GA–A25329

# EVALUATING ELECTRON CYCLOTRON CURRENT DRIVE STABILIZATION OF NEOCLASSICAL TEARING MODES IN ITER: IMPLICATIONS OF EXPERIMENTS IN ASDEX-U, DIII-D, JET, AND JT-60U

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APRIL 2006

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## DISCLAIMER

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This is a preprint of a synopsis of a paper to be presented at the 21st IAEA Fusion Energy Conference, October 16-21, 2006, in Chengdu, China, and to be published in the *Proceedings.*



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Work supported by the U.S. Department of Energy under DE-FG02-04ER54698, DE-AC05-00OR22725, by EURATOM, the UK EPSRC, and the European Fusion Development Agreement

GENERAL ATOMICS PROJECT 30200

APRIL 2006

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# Evaluating Electron Cyclotron Current Drive Stabilization of Neoclassical Tearing Modes in ITER: Implications of Experiments in ASDEX-U, DIII-D, JET, and JT-60U*

EX-S

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Neoclassical tearing mode (NTM) islands will place the principal limit on stability in ITER in the standard scenario, which has operation well below the ideal kink β limit. NTM control in ITER is predicted to be challenging both because of the relatively narrower marginal island widths and the relatively broader electron cyclotron current drive (ECCD). Existing devices (ASDEX Upgrade, DIII-D, and JT-60U) demonstrate that NTMs can be suppressed or avoided by applying continuous ECCD that is well aligned with the island or rational surface. In addition, an NTM can potentially be limited in size (mitigated in effect) by ECCD with less peak power modulated in phase with the island O-point. Benchmarking of the physics of the m/n=3/2 mode in existing devices (including JET) allows better prediction of the ECCD power needed for stabilization in ITER for both this mode and also for the more deleterious m/n=2/1 NTM (for which neither the tearing mode physics nor the stabilization experiments are yet as advanced in standard $q_{95} \gtrsim 3$ sawtoothing plasmas). In this paper, we show that the planned relatively wide ECCD in ITER should be capable of regulating the island widths and avoid mode locking (with the anticipated rotation in ITER) but there is little margin available for inevitable misalignment. Narrower ECCD of more power and/or more rotation in ITER would increase confidence in island control and successful operation.

The NTM island with poloidal mode number m=3 and toroidal mode number n=2 has received the most experimental study to-date in the areas of: (1) determination of the marginal island size $w_{marg}$ by beta rampdowns [1], (2) NTM stabilization by continuous electron cyclotron co-current drive of a previously saturated 3/2 NTM island [2-5], and (3) pre-emptive avoidance of NTMs using ECCD [6,7]. The empirical marginal island size is consistent in both sets of removal experiments and found to be about twice the ion banana width. The scaling for the marginal island with ECCD is shown in Fig. 1. A common methodology is developed for fitting the saturated m/n=3/2 island before (or without)

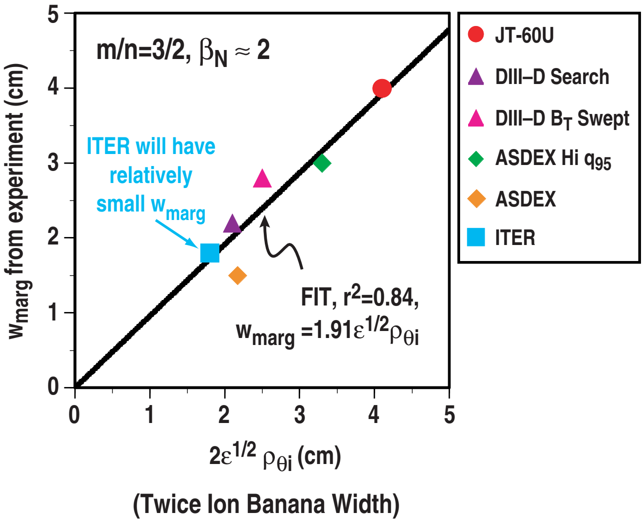


Fig. 1. Marginal island widths (in cm) for ECCD removal in ASDEX Upgrade (both high $q_{95}$ and ITER similar $q_{95}$), DIII-D (both with search and suppress alignment and with toroidal field $B_T$ swept as in ASDEX Upgrade), and JT-60U vs twice the ion banana width. Best linear fit has correlation $r^2$=0.84. The ITER value of $2\varepsilon^{1/2}\rho_{\theta i}$ at $q$=3/2 is shown.

*Work supported by U.S. Department of Energy under DE-FC02-04ER54698, by EURATOM, the UK EPSRC, and the European Fusion Development Agreement.

ECCD in all four experimental devices. To this is added (and model tested to experiments) the effect of unmodulated co-ECCD on island stabilization including both replacing the missing bootstrap current and making the classical tearing stability index more negative.

This model predicts that the original antenna concept for the ITER ECCD upper launch 20 MW, 170 GHz, system should be able to significantly reduce the size of both the 3/2 and 2/1 NTM islands [8], but the degree of effectiveness depends on the benefits of modulation, which needs to be confirmed in present devices. Removing the unstable parameter space in ITER with unmodulated ECCD would be difficult with the proposed power, launcher location, and original antenna concept because of the relatively wide current drive $\delta_{ec}$ (the full width half maximum) with respect to the anticipated marginal island width ($\delta_{ec}/2\varepsilon^{1/2}\rho_{\theta i} \approx$ 5-6 >> 1). However either the modulated or unmodulated ECCD should be sufficiently effective to remediate the deleterious effects of the NTMs on confinement and rotation. Required ratios of $j_{ec}/j_{bs}$ for either the m/n=3/2 or m/n=2/1 modes are about 1 for good alignment ($j_{ec}$ is the peak off-axis ECCD and $j_{bs}$ is the local bootstrap current density). This magnitude for the figure of merit, $j_{ec}/j_{bs}$, is within the planned capability of ITER [9]. Preliminary modeling suggests the ECCD in ITER can keep the m/n=2/1 island width below the locked mode threshold. This is shown in Fig. 2. For example, with the anticipated rotation of 0.4 kHz at q=2, $j_{ec}/j_{bs} \approx$ 1.0 prevents locking for relative misalignments of 0.25 comparable to existing devices. More rotation would expand the no locking space. A new concept [10] for narrower ECCD should also increase the margin.

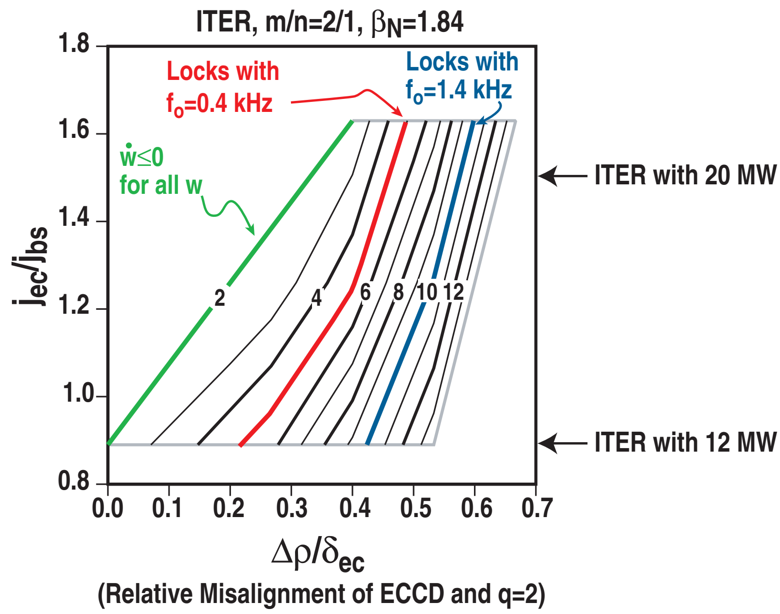


Fig. 2. Necessary modulated peak ECCD at $q$=2, normalized to the local bootstrap current density, calculated to regulate m/n=2/1 island widths (labeled 2 to 12 cm) vs misalignment with the $q$=2 surface. Here $\delta_{ec}$ is the full width half maximum of the ECCD using the original launcher concept. The island widths for locking with the initial $q$=2 plasma rotations of 0.4 and 1.4 kHz respectively are noted.

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