Topic: EX-S

Increased Stable Beta in DIII–D by Suppression of a Neoclassical Tearing Mode Using Electron Cyclotron Current Drive and Active Feedback*

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Experiments in DIII–D show that neoclassical tearing modes can be stabilized by means of precise, real-time feedback-controlled positioning of localized electron cyclotron current drive ("search and suppression"), allowing the stable beta to be increased. An example is shown in Fig. 1 in which the n=2 (m=3) rms Mirnov amplitude can be seen to become negligible by application of the ECCD.

The development of techniques for neoclassical tearing mode (NTM) suppression or avoidance is crucial for successful high beta/high confinement tokamaks. Neoclassical tearing modes are islands destabilized and maintained by a helically perturbed bootstrap current and represent a significant limit to performance at higher poloidal beta [1]. The m=3, n=2 mode alone, for example, can decrease plasma energy by up to 30%. The confinement-degrading islands can be reduced or completely suppressed by precisely replacing the "missing" bootstrap current in the island O-point with off-axis, radially localized radio frequency (rf) driven current as first demonstrated in the Asdex Upgrade tokamak [2]. Implementation of such a technique is accomplished in the DIII-D tokamak in the presence of periodic q=1 sawtooth instabilities, a reactor relevant regime.

Radially localized off-axis electron cyclotron current drive (ECCD) must be precisely located on the island. The second harmonic resonance $2f_{ce}$ for the 110 GHz gyrotron frequency in DIII–D is placed on the inboard midplane near the q=3/2 location in order to improve current drive over an outboard resonance location where electron trapping effects are

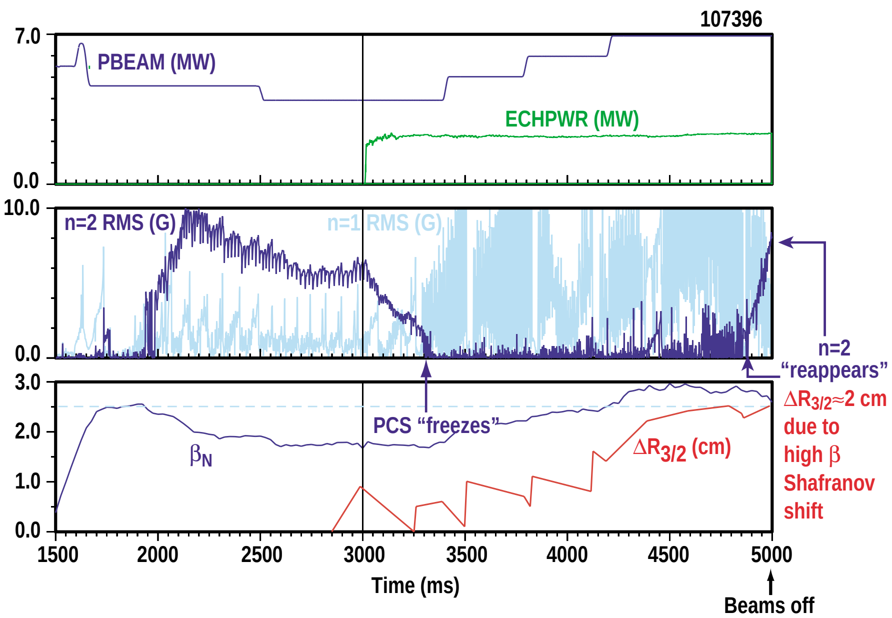

Fig. 1. Approximately 2.3 MW of ECCD is used to suppress an m/n=3/2 NTM in discharge #107396 after which neutral beam power is raised to increase beta. β_N is increased by 55% (despite large sawteeth and fishbones). The NTM reappears because the Shafranov shift has moved q=3/2 about 2 cm off the optimum ECCD location. Note that there is no further PCS position optimization once the NTM has been suppressed.

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larger. The plasma control system (PCS) uses a “search and suppress” method to make either small rigid radial position shifts (of order 1 cm), of the entire plasma (and thus the island) or small changes in toroidal field (of order 0.5%) which radially moves the second harmonic (and thus ECCD) location to find and lock onto the optimum position for complete island suppression by ECCD. An example (#106654) is shown in Fig. 2 starting from $\Delta R \approx 2$ cm off optimum along with another discharge (#106642) with fixed position on the optimum from scans of previous discharges. This is based on minimizing real-time Mirnov measurements of the mode amplitude. This experiment represents the first use of active feedback control to provide continuous, precise positioning. Successful stabilization of the m/n=3/2 mode resonant at safety factor q=1.5 is made despite changes in island location from discharge-to-discharge or from time-to-time within a given discharge (with sawteeth). A well-aligned (to $\Delta R \lesssim 1$ cm) level of peak ECCD current density of about twice the local equilibrium bootstrap current density is required for complete stabilization. The total rf driven current is about 2% of the plasma current I_p within the q=3/2 surface. Once the PCS is satisfied, it freezes the position as shown in Fig. 2. Note that by pre-programming a reset to the starting position at a later time with the ECCD still on, the mode reappears showing the pinpoint accuracy needed in placing the ECCD.

With the NTM suppressed, the supplementary neutral beam heating power can be programmed to gradually rise so as to increase beta. With the ECCD still on and the PCS frozen on the optimum position at lower beta, beta is raised 55% (20% higher than the peak before the onset of the NTM) before the mode reappears as shown, for example, in Fig. 1. Analysis of the location of the q=3/2 surface location change (from EFIT) shows that q=3/2 moves outboard by about 2 cm as beta is increased (consistent with the Shafranov shift). Thus the ECCD is not on the new, changed optimum position. Real-time tracking by the PCS is planned to respond to changes in the q=3/2 location (with beta and/or due to sawtooth crashes as noted by the jumps in $\Delta R_{3/2}$ in Fig. 1) so that the optimum location for ECCD suppression can be maintained in the absence of a mode.

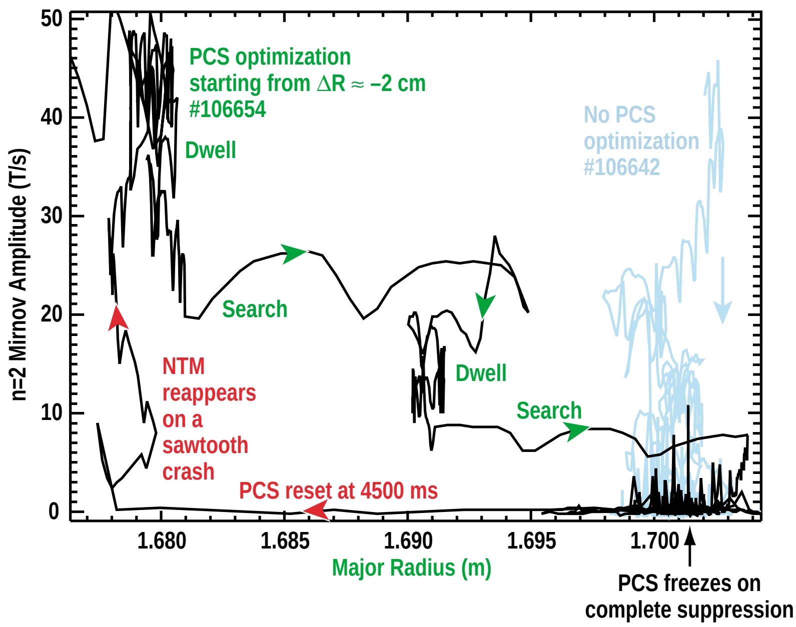

Fig. 2. Trajectory of n=2 Mirnov amplitude versus plasma major radius with (#106654) and without (#106642) real-time control of optimum rigid plasma position for ECCD suppression (m/n=3/2 NTM, three gyrotrons for 1.5 MW injected from 3000 to 4800 ms).

[1] O. Sauter et al., Phys. Plasmas **4**, 1654 (1997).
[2] G. Gantenbein et al., Phys. Rev. Lett. **85**, 1242 (2000).