Experimental study on quench protection of HTS magnet composed of multiple pancake-coils by use of auxiliary resistive shunt loop (ARSL) method

T. Ichikawa, A. Nomoto, H. Toriyama, T. Takao 1, K. Nakamura. O. Tsukamoto 1 and M. Furuse 2
1. Sophia University, Chiyoda-ku, Tokyo, Japan.2. National Institute of Advanced Industrial and Technology Lab., Tsukuba Ibaragi, Japan

Abstract

- ✓**A simulation experiment of a new quench protection method using ARSL was conducted. The method is that a current of a quenching sub-coil is quickly decreased by transferring its current to the other sub-coils of a magnet composed of multiple sub-coils.**
- ✓**Effectiveness of the new method was investigated by a simulation experiment using small scale test coils wound of YBCO tapes.**
- ✓**It was shown that the method can suppress hot-spot temperature and increase quench detection voltage to protect an HTS magnet from quench damage.**

Quench protection procedure of ARSL method

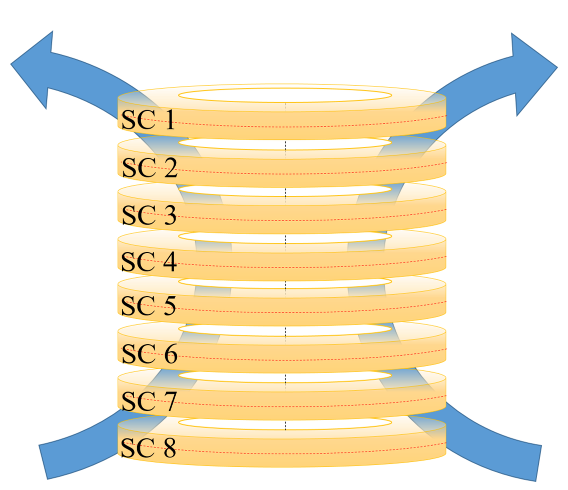


Fig. 1. Multiple pancake magnet composed of 8 Sub-coils and schematic illustration of magnetic flux of model magnet.

- ✓ Magnetic fields vertical to wide face of wires of Sub-coils (SC's) 1and 8 are larger than those of SC's 2-7.
- ✓ The critical currents I_c of SC's 1and 8 is smaller than those of SC's 2-7.

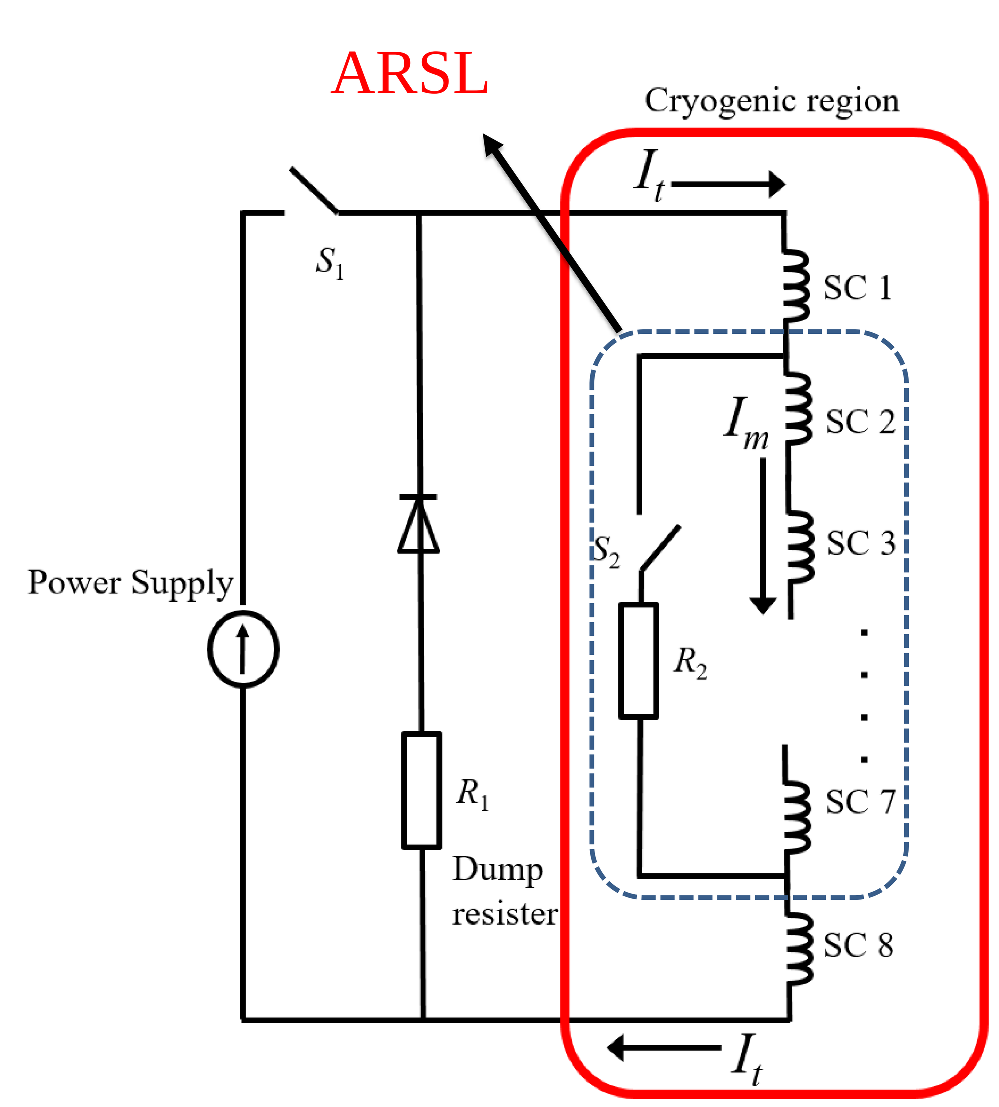


Fig. 2 . Circuit of new quench protection method using ARSL.

Sequence of ARSL method

1. SC 1 or 8 is quenching
2. Switch S1 is opened and S2 closed
3. Currents of SC's 1 and 8 with lower I_c are transferred to SC's 2-7 with higher I_c
4. Currents of SC's 2-7 increase while currents of SC's 1 and 8 decrease
5. SC's 1 and 8 are protected from quench damage

- ✓ Quench starts most probably in SC 1 or 8 because their I_c's are lower than those of SC's 2 - 7.

Hot spot temperature T_{HS} of the SC 1 or 8 can be suppressed by forming ARSL, because currents of SC's 1 and 8 are transferred to SC's 2 - 7

Case Study-Model Magnet

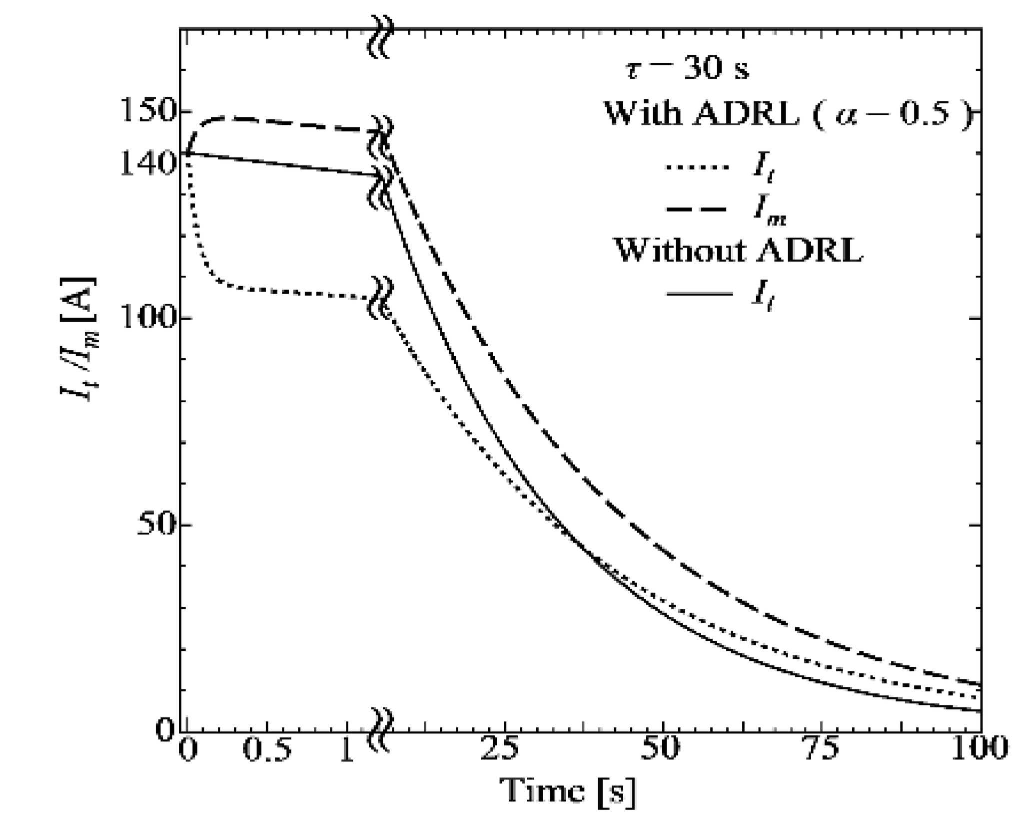


Fig. 3. Examples of calculated time evolutions of in case of I_t and I_m with and without ARSL during quench protection sequence.

SPECIFICATIONS OF MODEL MAGNET OF CASE-STUDY

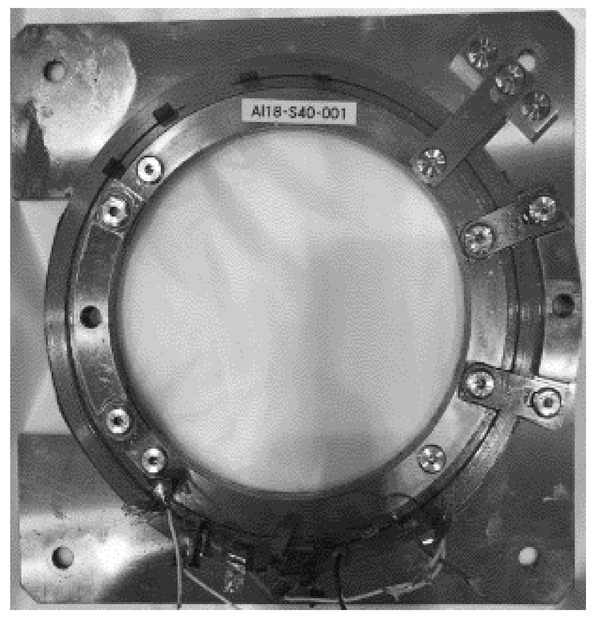
Wire	
Type	YBCO tape
Width	4.0 mm
Thickness	0.155 mm (Cu layer 80 µm thick)
Critical Current	≥ 165 A (at 77 K, self field)
Insulation layer thickness	25 µm
Composed magnet	
Number of sub coils	8
Height	98.6 mm
Withstand voltage	1 kV
Sub-coil	
Type	Double pancake-coil
I. D : O. D	500 mm : 612.8 mm
Number of turn	1300
Inductances	
・Composed magnet (L)	98.98 H
・Sub coil (L_s)	1.88 H
・Coil combined of Sub-coils 2-7 (L_m)	58.46 H

- ✓ In the case with the ARSL, current I_t flowing in SC's 1 and 8 starts to be transferred to SC's 2 - 7 and decreased quickly well below the value of I_t of the case without ARSL during the quench protection sequence .
- ✓ Current I_m flowing in SC's 2 - 7 becomes larger than I_t of the case without the ARSL
- ✓ There is a possibility that a quench occurs in one of SC's 2–7 due to the current transferred from SC's 1 and 8. This possibility needs to check.

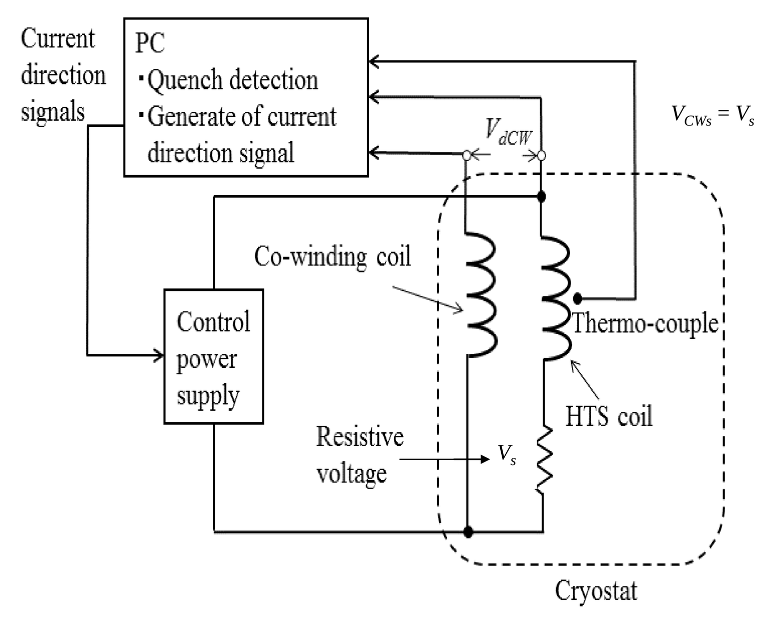
Simulation Experiment

SPECIFICATIONS OF TEST COIL

Single pancake-coil	
Inner diameter	120 mm
Outer diameter	136 mm
Number of turn	35
Height	4.4 mm
HTS tape (YBCO coater conductor)	
Width	4.0 mm
Thickness of Hastelloy substrate	75 µm
Thickness of Cu layer	80 µm
Critical current	>128 A (at 77.3 K, self field)
Insulation layer thickness (Kapton)	25 µm



(a) Test coil



(b) Test circuit

Fig. 4. Simulation experiment setup. Test coil and test circuit

Simulation experiment procedure

- ✓ Quench is started by heater and detected monitoring resistive voltage V_s exceeding quench detection threshold voltage V_q .
- ✓ A current of the YBCO test coil $I_t(t)$ is controlled by a controllable power supply (Fig. 4(a)) according to the same pattern of current during quench protection sequence of the model coil (Fig. 3) .

Thermal environment of the wires in the model magnet can be simulated by the test coils.
The hot-spot characteristics can be investigated by the experiment using the test coils.

Assumptions of local defect (A quench is triggered by a defect)

All sub-coils have the same size of defects

The same size means:

- Lengths of the defects (L_d) are the same.
- All defects have the same deterioration factor η .

$$\eta = (I_c - I_{Re}) / I_c$$

I_c: Critical current of no defect area

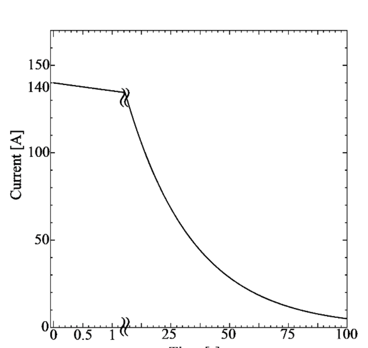
I_{Re}: Current at which a resistive zone start to spread at the defect area

(* **When I_c increases, I_{Re} increases.**)

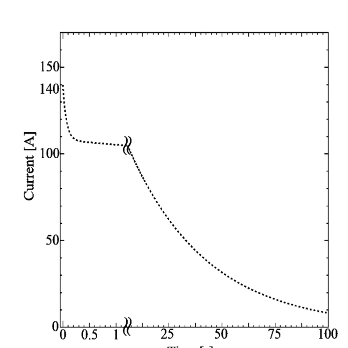
Values of I_{Re} of SC's 2 and 7 are 14% higher than that of SC's 1 and 8, because I_c of SC's 2 and 7 is higher than that of SC's 2 and 7.

Simulation Experimental Results

Behaviors of SC's 1 and 8



Without ARSL



With ARSL

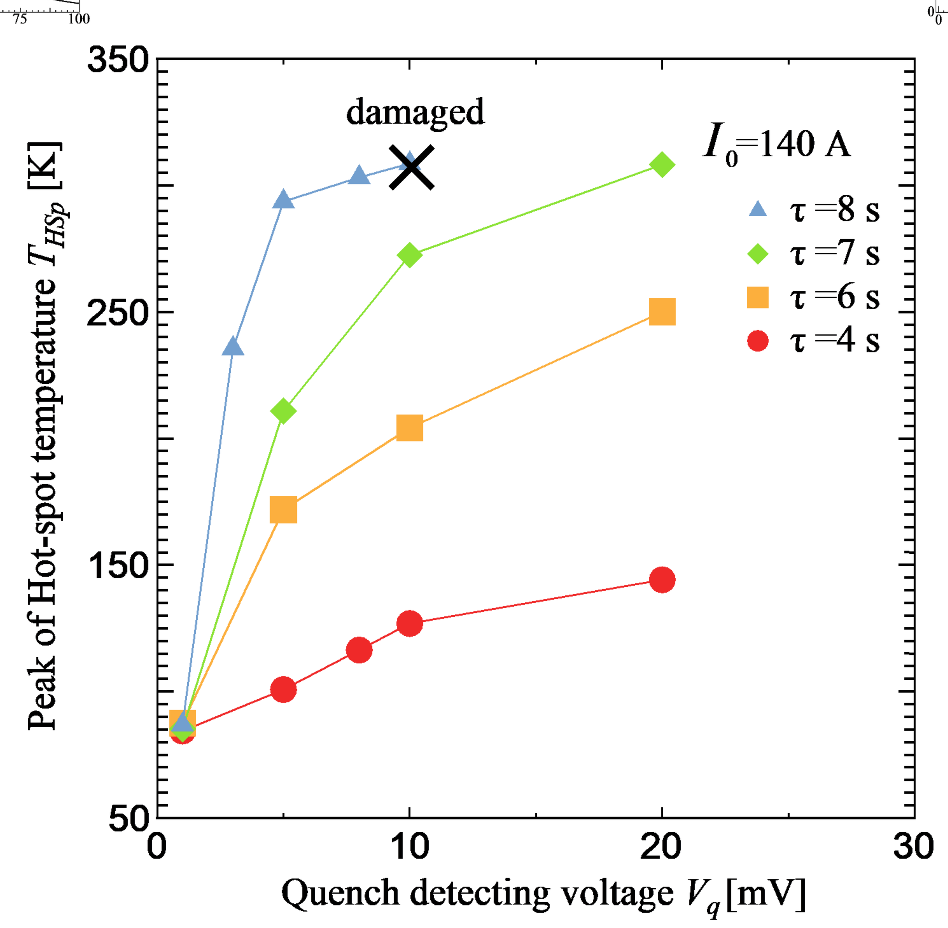


Fig. 5. Peak value T_{HSp} of T_{HS} vs. V_q for quench protection without ARSL for I_0 = 140 A and for various values of τ.

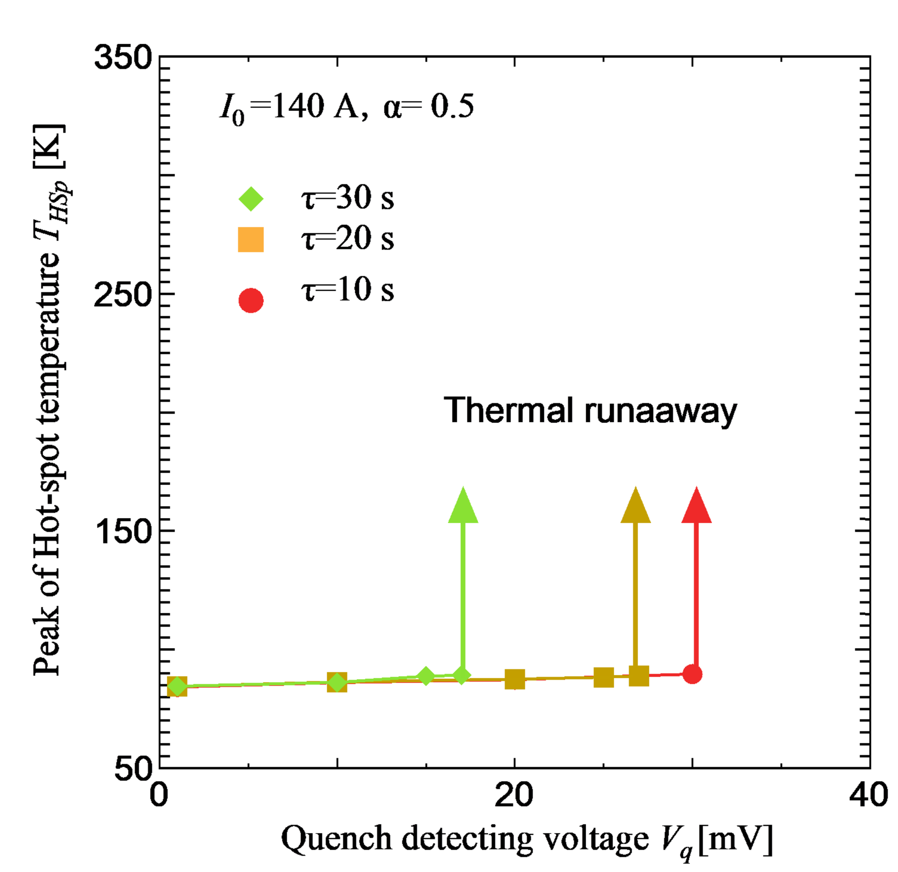


Fig. 6. T_{HSp} versus V_q for different values of τ for I_{0test} = 140 A. Thermal runaways occurred at the denoted points. Quench protection with ARSL

✓In the case without ASRL, test coil was safe at τ = 8 s and V_q = 8 mV and was damaged at τ = 8 s and V_q = 10 mV.

✓ By use of ASRL, V_q and τ are increased to 17 mV and 30 s, respectively, at α = 0.5 for the coil to be safe from quench damage.

Behaviors of SC's 2 and 7

Simulation of the defect with critical current (I_{Re})

✓ A defect was simulated by a heater inserted between the layers of the test coil. (The length of the heater 2 cm = L_d)

✓ Dependence of I_{Re} on the temperature at the heated T_{re} was measured (Fig. 7)

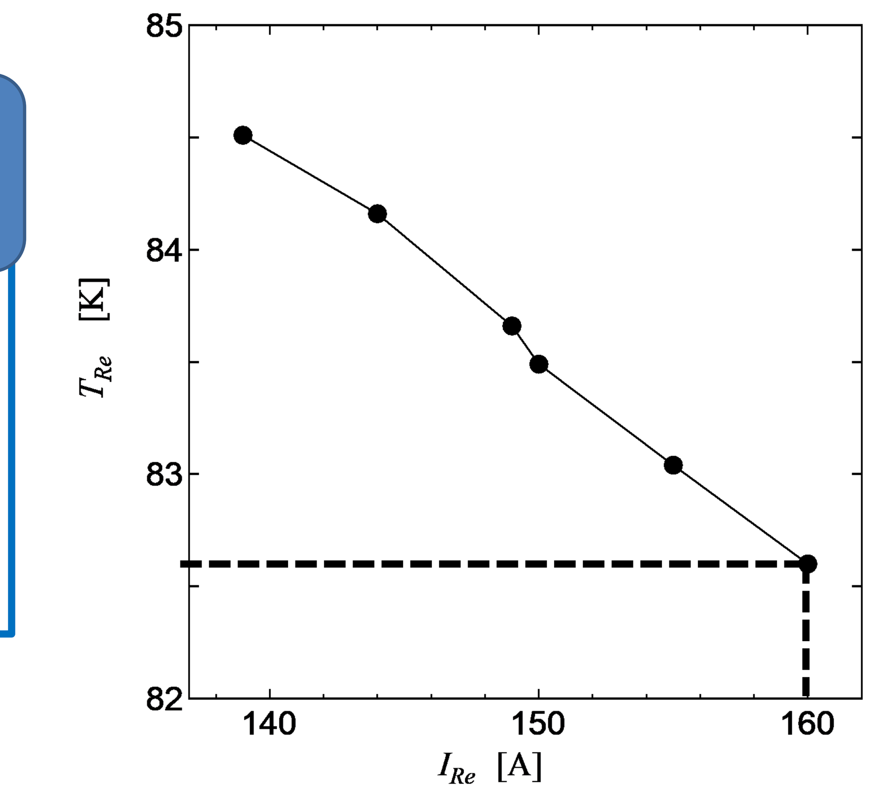


Fig. 7. Measured values of T_{re} plotted against I_{Re}

Hot spot temperature (T_{HS}) of SC's 2 and 7 to which the current was transferred from SC's 1 and 8

✓To check the possibility that SC 2 and or 7 is quenched by the transferred current, when SC 1 or 8 is quenched at the current I_0,

- Applying I_0 to the test coil, the wire was heated until T_{HS} became T_{Re} at I_{Re} (T_{Re} is 82.6 K at I_{Re} = 1.14 × 140 A, See Fig. 7).
- After that, the quench sequence started by putting the current to the test coil following to the current pattern of SC's 2 - 7 (Fig. 3).

Quench was not triggered in SC's 2 and 7 (See Fig.8)

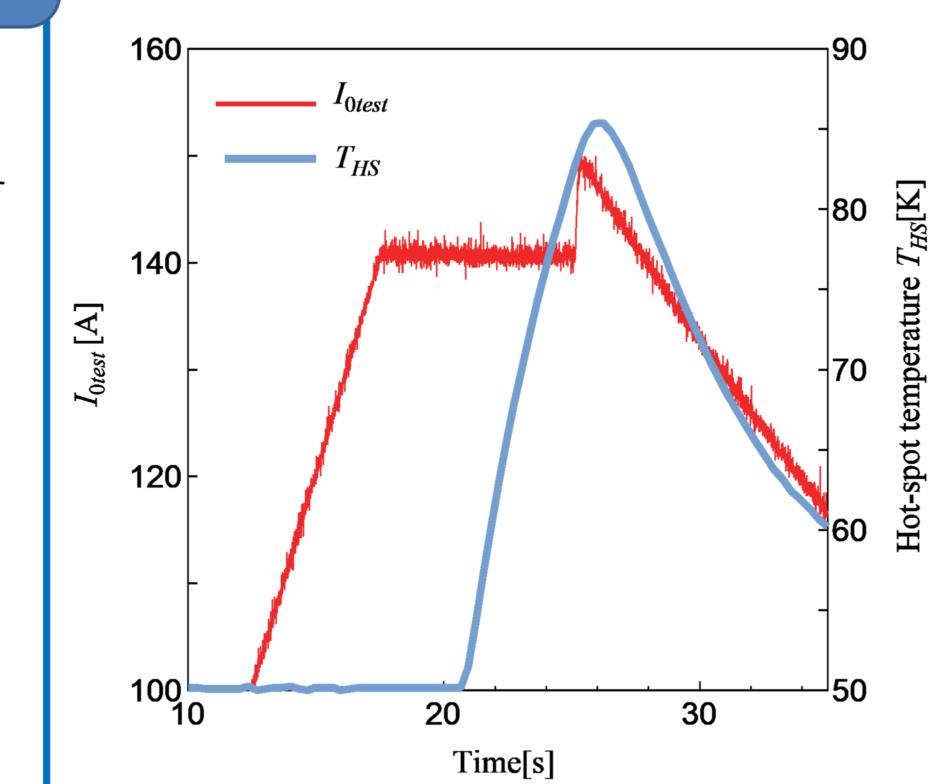


Fig. 8. Examples of time traces of I_{test} and T_{HS}. For the case of quench event of SC 2 or 7 due for I_0 = 140 A and τ = 30s. With ARSL of α＝0.5

Merits of ARSL

✓ In the case without ARSL, τ should be larger than 14 s to keep the peak terminal voltage V_{Cp} of the model magnet below the withstand voltage 1 kV for the operating current of 140 A. However, the magnet is damaged even with sensitive quench detection of V_q = 8mV.

✓ By use of ARSL method, the model magnet can be protected from the quench damages for much higher values of V_q = 0.17 mV for α = 0.5, and V_{Cp} is suppressed to 460 V well below 1 kV, while SC's 2 - 7 are not quenched by the transferred current.

Concluding Remarks

✓ Experiment is conducted by making small scale test pancake-coils wound with YBCO wires to simulate quench behaviors by putting the same pattern of currents calculated for the model magnet to the test coil .

✓ Experimental results show that the quench protection performance of the method with ARSL is much improved.

✓ In this study, the ARSL quench protection method is effective to suppress the hot-spot temperature and decrease the peak voltage during quench protection sequence, while increasing quench detection voltage to safely protect a magnet from quench damages.

Acknowledgment

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