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GENERAL ATOMICS

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ABSTRACT

A major modification made recently to the DIII-D tokamak was the rotation of one of the four neutral beam systems to allow injection of power in the opposite direction of the usual plasma current (counter-injection). Mixing the usual co-injection beams with the counter-injection beams provides a new capability that allows, for the first time, a partial decoupling of the injected energy and momentum during neutral beam heating experiments. To implement this capability, we have developed within the plasma control system (PCS) [B.G. Penaflor, et al., Fusion Eng. Design **71**, 47 (2004)] a model-based control algorithm for simultaneous regulation of plasma rotation and beta. The present work describes the development of the model, discusses its validation using actual experimental data, and presents the details of the implementation of the model within the PCS to allow simultaneous control of both plasma rotation and stored energy.

1. INTRODUCTION

The DIII-D tokamak has been operating since 1986 with four neutral beam injection systems supplying up to 20 MW of auxiliary plasma heating [1]. Until recently, all four of the two-source beamlines have injected power with the toroidal component in the same direction as the usual plasma current (co-injection). During the shutdown period of 2005-2006, one of the beamlines was rotated to change the angle of injection so that the toroidal component is in the opposite direction of the plasma current (counter-injection). This major modification to the tokamak was carried out to allow, for the first time on DIII-D, simultaneous control of the injected neutral beam energy and momentum.

Recent experimental results have shown that high-energy plasmas in the so-called "advanced tokamak" regime suffer from instabilities such as the resistive wall mode (RWM) that are significantly affected by the plasma rotation velocity [2]. Using counter-injection beams, a wide range of plasma rotation velocity is available to investigate these high beta plasmas. This is an advantage over previous techniques to control plasma rotation, such as magnetic braking, which have had only limited success.

2. PLASMA-BEAM MODEL

The development of a feedback control algorithm within the plasma control system (PCS) starts with the creation of a physics-based model. For the task described here, there are two physical parameters to be controlled: the plasma stored energy, E, and the plasma angular velocity, ω. The actuators for these controlled parameters are the injected beam power and the applied beam torque, which are varied with a mix of co- and counter-injected neutral beams.

The total beam power, P_b, is derived from seven ion sources, of which five are co- and two are counter-injection. (Presently, the power supply for the eighth source is unavailable.) Each source injects a power P_{bi} at an angle α_i relative to the toroidal direction, $\hat{\phi}$. Plasma stored energy depends directly on beam power, while rotation depends on the power and on the angle of injection. A simple linear relationship between the controlled parameters and the actuators expresses the change in the physical parameter as the combination of a source term and a sink term, as shown below in Eqns (1) and (2)

$$\frac{dE}{dt} = \sum_{i=1}^{7} \varepsilon_i P_{bi} - f_E \frac{E}{\tau_E} \quad , \tag{1}$$

$$\frac{d\omega}{dt} = \frac{\sum_{i=1}^{7} \varepsilon_i P_{bi} \cos\alpha_i}{m_{pl} R_0 v_b} - f_m \frac{\omega}{\tau_m} \quad , \tag{2}$$

where ε_i are the beam injection efficiencies, f_E and f_m are empirically derived scale factors for the loss terms, τ_E and τ_m are energy and momentum confinement times, respectively, m_{pl} is the mass of the plasma, and v_b is the velocity of the beam ions. The coupled differential Eqns (1) and (2) can be cast in linear state space form and combined with a proportional-integral-derivative (PID) transfer function to form a closed loop control algorithm for use by the PCS.

Although the model is only second order, it includes the important relevant physical effects. The beam injection efficiencies, ε_i, for example, are necessary because analytical results obtained from the ONETWO code [3] predict that the effects of orbit losses result in less absorbed power from counter-injected beams, or approximately 77% of the power from equivalent co-injected beams. In Eq. (2), the torque from an injected beam is proportional to the power, but varies with injection angle as $\cos\alpha_i$, resulting in negative torque for the counter-injection beams. The factors f_E and f_m are expected to be constants with a value of 1.0, but allow for the possibility that the loss terms are not completely characterized by a single confinement time constant. The values of f_E and f_m are checked with experimental data in the validation process described in the next section.

3. MODEL VALIDATION

The model described by Eqns (1) and (2) is checked for validity by comparing its predictions to actual experimental data. As a first step, transient effects are ignored and we simply equate the two terms on the right-hand side of each of the equations during steady state and calculate the factors f_E and f_m:

$$f_E = \frac{\tau_E \sum_{i=1}^{7} \varepsilon_i P_{bi}}{E} \quad , \tag{3}$$

$$f_m = \frac{\tau_m \sum_{i=1}^{7} \varepsilon_i P_{bi} \cos\alpha_i}{m_{pl} R_0 v_b \omega} \quad . \tag{4}$$

Using experimental data from an appropriate plasma discharge, we plot the values calculated for f_E and f_m, as shown in Fig. 1. In Fig. 1(a), the stored energy W_{MHD} represents the quantity E in Eq. (3). τ_E and P_{bi} are experimental parameters, and the constants ε_i are equated to 1.0 for co-injected beams and 0.77 for counter-injected beams. Note that this discharge has a changing mix of co- and counter-injected beam power, making it ideal for this test. As Fig.1(a) shows, the value calculated for f_E is approximately 1.0 and quite constant over the steady state phases of the discharge.

The test for the momentum expression, Eq. (2), performs a similar calculation of the factor f_m using Eq. (4) in steady state, as shown in Fig. 1(b). The experimental data for ω, P_{bi}, and τ_m are inserted into Eq. (4) using ω measurements from the charge exchange recombination (CER) diagnostic, which measures the impurity ion rotation. Two chords are necessary (T3 and T28) because each chord observes the light from different beams, which turn on or off during the discharge. A second, corroborating measure of plasma rotation shown in Fig. 1(b) is from magnetic probes measuring the rotation of an n=1, m=2 magnetic island, where n and m are the toroidal and poloidal mode numbers, respectively. The momentum confinement time τ_m is not measured directly, so a value of $0.8\tau_E$ is used, based on measurements made during step changes in the input torque. The remaining parameters in Eq. (4) are constants. The resulting value calculated for the factor f_m is again very close to 1.0 during the steady state phases.

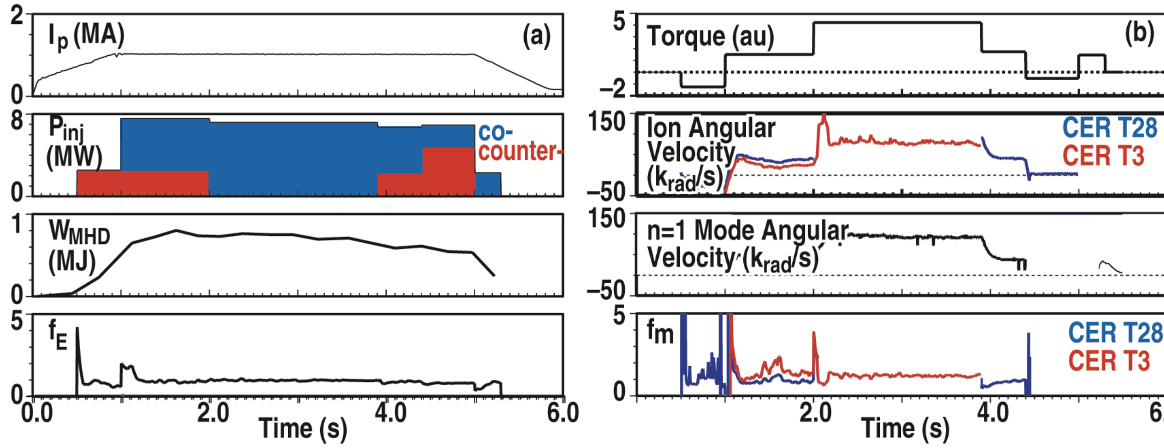

Fig. 1. (a) Energy parameter traces from discharge 124720, showing plasma current (I_p), neutral beam power (P_{inj}) from a mixture of co- and counter-injected beams, stored energy (W_{MHD}), and the energy scale factor (f_E) defined by Eq. (1). Note the steady state value of f_E is approximately 1.0. (b) Rotation parameter traces from discharge 124720. The torque is produced by beam power injected at different angles. Plasma rotation is measured using two CER chords for impurity ion rotation and magnetic probes for MHD mode rotation. Note that the rotating mode locks at 4.4 s, temporarily bringing rotation to zero. The momentum scale factor (f_m) defined by Eq. (2) has a steady state value of approximately 1.0.

The fact that both f_E and f_m are approximately 1.0 and constant during the steady state phases of the discharge suggests the model should work well as the basis for a linear feedback control scheme. The final validation step is to drive the model with the seven neutral beam source powers, P_{bi} derived from experimental data, and compare the model-predicted plasma stored energy and rotation with the measured experimental values. Results of this validation are shown in Fig. (2). Good agreement between the model-predicted states and the measured experimental data indicates the model is sufficiently accurate to allow design of an effective feedback control algorithm for implementation in the PCS.

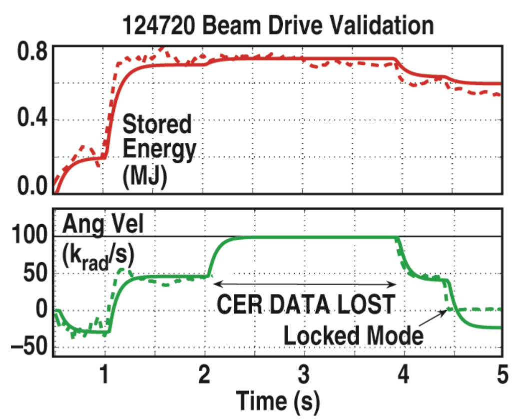

Fig. 2. Solid curves represent calculated plasma states of stored energy and rotation, using model of Eqns (1) and (2), and actual actuators (beam powers) from discharge 124720. Dashed lines show experimental values for the states. Note the source used by the CER chord for measured rotation is turned off between 2.0-3.9 s.

4. PCS CONTROL SCHEME

The plasma control system uses real-time closed loop feedback algorithms to control many of the parameters of a plasma discharge, including the stored energy. The recent availability of two types of neutral beams (co- and counter-) suggests that plasma rotation control can be added to the stored energy control algorithm, since two actuators can control two states in a linear system such as that described by Eqns (1) and (2). A block diagram of the PCS feedback control loop for this two-parameter control system is shown in Fig. 3.

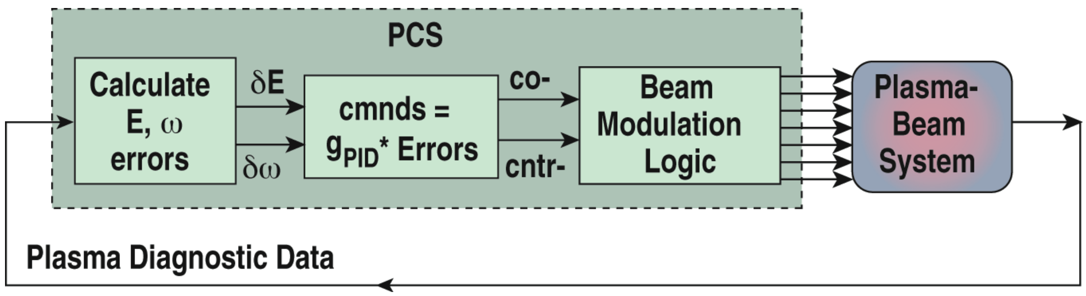

Fig. 3. Block diagram of the PCS closed loop feedback control scheme for simultaneous control of stored energy and plasma rotation.

The two states of the plasma to be controlled are the stored energy and the rotation, E and ω. These quantities are calculated from measured data with a high enough frequency to allow feedback control every few ms. Errors are calculated as the difference between the pre-programmed targets and actual parameter values, and passed to the PID gain routine, that calculates commands to the co- and counter-beams. The modulation control routine translates the two commands into seven, one for each source, with an output modulation command frequency up to 100 Hz.

5. CONTROL ALGORITHM DESIGN AND SIMULATION

Equations (1) and (2) are cast in a 2-input, 2-output state space form for control design, so that

$$\frac{d}{dt}\begin{bmatrix} E \\ \omega \end{bmatrix} = \overleftrightarrow{A}\begin{bmatrix} E \\ \omega \end{bmatrix} + \overleftrightarrow{B}\begin{bmatrix} P_{\mathrm{co}} \\ P_{\mathrm{ctr}} \end{bmatrix} \quad , \tag{5}$$

to which input and output delay blocks are added to represent the effect of beam averaging and the time required for computation of stored energy and rotation. A 2x2 control law of the form

$$\begin{bmatrix} \delta P_{\mathrm{co}} \\ \delta P_{\mathrm{ctr}} \end{bmatrix} = \overleftrightarrow{M}\begin{bmatrix} \left(\dfrac{G_{\mathrm{pe}} + sG_{\mathrm{dw}} + G_{\mathrm{ie}}/s}{1+\tau_{\mathrm{p}}s}\right) & 0 \\ 0 & \left(\dfrac{G_{\mathrm{pw}} + sG_{\mathrm{dw}} + G_{\mathrm{iw}}/s}{1+\tau_{\mathrm{p}}s}\right) \end{bmatrix}\begin{bmatrix} \delta E \\ \delta w \end{bmatrix} \quad , \tag{6}$$

is used. The G_{p}, G_{d}, and G_{i} represent proportional, derivative, and integral gains respectively, where the additional subscripts "e" and "w" refer to stored energy and rotation respectively. $\overleftrightarrow{M}$ is a matrix used to orthogonalize the control (so that commands to vary the energy have minimal impact on the rotation, and vice versa), δE and δw represent the difference between actual and reference (command) values of stored energy and rotation respectively, and δP_{co}, $\delta P_{\mathrm{ctr\,r}}$ represent the powers that must be added to any feedforward powers (e.g. calculated from the programmed energy/rotation trajectories).

Figure 4 shows the response of the system to step changes in the commanded parameters. A request for an instant increase of 1 MJ in the stored energy is fed into the system and the calculated system response is observed to be well damped with a response time of ~100 ms, and converging to zero error. The response to a separately commanded jump in rotation of 1 krad/s is also plotted. As Fig. 4 shows, the response to the energy state change does not affect rotation, and the state change in rotation does not affect the energy, indicating good orthogonality in the control system.

For the simulations shown in Fig. 4, some time constants have been included in the model to try to incorporate realistic system response times. A 12.5 ms "beam averaging" time is inherent in the beam modulation control algorithm, a 2 ms delay is included to represent the average time for the real-time equilibrium energy calculation, and a 10 ms delay is required to duplicate the combined filter and CER analysis for rotation computations. These time delays combine with the plasma confinement times and result in rise-time limitations and turn-on delays, which are evident in Fig. 4. The rotation response time is comparable to the energy response time (although the delays can be seen to be different, consistent with different computation times required to determine each quantity). The results of these simulations define operating windows on the feedback system and help determine the correct values for the gains and the PID control time constants to be used in the actual PCS control algorithm to be implemented.

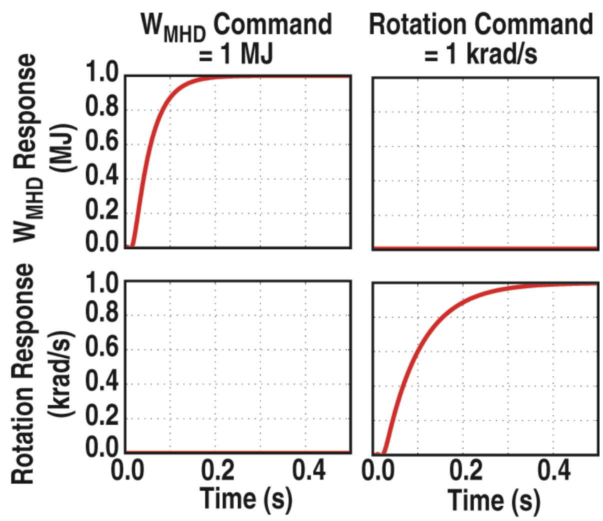

Fig. 4. Simulation of the closed loop system step response. Responses shown are to a commanded 1 MJ energy step and a commanded 1 krad/s rotation step.

6. SUMMARY AND CONCLUSIONS

We have developed a physics-based model of the plasma response to combined co- and counter-injected neutral beam heating and torque. The model is linear and orthogonal, and validations show good agreement between model predictions and actual experimental results. The closed loop feedback system response includes expected inherent delays and time constants and the response in simulations displays realistic time behavior. Results predicted from the simulations will be used to define the operating windows on the gains and PID feedback time constants within the PCS. Simultaneous PCS feedback control of the plasma stored energy and rotation will allow exploration of new physics regimes in experiments on the DIII-D tokamak.

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