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ABSTRACT

The position control of the JET plasma is based on the measurement of poloidal flux differences between desired inboard and outboard and between symmetric top and bottom reference positions inside the vessel. The error signals, assisted by preprogrammed functions, control the output voltages of 50 Hz thyristor power supplies which are connected to vertical and radial poloidal field coils. The precision achieved is about 1 cm and plasmas with elongation ratio $b/a \approx 1.6$ can be stabilised in the vertical direction.

The plasma current is controlled by appropriate preprogramming of the excitation voltage of a 2.6 G Joule flywheel generator convertor. Plasma current feedback will be applied in future experiments.

The control system is built with analogue electronics, but control functions are issued from CODAS which is the JET control and data acquisition system.

1. THE POLOIDAL FIELD CIRCUIT

The poloidal field system [1] is illustrated in fig. 1 and 2. It comprises a 2.6 G Joule flywheel generator convertor which supplies in parallel the magnetizing and the vertical field coils via a circuit breaker/reversing switch arrangement, a 50 Hz 4kV/25kA 2 quadrant thyristor power amplifier which is connected in series with the vertical field coil to provide the necessary corrections of the vertical field, and a 50 Hz 2kV/2kA 4 quadrant thyristor power amplifier which is connected to a separate radial field coil. The plasma shape is governed by selectable number of turns and polarities of three series connected sections of the vertical field coil.

The plasma current is started by commutation of the premagnetization current into a resistor. Typical current rates are 1 MA/s during the "fast rise" phase. About 0.8s later the flywheel generator is re-connected in opposite sense to drive the plasma current.

2. RADIAL POSITION CONTROL

2.1 General features

The position of the plasma surface is controlled by a method applied in ASDEX [2] and other experiments. The poloidal flux difference $\delta\psi_R$ between the limiter at the outboard side of the plasma and the desired inboard position of the limiter magnetic surface is obtained by a linear combination of integrated signals from saddle loops and internal discrete poloidal field pick up coils. Field gradients cause a systematic but acceptable error.

A proportional/derivative controller with continuously variable gain is used to control the vertical field amplifier from the flux error $\delta\psi_R$. A preprogrammed voltage provides the bias vertical field before the plasma start up and reduces the control error during the current rise. Integral feedback will be added in future experiments.

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The desired inboard plasma/wall distance can be varied during the pulse. For this purpose the integrated signal of the pick up coil at the inboard vessel wall is multiplied with a continuously controllable weighting factor D_R ref as indicated in fig. 1.

The radial position control system includes the possibility to automatically limit the vertical extension of the plasma. When the flux difference $\delta\psi_H$ between the limiter and two locations Z = ± H exceeds the error signal $\delta\psi_R$, then $\delta\psi_H$ is used for feedback control while $\delta\psi_R$ is ignored. This facility will be applied for plasmas with large elongation ratio until active control of the plasma shape is implemented.

2.2 Feedback characteristics

Under conditions where the output voltage of the flywheel generator convertor is changing only slowly the response of the vertical flux difference $\delta\psi_R$ upon a voltage perturbation δV_0 of the preprogrammed control voltage of the vertical field amplifier can be approximated by

$$\delta\psi_R \approx T_c\,\delta V_0 / \left\{1 + sT_D + 0.43\,sT_c(1+sT_1)(1+sT_2)\right\} \tag{1}$$

according to a simplified model. Here, the feedback voltage is = $\delta\psi_R\ (1+ST_D)/T_c$, and $T_c \geqq 55$ ms, T_D = 6.8 ms, $T_1 \approx 5.7$ ms, $T_2 \approx 3$ ms. T_1 and T_2 are related to the vessel time constant and to the response time of the vertical field amplifier. At maximum feedback gain (T_c = 55 ms) the system is nearly critically damped and the step response time is $\approx T_D + T_c/2.3 \approx 31$ ms.

2.3 Experimental results

The fig. 3 shows the plasma/wall distance for a pulse with I_p = 2.1 MA as deduced from magnetic measurements. The plasma boundary follows essentially the preprogrammed position. The measured error flux $\delta\psi_R$ and the associated feedback control error of the position $\delta X = \delta\psi_R/2\,\pi\,R_iB_i$ are also shown. The control error is < 1 cm except when I_p < 0.4 MA.

3. STABILIZATION OF THE VERTICAL POSITION

3.1 General features

Without feedback the vertical plasma position is unstable due to the quadrupole poloidal field required to produce elongated plasmas and due to the destabilizing forces of the iron circuit. Stabilization is essential. A failure of stabilization leads to a fast vertical displacement and to large vertical forces on the vessel. At extended performance ($I_p \approx$ 4.8 MA) forces of ~ 800 tons can be expected which are not acceptable with the present supports. Auxiliary vessel supports are being designed to cope with the forces in the event that the stabilization circuit fails during a high current pulse.

In JET the plasma is stabilized by feedback of the flux change $V_L = \dot{\psi}_L$ between symmetric locations Z = ± 2.7 m at $\bar{R}$ = 2.8 m. The stabilization circuit is shown in fig. 2. Voltage feedback is enabled from the start of the premagnetization, during the remaining phases the current of the radial field amplifier is controlled by current feedback and is set = 0.

3.2 Theoretical estimates

From a simplified model [3] the open loop growth rate γ, with zero output voltage of the radial field amplifier, can be estimated as

$$\gamma = \frac{1}{T_V} \cdot \frac{A''_{PP} - A'^2_{RP}/A_{RR}}{A'^2_{VP}/A_{VV} - A''_{PP}} \tag{2}$$

where $T_V \approx 3$ ms = effective vessel time constant for the penetration of radial flux

A_{RR} = 14.6µH = single turn radial field coil inductance (upper half)

$A_{VV} \approx$ 4.2µH = vessel inductance for differential currents (upper half)

$A'_{VP} \approx A'_{RP} \approx$ 1.4µH/m = mutual inductance changes for unit vertical displacement

A''_{PP} = normalized plasma self force $\approx$ 0.23µH/m² for a full size D shaped plasma ($\gamma \approx 135\ s^{-1}$).

If $0 < A''_{PP} < A'^2_{RP}/A_{RR}$ = 0.13/µH/m², then the growth time is governed by the L/R-time of the radial field coil $\approx$ 1.2 sec.

With feedback, the response of the differential voltage $V_L = \dot{\psi}_L$ upon a preprogrammed voltage perturbation V_o at the input of the radial field amplifier can be approximately expressed as

$$V_L \approx V_o \frac{T_i}{T_D G_c} \Big/ \left\{ 1 + \frac{1}{sT_D} + \frac{T_V}{G_o}(s-\gamma)(1+sT_A)(1+sT_u) \right\} \tag{3}$$

where T_i = 0.4 sec = integration time of V_L signal

T_D = 0.08 sec = derivative time constant of controller

G_o = adjustable low frequency voltage loop gain without plasma, presently $G_{o\ max}$ = = 2.1. $G_c \approx 1.9\ G_o$ = controller gain

$T_V \approx$ 3 ms = effective vessel time constant

$T_A = T_{iA}/G_A$ = effective integration time in the voltage feedback loop of the radial field amplifier (fig. 2), presently $T_A \approx$ 3.5 ms

$T_u \approx$ 1.5 ms = combined delay time due to filters in the position controller ($\sim$1 ms), the slew rate limiter ($\sim$0.2 ms) and the delay of the power stage of the radial field amplifier ($\sim$0.3 ms).

The range of stabilization is approximately

$$\gamma T_V < G_o < T_V\left(\frac{1}{T_A} + \frac{1}{T_u}\right)(1-\gamma T_A)(1-\gamma T_u) \tag{4}$$

the maximum growth rate which can be stabilized is

$$\gamma_m \approx \frac{1}{T_A + T_u} \approx 200\ s^{-1} \tag{5}$$

and the associated critical loop gain is

$$G_{o\ crit} \approx \frac{T_V}{T_A + T_u} \approx 0.6 \tag{6}$$

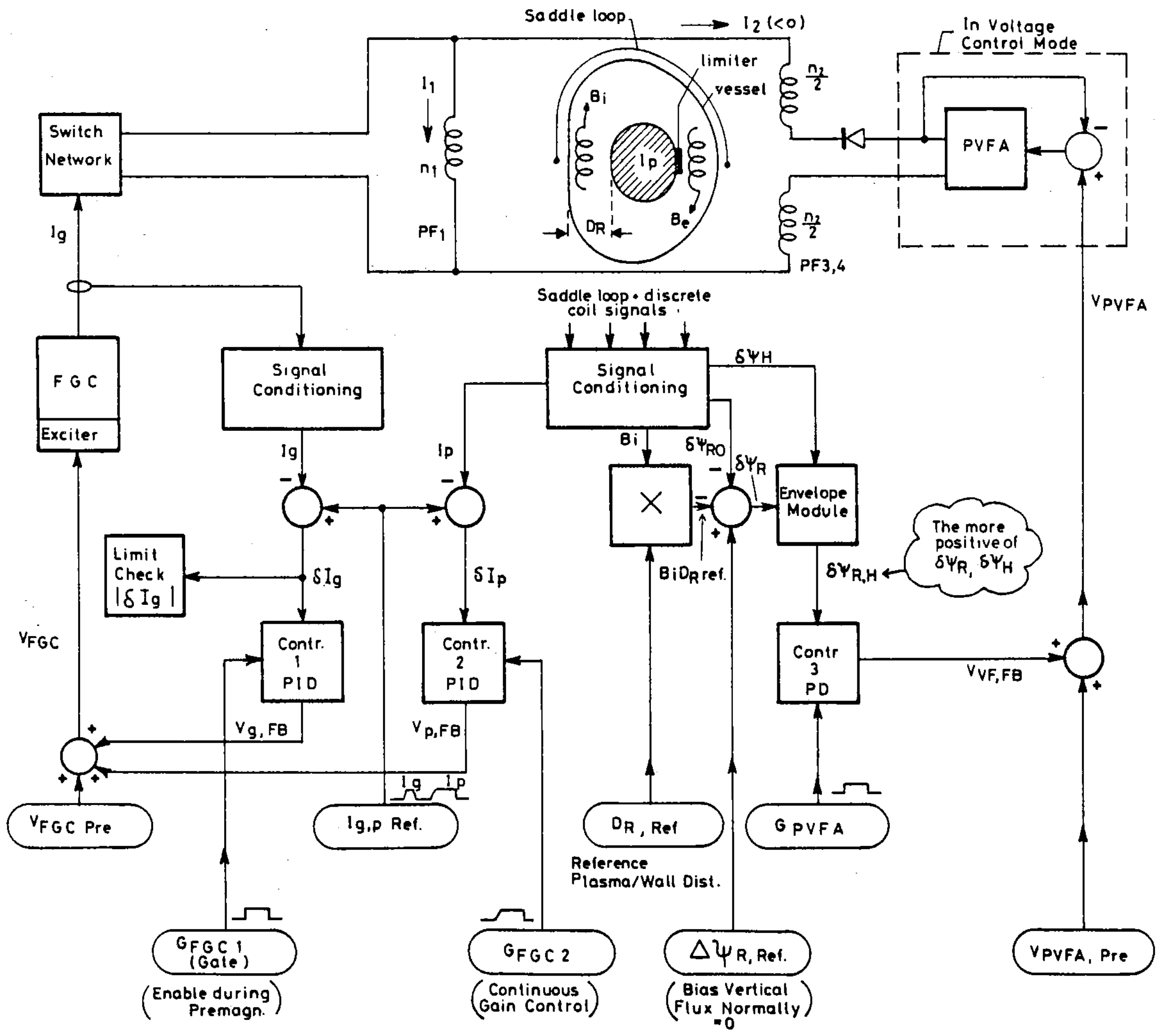

Fig. 1 Block diagram for the control of the plasma current, premagnetisation current and radial plasma position including automatic limitation of the plasma height.

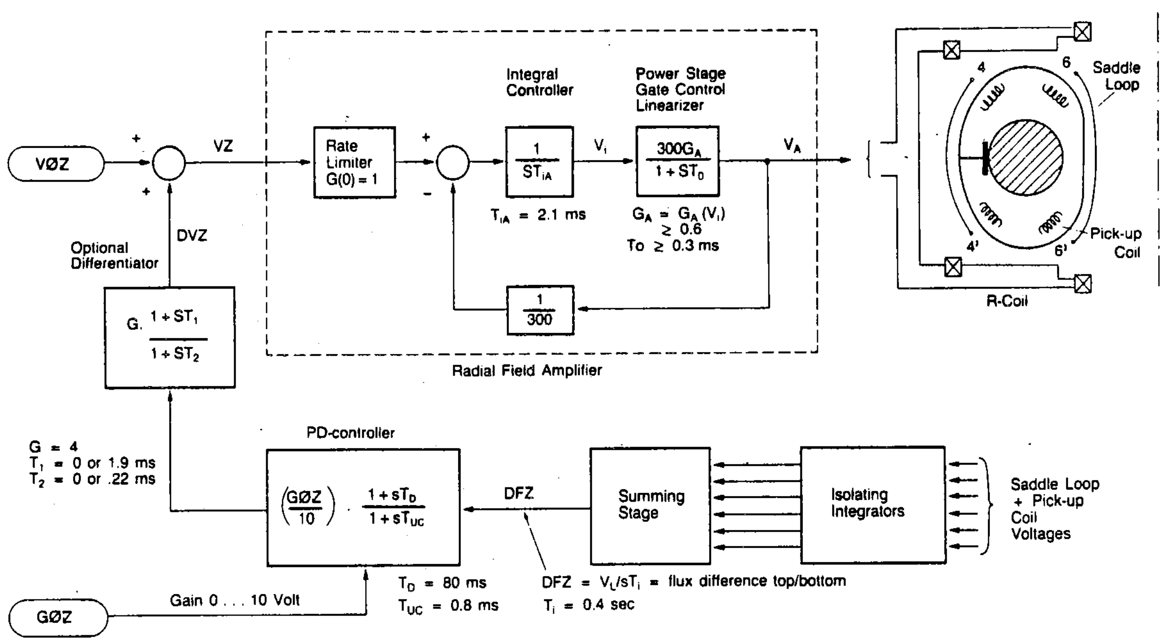

Fig. 2 Block diagram of the vertical position control. V_L = "differential loop" voltage between Z = + 1.7 m and Z = − 1.7 m at R = 2.8 m. $V\phi Z$ = preprogrammed voltage, normally set = 0. $G\phi Z$ = gain control voltage.

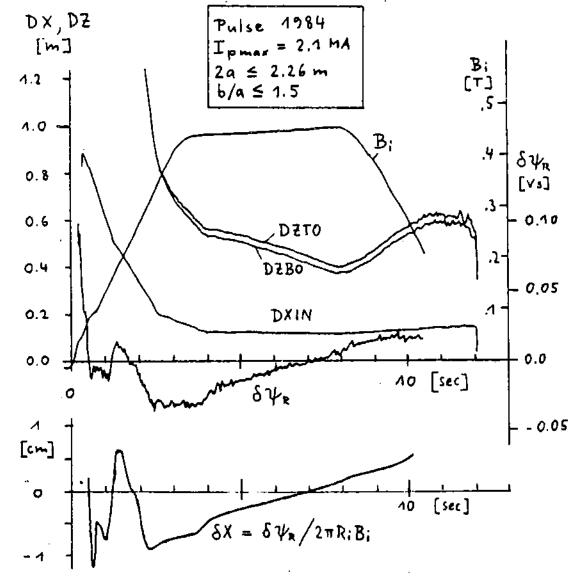

Fig. 3 Plasma/wall distances DXIN, DZTO, DZBO at the inside, top and bottom, error flux $\delta\psi_R$, magnetic field B_i at the inside, and resulting control error δX of the position of the limiter magnetic surface (plasma boundary).

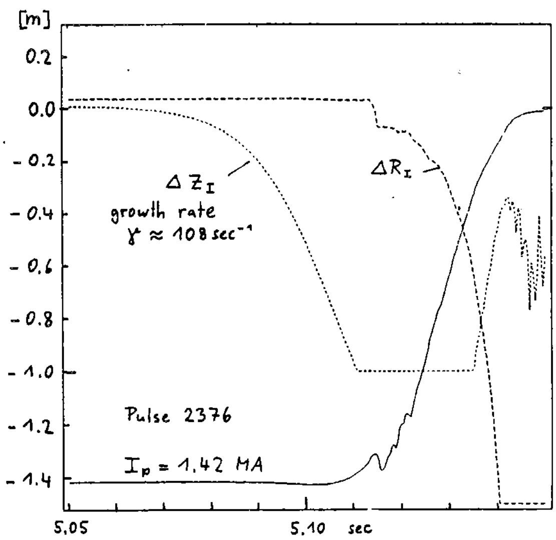

Fig. 4 Displacement ΔZ_I, ΔR_I of the current centre in a pulse where the vertical position feedback is disabled at t = 5.05 sec.

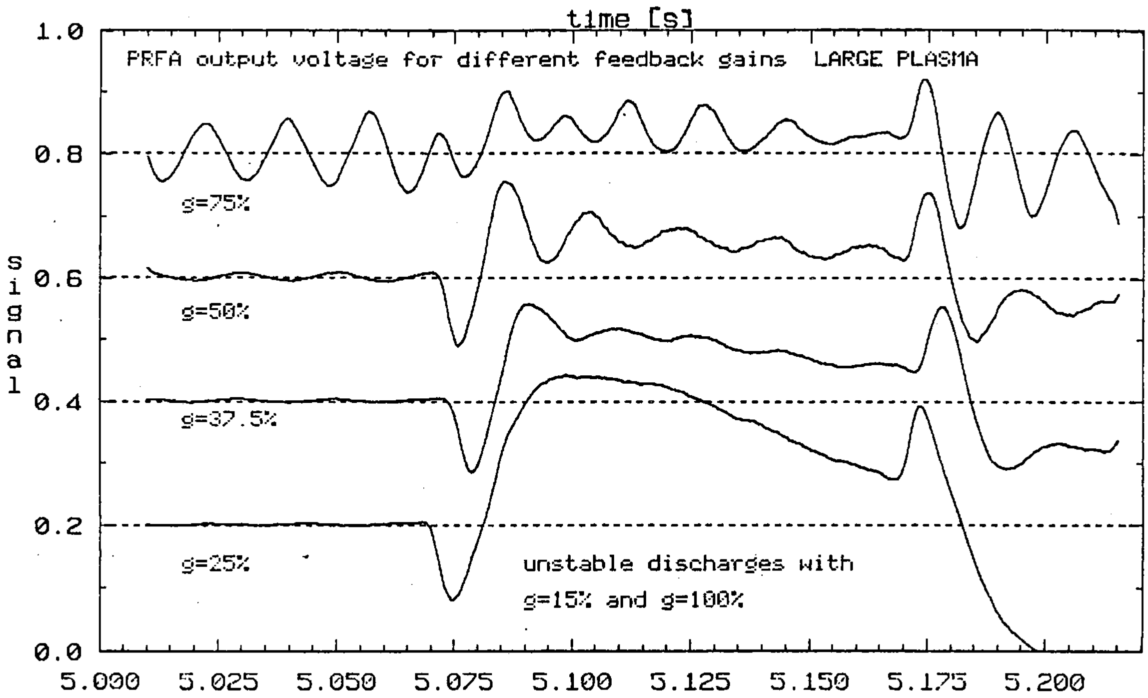

Fig.5 Square wave closed loop response of the radial field amplifier output voltage at different loop gains $g = G/G_{max}$, for plasmas with diameter $2a = 2.26$ m, $I_p \lesssim 1.5$ MA, growth rate $\gamma \approx 108\ \mathrm{sec}^{-1}$ (open loop).