Beta Limiting MHD Activity in Alcator C-Mod

J A Snipes, R S Granetz, A E Hubbard, Y In, D Mossessian, J E Rice, J J Ramos,
D Schmittdiel, G Taylor[*], S M Wolfe
MIT Plasma Science and Fusion Center, Cambridge, MA 02139, USA
[*]*Princeton Plasma Physics Laboratory, Princeton, NJ 08543*

Introduction

With high power ICRF heating ($P_{RF} \leq 5$ MW) on Alcator C-Mod, high performance plasmas are readily obtained with normalized beta values, $\beta_N = \beta_T/(I/aB_T)$, exceeding 1.2 and maximum values as high as 1.7 in H-mode. All of the 2000 campaign discharges with $\beta_N > 1.2$ (73 discharges) were analysed for low frequency ($f_{MHD} < 50$ kHz) MHD activity associated with high β, measured with 1 MHz sampled magnetic pick-up coils at the wall. At high density ($\bar{n}_e > 2.5 \times 10^{20}$) and high collisionality, $\nu_{q=2} = \left[\nu_i / (\varepsilon\omega_{*e})\right]_{q=2} \geq 1$, sawtooth precursors and small ELMs dominate the MHD activity with rapid chaotic spikes on top of an Enhanced D_α H-mode (EDA) [1]. At lower collisionality, $\nu_{q=2} \leq 0.5$, a small number of discharges in ELM-free H-mode had moderate to large amplitude MHD modes ($5 \times 10^{-5} < [\tilde{B}_\theta / B_\theta]_{wall} \leq 5 \times 10^{-3}$) with m/n = 2/1, 3/2, 4/3, and 5/4, in addition to sawtooth precursors, which were destabilized at $\beta_p > 0.52$ and increased in amplitude with increasing β until a rollover or collapse in β occurred. Because of the correlation with low collisionality and high β, comparisons were made with neoclassical tearing mode (NTM) theory [2-4] and with similar modes found on other tokamaks [4-7]. Calculations were done with the MARS code [8] to determine the MHD stability properties of one such mode.

Observations

Particularly large amplitude modes that appear to limit the maximum β_N achievable (Figure 1) were found in only two of the 73 high beta discharges. These discharges were in ELM-free H-mode with $I_p = 1$ MA, $B_T = 5.4$ T, $q_{95} \approx 4$, and $\nu_{q=2} \approx 0.1 - 0.2$. The mode amplitude increased with increasing β_p, suggestive of NTM's, then the frequency slowed down and the mode locked. The confinement degraded substantially after the mode locked, which then reduced β. Figure 2 shows the auto-power spectrum of an outboard midplane pick-up coil signal for the discharge of Figure 1 together with the RMS mode amplitude and β. Due to equilibrium changes after the mode locks, the mode amplitude cannot be determined accurately while the mode is locked, but the small irregular sawteeth and poor confinement throughout the remainder of the discharge indicate a substantial locked mode remains until the plasma disrupts at 1.51 s. An NTM would be expected to decrease sharply in amplitude with decreased β, so this suggests resistive tearing modes. The core toroidal plasma rotation frequency, measured from the Doppler shift of a trace concentration of argon impurity ions [9], was about 30 kHz at 0.77 s and began decreasing just after the mode locks at 0.8 s. The magnetic mode frequency just before the sawtooth does <u>not</u> track this rotation as it usually does [10] but is substantially slower, indicating a weak coupling of the sawtooth precursors to modes near the edge of the

plasma. Both the mode rotation and the plasma rotation are in the ion diamagnetic drift direction. The mode at 0.76 s with a frequency of about 14 kHz is predominantly an m=4, n=3 mode. After the next sawtooth crash, there is a faint mode with m=2, n=2 that peaks at 28 kHz after the crash, which is close to the core rotation frequency at that time. This mode slows down rapidly before the next sawtooth crash even though the plasma is still rotating. During this phase from 0.766s onward, the magnetic pick-up coil signals are dominated by a growing m=2, n=1 mode starting at 5 kHz and slowing down to lock at 0.802 s. A coupled m=4, n=2 mode is also present at twice the n=1 mode frequency. At 0.77 s, an aliased mode appears on the 20 kHz sampled ECE signals near the q=1 surface that is not coupled to the edge m=2, n=1 mode. But, just before 0.78 s, when the m=2, n=1 amplitude exceeds $[\tilde{B}_\theta / B_\theta]_{wall} \approx 1.9 \times 10^{-3}$, the core mode frequency becomes the same as the m=2, n=1 frequency indicating strong coupling between the two modes. Despite the fact that the core plasma is still rotating at 30 kHz when the mode begins to lock, the m=1, n=1 mode in the core rotates with the m=2, n=1 mode frequency and also locks at the same time (Figure 3). Once the m=2, n=1 mode couples strongly to the core m=1, n=1 mode, the core plasma rotation also begins to slow down and it stops rotating at about 0.85 s (Figure 1). Similar locking of core rotation to an m=2, n=1 mode has been observed on JET [11].

The large core mode is observed on eight ECE channels from the center to near the edge at the outboard midplane and the innermost 7 channels are in phase while there is a phase inversion on the 8th channel. So, the q=2 surface should lie between the 7th and 8th channels. However, EFIT using external magnetic measurements and kinetic profiles placed the q=2 surface about 5 mm inside channel 7, which may be within the uncertainties. When the m=2, n=1 mode couples strongly to the core m=1, n=1 mode, the confinement is seriously degraded going from a peak H factor before the mode appears, relative to the ITER89P scaling [12], of $H_{89} \sim 2.5$ to about 0.7 in less than one confinement time despite 3.5 MW of ICRF heating.

In addition to these two large amplitude m=2, n=1 modes, two other discharges had smaller amplitude m=4, n=3 and m=5, n=4 modes at high β and one discharge had an m=3, n=2 mode that was destabilized just after a large sawtooth collapse at the L-H transition at relatively low β. While this m=3, n=2 mode appeared to be triggered by a sawtooth 'seed' island, the fact that it appeared just after the L-H transition when $\beta_p \approx 0.52$ and $\beta_N \approx 0.88$ suggests that it may not be an NTM. The higher order modes in the other two discharges are unusual in that a mode from such a deep rational q surface is not usually observed with pick-up coils at the wall unless it is coupled to a q surface with larger q that is closer to the pick-up coils. In these cases, the mode amplitudes do not exceed $[\tilde{B}_\theta / B_\theta]_{wall} \leq 2.6 \times 10^{-4}$, which indicates that they do not have the strong nonlinear drive characteristic of NTM's. These discharges had $P_{ICRF} = 2.5$ MW, $I_p = 0.8 - 1$ MA, $B_T = 5.4$ T, $q_{95} \approx 3.9 - 4.8$, $\beta_N \approx 1.35 - 1.5$, $\bar{n}_e \approx 1.9 \times 10^{20}$ m^{-3}, and $\nu_{q=2} \approx 0.09 - 0.13$.

Comparison with Theory

Resistive MHD stability was analysed with the MARS code [8] at 0.77 s for the discharge shown in Figure 1 using a kinetically constrained EFIT equilibrium. While there are large uncertainties in the equilibrium since there are no internal magnetic field measurements, the MARS calculations indicate that a cylindrical equivalent $\Delta' > 0$ for all the rational surfaces q = 1, 2, 3, and 4. A large m=1, n=1 ideal internal kink mode is the most unstable in the core since $q(0) < 0$ and only smaller sidebands are also found. While the ECE measurements suggest that there may be an m=1, n=1 internal kink, the mode is strongly coupled to a large m=2, n=1 mode near the edge, which was not found in the MARS calculations.

Figure 3 shows the ratio $-\beta_p L_q/L_T$ where $\beta_p \equiv 2\mu_0(n_i T_i + n_e T_e)/B_\theta^2$ and $L_x = X/(dX/dr)$ is the local scale length at the q=2 surface. The bootstrap term of the modified Rutherford equation [4] for the change in the island width of a mode is proportional to $-\beta_p L_q/L_T$. This parameter increases by nearly a factor of two over this time range as the m=4, n=3 and m=2, n=1 island widths, calculated from magnetic field measurements at the wall [13], increase substantially. While the uncertainties are large, this does suggest that the bootstrap term may be playing a role in the increasing island widths of these modes.

The high β operational space so far obtained on C-Mod is shown in Figure 4 where $\beta_N/\rho_{*i}^{1.3}$ is plotted versus the collisionality $\nu \equiv \nu_i/(\varepsilon\omega_{*e})$, where $\rho_{*i} = \upsilon_{ti}/(\omega_{ci} a)$, υ_{ti} is the ion thermal velocity, ω_{ci} is the ion cyclotron frequency, a is the minor radius, ν_i is the ion collision frequency, $\varepsilon = r_s/R$, and ω_{*e} is the electron diamagnetic drift frequency calculated at the mode rational surface. The dashed curve is a recent fit to the DIII-D m=2, n=1 NTM boundary [7]. While all of the C-Mod high β points lie well below the DIII-D curve, the red points where large MHD activity was observed are some of the closest points to the curve. They also have $\nu < 0.5$, which is close to the value of 0.3 below which neoclassical effects are expected to become important [2]. These modes are only about a factor of three away from the DIII-D unstable boundary. Given the uncertainties in the theory and the experimental measurements, it is possible that at least the largest of these modes are NTM's. C-Mod will attempt to extend operations to lower ν and higher β_N in order to better test such NTM scalings.

References

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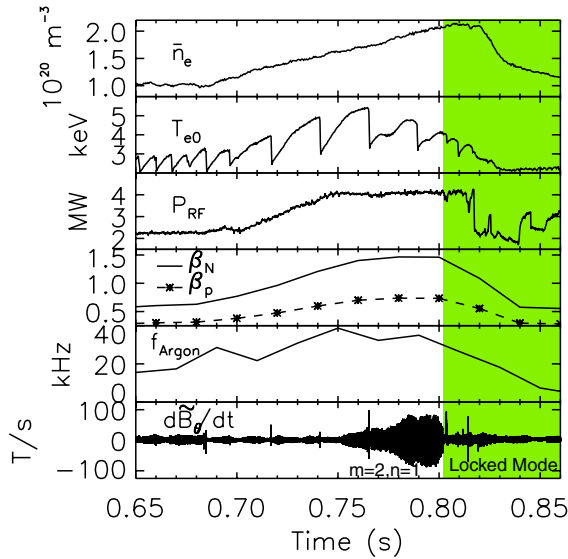
Figure 1 A high β discharge with an m=2,n=1 mode that leads to a β collapse showing the line averaged density, central T_e, ICRF power, β_N, β_p, toroidal rotation velocity, and dB_θ/dt.
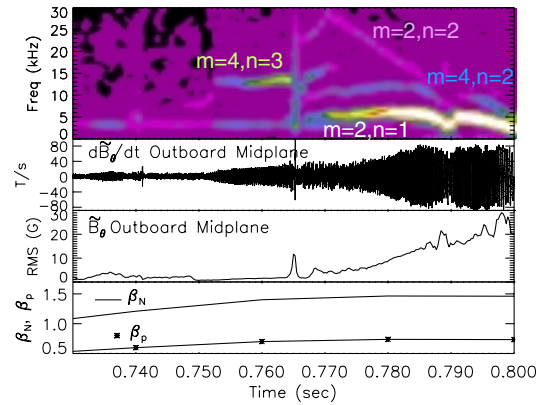
Figure 2 Auto-power spectrum of a pick-up coil signal from the outboard midplane and the RMS mode amplitude, β_N and β_p. Brighter color means higher amplitude.
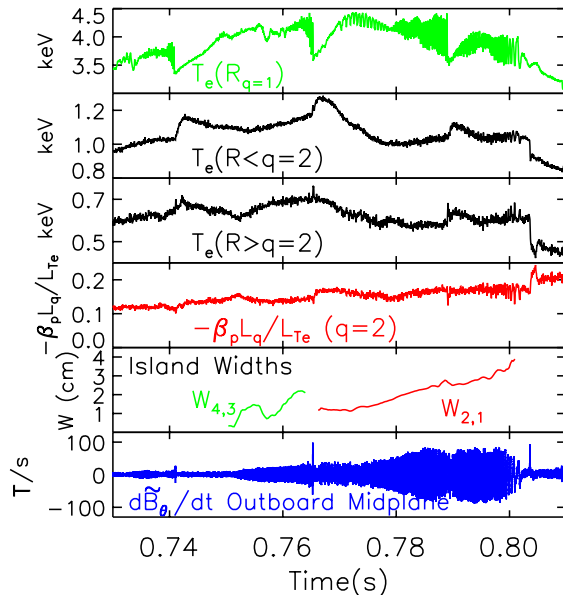
Figure 3 ECE T_e signals at the q=1 and straddling the q=2 surface and the bootstrap parameter $-\beta_p L_q/L_{Te}$ at q=2 showing an increase by about a factor of 2 as the m=4,n=3 and m=2,n=1 islands grow.
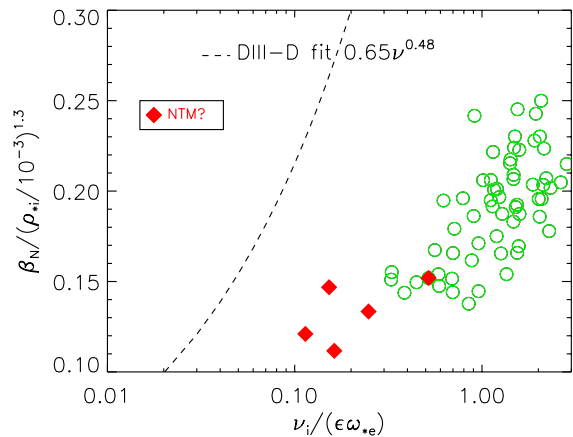
Figure 4 High β operational space at the q=2 surface showing the discharges with large MHD modes in red diamonds have low collisionality and are nearest to the DIII-D boundary for m=2,n=2 NTM's.