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Preliminary Analysis of Position and Shape Control of IGNITOR Plasmas*

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Abstract

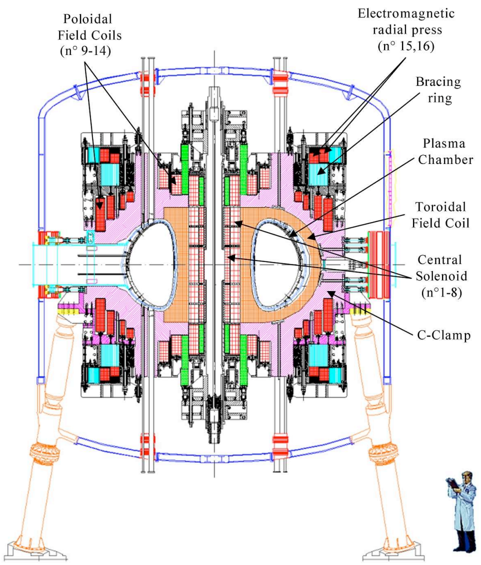
The CREATE_L linearized MHD deformable plasma response model[1] has been applied to the plasma configurations that Ignitor can produce. This model assumes an axisymmetric plasma described by few global parameters (β_{pol}, l_i, I_p and an effective resistance).

The growth rate of the vertical stability and the power required by active stabilization systems have been estimated, confirming the possibility of achieving an effective stabilization by the Poloidal Field Coil (PFC) system as presently designed. The position control involves two sets of coils with up-down anti-symmetric currents, while all the other coils have up-down symmetric currents. The two pairs of coils that provide the most efficient vertical control are P6 and P12. The required power and voltage match the present power supply system.

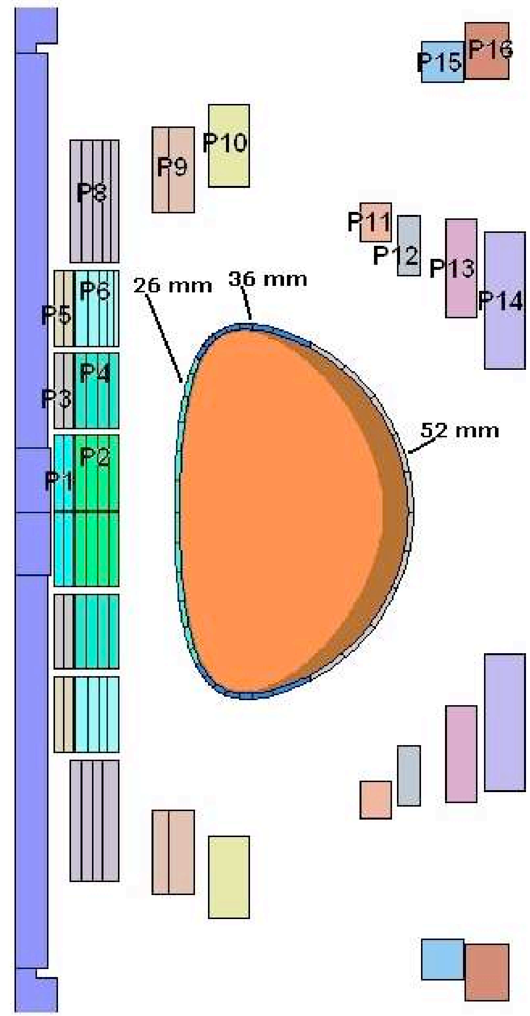
In addition, a preliminary assessment of the requirements for the control of the plasma cross section shape has been carried out. The results show that by using the PFC system it is possible in principle to reject undesired shape modifications due to plasma perturbations.

[1]R. Albanese, F. Villone, Nucl. Fusion 38, 723 (1998).

Ignitor Poloidal Field Coils (PFC) system



The Poloidal Field Coil (PFC) system of IGNITOR is a rather complex system, made up of 15 up-down symmetric coil pairs. The central solenoid includes 7 of these pairs (P1 - P8) and is a critical component of the machine because the relatively high temperatures they reaches at the end of the plasma shot and their role in the mechanical bucking of the toroidal magnet. Six pairs of coils (P9 – P14) are devoted to the shaping of the plasma, and the last two ones (P15 –P16) constitute the EM active radial press, contributing the mechanical holding of the Toroidal Field Coils.

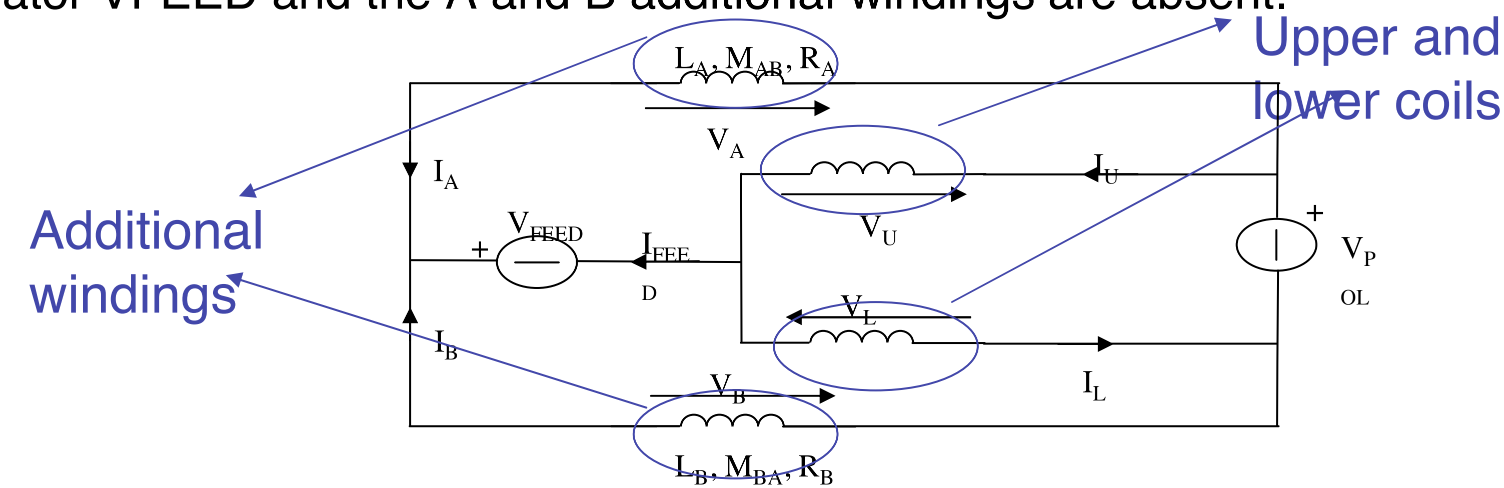


PFC connections

The following assumptions were assessed for the IGNITOR PFC electrical system:

- coils P1 and P3 are connected in series;
- coils P5 and P8 are connected in series;
- coils P15 and P16 (EM active radial press) are connected in antiseries;
- in all coils an up-down symmetric current is allowed;
- in some (position control) coils an up-down anti-symmetric current is allowed.

The last two points are accomplished by assuming the feeding scheme reported in the figure, where "U" and "L" are the upper and lower coils, and "A" and "B" are two additional windings. When no antisymmetric current is allowed, the voltage generator VFEED and the A and B additional windings are absent.

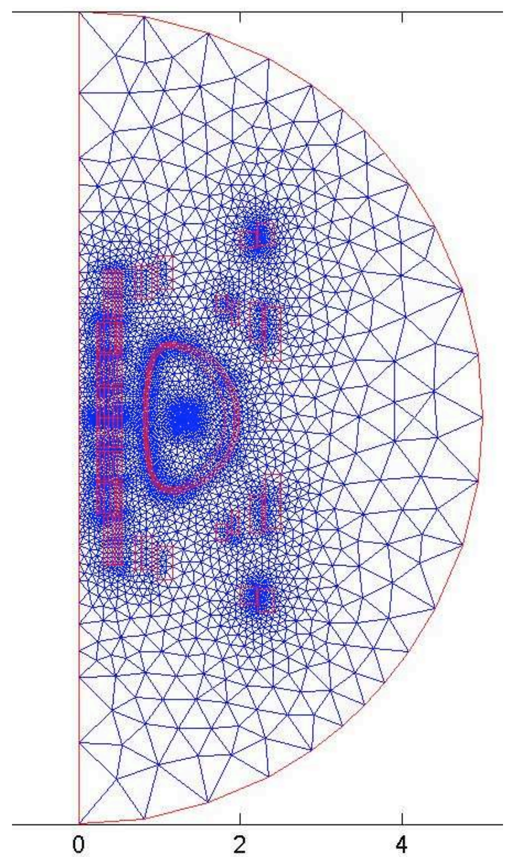


Plasma modelling

The modelling tool used is the CREATE_L linearized plasma response model[1]. This model assumes that the system is axisymmetric and that the electromagnetic interaction of the plasma with the surrounding structures is described by a small number of global parameters (poloidal β, internal inductance li and plasma current Ip). The plasma is assumed to have a global resistance such that its time constant is a given quantity.

In order to apply the model, a Finite Element discretization of the solution domain is given, with 15954 second order triangular elements and 31991 nodes. The vessel is divided in 118 conductors in the poloidal plane (each discretized in a number of triangles), each carrying a uniform current. For the time being, the PF coils are considered to be independently fed, in order to have maximum modelling flexibility.

[1] R. Albanese, F. Villone, "The Linearized CREATE_L Plasma Response Model for the Control of Current, Position and Shape in Tokamaks", Nucl. Fus., Vol. 38, no. 5 (1998).



CREATE_L linearized model

$$\underline{\underline{L}}^{*}_{coil}\frac{d\,\underline{x}_{coil}}{dt}+\underline{\underline{R}}_{coil}\,\underline{x}_{coil}+\underline{\underline{L}}_{Ecoil}\frac{d\,\underline{w}}{dt}=\underline{u}_{coil}$$

$$\underline{y}=\underline{\underline{C}}_{coil}\,\underline{x}_{coil}+\underline{\underline{F}}\,\underline{w}$$

$\underline{x}_{coil}$: perturbations of the currents in the 15 upper PF coils, 15 lower PF coils, 118 conductors representing the vessel and the plasma (149 components)

$\underline{u}_{coil}$: perturbations of the voltages applied to the various conductors (e. g. perturbations of the V_U, V_L defined in the PFC connections Section)

$\underline{w}$: profile perturbations (e. g. perturbations of poloidal β and internal inductance li)

$\underline{y}$: perturbations of generic output variables (e.g. simulated measurements, vertical position of the centroid, gaps, …)

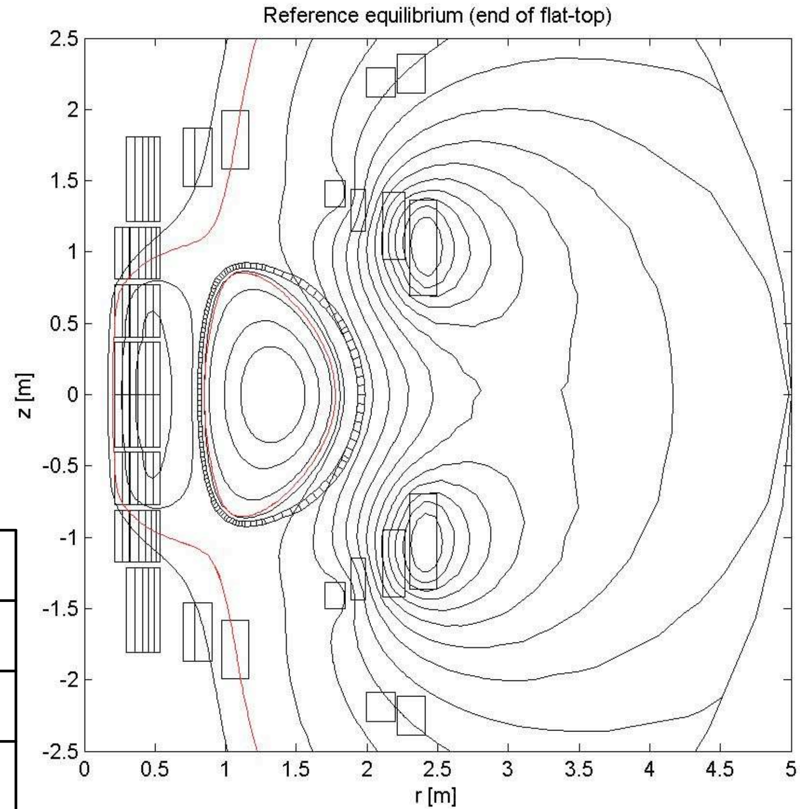
$\underline{L}^{*}_{coil}$, $\underline{R}_{coil}$, $\underline{L}_{Ecoil}$, $\underline{C}_{coil}$, $\underline{F}$: suitable matrices calculated by the model

Equilibrium configuration

The CREATE_L model needs a reference equilibrium configuration around which the equations are linearized. We assumed the reference equilibrium[2] at the end of flat-top.

2 G. Ramogida, V. Cocilovo, A. Coletti, A. Cucchiaro, G. Galasso, A. Pizzuto, C. Rita, M. Roccella, M. Santinelli, B. Coppi Bruno, "Optimization of the IGNITOR operating scenario at 11MA", Fus. Eng. Des., (2005).

Equilibrium parameter	*Reference*	*CREATE_L*
Plasma current	11 MA	11 MA
Internal inductance	0.84	0.82
Poloidal β	0.22	0.20
R_{AXIS}	1.348 m	1.340 m
Elongation	1.82	1.84
Triangularity	0.41	0.42



Poloidal flux map and plasma boundary for the reference equilibrium at the end of flat-top.

Coil ranking for vertical position control

To evaluate which are the coils that are expected to be maximally efficient in the control of the vertical instability, it is not sufficient to take into account the current efficiency per turn (i. e. the radial field that a given coil can produce, quantified with the variation of the vertical position of the plasma centroid due to a unit current in the coil itself). In fact, this estimate is purely static and neglect the following aspects:

• the controller cannot act directly on coil currents, but can only require a given voltage to generators;

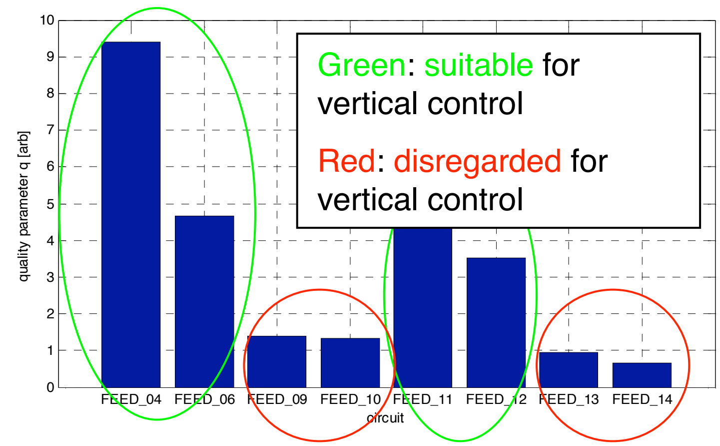
• changing one coil current to try to control the vertical position, eddy currents are induced in active and passive conductors, that may significantly shield, at least on a short time scale, the static effect;

• the system is unstable, so that even a shielding on a short time scale may result in a loss of control due to a rapid exponential growth of vertical position.

To address all these points, we evaluated the "best achievable performance" for the coils as the fastest response to an unwanted plasma vertical displacement, assuming that an ideal "bang-bang" controller with no delay instantaneously requires a voltage step to counteract this disturbance.

We can reasonably rank the coils looking at the quality parameter q (the higher q, the smaller is the voltage required to counteract the given perturbation).

$$\underline{q}^T = \underline{w}_u^T \underline{\underline{A}}^{-1} \underline{\underline{B}}$$



The figure, showing the figure of merit q for all the coils, points out that the most efficient coil is P4. Unfortunately, this coil is not easily usable for control, due to other engineering considerations. Hence, we investigated other assumptions on coil connections

Vertical Position Control Configurations

The quality parameter of a given coil may significantly depend on the chosen connection, due to eddy currents and the shielding effect of the nearest coils each other.

$V_{LIM} = Q \cdot z_0$ is the limiting value under which the given disturbance cannot be counteracted with a voltage step, then Q is the value of V_{LIM} for a unit initial vertical displacement (that could be, for instance, the error affecting the measure of vertical position).

11 and 12 shield each other if used together

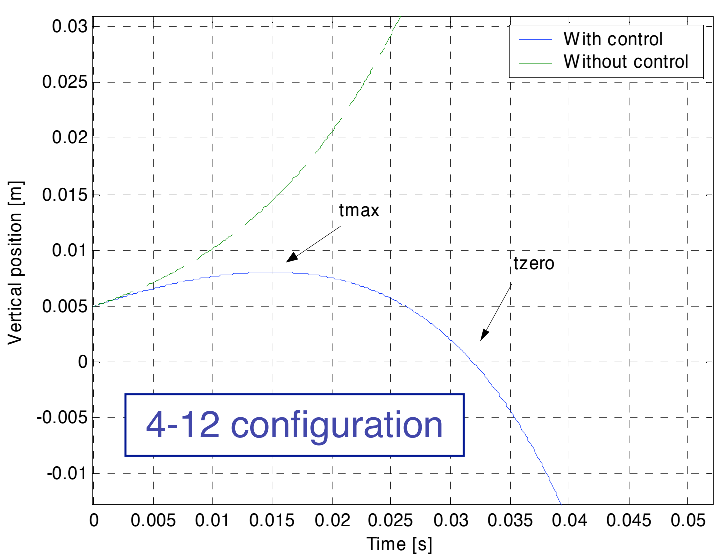
Voltage needed to counteract a 1cm displacement

		Up-down antisymmetric currents								
	Configuration	*4*	*6*	*9*	*10*	*11*	*12*	*13*	*14*	***Q (kV/cm)***
	4-6-9-10-11-12-13-14	9.25	4.58	1.38	1.31	4.58	3.46	0.92	0.65	***0.288***
too many coils	*6-9-10-11-12-13-14*	——	6.63	1.25	1.22	4.22	3.16	0.84	0.59	***0.441***
	6-11-12	——	6.82	——	——	4.99	5.25	——	——	***0.479***
acceptable	*6-11*	——	6.67	——	——	8.60	——	——	——	***0.546***
acceptable	*6-12*	——	6.77	——	——	——	8.19	——	——	***0.554***
unacceptable	*9-10*	——	——	1.53	1.93	——	——	——	——	***2.616***
disregarded	*11-12*	——	——	——	——	4.81	4.83	——	——	***0.887***
reference	*4-12*	10.18	——	——	——	——	8.67	——	——	***0.430***
	6	——	6.29	——	——	——	——	——	——	***1.429***
to be considered	*11*	——	——	——	——	8.13	——	——	——	***1.072***
to be considered	*12*	——	——	——	——	——	7.66	——	——	***1.132***
	4	9.18	——	——	——	——	——	——	——	***0.962***

Power requirements for an ideal bang-bang controller

Simulation of ideal bang-bang controller:

- no noise, no delay, no internal disturbances, no measurement errors
- z_0 = 0.5 cm initial vertical displacement
- controller reacting instantaneously to the disturbance with a step voltage of amplitude $V_{CONTR}=1.5 \cdot V_{LIM}$ in all the coils allowed for control, recovering all the displacement at t_{zero} (t_{max}, t_{zero} almost the same in all the configurations)

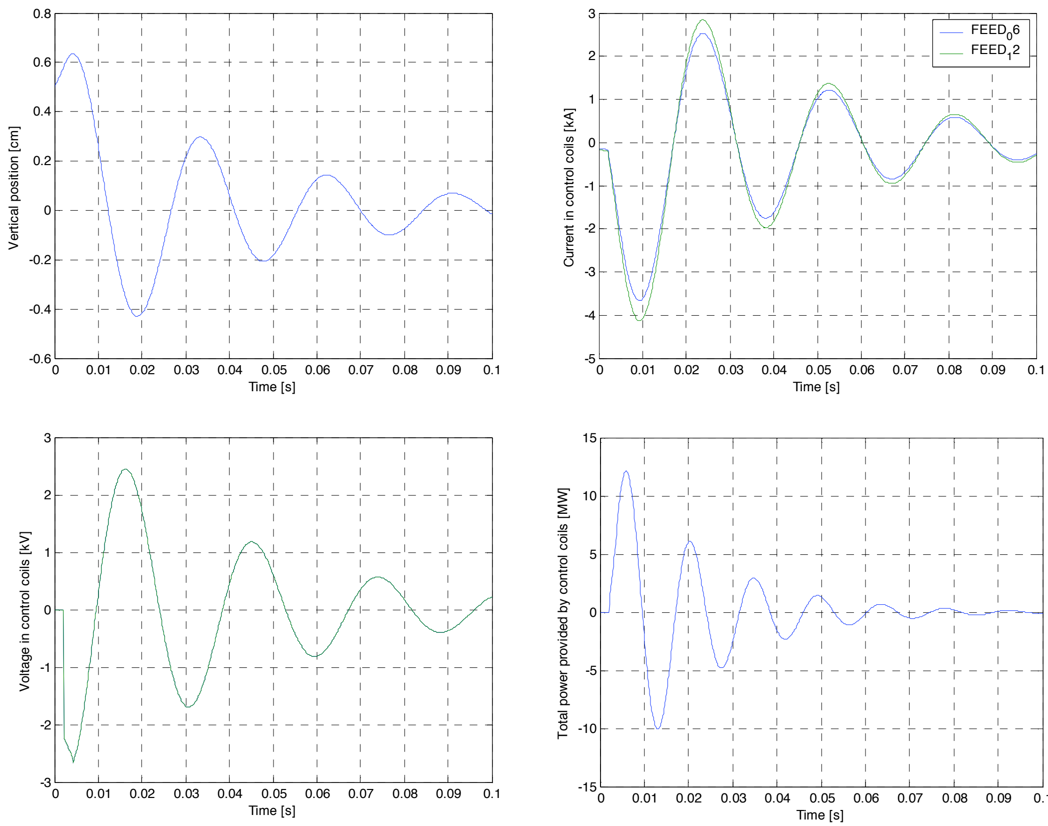


	Circuits with an up-down antisymmetric current					
	6 -12	*11-12*	*4-12*	*6*	*12*	*4*
V_{MAX} (V)	415	666	322	1072	849	722
$y(t_{max})$ (cm)	0.84	0.88	0.80	0.79	0.88	0.74
$P(t_{max})$ (MW)	1.72	2.96	1.30	4.24	3.60	2.67
$P(t_{zero})$ (MW)	**3.11**	**5.42**	**2.32**	**8.70**	**6.63**	**5.56**
$I_{FEED4}(t_{max})$ (kA)	——	——	2.24	——	——	3.70
$I_{FEED4}(t_{zero})$ (kA)	——	——	4.00	——	——	7.70
$I_{FEED6}(t_{max})$ (kA)	1.94	——	——	3.96	——	——
$I_{FEED6}(t_{zero})$ (kA)	3.52	——	——	8.12	——	——
$I_{FEED11}(t_{max})$ (kA)	——	2.69	——	——	——	——
$I_{FEED11}(t_{zero})$ (kA)	——	5.01	——	——	——	——
$I_{FEED12}(t_{max})$ (kA)	2.21	1.76	1.79	——	4.24	——
$I_{FEED12}(t_{zero})$ (kA)	3.97	3.12	3.21	——	7.81	——

Power requirements for a non-ideal PD controller

Simulation of a non-ideal PD controller:

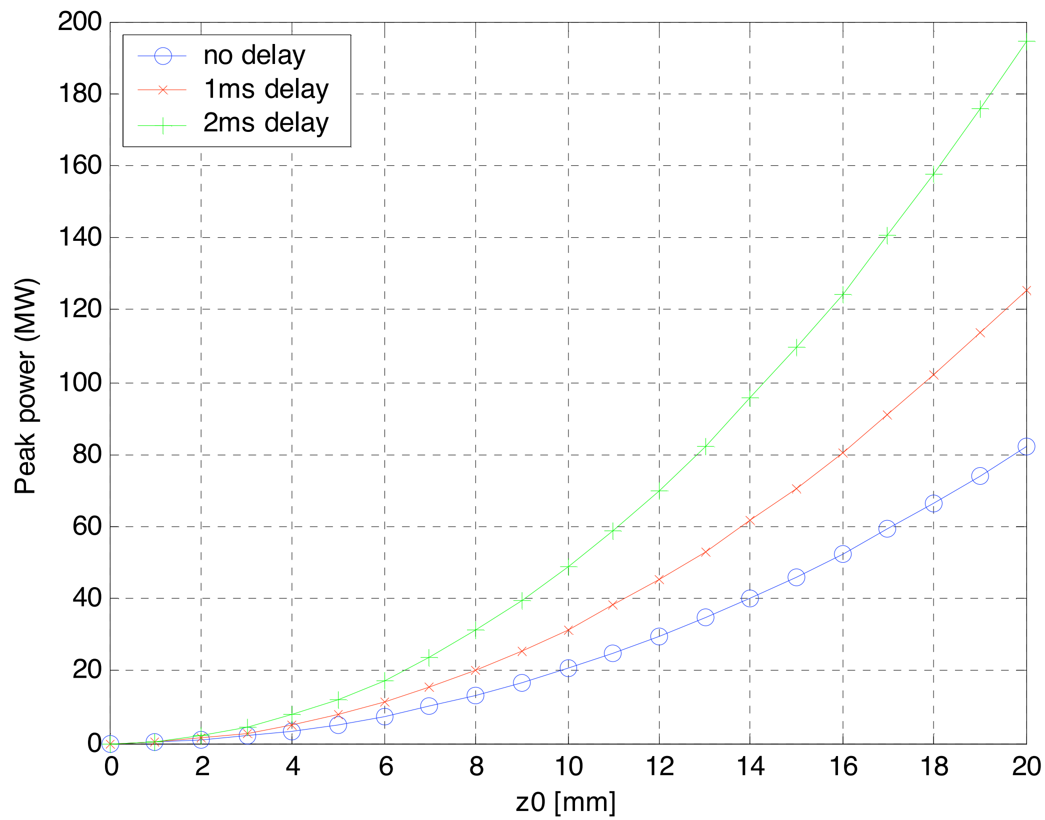
- no noise
- 2 ms delay
- no internal disturbances
- z_0 = 0.5 cm initial vertical displacement
- 6-12 configuration (from the comparison with other configurations this one turns out to show the best compromise among control efficiency, power required and other engineering constraints as candidate for the plasma vertical position control)



Errors in vertical position measurement

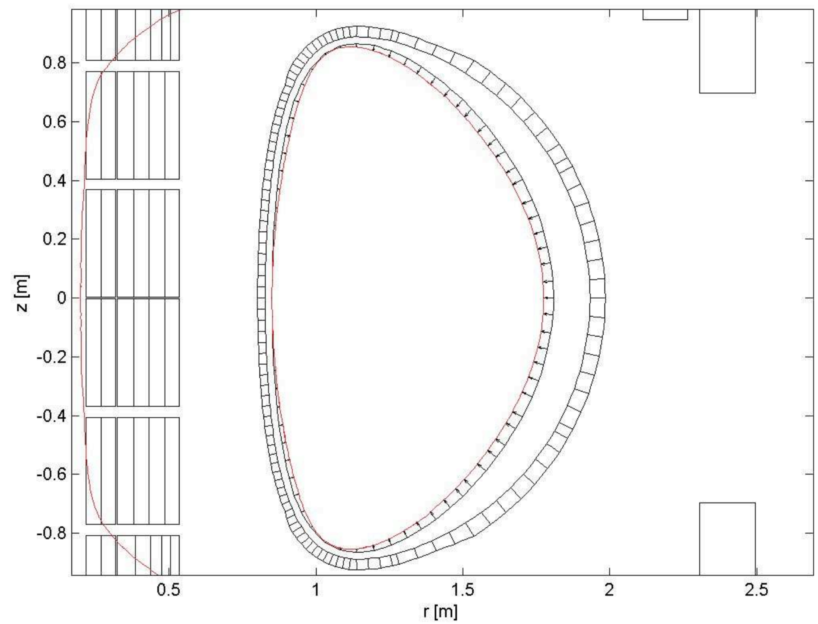
Estimation of the effect of noise and uncertainty on vertical position measurement:

- various values of delay
- various initial vertical position of the plasma (to simulate position measurement errors and noise)
- no internal disturbances
- 6-12 configuration
- uncertainties larger than 1 cm cause a substantial increase in the peak power required by the controller



Modelling assumptions for the plasma shape control

- Analysis has been based on gaps, supposed to be perfectly known at each time (73 gaps were considered, setting an upper limit to the achievable precision of the shape control, although 15 gaps provided very similar results);
- Independent perturbations of β_p, l_i, I_p have been evaluated;
- Two times in the reference scenario at 11 MA (SOF – start of plasma flat top, EOF – end of plasma flat top) have been analyzed;
- Various coils connections have been considered;
- The effect of passive structures has been neglected, because the shape control is slow as compared to the vessel characteristic times (~30 ms);
- The effect of additional windings in the coils used for vertical control has been neglected, because they behave as open circuits;
- The coupling with the vertical position control was not analyzed yet.



Location of the 73 gaps describing the reference configuration (in red)

Plasma shape perturbations at EOF

0.1 β_{pol} drop (~ 0.2 0.1)

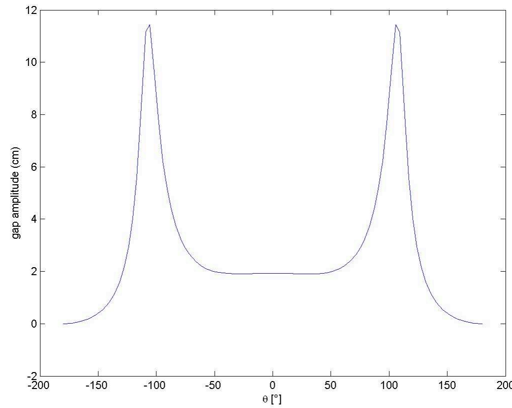
shrinking of the plasma shape with diminution of both elongation and triangularity

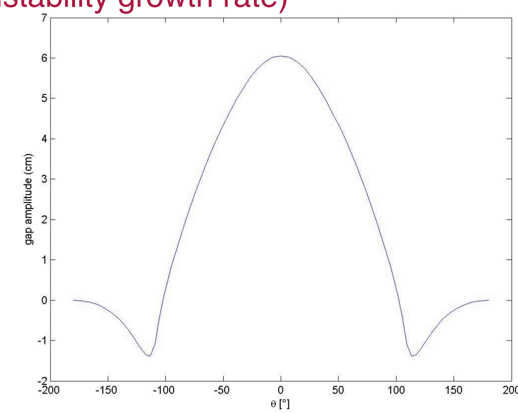
0.13 l_i drop (~ 0.82 0.69)

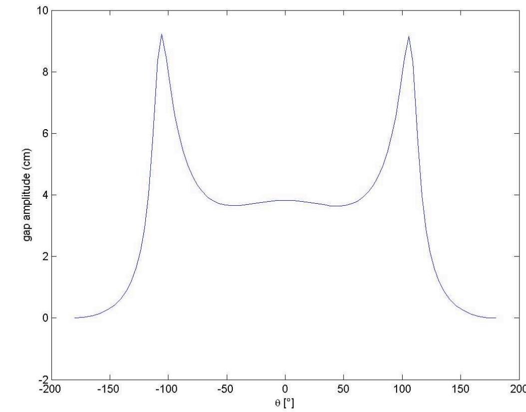
increase of elongation, with almost unchanged triangularity and possible implications for the vertical control (it could lead to a significant increase of the vertical instability growth rate)

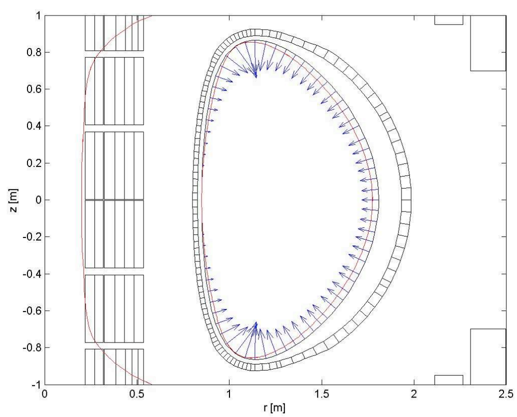
5% I_p drop (~ 11 10.45 MA)

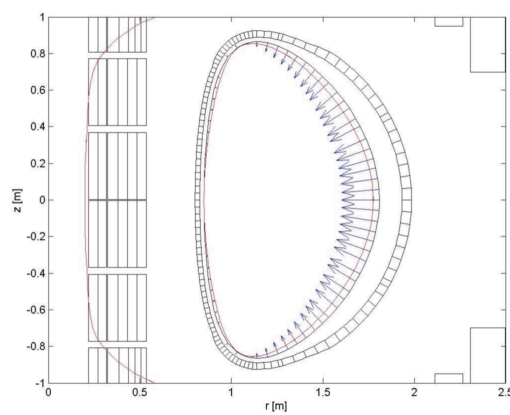
shrinking of the plasma shape with diminution of both elongation and triangularity

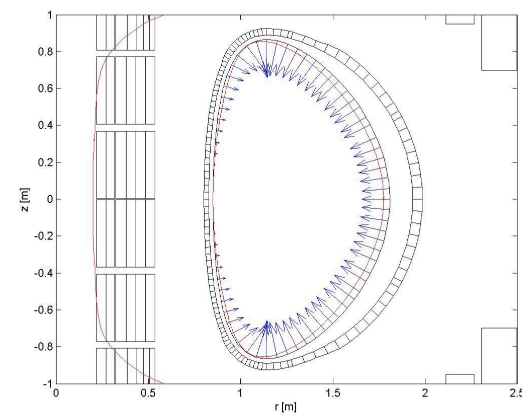












SVD static analysis

$$\underline{g} = \underline{\underline{C}}\,\underline{x} + \underline{\underline{F}}\,\underline{w}$$

Purely static analysis using the CREATE_L linearized model:

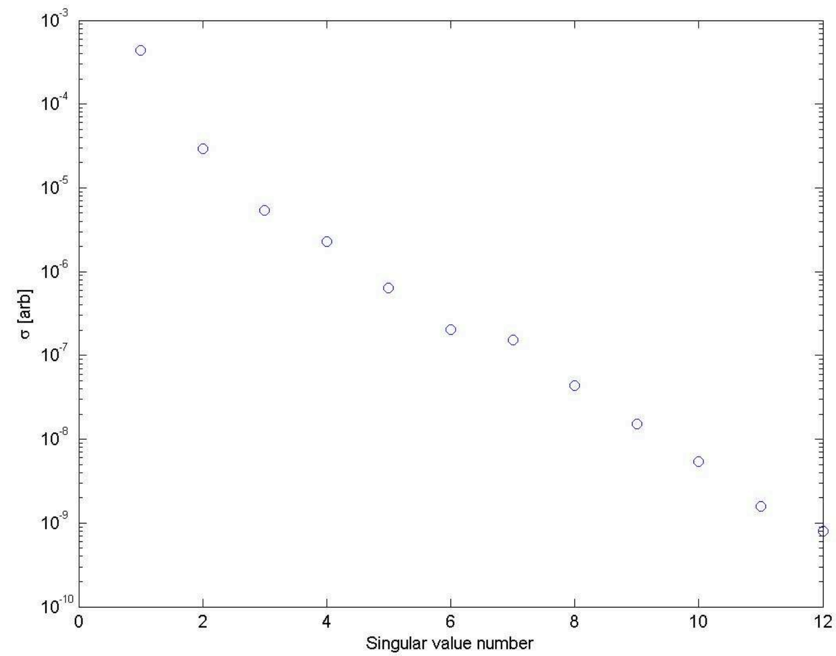
$\underline{x}$: PF coils axisymmetric current variations;

$\underline{w}$: "internal" perturbations (β_p, l_i, I_p);

$\underline{g}$: variations of plasma shape gaps;

C: matrix calculated by the CREATE_L code, representing the effect of PF coil currents perturbations on shape (rejection);

F: matrix calculated by the CREATE_L code, representing the effects of a given "internal" perturbation $\underline{w}$ on plasma shape, i. e. on gaps $\underline{g}$ (disturbance).



The shape control potentiality of the present PFC system has been assessed analyzing the singular vectors corresponding to the highest singular values obtained by a SVD decomposition of the matrix C. These singular vectors provide, when considered as current perturbations, the highest perturbations possible to the gaps and the singular values are a measure of the gap perturbation itself.

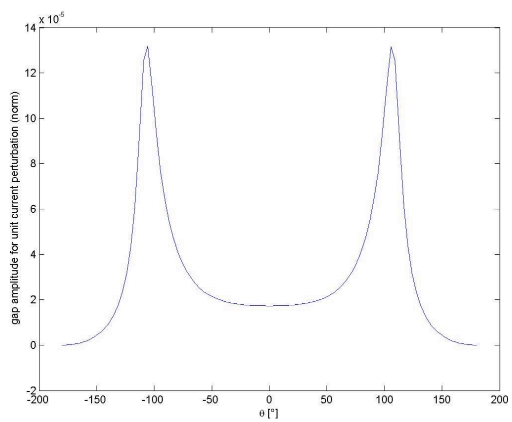
Singular values pattern, when all the up-down symmetric circuits are involved in shape control:

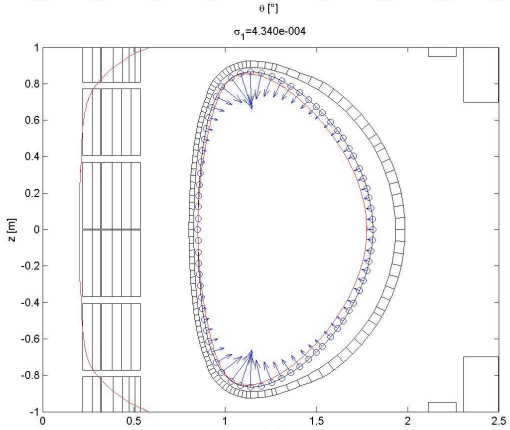
- one singular value is rather larger than any other one and then the related current combination is maximally effective in modifying the plasma shape;
- smallest singular values and related singular vectors could be used to modify PFC currents in the coils to match engineering limits without significant effects on plasma shape (scenario optimization).

Shape modifications by singular vectors

First singular value

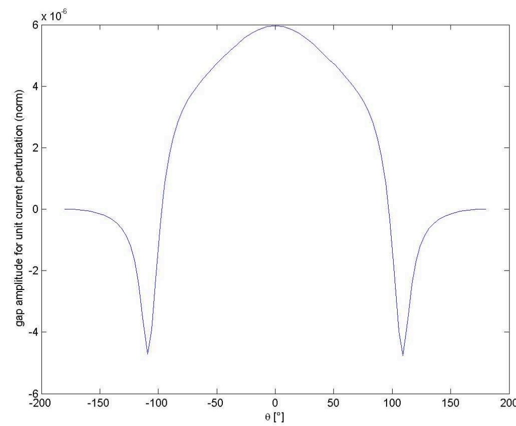
- “similar” to β_p and I_p drops
- “efficient” rejection of such disturbances by the present PFC system

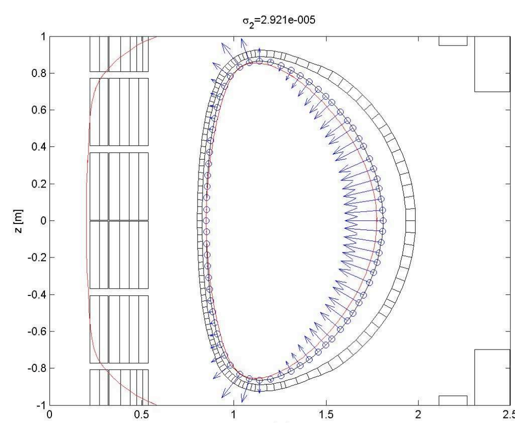




Second singular value

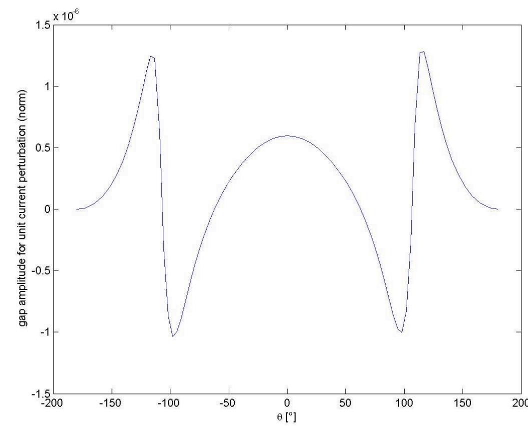
- “recall” (don’t match) l_i drop
- less “efficient” rejection of such disturbance by the present PFC system

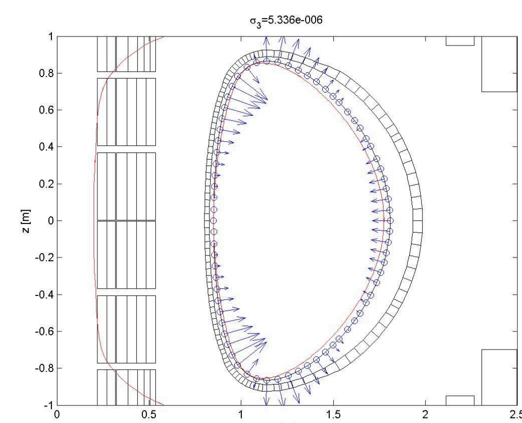




Third singular value

- high poloidal spatial variability
- useful for shape optimization





Residual gaps for static rejection

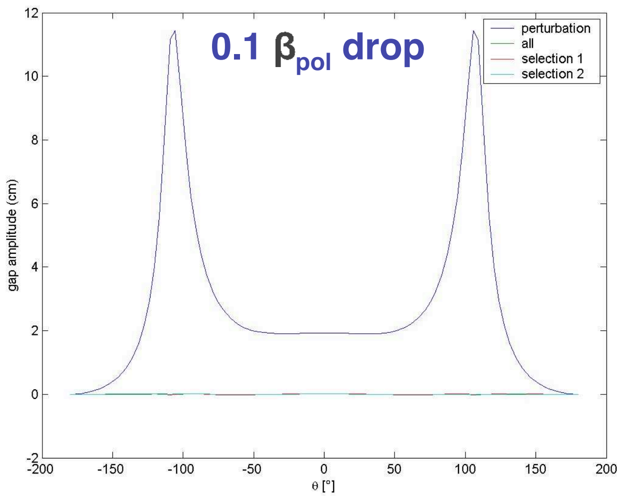
$$\underline{x} = -\underline{\underline{C}}^{+}\,\underline{g}_s$$

$\underline{x}$: optimal (with respect to the norm of residual gap perturbation $\underline{g}_r$) current perturbation vector to be injected in the coils for an "optimal" rejection of a given gap perturbation due to the disturbance $\underline{g}_s$.

$$\underline{g}_r = \underline{\underline{C}}\,\underline{x} + \underline{g}_s$$

$\underline{g}_r$: residual gap perturbation vector. It is not guaranteed to vanish because $n_{gap} > n_x$ and can be used to classify the efficiency for shape control of a given coil or set of coils.

A suitable regularization is then carried out (e. g. treating the smallest singular values as zero), in order to avoid that a very high current perturbation was required in some coils.

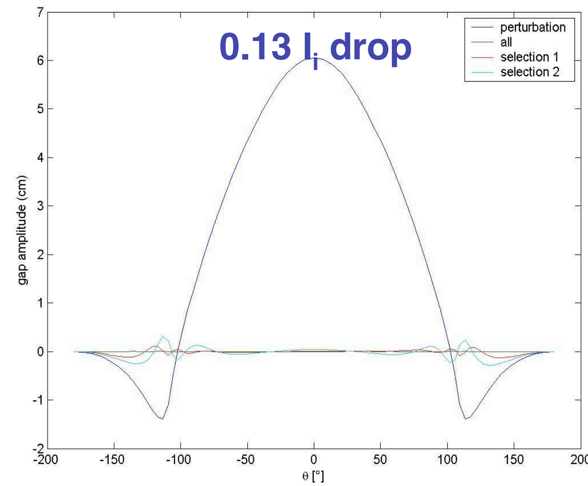


Residual gap at EOF for three possible choices of coil currents:

All: all the coils are allowed for shape control;

Selection 1: all the coils but P2, P4, P15 and P16 allowed;

Selection 2: only coils P6, P10, P11, P13 and P14 allowed.



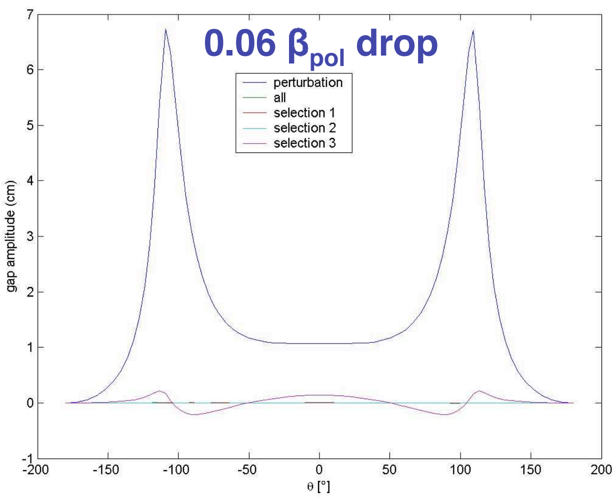
All the coils selections showed are able to statically reject the perturbation quite efficiently.

Selection 2 appear to be appropriate, giving rise to a small residual gap (~ 0.5 cm in the worst case) with a relatively small current perturbation.

Residual gap and current requirements at SOF

	Selection 2			*Selection3*		
Perturbation	*0.06 β_p drop*	*0.08 l_i drop*	*5% I_p drop*	*0.06 β_p drop*	*0.08 l_i drop*	*5% I_p drop*
δI P6 [kA]	0.70	-14.92	-6.52	-----------	-----------	-----------
δI P10 [kA]	0.36	3.07	-4.02	-0.08	-15.83	-7.76
δI P11 [kA]	-0.78	-7.01	-0.15	-----------	-----------	-----------
δI P13 [kA]	-1.13	-13.07	1.11	-----------	-----------	-----------
δI P14 [kA]	0.90	7.67	1.27	0.31	2.51	2.16

Currents required depend on: coils allowed for shape control; significant gaps; regularization.



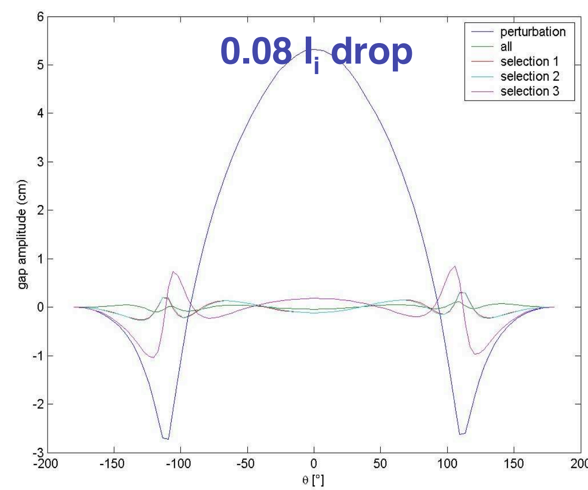
Residual gap at SOF with "optimal" rejection and different selections:

All: all the coils are allowed for shape control;

Selection 1: all the coils but P2, P4, P15 and P16 allowed;

Selection 2: only coils P6, P10, P11, P13 and P14 allowed;

Selection 3: only coils P10 and P14 allowed.



Open loop voltage required estimate at SOF

The voltage required for the shape control depends critically on the actual control strategy used and on the time interval admissible before shape recovery: we have considered a control time Δt_{contr} = 500 ms (>> 30 ms = t_{vessel}). In the table below the voltage values, at the end of the control interval, are reported.

Selection 2: current is allowed to vary only in coils P6, P10, P11, P13 and P14.

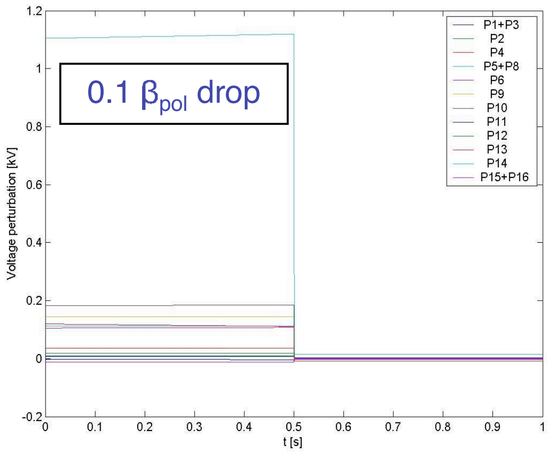
Selection 3: current is allowed to vary only in coils P10 and P14.

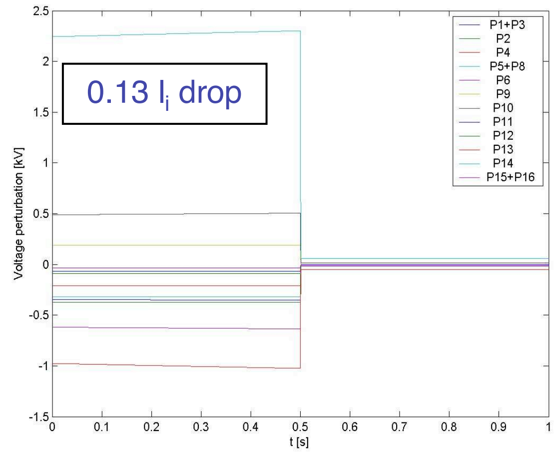
All others coils fed with voltage, such that current perturbation is zero.

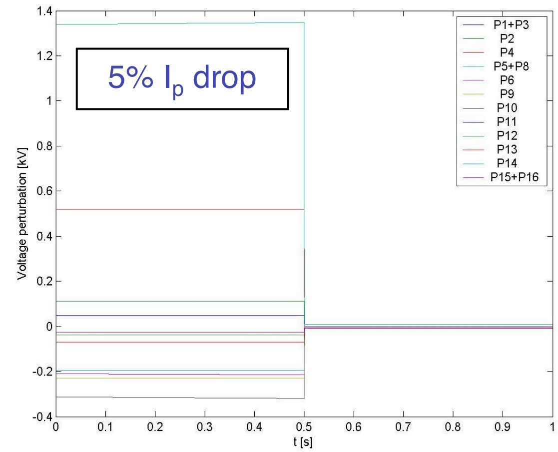
	Selection 2			*Selection3*		
Perturbation	***0.06 β_p drop***	***0.08 l_i drop***	***5% I_p drop***	***0.06 β_p drop***	***0.08 l_i drop***	***5% I_p drop***
δV P1+P3 [kV]	0.00	-0.05	-0.02	0.00	-0.01	-0.01
δV P2 [kV]	0.00	-0.07	-0.04	0.00	-0.03	-0.02
δV P4 [kV]	0.01	-0.16	-0.07	0.00	-0.04	-0.01
δV P5+P8 [kV]	0.03	-0.30	-0.19	0.01	-0.32	-0.12
δV P6 [kV]	0.03	-0.48	-0.21	0.01	-0.08	-0.02
δV P9 [kV]	0.04	-0.04	-0.21	0.01	-0.84	-0.36
δV P10 [kV]	0.04	0.10	-0.29	0.01	-1.31	-0.58
δV P11 [kV]	0.00	-0.20	0.07	0.02	-0.05	0.04
δV P12 [kV]	0.01	-0.20	0.12	0.03	0.04	0.11
δV P13 [kV]	0.04	-0.49	0.54	0.10	0.43	0.52
δV P14 [kV]	0.32	1.52	1.16	0.24	1.35	1.39
δV P15+P16 [kV]	0.00	-0.03	-0.02	0.00	-0.05	-0.03

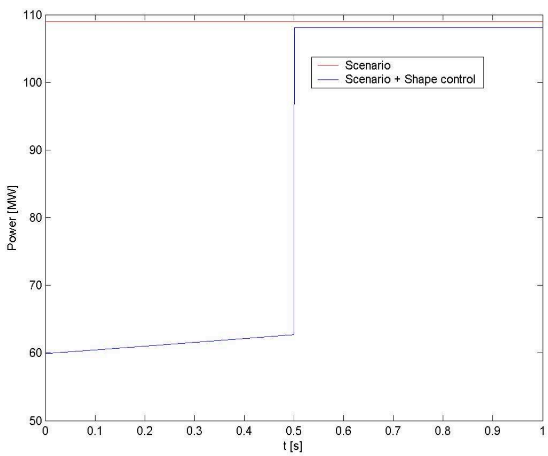
Voltage and power requirements

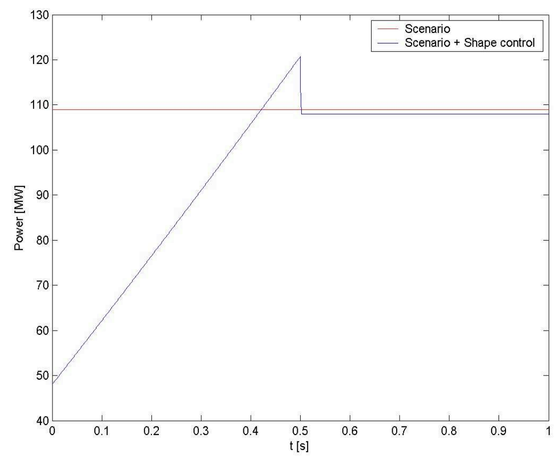
The total power required depends on the reference scenario currents and voltages: this estimate refers to a purely resistive scenario voltage and hence the scenario power represents only Joule losses in PF coils.

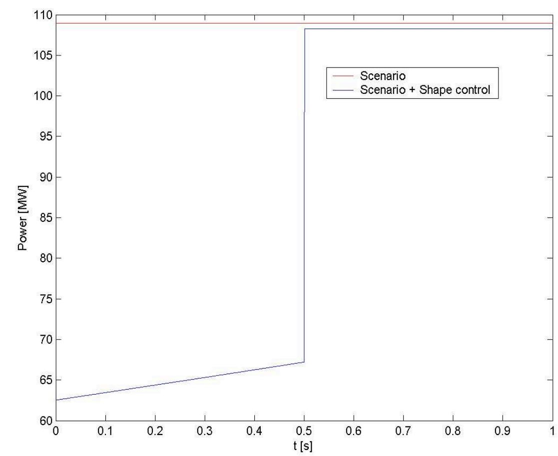












Conclusion and further work

The obtained results depend critically on the gaps that should be controlled: substantially lower currents could be required if, for instance, only the gaps in the outboard region should be controlled, relaxing the requirements of shape modification rejection in the inboard region. However, selecting a reduced number of gaps (for instance 15 out of the initial 73) uniformly distributed along the plasma boundary gives rise to almost the same results in terms of required currents.

Selection 3 appear to be the more reasonable choice among the analyzed configurations: it provides a static rejection with a maximum error equal or greater than selection 1 and 2 (and also spread around the whole boundary) but still acceptable and it is less demanding than other selections, because it involves few coil circuits.

The relatively high currents and voltages needed for the shape control deserve further analysis, in the l_i drop case above all.

A more realistic study, now in progress, will analyze:

- more physical significant disturbances (relations among β_{pol}, l_i and I_p);
- power constraints on admissible currents and voltages perturbations;
- coupling between shape and vertical position control;
- relaxed requirements on admissible shape modifications (tolerances and/or not controlled gaps);
- magnetic and non-magnetic diagnostic capabilities;
- possible alternative (to gaps) shape descriptors;
- 3D effects.