

W7-X DEMO coil cryogenic tests in the CEA/Saclay Test Facility

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Abstract^{3/4} In the frame of the W7-X stellarator project, CEA co-operates with Max-Planck-Institut für Plasmaphysik in performing the acceptance tests of all 70 superconducting coils of the W7-X magnet system. The test facility is now completed and its performance is being checked using the W7-X prototype coil. The main objective of the tests of the series coils is to demonstrate their proper function and to determine their margin of operation. Since many coils will be tested and compared to each other, it is important to measure the margin of operation in a reproducible way with sufficient accuracy. Either increasing the current, increasing the temperature or mixed operation can induce quenches. The test results on the prototype coil will be analyzed with respect to the temperature and current margin and compared to the expected values calculated from the superconducting strand data. The paper will summarize the results of these tests and the methods of evaluation.

I. INTRODUCTION

This paper will particularly focus on the so-called margin tests, i.e. the measurements of operating limit of the W7-X coils. The aim of this test is not only to prove that a coil can operate in nominal condition, but also to measure the critical superconducting limits (current sharing temperature) of the coil. It has to be noted that similar tests are currently performed on ITER prototype coils [1].

In order to find the proper method to perform that measurement with our test facility [2], experiment have been performed with the W7-X prototype coil, the so-called DEMO coil. This paper will particularly be focused on the current sharing test, i.e. the increase of temperature at constant current up to the quench. First, the experimental operating conditions of the coil within the test facility will be recalled, with a brief description of the coil itself. Then, the quench results will be sum up. Finally, a model developed for the analysis of these tests will be presented and discussed.

II. EXPERIMENTAL SET-UP

A. DEMO coil description

This section intends to give an elementary description of DEMO coil needed for the quench analysis. An exhaustive coil description has already been done elsewhere [3].

DEMO coil is composed of a winding pack and a casing. The winding pack is made of 6 parallel hydraulic channels made of about 180m of CIC each. Each channel corresponds to a double layer (labeled DL1 for the high field layer up to DL6 for the low field layer). The Figure 1 sums up the hydraulic scheme of the coil within the CEA test facility.

The 6 inlets are common and labeled "2104". The outlet of DL1 is labeled "2100", of DL2 and DL3 "2101", of DL4

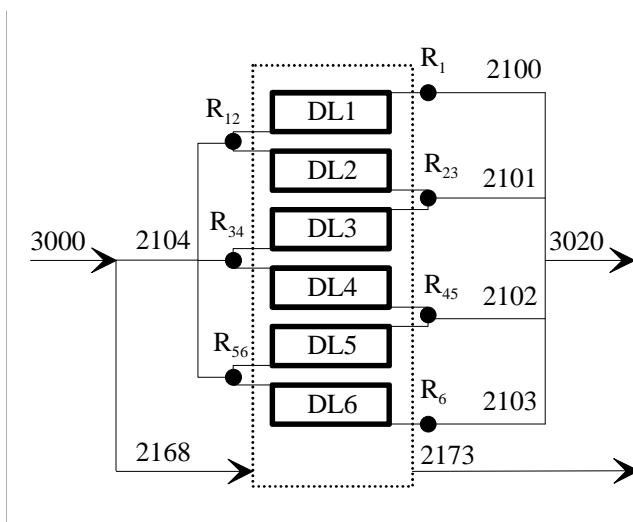


Fig. 1. DEMO Coil hydraulic scheme.

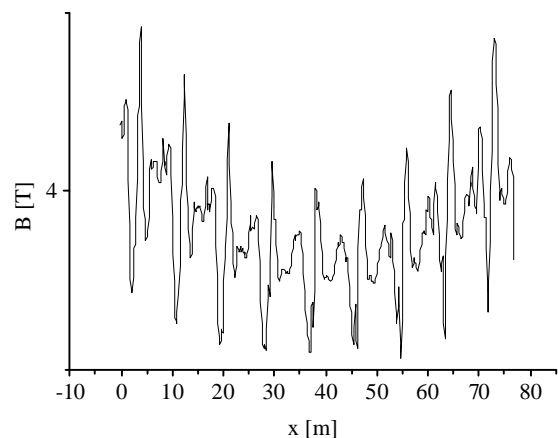


Fig. 2. Field strength along the inner layer for a current of 16 000 kA. Helium outlet is at x equal to 0.

and DL5 “2102”, and of DL6 “2103”. The highest field layer is in helium outlet.

Around the winding pack is the casing (symbolized in dashed line in Figure 1) cooled by a welded pipe. The inlet of the casing is labeled “2168” and the outlet “2173”.

Between each double layer is a resistive junction (symbolized by a black dot in Figure 1). R_{ij} is the resistance between DL_i and DL_j , R_1 the resistance at the outlet of DL_1 , and R_6 the resistance at the outlet of DL_6 .

For quench analysis, the field strength along the high field layer is required. Figure 2 [4] shows that the highest field point, 4.51 T, is at outlet (x equal to 0 m) of the inner layer. It is important to note that during TOSKA test [3] the maximum field point were in inlet.

B. Operating conditions

During the current sharing test, the inlet pressure “3000” is controlled at 6 bar, and the outlet pressure “3020” is controlled so that the total mass flow inside the winding pack is equal to 4.2 g/s. In parallel, the casing mass flow is controlled at 5 g/s. For each labeled tube in Figure 1, pressure (ex. PT3000), temperature (ex. TT3000) and mass flow (ex. FI2104) are measured.

The refrigerator before pipe “3000” can deliver up to 15g/s at three different temperatures: 7.5K, 5.7K and 4.8K. In order to control the coil temperature, pipes “3000”, “2104” and “2168” are equipped with heat exchanger of about 100W each for the temperature control.

The vacuum vessel is at about 10^{-6} mbar.

III. CURRENT SHARING TESTS

The aim of this test is to compare the current sharing temperature of the coil to the current sharing temperature of the strand. The method is to increase the coil current up to the nominal value, 14.7 kA for DEMO coil, and then to increase the temperature slowly. The results are presented in three sections: temperatures, interlayer junction resistance, and the quench event. The temperature and the resistance section will be especially needed to feed the model presented in the last section.

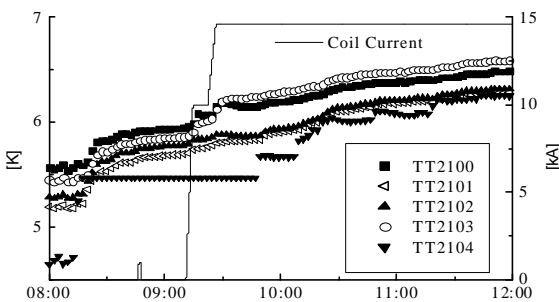


Fig. 3. Winding pack temperature during the current sharing test.

A. Temperatures

All these tests have to be performed in a quasi steady state condition. Roughly, the time needed to stabilize the winding pack is about half an hour. That means that the temperature has to be increased very slowly in order to ensure to work in stable condition, and not in transient. Figure 3 shows the inlet/outlet temperatures during the current sharing test. Table I, in the next section, presents operating condition at zero current, and for nominal current.

It is important to note that the thermal time constant between the casing and the winding pack is of several hours. This has already been observed during the test performed on TOSKA [3]. It means the casing is nearly never thermally stabilized during our test. Indeed during the current sharing test, the casing temperature increase from 8.4 K up to 9.4 K. Another effect observed during current test is the change of the temperature distribution on the casing: it means that the thermal contact between the casing and the winding pack is different according to the magnetic force distribution.

B. Interlayer resistance junctions

For the quench protection, DEMO is equipped with 6 voltage taps, one for each double layer. This wires are not compensated, but it has been possible to reach a sensitivity of about $10 \mu\text{V}$ at 15 kA, for a constant current, thanks to an over sampling rate at 5kHz. It means the sensitivity is about $1 \text{ n}\Omega$ at 10 kA. Figure 4 shows the voltage drop measured across each double layer as a function of the coil current. It is the possible to directly measure the interlayer junction resistance. R_{12} , R_{23} , R_{34} , R_{45} and R_{56} are respectively equal to 4.2 (1.0), 4.0 (1.6), 4.3 (4.3), 3.1 (2.5), 3.1 (14.3) $\text{n}\Omega$. Between parentheses the values found by a calorimetric method on TOSKA [3] has been recalled; only the total values are in rather good agreement ($19 \text{ n}\Omega$ compared to $23 \text{ n}\Omega$).

No direct resistance measurements were available for R_1 and R_6 (see §II.A). But by a calorimetric measurement, a resistance of $7.9 \text{ n}\Omega$, and $11.2 \text{ n}\Omega$ is found respectively on DL_1 and DL_6 . Then R_1 and R_6 can be deduced and are

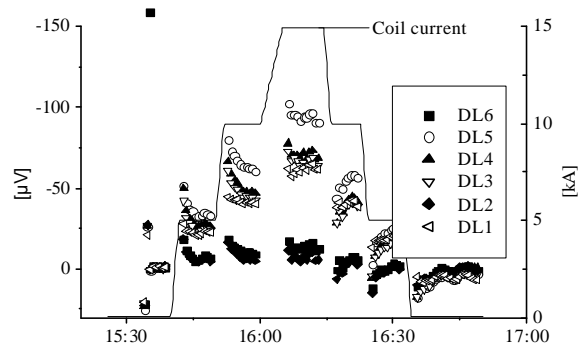


Fig. 4. Interlayer resistance measurement.

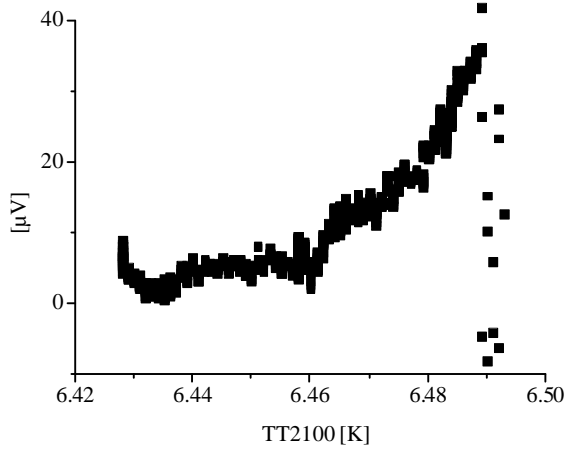


Fig. 5. Inner layer outlet temperature (TT2100) as a function of the voltage drop over the layer.

equal respectively to 5.8 nΩ, and 9.7 nΩ.

C. Current sharing measurement

As presented in Figure 3, the inlet coil temperature has been increased slowly up to the quench. Figure 5 presents the voltage over the inner layer as a function of the outlet temperature. The quench occurs for an outlet temperature of about 6.49 K. A very important point to note is that these measurements have been performed in a quasi-static mode as the coil has been operating in the current sharing region during about one hour. Besides a test has shown that it is possible to recover the coil before the quench. It demonstrates it is possible to operate in stable condition the DEMO coil even in the current sharing region. Now, for an assessment of the coil, it is very important to be able to compare this experimental result to the intrinsic properties of the strands inside the coil.

IV. ANALYSIS

For that purpose, a model has been developed in order to compare the strand properties to the coil experimental results. Indeed, regarding the highly inhomogeneous field (see Figure 2), it is clear that a model for calculating the temperature along the inner layer with the knowledge of inlet and outlet temperatures is needed.

A. Model hypothesis

① All calculation are performed in a quasi static regime.

② This a finite element calculation were a cell represent a conductor piece of length dx cooled by a mass flow dm/dt . Each cell is connected to the others by a turn-to-turn, layer-to-layer, double layer-to-double layer, turn-to-casing thermal resistance.

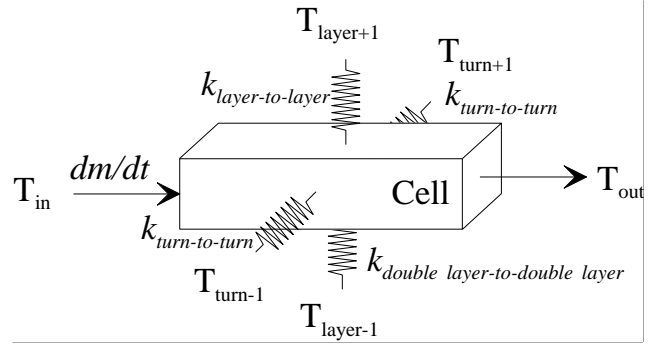


Fig. 6. Cell description.

③ The model is composed of six channels, one for each double layer

④ The casing temperature is assumed to be constant and equal to 8.4 K.

⑤ The inlet temperature and pressure are constant

⑥ An inlet and outlet resistance is given for each double layer.

⑦ Within a conductor cross section the temperature is uniform. It means that the helium temperature is equal to the conductor temperature. That is justified by the quasi-static regime.

Figure 6 presents a typical cell connected to the surrounding layers and turns. Using this view, it is possible to write the energy balance on this cell as a linear equation of the cells temperature; k_{l-to-l} , k_{l-to-t} , and $k_{dl-to-dl}$ are respectively the thermal conductance between turns, layers, and double layers, I_c is the critical current of the conductor for a given field and temperature [3] (the magnetic field is calculated using the field map presents in Figure 2 [4]), n is equal to 40.

$$\begin{aligned} dm/dt \cdot C_p (T_{in} - T_{out}) = V_c \rho I \cdot (I/I_c)^n + \\ k_{l-to-t} (T_{layer+1} - T_{in}) + k_{dl-to-dl} (T_{dl+1} - T_{in}) + \\ k_{t-to-t} (T_{turn+1} - T_{in}) + k_{t-to-t} (T_{turn-1} - T_{in}) \end{aligned} \quad (1)$$

There is one similar equation for each cell that can be written in a matrix form, where $\underline{\underline{M}}$ is a matrix which depend only on the coil thermal conductance, and $\underline{\underline{A}}$ is a vector including boundary conditions (as inlet temperature), and additional power (junction resistance, superconducting transition).

$$\underline{\underline{M}} \cdot \underline{\underline{T}} = \underline{\underline{A}} \quad (2)$$

Thanks to (2), it is then possible to calculate the temperature profile along each layer knowing only the inlet temperature, the mass flow in each layer, the thermal conductance and the junction resistances.

TABLE I
SIMULATION RESULTS

Pipe	TT2104 = 5.47 K		TT2104=5.47 K	
	I _{op} = 0 kA		I _{op} = 14.6 kA	
	Result	Model	Result	Model
2100	5.94	5.90	6.16	6.17
2101	5.69	5.73	5.83	5.90
2102	5.78	5.74	5.87	5.89
2103	5.86	5.93	6.24	6.35

The thermal conductance between the winding pack and the casing is equal to 0.65 W/m².K; this is the value calculated during TOSKA tests [3].

The value of the turn-to-turn insulation (Glass E) has been adjusted to fit the model results to the experimental ones without current. Table I shows that a constant value of 25 mW/m.K gives a good agreement for I_{op} equal to zero. At nominal current the agreement is also relatively good using the measured interlayer junction resistance in section III.B. These simulations show that the model is in agreement the inlet/outlet measurements within a range of about 0.1 K.

B. Current sharing simulation

It is now possible with our model to increase the inlet temperature up to the current sharing and to compare it with results as presented in Figure 7. A difference of 0.25 K at 3 μ V over the inner layer is found. Such a difference has also been observed during TOSKA test [2] in spite the helium inlet was connected in the opposite way. It is nevertheless hard to conclude if this deviation is physical or due to model accuracy as only one current sharing test has been performed.

An other result is that the quench is ignited at the inner layer outlet, x equal to 4 m (see Figure 8 the temperature margin curve ($T(x)-T_{cs}$)). In fact in our case, both the

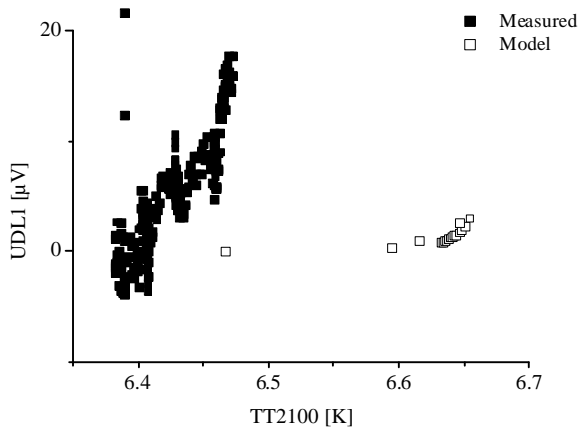


Fig. 7. Comparison between calculated current sharing, and the measured current sharing curve.

maximum temperature and the maximum field are at the same location. For serial tests the inner layer will be in inlet.

V. CONCLUSION

Our test facility has demonstrated its capacity to perform a current sharing test. Besides, the test has shown it is possible to operate a NbTi CIC coil as the DEMO coil in the current sharing regime in stable condition in spite of the large n value of the NbTi strand.

On the other hand, the finite element model developed to analysis the current sharing test has shown a rather good agreement with the experiment, and then will be an useful tool to analysis quench tests on serial coils. It has to be noted that only one test has been performed and analyzed with our code. Then it will be necessary to perform other at different current in order to confirm the validity of the model.

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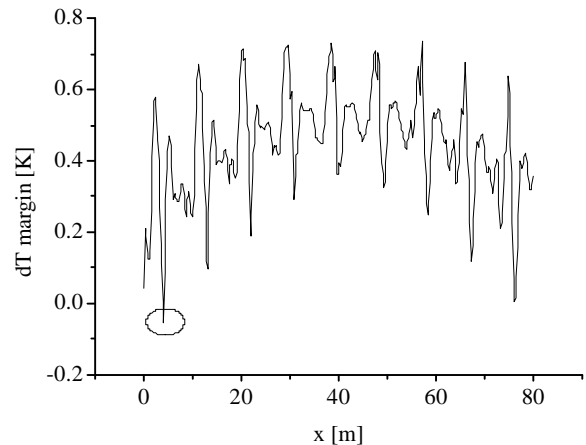


Fig. 8. Temperature margin along the coil inner layer for a voltage drop of 3.5 μ V.