Quench Analysis of the CFETR TF Coil Using the Gandalf Code

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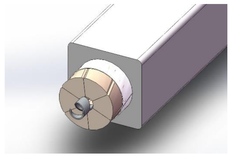
1. Abstract

The toroidal field (TF) coil is a crucial system in the tokamak, which provides the main magnetic field to confine the plasma. One TF coil of CFETR will be constructed next five years in the support of Chinese government. In order to give the design reference of quench detection and protection system, the assumed quench initiation and propagation at the location of the maximum and minimum temperature margin of TF coil is analyzed, respectively, also two different values of the quench detection threshold (0.1 V, 0.5 V) are considered. The results shows that the temperature at maximum temperature margin position is sensitive to the value of quench detection voltage, while the hot spot temperature at minimum temperature margin position is not significantly affected by quench detection voltage.

2. Therm-hydraulic model



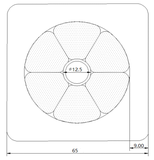
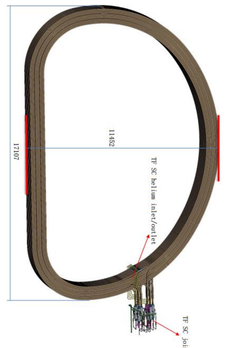


Fig. 1. Circle-in-square type of conductor used in TF coils

Table 1. Thermal-hydraulic parameters of the CFETR TF coil

Cooling channel length (m) (3 types of pancake)	493/307/129
Conductor outer dimension (mm)	65×65
Cable outer diameter (mm)	47
Stainless steel jacket cross section (m^2)	2.50e-3
Insulation cross section (m^2)	3.99e-4
Helium cross section in bundle region (m^2)	4.68e-4
Helium cross section in central hole (m^2)	1.23e-4
Void fraction	0.29



Full same Nb_3Sn conductor

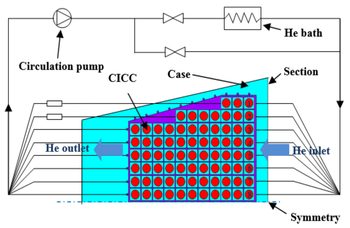


Fig. 2. Schematic of winding cooling circuit

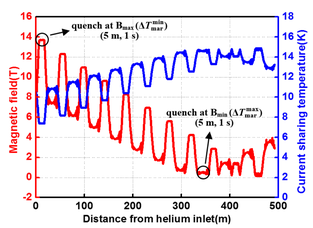


Fig. 3. Distribution of magnetic field and current sharing temperature along the length of pancakes 8

3. Simulation setup

The detailed parameter for two cases is in the following:
Case A: the quench detection threshold set as 0.5 V, quench at T_{mar}^{min} and T_{mar}^{max};
Case B: the quench detection threshold set as 0.1 V, quench at T_{mar}^{min} and T_{mar}^{max};

We considered quench initiation at two different locations in the TF coils based on the following reasons:

1) at T_{mar}^{max} (~10 K), expected to be highest hot spot temperature in principle, because of the lowest propagation speed and resulting delay in the quench detection. 2) at T_{mar}^{min} (~2.5 K), the most likely quench initiation zone.

Case A: the quench detection threshold set as 0.5 V

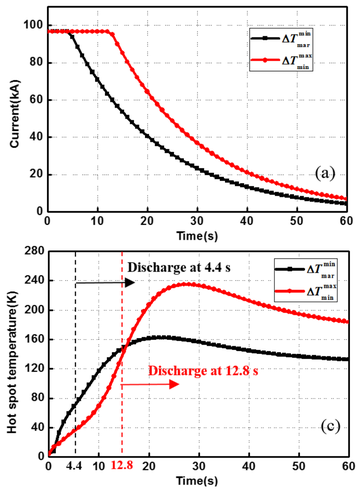


Fig. 5. Computed evolution of (a) current, (b) normal zone voltage, and (c) hot spot temperature of pancake 8 during the quench discharge. The quench initiation zone is considered at T_{mar}^{max} (red line) and T_{mar}^{min} (black line). The quench detection voltage is set as 0.5 V.

- From 1.1 s to 4.4 s, the hot spot temperature at T_{mar}^{min} is higher than that at T_{mar}^{max}, as shown in Fig. 5(c), which can be explained by the copper property of electrical resistivity, thermal conductivity and specific heat, as shown in Fig. 6-8.
- With the development of the quench, the hot spot temperature at T_{mar}^{max} is higher than that at T_{mar}^{min} after 15s, as shown in Fig. 5(c).
- In the end of the current dump, the hot spot temperature peak is ~235 K at T_{mar}^{max} and ~149 K at T_{mar}^{min} during the current dump, as shown in Fig. 5(c).

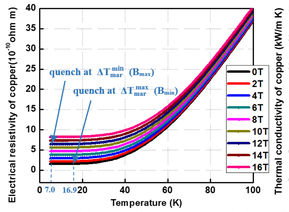


Fig. 6. Electrical resistivity of copper varying with temperature and magnetic field

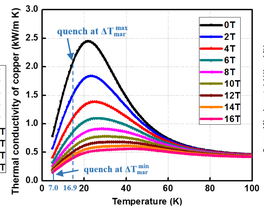


Fig. 7. Thermal conductivity of copper varying with temperature and magnetic field

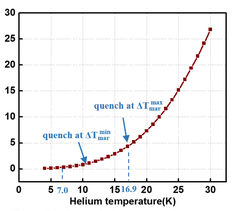


Fig. 8. Specific heat of copper varying with temperature

- The arrows in the figure indicate the values of physical parameters at the beginning of the quench (at 1.1 s).

1. At the beginning of the quench, the electrical resistivity of copper at T_{mar}^{min} is 7.35 ohm/m, which is about 4.2 times larger than that at T_{mar}^{max} (1.73 ohm/m), as shown in Fig. 6. So the larger electrical resistivity of copper at T_{mar}^{min} makes more heat generation.
2. It is shown that the thermal conductivity at T_{mar}^{min} is remarkably lower than that at T_{mar}^{max}in the quench initiation stage in Fig. 7. The lower thermal conductivity makes the slower heat diffusion along the conductor.
3. Notice the specific heat of copper is independent of magnetic field, but the quench at T_{mar}^{min} is induced at a lower helium temperature compared with that at T_{mar}^{max}. Thus the specific heat of copper at T_{mar}^{min} is lower than that at T_{mar}^{max}, and the lower specific heat of copper at T_{mar}^{min} makes the temperature increases easily.

Case B: the quench detection threshold set as 0.1 V

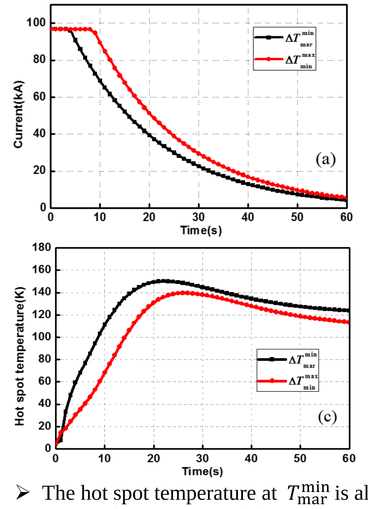


Fig. 9. Computed evolution of (a) current, (b) normal zone voltage, and (c) hot spot temperature of pancake 8 during the quench discharge. The quench initiation zone is considered at T_{mar}^{max} (red line) and T_{mar}^{min} (black line). The quench detection voltage is set as 0.1 V.

- The hot spot temperature at T_{mar}^{min} is always higher than that at T_{mar}^{max} during the current dump in Fig. 9 (c).
- In the end of the current dump, the hot spot temperature peak is ~135 K at T_{mar}^{max} and ~140 K at T_{mar}^{min} during the current dump, as shown in Fig. 9(c).

4. Discussion of the computed results

Table 2. Hot spot temperature in the coil

$T_{hot\ spot}^{max}$	Case	Quench detection voltage	T_{mar}^{max}	T_{mar}^{min}
	A	0.5 V	235 K	149 K
	B	0.1 V	135 K	140 K

- The maximum hot spot temperature at T_{mar}^{max} is higher than that at T_{mar}^{min} during the quench discharge, as shown in table 2, while we get the opposite result in case B. The reasons are that:

1. the hot spot temperature at T_{mar}^{max} is significantly affected by quench detection voltage. It is mainly due to the quenching at T_{mar}^{max} propagates slowly in principle, and the higher quench detection voltage makes the coil operation at full current for a longer time.
2. The hot spot temperature at T_{mar}^{min} is relatively small affected by the quench detection voltage, because the quench can be detected at a relatively shorter time, even though a higher quench detection voltage, then the hot spot temperature is limited.

5. Conclusion

1. In case A, the maximum hot spot temperature at T_{mar}^{max} is remarkably higher than that at T_{mar}^{min} during the quench discharge, while the maximum hot spot temperature at T_{mar}^{max} and T_{mar}^{min} is nearly the same in case B.
2. In both cases considered, the quench detected voltage should select small value to satisfy the currently ITER design criteria, considering the maximum allowed hot spot temperature (150 K) during the quench.

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