PERFORMANCE OF THE C-MOD SHAPE CONTROL SYSTEM.

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ABSTRACT

The poloidal field system for Alcator C-Mod (a high-field compact tokamak) can generate elongated, single or double null diverted plasmas. The shape control system[1] consists of hardware (hybrid multiplier, real-time control computer, and associated electronics), the user interface (a set of X-Windows applications), and the underlying algorithms used by the interface to calculate the control matrices. The shape control computer generates demands to the power supplies, based on programmed waveforms and feedback from the diagnostics. Beginning in April 1993 we have used the shape control computer to program and/or feed-back control coil currents, power supply voltages, magnetic field quantities and gas pressure during plasma breakdown, and to tailor the fields during the current ramp. Representative data from the 1993 run and an evaluation of the overall performance of the shape control computer will be presented.

Introduction

The C-Mod Tokamak presents interesting challenges in the area of startup and control. The vacuum vessel construction is thick-walled stainless steel with no insulating break, with a toroidal resistance of approximately 40 micro-ohms. Surrounding the vessel and coils is a massive steel superstructure, also conductive, which braces the toroidal and poloidal field coils. The coils themselves are liquid nitrogen cooled[2]. Just after breakdown and during most of the current ramp, the magnetics diagnostics are dominated by currents in the vessel and structure. These currents are not directly measured. Their amplitudes and spatial distribution must be deduced from the magnetics diagnostics and from their effect on the plasma shape[3].

Complicating the effect of these unknown currents in the passive structure is the fact that the poloidal field coil set is sparse, and placement of the coils is a compromise between shape control requirements and very severe engineering constraints. It is not obvious *a priori* that fields produced by currents induced in the passive structure can be canceled by the driven coils to yield a properly shaped and controlled plasma equilibrium.

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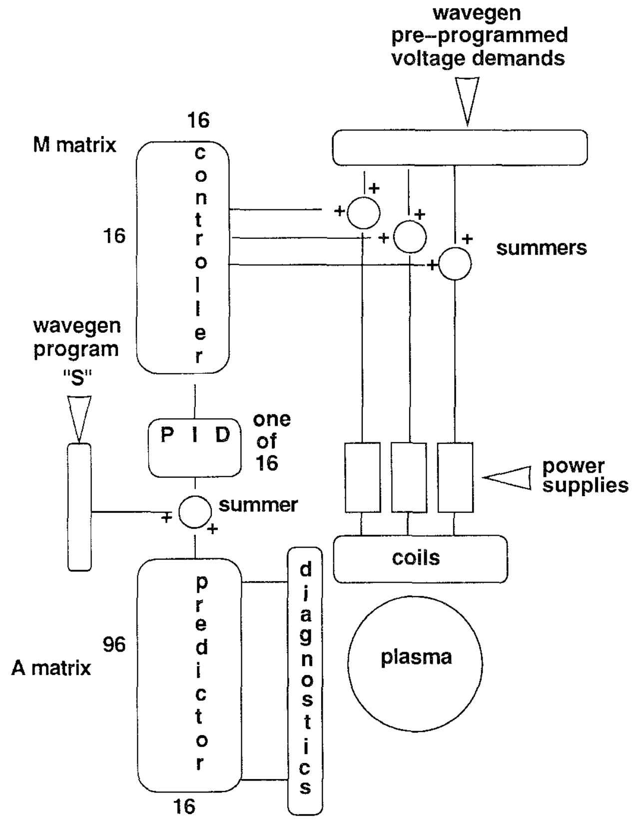
Figure 1.



Functional diagram of the control loop.

The control computer

Real-time control of the driven coils is accomplished by the Hybrid computer – so called, because it combines an analog signal path with digitally controlled gains. The computer is assembled of blocks, each of which implements an analog matrix multiplier. The essential idea is that a digital-to analog-converter (DAC) produces an analog output voltage equal to an analog input reference times a digital number. A set of DACs connected to a summing junction produces a dot product; a combination of such sets yields an analog matrix multiplier – a device which produces as outputs a set of voltages which are programmable linear combinations of input voltages. The basic block from which the computer is assembled (a

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DAC card) is a (16,4) multiplier – each of 4 outputs is a linear combination of 16 inputs. The card (a double-width Eurocard) also holds sufficient RAM to store 488 sets of 64 digital coefficients (gains), a microprocessor to control the gain switching, and assorted glue logic. A gain switch requires approximately one millisecond. Four of these cards plus a summer card form a 16 x 16 multiplier. These components are packaged into a 1/3 wide module with a front panel containing various input and output connections.

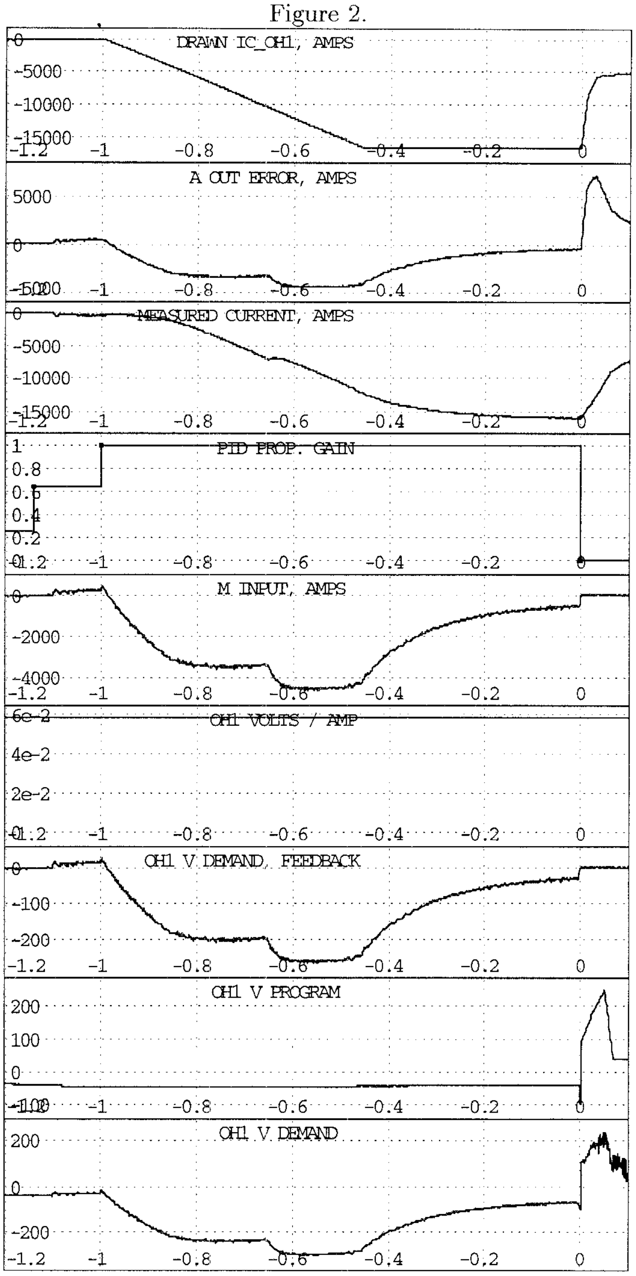
Figure 1 shows a functional block diagram of the control system, following one of the sixteen signal paths around the loop. For concreteness, we will assume this channel controls the current in the ohmic heating coil, OH1.

Diagnostics observe the plasma, producing voltages which are fed to the inputs of the computer. These include the magnetics diagnostics, and the Rogowski coils which measure the coil currents. The first processing block is the A matrix, a 96 x 16 multiplier. Its function is to multiply each of the input voltages by a digital gain, and to sum the result. In the case we are considering, all gains except that on the OH1 buss Rogowski are zero, and the OH1 Rogowski gain is set at -1. (This is the logical gain. The actual number loaded to the DAC depends on various calibration factors.) To this sum is added the wavegen programming for this channel. The analog output of this stage is the error, (programmed value - observed value). The next step provides Proportional/Integral/Derivative analog processing of the error signal. The analog gain available is [-10.,10.], with a 1.e-3 second differentiaion time constant, and a 0.1 second integration time constant. The result is distributed as demand to power supplies by the M matrix, a 16 x 16 multiplier. In the case we are considering, only the OH1 gain would be non-zero. An additional summing junction at this point allows programmed demand voltages to be added into the feedback-developed demands. This total is then fed to the individual supplies as demand voltages.

The power supplies act as amplifiers for their demand, placing their output voltage at the coil terminals. The inductance of the coils integrate their terminal voltage to produce currents and therefore fields. These soak through the structure and into the vessel. The plasma responds, the diagnostics observe, and the loop is closed.

The hybrid computer is itself the most complicated component in the control loop (with the possible exception of the plasma). To monitor its performance, the inputs and outputs of each block (A, PID, M, wavegen) are digitized and stored for post-shot analysis. Figure 2 shows digitized signals at various stages for the OH1 current. The time axis covers the pre-charge of the PF system; the coils are commutated to initiate the plasma at T=0.

Figure 2.



Signals recorded at various points through the OH1 current feedback path .

The top trace is the requested evolution of the current. This has been loaded into the wavegen from a trace drawn using a graphical editor which is one component of the user interface. The interface allows the user to program in physically relevant units (coil currents, plasma position, etc. are specified in SI) and hides (or tries to) the details of scaling from SI to the hybrid internal gains and voltages.

The next trace (A OUT error) is the difference between the drawn trace and the OH1 buss current, which is shown on the third trace (Predictor). The PID proportional gain is shown in the fourth trace. Derivative and integral gain are zero throughout. The proportional gain is switched to zero at T=0 because from that point on the OH1 supply will no longer be controlled by current feedback, but instead by the plasma current and radial position.

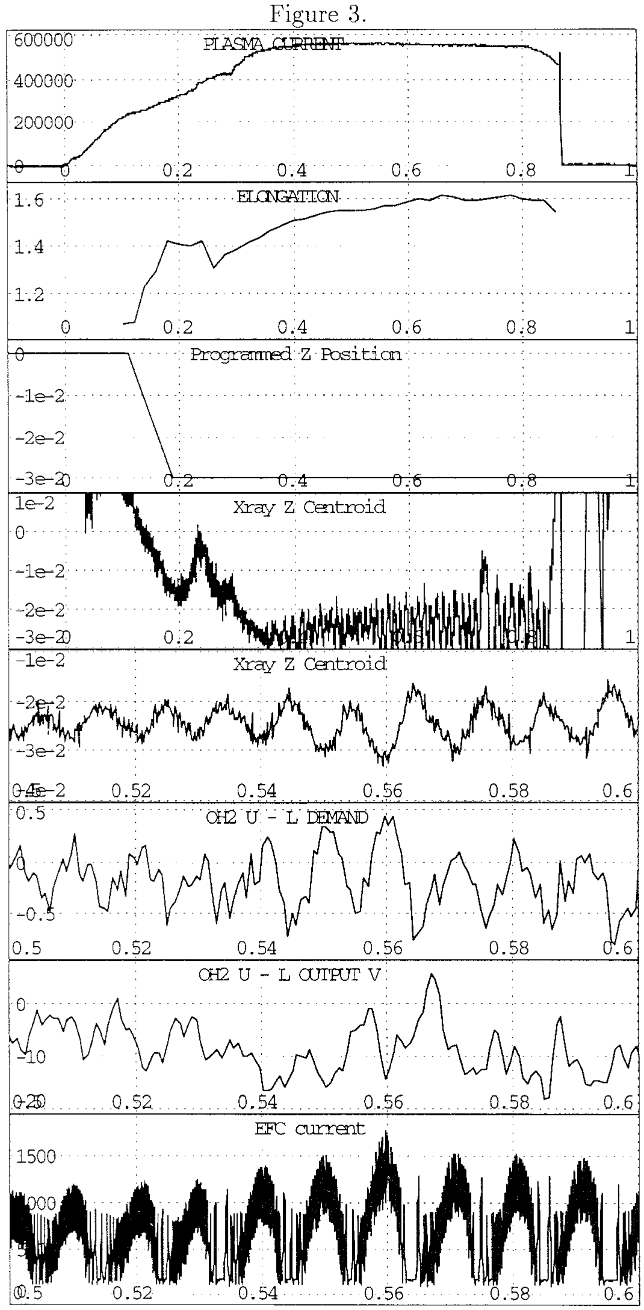
The next trace is the input to the M matrix. To this point, analog signals have represented amperes. The controller takes error as input, and emits voltage demands. In this case, since the error has units of amperes, the controller functions as a transconductance amplifier, with an impedance which has been programmed to .058 ohms. Dividing this into the coil inductance (5.8 mH) gives a characteristic time of 0.1 second for correction of errors, and can be adjusted by varying the proportional gain. This stage contributes a term to the demand due to feedback; the voltage is shown in the next trace (OH1 V DEMAND. FEEDBACK). To this voltage is added the programmed OH1 voltage, and the total demand is shown in the last trace.

Vertical Position Control

Of all the tasks performed by the control system, control of the plasma vertical position is the most demanding, because for reasonable elongations the axysymmetric mode is unstable. Control of the vertical position thus becomes increasingly difficult as the elogation, and with it the passive growth rate, increases. As our plasmas have developed from moderately elongated, limited plasmas towards higher elongation and diverted operation, tuning each element of the vertical control loop has been a priority.

Vertical position control is accomplished using two independent control channels. On the equilibrium time scale, the OH2 and EF1 coils are used as controllers. This system has a large dynamic range, but the bandwidth of this system is limited by a combination of power supply voltage, coil inductance and power supply phase delay. Control on faster timescales is provided by the EFC coils, a low inductance pair of 10-turn coils connected in antiseries, driven by a pulse width modulated chopper. This is a two-quadrant supply, which alternately connects the coil to a 1.0 kV capacitor bank, and a 1.0 kV bank of varistors, with the duty cycle controlled by the demand voltage. This combination yields a small signal bandwidth of about 1500 Hz., falling to about 300 Hz. at full power. However the dynamic range of this system is limited by the small number of turns and the 3000 A current limit on the chopper and coil. (The current limit is constrained by compression forces due to EFC current and vertical field.) A further complication is that the unipolar nature of this supply requires that it be biased at roughly 1500 A to provide optimal operation.

Figure 3.



Loss of vertical position control
due to phase lag in the OH2 power supplies.

An early attempt at exploring higher elongation is shown in figure 4. Plasma current is controlled at 0.5 MA. This plasma has an elongation increasing to 1.6. The third trace shows the programmed Z position, and the fourth the position derived through the X-ray detector arrays. The X-ray data show the Z position to average about 0.5 cm higher than requested.

Starting at an elongation less than 1.5, a vertical oscillation visible on the X-ray centroid appears and grows. On an expanded time frame, (next plot) this appears to be a coherent mode at about 100 Hz. The next frame shows the antisymmetric part of the demand to the OH2 supplies. This signal is developed by the hybrid computer via a position predictor which finds the current centroid of the plasma. It appears to be out of phase with the Z centroid, as it should. (Positive voltage in OH2 U drives positive current, which pulls the plasma up.) The actual power supply output, however, is almost exactly out of phase with the demand. The OH2 supplies show a 180 degree phase lag at 100 Hz. Convolution of the power supply output against the input confirms a .005 second lag. The power supply lag has destabilized the control loop. The last frame shows the current in the EFC system, which is attempting to hold the plasma position against the oscillation due to the OH2 supplies. The chopper is driven to zero current on each cycle, and for that period all high-frequency control of Z position is lost. The shot terminated in a vertical disruption.

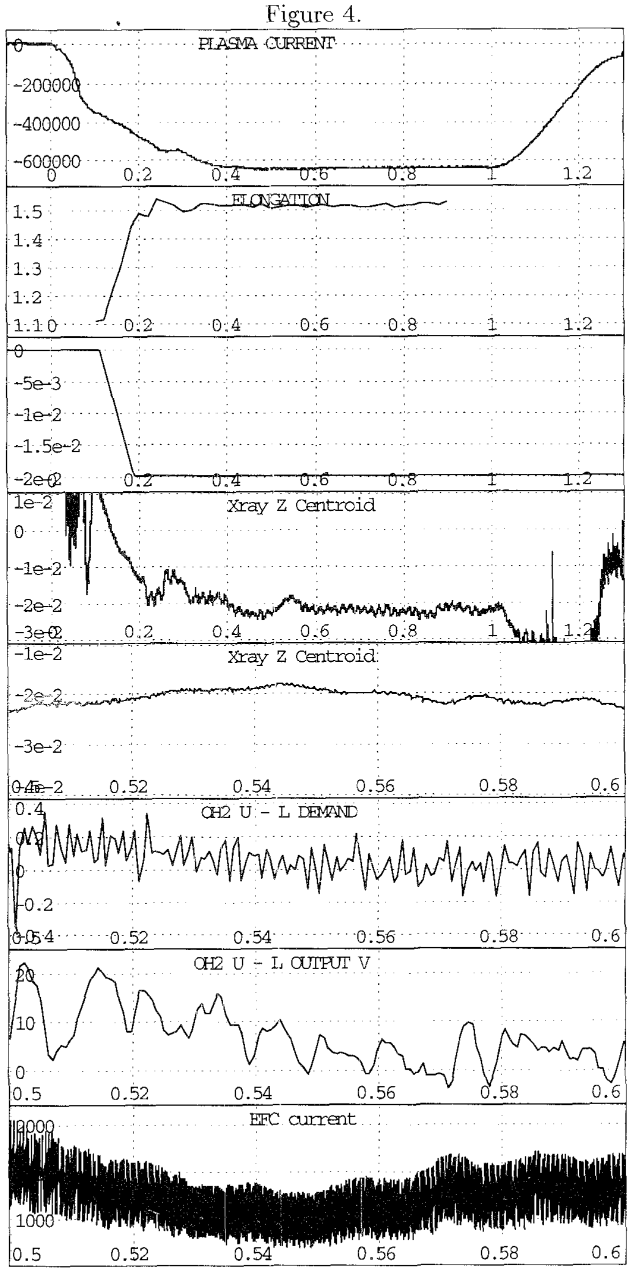
Figure 4 shows a similar shot with a different control law used in the equilibrium Z control loop. The proportional gain was reduced and integral gain was added. (The negative plasma current is not a graphics error; the machine was recently reconfigured by reversing poloidal field, toroidal field, and plasma current.) The oscillations in Z position are significantly reduced, if not eliminated. Increasing the integral gain beyond this point has been seen to cause a slow (10 Hz.) vertical oscillation.

We are proceeding with analysis of the axisymmetric instability on C-Mod, using a perturbed equilibrium model of the plasma and a detailed electromagnetic model of the vessel and structure. Initial attempts to model the passive growth rates have been compared to data and factor-of-two agreement is typically seen.

Conclusions, Current problems, Ongoing work

The C-Mod shape control system is still evolving. The hybrid hardware permits great programming flexibility, but certain areas, particularly the implementation of integral gain in the PID, are being rethought. The user interface used to program the computer has been through several revisions and will develop further, in response to increasingly ambitious requirements. As the experimental program moves towards higher plasma currents and higher elongations, the consequences of vertical disruptions (or loss of control in general) become increasingly serious, and the demands placed on the control system will only increase.

Figure 4.



Vertical position control improved by modifying proportional and integral gain.

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