KEK Effort for High Field Magnets

Tatsushi NAKAMOTO
KEK

Outline

- **Present R&D Status: < 15 T for HL-LHC**
    - **Nb_3Al Superconductor**
    - **13 T Subscale Magnet**
    - **Radiation resistance**
- **New Study Towards > 15 T**
    - **Stress, Strain Issues**
- **Summary**

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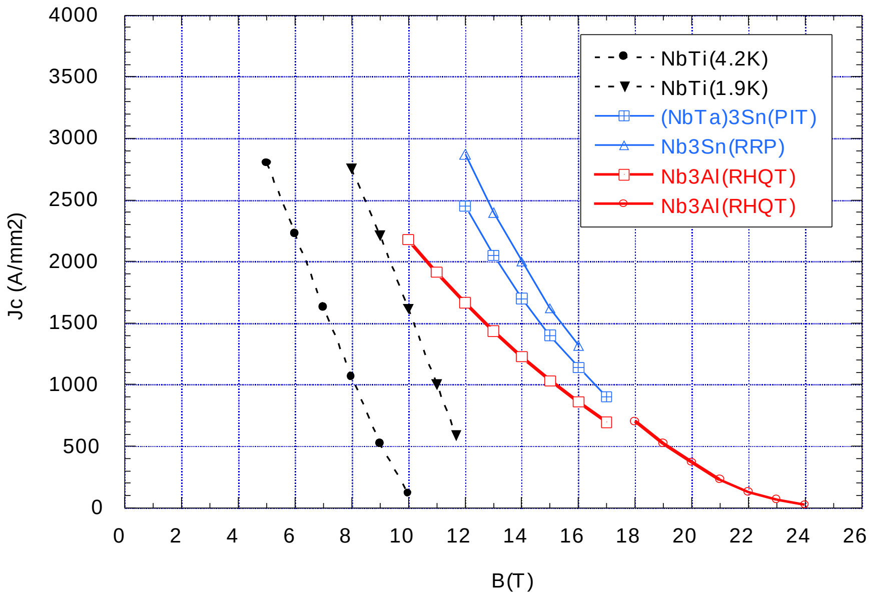
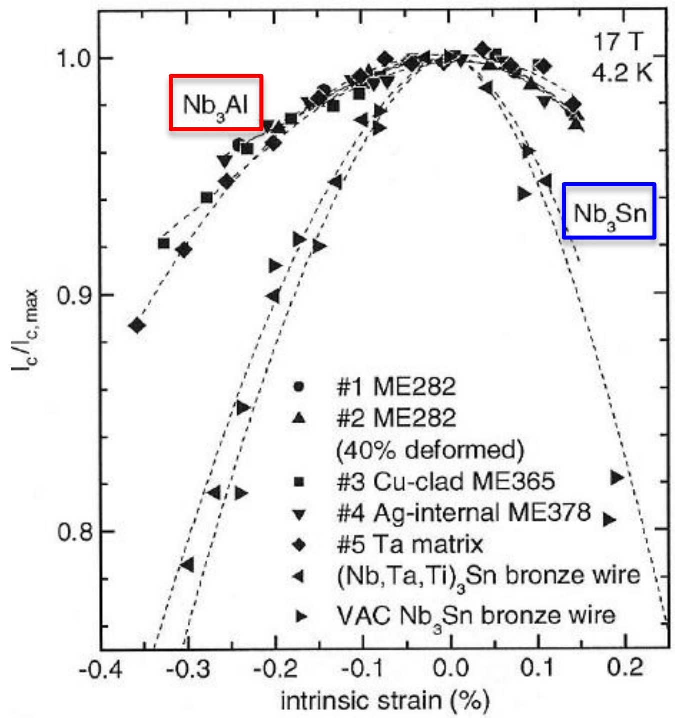
Motivation to Develop Nb_3Al

Critical current density (Jc) of Nb_3Sn is higher than Nb_3Al and advanced magnet technology has been developed by US-LARP……..

Jc vs. B





•**Better mechanical performance of Nb_3Al.**

•**KEK & NIMS has developed RHQ-Nb_3Al for accelerator HFM application with support by CERN.**

Nb_3Al Fabrication Process with RHQ Method: High Jc

Mono-filament

↓ **Jerry-Roll: Nb+Al sheets, Nb or Ta core**

Multi-filament

↓

Precursor (Nb/Al)

↓ ⇐ **Rapid Heating Quenching (RHQ)** ~2000°C

(Nb/Al)ss — **Strand w/o Cu**

↓

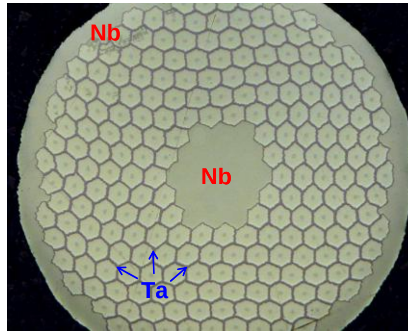
Cu stabilization / Area reduction

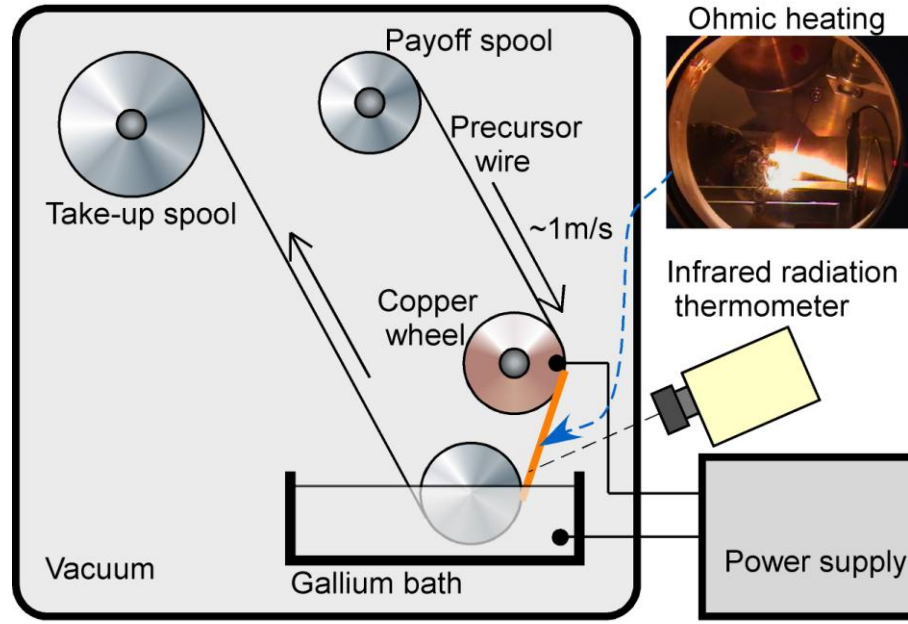
↓

Cabling, Coil Winding

↓ ⇐ **2^{nd} heating (800°C×10h)**

Nb_3Al — **A15 strand w/ Cu**



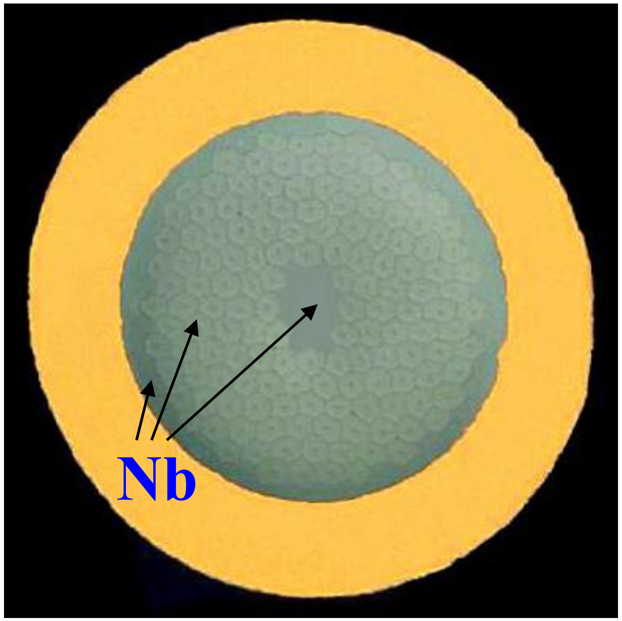


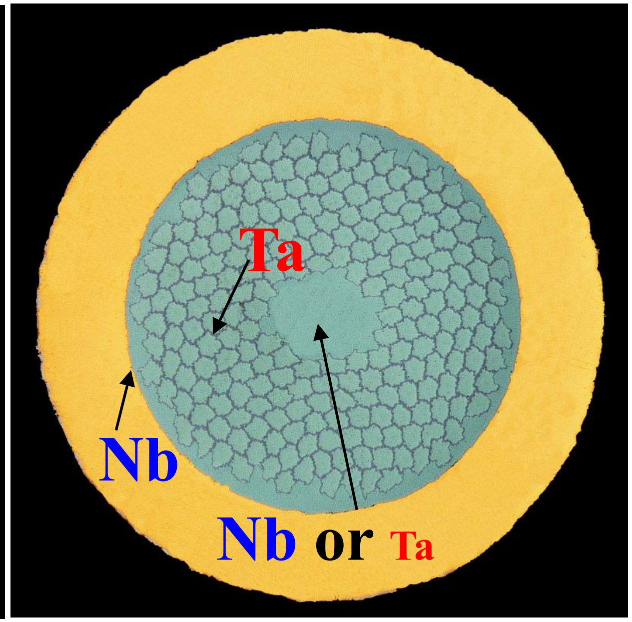
Continuous Electroplating for Ta-matrix Wire

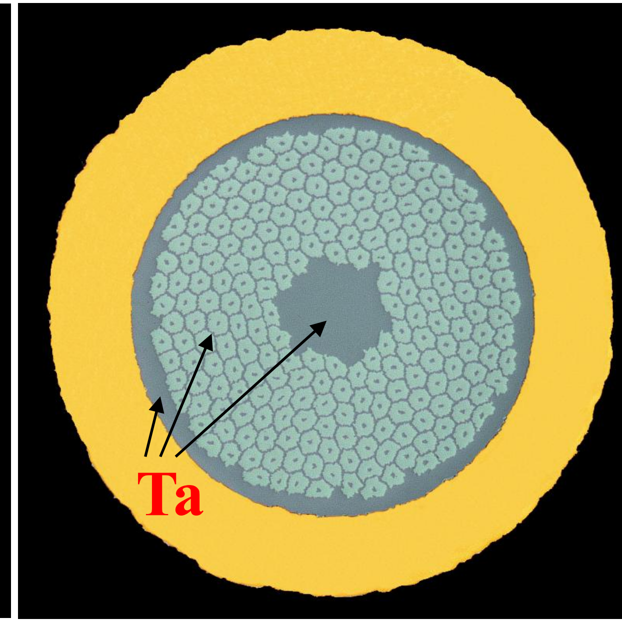
copper 0.17 mm thick
: 50 A/dm^2, 7 m/h

Cu Stabilized Nb_3Al Strands with Different Matrix

(a) F1 strand	(b) K1, K3, K4 strands	(c) K2 strand
(all Nb matrix)	(partial Ta matrix)	(all Ta matrix)



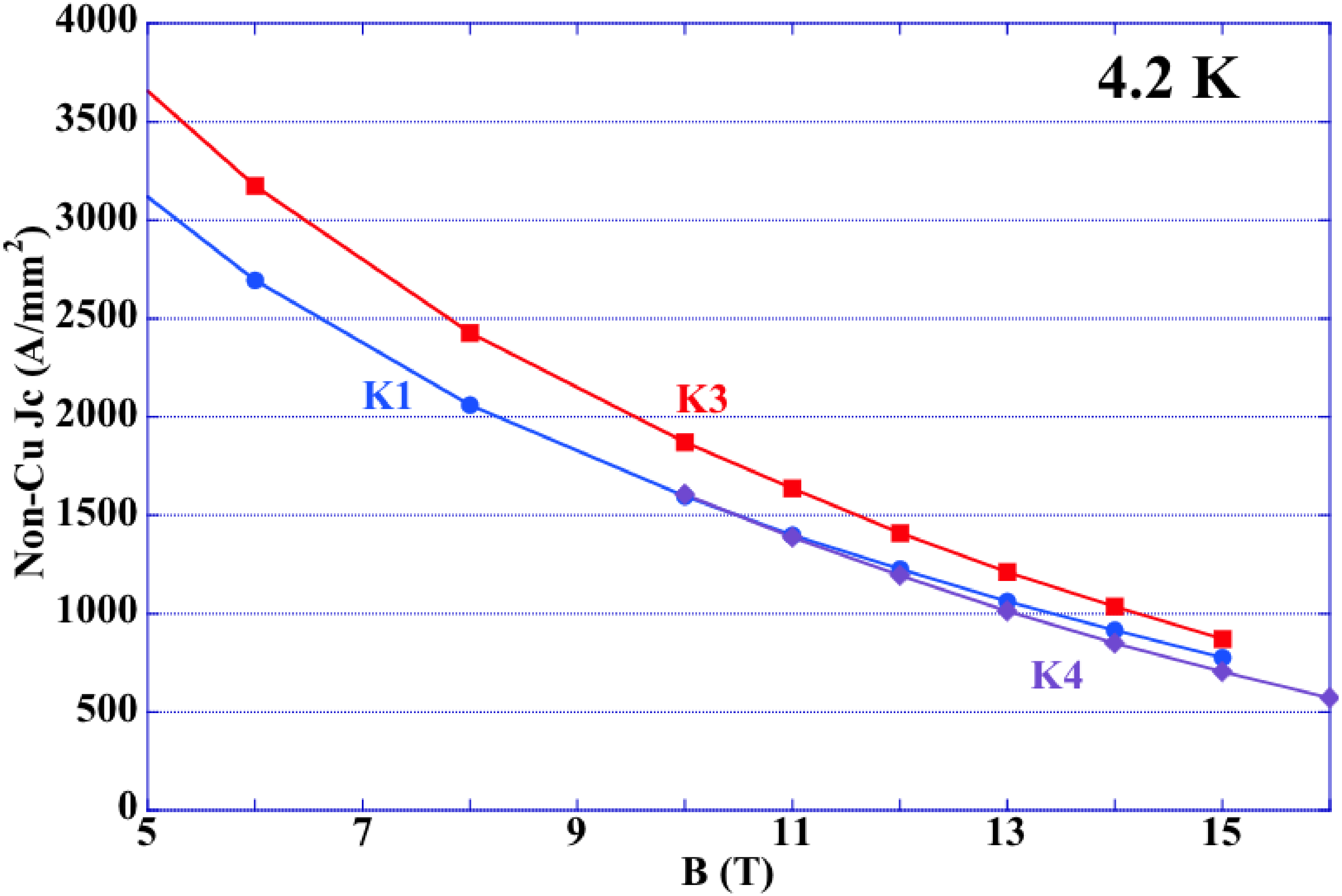




Dia. w/ Cu:	1.0 mm
Dia. w/o Cu:	0.7-0.73 mm
Area Reduction:	~70 %
Filament Dia.:	35 µm
Barrier Thickness:	4-6 µm
Twist Pitch:	45 mm
Piece Length:	< 1 km (400-ton extruder)

* ~2 lots production per year…
* Wire breakings

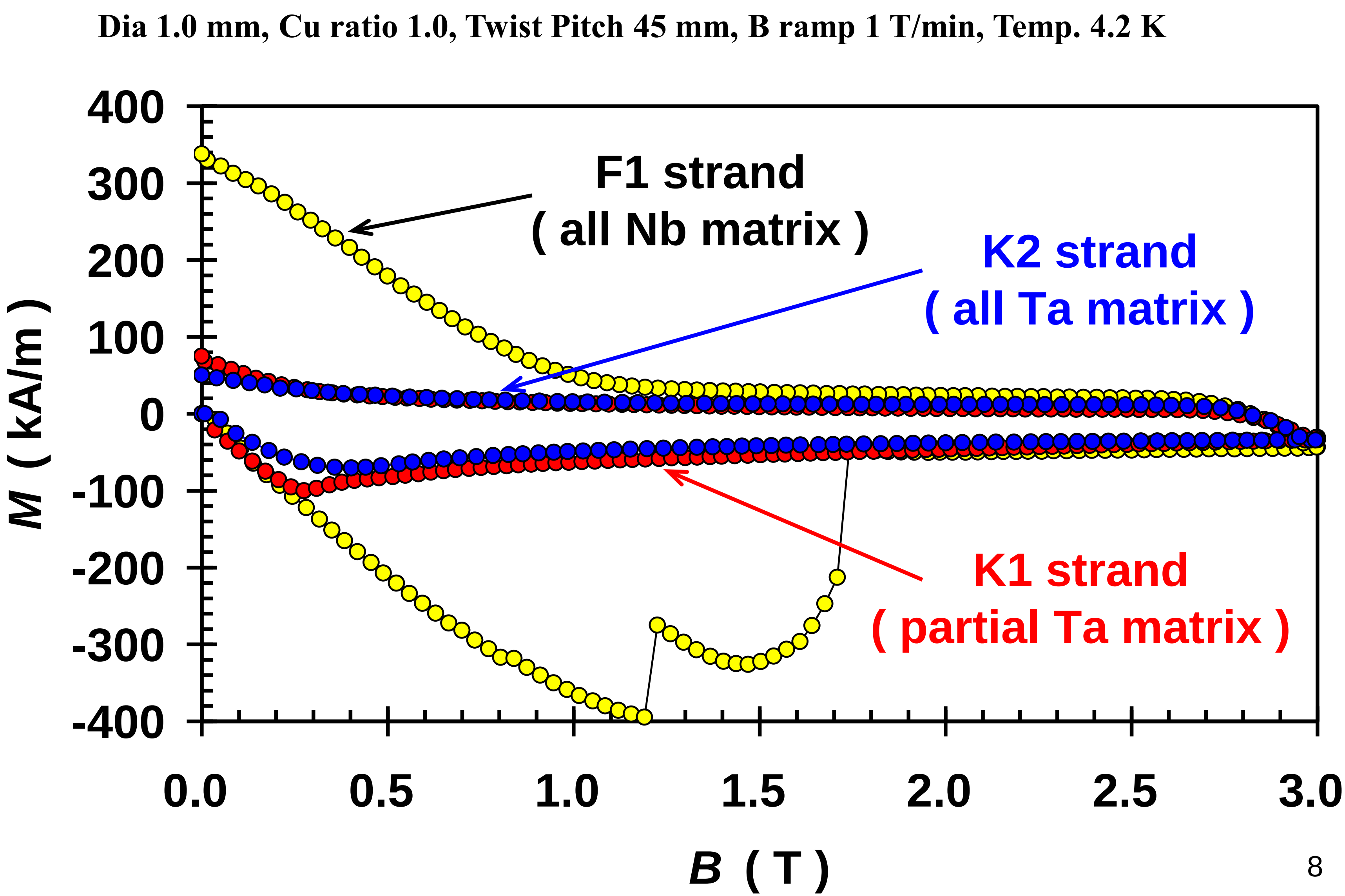
Non-Cu Jc of Nb_3Al



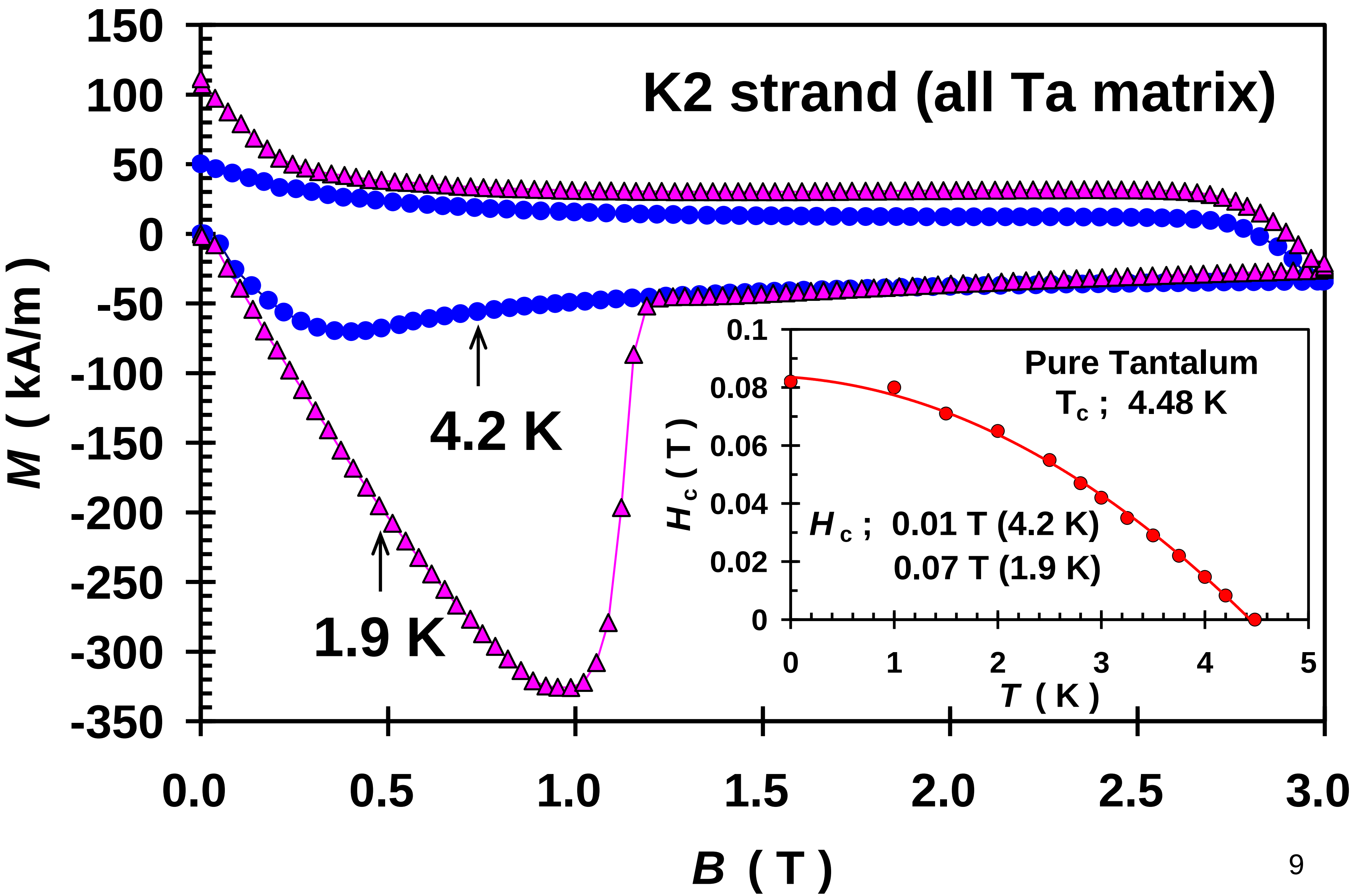
12T: 1200-1400 A/mm^2

15T: 700-870A/mm^2

Magnetization Curves at 4.2 K



Magnetization Curve at 1.9 K

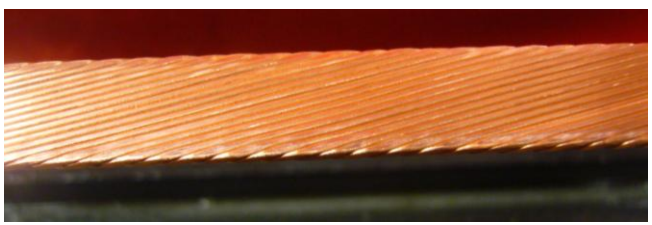


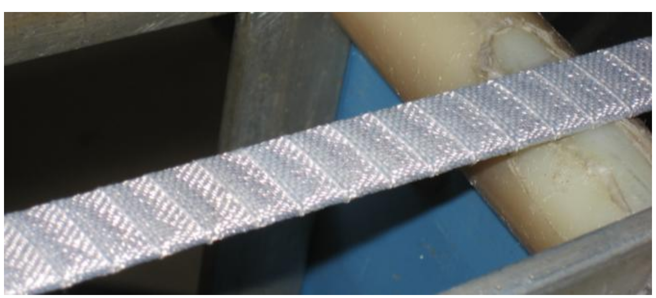
Demonstration of Cable Fabrication

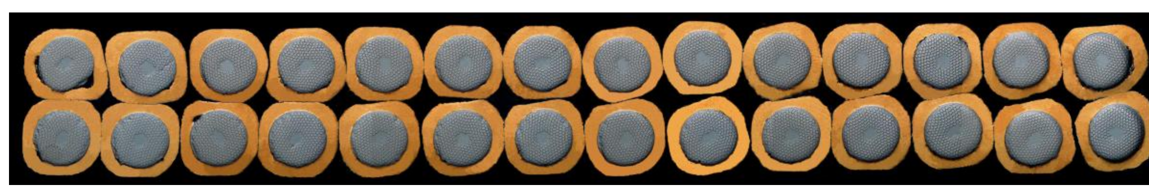
Collaboration with Fermilab

- Bonding strength of copper electroplating
- Cabling with ceramic insulation
  >> 28 strands, ~20 m long

◆ 13 T Sub-scale magnet
◆ Cable test at FRESCA
*3 cables available



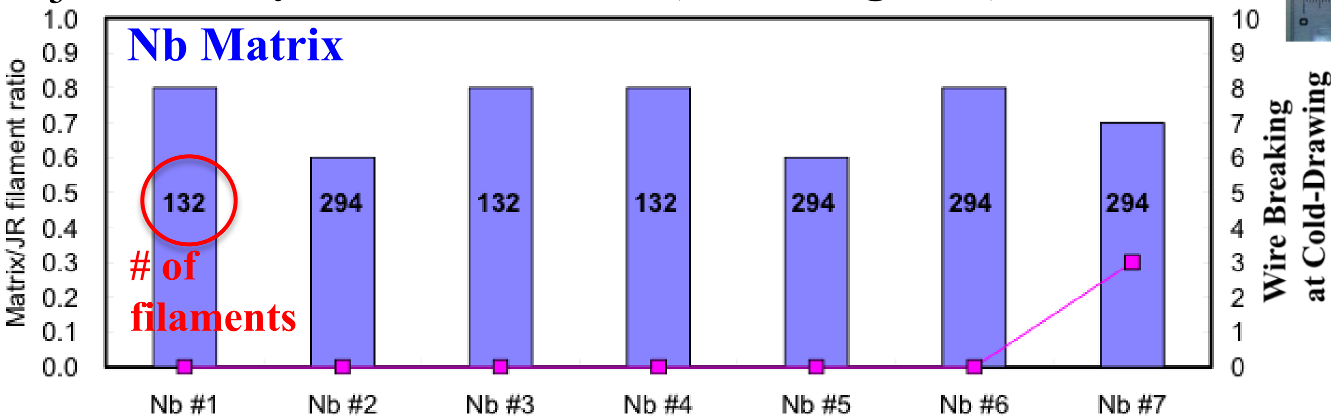


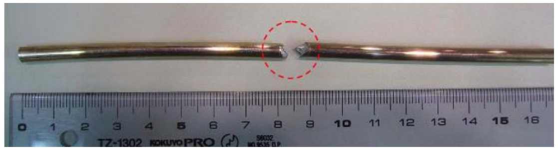


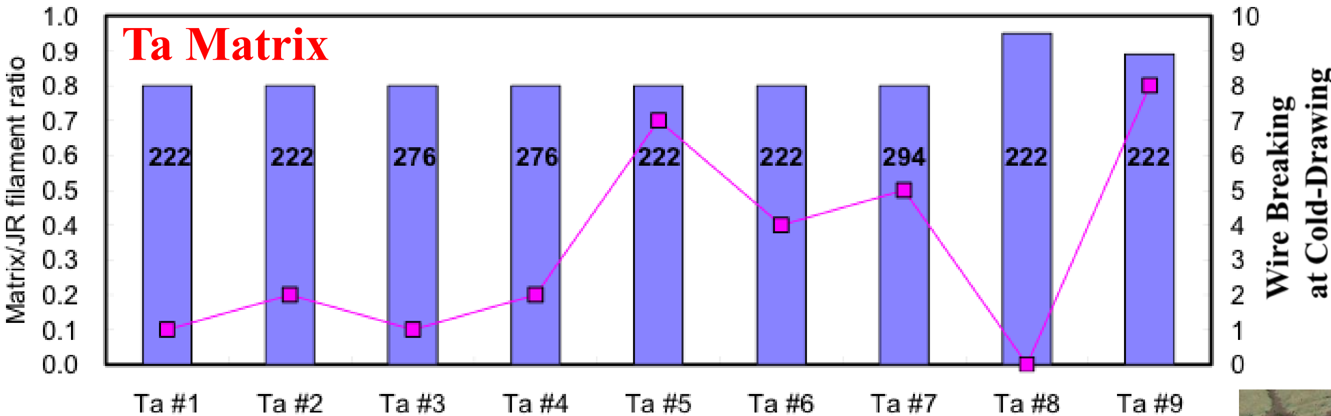
K1 cable: Cu ion-plating (<1 μm) + Cu electroplating (150 μm)

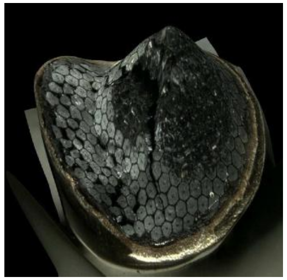
Wire Breaking with Ta Matrix

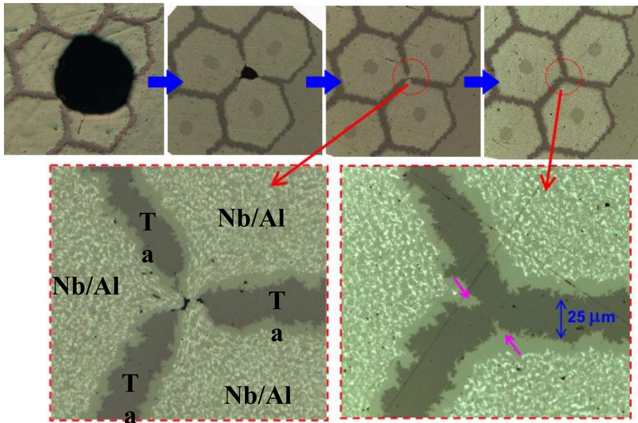
Nb_3Al wires by 400-ton extruder (1-km long wire) since 2004











- Many wire breakings with Ta matrix.
- Breaking initiated at Ta matrix.
- Need to reduce breaking rate for long wire production.

>> Quality check, improvement of Ta sheets.

>> Trials with 7 different Ta ingredients are underway.

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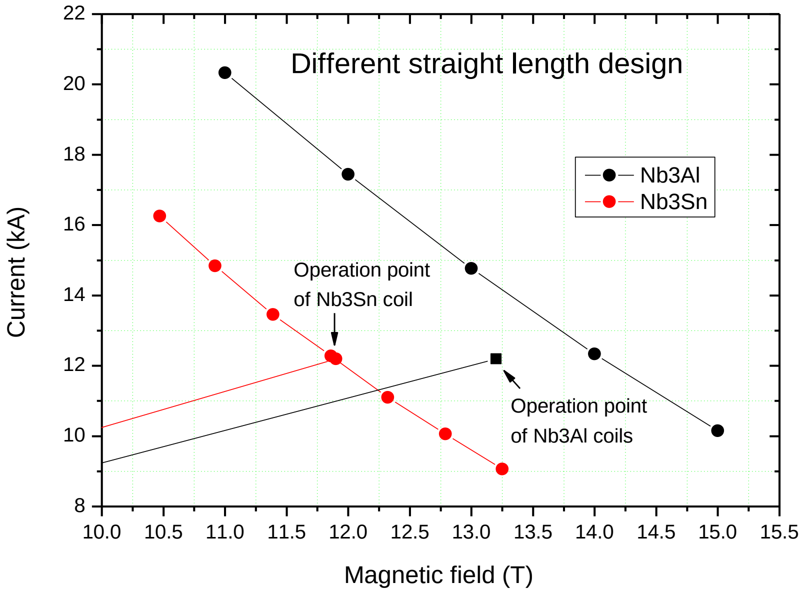
  - **Nb_3Al Superconductor**
  - **13 T Subscale Magnet**
  - **Radiation resistance**

- **New Study Towards > 15 T**
  - **Stress, Strain Issues**

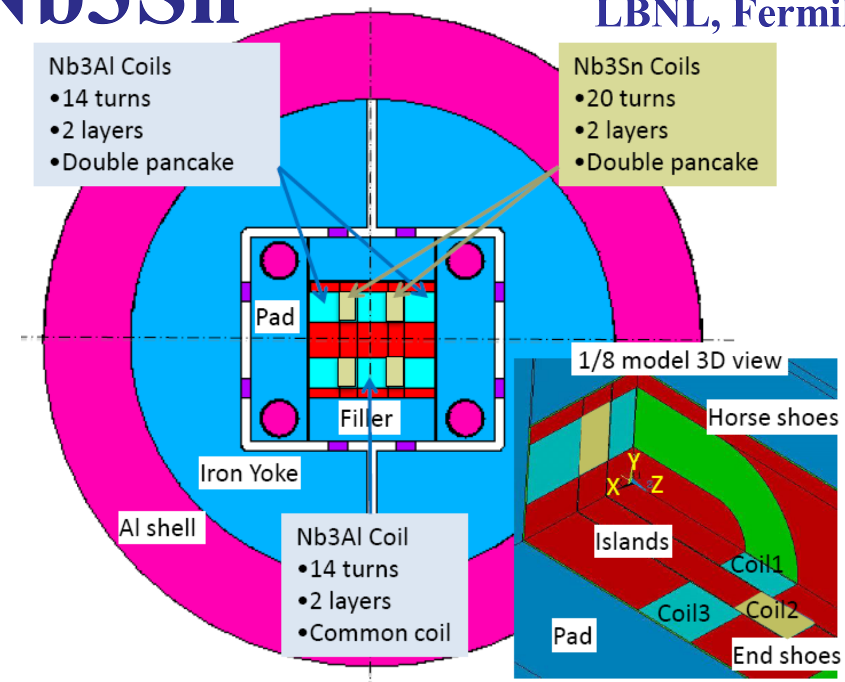
- **Summary**

13 T Sub-scale Nb3Al/Nb3Sn Hybrid Magnet

Collaboration with LBNL, Fermilab



Cross section of the magnet



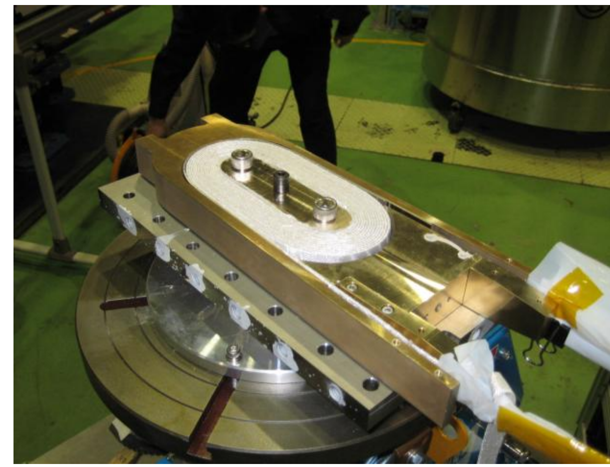
- **To demonstrate feasibility of Nb_3Al cable.**
- **Key design points**
  - **The common coil concept, and the shell structure,**
  - **Three Nb_3Al coils & two LBL-Nb_3Sn coils for Higher Peak Field.**

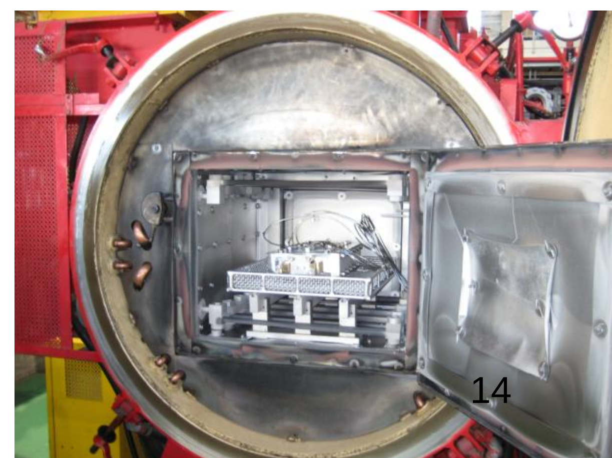
Item	Value
Operation current	12.1 kA
Peak field	13.1 T
Stored energy	71.8 kJ
Magnet Length	740 mm
Shell Dia.	680 mm
Nb3Al Strand Dia.	1 mm
Cu/Non-Cu ratio	0.96
No. of Stands	28
Cable dimension	13.93*1.84 mm2
Cable Insulation	0.25 mm
Nb3Al Coils No.	3
Turns No. per layer	14
Layers No. per coil	2
Nb3Sn Coils No.	2
Turns No. per layer	20
Layers No. per coil	2

Present Status - Coil Fabrication -

- **2 practice/dummy coil windings and heat treatment with alumina-ceramic tape completed.**
- **Temperature uniformity in vacuum furnace (800 °C) verified.**
- **Some vacuum impregnations done, but a leak problem…**
- **The 1st Nb_3Al coil will be wound in this month.**

New Development:
- **Thin alumina-ceramic tape (t0.08 mm)**
- **Cyanate Ester based resin**





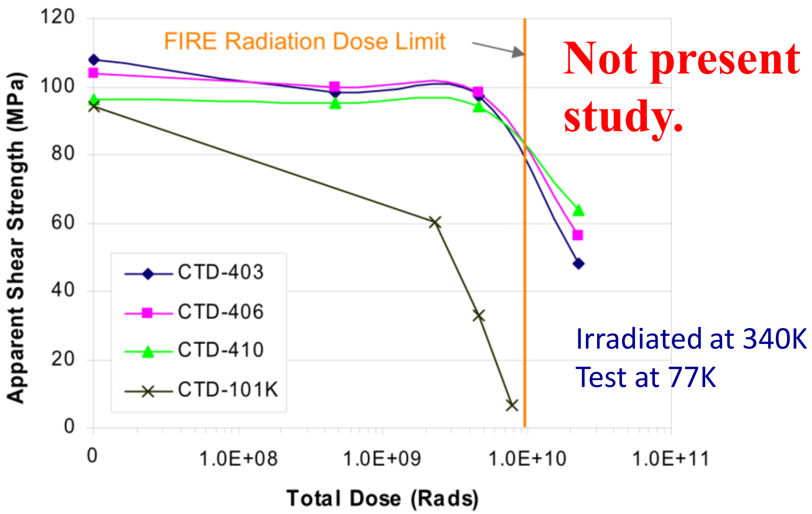
Development of Cyanate Ester Based Resin

- Better radiation resistance than Epoxy Resin
- Collaboration for accelerator HFM application (LHC upgrade):

Mitsubishi Gas Chemical: provider of Cyanate Ester resin
Univ. of Hyogo: evaluation (bonding & mechanical properties)
JAEA: gamma-ray irradiation, evaluation (evolved gas)

KEK: coil impregnation, evaluation

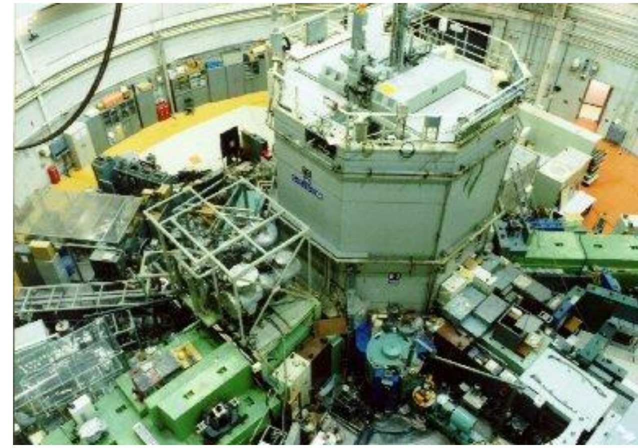
- 60 Cyanate Ester / 40 Epoxy
- low viscosity, low reaction temperature < 150 °C
- pot life: 24hr@ 60 °C
- mechanical strength



Fabian and Hooker et. al., presented at "HHH-AMT, Topical Meeting on Insulation and Impregnation Technologies for Magnets"

Impregnation trial with dummy coil

Neutron Irradiation at Cold

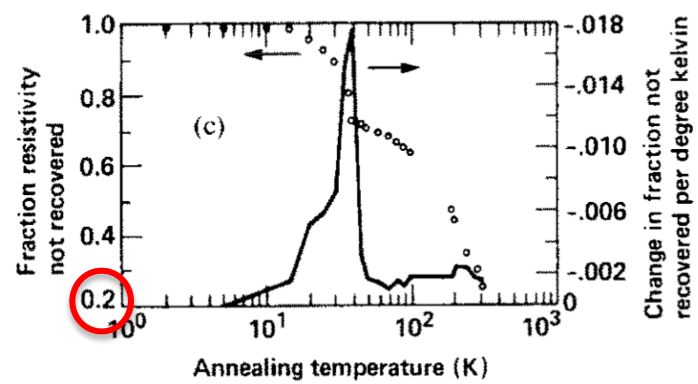


- Severe radiation in the beam insertion system for the LHC upgrade.
- Degradation of stabilizers: even below 10^{21} n/m^2 (??)
  - Quench protection is very concerned.
- Low temperature irradiation facility at KURR (Kyoto Univ. Research Reactor):
  $T_{irrad.}$ from 10 K to 370 K
  Max. fast-neutron flux: 1×10^{16} n/m²/s (5MW)
- Sample candidates: copper, Nb3Al, (Nb3Sn, HTS), pure aluminum,
  - Threshold fluence of degradation start
  - Anneal effect on recovery by warm-up to RT
- First irradiation test will be carried out in November 2010.

14MeV n on Cu at 4K

ρ0: 0.098
ρ-irrad: 0.191
(nΩm)

J. Nucl. Materials, 133&134, p357 (1985)



Fluence up to 1*10^21/m2.
Only 80% recovery by TC to RT.

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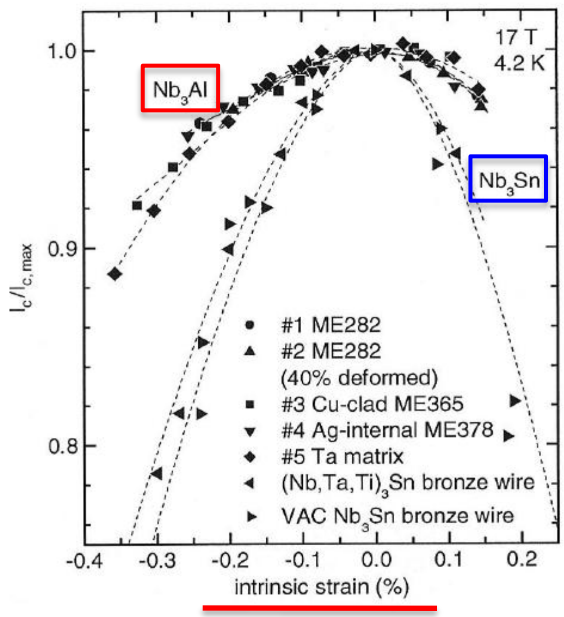
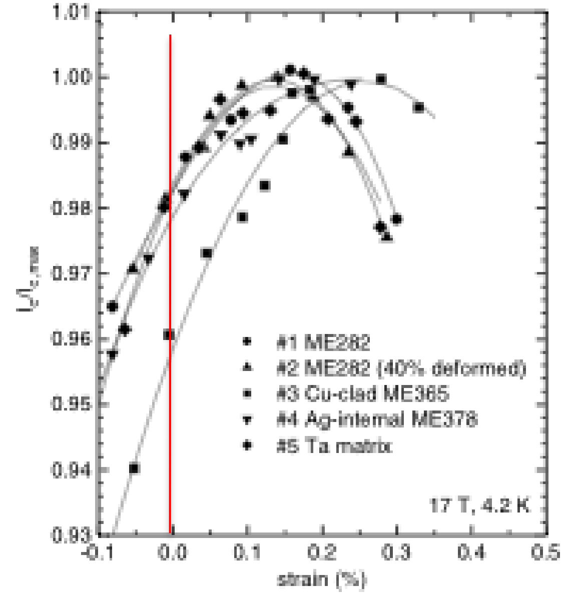
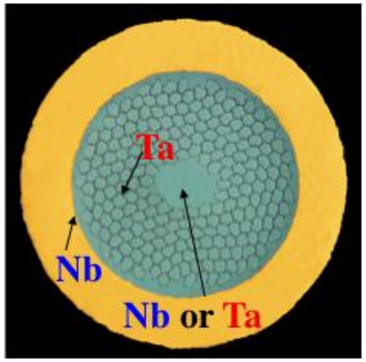
Strain Effects on Superconductor

Performance of superconductor (A15, HTS) strongly influenced by "Strains".



Supercond. Sci. Technol. 18 (2005) p. 284.
by N. Banno et al.





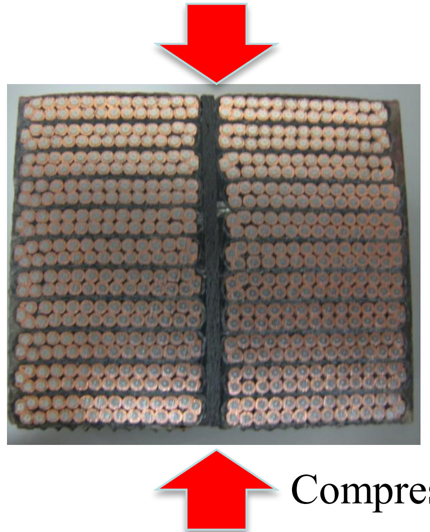
- Measurement with Walter Spring in High Field Magnet.
  - >> Strains applied by fixture.
- Residual strains in composite SC due to different thermal contractions.
  - >> ΔT ~1000 K

Could we know the real (3d) strains of SC in composite?

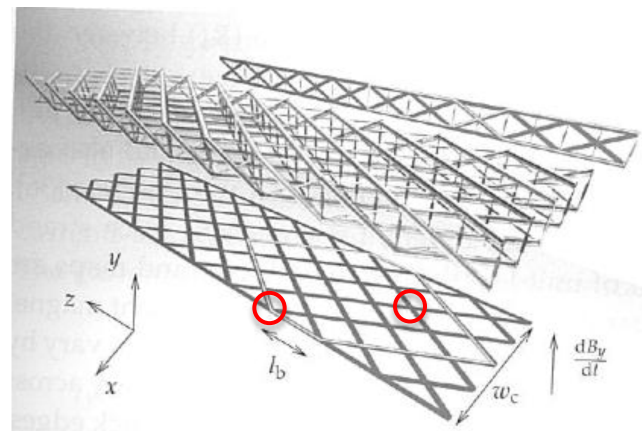
Stress/Strain in the SC Coil

Stress/Strain issues are unavoidable in HFM for HE-LHC (~20 T).

- Coil stress at operation: ~200 MPa at 15T (> 300 MPa at HE-LHC?)
  >> Higher local strain at crossover, kink??
- Role of impregnation as reinforcement: w/ or w/o resins



Compressive Load

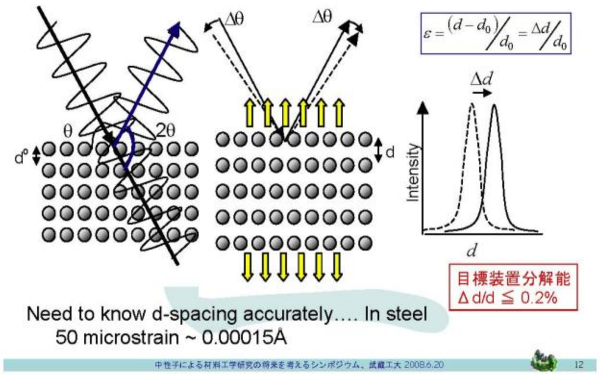


How could we have better understanding on local strain behavior in the SC coil?

Neutron diffractometer at J-PARC with 10-stack cable sample under various loads would be a nice tooling…

Strain Study at J-PARC Neutron Facility

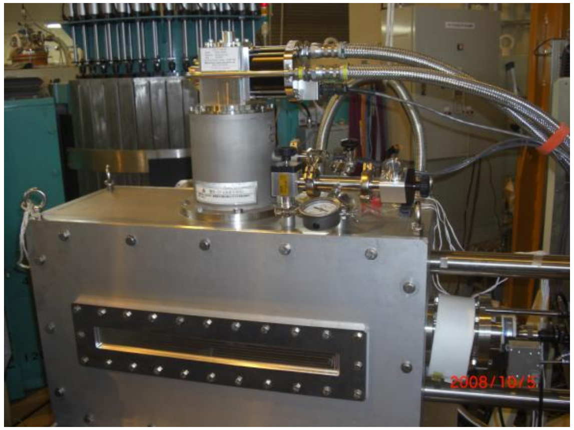
- Currently 120kW >> 1 MW
- The "lattice parameter" of Nb_3Al, Nb_3Sn, HTS by the neutron diffraction at 4 K to RT,
  - $\Delta\varepsilon/\varepsilon < 0.005\%$, penetration depth > 50 mm,
  - Residual strains of SC wires,
  - Direct strain measurement under loads,
  - Strain distribution of stacked cables.

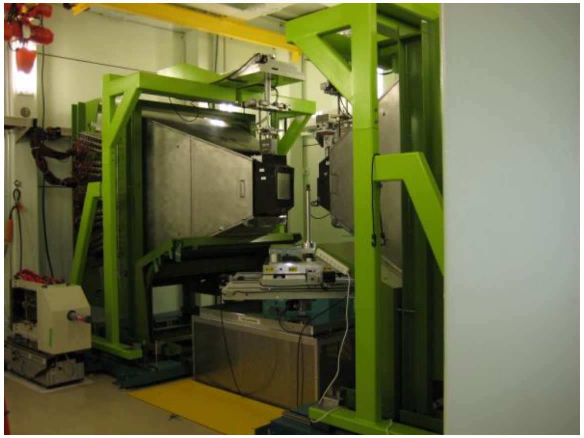


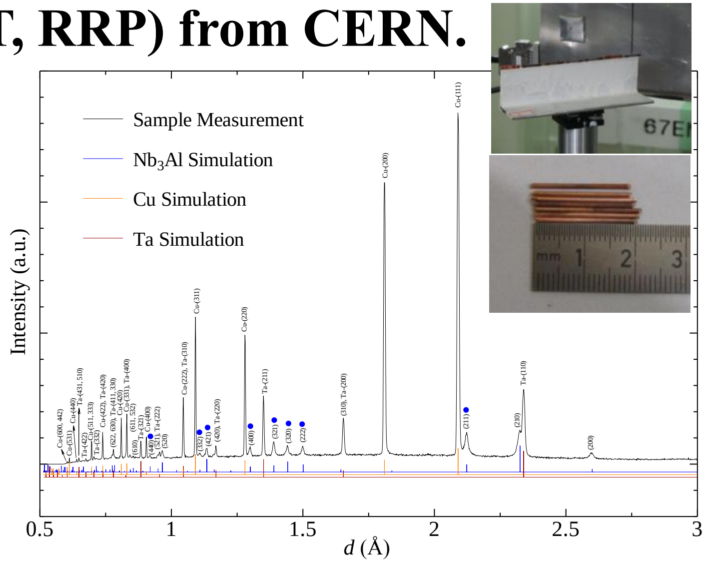
- Cryogenic loading frame (4K, 50kN) in JFY2010.
- Preliminary test:

  Clear peaks of Nb_3Al crystals. Residual strains by different matrixes.
- Beam time of 5 days in 2010B approved:

  >> Nb_3Al wires (K1-K4, F1), Nb_3Sn wires (PIT, RRP) from CERN.

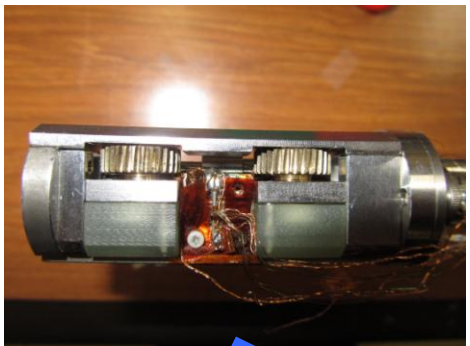


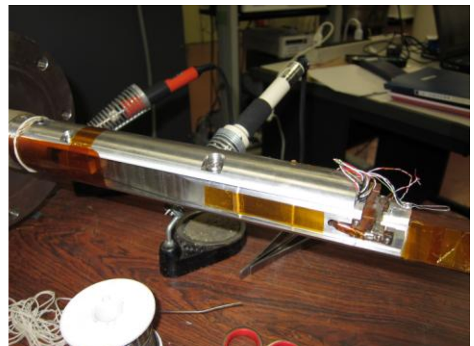




Strain Study at HFM Lab. at Tohoku Univ.

- Collaboration with HFM Lab. at Tohoku Univ. since this year.
- SC performance evaluation under various strains.
  - >> Correlation with neutron diffraction measurement at J-PARC.
  - >> Nb_3Al wires (K1-K4, F1), Nb_3Sn wires (PIT, RRP) from CERN.





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Summary

•**Development of Nb3Al superconductor is underway by KEK and NIMS with support of CERN.**

•**Industrialization of Nb3Al must be necessary for practical use.**

- cost, time, piece length, reduction of breaking, quality control

•**Magnet technology R&D with Nb_3Al:**

- 13 T sub-scale magnet

- radiation resistance

•**For HFM application like HE-LHC, strain study on superconductors (A15, HTS) should be done. Engineering neutron diffractometer would be a nice tooling.**

Participants / Collaborators

KEK:	T. Nakamoto, T. Ogitsu, K. Sasaki, N. Kimura, S. Kin, A. Terashima, K. Tsuchiya, Q. Xu, A. Yamamoto,
NIMS:	A. Kikuchi, T. Takeuchi, N. Banno

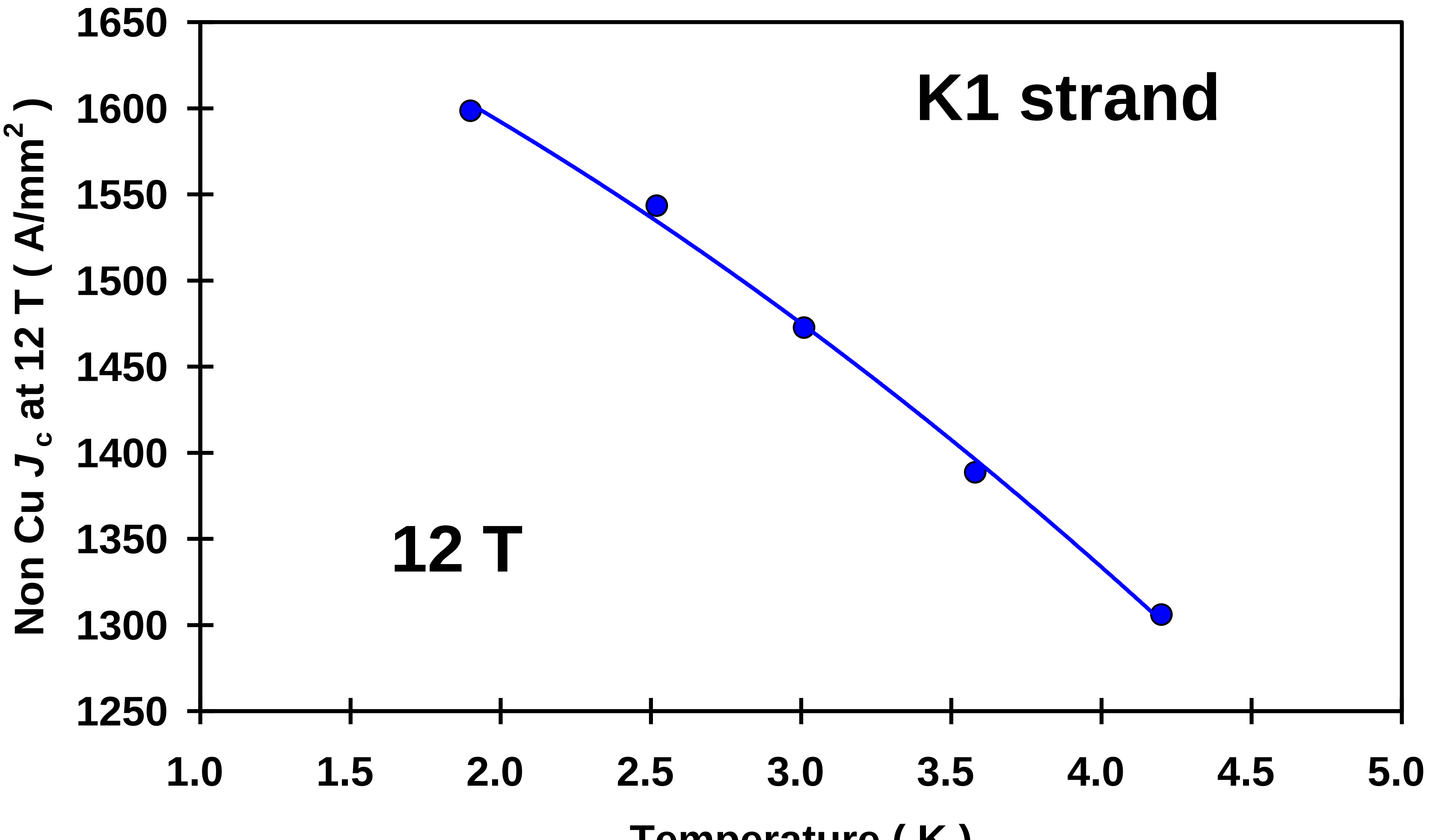
In cooperation with:

CERN:	L. Rossi, G. de Rijk, L. Bottura
LBNL:	G. Sabbi, S. Caspi et al.
Fermilab:	A. Zlobin, E. Barzi, R. Yamada
CEA/Saclay:	B. Bourdy et al.

Summary of Nb_3Al Strands

Wire No.	JFY2007-2008 K2 (ME492)	JFY2007-2008 K1 (ME493)	JFY2008-2009 K4 (ME502)	JFY2008-2009 K3 (ME501)	JFY2009-2010 K5	JFY2010-2011 K6
Matrix material	Ta	Ta	Ta	Ta	Ta	TBD
Core & Skin material	Ta, Ta	Nb, Nb	Nb, Ta	Nb, Nb	Nb, Nb	TBD
Matrix ratio	0.8	0.8	0.95	0.8	0.89	TBD
# of filaments	222	222	222 (241)	294 (313)	222 (241)	TBD
# of wire breakage	7	4	0	~10	>10	
RHQ						
Wire dia (mm)	1.35	1.38	1.35	1.30	1.35	TBD
Filam dia (µm)	69.8	70.4	66	57	67	TBD
Barrier thick(µm)	8	8.2	11	7.7	10.8	TBD
Twist pitch (mm)	0	0	54	0	54	TBD
RHQ I (A)	202	237	213	208		
Final strand						
wire dia (with Cu)	1.00	1.00	0.99	0.995		
wire dia (w/o Cu)	0.72	0.73	0.70	0.71		
AR ratio (%)	72	72	73	69.9		
filament dia (µm)	37	37	34.1	32		
barrier thick (µm)	4.2	4.2	5.7	4.2		
twist pitch (mm)	45	45	45	45		
Non-Cu Jc (A/mm2)						
@ 10T with AR	1776	1596.4	1610	1872		
@ 12T with AR	1320	1226.3	1197	1409		
@ 15T with AR	785	776.6	707	872		

J_c (12 T) vs Temperature



Fabricated or fabricating strands

	2003		2005			2006	2006		2007		2007		2008	2008
ê¸ç¼ No.	M21-3		ME451			ME458	ME476		ME492		ME493		ME1	ME2
Matrix material	Nb		Nb			Nb	Ta		Ta		Ta		Ta	Ta
Core material	Nb, Nb		Nb, Nb			Nb, Nb	Ta, Ta		Ta, Ta		Nb, Nb		Nb, Ta	Nb, Nb
Skin							Nb		Ta		Nb		Ta	Nb
Matrix ratio	0.8		0.69			0.79	0.8		0.8		0.8		0.8	0.8
Num of filam	144		294			546	222		222		222		222	222
Billet dia (mm)			55.5 ϕ			58 ϕ	57.5 ϕ		57.5 ϕ		57.5 ϕ			
Frequency of wire breaking			3			3 and crack	2		7		4			
RHQ														
Wire dia (mm)	0.8		1.35			1.35	1.35		1.35		1.35		1.35	1.35
Filam dia (μm)	51		62.7			44.2	69		69.8		69.8		69	69
Barrier thick(μm)	4.6		6.4			4.4	8		8		8		10	8
Al thickness (nm)	170		150			150	208		211		211		210	210
Twist pitch (mm)	32		55			0	54		0		0		54	54
RHQ I (A)	80.6	80.6	228	228		222	226	226		202				
Å@AR ratio (%)		32						45		72		66.2		
wire dia (w/o Cu)		0.66		0.94	0.72			1.00		0.715		0.785		
wire dia (with Cu)								1.40		1.00		1.00		
filament dia (μm)		34.7		44	33			38		37		40.6		
barrier thick (μm)		3.1		4.5	3.4			4.4		4.2		4.7		
twist pitch (mm)								98		45		45		
non-Cu Jc (A/mm2)														
@ 10T w/o AR	1602													
@ 12T	1172													
@ 15T	661					430	623							
@ 10T AR		2176			1720					1776		1669		
@ 12T AR		1663			1302					1320		1230		
@ 15T AR		1032	630	949	817			807		785		718		