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Quench simulation of a DEMO TF coil using a quasi-3D coupling tool

Quentin Le Coz, Daniel Ciazynski, Matti Coleman, Valentina Corato, Benoît Lacroix, Sylvie Nicollet, François Nunio, Roser Vallcorba and Louis Zani

***Abstract*—In the framework of the EUROfusion DEMO project, studies are conducted in several European institutions for designing the tokamak magnet systems. In order to generate the high magnetic fields required for the plasma confinement and control, the reactor should be equipped with superconducting magnets, the reference design being based on Cable-In-Conduit Conductors (CICC) cooled at cryogenic temperatures by forced circulation of supercritical helium.**

In order to be compatible with DEMO requirements, a proposed Toroidal Field (TF) Winding Pack (WP) design should satisfy the criteria in operation (minimal margin temperature) and off-normal conditions (hotspot temperature). Quenches are studied to ensure that the proposed conductor design and associated quench protection system guarantee the integrity of the magnet; it is of most importance since it is a matter of safety and protection of the device.

Quench propagation in a coil is a 3-dimensional problem. For this reason, a transient pseudo-3D modelling tool was developed for coupled thermal and thermo-hydraulic calculation in a tokamak superconducting coil. The coupling tool is based on a 1D model of the cable using the THEA code, considering current distribution, helium flow, thermal conduction in the strands and propagation of the quench along the conductor; the 2D transverse thermal diffusion across turns is modelled using the Cast3M code, considering the conductor jacket and insulation, on a selected set of cross-sections along the D-shaped coil.

The aim of the analysis is to assess the quench behaviour of the CEA proposal for DEMO TF coil. The hotspot temperatures, as well as normal length evolution are evaluated on a realistic quench scenario, emphasizing the impact of transverse heat diffusion.

***Index Terms*—CICC, code coupling, DEMO, magnet, quench, thermo-hydraulics.**

I. INTRODUCTION

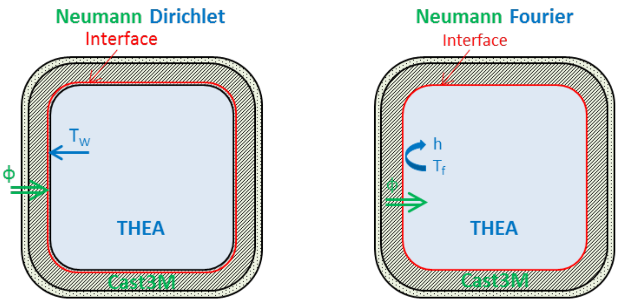
DEMO is the fusion demonstrator plant that is foreseen after ITER. The European fusion roadmap recommends that DEMO should be an ITER-like tokamak, using as much as possible technologies that will be tested in ITER [1]. For that reason, CEA has proposed a TF magnet design consisting of pancake wound double channel CICC with Nb_3Sn superconducting strands and a wind & react fabrication process [2], much like ITER. The main difference is the absence of radial plates, compensated by an increase of the conductor jacket thickness, for mechanical purpose. This point is of particular interest when studying quench behaviour of a coil, as the hotspot criterion focuses on the jacket maximal temperature, and in case of a thick jacket, thermal gradient can be significant, questioning the 1D approach usually retained. On DEMO, the 150 K ITER hotspot criterion is used [3].

In order to ensure consistency of the work performed in the different European laboratories, a common guideline for the design and analyses was issued [4]. In this document, it is recommended to take into consideration the transverse thermal coupling, which cannot be done with the standard version of THEA, the code that we use for the modeling of conductors [5]. Two strategies to implement such transverse coupling will be presented and analyzed in this paper. The first one is based on a stationary method using thermal resistances, this is the method suggested in the common guidelines. The second one, called TACTICS, after THEA-Cast3M-SimCryogenics (the latest is not used in the present paper), is based on a transient Finite Elements Model (FEM) with Cast3M [6] using code coupling.

II. TRANSVERSE THERMAL COUPLING METHODOLOGIES

A. *Finite elements method*

The coupling methodology is described in [7], where it has been applied on a burn scenario (weakly transient) of the CEA proposal for DEMO TF coil (2015 WP3 111 kA conductor).



Direct coupling with a thin layer of the jacket modelled in THEA.

Convective coupling with the interface being the inner face of the jacket.

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Fig. 1. Different options for the set of interface conditions with TACTICS.

THEA uses heat fluxes as boundary conditions (Neumann condition). The two options that can be implemented in Cast3M are direct coupling through prescribed temperature (Dirichlet condition) or convective coupling: helium temperature plus a convective heat transfer coefficient (Fourier condition), see Fig. 1. Both options are valid, but the Neumann Dirichlet coupling can be numerically instable when dealing with fast transients, due to the low thermal inertia of the jacket layer on which the fluxes are applied. This option was the one used in our stationary/weakly transient studies (heat exchanger or burn on DEMO TF coil [7]), and turned out to be not too penalizing regarding time discretization.

In any case, for the simulation of fast transients using TACTICS, the Neumann Fourier set of interface conditions seems to be the most appropriate. At least it is more stable since the time constants of the helium components, on which the fluxes are applied, are larger (high mass and specific heat). And moreover it allows non-uniform temperature profile on the inner side of the jacket, which is more realistic.

B. Thermal resistance method

The thermal resistance methodology is only valid in steady state, since thermal diffusion is not accounted for. Also the nonlinearities of material properties are approximated by calculating them at the average temperature of the components that are linked. For comparison purpose, the thermal resistance methodology will be applied to a burn scenario of the WP3 central clockwise (CW) pancake, on which thermal equilibrium is reached before the end of burn, and will be compared to the TACTICS model presented in [7]. This model will be referred as Case a, in which the inter-turn thermal coupling is calculated by means of a FEM comprising the jacket and the insulation. Case b is a standard 1D THEA model, in which no inter-turn coupling is considered. The models description is displayed on Fig. 2.

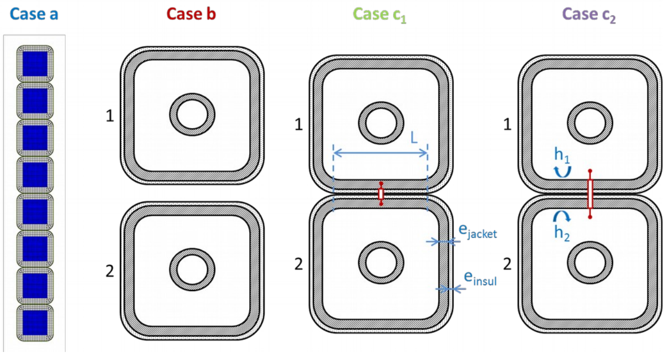

Fig. 2. Description of the models to be compared.

Different ways of implementing the interturn heat exchange with the thermal resistance method can be set up:

- The first one (Case c_1), recommended in [4], consists of coupling jacket to jacket, using only the insulation part in the thermal resistance. The corresponding equation is (1). As seen on Fig. 3 it does not correspond to the reference FEM results. This is due to the fact that the temperature of the external faces of the jacket should be used, but with the 1D THEA models, we have only access to the mean temperature. (Considering that the mean 1D temperature is the temperature of the middle of the thickness of the jacket and adding two times the half jacket thickness in the thermal resistance calculation does not work either);

$$\varphi_l\left[{}^{W}\!/_{m}\right]=\Delta T_{jacket\ 1\leftrightarrow 2}\cdot\frac{\lambda_{insul}\ L}{2\ e_{insul}} \tag{1}$$

- Another way (Case c_2) consists of coupling bundle to bundle, using the jacket and insulation in the thermal resistance, as well as the convective thermal resistance (2). As displayed on Fig. 3, the results are compliant with the TACTICS calculations.

$$\varphi_l\left[{}^{W}\!/_{m}\right]=\frac{\Delta T_{helium\ 1\leftrightarrow 2}}{\dfrac{1}{h_1\ L}+\dfrac{2\ e_{jacket}}{\lambda_{jacket}\ L}+\dfrac{2\ e_{insul}}{\lambda_{insul}\ L}+\dfrac{1}{h_2\ L}} \tag{2}$$

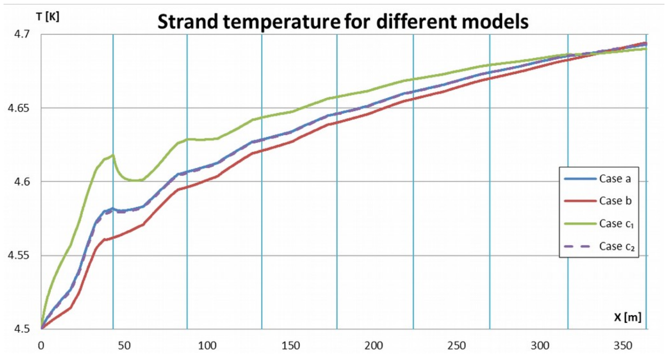

Fig. 3. Temperature plots at end of burn, depending on the model.

The thermal resistance methodology (Case c_2) is compliant with the TACTICS model in steady state, which means that such methodology can be applied to calculate results if a steady state is reached in the scenario/geometry considered. This is the case for the pancake conductors of WP3, but this is not true on designs based on layers, since the hydraulic lengths are more important. To some extent, the methodology can be employed on weakly transients, as it is performed in [8], where the experimental data of the JT-60SA TF coil tested at the Cold Test Facility are in agreement with the numerical model. The jacket thickness (2 mm) is less important than on the DEMO design considered here though (leading to smaller diffusion time constants).

The assessment of the validity of such methodology in transient conditions with important flux variation (e.g. quench scenario) will be performed later on.

III. QUENCH SIMULATIONS

A. Preliminary considerations

The quench scenario that will be considered hereafter is a quench initiated at maximum effective magnetic field (considered realistic) on the most constrained pancake regarding the minimal margin, i.e. the central CW one, for which the hydraulic path is the longest before reaching the high field location on the first turn. The perturbation is set at twice the Minimum Quench Energy (MQE = 1963 W/m on the considered pancake), applied for 0.1 s over a length of one meter. The middle of the quench initiation length is located at a curvilinear abscissa $s_{curv} = 28.671$ m, where the effective magnetic field is maximum ($B_{eff} = 11.689$ T), and close to the minimal temperature margin location ($\Delta T_{ma} = 1.465$ K at 28.9 m). No quench detection based on voltage threshold is considered; instead the Fast Safety Discharge (FSD) is triggered 3 s after the disturbance; this allows comparative studies between the different models independently of the conductor resistance (temperature dependent) at the beginning of the quench. The model considers neither nuclear heating nor heat exchange with the casing. The hydraulic correlations are the same as the ones used on burn studies and can be found in [7], and constant pressure and temperature 'reservoir' boundary conditions are prescribed at inlet and outlet of the conductor (no cryodistribution circuit). The current FSD is computed considering the heating of the discharge resistance. The magnetic field distribution decreases proportionally to the current decay during the FSD.

B. *Presentation of the coupling model*

Since the jacket is modelled in Cast3M, it is removed from the THEA components. In burn scenario, only the thermal behaviour of the jacket is of interest, and is well computed with TACTICS. But during a quench, where the superconducting materials have transited, the current gets redistributed, mainly in the copper wires, but a fraction of it also transits via the jacket. THEA computes the electrical behaviour of the whole conductor, taking into consideration the redistribution of current during a quench. For that reason, the electrical behaviour of the jacket has to be considered in THEA. This leads to considering the jacket ‘thermally’ in Cast3M and ‘electrically’ in THEA. The stainless steel resistivity is temperature dependent, so the integrated average temperature over the surface of each turn of the jacket calculated by Cast3M needs to be imposed in the jacket component in THEA. Note that within THEA, the jacket is not thermally linked to other components so that its enthalpy is not computed twice. Also no thermal connection is considered between the strands (superconductor or copper) and the jacket; since the contact area and the presence of wraps makes it difficult to estimate the thermal connection, it is considered that the heat exchange takes place through the helium in the bundle.

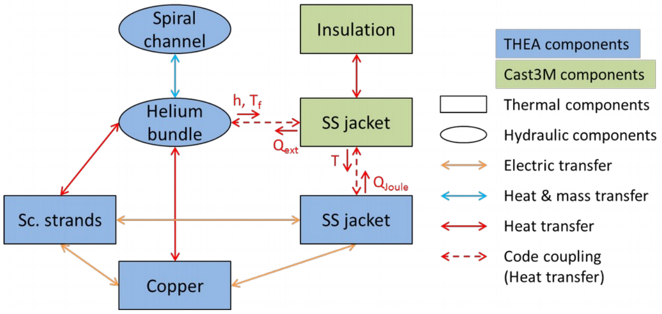

Fig. 4. Schematic of the coupling of the different components with TACTICS.

A hundred cross sections are considered in the Cast3M model, each through the eight turns of the pancake; this leads to a flux exchange between THEA and Cast3M calculated on 800 points along the conductor and then interpolated over the approximately 45 cm between two points (depending on the turn length). The limitation of the quasi-3D approach (1D + 2D transverse) is that the longitudinal conductivity of the stainless steel jacket is not considered. It has been checked to have no significant impact on the hotspot values and the quench propagation by performing a THEA simulation where the stainless steel conductivity was set to zero (0.306 K difference on T_{max} Sc. strands and 1.068 m difference on the normal length at 100 s).

C. *Results comparison over model choice*

The hotspot temperature results are given in Table I. With TACTICS, the hotspot temperatures of the strands (Sc. and copper) are higher than with THEA, but the maximum of the average temperature of the jacket is lower. This is due to the diffusion time in the jacket, which makes more time for the strands to heat up by joule effect. With the interturn model, the temperatures are colder, because the cooling of the first turn (quenched) by the second turn is instantaneous (infinite diffusion), which is not realistic.

TABLE I

Hotspot temperatures for each component for the different models.

Model	Component	T_{max} [K]	Time [s]	s_{curv} [m]
THEA (Case b)	Sc. strands	117.972	29.285	28.584
	Copper strands	118.929	28.555	28.584
	Jacket	100.304	100	28.604
TACTICS (Case a)	Sc. strands	126.987	29.195	28.503
	Copper strands	127.999	28.665	28.513
	Jacket	94.942	75.402	28.643
THEA interturn (Case c_2)	Sc. strands	111.973	26.225	28.524
	Copper strands	113.197	25.495	28.524
	Jacket	90.632	64.070	28.464

On Fig. 5(a) is displayed the normal length evolution. For the models with transverse thermal diffusion (i.e. TACTICS and THEA interturn), a change of slope can be seen (at respectively 41.783 s and 18.425 s), which corresponds to a quench initiation on the second turn because of the transverse thermal diffusion (before the warm helium is advected to the second turn).

The position of the quench fronts is displayed on Fig. 5(b). The quench initiation on the second turn can be seen at times corresponding to the change of slope on the normal length evolution. The initiation of the quench by transverse diffusion happens faster with the thermal resistance model because the diffusion is not accounted for. So the hypothesis of a negligible time constant of the diffusion through jacket and insulation makes the second quench initiation happen 23.359 s sooner than it should.

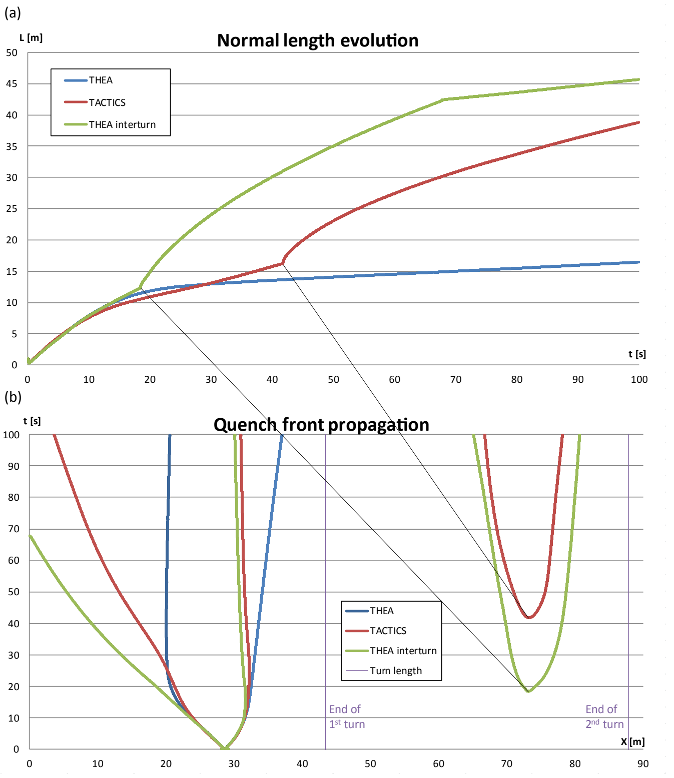

Fig. 5. (a) Normal length evolution for the different models. (b) Quench front propagation for the different models.

D. *Detailed results with TACTICS*

The maximum temperature in the jacket is reached in the cross section corresponding to $s_{curv} = 28.641$ m, which is on the first turn, in the middle of the quench initiation location. The temperature plots are given in Fig. 6. The point where the maximum temperature of 99.551 K is reached is T1-D1 (location displayed on the figure), but this is due to the adiabatic condition retained around the whole pancake; normally on the downside the first turn would be facing the insulation between WP and casing and on the lateral side another pancake (or insulation for a lateral one). Anyway, the maximum temperature difference over the jacket thickness is 21.904 K between T1-U1 and T1-U3. The maximum temperature difference through the 2 mm insulation thickness, between T1-U3 and T2-D3, is 39.879 K (Fig. 6).

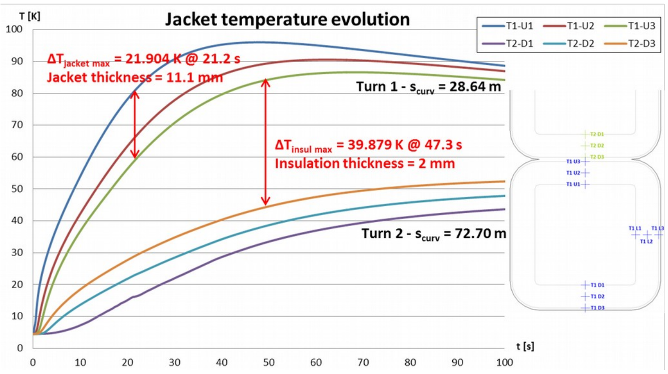

Fig. 6. Temperature plots in the jacket over the two first turns at the cross section located in the middle of the quench initiation ($s_{curv} = 28.64$ m).

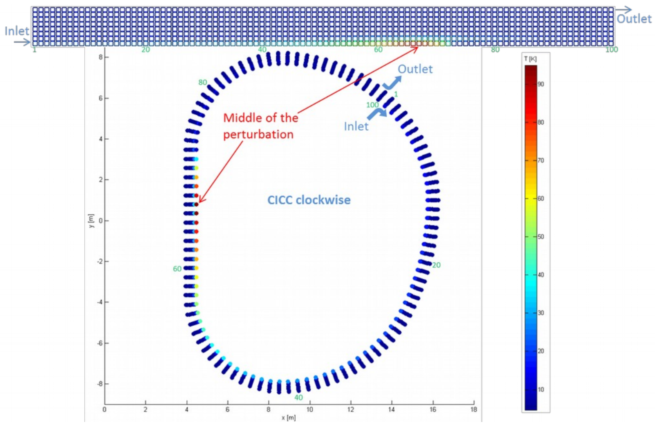

Fig. 7. Temperature field map over the 100 cross sections at t = 100 s.

Fig. 7 gives the temperature field map over the whole pancake (100 cross sections) at 100 s and Fig. 8 gives the temperature field map in the jacket and insulation of the two first turns of the pancake at the middle of the quench initiation at different times.

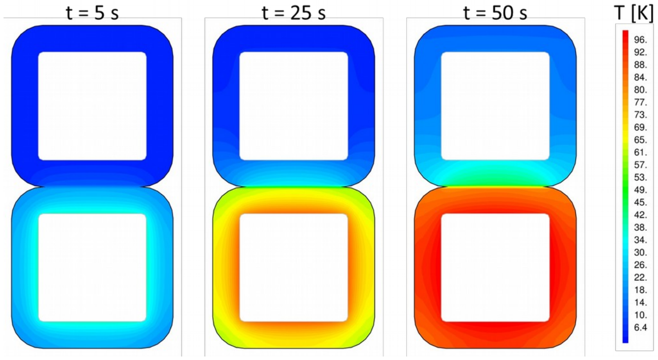

Fig. 8. Temperature field map in the two first turns at quench location.

Because of the absence of radial plates, the jacket thickness is increased on DEMO compared to ITER (11.1 mm instead of 1.6 mm). On ITER, the 150 K hotspot criterion in the jacket can be checked with a 1D approach since the transversal thermal gradient are negligible; but on DEMO, as shown in Fig. 6, 7 & 8, the jacket thermal gradient can reached up to 21.904 K, so a 1D approach is not sufficient to check the compliance of the design with the hotspot criterion.

IV. CONCLUSION

Two different ways of implementing the transverse thermal coupling during a quench have been presented, and the impacts on the hotspot temperature and quench propagation have been compared to standard 1D THEA calculations. It was shown that the method with thermal resistances that considers steady thermal coupling without diffusion does not match a detailed FEM analysis. The point of the thermal resistance strategy is to take into consideration transverse exchanges, but by doing so with a stationary approach; the results can be even less accurate than the standard 1D model without transverse coupling. Such a methodology may thus be not conservative and should be considered with precaution.

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