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COMPLETE SUPPRESSION OF THE m/n = 2/1 NEOCLASSICAL TEARING MODE USING RADIALLY LOCALIZED ELECTRON CYCLOTRON CURRENT DRIVE ON DIII–D AND THE REQUIREMENTS FOR ITER

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Complete Suppression of the m/n = 2/1 Neoclassical Tearing Mode Using Radially Localized Electron Cyclotron Current Drive on DIII–D and the Requirements for ITER

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Introduction: DIII–D experiments demonstrate the first real-time feedback control of the relative location of a narrow beam of microwaves to completely suppress and eliminate a growing tearing mode at the q=2 surface. Long wavelength tearing modes such as the m/n = 2/1 instability are particularly deleterious to tokamak operation. Confinement is seriously degraded by the island, plasma rotation can cease (mode-lock) and disruption can occur. The neoclassical tearing mode (NTM) becomes unstable due to the presence of a helically-perturbed bootstrap current and can be stabilized by replacing the "missing" bootstrap current in the island O-point by precisely located co-electron cyclotron current drive (ECCD). The geometry for the ECCD launch, the second harmonic resonance $2f_{ce}$ and the q=2 surface are shown in Fig. 1. The optimum position is found when the DIII–D plasma control system (PCS) is put into a "search and suppress" mode that makes small radial shifts (in about 1 cm steps) in the ECCD location based on minimizing the Mirnov amplitude.

1. "Hybrid Scenario" Stationary High-Performance Discharges

The suppression of tearing modes in DIII-D was carried out in high performance, long-pulse discharges with normalized beta $[\beta(\%)/I_p(MA)/a(m)B_T(T)]$ $\beta_N = 2.7$, normalized confinement time (to that of the L-mode scaling) $H_{89P} = 2.6$, $q_{95} = 4.3$ and fraction of plasma current non-inductively driven by the bootstrap effect $f_{bs} \approx 0.35$ [1]. These discharges are referred to as a hybrid scenario as they have sufficient bootstrap current to significantly reduce the volt-sec consumption but not enough for full non-inductive steady state. The key element is the relaxation of the current profile to a stationary state with safety factor on axis $q_{min} > 1$, without sawteeth and fishbones. Under the influence of a small m/n = 3/2 tearing mode, the current relaxes to a stationary state maintained for up to 40 energy confinement times τ_E and >2 resistive diffusion times τ_R. The confinement remains well above that of standard H-mode ($H_{89P} \approx 2.6 > 2$) despite the approximate $\lesssim 5\%$ reduction in τ_E due to the 3/2 tearing mode. Real-time feedback control of the energy content is done by regulation of neutral beam (NBI) power using the diamagnetic flux, and control of the particle inventory is performed by gas fueling and active cryopumping based on the CO_2 interferometer. The highest performance in β_N and $\beta_N H_{89P}$ is found to be limited by the

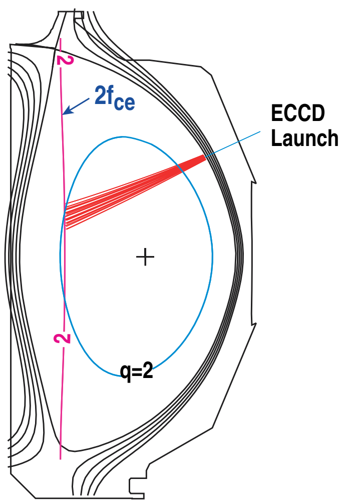

Fig. 1. Cross-section of the plasma equilibrium, the ECCD launch of rays towards the $2f_{ce}$ resonance and the q=2 surface. The rf frequency is 110 GHz.

m/n=2/1 tearing mode. Requesting a higher diamagnetic flux (and thus beta) such that the NBI power is increased causes an m/n = 2/1 NTM to appear. The hybrid scenario promises to be a robust, long-pulse operating regime for physics and engineering tests on ITER, highlighting the importance of stabilizing the 2/1 NTM.

2. Modified Rutherford Equation For NTM Stabilization By ECCD

The requirements on the ECCD for complete m/n = 2/1 island suppression in DIII-D are well-modeled by the modified Rutherford equation. The plasma is metastable to NTMs 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 (dw/dt = 0). This is shown by solving the modified Rutherford equation [2,3], Eq. (1), evaluated in Fig. 2 for saturated island widths for both no rf and two levels of precisely positioned ECCD [4],

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

and

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

with $\varepsilon=r/R_0$, $L_q=q/(dq/dr)$, $L_p=-p/(dp/dr)$, β_θ the poloidal beta and j_{ec}/j_{bs} the ratio of the peak ECCD current density normalized by the local equilibrium bootstrap current density. The rf effectiveness η has a coefficient η_0 = 0.4 for no modulation (as in DIII-D experiments described here) and is reduced 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 Gaussan rf current density of width parameter $3\delta_{ec}/5$.]. An example of the importance of precise ECCD positioning is shown in Fig. 3 in which B_T is swept with the rf on with the largest "dip" in the m=2, n=1 Mirnov amplitude occurring with the q=2 and peak j_{ec} positions coinciding. The location of the q=2 surface versus time is made

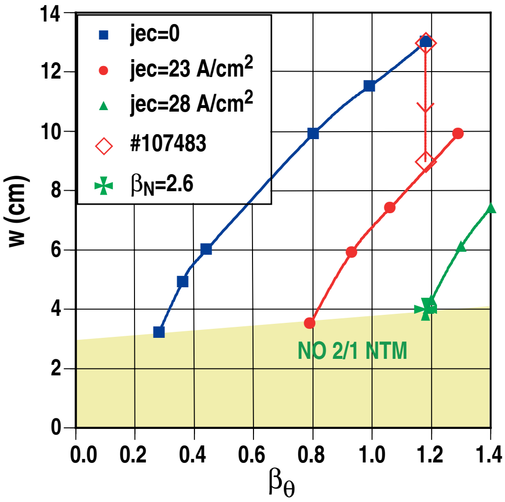

Fig. 2. Calculated full width in DIII-D of m/n = 2/1 saturated island from the modified Rutherford equation versus poloidal beta for different levels of precisely aligned rf current density. Δ'r=-1.3, j_{bs} = 14 A/cm² at β_θ = 1.2 and δ_{ec}=4cm.

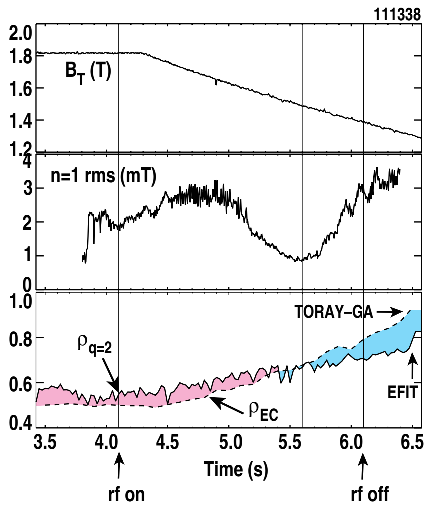

Fig. 3. Relative locations of ECCD and q=2 are scanned past one another using a toroidal field ramp down while constant rf power is applied. a) B_T, b) m=2, n=1 Mirnov amplitude, c) normalized radial locations of q=2 and peak j_{ec}.

by the MHD equilibrium reconstruction code EFIT using the 32 channel Motional Stark Effect (MSE) diagnostic of the radial profile of magnetic field pitch angle [5]. The calculation of the location of the peak rf current density uses the EFIT output as input to the code TORAY-GA [6].

The NTM is particularly well suited to the development of suppression techniques because the mode is linearly stable [$\Delta' r \approx -1.3$ is used in Fig. 2 evaluated by fitting to the model no rf saturated island width $w_{sat} \approx \varepsilon^{1/2} (L_q/L_p)\beta_\theta/(-\Delta')$ with the measured island width from ECE radiometer] although nonlinearly unstable. So if the island can be made to decrease below a threshold size, the mode will decay and vanish. Here the effective threshold is $w_{th} \approx \sqrt{3}\,(w_{pol}^2 + w_d^2)^{1/2} \approx 3.9$ cm from both the polarization threshold w_{pol} of order of the ion banana width and from the cross-field transport threshold w_d [7]. Note that all quantities in this paper (w, w_{pol}, w_d, L_q, L_p, ε, δ_{ec}, $\Delta' r$, etc.) are evaluated at the outboard midplane q = 2 location while β_θ is the global quantity [7]. Experiments in the 2001 DIII-D campaign could at best achieve only a partial suppression of the 2/1 island with well-aligned ECCD and NBI feedback to keep β_θ (and β_N) constant in the presence of the mode as shown by discharge #107483 marked in Fig. 2. The modeling uses $j_{bs} = 14$ A/cm^2 from code ONETWO and peak $j_{ec} \approx 23$ A/cm^2 with $\delta_{ec} \approx 4$ cm from the code TORAY-GA with about 2 MW injected rf power. Predictions were that about 25% more j_{ec} is needed at fixed β_θ to completely suppress the 2/1 NTM or a somewhat lower β_θ for smaller j_{bs}. In the 2002 DIII-D campaign with similar rf power and j_{ec} only slightly higher, β_θ was dropped by NBI feedback to just under 1 ($\beta_N = 2.2$) and complete suppression of the m/n = 2/1 NTM was achieved as shown in Fig. 4 for discharge #111367. Note that the plasma control system needed to make one $\Delta R \approx 1$ cm position adjustment to obtain complete suppression, demonstrating both how precise the alignment must be and how close to marginal the rf power and current drive were for this. Note also that from Eq. (1b), $\exp[-(5\Delta R/3\delta_{ec})^2] \approx \exp[-(5\times 1/3\times 4)^2] \approx 0.84$ or a 16% reduction in effectiveness for $\Delta R = 1$ cm while $\Delta R = 2$ cm would yield a 50% reduction. Experiments in the 2003 DIII-D campaign are planned with 6 gyrotrons for up to 3 MW of injected power so as to study the complete 2/1 NTM suppression at the unreduced $\beta_N = 2.6$ operating point shown in Fig. 2. This is chosen as representative of the hybrid scenario in ITER. The DIII-D result shown in Fig. 4 is the first use of ECCD for complete suppression of the m/n = 2/1 NTM and follows previous successes with ECCD on the m/n=3/2 NTM in ASDEX Upgrade, JT-60U and DIII-D [8,9,10].

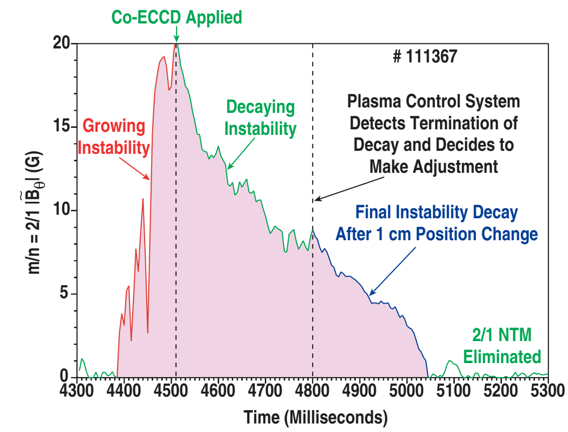

Fig. 4. Applying and adjusting the precise position of co-ECCD stops the growth of a long wavelength tearing mode and then completely eliminates it.

3. Hybrid Scenario In ITER And ECCD Requirements

The DIII-D hybrid scenario is extrapolated to ITER assuming the same shape, profiles, beta and q_{95} but with larger major radius [R_0=1.7 m (DIII-D) becomes 5.7 m (ITER)], higher toroidal field(B_T = 1.7 T becomes 5.3 T). $T_i = T_e$ instead of $T_i = 1.6\ T_e$ as the density $\bar{n}$ relative to the Greenwald density [I_p(MA)/πa(m)^2] is assumed to be increased to 1.0 from 0.4 in DIII-D. The consequences for the NTM threshold are that because the normalized ion gyroradius (the ratio of ion gyroradius ρ_i to the minor radius a) decreases at q=2 from 11.9×10^{-3} in DIII-D to 1.9×10^{-3} in ITER (while collisionality is similar if smaller), the relative threshold at q = 2 decreases from w_{th}/r = 3.9 cm/42 cm = 0.093 to 3.7 cm/127 cm = 0.029, about 3 times smaller. The effect of this is shown in Fig. 5, under the assumption that supplementary heating is adjusted to keep β_N and β_θ fixed. Note that: (1) without rf, the relative saturated island widths are similar as $w^{\angle}_{sat} \gg w^{\angle}_{th}$, (2) there is a critical j_{ec} for which all w have dw/dt < 0 so the mode is stabilized, and (3) the worst case, i.e. highest dw/dt, is at $w \approx w_{th}$ with no rf so the NTM if partially suppressed needs only a little more stabilizing rf current drive to achieve complete suppression; by reducing the saturated island (dw/dt≡0) further, the stabilizing effect of the threshold aids the complete suppression.

Experiments on DIII-D, so far, have maximized j_{ec} by minimizing δ_{ec} within launching constraints. This obtained the nearly optimal $\delta_{ec} \approx w_{th} \approx$ 4 cm as shown in modeling in Fig. 6. Comparison of the relative EC current density and of the relative total EC current versus EC

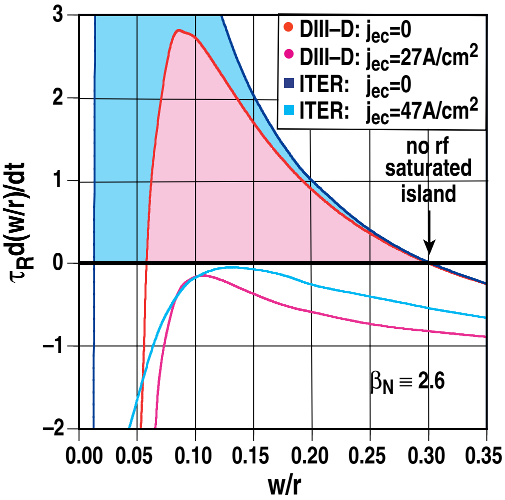

Fig. 5. Growth rate of m/n = 2/1 island width w versus relative island width w/r for both DIII-D and ITER with and without the critical rf current density j_{ec} for stabilization. [Assumed fixed parameters of note are β_N = 2.6, β_θ = 1.2, $\Delta' r$ = -1.3, and FWHM δ_{ec} = 4 cm. Relative NTM threshold island width w_{th}/r = 0.093 in DIII-D and 0.029 in ITER and j_{bs} = 14 A/cm^2 in DIII-D and 13 A/cm^2 in ITER].

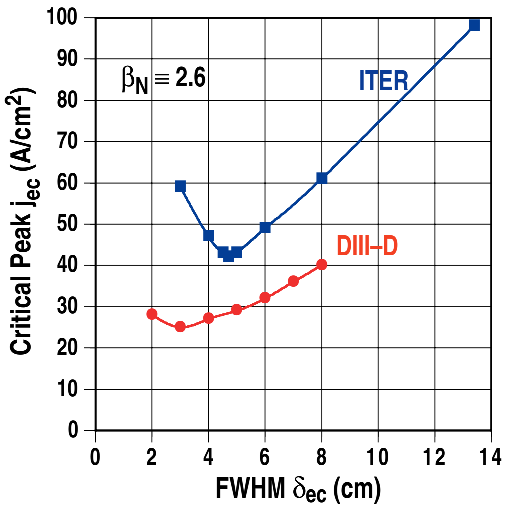

Fig. 6. Calculated critical peak rf current density j_{ec} which fully stabilizes the 2/1 mode versus FWHM width δ_{ec} (evaluated at q = 2 on outboard midplane) for DIII-D and ITER assuming fixed β_N ≡ 2.6 (β_θ ≡ 1.2), perfect alignment and with relative threshold w_{th}/r = 3.9 cm/42 cm in DIII-D and 3.7 cm/127 cm in ITER.

width for both DIII-D and ITER are shown in Fig. 7. Too wide a current drive could make the ITER requirements very demanding on both j_{ec} and I_{ec}.

The predicted optimum δ_{ec} for ITER is only 4-5 cm which may be difficult to execute. Assuming this is achievable, without modulation the required $j_{ec} \approx 40$ A/cm^2 with $j_{ec}/j_{bs} \approx 3$ and $I_{ec} \approx 250$ kA with $I_{ec}/I_p \approx 0.02$. However if the effectiveness of suppression is improved a factor of 2.5(η_0=0.4 → 1.0) by modulating the ECCD to drive current only at the island O-point (yet to be demonstrated in existing devices) the requirements at δ_{ec} = 4-5 cm drop to $j_{ec} \approx$ 17 A/cm^2 and $I_{ec} \approx$ 100 kA which would allow a tradeoff to larger δ_{ec}. Reducing the density to 0.4 of the Greenwald

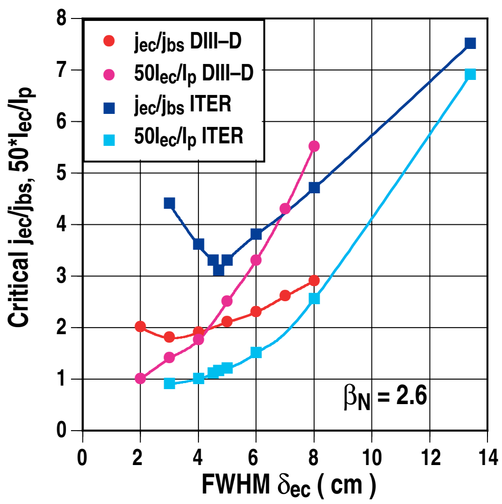

Fig. 7. Calculated width of ECCD determines both the peak EC current density (relative to bootstrap) and the total EC current needed (relative to total plasma current).

density (from 1.0) increases T_i and ρ_{i*} but only increases the NTM threshold modestly. However, the current drive $j_{ec} \propto P_{rf}\, T_e/n_e$ would increase by a factor of 6. The requirements with and without modulation are shown in Table 1.

Table 1

Optimized requirements for EC stabilization of the 2/1 NTM in ITER with and without modulation (η_O=1.0 or 0.4) and at 0.4 or 1.0 of the Greenwald density

	$\eta_o = 0.4, \bar{n}_{GW} = 1.0$	$\eta_o = 1.0, \bar{n}_{GW} = 1.0$	$\eta_o = 0.4, \bar{n}_{GW} = 0.4$	$\eta_o = 1.0, \bar{n}_{GW} = 0.4$
w_{th}/r	0.029	0.029	0.037	0.037
δ_{ec}/r (optimum)	0.037	0.037	0.049	0.049
j_{ec} (A/cm^2)	42	17	39	16

Future work on DIII-D includes increased injected rf power to achieve 2/1 NTM suppression at higher β, pre-biasing with ECCD to avoid the 2/1 NTM or keep it from ever growing to large amplitude (which will include active tracking of the q=2 location and ECCD alignment in the absence of the mode) and detailed comparisons of requirements by changing δ_{ec}, i.e., trading off j_{ec} and I_{ec}.

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