Characterization of Stable and Unstable Alfvén Eigenmodes in Alcator C-Mod

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Abstract. Experiments designed to characterize both stable and unstable Alfvén eigenmodes are a key part of the Alcator C-Mod physics program. Stable intermediate toroidal mode number ($3 \leq n \leq 14$) Alfvén eigenmodes, which are expected to be the most unstable in ITER, are excited with a set of active MHD antennas and their damping rates are measured as a function of plasma parameters. This is part of an international effort within the ITPA, which includes similar experiments on JET, JT-60U, and MAST. Alcator C-Mod provides results at the same toroidal field and density as ITER in the presence of an ICRF generated fast ion tail, while JET and JT-60U provide results in large high temperature plasmas and MAST provides results on aspect ratio and beta. Unstable toroidal Alfvén eigenmodes (TAEs) are also produced with fast ions generated by hydrogen minority ICRF heating and with fast electrons generated with Lower Hybrid Current Drive (LHCD). The fast ion driven TAEs are observed to be more unstable in steady H-mode discharges than in lower density L-mode discharges with the same ICRF power. The stability properties have been analyzed with the NOVA-K code. The fast electron driven Alfvén eigenmodes with LHCD have only been observed very early in the current rise phase of the discharge at very low densities. These modes, nonetheless, provide a measure of the early evolution of the resonant q and help to constrain the fast electron energy distribution together with hard x ray energy distribution measurements.

1. Introduction

Energetic particle-wave interactions are a concern for ITER both for control of the fusion burn and because such interactions could eject a beam of energetic particles that could damage the first wall. As the α particles from fusion reactions slow down, the velocity of these energetic particles will pass through certain velocities [1] that resonate with marginally stable Alfvén eigenmodes well before the energetic particles have thermalized with the bulk plasma. If this resonant interaction becomes large enough to eject the energetic particles from the core of the plasma, this could affect the fusion burn or even cause the energetic particles to be lost to the first wall. The International Tokamak Physics Activity (ITPA) Energetic Particles group is actively pursuing this research to understand and control energetic particle-wave interactions.

One such line of research that has been pursued first on JET [2-4] and then on Alcator C-Mod [5-7] is to launch a small amplitude magnetic perturbation with specially designed antennas from outside the plasma across a range of frequencies resonant with Alfvén eigenmodes at specific q values. As the frequency sweeps through a resonant frequency, the damping rate of the stable Alfvén eigenmode can be determined through measurements of the resulting plasma perturbation with magnetic pick-up coils at the wall. This allows a separate measurement of the damping rate of the mode to be measured in the absence of the energetic particle drive. Understanding how the damping rate depends on plasma parameters could then be used to control these modes and provide a sophisticated means for fusion burn

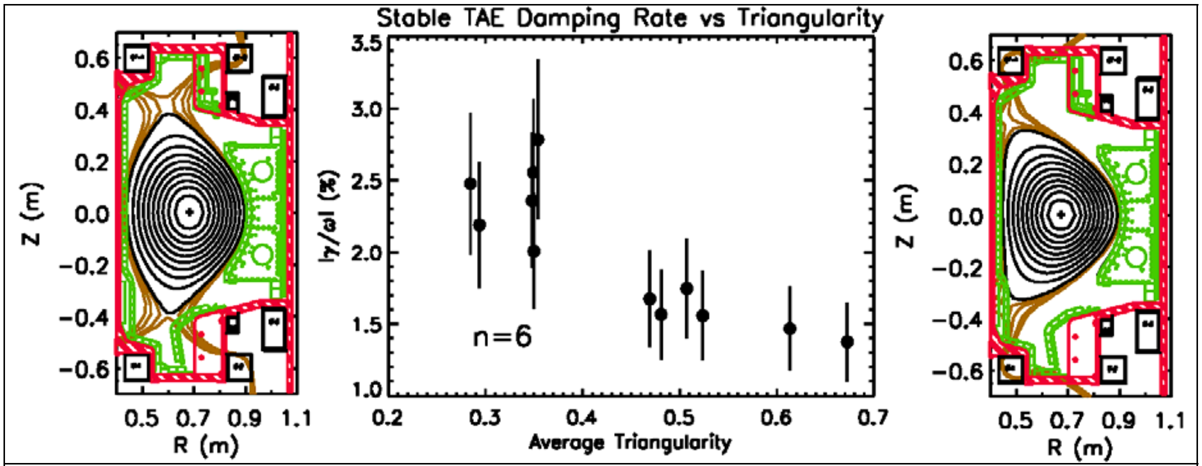

Fig. 1. The measured TAE damping rate for n=6 modes as a function of average triangularity in the C-Mod tokamak. The plasma equilibria poloidal cross-sections for the two extreme cases in the scan are also shown.

control. A similar antenna system has been installed on JT-60U and results have recently been obtained from a set of antennas installed on MAST [8].

Other studies on many devices are aimed at understanding unstable Alfvén eigenmodes excited by energetic particles. On C-Mod, fast ion instabilities are excited with hydrogen minority Ion Cyclotron Radio Frequency (ICRF) heating and fast electron driven modes are excited with Lower Hybrid Current Drive (LHCD). The latest research on unstable fast ion driven modes on C-Mod is to attempt to understand through experiments and NOVA-K [9] and AORSA/CQL3D [10] modeling why such modes are usually found unstable during the H-mode phase and only rarely in L-mode even though the density is much higher in H-mode than in L-mode. Since the drive for Alfven eigenmodes depends on energy rather than mass of the particles, fast electrons are also found to drive these modes unstable. Recent experiments with LHCD at the very start of the plasma [11] have excited unstable bursting high frequency modes in the Toroidal Alfvén Eigenmode (TAE) frequency range for q values deep inside the plasma. These modes provide a measure of the time evolution of q at the mode resonance.

2. Damping rate measurements of stable Alfvén eigenmodes

Understanding how the stability of intermediate *n* Alfvén eigenmodes will scale to ITER is important because the control of burning plasmas may depend sensitively on AE stability. Alcator C-Mod was the first machine to install and operate intermediate toroidal mode number Active MHD antennas for the purpose of exciting stable Alfvén eigenmodes to measure their damping as a function of plasma conditions [5]. Two antennas were installed in 2002 centered ±17 cm above and below the outboard midplane at one toroidal location. The antennas each have 5 rectangular turns 15 cm toroidally by 25 cm poloidally and they are excited with two amplifiers capable of driving up to 25 A of current across the frequency range from 100 kHz to nearly 1 MHz, producing a radial field perturbation of a few Gauss near the q=1.5 surface. The antennas excite a broad toroidal mode spectrum with full width half maximum of n ~ 16, which covers the range of mode numbers expected to be unstable in ITER. Given the broad range of excited n numbers, it is essential to measure the n numbers of the observed resonances in the plasma. Resonant n numbers from $3 \leq n \leq 12$ have been

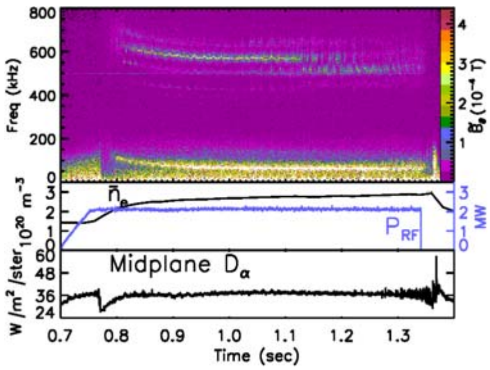

Fig. 2. Fourier spectrogram of a poloidal field pick-up coil signal during an EDA H-mode showing a QCM and several high frequency TAEs. The line averaged density, ICRF power, and D_α emission are also shown.

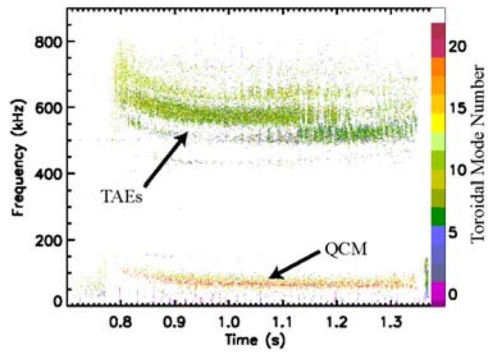

Fig. 3. Toroidal mode number color spectrum vs. time for the discharge shown in Fig. 1. The QCM and TAEs all rotate in the electron direction. The TAEs have n numbers between 6 and 11.

observed with a single dominant mode number. Measured damping rates are in the range of $0.5\% < |\gamma/\omega| < 5\%$. Figure 1 shows the measured TAE damping rate for n=6 modes as a function of triangularity [6] indicating at most a small decrease in damping with increasing triangularity, which is in sharp contrast to the strongly increasing damping rate with increasing triangularity for n=1 modes on JET [4]. In another experiment, comparing upper and lower single null plasma shapes, the intermediate n damping rate showed little change with at most a slight increase when the ion ∇B drift direction was toward the X point. This result again contrasts the previous results for n=1 modes in JET where the damping rate decreased substantially when the ion ∇B drift direction was toward the X point [4]. It seems that the damping rate of intermediate n modes is less sensitive to changes in the edge conditions than that of low n modes, perhaps because low *n* modes are more global across the plasma radius while intermediate *n* modes are more radially localized.

Comparisons of the measured damping rate on C-Mod were made with NOVA-K calculations for several Ohmic plasma conditions including inner wall limited and diverted plasmas [7]. All of these plasmas were sawtoothing indicating that the central q value ~ 1. Plasmas with measured damping rates from $0.76\% < |\gamma/\omega| < 3.0\%$ and *n* numbers between $4 \le |n| \le 9$ were chosen for this comparison. The sensitivity to the calculated q profile was examined by running NOVA-K three times multiplying the entire EFIT q profile by 0.9, 1.0, and 1.1. Reasonable agreement between the measured and calculated total damping rates can be obtained, but the results are very sensitive to these small changes in the q profile. The calculated damping rate can increase or decrease by as much as an order of magnitude with only 10% changes in q. This sensitivity appears to be due to changes in how well radially aligned the TAE gap is and thus in the radial location of the interaction of the mode with the continuum such that the mode may be less affected by continuum damping at mid radii or be more strongly damped near the edge, depending on changes in the q profile.

Several run days were devoted to measuring changes in the intermediate *n* damping rate as a function of increasing fast ion content. Earlier results for low *n* modes on JET indicated that the measured damping rate decreased with increasing fast ion content [3]. Since fast ions eventually drive AEs unstable, this is the expected result. However, in some of the recent C-Mod experiments, the measured damping rate first increases gradually with increasing ICRF power, then decreases sharply at power levels above 2.5 MW. Unstable

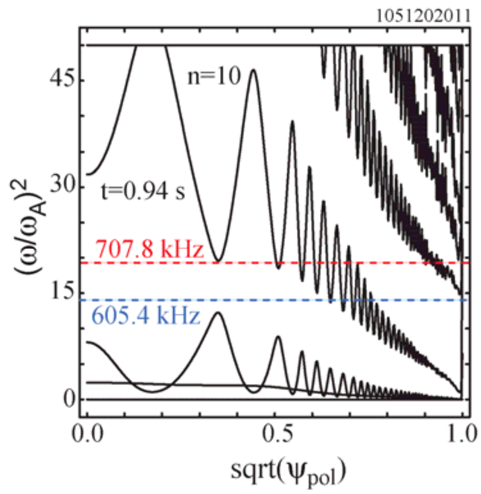

Fig. 4. NOVA calculated Alfvén continuum for n=10 at t=0.94 s in H-mode. The mode shown in Fig. 5 is at the top of the TAE gap at 707.8 kHz and a similar mode is found near the bottom of the gap at 605.4 kHz.

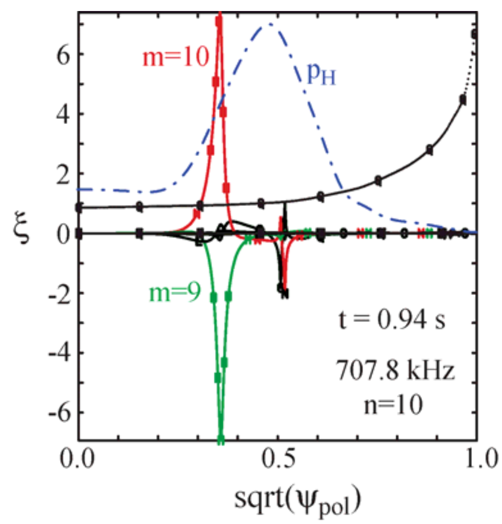

Fig. 5. NOVA calculated eigenfunction for the n=10 upper gap mode at 707.8 kHz for t=0.94 s in H-mode showing the dominant poloidal harmonics m=9, 10. The q profile and normalized fast ion pressure profile, p_H , are also shown.

modes are observed at ICRF power levels of at least 3.5 MW for these conditions. Modeling of these results is ongoing in an attempt to understand this behavior.

3. The stability of Alfvén eigenmodes in L- and H-mode

The stability of unstable ICRF driven TAEs appears to depend sensitively on whether the plasma is in L- or H-mode. Most unstable TAEs observed in the plasma current flattop on C-Mod occur in H-mode rather than L-mode. Analysis with NOVA-K has not yet been able to clearly identify why there is this observed difference in stability. Perhaps, improved energy and particle confinement in H-mode increases the fast ion drive relative to L-mode despite the accompanying increase in density. Obvious steepening in the edge profiles in H-mode compared to L-mode does not appear to be responsible for the stability changes, unless subtle changes in the profiles that may not be properly modeled in NOVA-K are responsible.

The measured rotation of the TAEs in H-mode is in the electron diamagnetic drift direction. The most likely way this could occur is if the fast ion profile is shifted well off-axis, despite an on-axis ICRF resonance. Figure 2 shows an example of a B_T = 5.6 T, I_p = 0.8 MA ICRF heated enhanced D_α H-mode with both a Quasi-Coherent Mode (QCM) [12] between 50 – 100 kHz and several Toroidal Alfvén Eigenmodes (TAEs) between 500 – 700 kHz. Note that the modes are stable in the preceding L-mode phase of the discharge before the drop in D_α emission and increase in density. Figure 3 shows the toroidal mode number in the color spectrum versus time measured from the phase difference of two closely spaced poloidal field pick-up coils on an outboard limiter. Both the QCM and the TAEs rotate in the electron direction opposite to the plasma current. The TAE mode numbers are in the range $6 \leq n \leq 11$ and the dominant mode has n=10.

For centrally peaked fast ion profiles, the negative gradient of the fast ion β typically drives TAEs in the ion direction. However, when the fast ion β is peaked off-axis and the

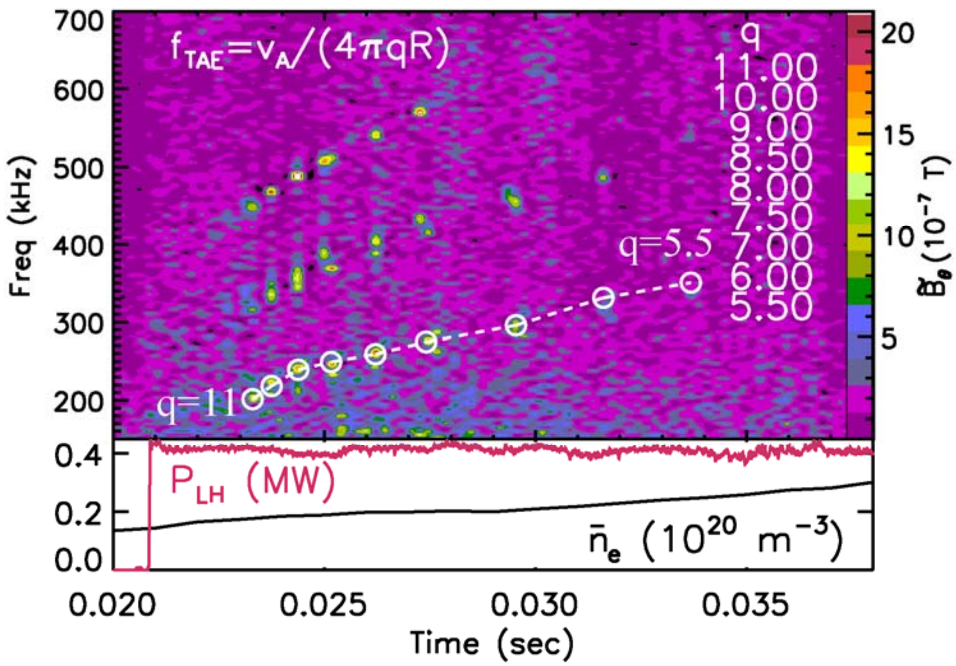

Fig. 6. Bursting high frequency modes early in the current rise with LHCD together with a fit to the center of the gap TAE frequency overlaid on each burst. The fitted resonant q values fall on integer and half integer values from 11 down to 5.5.

peak of a core localized mode occurs in the region of positive gradient in the fast ion β, unstable TAEs can rotate in the electron direction. For these discharges, the ICRF resonance is very nearly on the magnetic axis. Because the ICRF heating occurs predominantly at the turning points of the banana tips of the trapped particles, if the banana tips expand sufficiently outward along the vertical resonance line, the flux surface averaged fast ion profile can end up being peaked substantially off-axis. NOVA-K modeling can reproduce this rotation direction when the fast ion profile is shifted sufficiently off-axis. Figure 4 shows the calculated Alfven eigenmode gap structure for n=10 for a relatively flat q profile with q(0) = 0.88. Modes were found at the bottom and top of the TAE gap. This value of q(0) provided the best match with the measured mode frequency at 0.94 s (~580 kHz) when taking into account a plasma rotation of 12.5 kHz in the ion direction and n=10 for a Doppler shift frequency of 125 kHz. That is, the Doppler shifted mode frequency of ~705 kHz is close to the calculated mode frequency of 707.8 kHz. Figure 5 shows the radial eigenmode structure of this TAE superimposed on the assumed off-axis peaked fast ion profile. Attempts to model the fast ion distribution with both TORIC [13] and AORSA/CQL3D [10], however, do not indicate such a large off axis shift in the profile. While AORSA/CQL3D more accurately determines the fast ion distribution self consistently with the ICRF wave fields, it does not take into account finite orbit width effects, which may be very important for these discharges because of large banana widths of the fast ion orbits relative to the plasma minor radius.

4. Fast electron driven Alfvén eigenmodes in the current rise

By injecting sufficient LHCD power (≥ 0.3 MW) early in the current rise, a population of fast electrons is generated that excites unstable TAEs. A series of bursting high frequency modes typically with three frequency bands are observed on the magnetic pick-up coils on the

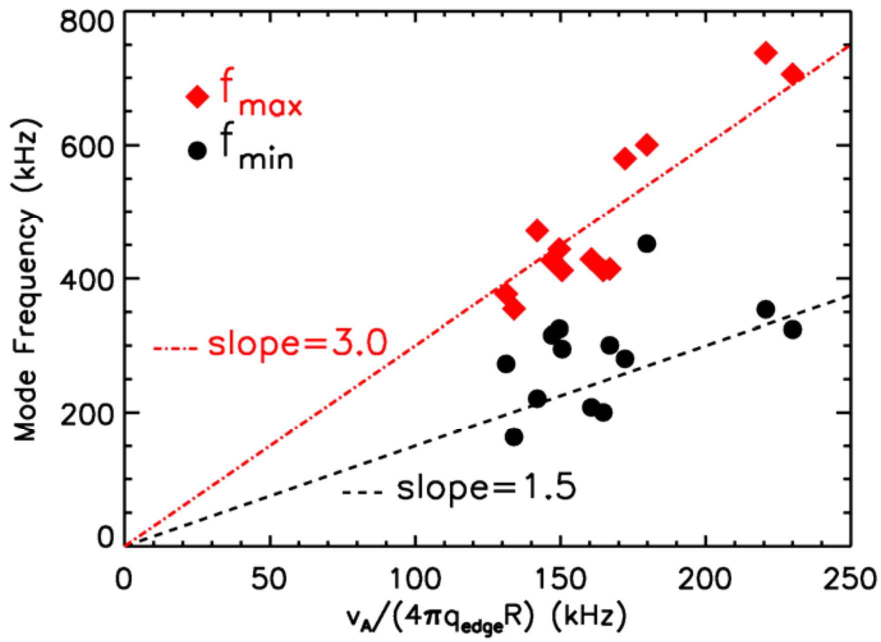

Fig. 7. Plot of the minimum and maximum mode frequencies at a given time during a series of discharges with toroidal fields ranging from 4.5 T to 6.3 T as a function of the TAE frequency, using the line averaged density in the Alfvén velocity and the edge q value. The linear dependence of the minimum and maximum frequencies indicates they are Alfvén eigenmodes.

outboard limiters just after the start of LHCD (Fig. 6). Lower hybrid waves are launched into Alcator C-Mod at a frequency of 4.6 GHz with a launcher with 22 operational waveguides toroidally by 4 waveguides poloidally [14]. Current drive phasing was used in these experiments with 60°, 90°, and 120° phasing corresponding to $n_{||}$ = 1.55, 2.3, and 3.09. The toroidal field was scanned from B_T = 4.5 T to 6.3 T and the plasma current was ramping from 0 up to 0.6 – 0.8 MA. Note that the LHCD begins to couple only 0.02 s into the discharge. The bursting modes were strongest at 90° phasing, where the current drive efficiency is strongest. The modes were present, but somewhat weaker at 60° phasing, which may be due to decreased electron absorption by the higher phase velocity waves. At 120° phasing, the modes were absent, indicating that the lower phase velocity of the LH wave at the higher $n_{||}$ leads to a less energetic electron tail that is insufficient to drive the modes unstable.

A toroidal field scan from B_T = 4.5 T to 6.3 T indicates that the minimum and maximum frequency bands scale linearly with the TAE frequency calculated using the line averaged density in the Alfvén velocity and the edge q value (Fig. 7). The slopes of the lines for the minimum and maximum frequencies are approximately 1.5 and 3.0, respectively. Since the local density is not being used in this simple comparison, it is not possible to determine the resonant q values of these modes from the frequencies alone, but the linear dependence indicates that the modes are likely to be Alfvén eigenmodes.

The calculated plasma shape at this time is nearly circular with the plasma near the inner wall and limited on the outboard limiter. Since the density at the beginning of the current rise is very low ($\bar{n}_e \sim 1 - 2 \times 10^{19}$ m^{-3}) and the minimum q is high, unstable TAEs are

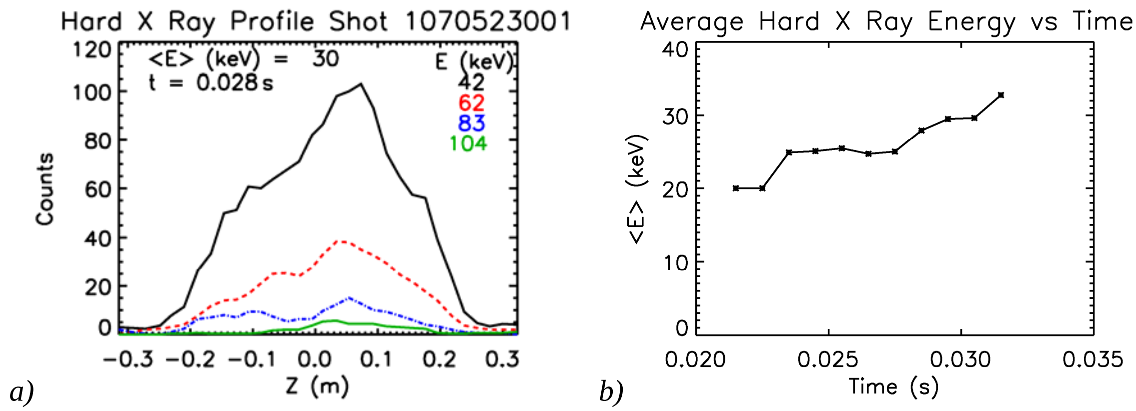

Fig. 8. a) Measured hard x ray line integrated profile for energy bins from 42 to 104 keV at the time of the bursting high frequency modes in Fig. 6. b) Average hard x ray energy across the profile as a function of time during the bursting high frequency modes of Fig. 6.

observed in bursts as they resonate at rational q values falling from 11 down to 5.5 (Fig. 6). Multiple frequency bands of these bursting modes have frequencies that scale as 3/2 and 2 times the frequency of the lower band. These high frequency bursting modes have relatively small amplitude ($\tilde{B}_\theta \leq 5 \times 10^{-6}$ T) measured with poloidal field pick-up coils on outboard limiters. The low densities appear to be required to drive sufficiently high energy electron tails to excite these modes. The high resonant q values also appear to be required to bring the fast electron energy into the range so that the precession drift frequency resonates with the mode frequency.

An important test of whether these high frequency bursting modes are indeed TAEs is whether or not they match a resonance condition for energetic electrons. Figure 8a shows the hard x ray line integrated profiles for energy bins from about 40 keV to just over 100 keV from a radially viewing hard x ray camera. The hard x ray profiles have significant counts out to at least 80 keV photon energy. Figure 8b shows that the average hard x ray photon energy increases from 20 keV to nearly 35 keV during the time that the high frequency bursting modes are observed. The measurements indicate that there are indeed high energy electrons responsible for the hard x ray emission across the plasma core with a broad radial profile. The hard x ray energy is in the same range of energies required for the fast electrons to have a precession drift frequency at the measured mode frequency [11,15].

Conclusions

Measurements of the damping rates of intermediate *n* stable Alfvén eigenmodes on C-Mod indicate that they are less sensitive to changes in the edge parameters, such as triangularity, than the previous low *n* results on JET, which may make intermediate *n* Alfven eigenmodes in ITER more difficult to control through changes in plasma shape. NOVA-K simulations, however, indicate that the damping rate should be very sensitive to changes in the q profile. It will require very precise measurements of the q profile to be able to check these predictions. The measured damping rate drops just before unstable modes appear as expected, but some experiments show an initial increase in damping with increasing ICRF power, which still requires detailed modeling to be understood.

Fast ion driven TAEs are found to be more unstable in H-mode rather than L-mode. These unstable modes are also found to rotate in the electron diamagnetic drift direction. NOVA-K finds modes near the top of the TAE gap that rotate in the electron direction if the fast ion profile is peaked sufficiently far off axis. While there are some measurements and modeling that indicates the ICRF generated fast ion profile could be peaked off-axis, the latest modeling with either TORIC or AORSA/CQL3D is unable to find sufficiently far off-axis peaked fast ion profiles for these relatively high density H-mode conditions. Perhaps, finite orbit width effects, which are not properly taken into account in these models, could be important to correctly model these effects on the fast ion profile. NOVA-K modeling has not yet been able to show why TAEs are more unstable in H-mode, possibly because this depends on details of the fast ion distribution which are not fully modeled.

Rapidly bursting fast electron driven TAEs are found very early in the current rise during LHCD with resonant q values falling from 11 down to 5.5. At these early times, these q values correspond to radii deep inside the plasma between one third and two thirds of the edge q value. In a similar way as with Alfvén cascades, these fast electron driven modes provide a measure of the evolution of the resonant q value and the bursting for given q values may be explained by reduced damping at particular rational q values. The measured average hard x ray energy at this time is in the range of the fast electron energy required to match the precession drift resonance condition for fast electron driven TAEs.

Acknowledgements
We would like to thank the C-Mod team for keeping the machine running well.
Supported by the United States Department of Energy contract DE-FC02-99ER54512

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