PREDICTIVE QUENCH INITIATION ANALYSIS OF THE ITER TF MODEL COIL

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In the ITER TF Model Coil, the experimental evaluation of the superconducting critical properties will only be possible by heating the helium upstream of the inner joint. The goal of this predictive heat slug propagation and quench initiation analysis is to assess if a quench will be initiated in the high field region of the conductor or in the joint. An instability of the cryogenic system occurs when only one pancake is heated. To avoid the unwanted quench in the joint the test must be performed with high helium mass flow rates and slow heating procedures.

1 INTRODUCTION

In the frame of the International Thermonuclear Experimental Reactor (ITER) program, the Toroidal Field Model Coil (TFMC) will be tested in the TOSKA facility at FZ Karlsruhe, Germany. The objective of this coil is to demonstrate the feasibility of Nb3Sn superconducting coils wound in pancakes, using a dual channel cable-in-conduit conductor (CICC). The TFMC is a racetrack coil consisting of 5 double pancakes (DP11/DP12-DP51/DP52), each with two joints at the inner and outer sides of the coil. Only the double pancake DP11/DP12 is equipped with external heaters. The TFMC conductor is a circular CICC using Nb3Sn strands and a thin stainless steel jacket. The supercritical helium flows in two channels, viz. the central cooling channel (alias hole) and the cable bundle, separated by a 1 mm thick stainless steel spiral [1]. In the TFMC, an experimental evaluation of the superconductor critical properties will only be possible by heating the helium upstream of the inner joint. The heat slug generated by the external heater propagates through the joint and downstream to the high field region of the conductor [2]. Here we present the predictive heat slug propagation and quench initiation analysis - single coil test, operating current 80 kA, heat slug in pancake DP11 - using simplified models of the hydraulic circuit and the joint. The analysis is performed with the thermal hydraulic code Gandalf. The uncertainty in the presently available set of joint input data is assessed parametrically.

2 MODEL

The main components of the model are: conductor (Table 1), joint, heater and cryogenic system (Fig. 1). The magnetic field reaches the peak value of 6.8 T in the conductor at X = 4.1 m (where X is the nodal coordinate), and only slightly lower values in the joint, i.e. 6.2 T at the inlet (X = 2 m) and 5.9 T at the outlet (X = 2.5 m) [3]. Uniform current and uniform magnetic field in conductor/joint cross sections are assumed, using the peak field modulus in each cross section (at X = 4.1 m the difference between maximum and minimum field in the cross section is 1.6 T). The DP11 resistive heater is mounted on a pipe (2 m length, 10 mm inner diameter, 1 mm steel jacket) and is designed for a peak power of 500 W/m. In this analysis the heater is included in the conductor model rather than in the hydraulic circuit model for enhanced accuracy (Fig. 1). The joint electrically connects adjacent pancakes on the same radial plate. Recent measurements in the

SULTAN test facility have shown that the electrical resistance of joints relevant to the TFMC is ~2 nOhm [4]. A detailed definition of the joint hydraulic properties is difficult and an accurate assessment is in progress. In this analysis the heat flux generated in the inner joint is uniformly distributed along the 50 cm joint length (Q_j = 25.6 W/m) and the joint superconducting properties are not degraded. The simplified joint hydraulic model includes two regions, viz. the mixing chamber (10 cm long) with perfect mixing of hole and bundle helium flows and an area of no mixing; geometry and heat transfer perimeters are the same in both regions (AHEH*0.8, AHEB*0.8, DHH*0.5, PHTC*0.6 and PHTJ*0.3, AJK*1.2, Table 1) [5].

The complex cryogenic circuit of the TOSKA facility is simulated with a simplified cold closed-loop system model retaining most of the essential features of the hydraulic circuit without unnecessary complications. This model includes a volumetric pump, a heat exchanger to keep the helium temperature constant at the coil inlet (4.5 K), a controller to keep the helium pressure constant at the pump inlet (3.2 bar), and a pipe hydraulically connected in parallel to DP11, to simulate the remaining 9 pancakes. The friction factor of this pipe is adjusted to provide the steady state helium mass flows G_{ss} in DP11, and 9*G_{ss} in the pipe. The analysis is performed at G_{ss} = 6 g/s, 12 g/s and 18 g/s, the first value corresponding to the standard and the latter to the extended TFMC test conditions. The nominal helium pressure at X = 0 m is 3.5 bar.

The conductor analysis is performed with Gandalf, a computer code for the thermal hydraulic analysis of CICC. Gandalf allows different thermodynamic states of the helium in the dual channel regions as well as variable channel geometry, hydraulic impedance, material cross section and properties along the hydraulic path. The capability of this code to analyze accurately the propagation of heat slugs has been recently assessed in a validation against data from the QUELL experiment in SULTAN [6] (the same equivalent mixing bundle/hole heat transfer coefficient is used here). Consistent hydraulic boundary conditions for the conductor analysis are provided by simulating the cryogenic circuit with the code Flower coupled to Gandalf [7]. Based on a numerical convergence study, the following FE mesh and numerical parameters are used: 260 nodes total, 200 nodes in the refined zone (0 m < X < 20 m), static mesh, 5 ms max. integration time step, first order solution method.

Input parameter	Symbol	Unit	Value
Hydraulic length (heater, joint and conductor)	XLENGT	m	74.5
Non-copper cross section	ASC	mm^2	154.43
Longitudinal strain	EPSLON	%	-0.60
Copper cross section	AST	mm^2	424.68
Copper RRR	RRR	-	100
Jacket cross section (316LN)	AJK	mm^2	277.54
Insulation cross section	AIN	mm^2	164.58
Helium cross section (hole)	AHEH	mm^2	76.764
Helium cross section (bundle)	AHEB	mm^2	355.21
Hydraulic diameter (hole)	DHH	mm	11.9
Hydraulic diameter (bundle)	DHB	mm	0.445
Heat transfer perimeter helium-conductor (bundle)	PHTC	m	2.3832
Heat transfer perimeter helium-jacket	PHTJ	mm	86.653
Heat transfer perimeter conductor-jacket	PHTCJ	mm	29.504
Heat transfer perimeter hole-bundle	PHTHB	mm	37.17
Perforation fraction of hole wall	PERFOR	%	27.75
Critical temperature at zero magnetic field	TC0M	K	16.90
Upper critical magnetic field at zero temperature	BC20M	T	29.10
Fitting constant for critical current surface	C0	$AT^{0.5}/m^2$	1.10E10
Conductor outer diameter = 40.5 mm, jacket thickness = 1.6 mm, insulation thickness = 2.5 mm. Experimental friction factor of hole and bundle $f_H = 0.0756Re^{-0.0707}$ and $f_B = (0.25/V^{0.742})*(0.0231+(19.5/Re^{0.7953})$ where Re is the Reynolds number and V = 36.85% the bundle void fraction [8].			

Table 1: Conductor input parameters (symbols as in the code Gandalf).

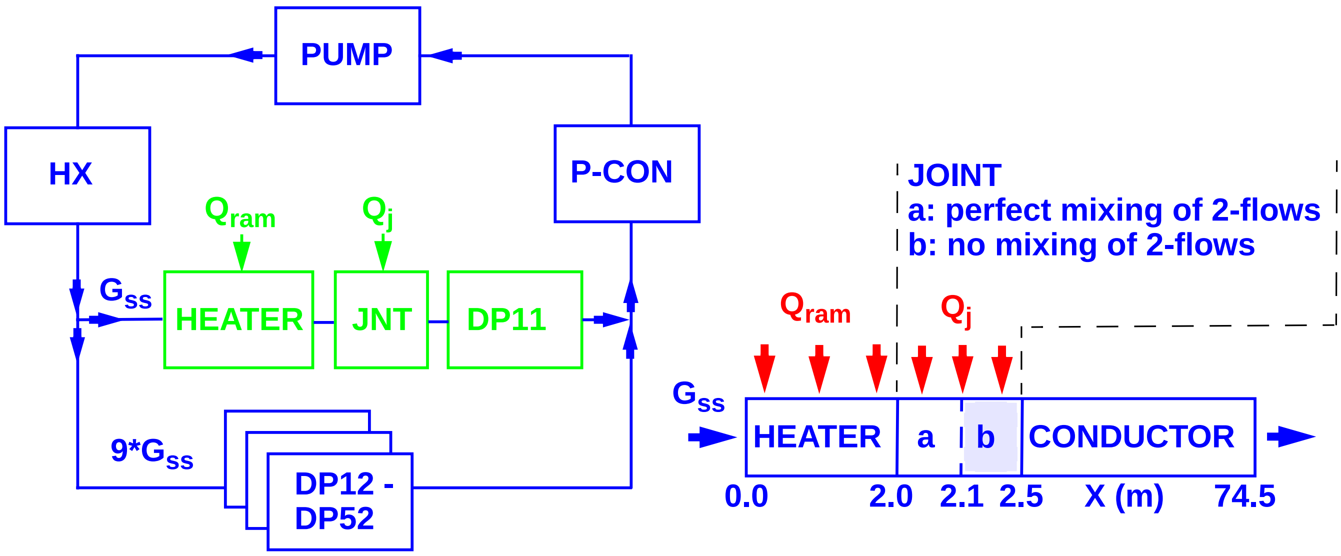

Figure 1. Left: Schematic representation of the TFMC model. The heated pancake (DP11), external heater and joint (JNT) are part of the extended conductor model simulated with code Gandalf. The pump, heat exchanger (HX), pressure control unit (P-CON) and unheated pancakes (DP12-DP52) are part of the hydraulic circuit model, simulated with code Flower. Right: Details of the extended conductor model. The powers Q_{ram} and Q_j are uniformly distributed along heater and joint, respectively.

3 RESULTS AND DISCUSSION

In all simulations the heat is generated by the DP11 external heater by means of linear ramps, with power Q_{ram} and duration t_{ram} as inputs. Heating starts after the time necessary for the simulated cryogenic system to reach steady state conditions (t = 20 s). The selected heating procedure is a ramp because it provides thermal fronts with minimum gradients. Other simulations, not reported here, show that the use of heating pulses (squared in time and space) is not possible because they generate thermal fronts propagating with steep gradients, i.e. quenches are initiated at the joint inlet regardless of the cooling conditions.

3.1 Global results

The global results are presented in form of the external heater power necessary to initiate a quench Q_{qu} at the time t_{qu}. For every helium mass flow rate the quantity Q_{qu} is plotted as a function of the heating ramp slope Q_{ram} /t_{ram} (W/m.s). Three characteristic regimes can be identified (Fig. 2). At low slopes (regime R1) Q_{qu} is quasi constant and quenches are initiated in the conductor, e.g. Q_{qu}(@18 g/s) = 210 W/m for Q_{ram} / t_{ram} < 1 W/m.s. At intermediate slopes (regime R2) Q_{qu} is quasi constant but at a lower value, and quenches are still initiated in the conductor, e.g. Q_{qu}(@18 g/s) = 160 W/m for 1.5 W/m.s < Q_{ram} /t_{ram} < 3.5 W/m.s. At higher slopes (regime R3) Q_{qu} is unchanged but the quench is initiated in the joint, e.g. Q_{ram} /t_{ram} > 3.5 W/m.s. The transition between these limiting cases is continuous. The transition R1-R2 depends on the residence time of the helium in the coil t_{res}, a function of G_{ss}, viz. 480 s at 6 g/s, 220 s at 12 g/s, 160 s at 18 g/s. Regime R1 is typical of quenches occurring at $t_{qu} > t_{res}$ while regimes R2 and R3 are typical of quenches occurring at $t_{qu} < t_{res}$. The transition R2-R3 depends on the joint critical properties and is discussed below. All these results are independent of the choice of Q_{ram} and t_{ram} for a given ramp slope; moreover, all quenches are initiated between the joint inlet and the high field region of the conductor.

When only one of the 10 parallel hydraulic channels is heated, an instability of the cryogenic system, referred to as helium choking, occurs. The helium temperature increases and the density decreases near the inlet of DP11. This causes the hydraulic impedance of the heated pancake to increase; as a consequence the mass flow G in the latter decreases while more helium flows in the unheated channels. During the heating G keeps decreasing and reaches a minimum at quench initiation G_{qu} = G(X = 2 m, t = t_{qu}) (Fig. 3). Incidentally, in the fast transient following the quench initiation, helium choking usually leads not only to a reduction of G but also to a quasi instantaneous reverse of the flow direction. The effect of helium choking is considerably stronger at lower G_{ss} since the ratio G_{qu}/G_{ss} is not linear. While Q_{qu} has two values as

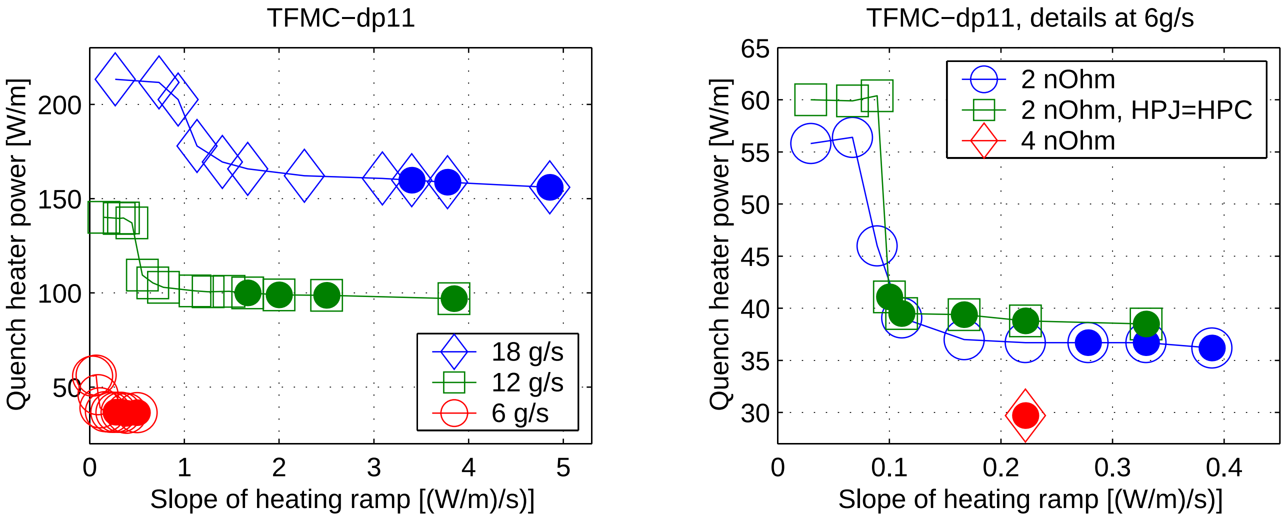

Figure 2. Summary of results using linear heating ramps. Open symbols indicated cases in which the quench is initiated in the high field region of the conductor, solid dots indicate cases in which the quench is initiated in the joint. Left: Nominal conditions (the joint electrical resistance is 2 nOhm). Right: Details at 6 g/s, including cases at nominal/double joint resistance, and cases in which the hydraulic properties of joint and conductor are the same (HPJ = HPC).

a function of the heating ramp slope, the ratio Q_{qu} /G_{qu}, proportional to the temperature increase at the heater outlet, is constant. This result is consistent with the fact that conditions are quasi steady state.

3.2 Detailed results

Three cases are discussed in detail. The time history of G and conductor temperature T_{con} at the joint inlet, as well as the spacial distribution of the temperature margin T_{mar} (defined as T_{cs}-T_{con}, where T_{cs} is the current sharing temperature, which is a function of the magnetic field) and T_{con} along X in the last seconds preceding the quench initiation are shown in Fig. 3. In case A (G_{ss} = 6 g/s, Q_{ram}/t_{ram} = 0.28 W/m.s) the effect of heat generation in the joint dominates and the quench is initiated at the joint outlet, i.e. T_{con} increases along the joint and the consequent T_{mar} reduction is larger than the T_{mar} increase due to a magnetic field reduction. This latter effect dominates in case B (18 g/s, 0.34 W/m.s) and the quench is initiated at the joint inlet, i.e. T_{con} is constant along the joint. In both cases (transition R2-R3) there is also a second quench initiated in the conductor at X = 3.2 m, which is near but not exactly at the peak field location. In case C (18 g/s, 220 W/m) the ramp duration is 300 s, almost twice the residence time. The conductor temperature is quasi constant along joint and conductor and the quench is initiated at the peak magnetic field location in the conductor, while in the joint the temperature margin exceeds 0.5 K.

3.3 Parametric assessment of the joint model

The uncertainty of the presently available model of the joint is assessed parametrically. We discuss first the case in which the hydraulic parameters of joint and conductor are the same. At 12 g/s and 18 g/s the results discussed above are unchanged while at 6 g/s there is a qualitative change (Fig. 2, right): the intermediate regime R2 vanishes and the quench is initiated either in the conductor (regime R1) or in the joint (regime R3). In addition, the transition between these two regimes becomes discontinuous. Oscillations of helium mass flow and temperature are responsible for this behavior, similar in nature to thermal-acoustic effects. They destabilize the hydraulic equilibrium at the joint inlet and, as a consequence, all quenches are initiated at this location. An example is shown in Fig. 3 (case D, 6 g/s, 900s). At Q_{ram} = 80 W/m the oscillation starts, increases, vanishes and, following this, the quench is initiated in the conductor. At 100 W/m the oscillation initiates a quench in the joint during its diverging phase. Based on these results it appears that the variation of the joint hydraulic properties is critical.

The effect of doubling the electrical resistance of the joint (4 nOhm) does not produce a qualitative but only a quantitative difference in the results. The quench in the joint is initiated at smaller Q_{qu} and at lower heating slopes, e.g. the line connecting points at transition R2-R3 is pushed toward the Y-axis in Fig. 2. Whereas this effect is negligible at 18 g/s and 12 g/s, it is evident at 6 g/s (Fig. 2, right).

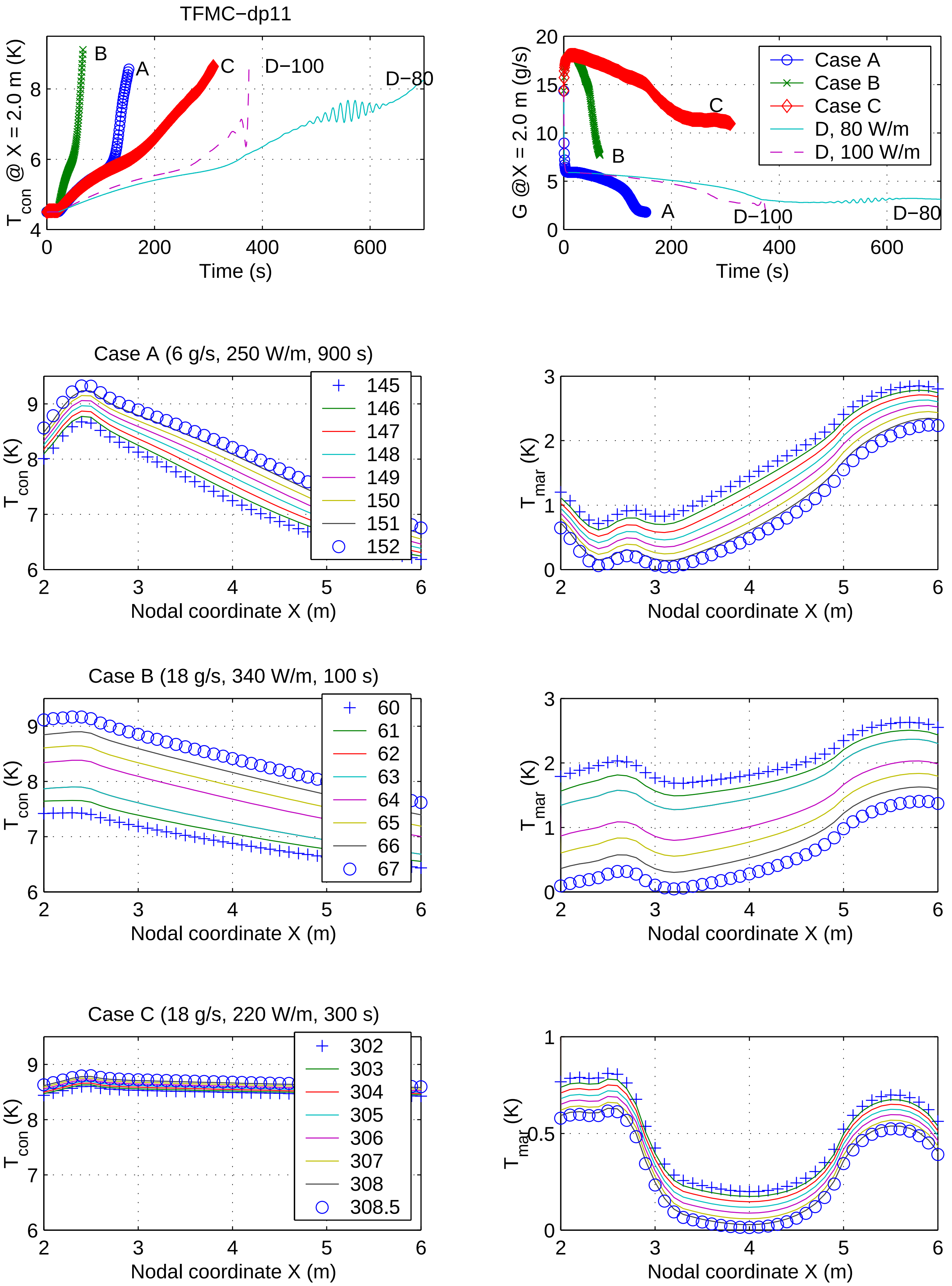

Figure 3. Results of cases A, B and C discussed in detail in the text (note that the heating starts at t = 20 s). Row #1: Time history of conductor temperature T_{con} and helium mass flow G, at X = 2 m. Rows #2-4: Spacial distribution of T_{con} and temperature margin T_{mar} just a few seconds preceding the quench initiation. In Row #1 the case D, in which the hydraulic properties of joint and conductor are the same, is also shown (6 g/s, 900 s, HPJ = HPC).

3.4 Discussion

The TFMC is being installed in the TOSKA facility. At this stage of the project major hardware modifications, such as external heaters for all pancakes and/or active control for the cryogenic system, are unlikely to be made. The flow instability between heated and unheated pancakes should be minimized anyway. During the test of the conductor critical properties the heater must be operated using ramps with low enough slopes to avoid a quench in the joint, i.e. far away from the transition R2-R3. This transition is more dependent on electromagnetic and hydraulic properties of the joint when cooling with low mass flows. Moreover, it is advisable to operate in the regime R1 away from the transition R1-R2 to obtain well defined experimental conditions.

The result of this analysis is twofold. Firstly, the range of the operational regime R1 diminishes considerably by reducing the mass flow rate, i.e. the margins are acceptable at 18 g/s, marginal at 12 g/s and insufficient at 6 g/s, although the thermal hydraulic qualitative behavior of the coil is similar in this range of cooling conditions. Secondly, the joint hydraulic properties, in particular at low mass flows, are critical and partly unknown. These results are also applicable to pancake DP12 since the operating conditions are similar to those of DP11, e.g. the peak magnetic field in DP12 is 7.2 T.

4 CONCLUSIONS AND PERSPECTIVE

The quench initiation analysis of the ITER TF Model Coil (single coil test, 80 kA, heat slug in DP11) shows a general result although known and unknown model uncertainties (joint model, electromagnetic model, etc.) could have an influence on the detailed results. An instability of the cryogenic system (helium choking) occurs when only one pancake is heated during the experimental evaluation of the superconducting critical properties. As a consequence:

- Whether the quench will be initiated in the high magnetic field region of the conductor or in the joint depends on the delicate balance between joint vs. conductor properties, e.g. regimes with competing effects.
- The test should be performed by heating with slow procedures, e.g. linear ramps with $t_{qu} > t_{res}$, no square pulses, etc., and by cooling with high mass flow rates, e.g. 18 g/s are sufficient, 6 g/s are not.

Test of the TFMC is due to start in the second half of 2000. The validation of this predictive analysis against experimental results will assess if a finer tuning of the model is necessary.

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