Version 2.0: 26 February 2008

Plasma equilibrium operational space during burn in 15MA scenario: Baseline 2001 vs. Baseline 2008

The work reported in this memo is investigation of operational space in terms of parameters [l_i(3), I_{CS1}], [l_i(3), Ψ_{axis}], [l_i(3), <Ψ>], [l_i(3), I_{PF6}] and [l_i(3), B_{PF6}] for ITER plasma equiliblium during the phase of driven burn in 15 MA inductive scenario. Here I_{CS1} is the current in one turn of the CS1 modules, I_{PF6} is the current in one turn of the PF6 coil, B_{PF6} is the maximum field on the PF6, Ψ_{axis} is the flux of total poloidal magnetic field on the magnetic axis and <Ψ> is the value of magnetic flux from the CS and PF coils (Ψ_{coils}) averaged over the plasma cross section:

$$\langle\Psi\rangle = \frac{1}{I_p}\int_{Sp} j_p \Psi_{coils} dS_p$$, where j_p is the density of plasma toroidal current.

1. Plasma equilibrium calculations

For the range of l_i (3) [0.6, 0.86], plasma equilibria were calculated with the code TOSCA [1] using as input profiles of plasma toroidal current obtained in ASTRA simulations of burning plasmas with the reference separatrix and $\beta_N \approx 1.85$ [2]. Plasma equilibria for l_i (3) = 1.0 and 1.2 were calculated with the toroidal current profile function in TOSCA code.

The limits imposed on the CS and PF coils currents, magnetic fields, vertical forces acting on the CS modules and the requirements on separatrix positioning are given in [3] (see Appendix).

The following two 15 MA magnetic configurations were calculated for each value of l_i (3).
Configuration with maximum current in CS1: the end of burn (EOB) magnetic configuration, when current in one of the CS1 modules or magnetic field on a module strikes the limit value.
Configuration with minimum current in CS1: the magnetic configuration with minimum value of current in the CS1 module (minimum in the sense of absolute value, because the current is negative, i.e. opposite to the plasma current).

2. Results

Figs. 1, 2, 3, 4 and 5 show the dependencies of $<\Psi>$, Ψ_{axis}, I_{CS1}, I_{PF6}, and B_{PF6} (defined above) as functions of $l_i(3)$. Here we compared three cases:

(1) The PF6 Baseline 2001 and the Divertor Baseline 2001 (**black** lines),

(2) The PF6 Option 3 and the Divertor Baseline 2001 (**blue** lines),

(3) The PF6 Option 3 and the Divertor Baseline 2008 (**green** lines),

(4) The PF6 Baseline 2008 and the Divertor Baseline 2008 (**red** lines).

Comparison of the plasma equilibrium operating windows in the space $<\Psi>$ - $l_i(3)$ obtained with the PF system and the divertor as they were in the baseline design 2001 with those obtained for the baseline design 2008 is shown in Fig. 6. **Black** lines correspond to the coils and divertor designed in 2001, **red** solid lines correspond to those proposed in 2008.

Figs 7 - 14 show the plasma boundaries for each value of l_i (3).

The plasma boundaries corresponding to the magnetic configuration with maximum current in CS1 are shown in Fig. 7 (the case of (1) mentioned above), Fig. 9 (the case of (2) mentioned above), Fig. 11 (the case of (3) mentioned above) and Fig. 13 (the case of (4) mentioned above).

The plasma boundaries corresponding to the magnetic configuration with minimum current in CS1 are shown in Fig. 8 (the case of (1) mentioned above), Fig. 10 (the case of (2) mentioned above), Fig. 12 (the case of (3) mentioned above) and Fig. 14 (the case of (4) mentioned above).

Some parameters characterizing of these plasmas are summarized in the attached EXCEL Workbook "***Operating space 15MA-Tables.xls***" (see pages "***PF6(2001)&Div(2001)***", "***PF6(Op.3)&Div(2001)***", "***PF6(Op.3)&Div(2008)"*** and "***PF6(2008)&Div(2008)***").

The EQDSK files are stored in the folder "***Operating space 15MA-EQDSK***". (Please note that positive sign of the plasma current in this files corresponds to the anticlockwise direction of the current, if look from the top of machine.)

The KeleidaGraph data are stored in the folder "***Operating space 15MA-KeleidaGraph***".

References

[1] H.Fujieda, “Task final report – Physics Tasks to JAERI for 2005”, N19TD12FJ, 30 March 2006.

[2] Y.Gribov, A.Polevoi, Plasma equilibrium operational space during burn in 15MA scenario, Issue 1: 6 March 2008.

[3] Y.Gribov, N.Mitchell, C.Jong, F.Simon, A.Loarte, CS and PF coils data and requirements to separatrix positioning for analysis of ITER plasma equilibria and poloidal field scenarios, ITER_D_2ACJT3, Version 2.0: 22 July 2008.

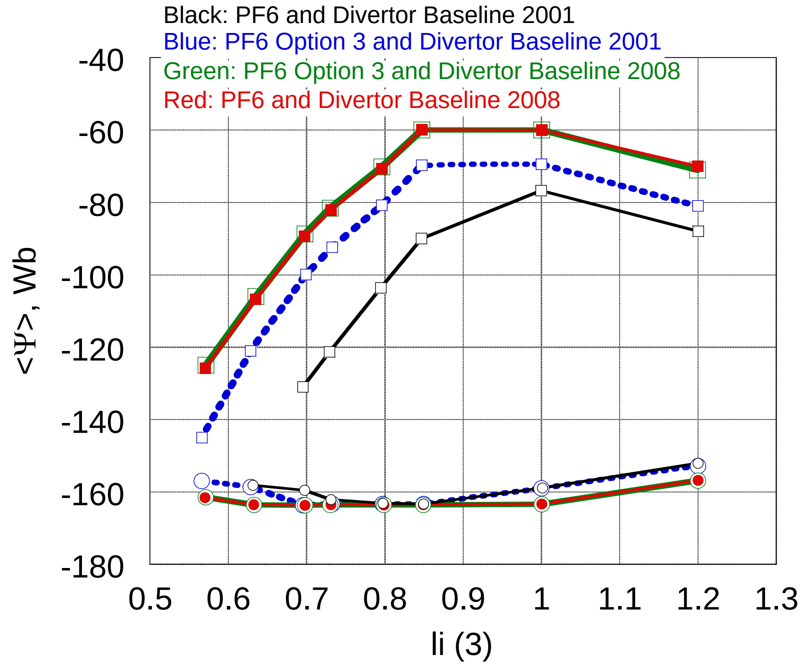


Fig.1

Dependence of $l_i(3)$ and $<\Psi>$

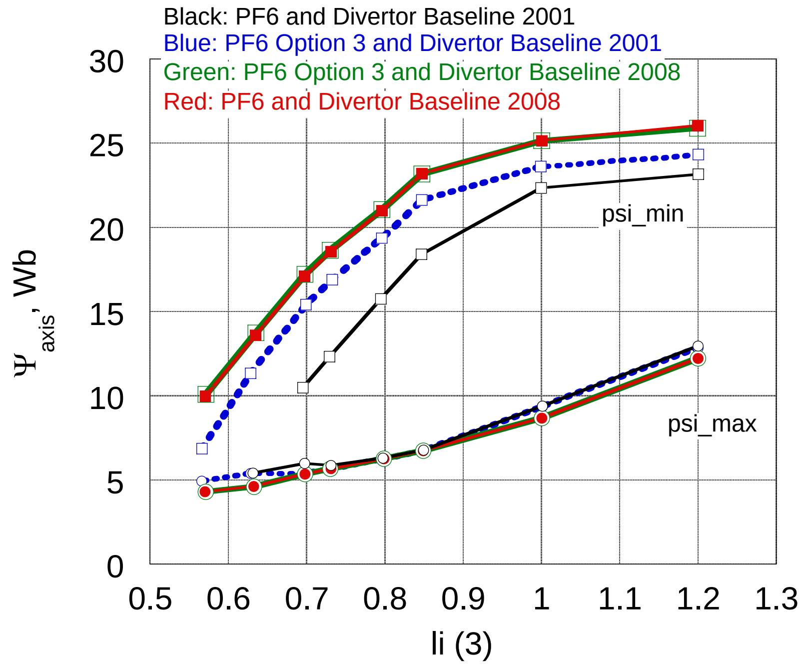


Fig. 2

Dependence of $l_i(3)$ and Ψ_{axis}

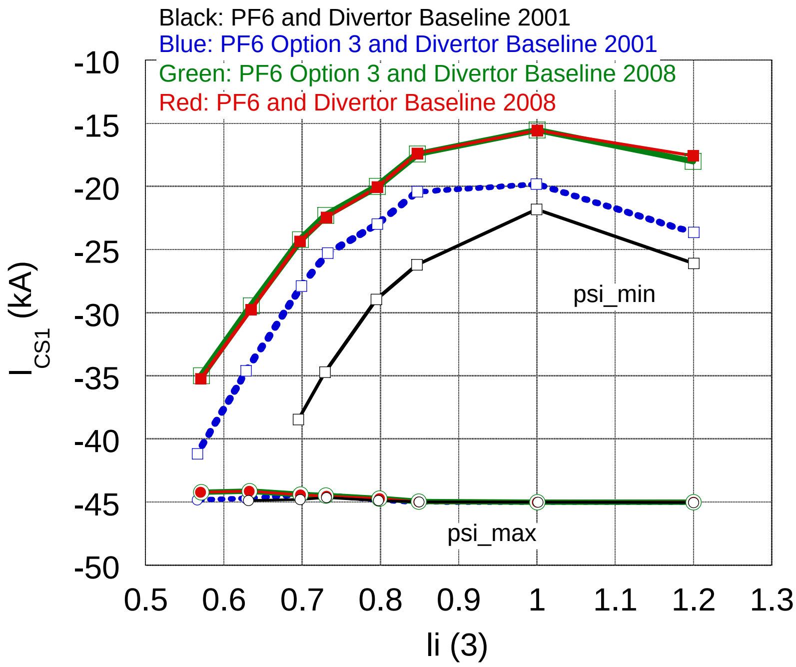


Fig. 3
Dependence of $l_i(3)$ and I_{CS1}

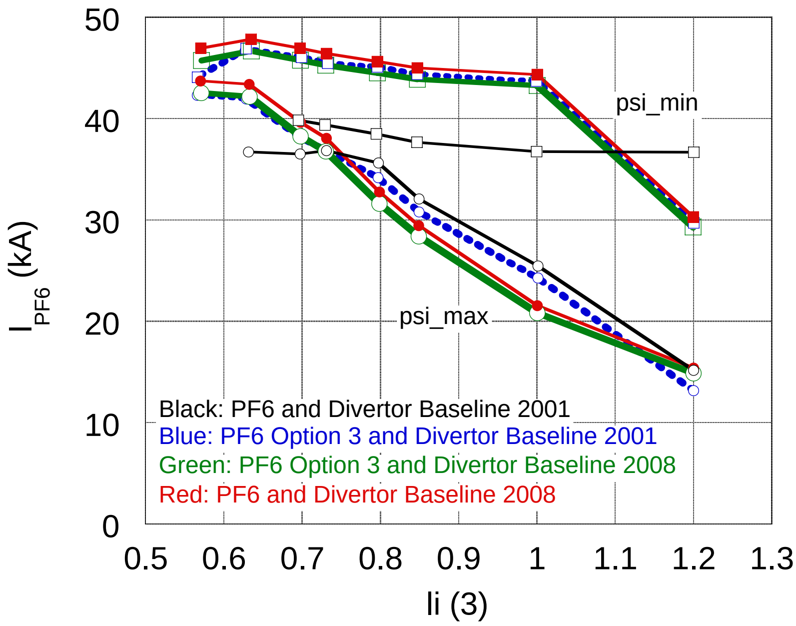


Fig. 4
Dependence of $l_i(3)$ and I_{PF6}

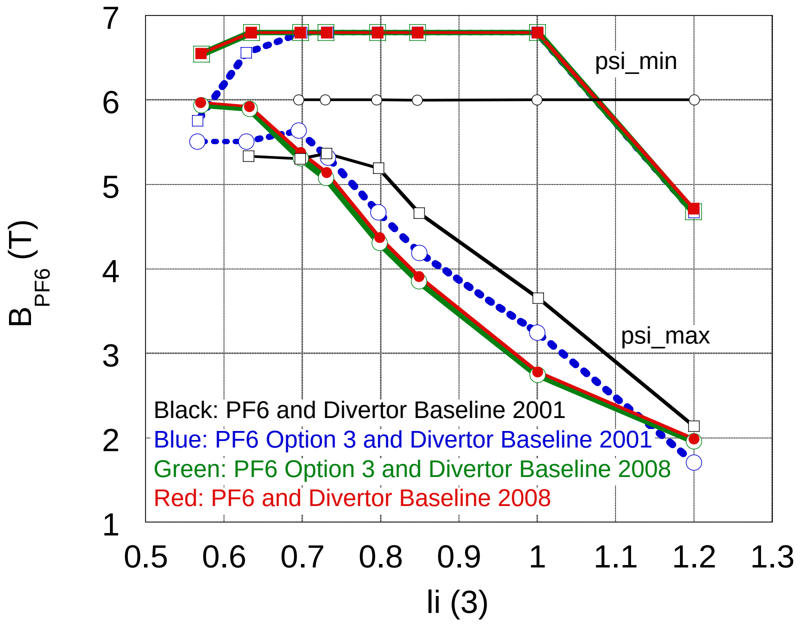


Fig. 5
Dependence of $l_i(3)$ and B_{PF6}

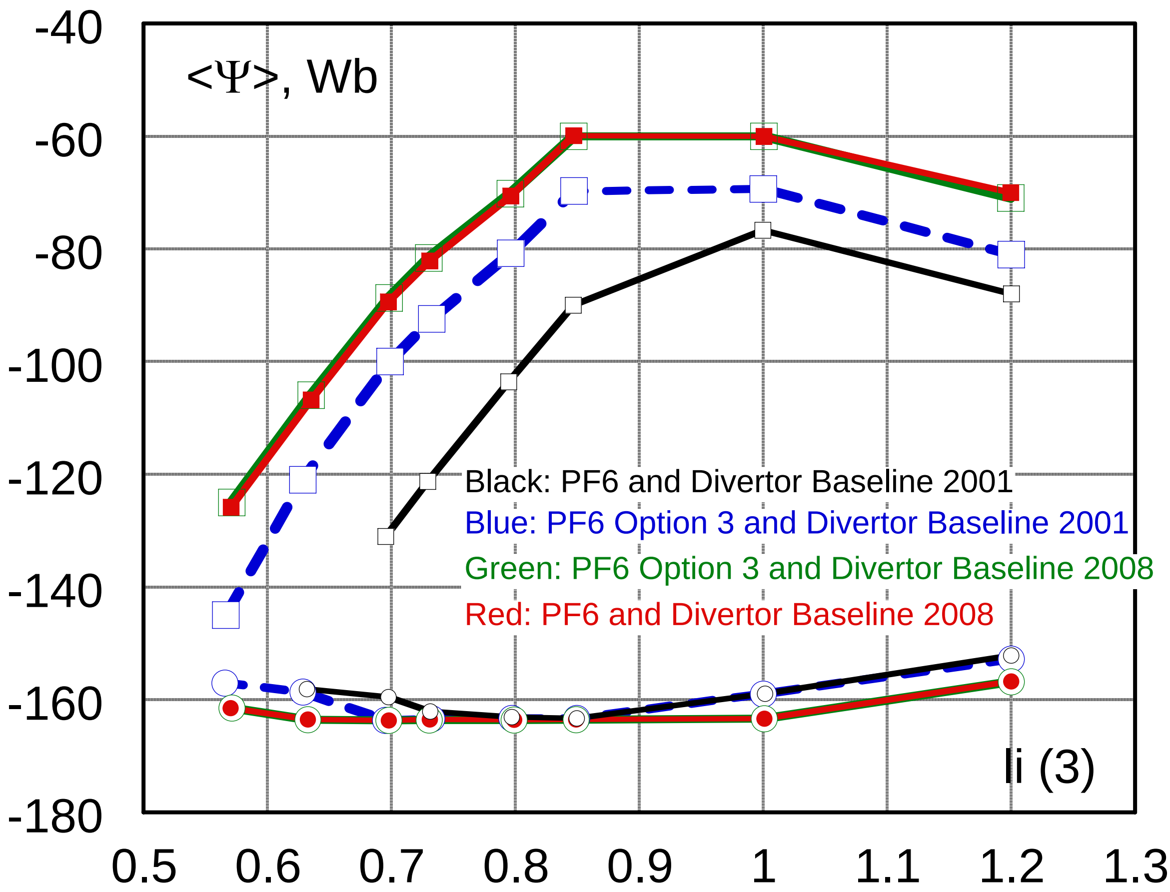
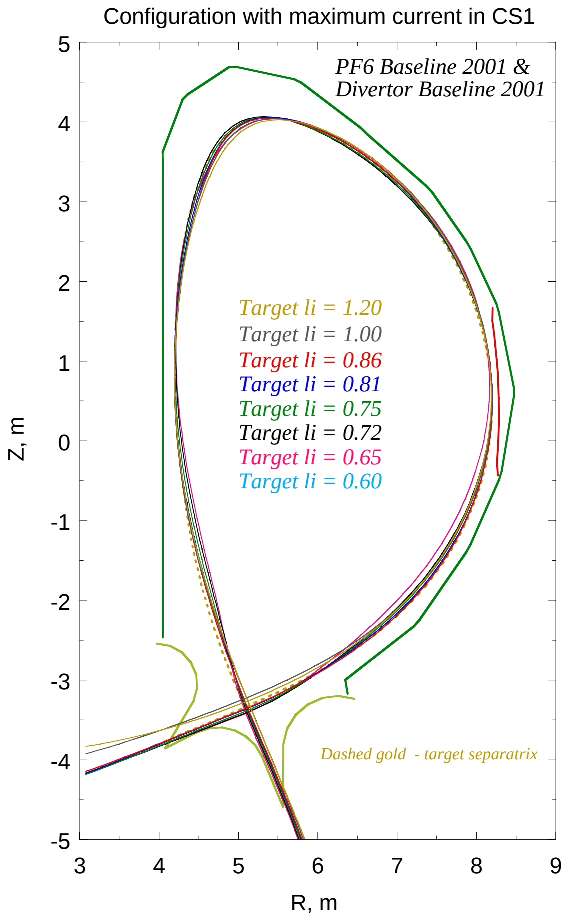


Fig. 6
Dependence of $l_i(3)$ and $<\Psi>$



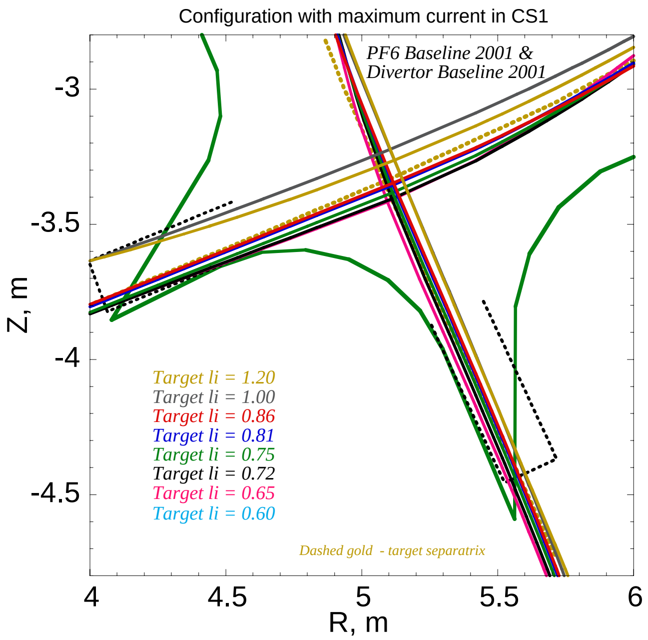


Fig. 7
Plasma boundaries for each value of l_i (3) with the maximum current in CS1
(for the PF6 Baseline 2001 and the Divertor Baseline 2001)

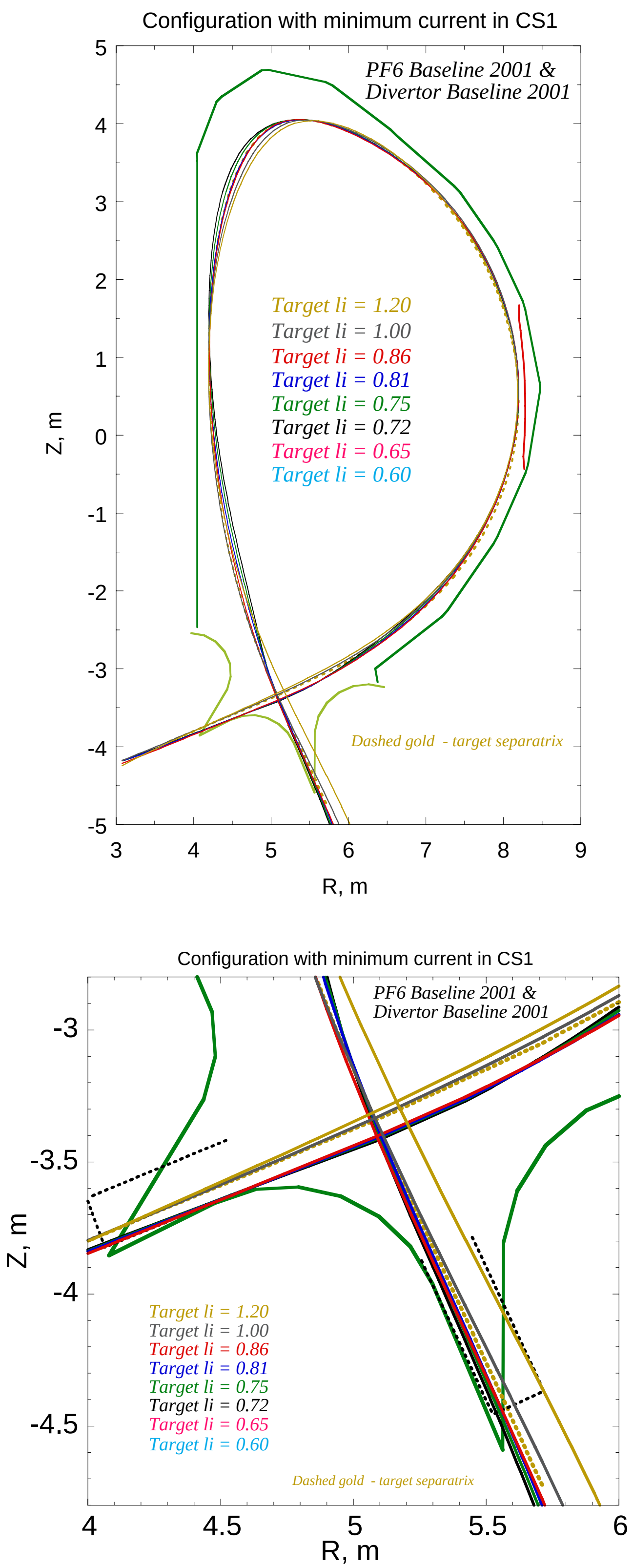


Fig. 8
Plasma boundaries for each value of l_i (3) with the minimum current in CS1
(for the PF6 Baseline 2001 and the Divertor Baseline 2001)

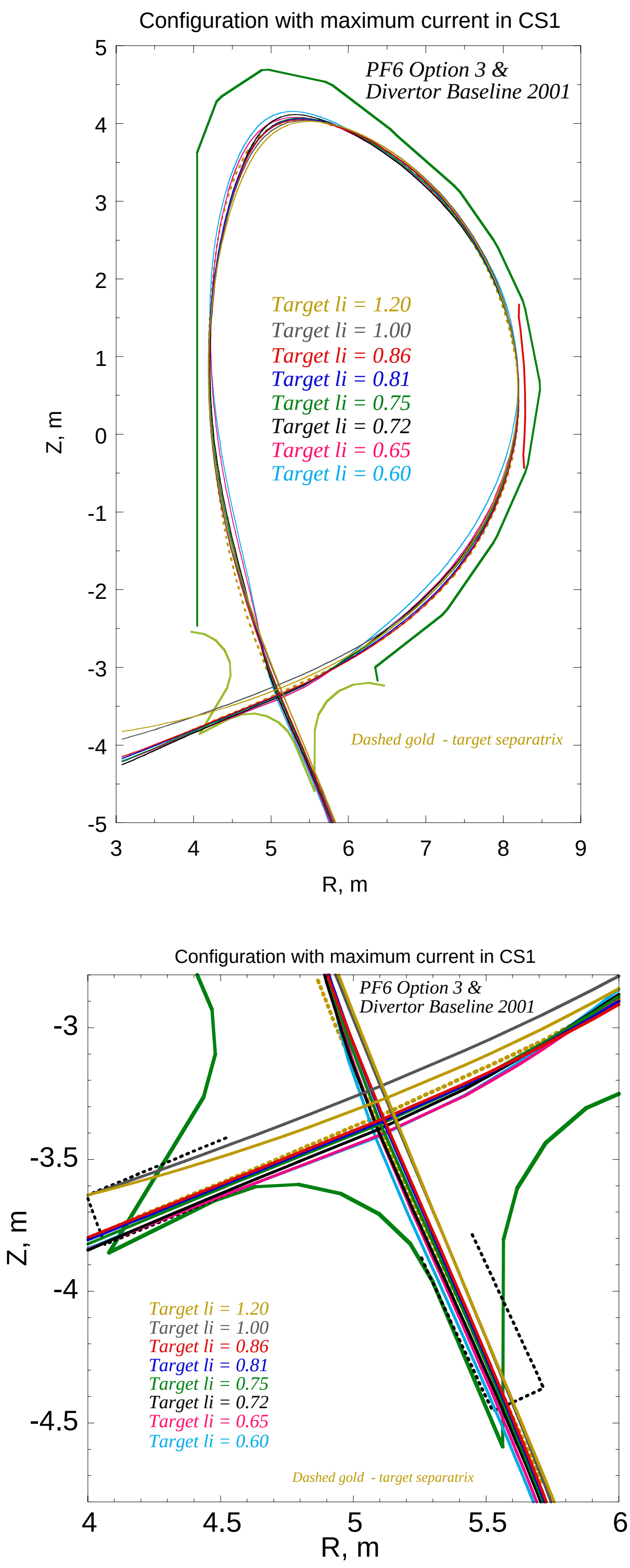
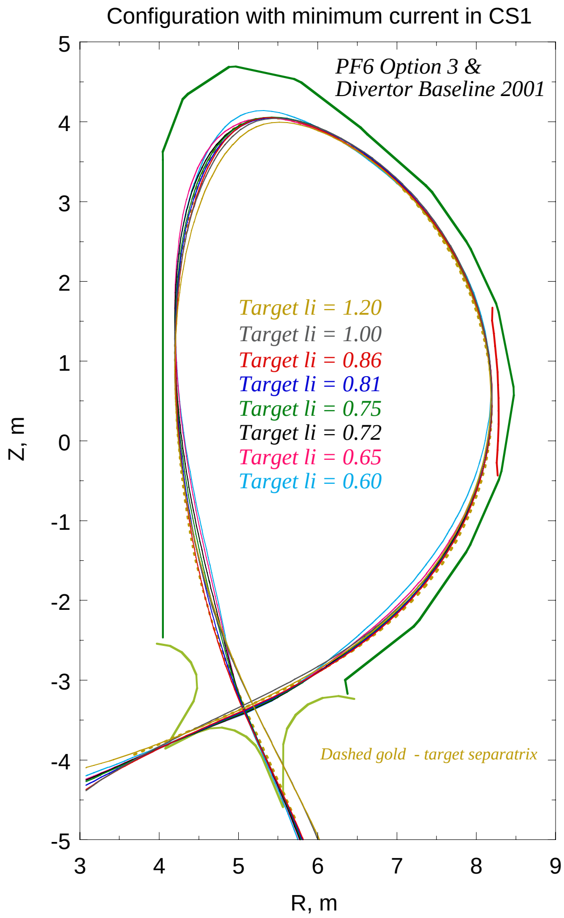


Fig. 9
Plasma boundaries for each value of l_i (3) with the maximum current in CS1
(for the PF6 Option 3 and the Divertor Baseline 2001)



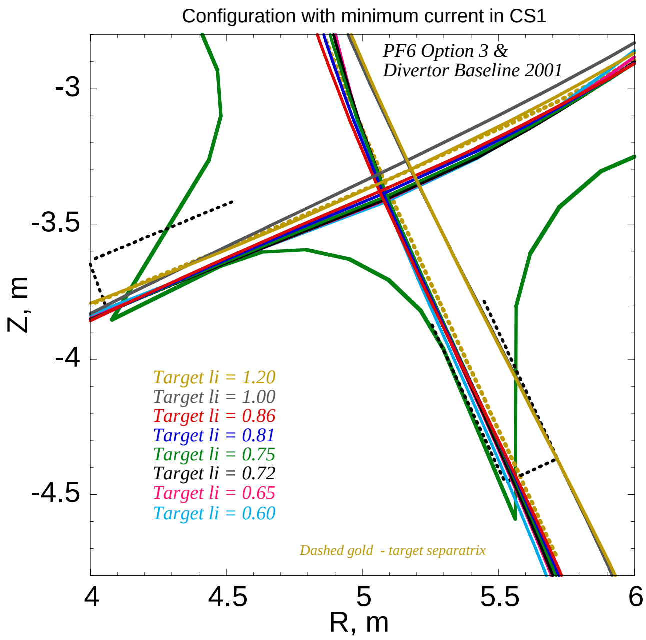
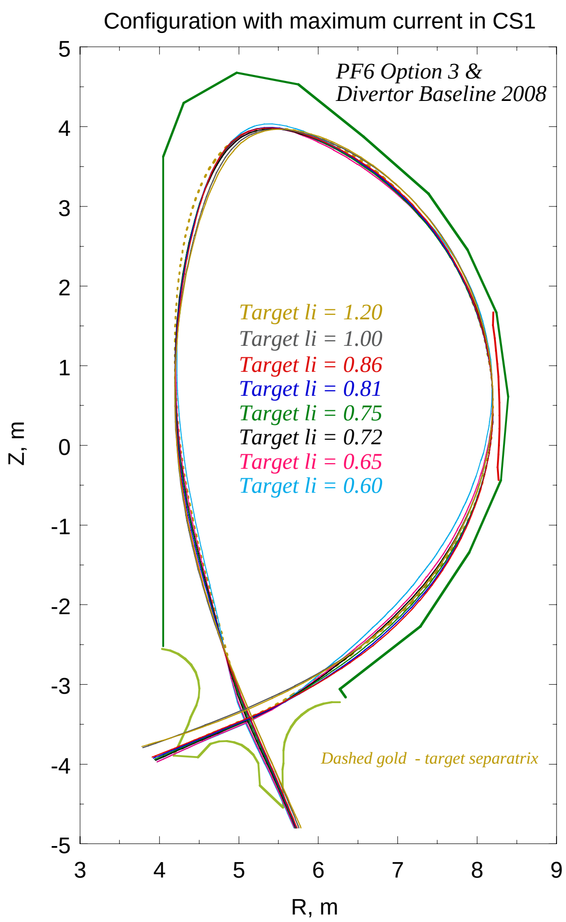


Fig. 10
Plasma boundaries for each value of l_i (3) with the minimum current in CS1
(for the PF6 Option 3 and the Divertor Baseline 2001)



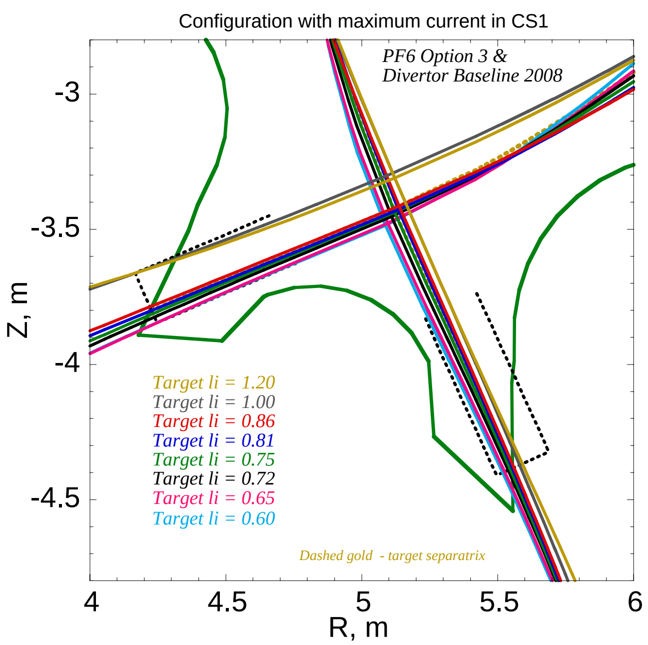
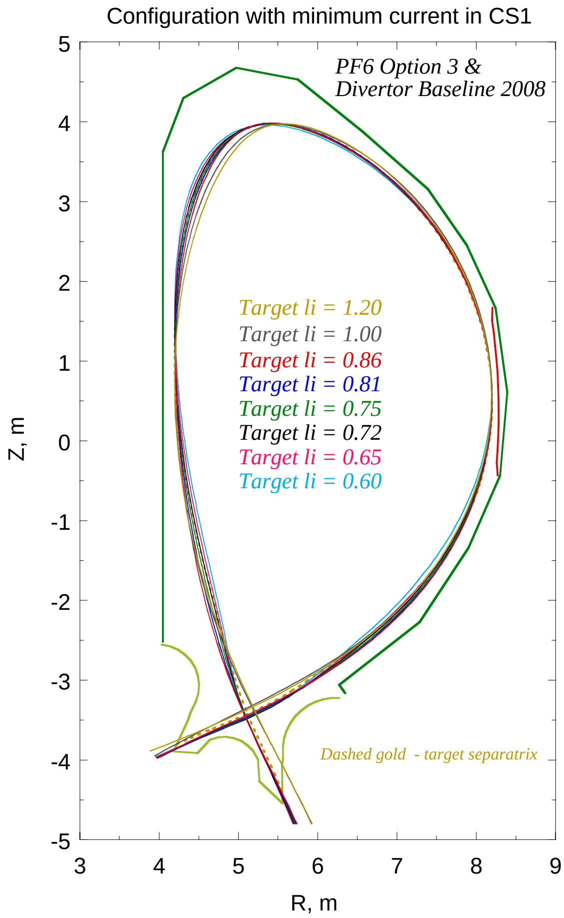


Fig. 11
Plasma boundaries for each value of l_i (3) with the maximum current in CS1
(for the PF6 Option 3 and the Divertor Baseline 2008)



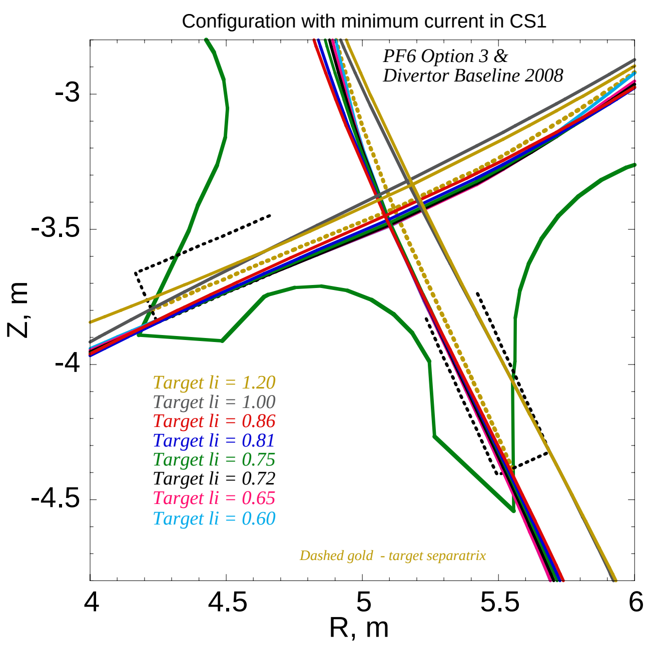
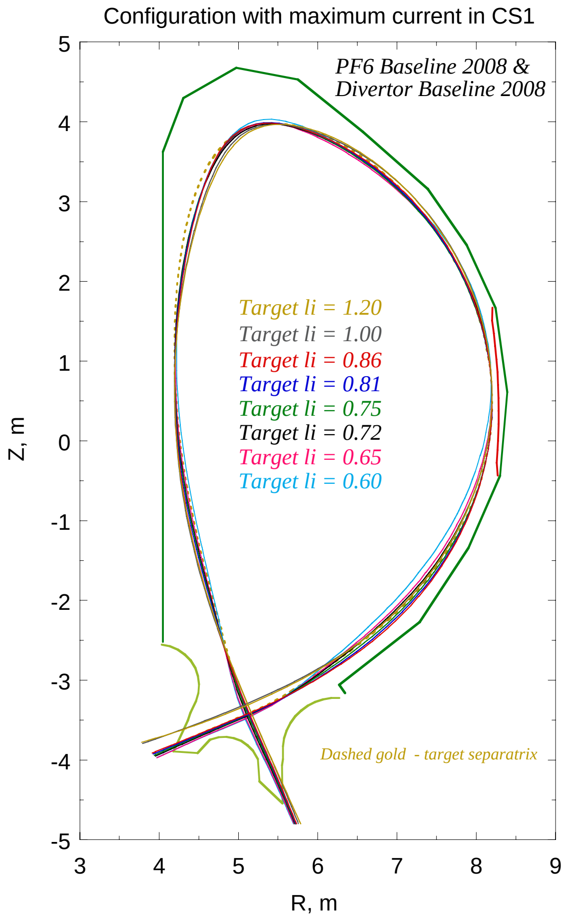


Fig. 12
Plasma boundaries for each value of l_i (3) with the minimum current in CS1
(for the PF6 Option 3 and the Divertor Baseline 2008)



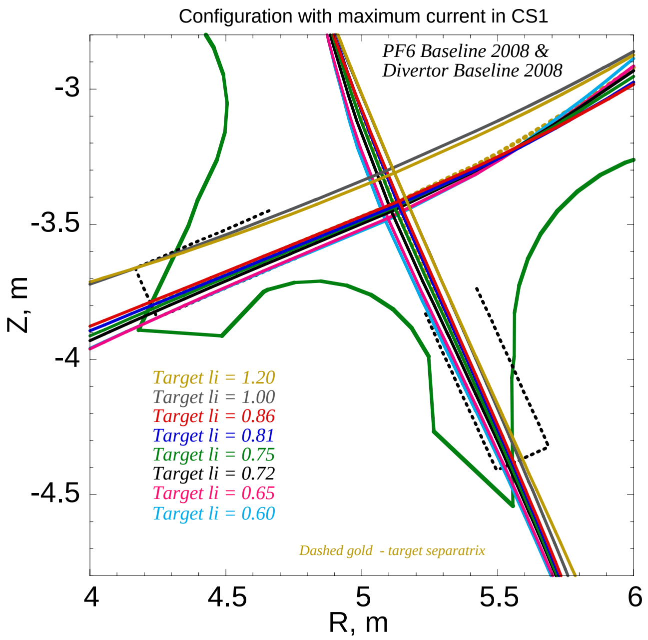
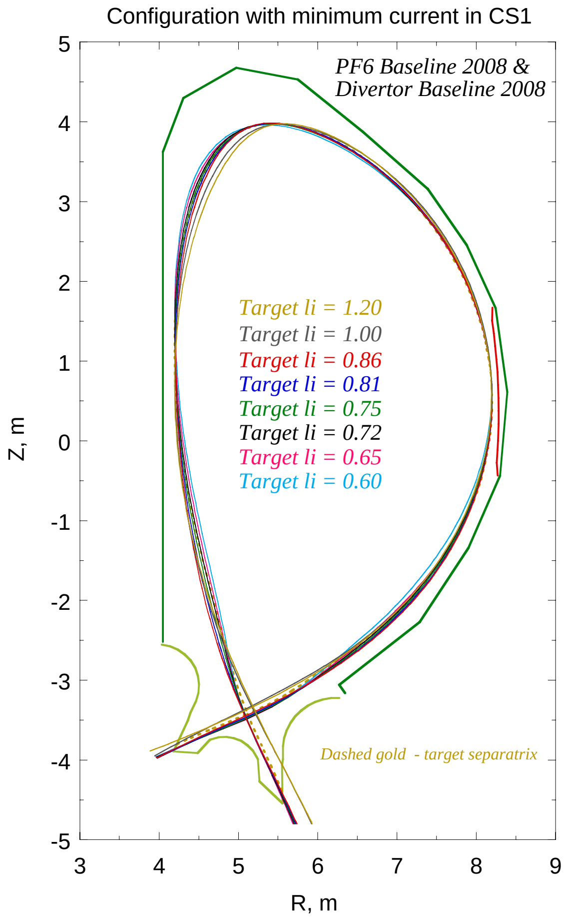


Fig. 13
Plasma boundaries for each value of l_i (3) with the maximum current in CS1
(for the PF6 Baseline 2008 and the Divertor Baseline 2008)



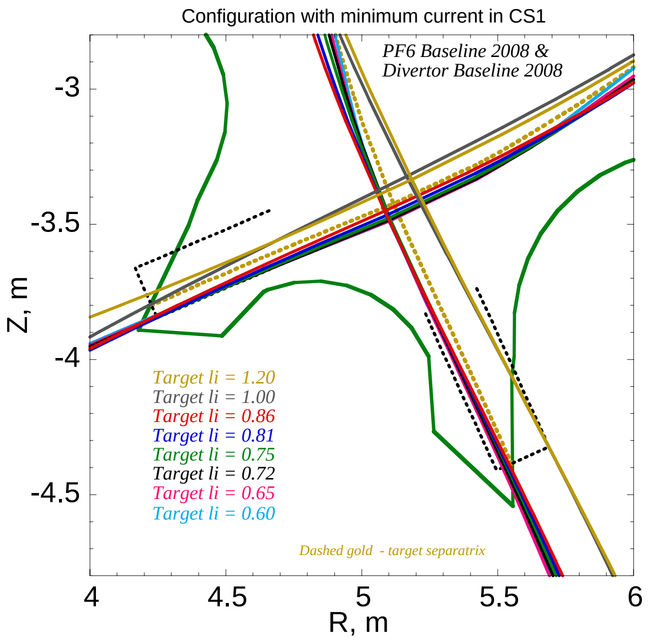


Fig. 14
Plasma boundaries for each value of l_i (3) with the minimum current in CS1
(for the PF6 Baseline 2008 and the Divertor Baseline 2008)

ATTACHMENT

CS and PF coils data and requirements to separatrix positioning for analysis of ITER plasma equilibria and poloidal field scenarios

Y.Gribov, N.Mitchell, C.Jong, F.Simon, A.Loarte
ITER Organization

Version 2.0: 22 July 2008

The memo describes CS and PF coils data and requirements to separatrix positioning for analysis of ITER plasma equilibria and poloidal field scenarios in the approximation of plasma equilibrium snapshots.

1. CS and PF coils

Coil location, size and number of turns

The CS and PF coils position (*R*, Z co-ordinates of the conductor cross section centre), the size of coil conductor cross sections (ΔR, ΔZ) and the number of turns (*N*) are given in Table 1. These data are given at the operating temperature in the system of co-ordinate with Z = 0 corresponding to the middle plane of the CS.

Table 1

Location of the CS and PF coils (*R*, *Z* co-ordinates of the cross section centre), their sizes (ΔR, ΔZ) and number of turns (*N*) (4K without ground insulation)

Coil	*R*, m	*Z*, m	ΔR, m	ΔZ, m	*N*
CS3U	1.722	5.313	0.719	2.075	548
CS2U	1.722	3.188	0.719	2.075	548
CS1U	1.722	1.063	0.719	2.075	548
CS1L	1.722	-1.063	0.719	2.075	548
CS2L	1.722	-3.188	0.719	2.075	548
CS3L	1.722	-5.313	0.719	2.075	548
PF1	3.9431	7.5637	0.959	0.9841	248.6
PF2	8.2847	6.5298	0.5801	0.7146	115.2
PF3	11.9923	3.2652	0.6963	0.9538	185.9
PF4	11.9628	-2.2436	0.6382	0.9538	169.9
PF5	8.3910	-6.7365	0.8125	0.9538	216.8
PF6 (Baseline 2001)	4.2632	-7.5643	1.6191	0.9841	424.4
PF6 (Option 3)	4.3132	-7.4760	1.6191	1.1075	477.4
PF6 (Baseline 2008)	4.3340	-7.4760	1.5590	1.1075	459.4

The table has three variants of the coil PF6 used in studies of plasma equilibria and poloidal field scenarios. The **PF6 Baseline 2001** was used since the ITER Final Design Report 2001 till the ITER Design Review 2006-2007. The **PF6 Option 3**, proposed during ITER Design Review 2006-2007, is the coil shifted closer to the X-point with an additional double pancake. The **PF6**

Baseline is modification of PF6 Option 3 better fitting the space and mechanical constraints[1]. This variant of PF6, which will be adopted as the baseline in 25 July 2008, should be used in studies of plasma equilibria and poloidal field scenarios.

Limits on coil currents and magnetic fields

The maximum values of current the PF coils and the maximum values of magnetic field on them are given in Table 2. The pairs of values define a limit line for the coil that may be extrapolated outside the range defined by the points.

Table 2

Maximum currents in one turn of the CS and PF coils and maximum values of the magnetic field on the coils

Coil	I_{max}	B_{max}
CS3U	45 kA 40 kA	12.6 T 13.0 T
CS2U	45 kA 40 kA	12.6 T 13.0 T
CS1U	45 kA 40 kA	12.6 T 13.0 T
CS1L	45 kA 40 kA	12.6 T 13.0 T
CS2L	45 kA 40 kA	12.6 T 13.0 T
CS3L	45 kA 40 kA	12.6 T 13.0 T
PF1	48 kA 41 kA	6.4 T 6.5 T
PF2	55 kA 50 kA	4.8 T 5.0 T
PF3	55 kA 50 kA	4.8 T 5.0 T
PF4	55 kA 50 kA	4.8 T 5.0 T
PF5	52 kA 33 kA	5.7 T 6.0 T
PF6	48 kA 41 kA	6.4 T 6.5 T
PF6 0.4K subcooling	52 kA 41 kA	6.8 T 7.0 T

[1] In previous communications between FS&T Department and Magnet Division the **PF6 (Baseline 2008)** was named **"PF6 Option 4b".**

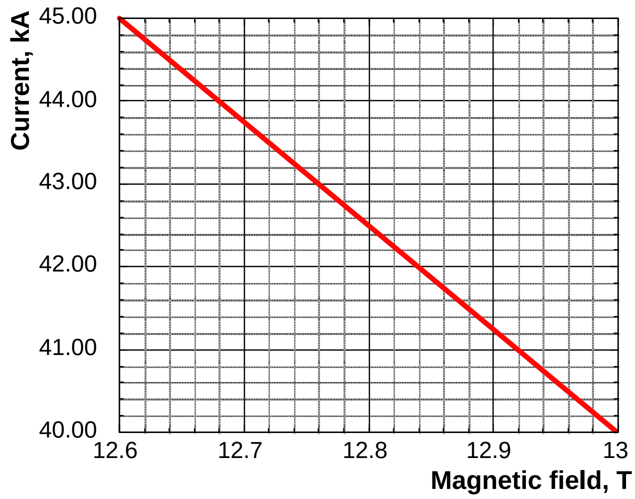


Fig. 1

Current in one turn of CS module vs. magnetic field on the module.

Dependence of the maximum current in one turn of each coil on the maximum magnetic field on the coil is obtained by the linear interpolation or extrapolation between or beyond pairs of values given in Table 2. An example of such dependence for CS modules is shown in Fig. 1.

Absolute value of the imbalance current in the coils PF2 - PF5 (the current flowing in the Vertical Stabilization Converter), calculated according to the formula:

$$I_{imb} = I_{PF2} + I_{PF3} - I_{PF4} - I_{PF5}$$

should not exceed 22 kA.

Limits on vertical forces acting on CS

Limits on vertical forces acting on CS modules are expressed as following:

$$\frac{|F_z(Upward)| + |F_z(Downward)|}{2} \le 120\ MN, \quad \left|\sum_{n=1}^{6} F_z(CS\ coil\ number\ "n")\right| < \approx 40\ MN\,.$$

note that F_z*(Downward)* has a negative sign.

Here F_z(*Upward*) is defined as <u>maximum</u> value among the following six values:

1) F_z(CS3U),
2) F_z(CS3U) + F_z(CS2U),
3) F_z(CS3U) + F_z(CS2U) + F_z(CS1U),
4) F_z(CS3U) + F_z(CS2U) + F_z(CS1U) + F_z(CS1L),
5) F_z(CS3U) + F_z(CS2U) + F_z(CS1U) + F_z(CS1L) + F_z(CS2L),
6) F_z(CS3U) + F_z(CS2U) + F_z(CS1U) + F_z(CS1L) + F_z(CS2L) + F_z(CS3L),

and F_z(*Downward*) is defined as <u>minimum</u> value among the following six values:

1) F_z(CS3L),
2) F_z(CS3L) + F_z(CS2L),
3) F_z(CS3L) + F_z(CS2L) + F_z(CS1L),
4) F_z(CS3L) + F_z(CS2L) + F_z(CS1L) + F_z(CS1U),
5) F_z(CS3L) + F_z(CS2L) + F_z(CS1L) + F_z(CS1U) + F_z(CS2U),
6) F_z(CS3L) + F_z(CS2L) + F_z(CS1L) + F_z(CS1U) + F_z(CS2U) + F_z(CS3U).

2. Limits on quasi-static control of separatrix (plasma equilibrium snapshots)

This section describes the limitations, which should be used in the analysis of plasma equilibrium and scenarios in the approximation of plasma equilibrium snapshots, where the eddy current, induced in the conducting structures (vacuum vessel, etc.), are not taken into account.

The maximum radius of the plasma edge is 8.2 m. (If after formation of divertor magnetic configuration the limiter is removed, the maximum radius might be 8.255 mm). To limit the interaction between the separatrix and the divertor dome in the case of large scale plasma disturbances, the separatrix deviation from the target separatrix is minimized within the following limits:

downward displacement of the inner leg (normal to the leg):	50 mm$_i$;
upward displacement of the inner leg (normal to the leg):	150 mm;
inward displacement of the outer leg (normal to the leg):	60 mm;
outward displacement of the outer leg (normal to the leg):	150 mm;
inward displacement near the limiter:	20 mm.

The minimum clearance between the separatrix and the inner part of the first wall is kept about 100 mm at low β_p (e.g. at start of heating), and about 150 mm at high β_p (e.g. at burn). The minimum clearance between the “40 mm” flux surface and the first wall is kept about 80 mm. (The “40 mm” flux surface is defined as the magnetic surface that passes through a point 40 mm outside the separatrix at the outboard equator.) The distance between inner and outer separatrices at the equatorial plane on the outboard side is kept higher or equal to 40 mm, for reliable operation in a single-null divertor configuration.

For improvement of the PF system plasma shaping capability at low l_i, X-point of the target separatrix was shifted downwards and the shape of divertor was changed accordingly. The plasma facing line of the first wall was also slightly modified since the Final Design Report 2001. In particular, the blanket modules numbers 13 and 14 located near equatorial plane were shifted towards the plasma for its better coupling with the IC antenna. The target separatrix and the plasma facing line of the first wall/divertor which should be used in studies of plasma equilibria and poloidal field scenarios are sown in red in Fig. 2 (Baseline 2008). For comparison, these elements used in the studies before 2008 (Baseline 2001) are shown in blue.

The *R*, *Z* co-ordinates of target separatrix and plasma facing line of the first wall/divertor of the Baseline 2008 are given in the Tables 3 and 4 respectively. The co-ordinates are given at the operating temperature in the system of co-ordinate with Z = 0 corresponding to the middle plane of the CS.

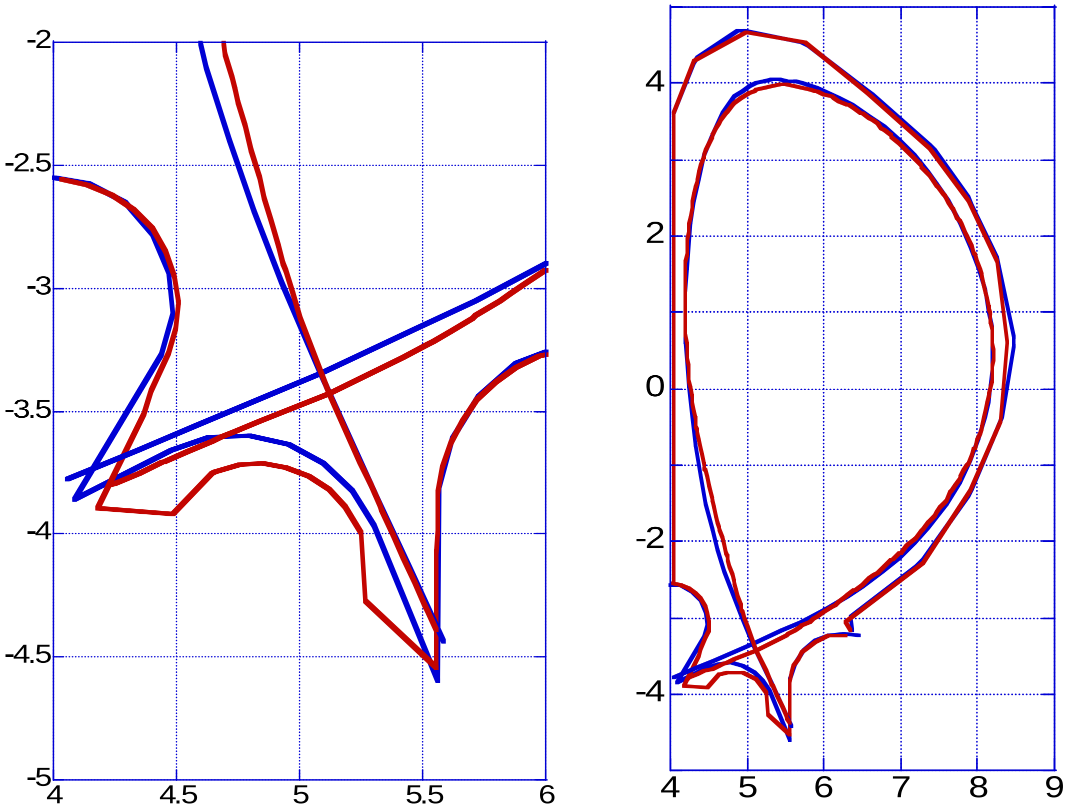


Fig. 2
Target separatrix and plasma facing line of the first wall and divertor.
Red lines – Baseline 2008, Blue lines – Baseline 2001.

Table 3
Co-ordinates of the target separatrix (Baseline 2008)

R, m	Z, m
5.5513	-4.3854
5.5171	-4.3076
5.5083	-4.2878
5.4646	-4.1902
5.4205	-4.0927
5.4195	-4.0905
5.376	-3.9951
5.3312	-3.8976
5.322	-3.8774
5.2864	-3.8
5.2417	-3.7024
5.1171	-3.4239
5.4195	-3.2812
5.5171	-3.2275
5.539	-3.2146
5.6146	-3.1697
5.6989	-3.1171
5.7122	-3.1087

5.8098	-3.0482
5.8531	-3.0195
5.9073	-2.9831
5.9967	-2.922
6.0049	-2.9164
6.1024	-2.8511
6.1404	-2.8244
6.2	-2.7818
6.2758	-2.7268
6.2976	-2.711
6.3951	-2.6413
6.4112	-2.6293
6.4927	-2.567
6.5376	-2.5317
6.5902	-2.4898
6.6588	-2.4341
6.6878	-2.4104
6.7762	-2.3366
6.7854	-2.3289
6.8829	-2.2474
6.8924	-2.239
6.9805	-2.159
6.9992	-2.1415
7.078	-2.0652
7.0994	-2.0439
7.1756	-1.9656
7.1938	-1.9463
7.2732	-1.8589
7.282	-1.8488
7.3621	-1.7512
7.3707	-1.7408
7.4413	-1.6537
7.4683	-1.6193
7.5167	-1.5561
7.5659	-1.4891
7.5874	-1.4585
7.6507	-1.361
7.6634	-1.3414
7.7129	-1.2634
7.761	-1.1838
7.7713	-1.1659
7.8228	-1.0683
7.8585	-0.9992
7.8727	-0.9707
7.9168	-0.8732

7.9561	-0.7835
7.9594	-0.7756
7.9959	-0.6781
8.0291	-0.5805
8.0537	-0.5072
8.0613	-0.4829
8.088	-0.3854
8.1112	-0.2878
8.1313	-0.1902
8.1493	-0.0927
8.1512	-0.0829
8.1672	0.0049
8.1802	0.1024
8.1897	0.2
8.1963	0.2976
8.2001	0.3951
8.2011	0.4927
8.1993	0.5902
8.1948	0.6878
8.1876	0.7854
8.1775	0.8829
8.1642	0.9805
8.1512	1.0519
8.1461	1.078
8.1282	1.1756
8.1082	1.2732
8.0855	1.3707
8.0596	1.4683
8.0537	1.4876
8.0285	1.5659
7.9968	1.6634
7.9622	1.761
7.9561	1.7764
7.9222	1.8585
7.881	1.9561
7.8585	2.0043
7.8349	2.0537
7.7876	2.1512
7.761	2.2016
7.7353	2.2488
7.6814	2.3463
7.6634	2.3763
7.6212	2.4439
7.5659	2.5285
7.5572	2.5415

7.4919	2.639
7.4683	2.6716
7.4191	2.7366
7.3707	2.7975
7.3407	2.8341
7.2732	2.9135
7.2572	2.9317
7.1756	3.0215
7.1684	3.0293
7.078	3.1228
7.074	3.1268
6.9805	3.2179
6.9735	3.2244
6.8829	3.3072
6.8662	3.322
6.7854	3.3909
6.7503	3.4195
6.6878	3.4688
6.6235	3.5171
6.5902	3.541
6.4927	3.6054
6.4785	3.6146
6.3951	3.6676
6.3201	3.7122
6.2976	3.725
6.2	3.7754
6.1293	3.8098
6.1024	3.8222
6.0049	3.8622
5.9073	3.8968
5.8761	3.9073
5.8098	3.9279
5.7122	3.9511
5.6146	3.9674
5.5171	3.9767
5.4195	3.9782
5.322	3.971
5.2244	3.9535
5.1268	3.9234
5.0875	3.9073
5.0293	3.8792
4.9317	3.8174
4.9213	3.8098
4.8341	3.736
4.8101	3.7122

4.7366	3.6283
4.7258	3.6146
4.6561	3.5171
4.639	3.4898
4.5984	3.4195
4.5491	3.322
4.5415	3.3054
4.5063	3.2244
4.4686	3.1268
4.4439	3.0539
4.4359	3.0293
4.4048	2.9317
4.3773	2.8341
4.353	2.7366
4.3463	2.7069
4.3316	2.639
4.3114	2.5415
4.2932	2.4439
4.2771	2.3463
4.263	2.2488
4.2506	2.1512
4.2488	2.1349
4.24	2.0537
4.2297	1.9561
4.2207	1.8585
4.2133	1.761
4.2073	1.6634
4.2025	1.5659
4.1989	1.4683
4.1964	1.3707
4.1948	1.2732
4.1943	1.1756
4.1948	1.078
4.1962	0.9805
4.1986	0.8829
4.202	0.7854
4.2064	0.6878
4.2117	0.5902
4.2179	0.4927
4.225	0.3951
4.2332	0.2976
4.2423	0.2
4.2488	0.1338
4.252	0.1024
4.2631	0.0049

4.2755	-0.0927
4.289	-0.1902
4.3035	-0.2878
4.3188	-0.3854
4.335	-0.4829
4.3463	-0.5489
4.3519	-0.5805
4.3698	-0.6781
4.3888	-0.7756
4.4087	-0.8732
4.4295	-0.9707
4.4439	-1.0373
4.4507	-1.0683
4.4727	-1.1659
4.4955	-1.2634
4.5192	-1.361
4.5415	-1.4508
4.5434	-1.4585
4.5679	-1.5561
4.593	-1.6537
4.6188	-1.7512
4.639	-1.8274
4.6447	-1.8488
4.6706	-1.9463
4.6971	-2.0439
4.7239	-2.1415
4.7366	-2.1884
4.75	-2.239
4.7762	-2.3366
4.8028	-2.4341
4.8301	-2.5317
4.8341	-2.5466
4.856	-2.6293
4.8825	-2.7268
4.9104	-2.8244
4.9317	-2.8976
4.9388	-2.922
4.9681	-3.0195
4.9997	-3.1171
5.1171	-3.4239
4.8341	-3.5403
4.7366	-3.5805
4.6783	-3.6049
4.639	-3.6214
4.5415	-3.6628

4.4492	-3.7024
4.4439	-3.7047
4.3463	-3.7472
4.2488	-3.7901
4.2266	-3.8

Table 4

Co-ordinates of the plasma facing line of the first wall and divertor (Baseline 2008).

R, m	Z, m	Comments
6.3454	-3.1623	First wall
6.2721	-3.0581	First wall
7.2877	-2.2715	First wall
7.9019	-1.3432	First wall
8.3019	-0.43574	First wall
8.394	0.61058	First wall
8.2462	1.6637	First wall
7.8793	2.4542	First wall
7.3872	3.1578	First wall
6.5716	3.8726	First wall
5.7488	4.5308	First wall
4.976	4.6753	First wall
4.3074	4.2993	First wall
4.0465	3.6213	First wall
4.0465	-2.5196	First wall
4.0321	-2.5555	Divertor
4.1375	-2.575	Divertor
4.2365	-2.6159	Divertor
4.325	-2.6765	Divertor
4.3988	-2.7542	Divertor
4.4549	-2.8456	Divertor
4.4908	-2.9466	Divertor
4.5049	-3.0529	Divertor
4.4966	-3.1597	Divertor
4.4662	-3.2626	Divertor
4.396	-3.4116	Divertor
4.3623	-3.5058	Divertor
4.1787	-3.8915	Divertor
4.4857	-3.913	Divertor
4.6393	-3.75	Divertor
4.6539	-3.7418	Divertor
4.7519	-3.7154	Divertor
4.8486	-3.7107	Divertor
4.9442	-3.7263	Divertor
5.0344	-3.7614	Divertor
5.1153	-3.8144	Divertor

5.1835	-3.8832	Divertor
5.2458	-3.9889	Divertor
5.2655	-4.2668	Divertor
5.5563	-4.5418	Divertor
5.5517	-4.0681	Divertor
5.5609	-3.9879	Divertor
5.5621	-3.8281	Divertor
5.5787	-3.7258	Divertor
5.6111	-3.6274	Divertor
5.6584	-3.5353	Divertor
5.7196	-3.4517	Divertor
5.7931	-3.3787	Divertor
5.8772	-3.3181	Divertor
5.9696	-3.2714	Divertor
6.0683	-3.2398	Divertor
6.1706	-3.2239	Divertor
6.2742	-3.2243	Divertor