Predictive study of the Poloidal Field Coil Insert behaviour under pulsed current tests

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Abstract. Within the ITER Poloidal Field conductor design validation, the Poloidal Field Conductor Insert (PFCI) has been manufactured and will be tested in the Central Solenoid Model Coil (CSMC) facility at JAERI Naka (Japan). In this test facility, the PFCI can be tested under ITER-relevant operating conditions, the field produced by the CSMC being varied to simulate the real situation of the PF coils in ITER. Predictive analyses have been performed in order to study the electromagnetic and thermal-hydraulic behaviour of the PFCI, under two scenarios proposed for pulsed current tests. During these scenarios, simulations have been performed with the THEA code, in which classical formulas for the AC losses in a cable have been introduced. The study focuses on the lower part of the winding, which is a 44 m long conductor including a joint. It covers the sample thermal-hydraulic behaviour with particular emphasis on the losses. Due to the overcompaction in the joint area, the total energy dissipated during a scenario can be equivalent in the joint and in the conductor, in spite of the reduced length of the joint (0.45 m). This particular point is discussed and has led to the analysis of the temperature margin in the joint.

1. Introduction
In the framework of the ITER project, the validation of the conductor used for the Poloidal Field (PF) coils has to be performed and has led to the manufacturing of the Poloidal Field Coil Insert (PFCI). This superconducting insert is a single-layer solenoid, made of about 50 m of ITER PF full-size dual-channel conductor. The PFCI is going to be tested inside the Central solenoid Model Coil (CSMC) at JAERI Naka (Japan). In this test facility, the background magnetic field is produced by the CSMC and is varied to simulate the real situation of the PF coils in ITER, allowing the conductor characterization under ITER-relevant conditions.

As shown in figure 1, the PFCI is composed of 9 turns of NbTi Cable In Conduit Conductor (CICC), divided in a lower main winding (44.3 m) and an upper busbar (5.2 m). Three superconducting joints provide electrical and cryogenic connections. The lower and upper termination joints interface with the main terminals of the CSMC facility, while the Intermediate Joint (IJ) connects the winding and the busbar to each other, and operates hydraulically as a parallel flow heat-exchanger.

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Among the planned tests, pulsed current runs should allow the PFCI characterization regarding thermal-hydraulics and electromagnetism. Two scenarios have been chosen for a predictive analysis performed in 2006 and the results have been presented in [1]. These scenarios are an exponential discharge and a trapezoidal mode of the CSMC, with no current in the PFCI. The 2006 study has focused on the winding and the intermediate joint. Losses have been computed in both components (i.e. the winding conductor and the joint), with several models. Two thermal-hydraulic calculations have then been performed in each component separately, leading to the temperature increases through the winding on one hand and through the joint on the other hand.

In this paper, we propose a single consistent thermal-hydraulic model for the winding and its both joints (lower termination and intermediate). The study focuses on the thermal effect of losses dissipated in the winding and in the intermediate joint, and on the temperature margin in the joint.

2. Model description and main parameters

2.1. Model description and objectives

The thermal-hydraulic model has been developed with the THEA code [2]. It describes the lower termination joint (0.45 m), the winding (43.42 m) and the intermediate joint (0.45 m). For each joint, a single half is modelled, without heat transfer to the non-modelled other half. The number of elements is 400, corresponding to a mesh size of 0.111 m.

Electromagnetic losses calculation has been introduced in the code, using the classical formulas for the two categories of AC losses, coupling and hysteretic:

- \( Q_{\text{comp}} = \frac{\pi r S_{\text{strands}}}{\mu_0} \left( \frac{dB_\perp}{dt} \right)^2 \) [W/m] with \( S_{\text{strands}} = \text{total SC strands area and } \mu_0 = 4\pi \times 10^{-7} \text{ H.m}^{-1} \)

- \( Q_{\text{hyst}} = \frac{2}{3\pi} \left( \frac{I}{J_c(B,T) S_{SC}} \right)^2 d_{\text{eff}} S_{SC} J_c(B,T) \left| \frac{dB_\perp}{dt} \right| \) [W/m]

with \( I = \text{sample current}, J_c = \text{critical current density}, S_{SC} = \text{superconducting material area and } d_{\text{eff}} = \text{strand effective diameter} \)

The single contribution of the field \( B_\perp \) perpendicular to the conductor has been taken into account. This AC losses calculation is applied in the winding and in the bottom joint. Losses in the intermediate joint have been calculated according to the model described in [3], and are divided in radial and parallel contributions. These two powers, depending on time and constant along the joint length, are applied in the THEA model, respectively in the jacket and in the strands of the IJ.

The model can then provide the prediction of temperatures at sensors location, particularly at IJ inlet and outlet, as well as the temperature margin associated to the induced currents in the IJ (no temperature margin is computed in the winding, since \( I_{\text{PFCI}} = 0 \text{ kA for both studied scenarios} \)).

2.2. Thermal-hydraulic characteristics

The geometrical parameters of the winding conductor have been taken from [4], for the wrapped sample. We have slightly modified the wetted perimeter \( P_w \) of the bundle, considering that all strands are wetted (instead of 5/6). New values for the bundle channel are then \( P_w = 3784.9 \text{ mm and } D_h = 0.351 \text{ mm} \).

For the compacted joints, both bottom and intermediate, we have taken into account a bundle void fraction of 25 % by adjusting the cable inner diameter and considering a total de-wrapping and an unchanged spiral outer diameter (12 mm). This has led to \( P_w = 3444.7 \text{ mm and } D_h = 0.243 \text{ mm for the joints bundle channel}. \) The cross section of each half joint is modelled by an equivalent thick jacket, considering the areas of copper and of stainless steel.
The friction factors are taken from the ITER Design Criteria (ITER-DC) for the bundle, \( f_{\text{ITER-DC}} = (1/V^{0.742}) (0.0231+19.5/Re^{0.7953}) \), and from [5] for the spiral, \( f = 0.047 \ Re^{0.0053} \). The heat exchange coefficient in each channel is deduced from the friction factor by the Colburn-Reynolds analogy [6].

2.3. Electromagnetic parameters

The main electromagnetic parameters useful for the AC losses calculation are listed below:

- strand effective diameter \( d_{\text{eff}} = 5 \mu m \), \( S_{\text{strands}} = S_{\text{Cu}} + S_{\text{SC}} = 353 + 250 \text{ mm}^2 \) [7],
- cable time constant \( \tau = 20 \text{ ms} \). This value, which comes from short samples tests [8], takes into account all kinds of coupling losses (interstrand resistance, all cabling stages) and corresponds approximately to \( N < 1000 \) cycles.

The critical current density \( J_c(B,T) \) used in the 2006 study [1] had been fitted with the classical formula (1) for NbTi [9], with the parameters \( C_0 = 3.384.10^{11} \text{ A/m}^2 \), \( B_{C20} = 14.83 \text{ T} \), \( T_{C0} = 9.02 \text{ K} \), \( \alpha = 1.69 \), \( \beta = 1.91 \), \( \gamma = 2.13 \) given in [10]. Due to the bad behaviour of this fit at low field (\( J_c \to 0 \) when \( B \to 0 \)), we had forced a constant \( J_c \) for \( B < 2.5 \text{ T} \). This assumption was expected to explain the difference observed in [1] between the losses computed by E Zapretilina (EZ) and those obtained with our model.

In this study, we have considered the same \( J_c \) formula, but with the fitting parameters corresponding to the Bochvar strand used in the PFCI, \( C_0 = 4.78021.10^{11} \text{ A/m}^2 \), \( B_{C20} = 15.07 \text{ T} \), \( T_{C0} = 8.99 \text{ K} \), \( \alpha = 1.96 \), \( \beta = 2.1 \), \( \gamma = 2.12 \) [11].

This fit having the same bad behaviour at low magnetic field, we have introduced a different correction. The magnetic field \( B_f \) giving the maximal \( J_c \) is computed from the \( J_c \) correlation, considering that at this field \( \partial J_c/\partial B = 0 \). For \( B < B_f \), we use the Kim correlation [12], taking \( J_c = 10^{10} \text{ A/m}^2 \) at \( B = 0 \text{ T} \) and for any temperature. This order of magnitude for \( J_c(B=0) \) is deduced from the \( J_c \) correlation proposed in [13]. Both fits, referred as 2006 and 2007, are presented on figure 2.

\[
J_c(B,T) = \frac{C_0}{B} \left( \frac{B}{B_{C2}} \right)^{\alpha} \left( 1 - \frac{B}{B_{C2}} \right)^{\beta} \left( 1 - \left( \frac{T}{T_{C0}} \right)^{\gamma} \right)^{\gamma} \text{ with } B_{C2} = B_{C20} \left( 1 - \left( \frac{T}{T_{C0}} \right)^{\gamma} \right) \quad (1)
\]

**Figure 1.** PFCI overview

**Figure 2.** Critical current density versus magnetic field, at \( T = 4.5 \text{ K} \). The 2006 and 2007 correlations correspond respectively to the ITER-DC and to the Bochvar strand.
3. Exponential discharge results

This scenario corresponds to a CSMC exponential discharge with $I_{PFCI} = 0$ kA, $I_{CSMC}(t=0) = 21.2$ kA, $\tau = 20$ s, $T_{in} = 4.5$ K, $P_{in} = 6$ bar and $Q = 10$ g/s. Computed temperatures have been examined at IJ sensors location. The IJ inlet temperature TinIJ corresponds to the bundle He temperature at $x = 43.5$ m from the bottom joint inlet, while the IJ outlet temperature ToutIJ corresponds to the mixture temperature of both channels, downstream of the IJ outlet.

TinIJ reaches 4.56 K at $t = 100$ s. ToutIJ has a maximum value of 4.82 K at $t = 12$ s. The temperature margin $\Delta T_{margin} = T_{cs} - T_{strands}$ has been computed in the joint, considering the induced currents. Its minimal value is located at the joint outlet, and is of $7.60 - 5.34 = 2.26$ K at $t = 7$ s.

Losses in the IJ (both halves) and in the winding are comparable: $E_{IJ} = 555$ J and $E_{winding} = 583$ J (319 J coupling + 264 J hysteretic). These winding losses are close to those obtained with the 2006 Jc correlation: $E_{coup}$ identical, $E_{hyst} = 194$ J. The difference with EZ results observed in [1] is much higher and is thus not only due to the assumption on $J_c$ at low field.

4. Trapezoidal scenario results

The trapezoidal scenario features are $I_{PFCI} = 0$ kA, flat top $I_{CSMC} = 21.2$ kA, $t_{ramp up} = t_{ramp down} = 12$ s, $t_{flat top} = 5$ s, $T_{in} = 4.5$ K, $P_{in} = 6$ bar and $Q = 10$ g/s. As for the exponential mode, IJ and winding losses have the same order of magnitude: $E_{IJ} = 2954$ J (prediction for both halves) and $E_{winding} = 2656$ J (2129 J coupling + 527 J hysteretic). With an IJ length of 0.45 m, the linear power dissipated in the half joint reaches substantial values, up to 171 W/m at $t = 12$ s (73 W/m in the strands + 98 W/m in the jacket). Temperature variations, shown in figure 3, are thus more important than for the exponential mode.

The $\Delta T_{margin}$ computed at the joint outlet, plotted on figure 4, is negative between $t = 9$ s and 17 s. At the most penalizing time, $t = 12$ s (end of ramp up), $T_{strands}$ reaches 8.56 K at IJ outlet and $\Delta T_{margin}$ is negative over 87 % of the joint length (from $x = 0.06$ m to 0.45 m inside the joint).

We also note that the $\Delta T$ across the IJ (ToutIJ – TinIJ) reaches 1.29 K at $t = 12$ s, which is higher than the value of 1.05 K predicted in [1]. This difference could be due to the temperature variation in the bundle, which induces a significant variation of the He specific heat in this channel, and has thus an impact on the mixture temperature calculation.

![Figure 3](image1.png)

**Figure 3.** Predicted temperatures at IJ inlet and outlet sensors location (trapezoidal scenario)

![Figure 4](image2.png)

**Figure 4.** $T_{cs}$ and $T_{strands}$ temperature at IJ outlet (trapezoidal scenario)

5. Detailed analysis of the trapezoidal scenario

5.1. Influence of hydraulic parameters

The effect of hydraulic parameters has been studied by varying the mass flow rate and the global heat exchange $h_{global}$ between annular and central channels [6]. Results are presented in table1 below.
Table 1. Effect of mass flow rate and of inter-channel heat exchange coefficient $h_{\text{global}}$ on temperatures at $t = 12$ s (end of ramp up).

| $Q$ (g/s) | $h_{\text{global}}$ | $T_{\text{inIJ}}$ | $T_{\text{outIJ}}$ | $\Delta T_{\text{IJ}} = T_{\text{outIJ}} - T_{\text{inIJ}}$ | $T_{\text{strands at IJ outlet}}$ |
|-----------|----------------------|-------------------|-------------------|-----------------------------|-------------------------------|
| 10        | $\times 1$           | 4.60              | 5.89              | 1.29                        | 8.56                          |
| 11        | $\times 1$           | 4.59              | 5.83              | 1.24                        | 8.29                          |
| 12        | $\times 1$           | 4.59              | 5.78              | 1.18                        | 8.03                          |
| 10        | $\times 1.5$         | 4.60              | 5.92              | 1.32                        | 7.96                          |

We note that an increase of 50 % on $h_{\text{global}}$ has nearly the same effect on the outlet strands temperature as an increase of 20 % on mass flow. In any case, at $t = 12$ s, $T_{cs}$ being equal to 6.80 K, $\Delta T_{\text{margin}}$ stays widely negative.

The results analysis has also shown that the mass flow rate is not stationary. As a matter of a fact, the THEA model is such that the initial mass flow is imposed by adjusting $\Delta P$ at the boundaries of the cable (more precisely by adjusting $P_{\text{outlet}}$ with $P_{\text{inlet}} = 6$ bar). These boundaries stay then at constant pressure, and the power deposition, as well in the winding as in the joint, modifies the initial mass flow rate, through compressibility effects that reduce the mass flow at the inlet and increase it at the outlet. This can be observed on figure 5. This mass flow variation can reach 20 % and has thus a non negligible impact on temperature calculations. For example, with $Q_{\text{initial}} = 10$ g/s, at $t = 12$ s and at the IJ outlet, the mass flow is of 11.5 g/s, what is favourable for the strands temperature.

**Figure 5.** Mass flow versus time (trapezoidal scenario)

**Figure 6.** IJ bundle temperatures computed with a parallel flow heat exchanger model

5.2. Influence of the cold upper side of the joint

The influence of the joint “cold” upper side is expected to be weak since temperatures at both IJ inlets are close, the maximum $\Delta T_{\text{inlet}}$ being of $4.75 - 4.5 = 0.25$ K at $t = 100$ s. The IJ operating as a parallel flow heat exchanger, the corresponding classical analytical formulas have been applied, with the previous inlet temperatures under steady state. The thermal resistance of the Cu jackets and saddle being very small, calculated bundle temperatures are equal at $\pm 10^{-3}$ K over 2/3 of the IJ length, as shown on figure 6. Strands temperatures should thus be very close in both sides at the IJ outlet.

In order to analyse this effect more precisely, a 2nd CICC describing the busbar has been introduced into the THEA model. The link between the two IJ halves is described by taking into account the low thermal resistance of the Cu saddle and jackets. The IJ upper side has a $T_{\text{inlet}}$ of 4.5 K and receives
the same power as the lower side (corresponding to the trapezoidal scenario joint losses), and no power is applied on the upper busbar conductor.

Unexpectedly, we obtain a slight increase of the outlet Tstrands in the lower side. At t = 12 s and at the IJ outlet, the calculation gives a lower side Tstrands of 8.70 K (instead of 8.56 K with a single half joint modelled) and an upper side Tstrands of 8.73 K. This is due to the impact of power deposition on mass flow described above, this effect leading to a lower mass flow in the upper joint: at t = 12 s, \( Q_{\text{upper side}} = 10.46 \, \text{g/s} \) and \( Q_{\text{lower side}} = 11.52 \, \text{g/s} \). Concerning the outlet mixture temperatures, the effect of the heat exchange through the joint is small, because most of the mass flow (~ 85 %) circulates in the joint central channels: at t = 12 s, the predicted \( \Delta T \) across the IJ are 1.32 K for the lower side (instead of 1.29 K with a single half joint modelled) and 1.39 K for the upper side.

6. Conclusion
The PFCI behaviour has been studied for two pulsed current tests without current in the sample. Results show that the energy dissipation is comparable within the winding and the intermediate joint. The joint being about 100 times shorter than the winding, the temperature variation is much more important in the IJ and especially in the strands, and the induced current loops lead to a negative \( \Delta T \) margin in the joint for the trapezoidal scenario. Besides, non negligible compressibility effects have been observed; even if this phenomenon can be attributed to the thermal-hydraulic model, it shows the interest for modelling the external cryogenic circuit around the sample. The influence of the joint upper side, which keeps a cold inlet temperature, is of second order for the trapezoidal scenario.

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