DE LA RECHERCHE À L'INDUSTRIE

Thermohydraulic Analyses on CEA Concept of TF and CS Coils for EU-DEMO

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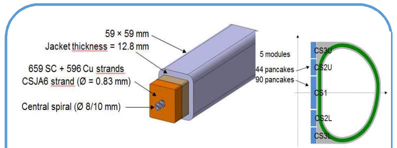
Background

In the framework of the European fusion program for energy, EUROfusion funds the studies for the future fusion power demonstrator reactor DEMO. CEA is involved in the conceptual design of the superconducting conductors for the **Toroidal Field (TF) and Central Solenoid (CS) magnets.** The CEA design proposal corresponds to Wind and React Nb_3Sn pancake-wound coils using Cable-In-Conduit Conductors (CICCs) cooled at about 4.5 K by forced flow of supercritical helium.

Artist's view of DEMO tokamak, courtesy EUROfusion



Schematic view of the CS conductor design and the 5 CS modules

Objectives

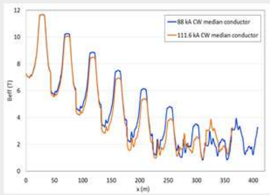
- ❑ Thermal-hydraulic analyses performed on TF and CS conductors.
- ❑ **Two TF conductor designs** have been analyzed, with nominal current of **111 kA** and **88 kA** respectively in normal (**burn**) and off-normal (**quench**) conditions.
  - ✓ **Burn simulations** : aim at assessing the temperature margin (ΔTma = T_{CS}-T_{op}) - Focused on the central and lateral pancakes with a head load corresponding to **neutron heating.**
  - ✓ **Quench studies** consider a quench initiated either on the innermost turn or at the middle of hydraulic length with the aim to assess the hot spot temperature (maximal jacket temperature).
- ❑ The CS conductor has been analyzed in **burn operation** with nominal current of **53.7 kA,** focusing on the **impact of AC losses** and of dwell duration.

Toroïdal Field Conductor (TF)

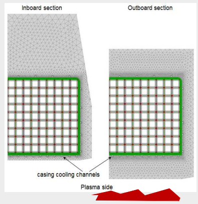
TF Design

ITER-type double channel CICC with a central spiral inserted in a square stainless steel jacket.

Conductor current (kA)	111.6	88
T_{CS} (K)	6.2	6.2
B_{max} (T)	12.23	12.27
Strand diameter (mm)	1.024	0.984
Number of Nb_3Sn strands	935	828
Number of pure Cu strands	913	790
Cos (θ)	0.95	0.95
Central spiral o.d x i.d (mm)	10x8	10x8
Cable void fraction (%)	29	29
Cable size (w/o wraps) (mm)	48.32	43.62
Conductor size (mm)	70.84	62.98
Number of double pancakes	**8**	**9**
Number of turns per pancake	**8**	**9**
Hot spot temperature criteria (K)	150	150
Temperature margin criteria (K)	1.5	1.5
Hydraulic length simple pancake (m)	**364**	**408**



Magnetic field distribution along 88 and 111 kA CW median conductors.



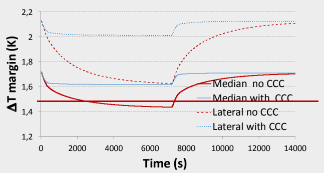
Winding Pack and casing for inboard/outboard TF cross-section (Cast3M) model for nuclear heat load on casing and jacket.

TF Results

TF Burn scenario

ΔTma criterion: (T_{CS}-T_{op}) > 1.5 K

Ref. scenario 88 kA – casing cooling channels (CCCs) influence. ΔTma at critical location (x=32 m from helium inlet) for CW median and lateral pancakes.



For CW median pancake, CCCs allow to increase the ΔT_{ma} by 0.18 K (88 kA) and 0.20 K (111 kA).

Thermal- hydraulic: 1D THEA model
Thermal model: 2D Cast3M
Magnetic field maps: TRAPS code

TF Quench scenarios

(Hot spot Temperature criterion: Tmax jacket < 150 K)

The current decay during the fast safety discharge (FSD) took into account the discharge resistance heating.

Main TF quench results

WP	conductor	disturbance location (DL)	B at DL	ΔTma at DL	quench detection	Ut (V)	$\tau_{da} = \tau_p + \tau_{delay}$ (s)	Tmax SC (K)	Tmax jacket (K)
111 kA	lateral CW	Minimum ΔTma on internal turn (27.75 to 28.75 m)	11.20 T	2.00 K	not modelled	0	3	117	101
					modelled	0.5	3.7 + 2	152	127
	median CW	Minimum ΔTma on internal turn (27.75 to 28.75 m)	11.69 T	1.61 K	not modelled	0	3	119	102
					modelled	0.5	4.3 + 2	162	134
	median CW	Maximum ΔTma on internal turn (5.2 to 6.2 m)	6.97 T	5.00 K	not modelled	0	3	108	94
					modelled	0.5	4.6 + 2	153	127
	median CW	middle of hydraulic length (181.5 to 182.5 m)	1.57 T	8.45 K	not modelled	0	3	106	90
					modelled	0.5	9.0 + 2	214	**170**
					modelled & Ut tuned	0.35	7.5 + 2	190	**152**
88 kA	lateral CW	Minimum ΔTma on internal turn (27.75 to 28.75 m)	11.18 T	2.09 K	not modelled	0	3	112	100
					modelled	0.5	4.1 + 2	148	129
	median CW	Minimum ΔTma on internal turn (27.75 to 28.75 m)	11.68 T	1.70 K	not modelled	0	3	113	101
					modelled	0.5	4.0 + 2	147	129
	median CW	Maximum ΔTma on internal turn (5.2 to 6.2 m)	6.99 T	5.04 K	not modelled	0	3	101	91
					modelled	0.5	5.5 + 2	151	131
	median CW	~ middle of hydraulic length (181.5 to 182.5 m)	2.21 T	8.05 K	not modelled	0	3	96	86
					modelled	0.5	9.7 + 2	199	**168**
					modelled & Ut tuned	0.35	8.1 + 2	176	**150**

Central Solenoïd Conductor (CS)

CS Burn scenario

- ❑ The conductor is made out of 659 strands CSJA6 strands and 596 pure Cu strands, of 0.83 mm diameter.
- ❑ The retained plasma reference scenario featured 80 s premagnetisation, 2 hours burn and 10 minutes dwell.
- ❑ The analysis focused on the impact of AC losses and dwell duration.
- ❑ The heat losses considered are **coupling** and **hysteresis** AC losses.

$$P_{coup} = \frac{n\tau * S_{sc\,strands}}{\mu_0} * \left(\frac{dB}{dt}\right)^2 \text{ with } \mu_0 = 4\pi * 10^{-7}\ \mathrm{T.m/A}$$

The nτ value was taken equal to 638 ms, corresponding to an upper estimate deduced from ITER CS insert tests performed at CSMC Naka

$$P_{hyst}(x,t) = \frac{dE_{lin,hyst}(B(x,t))}{dt} = \frac{dE_{lin,hyst}(B(x,t))}{dB} * \left|\frac{dB}{dt}\right|$$

ΔTma: 1.5 K criterion

CS WP Results

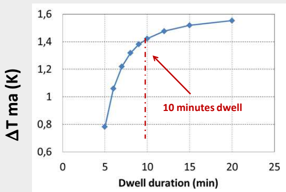
ΔTma – sensitivity to AC losses

Nτ (s)	Coupling losses	Hysteresis losses	ΔTma (K)	ΔTop (K)
0.25	Yes	Yes	1.50	0.12
0.50	Yes	Yes	1.45	0.17
0.638	Yes	Yes	**1.42**	**0.20**
1	Yes	Yes	1.35	0.27
0.638	Yes	No	1.49	0.13
0.638	No	Yes	1.55	0.07
0.638	No	No	1.61	0.01

Coupling losses contribution on ΔTop was **0.13 K**, showing a higher impact than **hystereris losses** with a contribution of **0.07 K.**

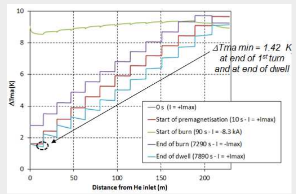
It can be noted that nτ should decrease to 250 ms to fulfill the 1.5 K criterion.

ΔTma sensitivity to dwell duration



10 minutes dwell seemed to be a good compromise, as shorter dwell duration significantly decreases ΔT_{ma} while higher dwell duration doesn't bring much benefit for the margin.

ΔTma along CS1 median conductor



The reference scenario simulation gave a minimum Δ_{Tma} of **1.42 K** at 15.24 m corresponding to the end of 1st turn and at the End Of Dwell.

Conclusion

CEA proposed conceptual designs for EU-DEMO TF and CS conductors, based on Nb_3Sn strands and inspired from ITER magnets. Thermo-hydraulic analyses focused on normal (burn) and off-normal (quench) scenarios for TF conductor, and on normal scenario for CS conductor. Two TF conductor designs (**111 kA and 88 kA**) were studied, focusing on ΔT_{ma} and $T_{hot\ spot}$ criteria assessment in burn and quench scenarios respectively. The hot spot criterion was satisfied for all cases except when it was initiated at middle of conductor, and when the quench detection was simulated with the aim to reduce the voltage threshold from **0.5 V to 0.35 V**. For the CS conductor, analyses focused on the ΔT_{ma} sensitivity to AC losses and to dwell duration, showing the dominant impact of coupling losses and the relevance of the **10 minutes** proposal for dwell duration.

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