Control Optimization for the Position and Shape of the Ignitor Plasma Column*

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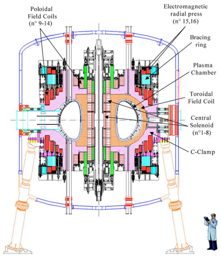
The performance of the control system for the position and shape of the elongated, tight aspect ratio plasma column of Ignitor has been analyzed using the CREATE L linearized MHD deformable plasma response model. The possible failure of the relevant electromagnetic diagnostics has been taken into account by considering the robustness of the position reconstruction strategy and the feasibility of vertical control by additional means, employing X-ray emission and thermography to evaluate displacements of the center of the plasma.

A realistic description of the power supplies has been introduced in the simulation scheme, allowing the selection of the most effective coil combination to stabilize the plasma and the optimization of the related PID (Proportional-Integral-Derivative) controller to minimize the response time and the required currents and voltages. Both a voltage and a current loop control scheme have been analyzed: the first has been found to be only marginally better than the second one in terms of power required by the active stabilization system.

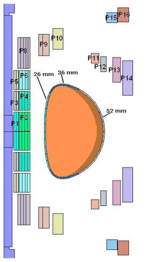
The problem of controlling the shape of the plasma cross section has been dealt with by considering shape deformations induced by varying one of the plasma macroscopic parameters (e.g. I_p, β_{pol}, l_i) by a few percent. The results of this simulation show that the undesired shape modification rejection is possible with the present PFC and power supply system.

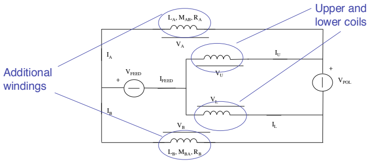
The IGNITOR machine



IGNITOR [1] has been the first experiment proposed and designed to achieve ignition conditions. The machine is characterized by an optimal combination of high magnetic fields (B_T = 13 T) and plasma currents (I_p = 11 MA in the high performance scenario), compact dimensions (R_0 = 1.32 m), tight aspect ratio (A = 2.8) and considerable plasma cross section elongation and triangularity (k=1.83, δ =0.4).

The Poloidal Field Coil (PFC) system of IGNITOR is a rather complex system, made 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 reach at the end of the plasma pulse and contribute to the mechanical bucking of the toroidal magnet. Six pairs of outer coils (P9 – P14) are devoted to the shaping of the plasma, and the last two (P15 –P16) constitute the EM active radial press, contributing to the mechanical support of the Toroidal Field Coils. The PFC electrical system [2] provides up-down symmetric currents in all the coils, except for those devoted to the vertical position control.





In the IGNITOR PFC electrical system:
pairs P1 and P3 are connected in series;
pairs P5 and P8 are connected in series;
pairs P15 and P16 (EM active radial press) are connected in antiseries;
in all pairs an up-down symmetric current is allowed;
in the vertical position control coils an up-down anti-symmetric current is allowed, by mean of the feeding scheme reported above, where “U” and “L” are the upper and lower coils, “A” and “B” are two additional windings.

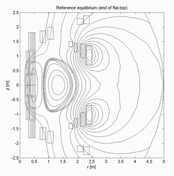
The CREATE_L linearized model

The modeling tool used is the CREATE_L linearized plasma response model [3]. 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 (β_{pol}, internal inductance l_i and plasma current I_p). The plasma global resistance, chosen such that its time constant is approximately 100 ms, has no major effect on the results.

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

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

$\underline{x}_{coil}$ are the perturbations of the currents in the 30 PF coils, the 118 conductors representing the vessel and the plasma (149 components);
$\underline{u}_{coil}$ are the perturbations of the voltages applied to the conductors (e. g. perturbations of V_U, V_L);
$\underline{w}$: are the profile perturbations (e. g. β_{pol} and l_i);
$\underline{y}$: are the perturbations of output variables (e.g. simulated EM measurements, centroid position, gaps);
$\underline{L}^*_{coil}$, $\underline{R}_{coil}$, $\underline{L}_{Ecoil}$, $\underline{C}_{coil}$, $\underline{F}$: are suitable matrices calculated by the model.

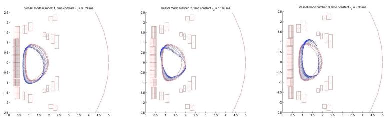


Poloidal flux map and plasma boundary of the equilibrium at the end of flat-top for the IGNITOR maximum performance scenario [4]. This equilibrium has been used as reference configuration around which the CREATE_L model is linearized.

Main plasma parameters are I_p = 11 MA, B_T = 13 T, internal inductance l_i = 0.84, β_{pol} = 0.22, R_{axis} = 1.848 m, elongation k = 1.82, triangularity δ = 0.41).

Plasma vertical position control

The time constants of the first three modes of the vessel (almost uniform with τ_1 = 30.2 ms, up-down antisymmetric with τ_2 = 13.7 ms and inboard-outboard antisymmetric with τ_3 = 9.4 ms, computed from the vacuum vessel inductance matrix L_o) and the value of the vertical instability growth time (about 15 ms, computed as the only positive eigenmode of the dynamic matrix) are in good agreement with simulations carried out with the equilibrium code MAXFEA [5].



	Up-down antisymmetric currents								
Configuration	4	6	9	10	11	12	13	14	Q (kV/cm)
4-6-9-10-11-12-13-14	9.23	4.58	1.38	1.91	4.58	9.46	0.92	0.65	0.288
6-9-10-11-12-13-14	—	6.63	1.25	1.22	4.22	9.16	0.84	0.59	0.443
6-11-12	—	6.82	—	—	4.99	5.25	—	—	0.479
6-11	—	6.67	—	—	8.60	—	—	—	0.546
6-12	—	6.77	—	—	—	8.19	—	—	0.554
9-10	—	—	1.55	1.93	—	—	—	—	2.656
11-12	—	—	—	—	4.81	4.83	—	—	0.887
4-12	10.18	—	—	—	—	8.67	—	—	0.430
6	—	6.29	—	—	—	—	—	—	1.429
11	—	—	—	—	8.13	—	—	—	1.672
12	—	—	—	—	—	7.66	—	—	1.332
4	9.18	—	—	—	—	—	—	—	0.962

VLIM = Q·z0 is the limit under which the given disturbance cannot be counteracted with a voltage step, then Q is the voltage needed to counteract a unit (1 cm) displacement).

Due to the eddy currents and the shielding effect of the nearest coils, the quality parameter of a coil pair significantly depends on the chosen connection.

To evaluate which coils are expected to be more 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, because this static estimate does not account for eddy currents and the intrinsic instability of the system.

The “best achievable performance” [6] of a coils pair proposed for the vertical position control has been then evaluated as the fastest response to an unwanted plasma vertical displacement, assuming that an ideal “bang-bang” controller with no delay suddenly requires a voltage step to counteract this disturbance. In the table Q is the.

Following this rating the coil pair P4 has been identified as the most efficient, but this pair is unusable for control purposes since already high scenario currents are programmed to flow on it. Then the combination of pairs P6 and P12 are the best compromise between vertical control efficiency and other engineering constraints [7].

References

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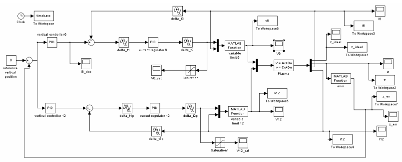
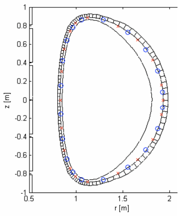
Controller performances



A PID vertical position controller has been designed to stabilize the system against sudden vertical displacements of the order of 0.5 cm along the unstable eigenmode.
A detailed simulation scheme has been set up in order to verify the performances of the vertical position controller and to estimate the power requirements needed for stabilization.
All the main features of the power supply systems have been taken into account in the model, including time delays, main filter responses and saturations. Indeed, the time delays (around 1 ms) are one of the major concerns in achieving better control performances.

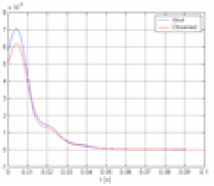


The capabilities of the magnetic measurement systems were analyzed [8] adding a set of simulated sensors (20 for the poloidal B field (O) and 20 for the flux (X)) to the model in the positions where they are expected to be located (betweeen first wall and plasma chamber). A suitable linear combination of such measurements is able to accurately reproduce the temporal evolution of the ideal vertical position of the plasma current centroid, even when two magnetic sensors are supposed to suddenly fail.

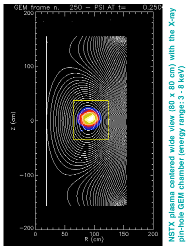
$$I_p = \iint_{S_p} J_p\,dS \cong \sum_n k_n^i B_n + \sum_n h_n^i \psi_n$$

$$zI_p = \iint_{S_p} z\,J_p\,dS \cong \sum_n k_n^z B_n + \sum_n h_n^z \psi_n$$

$$r^2 I_p = \iint_{S_p} r^2\,J_p\,dS \cong \sum_n k_n^r B_n + \sum_n h_n^r \psi_n$$

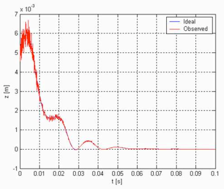


Two magnetic sensors failed “on the fly”

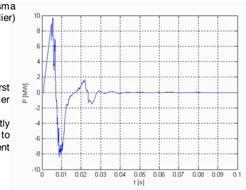


NSTX plasma centered wide view (80 x 80 cm) with the X-ray pin-hole GEM chamber (energy range: 3 - 8 keV)

A multiplicative Gaussian noise with unitary mean and 5% variance has been superimposed to simulated measurements, leading to acceptable performances, once a suitable filtering of the noise is applied. This analysis shows, on the one hand, the robustness of the system to measurement noise, while on the other hand allows a preliminary assessment of the performances of the control system if non-magnetic measurements of the vertical position (if assumed to be statistically correlated to magnetic measurements) are used. In fact, in a burning plasma environment, traditional magnetic measurements may be expected to fail because of the high neutron and gamma radiation background. A possible alternative method is being studied to measure the plasma position by detection of the soft X-ray emission from the plasma edge by means of fast GEM (Gas Electron Multiplier) detectors [9].



Gaussian noise added to measurements

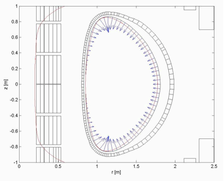


Both a current and a voltage controller scheme have been investigated and optimized. In the first case the maximum initial displacement that the system can recover is about 2 cm. The power required for vertical stabilization after a 0.5 cm initial displacement is around 10 MW.
The voltage controller scheme, obtained suppressing the current control loop and by directly computing through the vertical position controller the voltage command of the converter, appear to be marginally better than the current controller one: the maximum recoverable initial displacement increase to 2.3 cm with the same power requests.

Plasma shape control

- Analysis [7] has been based on gaps, describing the plasma shape and supposed to be perfectly known at each time (73 gaps were considered, in red in the figures, setting an upper limit to the achievable precision of the shape control, although 15 gaps provided 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 and 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);
- Additional windings in the coils used for vertical control have been neglected, because they behave as open circuits.

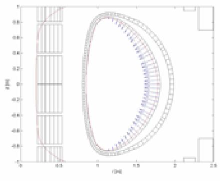
shape modifications due to static independent perturbations



0.1 β_{pol} drop (~ 0.2 0.1)

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

The effect of a 5% I_p drop (11 10.5 MA) is similar to this one



0.13 l_i drop (~ 0.82 0.69)

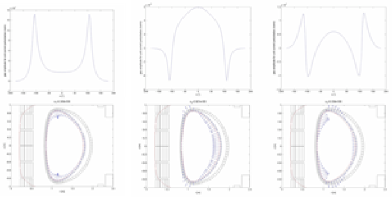
increase of elongation, with almost unchanged triangularity and possible implications for the vertical control due to an increase of the vertical instability growth rate)

SVD static analysis with the CREATE_L model

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 rejection matrix $\underline{\underline{C}}$. 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.

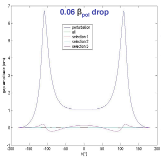
$$\underline{g} = \underline{\underline{C}}\,\underline{x} + \underline{\underline{F}}\,\underline{w}$$

$\underline{x}$: PF coils axisymmetric current variations;
$\underline{w}$: “internal” perturbations (β_p, l_i, I_p);
$\underline{g}$: variations of plasma shape gaps;
$\underline{\underline{C}}$: matrix representing the effect of PF currents variations on shape (rejection);
$\underline{\underline{F}}$: matrix representing the effects of a given “internal” perturbation $\underline{w}$ on plasma shape, i. e. on gaps $\underline{g}$ (disturbance).



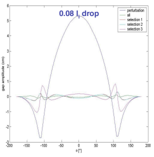
Shape modifications produced by the 1st, 2nd and 3rd singular vectors: the 1st is similar to a a β_{pol} or I_p drop and then permit an efficient rejection of such disturbances; the 2nd looks like (but don’t match) an l_i decrease and then give a less efficient rejection of it. Higher order singular vectors provide high poloidal variability and then are mainly usable for the shape optimization.

The residual gap perturbation vector (the vector of differences between unperturbed and recovered poloidal gaps) is not guaranteed to vanish and then can be used to classify the efficiency for the shape control of a given coil or set of coils. All set of coils analyzed was able to statically reject the perturbation quite efficiently. The set P10-P14 appear the more appropriate choice for the shape control, giving rise to a small residual gap (less than 0.5 cm in the worst case) with a relatively small current perturbation and power required. We are exploring the possibility to use thermographic methods to detect plasma deformations by and use the relevant signal for control.



Residual gap at SOF with “optimal” rejection for different selections

all: all the coil pairs allowed for shape control;
selection 1: only P1, P3, P5, P6, P8, P10, P11, P12, P13, P14 pairs;
selection 2: only P6, P10, P11, P13 and P14 pairs;
selection 3: only P10 and P14 pairs.



Conclusions

The vertical position controller for the IGNITOR plasma has been optimized, minimizing the time and the power (0.5 MW for a 0.5 cm initial displacement) needed to restore the initial position while fulfilling engineering constraints. The magnetic diagnostics that have been placed inside the plasma chamber have the capability of retrieving the plasma current and centroid position with sufficient accuracy for control purposes, even in the case of a sudden wrong behaviour of two magnetic sensors.
The optimal static rejection of the resulting plasma shape deformations has been demonstrated to be possible by suitable perturbations of the PF coil currents with a precision within 0.5 cm. Future work will be aimed at the analysis of combined perturbations of the aforementioned parameters, and their dynamical rejection.

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