Task: MAG-S.01.03-T031

Thermal-hydraulic analysis of the DEMO winding packs (2025)

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Task specification

Description:

The task is focused on thermal-hydraulic analyses of the available designs of the DEMO conductors and winding packs. In particular we foresee the following activities:

(i) thermal-hydraulic analysis of normal operation and quench analysis of the conductors designed by the EPFL-SPC team for the DEMO hybrid CS, ongoing

(ii) thermal-hydraulic analysis of normal operation and quench analysis of the conductors designed by the EPFL-SPC team for the DEMO PF coils. completed

Thermal-hydraulic analysis of normal operation and quench analysis of the DEMO LAR PF conductors (EPFL-SPC design)

Goal of the study

- Estimation of the global minimum temperature margin during normal operation of the DEMO LAR PF conductors and verification if it fulfills the acceptance criterion:

  min ΔT_{marg} > 1.5 K

  where $\Delta T_{marg}(x,t) = T_{cs}(x,t) - T_{sc}(x,t)$

  x - curvilinear coordinate along a conductor

  T_{cs} - current sharing temperature

  T_{sc} - superconductor temperature

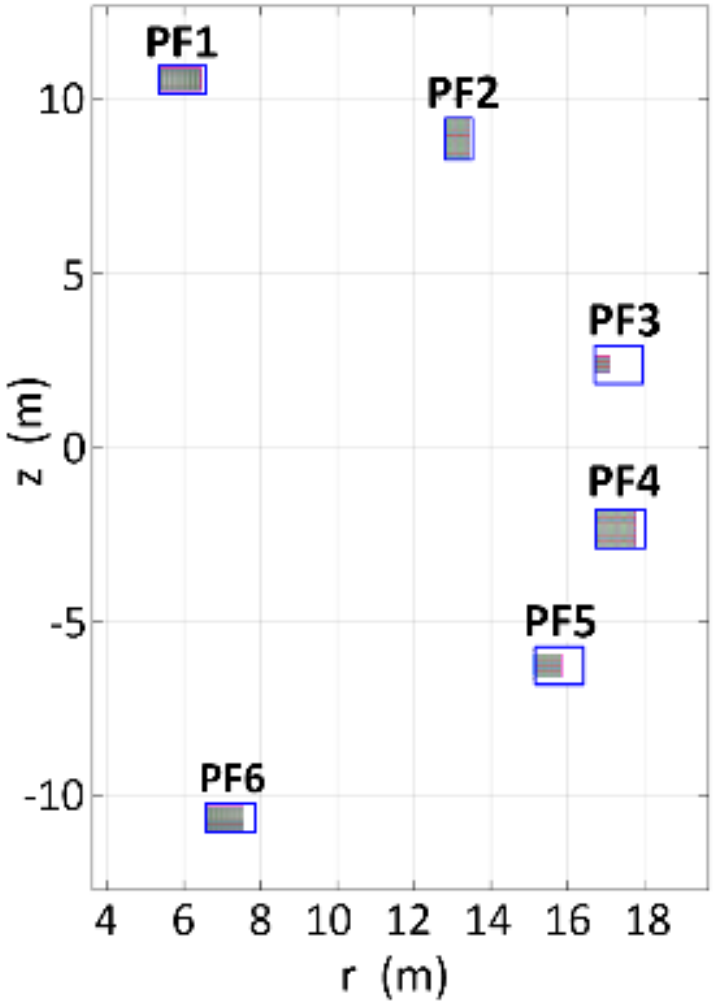
- Estimation of the maximum hot spot temperature margin during quench of the DEMO LAR PF conductors and verification if it fulfills the acceptance criterion:

  max T_{jacket} > 150 K

Coils and conductors characteristics [1,2]

Characteristics of the NbTi CICCs without additional cooling channels

Description (Unit)	PF1	PF2	PF3	PF4	PF5	PF6
Pancakes number (-)	8	14	6	12	8	8
Turns number (-)	25	11	8	18	14	21
Conductor length, L (m)	921	906	851	**1951**	**1363**	932
NbTi strands number (-)	1929	350	271	737	334	1619
Cu strands number (-)	0	893	971	701	913	140
Strands diameter (mm)	0.82	0.82	0.82	0.82	0.82	0.82
Mean twist pitch angle, cosq (-)	0.97	0.97	0.97	0.97	0.97	0.97
NbTi cross section (mm^2)	424.5	77.0	59.6	162.2	73.5	356.2
Cu in sc strands cross section (mm^2)	594.2	107.8	83.5	227.0	102.9	498.7
Cu in Cu strands cross section (mm^2)	0.0	471.6	512.8	370.2	482.2	73.9
He cross section (mm^2)	647.6	417.4	417.2	482.9	418.5	590.3
Void fraction (%)	38.14	38.15	38.16	38.15	38.14	38.13
Hydraulic diameter (mm)	0.596	0.591	0.592	0.593	0.591	0.595
Jacket cross section (mm^2)	786	2061	1617	2421	1837	958
Insulation cross section (mm^2)	204.5	226.3	210.2	244.8	218.5	204

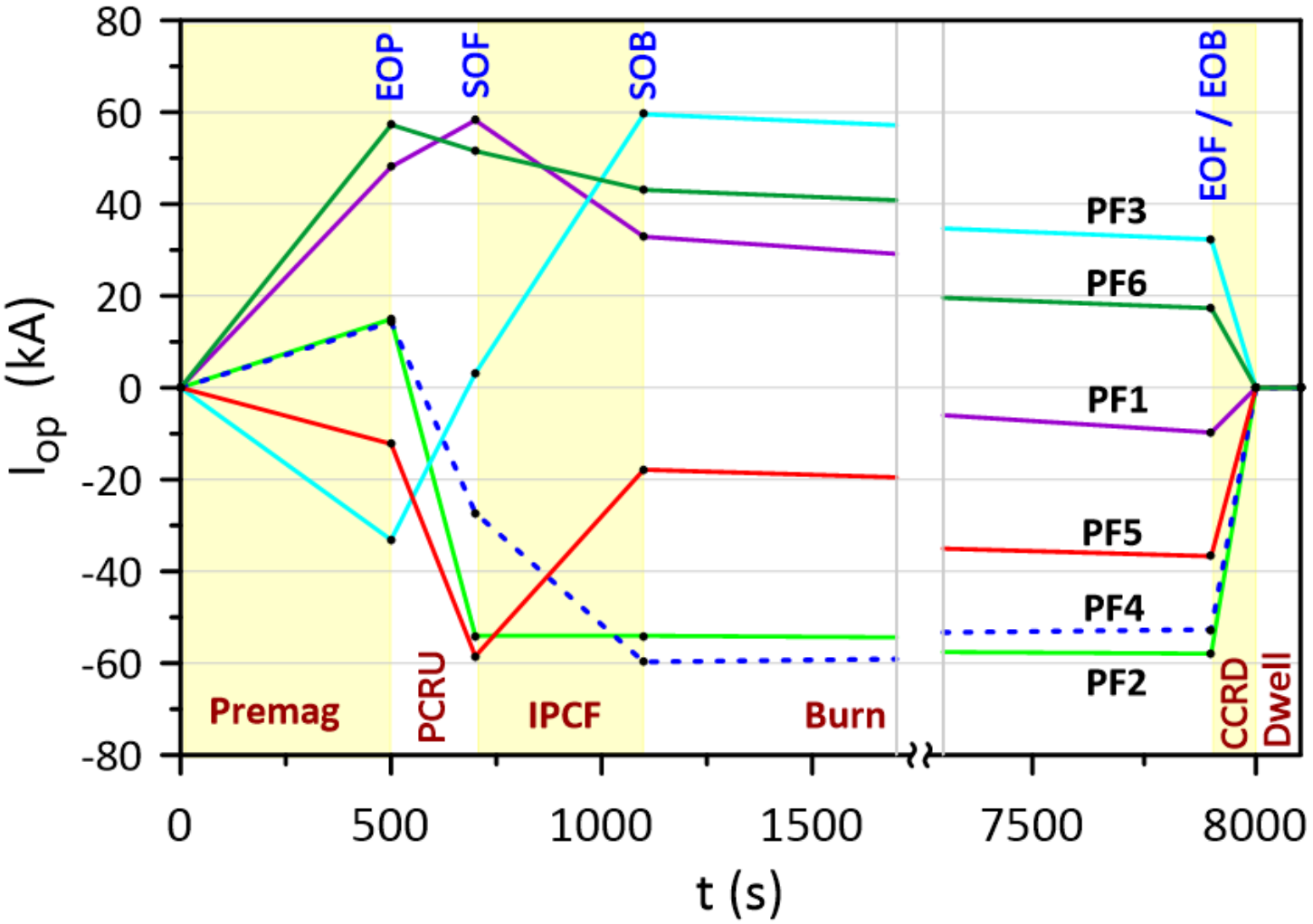


Locations of the DEMO PF coils boxes and winding packs in the machine (r,z) coordinate system

[1] N. Ambrosino, and E. Acampora, "2024 DEMO Single Null baseline with aspect ratio 2.8: reference electromagnetic plasma scenario," EUROfusion report, 2024, https://idm.euro-fusion.org/default.aspx?uid=2RZB6R

[2] T. Nes, PF coil preconceptual design for the 2024 DEMO baseline, Final report for the task MAG-S.01.01-T031-D002, 2025

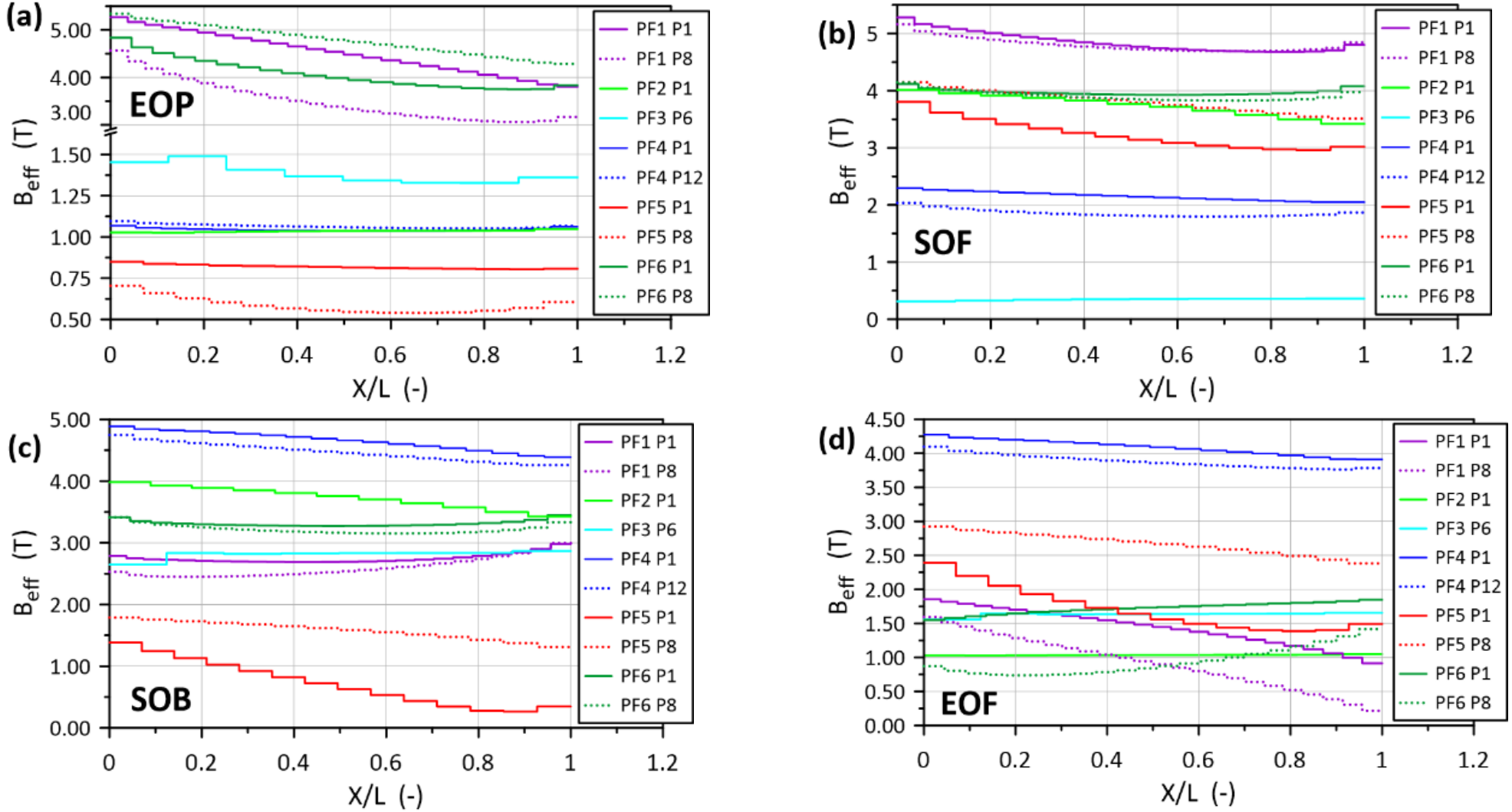
Assumed current scenario [1,3]



Phase	Duration (s)
Premagnetization (Premag)	500
Plasma Current Ramp-Up (PCRU)	**200**
Initial Plasma Current Flat-top (IPCF)	**400**
Burn	6800
Conductors Current Ramp-down (CCRD)	100
Dwell	100

[3] R. Guarino, et al.: Thermal-hydraulic analysis of alternative cable-in-conduit conductors for the European DEMO hybrid central solenoid, Fusion Eng. Des. 187 (2023) Art. no. 113368.

Effective magnetic field profiles at the characteristic points of the cycle [4]



We studied the $B_{eff}(X)$ and $dB_{eff}/dt\,(X)$ profiles along all pancakes in the PF coils and selected for further analysis the one or two most critical pancakes in each PF coil subjected to the highest magnetic field and/or heat loads.

[4] T. Nes: Electromagnetic analysis of the 2024 PF coil designs (SPC variant)," Final report for the task MAG-S.01.01-T031-D004

Heat loads due to AC losses

- Power of coupling losses (in W/m) [5]:

$$P_{coupling}(X,t) = \frac{n\tau S}{\mu_0}\left(\frac{\partial B_{eff}(X,t)}{\partial t}\right)^2 = \frac{n\tau S}{\mu_0}\left[\left(\frac{\partial B_{eff\,z}}{\partial t}\right)^2 + \left(\frac{\partial B_{eff\,r}}{\partial t}\right)^2\right]$$

where *S* is the total strands cross section, *n* is the dimensionless demagnetization factor and τ is the coupling loss time constant. We assumed $n\tau$ = 100 ms [6].

- Power of hysteresis losses (in W/m) [7]:

$$P_{hyst}(X,t) = \frac{2d}{3\pi} S_{NbTi} J_c \left|\frac{\partial B_{eff}(X,t)}{\partial t}\right|$$

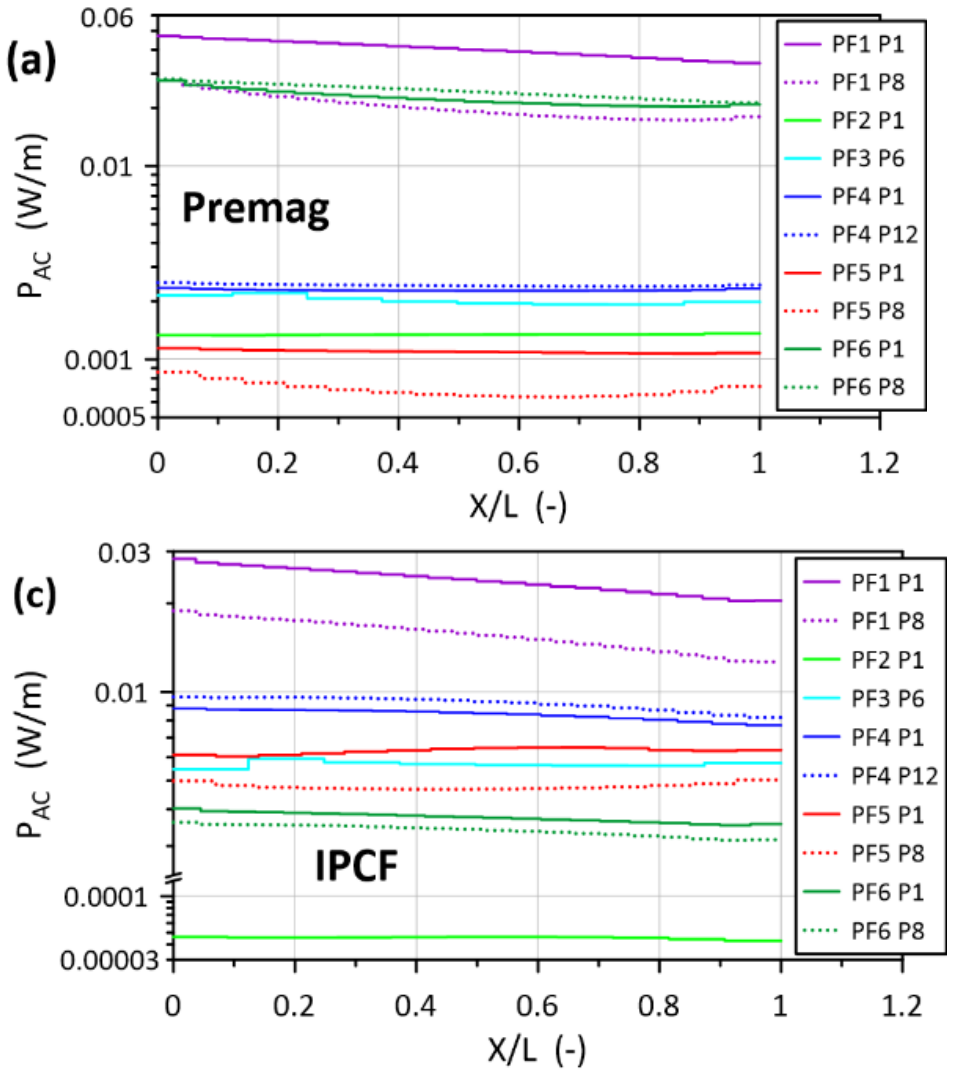
where S_{NbTi} is the pure NbTi cross section, d = 10 μm – filament diameter and J_c – critical; current density. Following [3], the critical current density was evaluated at T = 4.5 K and the maximum MF for a given conductor.

[5] M. Wilson, Superconducting Magnets, Clarendon Press, 1983.

[6] P. Bruzzone, et al.., A New Cabled Stabilizer for the Nb3Sn React&Wind DEMO Conductor Prototype, IEEE Trans. Appl. Supercond. 31 (2021) Art. no. 4802505.

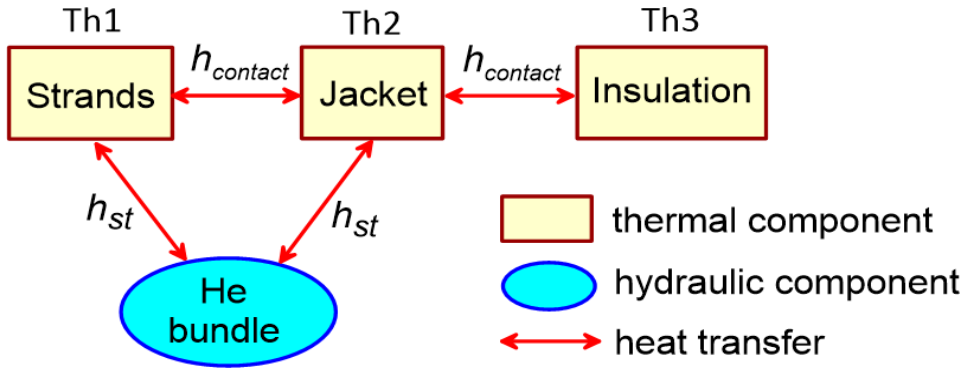
[7] M. Wilson, NbTi superconductors with low ac loss: A review, Cryogenics 48 (2008) pp. 381–395.

Heat loads profiles at the different phases of the current cycle



Heat loads due to AC losses ($P_{AC} = P_{Coupling} + P_{hyst}$) profiles along the selected pancakes of the PF coils

THEA model



- Cooling conditions (T_{in} = 4.5 K, p_{in} = 6 bar, Δp = 1 bar) and thermal links between the conductor components typical for TH simulations of the EU-DEMO conductors [8].
- Preliminary simulations at I_{op} = 0, $B_{eff}(X)$ = 0 and no heat load: starting from the constant initial conditions along the conductors: T = T_{in}, p = p_{in}, dm/dt = 5 g/s, and lasting until the steady stationary state was reached. The resulting steady state T, p, and dm/dt profiles were saved and served as initial conditions for the subsequent simulations of normal conductor operation during the whole current cycles.
- Validation of the THEA conductor model by comparison of the T, p, and ΔT_{marg} profiles with the respective predictions of the steady state model [9,10] at the initial steady state and at the EOF state.
- Simulations of normal operation were carried out until for a given conductor the temperature profiles at the end of the two subsequent cycles did not differ substantially. For most of conductors (PF1, PF2, PF3 and PF6) it was sufficient to simulate two cycles only, for PF5 we simulated 3 cycles, and for PF4 – 6 cycles.

[8] L. Savoldi and R. Zanino, Common approach for thermal-hydraulic calculations, Memo for WPMAG-2.1-D01 (2016) https://idm.euro-fusion.org/?uid=2LMECE

[9] M. Lewandowska, K. Sedlak, IEEE Trans. Appl. Supercond. 24 (2014) Art. No 4200305.

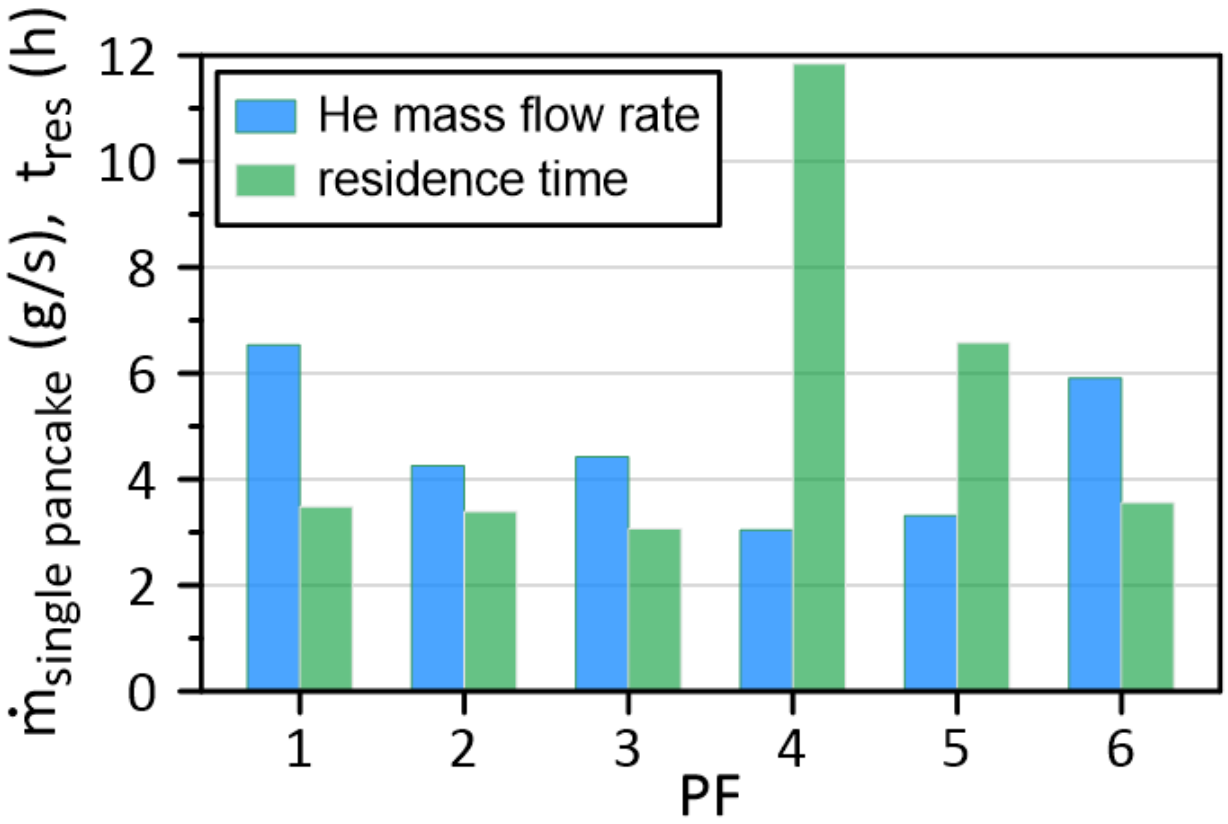
[10] M. Lewandowska, A. Dembkowska, R. Heller, M. Wolf, Cryogenics 96 (2018) 125-132.

THEA model – quench simulations

- One pancake per each PF coil, in which the lowest global (in space and time) ΔT_{marg} minimum was observed, were selected to perform quench simulations.
- When the global ΔT_{marg} minimum was reached the corresponding T, p, and dm/dt profiles were saved and served as initial conditions for the subsequent quench simulations.
- Quench was triggered by a heat pulse of length 0.1 m, duration 0.1 s and energy of twice Minimum Quench Energy (MQE) imposed at the location of the global min ΔT_{marg} [11].
- MQE was estimated for each conductor by trial and error procedure with accuracy +/- 0.1 J
- After applying the heat disturbance the operating current and magnetic field followed the normal scenario until the quench detection (i.e. exceeding the threshold voltage of 0.1 V) plus additional delay t_{delay} = 1.1 s (corresponding to typical time necessary for reaction of the quench]), after which the exponential current dump started with the characteristic time τ = 15 s. The MF profile was also dumped proportionally to the operating current.
- Quench simulations lasted 300 s, which was sufficient to observe the maximum temperatures of both strands and jacket in all considered conductors.

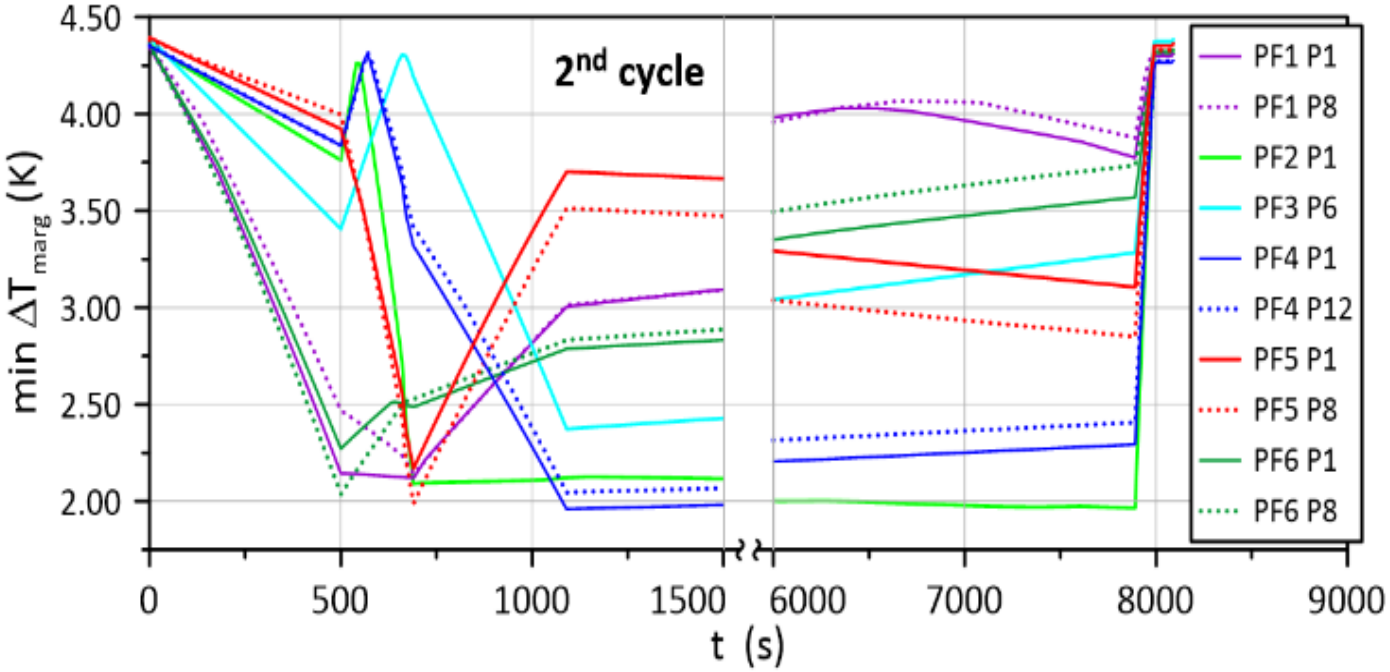
[11] V. Corato *et al.*, Common operating values for DEMO magnets design for 2016.

Results - hydraulic analysis



Nominal mass flow rate (at no heat load) and helium residence time in a single pancake of different DEMO PF coils

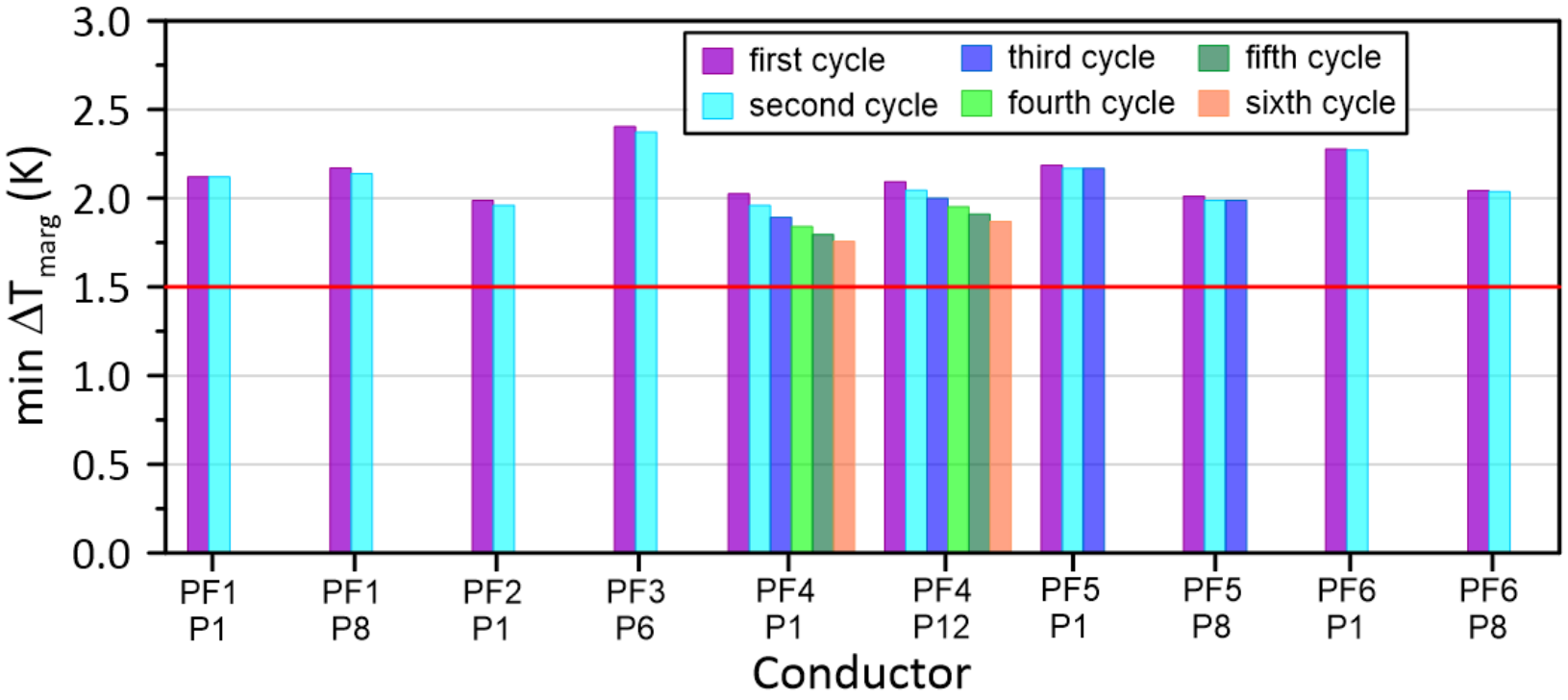
Results – Time evolution of the minimum ΔT_{marg}



Typical time evolution of the minimum ΔT_{marg} in all considered pancakes

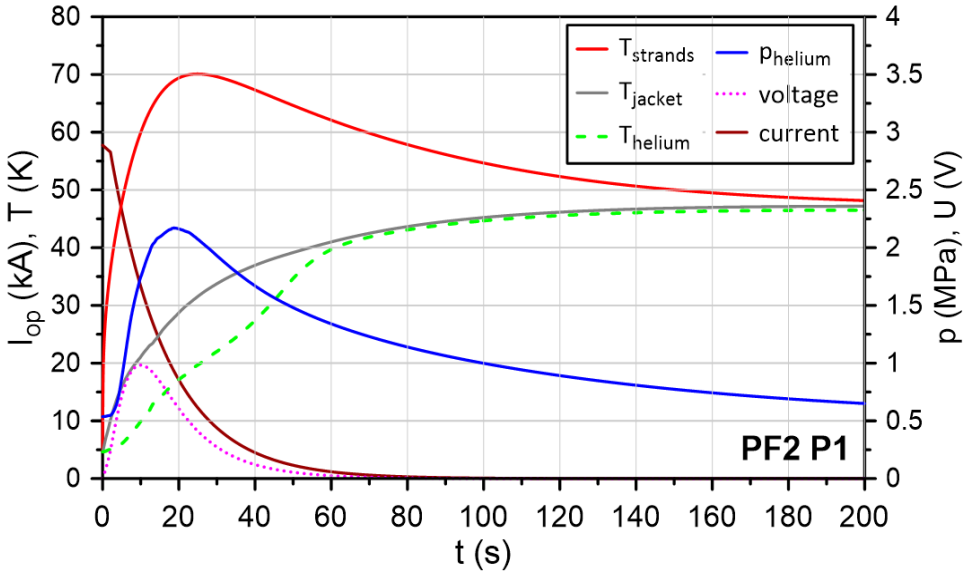
- Relatively low heat loads => moderate rise of conductors temperature => evolution of ΔT_{marg} was mostly affected by T_{cs} variations.
- The global minima (in space and time) of ΔT_{marg} were observed at EOP (in PF6), SOF (in PF1 and PF5), SOB (in PF3 and PF4) or EOF (in PF2), i.e. at the same moments when the minima of T_{cs} were reached

Results – Global minima of ΔT_{marg} in the subsequent current cycles



The acceptance criterion: **min ΔT_{marg} > 1.5 K** was fulfilled by all considered conductors ☺

Results – Quench analysis



Typical quench simulations results - quench evolution at the location of heat disturbance (X = 571.5 m) in the PF2 P1 conductor

Conductor	MQE (J)	$T_{max\ strands}$ (K)	$T_{max\ jacket}$ (K)
PF1 P1	2.40	60.3	49.6
PF2 P1	1.60	70.2	47.3
PF3 P6	2.20	71.2	48.1
PF4 P1	1.70	70.3	47.4
PF5 P8	2.00	76.0	50.8
PF6 P8	2.20	60.6	48.5

Summary of the quench analysis results

- The maximum hot spot temperatures for all considered conductors are safely low (i.e. well below the acceptance criterion: $T_{max\ jacket}$ < 150 K ☺

Summary and conclusions

- Normal operation of 10 selected NbTi DEMO LAR PF pancakes (EPFL-SPC design) was simulated using the THEA code by CryoSoft. A simplified current scenario that excluded the fast breakdown phase was considered.
- The analysis accounted for heat loads from AC coupling losses (characterized by the value $n\tau$ =100 ms) and hysteresis losses. Operation over several full current cycles was simulated.
- The nominal mass flow rate (obtained for the steady-state, no-heat-load condition) in all PF conductors was relatively low. The estimated nominal total mass flow rates (in g/s) for the PF coils are: 52.3 (PF1), 59.6 (PF2), 26.5 (PF3), 36.5 (PF4), 26.5 (PF5) and 47.3 (PF6). These values can serve as a reference for the designers of the DEMO cryogenic system.
- The global minimum of the temperature margin for all conductors is well above the 1.5 K acceptance criterion.
- The maximum temperatures of the considered conductors during quench were in the range 60-76 K (for the strands) and 47-50 K (for the jackets), meaning they were much lower than the 150 K criterion.
- The considered conductors fulfilled the thermal-hydraulic performance criteria agreed within the WPMAG project team. The only potentially problematic issue is the very long helium residence time in the PF4 conductors (over 5 times the duration of the current cycle).
- The poster: M. Lewandowska, A. Dembkowska, T. Nes: Thermal – hydraulic and quench analysis of conductors for the EU-DEMO LAR coil, was presented at EUCAS 2025, and the respective paper was submitted to IEEE Trans. Appl. Supercond.
- TH analysis of the DEMO LAR CS coil is nogoing

Thank you very much for your attention

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