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 βθ 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.

\[
\frac{\tau_R}{r} \frac{dw}{dt} = \Delta_r + \varepsilon^{1/2} \left( \frac{L_q}{L_p} \right) \beta_0 \left[ \frac{r}{w} \left( \frac{r^2}{w^3} - \delta_{ec} \right) \frac{8qr\delta_{ec}}{\pi^2w^2} \left( \frac{\eta_{ec}}{I_{bs}} \right) \right], \quad (1a)
\]

and

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

with j_{ec}/I_{bs} the ratio of the peak ECCD current density normalized to the local equilibrium bootstrap current density. The rf efficiency η has a coefficient η_0 ≅ 0.4 for no modulation and allows for a reduction if the peak ECCD is not placed precisely (ΔR = 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.
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 \( R_{\text{surf}} \). By applying precisely located \( j_{\text{ec}} \) of \( \approx 1.5 \) \( j_{\text{bs}} \) it is predicted that the island can be reduced to a level such that complete suppression should occur. Any less \( j_{\text{ec}}/j_{\text{bs}} \) or reduced rf efficiency (\( \Delta R/\delta_{\text{ec}} \neq 0 \)) should lead to only a partial suppression. For FWHM \( \delta_{\text{ec}} = 3 \) cm, a misalignment of only 1.9 cm reduces the predicted rf efficiency by a factor of 3.

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 \( (w/r \approx 20\%) \) \( m/n = 3/2 \) 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 \( (j_{\text{ec}} \propto P_{\text{ec}}T_{\text{e}}/n_{\text{e}} \) 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 \( j_{\text{ec}} \) 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.

**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 $j(\rho)$ for 1 MW for the three times indicated and the location and width of the initial island [from fast ECE radiometer $T_e(R)$ 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.

**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 $2f_{ce}$ 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 $|\tilde{B}_{B,32}|$ 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 only the rf term. Keeping all quantities fixed, $w \propto (|\tilde{B}_{B,32}|)^{1/2}$, $n_e$, $T_e$, $P_{rf}$, etc., the initial decay rate $\gamma$ is $\propto \exp(-5\Delta R/3\delta_{ec})^2$ where $\Delta R$ 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, i.e. $2f_{11} \neq f_{32}$ and for a $q_{95} = 4.3$ case with coupled sawteeth ($2f_{11} = f_{32}$) and rf launcher reconfigured for the different optimum $j_{ec}$ at higher $q_{95}$. Both cases show a FWHM width $\delta_{ec}$ 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 \(\beta_N\) 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 \(\beta_N\) without an NTM.

This is a report of work supported by the U.S. Department of Energy under Contract Nos. DE-AC03-99ER54463 and DE-AC05-76OR00033.