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Hotspot temperature calculation and quench analysis on ITER busbar

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HIGHLIGHTS

- The hotspot temperature is calculated in the case of different extra copper in this paper.
- The MQE (minimum quench energy) is carried out as the external heating to trigger a quench in busbar.
- The temperature changes after quench is analyzed by Gandalf code in the case of different extra copper and no helium.
- The normal length is carried out in the case of different extra copper by Gandalf code.

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ABSTRACT

This paper describes the analysis of ITER feeder busbar, the hotspot temperature of busbar is calculated by classical method in the case of 0%, 50%, 75% and 100% extra copper (copper strands). The quench behavior of busbar is simulated by 1-D Gandalf code, and the MQE (minimum quench energy) is estimated in classical method as initial external heat in Gandalf input file. The temperature and the normal length of conductor are analyzed in the case of 0%, 50% and 100% extra copper and no helium. By hotspot temperature, conductor temperature and normal length are contrasted in different extra copper cases, it is shown that the extra copper play an important role in quench protecting.

1. Introduction

Feeder systems provide power for ITER (International Thermonuclear Experimental Reactor), and busbar is a crucial component of feeder system, which adopted a superconducting CICC (cable-in-conduit conductor) [1]. The toroidal field (TF), poloidal field (PF), and central solenoid (CS) coil busbar are called main busbar (MB), and the corrector coil (CC) busbar called corrector busbar (CB) [2]. Superconducting busbar should work in superconducting state, however, inevitably it quenches partly because of thermal or electromagnetic perturbation, so it is necessary to investigate the quench behavior of busbar. What we study in this paper is whether it can restore the superconducting state after quench, the allowable hotspot temperature after quench is one of the important design criteria to determine the amount of extra copper (copper strands), the extra copper is shown in Fig. 1. Analytical methods to calculate the hotspot temperature of ITER TF coil have been proposed in several papers [3–5], however there are no detailed calculations on busbar of ITER. In this paper, hotspot temperature of busbar is studied.

2. Hotspot temperature in classical method

The hotspot temperature of busbar is calculated in adiabatic condition and exponential current decay at fast discharge, and in classical method, only discharge time is considered. Because the heat capacity of helium coolant is much smaller than that of cooper and NbTi up to room temperature, the helium effect on the strand cooling is neglected. And compared to copper and NbTi, Ni coating has a very small cross-section, so it is neglected too. After quench, the temperature at busbar is given by following equation [3,4]:

$$\frac{J_{\mathrm{cu}}^2\tau_0}{2}=\int_{T_0}^{T_m}\frac{\bar{C}(T)}{\rho(T)}dT$$

where ρ is the resistivity of copper, $\bar{C}$ is the average specific heat per unit volume, τ_0 is time constant of current exponential, the quench starts at temperature T_0, and J_{cu} is the current density after quench.

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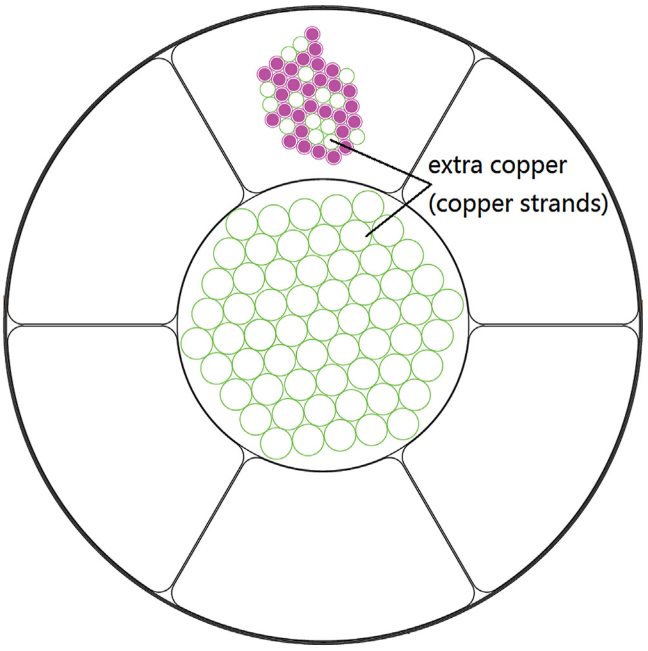

Fig. 1. The extra copper (copper strands) in the cable.

Table 1
The parameters of the busbar.

Items	MB (TF)	CB
SC strand		NbTi/Cu
Nominal peak field (T)		2.9
Inlet temperature (K)		4.5
Critical temperature (K)		9.25
Cu to non-Cu of strand		2.35
Busbar length (for the worst case) (m)	30	47
Design current (kA)	68	10
Discharge time constant (s)	11	14
SC cross-section (mm^2)	111.2	26.7
Cu cross-section (mm^2)	671.0	107.4
He cross-section (mm^2)	465.7	74.4 (bundle), 19.6 (hole)

The highest hotspot temperature allowable is 150 K according to the ITER design criterion, and 250 K in the adiabatic condition [2]. We defined the hotspot temperature is the maximum allowable temperature of the strand. The current in TF coil is much greater than that in PF and CS coils, so in this paper, only MB in TF coil and CB were studied. The parameters of MB and CB needed in this paper are listed in Table 1.

2.1. The resistivity

Because the resistivity of copper is much smaller than that ($\sim 5.6 \times 10^{-7}$ Ωm) of SC in normal state (no superconducting state), the resistivity of NbTi was neglected when calculating the highest temperature of busbar. The resistivity of copper is not constant which changes with temperature and magnetic field. The magnetic field is 2.9 T, so the resistivity of copper is given by following function (Ωm) [6]:

$$\rho_{cu}(T, B) = \begin{cases} 3.12 \times 10^{-10} & (T < 22.24) \\ 5.9 \times 10^{-11} T - 1.0 \times 10^{-9} & (T > 22.24) \end{cases}$$

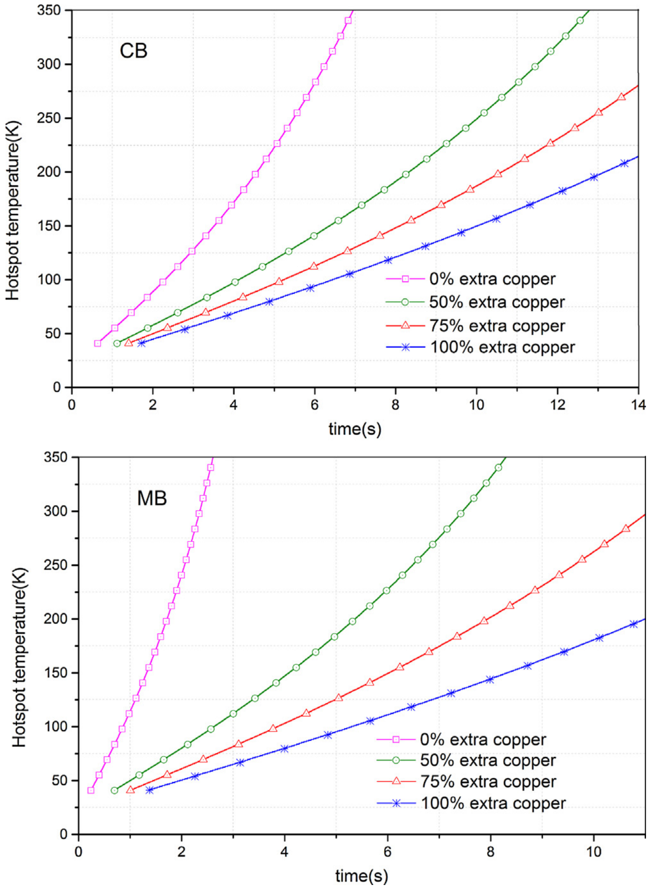

Fig. 2. The hotspot temperature of MB and CB in classical method in the case of different amount of extra copper.

2.2. The average specific heat

In the adiabatic condition, the specific heat of copper and NbTi consists of the average specific heat for that of helium neglected. So the average specific heat per unit volume is given [6]:

$$\bar{C} = \frac{C_{sc} A_{sc} + C_{cu} A_{cu}}{A_{sc+sc}}$$

where A_{sc} is the total cross section of superconductor, A_{cu} is the total cross section of copper, C_{sc} is the specific heat of superconductor, and C_{cu} is the specific heat of copper (C1020). The specific heat changes with temperature, it is used in a volumetric form ($J\,m^{-3}\,K^{-1}$) [6]:

$$C_{cu}(T) = \begin{cases} 6.67T^3 + 98.6T & (T < 40.8628) \\ -38(T - 320)^2 + 3.42 \times 10^6 & (T \geq 40.8628) \end{cases}$$

$$C_{sc}(T) = \begin{cases} 13.8T^3 + 870T & (T < 31.9985) \\ 0.24T^3 - 160T^2 + 36149T - 520779 & (T \geq 31.9985) \end{cases}$$

The extra copper areas are designed by the classical theory for the hotspot temperature. 0%, 50%, 75% and 100% of the extra copper area are considered for this parametric study, because the hotspot temperature is strongly dependent on the amount of copper in busbar. We got the hotspot temperature (MB) 199 K in the case of 100% extra copper, 297 K in the case of 75% extra copper, and very high in the case of 50% and 0% extra copper, shown in Fig. 2, and, the hotspot temperature (CB) 214 K in the case of 100% extra copper, 280.5 K in the case of 75% extra copper, and very high in the case of

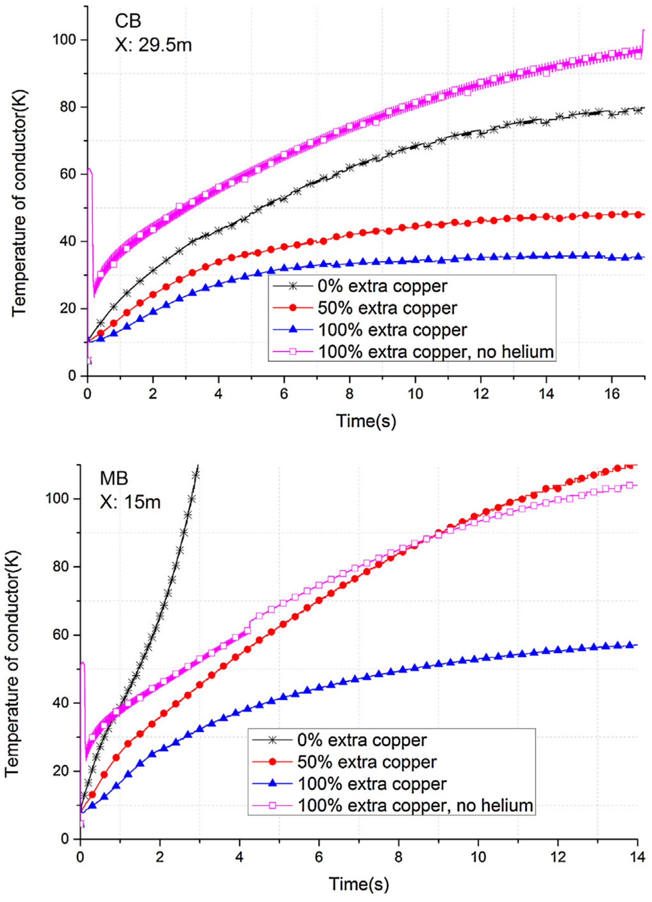

Fig. 3. Temperature of conductor after quench in different extra copper content and in the case of no helium analyzed by Gandalf code.

50% and 0% extra copper, shown in Fig. 2. It is known, the more extra copper, the lower hotspot temperature, so it is more helpful to protect superconductor after quench, selecting much more amounts of copper within reasonable limits, when designing superconducting cable.

3. Computer simulation

The numerical simulation of superconducting conductor is carried out by the 1-D quench simulation program (Gandalf) [8]. In the simulations, the external heat pulse was applied to cause the quench of superconductor.

3.1. Computation of MQE

The MQE is the energy which is just sufficient to trigger a quench in the cable, the short duration of ∼0.5 ms energy input applied a short length normal zone length of ∼60 mm. Thus this quench seems to have been triggered by a rather short pulse affecting a small volume. Assuming uniform temperatures over any cross section of the wire, the MQE is carried out by following function with 1-D form [7]:

$$\frac{d}{dx}\left(K(T)\frac{dT}{dx}\right)+\frac{I^2\rho(T)}{A_{\mathrm{cu}}^2}+Q_{\mathrm{ini}}(x,t)=H(T)\frac{P}{A_{\mathrm{cu+sc}}}+\bar{C}(T)\frac{dT}{dt}$$

where P is wetted perimeter of the busbar, $K(T)$ is thermal conductivity along the wire, average over copper and NbTi, $H(T)$ is heat transfer rate from wire surface to the liquid helium. According to [6], $H(T)$ and $K(T)$ are estimated, and then, the MQE is estimated by discrete finite difference method. Although the current in MB is much higher than that in CB, but there is much more mass flow of the superfluid helium and extra copper in MB, so relative to CB, MB needs much more energy to trigger quench.

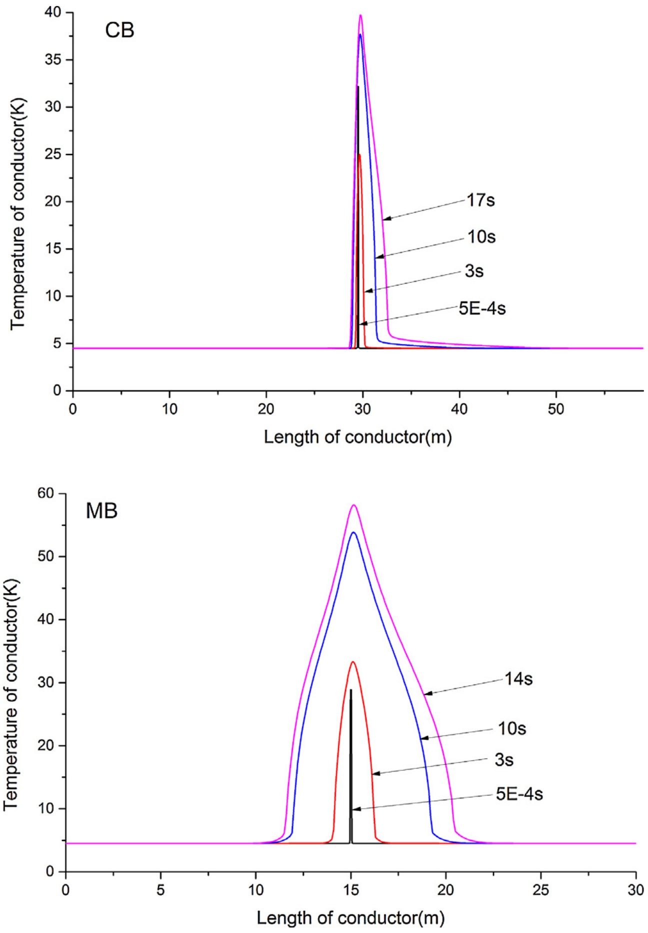

Fig. 4. Temperature distributions after quench in MB and CB.

3.2. Numerical simulation by Gandalf program

The model is a 30 m for MB and 59 m for CB length superconductor under a magnetic field of 2.9 T [2]. The conductor quench is initiated at the center of the conductor. The following conditions are used for the numerical simulation:

(a) The mass flow is 10.5 g/s for MB and 3.0 g/s for CB [2], and the inlet pressure is 6 bar [10].
(b) The helium pressure at the flow path inlet is 1.0 bar for MB and 0.9 bar for CB, and both operation temperatures is 4.5 K [2].
(c) The time step is short 10^{-3}–10^{-4} s to keep a stable numerical analysis, and mesh sizes are 0.01 m for MB (from 14.5 m to 15.5 m) and CB (from 29 m to 30 m), and 0.1 m for the rest.
(d) Initial external heat is 110% of the MQE whose duration is 0.5 ms and length is 60 mm.
(e) The delay time, detective time and discharge time of MB respectively are 1 s, 2 s and 11 s, and that of CB are respectively 1 s, 2 s and 14 s [2], the delay time in Gandalf code analysis is the sum of delay time and detective time.

The copper in superconductor is not separated from extra copper when analyzing busbar by Gandalf code, and all copper is included as a stabilizer, and this study has a higher stability margin. For analyzing quench, a heat pulse is applied in the middle (at 15 m

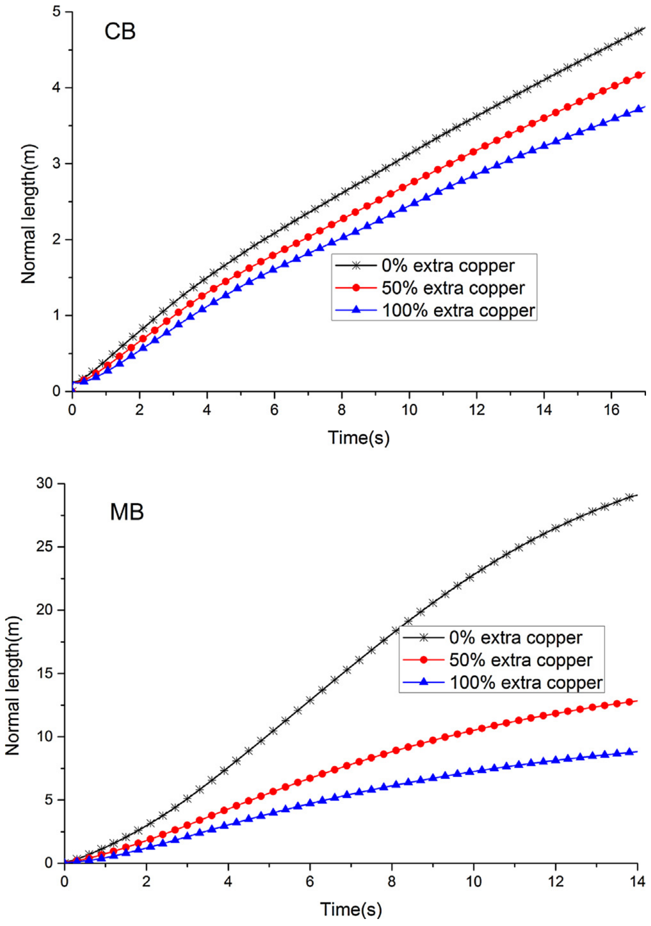

Fig. 5. Normal length of superconductor in the case of 0%, 50% and 100% extra copper.

for MB and 29.5 m for CB) of the busbar for triggering quench. The two-fluid model is used in this quench analysis, which is forced flow helium flowing in the hole and the bundle, this model is in agreement with the experimental results [9]. Because the duration and heating length of the initial external are very small, so compared to the joule heat, the initial external heat is quite small and can be neglected when quench analyzed. Taking heating conducting into account, the temperature of conductors are about 104 K (MB) and 103 K (CB); and taking both helium cooling and heating conducting into account, the temperature of conductors are about 57.1 K (MB) and 35.3 K (CB) after quench, which is lower than that in adiabatic condition, shown in Fig. 3.

We definite a no unit physical quantity, its value is greater, the more effect on quench behavior from different case of extra copper:

$$\varepsilon = \left(\frac{A_{\text{cu-extra}}}{A_{\text{cu-insuperconductor}}}\right)^2$$

where $A_{\text{cu-extra}}$ is extra copper (copper strands), $A_{\text{cu-in superconductor}}$ is the copper in superconducting strands. The value of ε in MB is much bigger than that in CB, which means that extra copper of MB have a greater role in terms of protecting superconductor, and the current in MB is much greater than that in CB. So compared with that in the case of 50% and 100% extra copper, the temperature of conductor in MB rises higher than that in CB in the case of 0% extra copper, shown in Fig. 3.

Because the superfluid helium flows from 0 m to 30 m (MB) or 59 m (CB), and the cooling effect near 0 m is better, so the temperature distribution of conductor is not symmetric, shown in Fig. 4. In the middle of conductor, after external heating time 5E−4 s, the temperature of conductor rise to 28 K (MB) and 31 K (CB), and the quench is triggered, shown in Fig. 3. After quench, the conductor gets resistance and joule heat is being produced, so the temperature of conductor rises gradually. Even though the ratio of copper to superconductor of CB is lower than that in MB, and the mass flow in MB is bigger than that in CB, however, the current in MB is much higher than that in CB, so after discharge is completed, the temperature of MB (about 60 K) is higher than that in CB (about 40 K), and the temperature distribution of conductor in MB is more symmetrical than that in CB. The quench starts in the place where the external heating happens in the middle of conductor, and the quench propagates along the conductor in both helium inlet and outlet directions, so the temperature curve along conductor is parabola, shown in Fig. 4.

4. Normal length

After quench, normal length (the length of quench conductor) of superconductor increasing was simulated by Gandalf code, shown in Fig. 4. In the case of 100% extra copper, the normal length in MB (8.81 m) is much longer than that in CB (3.75 m), because of larger ratio of current-square to mass flow in MB.

The value of ε in MB is much bigger than that in CB, which means that extra copper of MB plays a greater role in terms of protecting superconductor, so compared with that in the case of 50% and 100% extra copper, the normal length of conductor in MB rises higher than that in CB in the case of 0% extra copper, shown in Fig. 5.

5. Conclusions

The ratio of extra copper to copper in superconducting strands in MB is bigger than that in CB. In the adiabatic condition, the hotspot temperature of CB is bigger than that of MB in the case of 100% extra copper, however, if helium cooling and heat conducting are taken into account, the temperature of MB is higher after quench. Compared with CB, MB needs much more extra copper for quench protecting, however, in the case of 100% extra copper, the design of MB and CB is acceptable, according to the quench behavior.

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