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

MT25

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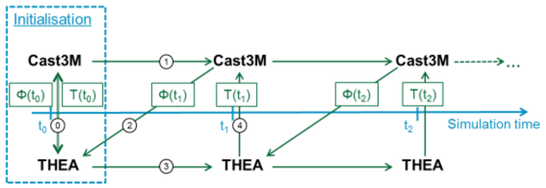
INTRODUCTION

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. For that reason, CEA has proposed a TF magnet design consisting of pancake wound double channel CICC with Nb3Sn superconducting strands and a wind & react fabrication process, 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.

In order to ensure consistency of the work performed in the different European laboratories, a common guideline for the design and analyses was issued. 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. Two strategies to implement such transverse coupling will be presented and analyzed in this study. 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 study), is based on a transient Finite Elements Model (FEM) with Cast3M using code coupling.

Presentation of TACTICS

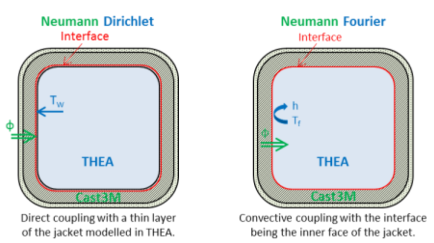
COUPLING METHODOLOGY



Code coupling for transient pseudo-3D simulation - **TACTICS**:

- THEA for 1D thermohydraulics in cables.
- Cast3M for 2D finite element transverse thermal diffusion.

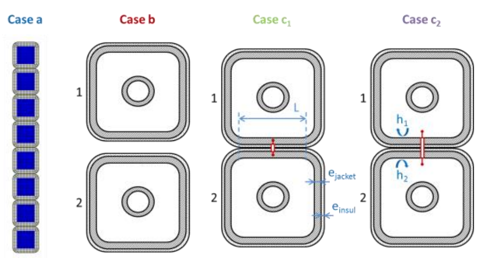
SET OF INTERFACE CONDITIONS



- THEA: heat fluxes as boundary conditions (Neumann condition).
- Cast3M: prescribed temperature (Dirichlet condition) or convective coupling (Fourier condition).

For the simulation of fast transients (e.g. quench), the **Neumann Fourier** set of interface conditions is the most appropriate. It is more stable and allows non-uniform temperature profile on the inner side of the jacket.

STEADY STATE APPLICATION



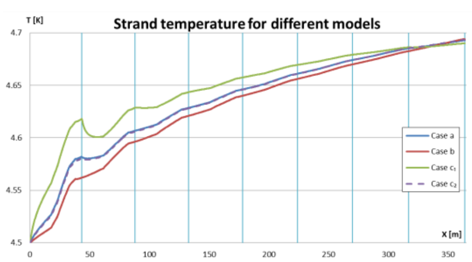
Different models to be compared at the end of a burn scenario :

- Case a: TACTICS
- Case b: standard THEA model (no transverse coupling)
- Case c_1: thermal resistance. Coupling jacket to jacket, using only the insulation part in the thermal resistance.

$$\Phi_l\,[W/m] = \Delta T_{jacket\ 1\leftrightarrow 2} \cdot \frac{\lambda_{insul} * L}{2 * e_{insul}}$$

- Case c_2: thermal resistance. Coupling bundle to bundle, using the jacket and insulation in the thermal resistance, as well as the convective thermal resistance.

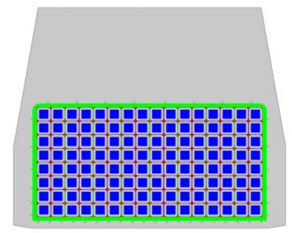
$$\Phi_l\,[W/m] = \frac{\Delta T_{helium\ 1\leftrightarrow 2}}{\frac{1}{h_1 * L} + \frac{2 * e_{jacket}}{\lambda_{jacket} * L} + \frac{2 * e_{insul}}{\lambda_{insul} * L} + \frac{1}{h_2 * L}}$$



Case c_2 is compliant with the finite element model TACTICS **in steady state.**

DEMO TF coil

INPUTS

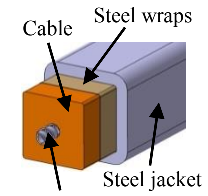


Inner leg

2015 TF WP3 reference conductor.

I_{TF}	Conductor current	111560 A
d_S	Strand diameter	1.024 mm
N_{Sc}	Number of Sc. strands	1029
N_{Cu}	Number of Cu strands	844
L_C	Cable size (square)	48.64 mm
W_{jack}	Jacket thickness	11.1 mm
ΔV_{max}	Max voltage to ground	5154 V
N_{pk}	Number of pancakes	16
N_{tr}	Number of turns	8

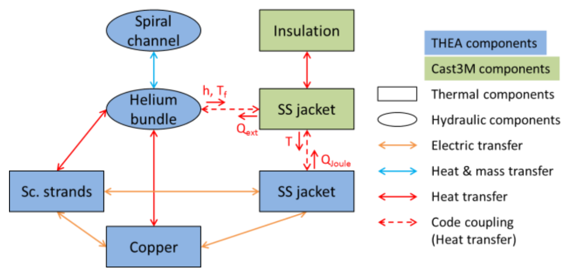
Cable-In-Conduit Conductor (CICC)



Quench simulations

QUENCH MODEL

Quench initiated at B_{eff_max} on the **central CW pancake.**
Perturbation = 2 * MQE applied for 0.1 s over 1 m length. (MQE = 1963 W/m)
Quench detection not considered: FSD triggered 3 s after the disturbance.



The jacket is considered 'thermally' in Cast3M and 'electrically' in THEA to account for the current redistribution during a quench.

RESULTS COMPARISON

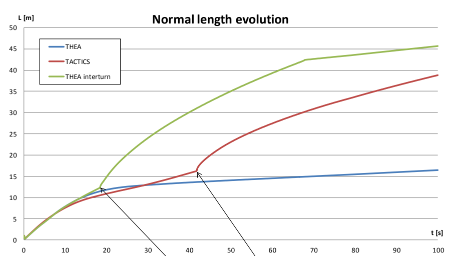
TACTICS: higher strands temperature but lower jacket temperature compared to THEA -> impact of the diffusion time in the jacket (more time for the strands to heat up by joule effect).

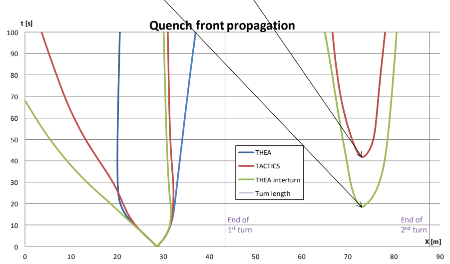
THEA interturn: lower temperatures, because the cooling of the first turn (quenched) by the second turn is instantaneous (infinite diffusion), which is not realistic.

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

PROPAGATION OF THE QUENCH





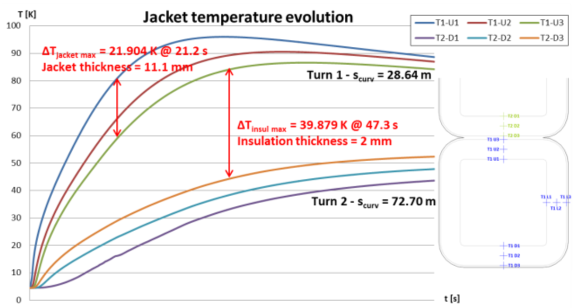
Quench initiation on the second turn because of the transverse thermal diffusion:

- **At 41.783 s with TACTICS**
- **At 18.425 s with THEA interturn**

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.

Detailed results with TACTICS

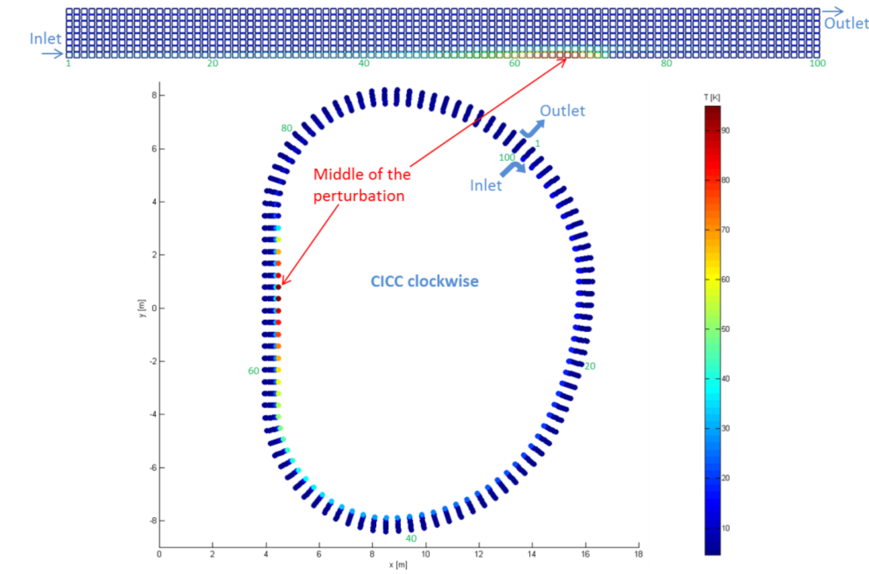
TEMPERATURE FIELDS



The point where the **maximum temperature of 99.551 K** is reached is T1-D1 at s_{curv} = 28.641 m (first turn, in the middle of the quench initiation location).

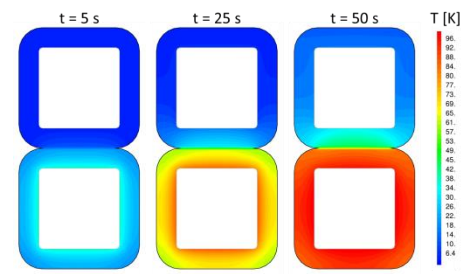
The maximum temperature difference over the jacket thickness is 21.904 K.

The maximum temperature difference through the 2 mm insulation thickness is 39.879 K.



Temperature field map over the whole pancake (100 cross sections) at 100 s.

Temperature field map in the jacket and insulation of the two first turns of the pancake at the middle of the quench initiation.



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 an 1D approach since the transversal thermal gradient are negligible; but on DEMO, the jacket thermal gradient can reached up to 21.904 K, so an 1D approach is not sufficient to check the compliance of the design with the hotspot criterion.

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.

EUROfusion

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