Development of
Advanced Superconducting Accelerator Magnets
for
the LHC Luminosity Upgrade

Phase 1: Superconductor Development

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Prepared for the 1st CERN-KEK Cooperation Committee
to be held at CERN, Dec., 8, 2006

Outline

- Objective
- Status of the development
- Global Cooperation Net-work proposed
- Plan for Further Development
- Summary

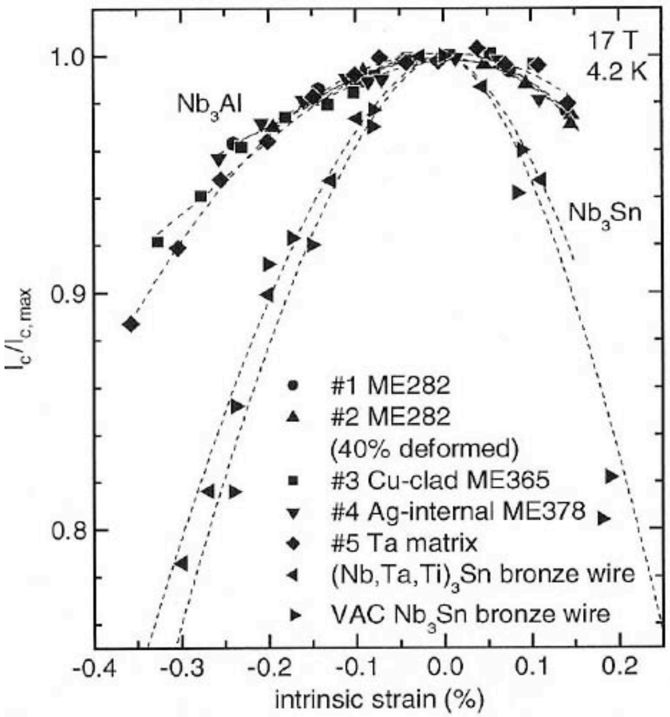
Objective for Phase I

- Develop:
  - High-field superconductor and cable for
    - Advanced Superconducting Magnets for the LHC luminosity Upgrade,
- Evaluate:
  - Performance the cable by using model coils at
    - field range ≥ ~ 15 Tesla

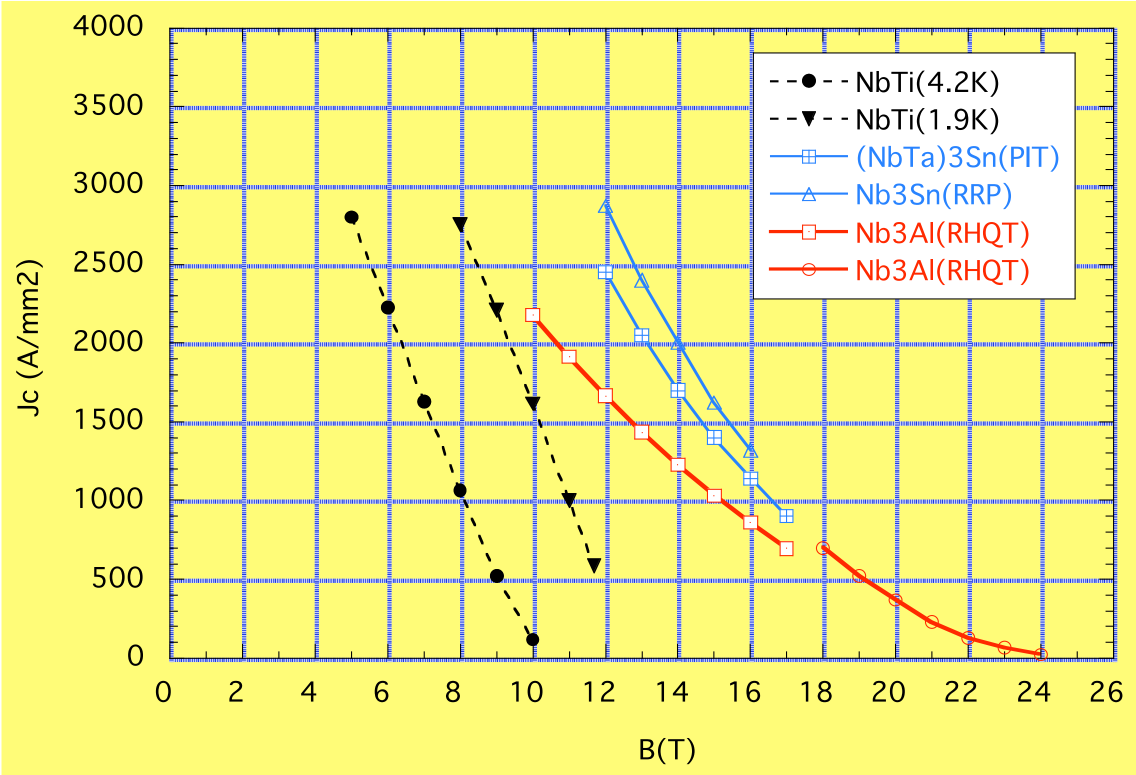
Specific Development

- Superconductor (strand) with
  - Nb_3Al superconductor
  - Non-Cu Jc to reach ~ 1,500 A/mm^2 at 15 T
  - Mechanical stability with keeping Jc
  - Cu-stabilizer mechanically stable enough,
  - Magnetization small enough,at low field
- Cable
  - Rutherford cable (comp. fact. ~90 %)
- Model Coils
  - Race-track coil to
    - Demonstrate the maximum field to reach 15 Tesla,
    - Investigate possible "react and wind" technique, and
    - Investigate radiation-hard technologies

Status of Nb3Al Development



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



- **Stable against mechanical strain,** and potential for **"React and Wind"**
- High Jc in high magnetic field at **> 15 T**

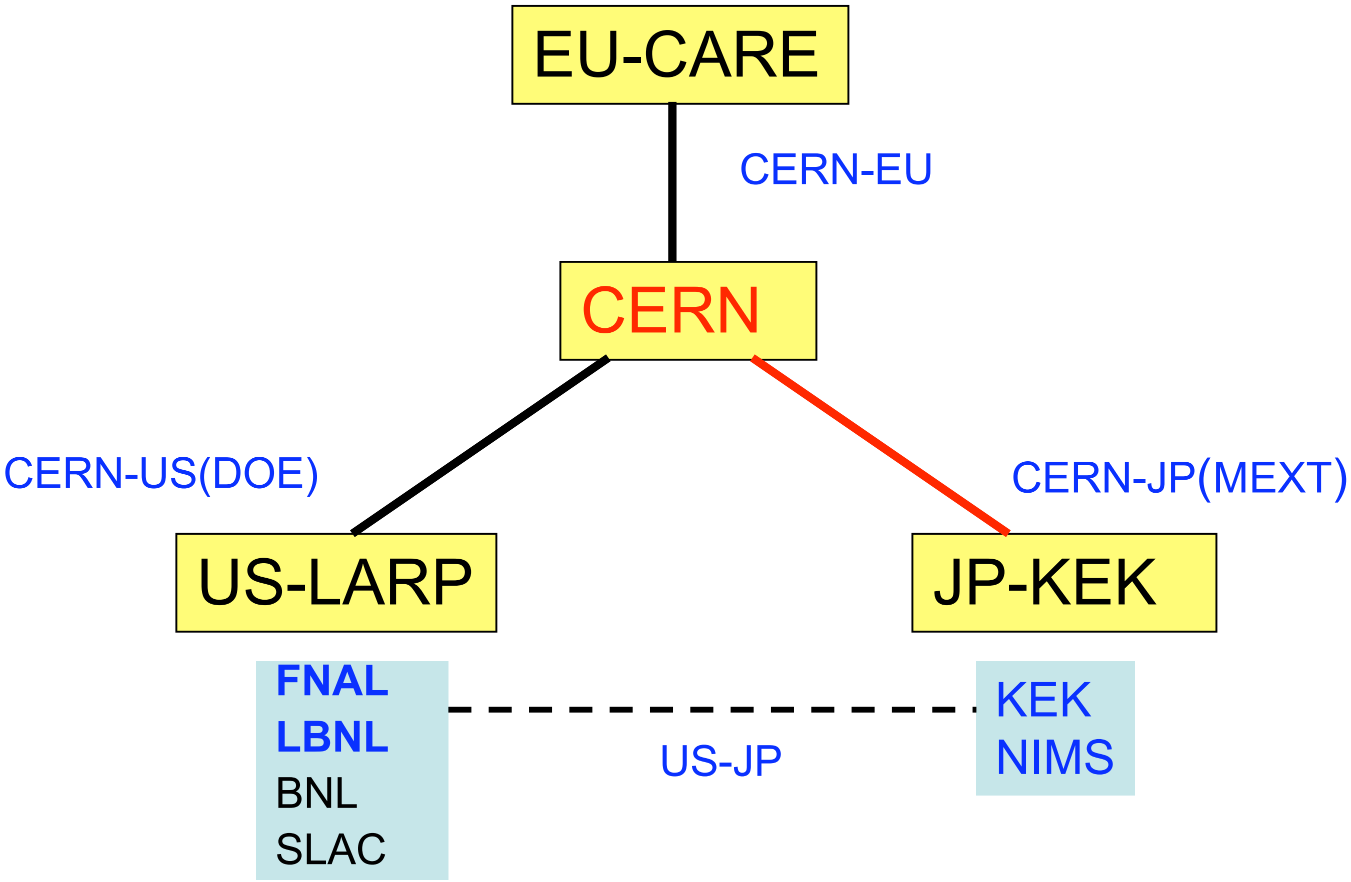
Status of Cooperation in Nb_3Al Development

as of Nov. 2006

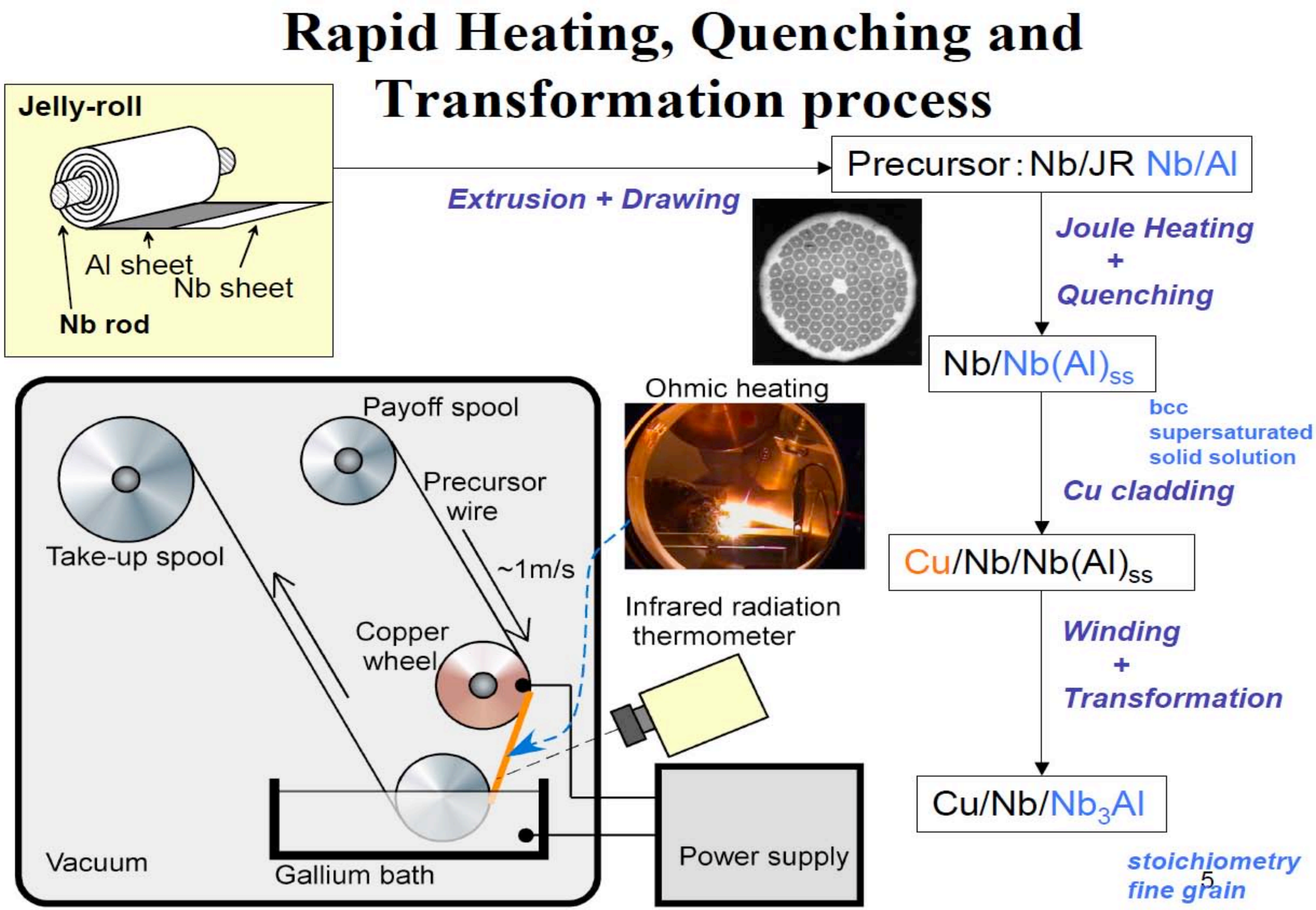
- **NIMS**
  - Fundamental Research focusing on > 20 T
    - Strand with Cu-stabilizer (ion plating + electro-plating)
- **Fermilab/NIMS**
  - Study for cabling and race-track coil
- **KEK/NIMS**
  - Strand development for accelerator application at ~ 15 T
    - Jc improvement study with optimizining RHQ process
    - Cu-stabilizer (electro-plating)
- **CERN-KEK**
  - Advanced superconducting magnets for the LHC luminosity upgrae

Global Cooperation Network

proposed



Fundamental Development at NIMS



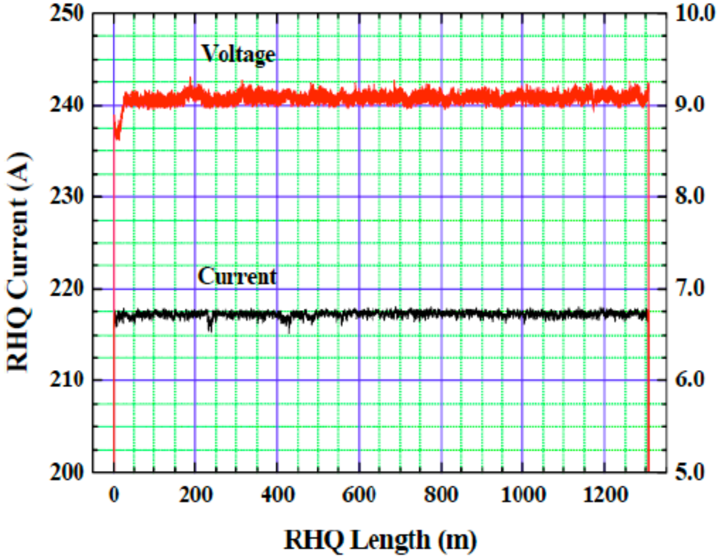
T. Takeuchi et al. IEEE Trans. Appl. Superc. 12, 1 (2002) 1088.

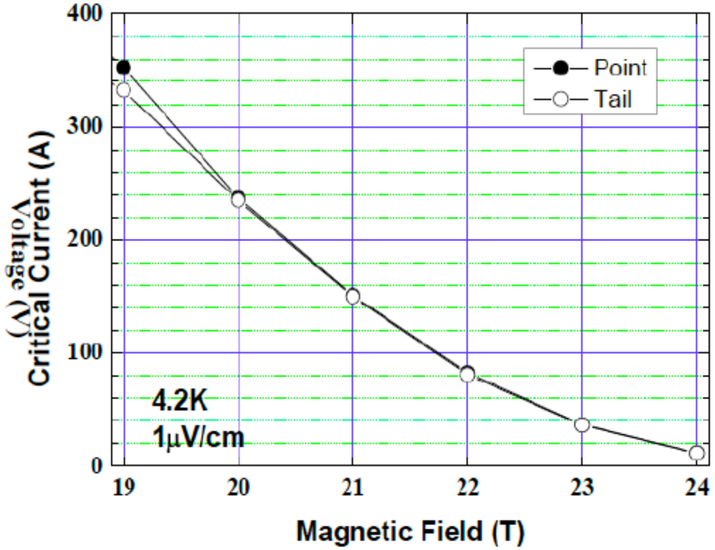
A RHQ Record of 1.3 km Operation at NIMS

Scale up

1.3 km RHQ operation

Power supply
constant current mode

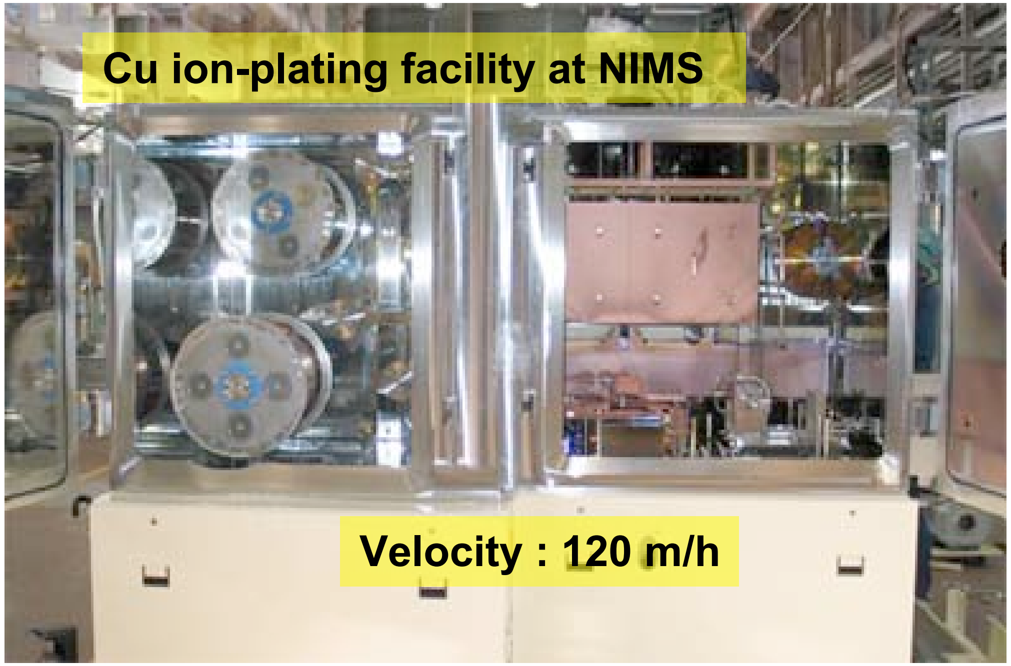


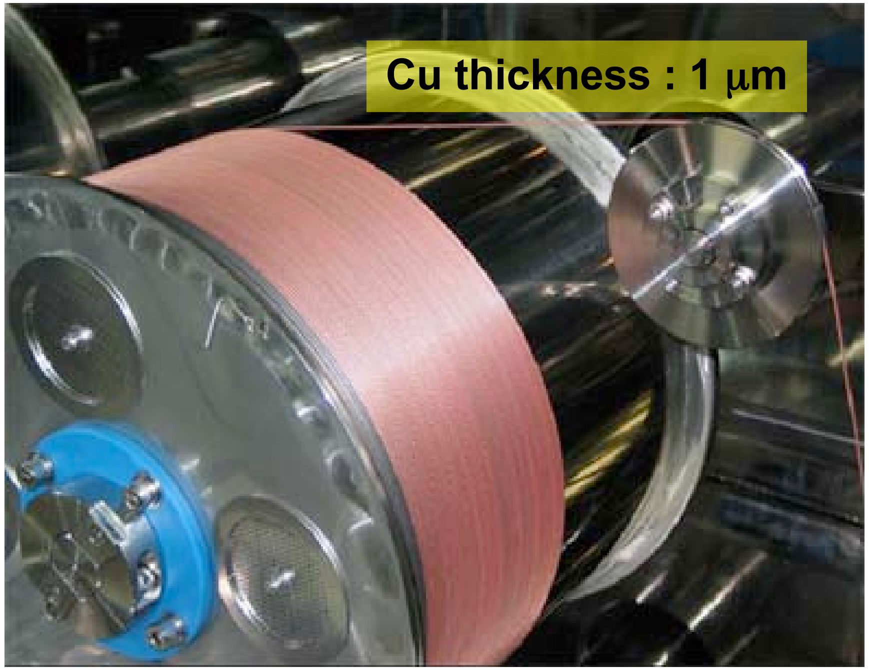


Small fluctuation of inter-electrode voltage and current over the whole length of RHQed wire

Little difference in I_c between a head (point) and a tail of 1.3 km-length of wire

Cu-Stabilizing Process Developed at NIMS





Piece Length : 1,200 m

Strand Dia. : 1 mm

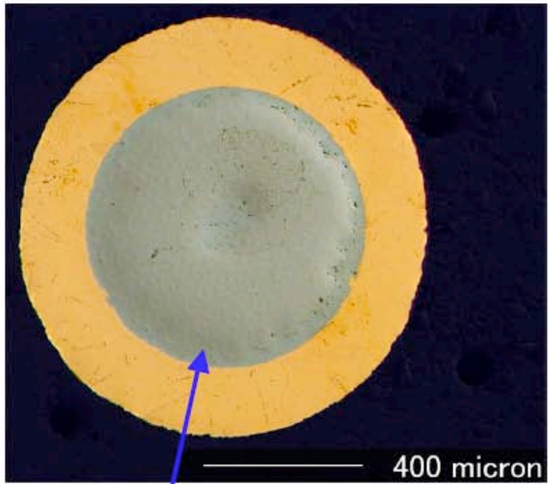
Cu/non Cu ratio : 50% / 50%

RRR : 200

K. Kikuchi et al.,
IEEE Trans. Appl.Superc., 16, 2, (2006) 1224.

Progress at NIMS
1.2 km long Nb3Al-Cu strand

1.2 km long Nb_3Al strand used for the cabling test



144 filaments

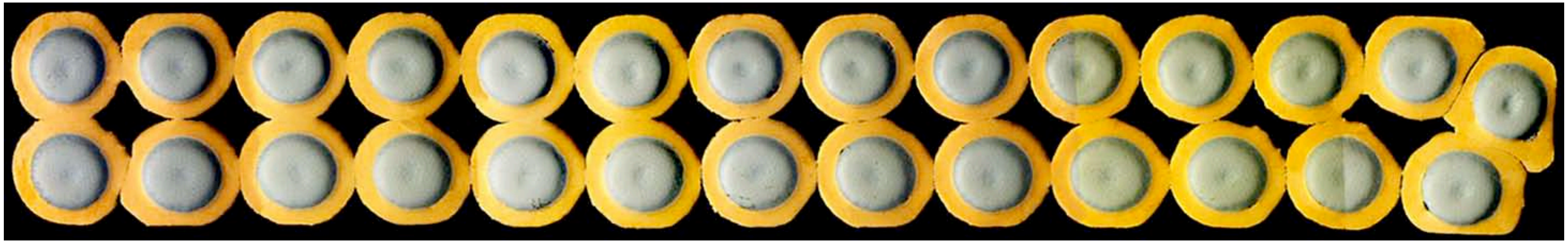
Ic @ 15T = 380 A
Non-Cu Jc @ 15 T = 930 A/mm2

Identification No.	HE2457
Final outer diameter	1.03 mm
Number of Nb_3Al filament	144
Nb_3Al filament diameter	50 μm
Nb/Nb_3Al filament ratio	0.6453
Cu/non-Cu ratio	1.0
Total length	1250 m
Outer diameter at RHQ	1.35
Area reduction after RHQ	71%
Anode oxidation process	done
Ion plating	1-2 μm
Electroplating	145 μm
Annealing after electroplating (air)	400 °C
Drawing (sizing) after electroplating	none

Fermilab-NIMS Collaboration
27 Strand Nb_3Al Rutherford Cable

A. Kikuchi et al., ASC06-4ML06
R. Yamada, et al., ASC06-3LB02,

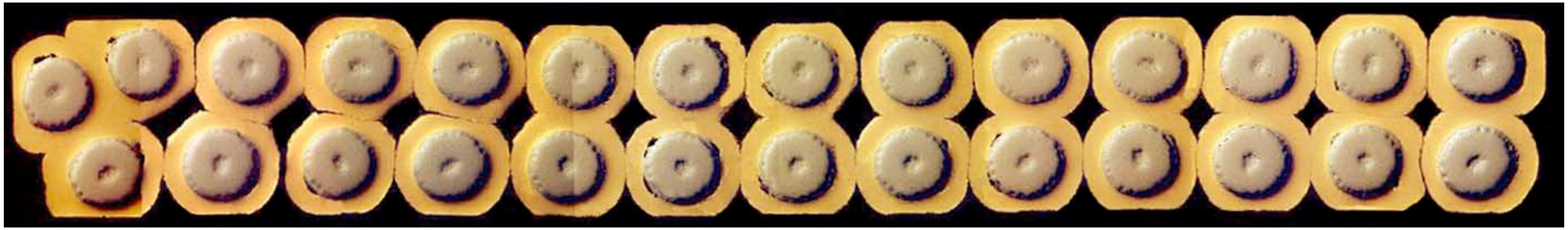
(a) Low Compaction Cable



Size (rectangular) : 14.2 mm x 2.0 mm

Compaction Factor : 82.5 %   Lay Angle : 15.0

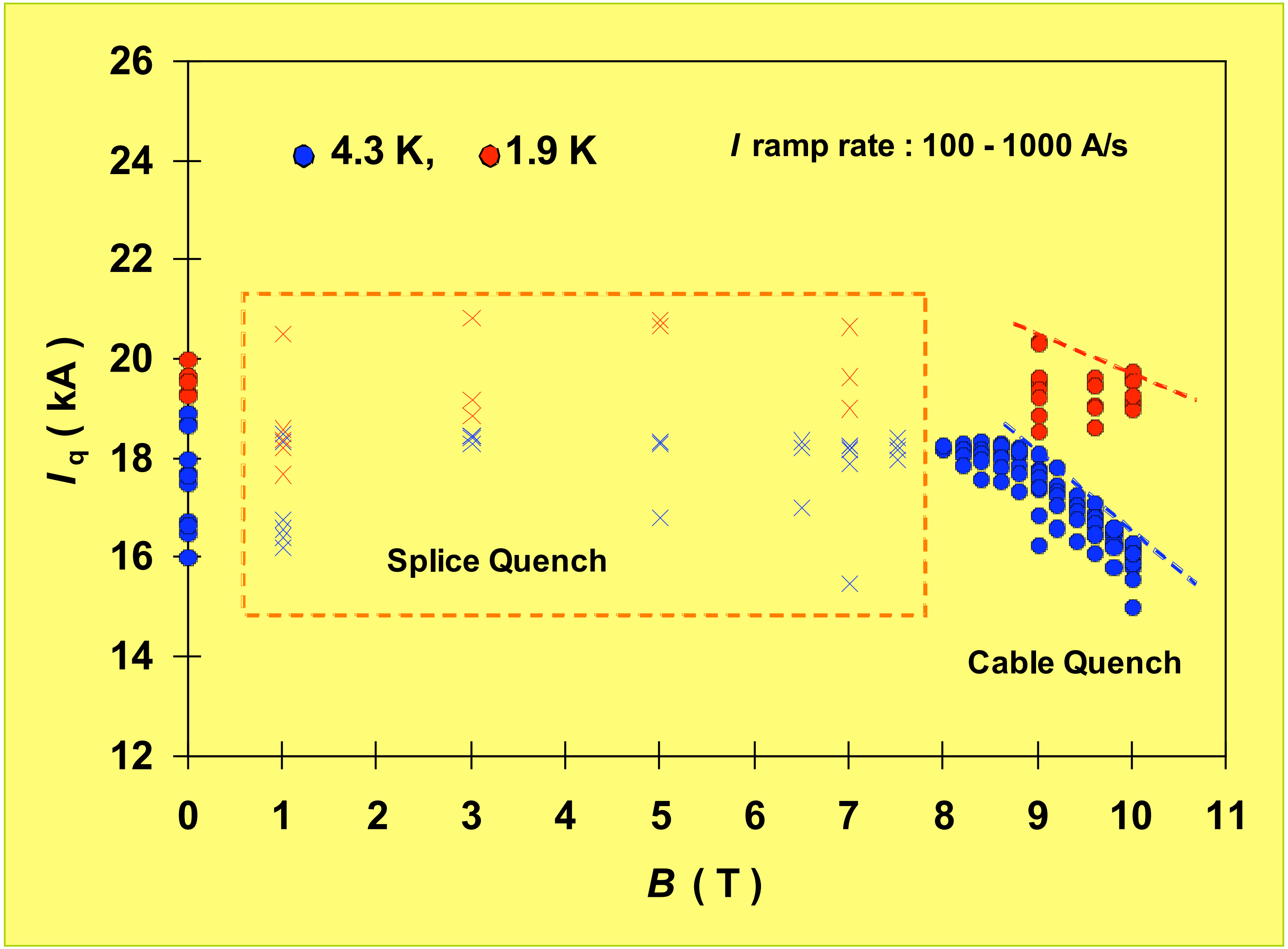
(b) High Compaction Cable



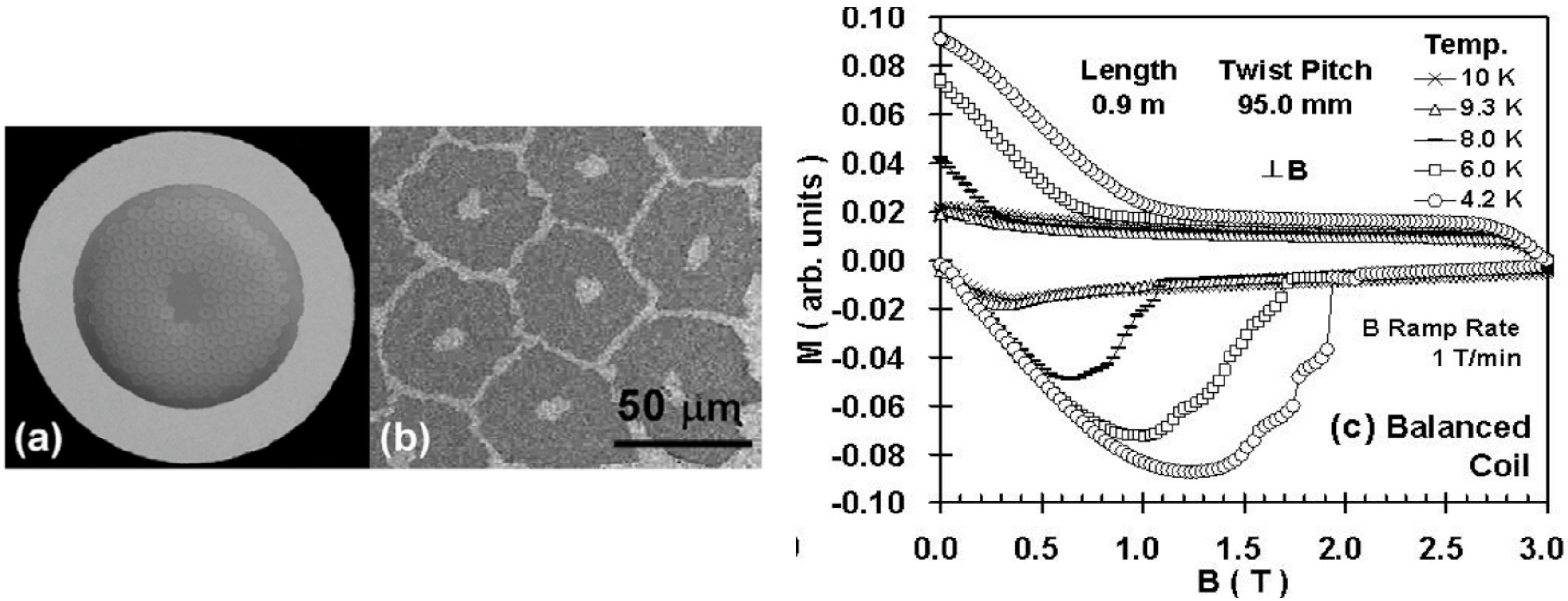
Size (rectangular) : 14.2 mm x 1.8 mm

Compaction Factor : 89.1 %   Lay Angle : 15.0

Fermilab/NIMS-CERN Collaboration Cable Test at FRESCA



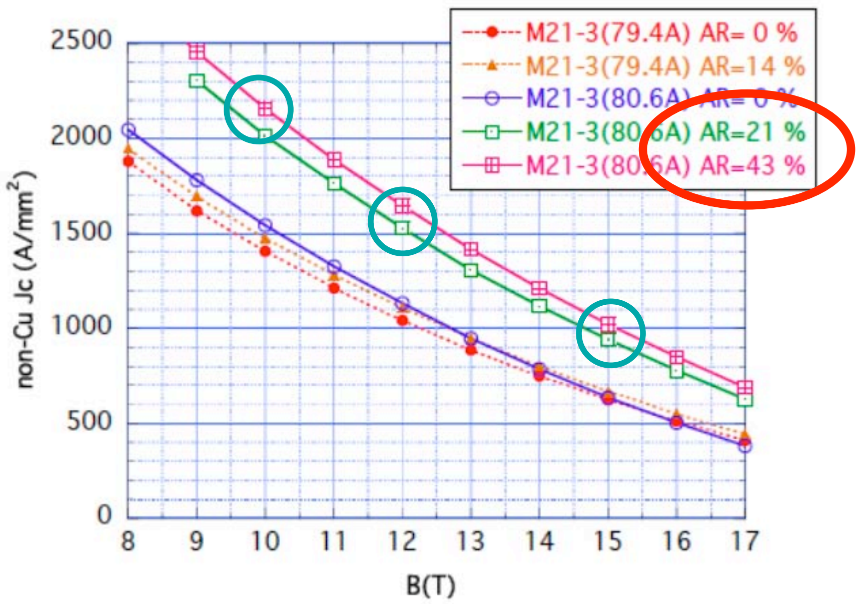
Magnetization in Nb3Al strands
a subject to be investigated

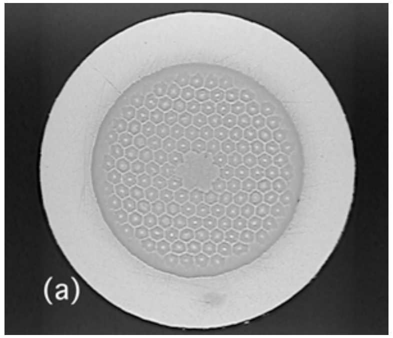


- Magnetization curve of reacted Nb3Al strands , tested using a balanced coil magnetometer
  - A. Kikuchi et al., presented in ASC-06, (4ML06), Seattle, 2006

Nb3Al development at KEK

KEK/NIMS/(Hitachi-Cable) Cooperation





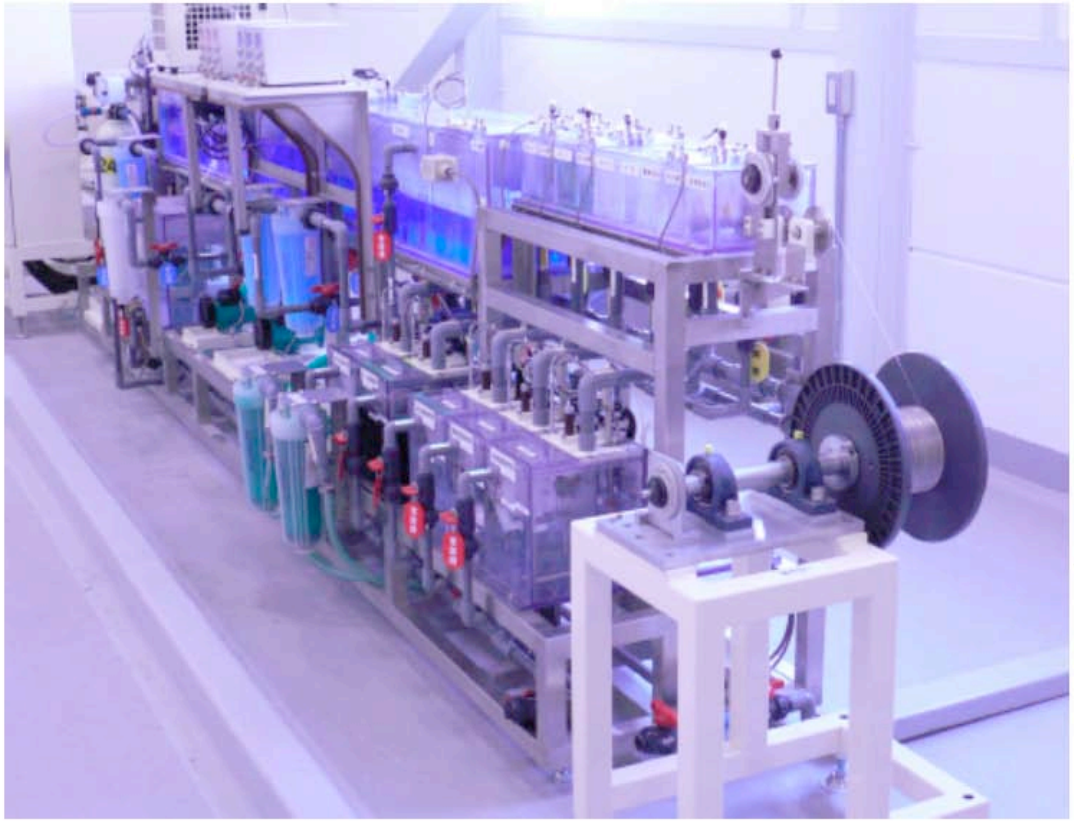
- Process
  - Rapid Heat & Quench
    - Current control important
  - Area Reduction
    - ~ 30 % reduction effective
- Non-Cu Current density
  - 2,150 A/mm2 @ 10 T
  - 1,600 A/mm2 @ 12 T
  - 1,000 A/mm2 @ 15 T
- Cu Stabilizer (Cu/NC ratio: 1:1)
  - Cu electro-plating
  - Cu/Non-Cu = 1.0 realized

K. Tsuchiya et al., (MT-19), IEEE Trans. IEEE Trans. 2, (2006) p.1204.
C. Mitsuda et al., ASC-06, 4ML036

Continuous Cu-Plating Facility

for long strands at KEK (Nomura-Plating)

Pilot plant for continuous electroplating



~0.4 m/h ~200 μm Cu

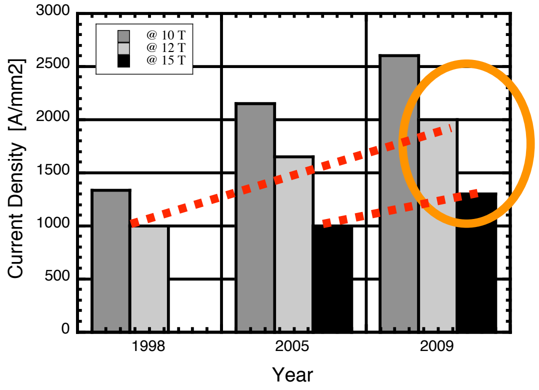
Plating speed may be improved to be ~ a few m/h

What understood ?

- Current density:
  - Jc achieved: ~ 1,000 A/mm^2 at 15 T, 4.2 K (KEK)
- Cu-stabilizer:
  - Electro-plating is positively examined up to a continous length of 1.2 km (NIMS)
- Cabling:
  - Successfully made at CF = 82 %, but Cu-stabilizer boundary not mechanically strong enough, (Fermilab-NIMS)
- Instability in low field found:
  - Associated with large magnetization in low field possibly because of Nb barrier/matrix
- Race track coil:
  - Successfully made and tested (Fermilab and NIMS).

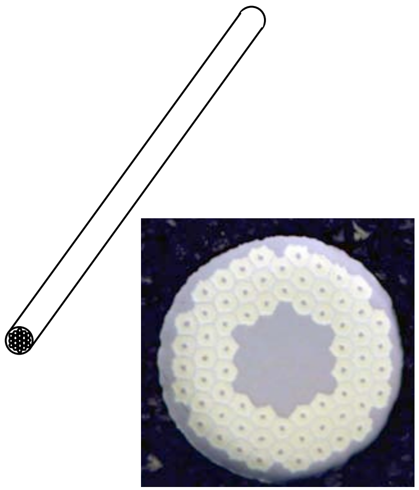
Subjects for further development

- Jc: > 1,300 A/mm^2
  toward 1,500 A/mm^2 at 15 T, 4.2 K,
  - Optimization of RHQ current,
  - Optimization of Area reduction
- Cu stabilizer
  - Mechanical stability & process speed,
  - Length: > 1 km,
- Magnetization: as small as possible,
  - Ta barrier/matrix instead of Nb
- Cabling: higher compaction up to ~ 90 %
- Race-track coil
  - Evaluation of cable performance to reach 15 T,
  - Radiation-hard epoxy impregnation / insulation,
  - Study of react and wind



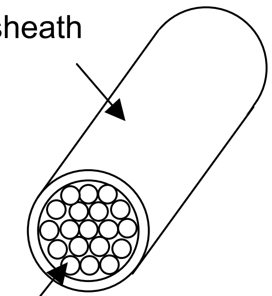
A Trial Process recently made at NIMS
Ta-matrix/sheath with Double stack and Cu-tubing

RHQ process ⇨ Re-stacking ⇨ Die-drawing ⇨ Post-annealing

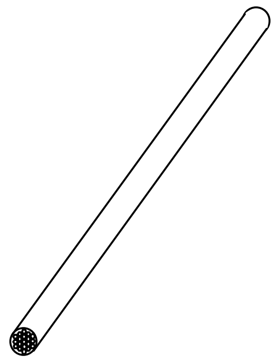


Ta sheath as-quenched
Nb/Al wire

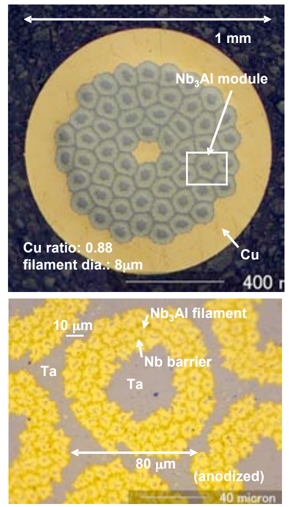
Cu sheath



quenched wire

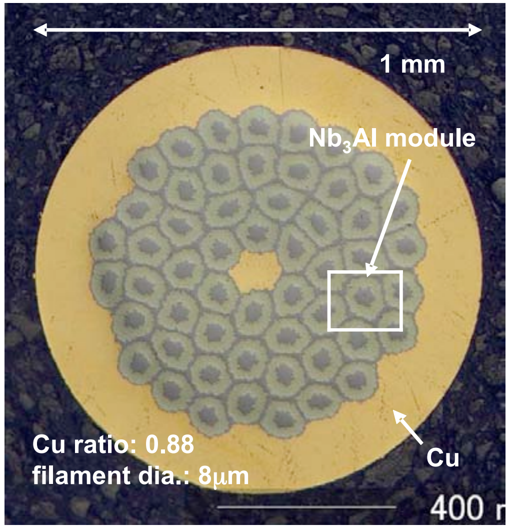


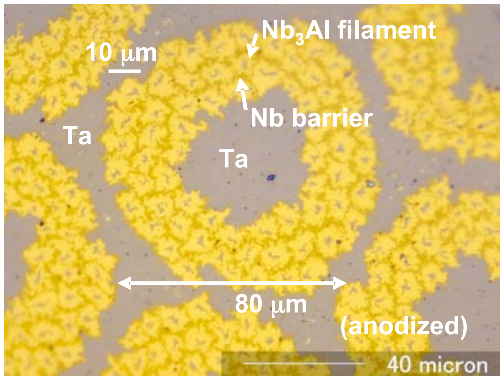
> strong deformation
~99% reduction in area
> test length : ~ 20 m
without breakage



Filament size drastically becomes small

Design parameters of Ta matrix Nb3Al conductor





	M28-4
Wire diameter (mm)	1.0
Filament diameter (μm)	7.7
Sheath material	Cu
Sheath thickness (μm)	115
Barrier material	Ta & Nb
Barrier thickness (μm)	1st: 9.6, 2nd: 1.0
Number of filaments	3564 (=66×54)
Matrix ratio to filaments	1.654
Cu/non-Cu ratio	0.84
Twist pitch (mm)	no
Bend strain limit for micro-cracking (equivalent bend strain at outermost filament location)	0.85% (0.66%)

Report of Recent Development at NIMS on Ta matrix

- Nb_3Al strand with "Ta matrix"
  - Effective to reduce magnetization
    - T. Takeuchi et al., IEEE Trans. Appl. Superc. 15 (2005), 3327-3375.

- "Cu-tubing" on Ta sheath/matrix strand
  - Aimed at fast process for Cu stabilizing
    - N. Banno et al., presented in ASC-06, Seattle, 2006.

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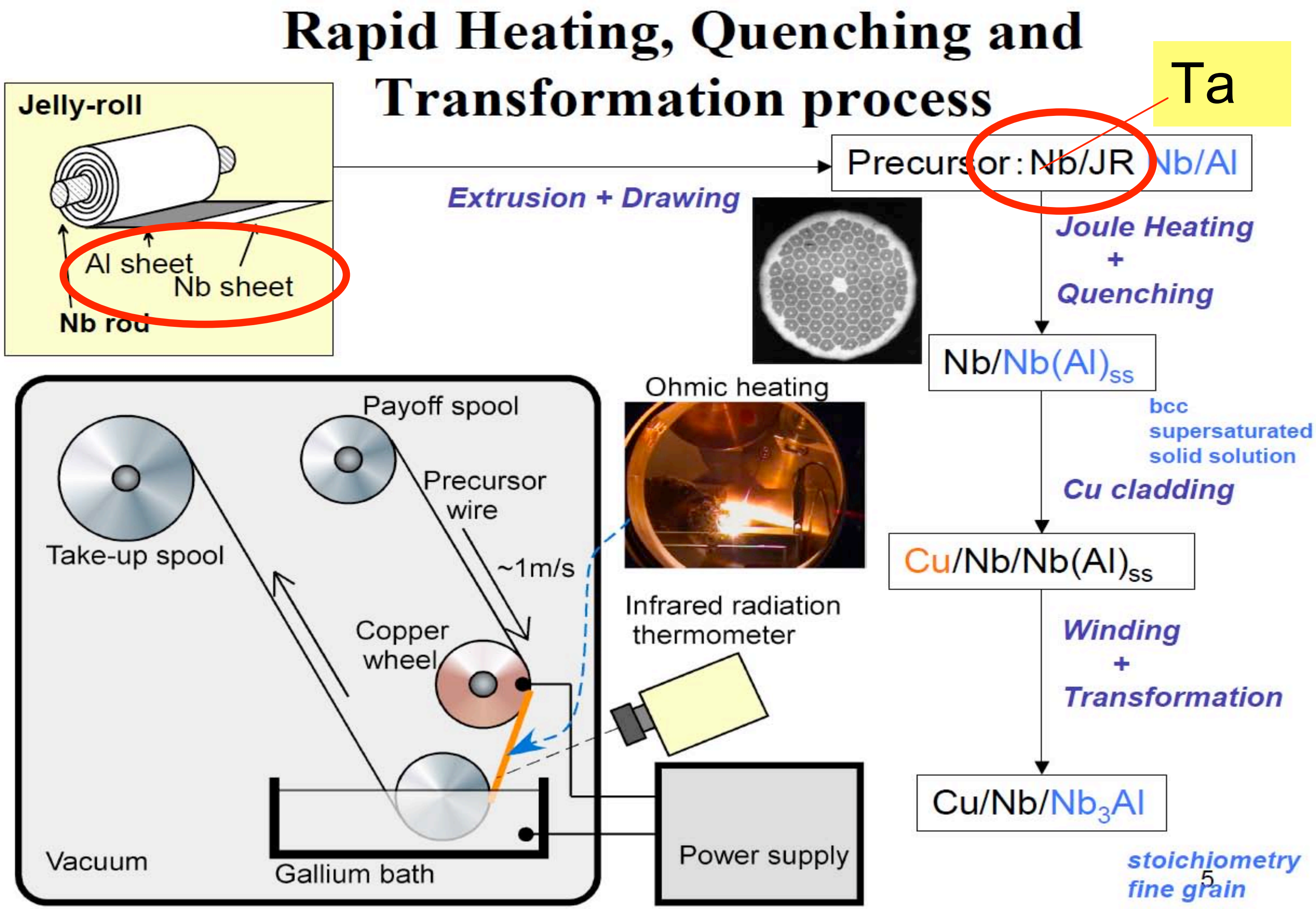
– *Budget for Nuclear Research of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), based on the screening and counseling by the Atomic Energy Commission*

Development Plan at KEK
JFY2006 - 2008

- Strand (FY2006-2007) with CERN-KEK Cooperation
  - Nb3Al/Nb-matrix/Cu-plating aiming at
    - Search for optimum and stable conditions
      --> 1000 A/mm2 at 15 T, at non-Cu J_c
    - Production of long strand (> 1km)
      - To enable cable production
  - Nb3Al/Nb-matrix/Cu-plating aiming at
    - Search for optimum condition for high J_C (>> 1000 A/mm2)
      - More uniform diffusion of Al into Nb (Al-sheet thickness opt.)
  - Nb3Al/Ta-matrix/C-tubing(or plating) to investigate
    - Reduce magnetization
    - Fast and cost-effective process for Cu-stabilizing
    - Short length (~ 100 m) for fundamental research
- Cable (2007-2008): with US-Japan Cooperation
  - See later.

What will be investigated?



T. Takeuchi et al. IEEE Trans. Appl. Superc. 12, 1 (2002) 1088.

Nb3Al conductor R&D Plan

(2006-2007) with CERN-KEK Cooperation

Matrix	Nb	Nb	Ta
Purpose	Cu-plating, Cable	High Jc	Magnetization reduction, Cu-tubing
Length	2 x 1 km	3 x 100m	100 m
Diameter	1.35>> 0. 76 mm X >> 0.76		1.35 >> 0.76
Al-thick.		150/200/250 nm	200 nm
Jc at 15 T	1,000 A/mm^2	>>1,000 A/mm^2	
Filament dia			69 >> 40 μm

Cable and Race Track Coil Development

(JFY2007~2008): with US-Japan Cooperation

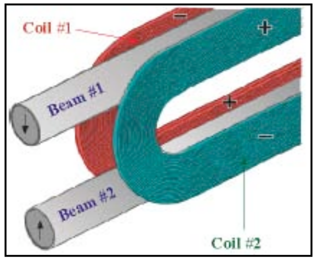
- Cable:
  - Mechanical stable, Rutherford cable in cooperation with FNAL
- Nb_3Sn (NbTi) race-track coil,
  - Technology transfer from LBNL for fabrication,
  - Practice with Nb3Sn(NbTi) cable,
    - Heat treatment, and insulation practice,
    - Possible R&D for radiation-hard epoxy-resin impregnation
- Nb3Al Race-track Coil,
    - Comparison with Nb3Sn coil,
    - Possible R&D for Wind & React, and React & Wind

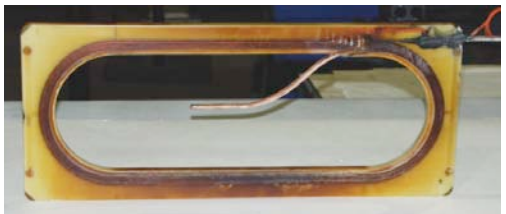
A US-Japan cooperation program to be proposed

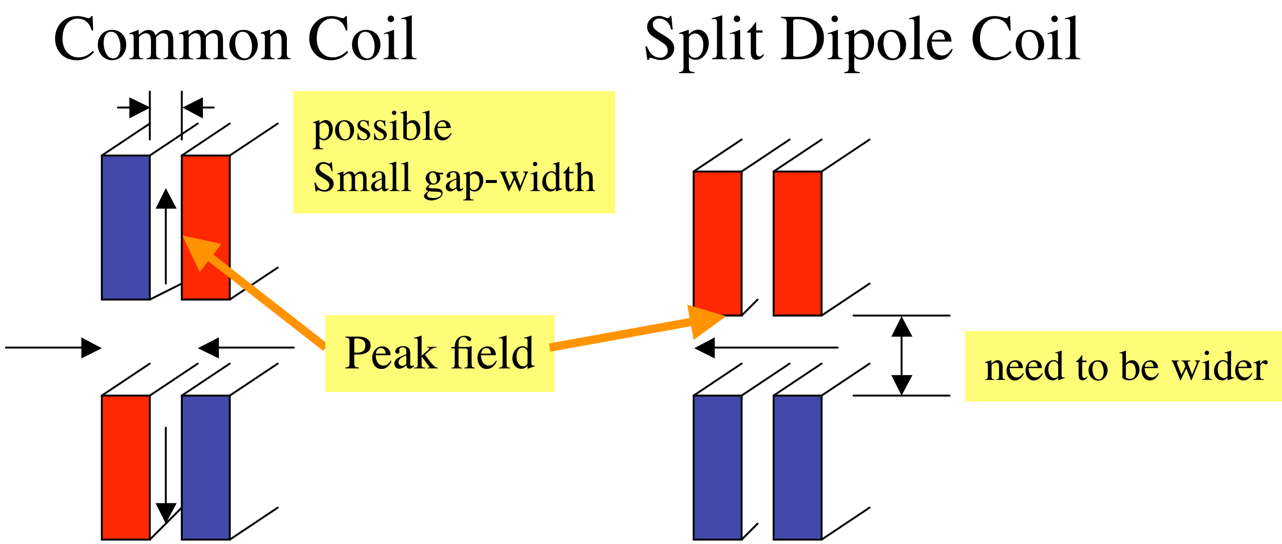
- Title:
  - Development of Advanced, High-field (A-15) Superconductor and Superconducting cable for the LHC luminosity upgrade
- Frame:
  - LARP magnet group and KEK-NIMS collaboration as part of the US-Japan cooperation program in high energy physics,

Race-track Coil for Cable Evaluation

- Quick development/feedback
- Common coil with small gap-width design
  - convenient to generate higher peak field in the coil, or
- Split Dipole Coil

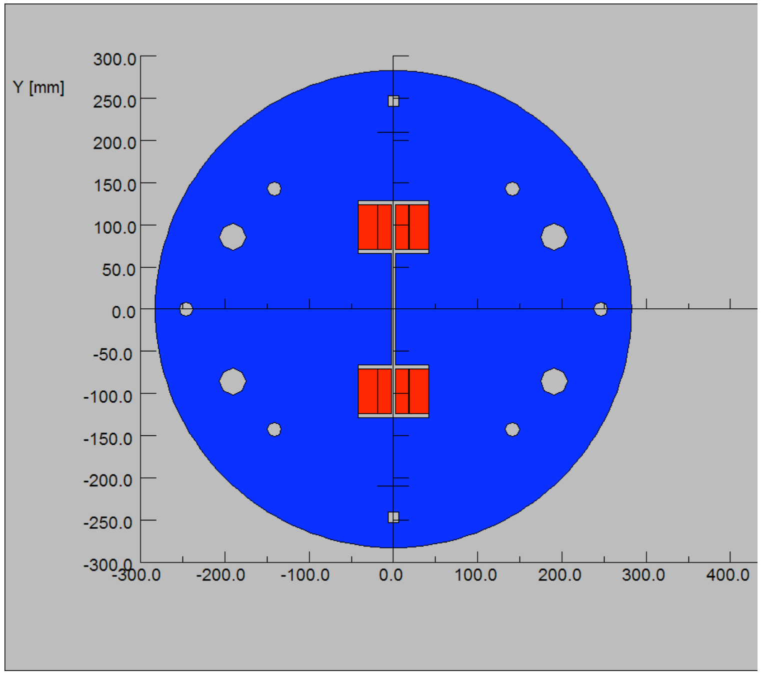


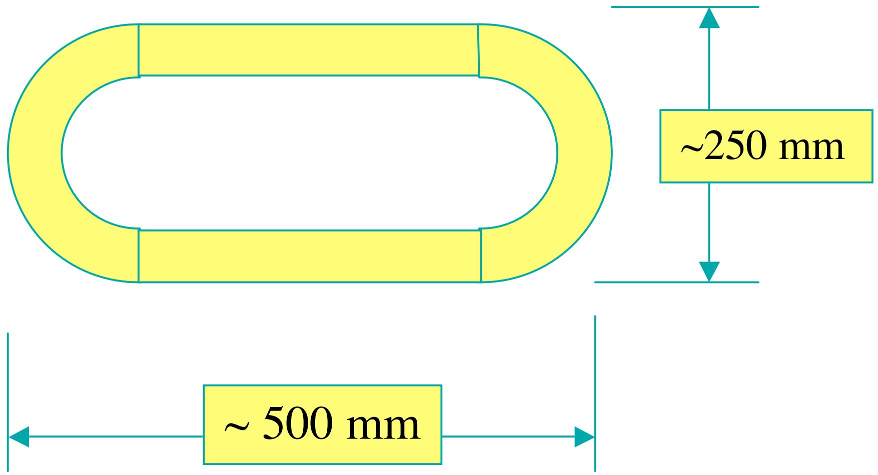




A design; Race-track Magnet with Common Coil Design

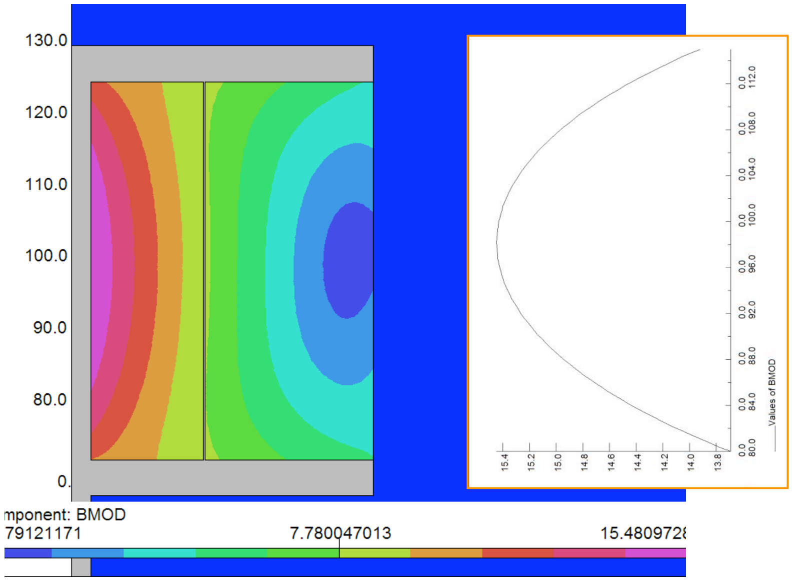
- Common coil with iron yoke
  - Hybrid coil consisting of Nb_3Al and NbTi layers

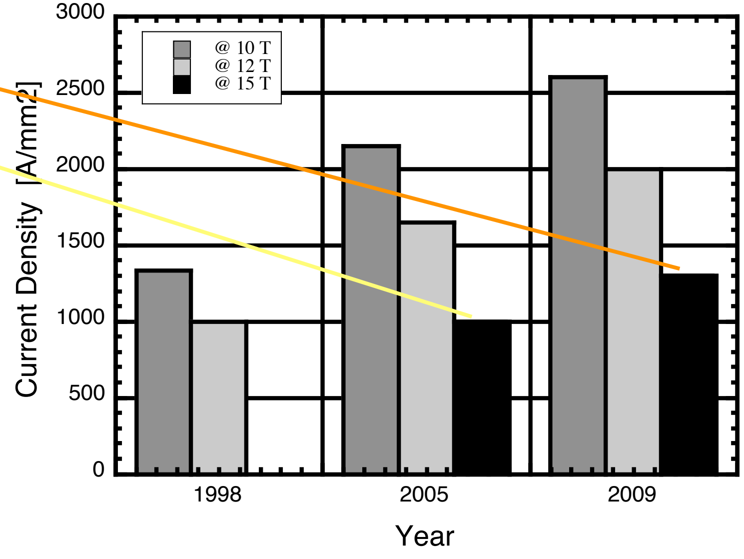




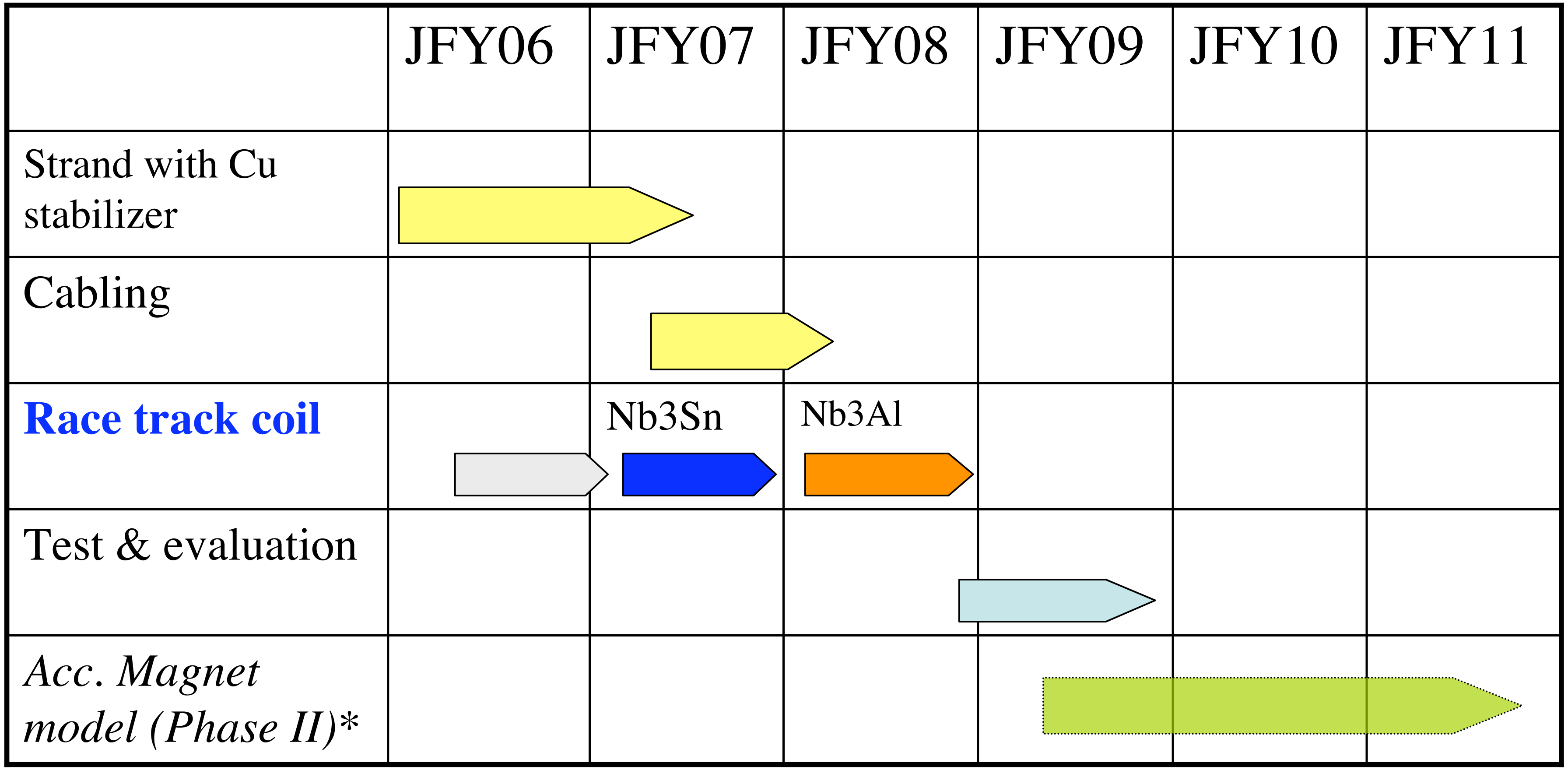
Race Track Coil Parameters

	Nb3Al Coil	NbTi Coil
Layers	2	3
Turns/layer	35	35
X section	7.4_w x 52.5_h	7.4_w x 52.5_h
Coil size(mm)	250 x 500	250 x 500
Bmax	15.5 T@ 2009 (14.4 T@ 2005)	8.22 T
J_{SC} (A/mm2)	936 (~95 % Jc)	1211
I (kA)	5.265	5.265
Superconductor: Cu/Super ratio Jc (SC) (A/mm2) strand dia. No. strands cable size w/insulation	 0.7 950 @ 15.5 T 4.2 K 0.7 mm 20 1.25 x 7.4 15 x 87.7	 1.2 1300 @ 8.2 T, 1.9 K 0.7 mm 20 1.25 x 7.4 1.5 x 7.8





Development Plan



＊The plan to be reviewed and to be updated for further extension by the end of FY-08.

Budget proposed

	JFY-06	JFY-07*	JFY-08*	JFY-09*
Strand	15,800	23,000	15,000	0
Cable	(US-JP)	(US-JP)	(US-JP)	(US-JP)
Model Coil	1,000	5,000	12,000	0
Test	2,000	3,500	6,500	1,500
Work Assist. Travel, etc,	1,200	1,500	1,500	500
Total	20,000	33,000	35,000	2,000

* tentative

Summary

- We are progressing development of Nb3Al superconductor and intending to realize applicable cable for the LHC luminosity upgrade,

- An R&D cooperation net work is proposed, based on two cooperation frame works of CERN-KEK cooperation and the US-LARP(magnet group)-KEK collaboration
  - CERN-KEK : to develop Nb3Al strand, and associated A-15 conductor technology (such as radiation-hard insulation technology),
  - LARP-KEK: to develop Nb3Al cable, and instruct A-15 race-track (sub-scale) magnet technology,

- The R&D is to realize the Nb_3Al cable applicable at ~ 15 Tesla and to evaluate the performance by 2009 to enable to:
  - Contribute to the LHC luminosity upgrade magnet development.