Comparison of Measured and Calculated TAE Damping Rates in Alcator C-Mod

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Introduction

- Moderate $n = 5 \rightarrow 10$ Alfvén Eigenmodes (AEs) are expected to be unstable in ITER and could redistribute the core fast $\alpha$ particles before they have had a chance to thermalize with the background plasma.
- Understanding and control of AEs could improve fusion burn control and lead to improved energy and fast $\alpha$ particle confinement.
- Stable AEs are excited in C-Mod with a pair of active MHD antennas that drive moderate $j_t \approx 16$ modes.
- Damping rates of these moderate $n$ AEs have been compared with MHD calculations using the Nova-K code including continuum, collisional, and Landau damping but radiative damping is not included.
- Sensitivity of the calculated damping rates to small changes in the $q$ profile has been studied for different edge magnetic configurations.

Active MHD Alfvén Eigenmode Diagnostics

- Two antennas above and below the outboard midplane at one toroidal location now with no protection from the plasma ~ 2.5 cm away radially.
- Two amplifiers drive ~ 25 A, each producing $B_R \approx 1$ G at $q = 1.5$.
- $10 \text{ Hz} < f < 1 \text{ MHz}$, broad toroidal spectrum $j_t \approx 16$ FWHM.

Magnetic Diagnostics in Active C-Mod

- 65 poloidal field pick-up coils in poloidal and toroidal arrays.
- Can measure $m < 14$ and $n < 75$, sampling between $1 \rightarrow 2.5$ MHz.
- With only two outboard limiter locations toroidally, low $n$ numbers are difficult to measure accurately.
- Active MHD perturbations are so small that they are not observed on other fluctuation diagnostics.

Nova-K AE Damping Rate Calculations

- Nova-K was used without fast particles to calculate the total damping rate of Alfvén eigenmodes in the same frequency range as the experiment including plasma rotation.
- Nova-K was run with a free boundary condition to allow finite fluctuation control and lead to improved energy and fast $\alpha$ particle confinement.
- Stable AEs were excited in C-Mod with a pair of active MHD antennas that drive moderate $j_t \approx 16$ modes.
- Measured damping rates from $0.76\% < \frac{\gamma}{\omega} < 3.0\%$ and measured modes from $3 \leq n < 5.9$ were modeled.
- Sensitivity of the damping rate to $q$ was calculated by scaling the $q$ profile with $0.9, 1.0, 1.1$ times the EFIT-based profile.
- Since no measurements of the $q$ profile are available on C-Mod, $q$ profiles were calculated from TRANSP and compared with EFIT-based profiles.
- Stability of AEs is excited in C-Mod with a pair of active MHD antennas.
- Both inner wall limited and lower single null diverted plasmas were modeled.
- Measured damping rates from $0.76\% < \frac{\gamma}{\omega} < 3.0\%$ and measured modes from $3 \leq n < 5.9$ were modeled.
- Calculated average perturbed poloidal field at the edge peaks near the top and bottom of the plasma.
- Top and bottom of the plasma near the edge also have larger amplitude than near the midplane.

Stable TAE Inner Wall Limited n=4 Mode with Ramping TF

- Constant active MHD frequency and ramping toroidal field through the TAE resonance.
- $f_{\text{TAE}} = 420 \text{ kHz}$, $n = -4$, $\gamma/\omega = 3\%$ inner wall limited case.
- $f_{\text{TAE}} = 420 \text{ kHz}$, $n = -4$, $\gamma/\omega = 3\%$.
- Measured $B_T \approx 2.5 \times 10^5 \text{T}$.
- $B_T \approx 2.5 \times 10^5 \text{T}$.

Nova-K Comparison of Peaked and Flat $q$ Profile for n=4 Inner Wall Case

- Clearest mode found by Nova-K without strong continuum interaction.
- Broad radial eigenmode structure peaked at mid radius and with a large edge component.
- Plasma rotation typically $< 5 \text{ kHz}$.
- Closest modes have a peaked $q$ profile $f = 418 \text{ kHz}$, $\gamma/\omega = 0.73\%$.
- Flat $q$ profile finds no modes without strong continuum interaction in the measured frequency range.
- Calculated average perturbed poloidal field at the edge peaks near the top and bottom of the plasma.
- $B_T \approx 2.5 \times 10^5 \text{T}$.
- $B_T \approx 2.5 \times 10^5 \text{T}$.
Stable n=3 TAE Resonance in Lower Single Null

- Constant active MHD frequency with ramping TF and a change in density that modulates the TAE frequency through the active MHD frequency for three successive resonances
- Measured \( f_{\text{TAE}} = 436 \text{ kHz} \), \( n=3 \), \( |\gamma/\omega| = 0.76\% \) for this lower single null case
- Note the small outer gap of 0.14 cm allows good coupling of the antennas to the plasma

Nova-K Finds Similar Results for Small Changes in q(r)

- Measured TAE resonance has \( n=3 \), \( f_{\text{TAE}} = 436 \text{ kHz} \), \( |\gamma/\omega| = 0.76\% \)
- Plasma rotation -4 to -8 kHz \( \Rightarrow \text{frequency range} = 12 \text{ to } 24 \text{ kHz} = 448 - 460 \text{ kHz} \)
- For both q profiles Nova-K finds a similar mode with \( f = 452 \text{ kHz} \), \( |\gamma/\omega| = 0.97\% \) and 0.58\% near the measured damping rate of 0.76\%

Nova-K Indicates Broad Mode Structure

- Closed mode found by Nova-K interacts with both core and edge continuum
- Broad radial eigenmode structure with large edge component
- Calculated \( |\gamma/\omega| = 0.76\% \) in good agreement with the measured \( |\gamma/\omega| = 0.76\% \)
- 2D poloidal field perturbation indicates mode peaks at mid radius and is anti-ballooning
- Calculated poloidal field perturbation at the edge peaks at the top and bottom of the plasma

Near Double Null Inner Wall Limited n=9 Mode

- Sweeping active MHD frequency through several TAE resonances
- \( f_{\text{TAE}} = 487 \text{ kHz} \), \( n=9 \), \( |\gamma/\omega| = 1.2\% \) near double null inner wall limited case

Damping Rate Sensitivity to q Profile Depends on Boundary Conditions

- Plasma rotation -2 to -5 kHz \( \Rightarrow f_{\text{meas}} = 18 \text{ to } 45 \text{ kHz} = 501 - 532 \text{ kHz} \)
- TRANSP q profile has \( q_0 = 0.54 \) and lower q overall compared to EFIT
- EFIT q profile modeled with \( q \cdot 0.9 \), \( q \cdot 1.0 \), and \( q \cdot 1.1 \) to check sensitivity of the calculated mode structure and damping rate
- Modes in this frequency range are found for all these q profiles with \( 1% < |\gamma/\omega| < 1.8\% \)

For TRANSP q Profile Modes Interact with the Alfvén Continuum

- Closed TAE gap gives interaction with the continuum but finds a mode at 508 kHz with \( |\gamma/\omega| = 1.2\% \), which agrees with the measured damping rate

Weak Continuum Interaction for EFIT q \( \sim 1.1 \)

- Multiplying the EFIT q profile by 1.1 leads to weaker continuum interaction in the core even though the gap is more closed since the mode peaks at mid radius
- Nova-K finds a mode at 523 kHz with \( |\gamma/\omega| = 0.12\% \), which is now much weaker than the measured damping rate of 1.2\%

More Core Continuum Interaction for EFIT q \( \sim 0.9 \)

- Measuring the EFIT q profile by 0.9 leads to slightly stronger core continuum interaction, Nova-K finds a lower frequency mode at 508 kHz with \( |\gamma/\omega| = 1.05\% \), which remains in agreement with the measured damping rate

Conclusions

- Moderate n stable TAEs are easily excited in C-Mod with a pair of active MHD antennas driving total perturbations ~ 1 G radial field
- TAE damping rates can be measured with synchronous detection of edge magnetic pick-up coil signals
- Small changes in q(r) can change the calculated TAE damping rate by as much as an order of magnitude due to accompanying changes in the mode structure relative to the Alfvén continuum
- The calculated damping rate is nearly always dominated by continuum damping, though radiative damping was not included in these calculations
- Good agreement between measured and calculated damping rates can be obtained for moderate n TAEs assuming reasonable q profiles but the solution is not unique
- The sensitivity of the calculated damping rate to changes in q(r) makes it difficult to properly benchmark the code with the measured damping rates due to uncertainties in the q profile

References