Calculation method for pulsed magnetic field energy supplied to Nb₃Sn ITER CS conductors during SULTAN stability tests

T. Bagni^{a,*}, M. Breschi^b, S. Jagga^a, A. Devred^c, A. Nijhuis^a

^a University of Twente, Faculty of Science & Technology, Enschede, The Netherlands

^b Università di Bologna, Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione, Bologna, Italy

^c CERN, Technology Department, Geneva, Switzerland

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ABSTRACT

Cable-In-Conduit Conductors (CICCs) for the ITER Central Solenoid (CS) magnets are designed to operate in the presence of fast changing current and magnetic field during the plasma-operating scenario. For ITER, the AC loss of several types of Nb₃Sn CICCs was experimentally tested, but only very limited experimental data is available for quantitative analysis of the minimum quench energy (MQE). In the SULTAN testing facility (Swiss Plasma Centre) few CS conductors were tested on MQE, but the magnetic field amplitude and ramp rate settings are far from the actual ITER operating conditions. Nevertheless, such tests are needed as a basis to calibrate and benchmark the codes that describe the quench behavior. Moreover, during the stability tests in Sultana, the temperature measurements show severe fluctuations, which can introduce a large error for the energy calculation. An interpretation is given for the temperature fluctuation and a procedure is proposed to significantly reduce the error in the pulsed energy calculation.

1. Introduction

The SULTAN [1] pulsed magnetic field stability tests are performed to explore the Minimum Quench Energy (MQE) [2] of ITER Cable In Conduit Conductors (CICCs) [3]. The tests are carried out in the presence of DC transport current and background DC magnetic field. It is possible to deposit a limited amount of energy in a superconducting magnet without causing a quench. In such case, the conductor is able to recover to the initial stable superconducting state after the pulsed energy deposition. If the conductor is not able to recover, it will quench and reach the normal state. The minimum energy necessary to initiate the quench is called MQE [4]. During the stability tests the energy is deposited using a single sinusoidal magnetic field wave [5], which generates coupling- and eddy current losses in the conductor. Due to the complexity of the conductor and the temperature fluctuation along the length of the region where the coupling- and eddy current losses are generated, it is difficult to define the exact location where the quench starts, defining a local peak value for the MQE. However, this location is assumed to be correlated with the volume fraction of helium flow having the highest temperature. For simplicity, the MQE measured during the stability tests, can be considered as a global MQE, although in reality there is at least one local spot where the quench starts due to a peak heat avalanche effect.

To produce a singular sinusoidal pulsed magnetic field wave, a capacitor bank connected to the AC coils in an RLC circuit is discharged with a 7.8 Hz resonating frequency (128 ms of time period) [1]. The capacitor discharge generates a sinusoidal magnetic field that can be cut either after one or half period. To reach the MQE, the amplitude of the pulse is stepwise increased until the quench occurs. The system is able to generate a quench by applying a magnetic field pulse, however, the maximum energy is limited to relatively small amplitudes. Therefore, the helium inlet temperature is set close to the current sharing temperature, which leads to severe temperature fluctuations in the helium flow. These fluctuations introduce a large error in the pulsed energy calculation.

The calculation of the deposited energy is based on the procedure described in [5]. It is determined considering the helium temperature difference, measured between upstream and downstream sensors and by using the mass-flow rate and the helium specific heat, see Eq. (1).

$$Q \propto C_p \dot{m} \int \Delta T dt. \quad (1)$$

For NbTi conductors, the deposited energy is calculated using the calorimetric method, based on the difference in enthalpy of the helium flow as described in [6], which is in good agreement with the results obtained using Eq. (1) [7]. Whereas in the case of the measurements

* Corresponding author.

E-mail address: t.bagni@utwente.nl (T. Bagni).

performed during the pulsed stability tests of the CS samples, the calorimetric method was not applicable due to the large temperature fluctuation. Therefore, the method described in [6] is not adequate for the applied testing method and it is necessary to modify the analysis strategy for an accurate calculation of the energy deposited in the conductor. After a brief introduction of the SULTAN experimental setup, the stability test of an ITER CS conductor is described in order to explain the cause of the temperature fluctuation and accordingly to introduce an alternative pulsed energy calculation methodology. The analyzed sample is the so-called ITER CSJA8, also used in [7] and [8] for the electromagnetic and thermal modeling with JackPot AC/DC and THEA codes.

2. SULTAN facility and conductor sample design

The SUPraLeiter Test ANlage (SULTAN) facility of the Swiss Plasma Center (SPC) was used to test short sections of ITER superconductors in forced flow helium condition with a background magnetic field up to 10.85 T [1]. The conductors were tested to study the evolution of AC loss, electromagnetic stability, and current sharing temperature as function of electromagnetic cycles [9].

The Nb₃Sn conductor samples are made of two conductor sections of the same length joined at one end in a praying hand configuration obtaining a hair pin shaped joint [10]. The central channel of the conductor is blocked; forcing the helium to flow only in the voids between the strands with a mass flow rate of 1–10 g/s. The instrumentation was optimized for the qualification of the ITER samples [9,11]. The sample voltage taps and temperature sensors are located upstream and downstream the High Field Zone (HFZ), see Fig. 1. Four temperature sensors are usually attached to the jacket at a conductor cross section, one for each of the four sides. The longitudinal distance between the voltage taps is 450 mm, which is about to the length of the HFZ while the distance between the temperature sensors is 800 mm. Two more temperature sensors are placed at the extremity of the conductor sample, one on each leg, and a single temperature sensor at the helium inlet outside the sample.

In the SULTAN facility, the sample is vertically inserted in the magnet bore and the upper terminations are electrically connected to the current leads of the superconducting transformer [1]. The SULTAN magnet system comprises a stationary split coil system and an AC and pulsed coil. The stationary magnet system is able to generate up to 10.85 T with a HFZ of about 500 mm. The split coil gap is about 100 mm, and allows a straight short conductor sample to be positioned in the HFZ. The AC magnet consists of two saddle shaped coils, placed in the HFZ bore of the DC coils. The saddle coil is orientated to generate an AC or a pulsed magnetic field perpendicular to the DC field. The effective magnetic field length of the AC coil is 390 mm. The coil can generate a sinusoidal varying magnetic field on the conductor to induce AC loss and if required a quench when used for Minimum Quench Energy (MQE) tests.

3. Definition of the temperature fluctuation

During the stability tests of the sample CSJA8 [8], where the quench is induced in the conductor applying a sinusoidal magnetic field pulse,

Fig. 1. Schematic of the SULTAN sample instrumentation with voltage taps and temperature sensors located upstream and downstream the HFZ at 225 and 400 mm distance from the center, respectively.

Fig. 2. Temperature measured during test run #CSJA8Q011206 as function of time. In blue, the temperatures measured upstream the high field zone (T_{up}) while the temperatures measured downstream (T_{down}) are given in red. The battery voltage used to generate the pulse magnetic field as function of time is in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

the temperature readings show large fluctuations. The fluctuations are clearly visible in Fig. 2, where the measured temperatures of test run #CSJA8Q011206 are shown. The test conditions are $B_{DC} = 9$ T, $I_{op} = 40$ kA, $T_{in} = 8.1$ K and the battery voltage is 340 V, which is equivalent to an applied magnetic field pulse B_a of 0.43 T.

The temperature sensors are commercial zirconium oxynitride films (Cernox) [12]. The manufacturer calibrated all Cernox sensors with an accuracy of ± 5 mK. An evaluation of the precision and reproducibility of the current sources as well as potential thermal voltages, led to the conclusion that the absolute error of the temperature readings is typically ± 30 mK [13].

First, it can be noted that the upstream T-sensors follow the same temperature profile in time, just as the downstream sensors, see Fig. 1. Following [6], the upstream and downstream temperatures are averaged before calculating the conductor temperature variation generated by the applied magnetic field pulse. The average temperatures are shown in Fig. 3. When excluding the peaks generated by the magnetic field pulse, the temperature profiles are both subjected to a fluctuation of ± 0.1 K. The average temperatures show a clear phase shift between upstream and downstream temperature fluctuations. Due to this shift, calculation of the conductor temperature increase, ΔT , due to the applied pulse by directly subtracting the two curves as shown in Fig. 4, does not give useful results. The calculated ΔT versus time still has a continuous fluctuation and the increase of temperature due to the applied field pulse is partially hidden in the fluctuation. Therefore, in the presence of such temperature fluctuations, the assumptions of [6] are not effective anymore and some improvements are needed.

4. Minimization of the temperature fluctuation

As shown in Fig. 3, the helium temperature is subjected to local fluctuations, which seem to propagate through the conductor at a speed determined by the helium mass flow. Moreover, the temperature profile at T_{down} is basically similar to the one observed at T_{up} , which signifies that the temperature profile present at T_{up} propagates as a bias slug towards T_{down} .

In order to cancel out the effect of the strong helium temperature fluctuation, a time shift can be applied to the upstream temperature before subtracting the average temperatures. The time delay is $t_{offset} = 7.5 \pm 0.3$ s and is determined empirically and defined here as the time difference between the measured temperature peaks, see Fig. 5. The effective velocity of the helium in the bundle, calculated from t_{offset} is $v_{eff} = 0.11$ m/s.

Alternatively, the time difference can also be determined by the

Fig. 3. Temperature measured during test run #CSJA8Q011206 as function of time. In blue, the average upstream temperature (T_{up}) while the temperatures measured downstream the high field zone (T_{down}) is in red. The battery voltage used to generate the pulse magnetic field is in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Fig. 4. Temperature variation of difference between upstream and downstream average temperatures measured during test run #CSJA8Q011206 as function of time. The battery voltage used to generate the pulse magnetic field is in black.

helium flow rate as the time needed for the helium slug to travel from T_{up} to T_{down} locations. It is assumed that the helium is flowing in a channel of 0.8 m length with velocity:

$$v_{helium} = \frac{\dot{m}}{\rho_{he} A_{he}} \quad (2)$$

Then the time needed for the coolant to transfer from upstream to downstream sensors is $t_{helium} = 5.8$ s, which is 20% less than the empirically obtained t_{offset} . This value is calculated using the hydraulic parameters listed in [8]. The agreement of empirical and calculated propagation times is fair since the parameters listed in [8] might have error bars that cumulate into such difference. However, looking at [14] and [15], $v_{eff} = 0.11$ m/s is a realistic value compared with the velocities determined for different CICC.

There are several elements, which support the hypothesis that the fluctuation is generated by the helium control system at inlet. First, the t_{offset} is different for every initial temperature as listed in Table 1. In addition, the t_{offset} variation is evidently connected with the helium density variation, since the ratio of ρ_{he} to t_{offset} is constant. Higher

Fig. 5. Temperature measured during test run #CSJA8Q011206 as function of time. In blue, the average upstream temperature (T_{up}), while the temperatures measured downstream the high field zone (T_{down}) is in red. The upstream temperature shifted by the time offset is in green and covering the red curve during the bias oscillations. The battery voltage used to generate the pulse magnetic field is in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1

Empirically calculated time delay between upstream and downstream temperature.

Temperature [K]	ρ_{he} [kg/m ³]	t_{offset} [s]
7.75 ± 0.05	99 ± 1	8.3 ± 0.3
8.10 ± 0.05	91 ± 1	7.5 ± 0.3
8.40 ± 0.05	85 ± 1	7.3 ± 0.3
8.59 ± 0.05	81 ± 1	6.9 ± 0.3

temperature corresponds to lower density and a smaller heat slug transport time considering the mass flow constant, see relation 2.

Second, the helium heat capacity per unit of volume, $\sim 10^5$ J/(m³K),

Fig. 6. Temperature measured during test run #CSJA8Q011206 as function of time. $T_{upstream}$ and $T_{downstream}$ are average temperatures, while T_0 left and T_{inlet} are measured by single sensors.

is about two orders of magnitude larger than the heat capacity of the superconductor plus copper composite, $\sim 10^3 \text{ J}/(\text{m}^3\text{K})$. Therefore, considering coolant and composite at similar temperature, the helium slug is capable to cross the conductor length with negligible small variation of temperature. Since the heat slug is propagating in the conductor with small variation, it is possible to visualize how the fluctuation crosses the conductor. In Fig. 6, the average upstream and downstream temperatures are compared to the T_{inlet} and T_0 left sensors, placed at the helium inlet and at the beginning of the conductor respectively, see Fig. 1. There is a first temperature peak visible in T_{inlet} , probably generated by the temperature controller, trying to compensate the temperature and pressure changes initiated during the magnetic field pulse. This peak propagates in the conductor and is measured by all the sensors at different times, depending on the helium flow. The peak is also followed by minor adjustments of the temperature controller, which likely generates the fluctuations at 340–350 s and 360–370 s.

Since, the temperature fluctuations decrease in time after the pulse, tending to the correct temperature, and the peak positions clearly correlate with the helium flow, the most probable origin for the fluctuation is the PID temperature controller. Altogether, subtracting the average temperatures after compensation for the helium flow time offset, allows to accurately calculating the temperature difference in time generated by the applied magnetic field pulse.

5. Energy calculation

In Fig. 5, after shifting the upstream profile, as $T_{up}(t + t_{offset})$, a very good match between both bias profiles is found. The temperature difference between upstream and downstream average temperatures is then calculated and shown in Fig. 7 as absolute value for simplicity. The large bias oscillations are annulled and the remaining temperature difference ΔT , versus time can be used to calculate the deposited energy using Eq. (1).

The integral of the temperature as function of time is calculated between the instant at which the magnetic field pulse is applied and the time where the temperature has returned to the stationary condition.

In the temperature difference profile, a second smaller fluctuation is observed while the curve is approaching zero, in this example between

Fig. 7. Absolute temperature difference (ΔT) between upstream and downstream temperatures as function of time, represented by the green line. The battery voltage used to generate the pulse magnetic field is in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

305 and 315 s. The fluctuation is generated during the second temperature peak, visible in both T_{up} and T_{down} , see Fig. 5. The two peaks upstream and downstream are not equivalent; therefore, the difference is not zero. This fluctuation is likely caused by the interaction between temperature controller and heat pulse deposited by the AC coil, and is observed in all the temperature measurements of the MQE tests performed on CSJA8. The oscillation is considered as relevant in the integration of the energy in order to avoid an underestimation of the deposited energy.

The temperature integral is then multiplied by the mass flow and specific heat of the helium. In this case the mass-flow is 3.3 g/s and the average specific heat at 8.1 K is 8325 J/kg·K. The resulting energy is 432 mJ/cm³.

Ignoring the minor peak and considering the system restored at about 310 s, the calculated energy is 353 mJ/cm³. The difference

Fig. 8. Temperature difference (ΔT) between upstream and downstream temperatures as function of time of sample CSJA8 and PFEU2. The PFEU2 temperature is scaled in order to compensate the different helium density and mass flow.

between both calculated energies is about 15% strengthening the estimate that the error for the energy measured during the stability test might be better than 10%, considering that the final energy is between the two calculated values.

The second peak is not observed during the test of PF conductors, where the MQE was measured below 6 K. In order to analyze the trend of the temperature difference, the ΔT measured during the stability test of sample PFEU2 [7] is compared to the peak in Fig. 7. The helium flow during the test of the PFEU2 at 5.7 K has lower mass flow, 2.5 g/s, and higher density. Therefore, the coolant spends about twice the time to travel along the same cable length. After applying a scaling correction factor to the PFEU2 helium velocity, the temperature variations are compared in Fig. 8. The PFEU2#Q010709 test was chosen because the temperature variation, as by coincidence, has the same amplitude as the CSJA8#Q011206 test, therefore it does not need any correction in temperature amplitude in order to be compared. The comparison strongly suggests that the small fluctuation at the end of the pulse, not observed during the PFEU2 test, is an anomaly generated by the temperature controller.

6. Conclusion

The temperature fluctuation measured during the stability test of the CSJA8 sample is analyzed and attributed to the helium temperature

controller, which is probably operating at the limit of its capability.

The energy generated by the pulsed magnetic field during the stability test of the CSJA8 sample can be calculated considering a correction for the coolant flow in the conductor. The calculated energy is somewhat affected by the minor peak observed in the temperature difference at the end of the pulse allowing a maximum error of about 10%.

In future analysis of SULTAN stability measurements on Nb₃Sn conductors the proposed calculation methodology is recommended in order to allow an accurate energy calculation.

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