Thermohydraulic behaviour of the cryogenic system during protected quenching of the superconducting magnet of a hybrid magnet

J Li, Z Ouyang and W Chen
High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei 230031, China

E-mail: lijj@hfcas.ac.cn

Abstract. The superconducting outsert of the hybrid magnet at CHMFL is cooled by 4.5 K supercritical helium contained in CICC (cable-in-conduit conductors), which must be capable of extracting any heat load (external and internal) during ramping and high field operating. In the event that the heat loads exceed the cooling capacity of the supercritical helium, superconducting transitions on CICC may happen and a quench protection will be triggered by the control system. The process will cause high heat input in a very short time to the supercritical helium, and consequently, large temperature and pressure fluctuations will occur in the related cryogenic system. In order to test the performance of the cryogenic system during the process of superconducting magnet quenching, quenching experiments with design operating currents of the superconducting magnet were carried out. The testing results shows that the helium cryogenic system can keep a stable operation in the worst protected quenching of the superconducting magnet, and also return to the normal situation automatically.

1. Introduction
In 2008, the High Magnetic Field Laboratory of Chinese Academy of Sciences (CHMFL) was started to be built with two missions: developing series of high field magnets (a hybrid magnet, four superconducting magnets and five water-cooled magnets), and doing research on physics, functional material, chemistry, life sciences and pharmacology in extreme high magnetic field [1]. The hybrid magnet at the CHMFL consists of a resistive magnet, and a superconducting magnet with a clear bore of 800 mm. The superconducting magnet contains four separate coils, all using Nb₃Sn cable-in-conduit conductor (CICC) technology [2-5]. The coils are totally divided into 26 cooling-channels which are hydro-dynamically connected in parallel, and cooled by forced-flow helium at 4.5 K in a closed loop [6-9].

All the installation work of the hybrid magnet and its helium cryogenic system were finished on September 30, 2016. Twenty-three days later, the superconducting coils were cooled to 4.5 K from room temperature. On 13 November 2016, 40T of magnetic field was achieved for the first time in the centre of the 32mm bore of the hybrid magnet. The superconducting coils operated only with current of 12.2 kA and contributed 10T on axis. The hybrid magnet was put into running as a research tool in early 2017. After one year of successful operation, the superconducting magnet was planned to increase the current to its design value (13.4 kA, 11 T) for the target of 45 T hybrid magnet. In order to test the performance of the cryogenic system during the process of superconducting magnet quenching, quenching experiments with design operating currents of the superconducting magnet were carried out
on 14 May 2018. In this paper, details of the thermo-hydraulic behaviour of the cryogenic system are presented.

2. Quenching test

Figure 1 shows the electrical circuit and cooling circuit of the superconducting CICC coils. The coils are forced-flow cooled in J-T cooling loop. When the coils are cooled to 4.5 K, it is charged by a DC current source with a maximum capacity of 16 kA. In parallel to the current source, an energy dump resistor (0.284 Ω) is configured to remove the stored energy out of the coils after a quenching. In a normal operation mode, the coils will produce 11 T magnetic field with storing 92.6 MJ energy totally.

In order to test the performance of the magnet, the current source and the helium cryogenic system after a quenching, we switch off the two breakers in the electrical circuit to simulate a quenching. Then the current in the coils decreases exponentially, and reaches 36.8% of the operating current in 3.6 s. 99.9% of the energy is transferred to the external resistor, and only 0.1% (~100 kJ) of the energy heats the coils in the way of eddy current (Figure 2).

![Figure 1](image1.png)

**Figure 1.** Schematic electrical circuit and cooling circuit of the superconducting CICC coils.

![Figure 2](image2.png)

**Figure 2.** Current change in the coils and heat produced on the energy dump resistor with time.

3. Behaviour of the cryogenic system after a protected quenching
The heat is transferred to the helium which encloses the superconducting cables, and causes a high pressure in the void space of the conduits of CICC coils. The results are that the temperature, the pressure and the flow field distribution in the whole cryogenic circuits are changed [10].

3.1. Behaviour of the cryo-distribution box

Figure 3. pressure and temperature change in the circuit of cryo-distribution box.

For the first tens of seconds, the heated helium flows to the pipes connected to the both ends of the coils, and makes fast temperature and pressure raises in the pipes. As is shown in Figure 3, the inlet pressure increases from 4.2 bar to 12.7 bar, at the same time the outlet pressure rises from 3 bar to 10.7 bar. The maximum temperature at the inlet and outlet pipes are 7.2 K and 9.7 K respectively. Warm helium flows into the liquid helium buffer and makes massive amounts of helium vapors. The pressure of the buffer increases from normal 1.26 bar to 1.42 bar in 2 minutes. In the whole process, about 60 L liquid helium are evaporated.

3.2. Behaviour of the cryoplant

As is shown in Figure 4, too much evaporated cold helium makes all the heat exchangers inside the coldbox too cold. The temperature of the pre-cooling stage decreases to 70 K, but usually it should be at 77-80 K since it is cooled by liquid nitrogen. The temperature change on the heat exchangers is shown in Figure 5(a). Vacuum of the MLI space of the coldbox become better because more of the residual gas is captured at a very low temperature (Figure 5(b)).

Figure 4. Flow chart of the cryoplant.
The situation change on the cryogenic circuit of coldbox also gives rise to fluctuations on the operating of turbines (speed, inlet/outlet pressure, inlet/outlet temperature, bearing temperature, braker temperature) which are shown in Figure 6.

![Figure 5. Temperature(a) and vacuum(b) change of the coldbox.](image)

![Figure 6. Situation of the turbines.](image)
3.3. Behaviour of the compressor station
As is shown in Figure 7, only small pressure fluctuations happened to the discharge side(PT290) and the charge side(PT105) of the compressor. The by-pass valve PCV275 closed ~10% to increase the discharge capacity of the compressor to recovery the gas helium caused by quenching. The unload valve PCV289 opened ~6% to transfer the gas helium to the buffer tank.

![Graphs showing compressor station behaviour](image)

Figure 7. Situation of the compressor station.

4. Summary
During quenching protection of the superconducting coils with design operating current, the helium cryogenic system can response successfully. Fluctuations are drastic, but not enough to make failures or emergency stop of helium cryogenic system. The system will take 30 minutes or more to recover to a normal mode completely.

References
[1] Kuang G 2010 IEEE Trans. Appl. Supercond. 20 680-3
[2] Tan Y, Chen W, Zhu J, Chen Z M, Pan Y, Wang F, Chen Z Y, He P, Ren Y and Kuang G 2011 IEEE Trans. Appl. Supercond. 21 2020-3
[3] Ren Y, Kuang G, Chen W, Wang F and Chen Z Y 2013 IEEE Trans. Appl. Supercond. 23 19-25
[4] Zhu J, Chen W, Pan Y, Huang P and Kuang G IEEE Trans. Appl. Supercond. 2014 24 67-71
[5] Tan Y, Wang X, Fang Z, Chen W, Qin J, Wang F, Pan Y, Chen Z M, Chen Z Y, Zhu J, Huang P, Zou G and Kuang G IEEE Trans. Appl. Supercond. 2015 25 1-4
[6] V. Kalinin, E. Tada, F. Millet, and N. Shatil Fusion Engineering and Design. 2006 81 2589-2595
[7] Zahn R and Heller R 2003 Proc. 19th Int. Cryogenic Engineering Conf. (Grenoble, France, 2002) ed Bagurer G and Seyfert P (New Delhi: Narosa Publishing House) 151-156
[8] Bai H, Bird M D, Cantrell K R, Dixon I R and Gavrilin A V 2009 IEEE Trans. Appl. Supercond. 19 1596-9
[9] Bai H, Bird M D, Bolte S T, Cantrell K R, Dixon I R, Gavrilin A V, Painter T A and Xu T 2009 Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conf. (Tucson, USA, 28 June-2 July 2009) ed Weisend J (New York: AIP Publishing LLC) 55 1231-1238
[10] Li J, Xie Y, Ouyang Z, Li H, Meng Q, Shi L, Ai X, Fang M, Chen X, and Kuang D 2018 IEEE Trans. Appl. Supercond. 28 08241385.