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VERTICAL STABILITY ANALYSIS FOR THE IGNITOR CONFIGURATION †

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An extensive numerical simulation of the Ignitor-Ult plasma dynamics has been carried out using both the free boundary equilibrium code TEQ and the transport and MHD free boundary code TSC. The stability behavior of the plasma - vacuum vessel - poloidal field coils - passive plate system has been analyzed for different machine and plasma configurations. The response of several feedback systems has been studied taking into account the real characteristics of the power supply. The converter and its controller behavior has been extensively studied by means of the simulation program CSMP that uses a lumped parameter model of the system. The results show a good stability behavior over a wide operating range.

1. INTRODUCTION

The external magnetic field used to elongate the plasma cross section makes the plasma potentially unstable to vertical motion. This occurs when the external field curvature becomes negative. The curvature is measured by the field index $n_v \equiv -(R_o/B_z) \times (\partial B_z/\partial x)$, where R_o is the plasma major radius, B_z the vertical component of the external applied magnetic field and x the horizontal coordinate.

In this situation, any perturbations of the plasma column from its equilibrium position gives rise to a fast vertical motion that is driven by the vertical force generated in the interaction between the plasma current and the radial component of the external poloidal magnetic field.

The rapid plasma displacement from the midplane induces, in the upper and lower halves of the vacuum vessel, a distribution of toroidal currents. These currents flow in opposite directions in the two halves and interact with the plasma current, producing a vertical force that slows the plasma vertical motion [1]. This stabilizing effect of the vacuum vessel increases the timescale of the vertical instabilities from an ideal MHD (microsecond) timescale to the L/R (millisecond) timescale of the conducting structure. On this smaller growth time it is possible to design an active feedback system that can control the plasma vertical position [2].

1.1 Ignitor Design Parameters[3,4]

plasma column parameters

$R_o \simeq 1.3$ m	major radius
$a \simeq .47$ m	minor radius
$\kappa \simeq 1.85$	elongation
$\delta \simeq .4$	triangularity
$B_T \simeq 13.$ T	vacuum toroidal field at R_o
$I_p \simeq 12.$ MA	toroidal plasma current

vacuum vessel parameters

$r_1 = 1.839$ m	outer radius
$r_2 = .781$ m	inner radius
$h = .94$ m	height
$s = .017$–$.026$ m	wall thickness
Inconel 625	material
$\eta \simeq 1.3 \times 10^{-2}$ ohm/m	elec. resistivity (T=295 K)

1.2 Computer Codes

Numerical simulations have been carried out using both the free boundary equilibrium code TEQ for sensitivity and parametric study, and the transport and MHD free boundary code TSC [5-8] for analysis of the plasma motion and the design of the feedback system.

Several analytic and numerical methods [9-14] (rigid displacement model, filament-circuit model, massless approximation, etc.) have been proposed to study the vertical control problem. The TSC method describes the plasma by a full nonlinear and nonrigid model [5,6] that follows the excitation of all the possible poloidal modes. The main limitation is the two–dimensional description of the vacuum vessel, by means of toroidal wires, that does not allow us to directly evaluate the effect of toroidal discontinuities (as the presence of horizontal ports) in the vacuum vessel structure. However, these discontinuities, located close to the midplane in the outboard part of the vacuum vessel, have a very small influence on the vertical instability problem due to the weak coupling of this part of the vacuum vessel with the plasma.

1.3 Machine Model

The vacuum vessel is represented by 110 toroidally continuous wires (see Fig. 1). The 12 large horizontal ports are simulated by increasing the vacuum vessel resistance proportionally to the increased path that the induced current has to cover around the ports in order to complete a

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toroidal loop. Outside the computational grid there are 11 up/down symmetric poloidal field coils (PFCs).

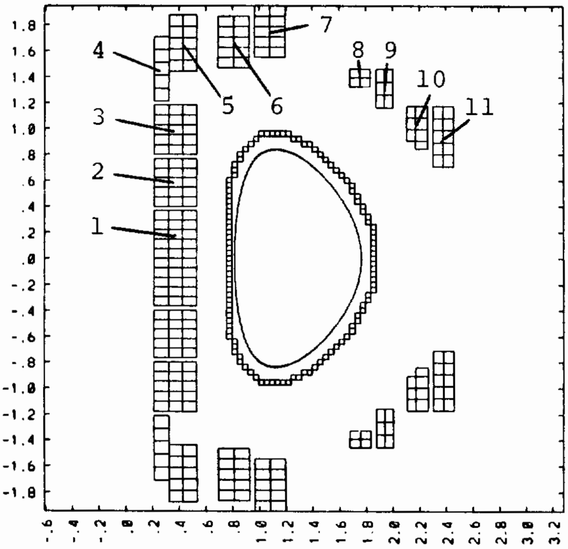

Figure 1: Model of plasma, structure, and coils used in TSC simulations.

The toroidal field coils have the additional beneficial effect of slowing the plasma motion, which has not been considered in the present analysis.

The vertical control system is not provided with dedicated coils; its action is obtained by superimposing a feedback current to one or more of the original PFCs.

2. PLASMA DYNAMICS

2.1 L/R Time Constant of the Structure

The L/R time constant of the structure in response to an antisymmetric distribution (with respect to the midplane) of induced currents strongly influences the vertical stability analysis. High L/R time constant requires close by conductors with low electrical resistance and toroidal electrical continuity.

In the present Ignitor design the vacuum vessel is the conductor that most strongly influences the L/R time constant of the total structure, being closer to the plasma and continuous in both toroidal and poloidal directions. The total toroidal resistance of the vacuum vessel has been evaluated to be $R \simeq 0.109$ mΩ and the L/R time constant of concern for vertical stability is $\simeq 6.4$ msec.

2.2 Plasma Vertical Growth Time

The plasma vertical growth time (τ_v) is the time value that characterizes the plasma vertical motion in the absence of active feedback control, and is defined as the reciprocal of the linear exponential growth rate of the plasma vertical position.

If there is no external stabilizing structure, the plasma is clearly ideal MHD unstable, with the instability proceeding on an Alfvén time scale (few μsec for $I_p = 12$ MA). With the stabilizing influence of the external vacuum vessel, the plasma is found to be no longer ideal MHD unstable and the remining instability evolves with $\tau_v \simeq 8$ msec. In this case, the TSC simulations have been carried out starting from an antisymmetric equilibrium with the plasma at 1 mm off the midplane. The subsequent plasma vertical motion is monitored for another 20 to 50 msec until the plasma displacement is about 5 to 10 mm off the midplane.

The influence on τ_v of the possibility to induced antisymmetric current in the symmetric PFCs, located in the upper and lower part, has been evaluated. Coils 2, 9 and 10 have the strongest influence on the plasma motion, and each increase the value of τ_v to $\simeq 9$ msec. Assuming that all the PFCs can have antisymmetric induced currents, except for coil 11 used for radial control, we obtain $\tau_v \simeq 12$ msec. These results have been confirmed by TEQ simulations.

2.3 Influence of Different Plasma Parameters

The influence of some plasma parameters on τ_v, such as the poloidal beta β_p, the internal inductance l_i and the elongation κ, has been evaluated. The results show that β_p and κ have a very weak influence on τ_v. The relatively mild influence of κ (for variation $\Delta\kappa = \pm 5$ %), for the same values of l_i and a, is mainly due to the presence of a close-fitting vessel. If κ is increased, a larger n_v is required for the equilibrium and the plasma becomes more unstable. However, a more elongated plasma also lies closer to the vacuum vessel and experiences a stronger stabilizing effect.

Larger values of l_i give rise to lower values of τ_v since for narrow toroidal plasma current distribution (large l_i) the plasma current lies, on average, farther away from the vacuum vessel. Furthermore the equilibrium requires a larger n_v given the same κ.

3. DESIGN OF THE FEEDBACK SYSTEM

3.1 Location of the Observation Loops

The observation loops are the code equivalent of the diagnostic magnetic pick-up coils. Some works [16-18] have shown the importance of the correct locations of these diagnostic loops in order to achieve the vertical control of the plasma. In our simulations we followed the procedure used in Ref. 15 to locate the loops in regions of the largest asymmetric flux for a vertically displaced plasma (this corresponds to the inboard part of the vacuum vessel, and more specifically to the locations $x = 0.88$ m, $z = \pm 0.7$ m).

3.2 Selection of the Vertical Feedback Coils

Several feedback systems that use one single coil or a combinations of two coils chosen from the PFCs that are closer to the plasma (coil 1, 2, 3, 6, 7, 8, 9, and 10) have been tested. We use only proportional gain chosen in such a way that its value gives a dimensionless gain of -1 (the dimensionless gain is the ratio of the gain used and the mutual inductance between the controlling coil and the flux loop). We assume that the power supply has a voltage limitation ($\pm$ 2500 V) but no delay in the response. We start all the simulations with the plasma 1 cm off the midplane.

The results show that one outboard coil (8, 9 or 10) can control the plasma motion by itself, the best results being given by coil 9. In contrast, the inboard coils are less coupled with the plasma and therefore their influence on the plasma motion is weaker. They are not able to control the plasma motion by themselves. However, with two coils, the best results have been obtained using a combination of one inboard coil (1, 2 or 3) and one outboard coil (9 or 10). The inboard coil produces a radial magnetic field that diffuses rapidly in the plasma and slows the vertical motion, reducing the power requirement on the outboard coil. The best combination of two coils is: coils 9 and 2.

Combinations of more than two coils have been tested, but the results show no significant improvements on the case with two coils.

3.3 Gain Optimization

We use a standar proportional – integral – derivative (PID) controller where proportional G_p^I and derivative G_d^I gains are used in the feedback algorithm for the current in the coils, and a simple proportional G_p^V gain is used to determine the voltage.

$$I_{feedback} = G_p^I(\Psi_{upper} - \Psi_{lower}) + G_d^I(\dot{\Psi}_{upper} - \dot{\Psi}_{lower})$$

$$V_{coil} = G_p^V(I_{feedback} - I_{coil})$$

The best ratio of the proportional to the derivative gain has been evaluated for coil 9 using a power supply that presents a voltage limitation of ± 2500 V and a 2 msec delay in the response. The results (see Fig. 2) show that without a derivative gain the plasma is unstable (curve a). The best result (curve c) is obtained using a value of G_d^I that is given by the value of G_p^I times the value of τ_v (this is only an empirical results). A lower value of G_d^I gives rise to a large overshot of the plasma (curve b), while a larger value produces plasma oscillations (curve d).

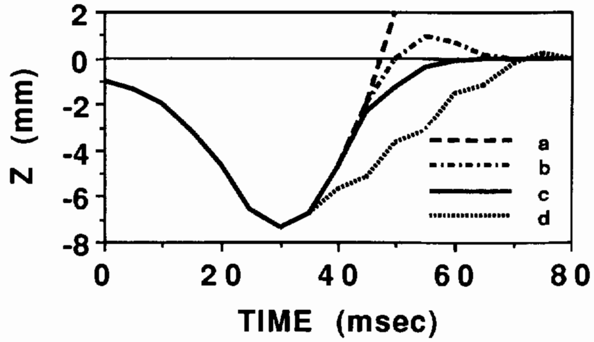

Figure 2: Plasma vertical position as a function of time for different value of G_d^I in coil 9.

Typical values of the gains are $G_p^I \simeq 4 \times 10^5$ amps/weber and $G_d^I \simeq 5 \times 10^3$ amps-sec/weber. For the combination of coil 9 and coil 2 the best result is obtained using only a proportional gain in both coils ($G_p^I \simeq 4 \times 10^5$ amps/weber for coil 9 and $G_p^I \simeq 2 \times 10^5$ amps/weber for coil 2).

3.4 Power Supply Influences

The influences of the power supply in terms of voltage limitation ($\simeq \pm$ 2500 V) has already been taken into account in some of the previous simulations. As far as the response time is concerned, if its value is of the order of 2 msec as designed, the feedback system can control the plasma vertical position for $\tau_v \gtrsim 12$ msec.

The real limitation is represented by the maximum power that the power supply must deliver. In fact, using only coil 9 a peak power of about 100 MW is required for about 40 msec, while coils 2 and 9 require about 50 MW in both coils for the same amount of time.

In order to reduce the power required, τ_v must be increased. This goal cannot be reasonably achieved increasing the thickness of the vacuum vessel and therefore the option to install passive coils between the vacuum vessel and the toroidal magnet has been considered.

3.5 Additional Passive Structure

The effect of an additional passive structure has been extensively examined by means of TEQ simulations. The most convenient position to locate a passive coil is in the outboard region, located on the vacuum vessel at a poloidal angle $\theta \simeq 75°$ measured counterclockwise from the midplane. The efficiency (ϵ) in slowing the plasma motion drops rapidly as the passive coil is moved away from the optimum location:

- assuming $\epsilon = 100\%$ for a passive conductor located on the vacuum vessel at $\theta \simeq 75°$, ϵ is $\simeq 50\%$ at $\theta \simeq 60°$ or $\theta \simeq 90°$ (see Fig. 3);

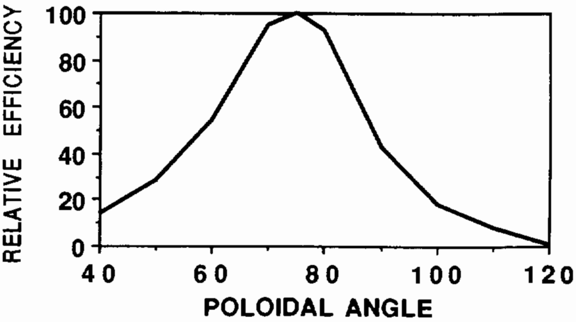

Figure 3: Relative efficiency of a copper conductor in slowing the plasma motion as a function of the poloidal angle.

- ϵ also drops rapidly as the passive coil is moved away from the plasma: ϵ is $\simeq$ 20% for a distance of 0.1 m from the vacuum vessel (see Fig. 4).

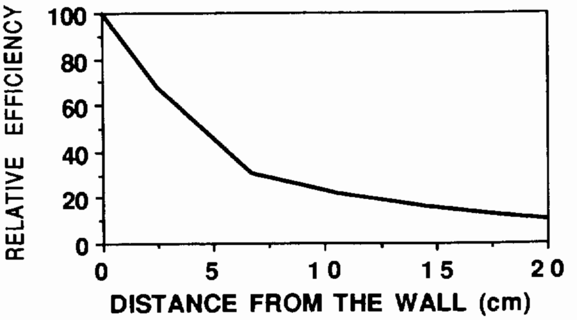

Figure 4: Relative efficiency of a copper conductor in slowing the plasma motion as a function of the distance from the vacuum vessel wall.

The use of a passive coil presents mechanical problems due to the disruption loads on these coils. In order to solve this problem and to maximize the efficiency in slowing the plasma motion, the effect on τ_v of a thin layer of copper, deposited by means of a plasma spray technique on the exterior surface of the vacuum vessel, has been evaluated.

Several values of the thickness of copper layer and different locations of the deposition on the vacuum vessel have been analyzed (see Fig. 5).

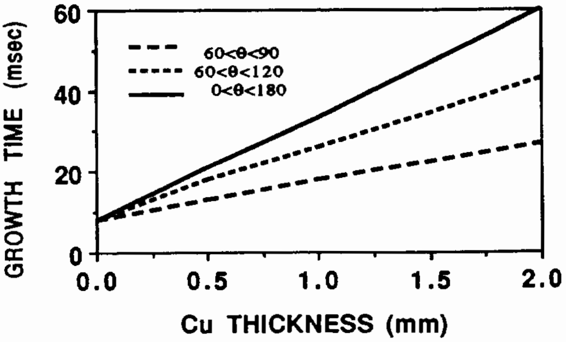

Figure 5: Plasma vertical growth time as a function of the thickness of the copper layer for different areas of deposition on the vacuum vessel.

The results reported in Fig. 5 do not take into account the effect of antisymmetric current induced on the PFCs.

If, for example, the deposition of a layer of $\simeq 0.5$ mm of copper for $60° \leq \theta \leq 120°$ is adopted, then the electrical resistance of the vacuum vessel becomes $R \simeq 0.039$ mΩ and the L/R time constant is $\simeq 17.9$ msec. This is sufficient to increase τ_v to about 20 msec while the power requirement is reduced by a factor two. If the thickness of the copper layer is increased to $\simeq 1$ mm then $\tau_v > 30$ msec and the power requirement is reduced by a factor 3 compared to the $\tau_v \simeq 12$ msec case.

The technological feasibility of this solution has been already tested, while a complete analysis of all the implications (increase in polodal flux requirement, effect of disruptions, etc.) is still under evaluation.

4. LUMPED PARAMETER MODEL

A lumped parameter model, where power supply, passive conductors, plasma, measurements and feedback control system are accounted, has been used to simulate the real characteristics of the power supply.

Taking only coil 9 as an active circuit, this analysis has developed the design of a control system whose general block diagram is shown in Fig. 6, which is similar to that made for the FTU machine [19,20]. The real characteristics of a power supply are described in the converter block diagram (see Fig. 7).

The sensor delay is assumed to be one msec. This delay is a bit larger than the response time of the power supply (that is 0.8 msec with a 100 Hz converter bridge) and has been chosen with some overestimation. The maximum voltage of 2500 V and the frequency of 100 Hz have been chosen in order not to utilize a chopper power supply. The PID controller was adopted in the active coil setting and its parameters were determined from simulation of the feedback control loop with the code CSMP III. A disturbance was added to the output of the control power supply. A square pulse of 30 msec width was used for the disturbance in order to produce a 2.5 mm z-variation.

The results were as follows: $G_p^I = 2.03$, $G_i^I = 0$ and $G_d^I = 0.05$; with these parameters control has been achieved: the plasma vertical position moves for 2.5 mm after the disturbance is imposed, then returns to its original position with few oscillations rapidly decaying (Fig. 8).

This model can be easily updated in order to make the simulation more realistic (e.g. taking into account more passive coils) or to verify a different controller.

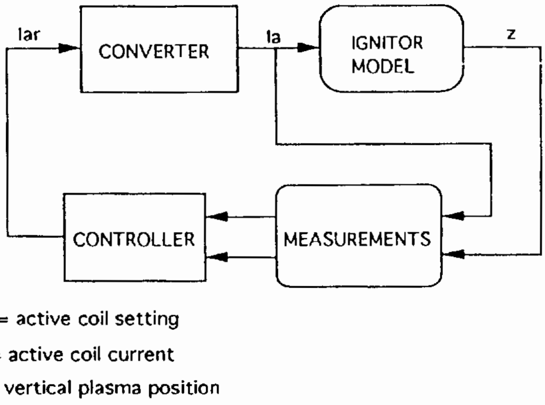

Figure 6: General block diagram for the control system

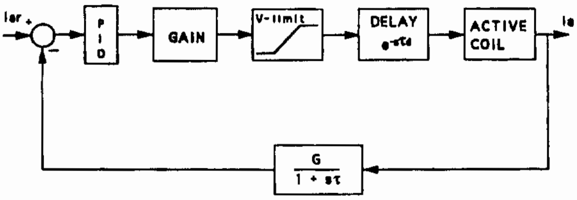

Figure 7: Block diagram for the converter

5. CONCLUSIONS

Plasma dynamics has been studied taking into account the plasma deformability by means of advanced computer codes and by modelling the real characteristics of the power supply. The influence of some plasma parameters has been analyzed.

The stabilizing effects of the vacuum vessel is not enough to ensure a good control of the plasma vertical position due to the large power requirement.

An additional thin layer of copper, deposited on the vacuum vessel, is able to increase the plasma vertical growth time and therefore reduce the power request of the feedback system.

The best feedback systems use one outboard coil (9) or a combination of one inboard coil (4) and one outboard coil (9); the optimum values for the proportional and derivative gains have been found.

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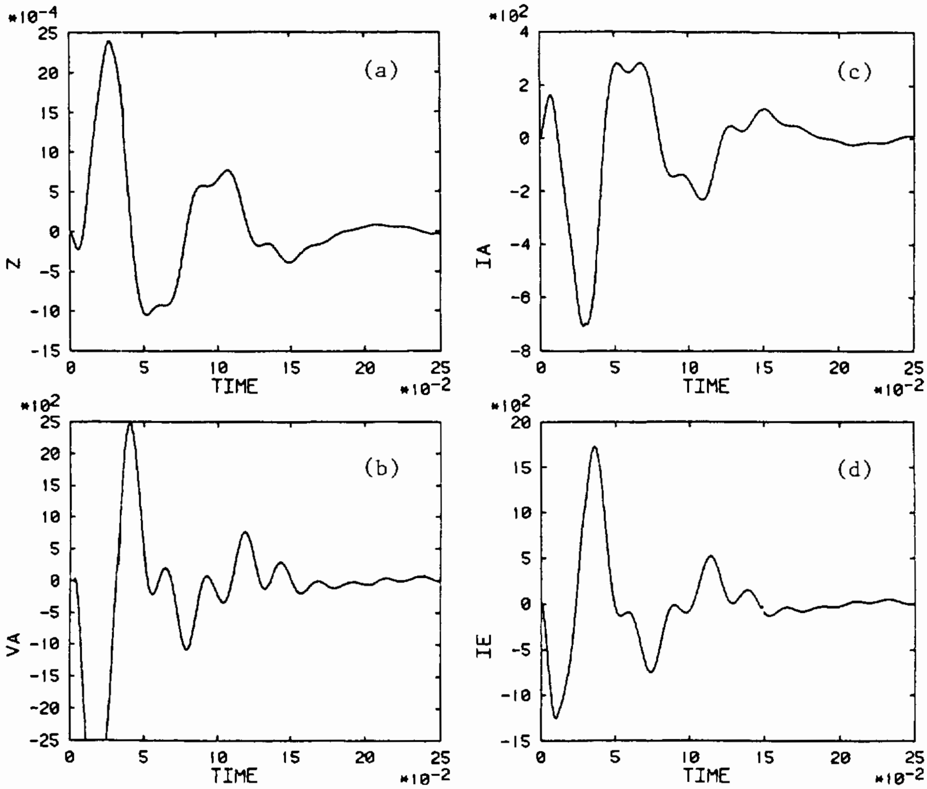

Fig. 8: a) controlled response of the vertical plasma position z at a 2.5 mm disturbance; time evolution of the voltage b) and current c) of the control power supply; time evolution of the current d) in the vacuum vessel circuits.

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