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ABSTRACT: a study of the vacuum vessel action on the plasma as a passive stabilizer is presented. The position feedback system is modelled in frequency domain to ascertain if the plasma position in TEXT-Upgrade can be stabilized.

1. Introduction

In the study of plasma equilibrium in TEXT-Upgrade[1,2] it became clear that the plasma position in that device is intrinsically unstable, mainly because of the iron core. Hence we need to investigate the feasibility of stabilizing it either with passive stabilizers or active plasma position feedback. In this report we study the effect of the vacuum vessel acting as a passive stabilizer, developping two extreme vacuum vessel models. Also we present a frequency domain linear perturbation study of the plasma position feedback system, closely following Ref. 3. We take into account the combined effects of iron core on equilibrium and stability, the vacuum vessel screening of external fields and the slowing down of plasma displacements due to vacuum vessel eddy currents. The plasma is modelled by a single filament.

The aim of this study is to stablish if the plasma position in TEXT-Upgrade can be stabilized, and under what conditions. In partcular we want to know if SCR power supplies (with characteristic response times between 2 and 5 ms) can handle the position feedback, or if we need faster transistor power supplies. Regretfully, we don't arrive at a real conclusion: the results ar strongly dependent on the modelling of the vacuum vessel, which needs to be considered in more detail. Nevertheless, we decided to publish this results here, as the methods used could be helpfull in the design of other devices.

2. Passive stabilization

A movement of the plasma induces eddy currents in nearby conductors; those currents oppose the initial plasma movement, slowing it down. Thus, an initial plasma position instability can be better controlled in the presence of passive stabilizers. The vacuum vessel itself acts as a passive stabilizer. We shall study its effect on plasma position control for TEXT-Upgrade, If the plasma position is being controlled by an active set of coils outside the vacuum vessel, the vessel screens their effect. The change in field observed inside the vessel is $B = B^{\text{ext}} - B^{\text{ves}}$, and the screening is characterized by $\alpha = (B^{\text{ext}} - B^{\text{ves}})/B^{\text{ext}}$. Because B^{ves} is calculated from the eigenvector current distribution, α should be calculated as $\alpha = 1 - pB^{\text{ves}}/B^{\text{ext}}$, where p is the scalar product of the vessel eigenvector and the current distribution produced by a change δI in the external coils. The screening is also characterized by its time constant, $\tau_v = L_v/R_v$. In Table 1 are shown the screening results for the two models of the vessel: the open vessel has a smaller screening effect and a shorter time constant than the closed vessel. Here it is important to notice that the two models of the vacuum vessel are rather extreme, and they produce very different results. It is easy to understand that the open vessel will have less of a stabilizing effect, particularly in an up-down movement of the plasma, because there is no current exactly in the position that would most efficiently push the plasma back in place: the top and bottom of the vessel. Only by introducing a full treatment of the feedback problem can we really establish how different the two extreme models of the vacuum vessel are. We proceed to do so in the next section.

2.1. Active position feedback description

First of all, let's outline the sequence of events we need to simulate:

1. The plasma position changes (δR and/or δZ).

2. Image currents appear in the vacuum vessel, opposing the plasma movement, and the position sensing system detects δR and/or δZ, producing a voltage proportional to $I_p\delta$.

3. The image currents in the vacuum vessel decay in a few miliseconds. The error amplifier receives the signal from the transducer and produces an output voltage V_G, which modifies the current of the feedback windings I_f (vertical and/or horizontal field).

a) Error amplifier $\xrightarrow{V_T}\boxed{\text{E}}\rightarrow V_E$

The input is the signal from the position detection transducer, proportional to the plasma displacement δ and to the plasma current I_p. The output is the voltage V_E. To compensate for possible delays in the detection, a lead time τ_E is introduced in the error amplifier. G_E is the gain of the system

$$\frac{V_E}{V_T} = G_E\,(1 + s\tau_E)\,. \tag{2.1.1}$$

b) Power amplifier $\xrightarrow{V_E}\boxed{\text{A}}\rightarrow I_f$

The current in the feedback windings, I_f, is proportional to the amplified error signal, V_E. The Laplace transform of the circuit equation of the feedback windings is

$$G_A V_E \;=\; sL_f I_f + R_f I_f \tag{2.1.2}$$

and the partial transfer function of the power supply is

$$\frac{I_f}{V_E} \;=\; \frac{G_A \tau_f}{(1 + s\tau_f)\,L_f} \tag{2.1.3}$$

with $\tau_f = L_f/R_f$ the time constant of the power supply, with the load of the windings.

c) Active windings–vacuum vesssel $\xrightarrow{I_f}\boxed{\text{FV}}\rightarrow B^f$

When a current change occurs in the feedback windings, outside the vacuum vessel, the circuit equation for the eddy currents is

$$sL_v I_v + R_v I_v + sM_{vf} I_f = 0 \tag{2.1.4}$$

and the total field at the plasma position is

$$B^f \;=\; K_f I_f + K_v I_v. \tag{2.1.5}$$

Combining the above equations, the transfer function is

Here we have ignored the high-frequency oscillations given by the poloidal Alfvén time scale, associated with the plasma mass m_p. The transfer function is

$$\frac{I_p \delta Z}{B_R^f} = -\frac{4\pi R_0^2}{\mu_0 f n_{\mathrm{ud}}} \frac{1 + s\tau_s}{1 - s\tau_g} \tag{2.1.13}$$

with

$$\tau_g = \tau_s \frac{n_{\mathrm{ud}} + n_c}{-n_{\mathrm{ud}}}, \tag{2.1.14}$$

which is the growth rate of the plasma movement inside the vacuum vessel if $n_{\mathrm{ud}} < 0$. The index n_c represents the largest possible value of n_{ud} that can be stabilized by the vessel.

On the other hand, we now look at the gain function for an in-out plasma displacement, δR. The equilibrium equation is

$$m_p \ddot{R} = \frac{\mu_0 I_p^2}{4\pi} f + R_0 I_p B_Z, \tag{2.1.15}$$

where $B_Z = B_Z^{\mathrm{eq}} + B_Z^v + B_Z^f$. Manipulating the equation as we did in the up-down case we obtain

$$\frac{I_p \delta R}{B_Z} = \frac{4\pi R_0^2}{\mu_0 f \left(n_1 - n_{\mathrm{io}}\right)} \frac{1 + s\tau_v}{1 - s\tau_g}, \tag{2.1.16}$$

where

$$n_{\mathrm{io}} = -\frac{R_0}{B_{Z0}} \frac{dB_Z}{dR}, \qquad n_1 = 1 - \frac{1}{f_0} \simeq .7, \qquad \tau_g = \left[\frac{n_c}{n_{\mathrm{io}} - n_1} - 1\right] \tau_v, \qquad n_c = -\frac{4\pi R_0^2}{\mu_0 f} \frac{M'_{pv} K_v}{L_v}. \tag{2.1.17}$$

Again, τ_g is the instability's growth rate, and n_c a critical index.

e) Position transducer $\xrightarrow{I_p\delta}\boxed{\mathrm{T}} \rightarrow K_T \delta$

An ideal transducer does not introduce any delay time. Its response is proportional to plasma current and plasma displacement.

$$\frac{V_T}{I_p \delta} = G_T \tag{2.1.18}$$

and typically $G_T = 1 Volt/200 kA.1cm = 5 \times 10^{-4} V Amp.cm.$

supply. But if the "open vessel" is considered as a better model of the real vessel, 1.5 ms is just too fast for a normal SCR power supply to handle. A more carefull description of the vaccum vessel eddy currents becomes necessary, and a carefull simulation of the power supply itself is needed to establish if it would succeed in stabilizing the plasma position. Similarly, in the case of in-out stability, the transfer function is

$$G = G_E\left(1 + s\tau_E\right)\frac{G_A}{\left(1 + s\tau_{\mathrm{VF}}\right)}\frac{\tau_{\mathrm{VF}}}{L_{\mathrm{VF}}}K_{\mathrm{VF}}\frac{\left(1 + s\alpha\tau_v\right)}{\left(1 + s\tau_v\right)}\frac{4\pi R_0^2}{\mu_0\left(n_1 - n\right)f}\frac{\left(1 + s\tau_v\right)}{\left(1 - s\tau_g\right)}G_T, \tag{3.0.22}$$

the feedback being carried out by the vertical field (VF) windings. The stability conditions are

$$G_E G_A > \left(n - n_1\right)\frac{\mu_0 f}{4\pi R_0^2}\frac{L_{\mathrm{VF}}}{\tau_{\mathrm{VF}}}\frac{1}{K_{\mathrm{VF}}G_T} = G_0 \tag{3.0.23}$$

$$G_E G_A > G_0\frac{\tau_{\mathrm{VF}} - \tau_g}{\alpha\tau_v + \tau_E} \tag{3.0.24}$$

$$G_E G_A > G_0\frac{-\tau_{\mathrm{VF}}\tau_g}{\alpha\tau_v\tau_E}. \tag{3.0.25}$$

In the case of the TEXT vertical field power supply the L/R time of the windings is 85 ms, the resistance is $R_{VF} = 5.6m\Omega$ and the field per unit current, K_{VF}, is $3.64x10^{-2}$ Gauss. The results of the feedback simulation in this case are shown in Table 3, again assuming an initial displacement of 1 cm, and with $\alpha\tau_v + \tau_E = \tau_v$. Again, it is easy to stabilize the position of the limited plasma, T200, and harder to stabilize the diverted one, S200.200. In the case of a solid vessel, the growth rate is 10 ms, easy to handle, but again the open vessel produces a faster instability growth rate, 3.2 ms. This is just in the limit of what a normal SCR power supply can handle, and carefull simulation of the supply itself needs to be undertaken to establish the posibility of stabilizing the plasma in the case when the open vessel model is presumed adequate. Actually, it is important to point out that intuitively the "closed vessel" model is closer to reality than the "open vessel", as there will be eddy currents present in between the ports, and it is most likely that their global effect on the plasma stability will

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	α	τ_v(ms)	vessel model
up-down	.25	8.4	solid
	.27	4.5	open
in-out	.17	7.1	solid
	.33	4.6	open

Table 1: Screening factor and vessel time constant calculated with the two extreme models of the vacuum vessel, "closed" and "open".

Plasma Configuration	n_{io}	n_c	τ_g (ms)	$G_E G_A$ ($= V_{\mathrm{VF}}/\mathrm{cm}$)	vessel model
T200	1.1	5.0	82	.2	closed
		3.5	36	4	open
S200.200	2.8	5.0	9.9	20	closed
		3.5	3.2	35	open

Table 3: Same as Table 2, for an in-out plasma displacement.

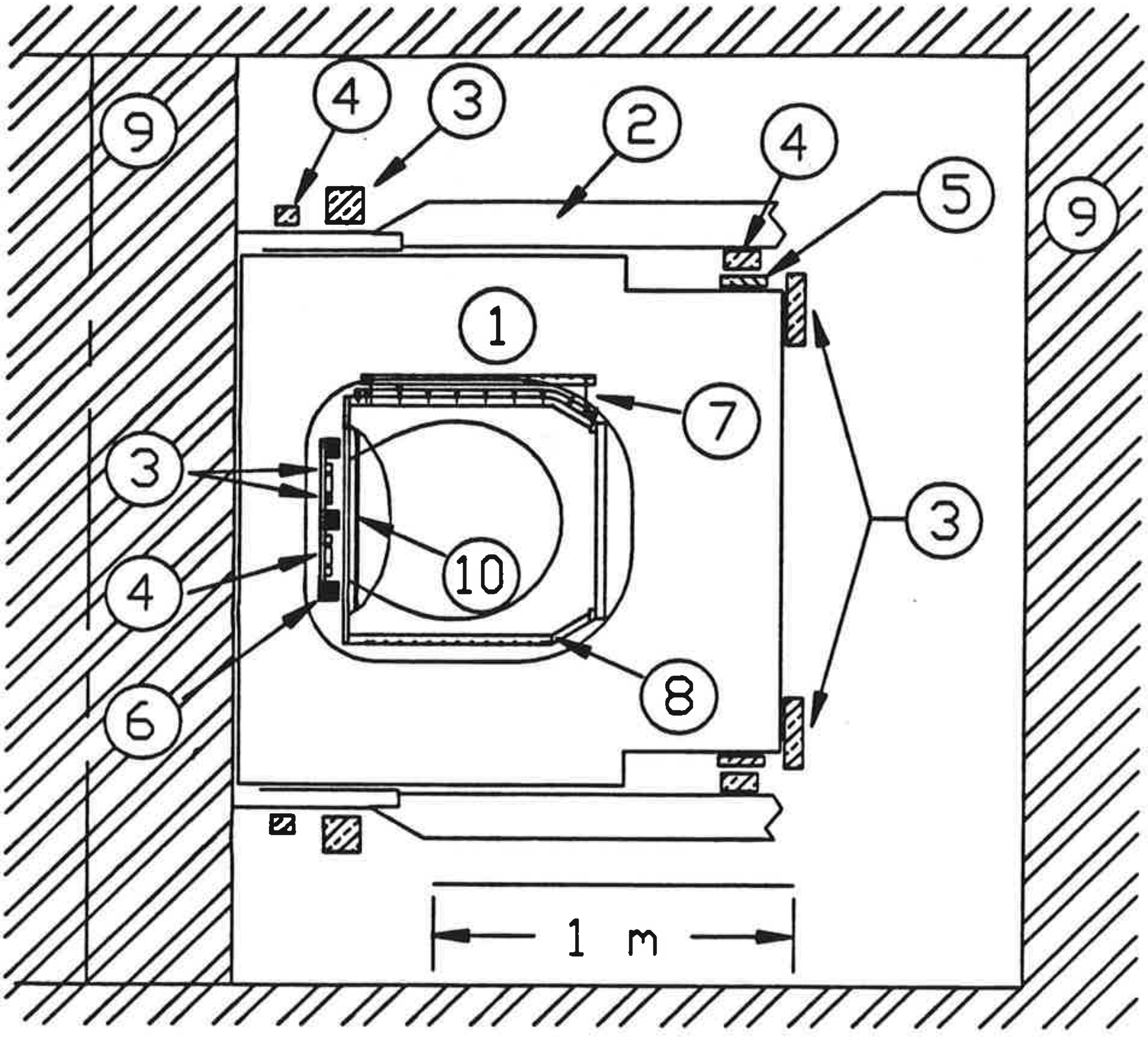
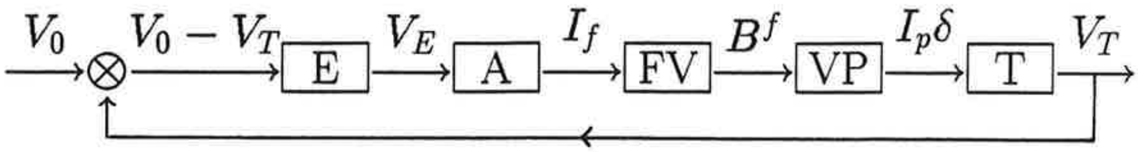


Fig.1



E	is the error amplifier
A	is the power supply
F	are the feedback windings
V	is the vacuum vessel
P	is the plasma (filament model)
T	is the position transducer
δ	is the plasma displacement (δR or δZ)

Figure 3: Representation of feedback system model.