

SC Magnet III:

# Development of Radiation-resistant Superconducting Magnet



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## **1. COMET Magnet (NbTi)**

- 1. 1. Overview of the J-PARC and COMET Experiment**
- 1. 2. Design Features of the Muon Beamline Solenoid**
- 1. 3. R&D on Radiation-Resistant Magnet Technology**

## **2. Solenoid for a future muon source (HTS)**

- 2. 1. Conceptual Design of Solenoids for Future Muon Sources**
- 2. 2. Irradiation effect on HTS conductor**
- 2. 3. R&D of mineral insulated HTS coils**

# 1. COMET Magnet (NbTi)



# J-PARC COMET (COherent Muon-to-Electron Transition)

January 22, 2016

LINAC  
400 MeV



J-PARC Facility  
(KEK/JAEA)

Rapid-Cycling  
Synchrotron  
(RCS) 3 GeV

Neutrino Experimental  
Facility

Materials and Life Science  
Experimental Facility (MLF)

MR (Main Ring  
Synchrotron) 30 GeV

Hadron  
Experimental  
Facility

Proton beam is extracted  
to the production target  
of each facility

□ RCS(3 GeV)

→ MLF

□ MR(30 GeV)

→ Neutrino Facility

→ Hadron Facility



8 GeV (56 kW)  
for COMET

South to North

# Search for $\mu$ -e conversion (CLFV process)

- CLFV processes are believed to provide a path to new physical concepts

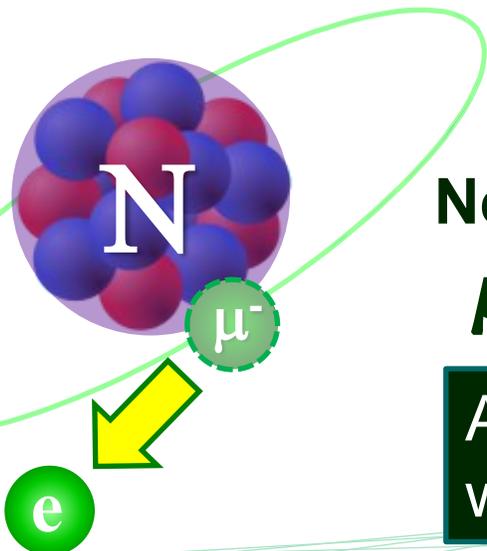
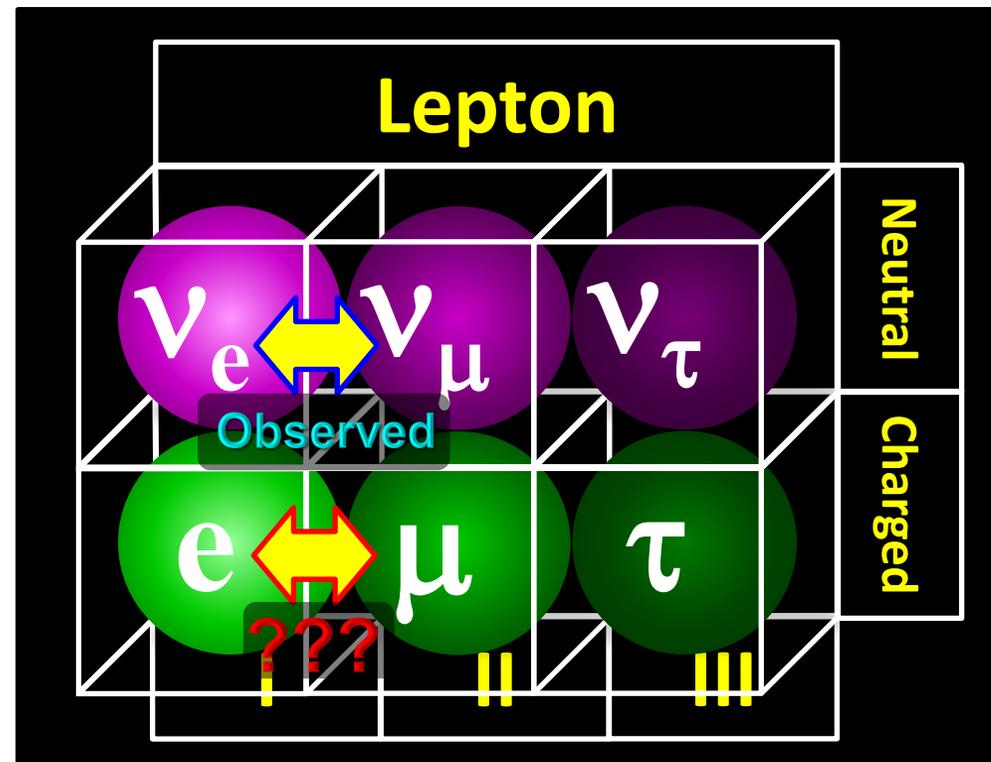
“Standard Model”

$$B(\mu \rightarrow e\gamma) < 10^{-54}$$



Various BSM models predict large branching ratios

It has not been observed...



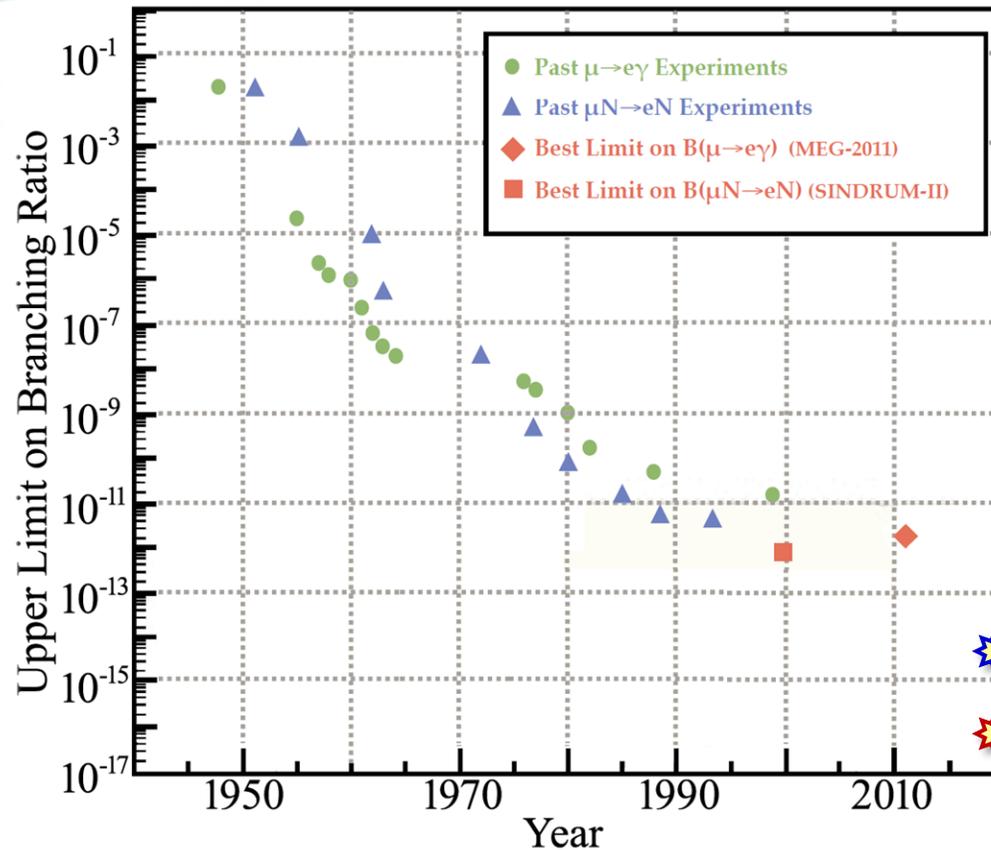
Neutrino-less muon capture



A next-generation experimental search for  $\mu$ -e conversion will be carried out at J-PARC

# Experimental Goal of COMET

## Long history of $\mu$ -e conversion search



### Phase-I



$$< 7 \times 10^{-15} \text{ (90\% C.L.)}$$

### Phase-II



$$< 6 \times 10^{-17} \text{ (90\% C.L.)}$$

## To achieve the sensitivity

1. High intensity muons:  $10^{11} \mu/\text{sec}$
2. Extreme background reduction
3. High-precision detector system



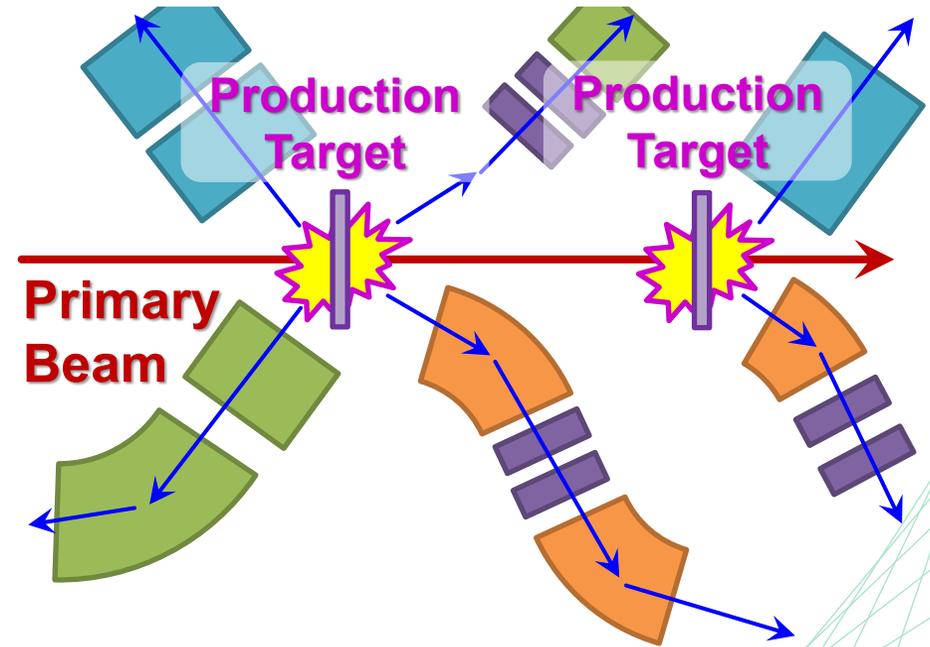
**Superconducting solenoid muon beamline is under construction**

# Muon Production

## □ Conventional Secondary Particle Beam line (Muon, Pion, Kaon, ...)

1. Multistage production point  
    ↑ **Thin target** ( $\ll$  Interaction length)
2. Multiple extraction lines

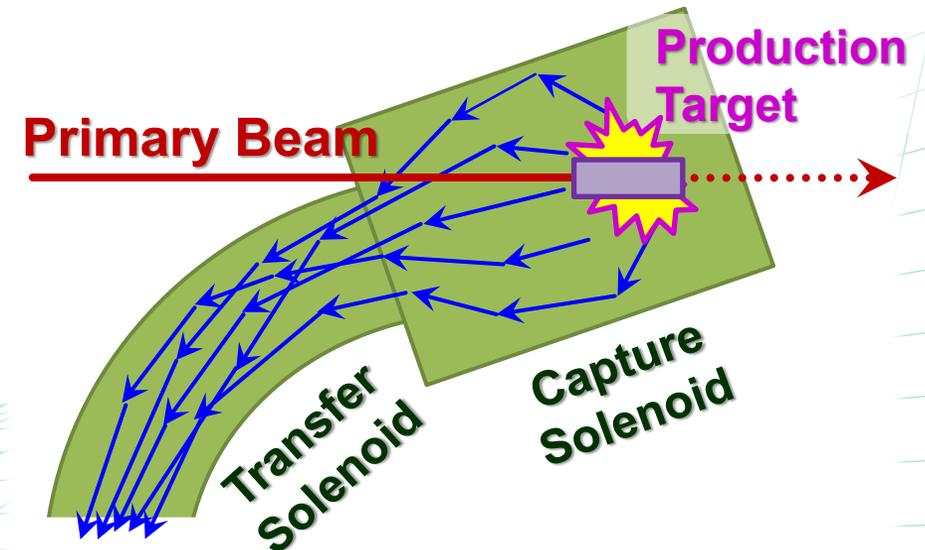
Several experiments can be conducted in parallel



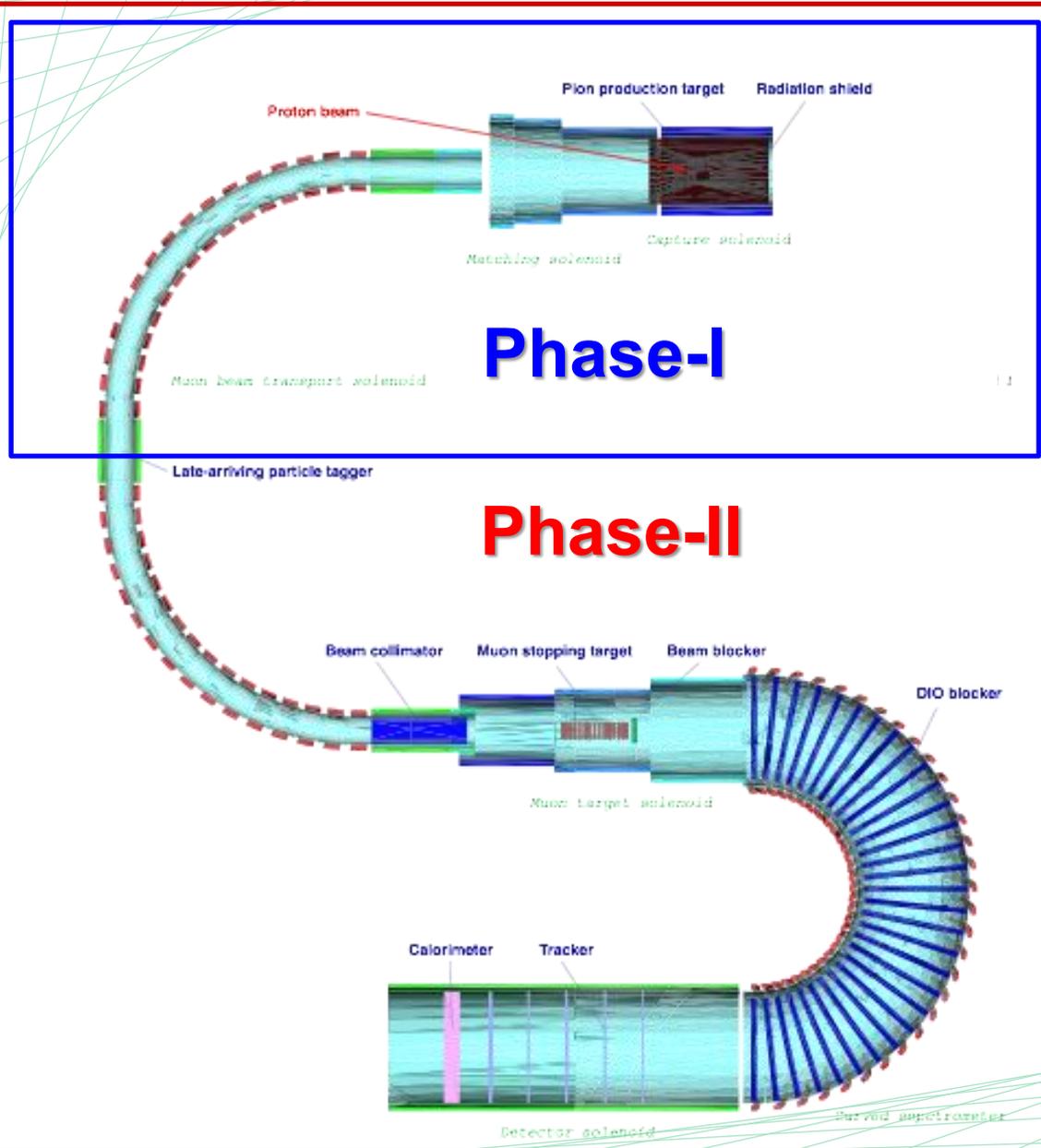
## □ Dedicated Beam line for Muon

1. **Thick Target** ( $\sim$  Interaction length)
2. **Large solid angle**

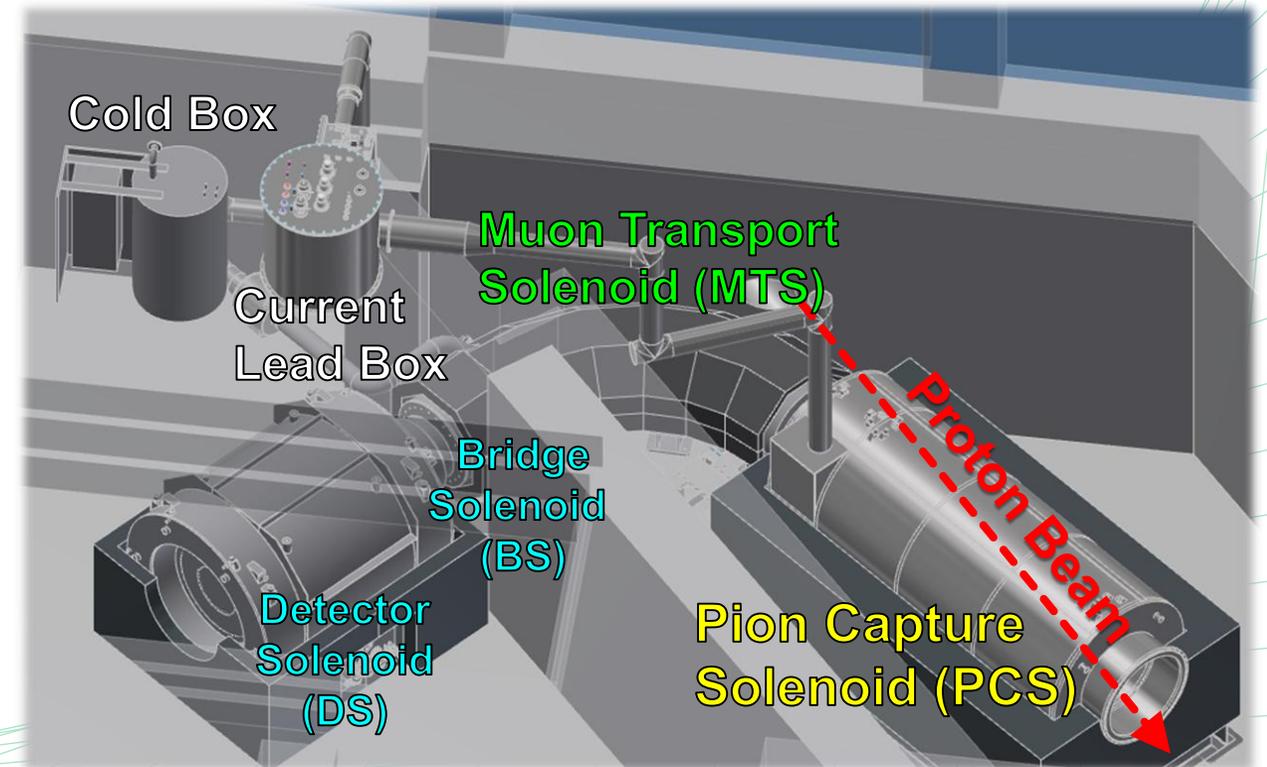
This method captures pions (muons) more efficiently than conventional methods



# Superconducting solenoid beam line for COMET

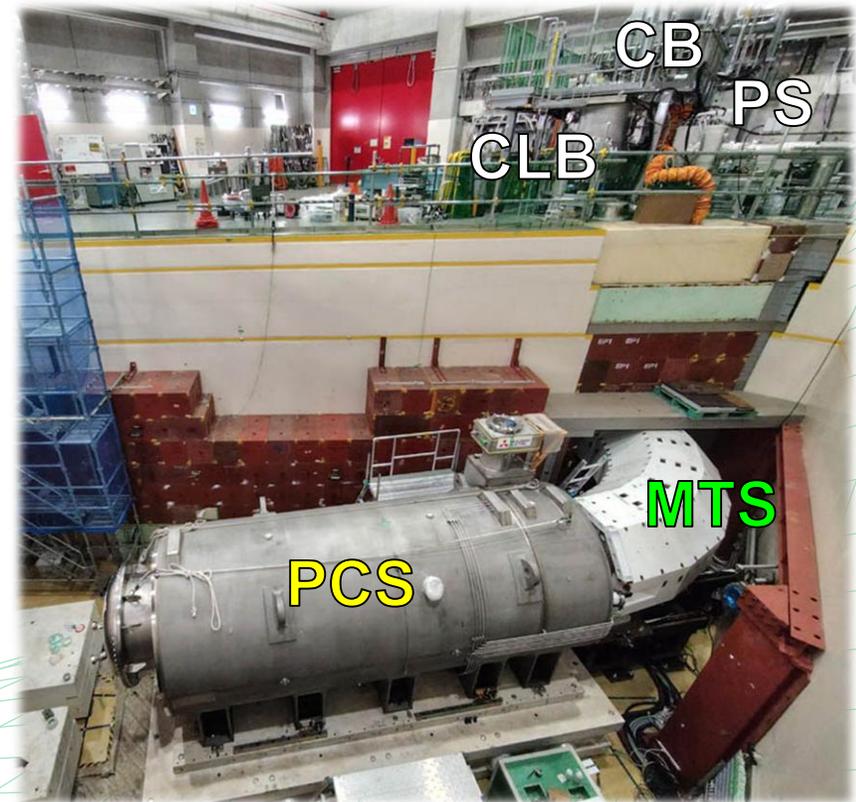


- ❑ S-shaped series of long solenoids from end to end
- ❑ Staging approach is adopted for COMET
- ❑ Construction is underway in Phase-I configuration



## Delivery of all solenoids for Phase-I has been completed

- ❑ **Pion Capture Solenoid**: Final on-site assembly in progress
- ❑ **Muon Transport Solenoid**: **Ready** (cooling for test)
- ❑ **Bridge Solenoid**: Installation completed (cooling in progress)
- ❑ **Detector Solenoid**: Installation completed (cooling in progress)

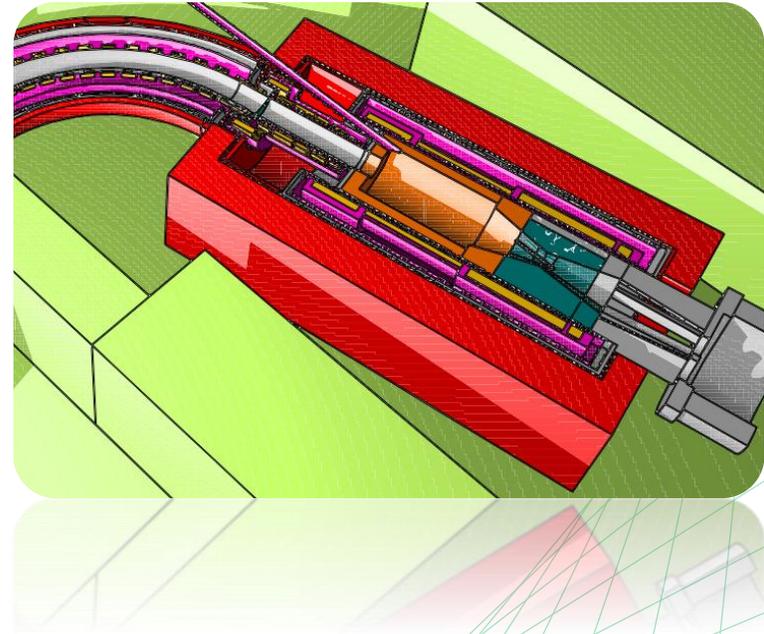


## □ Magnet Specification

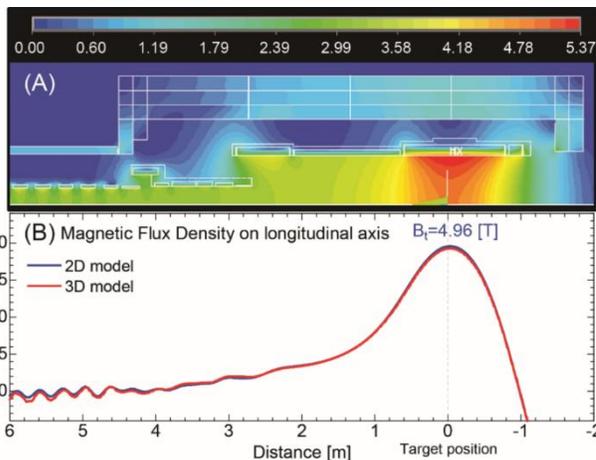
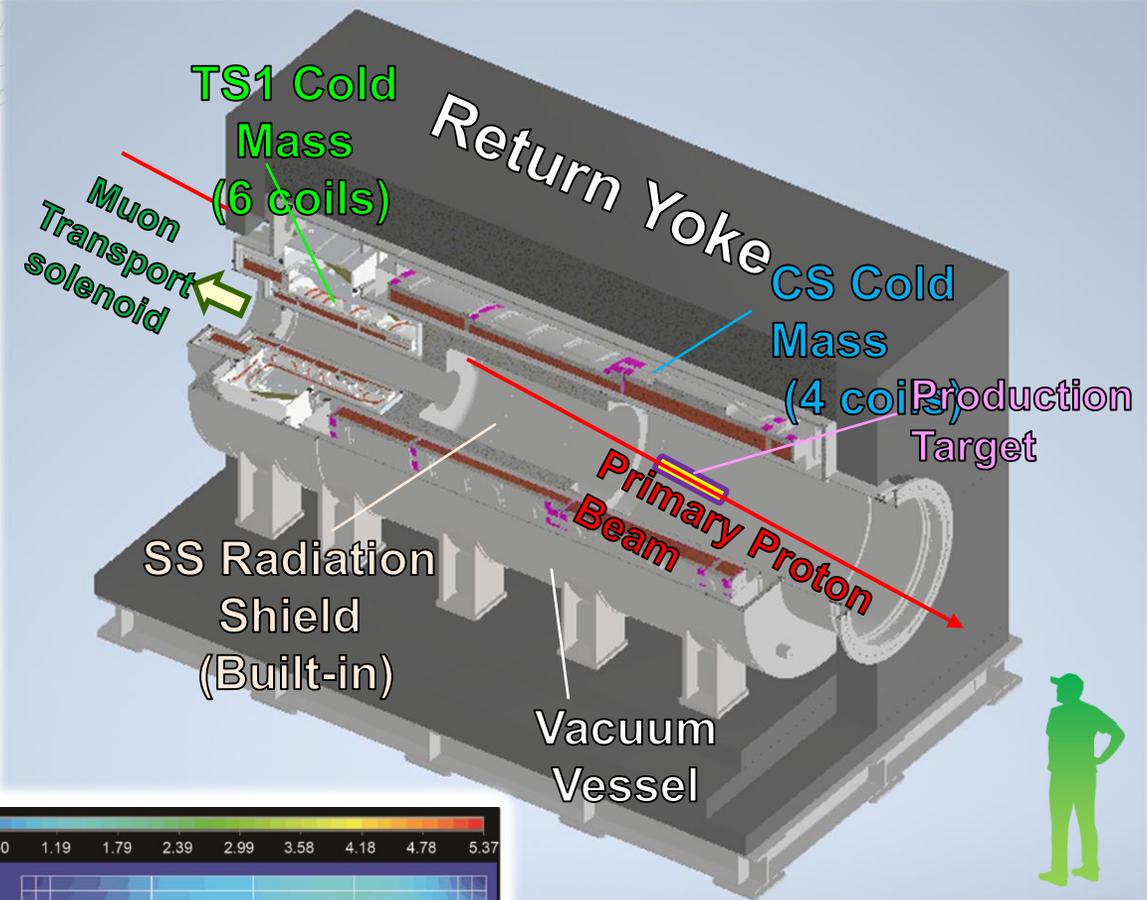
- Large bore for radiation shield: **D=1200 mm**
- High field on production target: **B=5 T**
- Smoothly decreasing field: **5 T → 3 T**

## □ Radiation-Resistant system

- Operation in high-radiation environment:  **$\sim 10^{21}$  n/m<sup>2</sup>**
  - **280 W** heat load on 4K cold masses
  - Radiation resistance of magnet materials up to **several MGy**
- Minimization of radioisotope production in refrigerants



# Overview of PSC

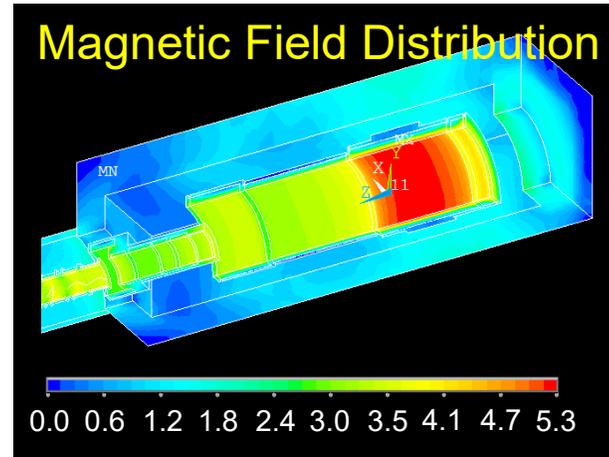
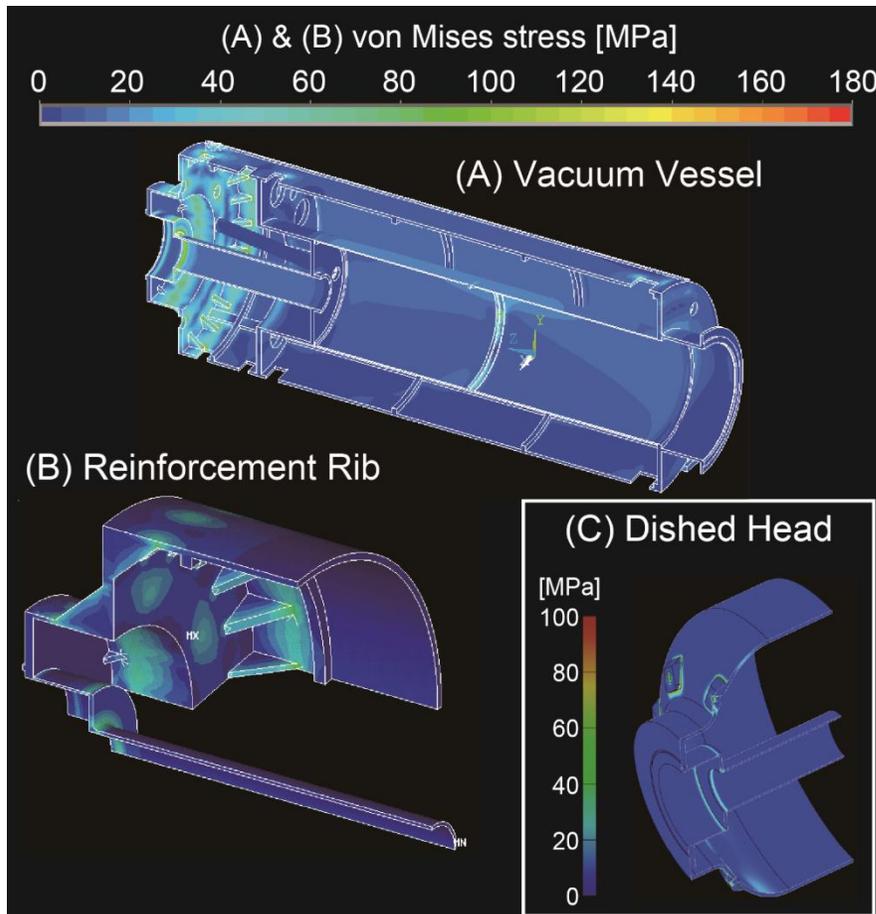


PARAMETERS	VALUE
Cable type	Aluminum stabilized NbTi-Cu cable Al/Cu/NbTi = 7.3/0.9/1
Coil configuration	10 coils in series (4 + 6)
Inner dia. of coils	1344 mm / 496 mm / 820 mm
Number of 4K cold masses	2 (CS & TS1)
Peak field / Stored energy	5.3 T / 47 MJ
Bore dia.	1200 mm / 878 mm / 360 mm
Outer dia. of main unit	2300 mm
Weight of main unit	40 t
Yoke dimensions	H 3240 mm × W 3240 mm × L 6340 mm
Weight of return yoke	240 t

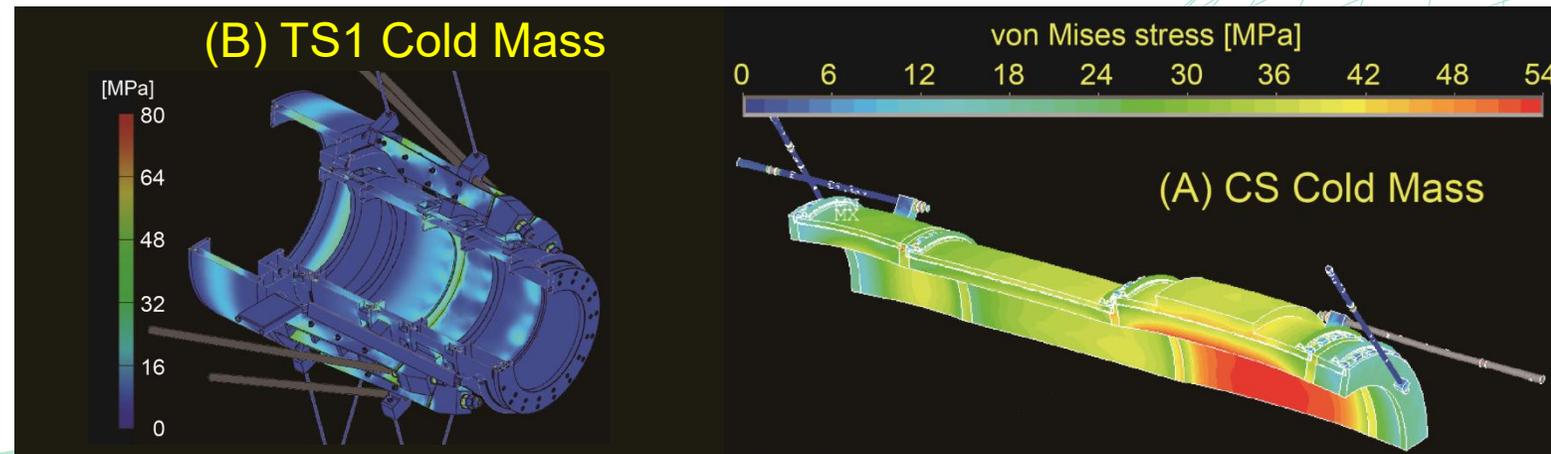
# Mechanical design of PCS

## □ Mechanical design of supports and vacuum vessel taking into account various conditions

- Acceleration (Earthquake, Transportation)
- Magnetic force (Steady operation, Quench case)
- Thermal contraction
- Experimental conditions

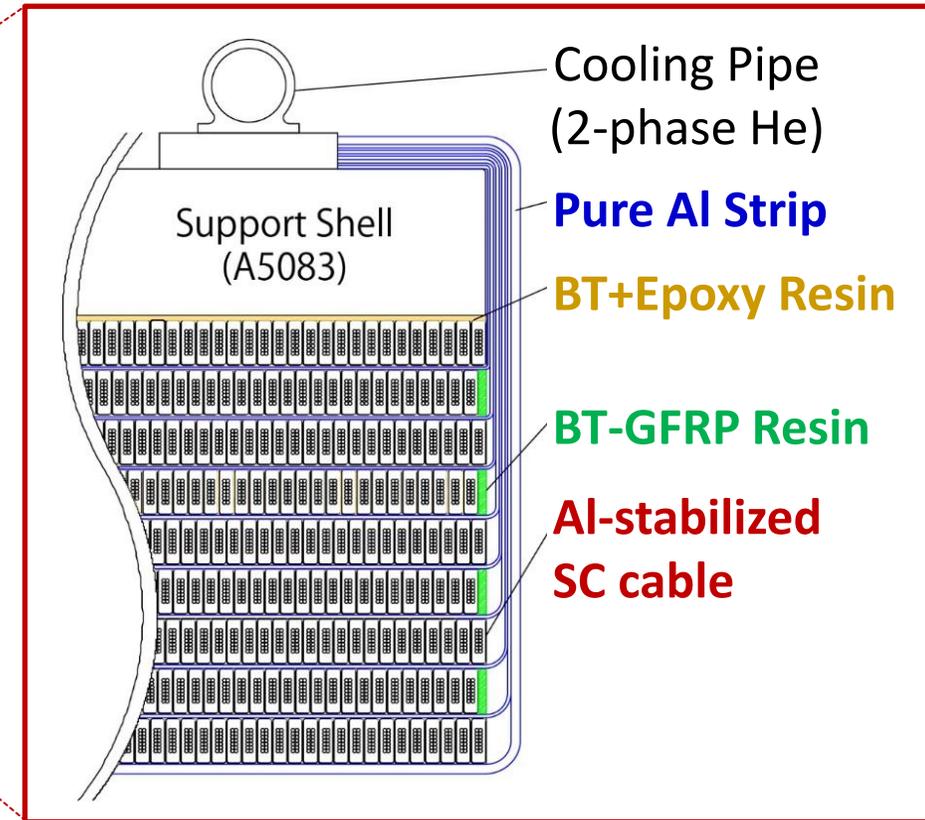
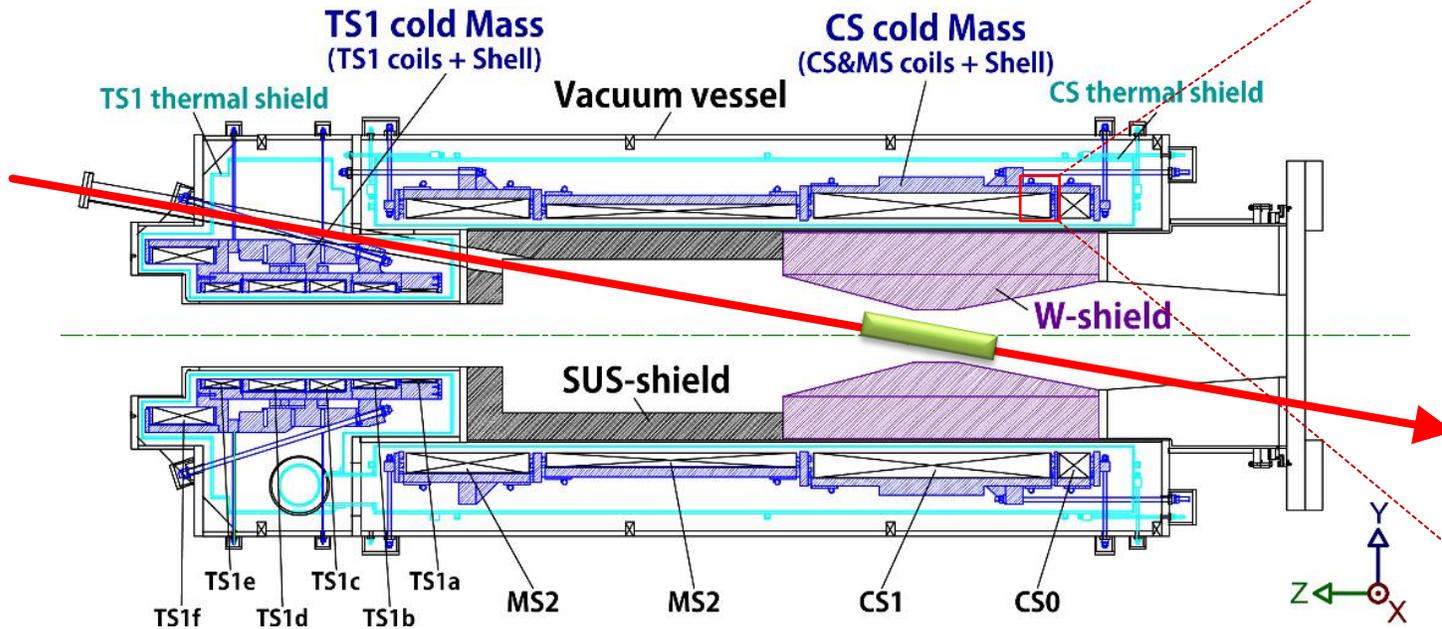


Coil ID	ID [mm]	T [mm]	L [mm]	No. of turn	No. of layer	I [A]
CS0	1344	152	180	35	9	2700
CS1		152	1391	270	9	
MS1		84	1468	285	5	
MS2		118	721	140	7	
TS1a	500	16	200	40	1	2700
TS1b		48	240	48	3	2581
TS1c		64	200	40	4	2700
TS1d		64	320	64	4	2619
TS1e		48	200	40	3	2538
TS1f		820	96	350	70	6



# Key Technologies for Radiation-Resistant Coils

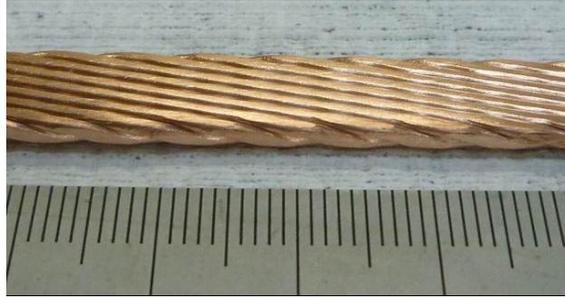
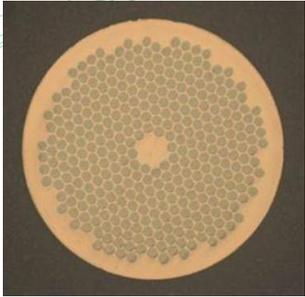
High radiotransparency of the coils  
minimizes radiation effects  
(Heat load, characteristic degradation, activation)



Conduction-cooled structure based on aluminum materials

- Aluminum stabilized SC cable
- Radiation resistant organic materials
- High purity aluminum cooling strips
- High strength and high weldability aluminum alloy

# Al-stabilized Superconducting Cable



## [NbTi strand]

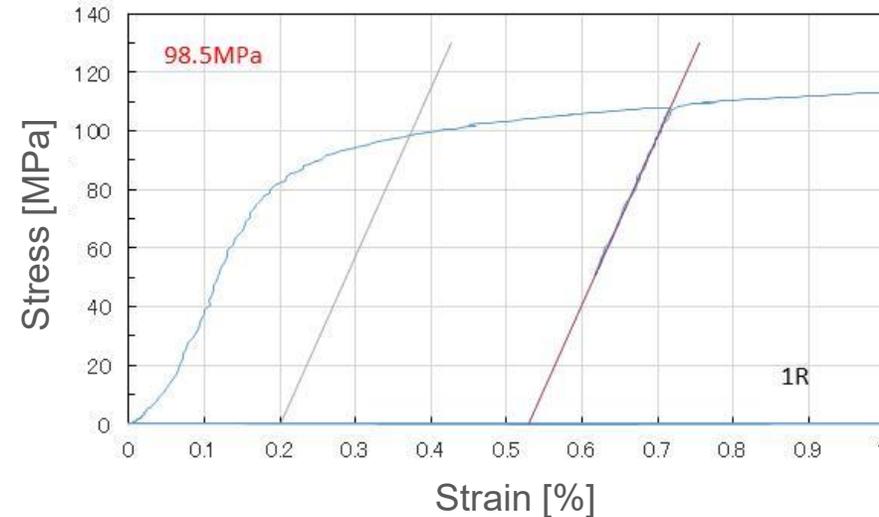
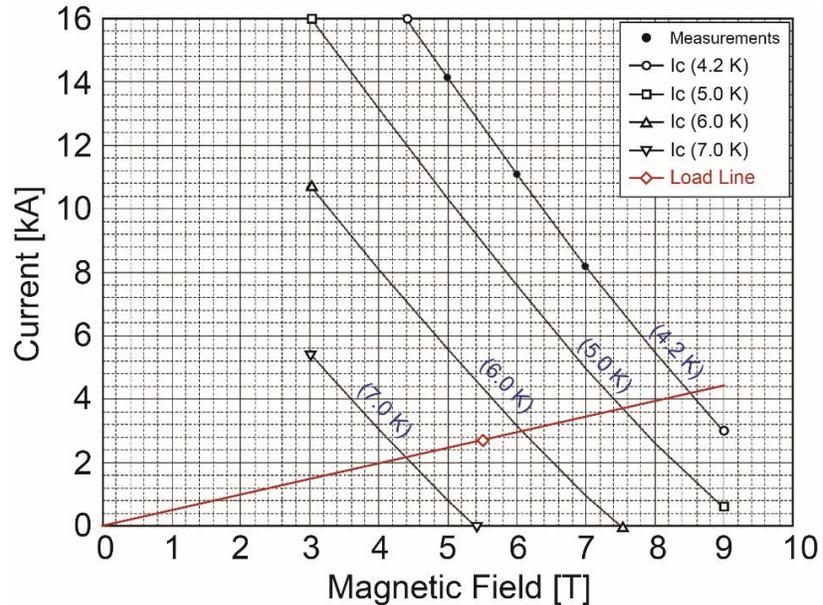
- dia.:  $\phi 1.21$  mm
- No. of filaments: 342
- Filament dia.:  $\phi 44$   $\mu\text{m}$
- Cu/SC ratio: 1.0

## [Rutherford cable]

- Thickness:  $2.18 \pm 0.1$  mm
- Width:  $8.47 \pm 0.1$  mm
- No. of strands: 14
- Twist pitch:  $80 \pm 5$  mm

## [Al-stabilized Superconductor]

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



# Irradiation Effects in Magnet Materials

- Organic polymer

- Insulator
- GFRP
- Adhesive
- Impregnation

**Molecular chain scission** induced by ionization effects is dominant

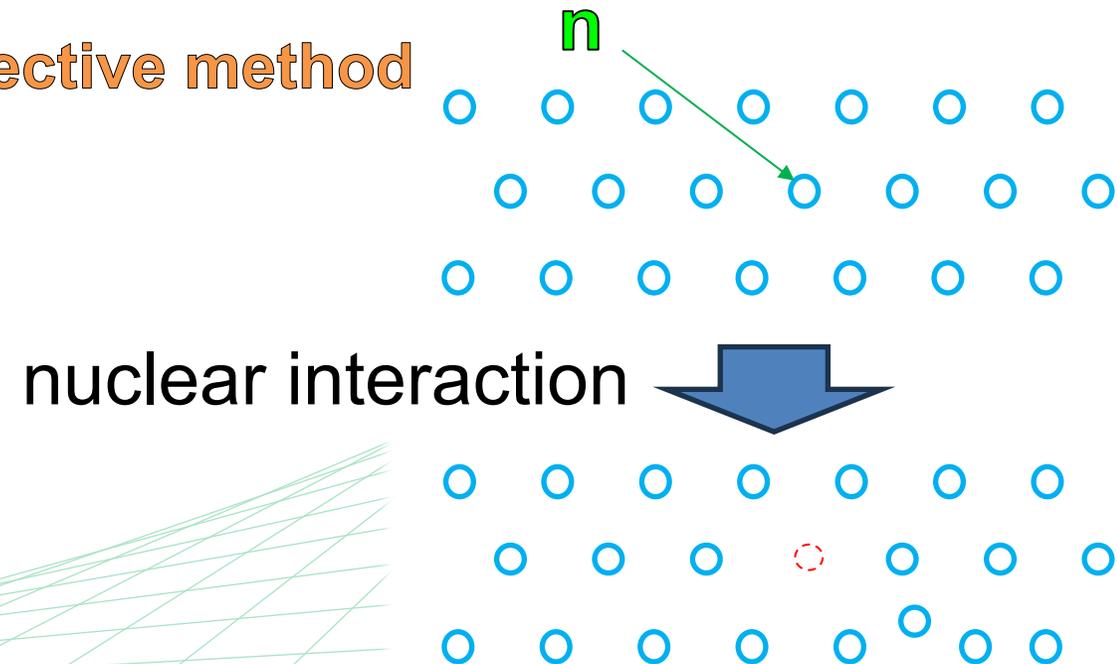
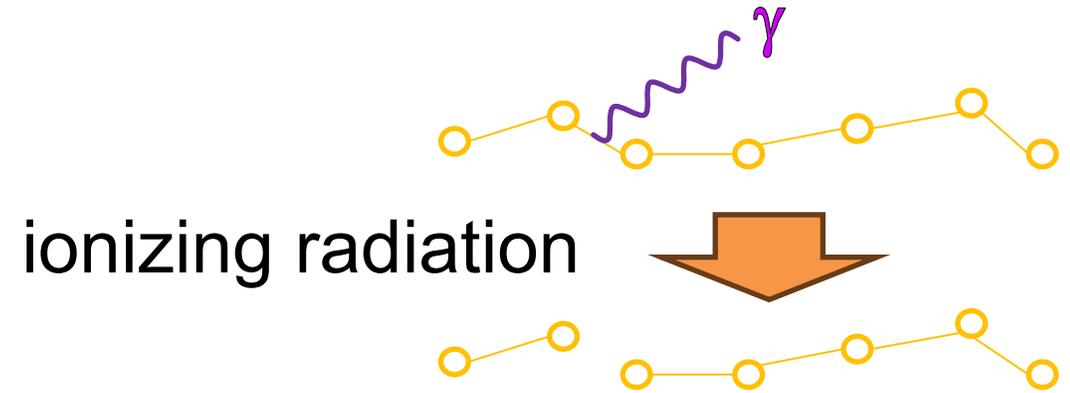
→ **Gamma-ray irradiation testing is an effective method**

- Metal

- Stabilizer
- Thermal conductor

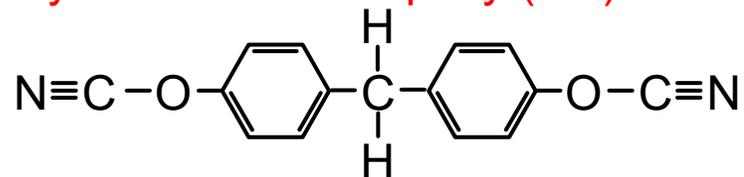
**Defect and vacancy formation** due to nuclear reactions is dominant

→ **Ion or neutron irradiation testing is an effective method**

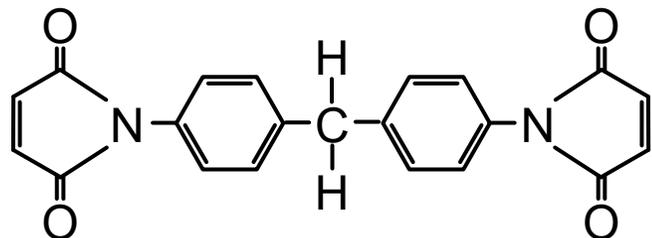


## Conventional epoxy resins have poor radiation resistance

Cyanate Ester & Epoxy (CE)

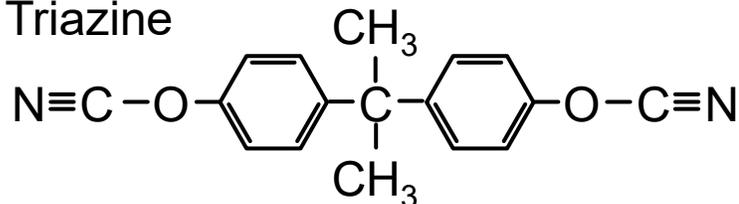


Bismaleimide (BMI)



+ Bismaleimide Triazine (BT)

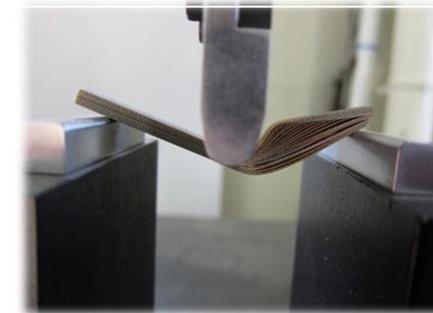
Triazine



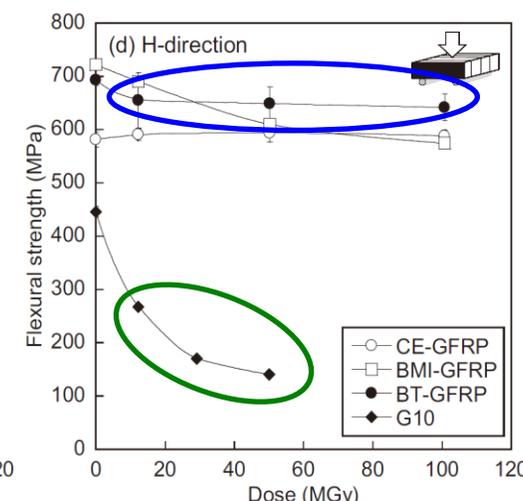
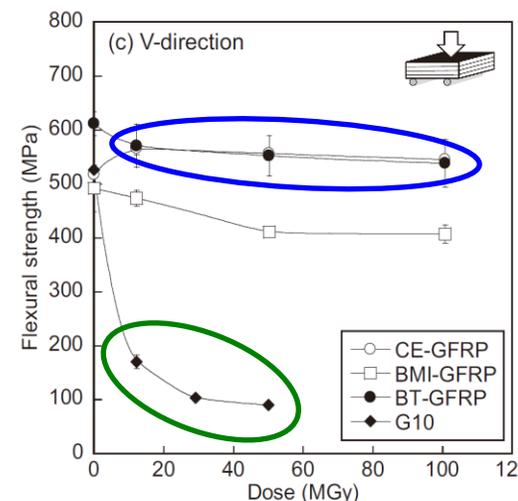
G10 CE BT BMI



Flexural strength test



$\gamma$ -ray Irradiation @JAEA Takasaki ( $^{60}\text{Co}$ , 14-16 kGy/h)



A. Idesaki *et al.*, *Fusion Eng. Des.* 112 (2016) 418-424.

3 types of GFRP with S-2 glass (boron free) are jointly developed by COMET and HI-LHC magnet group

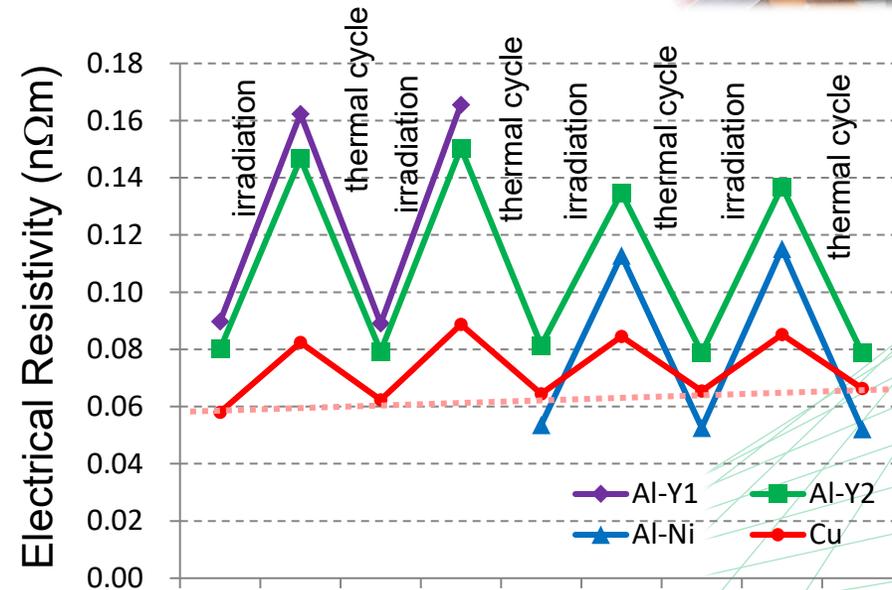
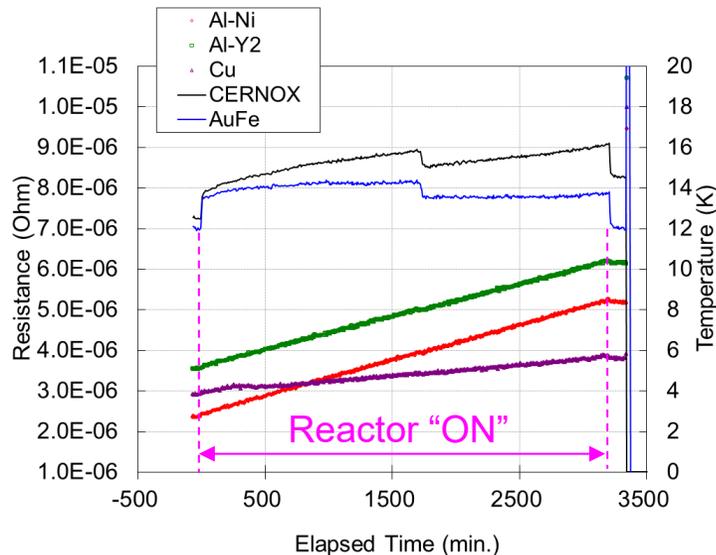
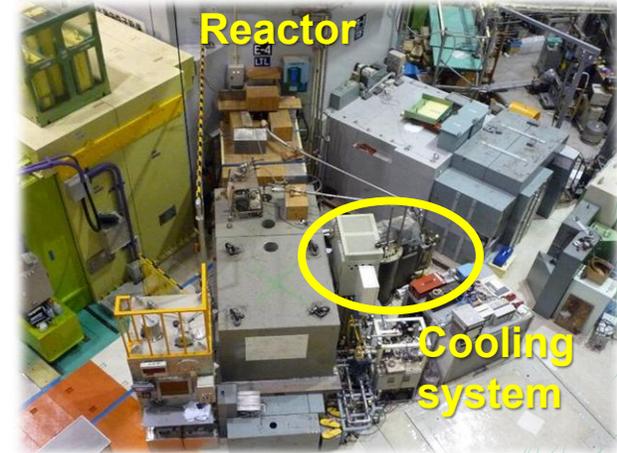
BT resin is adopted as insulation tape, wet winding resin and coil spacers (GFRP)

# Neutron Irradiation of metal materials

❑ Degradation of electrical and thermal conductivity is significant problem for the **conduction cooling magnet**



Neutron irradiation at **cryogenic temperature** was performed at Kyoto Univ. Research Reactor Institute (KURRI)



▶ Neutron induced resistance at cryogenic temperature

Al ~ 0.03 nΩm for  $10^{20}$  n/m<sup>2</sup>

Cu ~ 0.01 nΩm for  $10^{20}$  n/m<sup>2</sup>

Perfect recovery was observed in Al by annealing at 300 K

2011Nov bel  
2011Nov a  
2012Nov bel  
2012Nov a  
2013Jul bel  
2013Jul a  
2014Apr bel  
2014Apr a  
2014Dec a

# Temperature Rise of Coils

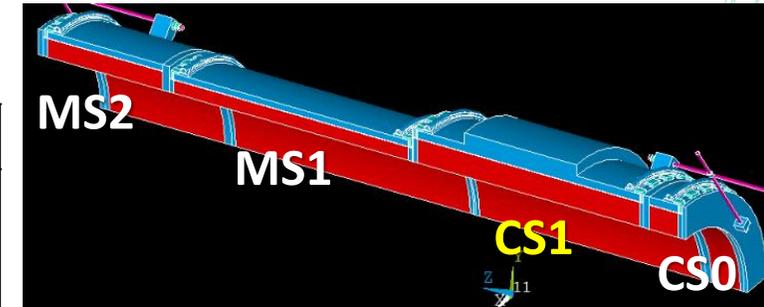
- ❑ Thermal conductivity of the cooling pass degrades by radiation
- ➔ Coil temperature rises during the experimental period



## Analytical studies on thermal property of CS and MS coils

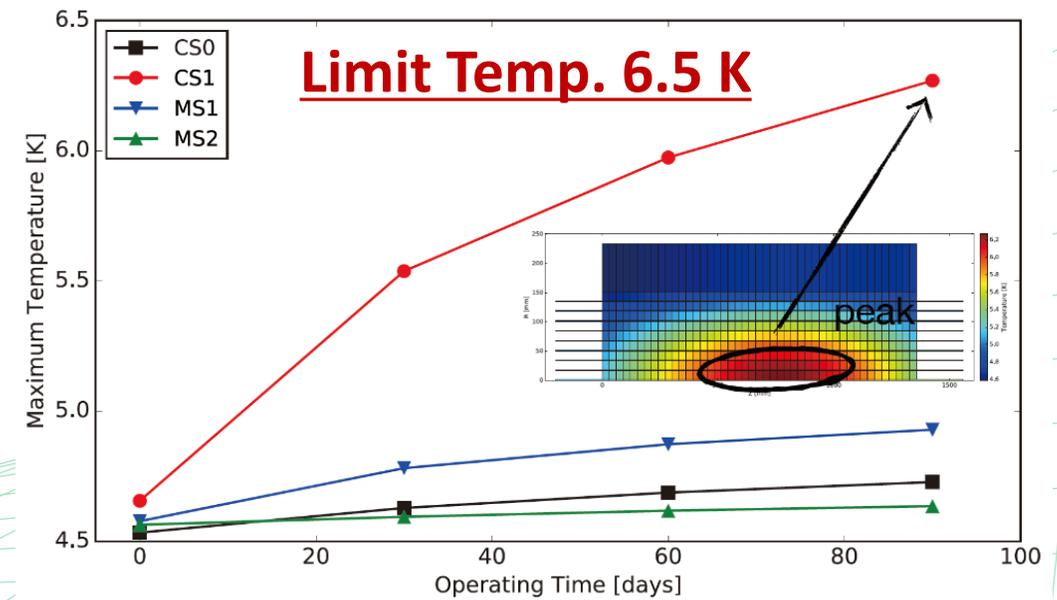
Radiation Estimation by PHITS (<http://phits.jaea.go.jp/>)

magnet	peak dose [Gy/sec]	peak neutron flux [n/m <sup>2</sup> /sec]	peak DPA [DPA/sec]	peak dose [MGy/280 days]	peak neutron flux [n/m <sup>2</sup> /280 days]	peak DPA [DPA/280 days]
CS0	2.04E-02	7.82E+13	6.14E-12	0.49	1.89E+21	1.49E-04
CS1	3.50E-02	1.42E+14	1.14E-11	<b>0.85</b>	<b>3.44E+21</b>	<b>2.76E-04</b>
MS1	1.50E-02	7.97E+13	6.07E-12	0.36	1.93E+21	1.47E-04
MS2	3.32E-02	2.10E+13	1.56E-12	0.80	5.08E+20	3.77E-05



### Simulation:

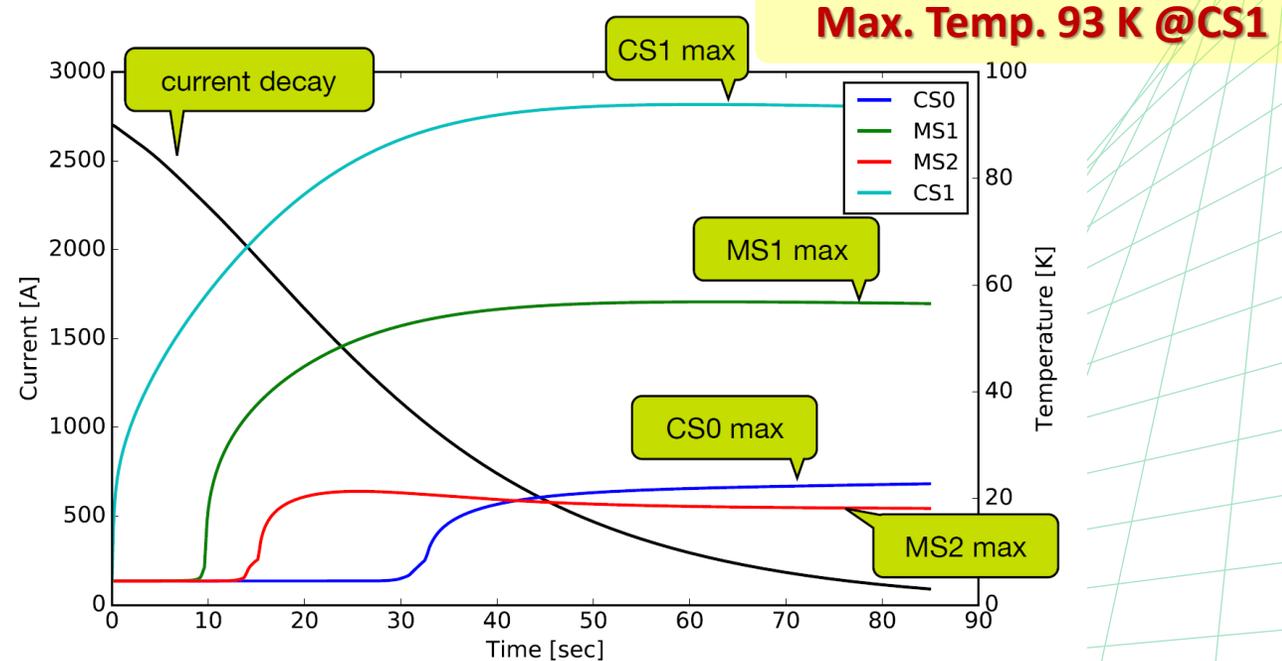
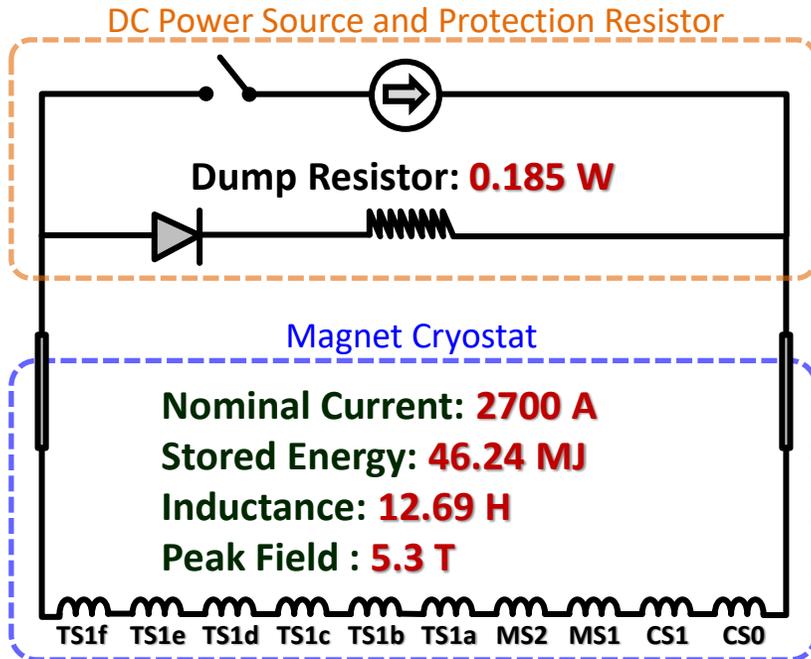
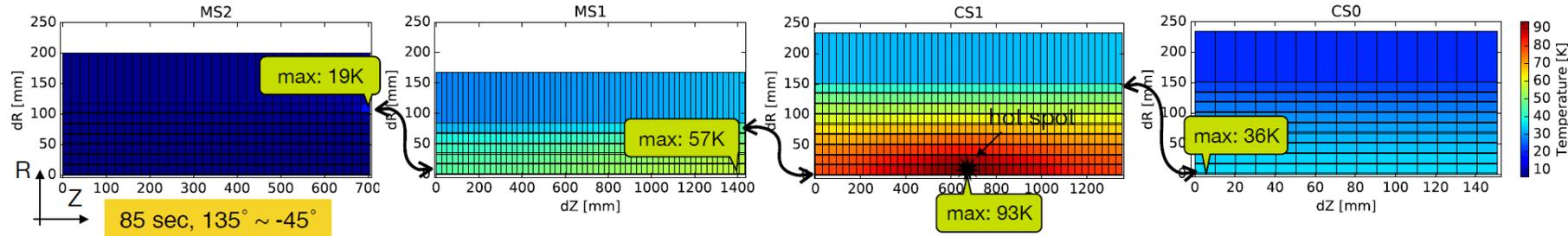
- Energy deposition and radiation dose estimated by PHITS code
- Magnetic field: 5.5 Tesla (CS0, CS1), 4.5 Tesla (MS1, MS2)
- RRR calculated with experimental data (KURRI)



**CS1 coil temperature: ~6.3 K**  
**(after 90 days operation)**

# Quench Tolerance

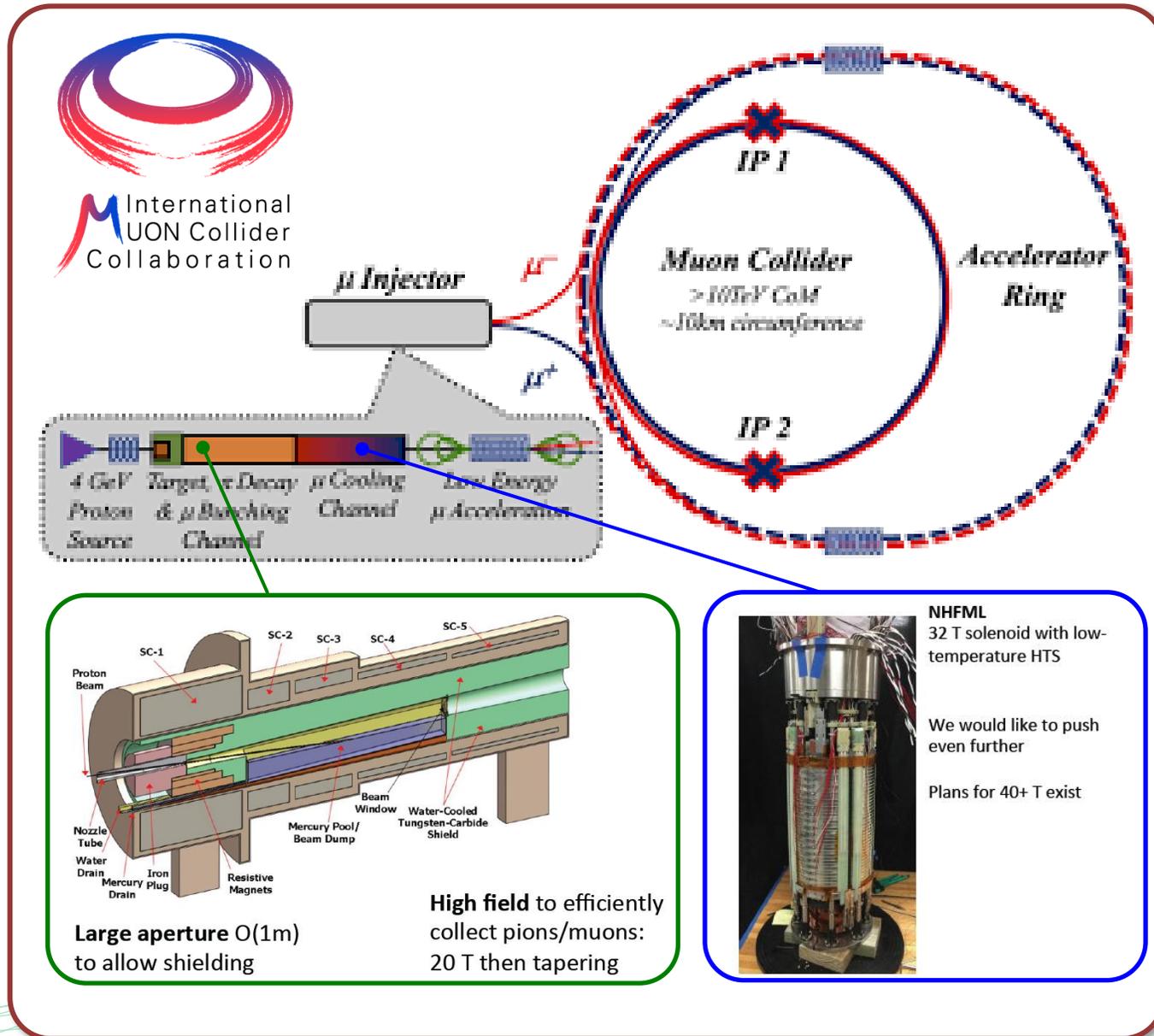
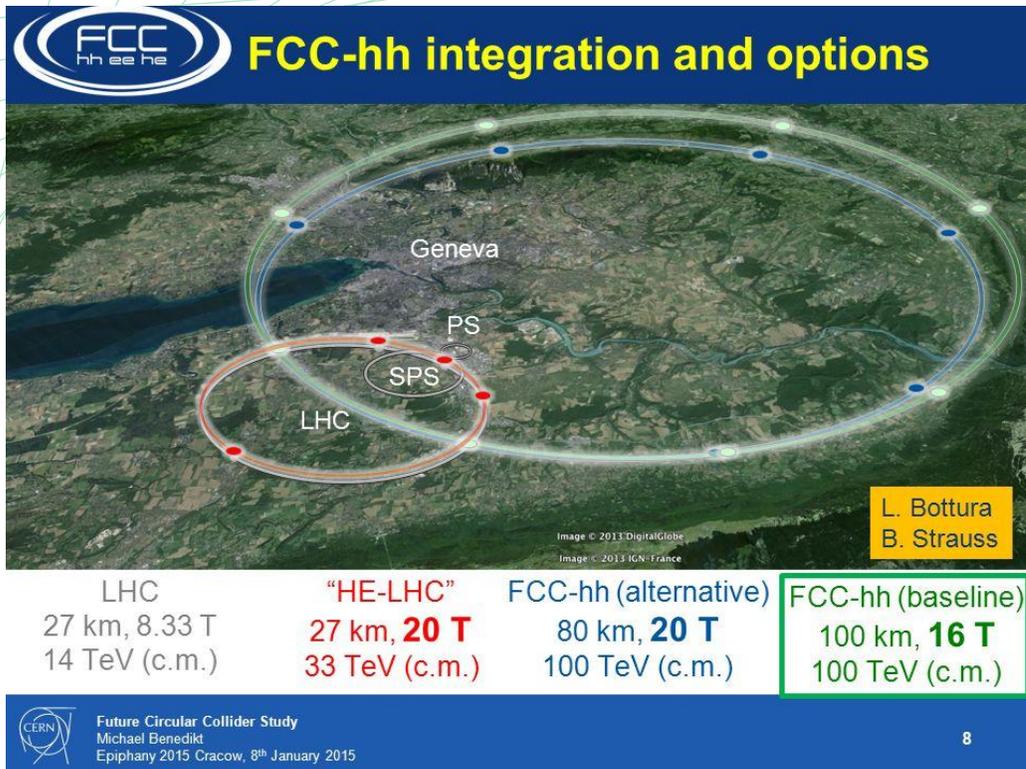
Temperature rise due to the quench is simulated in consideration of characteristic degradation after 90 days beam operation



The maximum temperature of 93 K at the quench spot is estimated to be sufficiently low to ensure the magnet's soundness

## **2. Solenoid for a future muon source (HTS)**

# Future accelerator construction plans

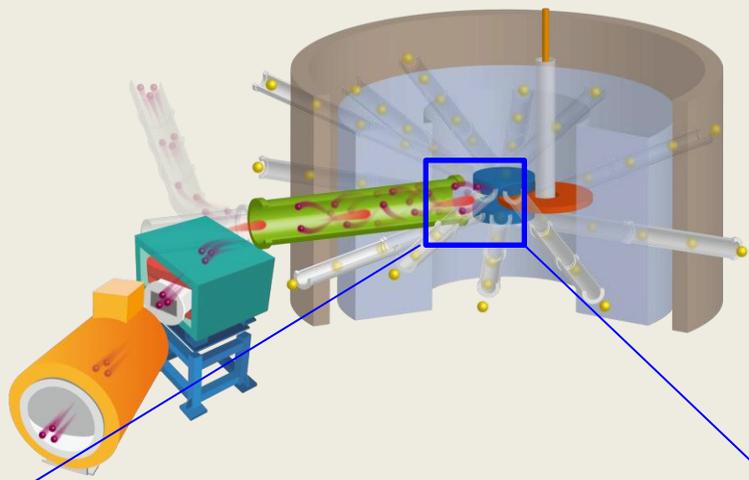


FCC magnet: **20 T**,  $\sim 300 \text{ MGy}$ ?  
 - Integrated luminosity:  $20\text{-}25 \text{ ab}^{-1}$  (FCC)  $> 3\text{-}4 \text{ ab}^{-1}$  (HL-LHC)

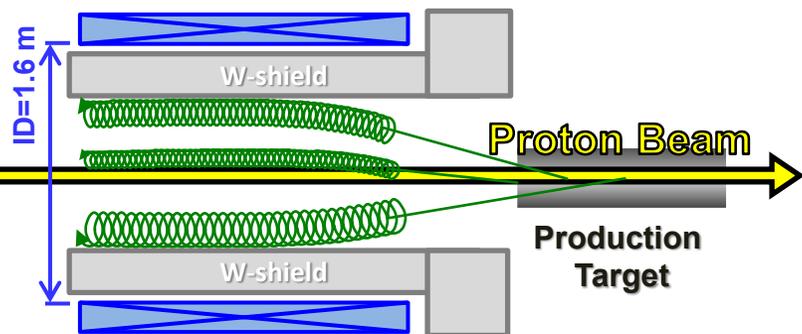
MC magnet: **20 T**,  $\sim 300 \text{ MGy}$ ?  
 - Power of the primary proton beam: **3 MW**

# J-PARC MLF 2nd target station

## Construction plan for MLF-TS2



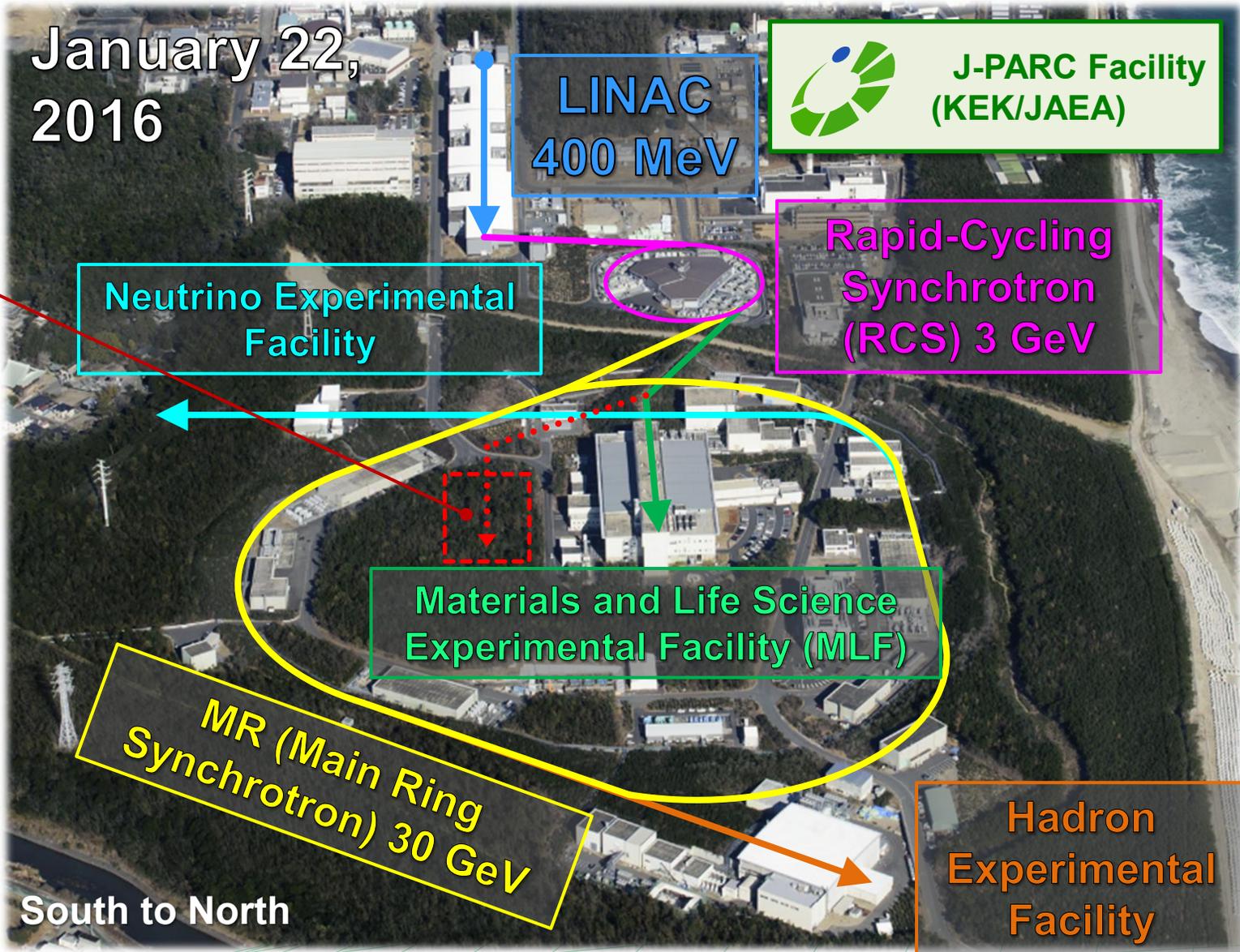
### Pion Capture Solenoid (PCS)



**TS2-PCS: 1 T, 100 MGy?**

- Power of the primary proton beam: **1 MW**

January 22,  
2016



# Challenging issue 1: Conductor

## NbTi conductor

- Its superconductivity is not maintained at magnetic field above 10 T
- It is difficult to maintain a temperature of about 5 K under a large heat load due to radiation (450 W).

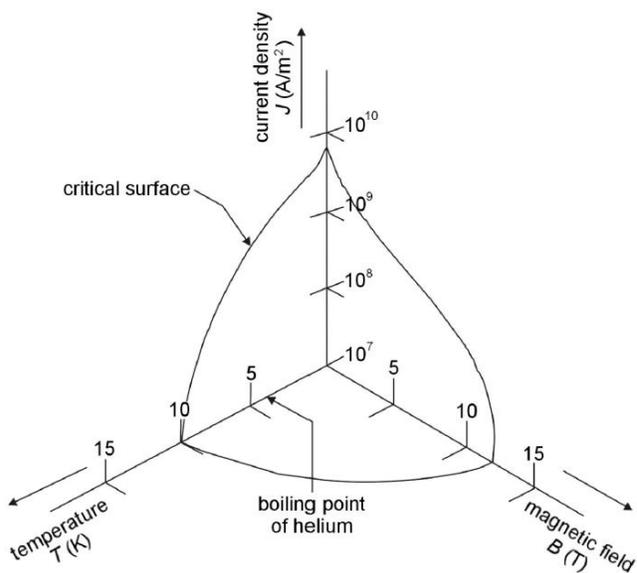
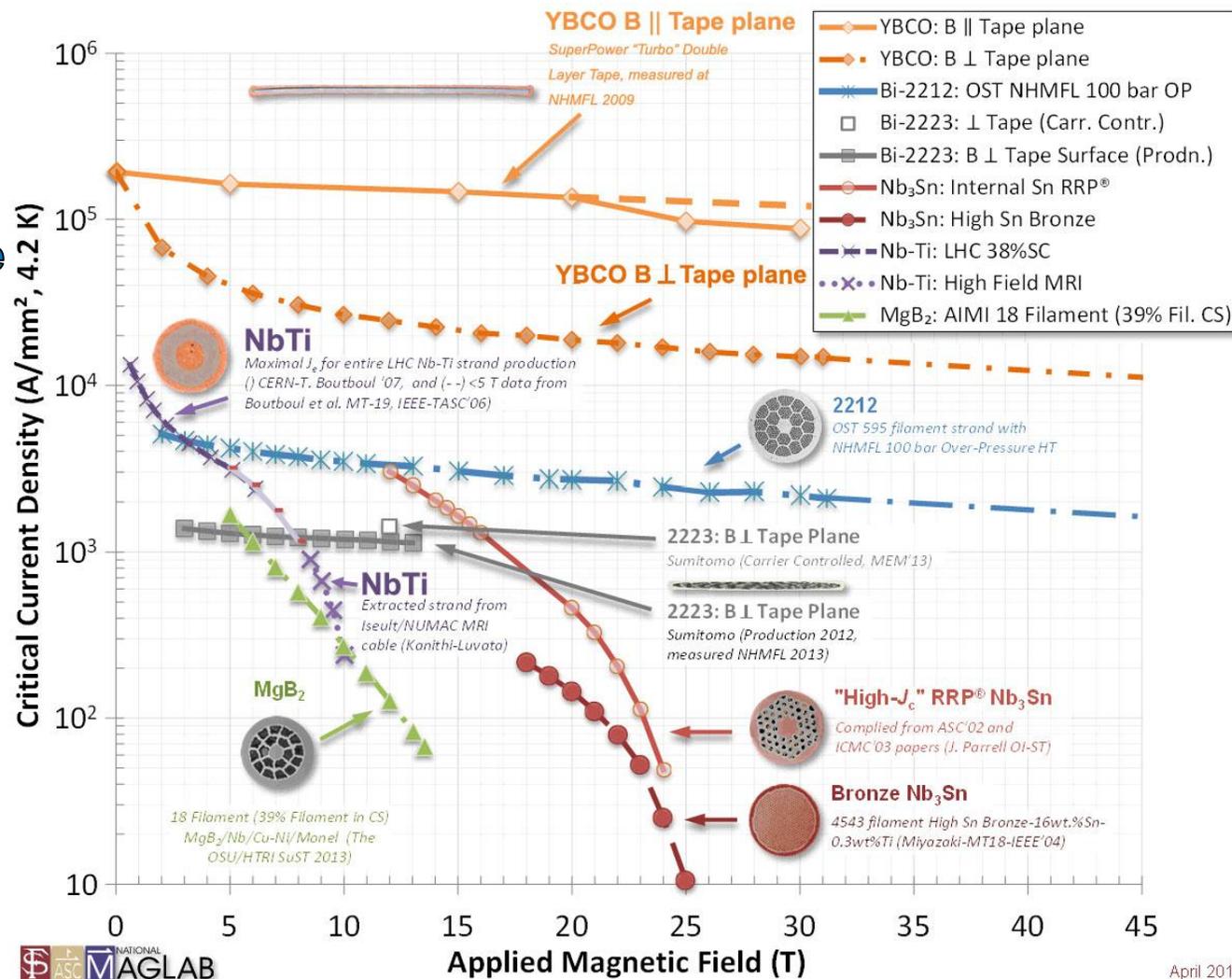


Figure 2.1 The critical current density  $J_c$  of NbTi is plotted as a function of temperature  $T$  and magnetic field  $B$ . The material is superconducting below the surface, and normal conducting above it. Ref. M. Haverkamp, Ph.D. thesis University of Twente, 2003

## $I_c$ -B curves of various conductors



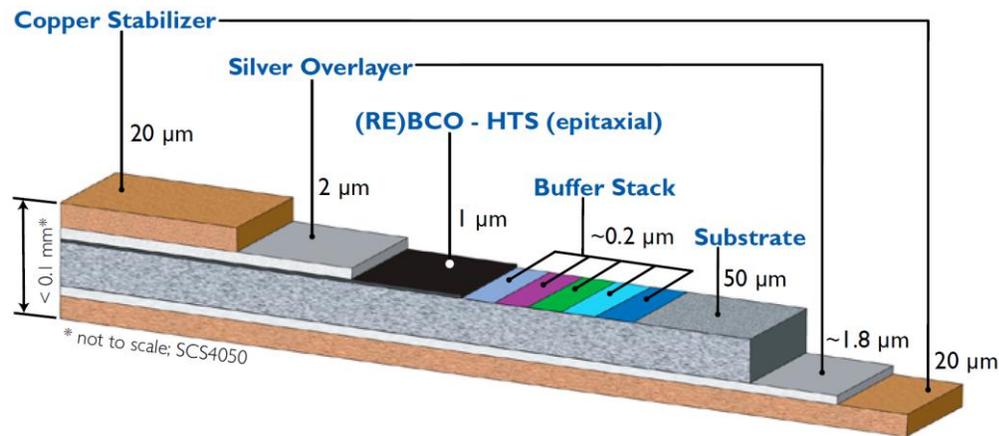
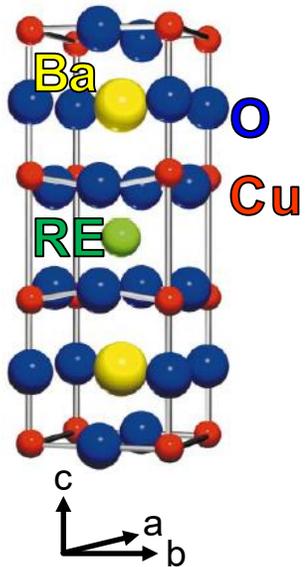
ASC NATIONAL MAGLAB

April 2014

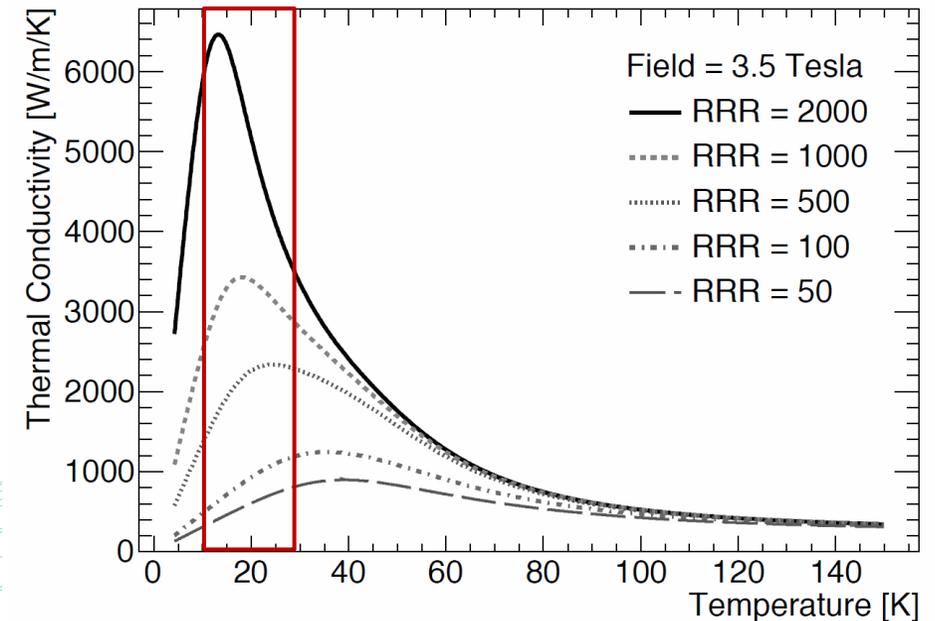
HTS are candidates for future radiation-resistant high-field magnets

# REBCO (rare-earth barium copper oxide)

- ▶ High magnetic field tolerance of  $I_c$ 
  - Potential for 20T class high field magnet
- ▶ High temperature margin ( $T_c=93$  K)
  - Conduction cooling operation in the temperature range of 20 K



Thermal Conductivity of Aluminium



# Challenging issue 2 (Insulation materials)

## ❑ Radiation reduces the strength of polymer materials due to molecular chain scission

- Epoxy deteriorates at doses higher than a few MGy
- Polyimide may be acceptable for use below 80 MGy
- Cyanate and BT based materials appear to be able to tolerate doses above 100 MGy.

Ref.: CERN Yellow Reports 2001-006

Table 2: Classification of adhesives according to their radiation resistance

Aromatic cured epoxy (special formulation)

Polyimide (PI)

Polyurethane (PUR)

Silicone (unfilled)

Polyamide 4.6

Epoxy (EP)

Phenolic (unfilled)

Melamine-formaldehyde (MF)

Urea-formaldehyde (UF)

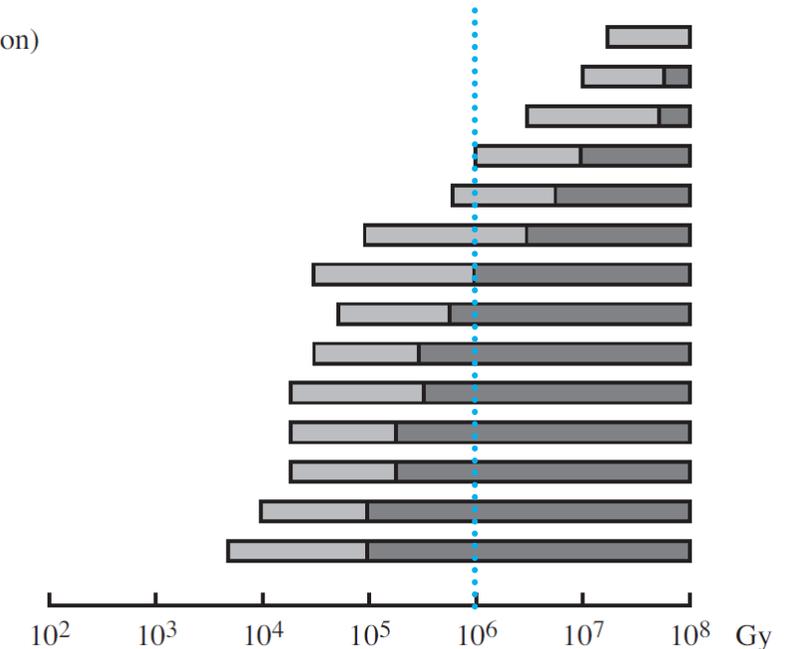
Polyamide 6.6 (PA)

Acrylates and cyano-acrylates

Cellulose acetate

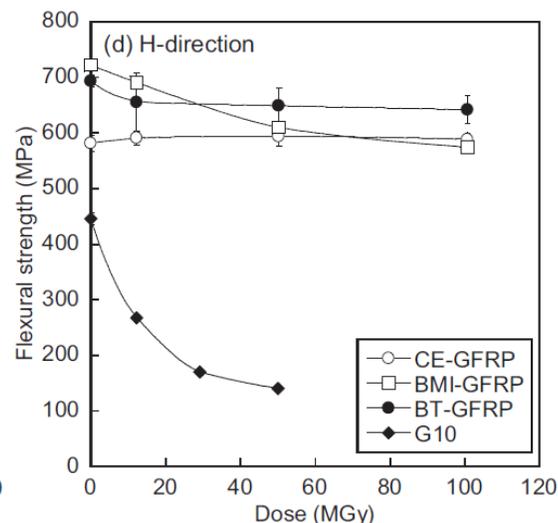
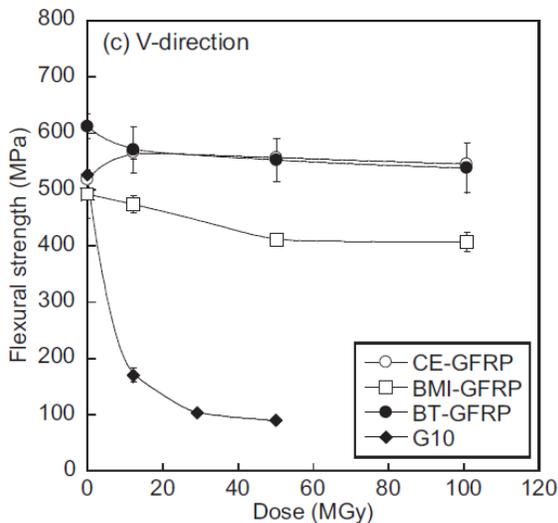
Polyester (unfilled)

Aniline-formaldehyde (AF)



mild to moderate damage, utility is often satisfactory  
 moderate to severe damage, use not recommended

The end-point criterion is chosen at **50%** of the initial value (prior to irradiation) for the **strength** or for the **deformation at break**.



# Mineral insulated accelerator magnet

□ Inorganic materials are attracting attention as insulation for magnets in >100 MGy radiation environments

Accelerator magnets based on magnesium oxide insulated copper conductors (MIC) are already in practical use around the world.



KEK has been performing application researches of mineral insulation to superconducting magnets

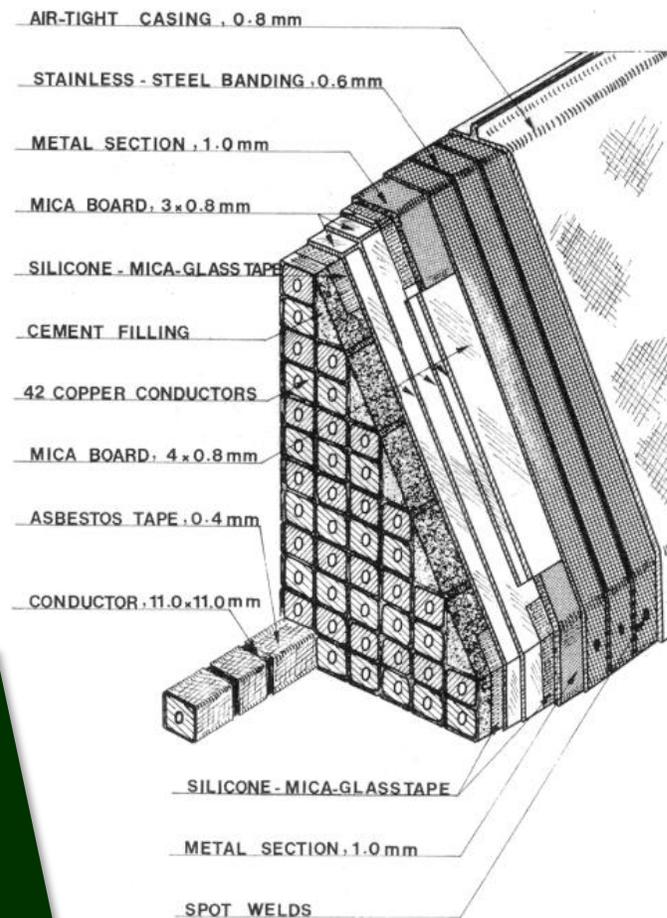


Fig. 20 QNL-B coil construction

Ref.: CERN Yellow Reports 1982-005

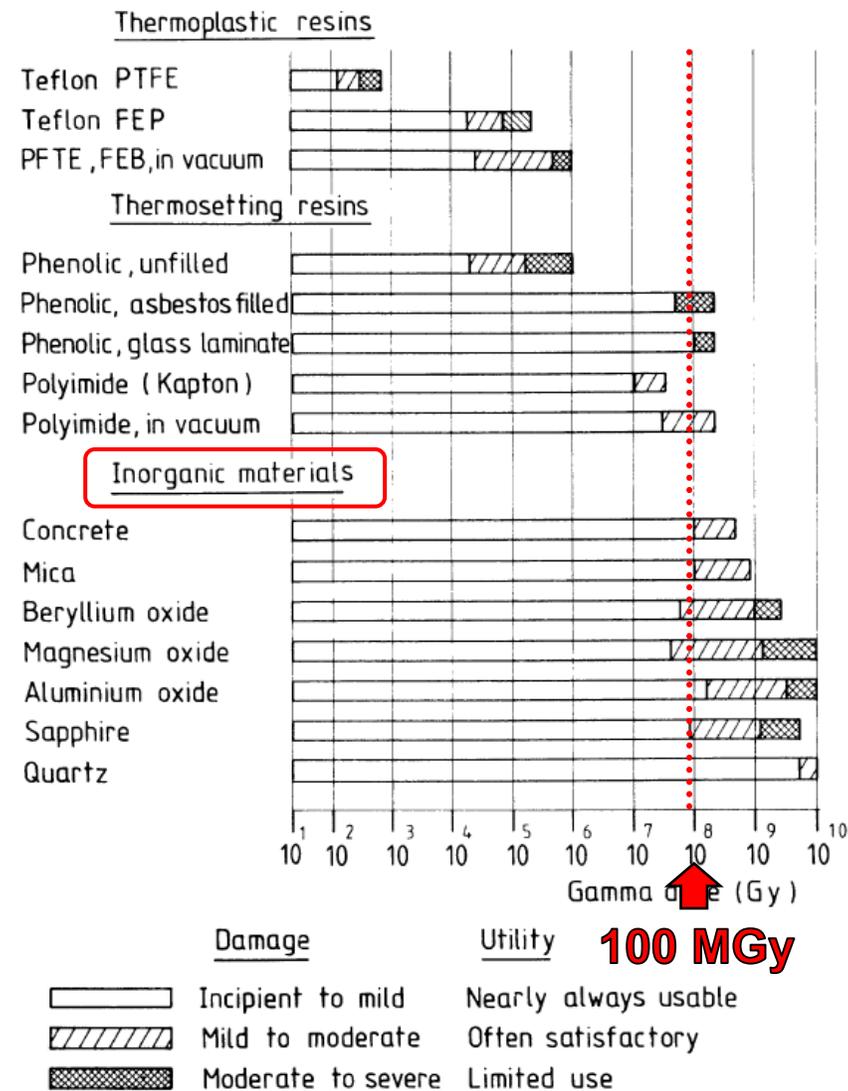
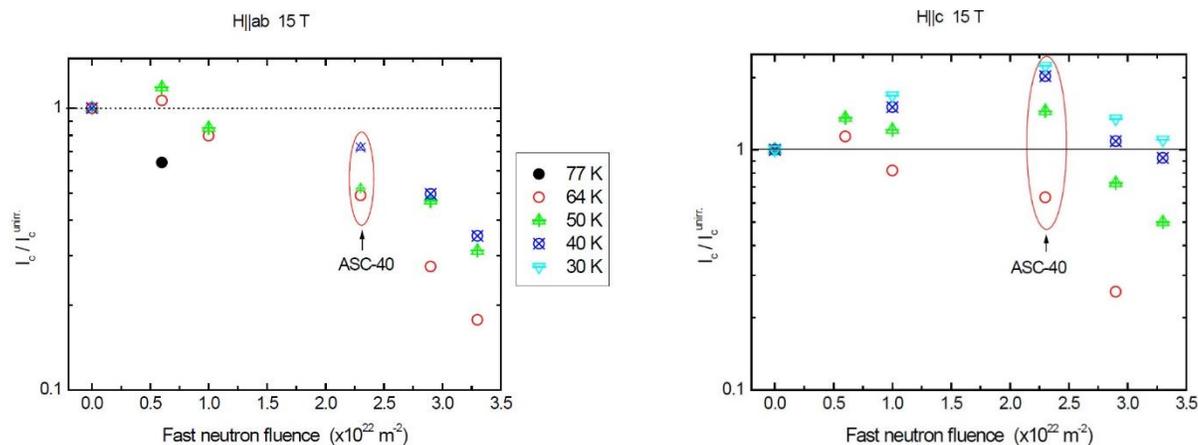


Fig. 2 Radiation resistance of several electrically insulating materials

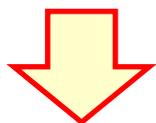
# TS2-PSC conceptual design

R. Fuger et al., Physica C 468 (2008) 1647., M. Eisterer, RESUMM2015.

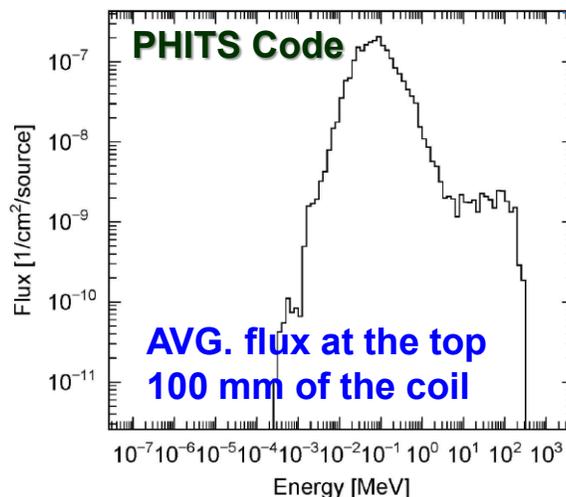


$I_c$  of REBCO degrades from  $1 \times 10^{22} \text{ n/m}^2$  ← Target fluence

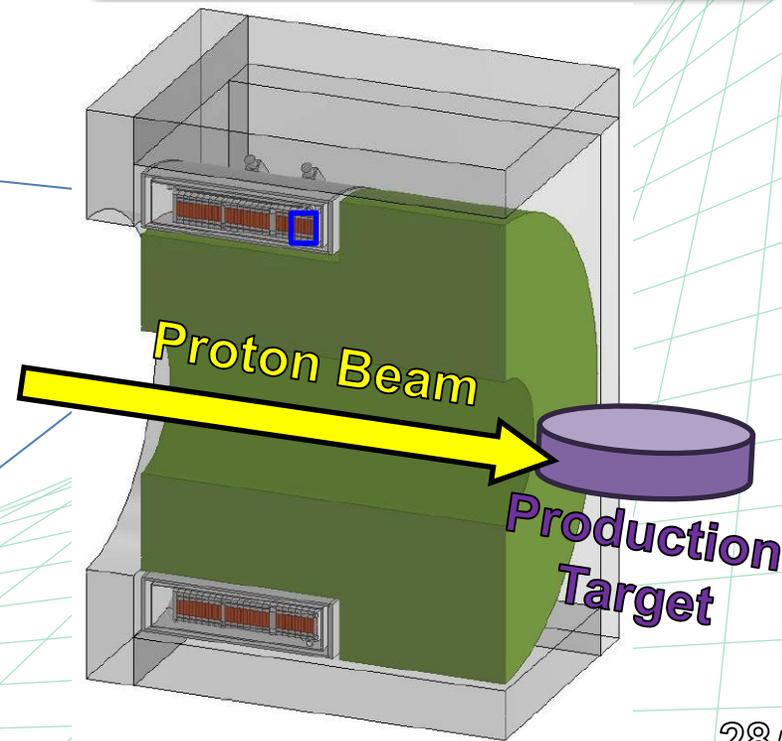
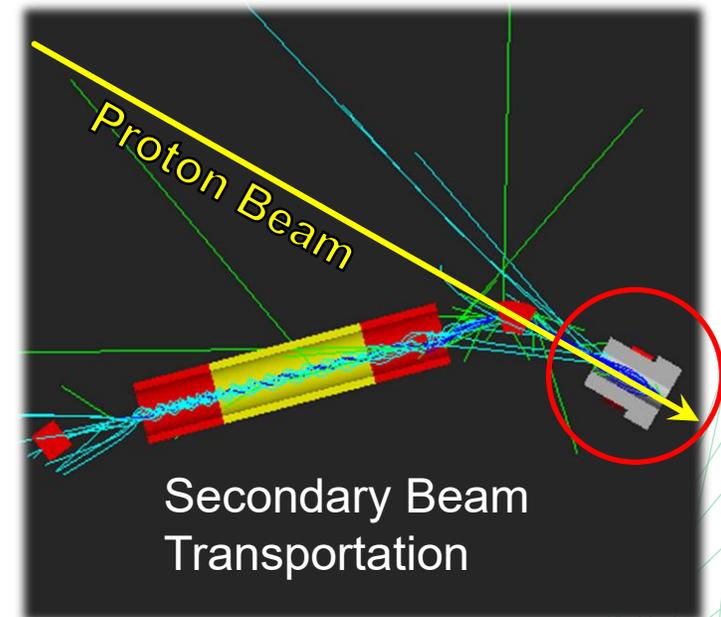
**Design neutron fluence:**  
 $7.8 \times 10^{20} \text{ n/m}^2$  over 10 years  
 (~100 MGy, 450 W)



**Massive tungsten alloy radiation shield is required**



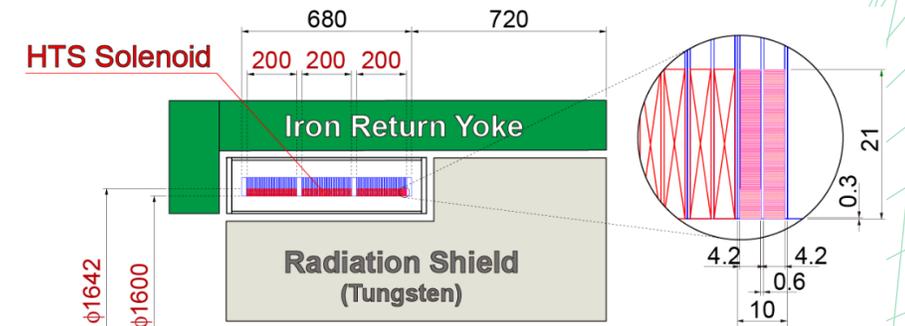
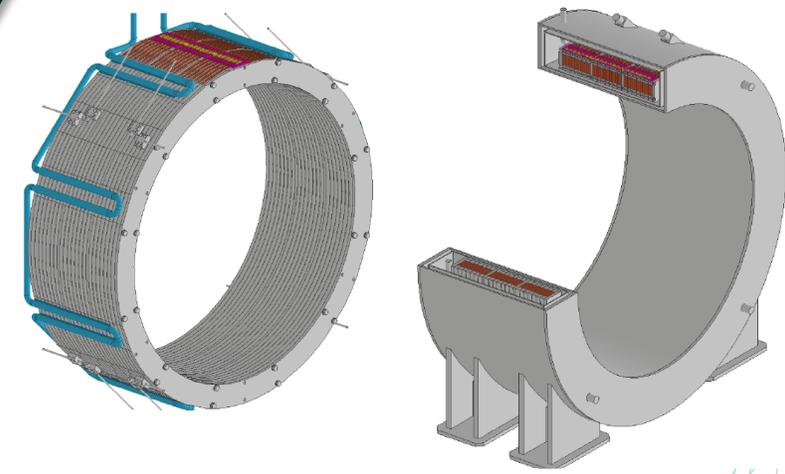
**Integrated flux:**  
 $7.8 \times 10^{20} \text{ n/m}^2/\text{y} (@1 \text{ MW})$



# Structure of TS2-PSC

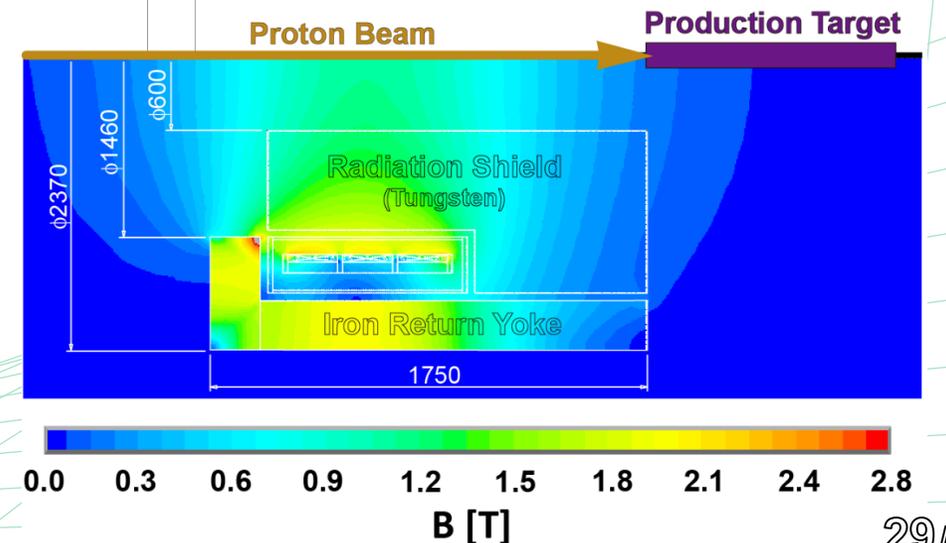
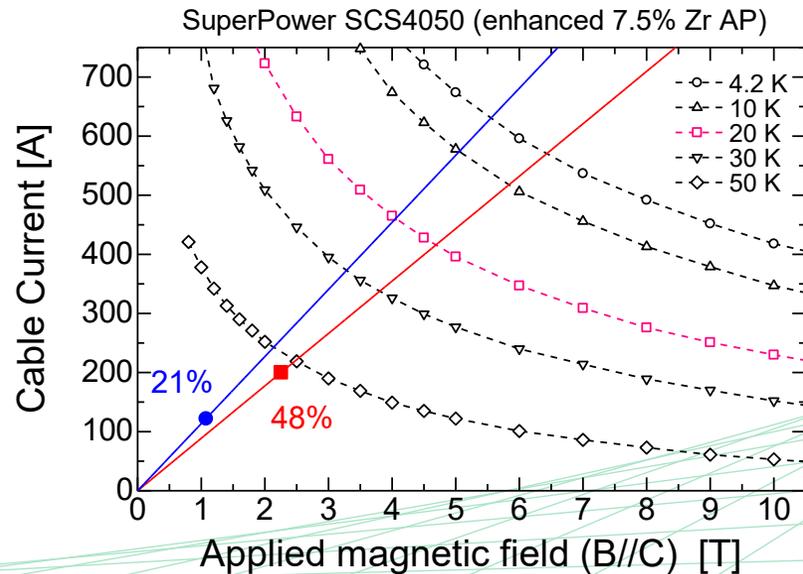
## Stack of double pancake coil

- ID=1600 mm, T=21 mm, L=10 mm, **70** turns/layer
- Number of double pancake coils: **60** (20 x3)
- Conductor : **REBCO**, W=4 mm, T=0.1 mm
- Insulation: Mineral, t=0.1 mm
- Operation Temperature: **20 K** (He gas cooling with pipe)
- Transport current: **200 A** (Load line ratio: 0.48)
- Peak Field: **1.11 T** at center, **2.25 T (B//c)** at coil (200 A)



Current density:  
**128 A/mm<sup>2</sup>**

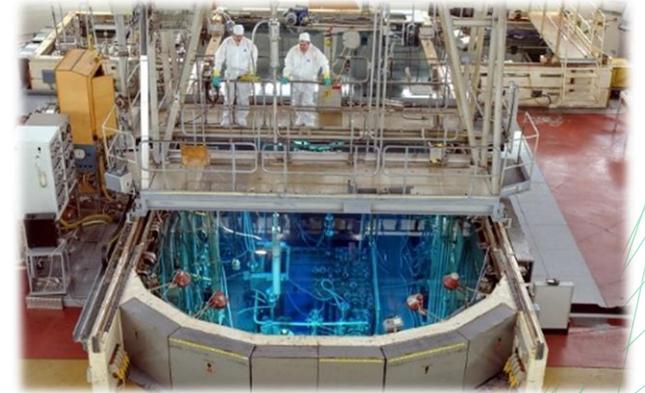
Load line ratio:  
**48%**



## ▣ Studies on radiation resistance

- **Neutron irradiation**
  - REBCO tapes, Ceramic coating samples, BT-GFRP
- **Gamma-ray irradiation**
  - REBCO tapes, Ceramic coating samples

BR2 @Belgian nuclear research center



## ▣ Ceramic coating and bonding technology

- **Ceramic coating on REBCO and magnet materials**
- **Demonstration of coil assembly with ceramic adhesive**
- **Cooling and excitation test**

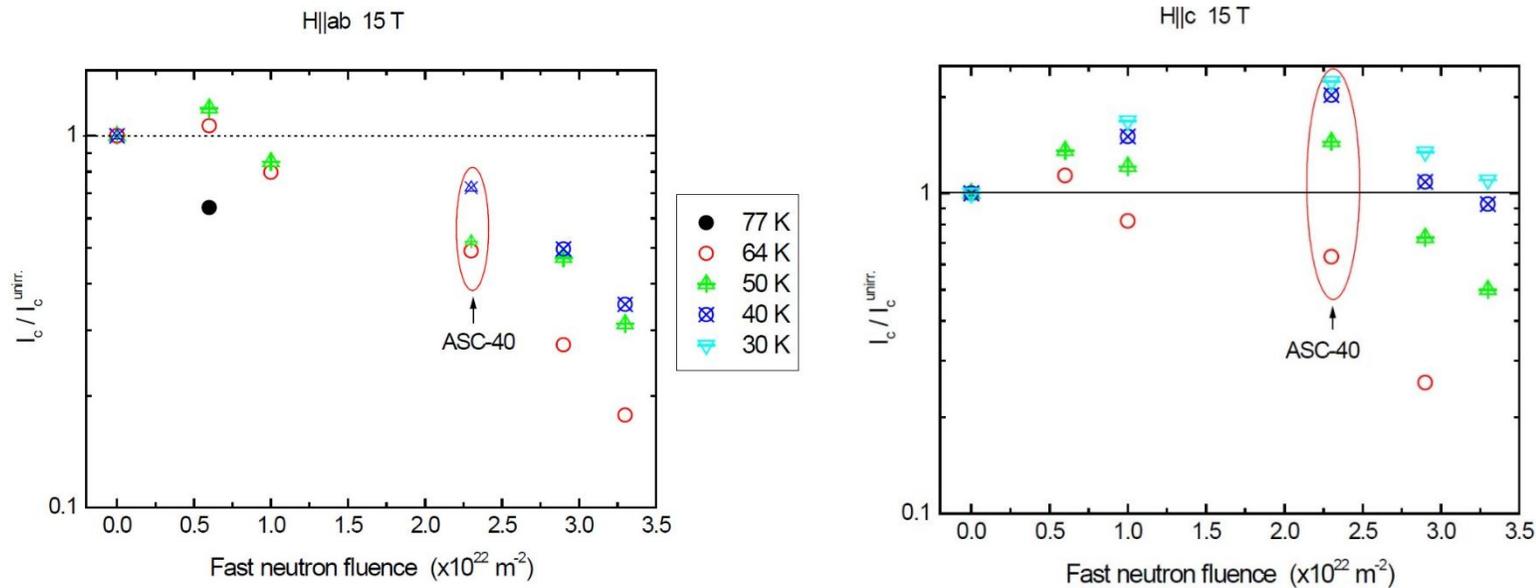


## ▣ **Development of AL-stabilized HTS conductor**

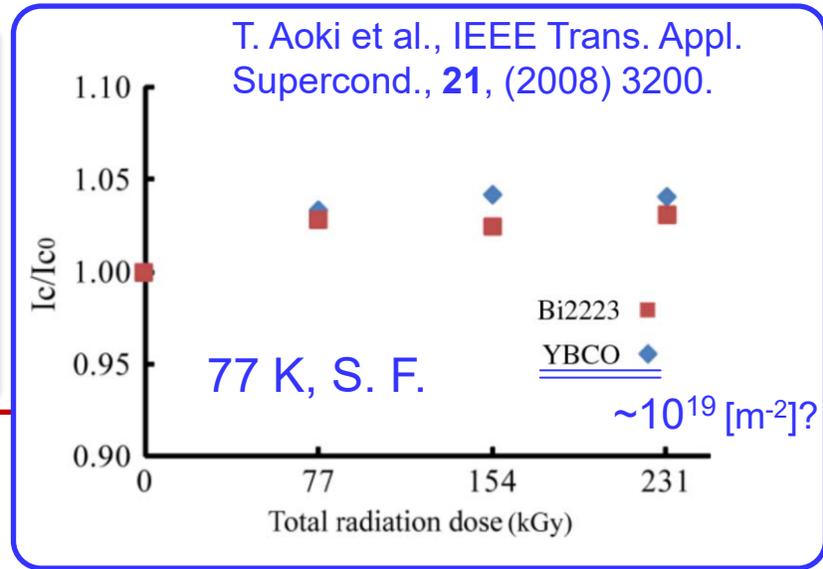
# Irradiation effect on HTS conductor

# Neutron irradiation research on REBCO conductors

- Low-dose irradiation for introducing artificial pins into materials, (bulk, conductor)
- High-dose irradiation of conductors for application to nuclear fusion (Vienna University of Technology)



R. Fuger et al., Physica C 468 (2008) 1647., M. Eisterer, RESUMM2015.

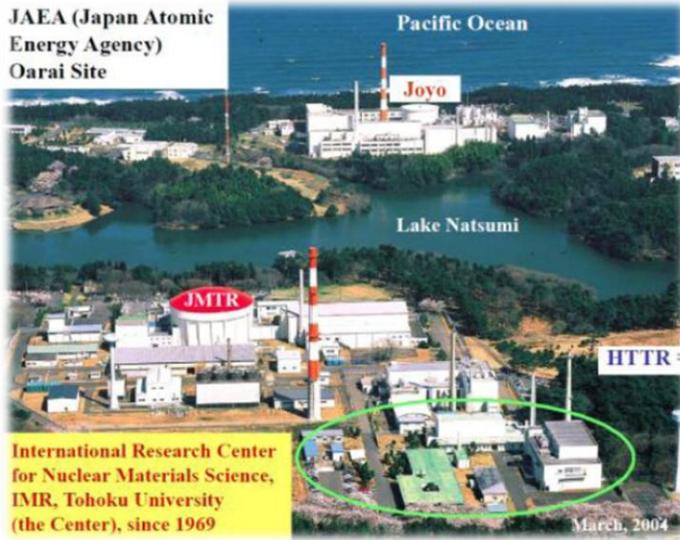


## Purpose of neutron irradiation

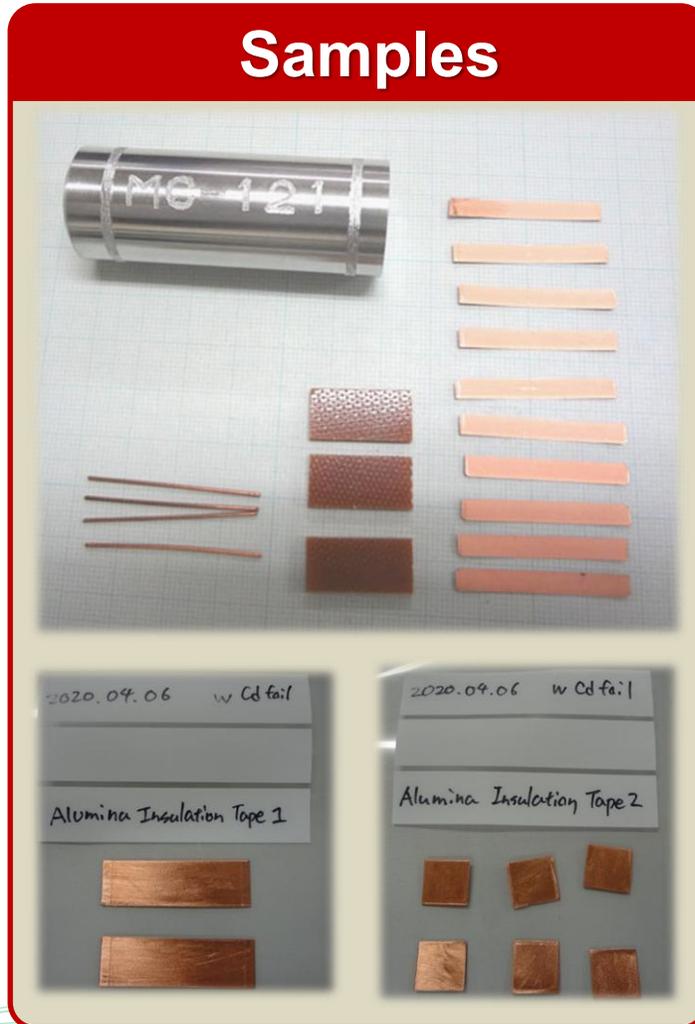
- Confirmation of reproducibility, understanding of phenomena, data acquisition (fluence, temperature, magnetic field)

# Scheme of neutron irradiation

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



### Samples



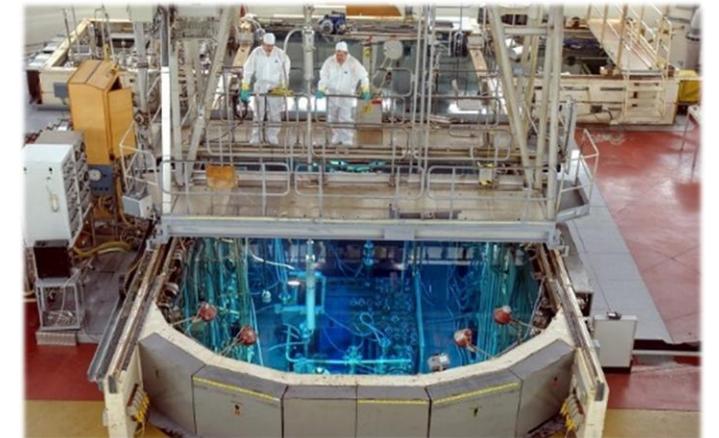
- Target fluence range:

$$0.1 \sim 10 \times 10^{22} \text{ n/m}^2$$

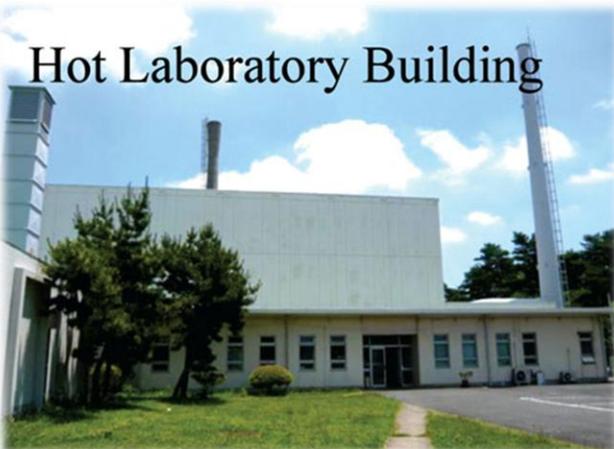
$$(E_n > 1 \text{ MeV}, T < 100^\circ\text{C})$$

- TS2-PCS <  $1 \times 10^{22} \text{ (n/m}^2)$

### BR2 @Belgian nuclear research center



### Hot Laboratory Building

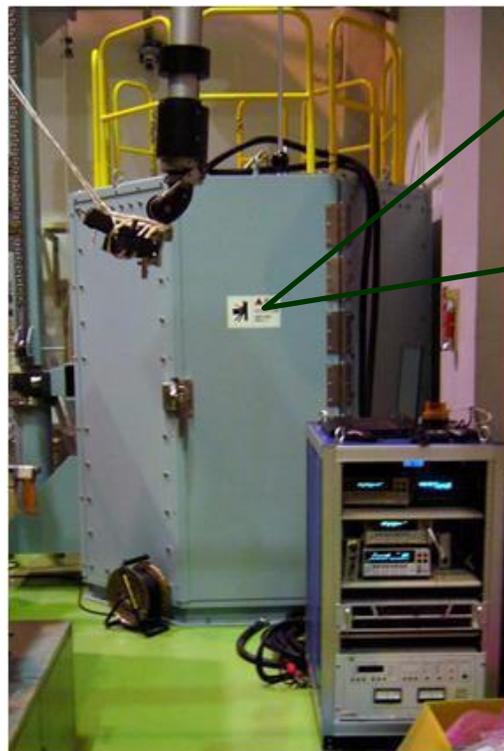


# Superconducting Properties Evaluation

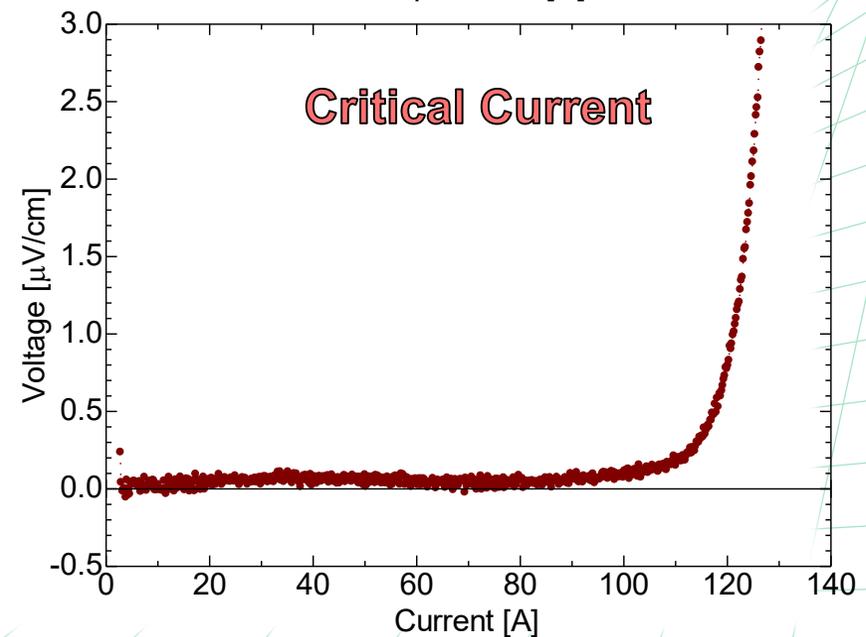
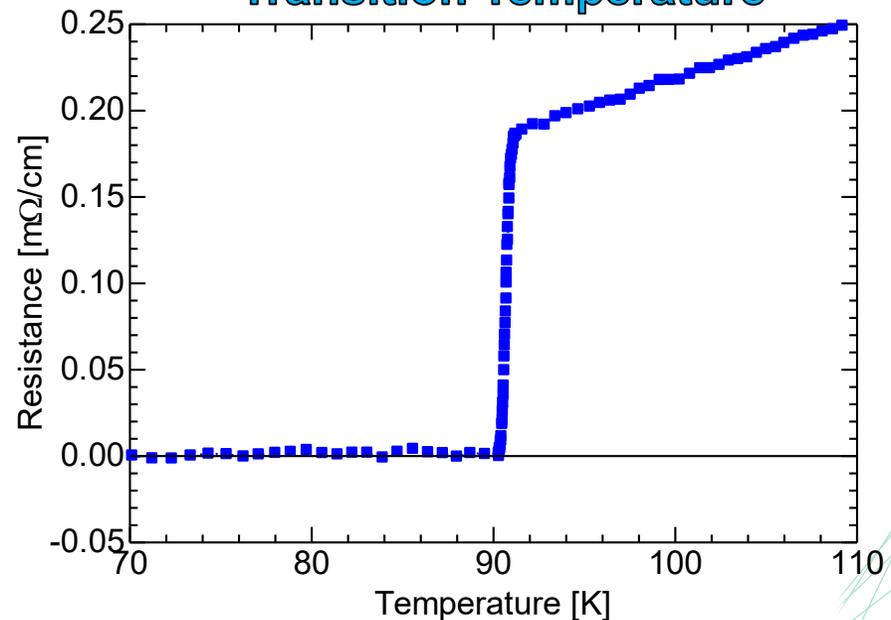
## PIE at IMR Oarai Center

- 15.5 T SC magnet with conduction cooling Variable Temperature Insert (VTI)

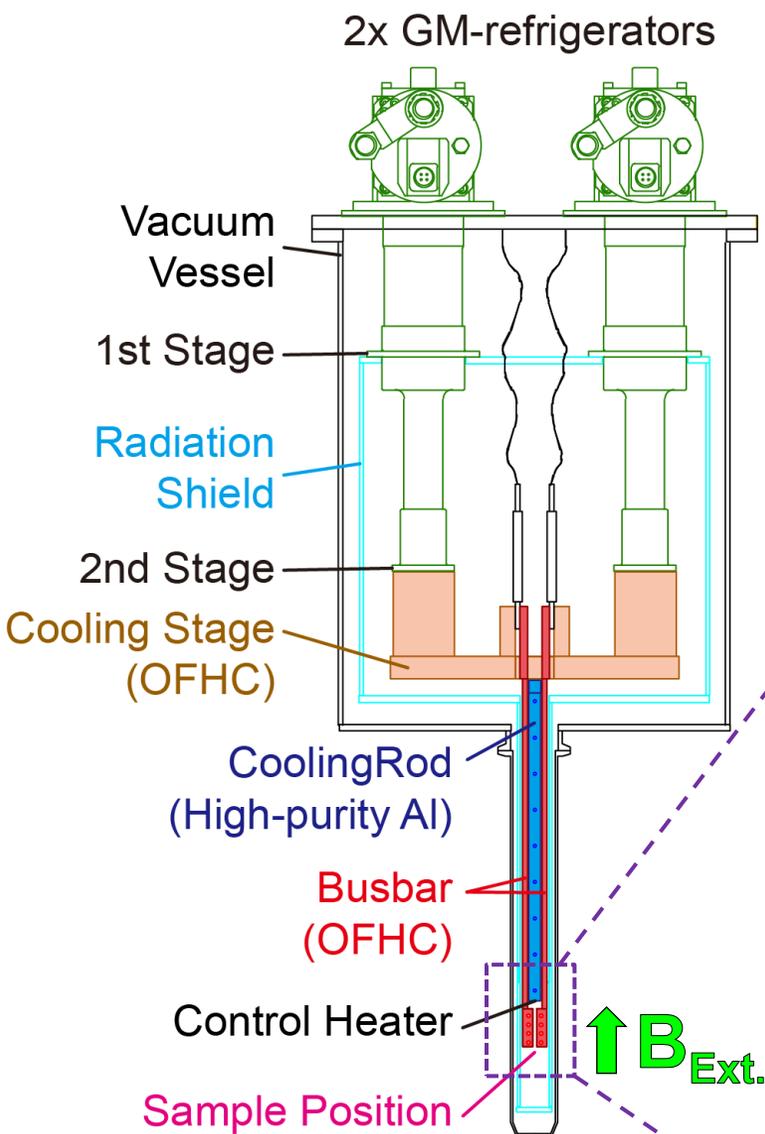
Temperature Range	4 ~ 80 K
Max. Current	500 A
Max. External Field	15.5 T



## Superconducting Transition Temperature



# Variable Temperature Insert (VTI)

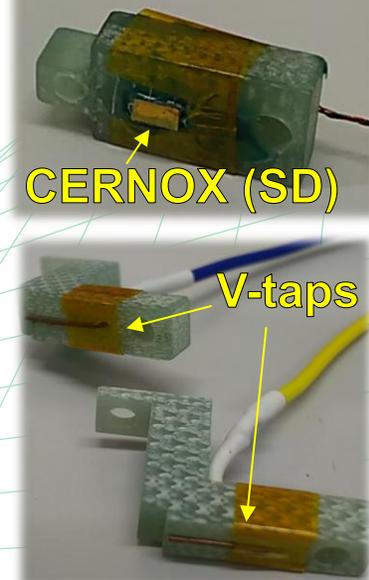
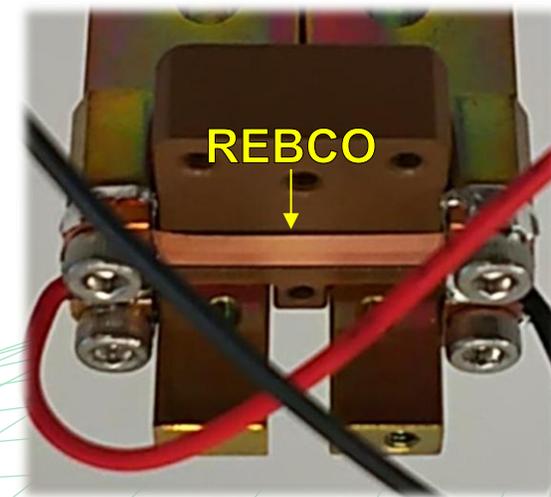
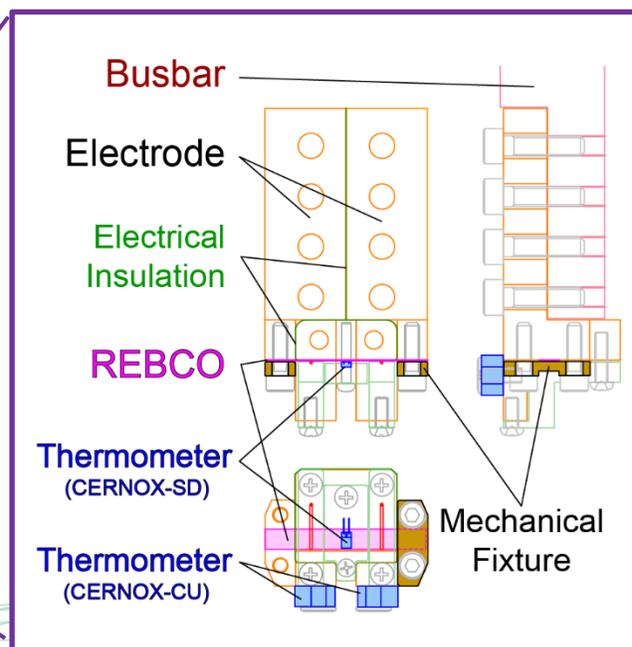
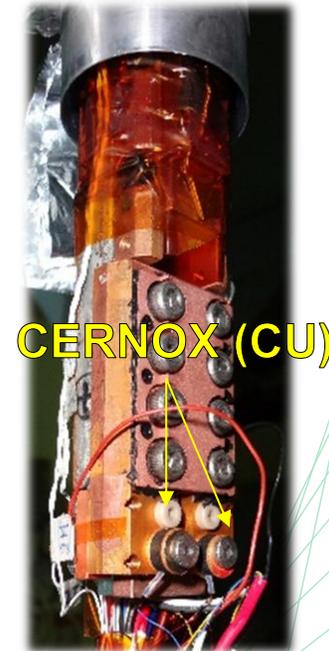


## Conduction Cooling

GM Refrigerators → Cooling Rod (Al) → Busbars (Cu) → Electrodes (Cu) → REBCO Sample

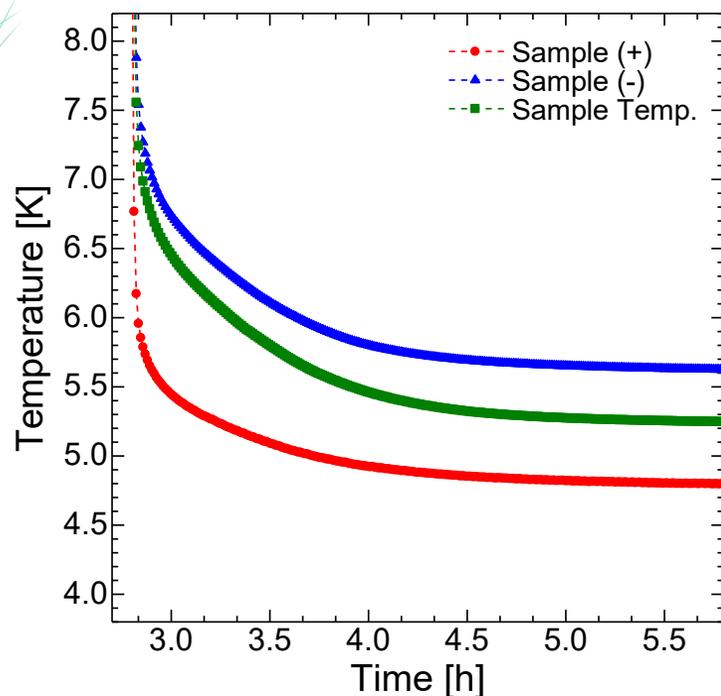
Easy and Quick handling  
to minimize radiation expose

- Mechanical contact **w/o soldering**  
Temperature rise due to ohmic heat  
is non-negligible

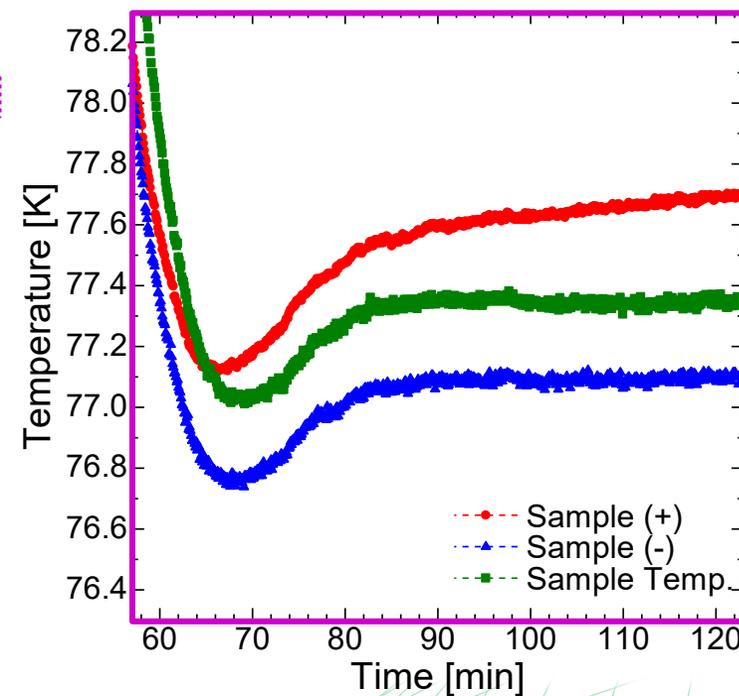
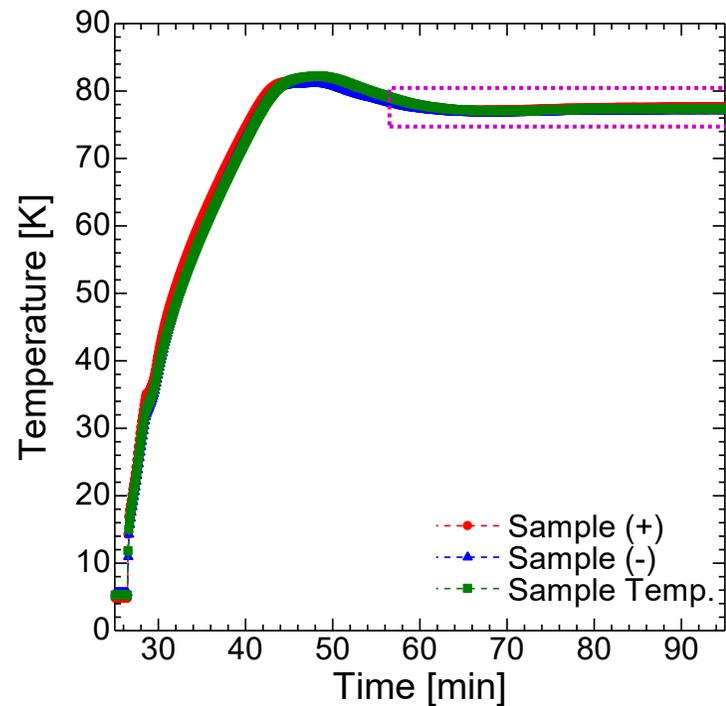


# Achieved temperature and temperature control

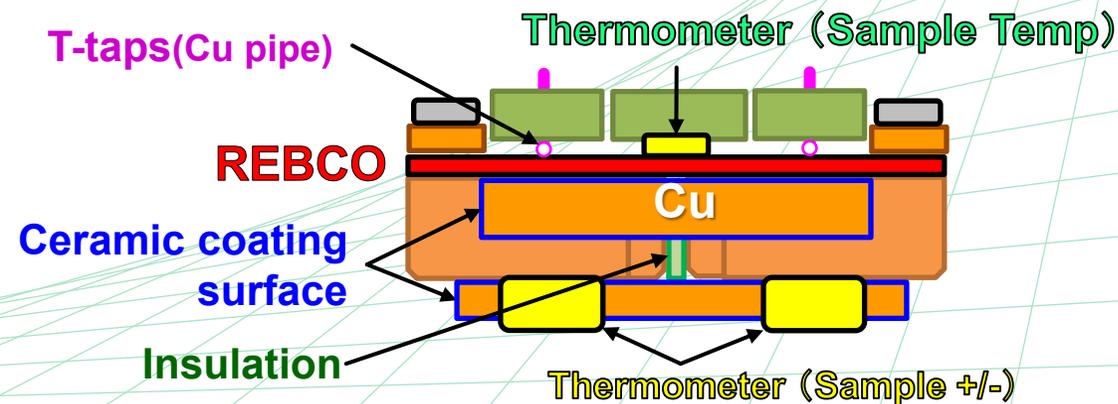
## Achieved temperature



## Temperature control at 77.3 K

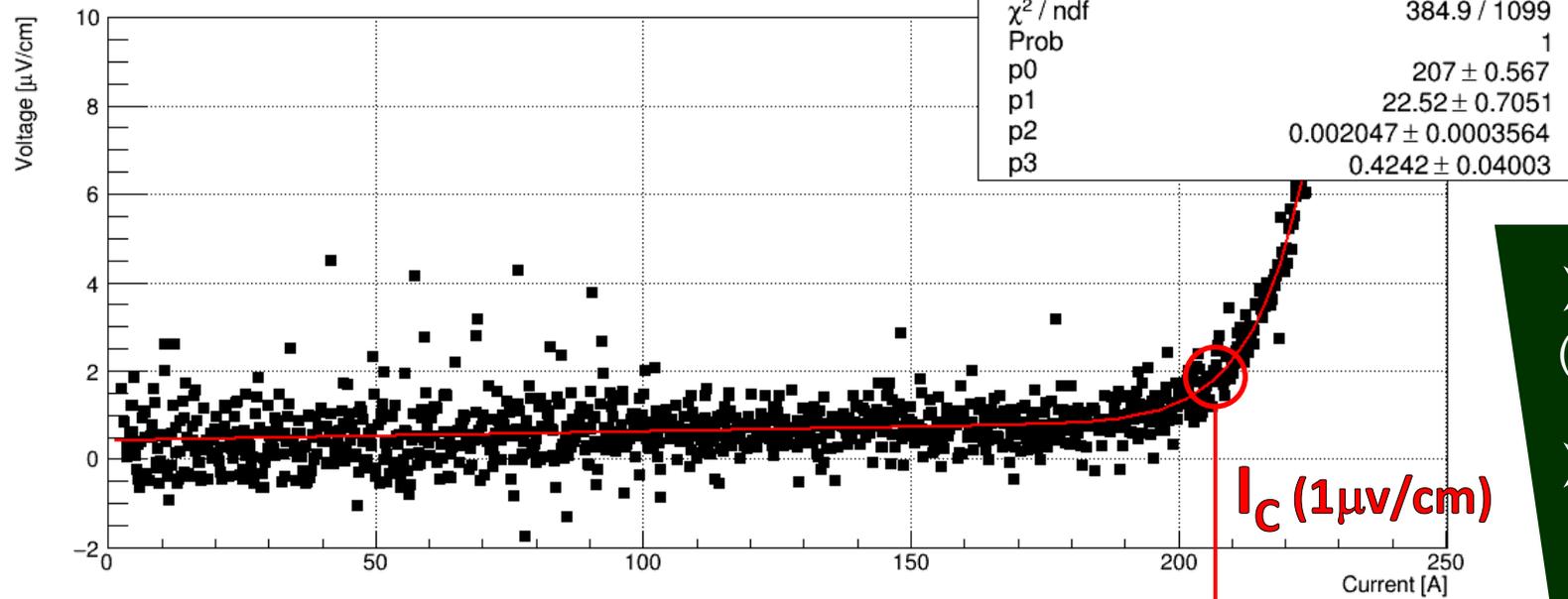


- There is a temperature difference between the electrodes
- There is a difference in thermal resistance in contact with the insulating materials



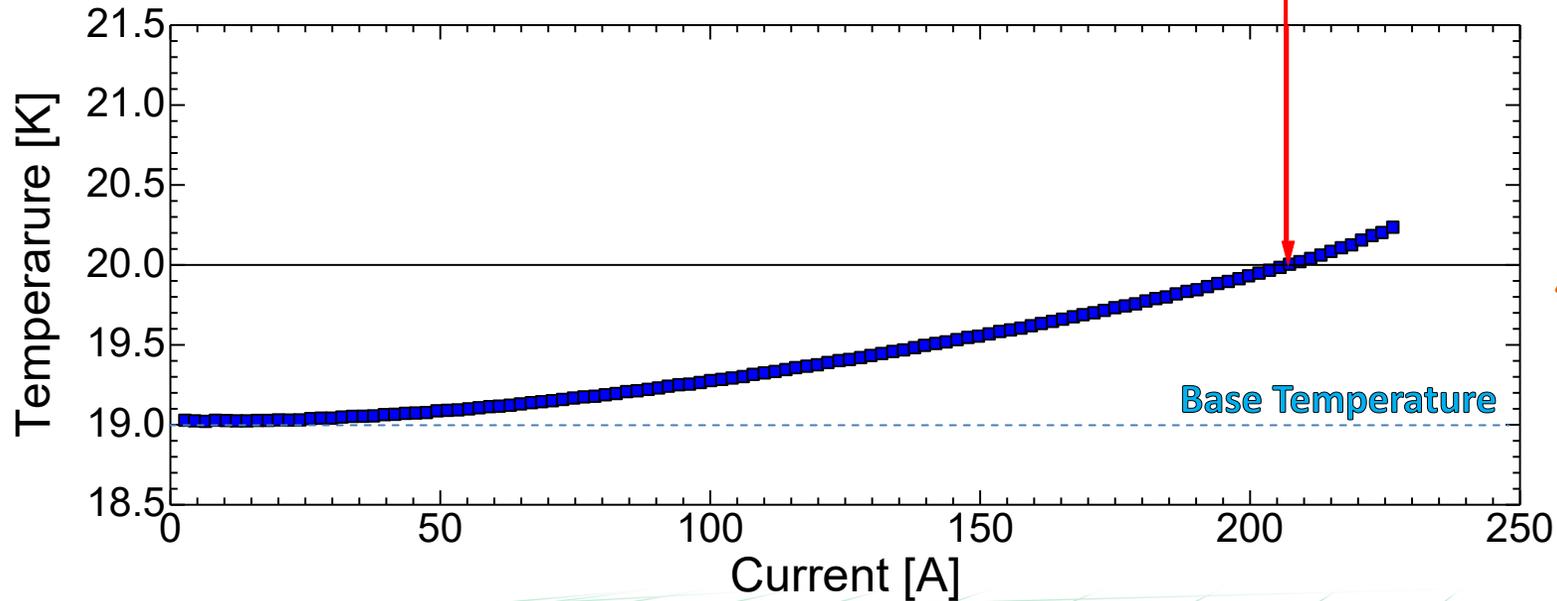
# $I_C$ definition and Joule heat generation

T=20K, B=5T, SCS4050-AP



➤ Definition of  $I_C$ : 1 mV/cm  
(Distance between voltage taps: 1.4 cm)

➤ Base temperature is adjusted in anticipation of temperature rise



↑ Temperature rise: 0.98 K

# Recent Status of Neutron Irradiation Studies

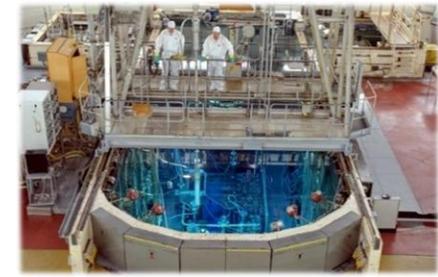
- Neutron irradiation at BR2(Belgium) & JRR3(Japan)
- Fluence range:  $0.1\sim 10 \times 10^{22} \text{ n/m}^2$ , ( $E_n > 1 \text{ MeV}$ ,  $T < 100^\circ\text{C}$ )

## □ Previous studies at BR2

- GdYBCO (SCS4050-AP) → Degradation observed at  $8.2 \times 10^{21} \text{ n/m}^2$  ( $E > 0.1 \text{ MeV}$ )

## □ Hydraulic Irradiation Facility HR-1 at JRR-3

- Irradiation conditions:  $< 100^\circ\text{C}$  for 24h
- Fluence:  $1.5 \times 10^{21} \text{ n/m}^2$  ( $E > 0.1 \text{ MeV}$ ) and  $8.3 \times 10^{22} \text{ n/m}^2$  (Thermal) ← Suppression by Cd-shield
- Irradiation with and without Cd-shielding for thermal neutron suppression



BR2 @Belgian nuclear research center



JRR-3

## [Samples]

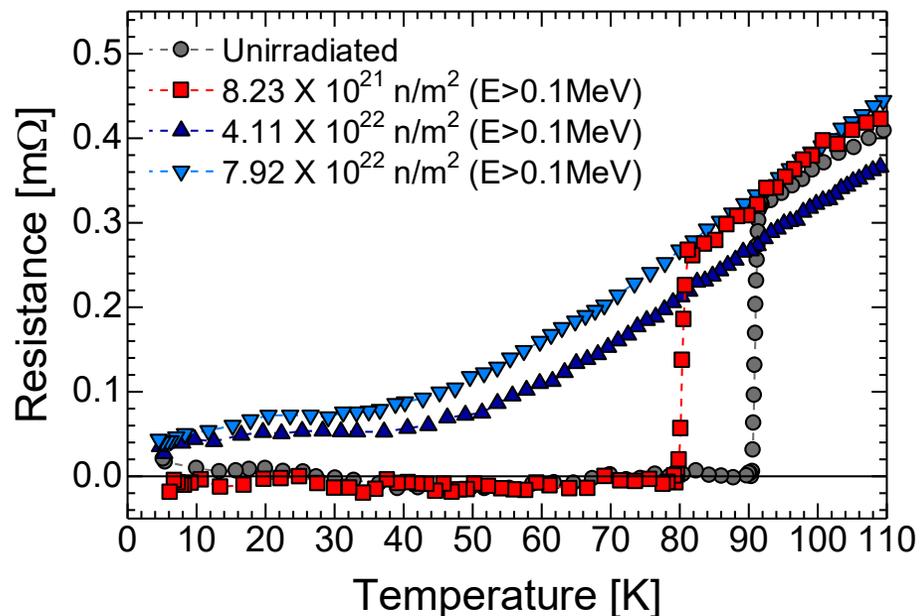
- GdBCO (FYSC-SCH02 w/o AP),  $w_{\text{tape}} = 2 \text{ mm}$ ,  $t_{\text{sub}} = 75 \text{ }\mu\text{m}$ ,  $t_{\text{Cu}} = 20 \text{ }\mu\text{m}$  (one side)
- EuBCO (FESC-SCH02 w AP),  $w_{\text{tape}} = 2 \text{ mm}$ ,  $t_{\text{sub}} = 50 \text{ }\mu\text{m}$ ,  $t_{\text{Cu}} = 20 \text{ }\mu\text{m}$  (one side)
- YBCO (SCS4050-HM w AP),  $w_{\text{tape}} = 4 \text{ mm}$ ,  $t_{\text{sub}} = 50 \text{ }\mu\text{m}$ ,  $t_{\text{Cu}} = 10 \text{ }\mu\text{m}$  (one side)
- YBCO (SCS2030-HM w AP),  $w_{\text{tape}} = 2 \text{ mm}$ ,  $t_{\text{sub}} = 30 \text{ }\mu\text{m}$ ,  $t_{\text{Cu}} = 5 \text{ }\mu\text{m}$  (one side) ← reference only

# Degradation of $T_c$ under neutron irradiation

- Neutron irradiations with and without Cd-shielding of REBCO are underway
  - Irradiation with Cd-shielding effectively suppresses low-energy neutrons

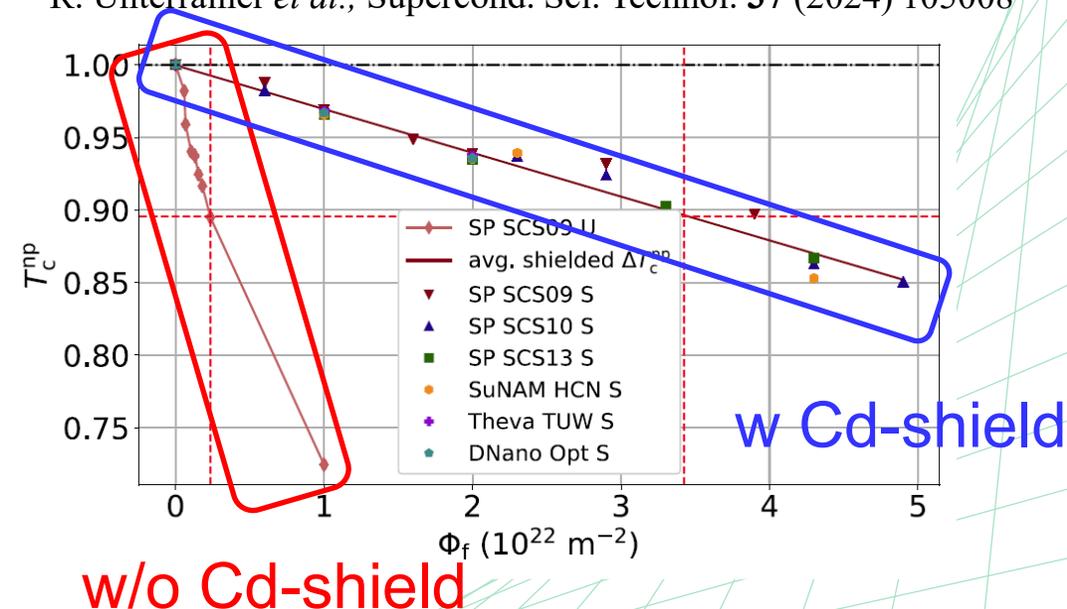
## KEK, w/o Cd-shielded

M. Iio, et al., *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, (2020) 4600505.



## TU Wien

R. Unterrainer et al., *Supercond. Sci. Technol.* **37** (2024) 105008



w/o Cd-shield (Full spectrum of energy) :

Rapid degradation at fluences in the order of  $10^{21} \text{ n/m}^2$

w Cd-shield (Low-energy neutron suppression):

Gradual degradation at fluences in the order of  $10^{22} \text{ n/m}^2$

Both results suggest a large contribution of low-energy neutrons

# Thermal neutron-induced nuclear reaction

- At low neutron energies, nuclear processes are mainly neutron capture reactions

Molecular formula:  $\text{ReBa}_2\text{Cu}_3\text{O}_7$

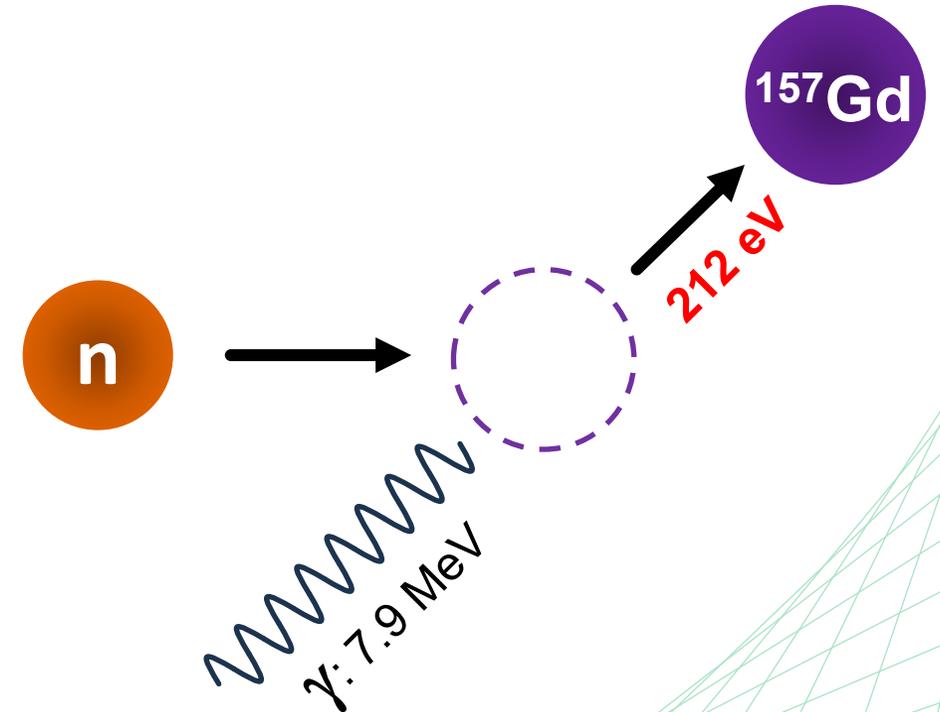
## Thermal Neutron Capture Cross Section

$$\sigma_{GdBCO} = 48633 \text{ b}$$

$$\sigma_{EuBCO} = 4560 \text{ b}$$

$$\sigma_{YBCO} = 15 \text{ b}$$

O. Iwamoto, et al., "Japanese evaluated nuclear data library version 5: JENDL-5", *J. Nucl. Sci. Technol.*, 60(1), 1-60 (2023).



Recoil energy of REBCO atoms by  $(n, \gamma)$  reactions:  $\sim 100\text{-}300 \text{ eV}$

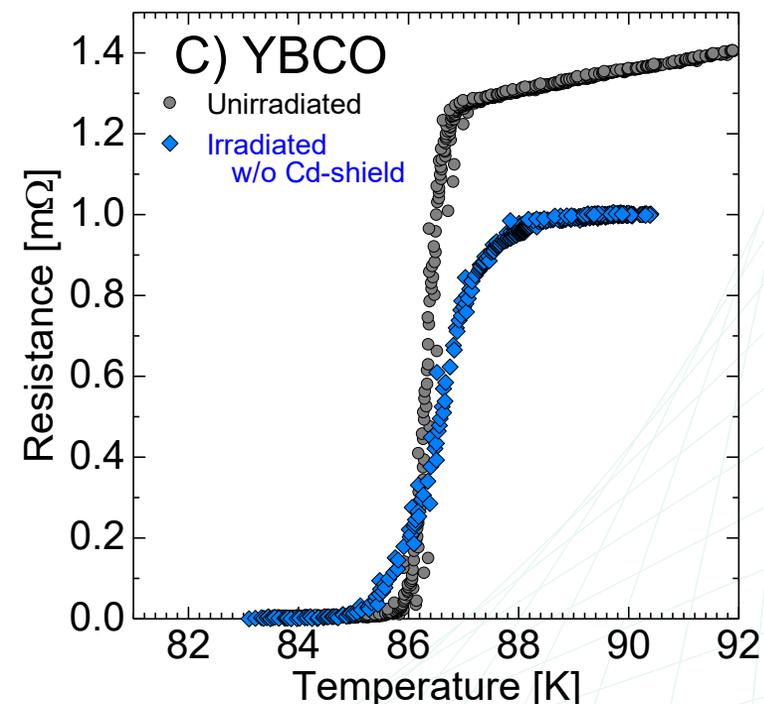
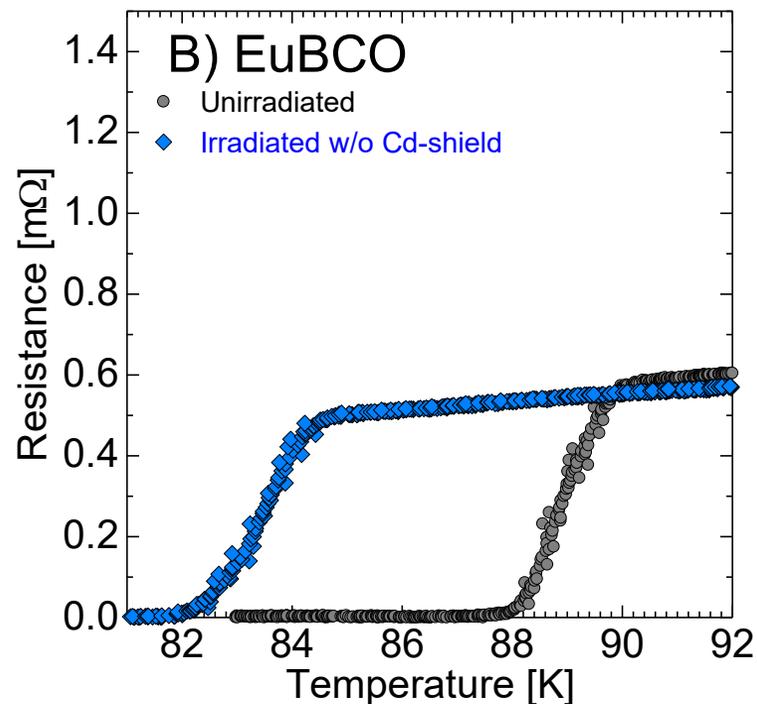
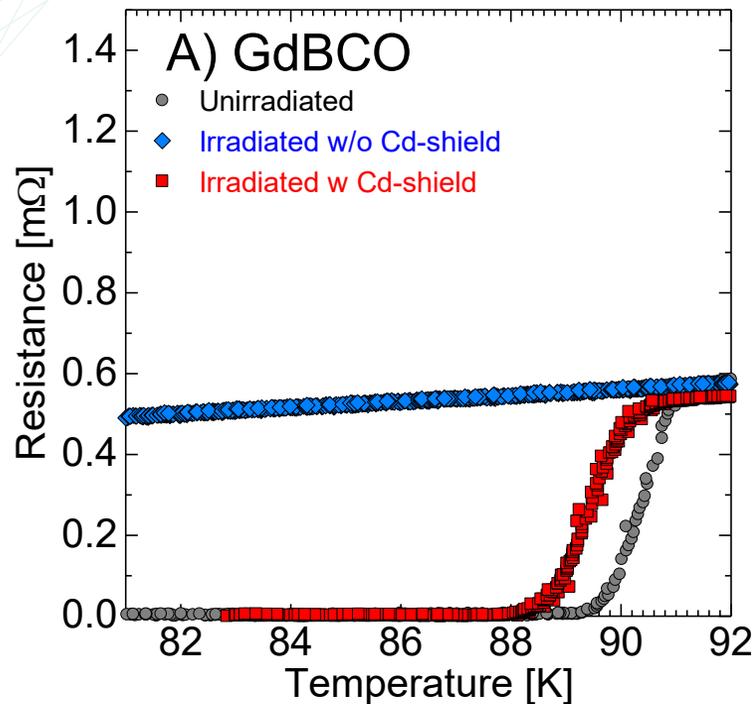
> Displacement threshold energy:  $\sim 10\text{-}50 \text{ eV}$

→ Neutron capture reactions are expected to generate defects within REBCO

Neutron irradiation has been performed on three rare-earth samples (Gd, Eu, Y) both with and without Cd-shielding

# Results of critical temperature measurement

□ External field: 0 T, Transport current: 0.1 A



[GdBCO]

Sample w/o Cd-shield: **Loss of superconductivity**

Sample w Cd-shield: Negligible degradation

[EuBCO]

Sample w/o Cd-shield: **3.5 K drop in  $T_C$**

[YBCO]

Sample w/o Cd-shield: Negligible degradation

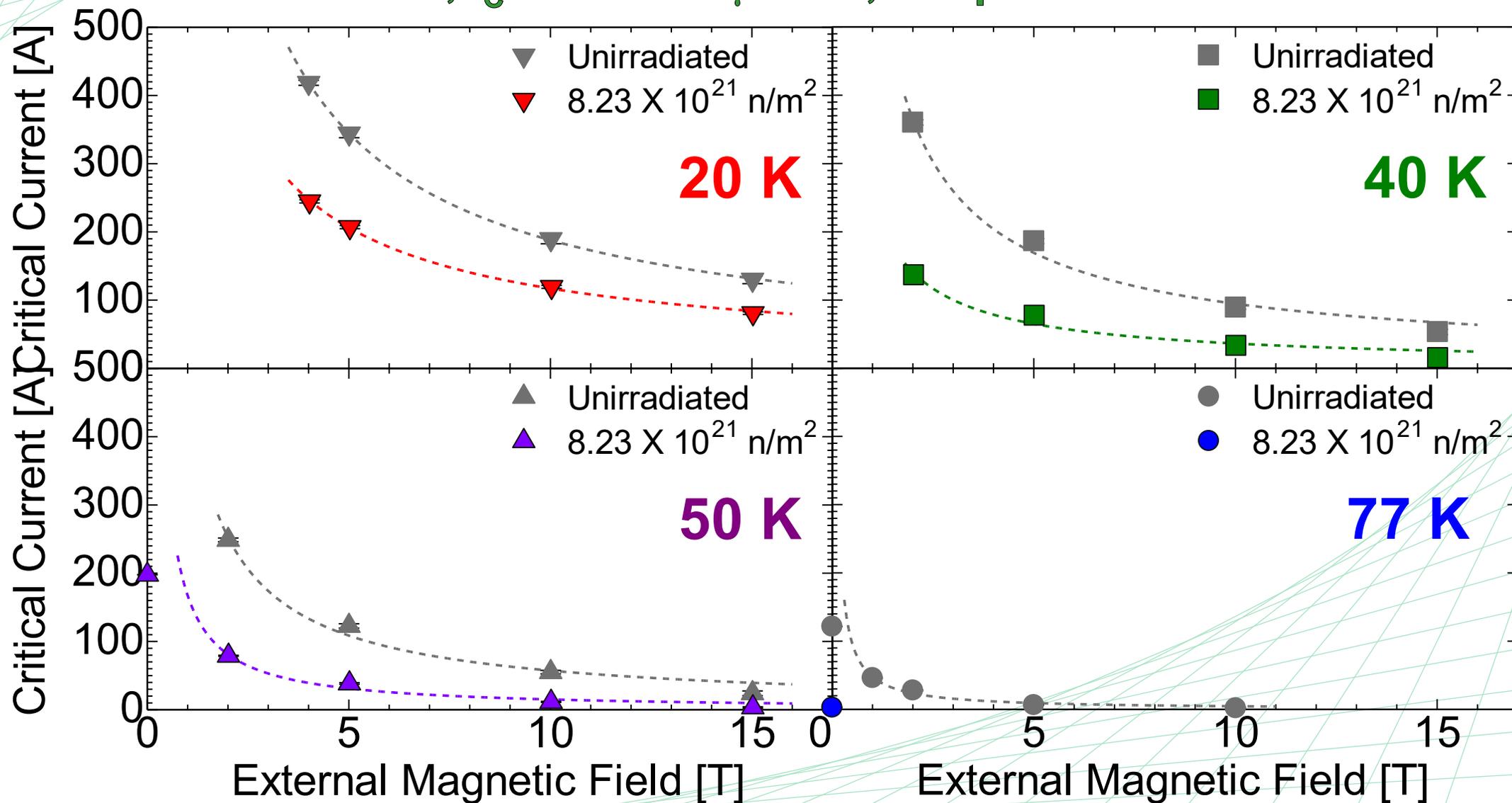
$$\Delta T_{C\_GdBCO(w\ Cd-shield)} = -0.8 \pm 2.6$$

$$\Delta T_{C\_EuBCO(w/o\ Cd-shield)} = -3.5 \pm 2.9$$

$$\Delta T_{C\_YBCO(w/o\ Cd-shield)} = 0.7 \pm 2.7$$

# $I_c$ -B curve for irradiation at BR2

GdYBCO,  $I_c$  criteria:  $1 \mu\text{V}/\text{cm}$ , V-tap distance: 1.4 cm

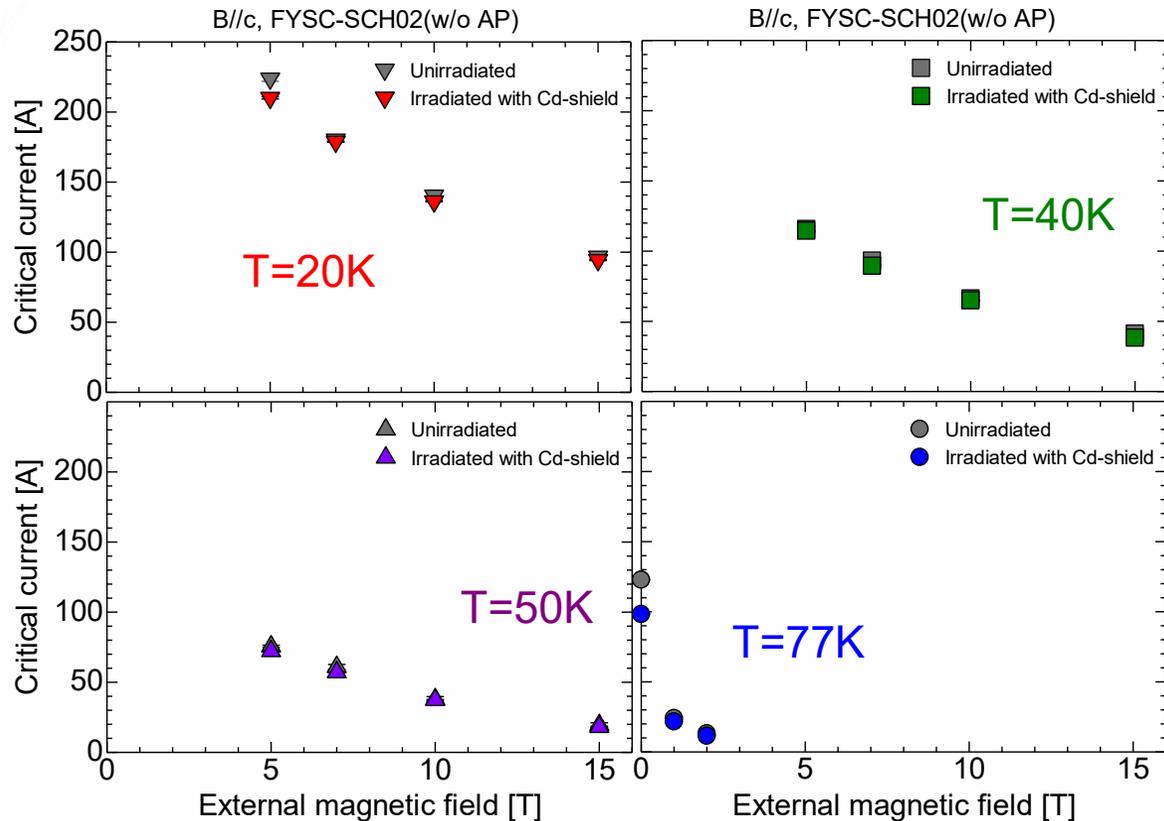


Fitting Function: C. Senatore, et al., Supercond. Sci. Technol, vol. 29, Dec. 2015, 014002.

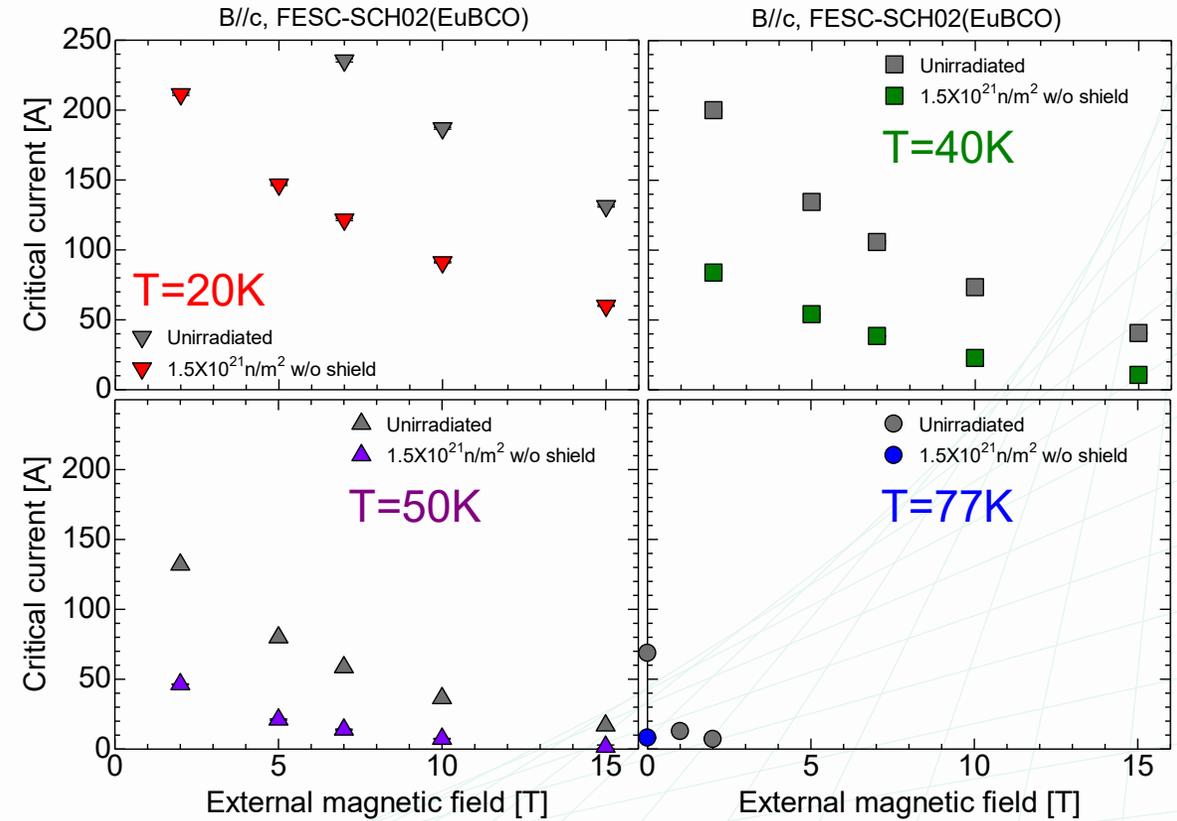
# $I_c$ -B curve for irradiation at JRR-3

$2.4 \times 10^{21} \text{ n/m}^2$  ( $E > 0.1 \text{ MeV}$ ),  $I_c$  criteria:  $1 \mu\text{V/cm}$ , V-tap distance:  $1.4 \text{ cm}$

## GdBCO with Cd-shield



## EuBCO without Cd-shield



[GdBCO]

Sample w/o Cd-shield: **Loss of superconductivity**

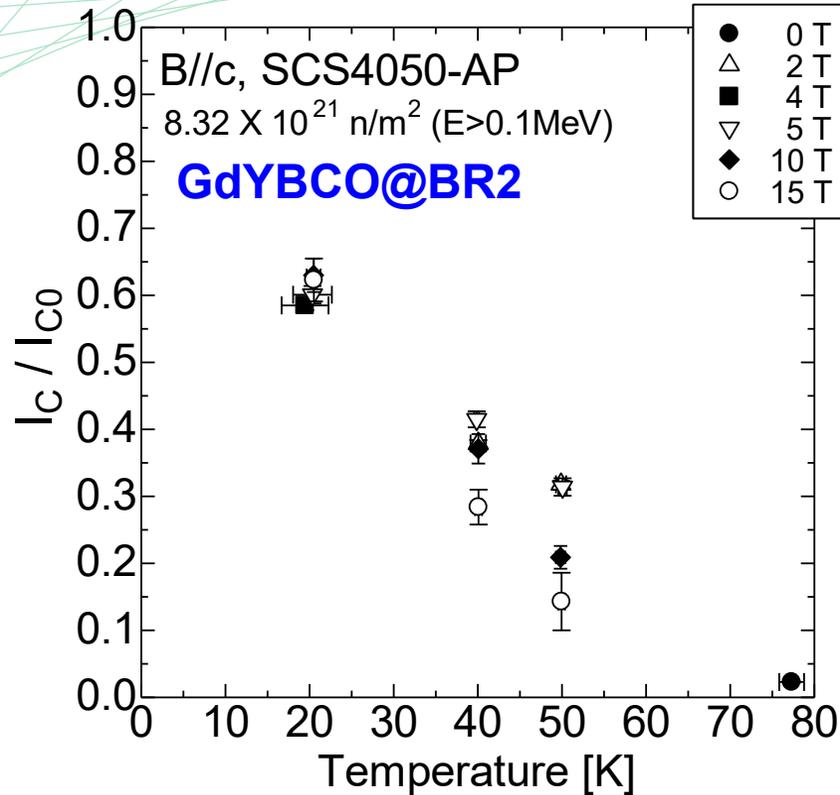
Sample w Cd-shield: Negligible degradation

[EuBCO]

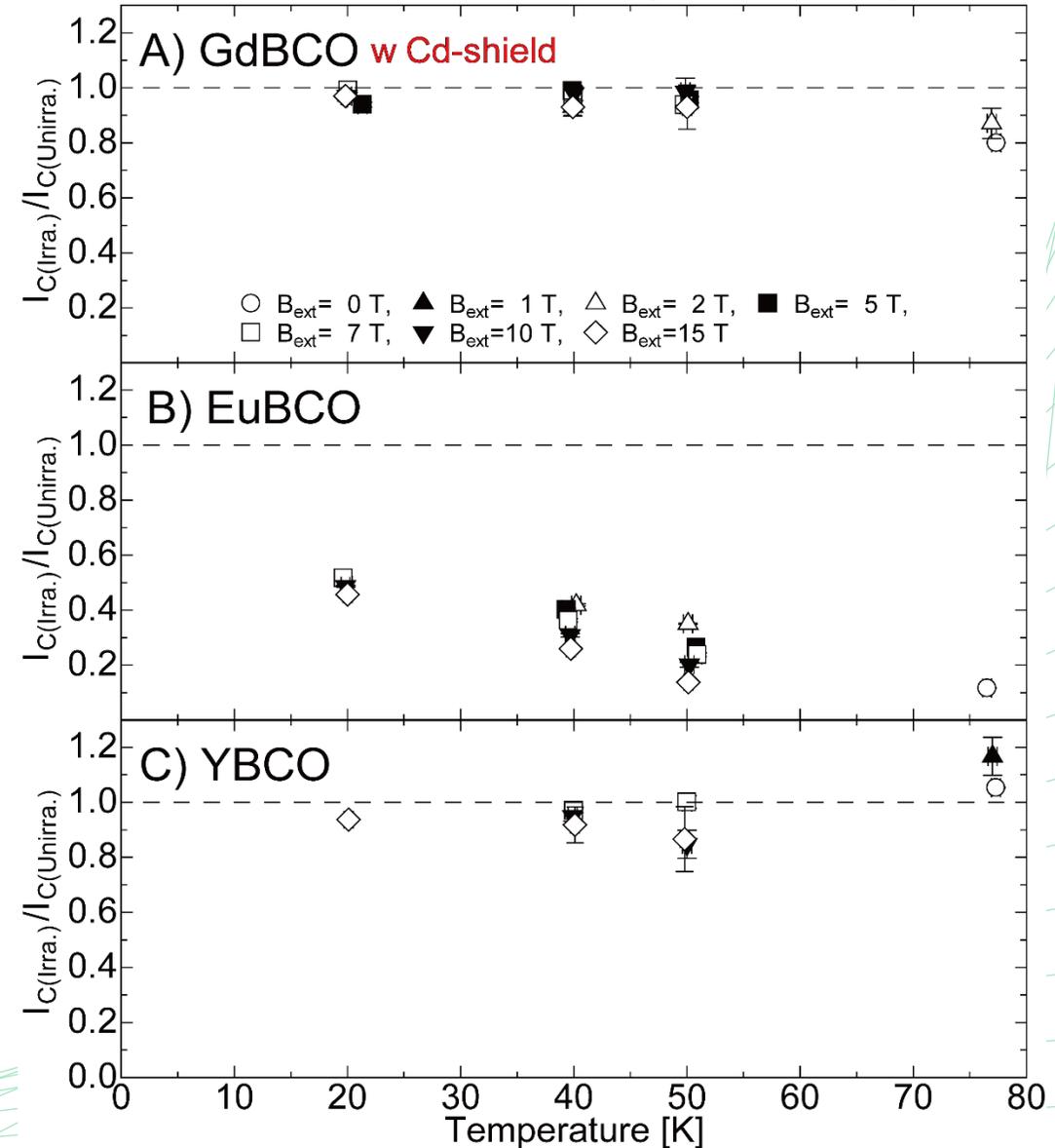
Sample w/o Cd-shield: **Significant degradation**

# Degradation Rate ( $I_C/I_{C0}$ )

$2.4 \times 10^{21} \text{ n/m}^2 \text{ (E>0.1 MeV)}$



- The degradation rate of  $I_C$  is independent of the magnetic field
- A larger degradation of  $I_C$  is observed at higher temperatures
- GdBCO at JRR-3 exhibits larger  $I_C$  degradation even at a low fast neutron fluence

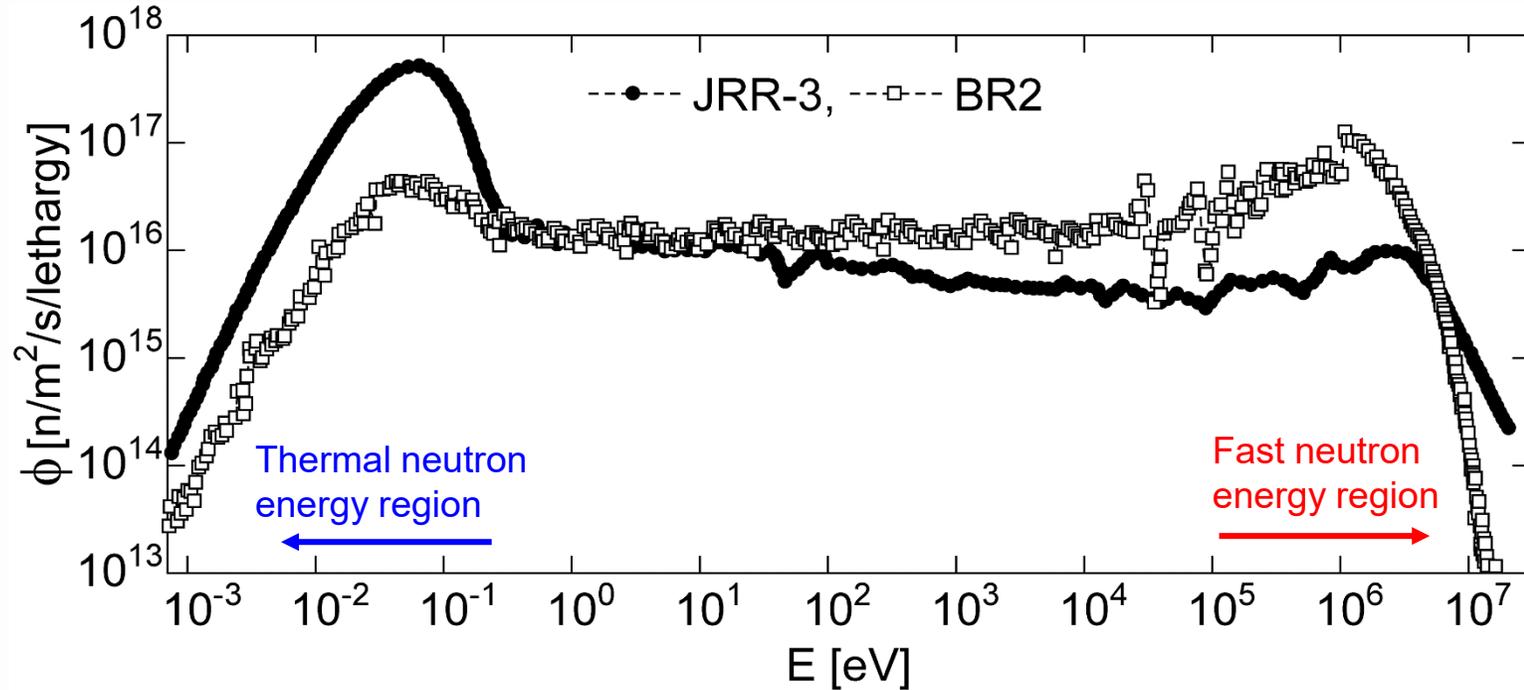


# Variation in neutron flux across research reactors

- ❑ The fast neutron flux is higher in BR2 than in JRR-3
- ❑ The thermal neutron flux at JRR-3 is significantly higher than that at BR2



The degradation of superconducting properties caused by neutron capture reactions is more significant for irradiation at JRR-3 than at BR2.



Neutron fluence in two research reactor irradiations

Reactor	Thermal ( $E < 0.68 \text{ eV}$ )	Fast ( $E > 0.1 \text{ MeV}$ )
BR2	$4.1 \times 10^{21} \text{ n/m}^2$	$8.3 \times 10^{21} \text{ n/m}^2$
JRR-3	<b><math>7.9 \times 10^{21} \text{ n/m}^2</math></b>	<b><math>2.4 \times 10^{21} \text{ n/m}^2</math></b>

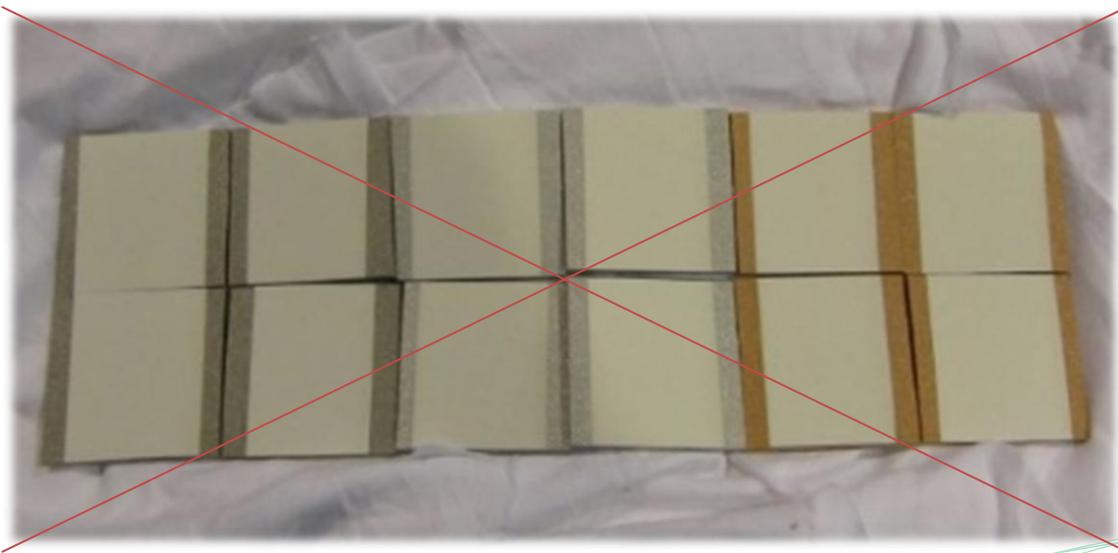
# R&D of mineral insulated HTS coils

## Advantages ceramic insulation

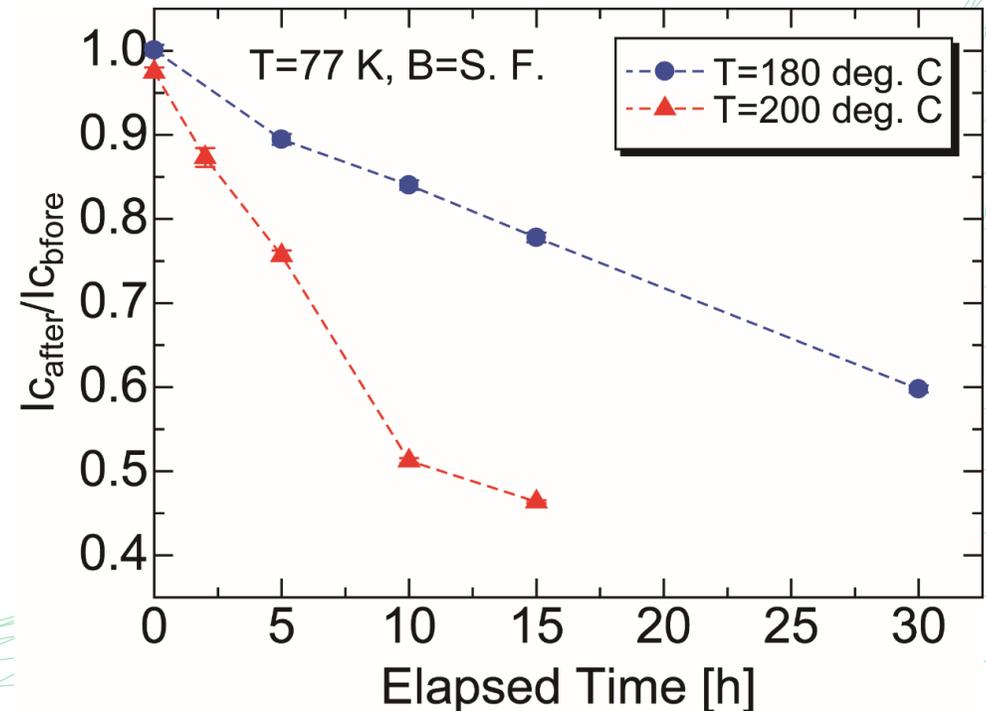
- Higher radiation tolerance of mechanical strength than resin materials
- Better thermal conductivity ( $\text{Al}_2\text{O}_3:32, \text{SiO}_2:10 \gg \text{EP resin}:0.3$  [ $\text{W}/\text{m}\cdot\text{K}$  @300K])
- Close to the coefficient of thermal expansion of cable

## Ceramic firing temperature $>1000^\circ\text{C}$

- Superconductivity of REBCO disappears

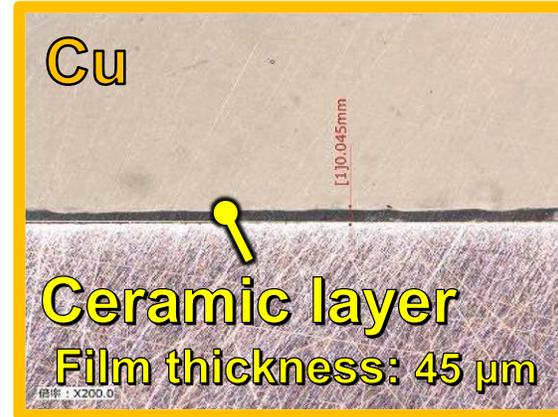
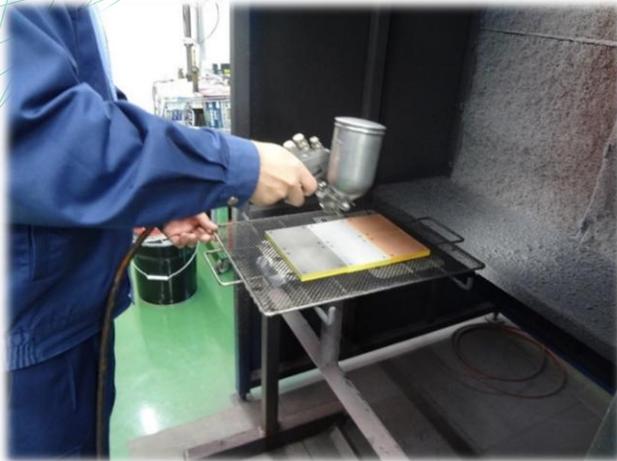


## Decrease in $I_c$ due to heat load



# Application of ceramic coating technology

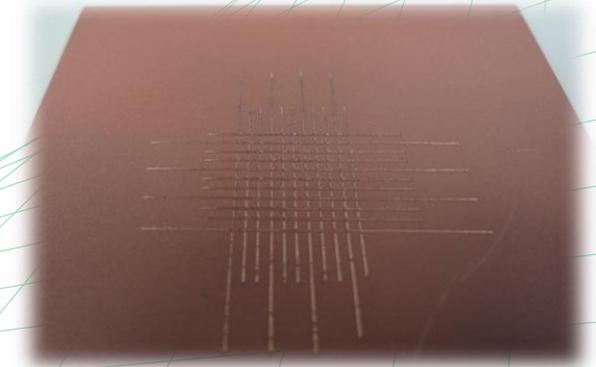
Target film thickness: 50  $\mu\text{m}$ , Withstand voltage: > 2 kV



## Optimized coating conditions

- Coating material:  $\text{Al}_2\text{O}_3 : \text{SiO}_2 = 1 : 1$  (G-92-5, NIKKEN .Ltd)
- Cycle forming of 10  $\mu\text{m}$  thick by spray method (Drying temp. 80°C)
- Final heat treatment: 100°C, 20 min

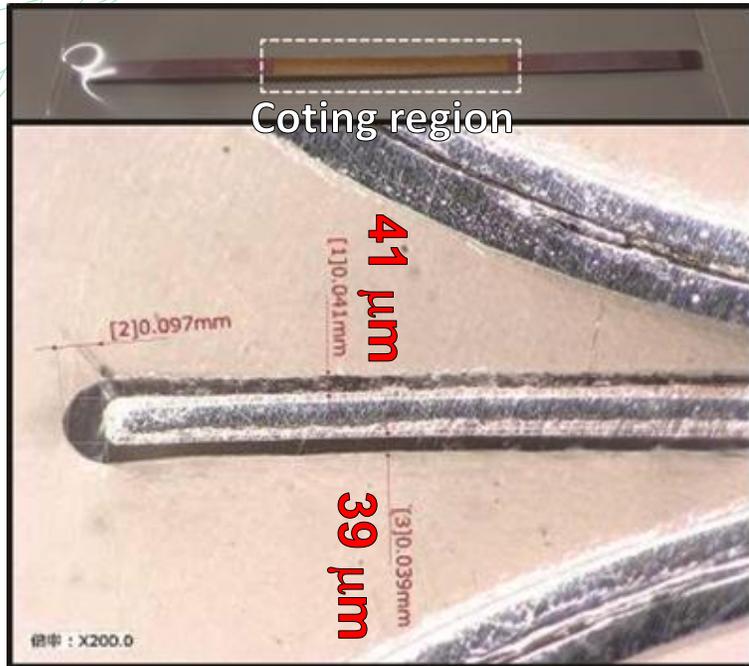
Cross-cut test  
(ISO 2409, Paints and Varnishes )



Class 0 (0/100)

# Ceramic coating trial of REBCO tapes

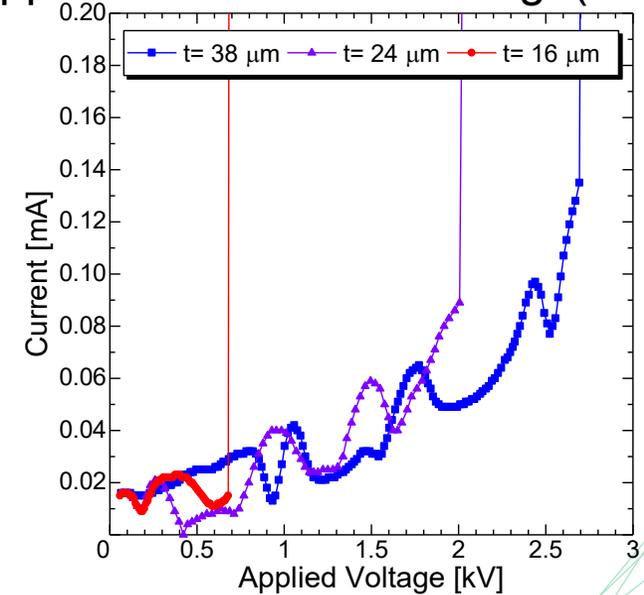
## SCS4050-AP (SuperPower)



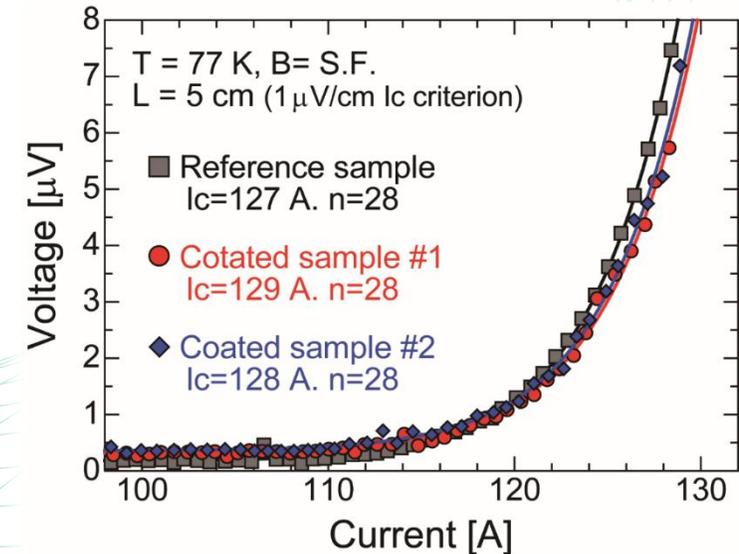
### Withstand voltage

- $t=16 \mu\text{m}$  : 0.679 kV
- $t=24 \mu\text{m}$  : 2.006 kV
- $t=38 \mu\text{m}$  : 2.693 kV

### Applied load with AC voltage(50 Hz)



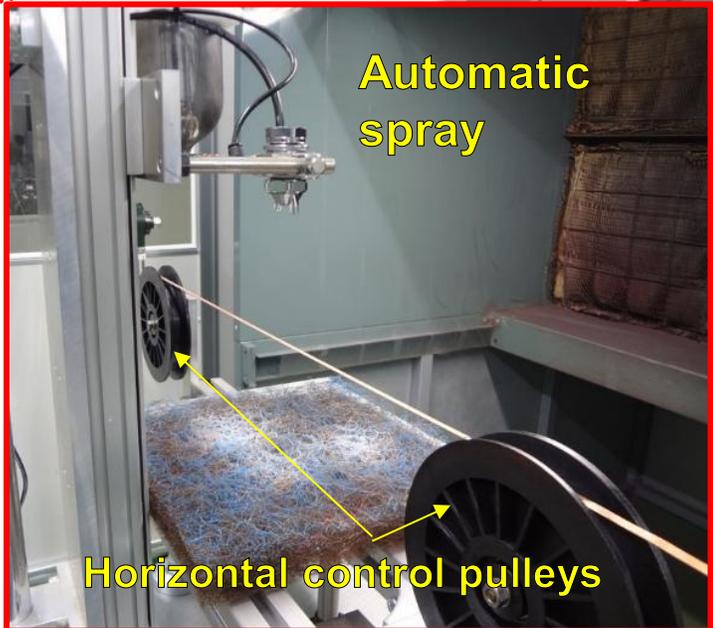
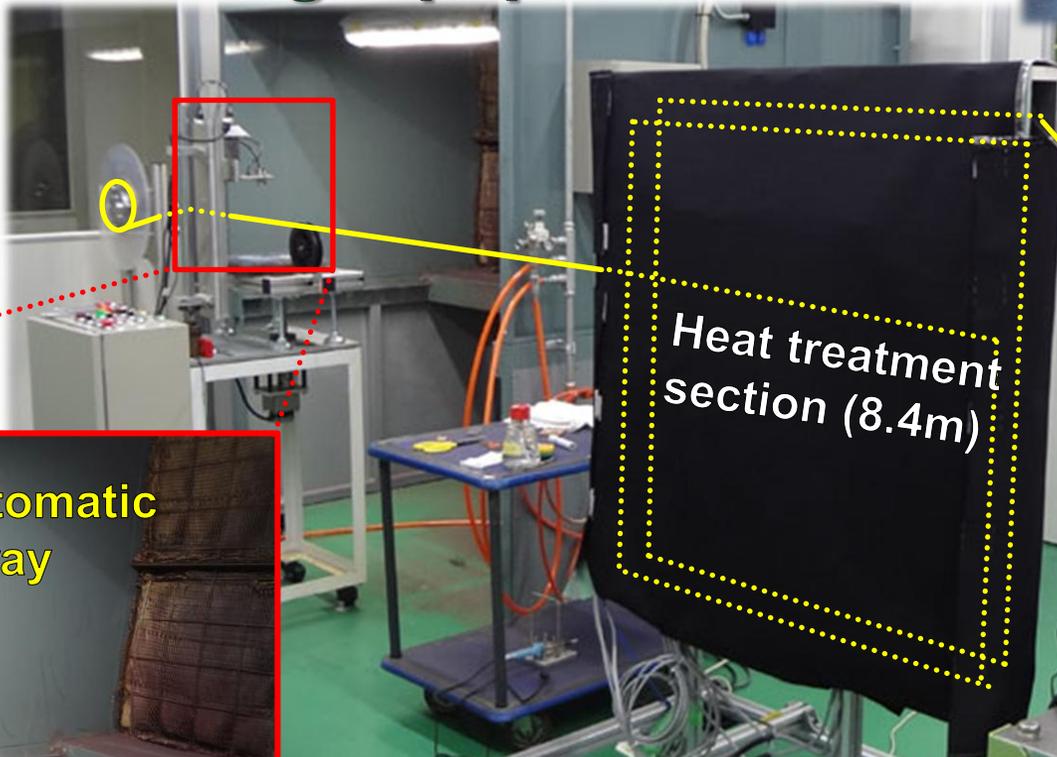
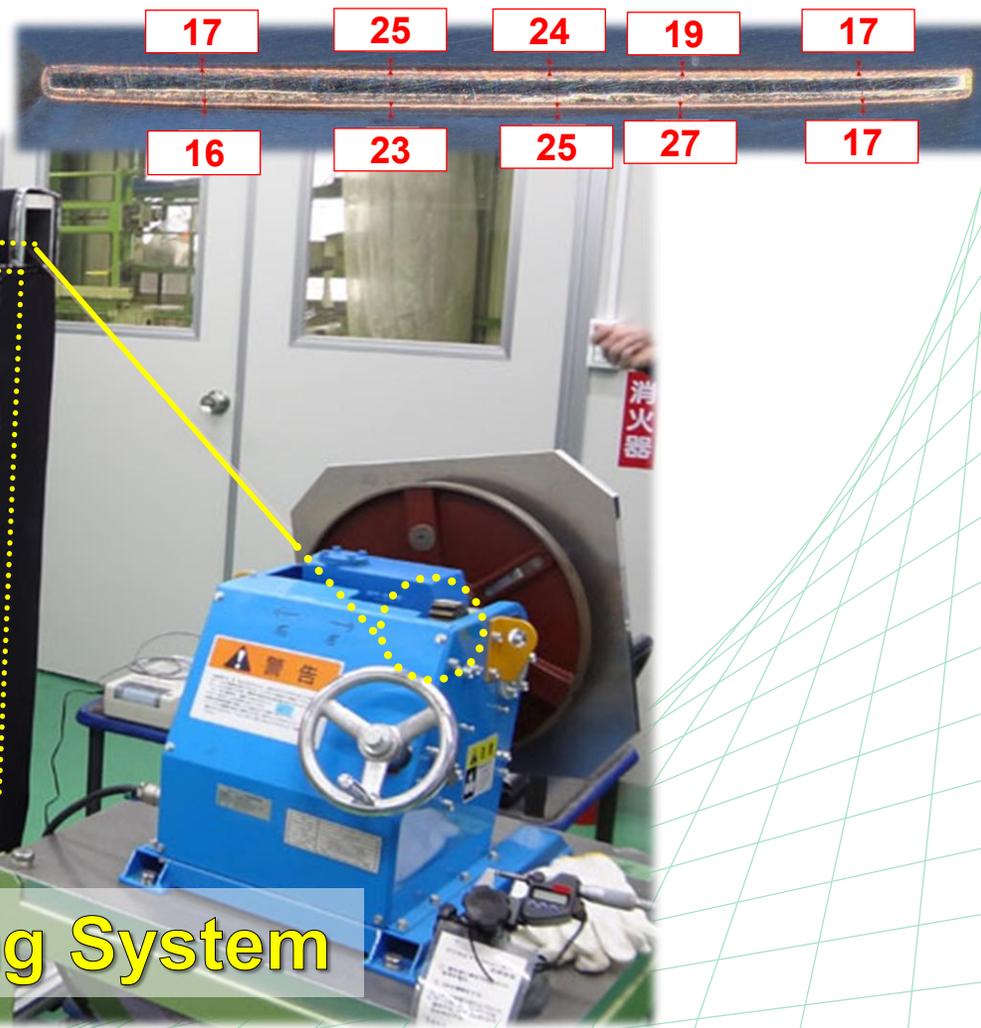
- The withstand voltage is well above 2 kV with a thickness of 30 μm.
- No deterioration of the  $I_c$  of the REBCO due to the coating process was observed.



# Continuous coating on long tapes with reel-to-reel

## Development of automated continuous coating equipment

Cross section of 10 m long trial  
(Unit: mm)

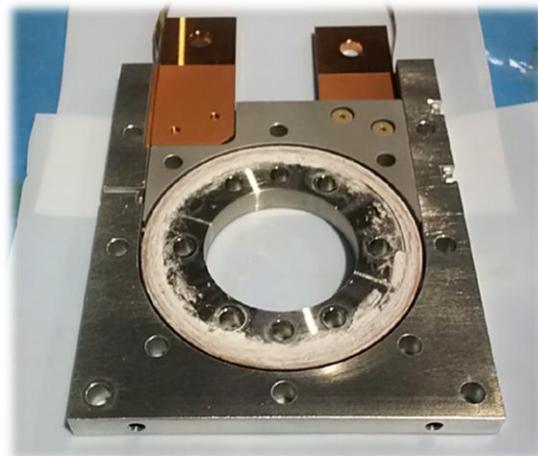


## Reel to Reel Coating System

Succeeded in  $25 \pm 4.7 (\sigma) \mu\text{m}$  thick ceramic coating  
40 m length on both sides of a REBCO tape

# Trail winding of mineral insulated coil

□ Small demonstration double pancake coil was wound using wet winding technique with ceramic adhesives



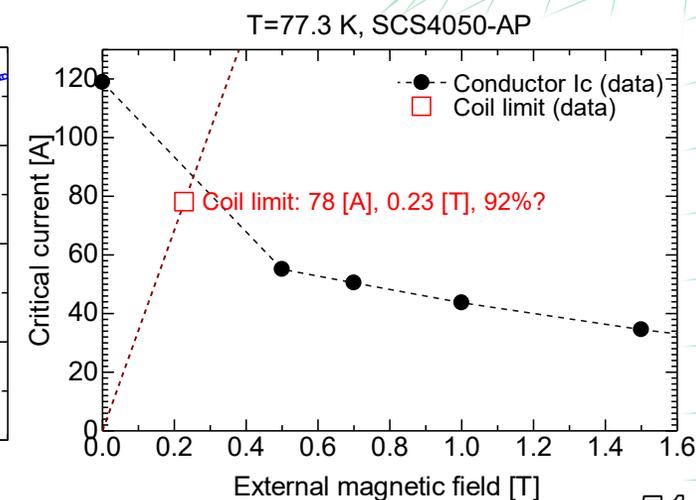
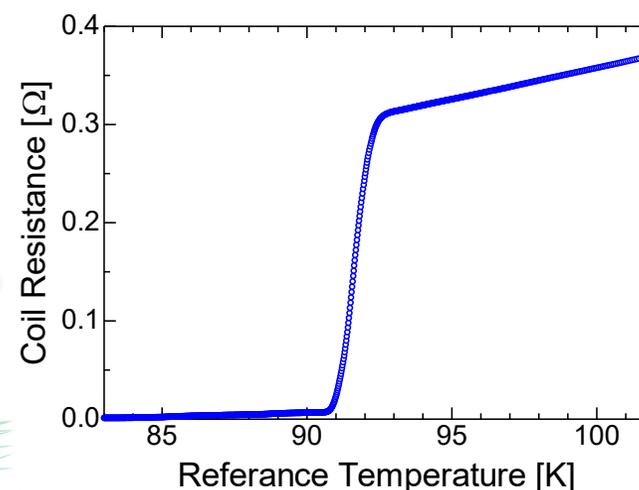
## Aron Ceramic Type C (Toagosei Co., Ltd)

Main Ingredients	Silica (SiO <sub>2</sub> )
Viscosity	70,000 mPa·s
CTE	13 X 10 <sup>-6</sup> (0-600°C)
Heat Treatment	16 h at R.T. → 1 h at 90 °C → 1 h at 150 °C

**Tape: L=14 m, W= 4 mm (Ceramic coated)**

**Coil: ID = 80 mm,  
1st: 26 turns, 2nd: 24 turns**

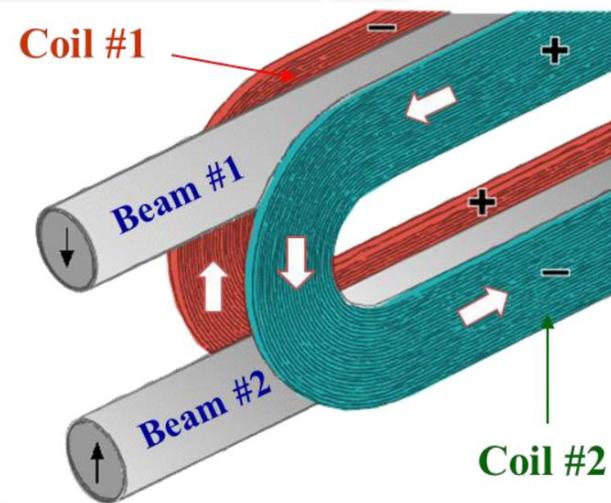
- No significant change in T<sub>C</sub> due to coil manufacturing process
- I<sub>C</sub> decrease is less than 10%



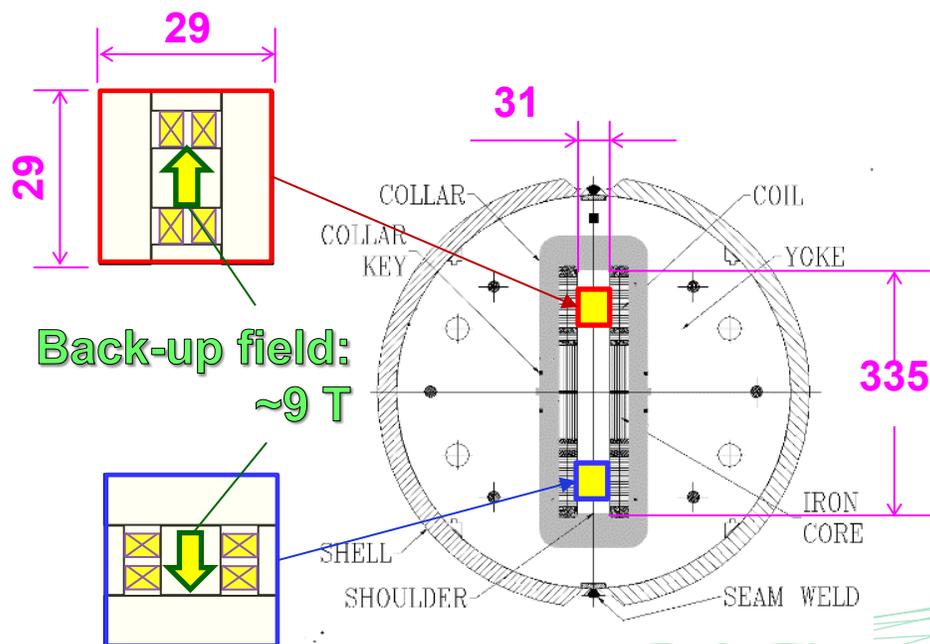
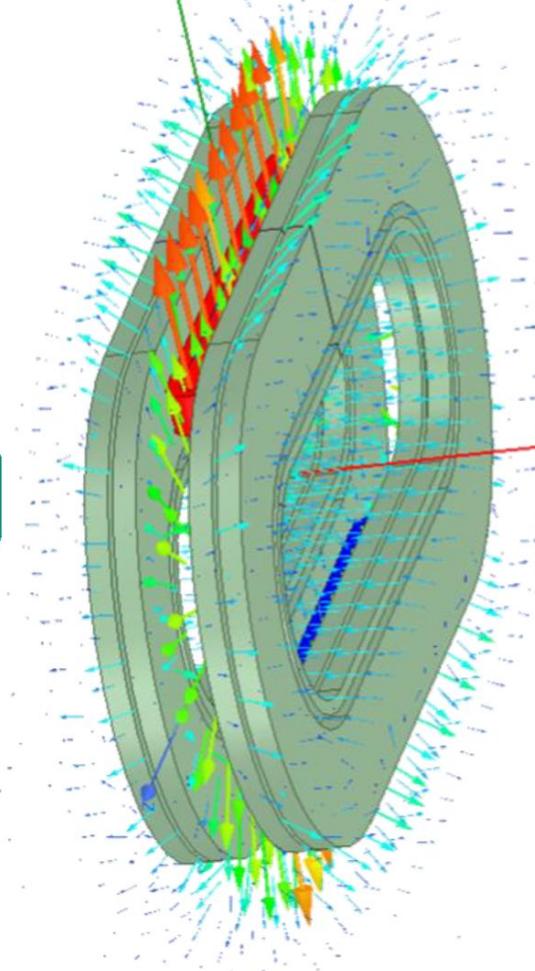
# Cooling and excitation test @BNL

[Common coil type test stand with  $\text{Nb}_3\text{Sn}$  coils]

- Temperature: 4.2 K (LHe bath cooling)
- External magnetic field: ~9 T
- Insert opening: 31 mm x 335 mm



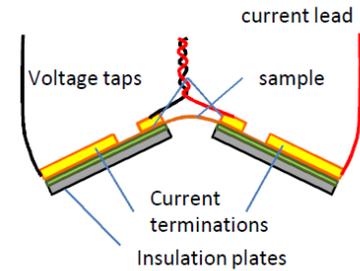
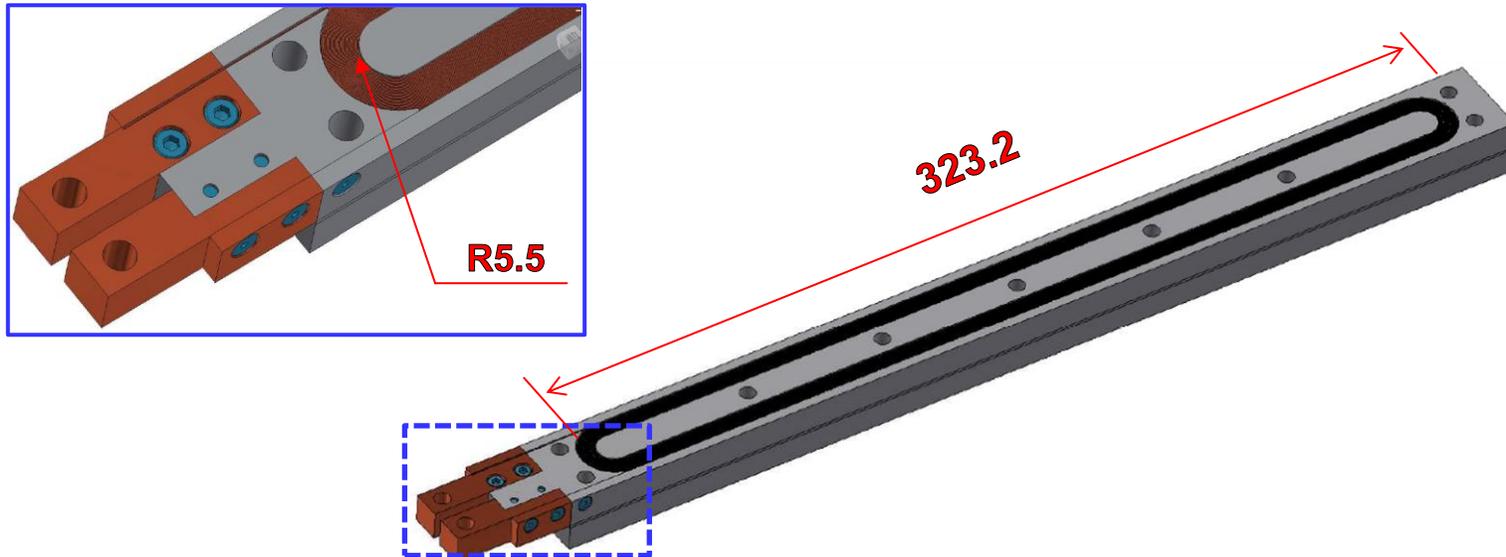
**DCC017**  
(with an insert coil)



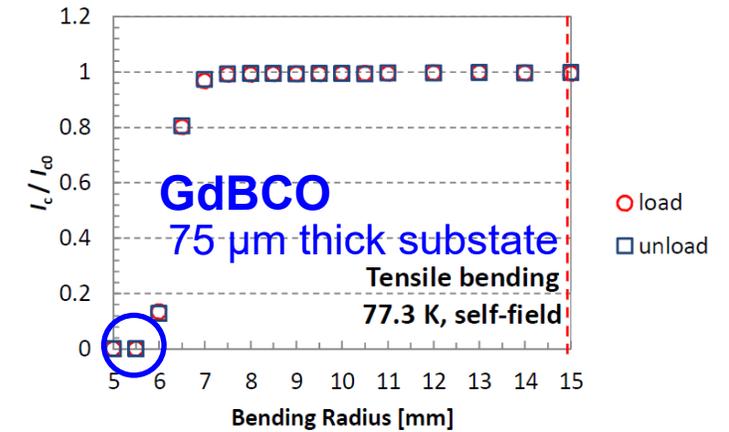
# Insert coil design

## Fujikura FESC-SCH04(40)

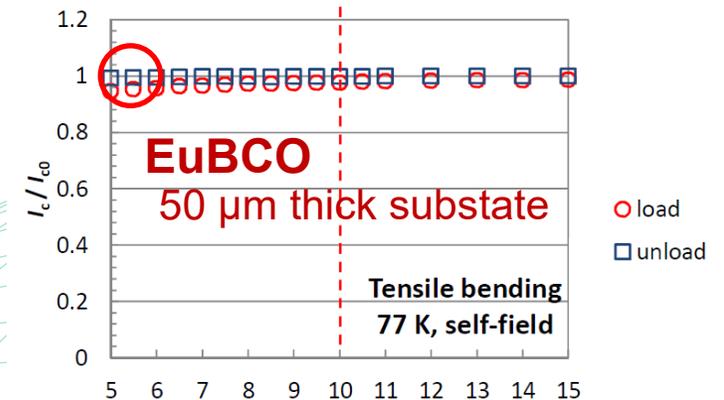
- Type: **EuBCO**,  $I_C$  (77K, S.F.): **201 A**
- Thick. of substate: **50  $\mu\text{m}$** , Thick. of Cu: 40  $\mu\text{m}$  (one side)
- Width (Avg. of meas.): 4.08 mm
- Thickness (Avg. of meas.): **0.16 mm**
- Thickness of coating: **0.025 mm (one side)**
- Thickness per turn: **0.25 mm (Tape + Coating+ Adhesive)**
- Number of turns per layer: **24 turns**



the HTS layer upper side in the figure



the HTS layer upper side in the figure

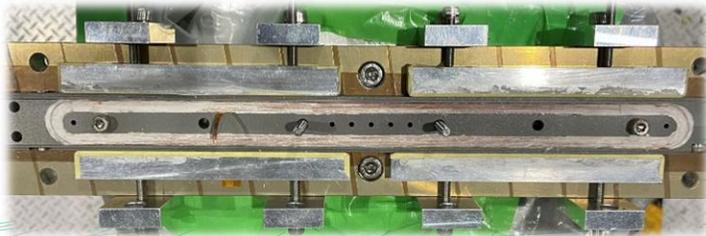
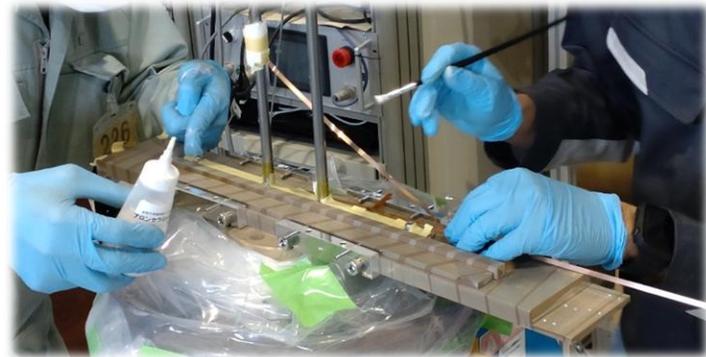
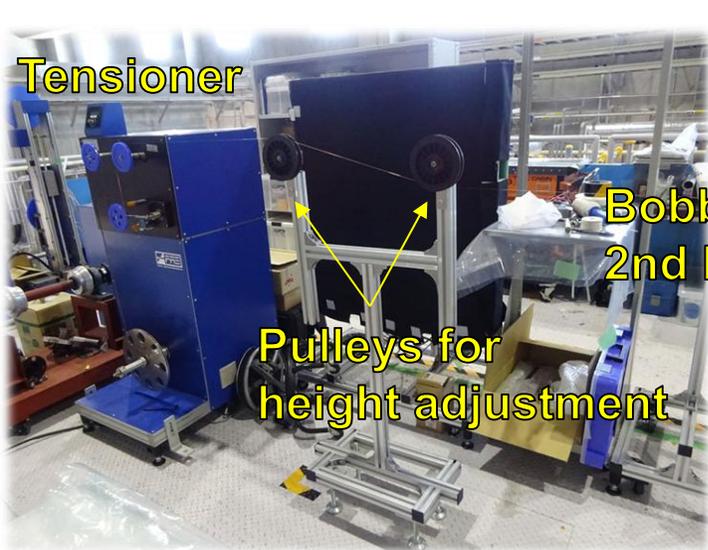


# Insert coil production

□ Double pancake long race track coils were wound using wet winding technique with ceramic adhesives

## Aron Ceramic Type C (Toagosei Co., Ltd)

Main Ingredients	Silica (SiO <sub>2</sub> )
Viscosity	70,000 mPa·s
CTE	13 X 10 <sup>-6</sup> (0-600°C)
Heat Treatment	16 h at R.T. →1 h at 90 °C →1 h at 150 °C



# Present status

## □ Three coils were assembled and they were tested at 77 K and a self-magnetic field before shipping

- Transport current limit of two coils is **100 A**, which is **17% lower** than the expected value (120 A, ~0.15 T).
- Two of the three coils appeared to have some conductor damage during the winding and assembly process.
- The coil without problems (#1) and the coil with relatively minor damage (#2) were transported to BNL.

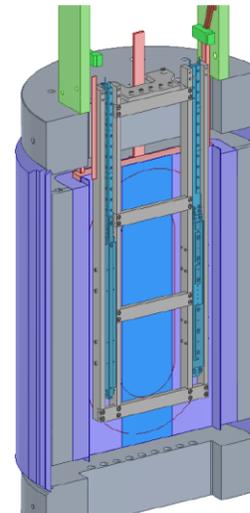
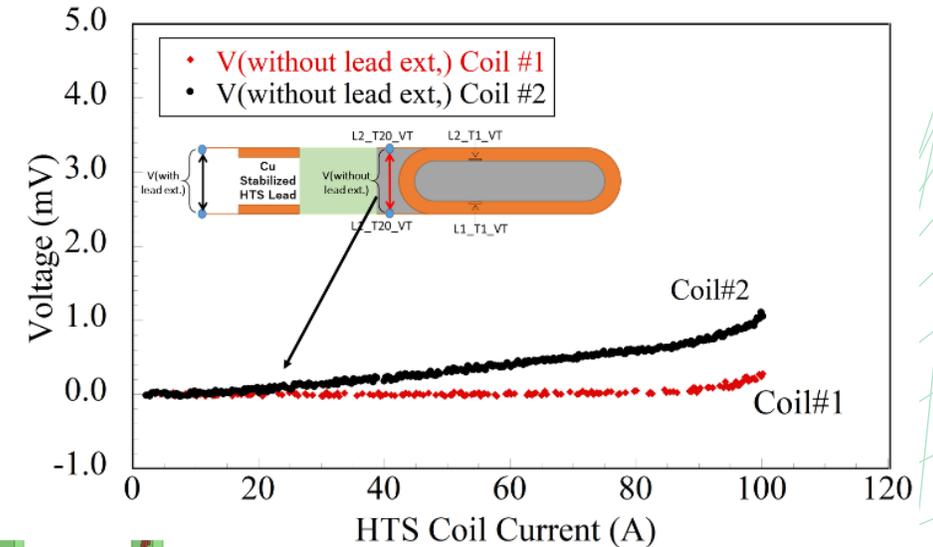
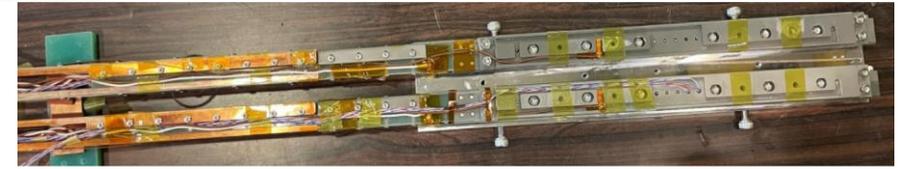


## □ The transported coils were tested at 77 K and a self-magnetic field at BNL

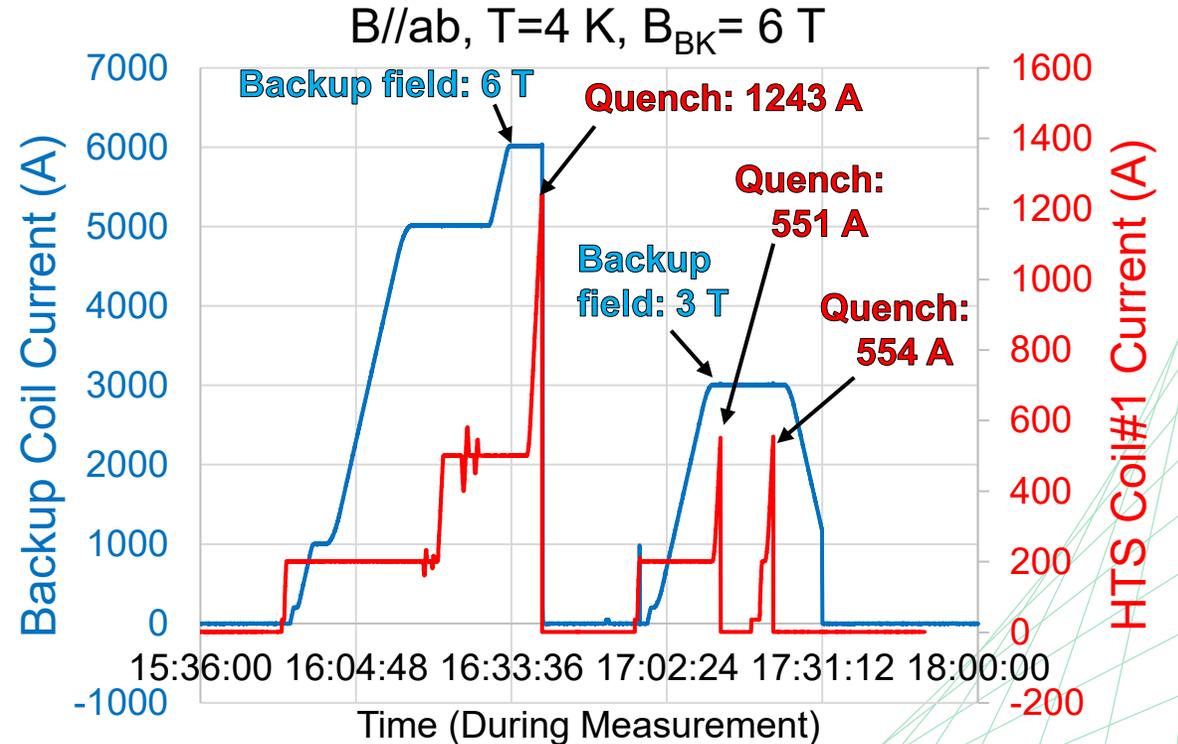
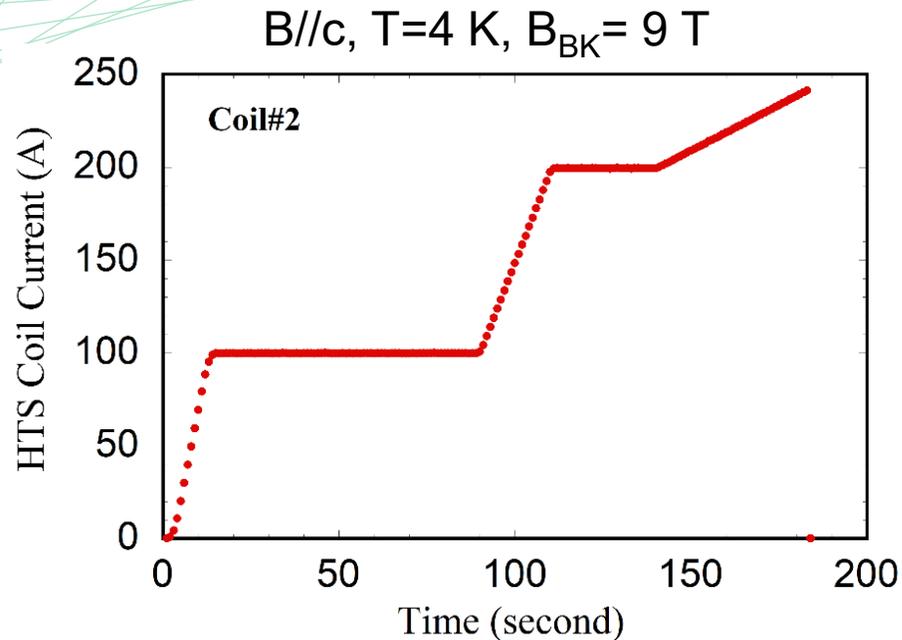
- Results similar to the pre-shipment test at KEK were obtained.

## □ The setup and cooling and excitation test at BNL

- **Pre-test:** current transfer of  $\pm 200$  A to coil#1 and coil#2 cooled to 4.5 K was carried out without backup magnetic field
- **Excitation test:** Stepwise current transfer to HTS coils with backup magnetic field



# Latest results of the excitation test



## Coil # 2 (Damaged, B//c)

- ❑ The quench trigger was activated at 241A due to the voltage increase caused by the normal conductive component

## Coil # 1 (B//ab)

- ❑ 1st quench occurred at **1250A** in an external magnetic field of **6T** (1st layer coil) → ~60% of the predicted value [ $\sim 8.5$ T ( $B_{BK}+S.F.$ ), 17% degradation]
- ❑ 2nd quench: **541A**,  $B_{Ext}=3$ T, 3rd quench: **554 A**,  $B_{Ext}=3$ T (Degraded)

Analysis of experimental data and verification by FEM simulation are currently underway

# Summary

# Summary

- ▶ A lightweight magnet structure based on aluminum is advantageous for enhancing radiation tolerance (Aluminum-stabilized conductors, conduction cooling schemes, etc.).
- ▶ Organic materials are generally sensitive to ionizing radiation, whereas polyimide, cyanate ester, and bismaleimide triazine show relatively high radiation tolerance.
- ▶ In metallic materials, properties degrade due to the accumulation of defects induced by nuclear reactions; however, recovery through annealing is also effective.
- ▶ Neutron irradiation studies of REBCO (HTS) are ongoing, and the contribution of thermal neutrons is becoming increasingly evident..
- ▶ For magnets operating in environments with absorbed doses exceeding 100 MGy, demonstration studies are underway on the application of ceramic coating and ceramic bonding technologies for electrical insulation.

**Thank you**

# Thermal neutron-induced nuclear reaction

## □ Neutron capture reactions dominate at low neutron energies

O. Iwamoto, et al., "Japanese evaluated nuclear data library version 5: **JENDL-5**", *J. Nucl. Sci. Technol.*, 60(1), 1-60 (2023).

Molecular formula: **ReBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>**

### Thermal Neutron Capture Cross Section

$$\sigma_{GdBCO} = 48633 \text{ b}$$

$$\sigma_{EuBCO} = 4560 \text{ b}$$

$$\sigma_{YBCO} = 15 \text{ b}$$

Recoil energy of REBCO atoms  
by (n,  $\gamma$ ) reactions: **~100-300 eV**

>Displacement Threshold Energy:  
**~10-50 eV**

Neutron capture reactions are  
expected to generate defect in REBCO

Neutron irradiation has been performed on three rare-earth  
samples both with and without Cd-shielding

Gd	Nat. Abun.	0.0253 eV	
		(n, $\gamma$ ) [b]	Effective [b]
Gd-152	0.002	735	1
Gd-154	0.022	86	2
Gd-155	0.148	60740	8990
Gd-156	0.205	2	0
Gd-157	0.157	253200	39626
Gd-158	0.248	2	1
Gd-160	0.219	1	0
		<b>Total [b]</b>	<b>48620</b>

Ba	Nat. Abun.	0.0253 eV	
		(n, $\gamma$ ) [b]	Effective [b]
Ba-130	0.001	7.995	0.0
Ba-132	0.001	8.075	0.0
Ba-134	0.024	1.501	0.0
Ba-135	0.066	5.797	0.4
Ba-136	0.079	0.680	0.1
Ba-137	0.112	3.601	0.4
Ba-138	0.717	0.404	0.3
		<b>Total [b]</b>	<b>1.2</b>

Eu	Nat. Abun.	0.0253 eV	
		(n, $\gamma$ ) [b]	Effective [b]
Eu-151	0.478	9169	4383
Eu-153	0.522	313	163
		<b>Total [b]</b>	<b>4546</b>

Y	Nat. Abun.	0.0253 eV	
		(n, $\gamma$ ) [b]	Effective [b]
Y-89	1.000	1.284	1.3
		<b>Total [b]</b>	<b>1.3</b>

Cu	Nat. Abun.	0.0253 eV	
		(n, $\gamma$ ) [b]	Effective [b]
Cu-63	0.6915	4.506	3.1
Cu-65	0.3085	2.128	0.7
		<b>Total [b]</b>	<b>3.8</b>

O	Nat. Abun.	0.0253 eV	
		(n, $\gamma$ ) [ $\mu$ b]	Effective [b]
O-16	0.9976	189.9	0
O-17	0.0003	670.0	0
O-18	0.0020	140.8	0
		<b>Total [b]</b>	<b>0</b>