AN ADVANCED PLASMA CONTROL SYSTEM FOR THE DIII–D TOKAMAK

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Abstract: An advanced plasma control system is being implemented for the DIII–D tokamak utilizing digital technology. This system will regulate the position and shape of tokamak discharges that range from elongated limiter to single-null divertor and double-null divertor with elongation as high as 2.6. Development of this system is expected to lead to control system technology appropriate for use on future tokamaks such as ITER and BPX. The digital system will allow for increased precision in shape control through real time adjustment of the control algorithm to changes in the shape and discharge parameters such as β_p, ℓ_i and scrape-off layer current. The system will be used for research on real time optimization of discharge performance for disruption avoidance, current and pressure profile control, optimization of rf antenna loading, or feedback on heat deposition patterns through divertor strike point position control, for example. Shape control with this system is based on linearization near a target shape of the controlled parameters as a function of the magnetic diagnostic signals. This digital system is unique in that it is designed to have the speed necessary to control the unstable vertical motion of highly elongated tokamak discharges such as those produced in DIII–D and planned for BPX and ITER. A 40 MHz Intel i860 processor is interfaced to up to 112 channels of analog input signals. The commands to the poloidal field coils can be updated at 80 μs intervals for the control of vertical position with a delay between sampling of the analog signal and update of the command of less than 80 μs.

Introduction

The flexible poloidal field coil and power supply system in use on the DIII–D tokamak allows for the production of discharges with a wide variety of shapes. Elongated limiter discharges, single-null divertor discharges and double-null divertor discharges with elongation as high as 2.6 are produced routinely. Discharge shape parameters such as major radius, minor radius, elongation, triangularity, aspect ratio and X–point position are variable over a wide range. This paper describes a new plasma control system for the DIII–D tokamak that will provide improved capability to make use of this flexibility in tokamak physics experiments.

The discharge shape is maintained by a feedback control system which uses measured magnetic field and magnetic flux values to regulate the current in the poloidal field coil set. For this control function, each discharge shape is characterized by a specific set of shape parameters. For example, five shape parameters of the single-null divertor (Fig. 1) are regulated by the present control system [1]: the radial position of the center of the separatrix flux surface (R_{surf}), the vertical position of the current center (Z_{cur}), the vertical position of the X–point (Z_x), and the gaps between the separatrix and the inside and top wall limiters (GAP_{in}, GAP_{top}). In the present control system an analog computer which finds the difference between the actual value of a shape parameter and the intended value of the parameter is constructed from analog adders, multipliers and dividers [2] with gains and wiring configuration that are fixed during a discharge. The shape difference is used to generate commands for the poloidal field power supplies [1].

The fixed algorithm for shape computation used by the analog system must be designed to work with discharges having a wide range of values of the shape parameters. Experience has shown that on the average, with this type of algorithm a given shape parameter can be maintained close to the intended value [1]. However, there is often a noticeable error between the computed shape parameter and the actual value in the discharge because the fixed algorithm cannot match well to every discharge. In addition, variations in plasma parameters such as internal inductance (ℓ_i), stored energy (or poloidal beta β_P), or current flowing in the scrape-off-layer (J_S) can cause changes in shape parameters which cannot be recognized correctly by a fixed control scheme, usually resulting in differences between the actual discharge shape and the intended shape which can vary with time during a discharge as the intended shape is varied and as parameters such as ℓ_i, β_P and J_S vary.

The shape errors can be significantly reduced by using a control scheme which is tuned for discharges with a narrow range in the shape parameters and plasma parameters. However, this requires a control algorithm which can be varied in time during

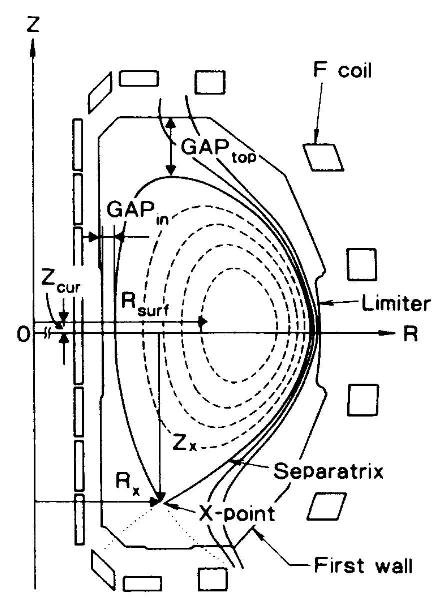

Fig. 1. Shape parameters in a single-null divertor discharge.

a discharge as the desired shape changes and as the plasma parameters change. The present analog system is not capable of this because the gains and wiring scheme are fixed and can only be changed by hand.

This paper describes an advanced plasma control system that is being implemented for the DIII–D tokamak which will provide the capability of variation of the control algorithm during a discharge and so will provide more precise control of the discharge shape. It will be possible to tune the control scheme in real time to the actual discharge shape and values of ℓ_i, β_P, and J_S. In addition there will be improved ability to control a wider range of discharge shapes and to control shape parameters not presently regulated, increased capability for widely varying shapes in a single discharge or in successive discharges, and increased ease of operation.

In addition to control of the discharge shape, the advanced control system will be capable of optimization of discharge performance through real time application of plasma physics-based algorithms. For this function the control system determines the required values of some discharge parameters in real time rather than strictly following a preprogrammed time evolution. One application of discharge optimization involves the specification of a parameter space to which the discharge should be restricted and action to be taken when the edge of the parameter space is approached. This is useful for avoidance of a density or beta limit or other causes of disruption. Other applications involve feedback regulation of a complex parameter such as the safety factor (q), the ratio of the decay index to the critical decay index for the $n = 0$ instability (n/n_c), or the loading impedance of an rf antenna. Also appropriate is control of up/down heat flux balance in a double-null divertor, control of divertor tile temperature through regulation of divertor strike point locations and control of plasma current density and pressure radial profiles through control of heating and current drive sources.

Both precision control of the discharge shape and techniques for discharge optimization are essential ingredients in a plasma control system for future tokamaks such as BPX and ITER. Development of the DIII–D advanced plasma control system described here is expected to lead to technology appropriate for use on these devices. The control system is being implemented utilizing digital technology in a way that is unique in that it is designed to have the speed necessary to control the unstable vertical motion of highly elongated tokamak discharges such as those produced in DIII–D and planned for BPX and ITER yet it still has a much simpler design than is used for digital control on other tokamaks [3,4].

Implementation of the Control System Hardware

The control system, shown by block diagram in Fig. 2, has a relatively simple design: analog signals are digitized, the digital data is transmitted to a high speed microprocessor, the microprocessor executes the shape control algorithm, and the result is written to digital to analog converters which drive the controlled systems. Initially 18 poloidal field coil power supplies will be controlled but additional inputs and outputs are provided for future use in discharge optimization algorithms.

Up to 112 analog signals from tokamak diagnostics are inputs to 7 μs conversion time, 12 bit A/D converter modules with a separate A/D converter provided for each input signal. The digitizers are CAMAC format, TRAQ system modules manufactured by DSP Technology Inc. (Table I). The TRAQ system modules have a private digitizer interface bus which is used by a custom-built digitizer controller module to control the transfer of data from the A/D converters to the real time computer. The CAMAC bus is not used except to provide power.

The real time computer is the SuperCard-2 manufactured by CSP Inc., a VME format, single board computer based on the Intel i860 RISC-design microprocessor. The processor is

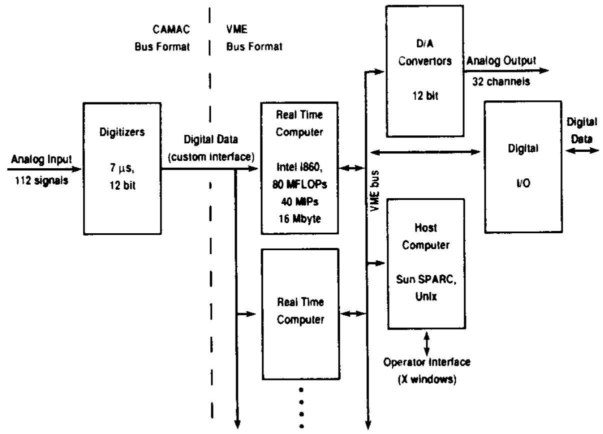

Fig. 2. Block diagram of the DIII–D digital plasma control system.

Table I. Plasma Control System Hardware

A/D converter	DSP Technology Inc., 2812A, 8 channel/ module, 12 bit, 7 μs conversion time
Real time processor	CSP Inc. SuperCard-2, Intel i860 processor, 16 Mbyte memory.
Daughter board	General Atomics, custom design, first-in, first-out memory buffer
D/A converter	DATEL Inc., DVME-628, 8 channel, 12 bit, 6 μs settling time
Host processor	Sun Microsystems, SPARCengine 1E with expansion board, 36 Mbyte
Digital I/O	VME Microsystems, VMIVME-2511

capable of performing 8×10^7 floating point operations per second simultaneously with 4×10^7 scalar unit operations per second. This processing speed can be realized during vector operations and multiplication of large matrices, the operations that are required for the tokamak discharge shape control algorithm described here. This high processing speed allows the shape control function to be performed with one processor rather than multiple processors as in other schemes [3,4]. Provision has been made, though, for the diagnostic data to be provided simultaneously to several processors. The additional processors would be used to execute the discharge optimization algorithms.

The i860 processor utilizes a 64 bit wide data bus with a 50 ns cycle time allowing peak data transfer rates between the processor and memory of 160 Mbyte/s. It is this high data transfer rate combined with the high processing speed which makes the i860 a better choice for this application than specialized digital signal processors or other general purpose microprocessors. The SuperCard-2 has a daughter board port which allows an external device to transfer data directly to the main processor memory at the full 160 Mbyte/s rate. A custom daughter board has been constructed which provides the interface between the TRAQ system digitizers and the SuperCard-2. With this custom interface, data can be transferred from the digitizers to the processor memory at 4×10^7 samples per second so that one sample from each of the 112 data input channels can be transferred to the SuperCard memory in 2.8 μs. An additional 2.8 μs is required to convert the data to floating point format from the integer format provided by the A/D converters. The total time from sampling the analog input to completion of conversion to floating point is 12.6 μs. This high speed data acquisition is a key to providing a short control cycle time with low phase shift between the input data and the output control signals.

The result of the real time calculations is transferred over the VME bus to the D/A converter modules and the analog output is used to drive the poloidal field power supplies. A digital input/output module is used for synchronization to the DIII–D discharge timing. The host computer, a Sun Microsystems SPARC architecture, VME format single board computer is used for software development and to run operator interface software. The operator interface is through X terminals which provide a graphical interface environment.

The Control System Processing Cycle

During the production of a discharge, the shape control system processor loops continuously, executing the shape control algorithm in each cycle of the loop. A brief outline of the steps involved in a control system cycle is as follows.

1. Measurements of magnetic flux, magnetic field, diamagnetic flux, poloidal field coil current and plasma current Rogowski coil signal are made to produce the data vector $\vec{D}$. Presently $\vec{D}$ has 96 elements.
2. The data vector is used to compute values of 18 discharge shape parameters resulting in the shape vector $\vec{S}$. β_P and ℓ_i are also computed for a total of 20 computed values. J_S can also be computed in this step.
3. The computed shape parameter values are compared to the target shape vector ($\vec{T}$) to generate a vector of error values: $\vec{E} = \vec{S} - \vec{T}$.
4. A total error vector is computed from terms directly proportional to $\vec{E}$, proportional to the time integral of $\vec{E}$, and proportional to the time derivative of $\vec{E}$ (a "PID" algorithm) resulting in the vector $\vec{P}$.
5. $\vec{P}$ is translated to commands to increase or decrease the current in the poloidal field coils: $\vec{I} = \vec{P} \cdot \mathbf{M}$. There are 18 poloidal field coils and 18 shape parameters so $\mathbf{M}$ is an 18×18 matrix. $\mathbf{M}$ specifies which coil currents should be changed in order to adjust each of the shape parameters.

Step 2 here, computation of the discharge shape from the measured field and flux values, is the key part of the shape control process. There are several possible algorithms for this and a digital processor, rather than an analog or analog/digital hybrid processor, was chosen specifically because of the ease with which the shape computation algorithm can be changed. Algorithms to be considered in the future include those based on neural network technology [5] or real time solution of equilibrium models.

The algorithm to be used initially is based on linearization near a specific target shape of the controlled shape parameters as a function of the magnetic field and flux values. To generate a vector of values of the shape parameters, the control system performs a multiplication of the control matrix $\mathbf{C}$ and the vector of measured data values: $\vec{S}_1 = \vec{D} \cdot \mathbf{C}$. With 18 poloidal field coils in DIII–D it is in principle possible to control 18 different shape parameters. In addition, $\mathbf{C}$ is used to compute β_P and ℓ_i. Therefore $\mathbf{C}$ is a 96×20 matrix and $\vec{S}_1$ contains the 18 element shape vector $\vec{S}$ plus β_p and ℓ_i. The control matrix for a given target discharge shape is pre-computed using a database of computed equilibria with shapes close to the target shape. A linear least squares fit is used to find the best fit between linear combinations of the magnetic field and flux values and the shape parameters that are to be controlled.

The matrix multiplication $\vec{S}_1 = \vec{D} \cdot \mathbf{C}$ (Step 2 above) consumes ~50% of the time used for each control system cycle. In a matrix multiplication routine the Intel i860 processor can make use of instructions which allow a floating point addition, a floating point multiplication and an integer unit instruction to be completed on each clock cycle. The routine presently in use achieves 79.4 MFLOPS plus 35.5 MIPS, close to the theoretical maximum, to complete the matrix multiplication in 49.7 μs. The $\vec{P} \cdot \mathbf{M}$ matrix multiplication requires 12.5 μs.

The remainder of the control system cycle includes the acquisition of data, described in the previous section, the PID computation, the selection of the control matrix and some other housekeeping functions. The total time for a single control system cycle as described above is ~100 μs (a 10 kHz rate).

An improvement in the control cycle is possible by executing the control algorithm on two time scales, a fast loop for control of the unstable vertical motion and a slower loop for control of the other shape parameters which are stable and respond relatively slowly to poloidal field coil current changes. To do this, vertical position control commands can be computed several times in each computation loop for the other shape parameters. This allows the power supply commands to be updated at approximately 12.5 kHz (80 μs intervals) for vertical position control so that frequency components up to 6.25 kHz are retained. The power supply frequency response is 3 kHz (in the best case which is for small signals) so the control system frequency response is larger than required. However, a short cycle time is necessary to maintain a small delay between sampling of the analog data and output of the power supply command. The delay is expected to be approximately 80 μs which represents a relatively small phase shift of 14° in the 500 Hz component. The rate at which other shape parameters can be changed is determined primarily by the skin time of the vacuum vessel which is several milliseconds. For this a 4 kHz cycle rate is expected.

The Shape Computation Algorithm

As described in the previous section, the discharge shape is computed from a linear combination of the diagnostic signals. Figure 3 illustrates the improved accuracy of the shape calculation with this linearization technique using the vertical position of the X–point in a single-null divertor (Z_x, Fig. 1) as an example. Figure 3(a) shows the actual value of Z_x obtained from an equilibrium calculation as a function of the value computed using the non-linear algorithm implemented in the present DIII–D analog control system [1]. Each point on the plot represents the result for a single equilibrium. The equilibria plotted in the figure have shape parameters and plasma parameters (ℓ_i, β_P) which vary over a wide range. There is a significant amount of deviation from the ideal case illustrated by the solid line where the actual and calculated values are identical.

Figure 3(b) is a similar plot for the case where the calculated value of Z_x is from a linear combination of the same magnetic measurements used in the calculation in Fig. 3(a), the equilibria in the database vary by a relatively small amount from the average shape, and β_P and ℓ_i are fixed. The linear combination method applied to this restricted set of equilibria results in a standard deviation of the difference between the calculated and actual values that is a factor of 20 smaller than in Fig. 3(a).

Figure 3(c) shows the result from a linear combination of magnetic measurements as in Fig. 3(b), but the values of β_P and ℓ_i vary in the range $0 < \beta_P < 1.6$, $0.9 < \ell_i < 1.4$. The variation in plasma parameters increases the standard deviation by a factor of 5 over the case in Fig. 3(b) illustrating the improvement that can be made by using a control matrix which is derived from equilibria having values of β_P and ℓ_i in a restricted range.

The current in the scrape-off-layer is also expected to have a strong effect on the choice of the control matrix. Figure 4 shows, for example, that the result of the equilibrium calculation of Z_x for a single-null divertor discharge is a strong function of the assumed value of the current density at the separatrix (J_X). Thus, in discharges which would be expected to have significant current at the plasma edge, the calculation of the location of the plasma boundary should include a measurement of this current.

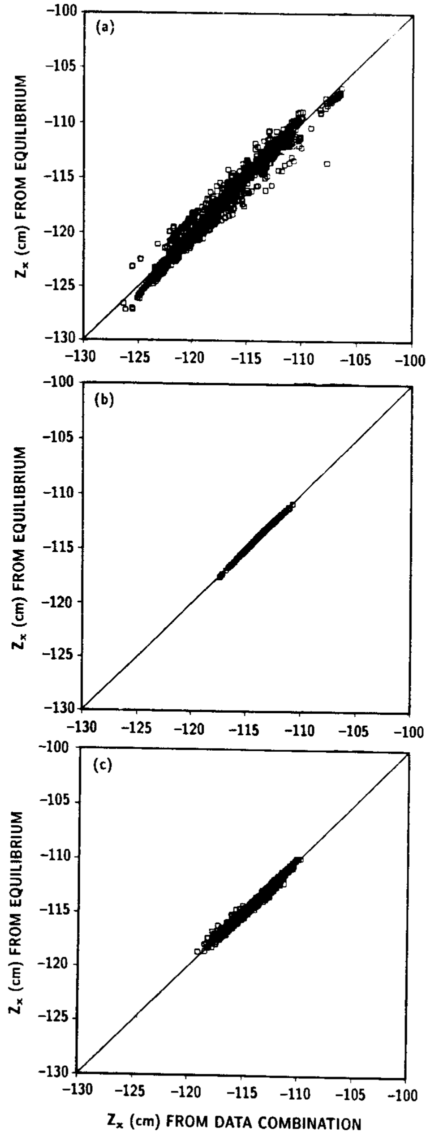

Fig. 3. Values of Z_x (Fig. 1) obtained from a full equilibrium calculation plotted versus values of Z_x obtained from several shape calculation algorithms. (a) The Z_x calculation used by the analog control system plotted for a database of discharges with widely varying single-null shapes and values of β_P and ℓ_i. The standard deviation (σ) of the difference between the equilibrium result and the control algorithm result is 0.8 cm. (b) Z_x calculated from a linear least squares fit with a database of discharges with constant ℓ_i and β_P and shapes varying in a small range. σ = 0.04 cm. (c) Z_x calculated as in (b) with a database which includes variation in ℓ_i and β_P. σ = 0.2 cm.

A given control matrix computed by linearizing near a specified discharge shape can be used to compute the discharge shape as long as the shape parameters and plasma parameters vary by only a small amount. In order to vary the shape parameters within this small range the value of the target vector $\vec{T}$ is varied. In order to change the shape parameters to values outside the valid range for a given control matrix it is necessary to change the control matrix.

For each discharge shape a set of control matrices is provided, each of which is valid for a specific range of β_P, ℓ_i and

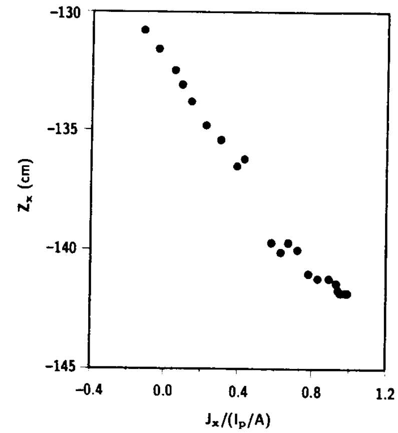

Fig. 4. The value of Z_x (Fig. 1) obtained from equilibrium calculations of a single-null divertor discharge using a fixed set of input magnetic data as a function of the assumed ratio of the current density at the X-point (J_X) to the average current density. In this example, the best fit to the magnetic diagnostic signals is at $J_X/(I_P/A) \approx 0.46$.

J_S. At each cycle of the control system these three plasma parameters are computed and the appropriate control matrix is chosen for the next cycle. Before the production of a discharge, the real time processor is programmed with all of the control matrices necessary for control of the planned shapes and a table is provided which specifies which set of control matrices should be used for each control cycle during the discharge. In addition, the target vector can be changed at regular intervals during the discharge. Together, the preprogrammed time evolution of the control matrix set and the target vector allow the discharge shape to accurately follow a programmed time evolution.

Summary

The new, digital plasma control system for DIII–D has been described. Through use of a control algorithm which can be varied in real time this system is expected to provide more precise control of the DIII–D discharge shape than is possible in the analog control system presently in use. In addition to shape control the system will provide a platform for research on real time optimization of discharge performance. A relatively simple design has been achieved through the use of a small number of very high speed digital processors coupled with high speed data acquisition hardware. The frequency response is expected to be adequate to control the unstable vertical motion of highly elongated discharge shapes.

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