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Real-time mirror steering for improved closed loop neoclassical tearing mode suppression by electron cyclotron current drive in DIII-D

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HIGHLIGHTS

- We developed neoclassical tearing mode (NTM) control system for DIII-D, which uses six sets of real-time steerable mirrors in order to move the electron cyclotron current drive (ECCD) deposition location in plasma.
- This algorithm accurately finds the NTM island location employing motional Stark effect EFIT MHD equilibrium reconstruction.
- Successful NTM suppression and preemption has been achieved in DIII-D using this control system to automatically switches on and off gyrotrons when NTM is detected and rapidly align the NTM island and the ECCD deposition location.

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ABSTRACT

The development and operation of the neoclassical tearing mode (NTM) avoidance and control system for DIII-D, which uses six sets of real-time steerable mirrors in order to move the electron cyclotron current drive (ECCD) deposition location in plasma, is described. The real-time DIII-D NTM control algorithm residing in the Plasma Control System (PCS) automatically detects an NTM by analysis of the Mirnov diagnostics, employs motional Stark effect (MSE) EFIT MHD equilibrium reconstruction to locate the rational q-surface where the NTM island can be found, then calculates the appropriate mirror position for alignment of the ECCD with the island using ray tracing. The control commands from PCS are sent to the electron cyclotron system to switch on and off or modulate the gyrotrons and to the steerable mirror system to move the steerable mirrors to the requested positions. Successful NTM suppression has been achieved in DIII-D using this control system to rapidly align the NTM island and the ECCD deposition location, and to actively maintain the alignment as plasma conditions change.

1. Introduction

The tearing mode is a magnetic island that is caused by a perturbation to the plasma current of the same helicity as the field line on a rational flux surface. The NTM is a tearing mode which is classically stable but can be destabilized by a helical perturbation of the bootstrap current. Fully grown neoclassical tearing modes (NTMs) with $m/n = 3/2$ degrade the energy confinement by typically 10–30%, while modes with $m/n = 2/1$ lead to severe energy loss and frequently to disruption [1].

Microwave powered co-current drive at the mode rational surface can suppress the NTM by increasing the linear stability and replacing the missing bootstrap current. There are many ways of producing current drive in tokamaks, but for NTM control electron cyclotron current drive (ECCD) has the advantages of narrow current drive placed at a specific harmonic cyclotron resonance, higher efficiency, scalable high power and long pulse operation [2]. Keeping these and many other scientific uses of ECCD in mind, 6 sets of gyrotrons, waveguides and EC launchers have been installed at DIII-D.

Electrons gyrate around magnetic field lines as they travel in the toroidal direction. A microwave beam at the electron cyclotron resonant frequency will deposit energy into the electrons. By adjusting the beam injected direction to be perpendicular, more heating effect is obtained; by tangential deposition, more ECCD is obtained. At DIII-D, a microwave beam is generated with up to 6 gyrotrons with a total injected power of ~3 MW that can be generated for up to 5–10 s, passed through ~100 m of waveguide,

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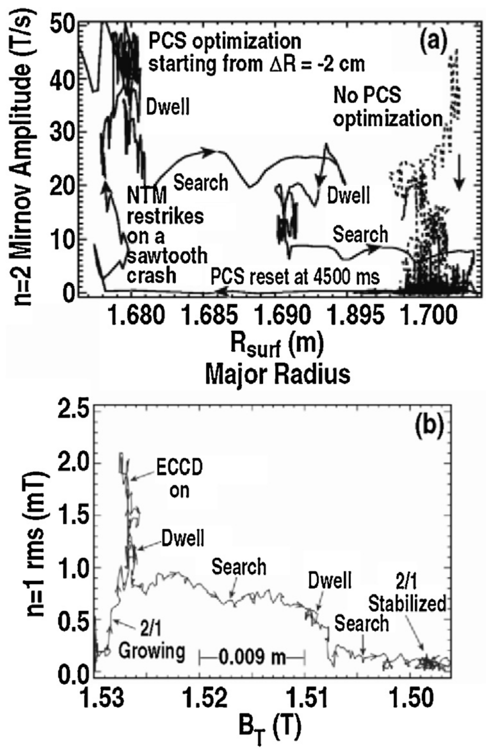

Fig. 1. Examples of previous NTM suppression experimental results from DIII-D: (a) 3/2 suppression by moving the plasma in and out radially (NTM island moved with respect to the $2f_{ce}$ resonance); (b) 2/1 suppression by changing the toroidal field and thus the $2f_{ce}$ resonance location [2,3].

then directed by the electron cyclotron heating (ECH) launchers [4,5].

2. The need for steerable mirror ECCD NTM control at DIII-D

The use of ECCD for NTM control has been studied in various tokamaks including ASDEX Upgrade [7], DIII-D [2], TEXTOR [8], Tore Supra [10], JT-60U [11]. In DIII-D, successful NTM stabilization has been achieved, and it has been shown that preemptive stabilization of NTMs by application of highly localized ECCD has led to operation at increased plasma pressure, up to the no-wall kink limit [2]. In these experiments, ECCD deposition locations were changed by moving the plasma in and out radially (NTM island moved with respect to the $2f_{ce}$ resonance) or by changing the toroidal field and thus the $2f_{ce}$ resonance location as shown in Fig. 1. However, these methods are slow and change the plasma equilibrium. Because of these drawbacks, they have not been used in regular DIII-D physics experiments.

In order to overcome these limitations, a new real-time steerable mirror control system to move the EC deposition location was installed this year. The new method of using the steerable mirror has three advantages over the previous ones. The first advantage of the new method is the ability to keep the radial position and toroidal field constant during NTM avoidance/suppression. This facilitates physics experiments in which the constancy of the plasma conditions is of importance for interpreting and understanding the experimental data for plasma physics and for exploring the range of achievable steady state conditions using advanced island control schemes. The second advantage is faster NTM suppression capability of the mirror actuation. Finally, since there are several mirrors, power management can be utilized for multiple purposes, such as simultaneous control of multiple magnetic islands (such as $m/n = 2/1$ and 3/2 islands).

3. Architecture of the real-time mirror steering NTM control system in DIII-D

Architecture of the real-time mirror steering NTM control system in DIII-D is shown in Fig. 2. The system consists of the diagnostic measurement, Plasma Control System (PCS) logic, and the mirror and gyrotron actuators.

The condition inside the DIII-D plasma is monitored with many diagnostic signals. The real-time NTM control system uses the Mirnov diagnostics, motional Stark effect (MSE) measurement, Magnetic sensors and interferometer signals. The real-time equilibrium reconstruction is obtained by the MSE constrained EFIT. A dedicated computer running real-time NEWSPEC analyses the Mirnov measurements to obtain the $n = 1$, 2 mode amplitude, frequency and the phase. The density in the plasma (which can cause refraction of the *rf* beam) is obtained from the interferometer signals.

The main control algorithm, which detects the island formation, makes the decision to turn on the ECCD system and selects the location of the deposition, resides in the PCS. The PCS NTM control logic calculates the q = surface location corresponding to the NTM mode (3/2, 2/1) from the MSE-EFIT reconstruction. Alternative diagnostic for NTM location detection with oblique ECE has been installed at DIII-D. This diagnostic coupled with a notch filter can find the relative ECCD deposition location with respect to NTM as opposed to the method of finding the two values separately [8]. This method has the advantage of getting rid of the relative calibration issues but due to high noise issues of this system, and the robust and accurate MSE diagnostics at DIII-D, MSE diagnostic based control has been implemented. The target for the ECCD is then obtained by the intersection of the q-surface with the $2f_{ce}$. The ECH launch mirror angle that aligns the ECCD with the target is obtained by using a linearized ray tracing algorithm and is compensated for the refraction due to changes in the density. The TORAY-GA code [9] is ran offline around the plasma equilibrium of interest with various mirror angles and plasma densities to obtain these linearization coefficients. The island formation is detected when a preset Mirnov amplitude level is exceeded for a predetermined period of time (with typical values between zero and 10 ms); this is adjusted to reject false positives.

The PCS sends the absolute encoder position request corresponding to the calculated mirror angle to the ECH launcher system through a private network. These commands are directed to the six motor control units via UDP Internet protocol. In-house-built control boards with a 40 MHz Micro Controllers unit set the voltage level of the power supplies (50 V and 60 A) with pulse width modulation frequency of 30 kHz based on the error in the position. These boards are placed close (∼4 m) to the DIII-D tokamak in a rack with neutron protection shield to reduce the noise in communication with the motor and encoder. Each motor, Motor Technology part 121A201-10, a 27-V armature with a 5.54:1 speed reduction ratio, is connected to a gear set outside the vessel and moves a mechanical assembly that is designed to smoothly rotate a mirror inside the vessel, which in turn directs the electron cyclotron waves. Because of the extremely low duty cycle, the motor is run at ∼50 V in order to obtain improved performance. Mirror rotation is measured with a 14-bit absolute rotary encoder, which turns at the same rate as the leadscrew nut 1/3 of the motor speed. A dc gear motor is used to drive the mirror. Encoders send the absolute positions to the motor control units, which are compared to the requested values from PCS, thereby closing the feedback control loop. Cyclic execution of the fast feedback algorithms enables rapid alignment between the NTM island and the ECCD deposition location, as well as active maintenance of this alignment as plasma conditions change.

Similarly, the PCS sends the gyrotron power and pulse request to the ECH Multiple Gyrotron Control System. This system uses

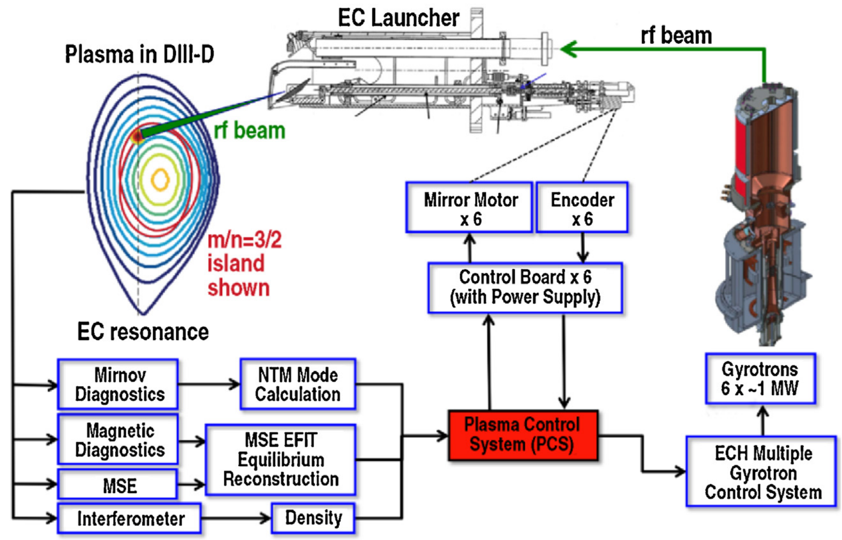

Fig. 2. Block diagram of the real-time NTM control system.

software distributed among networked computers, interfaced to a programmable logic controller (PLC), the timing and pulse system, power supplies, vacuum and waveguide controls, and instrumentation [5].

4. Performance of the real-time control system

The mirror control board operations and the communications between the PCS, the mirror control board and the encoder system has been streamlined for fast response time. As seen in Fig. 3 the response time of the mirror control depends mostly on the mechanical force that the motor has to overcome in order to move the system and to a lesser degree on the encoder readings. The mechanical response depends on the initial position of the mirror and the gear assembly. Once the motion commences, the mirror can be moved such that the center deposition location of the ECCD moves at a top speed of ≈4 mm/ms along the $2f_{ce}$ surface.

The motion of the motor is controlled with a modified Proportional-Integral-Derivative (PID) algorithm. The main algorithmic use of the control is to follow the q-surface during the shot. In many experiments, due to the physical location of the ECH launcher ports, the mirrors have to operate close to the port boundaries to direct the *rf* to the plasma rational surface of interest. This makes overshoot of the mirror motion hazardous. Thus, each controller is tuned separately using relay-feedback for tracking performance with minimal overshoot to avoid hitting the limits [6]. The first modification to the regular PID algorithm is aimed at overcoming the initial stickiness. The full 50 V is fed to the motor when starting the motion no matter the error until the mirror starts moving. The second modification was to avoid overuse to extend the hardware lifetime by turning the voltage command off when the mirror is close to the target value with negligible velocity.

Multiple step responses of the mirror control are shown in Fig. 4. The mirrors align and stop within 3 counts, which corresponds to ∼3 mm along the $2f_{ce}$ surface, of the requests. Tracking performance from an experiment is shown in Fig. 5. In this example, the requested value corresponds to the 3/2 surface calculated by the PCS. The control keeps the alignment with the 3/2 surface well within the full width maximum of the ECCD, which is in the order of 2–3 cm.

5. Use of the real-time steerable ECCD control system for NTM control

The real-time steerable ECCD control system has been used reliably for NTM suppression and preemption. An example of an NTM suppression using real-time $q = 3/2$ surface following is shown in Fig. 6. The PCS algorithm detects the island formation and turns on the gyrotrons and moves the mirrors to make a 4–5 cm adjustment to align the ECCD with the island. Then,

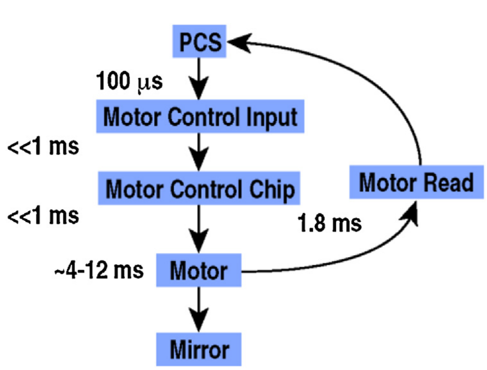

Fig. 3. Latency in the real-time control system.

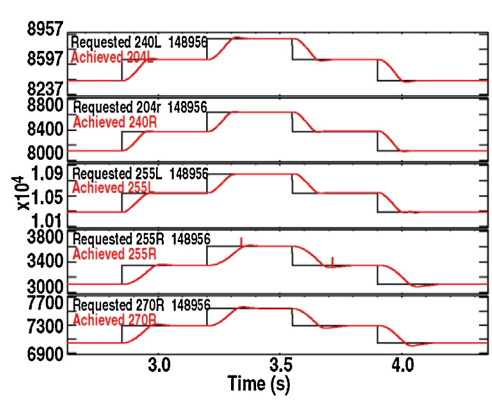

Fig. 4. Multiple step response of the mirror control.

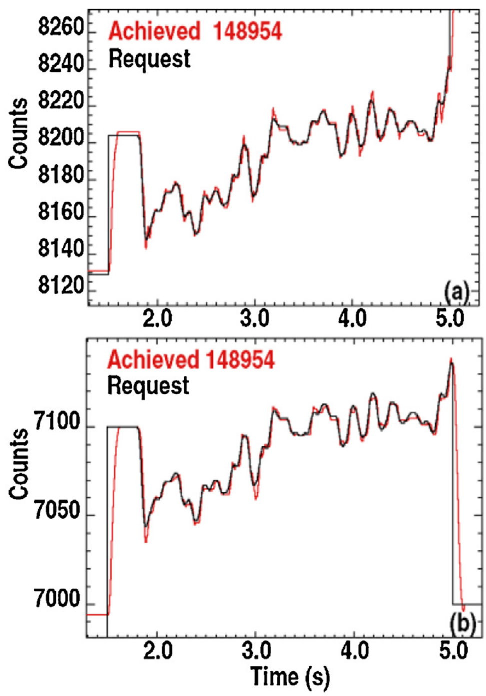

Fig. 5. Tracking performance of the mirror control system: shown are the requested and the achieved position requests; (a) 240L mirror and (b) 285R mirror.

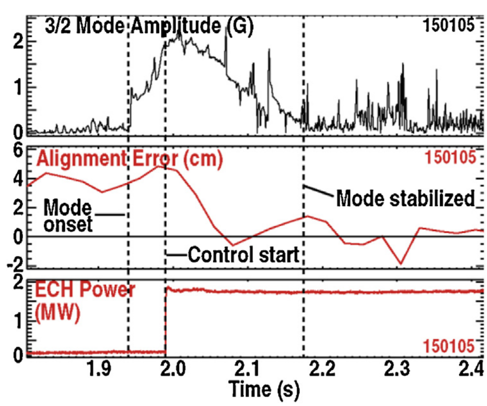

Fig. 6. NTM suppression using real-time $q = 3/2$ surface following (absent ECCD, the mode grows to about 7 G in 0.4 s, not shown). Shown are the magnitude of the 3/2 mode; the misalignment between the calculated ECCD deposition location and the island location along the $2f_{ce}$ surface and the gyrotron power.

the mirror alignment in response to variations of q-surface. With the gyrotrons on and the ECCD aligned with the NTM, the mode reduces in size and is finally fully suppressed. It takes less than 200 ms from the start of the control activation until its full suppression.

In this example, the ECCD deposition location is deliberately misaligned approximately 4 cm high when the algorithm detects the island formation. The “dud” detector control requires a Mirnov amplitude trip level to be exceeded for a minimum time; this is adjusted to reject false positives. Consecutively, the control automatically fully turns on the gyrotron and aligns the current drive with the island location via real-time mirrors. It takes less than 0.3 s from the start of the mode growth until its full suppression (0.2 s from control activation).

6. Conclusion

The development and operation of the new NTM avoidance and control system for DIII-D, which uses six sets of real-time steerable mirrors in order to move the ECCD deposition location in plasma as foreseen in ITER, is described. Successful NTM suppression has been achieved in DIII-D using this control system to rapidly align the NTM island and the ECCD deposition location, and to actively maintain the alignment as plasma conditions change.

Acknowledgments

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