§21. Quench Analysis of A 13 T Superconducting Magnets with A 700 mm Bore

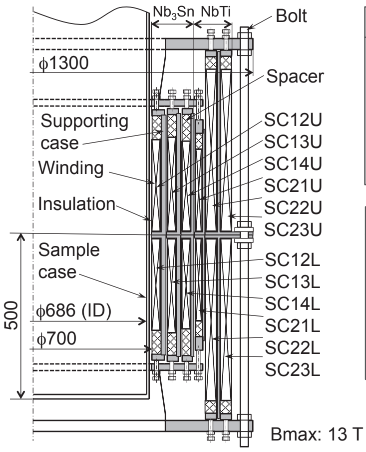
Imagawa, S., Obana, T., Takada, S., Yanagi, N.

A 13 T test facility with a 700 mm cold bore is being prepared for the research of high-field and high-current superconductors[1]. 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, as shown in Fig. 1. 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, as shown in Fig. 2[2]. 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. For flexibility and maintainability, general DC circuit breakers with the nominal current of 800 A and shut-off voltage of 1 kV are adopted.

The values of the protection resistors are determined to maintain the adiabatic hot spot temperatures below 250 K. For more precise estimation of the temperature rise, 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 or turn-to-turn (radial) direction is estimated by analytical equation under adiabatic condition, and the temperature distribution in the vertical direction can be estimated with the regression curve that is obtained from the one-dimensional analysis.

Simulation results are shown in Figs 3a, 3b for the coil quench in SC12 and 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. 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, it takes 3.7 s for the normal zone to propagate to the next coil, SC13 due to slow propagation velocity of the Nb_3Sn conductor. Therefore, the effect of the propagation to the next coil is small for Nb_3Sn coils. 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.

1) Imagawa, S. et al.: Plasma and Fusion Research, Vol. 10 (2015) 3405012.
2) Imagawa, S. et al.: IEEE Transactions on Applied Superconductivity, Vol. 26 (2016) Art. ID. 4701504.



Nb_3Sn coil	
Maximum field (T)	13.0
Stored energy (MJ)	12.0
Self inductance (H)	18.0
Cu/SC ratio (-)	0.8-0.9
Operating current (A)	765
Weight (tons)	1.9

NbTi coil	
Maximum field (T)	6.73
Stored energy (MJ)	22.5
Self inductance (H)	54.2
Cu/SC ratio (-)	>2.2
Operating current (A)	765
Weight (tons)	2.9

Fig. 1 Cross-section of the external field coils. The highest field is planned to be increased to 15 T by installing an innermost coil SC11.

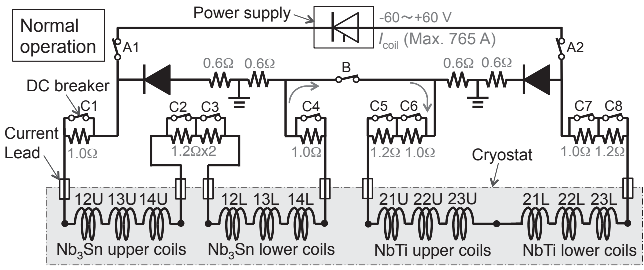


Fig. 2 Quench protection circuit for the 13 T-700 mm setup. All DC breakers are opened for shut-off.

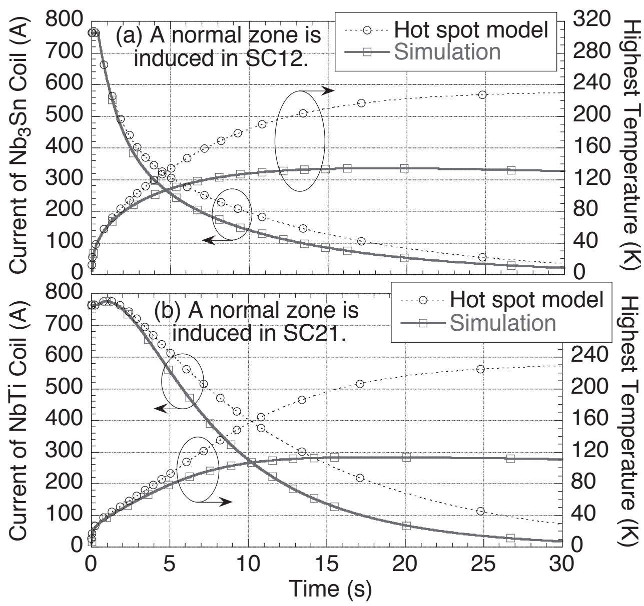


Fig. 3 Calculated currents and temperatures during shut off after quench in SC12 (a) and SC21 (b).