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Stabilization of Neoclassical Tearing Modes by Active Control of Electron Cyclotron Current Drive Alignment in DIII-D

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I. Introduction

Neoclassical tearing modes (NTMs) are completely suppressed and/or avoided and stable beta increased in DIII–D by use of well-aligned radially localized electron cyclotron current drive (ECCD). Real-time alignment of the ECCD on the mode rational surface with a mode ("search and suppress") or without a mode ["active tracking" either by an adaptive network predictor (2003 campaign) or by real-time equilibrium reconstruction (2004 campaign)] is done by the DIII–D plasma control system (PCS). Best use is made of the limited radio frequency power by: (1) radially narrow current drive matched in width to the "marginal" island size determined by the threshold physics and (2) precise alignment of the peak ECCD current density j_{ec} on the island O-point with a mode or on the q=m/n rational surface without a mode.

This paper will first discuss how the "effectiveness" of use of the ECCD for neoclassical tearing mode stabilization is maximized in theory and practice. Successful control by the PCS from the 2003 DIII-D campaign ("search and suppress" handing off to "active tracking" by an adaptive network predictor) is shown along with its limitations. Next the improvements implemented in the 2004 DIII-D campaign using real-time alignment to address these limitations are presented. Finally, future plans will be briefly noted.

II. ECCD Effectiveness

The stabilizing effect of co-ECCD in replacing the "missing" bootstrap current due to an island enters into the right hand side (RHS) of the Modified Rutherford equation for stability as a term proportional to $K_1\, j_{ec}$ [1]. K_1 can be numerically evaluated as a function of current drive width δ_{ec}, island width w, and misalignment ΔR. Here δ_{ec} is the full width half-maximum of a Gaussian current drive and w is the full width of an island. Assuming well-aligned current drive and no modulation of the rf, K_1 peaks at a value of $1/\sqrt{3}$ at $w/\delta_{ec} \approx \sqrt{3}$ and is well-represented by the function $K_1\ (\Delta R/w \equiv 0) \approx (2w/\delta_{ec})/[3+(w/\delta_{ec})^2]$. An effective marginal island width can be estimated as $w_{marg} \approx 2\varepsilon^{1/2}\ \rho_{\theta i}$, i.e. twice the local ion banana width. At this value of w, the NTM self-stabilizes without ECCD due to the threshold physics. As K_1 peaks at $w/\delta_{ec} \approx \sqrt{3}$, the minimum requirement for peak rf current drive j_{ec} should occur at about $\delta_{ec} \approx w_{marg}/\sqrt{3}$ in order to take advantage of the thresholds, i.e., stabilizing effects [2]. In DIII-D, $\delta_{ec}/w_{marg} \approx 1$ is not far from being optimized. Experiments to examine a broader current drive to test this are planned but not yet carried out. An example of how well-aligned ECCD reduces the island width to the marginal value followed by complete suppression is shown in Fig. 1.

Experimental results to map out the effect of misalignment in the rf term of the Modified Rutherford equation are shown in Fig. 2 [3]. The rf is applied to a previously saturated m/n = 3/2 island and the initial decay rate γ of the n=2 Mirnov amplitude (proportional to the rf term on the RHS of the Modified Rutherford equation) is measured. Toroidal field B_T is slightly adjusted, shot-to-shot, to change ΔR. Fitting $\gamma\,(\Delta R)$ to $\exp[-(5\Delta R/3\delta_{ec})^2]$ yields $\delta_{ec} = 3.8 \pm 0.8$ cm which is close to the calculated value of 2.7 cm from the current drive analysis code TORAY-GA. A misalignment of only 2 cm reduces the ECCD effectiveness a factor of 2 but $\Delta R = 1$ cm by only 20%. Thus alignment needs to be maintained with ±1 cm (out of minor radius a = 60 cm) to be effective. This is the goal of the DIII-D PCS real-time alignment.

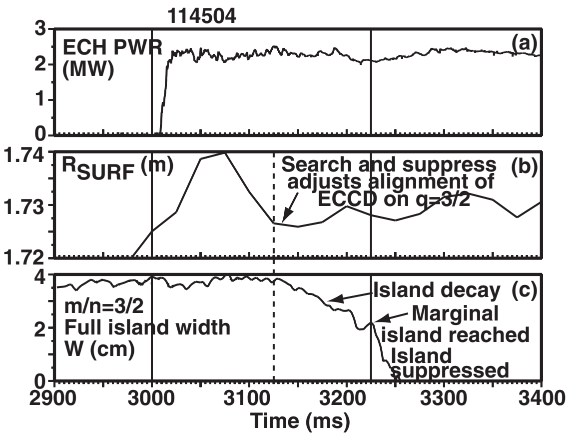

Fig. 1. "Search and suppress" for DIII-D discharge 114504 showing (a) rf power, (b) plasma major radius adjusted to align q = 3/2 on ECCD, (c) m/n = 3/2 full island width calculated from the n=2 Mirnov signal. Note break in the slope of w(t) when the marginal island is reached.

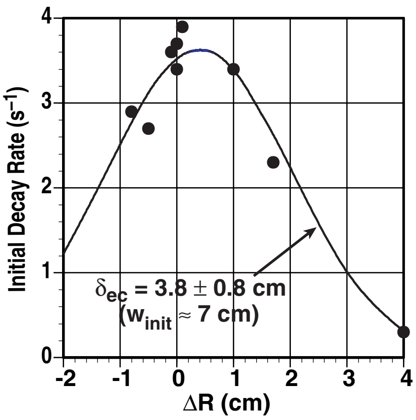

Fig. 2. Initial decay rate of the n=2 Mirnov amplitude upon applying ECCD to a previously saturated m/n = 3/2 island. Misalignment ΔR is varied shot-to-shot by adjusting the toroidal field and thus the second harmonic resonance ($2f_{ce}$) location radially.

III. Search and Suppress, Handing Off to an Adaptive Network Predictor

An example of the various alignment techniques for the m/n = 3/2 NTM is shown in Fig. 3. Upon initiation of the 110 GHz rf power, the search and suppress adjusts the plasma major radius R_{surf} to sufficiently align the island on the ECCD to achieve complete suppression as shown in Fig. 1 in detail. After suppression, the search and suppress hands over alignment to active tracking, which uses an adaptive network predictor. This algorithm maintains the alignment, without a mode, particularly as the rising beta and increased Shafranov shift would otherwise cause the q = 3/2 flux surface to shift outward. Thus, the well-aligned ECCD maintains stability, even as beta rises above the initial onset value. While successful, one limitation of this approach is that suppression of a prexisting mode is required to establish the alignment which is subsequently maintained by the adaptive network predictor. Any misalignment is propagated and a specific configuration must be run repeatedly to train the predictor.

IV. Real-Time EFITS for Alignment of Early ECCD and NTM Avoidance

Faster processors in the upgraded plasma control system make calculation of MHD equilibrium reconstruction with EFIT [4] including the motional Stark effect (MSE) diagnostic of magnetic field pitch about 15 times faster than previously available. The cycle time is about every 3-1/4 ms. Inclusion of MSE data allows determination of the q profile. Using EFITs for ascertaining the location of a rational surface does not require training to a specific kind of discharge and does not propagate any misalignments on hand-off from search and suppress to the adaptive network. By applying the ECCD early, i.e. before the NTM onset, the real-time EFIT alignment and tracking can avoid the initiation of the NTM and allow higher stable beta without the NTM ever appearing. Note that the presence of sufficiently well-aligned ECCD alone can in principle stabilize an NTM for all island widths (Fig. 2 of Ref. [3]) without any change in the classical stability index Δ'. An additional stabilizing effect of applying the ECCD before the onset of an island could also arise from making Δ' more negative [5,6].

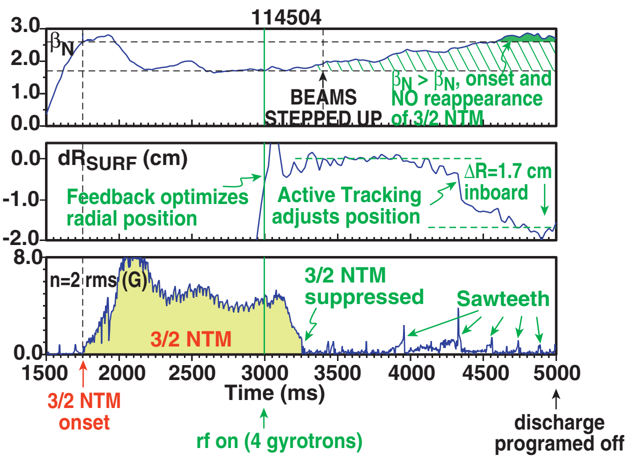

Fig. 3. Alignment of the ECCD on the q = 3/2 rational surface is done by the "search and suppress" in the presence of the mode and by an adaptive network predictor without the mode. (a) β_N, (b) change in plasma major radius R_{surf}, (c) n=2 Mirnov amplitude.

An example of successful real-time MSE alignment of early ECCD on the q = 3/2 surface, avoiding the mode initiation, is shown in Fig. 4. TORAY-GA [7] is used to calculate the peak rf current density location to give an alignment target. The m/n = 3/2 NTM was avoided as beta was increased up to the eventual onset of an m/n = 2/1 NTM which is not being controlled. Otherwise identical discharges without early ECCD exhibited a 3/2 NTM during the initial beta rise. Note the noise in real-time MSE EFIT major radius of q = 3/2 shown in Fig. 4(c). This noise seems to be correlated with ELMs [Fig. 4(b)] whose fast non-axisymmetric poloidal field variations are input to EFIT by a single toroidal location of poloidal magnetic probes. Thus a 10 Hz causal Butterworth filter is used for control as also shown in Fig. 4(c). Effects of q=1 sawteeth then represent the largest source of variation that the PCS has to deal with in maintaining alignment. Figure 5 better shows the ECCD target radius, the unfiltered and filtered (control) q = 3/2 major radius and the plasma major radius (offset to overlay) which is changed to maintain alignment.

V. Future Work

Real-time mirror steering is planned to provide accurate localization of the ECCD so that the plasma shape can be fixed in time. Early ECCD and real-time MSE EFIT will be applied to q=2 for m/n = 2/1 NTM avoidance in these sawteething q_{95} < 4 plasmas to follow up previous successful work in hybrid scenario plasmas (higher q_{95} and no sawteeth) using search and suppress [8]. Real-time TORAY-GA (or a faster equivalent) needs to be implemented to track any changes in the location of peak electron cyclotron current density, a higher order effect than a change in q-position.

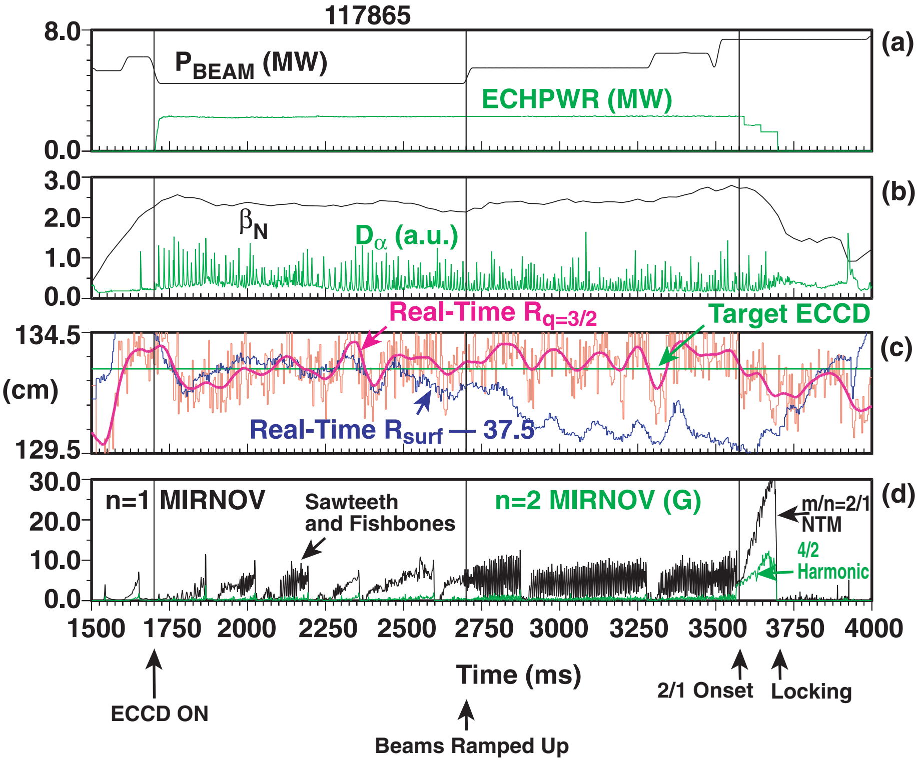

Fig. 4. Successful applicaton of early ECCD aligned to q = 3/2 by real-time MSE EFITs to avoid initiation of an m/n = 3/2 NTM. (a) Beam and rf power, (b) β_N and D_α, (c) unfiltered and filtered (used to control) major radius of q = 3/2, and plasma major radius (shifted by 37.5 cm to overlay) used to align, (d) n=1 and n=2 Mirnov $|\tilde{B}_\theta|$ amplitudes.

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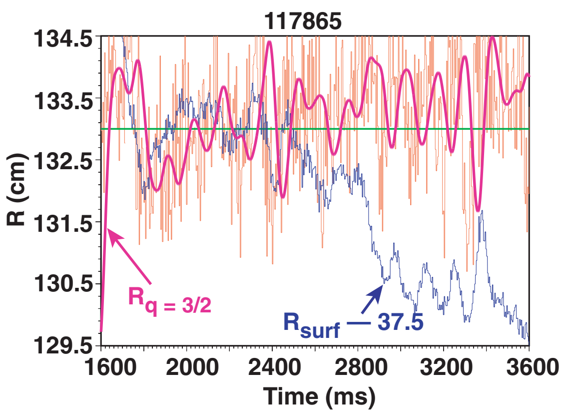

Fig. 5. Filtered (magenta, control) and unfiltered (red) real-time MSE EFIT q = 3/2 inboard major radius, target (green horizontal line) for ECCD alignment (from TORAY-GA pre-calculation) and plasma major radius (blue, offset to overlay) showing change to maintain ECCD alignment on q = 3/2

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