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Stability Analysis of ITER Side Correction Coils

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Abstract

The stability of the Side Correction Coils (SCC) cable-in-conduit conductors (CICC) for the International Thermonuclear Experimental Reactor (ITER) has been analyzed by the formulas and the code Gandalf. This paper describes the 1-dimensional mathematical code Gandalf, uses the code to simulate the quench and the recovery status of ITER SCC CICC, discusses the dependence of the stability margin on various operating parameters including operating current, operating temperature and mass flow rate, and analyzes the differences between the simulated values and the calculated values. The ITER SCC's quenching is also simulated to investigate its temperature distribution and temperature margin. Dependence of temperature margin on magnetic fields and operating temperature has been researched. The studies of ITER SCC provide a basis for the stable operation and optimization design of SCC CICC.

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Keywords: CICC; Side Correction Coil; Gandalf; Stability Margin; Temperature margin

1. Introduction

ITER is an international nuclear fusion research and engineering project that aims to make the long-awaited transition from experimental studies of plasma physics to full-scale electricity-producing fusion power plants [1-3]. The ITER magnet system is made up of four main sub-systems: the Toroidal Field (TF) coils, the Central Solenoid (CS) coils, the Poloidal Field (PF) coils, and the correction coils (CC). SCC is one of the correction coils system, which is constituted by NbTi/Cu CICC and aims to reduce the range of magnetic error fields created by imperfections in the location and geometry of the other coils used to confine, heat, and shape the plasma [4].

The stability of CICC is important for operating safe and parameters design, and consequently the simulation of the stability under different operating conditions is necessary [5]. Few researchers have paid attentions to the stability

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characteristics of the ITER SCC which is the CICC without central cooling channel. We tested the SCC CICC designed by CRPP, aimed to provide the basis for its safe operation and optimization design. In this paper, 1-D mathematical model code GANDALF is used to simulate the stability of SCC CICC.

2. 1-D Mathematical Model and Simulation Parameters

The finite element code Gandalf is the numerical implementation of a 1-dimensional model for thermal-hydraulic, quenching and stability analysis of SCC CICC. The 1-D model consists of three components: the helium, strands and a conduit. The temperatures of these three components are treated separately and the energy balances are coupled through heat transfer coefficients at the wetted surfaces. The heat balance equations are given by [6]:

$$A_{St}C_{St}\frac{\partial T_{St}}{\partial t}+A_{St}\frac{\partial}{\partial x}(K_{St}\frac{\partial T_{St}}{\partial x})=Q_{EXT}+Q_{joule}-P_w h(T_{St}-T_{He})-P_{ja-St}h_{ja-St}(T_{St}-T_{ja}) \quad (1)$$

$$A_{ja}C_{ja}\frac{\partial T_{ja}}{\partial t}+A_{ja}\frac{\partial}{\partial x}(K_{ja}\frac{\partial T_{ja}}{\partial x})=Q_{EXT}-P_w h(T_{ja}-T_{He})-P_{ja-St}h_{ja-St}(T_{ja}-T_{St}) \quad (2)$$

$$A_{He}C_{He}\frac{\partial T_{He}}{\partial t}+A_{He}\frac{\partial}{\partial x}(K_{He}\frac{\partial T_{He}}{\partial x})=Q_{EXT}-P_w h(T_{He}-T_{St})-P_w h(T_{He}-T_{ja}) \quad (3)$$

where K is heat conductivity, C_{St} is average strand volumetric heat capacity, A is the cross-section, Q_{EXT} and Q_{joule} are the external and Joule heat power (per unit strand length) provided [7], T is the temperature, P_w is wetted perimeter, h is heat transfer coefficient. The indices *st*, *ja* and *He* are referred to superconducting strands, jacket and helium, respectively.

The main parameters of the SCC CICC which we tested are summarized in Table.1. The structure of SCC CICC is shown in Fig.1.

Table 1. ITER SCC conductor and coils specifications

Parameters		Parameters		Parameters	
Type of strand	NbTi	Diameter of Ni-plated SC strand (mm)	0.73	Sc cross section (mm^2)	38.05
Nominal peak field (T)	5	Number of SC strand	300	Cu cross section (mm^2)	87.51
Operating temperatures (K)	5	Cable layout	3×4×5×5	He cross section (mm^2)	75.6
Max operating current, I_{op} (kA)	10	Cable dimensions (mm^2)	14.8×14.8	Void fraction (%)	35.76
Mini TEMP margin, T_{cs}-T_b (K)	1.5	Jacket dimensions (mm^2)	19.2×19.2	Strand Cu:nonCu ratio	2.3

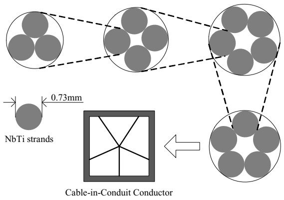

Fig.1. The structure of SCC CICC

3. Results and Discussion

3.1. Stability margin

The stability margin is defined as the largest sudden heat deposition in the strands that the conductor can absorb and still recovery the superconducting state. There is a transition region between the "well-cooled" stability region and low energy margin "ill-cooled" region. The lower boundary of transition is low limiting current and the upper boundary is upper limiting current [8].

$$I_{upp,\lim}=(P_w h A_{Cu}(T_c-T_{op}))^{0.5} \quad (4)$$

$$I_{low,\lim}=P_w h A_{Cu}(T_c-T_{op})/\rho_{Cu}/I_c \quad (5)$$

where T_c is the critical temperature, T_{op} is the operation temperature, ρ_{Cu} the copper resistivity and I_c is the critical current. For the operating current of ITER SCC is 10kA, the upper limiting current calculated by equation (4) is 27.651kA and the low limiting current calculated by equation (5) is 5.162kA, therefore the SCC CICC is operating in the transition region and the stability margin per unit volume of conductor can be given approximately by (The values in Fig.2- Fig.4 are calculated by the equations):

$$Q_{tran} = \rho C_p (1-\alpha)(1-f_{Cu}-f_{nc})(T_c - T_{op}) / (f_{Cu}+f_{nc}) \qquad (6)$$

$$\alpha = \rho_{Cu} I_{op}^2 / (phA_{Cu}(T_c - T_{op})) \qquad (7)$$

where f_{Cu} is the fraction of copper in the cable space area, f_{nc} is the fraction of non-copper, ρ is the density of the helium, C_p is the specific heat of the helium and T_c is the critical temperature.

The ITER SCC CICC is 68m, which is designed by CRPP. The stability margin is studied with initial conditions: the heating region is from 31.5m to 36.5m, the inlet pressure P_{inlet}=6Bar, the heating time t_h=0.1s, the delay time t_d=0.5s and the current decay time constant τ=5s.

A. Operating Current

When operating temperature T=4.5K or 5K, magnetic field B=5T, mass flow rate dm/dt=1.0g/s and the operating current I_{op} is from 8kA to 12kA, dependence of stability margin of SCC CICC on operating current is calculated by equations (6)-(7) and simulated by Gandalf, the results are shown in Fig.2. We can clearly tell that the stability margin at 4.5K is much higher than at 5K and the trends are the same basically. The calculated values of stability margin substantially decrease linearly with current and the slope dQ/dI is 0.068W/(m•A). But the simulated values by Gandalf decrease with current rapidly (dQ/dI=0.113W/(m•A)) when I_{op}<10000A, but they decrease with current slowly (dQ/dI=0.044W/(m•A)) when I_{op}>10000A.

B. Operating Temperature

When T=5K, B=3T or 5T, dm/dt=1.0g/s and I_{op}=10kA, the dependence of SCC CICC stability margin on operating temperature is shown in Fig.3. The stability margin decreased with the operating magnetic field. At B=3T, curves of the stability margins calculated by equations (6)-(7) and simulated by Gandalf code are the parallel lines with a slope of dQ/dI=400W/(m•K) and the simulated results are larger than calculated ones. At B=5T, the simulated results are smaller than calculated results when the operating temperature is lower, but the simulated results are larger than calculated ones when the operating temperature is higher.

C. Mass Flow Rate

When T=4.5K or 5K, B=5T, dm/dt is from 1.0g/s to 5.0g/s and I_{op}=10kA, dependence of SCC CICC stability margins on mass flow rate is shown in Fig.4. The stability margin values of SCC CICC increase significantly with the mass flow rate, and the stability margin at 5K is lower than that at 4.5K. Stability margin increases a little faster with the mass flow rate when the operating temperature is 4.5K. According to Fig.4, when mass flow rate ranges from 1.0g/s to 5.0g/s, the stability margin increases by 358W/m at 4.5K while it increases by 298W/m at 5.0K.

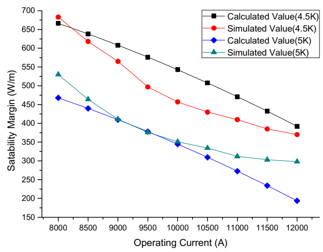

Fig.2. Dependence of SCC CICC stability margin on operating current

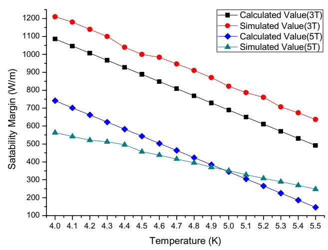

Fig.3. Dependence of SCC CICC stability margin on operating temperature

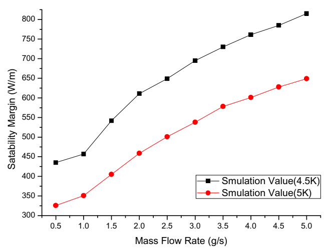

Fig.4. Dependence of SCC CICC stability margin on mass flow rate

3.2. Temperature margin

The temperature margin of SCC CICC is the difference between operating temperature and the current shunt temperature, the T_{op}-B-ΔT characteristic can be fitted by equations:

$$T_c = T_{c0}(1 - B / B_{c20})^{1/n} \quad (8)$$

$$T_{cs} = T_{op} + (T_c - T_{op})(1 - i) \quad (9)$$

$$\Delta T = T_{cs} - T_{op} = (T_c - T_{op})(1 - i) \quad (10)$$

where i is I_{op}/I_c, T is the temperature margin, T_{c0}=8.79K is the critical temperature (at B=0), B_{c20}=13.72T is the upper critical field (at T=0), and the exponent n=1.7 appears to provide a satisfactory fit to most alloy compositions. The T_{op}-B-T characteristic curves are shown in Fig.5, the temperature margin decreases when the magnet field increases or the operating temperature increases. The minimum temperature margin designed by CRPP is 1.5K, according to equations (8)-(10) and Fig.5, we can choose the appropriate magnetic field and operating temperature to fit the temperature margin when the operation conditions are changed. In Fig.5, when ΔT is larger than *1.5K,* the appropriate magnetic field and operating temperature can be found.

When the SCC CICC is quenched, as shown in Fig.6, the maximum temperature of the CICC is at x=34m, where is the min-point of the heating region. Thermal stress produced in SCC CICC can damage the structure of SCC. According to the characteristics of quenching, we can design the quench protection system, to reduce the hot-spot temperature of superconductors. In Fig.7, we can see that at the normal zone, the temperature margin is 0K, at the superconducting zone, the temperature margin is about 2K, the temperature margin of superconducting zone increases with time slowly until it transformed into normal zone when the temperature margin plummet to 0K.

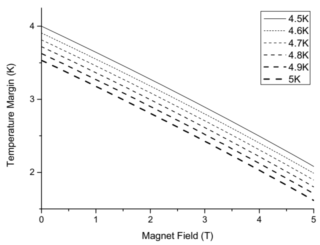

Fig.5. The T-B-ΔT characteristic of SCC CICC

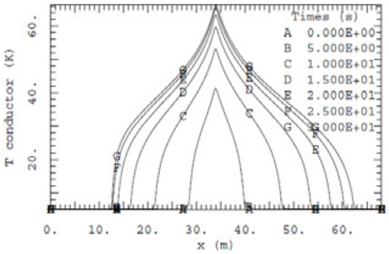

Fig.6. Temperature distribution of SCC CICC when quenching occurs

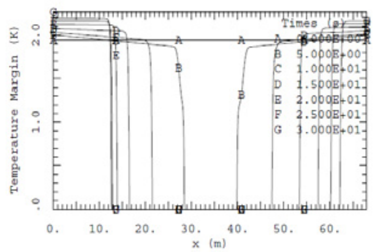

Fig.7. Temperature margin of SCC CICC when quenching occur

4. Conclusions

1) When the ITER SCC is quenching, and peak pressure of the heating point (7.8Bar) is much higher than the inlet pressure (6Bar), the temperature of the heating point, the voltage and the normal length of the superconductor keep rising until the normal zone is propagated to the whole SCC CICC.

2) The stability margin has a significant decrease when the operating current and the operating temperature increase or the mass flow rate decreases. The comparison between the calculated values and the simulated values indicates that Gandalf is a reliable tool for the ITER SCC CICC's simulation.

3) Operating temperature, operating current and magnetic field have an effect on temperature margin. The minimum temperature margin designed by CRPP is 1.5K and this aim can be realized by selecting the appropriate magnetic field and operating temperature.

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