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# Thermo-hydraulic analyses associated with a CEA design proposal for a DEMO TF conductor.

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**Abstract** - The future DEMO Toroidal Field (TF) magnets are likely to feature cable-in-conduit conductors (CICC) cooled by forced flow of supercritical helium. Design activities were carried out at CEA to provide a winding pack compatible with DEMO plant requirements. The CEA proposal comprises, for each of the 16 D-shaped windings, 10 double-pancakes (2x 392 m long) wound in 10 turns. The conductor is a square-shaped Nb<sub>3</sub>Sn double channel conductor with a central spiral, carrying a nominal current of 95.5 kA. We present a thermo-hydraulic analyses focused on the central, most critical pancake, where the maximum field is reached, aiming at evaluating the integrity of the proposed conductor design. Both normal and off-normal simulations were performed using detailed electromagnetic and neutron heating load maps as input, and evaluating operational quantities such as the temperature margin in burn conditions, and the hot spot temperature in quench conditions. We assessed the sensitivity of these quantities to some driving parameters, notably mass flow rate and the choice of friction factor correlation for the temperature margin, and quench initiation features for the hot spot temperature. Furthermore, the influence of the casing cooling on the temperature margin is analyzed. The study is carried out using two thermohydraulic models.

**Index Terms** — DEMO, CICC, fusion, superconducting magnets, modelling, thermal-hydraulics

## 1. INTRODUCTION

According to the European roadmap [1], a demonstration fusion power plant (DEMO) is foreseen to start operation in the early 2040s to produce net electricity by 2050; it will be the major step between ITER and a commercial fusion plant. In this framework DEMO is currently in the conceptual design phase, and the EUROfusion Consortium supplies programs concerning, among others, the conceptual study of the magnet system, including the TF conductor and winding packs (WPs) which will be compatible with the DEMO design point originally specified by the PROCESS system code [2]. The key aspects of PROCESS are to simulate, with relatively simple models, the interaction between physics, engineering, and technological parameters. The initial DEMO baseline design specified by PROCESS and EUROfusion provide a starting point for more detailed models in each devoted field. Three TF winding pack (WP) concepts were issued in 2014 by CRPP, ENEA and CEA [3]. The CRPP design consists of 9 double layers (DLs) wound using flat multistage cables with two side cooling channels, ENEA proposes 8 DLs wound using rectangular CICC with a central cooling channel delimited from the bundle region with a thick steel perforated tube [6], whereas the CEA design consists of 10 stacked double pancakes (DP) with 10 turns wound using a square CICC with a central cooling channel delimited from the bundle region with a steel spiral [7]. The CRPP and ENEA designs are iterations of the designs proposed in 2012 and 2013 [4], [5], whereas the CEA design is a new concept. The present work deals with the thermo-hydraulic analysis of the CEA design.

The CEA proposal is mainly based on the ITER experience regarding design and qualification tests. We recommend to use the best presently available Nb<sub>3</sub>Sn strands, TFEU4, as demonstrated by SULTAN tests on

TFEU4 OST conductor samples [8]. The study aims more particularly at assessing the parameters that will test the robustness of the proposed operating values and stability criteria from the thermohydraulic point of view.

We assume that cooling conditions of the DEMO TF coil are similar to those of ITER, namely the conductors are cooled with the circulating flow of supercritical He at the inlet temperature  $T_{in} = 4.5$  K and the inlet pressure  $p_{in} = 0.6$  MPa, whereas the expected pressure drop is of about 0.1 MPa. One of the parameters analyzed in the present study is the influence of the heat transfer from casing on the conductor temperature. This effect is investigated considering the diffusion of the neutron heating throughout the casing and the impact of casing cooling channels. The first evaluation of thermal-hydraulic performances is done for two relevant scenarios: the burn scenario, aimed at the estimation of the temperature margin, and the quench scenario, in order to assess the hot spot temperature during quench. The results come from two models: a simplified heat removal model, described in detail in [9], [10] that proposes a reference point, from which more detailed analyses are performed using the THEA code [11].

Section 2 gives the conductor parameters [12], followed by the magnetic field description [13] in Section 4. Section 5 describes a new proposal for neutron heat load mapping [14] under the burn reference scenario of two hours plasma burn, as well as the model of heat transfer in the casing. An overview of the operating temperature, criteria and, hydraulic model is presented in Section 6. Finally selected results for burn and quench scenario are discussed in Section 7.

## 2. CEA CONDUCTOR PROPOSAL

The conductor parameters and the winding pack arrangement for the present analysis are compiled in Table 1. Figure 1 shows a simplified sketch of the conductor implemented in the WP as shown in Figure 2. In our design both Cu and s/c strands have the same diameter in order to simplify the cable deformation and to get a more uniform void fraction during the compaction and square shaping processes.

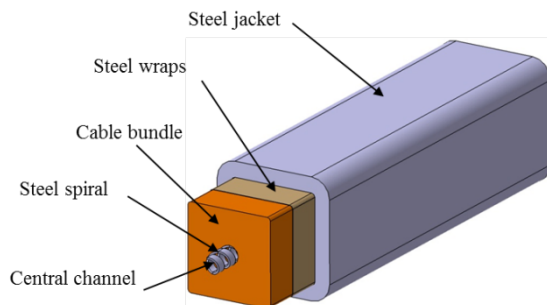


Figure 1: *Simplified sketch of the DEMO CEA conductor*

The practical operating strain is -0.664 % while the retained “strand-in-cable” effective n-value is equal to 6.

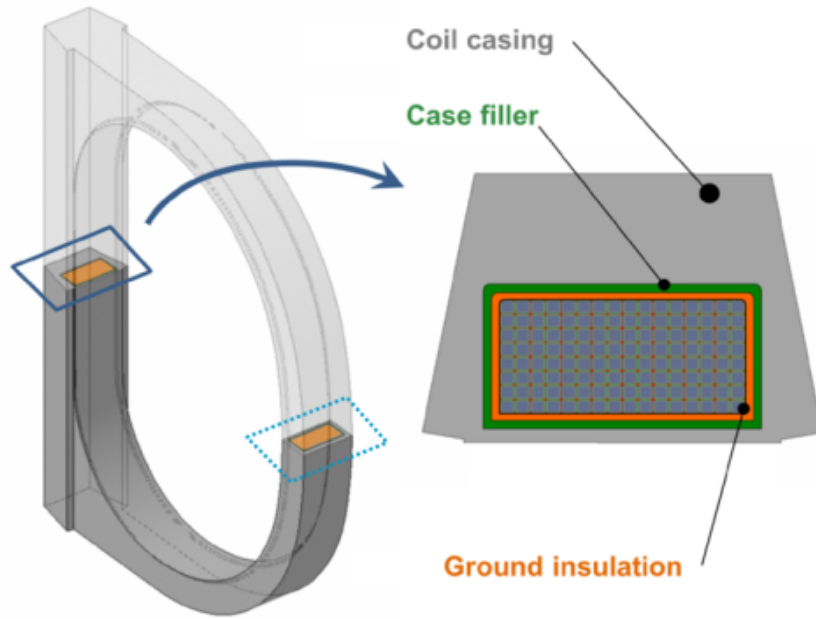


Figure 2: DEMO TF coil with the WP cross section.

Table 1

Summary of the CEA TF WP design.

Parameter	Value
Conductor operating current	95500 A
Current sharing temperature at the nominal peak field	6.2 K
Nominal peak field	13.69 T
Nb <sub>3</sub> Sn Strand type	TFEU4 OST
Strand (s/c and Cu) diameter	1.024 mm
Cr plating (s/c and Cu strands)	2 μm
Number of Nb <sub>3</sub> Sn strands	1392
Number of pure copper strands	294
Cos(θ)	0.95
Central spiral o.d x i.d.	10 x 8 mm
Cable void fraction	29 %
Cable outer size (w/o wraps)	46.23 mm
Cable wraps	2x0.080 mm
Jacket thickness	8.07 mm
Cable outer size (square)	62.69 mm
Number of DP	10
Number of turns per P	10
Current decay	Controlled Fast Save Discharge (FSD)
<b>Hot spot temperature (envisaged)</b>	<b>148 K</b>
Conductor unit length (one DP)	784 m
Average turn length	39.2 m
Hydraulic length (single P)	392 m
Total length of s/c strands	183,803 km

Total mass of s/c strands	1.36·10 <sup>6</sup> kg
Copper RRR in s/c strands	100
Copper RRR in pure Cu strands	100

### 3. TEMPERATURE MARGIN AND HOT SPOT TEMPERATURE

The current sharing temperature is defined as the temperature at which the critical current equals the operating current. In practice, this temperature is defined as the one at which the average electric field along the cable reaches 10 mV/m. This involves the computation of the average electric field across cable area, taking into account the magnetic field gradient and the value of  $n_{eff}$ . In order to provide some margin against uncertainties due to unknown phenomena, e.g. related to plasma disruptions, it is mandatory to ensure a safe margin and to define a minimum value for the temperature margin. The TF conductor was designed to satisfy the following criterion for the temperature margin:  $DT_{margin} = T_{cs} - T_{op} > 1.5$  K for the operating conditions (nominal current, magnetic field distribution and strain) and the critical location, i.e. maximum field region in the innermost turn. The choice of temperature margin has a strong impact on the dimensioning of the conductor, so it is crucial to verify by simulations if the 1.5 K criterion is fulfilled.

### 4. MAGNETIC FIELD DISTRIBUTION

The object of our analysis is the central pancake, which is the most critical pancake from the magnetic field point of view. The effective magnetic field  $B_{eff}$  profiles along the conductor (i.e. the equivalent uniform field giving the same  $T_{cs}$ ) was computed by the TRAPS code, as described in detail in [13]. Figure 3 shows the  $B_{max}(x)$ , the  $B_{med}(x)$  and the  $B_{eff}(x)$  distribution computed along the central pancake. The  $B_{eff}(x)$  distribution is considered in our simulations with the maximum field  $B_{eff} = 13.093$  T located in the inboard straight leg at  $x = 22.09$  m.

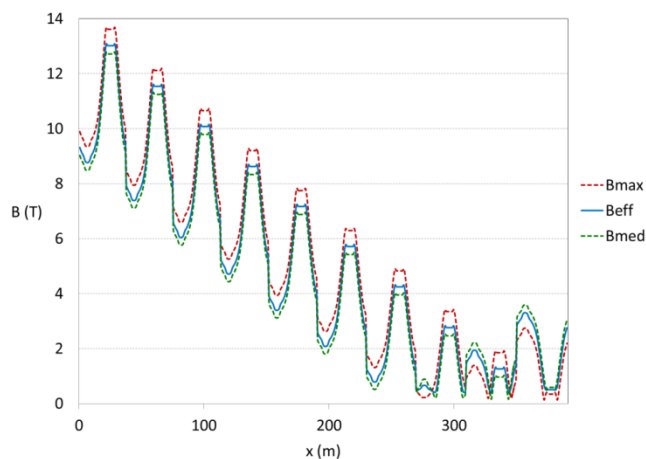


Figure 3: Magnetic field distribution along central pancake

### 5. NUCLEAR HEAT LOAD

Most of the fusion energy is carried by neutrons which interact mostly with the actively cooled in-vessel components. Of these, the blanket in particular absorbs energy from the neutrons and breeds tritium through a reaction with lithium. The in-vessel components and the water-cooled steel vacuum vessel partially shield the superconducting coils enveloping the vacuum vessel from neutrons. Nevertheless some of the neutron flux is deposited in the coils, in particular the TF. Knowledge of the nuclear heat load distribution is an important input for design as it impacts the conductor temperature margin, but its assessment is not obvious, since at the present stage the design of the neutron shield is not finalized yet. In the earlier thermal-hydraulic studies of the DEMO TF coils [9],[10] it was assumed that the NH load of 100 W is totally deposited in the 1<sup>st</sup> double layer of the each TF coil. In 2014 an alternative approach for the reference TF NH mapping was proposed in [14]. According to

[14] we assume that the neutron flux is gradually dumped in the material passed across and the associated NH deposition decreases exponentially with the radial distance  $R_{CASE}$  from the TF case inner edge (see Fig. 4):

$$P_{NH} = 50 \cdot \exp(-R_{CASE}/140 \text{ mm}) \text{ W/m}^3. \quad (1)$$

It is also assumed that in the equatorial plan  $P_{NH}$  value is constant in poloidal direction (e.g. along a given turn), which is a conservative approach assuming that the NH load value in inboard midplane is constant along the length of TF coil. Integrating of Eq. (1) gives the neutron heating impact over the casing and over each turn of a single conductor as shown in Fig. 5. The resulting NH deposition in the WP (jacket and conductor) of each TF is of about 184 W, whereas the total NH load in each TF coil is of about 380 W.

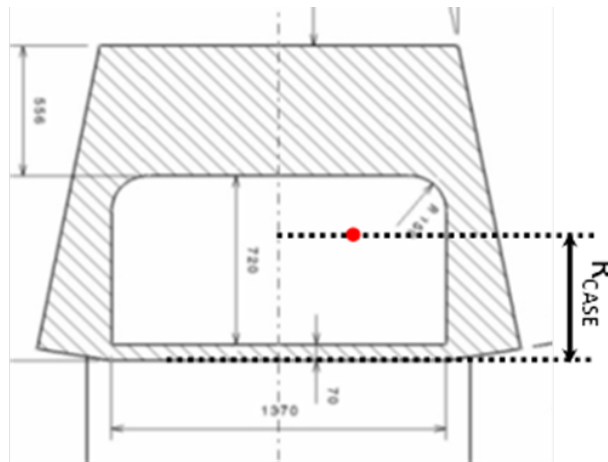


Figure 4:  $R_{CASE}$  definition. Red dot is the location where  $P_{NH}$  is evaluated

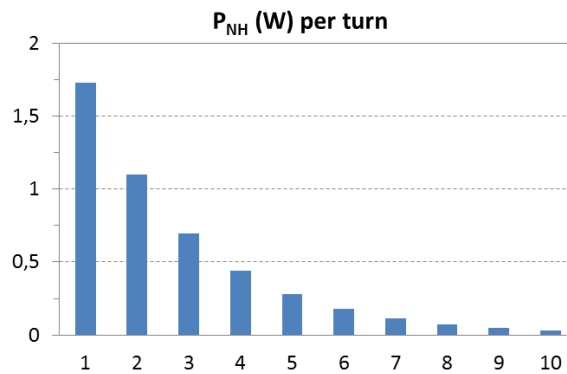


Figure 5: Neutron power directly deposited in the CEA conductor

### 5.1 Thermal load from the casing to winding pack

The NH load in the front case is very large. To assess its impact on the heat deposition in the conductor, the transient thermal diffusion from the TF casing to the conductor was analyzed by means of a Cast3M 2D finite element model, as described in detail in [16]. The temperature and heat flux distribution in both internal and external sections located in the equatorial plane (see Fig. 6) was computed for the scenario of 2 h burn. We considered two cases: with and without cooling channels in the casing. To minimize the impact on the conductor temperature due to the large thermal loads generated in the stainless steel casing and jacket, we modeled the cooling channels in the casing with an internal diameter of 8 mm at the interface to the winding pack with 20 channels arranged at the plasma facing wall (see Fig. 6c-2). An overview of meshing that considers the ground insulation and case filler is given in Figure 6. Figure 7 shows the heat flow in metal components and the temperature map at the end of burn (i.e. at 7200 s) for a half of an equatorial mid-plane TF cross-section for the case with cooling channels. The inner boundary of the 2D sections (see Fig. 6a) corresponds to the conductor inner jackets, where the temperature is conservatively fixed at 4.4K (although the initial temperature was equal to 4.5 K for thermohydraulic analysis), thus maximizing the flux transferred to the conductors. We assumed that temperature in the cooling circuit in casing is constant, equal to 4.4 K.

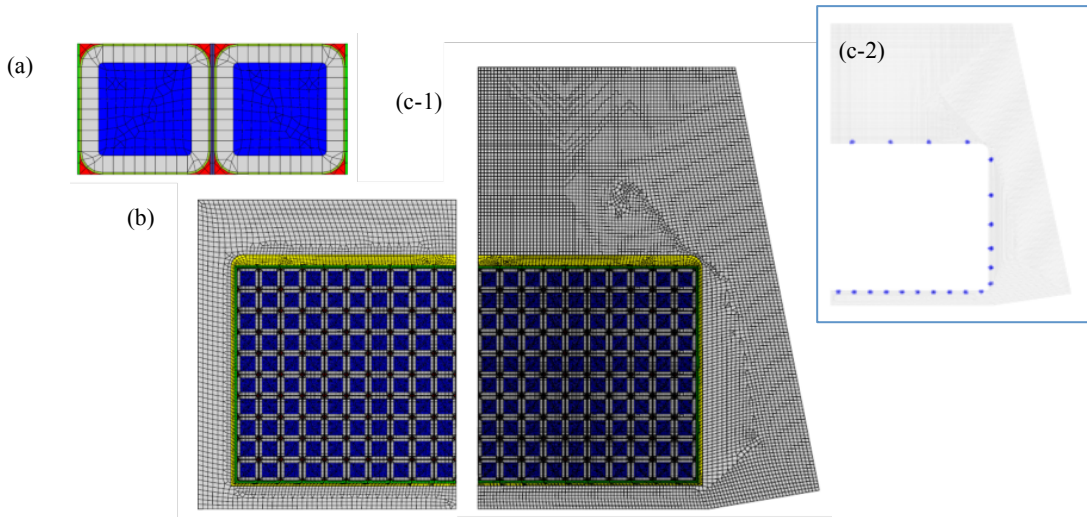


Figure 6: Overview of the TF cross-section mesh: (a) detail at the level of the DP (b) outer leg half section (c-1) straight leg half section without cooling channels (c-2) straight leg half section with cooling channels

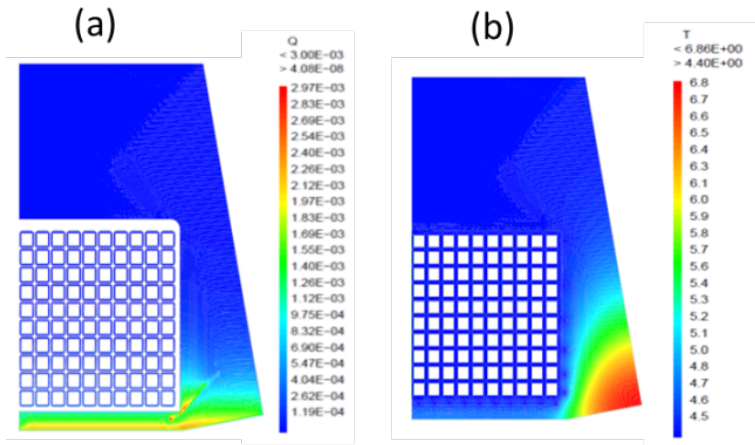


Figure 7: (a) Heat flow in metal components (casing and jacket), (b) Temperature in the internal leg at the End Of Burn

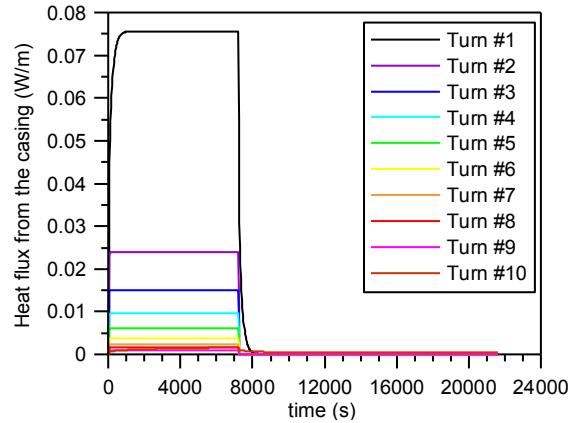


The maximum temperature in the case in the reference scenario (without cooling channels) is equal to 7.7 K while the maximum temperature in the case of cooled casing is 6.8 K (see Fig. 7b); so an improvement is of 1.1 K.

### 5.2 Thermal load from plasma to winding pack

The expected total nuclear power deposited directly in a single conductor, resulting from Eq. (1), is equal to 4.7 W, whereas its distribution turn by turn is shown in Figure 5. Figure 8 shows the additional transient heat flux from the casing, obtained with the 2D model discussed in previous section, for both scenarios: with and without cooling channels in the case.

a)



b)

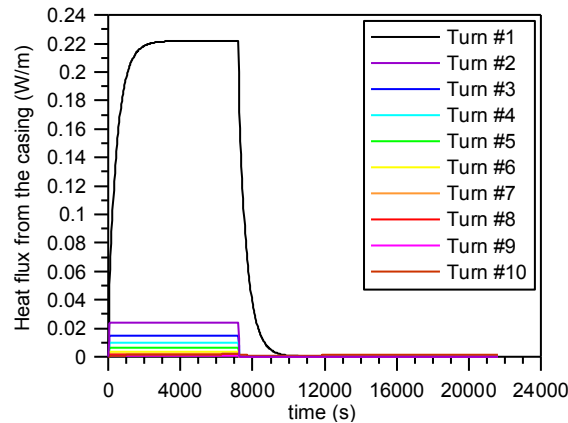


Figure 8: Transient heat flux from the casing resulting from the 2D model (a) case with cooling channels, (b) uncooled case.

## 6. HYDRAULIC MODEL

The conductor is cooled by supercritical helium that flows in the central channel at high speed and at much lower speed in the bundle region. During the normal operation (burn), the central channel increases the heat removal rate, while during the quench it prevents over high pressure raise. The inlet temperature is equal to 4.5 K, whereas at no heat deposition the outlet temperature is of 4.6 K due to the Joule-Thomson effect. The friction factor correlations used in the bundle and central region are described hereafter as well as the heat transfer correlations.

### 6.1 Thermal-hydraulic scaling laws

Two predictive friction factor correlations available in the literature were used to assess the hydraulic resistance in the bundle region. First one is the correlation based on the Darcy-Forchheimer momentum balance equation for the flow in porous medium ( $f_{DF}$ ), obtained in [17] by the analysis of an extensive database that included the results of pressure drop tests of 23 CICC with the void fraction ranging from 0.25 to 0.365. This correlation

gives a conservative approach. The second one is the well-known Katheder correlation [18] which has been developed for conductors with the void fraction of about 0.40 and typically predicts much larger mass flow rates than the porous medium correlations, particularly for conductors with low void fraction [19]. The friction factor correlation for the flow in the central channel is given by the measurements obtained on the preconized 8/10 spiral [20] with

$$f_{EU} = 0.42 / \text{Re}^{0.1}, \quad (2)$$

where  $D_h$  and Re are based on  $D_{out}$ .

As agreed with the project team [21], the heat exchange coefficients between the solid cable components and helium are computed using the standard smooth tube correlations, namely the Dittus-Boelter correlation for the turbulent flow and  $\text{Nu} = 4$  for the laminar flow, which is a conservative approach.

## 7. RESULTS FOR THE CENTRAL PANCAKE

This paragraph presents the results of simulations of the central pancake under nominal operating conditions, as well as in quench conditions. At the operating conditions under the NH load we are particularly interested in the outlet temperature, which is the highest temperature in the conductor, and the temperature at the critical point (at the end of the maximum field region in the innermost turn) located at  $x = 28.6$  m.

### 7.1 Burn Studies

A transient thermohydraulic scenario of 2 hours burn was performed on the central pancake. Two cases with and without cooling channels in the casing are considered. The reference scenario computed by the THEA code is compared with the simplified model (SS) results. Table 2 gives the mass flow rates at the end of conductor obtained with both models for the case with cooling channels in the casing. The agreement between the predictions of both models is very good. It is also seen in Table 2 that the mass flow rate in the bundle region increases by about 39.5 % using the Katheder correlation with  $f_{DF}$  as the reference.

Table 7.1

Mass flow at the outlet of conductor computed with THEA and with the simplified model for the case with cooling channels in the casing.

Mass flow (g/s)	Bundle region		Central Channel	
	THEA	SS	THEA	SS
$f_{DF}$ correlation	5.57	5.57	5.82	5.85
Katheder correlation	7.77	7.77	5.85	5.86

The detail of temperature profile over the conductor at four representative times: Start of Burn (SOB), End of Burn (EOB), 1 hour after EOB and after 4 hour Dwell is showed in Figure 9 in the case of an uncooled casing. The green curve gives the initial temperature with a gradient of 0.1 K corresponding to the Joule-Thomson expansion. The red one is the profile at the end of plasma burn when the temperature profile is highest. We observe the highest constant temperature gradient over the first turn reaching a value of 4.75 K at the end of the first turn. The maximum value of 4.92 K is reached at the end of the pancake. Then, the initial profile is completely recovered 4 hours after the EOB. The improvement due to the presence of the cooling channels in the casing is illustrated in Figure 10; indeed the maximum temperature at the end of conductor falls from 4.92 K to 4.79 K with an additional margin of 0.13 K. From the 230 W deposited by nuclear heating in the casing (excluding the jacket), 206 W are removed by channels [19].

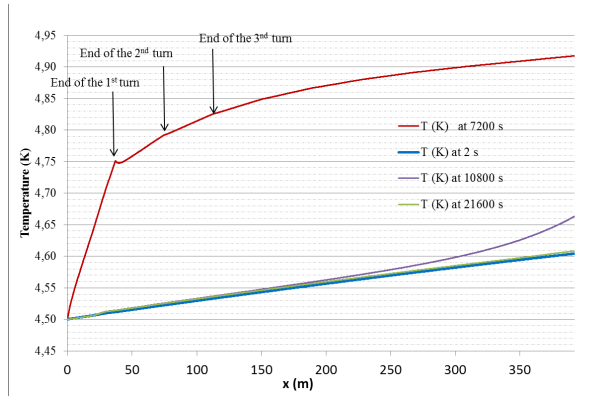


Figure 9: Conductor temperature as function of space and time

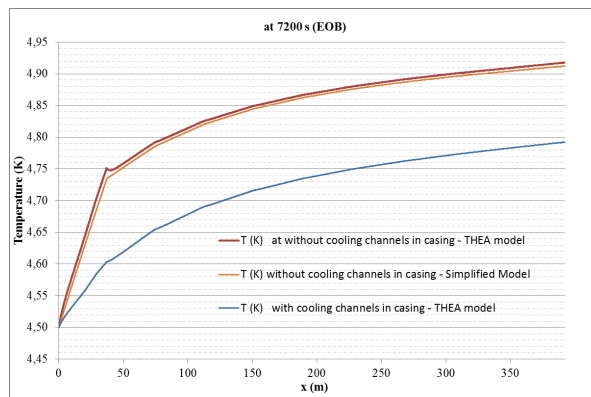


Figure 10: The influence of the cooling channels in the casing on the temperature profile at the end of burn.

$\Delta T_{\text{margin}}$  is a function of space and time with the minimum value reached during the burn period in the high magnetic field region about 2160 s after the SOB and then gradually recovers the initial value of 1.69 K. The high magnetic field region is comprised between  $x=22.15$  m and  $x=28.6$  m. As shown in Figure 11 for the uncooled casing,  $\Delta T_{\text{margin}}$  at the entry location ( $x = 22.15$  m) is equal to 1.54 K, while the minimum  $\Delta T_{\text{margin}}$  obtained at the end of the high field region ( $x = 28.6$  m) reached a minimum value of 1.50 K. The margin increases by  $\sim 0.12$  K if the casing is cooled.

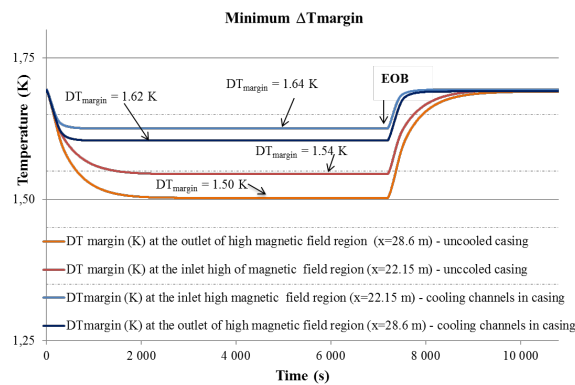


Figure 11:  $\Delta T$  margin vs time

## 7.2 Quench

The study deals with the different phases of quench initiation (assessment of Minimum Quench Energy (MQE), detection and propagation), considering one of the most realistic scenarios (quench initiated at the region of minimum  $\Delta T_{\text{margin}}$ ) to assess the hot spot temperature criterion ( $< 150$  K [22]). As agreed with the project team [23], quench is initiated by a heat disturbance of length 1 m, duration 100 ms and energy equal to  $2 \times \text{MQE}$  deposited at the high field location, considering a realistic magnetic field distribution, at distance of about 25 m (in the middle of the high magnetic field region) from the He inlet. The minimum quench energy value (MQE) is found equal to  $2700$  W/m. This value corresponds to  $2.24$  mJ/cm<sup>3</sup> of twisted SC strand, its reference area in cable cross section being equal to  $12.07$  cm<sup>2</sup>. The detection and protection features are a voltage threshold ( $U_t$ ) of  $0.5$  V with a holding time  $\tau_{\text{holding}}$  of  $1.5$  s before starting the magnetic energy dump. The simulation shows that the fast safety discharge is initiated  $4$  s after start of perturbation as shown in Figure 12 with a hot spot temperature of  $148$  K. The normal zone expands under the combined actions of heat conduction and ohmic heating, to reach  $\sim 32$  m of quenched length at  $60$ s.

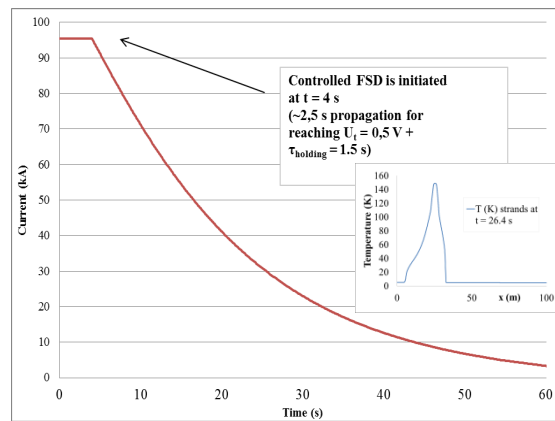


Figure 12: Current evolution during detection and propagation phases

## 8. CONCLUSION - PERSPECTIVES

Transient thermo-hydraulic studies are performed on the CEA conductor design for the winding pack of DEMO TF magnet in the currently allocated space supplied by PROCESS system code. Two different tools, the THEA code and the simplified steady state model, are used in a complementary approach to investigate the conductor temperature margin behavior. Both the currently available plasma burn reference scenario and one of the most likely quench scenarios are analyzed for the most critical pancake, i.e. the central one. The long pulse operation of 2 hours plasma burn is analyzed, considering the proposed operating values and evaluating thermohydraulic criteria such as temperature margin. We consider a detailed magnetic field and neutron heating load maps (heat load diffusing from the casing and falling directly onto the conductor). We have also analyzed the influence of the cooling channels in the casing on the temperature margin. In all considered cases the temperature margin was sufficiently large, i.e. greater than  $1.5$  K recommended in [15], with an additional margin of  $\sim 0.12$  K associated with the casing cooling. The analysis of the quench scenario shows that the primary electrical quench detection parameters and the current fast discharge method are strongly linked to the hot spot temperature. The criterion of  $T_{\text{hotspot}} < 150$  K is respected, with the maximum quench temperature value of  $148$  K, taking into account the warm-up of the dump resistance and the associated acceleration of current decay. Thus, it was shown that the conductor design proposed by CEA is safe from the thermal-hydraulic point of view. However, considering that the magnet must be structurally strong enough to withstand large stresses under operating and fault conditions, ongoing mechanical analyses could soon lead to updated winding pack area features, thus requiring to propose the next iteration of the WP and conductor design, which will be subjected to a similar thermo-hydraulic analysis.

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