Twenty-One Years Establishing ECCD Stabilization of NTMs in DIII-D

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Background

Since the seminal predictions in 1997 [1-3] that narrow radially localized electron cyclotron current drive (ECCD) could stabilize neoclassical tearing modes (NTMs) by replacing the "missing" bootstrap current in an island, DIII-D has been at the forefront of experimental validation. This was enabled by the installation of 110 GHz gyrotrons, waveguides and mirrors [4] for electron heating, with DIII-D ECCD experiments on stabilizing NTMs beginning in 2000.

Initial Experiments and the Development of Real-time Alignment Control

Initially there was no real-time capability for ECCD alignment on a rational surface. *Complete* stabilization on DIII-D of an NTM (m/n=3/2) using two gyrotrons injecting 1 MW was achieved in 2000 (following ASDEX-Upgrade). This is shown in Fig. 1a. The alignment was varied from shot-to shot by changing the toroidal field BT to linearly move the second harmonic resonance and thus the ECCD location with respect to the island location (a higher order change in BT); this is shown in Fig. 1b. Precise alignment is necessary for complete stabilization for this mode in this plasma with only 1 MW injected [5].

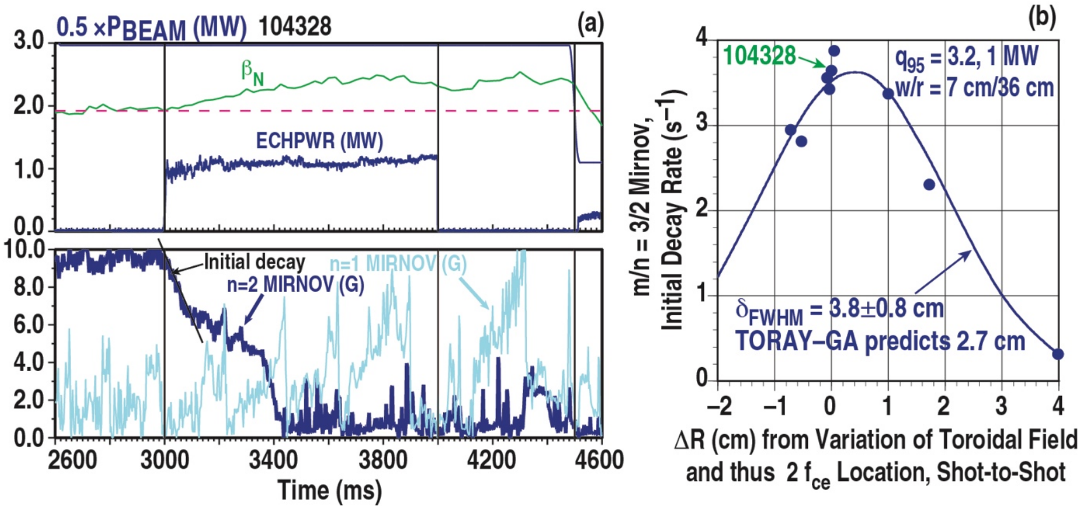

Fig. 1. *First case of ECCD stabilization of an NTM (m/n=3/2) in DIII-D. (a) NBI (6.0MW) and EC (~1 MW) powers, normalized beta, and n=2 and n=1 Mirnov amplitudes. (b) Initial n=2 Mirnov decay rate versus fixed toroidal field varied shot-to-shot.*

Initially in 2000, mirrors could only be moved between shots, and unlike AUG which swept BT to get a transient alignment, BT in DIII-D could not then be changed during a discharge. The state-of-the-art shape control was then utilized to move the island with respect to the ECCD at fixed BT by changing the plasma major radius RSURF [5]. The plasma control system (PCS) used a real-time Mirnov signal and adjusted RSURF in a series of dwells and searches (steps) to dynamically stabilize the mode ("Search and Suppress") provided the EC power is high enough. This is shown in Fig. 2; an alternate was later developed (after power supply modifications) to keep RSURF fixed and instead vary BT in steps, which is topologically equivalent [6]. While "Search and Suppress" works to stabilize a mode, another PCS algorithm was subsequently developed called "Active Tracking"; this takes over after "Search and Suppress" has removed the mode or is applied to prevent appearance of a mode by pre-emptively applying current drive [7-8]. This was enabled by the development of real-time EFIT with the MSE diagnostic for locating the q-surface and initially an algorithm using the density profile for ECCD location to correct for refraction. Real-time Thomson profiles subsequently enabled real-time TORBEAM for ECCD location calculation.

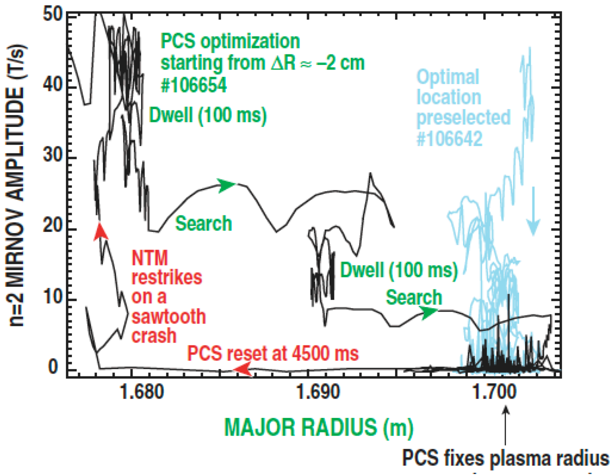

Fig. 2. *Real-time PCS control of major radius to put the q-surface for m/n=3/2 on the location of the ECCD. PCS dwells to see response and if mode not stabilized searches by stepping radius, dwells etc until stability, then freezes until reset to starting radius at preprogrammed time.*

Development of Stabilization of the m/n=2/1 NTM for High Beta Discharge Improvement

Techniques developed for the relatively benign 3/2 mode (10~20% loss of stored energy, moderate wall drag on plasma rotation) were subsequently applied to the more deleterious 2/1 mode (up to 40% loss in stored energy, wall drag resulting in mode locking, loss of H-mode and disruption at lower q95) [9-11]. Such 2/1 stabilization was only possible with the addition of more gyrotrons and mirrors as the q=2 surface is further out in rho, T_e is thus lower and j_{eccd} / P_{ech} ~ T_e / n_e. An example is shown in Fig. 3 in which the "Search and Suppress" makes one step (search) in BT to stabilize the 2/1 mode followed by a PCS NBI controlled beta rise with tracking adjusting BT to stay on the stable target. Details of PCS control and more examples are given in Refs. 12-13. Other advanced techniques studied

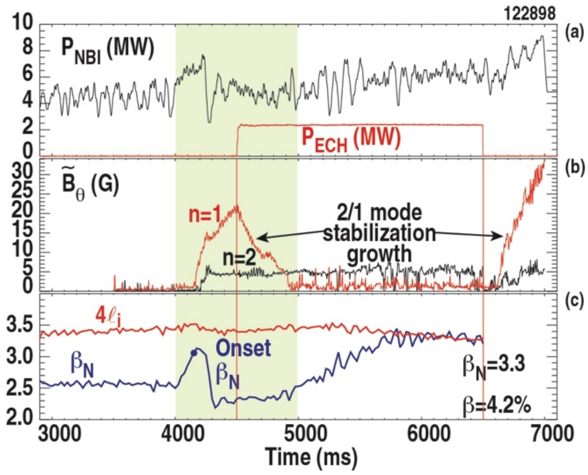

Fig. 3. *(a) NBI and EC powers; (b) the n =1 (red) and n = 2 (black) components of the Mirnov at the outer midplane of the vacuum vessel; (c) internal inductance multiplied by 4 (red) and normalized beta (blue).*

include real-time electron cyclotron emission (ECE) for mode identification and location [14].

Advanced control, without changing the toroidal field or the shape of the plasma, requires real-time movable mirror control and this was implemented and successfully demonstrated for use [15-16]. The schematic is shown in Fig. 4 This is a testbed for ITER's 24 gyrotrons.

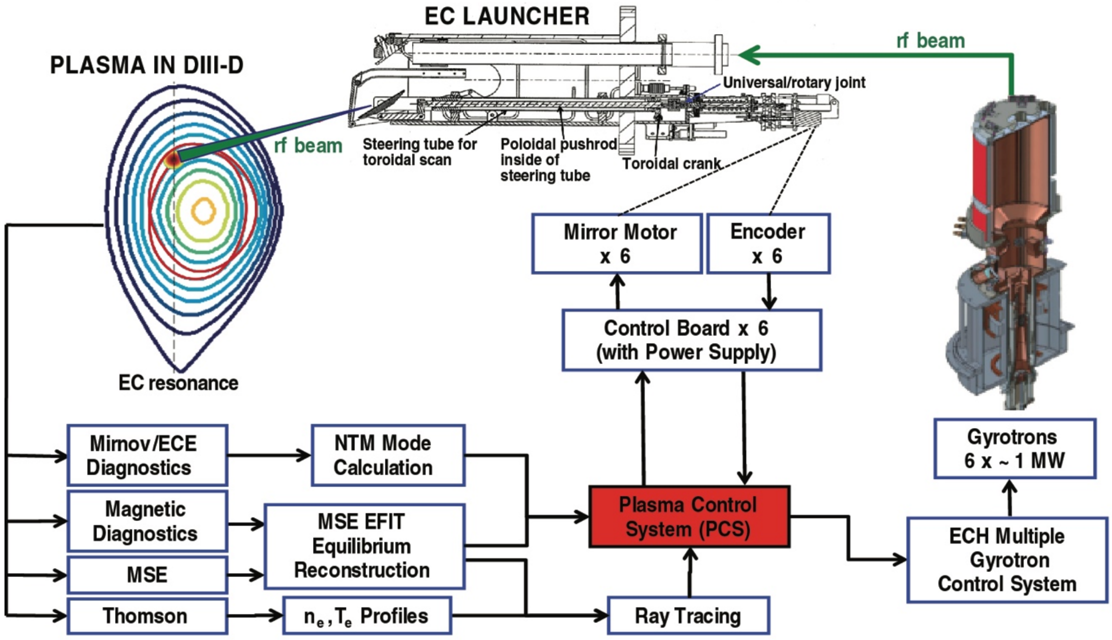

Fig. 4. *Schematic of DIII-D real-time ECCD tearing mode control system as now fully implemented. Each of up to 6 gyrotrons on a separate mirror can be independently directed to separate q-surfaces. Up to 8 in 2019.*

Studying 2/1 NTM Stabilization in the Low-Torque Low q95 ITER Baseline Scenario

ITER relies on stabilization of NTMs by ECCD [17-21]. The scaling with size and toroidal field for NTM destabilization is unfavorable for ITER; the large inertia and low torque make for predicted mode wall locking in a relatively short time. Either continuous wave (CW) preemption must be applied or a very prompt catch at low amplitude for rapid stabilization must be made to work with little time to optimize alignment. The most recent and ongoing DIII-D experiments are in a low-torque ITER baseline scenario (IBS) and mimic the ITER geometry for ECCD aligned to the q=2 surface. This is shown in Fig. 5. As the q=2 location is high, the natural density makes for severe refraction out of the plasma before absorption. Thus, the EC was applied before the L to H transition so density pump out occurs in H-mode. The resulting higher T_e and longer resistive diffusion time [by electron cyclotron resonant heating (ECRH) w/wo ECCD] may be making a stabilizing change in stability by altering the current profile evolution that lasts until the end of flattop. See Ref. 22 which with or without EC varies the I_p and NBI timing to produce a zero-torque IBS which runs stably. A preliminary evaluation of the EC control system aimed around q=2 is shown in Figure 6. The real-time q and EC location tracking compensate for varying refraction. Follow up with more gyrotrons remains to be done. Comparison of CW to standby ECCD to "catch" a growing mode to "subdue" it with return to standby is under development as ITER will need to keep the *average* EC power for NTM stabilization at a minimum in order to maximize Q. Our research seeks to confirm models (or develop empirical scalings) that can be used to predict requirements on EC power for j_{eccd} and/or localized heating dP_{ecrh}/dV.

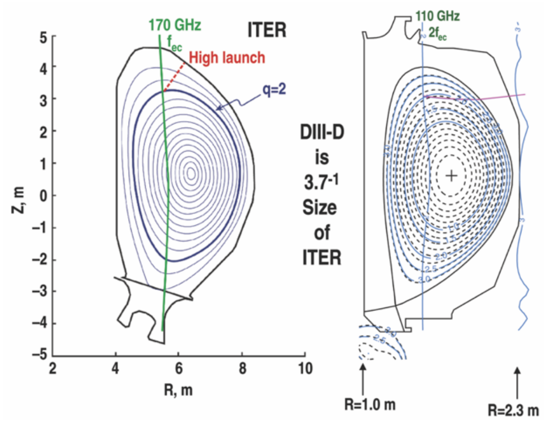

Fig. 5. *Cross-sections of ITER and of a DIII-D ITER Baseline Scenario discharge showing the launch of rays (170 GHz 1*f_{ec} and 110 GHz 2*f_{ec} respectively) to drive co-ECCD at q=2.*

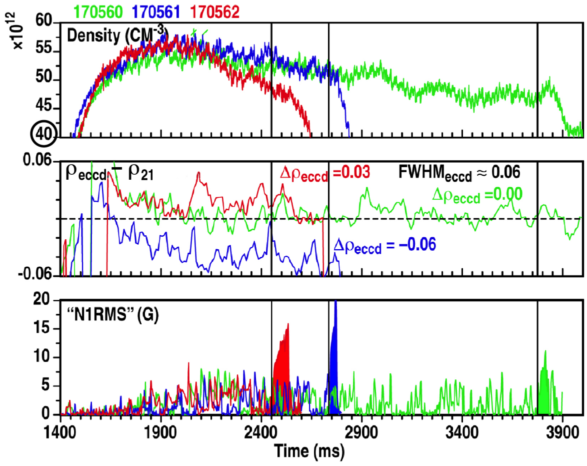

Fig. 6. *Preemptive CW EC at q~2. j_{eccd}/j_{boot}~0.8 and dP_{ecrh}/dV~7*<P_{nbi}/V> with 4 gyrotrons of 2.2 MW. a) density evolution, b) alignment target varied, c) n=1 Mirnov. Verticals 2/1 onset. In this set, q=2 aiming delays mode onset the longest; ECRH-only 170563 (not shown) also delays mode similarly to 170560.*

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