Quench Protection System for a 13 T Magnet with a 700 mm Bore

S. Imagawa, *IEEE Member*, H. Chikaraishi, *IEEE Member*, T. Obana, S. Takada, and N. Yanagi

***Abstract*—A 13 T test facility with a 700 mm cold bore is being prepared for the research of high-field and high-current superconductors. Considering reuse of the existing cryostat, we select a pool-cooled and closely wound coil for the background field magnet to attain a large bore with the restricted outer diameter. The magnet is divided into two in the longitudinal direction and six in the radial direction. Rectangular monolithic conductors of Nb_3Sn and NbTi are selected for the inner six coils and the outer six coils, respectively. In order to reduce the highest voltage of the Nb_3Sn coil below 1.5 kV, the protection circuit of the Nb_3Sn coils is separated by a circuit breaker from that of the NbTi coils. In addition, the half of protection resistors for the Nb_3Sn coils is connected between the upper half and lower half of the Nb_3Sn coils. The quench protection system consists of eleven 1 kV DC circuit breakers, ten protection resistors, and two diodes. According to the quench analyses with taking account of heat transfer between layers and the effect of resistance of a propagating normal zone on the current, the highest temperature is considerably lower than the adiabatic hot spot temperatures.**

***Index Terms*—high magnetic field, hot spot temperature, quench analysis, quench protection.**

I. Introduction

HIGH FIELD and high current superconductors are needed for future fusion reactors. Degradation of critical currents of superconductors by electromagnetic forces was observed in the Nb_3Sn conductors for the ITER magnets [1], [2]. Degradation should be considered more seriously in the higher field magnets. Then, high field test facilities are necessary to examine the conductors for fusion reactors in real conditions.

A 13 T test facility with a cold bore of 700 mm is under preparation to examine coil-shaped conductor samples, as shown in Fig. 1 [3]. The highest field can be increased to 15 T by installing an additional coil with the cold bore of 600 mm. Considering reuse of the existing cryostat, we select a pool-cooled and closely wound coil for the background field magnet to attain a large bore with the restricted outer diameter. Since precise measurement of current sharing temperatures is needed for evaluation of the degradation of superconductors, the new test facility is equipped with a pair of temperature-variable current leads and a sample case inside the background field magnet. The conductor samples are cooled with pressurized helium, the supply temperature of which is variable from 4.4 K to 50 K by mixing the supercritical helium at 4.4 K and gaseous helium at medium temperature [4]. The nominal sample current is 50 kA, which can be increased up to 75 kA by installation of additional current feeder line from the third 25 kA unit bank of the power supply.

The background field magnet with the cold bore of 700 mm is designed to induce the highest field of 13 T at the operation current of 764.3 A. The total magnetic stored energy is 34.4 MJ. External protection resistors are adopted to reduce the loss of helium during quench protection. The reduction of the highest voltage in the magnet during shut off is crucial for such large closely wound coil. In this paper, the design of the quench protection system and analyses of temperature rise during quench are summarized.

II. Background Field Magnet

The design concept and the criteria for the closely wound background field magnet are as follows: (1) Monolithic conductors of NbTi and Nb_3Sn are adopted for outer and inner coils, respectively, in order to attain high current densities. (2) The adiabatic hot spot temperature is lower than 250 K. (3) Shut-off voltage between layers is lower than 150 V in order to adopt thin ceramic insulation for Nb_3Sn conductors. (4) Temperature margins of Nb_3Sn and NbTi conductors are larger than 2.0 K and 1.0 K, respectively. (5) Hoop stress of supporting cases made of SUS316 is lower than 600 MPa. (6) Tensile strain of Nb_3Sn by the electromagnetic force is less than 0.35% in order to maintain high critical currents.

The magnet is divided into two parts in the longitudinal direction to decrease the shut-off voltage between layers. In addition, each is divided into six concentric solenoid coils to support the conductors with thick cases made of SUS316, as shown in Fig. 2a. Since the large current is preferred to reduce the shut-off voltage, the largest rectangular monolithic conductors in the lineups are selected. The copper ratio of the Nb_3Sn conductor is set at 0.9 to attain the temperature margin of more than 2 K at 15 T at the operation current of 760 A. In order to reduce the shut-off voltage, the copper ratio of the NbTi conductor is set at 2.4, and the dumping time constant of the outer coil is 15 s, which is almost three times as long as the inner coil. The residual resistance ratios of Nb_3Sn and NbTi conductors are higher than 196 and 181, respectively.

The highest field can be increased to 15 T by installing an additional coil with the cold bore of 600 mm, as shown in Fig. 2b. All the coils except the outermost coil are supported by individual cases, the thicknesses of which are 16 mm, 15.3

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mm, 12.6 mm, 7.6 mm, 6.6 mm, and 6.2 mm from the inside. The length of the innermost coil of the NbTi coils, SC21 is shortened to reduce the highest field lower than the next coil, SC22. The layer/turn numbers of the coils are 12/89, 12/78, 12/83, 10/83, 10/58, 16/116, and 16/116 from the inside. The turn numbers of coils are adjusted to minimize the total number of drums of conductors. The final design is listed in Tables 1 and 2. The total magnetic stored energy is 34.4 MJ and 40.1 MJ for the highest field of 13 T without SC11 and 15 T with SC11, respectively.

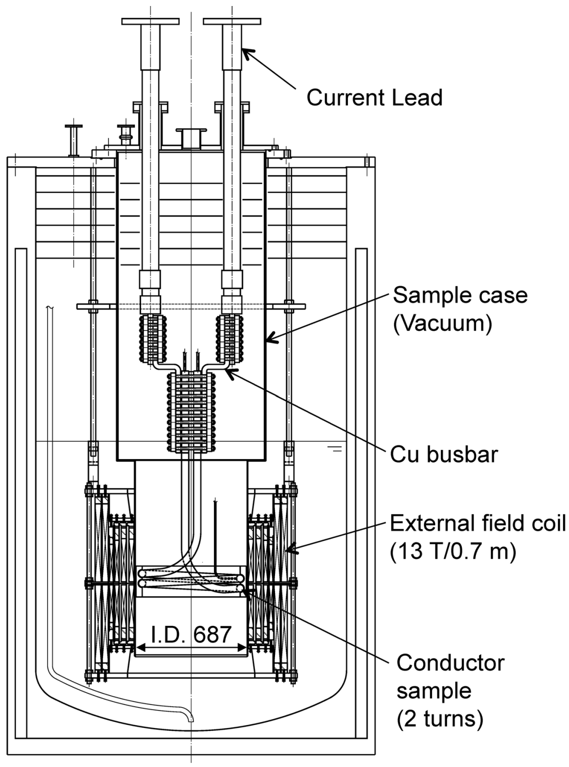

Fig. 1. Setup of the new test facility with a 13 T–700 mm background field magnet, 75 kA current leads, and a sample case. A coil-shaped conductor sample is planned to be fixed to the current leads.

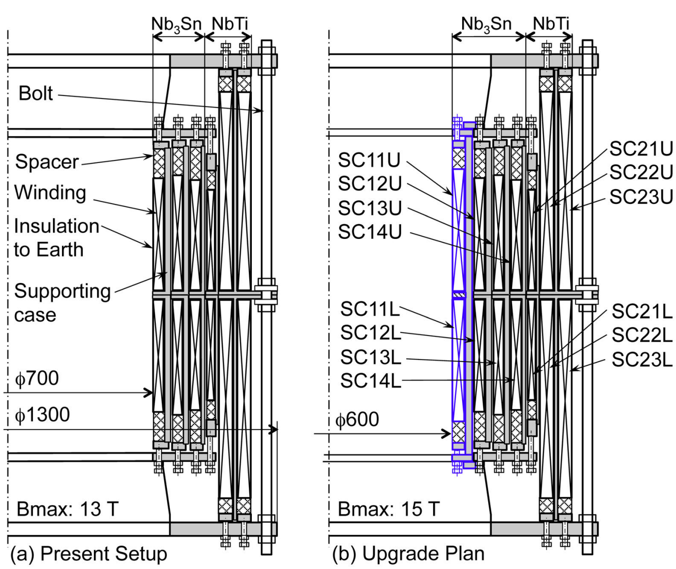

Fig. 2. Cross-section of the present background field magnet (a). The highest field is planned to be increased to 15 T by adding an insert coil (b).

TABLE 1. MAJOR PARAMETERS OF THE BACKGROUND FIELD MAGNET WITH THE INNERMOST COIL, SC11 (WITHOUT SC11)

	Inner coil	Outer coil
Superconductor	Nb_3Sn	NbTi
Maximum field, B_{max} (T)	15.0 (13.0)	6.85 (6.73)
Stored energy (MJ)	16.4 (12.0)	23.8 (22.5)
Self inductance (H)	28.8 (18.0)	54.2
Mutual inductance (H)	27.9 (22.9)	←
Cu/SC ratio (-)	0.9	2.4
Winding inner diameter (m)	0.606 (0.702)	0.957
Winding outer diameter (m)	0.933	1.176
Magnetomotive force (MA)	5.83 (4.29)	6.53 (6.57)
Operating current, I_{op} (A)	760.0 (764.3)	760.0 (764.3)
Conductor width (bare) (mm)	3.2	4.0
Conductor height (bare) (mm)	2.1	2.0
Layer insulation (mm)	0.2	0.1
Insulation to earth (mm)	> 0.8	> 0.8
Coil current density (A/mm^2)	93.1 (93.6)	88.4 (88.9)
Dump resistance (ohm)	8.0 (5.6)	6.0 (5.6)
Voltage between layers (V)	149 (138)	131 (122)
Allowable voltage to earth (V)	1,500	2,500

TABLE 2. INDUCTANCE MATRIX [UNIT: H]

	SC11	SC12	SC13	SC14	SC21	SC22	SC23
SC11(U+L)	1.90	1.63	1.58	1.24	0.847	2.15	2.05
SC12(U+L)		2.01	1.95	1.51	1.04	2.56	2.44
SC13(U+L)			2.67	2.10	1.44	3.50	3.35
SC14(U+L)				2.18	1.51	3.60	3.44
SC21(U+L)					1.33	2.97	2.84
SC22(U+L)						10.07	9.80
SC23(U+L)							11.54

III. QUENCH PROTECTION SYSTEM

A. *Quench Protection Circuit*

Quench heaters on superconducting magnets and/or protection resistors inside cryostat are commonly used for closely wound coils such as MRI magnets [5], [6]. External protection resistors, however, are adopted to reduce the loss of helium and to avoid huge safety valves.

The protection circuit for the 13 T - 700 mm magnet is shown in Fig. 3. In order to decrease the highest voltage of the inner coil lower than 1.5 kV, the protection circuit of the inner coil is separated by a circuit breaker from that of the outer coil. In addition, the protection resistor for the inner coil is divided into two halves, which are alternately connected in series with the upper half and lower half of the inner coil. The values of the protection resistors are determined to maintain the adiabatic hot spot temperatures below 250 K. For flexibility and maintainability, general DC circuit breakers with the nominal current of 800 A and shut-off voltage of 1 kV are adopted. Each breaker is connected in parallel to the resistor of 1.0 or 1.2 ohm. The quench protection system consists of eleven DC circuit breakers, ten protection resistors, and two diodes. When the magnet is upgraded to 15 T - 600 mm setup, another set of resistors is added in series, as shown in Fig. 4.

B. *Quench Detection*

The balance voltage between the upper coil and the lower coil is used for detection of the coil quench. In the protection circuit for 13 T (Fig. 3), two quench detectors are adopted, and each monitors the balance voltage between the upper three coils and the lower three coils in the Nb_3Sn or NbTi coils. In the circuit for 15 T (Fig. 4), another quench detector is needed to monitor the balance voltage between SC11U and SC11L.

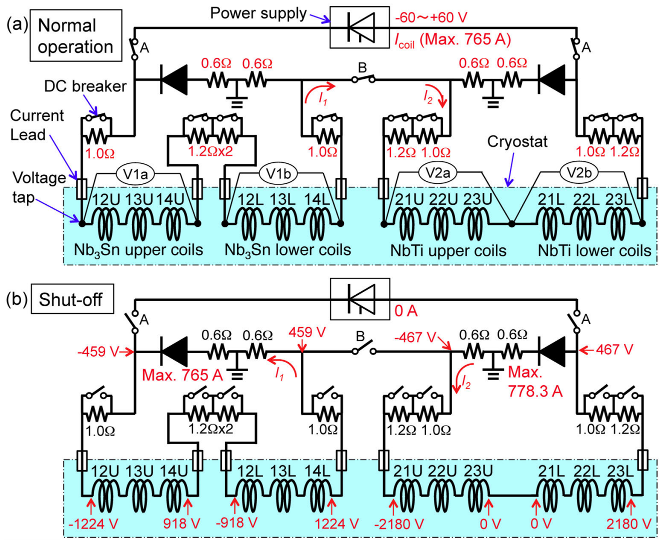

Fig. 3. Quench protection circuit for the 13 T-700 mm setup. All breakers are closed at normal operation (a) and opened at shut-off (b).

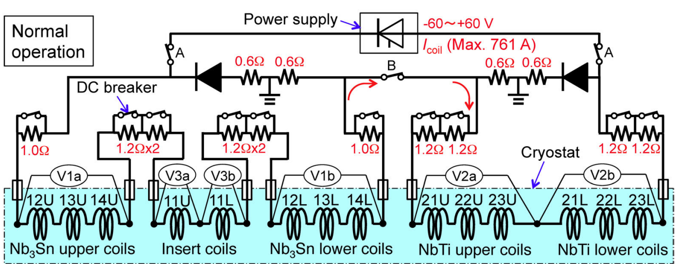

Fig. 4. Quench protection circuit for the 15 T-600 mm setup.

IV. Quench Analysis

A. Analysis Model

It is known that the adiabatic hot spot temperature, which is estimated under the adiabatic condition, is considerably higher than the real temperature. For more precise estimation, finite difference models have been developed with taking account of the heat transfer between the layers and the effect of coil resistance caused by propagation of a normal zone. The heat balance equations are solved by using the coil currents calculated by considering the coil resistance at each time step. The propagation velocity in the longitudinal (θ in Fig. 6) or turn-to-turn (z in Fig. 6) direction is estimated by analytical equation under adiabatic condition [7]. The temperature distribution in the z direction under the adiabatic condition can be calculated by using the propagation velocity, as shown in Fig. 5a. The resistance $R(z)$ can be fitted by

$$R(z) = R_0 + (R(0) - R_0)(1 - z/L)^a \qquad (1)$$

with z: position in the turn-to-turn direction, L: length of the normal zone, and R_0: resistance at 4 K. The regressed power coefficient a is 1.7 for Nb_3Sn conductor, as shown in Fig. 5b, and 2.0 for NbTi conductor. In order to consider the temperature distribution in one turn (θ direction in Fig. 6), the temperature at the opposite side to the start point of the propagation is calculated in parallel, and their average temperature is adopted to estimate the coil resistance.

Two simulation models have been developed. In Model 1, only the quenched coil is considered. In Model 2, all coils are considered, and heat transfer between the coils is considered. Since the gap between the coils is narrow (2 to 3 mm), heat transfer coefficient of 100 W/m^2/K, which is a typical value for natural convection of gaseous helium to the vertical plate, is used for the heat transfer between the coil case and the insulation of the next coil. The heat transfer in liquid helium is used for the innermost and outermost surfaces. In both models, the metal plate between the upper and lower coils is ignored. As the worse cases, a normal zone is induced at the end turn, and the normal zone propagates to one side, as shown in Fig. 6.

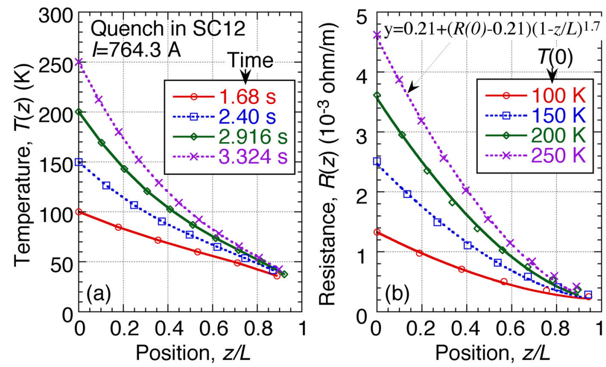

Fig. 5. Distribution of temperature (a) and resistance per unit length (b) along a normal zone propagating from the end turn in SC12.

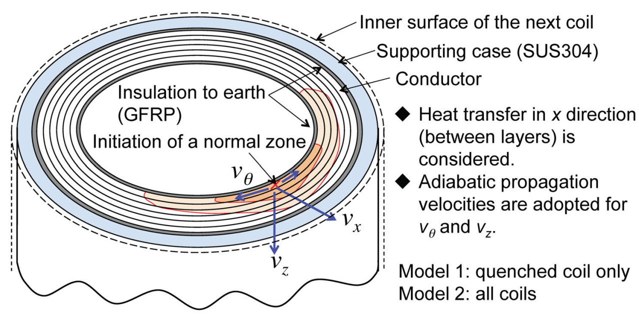

Fig. 6. Schematic drawing of analysis model.

B. Calculated Results

Simulation results are shown in Figs 7a, 7b, 8a, and 9a for the coil quench in SC12 and Figs. 8b and 9b for SC21, respectively, which are the most probable events. Initial temperature of a normal zone is set at 20 K for a Nb_3Sn conductor and 10 K for NbTi. The delay of shut off after initiation of a normal zone is set 0.4 s, considering the time for the resistive voltage to exceed the quench detection voltage of 0.2 V and the duration of 0.2 s for validation. The temperature difference in the layers is around 30 K, as shown in Fig. 7. The effect of surface cooling on the highest temperature is small, because the temperature gradient is formed in the layers. As the results for the quench in SC12 with Model 2, it takes 3.7 s for the normal zone to propagate to the next coil due to slow propagation velocity of the Nb_3Sn conductor. Therefore, both the highest temperature and the current are almost the same between Model 1 and Model 2. In the case of quench in SC21, the faster propagation of a normal zone in the NbTi conductor results in substantial increase of coil resistance that accelerates the current decay of the NbTi coils.

According to the simulation, the highest temperatures during quench protection are estimated at lower than 150 K in both Nb_3Sn and NbTi coils, whereas the adiabatic hot spot temperatures are higher than 230 K. The heat transfer between layers reduces the peak temperature in the layers, and the effect of the coil resistance on the current plays an important role to reduce the total heat generation at the hot spot region.

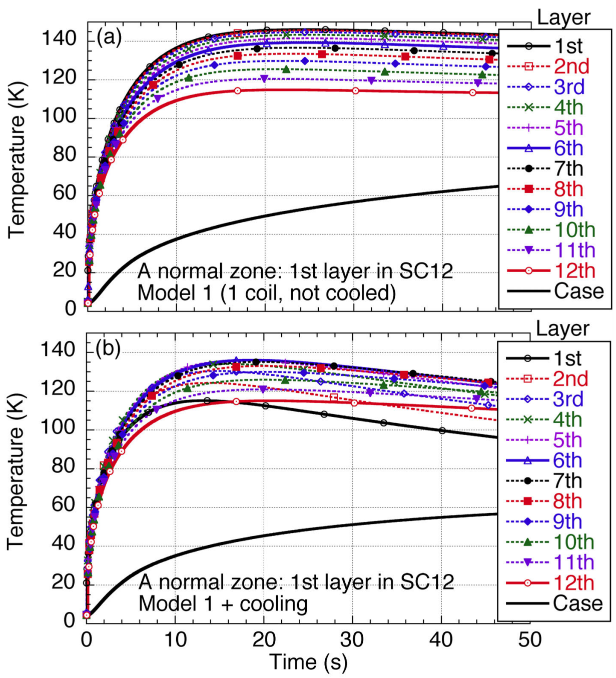

Fig. 7. Calculated currents and temperatures during shut off at 13 T-700 mm set-up with Model 1 without (a) and with (b) cooling effects.

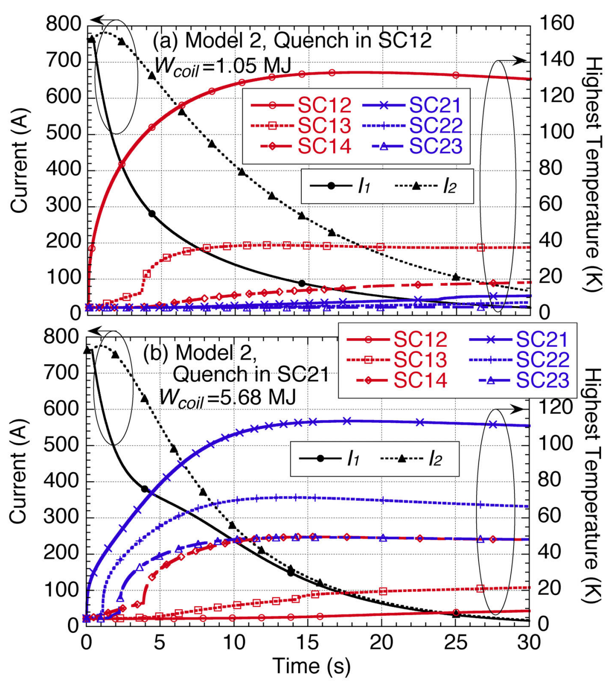

Fig. 8. Calculated currents and temperatures during shut off at 13 T-700 mm set-up with Model 2 (all coils) for the quench in SC12 (a) and SC21 (b). I_1 and I_2 are the currents for Nb_3Sn and NbTi coils, respectively. W_{coil} is the dissipated energy in the coils. A normal zone is induced at the end of each innermost conductor.

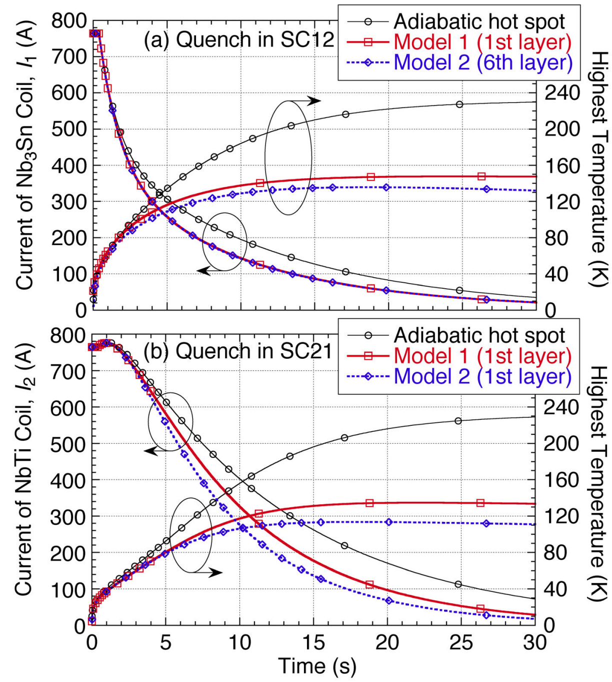

Fig. 9. Comparison of currents and temperatures among hot-spot model, Model 1 (1 coil), and Model 2 (all coils) for the quench in SC12 (a) and SC21 (b).

V. Conclusion

A flexible quench protection system using general DC circuit breakers has been designed for a 13 T magnet with a 700 mm bore. In order to decrease the highest voltage in the Nb_3Sn coil less than 1.5 kV, the protection circuit of the inner Nb_3Sn coils is separated by a circuit breaker from that of the outer NbTi coils. In addition, the half of protection resistors for the Nb_3Sn coils is connected between the upper half and the lower half of the Nb_3Sn coils. Two types of finite difference models have been developed for quench analyses with taking account of heat transfer between layers and the effect of resistance of the normal zone. According to the analyses, the highest temperatures of both coils are estimated at lower than 150 K whereas the adiabatic hot spot temperatures are higher than 230 K. In addition, the highest temperature is decreased by considering the propagation of a normal zone to neighbor coils, especially for the case of quench in NbTi coils because of rapid propagation velocities.

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