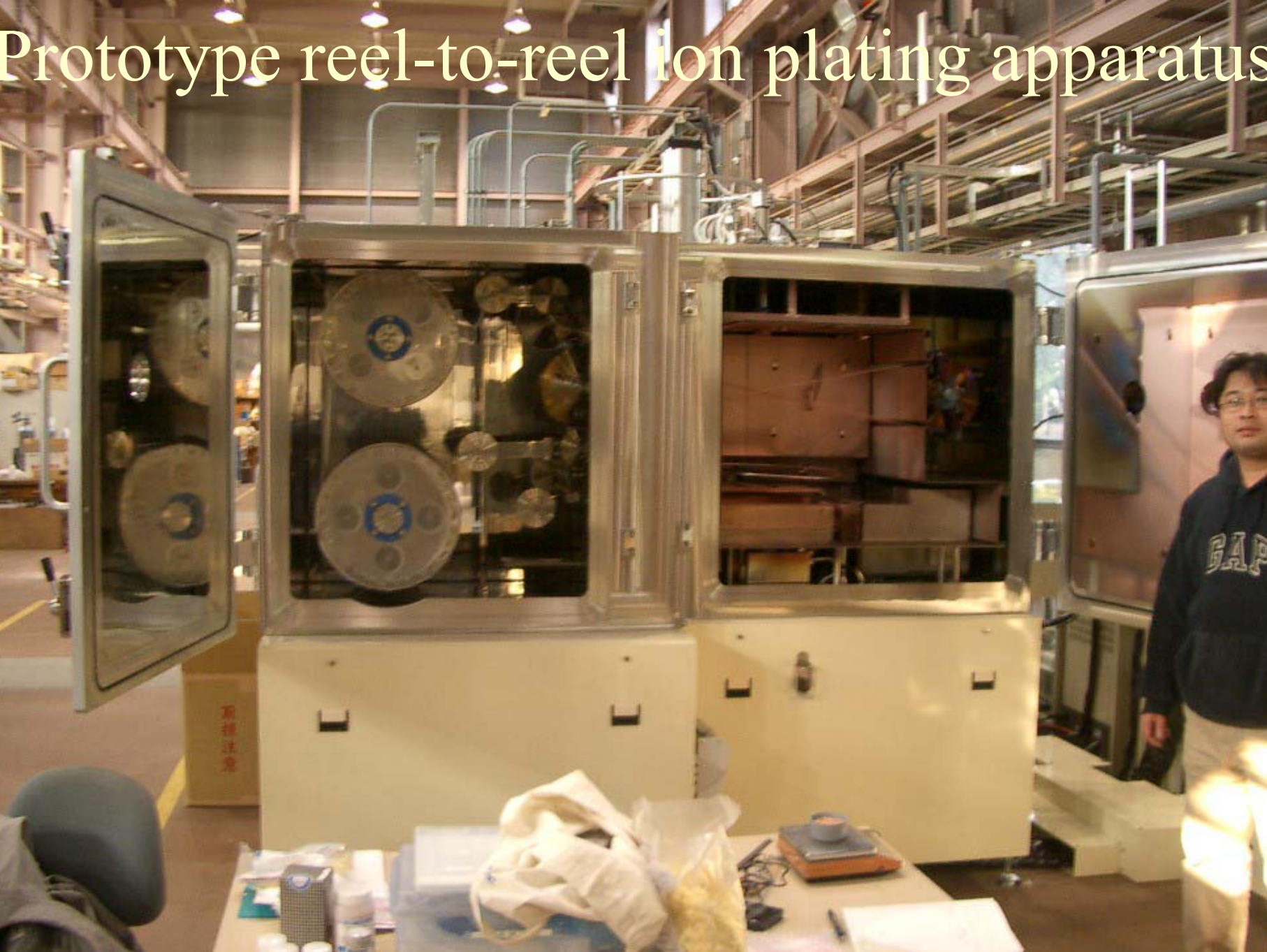
Φ 1. 50 mm

Prototype RHQ-apparatus

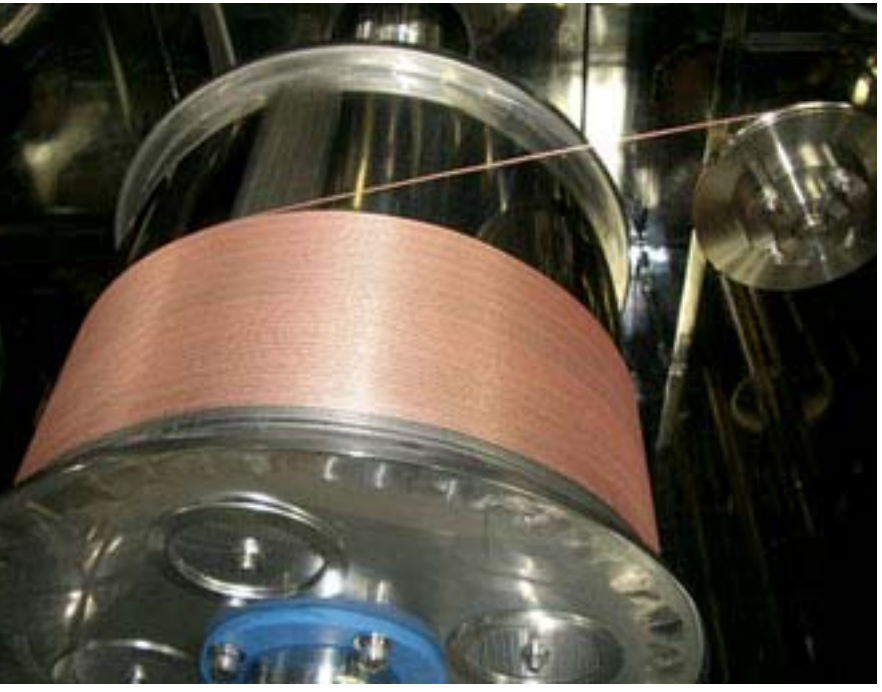


- >2 km length of 1.35mmΦ precursor-wire

Prototype reel-to-reel ion plating apparatus



Reel-to-reel Cu ion plating apparatus_2



Summary

- Large multifilament billet: 52 kg
- Piece length of precursor (1.35 mm): 2.6 km
- RHQ apparatus: just installed

  300 m → ? km
- Non-Cu Jc improvement (21T): Ongoing
- Stabilization of a round wire

  internal stabilization

  Cu ion plating and electroplating