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Thermal-Hydraulic Analysis of the DEMO PF Coils Designed by CEA

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- Basic assumptions
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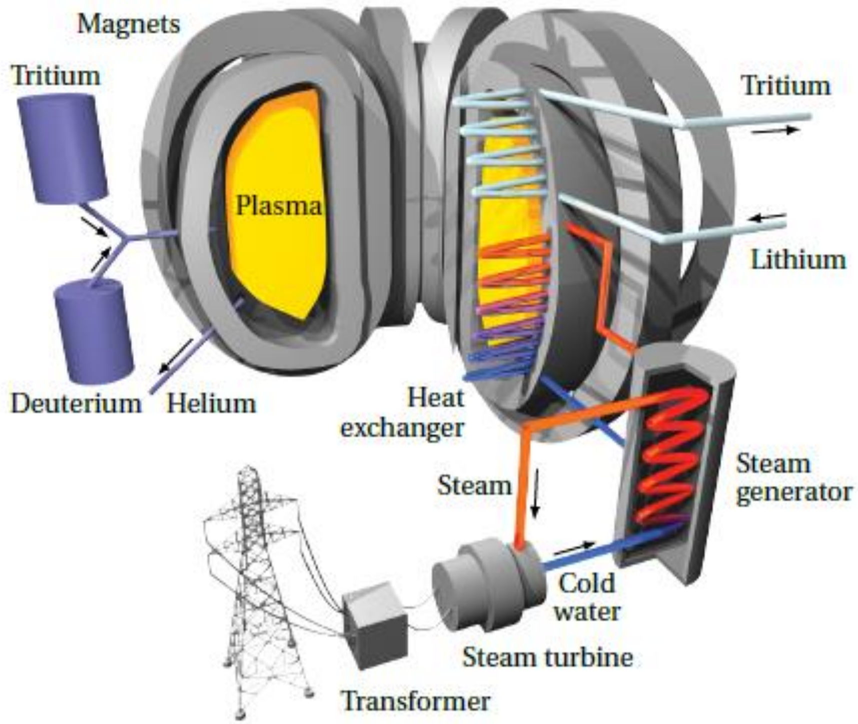
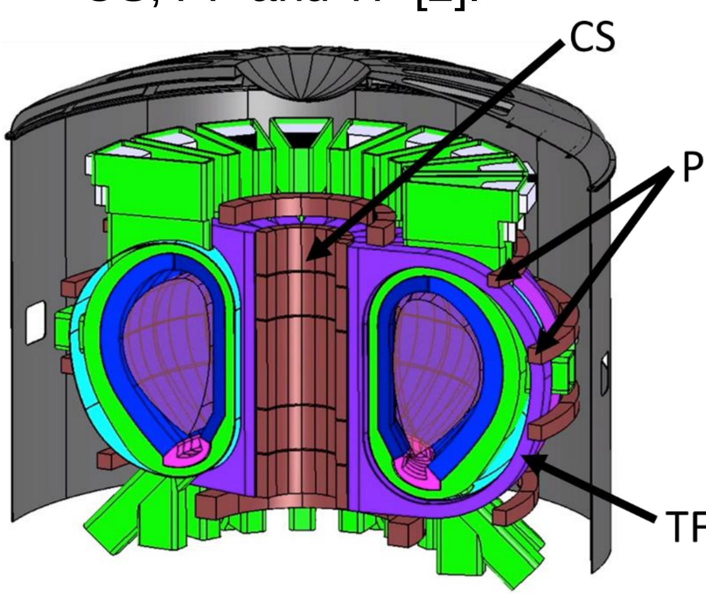
EU – DEMO and its magnet system



EU - DEMO – European DEMOnstration fusion power plant based on the tokamak concept [1]

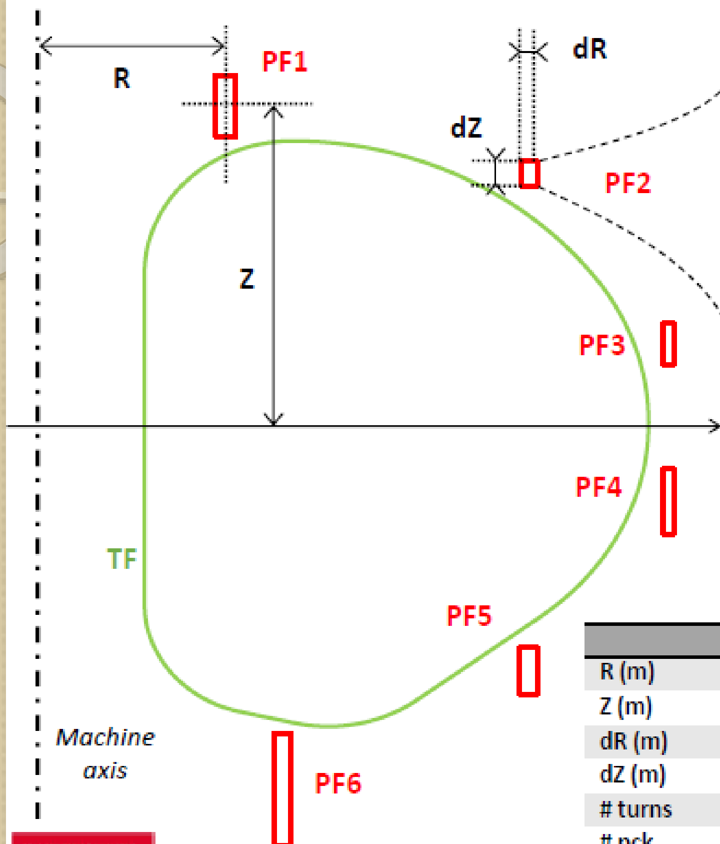
- Step between ITER and a commercial power plant
- Net electricity production of a few hundreds MW
- Achievement of tritium self-sufficiency
- DEMO construction should start in the early 2030s to achieve fusion electricity by 2050

View of the DEMO coils: CS, PF and TF [2].

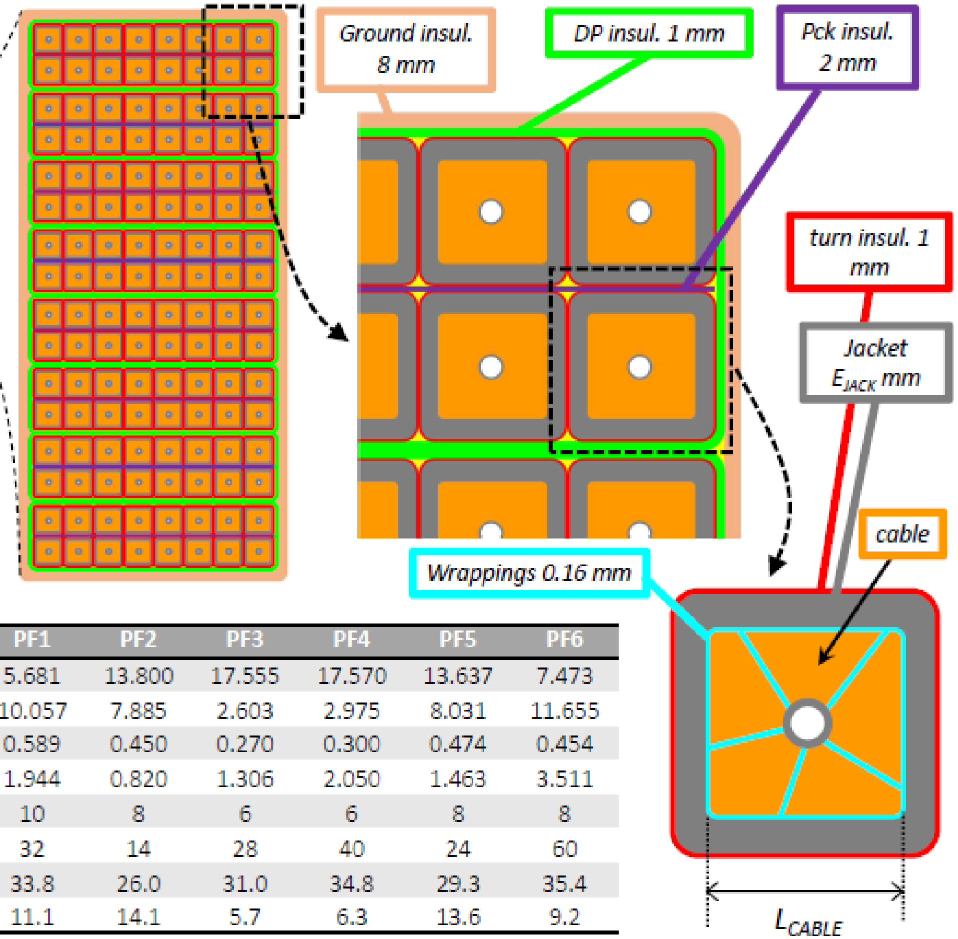


[1] ITER and fusion energy, http://iter.rma.ac.be/
[2] B. Meszaros, H. Hurzlmeier, *EU DEMO1 2015 - DEMO_TOKAMAK_COMPLEX*

DEMO PF coils



MAG.PF-DEF-3-CD1
Drawing of variant 1



	PF1	PF2	PF3	PF4	PF5	PF6
R (m)	5.681	13.800	17.555	17.570	13.637	7.473
Z (m)	10.057	7.885	2.603	2.975	8.031	11.655
dR (m)	0.589	0.450	0.270	0.300	0.474	0.454
dZ (m)	1.944	0.820	1.306	2.050	1.463	3.511
# turns	10	8	6	6	8	8
# pck	32	14	28	40	24	60
L_{CABLE} (mm)	33.8	26.0	31.0	34.8	29.3	35.4
E_{JACK} (mm)	11.1	14.1	5.7	6.3	13.6	9.2

Main features of the DEMO PF coils design proposed by CEA [3]

Each of 6 PF coils is double pancake (DP) wound using a different square NbTi Cable-in-Conduit conductor [3].

[3] L. Zani. *CEA PF winding pack design*, Final report for the task MAG-2.1-T026-D002 (2020), https://idm.euro-fusion.org/?uid=2N9WUY

Goal of the study

Our study is focused on the thermal-hydraulic analysis of the CEA design of the DEMO PF coils at normal operating conditions, using the THEA code by CryoSoft .

It was aimed at verification if the proposed conductors' design fulfill the performance criterion:

$$\textbf{minimum } \Delta T_{marg} > 1.5\ \text{K} \quad [4]$$

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

[4] V. Corato et al., *Progress in the design of the superconducting magnets for the EU DEMO*, Fus. Eng. Des. 136 (2018) 1597–1604

Conductors characteristics

Description / Unit	PF1	PF2	PF3	PF4	PF5	PF6
Max. Magnetic field (T)	6.137	3.720	4.600	4.463	3.793	5.388
Max. operating current (kA)	51.66	52.59	50.42	50.13	51.61	50.06
No. sc strands	1657	188	296	270	191	561
No. Cu strands	0	730	1015	1385	1070	1140
Strand diameter (mm)	0.73	0.73	0.73	0.73	0.73	0.73
Jacket thickness (mm)	11.10	14.10	5.70	6.30	13.50	9.20
Spiral outer diameter (mm)	12.0	11.5	13.6	15.43	10.0	15.8
Conductor length (m)	356.8	694.1	663.3	663.3	685.3	375.9
NbTi cross section (mm^2)	303	34	54	49	35	103
Cu cross section (mm^2)	427	370	523	680	521	647
Bundle He cross section (mm^2)	299	168	238	295	224	308
Bundle hydraulic diameter (mm)	0.35	0.35	0.35	0.35	0.35	0.35
Bundle void fraction (-)	0.29	0.29	0.29	0.29	0.29	0.29
Jacket cross section (mm^2)	1921	2122	835	1030	2207	1601

Model assumptions – cooling conditions

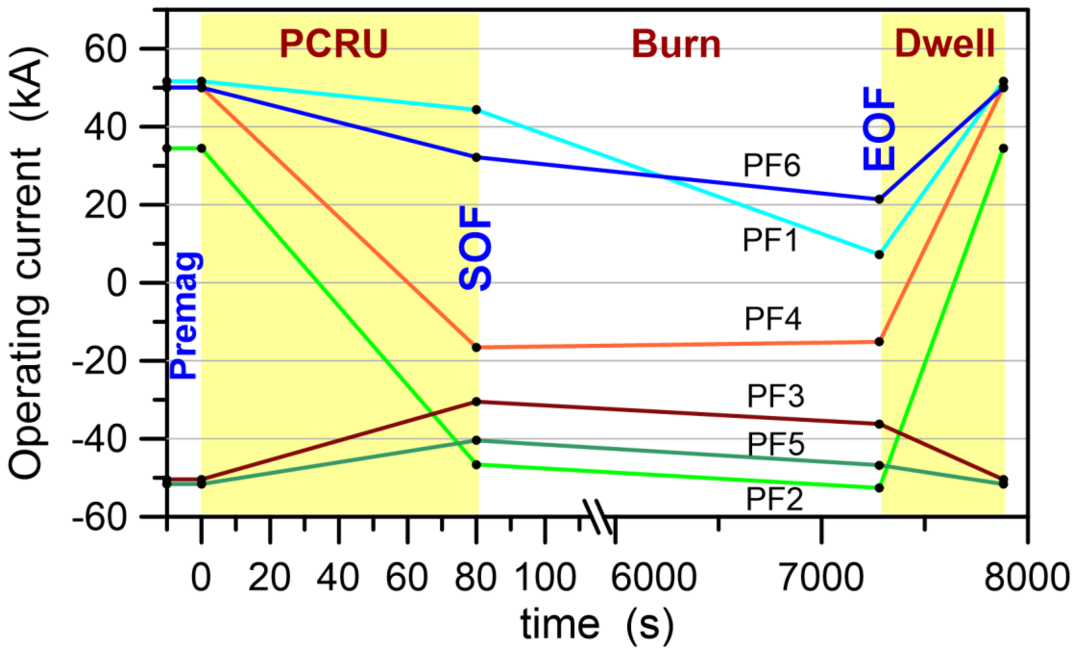
- Forced flow cooling with supercritical helium at:

  T_{in} = 4.5 K, p_{in} = 6 bar, Δp = 1 bar

- Friction factor correlations:
  - bundle region - correlation based on the Darcy-Forchheimer equation for flow in porous media [5]
  - central cooling channel
    - experimental correlation: $f_{EU} = 0.42\ Re^{-0.1}$ suitable for spiral with outer diameters ~ 10 mm was applied for PF2 (D_{out} = 11.5 mm) and PF5 (D_{out} = 10 mm) [6],
    - for spirals with larger diameters (D_{out} = 12, 13.6, 15.43 and 15.8 mm in PF1, PF3, PF4 and PF6 respectively), the experimental correlation for the Showa spiral (D_{out} = 11.9 mm) was applied: $f_{EU}(Re) = 0.3024\ Re^{-0.0707}$ [7].

[5] Bagnasco M, Bottura L, Lewandowska M, *Friction factor correlation for CICC's based on a porous media analogy*, Cryogenics 50 (2010) 711–719.
[6] R. Bonifetto et al., *Common approach for burn studies*. https://idm.euro-fusion.org/?uid=2LCLKZ
[7] S. Nicollet et al., *Calculations of pressure drop and mass flow distribution in the toroidal field model coil of the ITER project*. Cryogenics 40 (2000) 569-575.

Model assumptions – current scenario



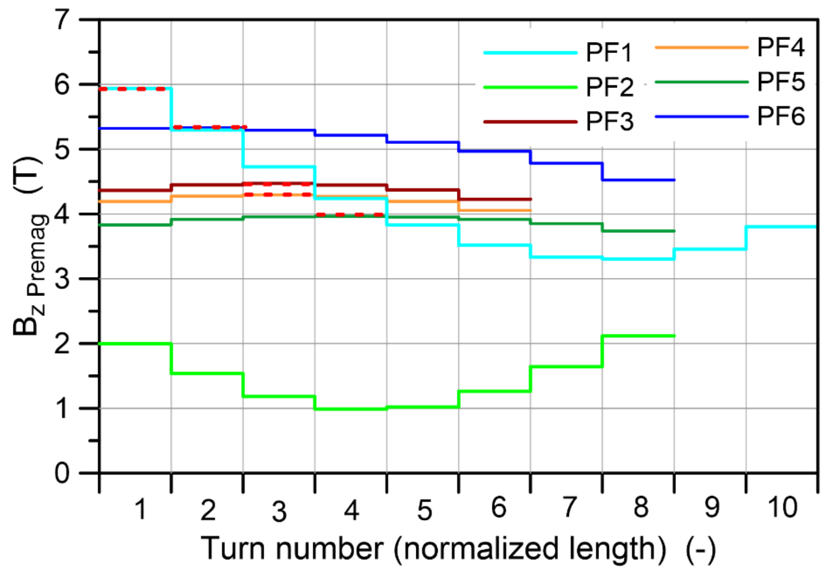
Normal operation „4 points" simplified current scenario (fast breakdown not included)

Premagnetization: 10 s
Plasma **C**urrent **R**amp-**U**p (**PCRU**): 80 s
Burn: 7200 s
Dwell: 600 s [8]

Point	Time (s)	Conductor current (A)					
		PF1	PF2	PF3	PF4	PF5	PF6
Premag (end)	0	51656	34464	-50416	50125	-51614	50062
SOF	80	44344	-46607	-30476	-16583	-40416	32208
EOF	7280	7250	-52589	-36190	-15167	-46770	21354
Premag (begin)	7880	51656	34464	-50416	50125	-51614	50062

[8] G. Federici, et al., *DEMO Design Activity in Europe: Progress and Updates*, Fus. Eng. Des. 136, Part A (2018) 729-741

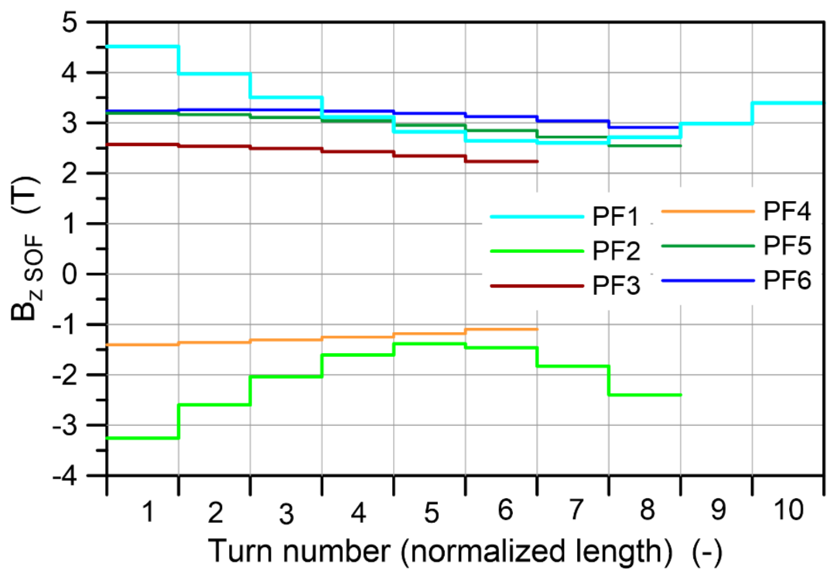
Magnetic field maps

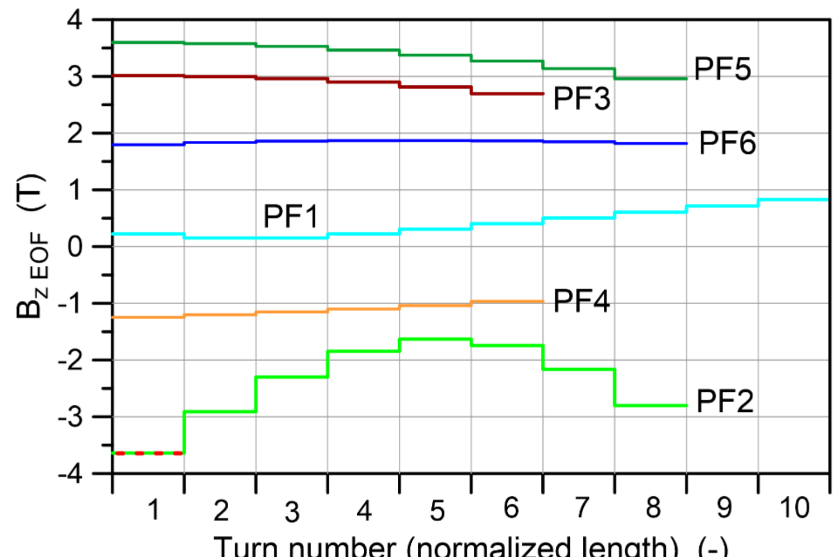


Maximum magnetic field and maximum value of current (and thus minimum T_{cs}) is observed in the Premag phase in PF1, PF3-PF6, and at EOF in PF2.

B_z and operating current change their direction in PF2 and PF4.

MF between Premag, SOF and EOF is obtained by linear interpolation.





Heat loads due to AC losses

- Coupling losses

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

calculated using a trial value $n\tau = 100$ ms

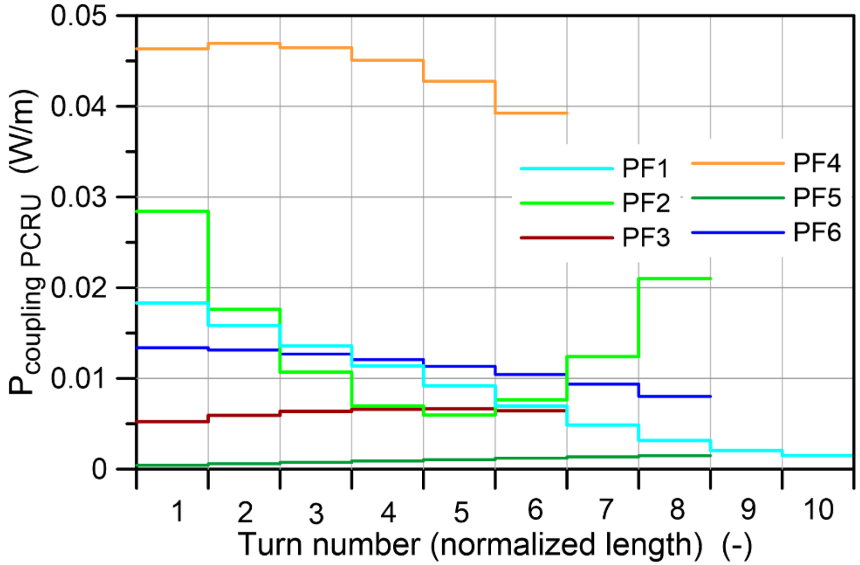
- Hysteresis losses

$$P_{hyst}(x,t) \approx \frac{2}{3\pi} J_c(B_{z\,eff}, T) d_{eff} \left|\frac{\partial B_{z\,eff}(x,t)}{\partial t}\right|$$

where: J_c - critical current density,

$d_{eff} \approx 5$ μm - effective filament diameter

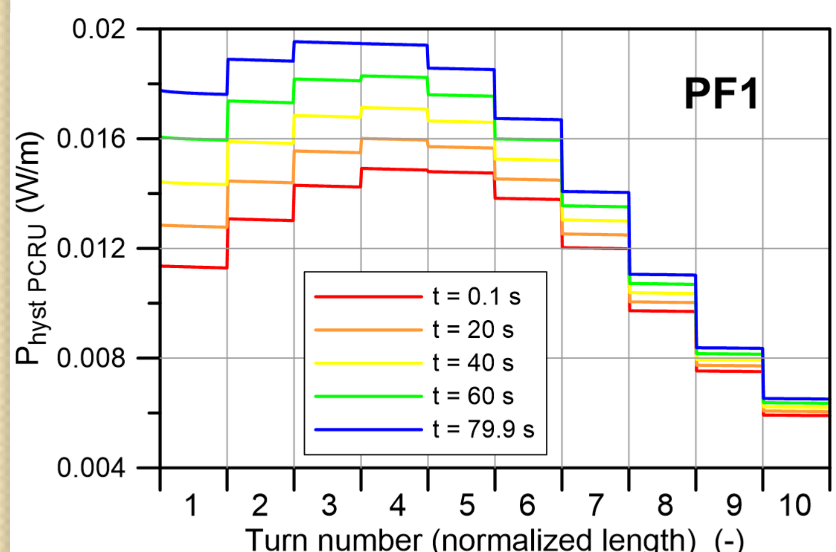
Heat load maps – Plasma Current Ramp-Up

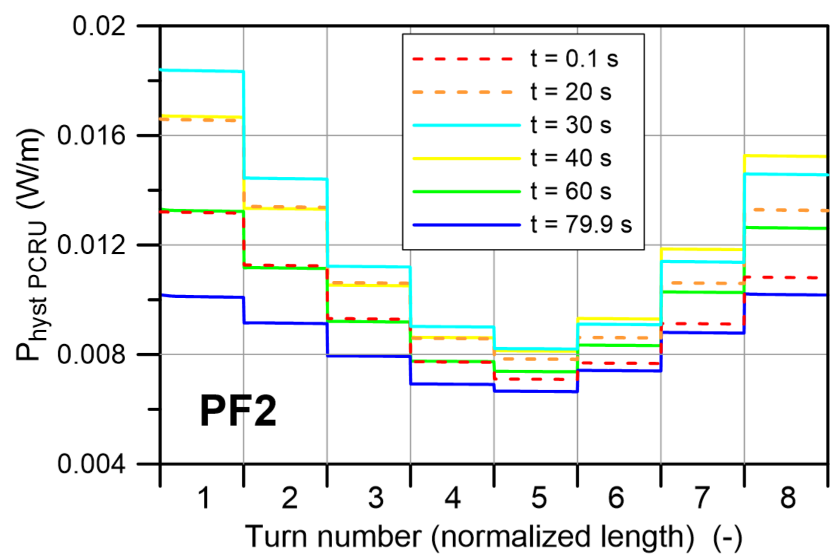


Due to fast variations of MF the PCRU phase features the highest coupling losses.

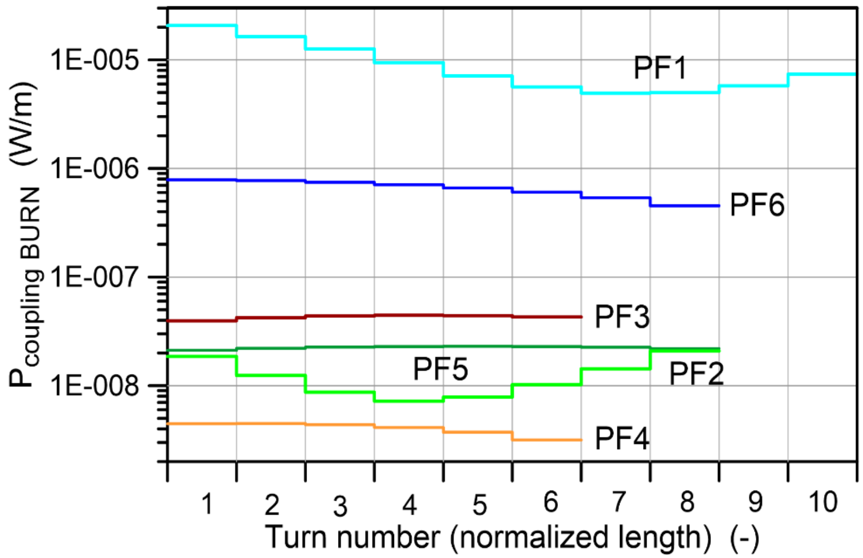
Hysteresis losses are sligthly smaller than coupling losses.

In PF1, PF3, PF5 and PF6 conductors P_{hyst} profile increases with time, which is not the case in PF2 and PF4 conductors.

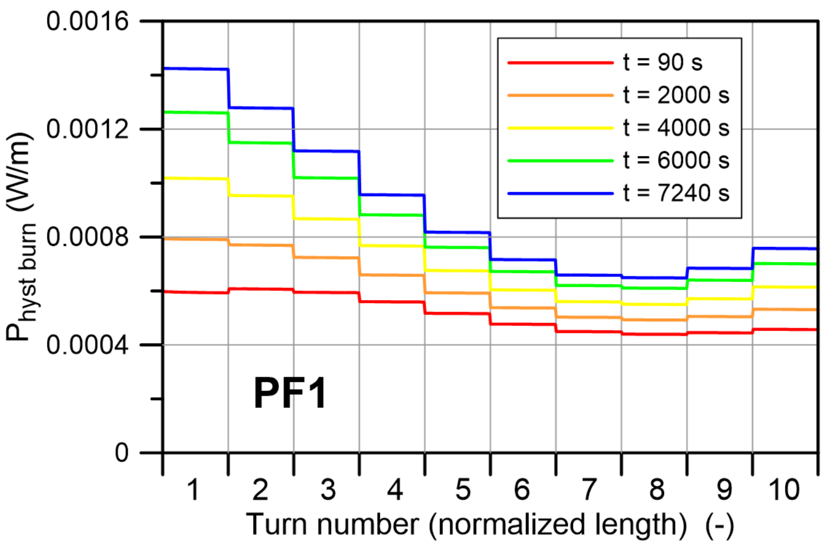


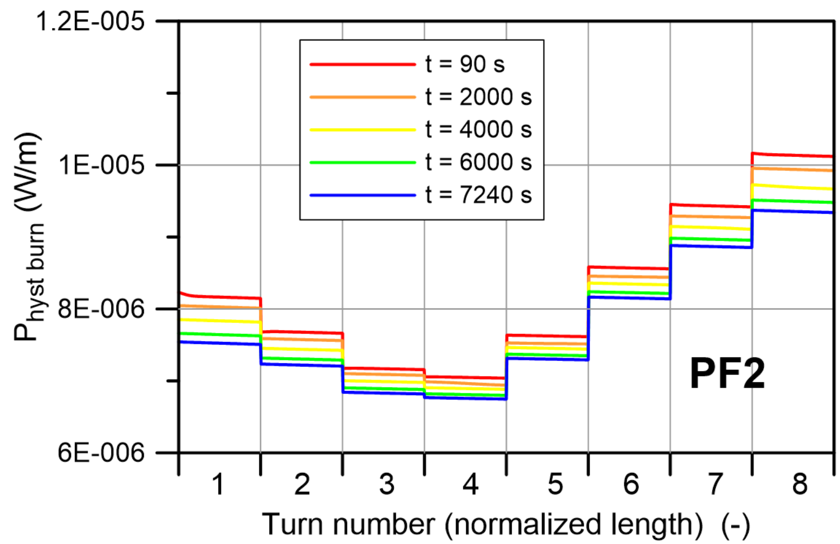


Heat load maps – burn phase

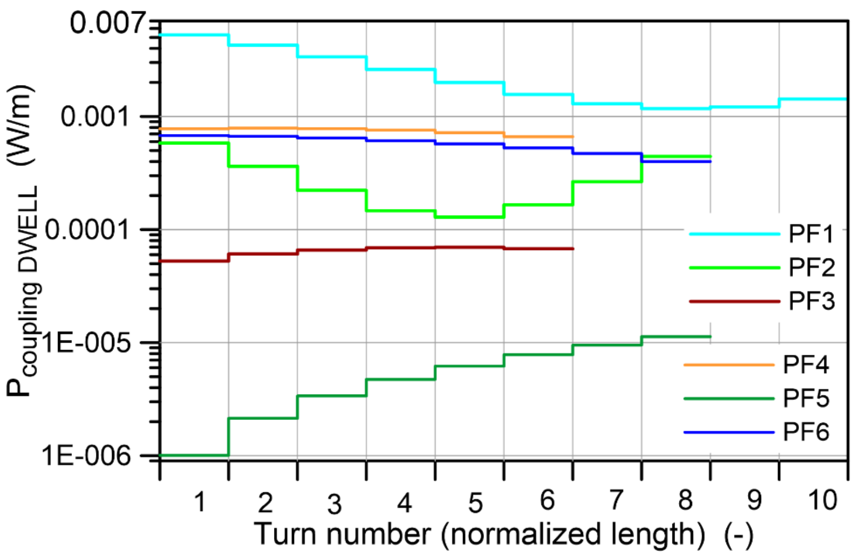


Due to the very slow changes of MF, the coupling losses in the burn phase are negligibly small.
The hysteresis losses may have a small effect on temperature profile only in PF1.



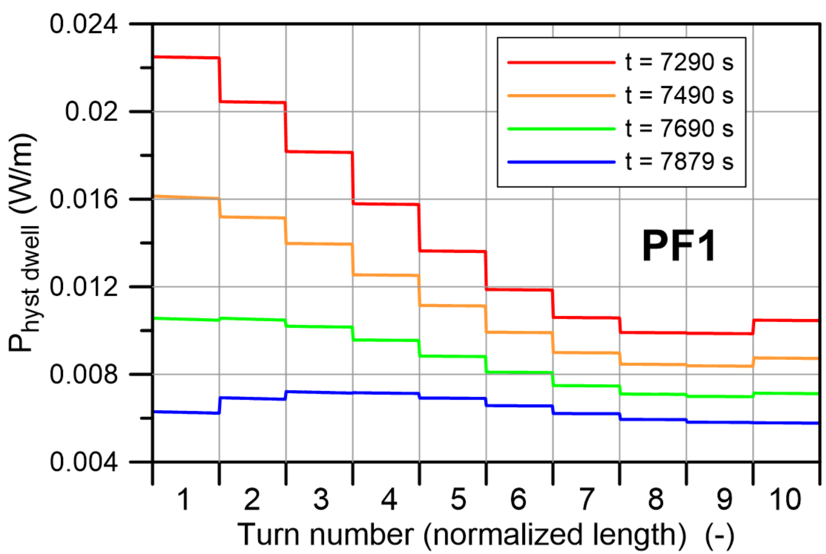


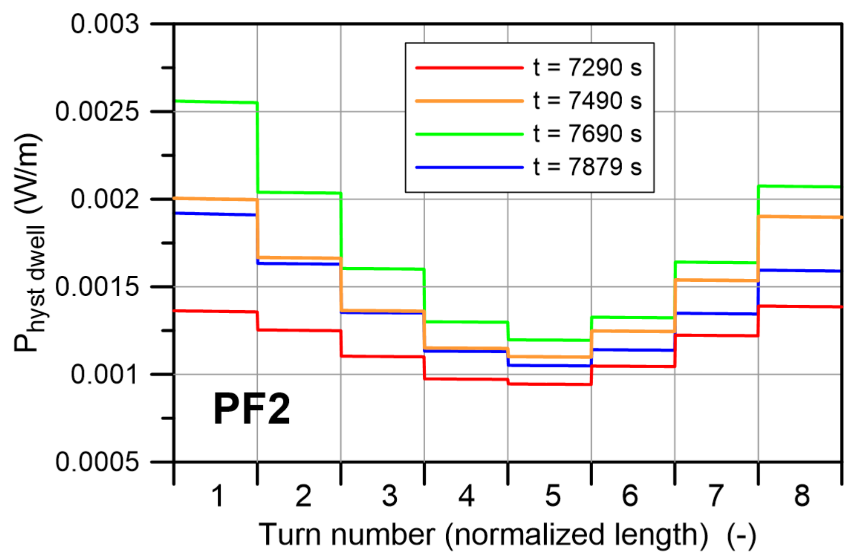
Heat load maps – dwell phase



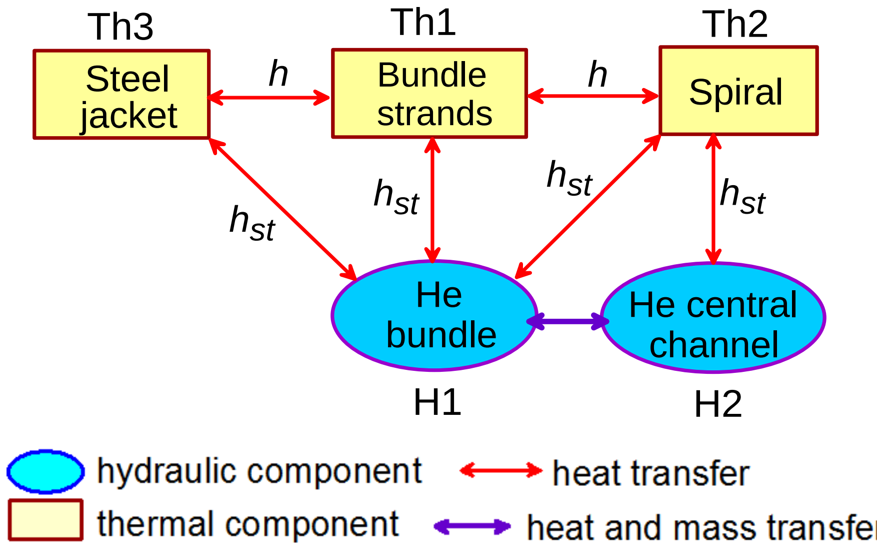
In the dwell phase the coupling losses may have an observable effect on temperature profiles only in PF1, PF4 and PF6.

The hysteresis losses are particularly large in PF1.





THEA [9] model



Conductor components in the THEA model and links between them

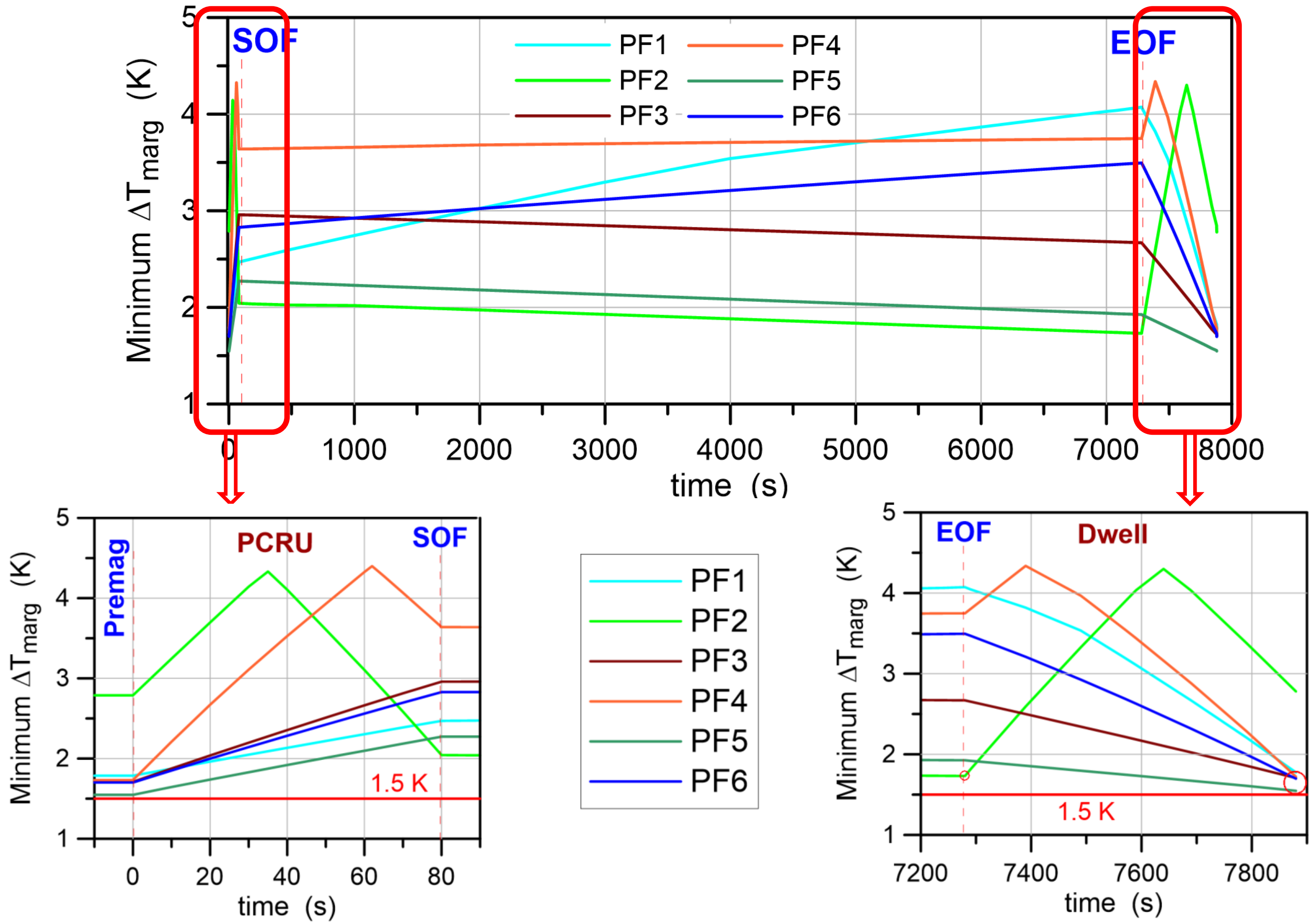
- Full conductor length subjected to the expected MF was simulated.
- Adiabatic and fixed pressure (infinite reservoir) boundary conditions were imposed at both ends of each conductor.
- Coupling between the solid conductor components via thermal resistances R=1/(hp), where h = 500 W/(m^{2}K). Standard smooth tube heat transfer correlations were used for the hydraulic components.
- At first simulations of normal operation during the *Premag* phase were performed, starting from the constant initial conditions: $T(x) = T_{in}$, $p(x) = p_{in}$ until the steady state was reached. The obtained steady state temperature, pressure and mass flow profiles, after validation against the simplified model [10] (SM), were used as the initial conditions for the subsequent simulations of the operation during the whole „4 points" current cycle.

[9] THEA—Thermal, Hydraulic and Electric Analysis of Superconducting Cables. User's Guide Version 2.3, CryoSoft, 2016, https://supermagnet.sourceforge.io/manuals/Thea_2.3.pdf

[10] M. Lewandowska, K. Sedlak, IEEE Trans. Appl. Supercon. 24 2014) 4200305

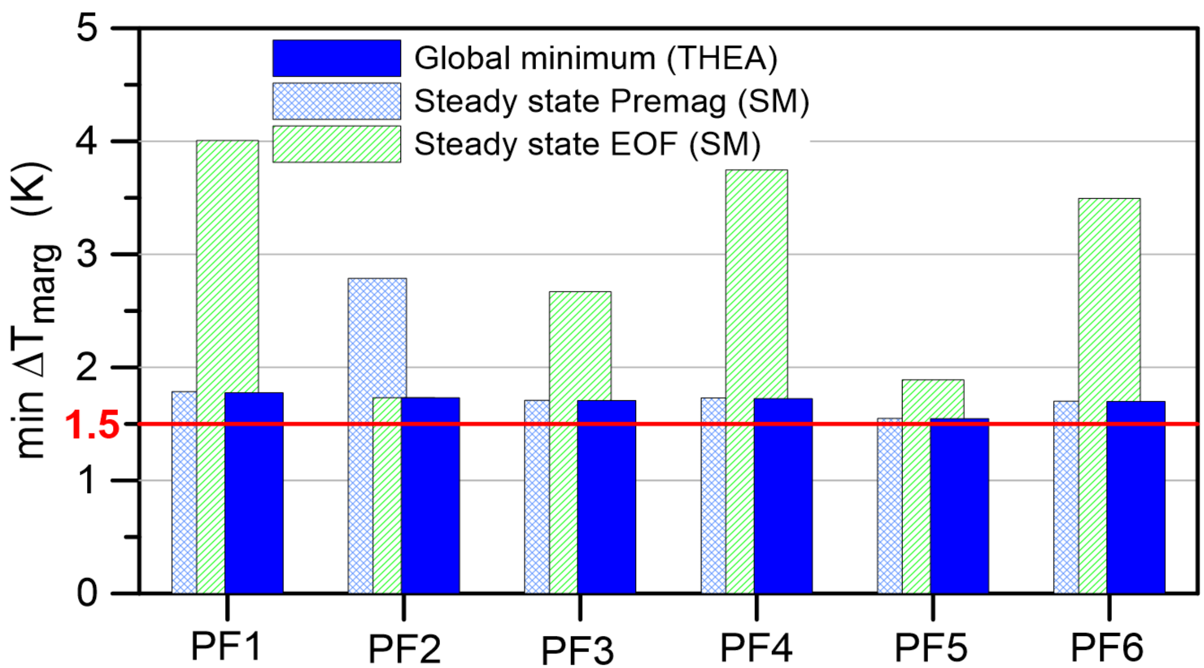
Results – minimum temperature margin evolution

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



Global minimum of ΔT_{marg} is observed in the very last moment of the current cycle (t = 7880 s) in PF1, PF3-PF6 or at EOF in PF2.

Results – global minimum of ΔT_{marg}



- **In all PF conductors the global minimum ΔT_{marg} obtained in our simulations fulfilles the 1.5 K acceptance criterion ☺**
- In PF1, PF3-PF6 the global min ΔT_{marg} observed at the end of current cycle is only slightly smaller than that obtained at the initial steady state corresponding to Premag. This is not the case in PF2, where the minimum T_{cs} observed at EOF is much lower than that in Premag. The ΔT_{marg} evolution is mainly affected by T_{cs} behaviour.

Summary, conclusions and perspectives

- Normal operation of the recent iteration of the NbTi conductors designed by CEA for the 6 EU-DEMO PF coils was simulated using the THEA code by CryoSoft.
- Simplified „4-points" current scenario was considered. Heat loads due to AC coupling losses (characterized by trial value $n\tau$ = 100 ms) and hysteresis losses were taken into account.
- The global minimum of ΔT_{marg} was observed either at the end of the current cycle (in PF1, PF3-PF6) or at EOF (in PF2).
- In all considered PF conductors the global minimum of ΔT_{marg} obtained in our simulations fulfilles the 1.5 K acceptance criterion.
- Simulations of the fast breakdown (in the first second of PCRU) are planned as soon as the actual current evolution for the 2018 EU-DEMO reference will be available.
- Validation (experimental and/or CFD) of predictive capability of the spiral friction factor correlations would be desirable.

Thank you for your attention

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Question Time