Research and development of high radiation-resistant superconducting magnet based on REBCO coated conductors

Masami IIO

Cryogenics Section, J-PARC

Cryogenics Science Center, KEK

Contents

1. Introduction

2. Superconducting solenoid system for high intensity muon source

3. R&D Items
   - 3. 1. Neutron irradiation
   - 3. 2. Feasibility study of mineral insulated coil
   - 3. 3. Development of demonstration magnet

4. Summary

Contents

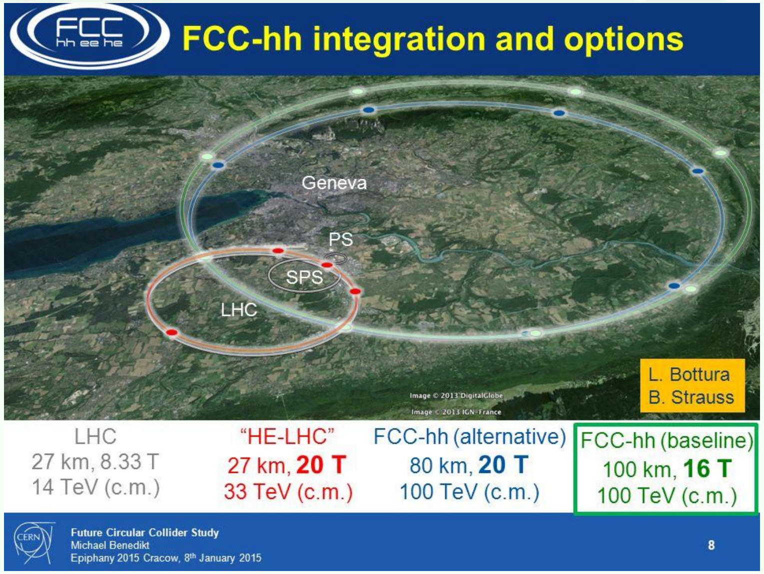
Future accelerator magnets

FCC@CERN: 100 TeV

- 20 T class high-field magnet
  → Absorbed Dose: 100 MGy?

J-PARC MLF 2nd Target station

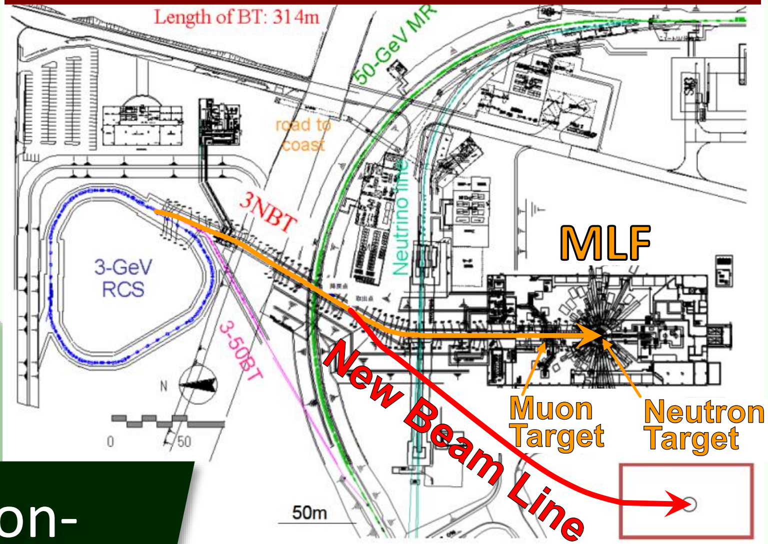
- Solenoid covering production target
  → Absorbed Dose: 130 MGy???



Conventional Magnet Technology

- **NbTi Cable**
  → T=5 K with heat load reaching 650 W? due to nuclear heating
- **Organic Material for Insulation**
  → Degradation of the machine strength from 10 MGy

J-PARC



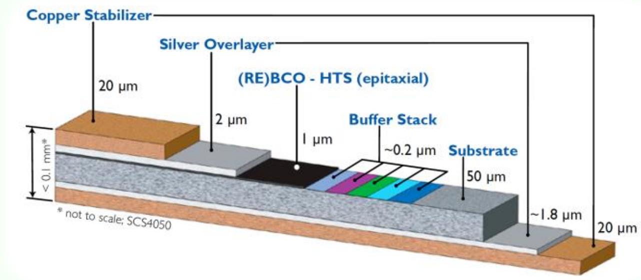
MLF 2nd Target Station

Development of next-generation radiation-resistant high field magnet has been awaited

1. REBCO coated conductor

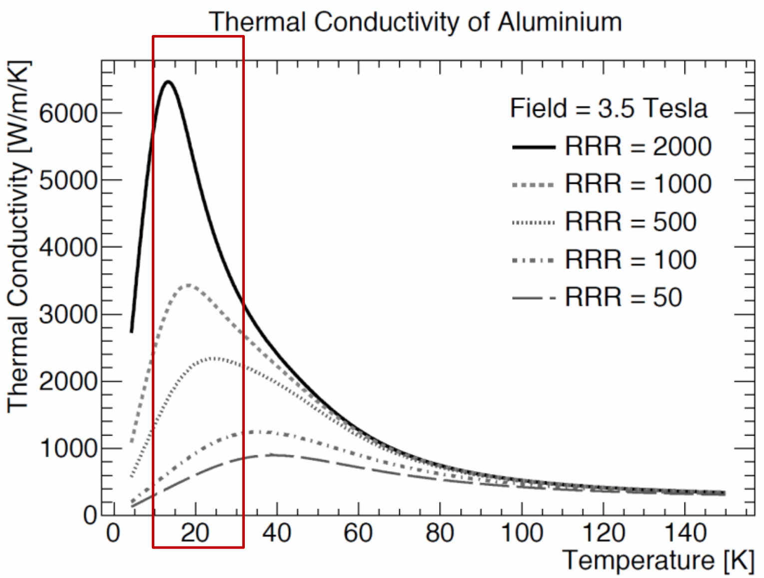
➤ **High temperature margin** (T_C=93 K)

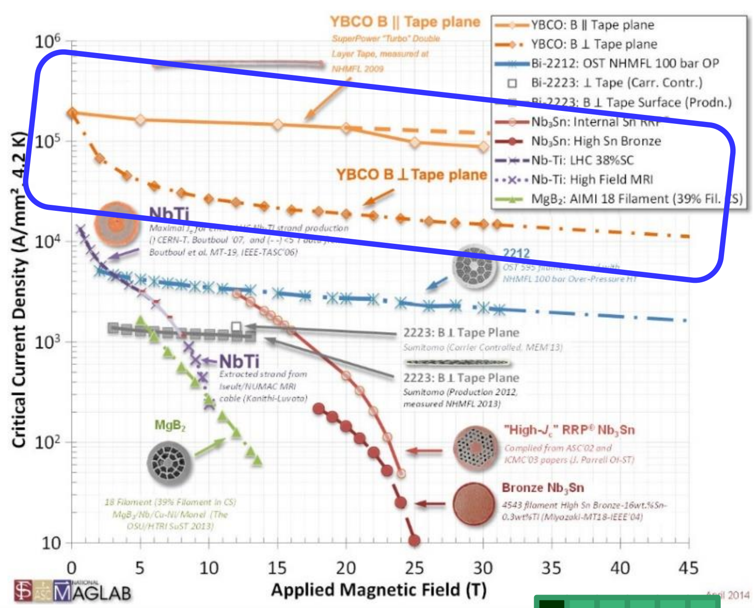
- Conduction cooling operation in the temperature range of 20 K



➤ **High magnetic field tolerance of Ic**

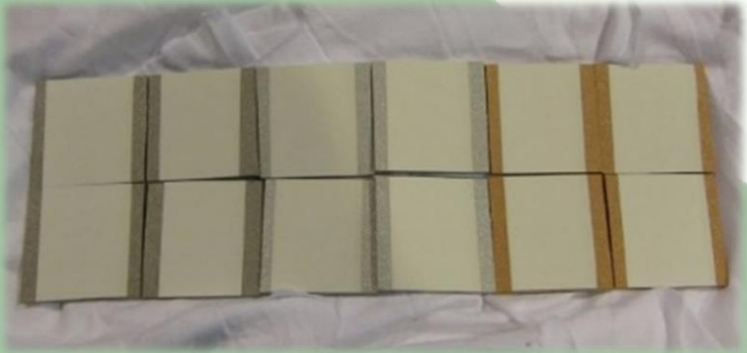
- Potential for 20T class high field magnet





2. Mineral insulation by Ceramic coating & bonding

- **High radiation tolerance of mechanical strength**
- **Better thermal conductivity**
  - MgO:59, Al_2O_2:32, SiO_2:10 >> EP resin:0.3 [W/m·K @300K]
- **Close to the coefficient of thermal expansion of cable**

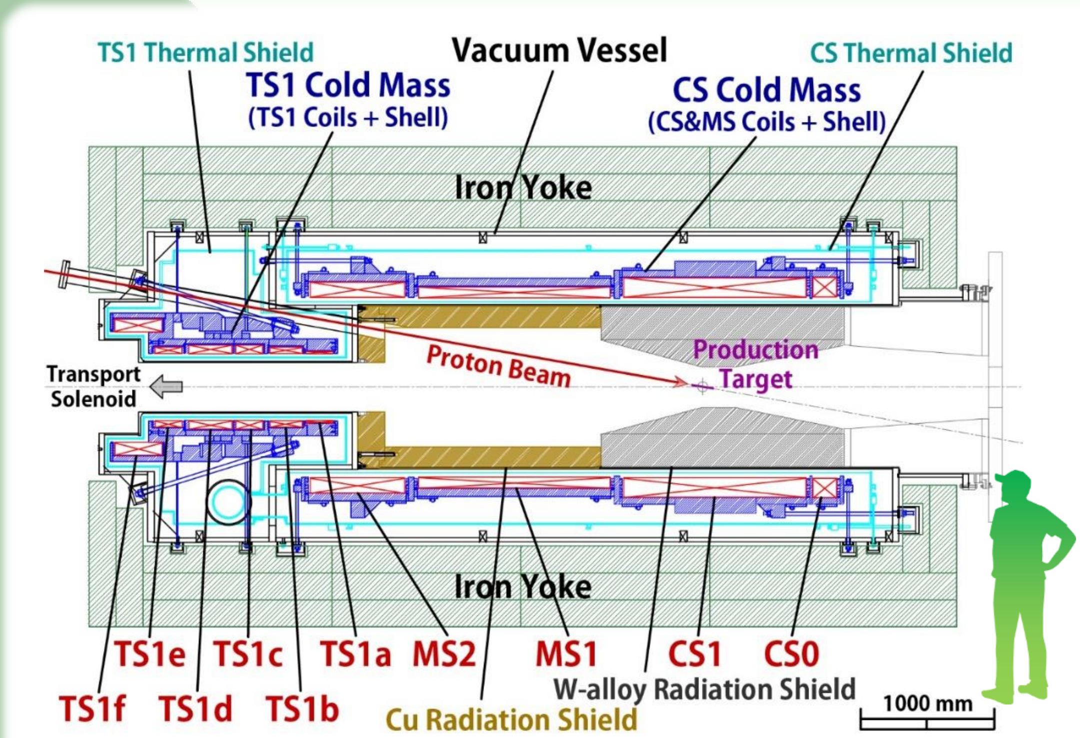


Research and development of mineral insulated superconducting magnets are in progress using REBCO coated conductors

Contents

COMET muon source (5 T-class solenoid)

In case of the recent muon source,
the production target is equipped in a solenoid magnet
→ High radiation resistance is required



- OD of cryostat: **2.3 m**
- Length of cryostat: **6.5m**
- Weight of cryostat: **45 t**
- Peak field at target: **5 T**
- Proton beam power: **56 kW**
- Weight of Radiation shield
  : **~40 t** (W-alloy + Cu)
- Absorbed dose: **~1 MGy**
- Nuclear Heating: **191 W**

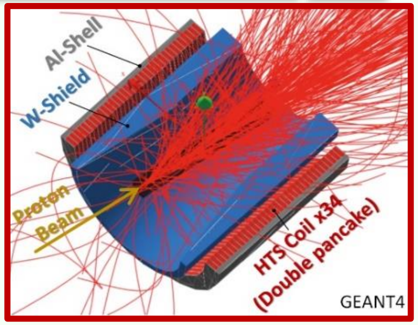


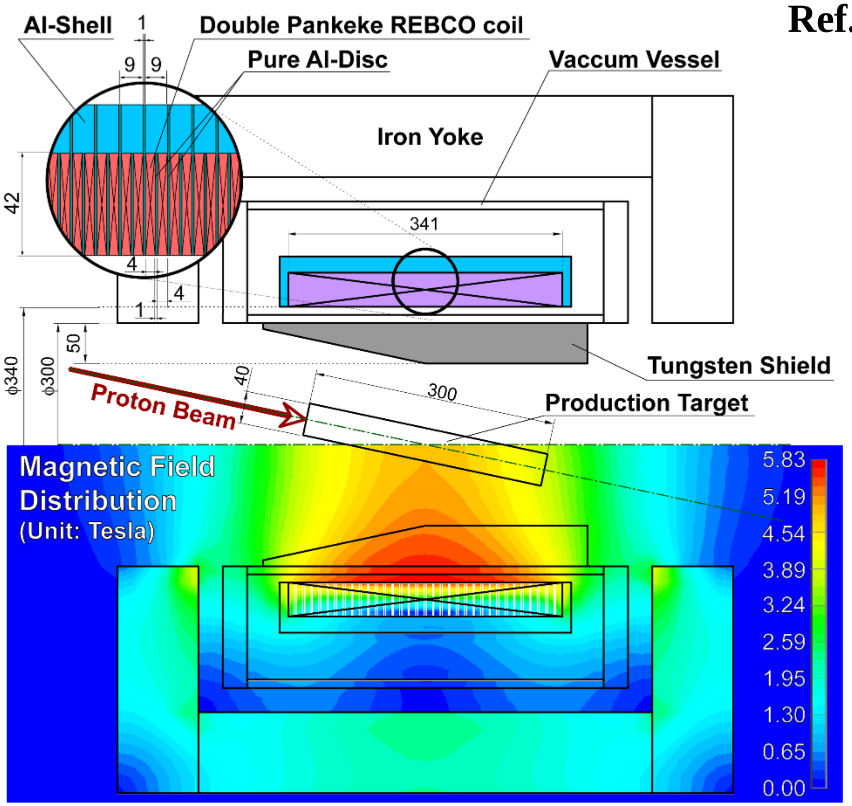



Compact muon source

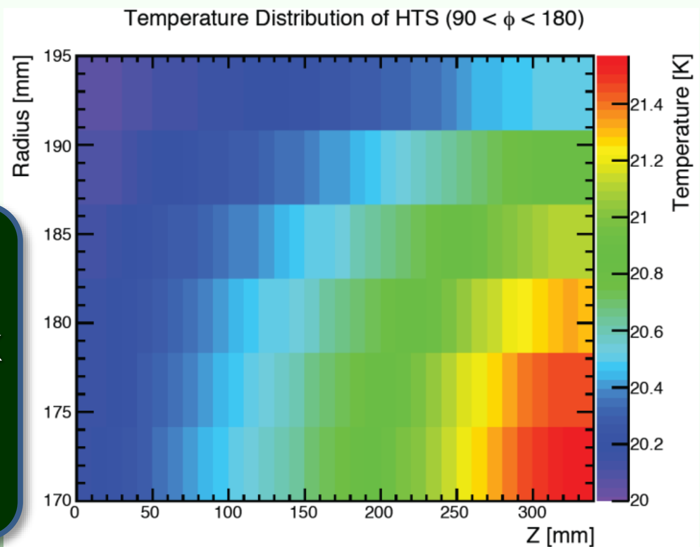
➤ **Design study of muon source like COMET system using REBCO was performed**

Ref. : Y. Yang *et al* 2015 *IOP Conf. Ser.: Mater. Sci. Eng.* 101 012054





PARAMETERS	VALUE
$T_{Operating}$	20 K (Conduction cooling)
Peak field on target	5 T
Conductor / Cable	REBCO / W=4 mm, T=0.1 mm
$I_{Operating}$ / Load factor	100 A / 40 %
Coil type	Double pancake solenoid
No. of turns per layer	277
Total No. of coils	34
Coil dimension	ID=340 mm, T=42 mm, L=9 mm

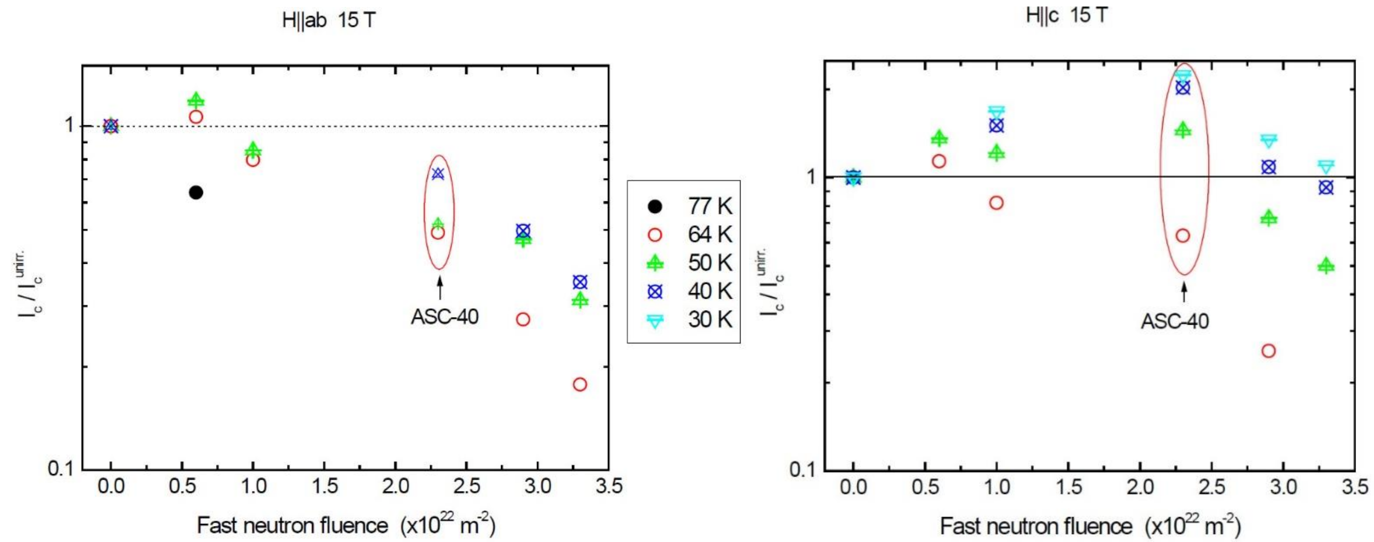


1. Size Reduction : **1/100** (W= 45 t → 0.43 t)
2. High Temperature Margin: **T_{max}= 21.6 K** < T_C=59 K
   (Heat deposit by radiation: 0.48 W/kg > COMET case)
3. High Magnetic Field?: 5 T (**39%**), 10 T (**78%**)

- **Neutron irradiation**
  → REBCO, MgB_2, MI-Cu tape, BT-GFRP
- **Feasibility study of mineral insulated coil**
  → Ceramic coating to REBCO tape (Al_2O_3, SiO_2 …)
  → Ceramic coating to magnet materials
  → Coil winding with the ceramic bond
- **Development of small-scale conduction cooled demonstration magnet**
  → Customization of pulse tube Cryocooler
  → Assembly, cooling and excitation test

Contents

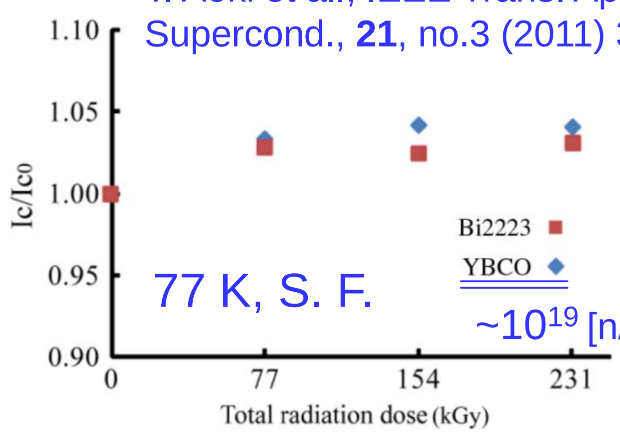
How is the radiation tolerance of REBCO tape?



R. Fuger et al., Physica C 468 (2008) 1647.
M. Eisterer, RESUMM2017.

There are some research activities

T. Aoki et al., IEEE Trans. Appl. Supercond., **21**, no.3 (2011) 3200.



Purpose of our irradiation test

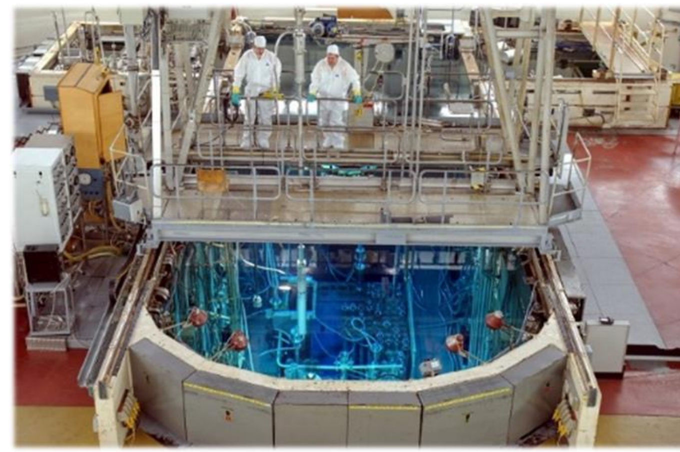
- Confirmation of phenomena
- Increase of data
  (Dose, Temperature, Applied Field)

Inter-university cooperative research program

International Research Center for Nuclear Materials Science, Institute for Materials Research, (IMR-Oarai) Tohoku University

Sample (REBCO tape)

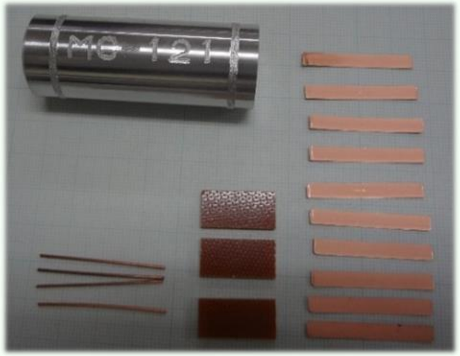
BR2 @Belgian nuclear research center



Superconducting Properties Evaluation System @IMR-Oarai

Temperature Range	4 ~ 80 K
Max. Current	500 A
Max. External Field	15.5 T

Current status of neutron irradiation



Irradiated samples at BR2 in FY2016

2 capsules (It returned in FY2017)

→ HTS (SCS4050-AP) x10, BT-GFRP x3

→ Neutron fluence: 1.80×10^{22}, 8.37×10^{22} n/m^2 (En>0.1 MeV, T< 100 ℃)

→ Equivalent dose of HTS: 150, 650 mSv/h (Distance: 0.5 m)

Irradiated samples at BR2 in FY2017

2 capsules (It will return in FY2018)

→ HTS: SCS4050-AP x5 & FYSC-SCH04 x5, BT-BFRP x3

→ Neutron fluence: 1×10^{22}, 5×10^{22} n/m^2 (En > 0.1 MeV, T< 100 ℃)

Irradiated samples at BR2 in FY2018 (Shipped soon)

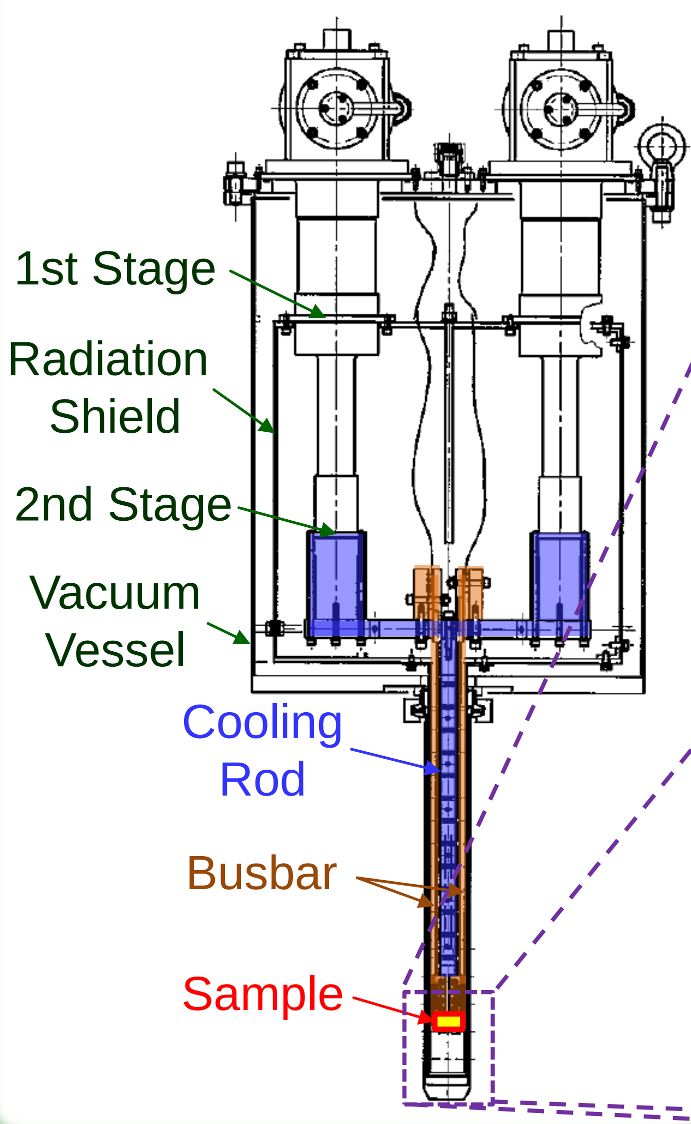
2 capsules (It will return in FY2019)

→ HTS: SCS4050-AP x5 & FYSC-SCH04 x5, MgB_2 x3, BT-BFRP x3, MI-Cu

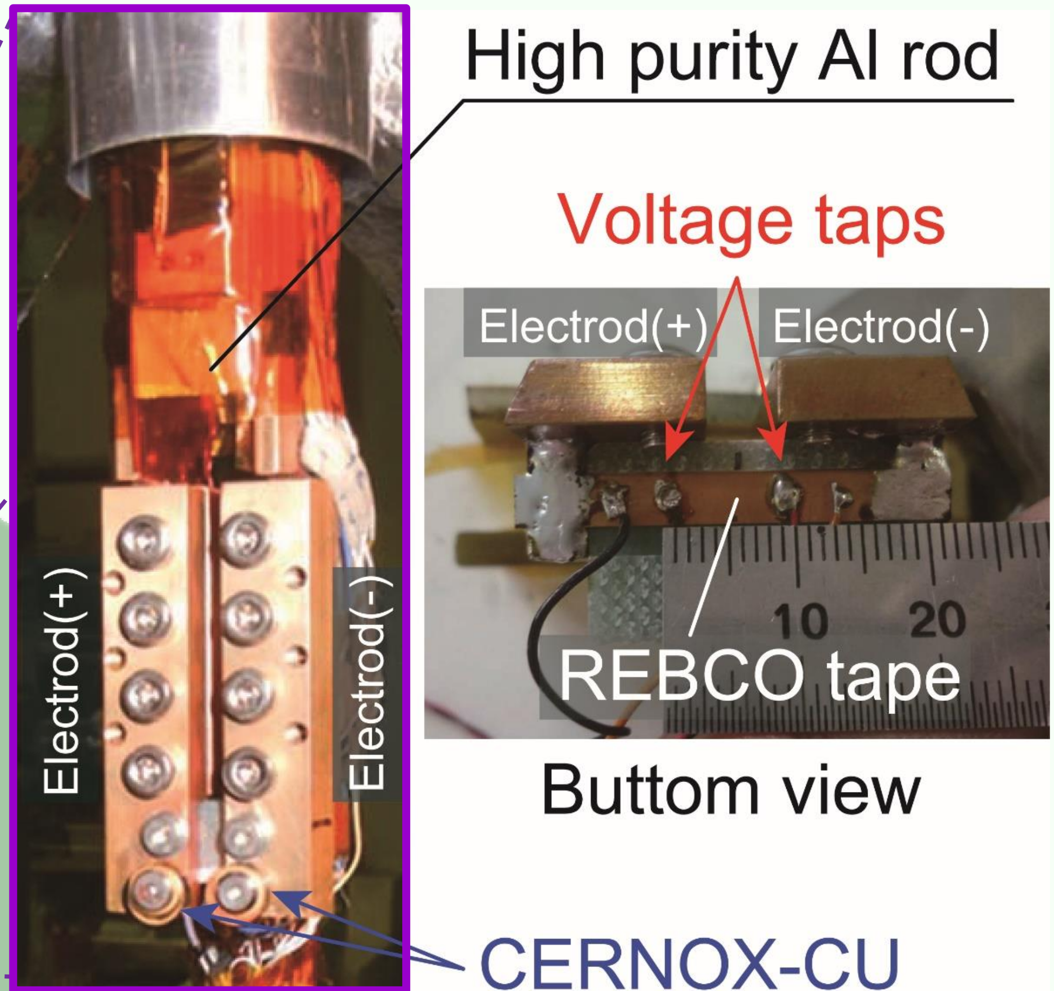
→ Neutron fluence: 1×10^{21}, 5×10^{21} n/m^2 (En > 0.1 MeV, T< 100 ℃)

We are preparing for PIE (post irradiation examination)

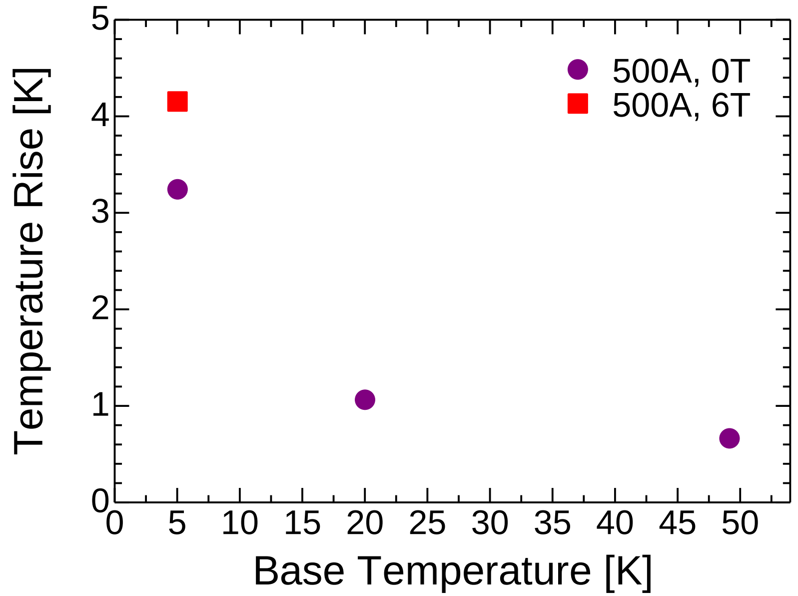
Commissioning of VTI for 15.5 T magnet

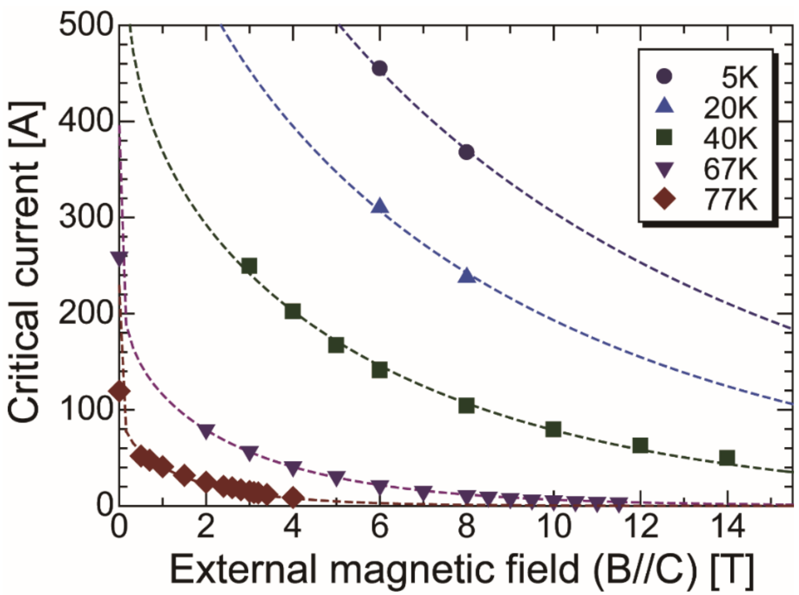


Commissioning of the evaluation system has been performing with un-irradiated sample



Commissioning of VTI and 15.5 T magnet





Confirmed Items

- **Transport current of 500 A with external field of 0 T and 6 T**
- **Stable temperature control of sample holder up to 77 K**
- **Critical current measurement of HTS sample up to 77 K**
- **Demonstration of new HTS sample holder (//c) under Lorentz force (8 T, 300 A)**

PIE (post irradiation examination) of HTS samples will start soon

Contents

Trials of ceramic coating

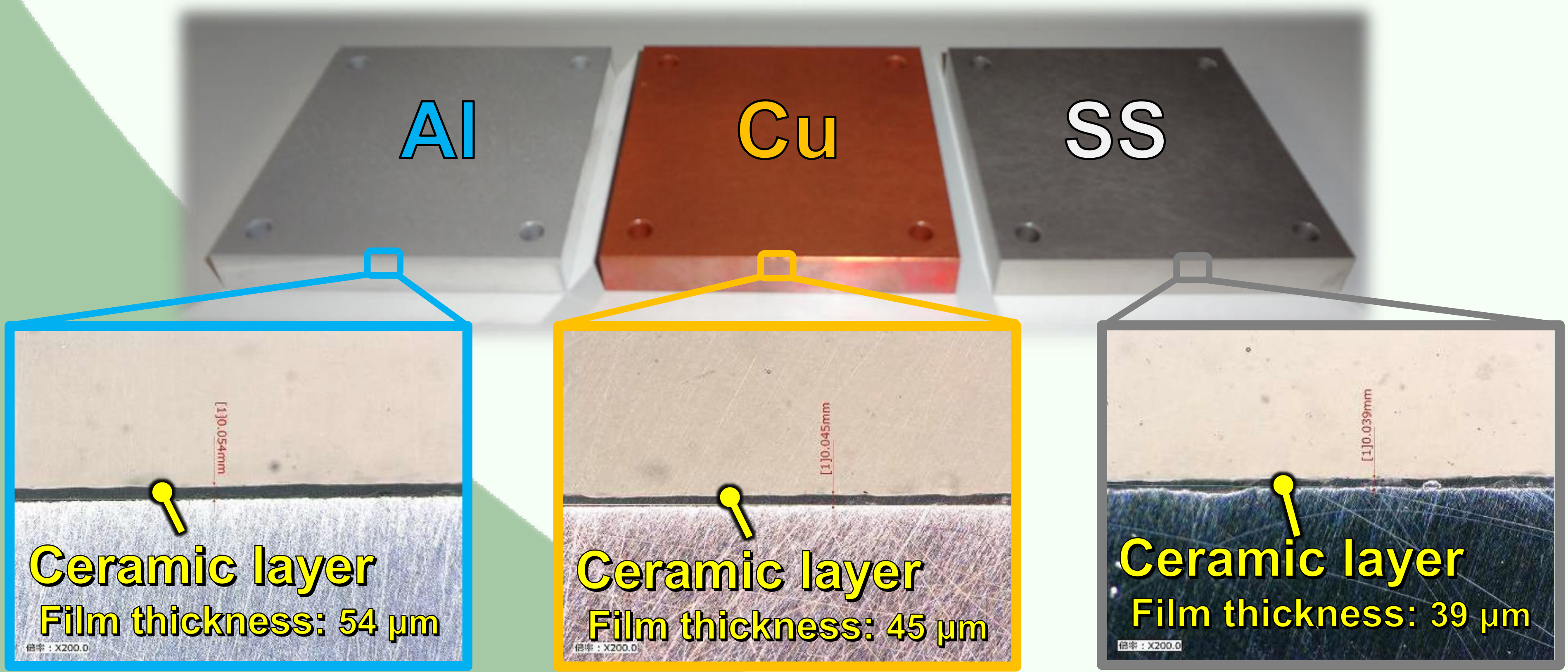
ITEMS	1ST TRIAL	2ND TRIAL
Base material	**Al** (Al-123 Mg4.5Mn0.7), **Cu** (Cu-OF R1337), **SS** (L-No6X5CrNi18-9), **REBCO** (SCS4050-AP)	
Coating material	G-92-5 (NIKKEN .Ltd)	
	Al_2O_3 : SiO_2 =1:3	Al_2O_3 : SiO_2 =1:1
Target thickness	50 μm	30 μm, 20 μm, 10 μm
Final heat treatment	180℃, 20 min	100℃, 20 min

➤ Coating Process

Spraying → Drying → Spraying → Drying … → Final heat treatment

Thickness control

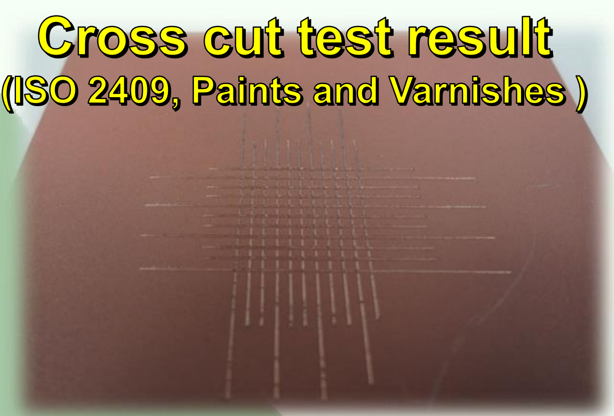
1st trial results of metal plates

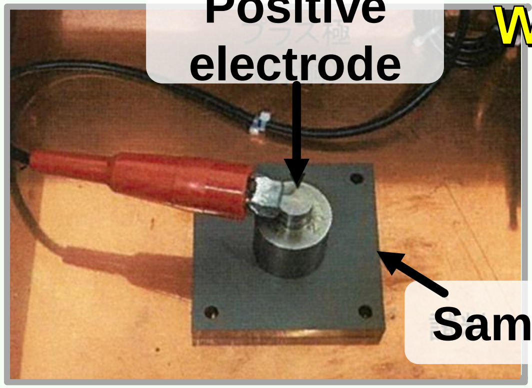


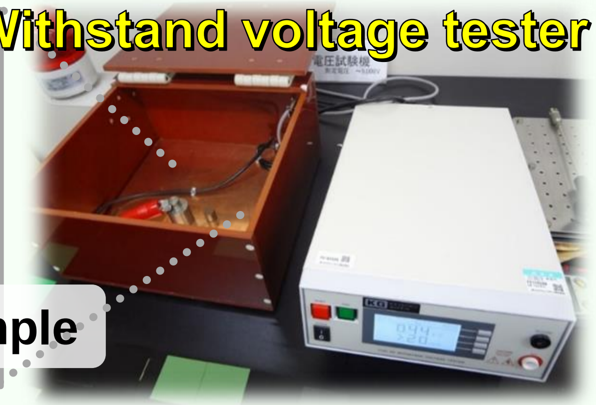
- Withstand voltage: > 2000 [V]
- A few cracks layer was observed (Withstand voltage: 700 [V])

The target film thickness should be smaller

Cross-cut test & Withstand voltage test





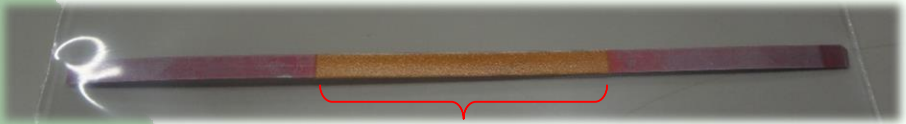


Al		Cu		SS	
Film Thickness	Cross-cut	Film Thickness	Cross-cut	Film Thickness	Cross-cut
30.9 μm	Class 0 (100/100)	37.4 μm	Class 0 (100/100)	30.5 μm	Class 0 (100/100)
18.3 μm	Class 0 (100/100)	18.9 μm	Class 0 (100/100)	21.6 μm	Class 0 (100/100)
10.3 μm	Class 0 (100/100)	12.6 μm	Class 0 (100/100)	11.7 μm	Class 0 (100/100)
Film Thickness	Withstand voltage	Film Thickness	Withstand voltage	Film Thickness	Withstand voltage
44.7 μm	> 2000 V	44.9 μm	> 2000 V	53.8 μm	> 2000 V
28.3 μm	600 V	38.6 μm	1000 V	37.6 μm	1300 V
16.8 μm	400 V	22.4 μm	400 V	22.3 μm	300 V
8.5 μm	300 V	8.7 μm	200 V	11.5 μm	300 V

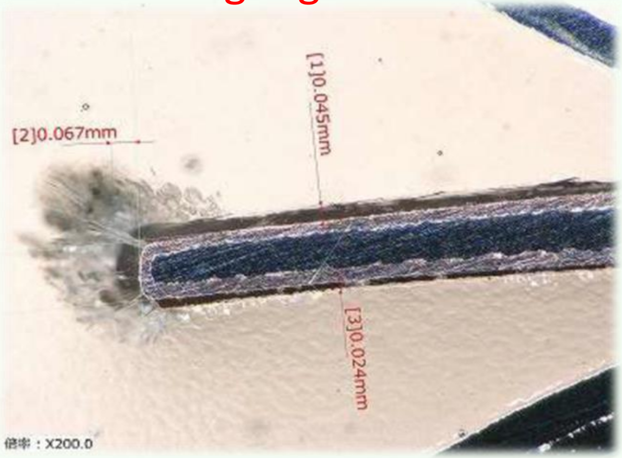
There was no peeling of one piece of ceramic layer

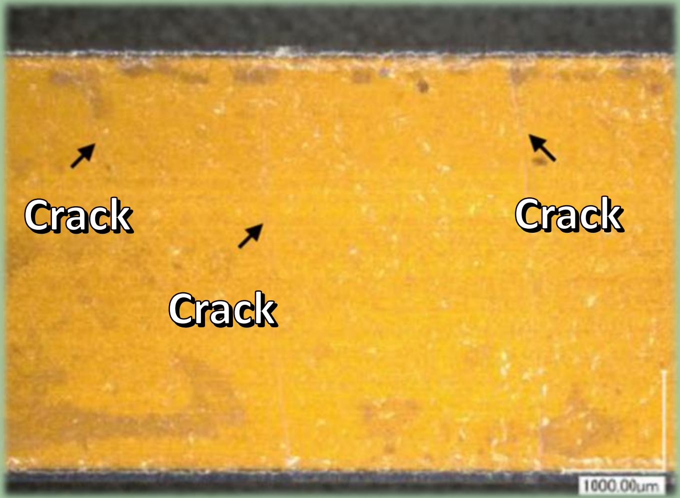
Cross-section observation of HTS tape (1st Trial)

SCS4050-AP (SuperPower)



FYSC-SCH04 (Fujikura)



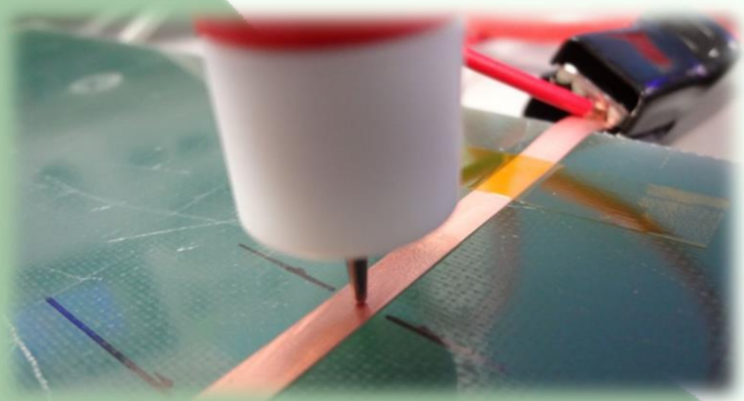


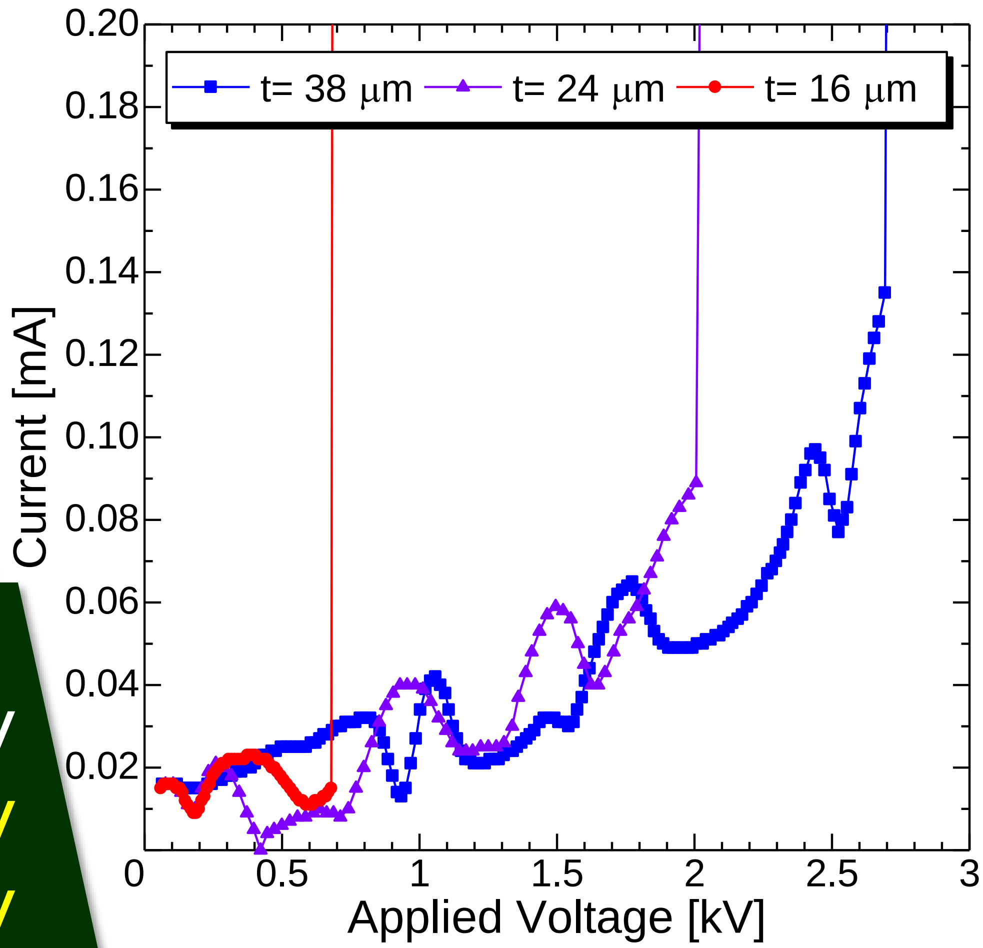
Several cracks were observed

There is no crack in the 2nd trial with the target film thickness of 30 - 10 mm and the final heat treatment temperature of 100 °C.

Withstand voltage test

Withstand voltage test by point probe is performed for evaluation of insulation. The load is applied with an AC voltage with a frequency of 50 Hz.



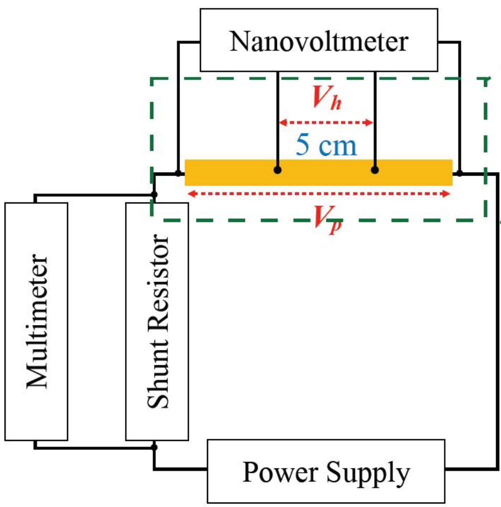


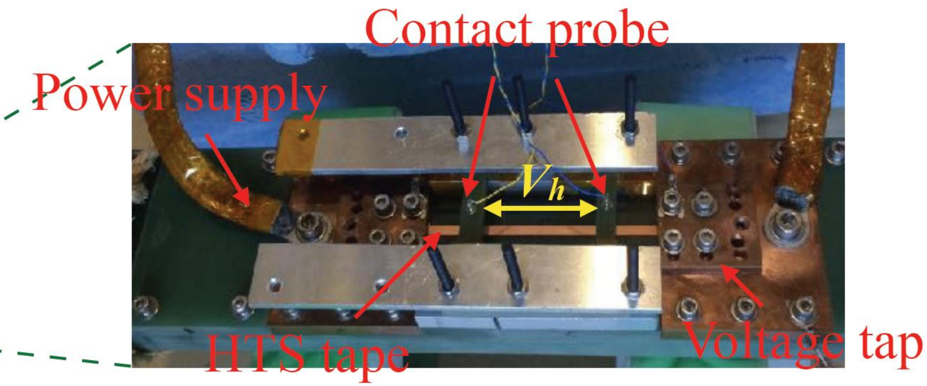
Withstand voltage

- t=16 μm : 0.679 kV
- t=24 μm : 2.006 kV
- t=38 μm : 2.693 kV

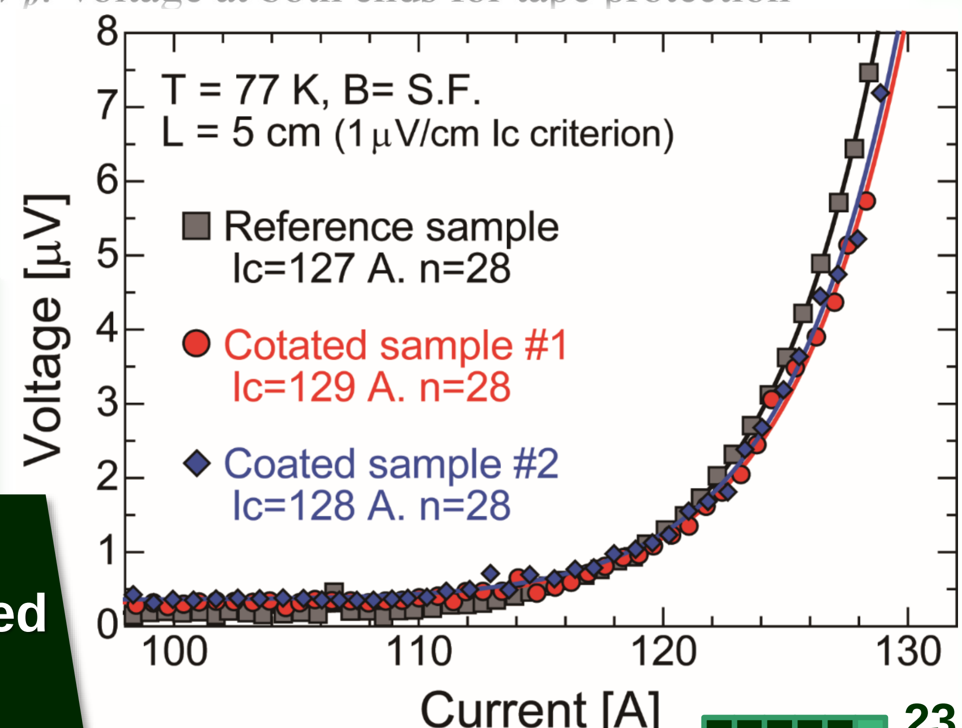
Critical current measurement in LN_2 Bath

A. Experimental Setup





V_h: HTS voltage for the determination of I_c
V_p: Voltage at both ends for tape protection



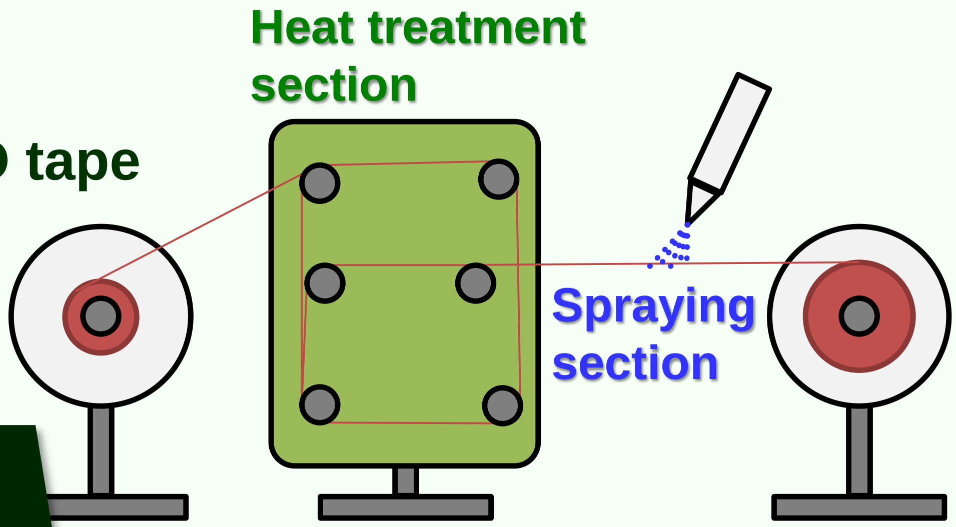
- **Final heat treatment:**
  180℃ for 20 minutes
- **Thermal cycle:**
  > 10 times (R.T.⇔ 77 K)

This coating is workable method for realizing the mineral-insulated superconducting magnets

Contents

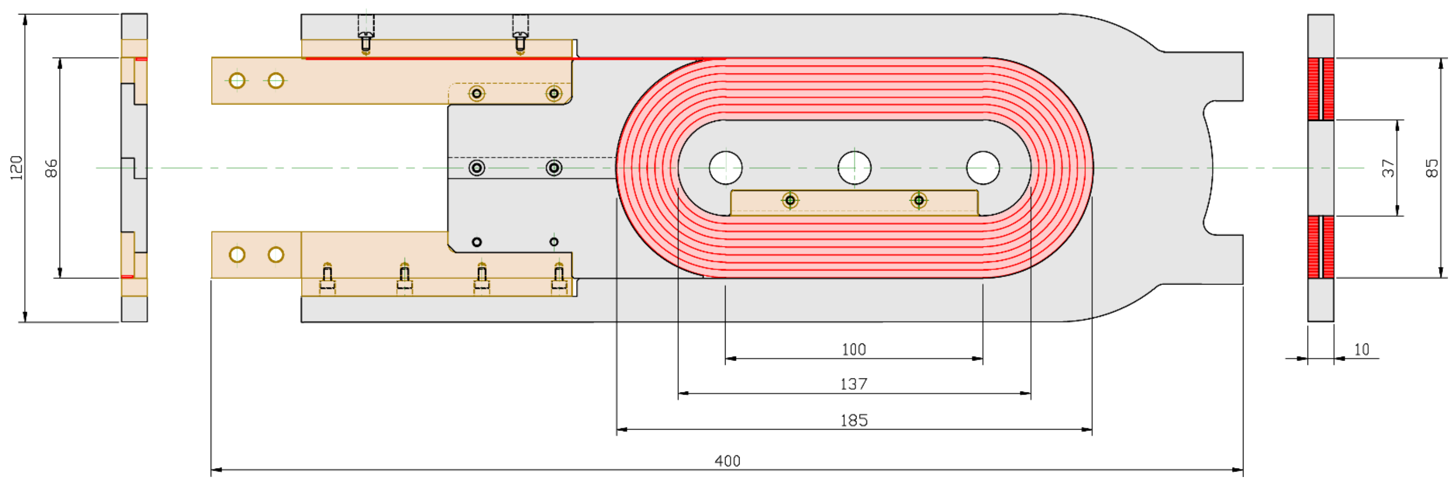
Ongoing R&D activities

- Ceramic coating to long REBCO tape
- Optimization of coil structure



Coil winding (wet-winding)

Double pancake type race track coil



We are planning two cooling and excitation tests

Single coil test in conduction cooling system

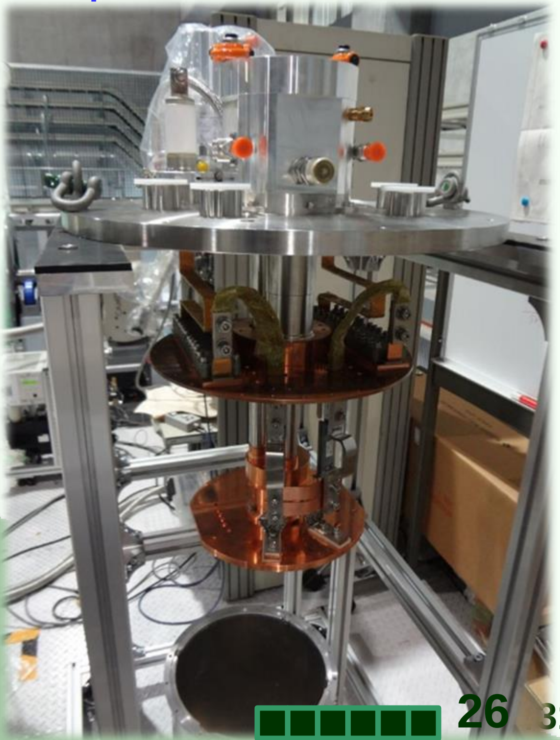
➤ Pulse tube cryocooler customaized for high radiation environment

Item	Standard	Modification
2nd Stage Capacity	0.9 W @ 4.2 K	**10 W @ 20 K**
Cooling storage material	Magnetic materials	**Bi**
Sleeve	PTFE	**Polyimide**
O-ring	NBR (nitrile rubber)	**1111A**

HAYAKAWA RUBBER <http://www.hrc.co.jp/product/wpcivil/radiation/>

Prototype of radiation-resistant magnet system

1. **Customized pulse tube cryocooler**
2. **Thermal anchor of bus bar with AlN**
3. **HTS current lead**
4. **Mineral indurated REBCO coil**



Test Items

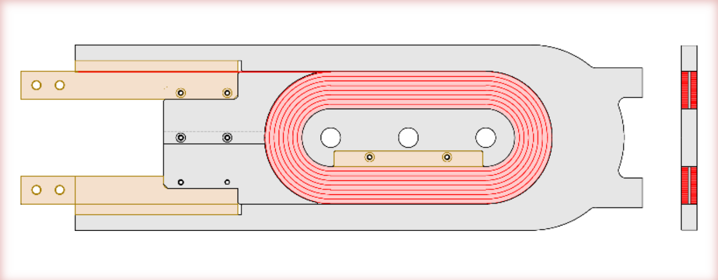
- **Temperature control up to 80 K**
- **Excitation test up to 500 A in self field**

High field test with common coil configuration

Test facility for A15 subscale magnet

For backup field
- Nb_3Sn coil x2
- (Nb_3Al coil x2)

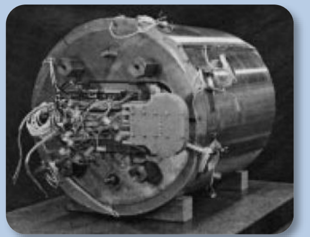
New development



MI-Double pancake racetrack coil based on REBCO

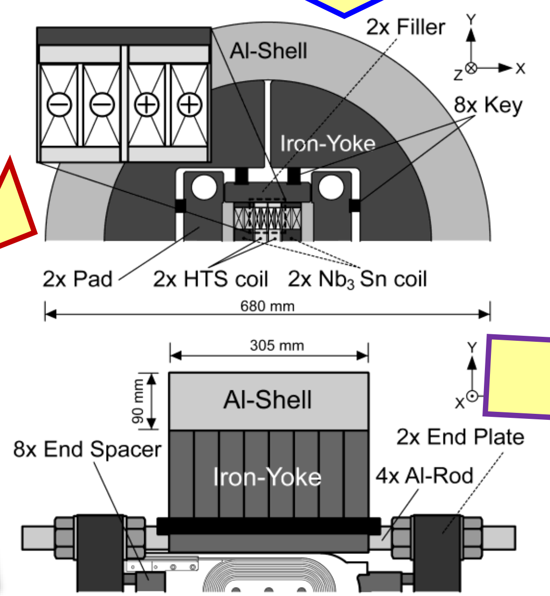
Excitation test at high field of 15 T in Liq. He bath

LBNL



Magnet Technology

2x Nb_3Sn coils



4. Summary

Summary

- **KEK has been performing R&D of radiation-resistant magnet based on REBCO coated conductors.**
- **As the results of the design study, great advantage on thermal performance of REBCO based muon source was confirmed.**
- **Neutron irradiation of REBCO tape and magnet materials at IMR-Oarai is ongoing. PIE of REBCO samples will start soon**
- **In the trials of the ceramic coating target thickness of 30 μm is optimum in consideration of the withstand voltage higher than 2 kV and the cracking of layer. This ceramic coating is workable method for realizing the mineral-insulated magnets.**
- **After R&D of the coating to the long tape and the wet-winding technique by stack sample fabrication, Double pancake coils will be wound with the ceramic coating agent.**
- **Preparations for single coil test in conduction cooling system and high field test with common coil configuration with Liq. He bath are ongoing.**

Collaborators

M. IIO[a,b], M. Yoshida[a,b], Y. Yang[c], T. Nakamoto[a,b], K. Suzuki[b], M. Sugano[a,b], and, T Ogitsu[a,b]

[a]*J-PARC*, [b]*KEK*, [c]*Toshiba*

Acknowledgments

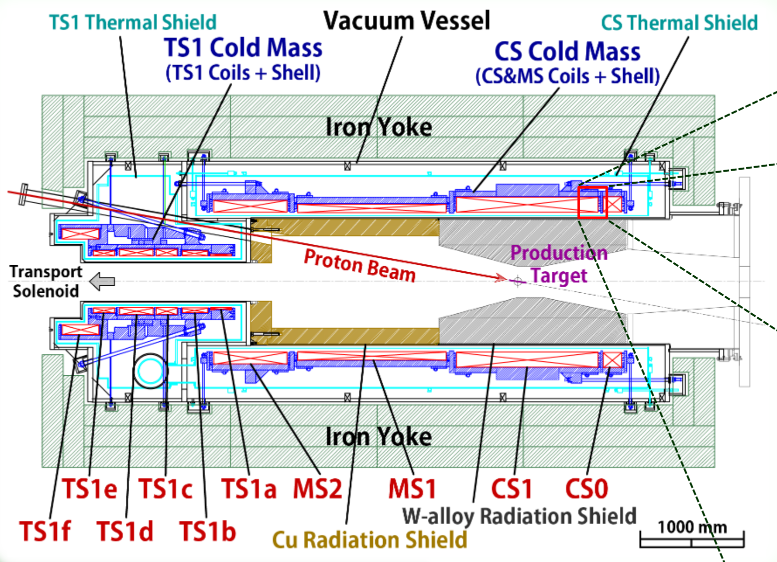
Neutron irradiation has been performing under the inter-university cooperative research program of the **International Research Center for Nuclear Materials Science, Institute for Materials Research, Tohoku University**.

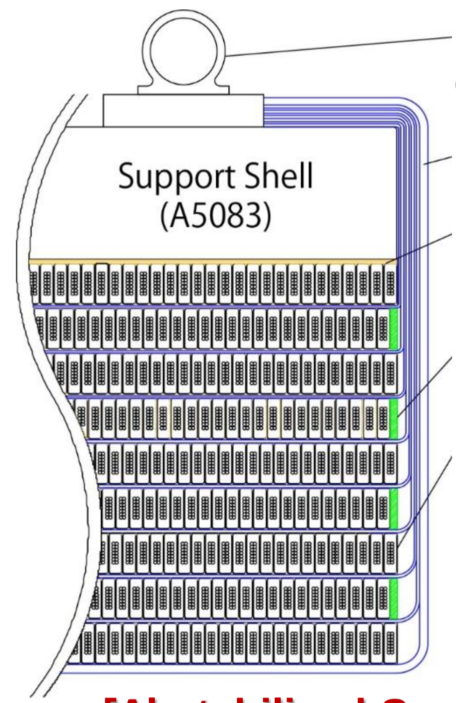
This work was supported by JSPS KAKENHI Grant Number JP16H06008, JP18KK0087 and U.S.-Japan Science and Technology Cooperation Program.

Thank you

Appendix

Key Technologies for Radiation-Resistant Coil





[Al-stabilized Superconductor]

- Thickness : 4.70±0.05 mm
- Width : 15.0±0.05 mm
- RRR : >400
- Proof stress@4.5 K: >95 MPa

- **Minimization of nuclear heating**
  - Lightweight coils have an advantage in reducing energy deposition by radiation

  → **Al-stabilized cable**

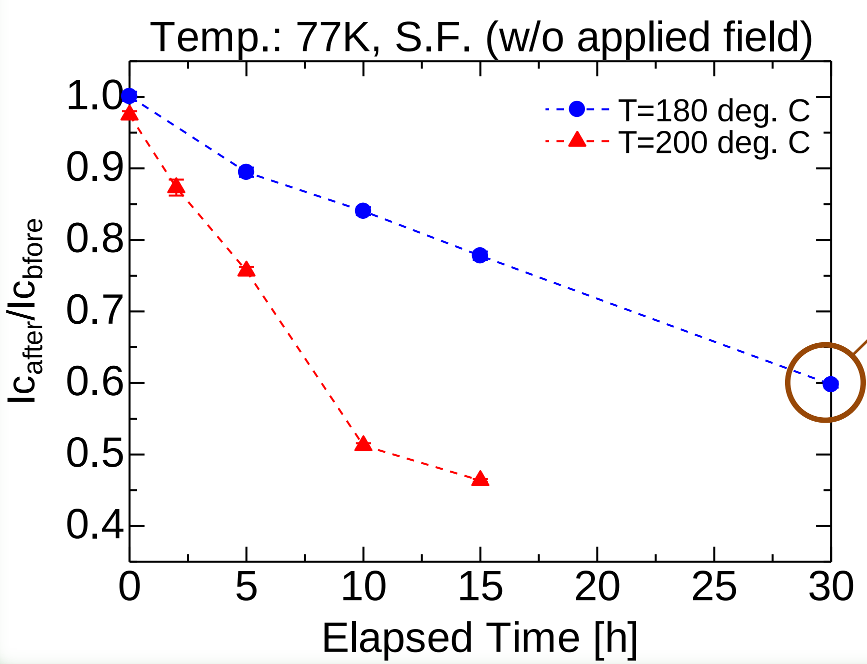
- **Minimization of radioisotope generation**
  - Bath cooling could cause liquid helium activation (Tritium production)

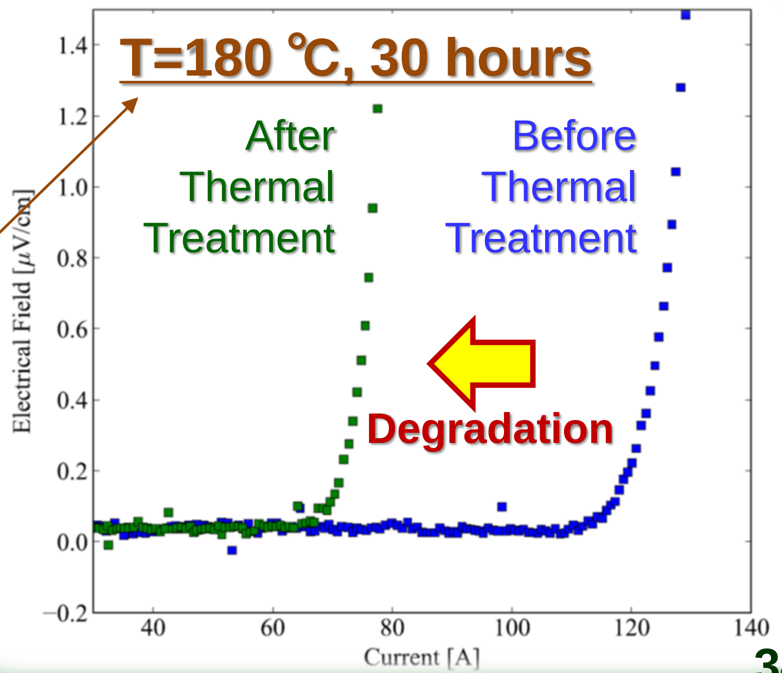
  → **Conduction cooling method**

Coils are cooled with small amount of Liq. He through Al-strips

➤ Selection conditions of coating agent

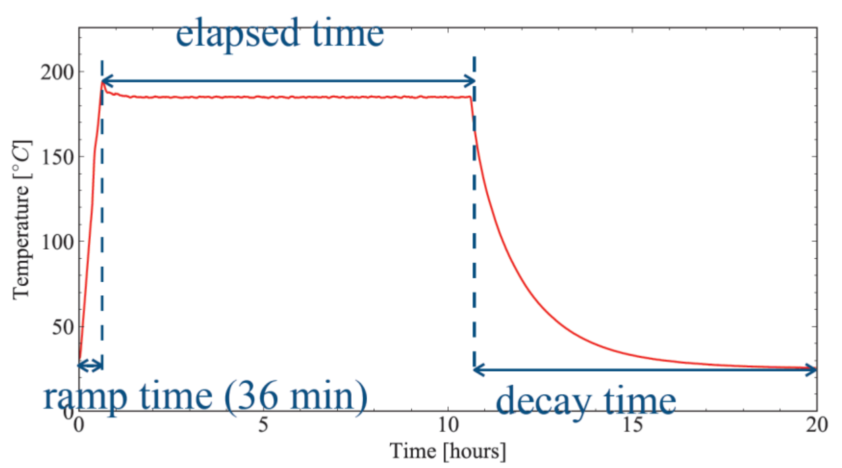
1. Electrical insulation
2. Thermal conductivity
   (AlN:150, Al_2O_2:32, SiO_2:10 >> EP resin: 0.3) [W/m·K]
3. Coefficient of linear expansion
4. Temperature of heat treatment

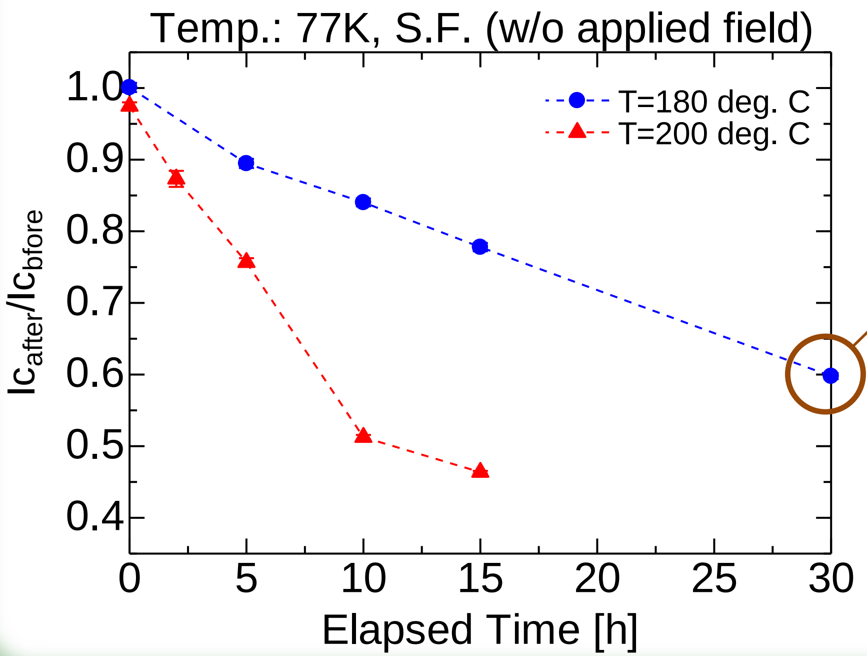


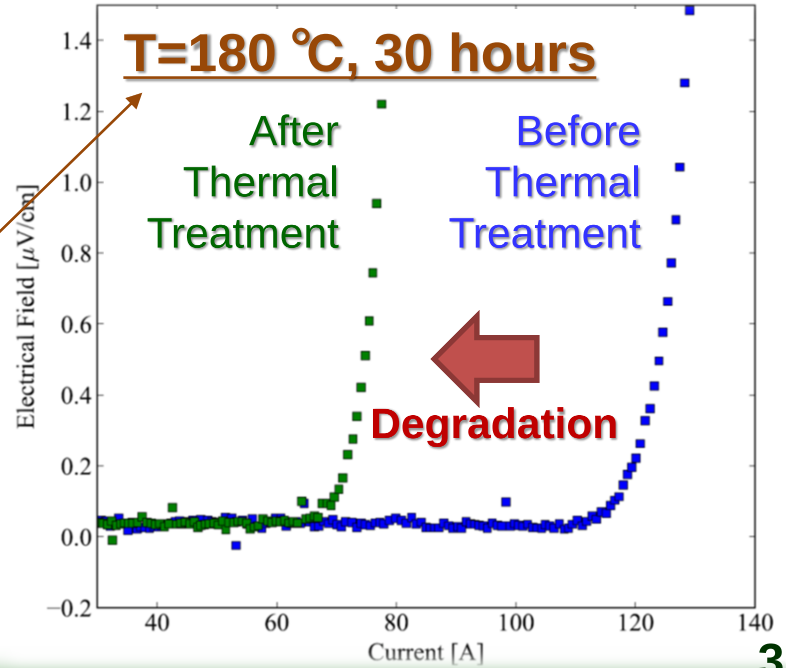


Degradation of Critical Current by Heat Treatment

Sample:SCS4050-AP
Ic average: 118 A







517LT vs 1111A