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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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Abstract. In DIII-D, the first real-time active control of the electron cyclotron current drive stabilization of a neoclassical tearing mode (here m/n=3/2) is demonstrated. The plasma control system is put into a "search and suppress" mode to align the ECCD with the island by making 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 resonance location (and thus the rf current drive). The optimum position minimizes the real-time mode amplitude signal and stabilization occurs despite changes in island location from discharge-to-discharge or from time-to-time. When the neutral beam heating power is programmed to rise after mode suppression by the ECCD, the plasma pressure increases above the peak at the onset of the neoclassical tearing mode until the magnetic island reappears due to the ECCD no longer being on the optimal position. Real-time tracking of the change in location of q=3/2 due to the Shafranov shift with increasing beta is necessary to position the ECCD in the absence of a mode so that higher stable beta can be sustained. The control techniques developed for the m/n=3/2 NTM are also being applied to the more deleterious m/n=2/1 NTM. For the first time in any tokamak, an m/n=2/1 mode has been completely suppressed using radially localized off-axis ECCD.

1. Introduction

The development of techniques for suppression or avoidance of neoclassical tearing modes (NTM) 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 m=2, n=1 mode can also cause loss of H–mode and lead to disruption. The islands which degrade confinement can be reduced or completely suppressed by precisely replacing the "missing" bootstrap current at 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 which can provide repeated seed islands to trigger NTMs, a reactor relevant regime [3].

2. Real-Time Active Control "Search and Suppress" of the m/n=3/2 NTM

To stabilize the NTM, radially localized off-axis co-electron cyclotron current drive (ECCD) must be precisely located on the island [4,5]. 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 through minimization of electron trapping effects. Discharges are run with 2, 3, or 4 gyrotrons after m/n = 3/2 mode saturation. Plasma current I_p is 1.0–1.2 MA, toroidal field B_T = –1.52 to –1.64 T, line-averaged density $\bar{n} \approx 4\times10^{19}$ m^{-3}, local q = 3/2 $T_e \approx T_i \approx$ 1200–1600 eV, with a safety factor at the 95% flux surface q_{95}=3.2–4.3. The approximate optimal location is found by sweeping the toroidal field B_T with ECCD in the presence of an existing m/n=3/2 NTM as shown in Fig. 1. Note that: (1) the peak rf current density (calculated from TORAY-GA [6]) exceeds the local bootstrap current density (calculated from ONETWO [7]), (2) the dip in the n=2 Mirnov amplitude is greatest with j_{eccd} centered on the island as determined by the electron cyclotron emission (ECE) radiometer, and (3) the effect is negligible for misalignment of only $\Delta R \approx \pm$ 2.5 cm.

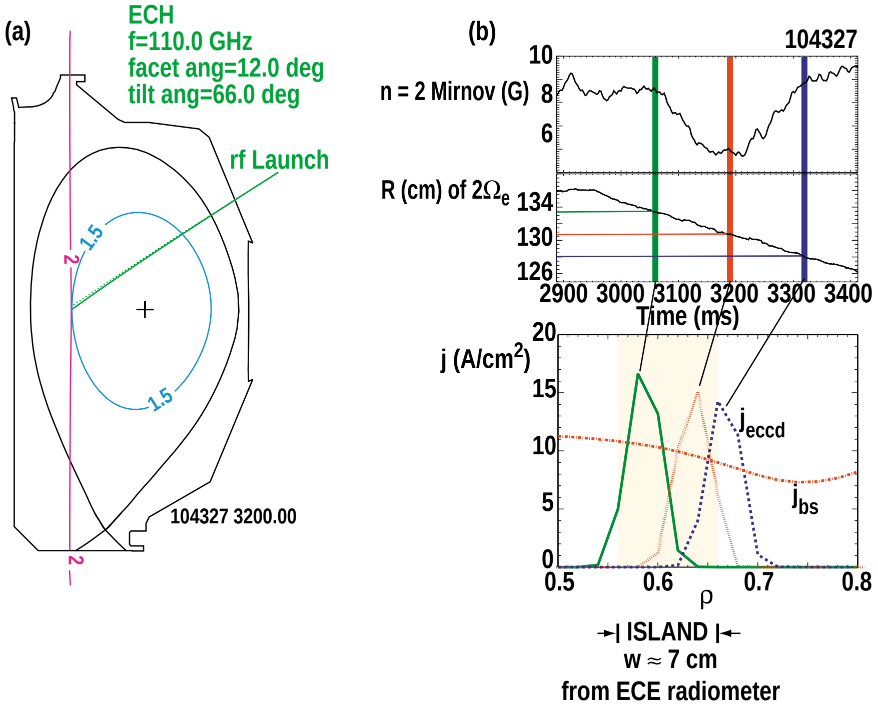

Fig. 1. (a) The configuration for NTM suppression by ECCD showing the q=3/2 surface, $2f_{ce}$ location and projection of the rf trajectory to cross $2f_{ce}$ near q=3/2 on the inboard midplane. The facet angle of the mirrors sets the co-ECCD launch and the tilt angle determines the poloidal launch shown. (b) A B_T sweep to move the $2f_{ce}$ location past the 3/2 island. Note dip in n=2 Mirnov amplitude at 3200 ms. This discharge uses two gyrotrons for 1 MW injected ECH power. j_{eccd} from TORAY-GA and j_{bs} from ONETWO are shown at the three different times indicated in comparison to the full island width and location from ECE radiometer at 3000 ms.

This experiment represents the first use of active feedback control to provide continuous, precise positioning. The plasma control system (PCS) uses a “search and suppress” method to align the ECCD with the island. Feedback either requests 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. Search and suppress feedback is illustrated in Fig. 2 using three gyrotrons with a starting location about $\Delta R = -2$ cm off optimum. Another discharge with fixed position on the optimum location based on scans of previous discharges is also shown. The feedback is based on minimizing real-time Mirnov measurements of the mode amplitude. 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 fixes 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.

3. Raising Beta After Complete Suppression of a m/n=3/2 NTM

With the ECCD still on and the PCS fixing the plasma radius on the optimum position at lower beta, the neutral beam heating power is programmed to gradually rise so as to increase beta. Beta is raised 60% (20% higher than the peak before the onset of the NTM) before the mode reappears as shown in Fig. 3. Analysis of the location of the q=3/2 surface location change (from the equilibrium reconstruction of the code EFIT [8]) shows that q=3/2 moves

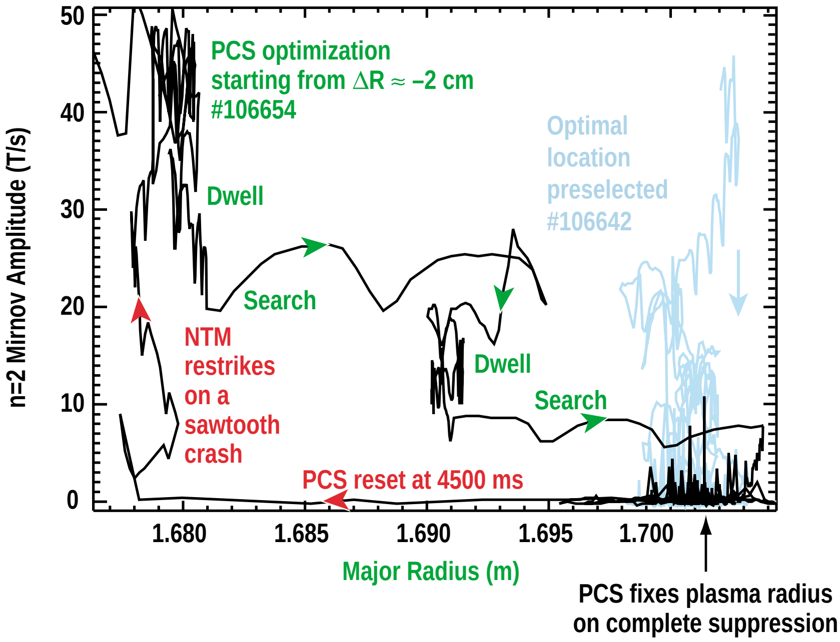

Fig. 2. Trajectory of n=2 Mirnov amplitude versus plasma major radius with (#106654) and without (#106642) real-time control of the plasma position for ECCD suppression (m/n=3/2 NTM, three gyrotrons for 1.5 MW injected from 3000 to 4800 ms).

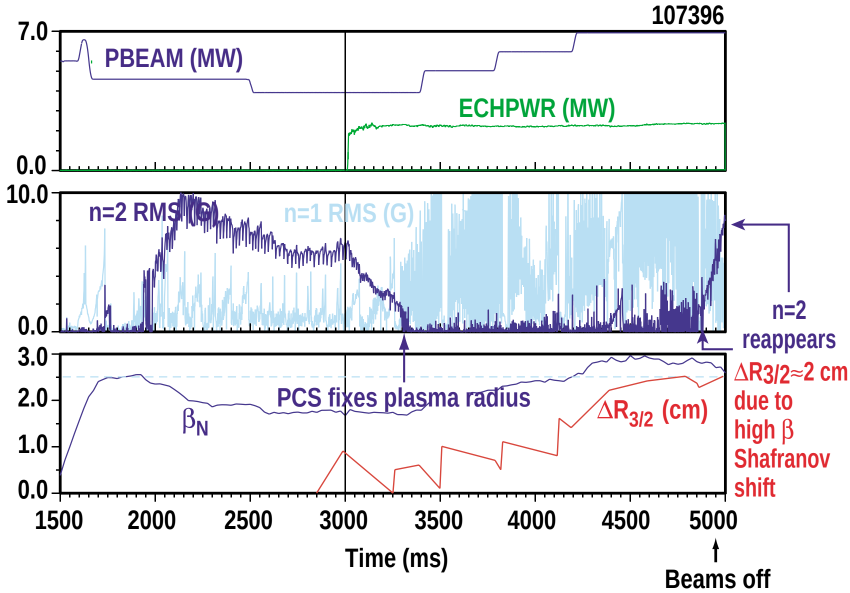

Fig. 3. Four gyrotrons injecting 2.3 MW of ECCD are used to suppress an m/n=3/2 NTM in discharge #107396 after which neutral beam power is raised to increase beta. β_N is increased by 60% (despite large sawteeth and fishbones). The NTM reappears because the Shafranov shift has moved q=3/2 about 2 cm off the optimum ECCD location. Note that there is no further PCS position optimization once the NTM has been suppressed in the absence of a mode to do the "search and suppress.".

outward by about 2 cm as beta is increased (consistent with the expected Shafranov shift). Thus the ECCD location is not on the new, changed optimum position. This is better shown in Fig. 4 for the discharge of Fig. 3 in the period during which beta is raised. The inboard major radius of the q=3/2 surface moves outward. Note that the jumps in the radius are due to the sawtooth crashes and the sudden increase of q on axis to about one. The effect of raising beta also increases the destabilizing perturbed bootstrap current. However, this is obviated in

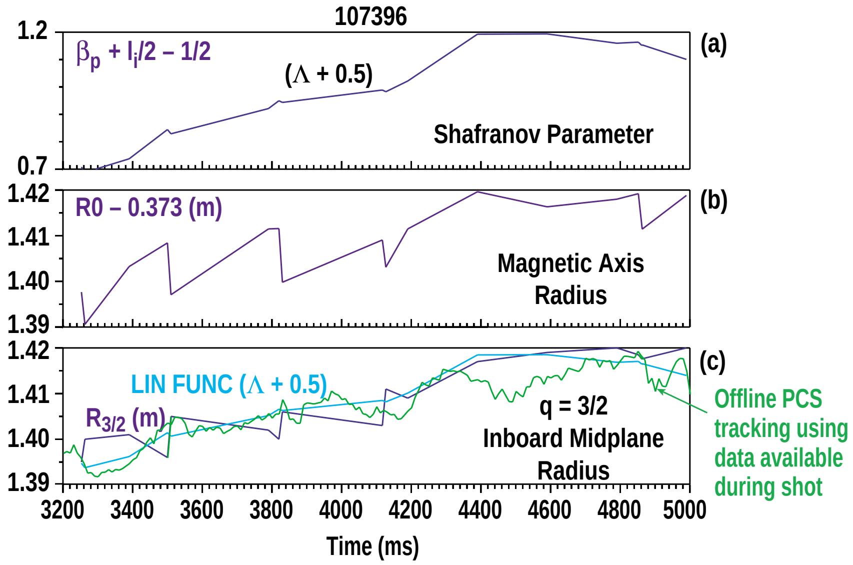

Fig. 4. For the discharge 107396 of Fig. 3 during the period in which beta is raised, (a) the Shafranov parameter Λ+0.5 increases, (b) the plasma magnetic axis R0 increases as a result (the plasma separatrix boundary is held fixed) and (c) the inboard midplane major radius $R_{3/2}$ of q=3/2 also shifts outward. Also shown in (c) is a simple linear fit to Λ+0.5 as well as the subsequently developed PCS tracking of the change in the q=3/2 location ready to be used in future work.

two ways. First, with the electron density held constant by use of the cyropump, the electron temperature increases in proportion to beta. This increases the ECCD as $j_{eccd} \propto P_{rf}\, T_e/n_e$ so that the ratio of j_{eccd} to j_{bs} tends to remain constant as beta is increased. Second, the ion temperature also increases in proportion to beta. This increases the ion banana width which acts as the principal threshold for exciting the NTM [3]. Taken together, these two effects predict that if the alignment can be maintained the ECCD can suppress the m/n=3/2 NTM up to the ideal beta limit of $\beta_N \approx 4\, \ell_i$ = 3.8 in these plasmas. However, a misalignment of as little as ΔR=1.5 cm would allow the mode to reappear with the same rf power etc. assumed as modeled using the modified Rutherford equation of Eq. (1) of Ref. [3]. Of course the m/n=2/1 NTM may appear before $\beta_N \approx 4\, \ell_i$ is reached making suppression of the m/n=3/2 NTM a secondary concern.

While real-time PCS determinations of the location of a given q=m/n surface are not (yet) available, the PCS now has a new algorithm added which can take the real-time shape control data and calculate changes in a given q surface location. This is shown in Fig. 4(c) calculated using archived PCS data from this discharge which was available during the discharge. Real-time tracking by the PCS is ready to respond to changes in the q=3/2 location so that the optimum location for ECCD suppression can be maintained even in the absence of a mode in DIII–D experiments in the 2003 campaign.

4. Real-Time Active Control “Search and Suppress” of the m/n=2/1 NTM

The PCS tools developed for the m/n=3/2 NTM are also used to completely stabilize the m/n=2/1 mode. The configuration is shown in Fig. 5(a) and the effect of sweeping B_T on the n=1 Mirnov amplitude is shown in Fig. 5(b). Discharges are run with 4 or 5 gyrotrons after m/n=2/1 initiation but not saturation. Plasma current I_p is 1.2 MA, toroidal field B_T = –1.52 to –1.70 T, line-averaged density $\bar{n} \approx 4\times10^{19}$ m^{-3}, local q = 2/1 $T_e \approx$ 2300 eV, $T_i \approx$ 3100 eV, with a safety factor at the 95% flux surface q_{95} = 4.0–4.4. The peak rf current density (from TORAY-GA) exceeds the local bootstrap current density (from ONETWO). Constraints require placing the rf absorption near the top of the plasma for q=2, as compared to the

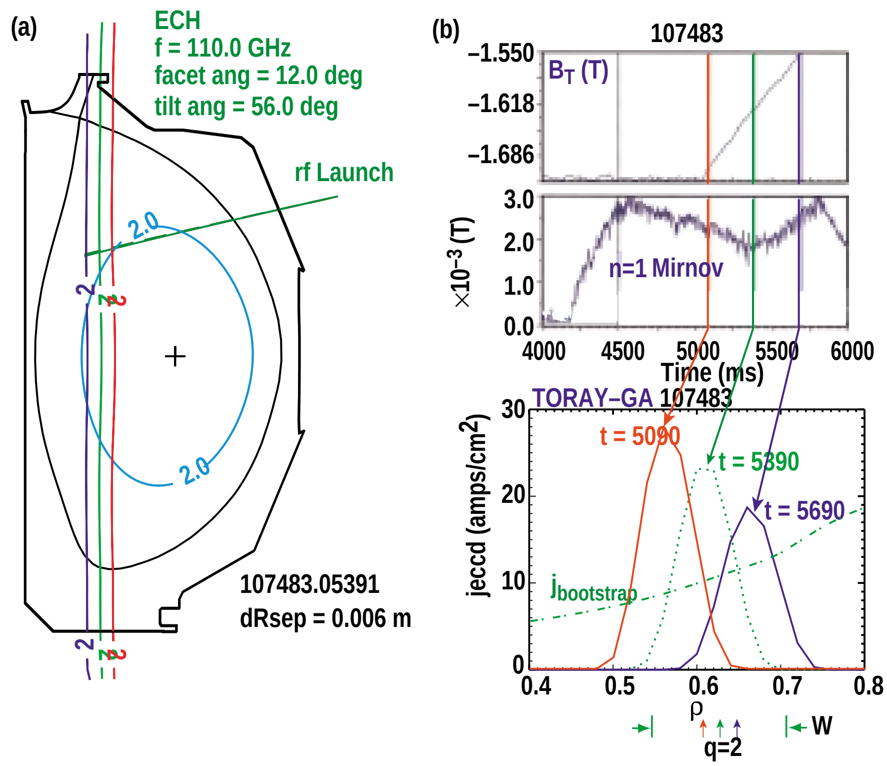

Fig. 5. (a) The configuration for ECCD suppression of the m/n=2/1 NTM. The locations of $2f_{ce}$ as B_T is swept along with the q=2 surface (little changed) and the projection of the rf trajectory are shown. (b) A B_T sweep to move the $2f_{ce}$ location past the 2/1 island. Note the dip in n=1 Mirnov amplitude. ECCD on at 4500 ms (four gyrotrons for ≈2 MW injected). j_{eccd} from TORAY-GA and j_{bs} from ONETWO are shown at the three different times indicated in comparison to the full island width and location from the ECE radiometer at 4500 ms.

inboard midplane for *q*=3/2 as was shown in Fig. 1(a). Thus the sweep in B_T has a smaller effect on the n=1 Mirnov amplitude [$\Delta B_T/B_T$ = –8.5% in the three times marked in Fig. 5(b)] compared to the B_T sweep for the n=2 Mirnov amplitude [$\Delta B_T/B_T$ = –4.2% in the three times marked in Fig. 2(b)]. With absorption exactly on the "top" of the surface one would thus expect little sensitivity to changing B_T or the radial position of the plasma; therefore the PCS is also provided with a vertical plasma position control for future use.

Complete suppression of an m/n=2/1 NTM was obtained with 2.3 MW injected ECH power and PCS B_T control search and suppression as shown in Fig. 6. β_N was temporarily increased to about 3.5 to excite the mode with suppression achieved at β_N = 2.3. The PCS makes the real-time decision 300 ms after application of ECCD to adjust B_T by one step, ΔR≈1 cm, which enhances the n=1 Mirnov decay rate and achieves complete stabilization. For comparison a discharge (#111335) with fixed B_T well off optimum (ΔR≈10 cm) is also shown on which the rf has little effect. Note that dropping beta further in this plasma, below the level stabilized in #111367, does not eliminate the 2/1 mode. The NTMs are very robust and require beta to be greatly reduced to be removed, absent well-aligned ECCD of sufficient magnitude. The trajectory of the n=1 Mirnov amplitude versus B_T is shown in Fig. 7 for #111367.

No attempts have been made as yet to raise the 2/1 NTM stable beta. However, as for the 3/2 NTM, the necessary feedback control has been developed including active tracking of changes in the location of the *q*=2 surface.

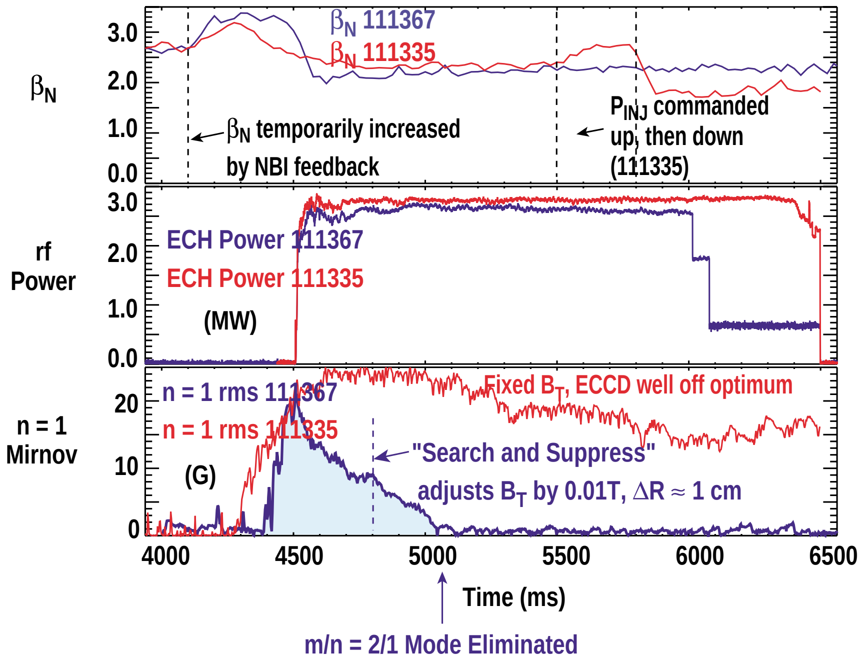

Fig. 6. Demonstration of complete suppression of the m/n=2/1 NTM by radially localized ECCD. (a) β_N is feedback controlled to temporarily excite the mode. (b) Five gyrotrons are turned on making >2 MW injected. (c) The n=1 Mirnov amplitude is reduced and then eliminated by PCS B_T “search and suppress” in #111367. Fixed B_T well off-optimum (ΔR≈10 cm) in #111335 makes the ECCD have little effect.

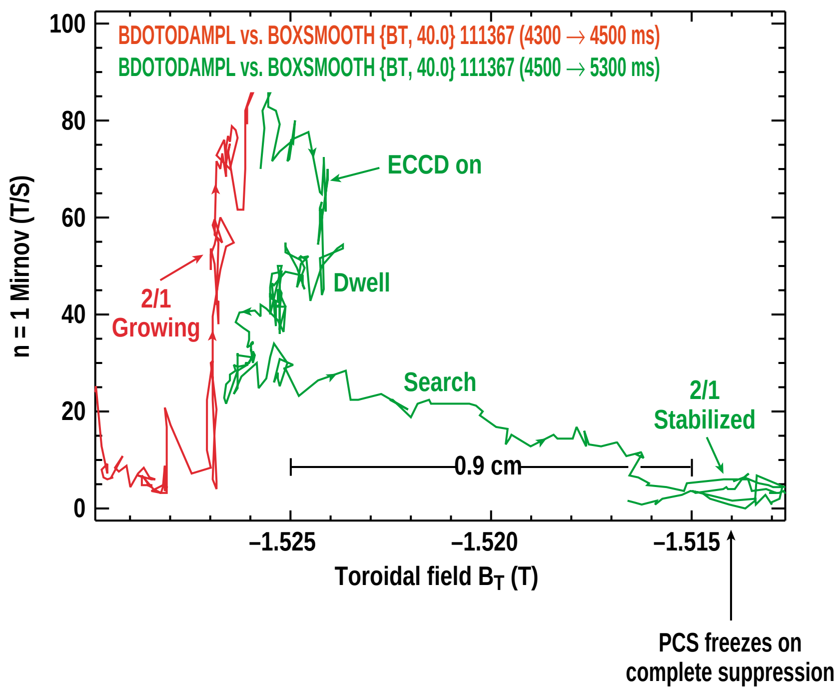

Fig. 7. Trajectory of n=1 Mirnov amplitude versus toroidal magnetic field with real-time control of optimum position of ECCD (m/n=2/1 NTM, five gyrotrons for 2.3 MW injected from 4500 to 5300 ms).

5. Conclusions

Large m/n=3/2 neoclassical tearing modes in the presence of sawteeth are completely suppressed by precisely located (to ± 1 cm) off-axis electron cyclotron current drive. The sensitivity of positioning is as expected for “broad” islands and “narrow” current drive. A level of peak j_{eccd} of about twice j_{bs} is required for complete stabilization. The DIII–D plasma control system has been successfully developed to do real-time search and suppress position control using either rigid radial plasma shifts or adjustment of the toroidal field and thus second harmonic electron cyclotron resonance location. This represents the first use of active feedback control to position the ECCD. After NTM suppression, with continued ECCD, beta was substantially increased above the onset level. Eventually, as the PCS freezes after stabilizing the NTM, the Shafranov shift due to increased beta moves the q=3/2 surface about 2 cm off optimum and the NTM reappears.

Future work is to apply ECCD to inhibit the onset of NTMs and will require the PCS to locate the q=3/2 surface, for example, and position the ECCD resonance location in the absence of the NTM, particularly as beta is increased and a Shafranov shift occurs. Real-time alignment in the absence of a mode is now implemented and ready. All tools developed for the m/n=3/2 NTM also apply to the m/n=2/1 NTM which has also been completely eliminated using the “search and suppress” control. Eventually with eight gyrotrons on four launchers, it is planned to do simultaneous control of both m/n=3/2 and 2/1 NTMs.

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