[Wed-Mo-Po3.01-06]

CEA Broad Studies on EU DEMO CS and PF Magnet Systems

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Introduction

In the framework of EU design activities in view of fusion demonstration reactor (DEMO), extensive analyses are conducted by a group of EU laboratories to address the magnet system design.

In this regard the DEMO reactor global configuration and its operation conditions were updated in 2018 resulting in a new top-level system features inducing improved performances.

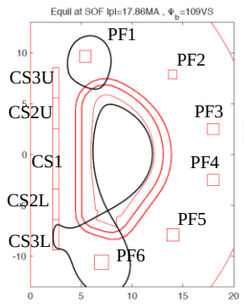
CEA carried out broad studies on both Poloidal Field (PF) coils system and Central Solenoid (CS) to tentatively establish the most appropriate designs and provide an educated evaluation. Former analyses conducted on previous DEMO CS configuration are referred and discussed in support of the present optimization approach methodology.

Together with the resulting CS and PF designs recommendation and perspectives are provided.

PF system design

tools

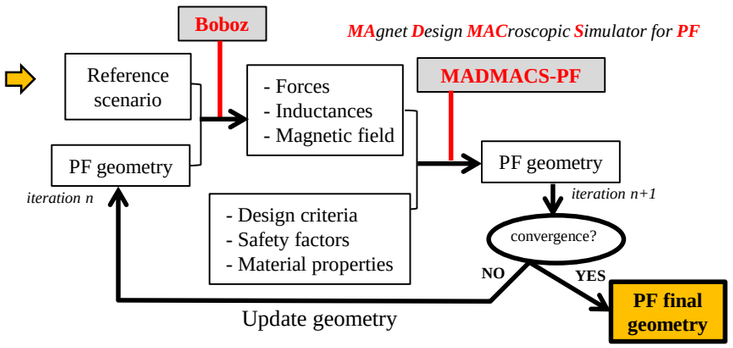
Objective: From a reference scenario database, establish as suitable PF design as optimized as possible



Analysis from CREATE (IT)

NI (MA.T)	PREMAG	SOF	EOF
CS3U	29.11	13.63	-5.94
CS2U	29.11	-1.42	-29.11
CS1	58.23	-9.6	-58.23
CS2L	29.11	-7.17	-29.11
CS3L	28.13	25.14	-12.44
PF1	16.53	14.19	2.32
PF2	3.86	-5.22	-5.89
PF3	-8.47	-5.12	-6.08
PF4	12.03	-3.98	-3.64
PF5	-9.91	-7.76	-8.98
PF6	24.03	15.46	10.25
Plasma	0	17.86	17.86

Plasma reference scenario



Design approach: 1) PF aspect ratio kept close to reference geometry (provided DP length < 1.5 km)
2) PF optimized versus SC amount (for PF1 & PF6)

PF Design results:

ΔT_{MARG} = 1.5 K
T_{OP} = 4.7 K
σ_{HOOP} = 667 MPa
V_{MAX} = 5.5 kV
Current lines positions unchanged
Convergence = both PF sizes vary < 1% across iteration
Pancakes winding

	PF1	PF1 OPTIM	PF2	PF3	PF4	PF5	PF6	PF6 OPTIM
Maximum field (T)	6.536	6.362	4.679	5.050	4.980	5.010	6.556	6.117
Operating current (kA)	51.02	51.66	52.59	50.42	50.13	51.61	50.48	50.06
N SC strands	4966	2747	316	401	377	398	5344	1496
N Cu strands	0	←	665	960	1340	970	0	490
Spiral outer diameter (mm)	12	←	11.5	13.6	15.43	13.7	15.8	←
Jacket thickness (mm)	3.56	4.62	6.79	3.28	2.83	6.09	3.18	4.50
T hotspot (K)	38	62	248	247	249	250	48	250
Number of pancakes	18	32	14	28	40	24	28	60
Number of turns	18	10	8	6	6	8	17	8
WP vertical dimension (m)	1.223	1.798	0.624	1.186	1.815	1.154	1.958	3.067
WP radial dimension (m)	1.189	0.544	0.343	0.244	0.262	0.371	1.157	0.395
Discharge time (s)	15.9	15.7	9.0	24.1	44.5	23.2	44.0	42.3
L (H)	1.710	1.674	0.940	2.624	4.885	2.475	4.789	4.648
Pancake hydraulic length (m)	612.9	339.1	691.0	661.3	661.7	682.9	739.0	350.6
Total SC amount (t)	**192.0** →	**104.5**	10.7	26.0	35.0	22.9	**387.5** →	**110.3**

- Design close to reference can be proposed for all PFs ; high SC amount for PF1 & PF6
- PF1 & and PF6 optimization lead to a saving factor of ~2-3 on the SC amount (total Δ ~ 350 tons NbTi)
- All PFs can be wound on double pancakes (DP) total length < 1.5 km. Optimized PF1&6 can be wound with quadri-pancakes
  - ⇨ A check is made to assess the PF system integration

PF integration check:

PF are positioned around the TF external contour

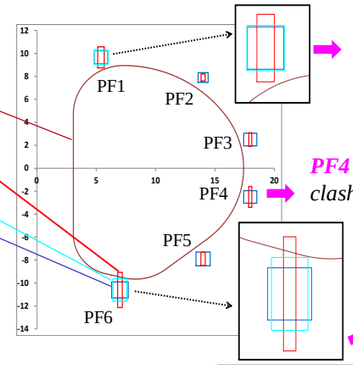
PF optimized

PF design

PF reference

Check assembly consistency

Warnings…



PF1 Low space for clamps

PF4 Possible clash with port

PF6 clash with TF

- PF1 & PF6 (+PF4) could be moved
  - ⇨ *consequence on plasma equilibrium ?*
- PF1 & and PF6 further optimization (switch to Nb_3Sn / subcool)
  - ⇨ *cost impact ?*
- Positive point: PF2~5 can be moved closer to plasma
  - ⇨ *enhanced plasma control ?*

➔ DEMO 2018 PF design to be further conducted in a system-scale loop

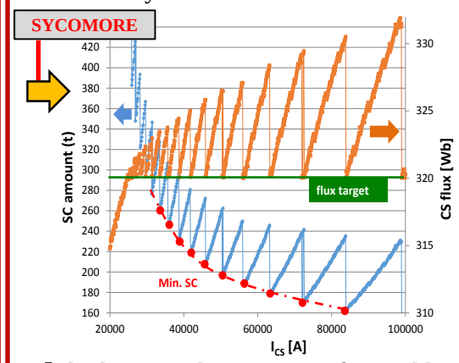
CS broad studies

tools

DEMO 2015 CS: assess the sensitivity of CS design to selected inputs

- sensitivity to **conductor current**

SYCOMORE

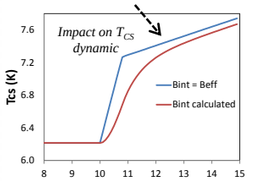


➔ high CS conductor current favourable

- sensitivity to **nτ** & plasma **Break-Down time** (T_{BD})

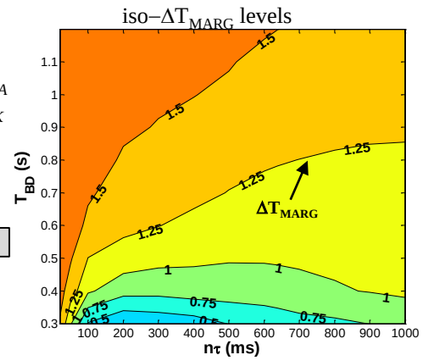
$$\begin{cases} B_{int} + \tau \dot{B}_{int} = \dot{B}_{ext} \\ P = \frac{n\tau}{\mu_0} \dot{B}_{int}^{\,2} \end{cases}$$

$\Delta T_{MARG} = T_{CS}(B_{int}) - T_{OP}(P, T_{BD})$



ΔI_{CS}=6 kA
T_{IN}=4.5 K

THEA



➔ BD check may drive plasma scenarios
➔ Check to be applied to CS designs

DEMO 2018 CS: establish the updated CS design & BD study

- Establish **CS design**
  - CS R_{EXT} consistent with TF WP#3 reference design
  - Target flux at plasma center = 305 Wb (ref scenario)

MADMACS-CS

Boboz

ΔT_{MARG}=1.5 K
T_{OP}= 4.7 K
σ_{HOOP}=667 MPa
V_{MAX}=10 kV

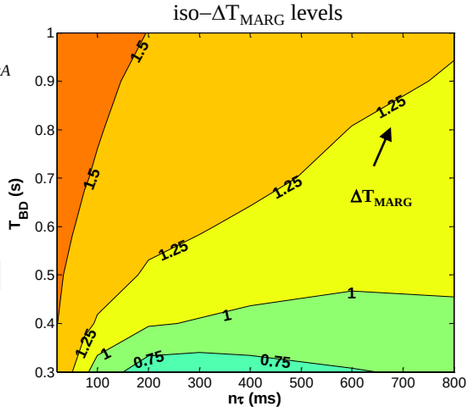
DEMO 2018 CS DESIGN	
Conductor current (kA)	98
# of SC strands	2215
# of Cu strands	0
$T_{HOTSPOT}$ (K)	233.5
Jacket thickness (mm)	17.60
cable size (mm)	43.68
# of turns	11
# of pancakes (total in CS)	214
# pck small / central module	34 / 78
B_{MAX} on conductor (T)	15.67
Central module L (H)	1.56
T_{DELAY} / $T_{DISCHARGE}$ (s)	3 / 7.7
$\Psi_{CS\ PLASMA}$ (Wb)	356.6
SC amount (t)	386.4

➔ Compliant CS design (overperforming Ψ_{CS})
➔ Excess of SC amount suspected (low hotspot T)

- Confront with **BD parametric check**

ΔI_{CS}=11 kA
T_{IN}=4.5 K

THEA



➔ In first plasma studies T_{BD} ~ 0.8 s > acceptable margin
➔ Better CS safety margin than for DEMO 2015

➔ **DEMO 2018 CS design is established and appears robust**. BD features could induce further 2nd order optimization.

Conclusions - perspectives

- DEMO 2018 PF system design was conducted, fairly compliant but some warning on integration highlight need of system-scale approach including e.g. plasma considerations.
- Parametric studies on DEMO 2015 CS, guided inputs choice (►high I_{CS}) and transient check (► BD time vs. cable nτ)
- DEMO 2018 CS design was established and found robust at pre-dimensioning stage.
- DEMO 2018 CS design parametric check versus BD showed safety considerations in transient operation.

perspectives ➔ ***stabilize PF design with system-scale considerations (plasma, assembly…)***
➔ ***conduct detailed analyses (mechanical & thermo-hydraulics) on both PF & CS systems***