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SUPPRESSION OF NEOCLASSICAL TEARING MODES IN THE PRESENCE OF SAWTEETH INSTABILITIES BY RADIALLY LOCALIZED OFF-AXIS ELECTRON CYCLOTRON CURRENT DRIVE IN THE DIII–D TOKAMAK

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Neoclassical tearing modes (NTMs) are islands destabilized and maintained by a helically perturbed bootstrap current and represent a significant limit to performance at higher poloidal beta in tokamaks [1]. The m=3, n=2 mode alone can decrease stored energy by up to 30% [2]. Radially localized off-axis co-current drive could replace the “missing” bootstrap current in the island O-point and stabilize the NTM [3,4]. This was confirmed both in ASDEX Upgrade [5] and in JT-60U [6] with electron cyclotron current drive (ECCD). Periodic long-lived q=1 sawteeth instabilities can provide seed islands to trigger the NTM (and are expected to occur in reactor grade tokamaks such as ITER-EDA). In ASDEX Upgrade, the sawteeth were abated by the m/n = 3/2 NTM and tended not to return with stabilization by the ECCD. In JT-60U, discharges with $q_{min} > 1$ were run to avoid sawteeth.

Complete suppression of an m/n = 3/2 NTM island of full width w ≈ 7 cm (w/r ≈ 20%) was achieved in DIII-D in the presence of sawteeth. Up to four 110 GHz gyrotrons producing up to 2.3 MW (injected) for at least 1 second are used for co-current drive well off-axis (ρ ≈ 0.6). The toroidal launch angle is chosen to maximize J_{ec} at the island location rather than I_{ec}. Discharges in which the q=1 sawteeth instabilities are “frequency coupled” to the m/n = 3/2 NTM island rotation were more resistant to full suppression. Diagnostics and codes for measurement and analysis of the suppression physics include: (1) 35 channel motional Stark effect (MSE) poloidal field profile measurement for MHD equilibrium reconstruction, (2) 32 channel fast electron cyclotron emission diagnostic for NTM island location and structure and (3) the TORAY-GA code for calculation of the predicted local rf current density.

MODIFIED RUTHERFORD EQUATION FOR NTM STABILITY

The NTM is metastable in that the high β_θ plasma without the island must be excited above a threshold island width for the island to grow large and saturate. This is shown by the modified Rutherford equation and in Fig. 1. See also, D. Brennan poster, this conference.

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + \varepsilon^{1/2}\left(\frac{L_q}{L_p}\right)\beta_\theta\left[\frac{r}{w} - \frac{r w_{pol}^2}{w^3} - \frac{8qr\delta_{ec}}{\pi^2 w^2}\left(\frac{\eta\, j_{ec}}{j_{bs}}\right)\right] \quad , \tag{1a}$$

and

$$\eta = \eta_0 \left(1 + 2\delta_{ec}^2/w^2\right)^{-1} e^{-\left(5\Delta R/3\delta_{ec}\right)^2} \quad , \tag{1b}$$

with j_{ec}/j_{bs} the ratio of the peak ECCD current density normalized to the local equilibrium bootstrap current density. The rf efficiency η has a coefficient $\eta_0 \cong 0.4$ for no modulation and allows for a reduction if the peak ECCD is not placed precisely ($\Delta R = 0$) on the island O-point and/or if the ECCD width is greater than that of the island [δ_{ec} is the full radial width-half maximum (FWHM) of a Gaussian rf current density]. For no rf, the island is excited at w ≈ 2 cm and grows to saturation at w ≈ 7.5 cm for typical DIII-D parameters given in Fig. 1. The minor radius r is taken at the q = 3/2 surface on the midplane with respect to the effective major radius of the separatrix surface R_{surf}. By applying precisely located j_{ec} of $\gtrsim$1.5 j_{bs} it is predicted that the island can be reduced to a level such that complete suppression should occur. Any less j_{ec}/j_{bs} or reduced rf efficiency ($\Delta R/\delta_{ec} \neq 0$) should lead to only a partial suppression. For FWHM δ_{ec} = 3 cm, a misalignment of only 1.9 cm reduces the predicted rf efficiency by a factor of 3.

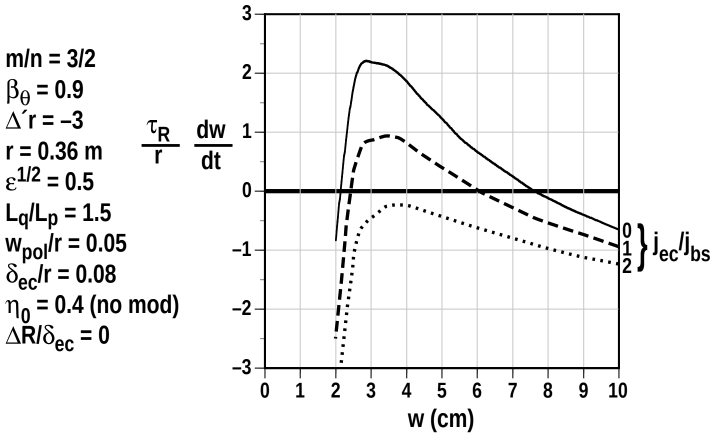

Fig. 1. Island growth (decay) rate calculated for different levels of precisely aligned peak rf current density.

Coupling to other instabilities such as the q=1 m/n = 1/1 and 2/2 sawtooth precursors which can act to drive "seed" islands is not included in Eq. (1). Such coupling can both make the destabilizing seed (w $\gtrsim$ 2 cm in Fig. 1) and inhibit the suppression by rf. (See A. Popov poster, this conference.)

CONFIGURATION FOR OFF-AXIS ECCD IN DIII-D

ELMing H-mode discharges with sawteeth were run in DIII-D in which large (w/r ≈ 20%) m/n = 3/2 NTMs were made and allowed to come into saturation. The periodic sawteeth continued in the presence of the NTM island. A cryopump was used to reduce the electron density (and concomitantly increase the electron temperature) so as to improve the rf current density driven ($j_{ec} \propto P_{ec}T_e/n_e$ is expected). The second harmonic resonance for the 110 GHz gyrotron frequency is placed on the inboard midplane near the q = 3/2 location as shown in Fig. 2. This tends to improve j_{ec} over an outboard location where electron trapping effects are larger. Two separate launchers are used, each with two gyrotrons; the launchers are independently steerable between discharges but not during a discharge. The rf absorption at the third harmonic resonance is expected to be small.

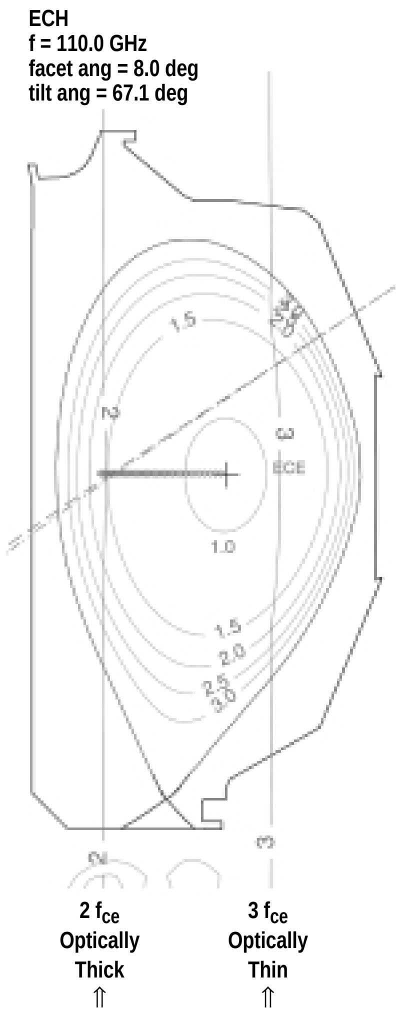

Fig. 2. Configuration for ECCD/NTM suppression showing q = 1.5 surface, 2 f_{ce} location and projection of rf trajectory to crossing at 2 f_{ce} and q = 3/2 on inboard midplane.

OPTIMIZING THE ECCD LOCATION FOR 3/2 NTM SUPPRESSION

The ASDEX Upgrade work [5] relies on a feed forward slow sweep of the toroidal field in each discharge and, thus, the second harmonic resonance, so that at some time during the sweep the positioning is transiently correct. In JT-60U [6] the optimum electron current (EC) wave injection angle was determined by scanning a steerable mirror during a discharge and then fixed in a subsequent discharge at the optimum angle (as determined from the dip in Mirnov amplitude during the scan). DIII-D uses a B_T sweep to find the optimum and then a fixed B_T at the optimum in subsequent discharges.

B_T Sweep

In DIII-D, the continued sawteeth even in the presence of the m/n = 3/2 NTM and with ECCD cause the on-axis q to vary from 0.85-1.00 which can also affect the q = 3/2 location. Thus, time-to-time and shot-to-shot variations are both of concern for precise ECCD location. The optimum is first found by a B_T sweep as shown in Fig. 3, too fast to achieve complete suppression with only two gyrotrons. The TORAY-GA prediction of j(ρ) for 1 MW for the three times indicated and the location and width of the initial island [from fast ECE radiometer $\tilde{T}_e(R)$ at the n=2 Mirnov frequency] show: (1) the need for alignment within 2 cm and (2) $j_{ec}/j_{bs} \approx 1.5$ is marginal at 1 MW in agreement with Fig. 1.

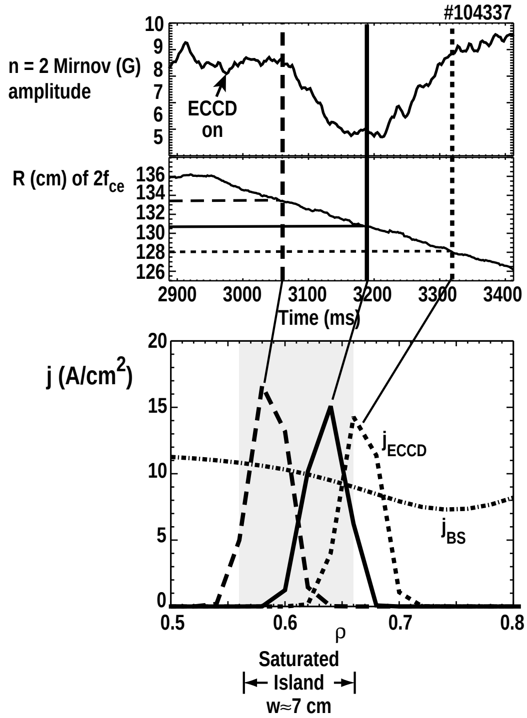

Fig. 3. (a) B_T sweep to move 2 f_{ce} location past island. ECCD on at 3000 ms (2 gyrotrons for ≈1 MW injected) (b) calculated j_{ECCD} from TORAY-GA and j_{bs} from ONETWO code reconstruction. Island width and location from ECE radiometer.

B_T Flattop Value Adjustment

Best results (i.e. complete 3/2 NTM suppression) occur by setting the flattop B_T to the value of the biggest n=2 Mirnov dip of Fig. 3. The importance of fine tuning B_T to place the 2 f_{ce} location (and thus ECCD) on the 3/2 island is further shown in Fig. 4. Before the ECCD is applied, the n=2 Mirnov amplitude $|\tilde{B}_{\theta,32}|$ is in steady state, i.e. dw/dt = 0 and all terms on the right-hand side (RHS) of Eq. (1) add to zero. Upon turning on the rf, initially the RHS has <u>only</u> the rf term. Keeping all quantities fixed, $w \propto (|\tilde{B}_{\theta,32}|)^{1/2}$, n_e, T_e, P_{rf}, etc., the initial decay rate γ is $\propto \exp^{-(5\Delta R/3\delta_{ec})^2}$ where ΔR is the misalignment. A shot-to-shot scan is shown in Fig. 4 in flattop B_T for a q_{95} = 3.2 case with sawteeth "uncoupled" to the 3/2 island,

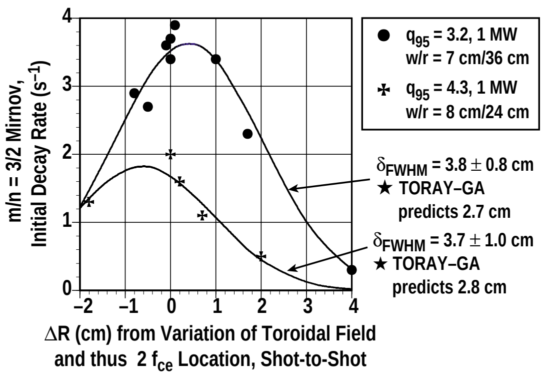

Fig. 4. Initial decay rate of n=2 Mirnov amplitude upon application of ECCD versus shift in 2 f_{ce} location (and, thus, relative displacement of island and peak current drive).

i.e. $2\,f_{11} \neq f_{32}$ and for a q_{95} = 4.3 case with coupled sawteeth ($2\,f_{11} \approx f_{32}$) and rf launcher reconfigured for the different optimum j_{ec} at higher q_{95}. Both cases show a FWHM width δ_{ec} somewhat wider than predicted by TORAY-GA. This may be due to the model, difference in the current drive locations of the two gyrotrons or radial diffusion (not included in TORAY-GA) broadening the spot size [7].

Real-Time Control of Optimum Position

To allow for shot-to-shot and time-to-time variation in the optimum position , particularly due to q(0) variation with sawteeth affecting the q = 3/2 location, DIII-D has developed real-time control. For fixed B_T and rf launch angles, the plasma control system (PCS) makes small rigid horizontal shifts of the plasma cross-section (and, thus the island) across the peak ECCD. A "search and suppress" logic looks at the real-time n=2 Mirnov signal so as to determine which way and by how much to move the plasma to optimize the ECCD suppression. An example is shown in Fig. 5. This is done for a q_{95} = 3.6 coupled sawtooth case and with three gyrotrons for 1.5 MW injected. Doing the B_T sweep as in Fig. 3 allows setting B_T to an optimum. Complete NTM suppression is achieved (at fixed B_T and R_{surf}) in #106642. Given a demonstration of a condition for complete suppression, the PCS in the example of #106654 is deliberately started with $\Delta R \approx -2$ cm during ECCD and searches and dwells etc. until the optimum is adjusted and complete suppression obtained. Sawteeth continue but the 3/2 NTM does not restrike with ECCD until at a preset time the PCS resets R_{surf} to the starting point and a sawtooth crash induces the mode with ECCD on but now off-set.

COMPLETE ECCD SUPPRESSION OF AN m/n = 3/2 NTM

An example of a complete two gyrotron suppression of a 3/2 NTM in the presence of uncoupled sawteeth is shown in Fig. 6. B_T and R_{surf} are fixed at "best" settings. Note that β_N increases by about 25% and remains at this level.

Future work includes suppression of the 2/1 NTMs, continued development of real-time control optimization, use of ECCD to prevent the growth of NTMs and raising the β_N without an NTM.

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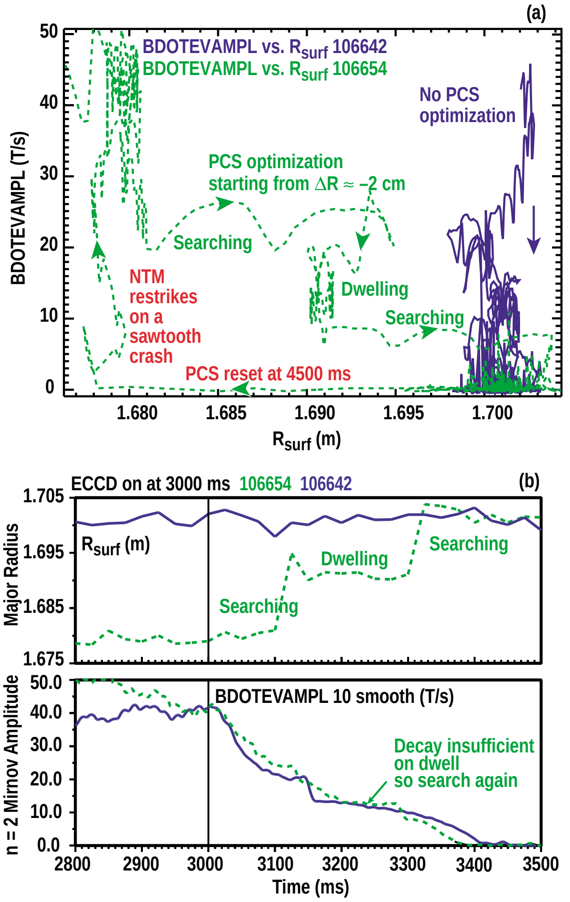

Fig. 5. (a) Trajectory of Mirnov amplitude with plasma major radius with and without PCS real-time control of optimum rigid plasma position (R_{surf}) for ECCD suppression of an m/n = 3/2 NTM (ECCD with 3 gyrotrons, 1.5 MW, on from 3000 to 4800 ms, B_T = -1.54 T flattop, q_{95} = 3.8 coupled sawtooth case). (b) Same traces versus time, 2800 to 3500 ms only to better show suppression.

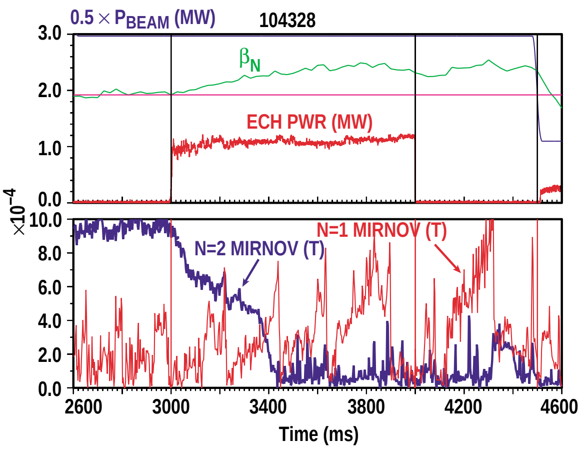

Fig. 6. Complete suppression of an m/n = 3/2 NTM by ECCD in the presence of continued frequency uncoupled sawteeth ($P_{rf}/P_{beams} \approx$1 MW/6 MW, fixed B_T and R_{surf}).