Moderate Toroidal Mode Number Alfvén Eigenmode Damping Rate Measurements on Alcator C-Mod

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Introduction Stable Toroidal Alfvén Eigenmodes (TAEs) with a broad spectrum of moderate toroidal mode numbers ($3 \le |n| \le 14$) are excited on Alcator C-Mod with a pair of antennas at one toroidal location [1]. This is in the range of mode numbers expected to be unstable in ITER [2,3], at the same toroidal field and density as ITER. By sweeping the frequency through the expected center of the TAE gap frequency ($\omega_{TAE} = \mathrm{v}_A / 2qR$) for a given q value, the width of the mode resonance can be measured with magnetic pick-up coils to find the damping rate as a function of plasma parameters, as has been done previously on JET for $n \le 2$ [4]. Understanding the physics of moderate n TAEs may prove to be important for fusion burn control or controlling the loss of fast ions in ITER.

Measured Damping Rates Recent experiments have measured the damping rate of stable TAE resonances as a function of triangularity, ion ∇B drift direction, density, toroidal field, and ICRF power. The damping rate does not increase for n=6 modes with increasing triangularity (Figure 1), in contrast to the JET result for n = 1 [5] where increased triangularity increased the damping rate. This suggests that the radial structure of moderate n modes is not dominated by edge shaping effects as expected for the low n modes.

In experiments where the toroidal field and plasma current were reversed relative to the usual configuration, the TAE damping rates in USN and LSN diverted plasmas were compared. USN is with the ion ∇B drift directed towards the X point. The measured damping rates vary from $2\% < |\gamma/\omega| < 7\%$ in LSN and from $3\% < |\gamma/\omega| < 8.5\%$ in USN. This is again in sharp contrast with the JET result for n = 1 modes where the damping rate was 3 times higher when the ion ∇B drift was directed away from the divertor [6]. Note, however, that the n numbers are not all clearly defined for these resonances in C-Mod, so changes in the mode number could also affect the damping rate. This again suggests that edge effects on the damping of moderate n modes are not as strong as for low n modes.

ICRF Power Scan To attempt to measure the fast ion drive reduction in the effective damping rate, a series of low density ($1.1 < \bar{n}_e < 1.5 \times 10^{20}$ m^{-3}) discharges were run with

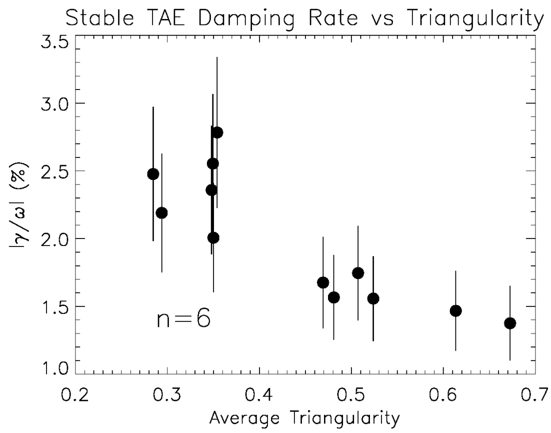

Fig. 1. Measured TAE damping rate vs average triangularity for *n*=6 modes.

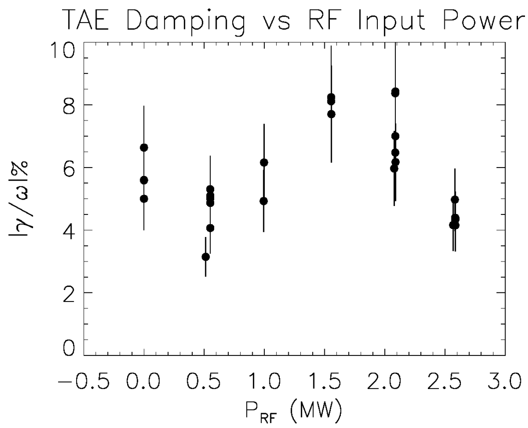

Fig. 2. Measured TAE damping rate vs ICRF input power for various *n* modes.

increasing ICRF power (H minority heating) from 0 to 2.5 MW while sweeping the frequency of the active MHD antenna current through the center of the TAE gap for q=1.5. Figure 2 shows the measured TAE damping rate vs ICRF power. While there is a large scatter in the data, there is no clear dependence of the measured damping rate with increasing ICRF power. Unstable TAEs have been observed under other conditions in C-Mod with 2.5 MW of ICRF, so this should be sufficient power to see an effect on TAE stability. It was expected that an increasing amount of fast ions with increasing ICRF power would decrease the damping rate as seen on JET [7]. Measurements of the fast ion tail were made with a core vertically viewing Compact Neutral Particle Analyzer (CNPA) together with a Diagnostic Neutral Beam (DNB) to improve the count rate. TRANSP [8] was run with a TORIC [9] ICRF model to calculate the fast ion distribution. There is good agreement between the CNPA measured effective peak fast ion temperature and the TRANSP calculations (Figure 3). The TRANSP fast ion profiles indicate that the fast ions are all inside of r/a ~ 0.5 while the q=1.5 surface is at r/a = 0.5 for these discharges.

NOVA-K Modeling To get an idea of the radial mode structure, a measured resonance with f=609 kHz, *n*=-4, and $|\gamma/\omega| \sim 8\%$ at 1.0 s in the discharge with 1.5 MW of ICRF power was modelled with the NOVA-K code [10] using the EFIT q profile. The plasma rotation was not measured for this shot, but estimates from previous shots indicate that it should be in the electron diamagnetic drift direction with $f_{rot} \sim 6$ kHz. Since the mode was also rotating in the electron diamagnetic drift direction, the frequency in the plasma frame should be smaller than the measured frequency by a Doppler shift of $|n \cdot f_{rot}| \sim 24$ kHz, so the mode frequency in the plasma frame should be ~ 585 kHz. Figure 4 shows the calculated

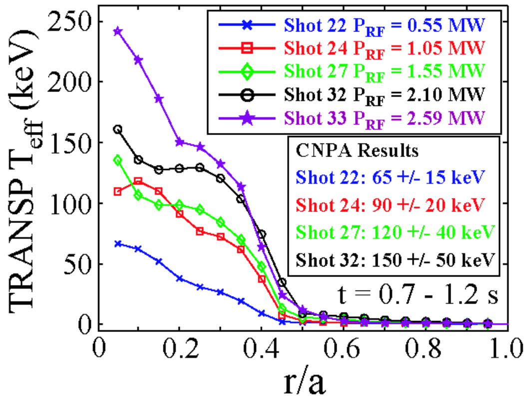

Fig. 3. TRANSP calculated effective fast ion temperature profiles with increasing ICRF power. Measured CNPA peak T_{eff} values agree well with TRANSP.

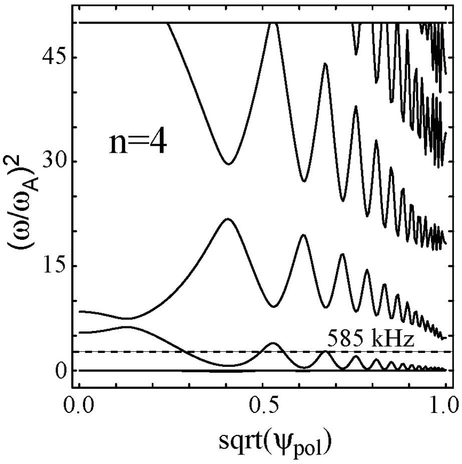

Fig. 4. NOVA-K calculated TAE gap structure for n=4 for the 1.5 MW ICRF discharge to model the measured TAE resonance at 609 kHz with $|\gamma/\omega| \sim 8\%$.

TAE gap structure for an *n*=4 mode. A mode at 585 kHz would intersect the continuum near sqrt(ψ_{pol}) ~ 0.5, which would suppress the mode within this radius. Due to the particularly large damping of this mode, NOVA-K is unable to properly model it since some of the assumptions in the code, such as the perturbative mode treatment, breakdown. Since the mode would be suppressed where the fast ions are located (see Figure 3), it is plausible that there would be little effect of the fast ions on the measured damping rate of this mode. If the fast ion distribution is indeed centrally peaked, a TAE rotating in the electron direction will not be in resonance with the fast ions, and thus is not expected to be destabilized for these conditions. Either of these effects could explain why there was little change in the measured damping with increasing ICRF power. However, it should be noted that the NOVA-K results are very sensitive to changes in the assumed q profile [11].

Dimensionless Parameter Scans Through density, power, and toroidal field scans, the dimensionless plasma parameters $\nu_{*e}=6.9\times10^{18}qRn_e\ln\Lambda_e/(T_e^2\varepsilon^{3/2})$, $\rho_{*i}=2.0\times10^{-4}\ T_e^{1/2}/(aB_T)$, and $\beta_N=aB_T\beta_T/I_p$ have been varied over reasonable ranges to look for changes in the measured TAE damping rate. The collisionality varied over a range from $0.02 < \nu_{*e} < 0.3$ and while there was no clear variation in damping rate at high collisionality, the damping rate appears to increase substantially at very low collisionality (Fig. 5). The normalized ion gyroradius varied over a range from nearly $0.005 < \rho_{*i} < 0.01$ and the damping rate appears to increase with increasing ρ_{*i} (Fig. 6). To ensure that the TAEs remain stable, the ICRF power was limited to 2.5 MW so the variation in β is modest over the range from

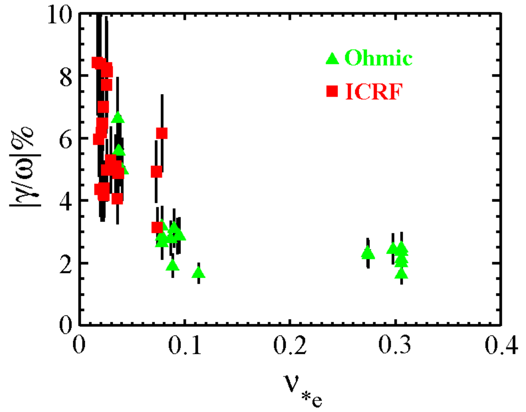

Fig. 5. Measured TAE damping rate vs electron collisionality for an Ohmic density scan and an ICRF scan with various *n* numbers.

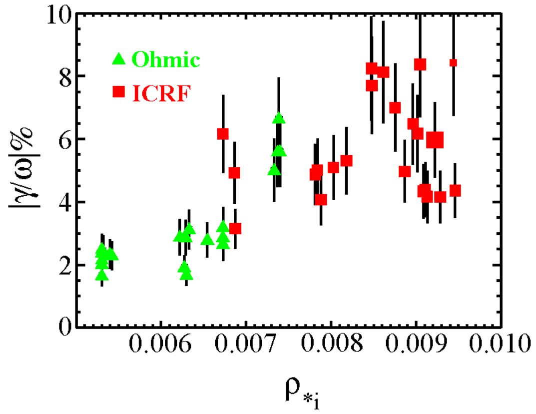

Fig. 6. Measured TAE damping rate vs normalized ion gyroradius for an Ohmic density scan and an ICRF scan with various *n* numbers.

$0.3 < \beta_N < 0.9$ and while there is considerable scatter in the data, there is perhaps a slight trend toward increasing damping rates with increasing β_N.

Conclusions Measured moderate *n* TAE damping rates decrease with triangularity and appear to be nearly independent of the ion ∇B drift direction in diverted plasmas. These results indicate that moderate *n* TAE damping is not strongly affected by edge conditions in contrast to low *n* TAE damping measured on JET. The moderate *n* damping rate was also independent of ICRF power, possibly because the fast ion toroidal precession was opposite to the TAE direction or that the fast ion drive was at a different radial location than these modes. The measured damping also appears to increase at very low ν_* and increase with ρ_* and β. TAE damping rates depend sensitively on a number of plasma parameters that are difficult to measure to the required precision, such as the detailed shape of the q and density profiles. So, it is possible that changes in these or other parameters, such as the toroidal mode number, could confuse the parametric dependences presented here.

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