PAPER

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Electromagnetic and thermal stability of the ITER Central Solenoid during a 15 MA plasma scenario

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Abstract
The combination of the electromagnetic conductor model JackPot ACDC with the thermo-hydraulic model THEA is able to reproduce and predict the behavior of cable-in-conduit conductors (CICCs) under any varying current and magnetic field. The combined JackPot-THEA model is used to simulate the turns of the CSU2 quadrapacake of the ITER Central Solenoid (CS) that are subjected to the most demanding conditions of the 15 MA plasma scenario. The considered section is a pancake with a 150 m length of Nb3Sn CICC from helium inlet to helium outlet, from the inner towards outer turns. The simulation results in terms of temperature and local strand electric field levels are compared to those obtained from earlier minimum quench energy analysis in order to evaluate possible risk of quench. The results confirm sufficient stability of the ITER CS coil, both from electrical and thermal point of view. The temperature evolution and flow of a helium heat slug along the conductor during the 15 MA plasma scenario is also analyzed. It appeared that sequential multiple burn cycles can be carried out without accumulation of temperature in the helium heat slug, essential for continuous energy production for a fusion power plant.

Keywords: ITER, fusion magnets, stability, modeling, Central Solenoid

(Some figures may appear in colour only in the online journal)

Introduction

The conductors in the ITER magnet system are subjected to fast changes of current and magnetic field during the plasma operating scenario [1]. Most critical concerning the level of the magnetic field rate is the Central Solenoid (CS), discharging from 13 T at a maximum rate of −1.5 T s⁻¹ after the start of discharge (SOD) [2]. This extreme condition is not reproducible in existing experimental conductor test facilities. The only experimental data available for quantitative analysis were produced at the ITER CS Model Coil (Naka, Japan) [3] and at the SULTAN conductor test facility (Swiss Plasma Center, Switzerland) [4]. Conductor layout, time and magnetic field settings are different from the ITER operating conditions. Particularly for the latter, the test conditions for quenching with a short magnetic field pulse do not cover the ITER operating conditions. Nevertheless, the test results [5] are useful for calibrating the simulation codes as used in the present analysis [6]. Accordingly, the codes are used to study the stability of the conductors during plasma operating conditions.

The purpose of the analysis is to model the electromagnetic and thermal behavior of the most critical turns of the ITER CS. To achieve the result, a code is required that is able to accurately calculate the AC loss of a cable-in-conduit conductor (CICC), considering all the variations of currents, magnetic field amplitude and temperature. In addition, the code has to consider the cooling system and the possible quench generation and propagation. JackPot-THEA [7] is the combination of JackPot-AC/DC [8–10] and THEA [11] codes. JackPot reproduces the complete geometry of a CICC with strand level precision. It generates a network of super-conductive and resistive elements, used to simulate the electromagnetic behavior of the conductor. THEA is a thermal...
code modeling the coolant flow inside the conductor and it is able to reproduce the thermal quench and its propagation. The two models were combined to study the stability tests performed on the SULTAN sample CSJA8 in [7]. The combination of models was used to study the CS conductor performance subjected to longer sinusoidal magnetic field pulses, more relevant to plasma operating condition in [6].

JackPot can simulate the performance of a section of CICC during the plasma scenario, considering the interaction with the entire magnet system and the magnetic field generated by the plasma current [12]. The electric field calculated in the conductor during the most critical phase of the plasma scenario, i.e. the SOD, is compared to the peak and average electric field simulated for long magnetic field pulses [6]. The comparison can highlight a possible electromagnetic stability issue on strand level, not visible with the pure thermal analysis on a global scale.

With the JackPot-THEA analysis, it is possible to precisely estimate the temperature evolution inside the conductor during the plasma scenario. This is used to investigate the temperature evolution of one full layer of the CSU2 coil, with the most severe magnetic field conditions. The purpose is to define the maximum temperature reached in the CICC during the plasma scenario and the capability of the CS for continuous cycling.

**ITER CS design and plasma scenario**

The CS consists of a stack of six identical coils built with Nb3Sn CICCs. The total solenoid height is about 13 m and the diameter amounts to 4.3 m. Each coil comprises seven pancakes wound with total 390 layers of 14 turns each, six hexapancakes and one quad-pancake [13]. The coils are identical and interchangeable.

The supply and return lines from the feeder ducts provide helium cooling. Helium is supplied with 20 inlets connected to the inner turns of the module. The inlets are located in the inner bore between every two supply ports to supply the high magnetic field region with the coldest helium. Helium flows in both conductor directions away from the inlet joint. The helium outlet is reached after approximately 14 turns (one layer). Every outlet receives helium from two different inlets and they are placed at the outer side of the pancakes [14]. The plasma scenario chosen for the present study is the 15 MA plasma scenario as previously implemented in JackPot [12].

Figure 1 shows the currents in the CS modules during the 15 MA plasma scenario. From $-300$ to $0$ s the currents in the coils are ramped up, and then quickly swept down generating the magnetic field rates.

**JackPot plasma scenario short sample simulation**

JackPot is able to simulate a plasma scenario for a relatively short section of conductor to limit the computation time for the given size of the matrix dimensions [10]. One meter of CICC is a good compromise between computation time and minimum relevant sample length. The backbone of JackPot is the accurate modeling of the internal geometry of the cable down to strand level. The first step in every simulation is to determine the strand trajectories from which the electromagnetic parameters are defined [8]. The inter-strand contact resistivity per unit of surface is the only free parameter used in the JackPot model and it can be obtained from inter-strand contact resistance measurements, e.g. as performed in the Twente Press experiment [15, 16] or indirectly by fitting the $\rho_s$ to the results of a coupling loss experiment [12].

During the plasma scenario, the magnetic field and transport current are varying continuously. The variation of the copper magnetoresistance and the Lorentz forces, resulting from the changes in the applied current and magnetic field, have an effect on the inter-strand contact resistance. The coupling and eddy current losses generated in the conductor also depend on these two parameters. Unfortunately, the effects of these two phenomena cannot be easily predicted because it is not possible to directly measure the resistance variation in the conductor during operating conditions. The effect of the Lorentz force on the strand contact resistance was investigated in [15] and [17], but without transport current. The SULTAN AC loss results after cycling of the CSJA8 sample are used to estimate the effects of current and magnetic field variation on the inter-strand contact resistance. The CSJA8 conductor sample was tested at three different conditions, for each of them JackPot solved an inter-strand resistivity to match the coupling loss results, see [6]. The CSJA8 test conditions, inter-strand resistivities and coupling loss n$\tau$ are listed in table 1.

Assuming a linear dependence of the resistivity on magnetic field and current, a plane can be defined based on the three resistivities, see figure 2. A similar CS conductor, measured in the Twente Press facility, showed an almost linear dependence of the contact resistance due to the applied
The inter-strand resistivity is described using the surface equation. In order to avoid negative values for the resistivity, a minimum is defined as $\rho_{\text{min}} = 0.1 \times 10^{-5} \ \text{\mu}\Omega\text{m}^2$, although in practice the simulations did not reach this limit. The black line in figure 2 represents the resistivity evolution in the most inner turn of the CSU2 unit as a function of the background magnetic field and current during the 15 MA plasma scenario. To simplify the figure, only the absolute value of the current is displayed.

The strand critical current density is accurately modeled as function of temperature, magnetic field and strain [19, 20]. CSJA8 sample design and critical current scaling law parameters are reported in [6].

Simulation results

The first 100 s of the ITER 15 MA plasma scenario were simulated. The chosen interval is the most severe for the coil. The inter-strand resistivity is defined using the surface displayed in figure 2. The applied current and average magnetic field during the first 100 s after SOD of the coils are shown in figure 3. The entire ITER magnet system is taken into account for the JackPot computation, modeling the precise effect of the changing external magnetic field magnitude and orientation in time on the cable section. The magnets are represented using the current center lines [21]. This simplified model allows for description of the ITER magnetic field distribution and identifying and defining the region with the most extreme magnetic field conditions. The magnetic field calculation precision increases for the modeled CS coil to which the simulated conductor belongs by taking into account each individual turn.

The resulting coupling loss profile, see figure 4, is comparable with the simulation performed for the analysis of the short twist pitch sample presented in [12]. The performance of the conductors are not directly comparable because the Lorentz force effect was not considered in [12], but still the results are quite similar. The highest coupling dissipation occurs during the first two seconds of the plasma scenario. At $t = 0$ s the coupling and eddy current losses are about zero but due to the logarithmic scale the initial ramp is not visible. The initial power is not zero because of the charging of the coils, see figure 1. The current ramp up and the increase of the background magnetic field generate small coupling and eddy current losses in the conductor, but they are negligible compared to the power loss after the plasma initiation.

Lorentz force [18]. The sample CSJA8 was tested in different conditions of magnetic field and current, therefore a straightforward comparison is not possible, but as first approximation, it is realistic to consider a linear dependence of the resistivity to the applied Lorentz force. The inter-strand resistivity for every applied current and magnetic field is described by using the surface equation. In order to avoid negative values for the resistivity, a minimum is defined as $\rho_{\text{min}} = 0.1 \times 10^{-5} \ \text{\mu}\Omega\text{m}^2$, although in practice the simulations did not reach this limit. The black line in figure 2 represents the resistivity evolution in the most inner turn of the CSU2 unit as a function of the background magnetic field and current during the 15 MA plasma scenario. To simplify the figure, only the absolute value of the current is displayed.

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The hysteresis loss [23], see figure 5, shows a similar behavior in the first seconds after the SOD compared to the coupling loss, but shows a prominent peak around \( t = 50 \) s. The peak is the result of a strong reduction of the magnetic field combined with a change of the angle between magnetic field and strands [12]. The hysteresis loops are widest in magnetization around zero magnetic field. The hysteresis loss magnitude is negligible for most of the time; it is comparable to the coupling loss only during the peak at 50 s.

The stability of the conductor can be defined using the peak and average electric fields, as shown in [6]. The average electric field of the conductor is compared to the electric field at quench measured during the SULTAN DC \( T_{cs} \) tests. The average electric field, \( E_{\text{avg}} \), is always lower than the quasi-steady-state quench electric field limit in the range of 200–400 \( \mu \text{V m}^{-1} \) [24]. The stability is related to the time duration and space distribution of the disturbance [25]. As observed in [6], a conductor in transient condition is able to reach higher local electric field and power deposition depending on the pulse duration. The CSJA8 short sample peak electric field simulated with JackPot-THEA is used as a threshold to study the stability of the conductor. The peak and the average electric fields after SOD reaches 7–8 \( \text{mV m}^{-1} \) and 180–190 \( \mu \text{V m}^{-1} \), respectively, for a perturbation period of about 1 s, see figure 6.

Crucial for the critical current of \( \text{Nb}_3\text{Sn} \) is the strain applied to the superconducting filaments. The effective strain applied to the strands depends on the conductor cable pattern, coil design and forces applied to the conductor. The study performed on the ITER CS insert shows that the hoop strain mitigates the effective strain of the CS conductors by about 0.1% compared to the straight SULTAN samples, improving the \( T_{cs} \) with about 0.6 K [26]. In order to study the impact of the different effective strain on the electromagnetic performance of the CS, several simulations are performed varying only the effective strain applied to the superconducting strands. The results are presented in terms of peak and average electric field and compared to the stability electric field thresholds calculated with JackPot-THEA in [6], see figure 7. The peak and average electric fields during the plasma scenario are one order of magnitude lower than the stability threshold. The variation caused by the different effective strain is within 10%. Based on the defined electric field criteria, the 15 MA plasma scenario should not have any stability issues.

**Temperature evolution in a layer of CSU2 module**

The second goal of this study is to model the thermal behavior of the most critical layer of the CSU2 pancake from inlet to outlet during a full 15 MA plasma scenario cycle and subsequent cycles. The simulation is performed using the JackPot-THEA model as already validated and calibrated with the SULTAN short sample tests results in [6] and [7]. The simulation involves one layer of the CSU2 quadra-pancake, i.e. about 150 m of \( \text{Nb}_3\text{Sn} \) CICC, which spirals radially from the innermost layer outward to the low field region. It is not
practical to model such length of conductor at once with JackPot considering the amount of memory and CPU time necessary to simulate the entire conductor. A good compromise in terms of conductor length, computation time and available memory is to model fourteen 1 m long sections of CICC, one section for every turn. Afterwards, the electromagnetic performance of each section is scaled to the length of the entire turn. This approximation is valid because the current applied to the conductor is the same in all turns and the external magnetic field changes radially depending on the distance to the axis of the coil. Therefore, the external magnetic field can be considered constant in each turn. The simulated time interval is 1800 s, corresponding to the duration of the 15 MA plasma scenario from the coil charge to the end of the recovery time, see figure 1.

The coupling and eddy current losses computed with JackPot are used as input for THEA to calculate the temperature evolution in the pancake layer from the helium inlet to the helium outlet. Both hysteresis loss and coupling loss are considered describing the thermal behavior as accurate as possible within this method. In THEA, the power is injected as heating power directly in the superconducting element of the model, since the dissipation is generated mainly in the superconducting elements. The model does not consider other types of loss and thermal exchange between the turns is neglected. The conductor and the helium cooling are modeled using the same parametrization as for the CSJ8 short sample simulations [27, 28]. The helium flowing in the central channel is considered thermally linked to the helium in the bundle [29, 30], i.e. the helium in the bundle and the helium in the channel are treated as separate coolant elements with a thermal contact. This allows to model the bundle and channel helium flow speed and temperature separately.

\textit{JaskPot-THEA results}

The results of the simulation are presented in two different views: 3D in figures 8 and 2D in figure 9. The evolution of the temperature is shown as a function of conductor length and time from the plasma initiation to the end of a full 15 MA plasma scenario cycle. The helium inlet is located at the origin of the axis, whereas the helium outlet is at 150 m. The temperature maximum is generated in the first turns of the pancake layer during the plasma initiation, where the electromagnetic conditions are most severe. Then the heat slug with higher temperature moves along the conductor transported by the helium mass flow. The temperature peak, about 5.5 K, propagates almost unvaried along the conductor and after about 800 s, the peak reaches the outlet.

The absolute maximum temperature is located in the second turn, which is visualized for \( t = 100 \) s. The helium flows from the first to the second turn collecting heat from both turns and reaches the maximum temperature of about 5.6 K. The temperature peak becomes smoother in the following seconds, spreading the heat towards the coldest region, i.e. backward towards the helium inlet. The temperature maximum reaches the outlet after about 850 s from the start of the scenario. After this time, the temperature decreases progressively to less than 5 K. After \( t = 1500 \) s a new plasma scenario cycle can start with the current ramping up, see figure 1. The aim of a tokamak is to drive multiple plasma cycles for a quasi-continuous energy generation, necessary for a power plant. From the final temperature, 4.5 K at the inlet and lower than 5 K at the outlet, multiple plasma cycle can be handled by the ITER CS without overheating. It can be noted that turn to turn heat conduction is not taken into account, making the approach actually worst case.

\textbf{Discussion}

Combining the JackPot and THEA codes, there could be the concern of a possible overestimation of the Joule heating effect, since both codes consider it during their simulations. The Joule heating effect contribution for the two codes is addressed in this section. It is important to mention that JackPot-THEA simulation results are fully compatible with the experimental data obtained from the SULTAN and University of Twente facilities, therefore JackPot-THEA simulation can be reliably extended to the 15 MA plasma scenario.

The loss in the conductor is composed mainly of the coupling and eddy currents generated by the alternating magnetic field. This is true until the conductor reaches the quench transition. During the transition phase to the normal state, the joule heating, generated by the current sharing, the current flowing into the normal material and the superconducting material in the transition state becomes gradually dominant. JackPot is considering the Joule heating using the critical current scaling law, to calculate the voltage drop for the superconductive strands and the segregated copper in contact with the superconducting strands. However, THEA is also able to account for the Joule heating. When the superconducting material starts the transition, THEA calculates the Joule heating effect and the avalanche effect, which causes a quench, but is not incorporating the current sharing dissipation. Since both codes consider the Joule heating, the
JackPot-THEA combination could possibly slightly overestimate the energy generated in the conductor, but still the results fall within the measurement error bars [6].

The conductor modeled in THEA is an extreme simplification of the real cable. In THEA, the superconducting and normal materials are described as single bulk elements, there is no heat generation by current sharing between strands and the entire superconductor element has to reach the transition before starting the heat generation by the normal material. While in JackPot, the current sharing is considered locally for each individual strand already from the beginning of the transition, which is not considered in THEA because of the geometry simplification. On the other hand, the temperature used in JackPot is a static parameter since the initial temperature is fixed for the calculation. When the code is approaching the transition, JackPot is slightly underestimating the dissipated energy, because the critical current is still calculated on the initial temperature. This simplification is negligible up to almost the full quench for JackPot since it is able to reproduce accurately the energy dissipated in the conductor for the applied pulses with a recovery phase in the SULTAN stability tests.

The slight JackPot underestimation is difficult to quantitatively because of the lack of stability measurements in AC condition and the poor precision of the measurements (about 10% of error). We cannot stress enough the importance of more MQE measurements on various (Nb3Sn) conductors in order to correctly describe the phenomenon related to stability.

In summary, when JackPot-THEA calculates the quench evolution, JackPot is following the evaluation of the current sharing process and probably slightly underestimating the Joule effect, while THEA is not considering the current sharing phase and the Joule heating is starting much later than in reality, because of the single bulk element structure. Therefore combined together, they could slightly overestimate the MQE, but the result is still within the experimental error bar.

**Conclusion**

It is essential for ITER’s operation to make sure that during a plasma scenario involving high field ramp rates, the conductors in the CS remain stable, and no quench will occur during the peak value of the magnetic field change.

During the 15 MA plasma scenario, the magnetoresistance and Lorentz force are taken into account considering linear dependences from operating current and applied magnetic field. The approximation allows simulating a more accurate model of the plasma scenario for determining the conductor stability.
An electric field threshold for starting a quench in a characteristic CS conductor was defined using JackPot-THEA simulations resulting from different sinusoidal pulse time periods. The peak electric field during the plasma scenario always remains significantly below such quench electric field threshold. At the same time, the average electric field of the conductor is less than the electric field at quench under stationary condition. Given the defined electric field criteria, the ITER CS does not show stability issues.

The simulation of the whole layer of the quadra-pancake of the CSU2 module provides a peak temperature of 5.6 K reached in the conductor. At the same time, it describes the flow of the heat slug through the 150 m conductor in the pancake layer. The JackPot-THEA model confirms the capability of the CS for continuous pulsed operation when exposed to the 15 MA plasma scenario burn cycles.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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