FEEDBACK CONTROL OF
THE DIII–D ECH SYSTEM

by
J. LOHR, J.R. FERRON, Y.A. GORELOV, K. KAJIWARA,
D. PONCE, and M.R.WADE

AUGUST 2002

DISCLAIMER

GA–A24039

FEEDBACK CONTROL OF
THE DIII–D ECH SYSTEM

by
J. LOHR, J.R. FERRON, Y.A. GORELOV, K. KAJIWARA,[*]
D. PONCE, and M.R.WADE[†]

[*]Oak Ridge Instiutute for Science Education, Oak Ridge, Tennessee.
[†]Oak Ridge National Laboratory, Oak Ridge, Tennessee.

GENERAL ATOMICS PROJECT 30033
AUGUST 2002

Feedback Control of the DIII-D ECH System

J. Lohr, J.R. Ferron, Y.A. Gorelov, K. Kajiwara,[a] D. Ponce, M.R. Wade[b]

General Atomics, P.O. Box 85608, San Diego, California 92186-5608
[a]Oak Ridge Institute for Science Education, Oak Ridge, Tennessee.
[b]Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Abstract. The output power of the DIII-D gyrotron complex has been modulated by the plasma control system using feedback on the difference between a desired electron temperature and the ECE measurement. Operation was stable and permitted control of the flux penetration during initiation of the discharge.

I. INTRODUCTION

One of the main advantages of electron cyclotron waves for improvement of tokamak performance is that the localized absorption permits specific locations in the plasma, characterized by values of normalized flux, ρ, to be targeted for the heating and or current drive. Typically, the power absorption is localized poloidally, toroidally and radially to within a range of less than 10 cm. As an example of the use of this unique characteristic, modulated rf power, has been used to provide a local increase in T_e. The resultant propagating heat wave can be followed with very high signal to noise ratios using synchronous detection, yielding a direct measurement of energy transport in the electron channel.

Another role for electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD), which is the subject of this paper, is to force a specific time evolution of one of the plasma parameters affected by the absorbed power using a control signal derived from the difference between the desired temporal evolution and the measured evolution. The ultimate example of this would be to require the cw output of a reactor to be, say, 950 MW, and to increase the output power of the gyrotron complex until this power level was achieved. A more practical example could be to force the value of $T_i(0)$ to equal $T_e(0)$ for the duration of the discharge or to fix j ($\rho = 0.5$) to be held constant at a specified value.

In order to lead toward such advanced applications of ECH and ECCD, the DIII-D plasma control system (PCS) has been configured to provide an analog control signal to the ECH gyrotron system, which can modulate the output power in real time, using feedback. The output power can be varied over a range from 100% to 10% of the maximum power available from the system. The flexible signal processing capability of the PCS can digitally filter the response or introduce a phase shift between the error signal and the control signal sent to the ECH system.

II. EXPERIMENTAL RESULTS

Feedback control of the output power of the ECH system depends on establishing a relationship between a controllable gyrotron operating parameter and the generated power. In Fig 1, the output power is plotted as a function of the applied high voltage for a high power gyrotron operating at 110 GHz. The power can be modulated over ~90% of the normal range by varying the applied high voltage from its maximum to ~80% of the maximum. The time response for maximum to minimum output is about 0.1 ms, so rapid response to demand for more or less power can be accommodated. Significantly, the power is a monotonic function of the voltage, so no regions of positive feedback with associated control instability can arise.
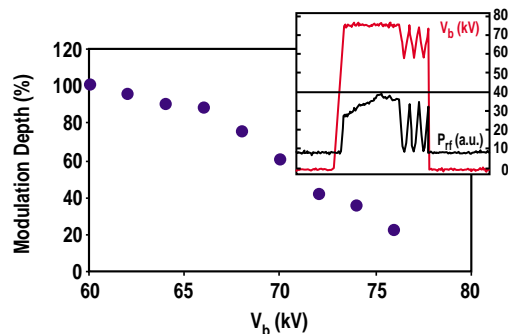

Fig. 1. The output power of a gyrotron at 110 GHz is a monotonic function of the applied high voltage, which permits feedback controlled modulation of the power supply to be used to affect the evolution of the tokamak discharge.

The electron temperature provides a first order response to ECH power. In Fig. 2(a-d), a series of four consecutive tokamak shots demonstrates the feedback control of the electron temperature at a point about halfway between the center and the edge of the plasma. The solid curves are T_e ($t,\rho = 0.5$) as measured by the ECE system. The dashed curves are the preprogrammed target T_e evolutions and the hashy short dash curves are the total
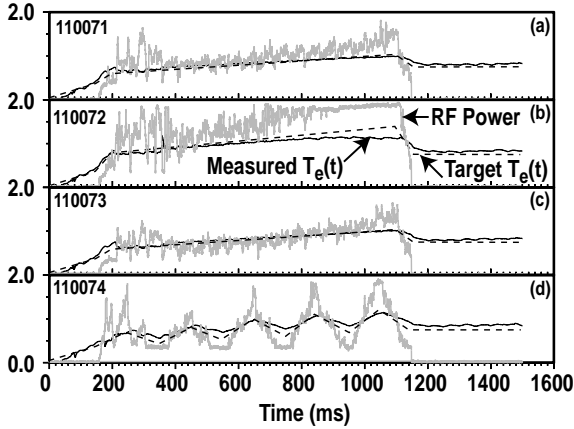
Fig. 2. Measured electron temperature (solid), commanded electron temperature (dashed) and injected ECH power (grey) for four discharges with different pre-programmed T_e evolutions at $\rho=0.5$.
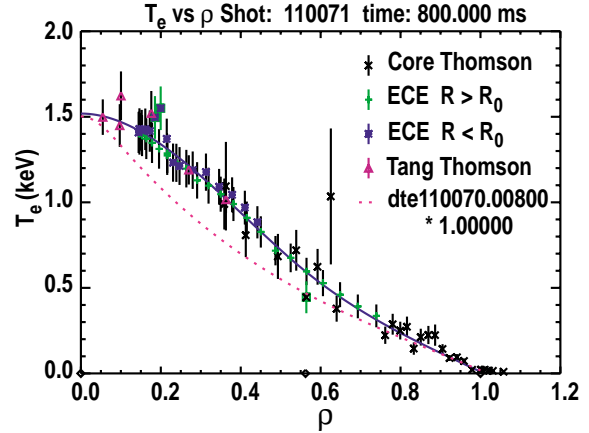

Fig. 3. Electron temperature profiles for the discharge in Fig. 2(a) and for a comparison discharge without ECH taken at 800 ms showing the control available with the ECH system.

gyrotron output power applied to the plasma. In Fig. 2(a,c) the temperature tracks the desired value fairly accurately, but in Fig. 2(b), after ~800 ms, the T_e request exceeds the ability of the system even at full output power to achieve the desired temperature. Figure 2(d) is a demonstration of the ability of the system to follow a complex time dependent waveform. Notice that the tracking has good fidelity when the temperature is commanded to increase, but lags when decreases are commanded, because the confinement time then becomes important.

The constraints of "profile consistency," that is, the tendency of the electron temperature profile to, with considerable accuracy, have a generic shape in tokamak discharges, are relaxed when T_e control is applied. This is shown in Fig. 3, for two discharges, one of which was without ECH, while the second was the discharge of Fig. 2(a) in which ECH was applied to control the temperature evolution. The figure shows the potential for continuous control of the electron temperature profile or of the current density profile if the feedback control is based on a $j(\rho)$ measurement.

Real time control of T_e provides real time control of the rate of current penetration early in the discharge. In Fig. 4, a series of discharges is shown in which successively higher electron temperatures were commanded in order to reduce the rate of current penetration. As T_e increased, longer skin times were indicated by the lower central current density measured by the motional Stark effect (MSE) diagnostic. Using a control signal derived directly from the MSE diagnostic should enable the evolution of the current density profile to be controlled.
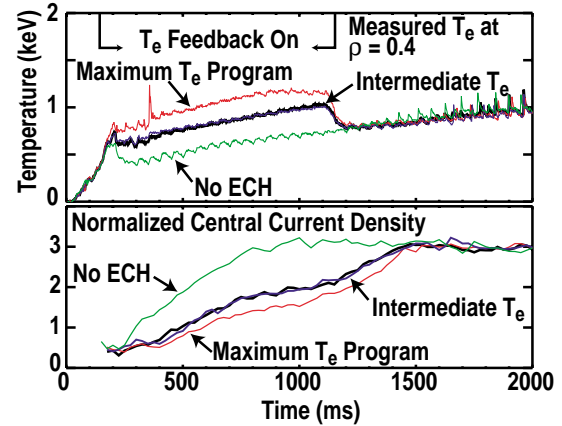
Fig. 4. Commanding higher T_e inhibits the current penetration early in the discharge and gives control over the $j(\rho)$ evolution.

III. CONCLUSION

Feedback control of the output power of the DIII-D gyrotron complex has been demonstrated using control signals derived from the measurements of the electron temperature. The technique has promise for providing real time control of electron temperature and current density profiles leading to advanced tokamak operation.