RADSUM 2025

Irradiation Studies on HTS Materials in Japan: Results and Future Directions

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High Energy Accelerator Research Organization (KEK), Tsukuba

J-PARC

KEK

Contents

1. Introduction
   - J-PARC Overview
   - MLF 2nd Target Station
   - REBCO Coted Conductors
2. Present Status of Neutron Irradiation
3. Latest results of PIE
   - Commissioning of Superconducting Evaluation System
   - Superconducting Transition Temperature
   - Degradation of Critical Current
4. Summary

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J-PARC Overview

Purpose of J-PARC:

Research for the creation and structure of our universe by investigating matters at all levels, from quarks to atoms.

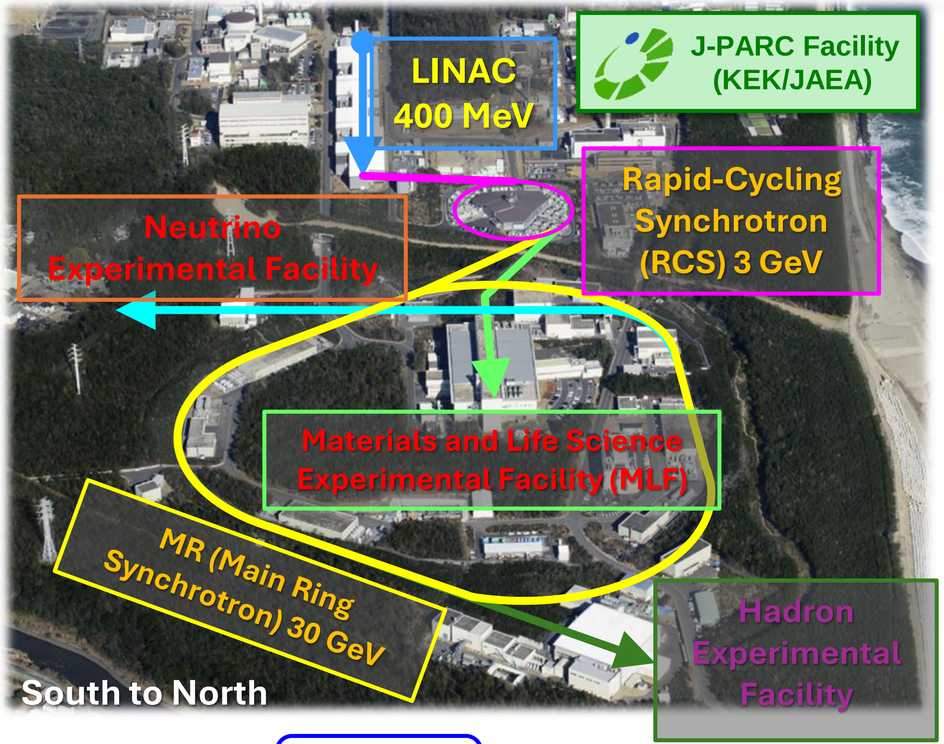
MW-class High Power Proton Driver

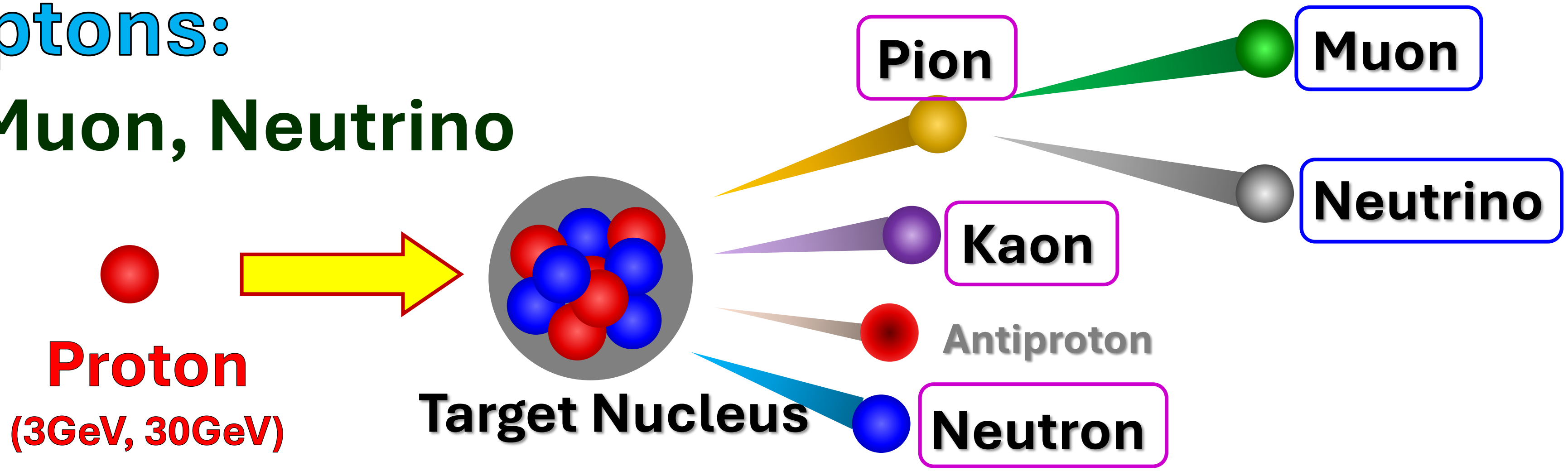
→ **Hadrons:**

Neutron, Pion, Kaon

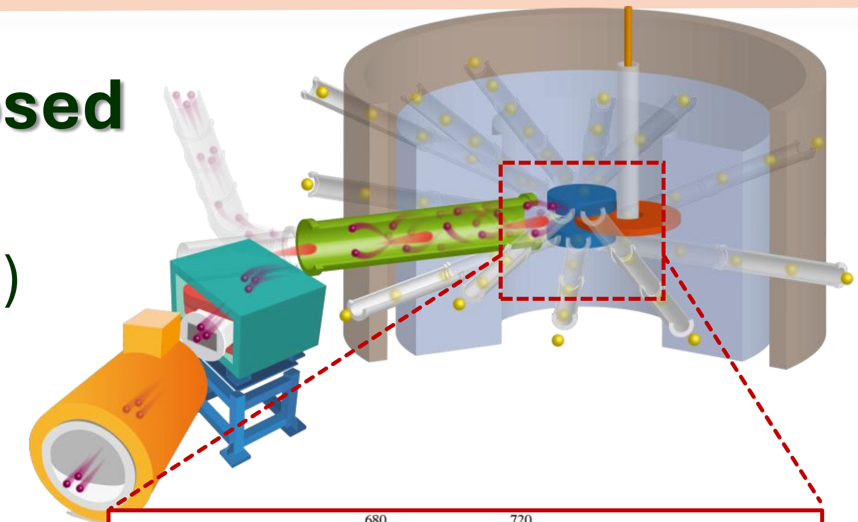
→ **Leptons:**

Muon, Neutrino





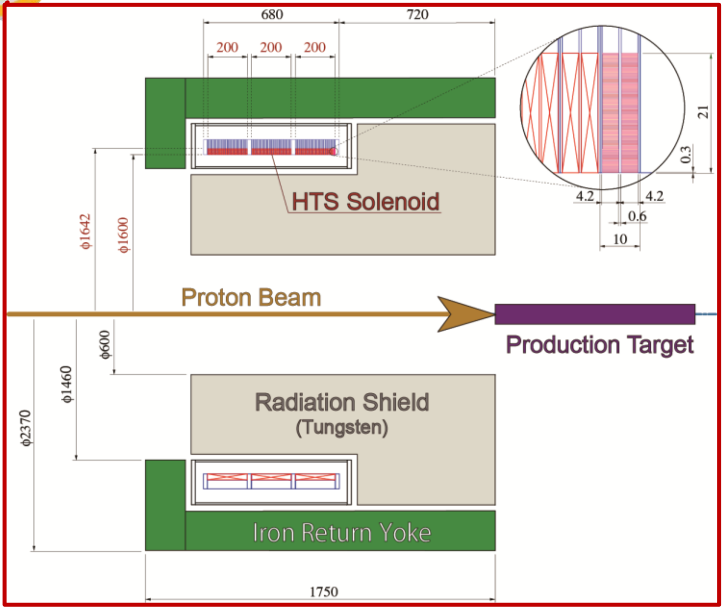
MLF 2nd Target Station



Construction of MLF 2nd Target Station is proposed

TS2-Pion Capture Solenoid (10 years operation)

- **Heat Deposit: ~ 450 W**
- **Neutron flux: 7.7 x 10^{21} n/m^2**
- **Absorbed Dose: > 100 MGy**



Conventional NbTi Magnet

- **Small temperature margin**

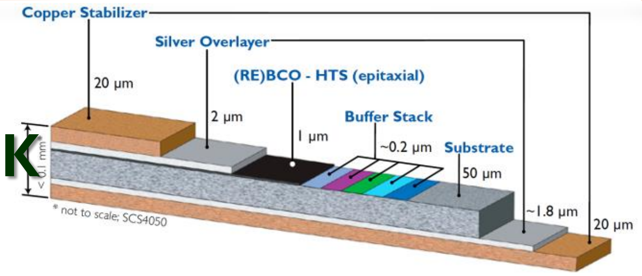
→ T = ~ 5 K with a heat load of 1 kW

- **Organic Material for Insulation**

→ Degradation of the machine strength **(Design limit: ~10 MGy)**

Requirement of High Radiation Resistant SC Magnet

Rare-Earth Barium Copper Oxide (Re: Y, Gd, Eu, Sm)

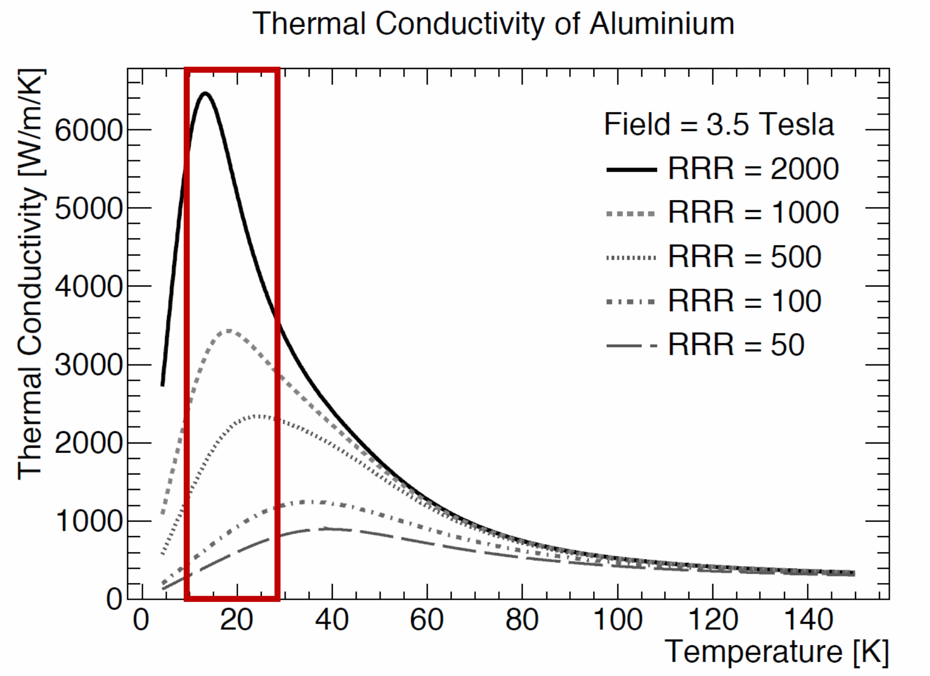


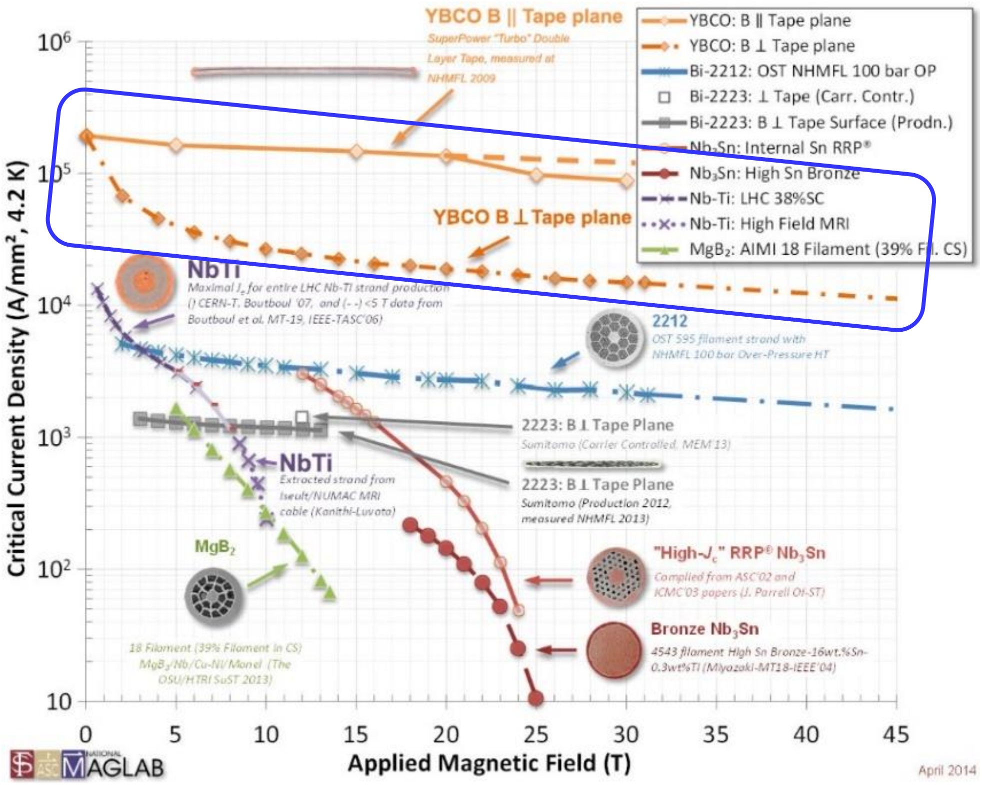
<u>High temperature margin</u> (T_C=93 K)

- Conduction cooling operation in the temperature range of 20 K

<u>High magnetic field tolerance of Ic</u>

- Potential for 20T class high field magnet





Radiation Resistance of REBCO is an important issue

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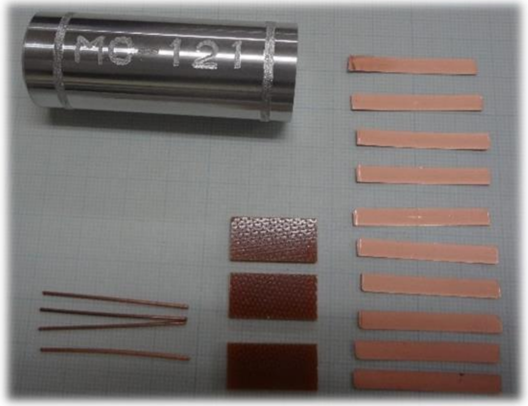
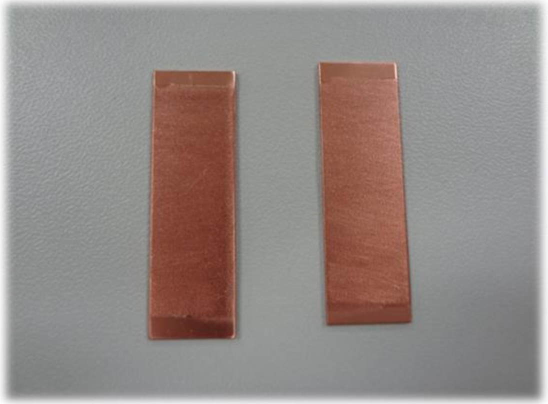
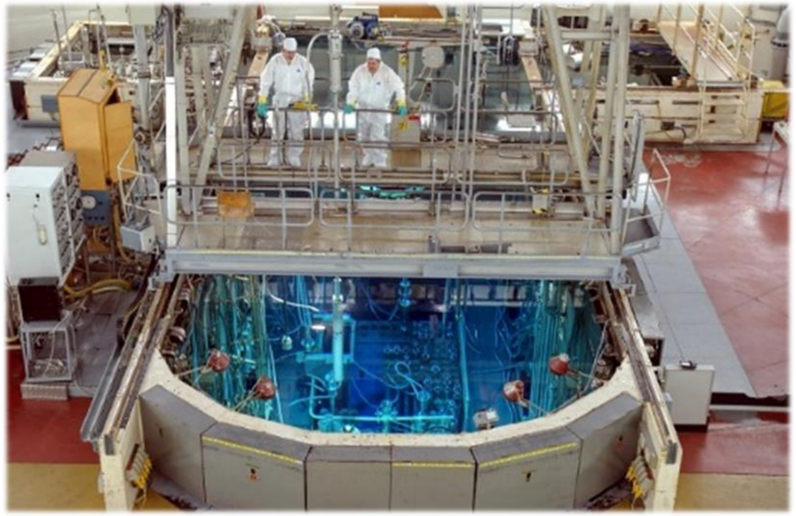
Neutron Irradiation @ BR2

- **Fluence range:** $0.1\sim10 \times 10^{22}$ n/m^2, (E_n>1 MeV, T < 100° C)
  - Target for HTS SC magnet for MLF 2nd TS: > 1×10^{22} (n/m^2) w/ fast neutron
- **Samples:**
  - ***REBCO tape (GdBCO, EuBCO)***
  - MgB_2 wire
  - GFRP (BT resin w/ S-2 glass fiber)
  - Electrical insulation with ceramic coating





BR2 @Belgian nuclear research center



Neutron Irradiation @JRR-3

Irradiation at the JRR-3 (Japan Research Reactor No. 3) in FY2023

Hydraulic irradiation facility

- Thermal neutron flux ：1.0×10^{18} n/m^2/s
- Fast neutron flux ：1.5×10^{16} n/m^2/s
- Irradiation temperature ：< 100℃
- fluence：**~1.47×10^{21} n/m^2**
- Irradiation with and without shield for thermal neutron suppression

Samples for irradiation: GdBCO, YBCO, EuBCO

Post Irradiation Examination is undergoing at IMR, Oarai

BR-2

ID	Sample Type	N	Cd Shield	Fluence [n/m^2]	Loading for Irradiation	Irradiation Period	Radioactivity [Bq/sample] (2021.05.12)	Dose Equivalent Rate [mSv/h/sample]	PIE	Remarks
MC121	SCS4050-AP (GdBCO)	10	No	8.37E+22 (E>1MeV) 1.71E+23 (E>0.1MeV)	Nov. 14, 2016	2017.03.14-04.11 (28.2d)	5.204E+08	1.370 (D15cm, 2021.05.12)	-	
MC122	SCS4050-AP (GdBCO)	10	No	1.80E+22 (E>1MeV) 4.11E+22 (E>0.1MeV)			1.119E+08	0.295 (D15cm, 2021.05.12)	**Yes**	Vanishment of superconductivity
MC131	SCS4050-AP (GdBCO)	5	No	7.06E+22 (E>1MeV) 1.97E+23 (E>0.1MeV)	Feb. 09, 2018	2018.04.24-05.25 (28.2d)	5.682E+08	1.495 (D15cm, 2021.05.12)	-	
	FYSC-SCH04 (GdBCO)	5					7.525E+08	1.980 (D15cm, 2021.05.12)	-	
MC132	SCS4050-AP (GdBCO)	5	No	2.53E+22 (E>1MeV) 7.92E+22 (E>0.1MeV)			2.039E+08	0.466 (D15cm, 2021.05.12)	**Yes**	Vanishment of superconductivity
	FYSC-SCH04 (GdBCO)	5					2.699E+08	0.612 (D15cm, 2021.05.12)	**Yes**	Vanishment of superconductivity
MC137	SCS4050-AP (GdBCO)	5	No	1.85E+22 (E>1MeV) 4.12E+22 (E>0.1MeV)	Jan. 10, 2019	2019.07.03-08.06 (34.1d)		1.3 (D50cm, 2021.01.27)	To be done	
	FYSC-SCH04 (GdBCO)	5								
LIBERTY 12	SCS4050-AP (GdBCO)	5	No	3.40E+21 (E>1MeV) 8.23E+21 (E>0.1MeV)	Nov. 26, 2018	2019.11.06-11.06 (10.83h)		0.350 (D20cm, 2021.01.12)	**Done! (June. 2021)**	**Degraded**
	FYSC-SCH04 (GdBCO)	5								

JRR-3

-	SCS2030-HM	3	Yes	1.47E+21 (E>0.1MeV)					Nov 2024-Jan2025	**Irradiated**
	FYSC-SCH04 (GdBCO)	3								
	FESC-SCH04 (EuBCO)	3								
-	SCS4050-AP	3	No	1.47E+21 (E>0.1MeV)					Nov 2024-Jan2025	**Irradiated**
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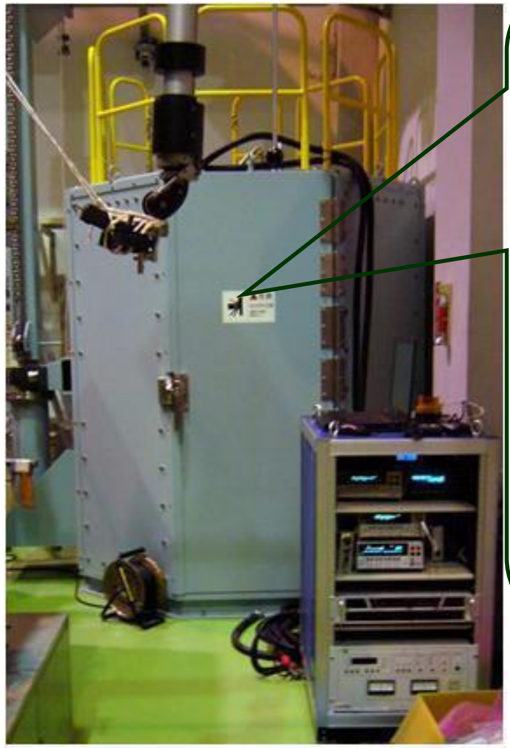
Superconducting Properties Evaluation System

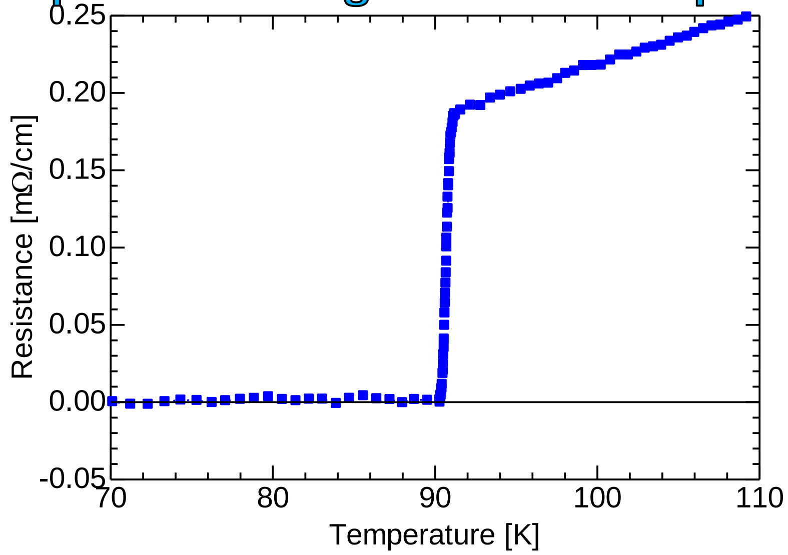
PIE at IMR Oarai Center

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

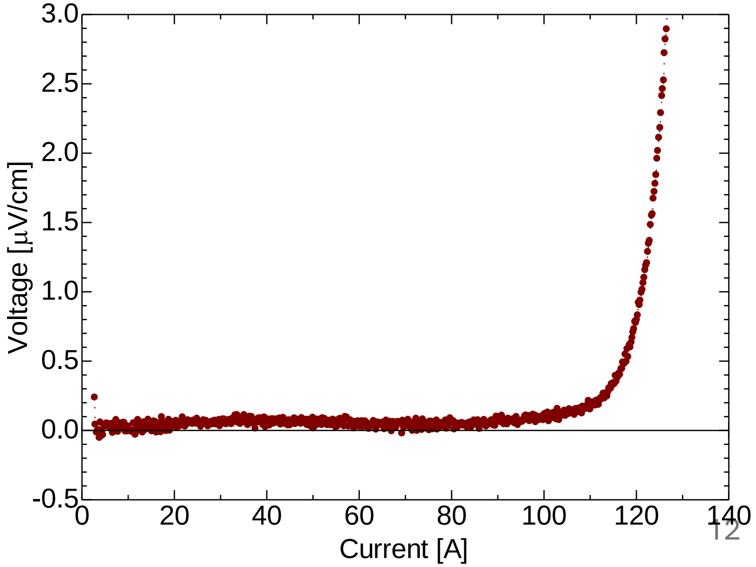
Temperature Range	4 ~ 80 K
Max. Current	500 A
Max. External Field	15.5 T



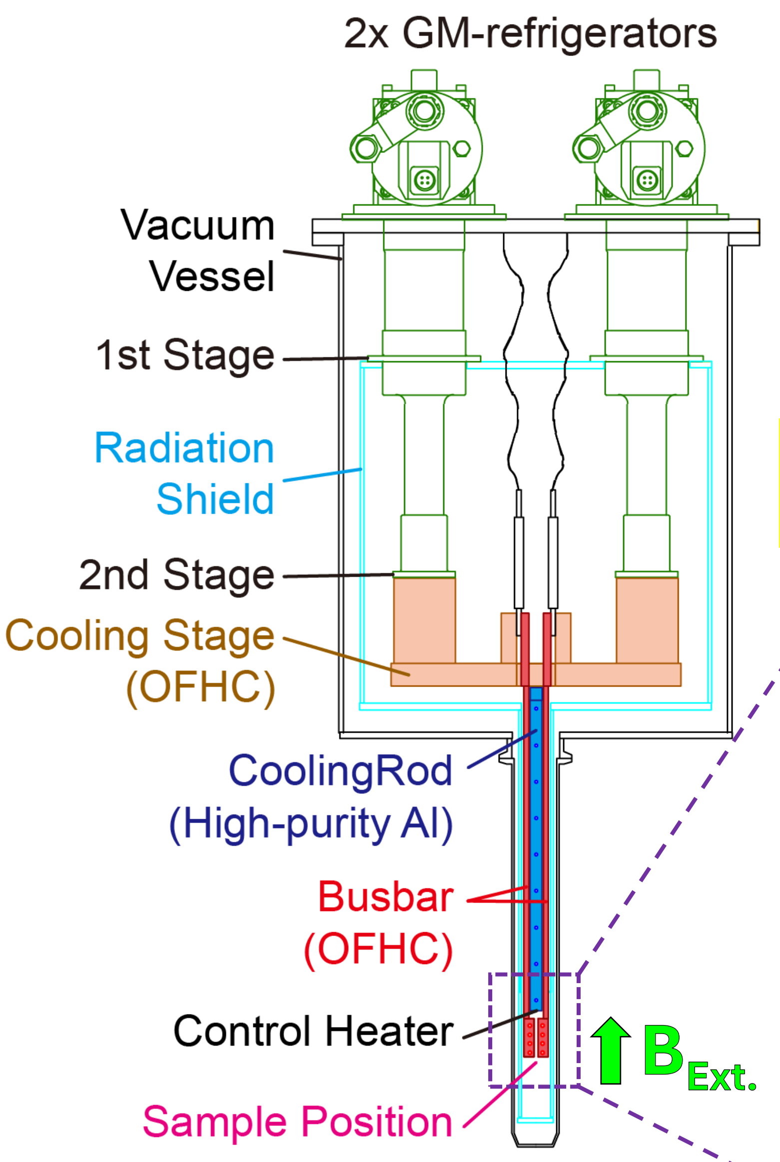
Superconducting Transition Temperature



Critical Current



Variable Temperature Insert (VTI)



Conduction Cooling

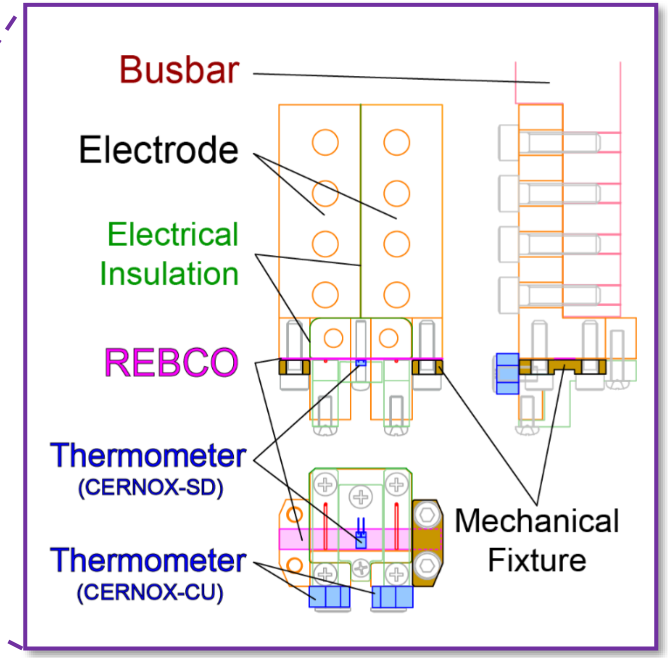
GM Refrigerators → Cooling Rod (Al) → Busbars (Cu) → Electrodes (Cu) → REBCO Sample

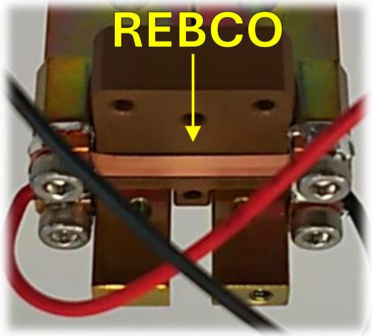
Easy and Quick handling to minimalize radiation expose

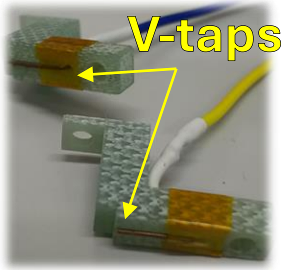
- Mechanical contact **w/o soldering**

Temperature rise due to ohmic heat is non-negligible

For higher I_C around 350A, temperature rise becomes larger (~15 K or more) for 20K measurement

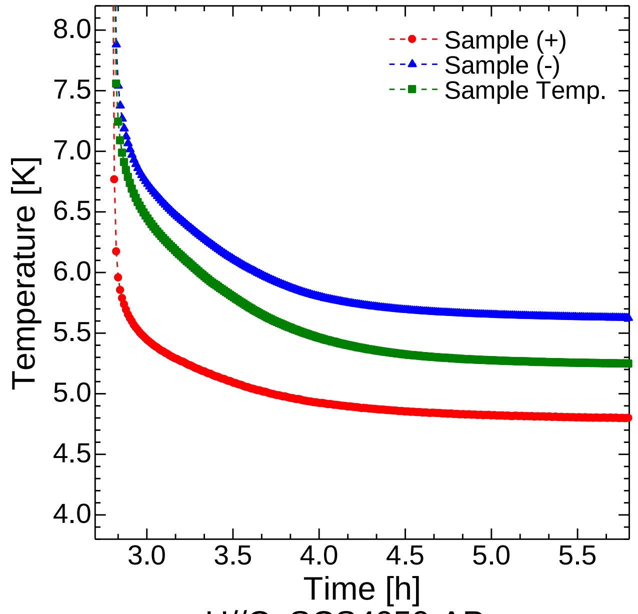




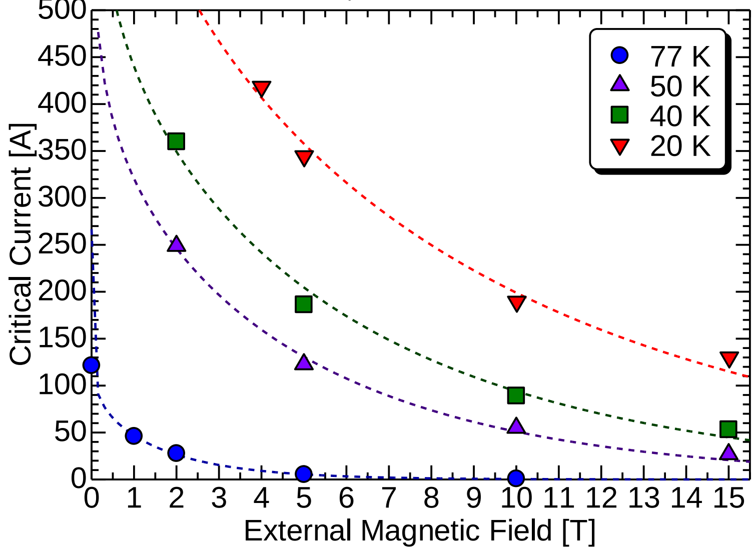


Commissioning with Mechanically Mounted Sample Holder

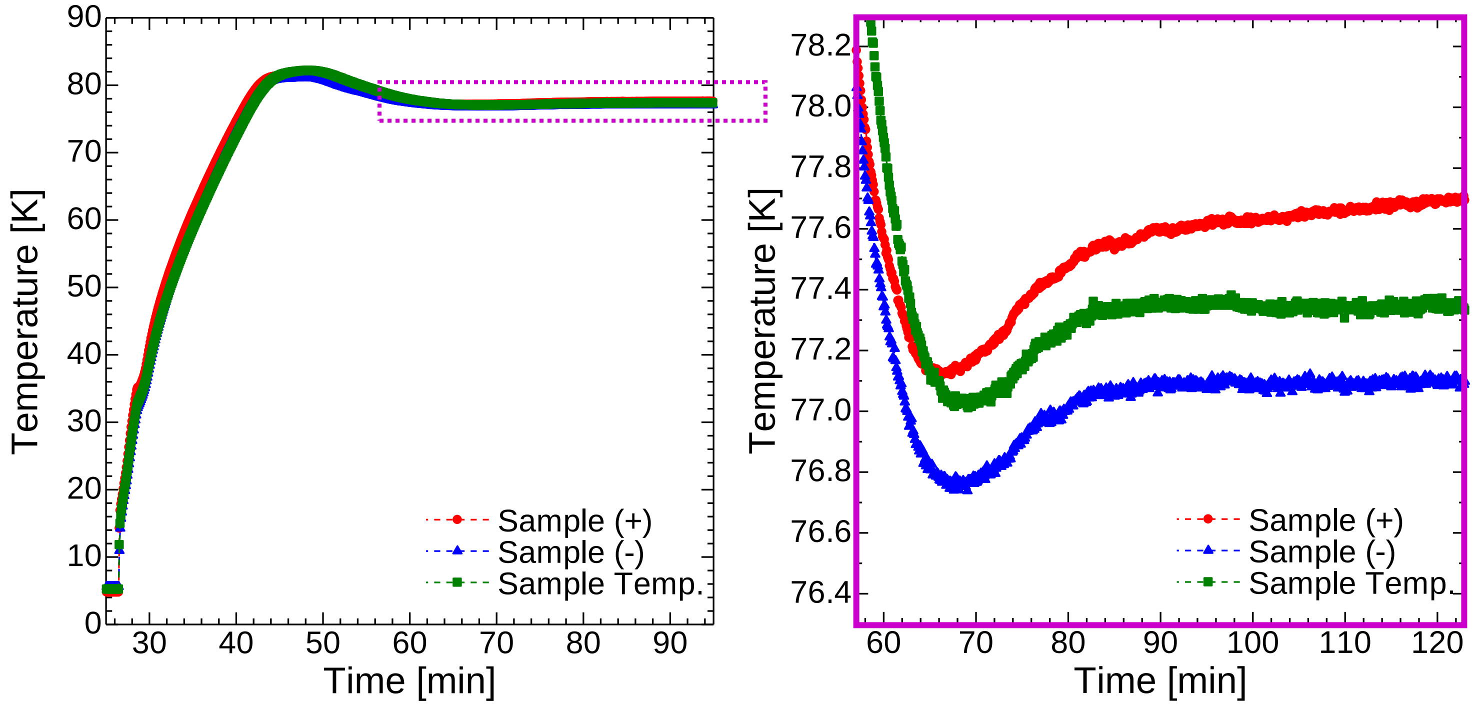
Reached Temperature



H//C, SCS4050-AP



Temperature control at 77.3 K



Confirmed Items

- **Temperature control of sample holder up to 77 K**
- **Critical current measurement of HTS sample up to 77 K**
- **We may suffer from excluding the temperature effect to determine Ic**

BR-2

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LIBERTY 12	SCS4050-AP (GdBCO)	5	No	3.40E+21 (E>1MeV) 8.23E+21 (E>0.1MeV)	Nov. 26, 2018	2019.11.06-11.06 (10.83h)		0.350 (D20cm, 2021.01.12)	**Done! (June. 2021)**	**Degraded**
	FYSC-SCH04 (GdBCO)	5								

JRR-3

ID	Sample Type	N	Cd Shield	Fluence [n/m^2]	Loading for Irradiation	Irradiation Period	Radioactivity [Bq/sample] (2021.05.12)	Dose Equivalent Rate [mSv/h/sample]	PIE	Remarks
-	SCS2030-HM (YBCO+BZO)	3	Yes	1.47×10^{21} (E>0.1MeV)	Jan. 25, 2024	2024.01.03-01.04 (24h)			Nov 2024-Jan2025	**Irradiated**
	FYSC-SCH04 (GdBCO)	3								
	FESC-SCH04 (EuBCO)	3								
-	SCS4050-HM (YBCO+BZO)	3	No	1.47×10^{21} (E>0.1MeV)					Nov 2024-Jan2025	**Irradiated**
	FYSC-SCH04 (GdBCO)	3								
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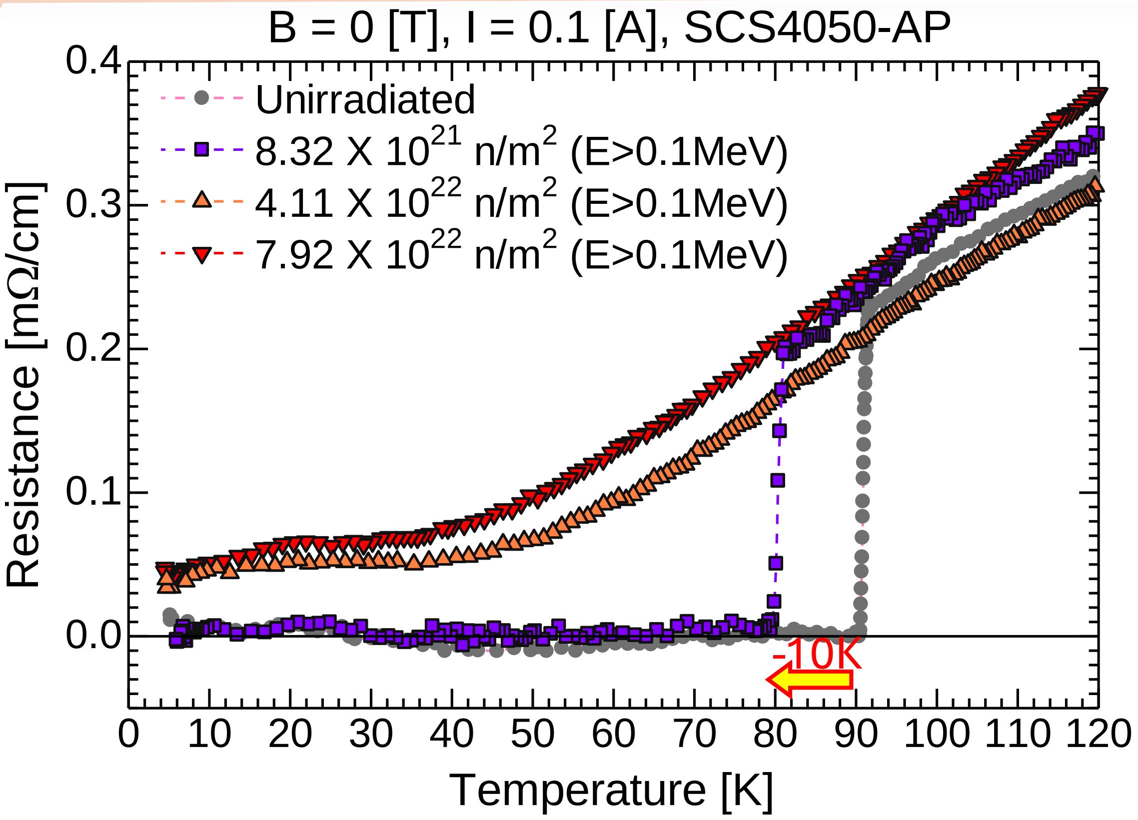
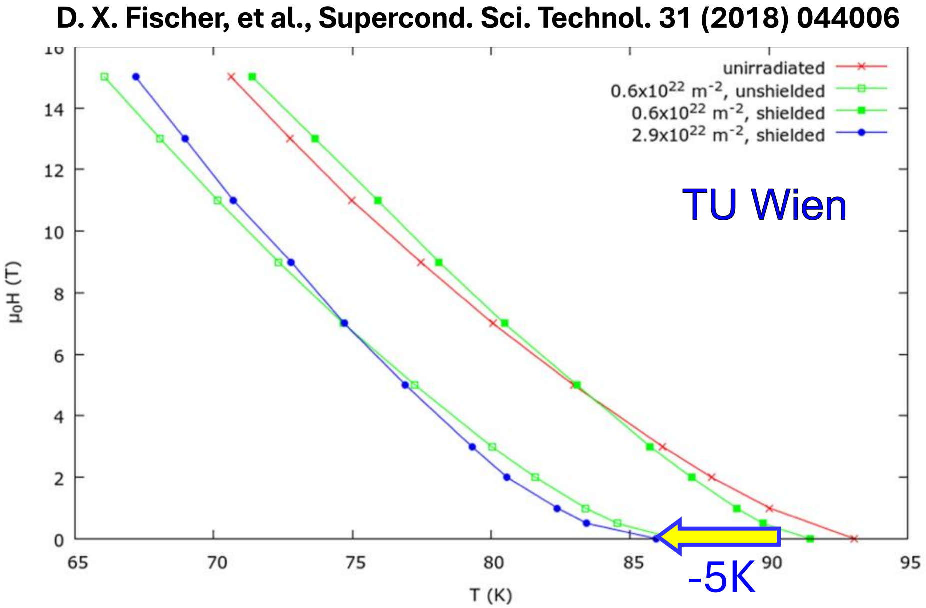
PIE (Superconducting Transition Temperature)





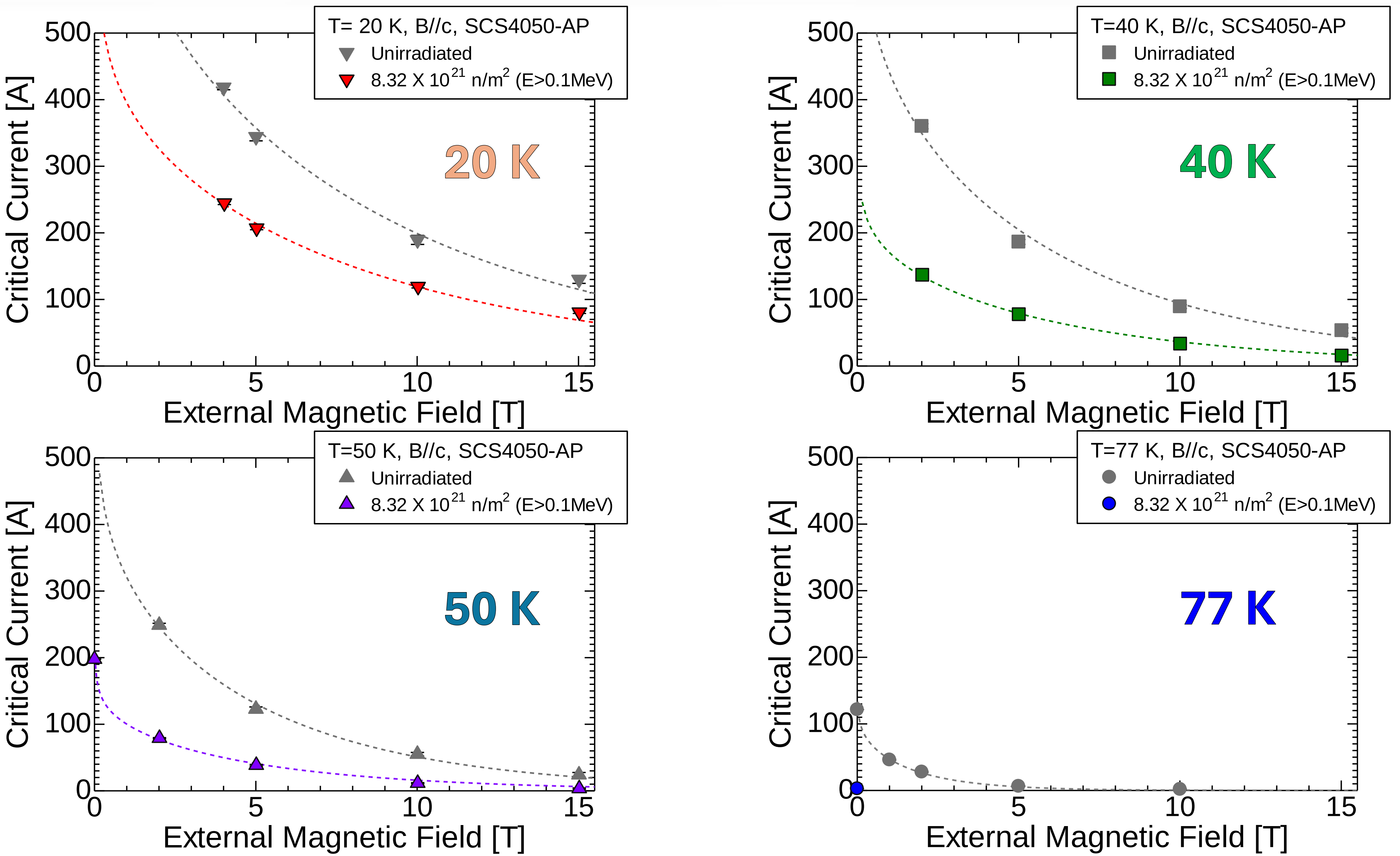
- **No significant degradation in shielded HTS tape at 6 x 10^{21} n/m^2 (E>0.1MeV).**
- **Reduction of Tc by 5 K in unshielded sample.**
- **Reduction of Tc by 5 K in shielded sample at 2.9 x 10^{22} n/m^2 (E>0.1MeV)..**

Superconductivity vanished in GdBCO tapes even at 4.11 x 10^{22} n/m^2.

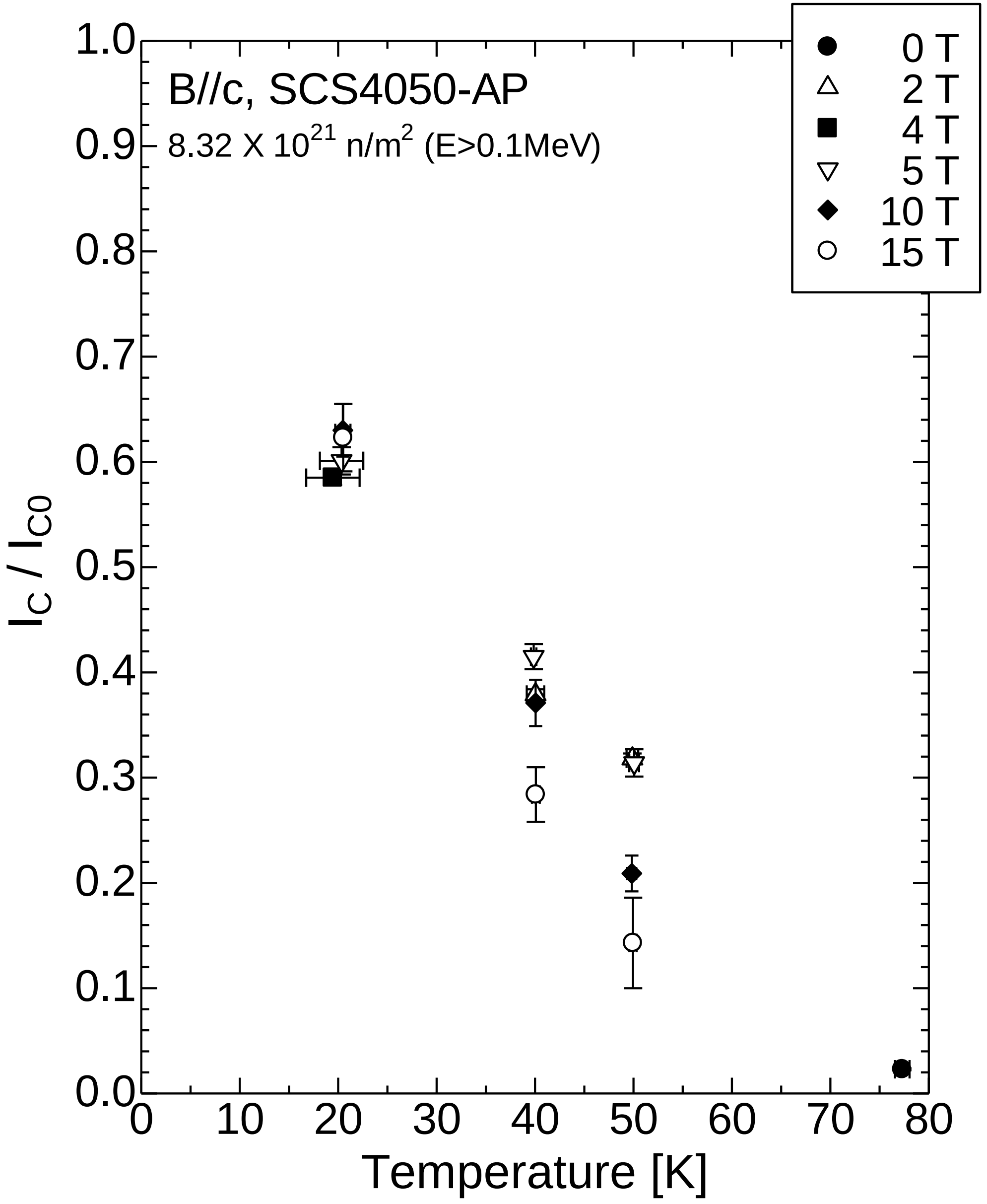
Tc reduction of 10 K at 8.32 x 10^{21} n/m^2.

Our results are similar to the reference data.

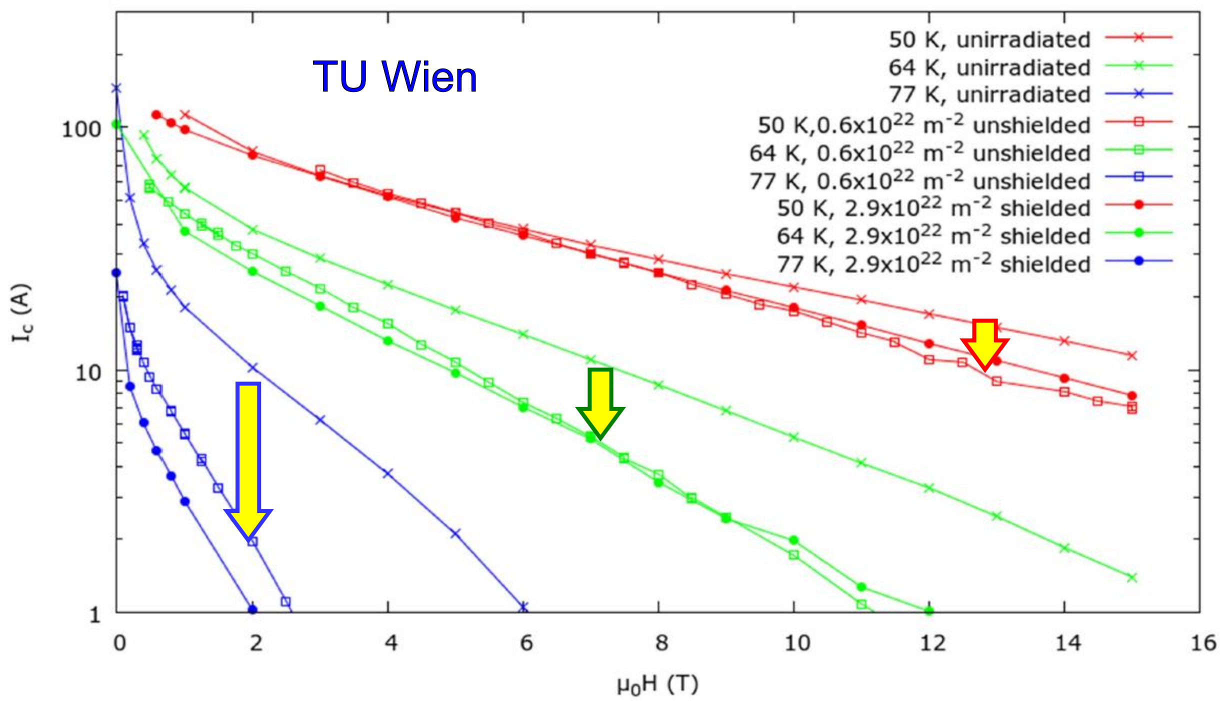
PIE (I_c -B curve): I_c criteria: 10 μV/cm, V-tap distance: 1.4 cm



Degradation Rate (I_c / I_{c0})



D. X. Fischer, et al., Supercond. Sci. Technol. 31 (2018) 044006



- **Degradation rate is not constant**
- **Relatively small effect in the low temperature range. Ic/Ico➔ (0.6@20K ⇔ 0.02@77K)**
- Our results are similar to the reference data.

BR-2

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ID	Sample Type	N	Cd Shield	Fluence [n/m^2]	Loading for Irradiation	Irradiation Period	Radioactivity	Dose Equivalent Rate	PIE	Remarks
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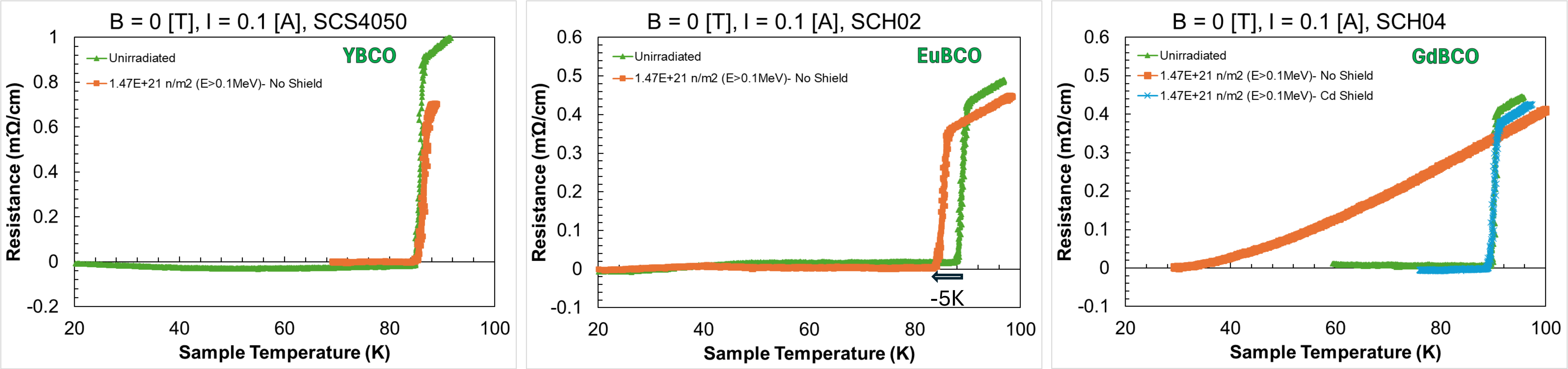
	FYSC-SCH04 (GdBCO)	3	Yes	1.47×10^{21} (E>0.1MeV)						
	FESC-SCH04 (EuBCO)	3								
-	SCS4050-AP (YBCO+BZO)	3	No	1.47×10^{21} (E>0.1MeV)					Nov 2024-Jan2025	**Irradiated**
	FYSC-SCH04 (GdBCO)	3								
	FESC-SCH04 (EuBCO)	3								

PIE (Superconducting Transition Temperature)

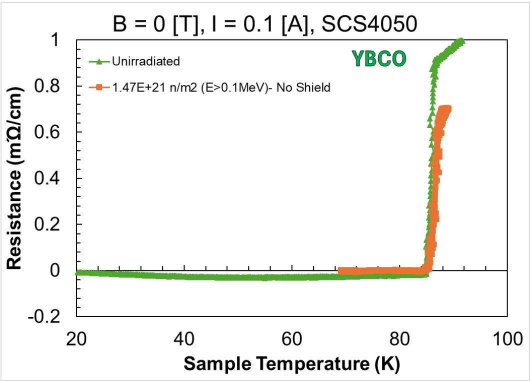


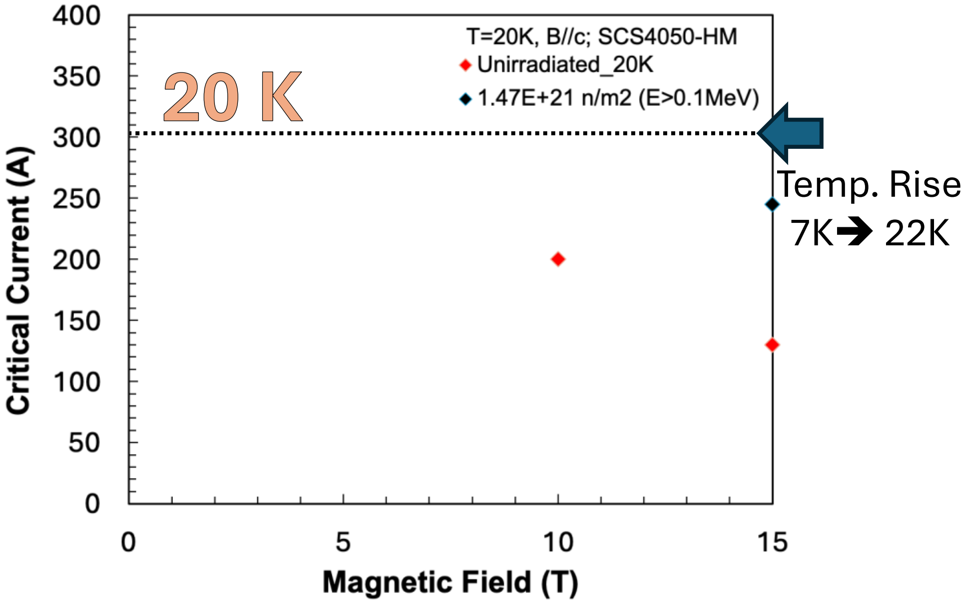
No reduction in T_c in YBCO at 1.47 x 10^{21} n/m^2. (No Cd Shield)

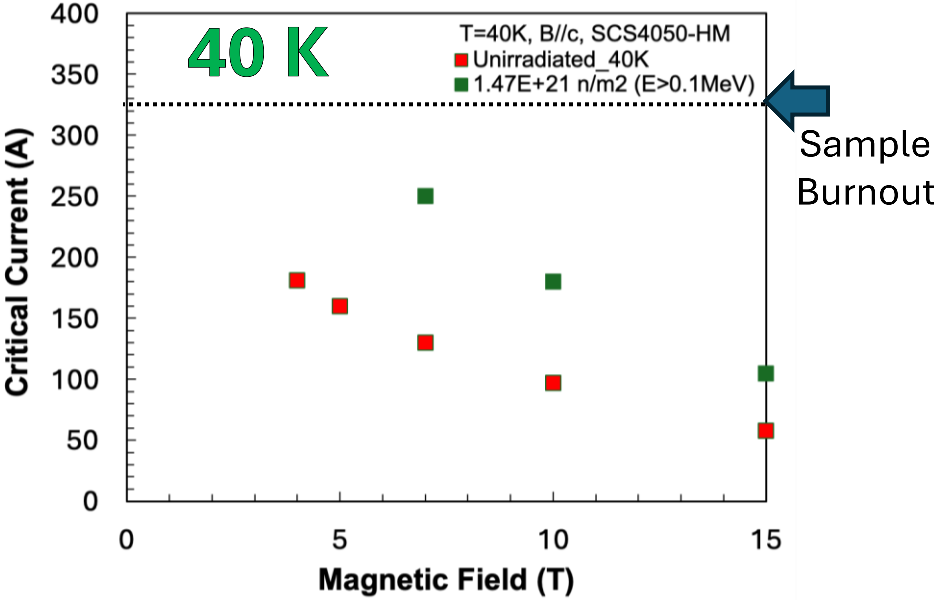
Reduction in T_c by 5K in EuBCO at 1.47 x 10^{21} n/m^2. (No Cd Shield)

Reduction in T_c by 60K in GdBCO tapes even at 1.47 x 10^{21} n/ m^2. (No Cd Shield)
No Reduction in T_c in GdBCO tapes even at 1.47 x 10^{21} n/ m^2. (With Cd Shield)

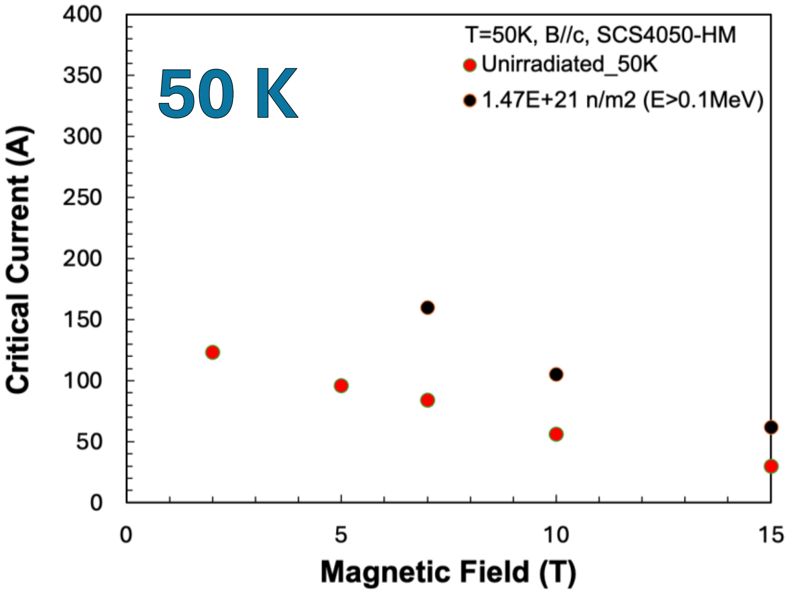
PIE (I_c-B curve): I_c criteria: 10 μV/cm, V-tap distance: 1.4 cm

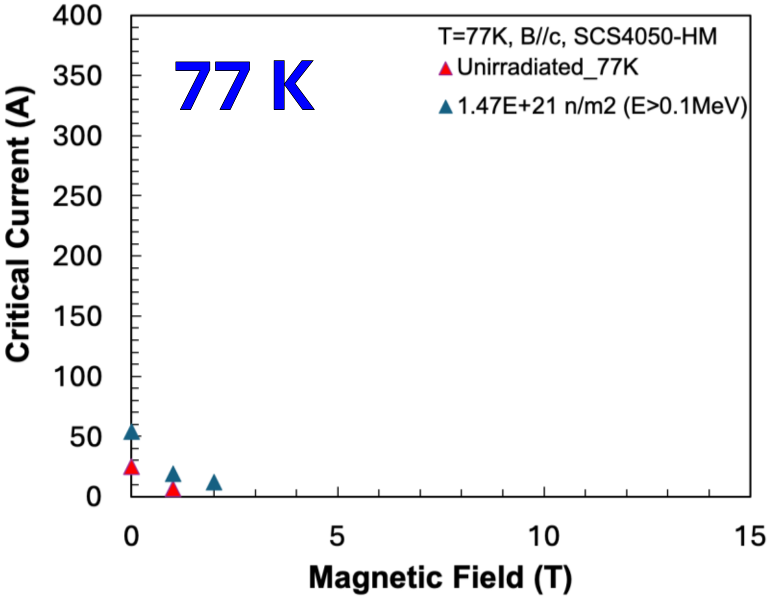




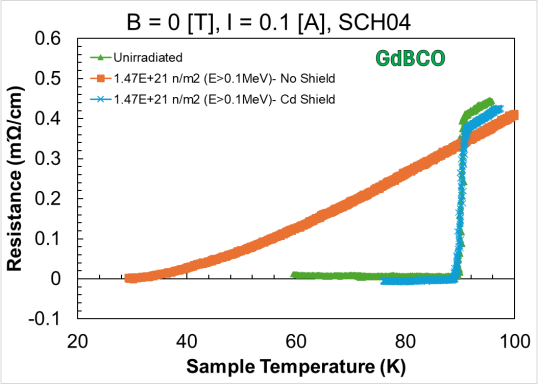


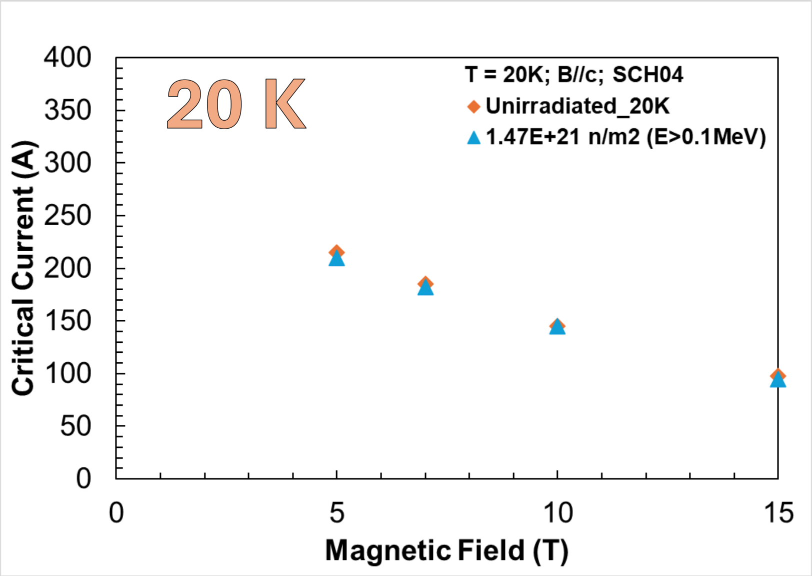
Irradiated sample I_c is double as tape width is double that of unirradiated tape

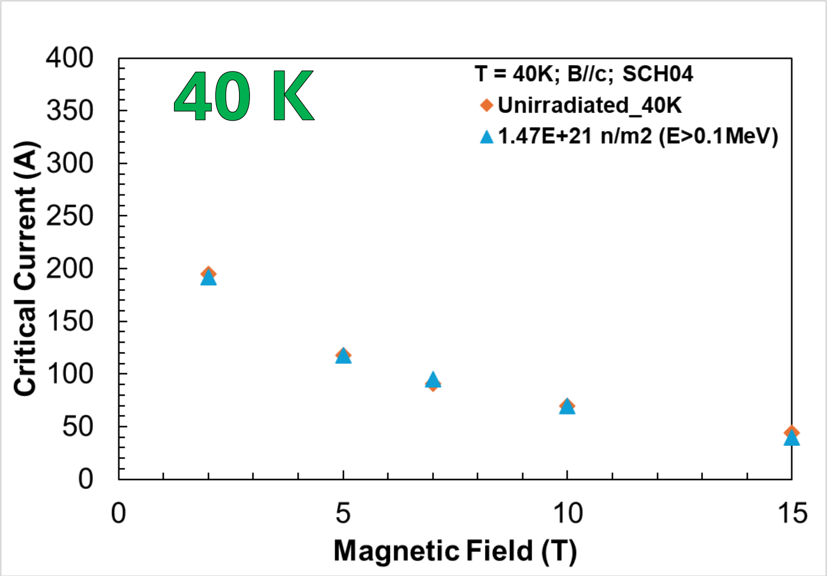




PIE (I_c -B curve): I_c criteria: 10 μV/cm, V-tap distance: 1.4 cm



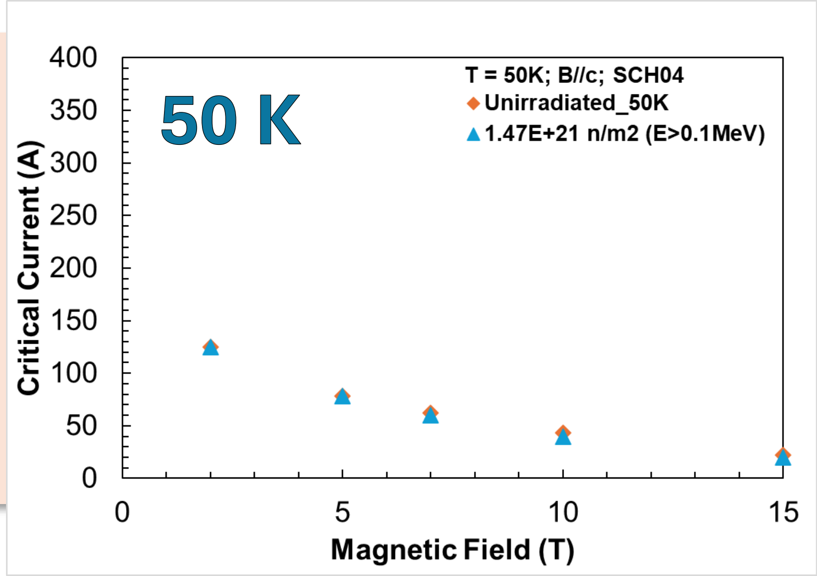


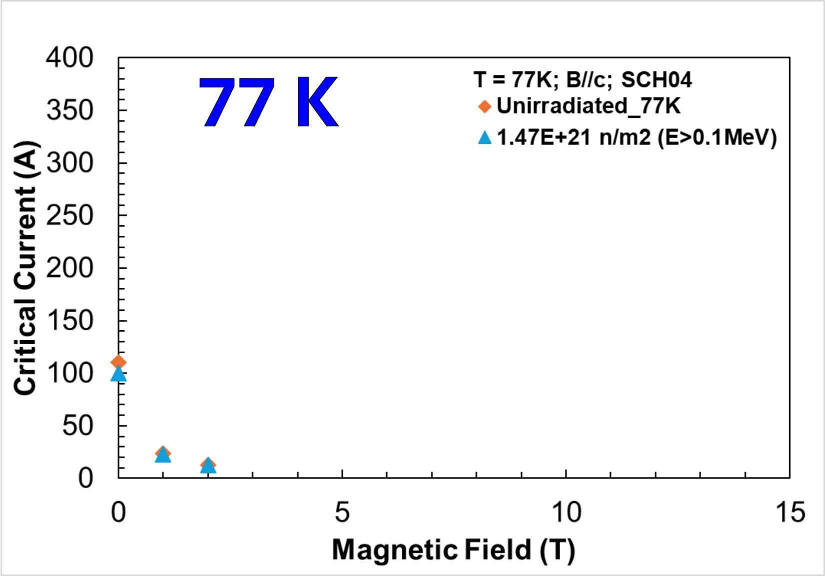


Irradiated sample

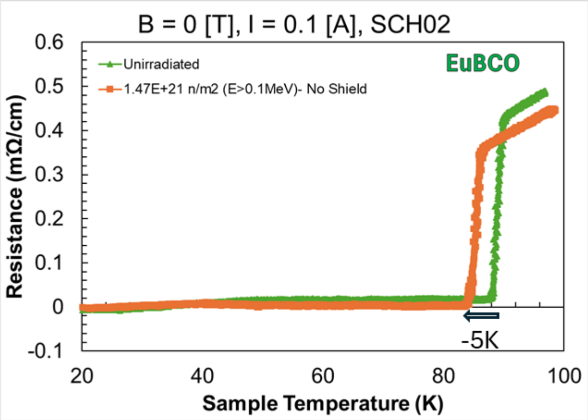
Cd Shield I_c ➔
No degradation

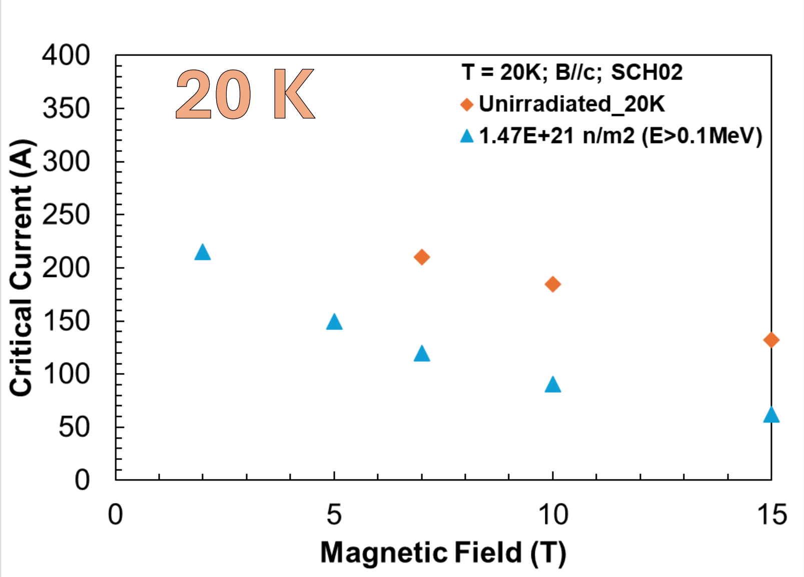
Without shield I_c ➔
completely vanished

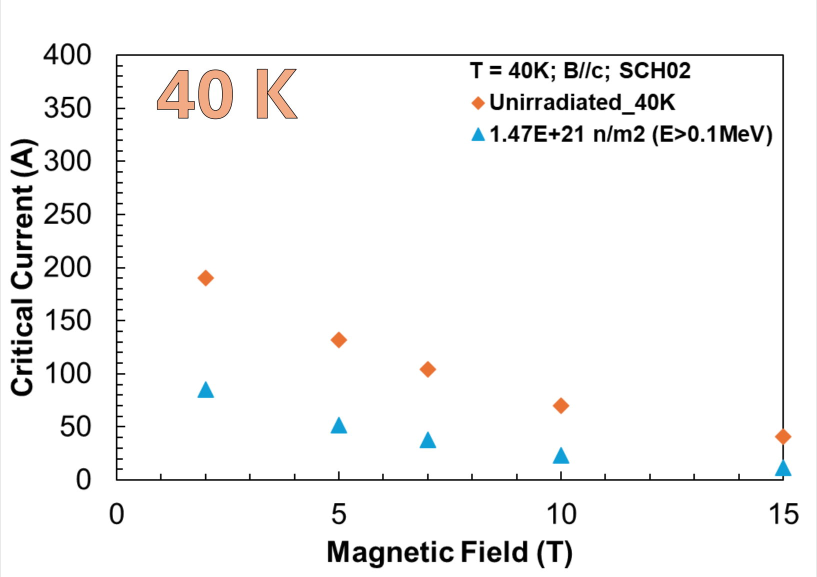




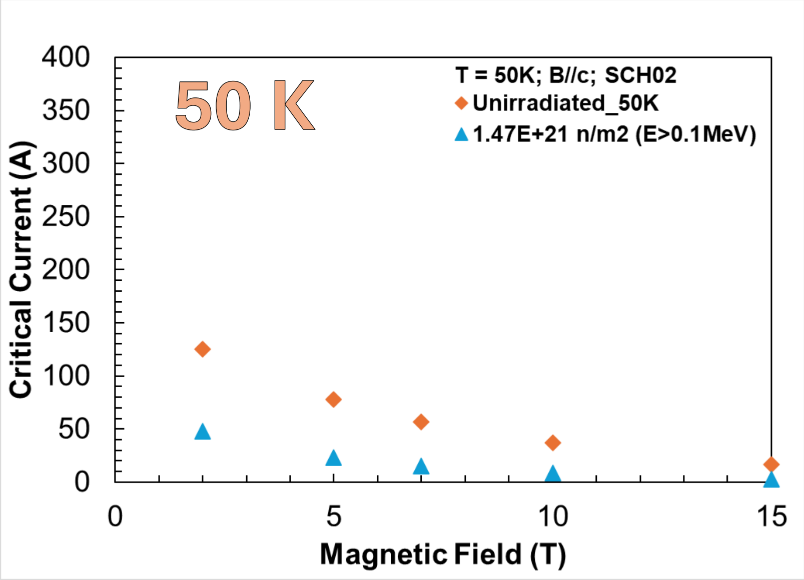
PIE (I_c -B curve): I_c criteria: 10 μV/cm, V-tap distance: 1.4 cm

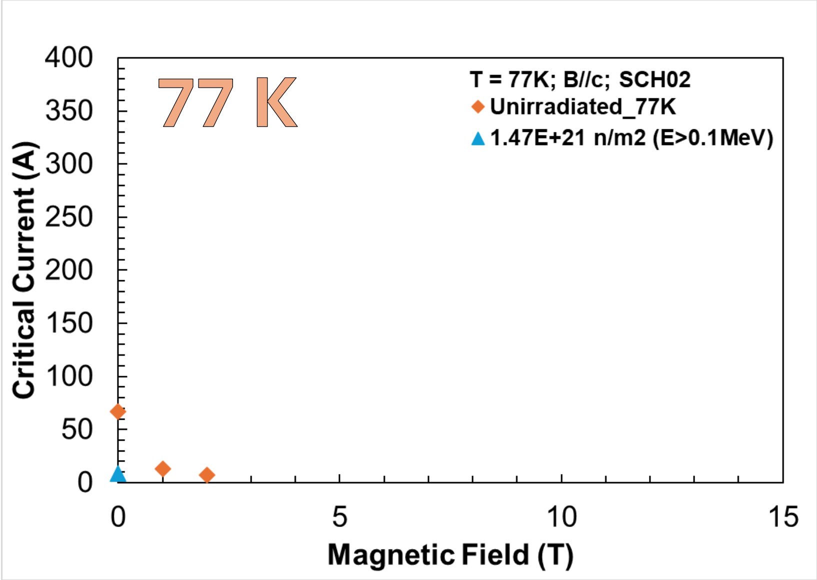






Irradiated sample I_c degraded by approx. 50% at 20K and 90% at 77K





Summary

- R&D of radiation-resistant REBCO magnet is underway.
- Neutron irradiation effects on REBCO tapes have been investigated at IMR-Oarai center, Tohoku Univ.
- Superconductivity of GdBCO tape irradiated at BR-2 disappeared even at 4.11 x 10^{22} n/m^2. (No Shield)
- T_c decrease and Ic degradation are confirmed at 8.32 x 10^{21} n/m^2.
- The degradation rate of I_c seems to change depending on the measurement temperature.

- The irradiation with and without Cd shield is completed at the JRR-3 hydraulic irradiation facility with a target fluence of ~1.47 x 10^{21} n/m^2.
- No degradation in superconductivity and T_c of without shield YBCO tape and Cd Shielded GdBCO samples irradiated at JRR-3.
- T_c decrease and Ic degradation are confirmed at 1.47 x 10^{21} n/m^2 in GdBCO and EuBCO

- Investigation is undergoing for Cd Shield EuBCO.
- The next target is to increase the fluence in the next fiscal year

Thank you