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Applicability evaluation of quench detectable hybrid REBCO tape to HTS magnet for fusion reactors

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Outline

HTS coil option for a helical fusion reactor, FFHR-d1 designed by NIFS has been investigated as the challenging option including segment-fabrication.

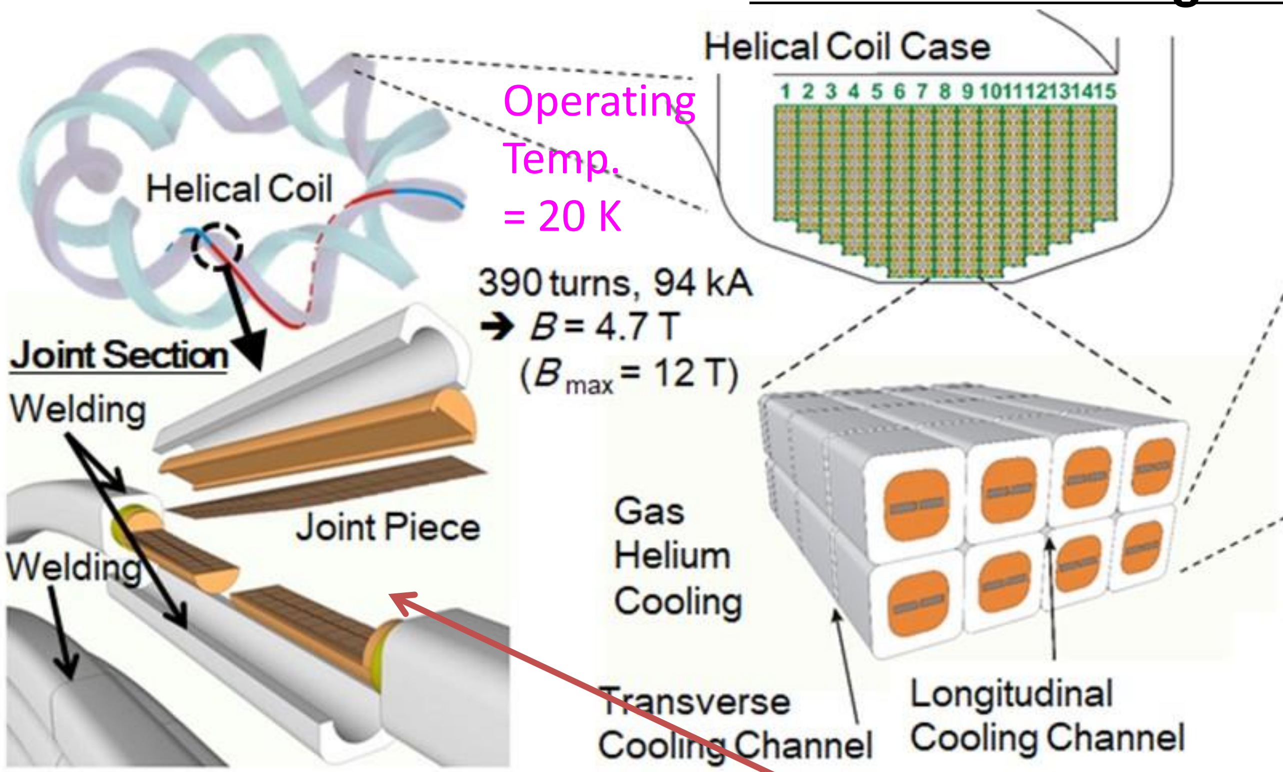
This study addresses quench detection and protection of REBCO tapes and conductors in the helical coils using REBCO/LTS_d tape.

Outline of this presentation

1. Introduction
2. Proof-of-principle test of REBCO/LTS_d tape
3. Material and field dependence of quench detectability
4. Applicability evaluation for a fusion reactor
5. Summary

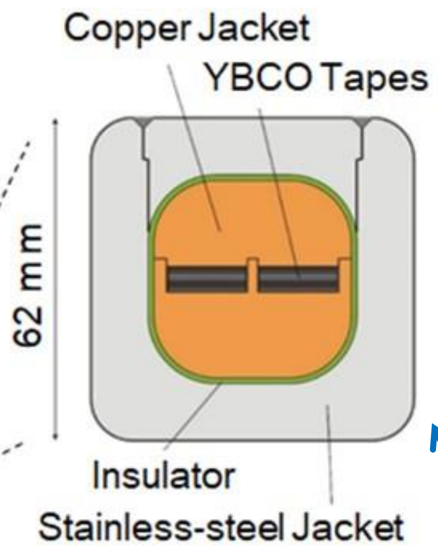
1. Introduction

1-1. Joint-winding of HTS helical coils



Design of a helical coil of FFHR-d1 [1][2]
(Joint-winding [3] as challenging option)

➔ solve the technical issue of difficulty with fabricating helical coils



HTS Stacked Tapes Assembled in Rigid Structure (STARS) conductors [4]

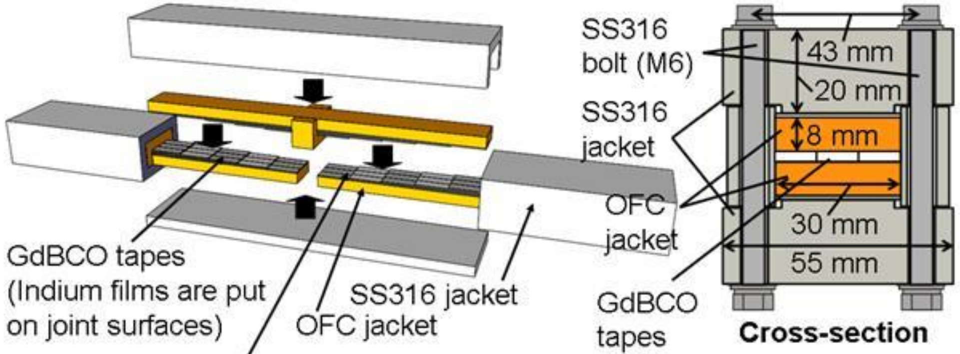
Bridge-type mechanical lap joint [5]

- The joint has a stepwise structure for face-to-face connection of REBCO surfaces
- REBCO tapes are joined by mechanical contact and just pressed together (indium foils are inserted between joint surfaces).
- Stainless steel jacket is welded to ensure tensile strength.

[1] A. Sagara et al., Fusion Eng. Des., 89, 2014, 2114-.
[2] A. Sagara et al., Nucl. Fusion, 57, 2017, 086046.
[3] N. Yanagi et al., Fusion Sci. Technol., 60, 2011, 648-652.
[4] N. Yanagi, S. Ito et al., Nucl. Fusion, 55, 2014, 053021.
[5] S. Ito et al., Plasma Fusion Res., 9, 2014, 4602305.

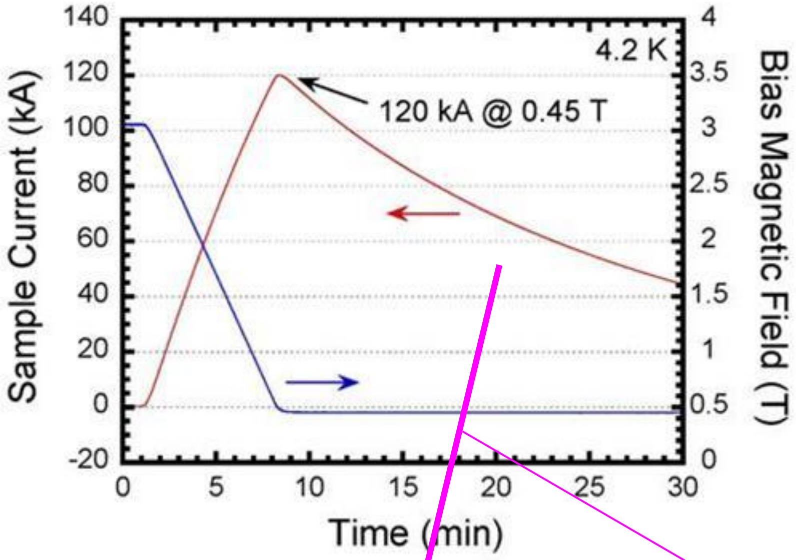
1. Introduction

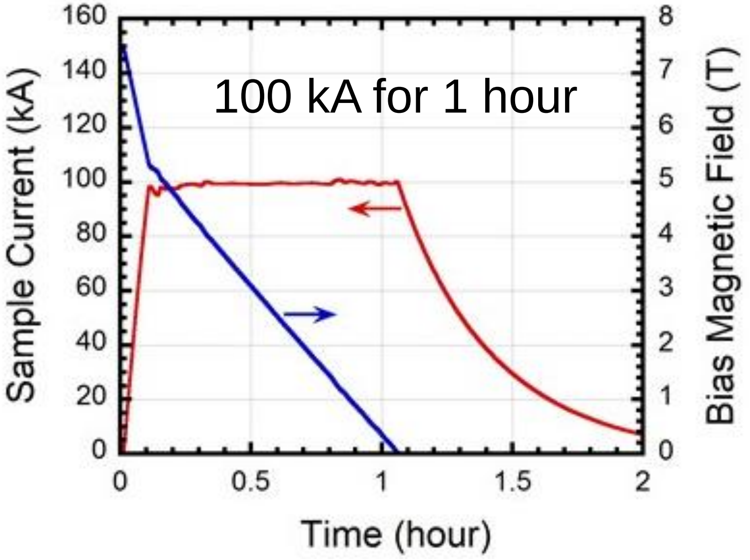
1-2. Test of a prototype STARS conductor joint

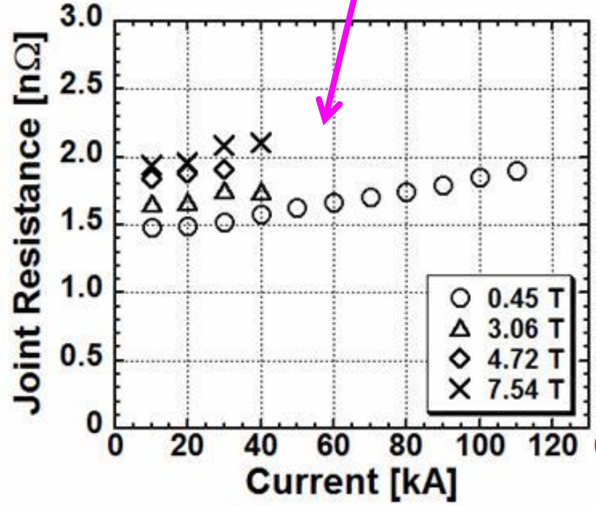


Actual layout is 3-row and 14-layer (42 GdBCO tapes having 10 mm wide)
Length of one joint: 30 mm/1-layer x 14-layer = 420 mm

Prototype STARS conductor joint [4, 5]







Joint resistance is evaluated by decay time constant

1.8 nΩ at 100 kA ⇒ **~10 pΩm² (~100 nΩcm²)**

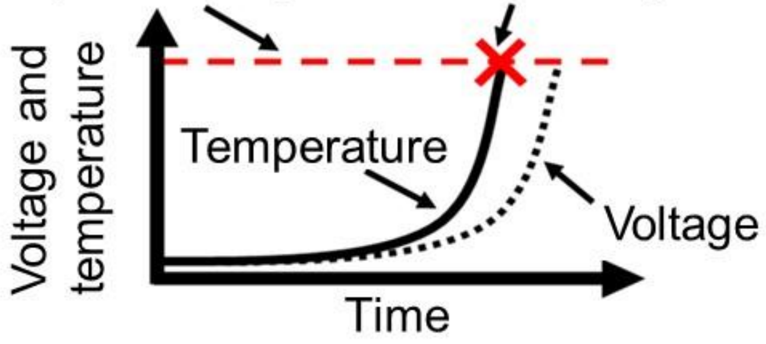
Sufficiently small from a viewpoint of the electric power to run a cryoplant

[4] N. Yanagi, S. Ito et al., Nucl. Fusion, 55, 2014, 053021.
[5] S. Ito et al., Plasma Fusion Res., 9, 2014, 4602305.

1. Introduction

1-3. Quench detection and protection of HTS helical coil

Though the cryogenic stability of the STARS conductor is sufficiently high with its high critical temperature and massive copper stabilizer, protection of the magnet system should be well prepared for unexpected incidents.



Difficulty in Quench Detection for REBCO tapes

Slow quench propagation in REBCO tapes
at very low temperature

Quench detection by voltage measurement is difficult
(At least 0.1 V is needed while the local temperature of REBCO tapes is < 50 K) [6]

➡ Several quench detection methods have been proposed
(e.g. Magnetic coupling [7], using an optical-fiber temperature sensor [8])

So far…

A large scale compensation coil is needed?

Accuracy becomes lower at <50 K

[6] O. Tsukamoto et al., Cryogenics, 63, 2014, 128-154. [7] S. Nie, et al., IEEE Trans. Appl. Supercond, 25, 2015, 5700605.
[8] F. Scurti, et al., Supercond. Sci. Technol., 29, 2016, 03LT01.

1. Introduction

1-4. Proposal of REBCO/LTS$_d$ tapes

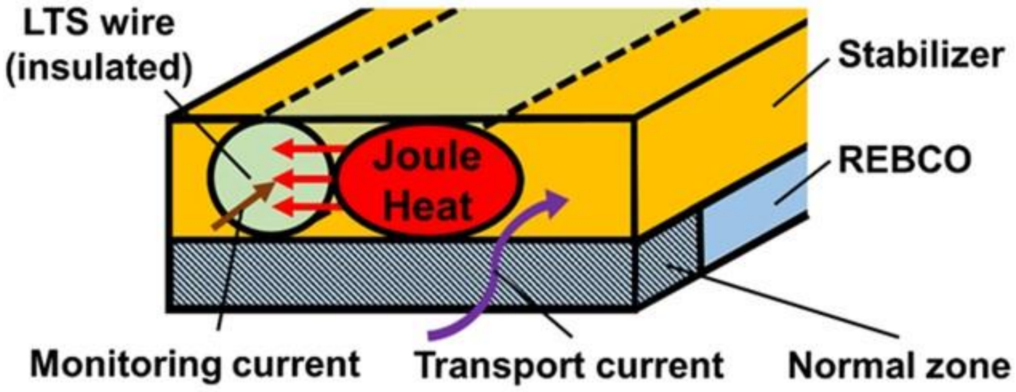
REBCO/LTS$_d$ tape
(Quench detectable hybrid REBCO tape)

- REBCO tape: Current transportation
- LTS wire: Quench detector with a low monitoring current

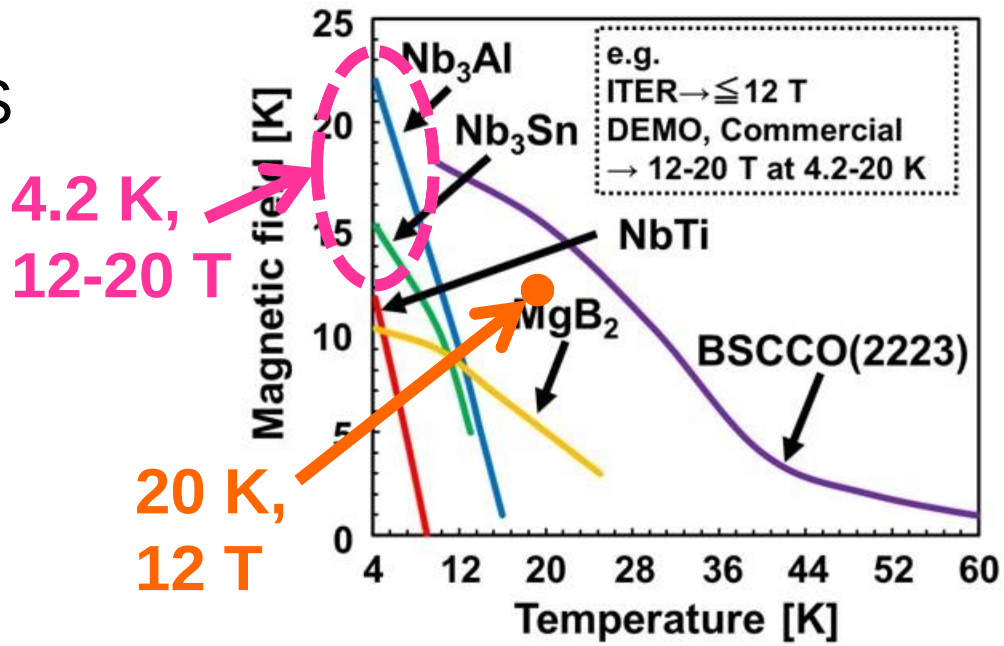
High voltage is induced by quench in LTS detector when quench events occur in REBCO tapes

The quench signal of REBCO tapes is possibly detected before it burns out

The concept is similar to liquid level sensors for cryogenic applications



REBCO/LTS$_d$ tape [9]



Temperature and field ranges for SC detectors

[9] S. Hasegawa et al., MT-25, Amsterdam, Netherland, Aug. 27-Sep. 1, 2017, Thu-Af-Po4-09.

1. Introduction

1-5. Objective

Investigating quench detectability of REBCO/LTS_d tape and its applicability to fusion reactor HTS magnets.

Proof-of-principle test of REBCO/LTS_d tape [9]

Experimentally verifying the quench detection performance of REBCO/LTS_d tape using YBCO/$NbTi_d$ tape at 4.2 K, self-field

Material and field dependence of quench detectability

Numerically evaluating quench detectability influenced by the detector choice (LTS detectors: NbTi, Nb_3Sn, Nb_3Al) and magnetic field

Applicability evaluation for a fusion reactor

Numerically evaluating the temperature rise of STARS conductors in HTS helical coils of a helical fusion reactor, FFHR-d1 after quench, with or without an LTS quench detector (Operated at 4.2 K, 12 T)

[9] S. Hasegawa et al., MT-25, Amsterdam, Netherland, Aug. 27-Sep. 1, 2017, Thu-Af-Po4-09.

Outline

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This study addresses quench detection and protection of REBCO tapes and conductors using REBCO/LTS_d tape.

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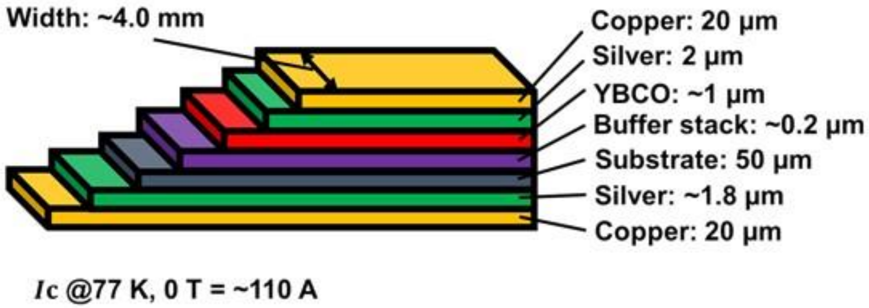
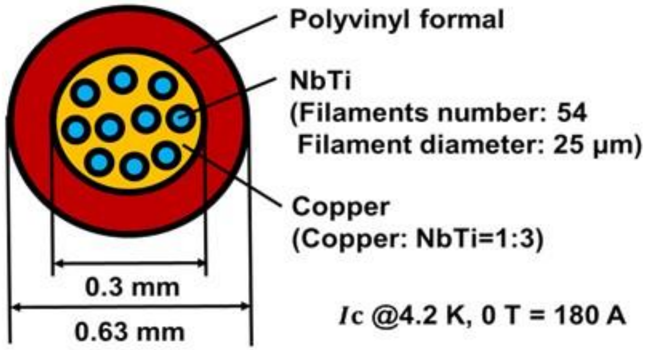
2. Proof-of-principle test of REBCO/LTS$_d$ tape [9]

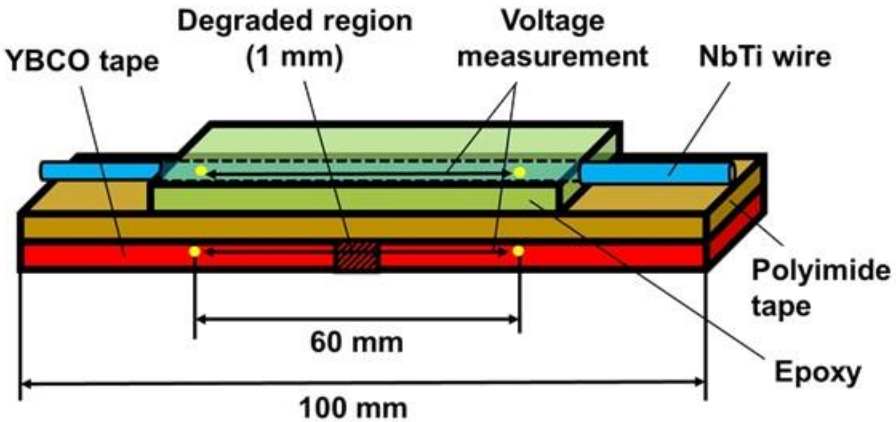
2-1. Sample preparation and experimental set-up



YBCO tape
(Superpower SC4050)

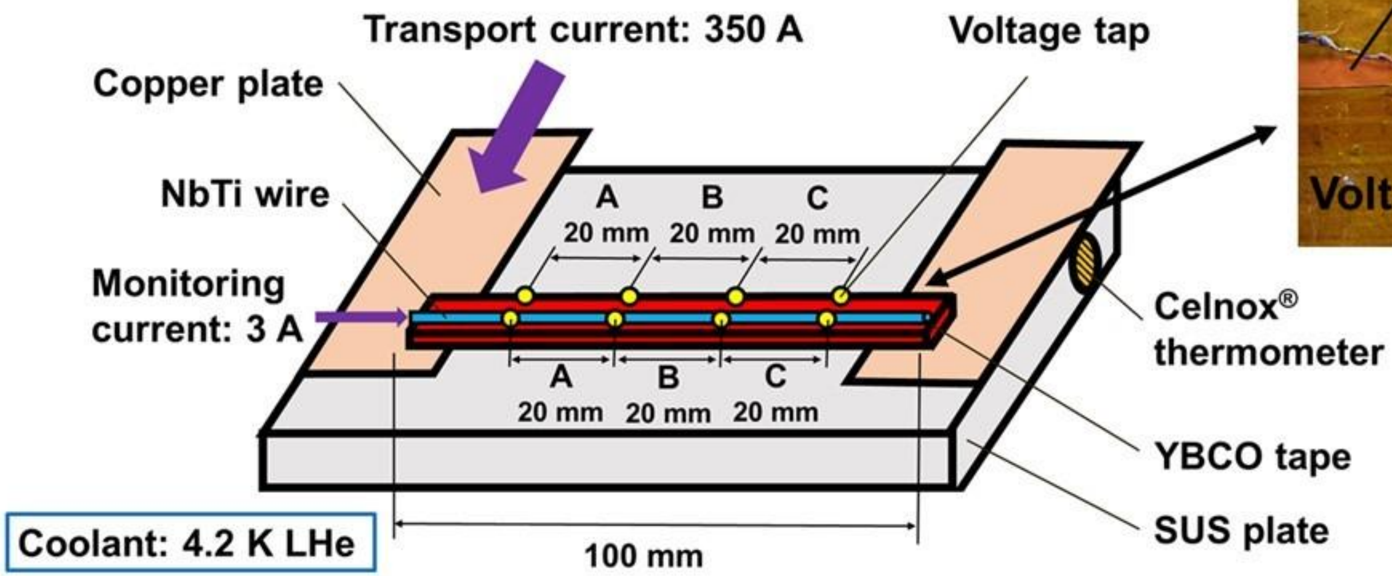


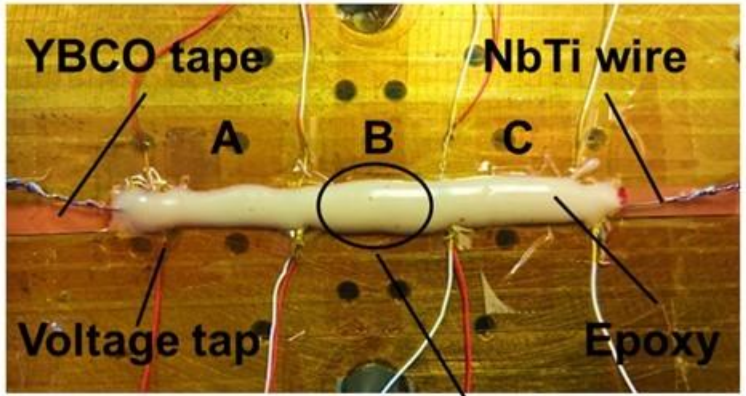
NbTi wire (Supercon 54S43)



YBCO/NbTi$_d$ tape

NbTi wire with or without a copper stabilizer was used for a quench detector



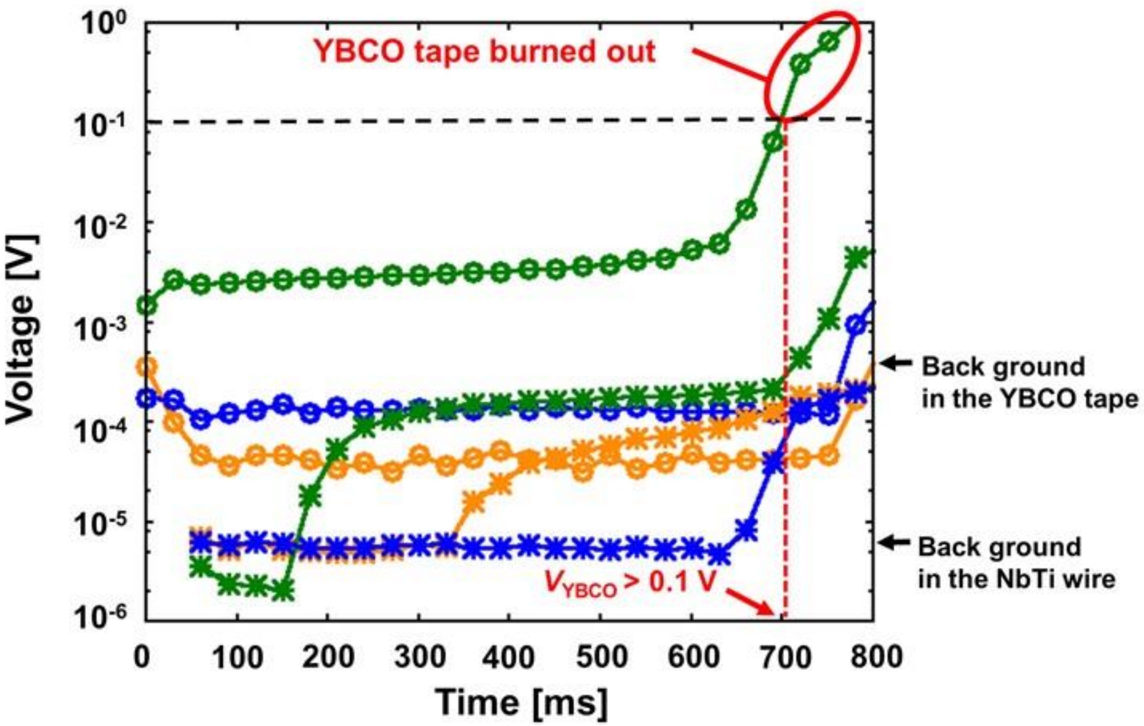


Critical current of the YBCO tape was degraded to 0 A

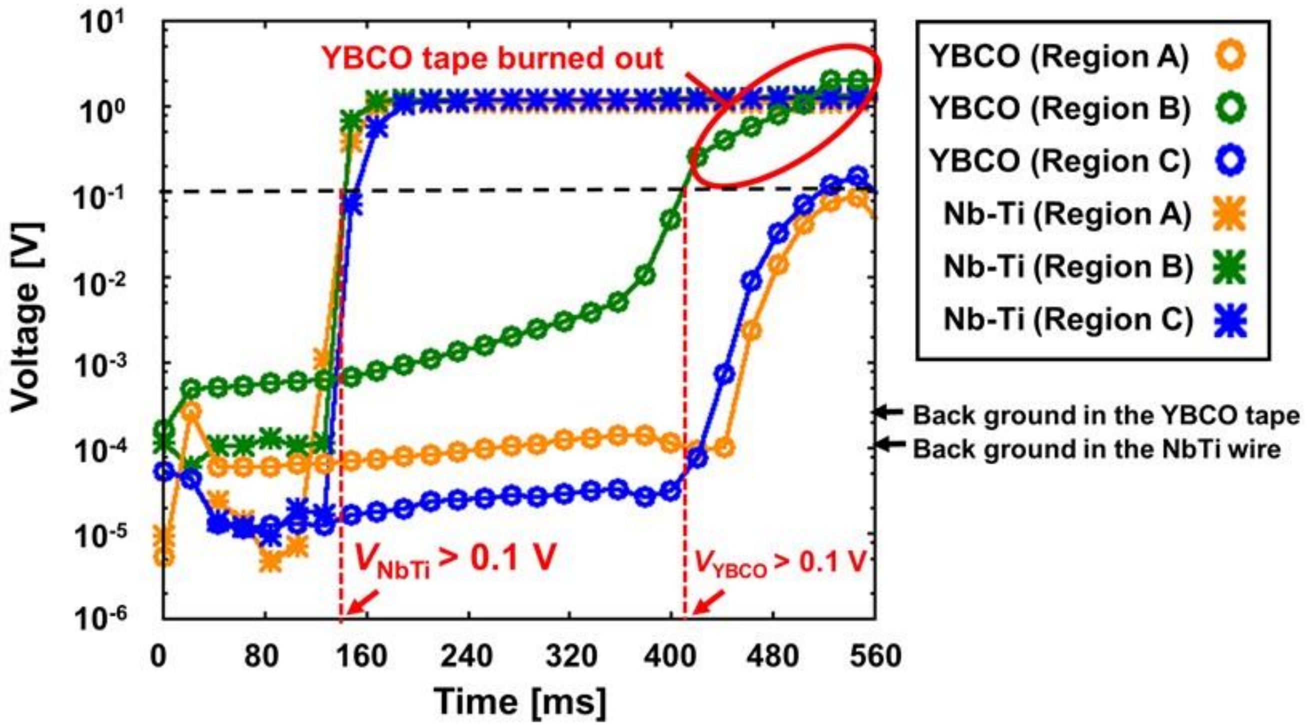
[9] S. Hasegawa et al., MT-25, Amsterdam, Netherland, Aug. 27-Sep. 1, 2017, Thu-Af-Po4-09.

2. Proof-of-principle test of REBCO/LTS$_d$ tape [9]

2-2. Experimental results



Case i (NbTi detector with a copper stabilizer)



Case ii (NbTi detector without a copper stabilizer)

Detectable voltage in the NbTi wire was smaller than that in the YBCO tape in Case i (0.1 mV~)

1 V scale voltage was measured in the NbTi wire before the YBCO tape burned out in Case ii

Quench in the YBCO tape can be detected by using the NbTi wire without a copper stabilizer

[9] S. Hasegawa et al., MT-25, Amsterdam, Netherland, Aug. 27-Sep. 1, 2017, Thu-Af-Po4-09.

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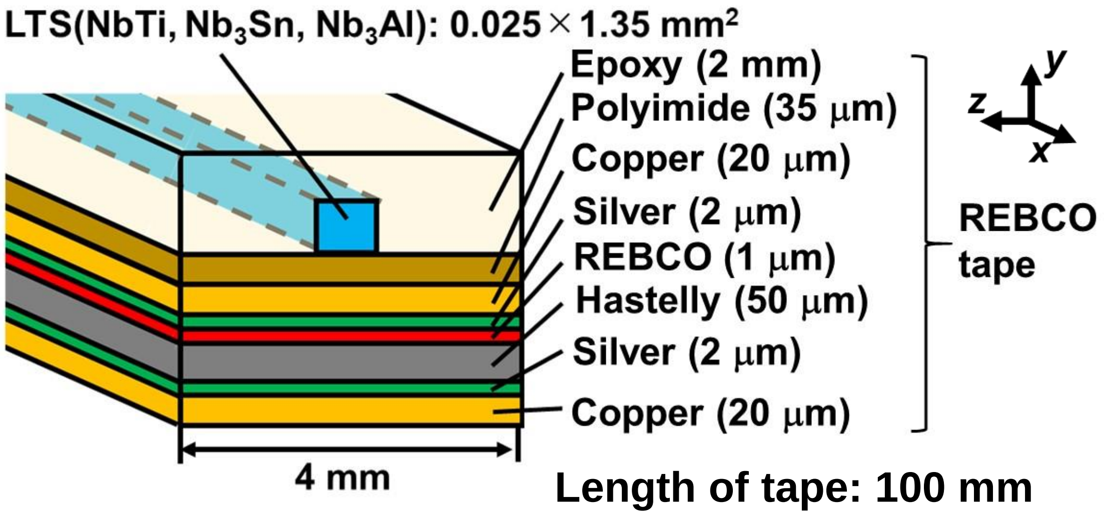
3. Material and field dependence of quench detectability

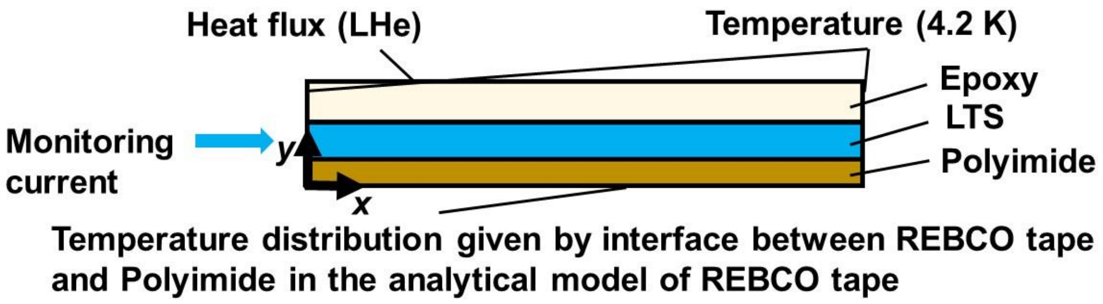
3-1. Analytical model



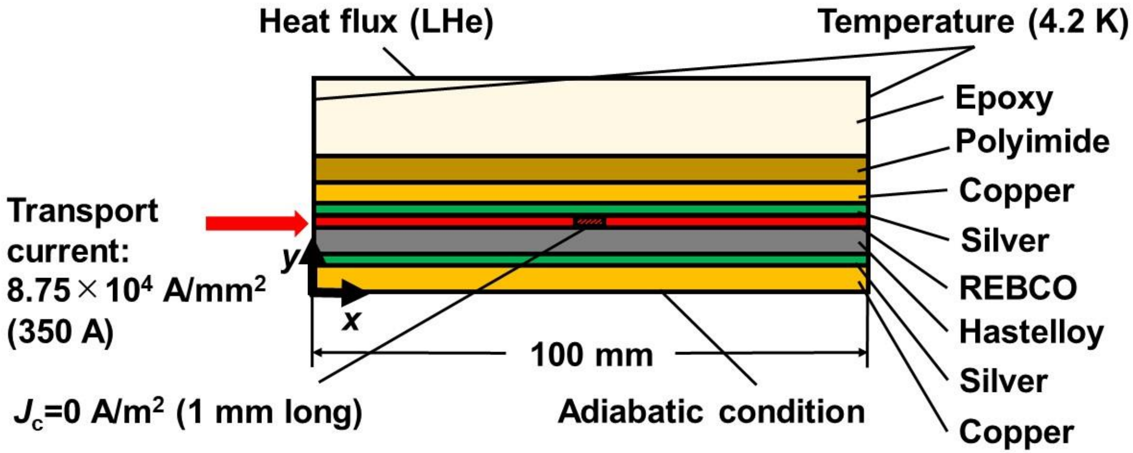
Analytical model of REBCO/LTS_d tape

LTS detectors

LTS	T_c [K]	B_{c2} [T]
NbTi	9.5	11.5
Nb_3Sn	18.3	~28.0
Nb_3Al	18.9	~30.0



Analytical model for LTS detector

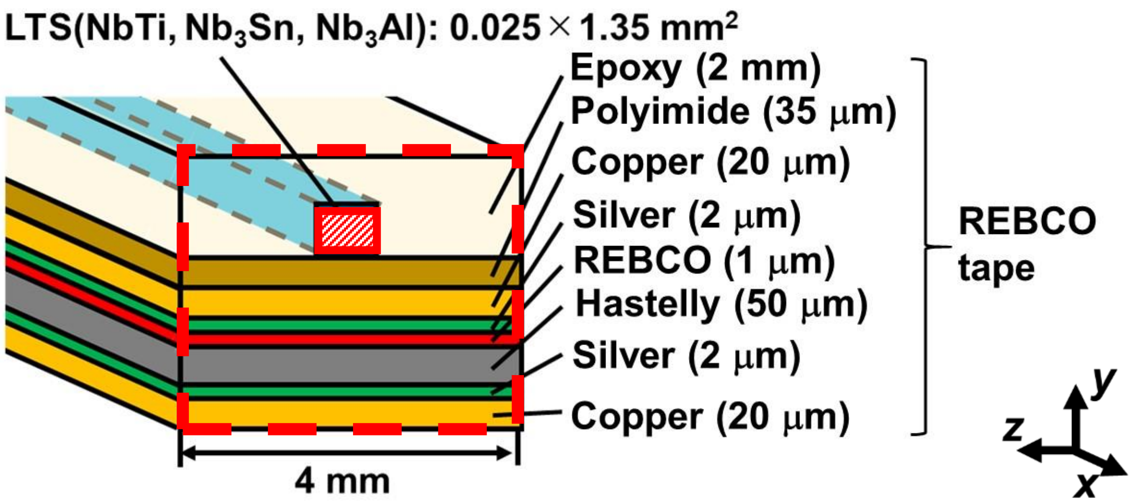


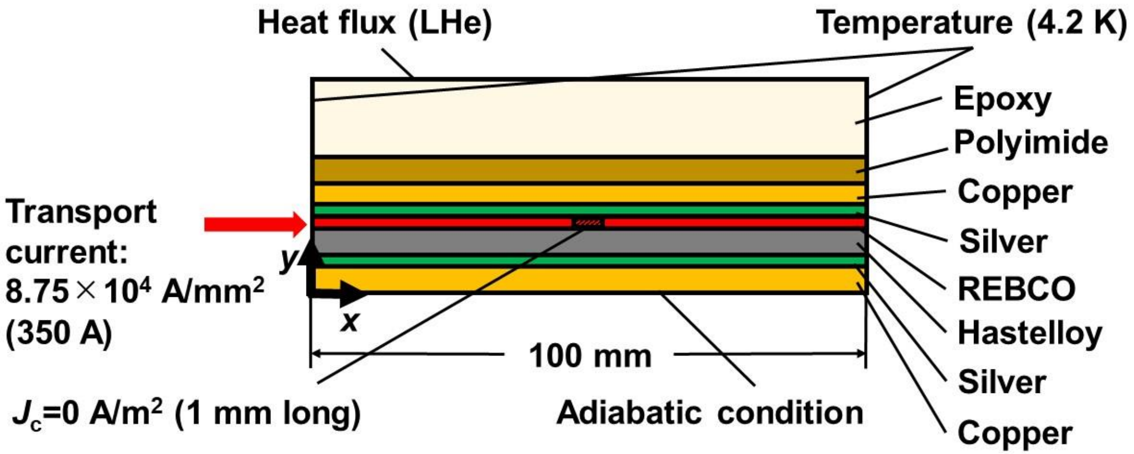
Analytical model for REBCO tape

- Weakly coupled thermal/electrical analysis (temperature and electro-static potential distributions)
- Load factor (= monitoring current I_m / critical current I_c) for an LTS detector: 0.1-0.9
- External magnetic field: 0-20 T

3. Material and field dependence of quench detectability

3-2. Model for evaluation analysis of REBCO tape





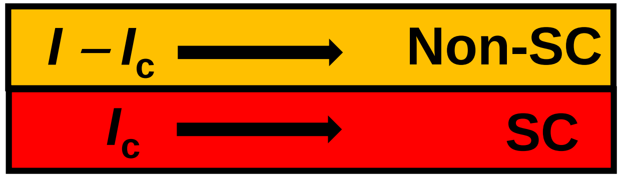
Analytical model for REBCO tape

1. Potential distribution is evaluated by 2D charge conservation equation except in epoxy and polyimide regions

Electrical conductivity of REBCO [10]

(1). $\sigma_{\mathrm{REBCO}}{}^{(0)} = \sigma_{\mathrm{REBCO0}}$ (σ_{RECO0} is sufficiently large value)

(2). $\left|\boldsymbol{J}_{\mathrm{REBCO}}\right| \geq J_{\mathrm{cREBCO}}(T) \rightarrow \sigma_{\mathrm{REBCO}}{}^{(n+1)} = \dfrac{J_{\mathrm{cREBCO}}}{\left|\boldsymbol{J}_{\mathrm{REBCO}}\right|}\sigma_{\mathrm{REBCO}}{}^{(n)}$



➡ Current density over J_c flows in the non-superconducting regions

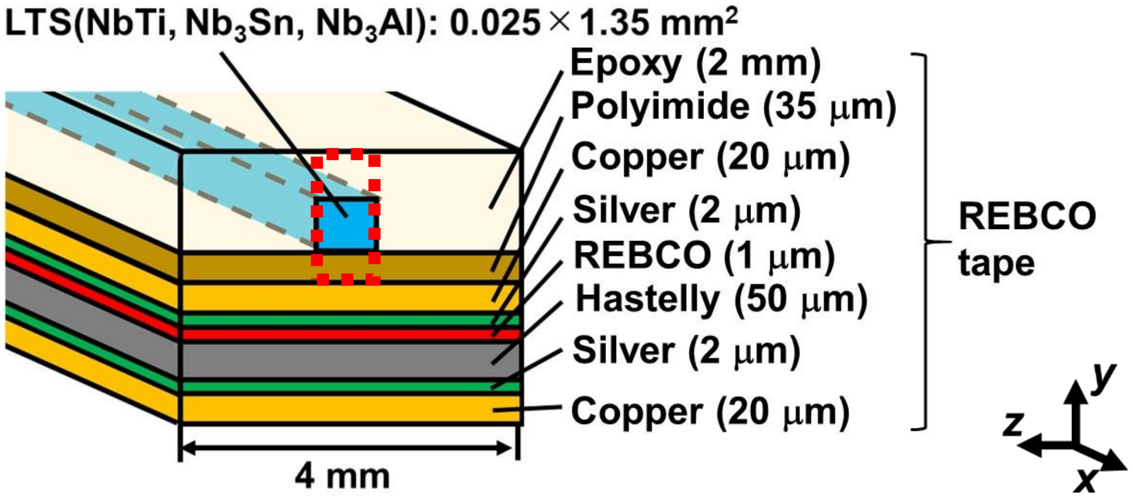
2. Temperature distribution is evaluated by 2D heat equation

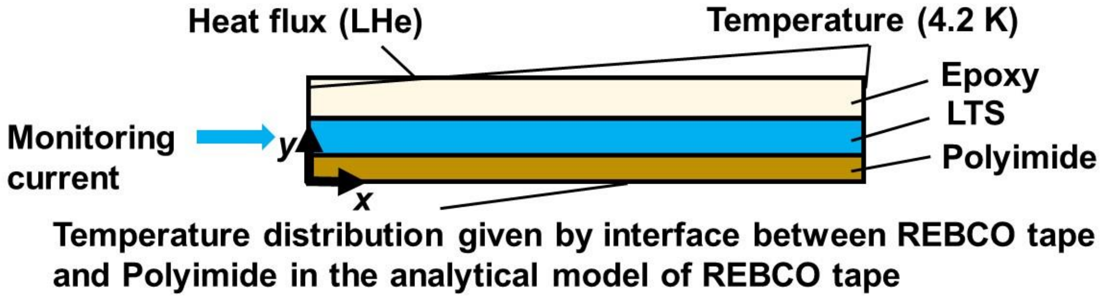
Temperature distribution along interface between copper and polyimide
➔ Boundary condition in analytical model of LTS detector

[10] H. Hashizume, et al., Cryogenics, 31, 1991, 601–606.

3. Material and field dependence of quench detectability

3-3. Model for evaluation analysis of LTS detector





Analytical model for LTS detector

1. Temperature distribution is evaluated by 2D heat equation

> Temperature distribution along interface between REBCO tape and polyimide
> ➔ Boundary condition in analytical model of LTS detector

2. Potential distribution is evaluated by 1D charge conservation equation

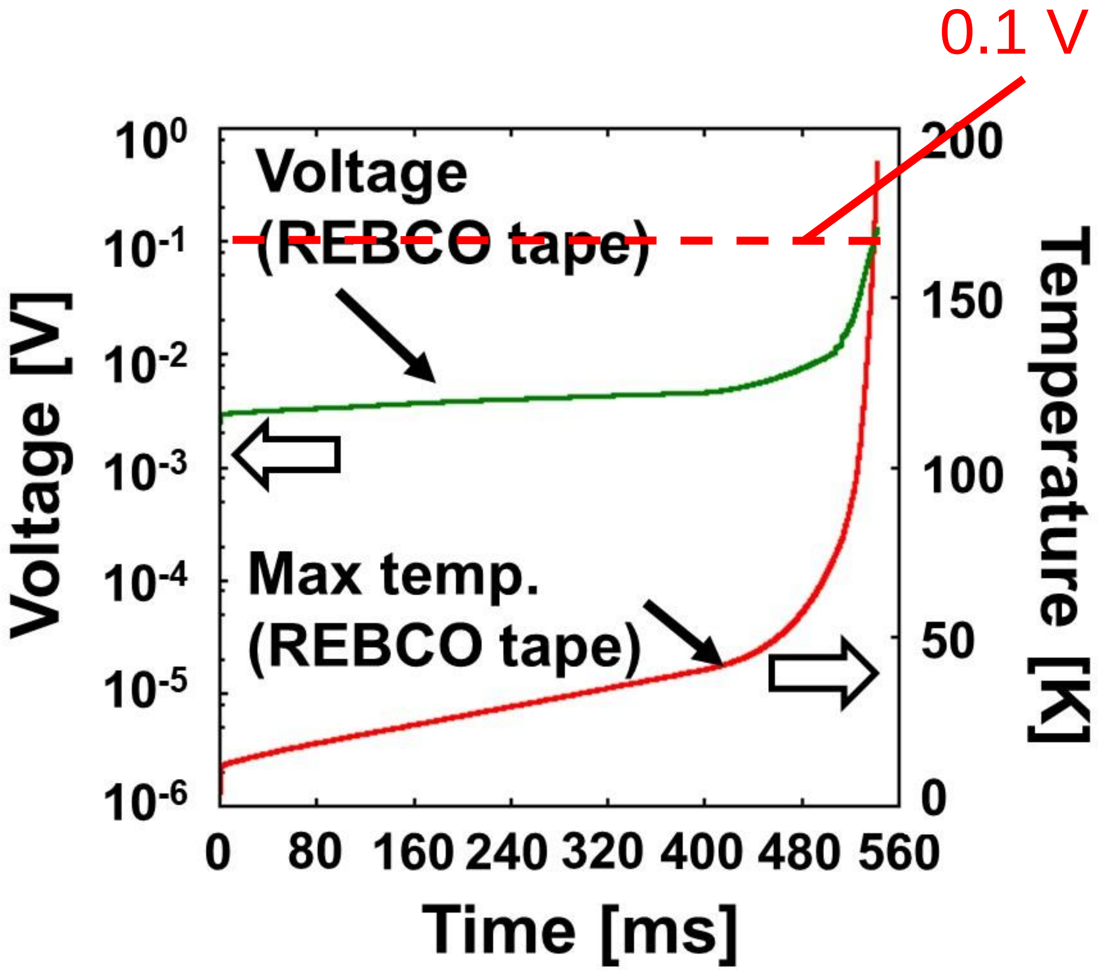
Electrical conductivity of LTS detector

$$\sigma_{\mathrm{LTS}} = \begin{cases} \infty & (T \le T_{\mathrm{cs}}) \\ \sigma_{\mathrm{normal}}(T_{\mathrm{c}}) \cdot \dfrac{T_{\mathrm{c}} - T_{\mathrm{cs}}}{T - T_{\mathrm{cs}}} & (T_{\mathrm{cs}} < T \le T_{\mathrm{c}}) \\ \sigma_{\mathrm{normal}}(T) & (T > T_{\mathrm{c}}) \end{cases}$$

T_{cs}: Current sharing temperature

3. Material and field dependence of quench detectability

3-4. Result for REBCO tape without LTS detectors



Voltage and temperature changes in REBCO tape without LTS detectors

Max. temp. ≥ 50 K
Temperature rises quickly

If. Detection voltage V_d = 100 mV

When voltage of REBCO tape reaches 100 mV…

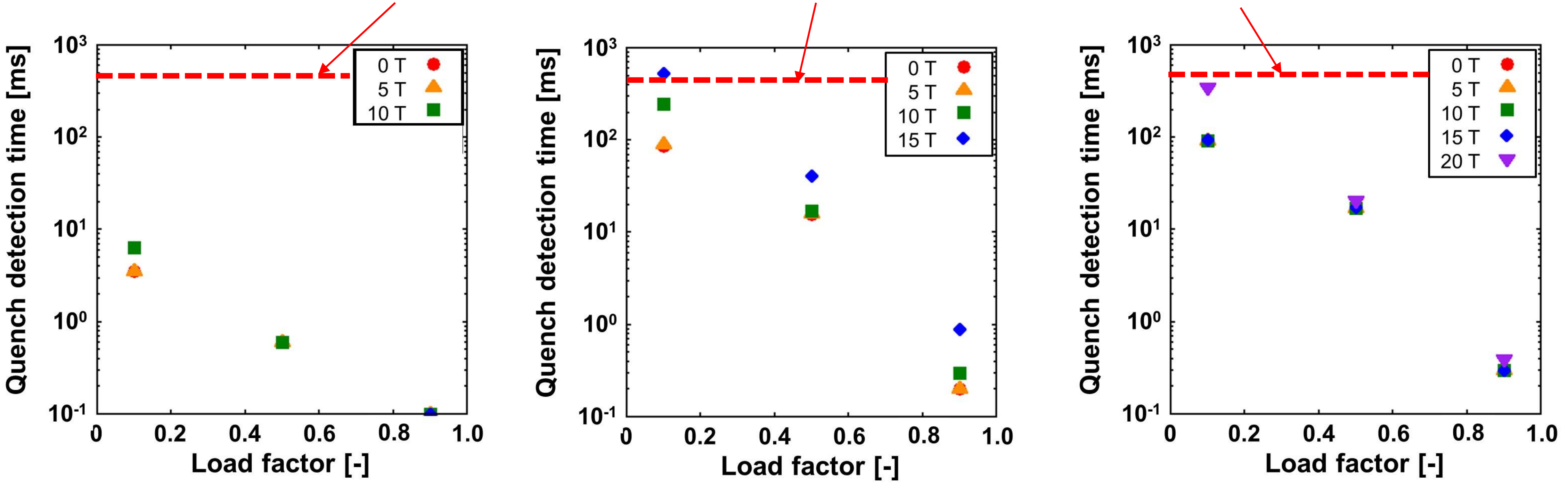
Max. Temp ≥ 150 K

REBCO tape burns out

3. Material and field dependence of quench detectability

3-5. Quench detection time for each LTS detector

The temperature of REBCO tape reached 50 K



NbTi (T_c = 9.5 K) Nb$_3$Sn (T_c = 18.3 K) Nb$_3$Al (T_c = 18.9 K)

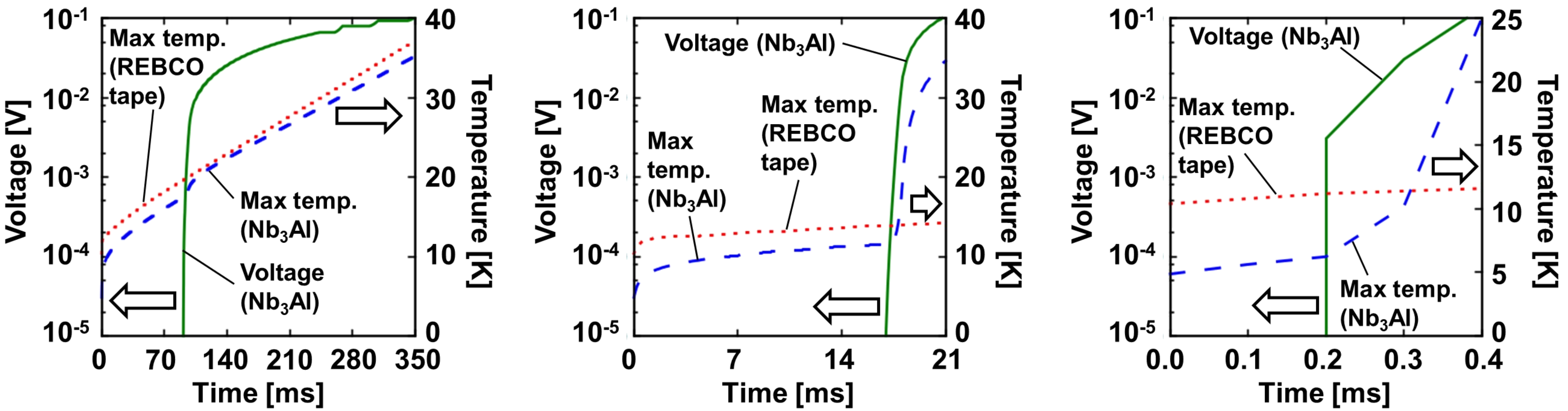
Earlier quench detection ➡ Higher load factor (LTS detector)

➔ Lower T_{cs}

➔ Higher current density

3. Material and field dependence of quench detectability

3-6. Results for REBCO/Nb_3Al_d tape (20 T)



Load factor = 0.1 **Load factor = 0.5** **Load factor = 0.9**

Higher load factor (Lower T_{cs} of LTS) ➔ Earlier quench detection
➔ Higher heat generation at LTS (burns out…)

Higher load factor is desirable, but taking into account the heat generation

Next: Applicability evaluation of REBCO/Nb_3Al_d tape for a fusion reactor (FFHR-d1, 4.2 K, 12 T)

Outline

HTS coil option for a helical fusion reactor, FFHR-d1 designed by NIFS has been investigated as the challenging option including segment-fabrication.

This study addresses quench detection and protection of REBCO tapes and conductors using REBCO/LTS_d tape.

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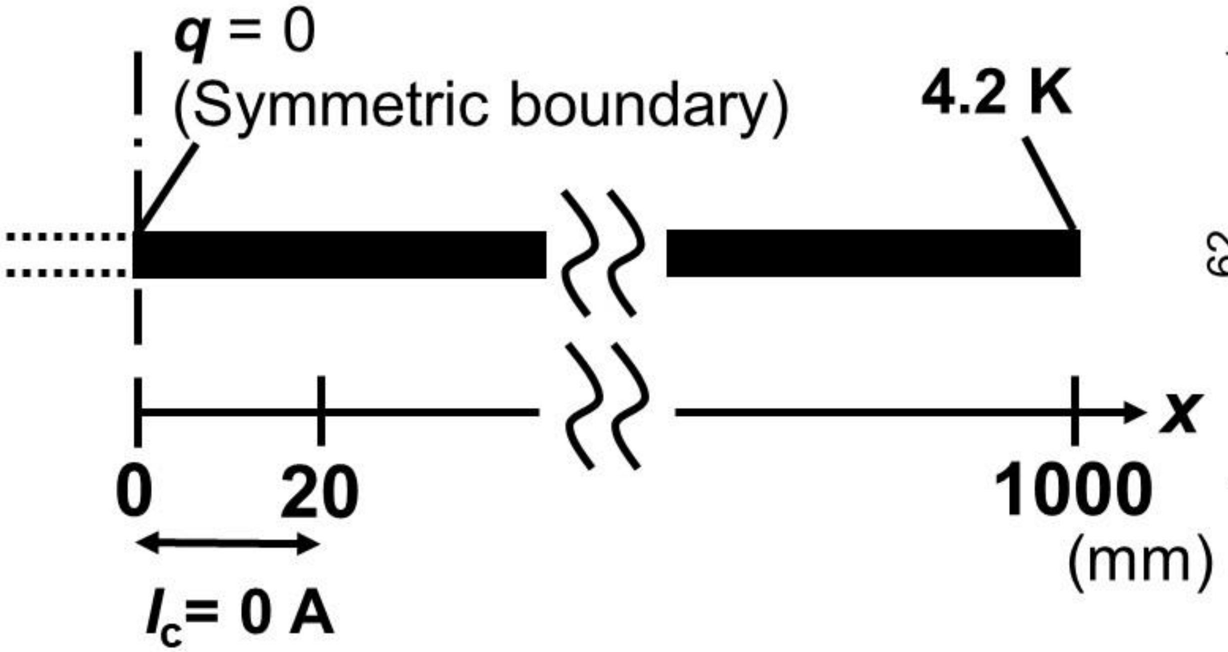
4. Applicability evaluation for a fusion reactor

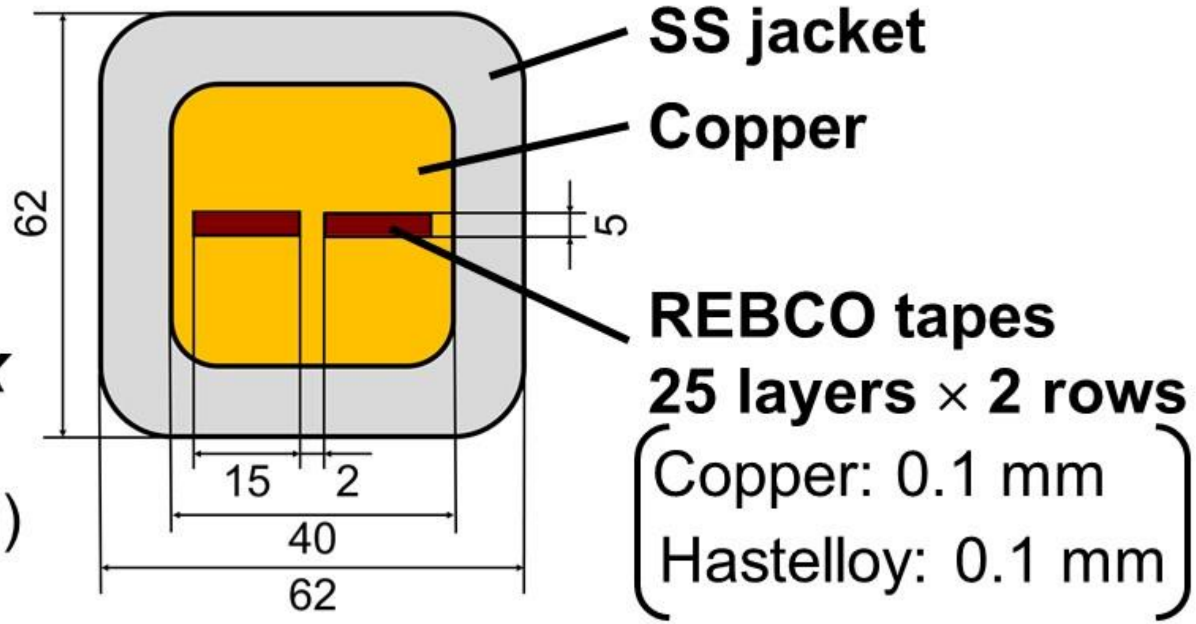
4-1. Analytical model

HTS conductor STARS conductor for FFHR-d1 (T_{op} = 4.2 K, B_{max} = 12 T, B_{min} = 6 T)
Operation current I_{op} = 94 kA (Load factor = 0.78 at 4.2 K, 12 T)

LTS detector Material: Nb_3Al (∅0.2 mm without a copper stabilizer)
Monitoring current I_m = 0.52 A (Load factor = 0.01 at 4.2 K, 12 T)

Analytical conditions 1D model (Adiabatic condition in the *y* and *z* direction)
I_c = 0 A for 20 mm ➔ Quench





4. Applicability evaluation for a fusion reactor

4-1. Analytical model

HTS conductor
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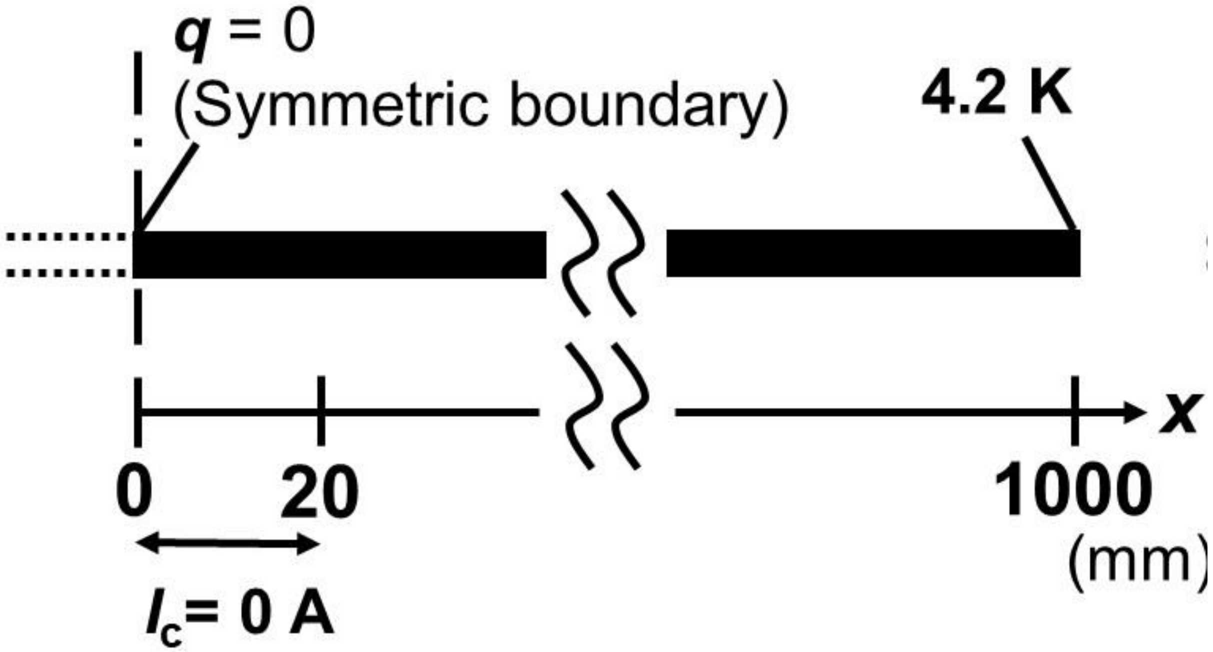
Operation current I_{op} = 94 kA (Load factor = 0.78 at 4.2 K, 12 T)

LTS detector
Material: Nb_3Al (∅0.2 mm without a copper stabilizer)
Monitoring current I_m = 0.52 A (Load factor = 0.01 at 4.2 K, 12 T)

Analytical conditions
1D model (Adiabatic condition in the *y* and *z* direction)
I_c = 0 A for 20 mm ➔ Quench



Quench detection ➔ Protection

Detectable voltage V_d = 100 mV or 200 mV
(REBCO tape or Nb_3Al detector)

➔ I_{op} decreases exponentially
(Time constant τ = 30 sec)
$I_{op}=I_{op0}\exp(-t/\tau)$

4. Applicability evaluation for a fusion reactor

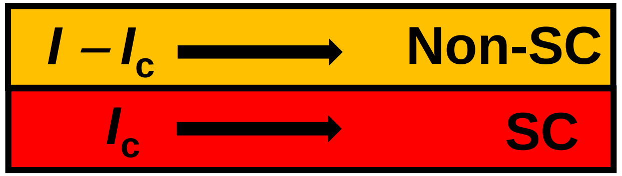
4-2. Model for evaluation analysis

REBCO conductor (STARS conductor)

Temperature distribution is evaluated by 1D heat equation

Potential distribution is evaluated by 1D charge conservation equation

$$E_{\text{REBCO}} = \begin{cases} 0 & (T \leq T_{\text{cs}}) \\ \dfrac{J_{\text{op}} - J_{\text{c}}(T)}{\sigma_{\text{copper}}(T)} & (T > T_{\text{cs}}) \end{cases}$$



Current over I_c flows in the non-superconducting regions

Nb_3Al

Temperature distribution is estimated by 1D heat equation

Heat load by STARS conductor

$$Q_{\text{in}} = \frac{q_{\text{in}}}{\overline{P}} \approx \frac{1}{\overline{P}} \max(\kappa \frac{T_{\text{REBCO}} - T_{\text{Nb}_3\text{Al}}}{d}, 0)$$

Potential distribution is evaluated by 1D charge conservation equation

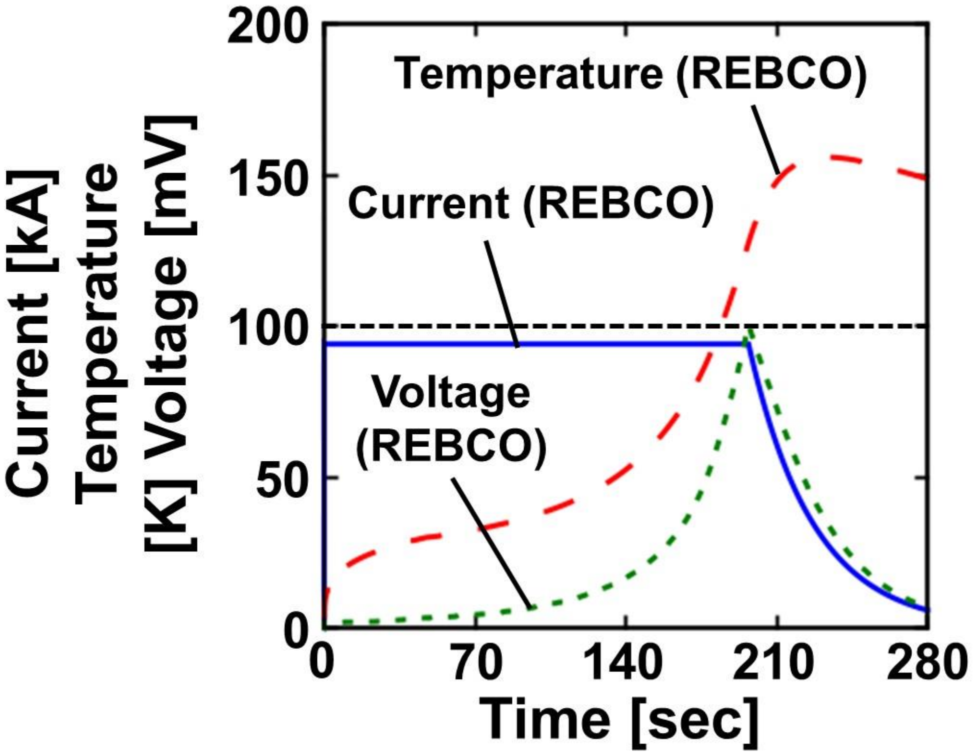
Electrical conductivity of Nb_3Al detector

$$\sigma_{\text{Nb}_3\text{Al}} = \begin{cases} \infty & (T \leq T_{\text{cs}}) \\ \sigma_{\text{normal}}(T_{\text{c}}) \cdot \dfrac{T_{\text{c}} - T_{\text{cs}}}{T - T_{\text{cs}}} & (T_{\text{cs}} < T \leq T_{\text{c}}) \\ \sigma_{\text{normal}}(T) & (T > T_{\text{c}}) \end{cases}$$

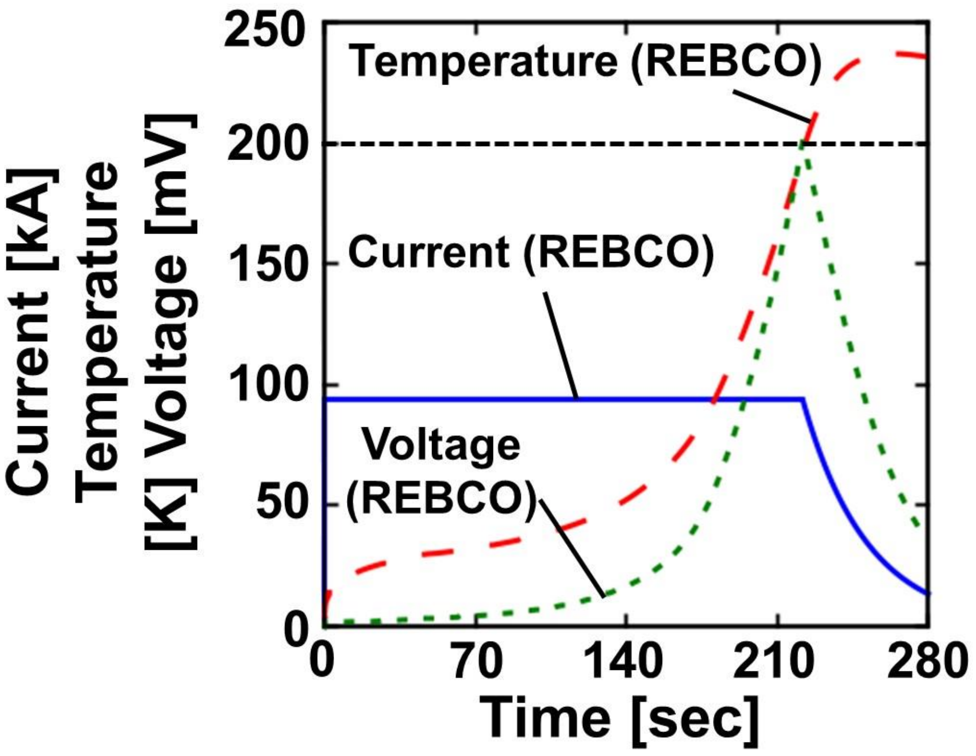
$\overline{T_{\text{REBCO}}}$: Average temperature of copper jacket
$\overline{P}$: Perimeter of Nb_3Al
d: Thickness of insulator for Nb_3Al
κ: Thermal conductivity of polyimide

4. Applicability evaluation for a fusion reactor

4-3. Results (without LTS detectors)



V_d = 100 mV



V_d = 200 mV

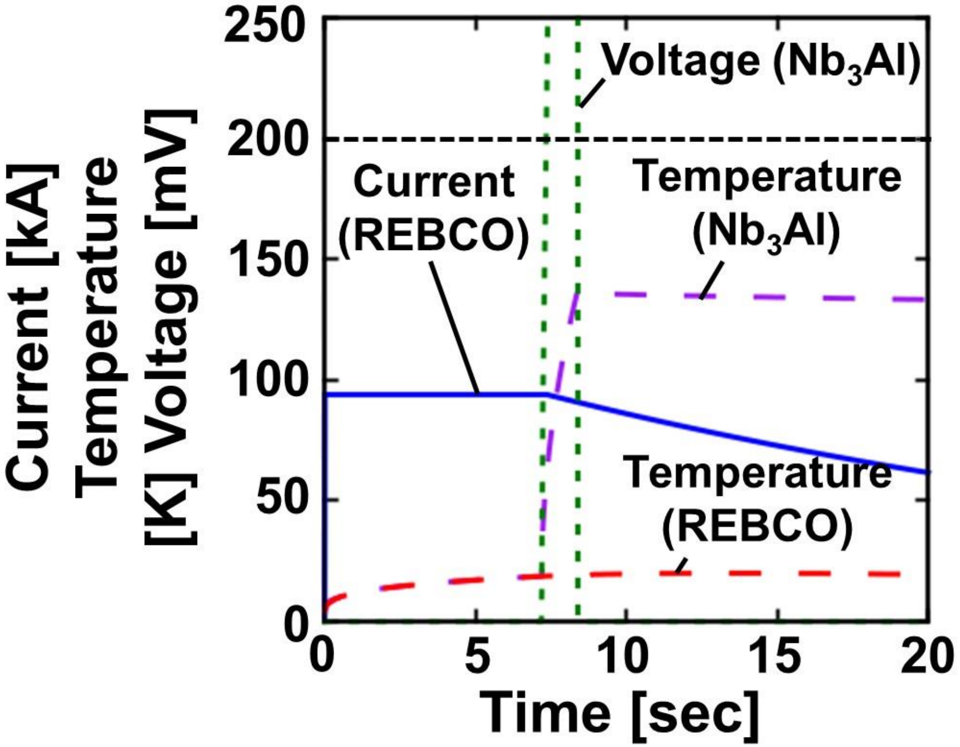
V_d = 100 mV at REBCO tape
➔ T_{max} = 155 K

V_d = 200 mV at REBCO tape
➔ T_{max} = 240 K

The temperature rise is slowly compared to single REBCO tape case because STARS conductor has massive metal jacket.

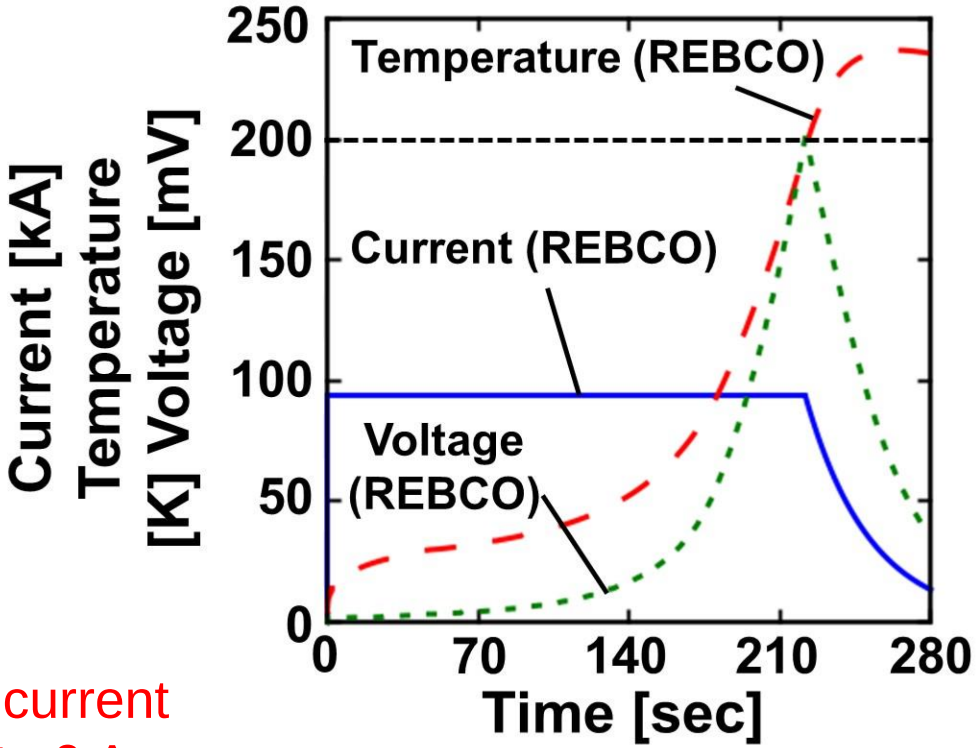
4. Applicability evaluation for a fusion reactor

4-3. Results (with Nb_3Al detector)



V_d = 200 mV (12 T)
(Load factor, I_m/I_c = 0.01)

The monitoring current I_m decreases to 0 A after quench detection



V_d = 200 mV

V_d = 200 mV at REBCO tape
➔ T_{max} = 240 K

Quench detection at Nb_3Al ➔ T_{max} = 20 K   Voltage of Nb_3Al = ~3 V (V_d = 1 V is OK)

➡ Achieving earlier quench detection & lower maximum temperature

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5. Summary

Proof-of-principle test of REBCO/LTS$_d$ tape

➡ The gradual temperature rise due to local degradation of I_c in a YBCO tape can be detected using a NbTi wire with high resistivity.

Material and field dependence of quench detectability

➡ Nb_3Al with high load factor is available as a quench detector at 4.2 K and upto 20 T for fusion HTS magnet.

Applicability evaluation for a fusion reactor

➡ Nb_3Al can detect quench of a STARS conductor with high voltage signals of 0.2-1.0 V and it can reduce the temperature rise to 20 K.

Future tasks

- Influence of variable field (AC loss) and strain to quench detectability
- Suitable position of the detectors depending on HTS applications
- HTS detectors used at elevated temperatures such as 20 K for FFHR-d1