Fast Electron Driven Alfvén Eigenmodes In the Current Rise in Alcator C-Mod

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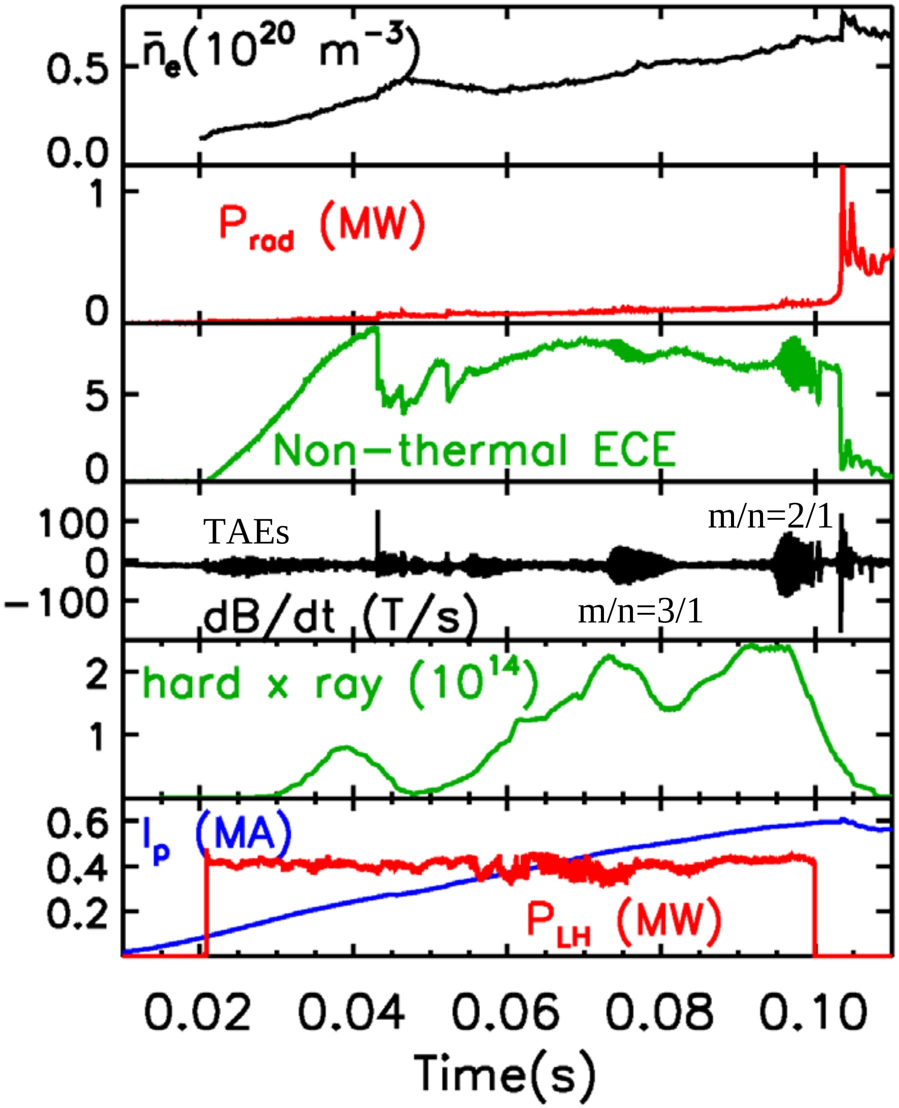
Lower Hybrid Generates Fast Electron Driven Modes in the Current Rise

Alcator C-Mod

- Very early injection of LHCD starting at 0.02 s excites rapidly bursting high frequency modes driven by fast electrons in the current rise
- The frequencies of these modes are in the range of 100 kHz – 700 kHz with increasing frequency as q falls indicating Alfvén eigenmodes
- AE drive depends on the fast particle energy not the mass so that fast electrons can also drive AEs unstable
- Fast electron driven TAEs were first observed on Compass-D with combined ECH+LHCD [1]
- Lower frequency fast electron driven fishbone-like bursting modes have also been observed driven with ECCD on DIII-D [2] and with LHCD on FTU [3]

[1] M Valovic, *et al*, 2000 *Nucl Fus* **40** 1569
[2] K-L Wong, *et al*, 2000 *Phys Rev Lett* **85** 996
[3] F Zonca, *et al*, 2007 *Nucl Fus* **47** 1588

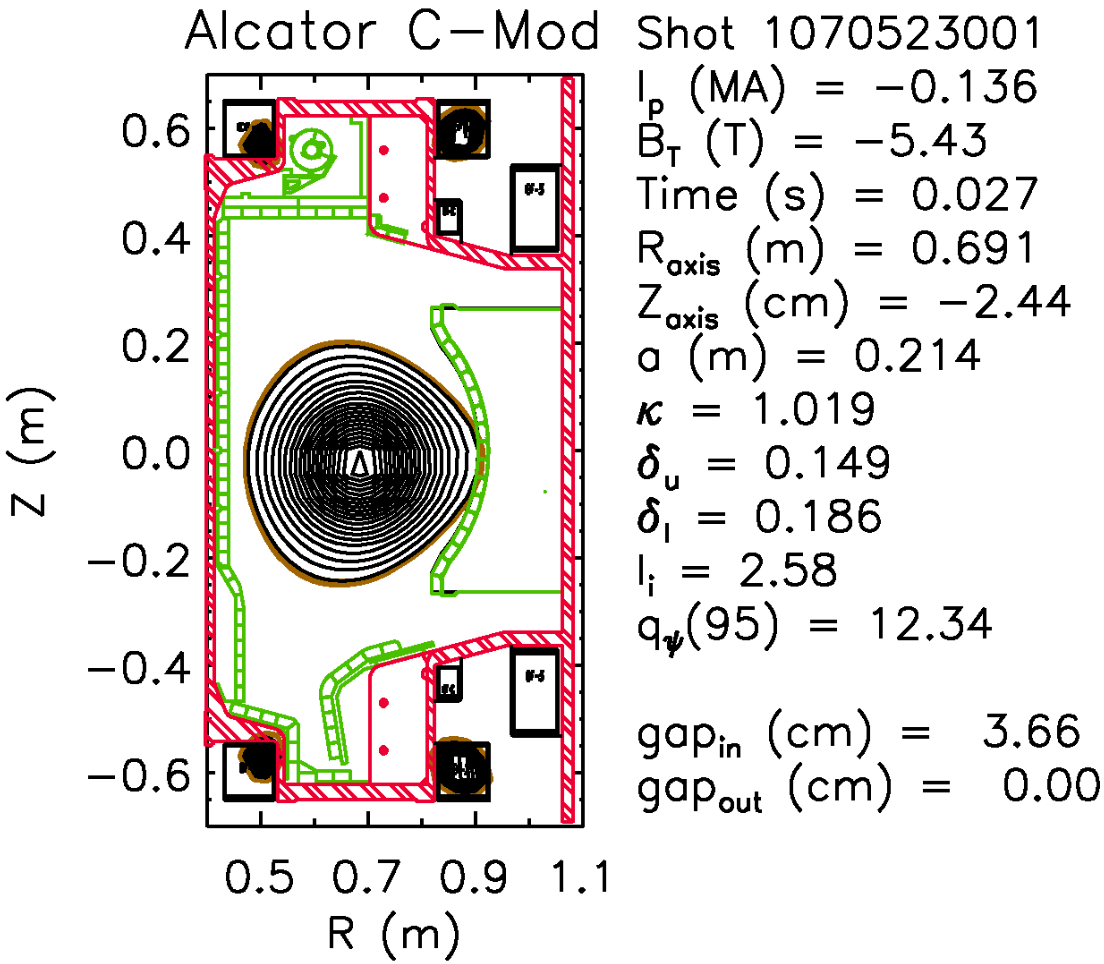
Lower Hybrid Heating in the Current Rise



- Hard x rays + ECE indicate LH generates a fast electron tail
- High frequency TAEs are observed from 0.02 to 0.035 s
- Large non-thermal ECE signals indicate effective pitch angle scattering from $v_{\|}$ to $v_{\perp}$ [4]
- LHCD also drives very low frequency m=3, 2, n=1 tearing modes that can cause disruptions

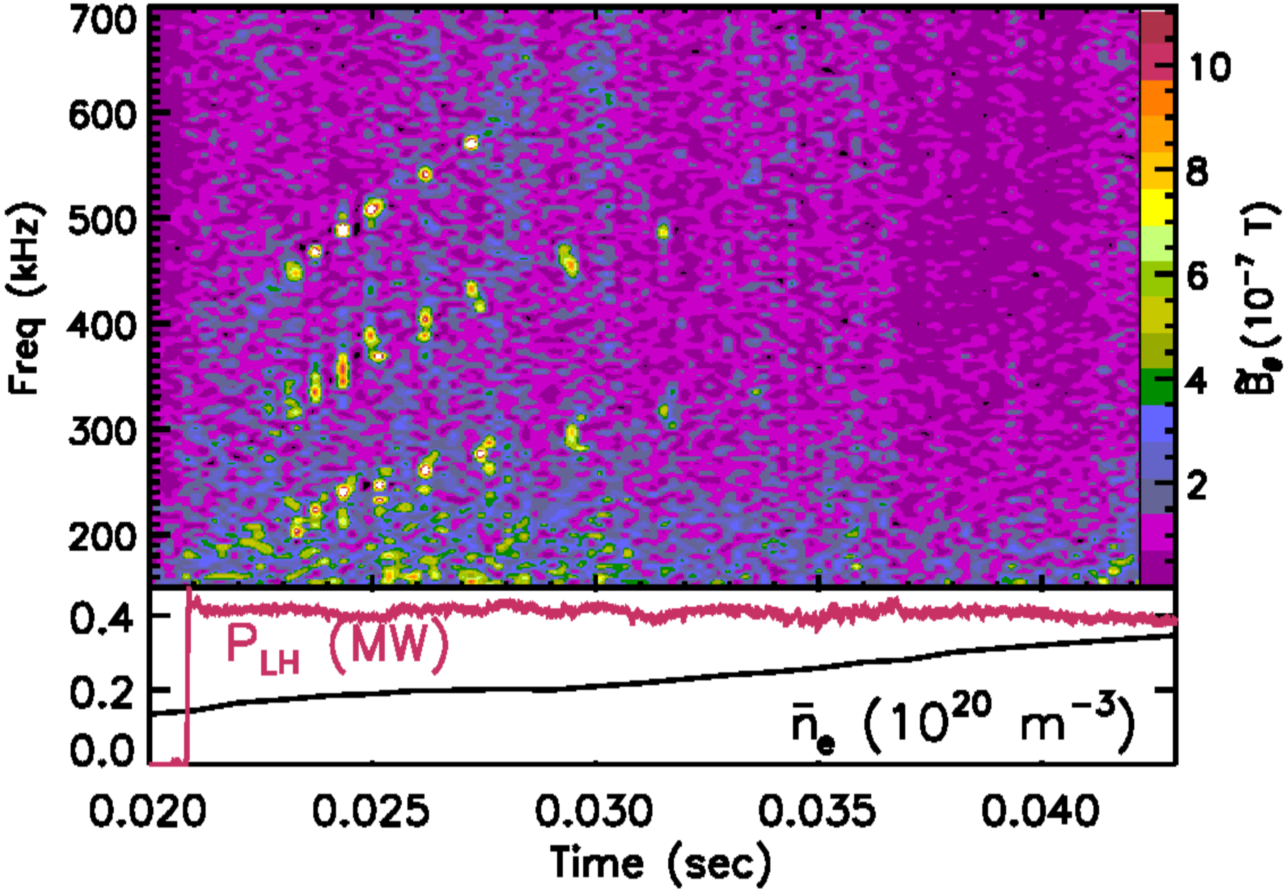
[4] Fuchs, et al, 1985 *Phys Fluids* **28** 3619

Low Elongation Outer Wall Limited Plasma



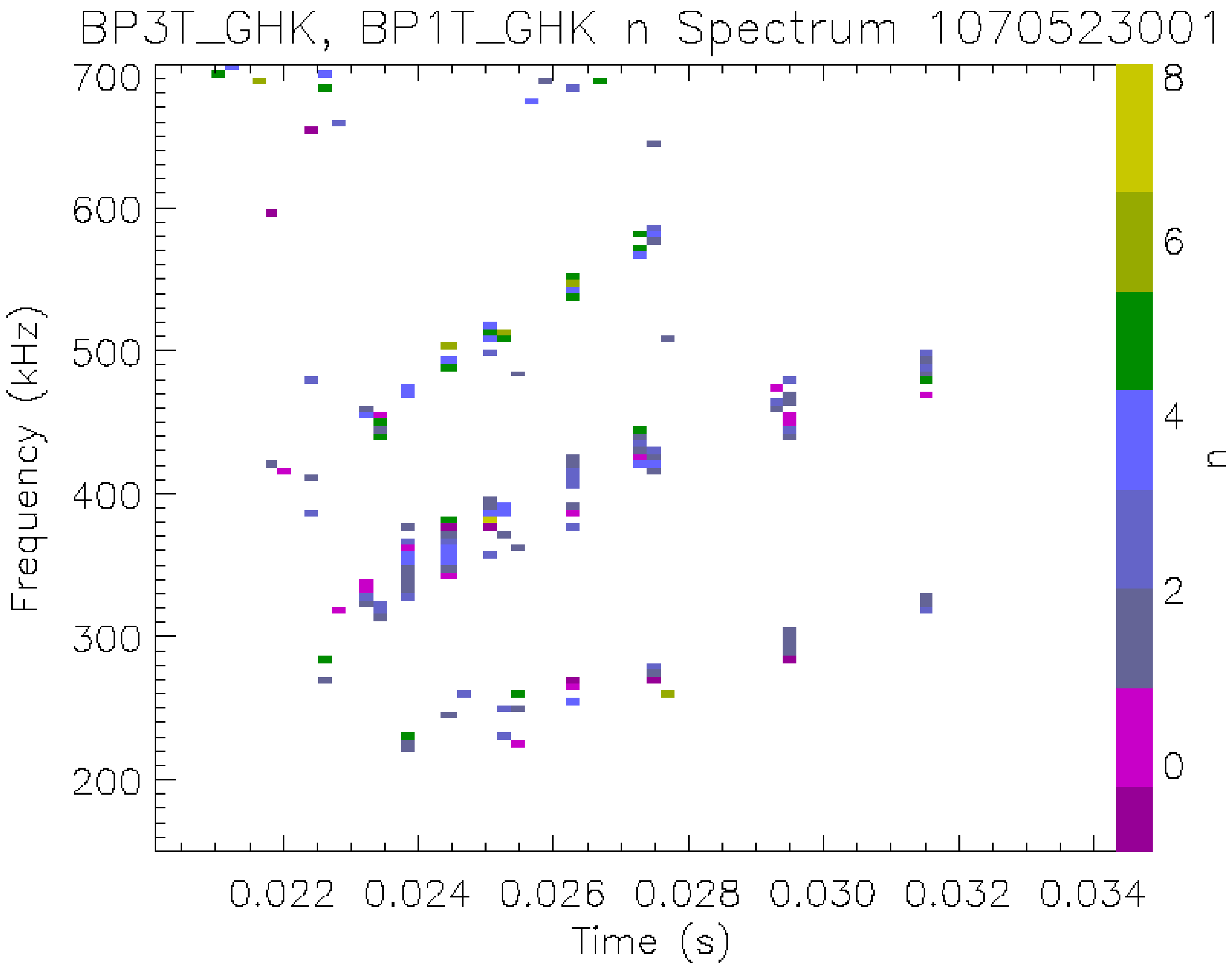
- EFIT reconstructions give a nearly circular plasma at 0.027 s
- Plasma is outer wall limited, couples well to LHCD grill, and nearly fills the cross-section
- TAEs are possible, but EAEs and NAEs are unlikely in this plasma shape

Mode Frequencies Increase with Time as q Evolves



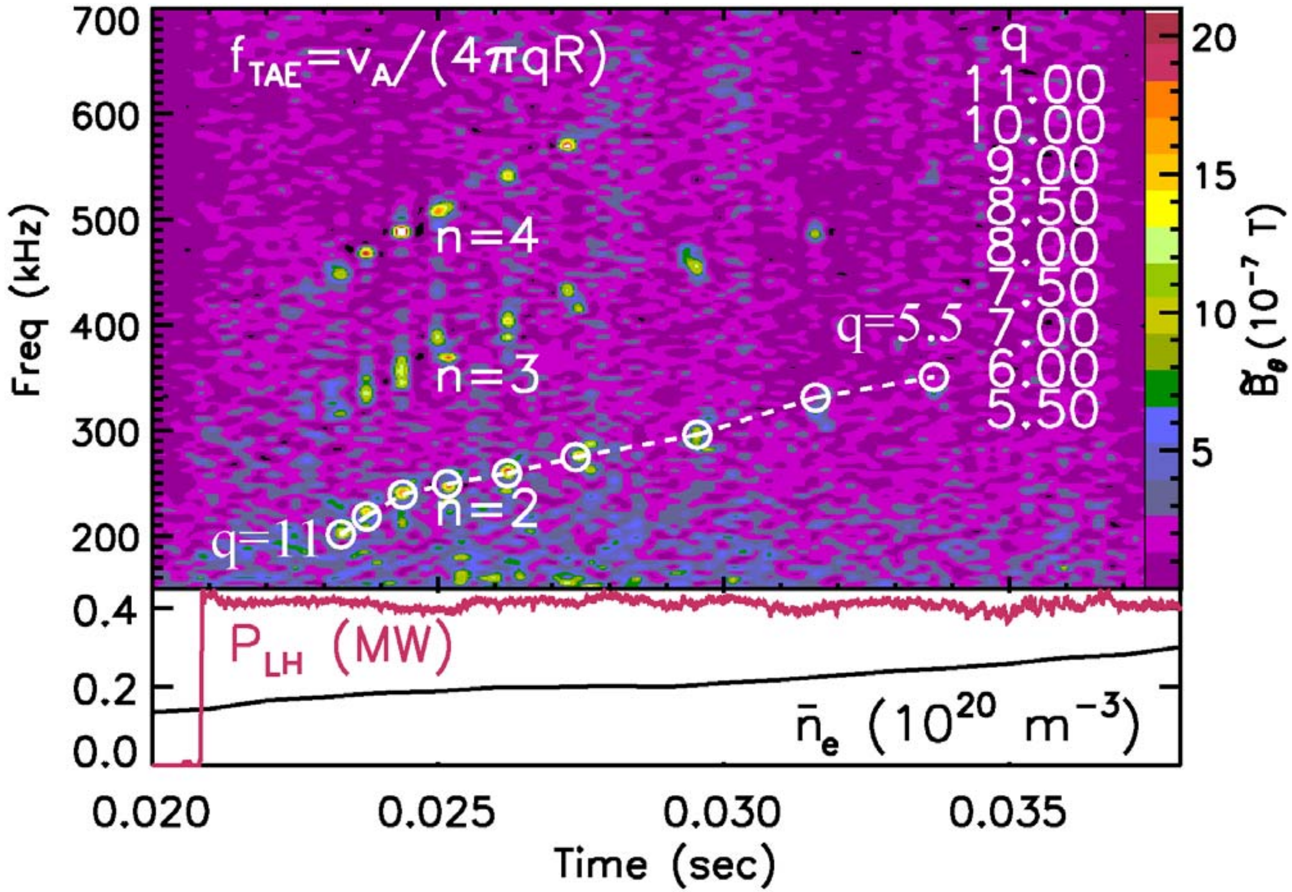
- Mode frequency increases with time often with three frequency bands
- Time between bursts also increases with time as n_e and q profiles evolve

Fast Electron Modes Rotate in the Electron Direction



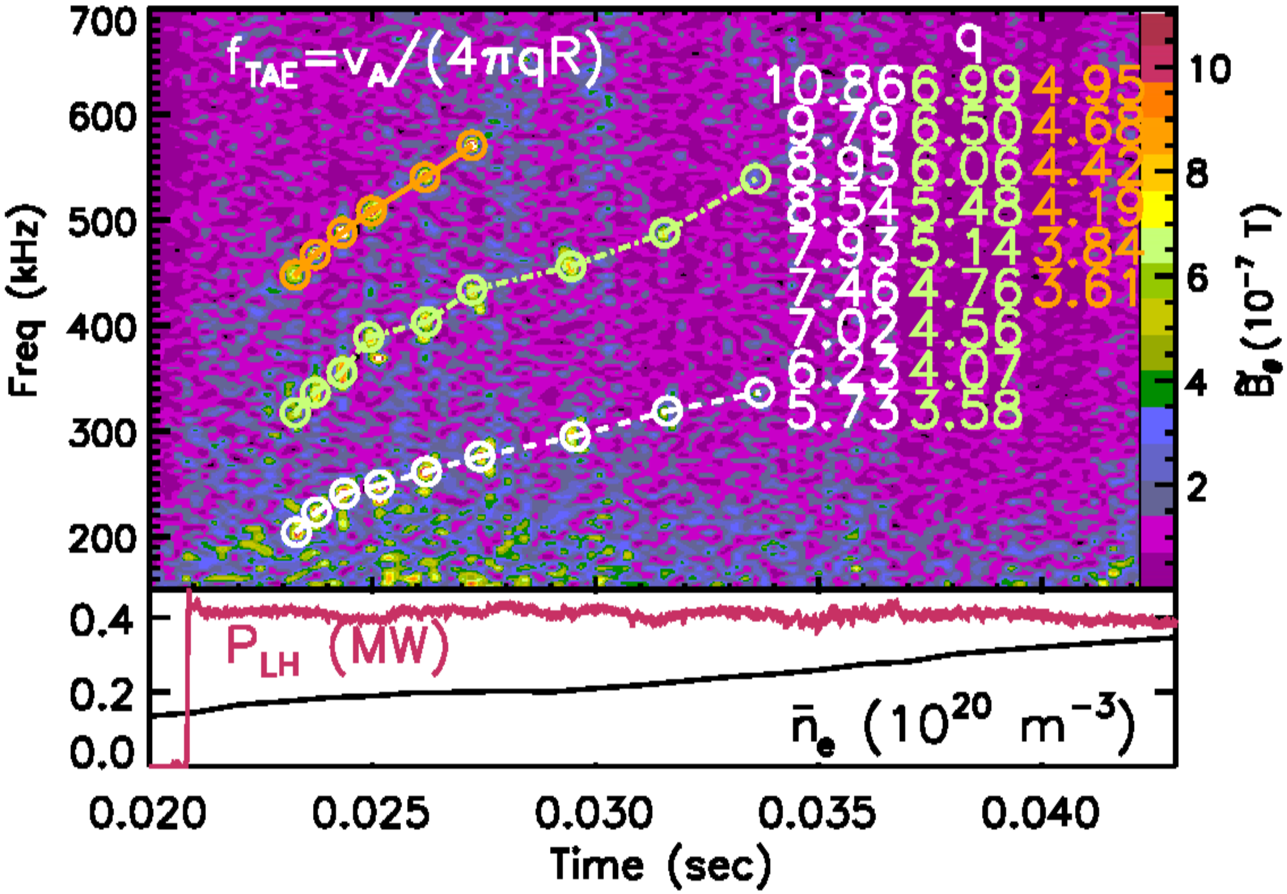
- Toroidal mode numbers are in the range of n ~ 1 – 6
- Modes rotate in the electron direction (counter-I_p)

Mode Frequencies Scale as TAEs for Intermediate q Values



- Mode frequencies fit well $f_{TAE} = v_A/(4\pi qR)$ for intermediate q values and bursts occur at ~ integer and half-integer q values from 11 down to 5.5
- Three frequency bands scale as n=2, 3, 4 but cannot have f_ϕ = 100 kHz!

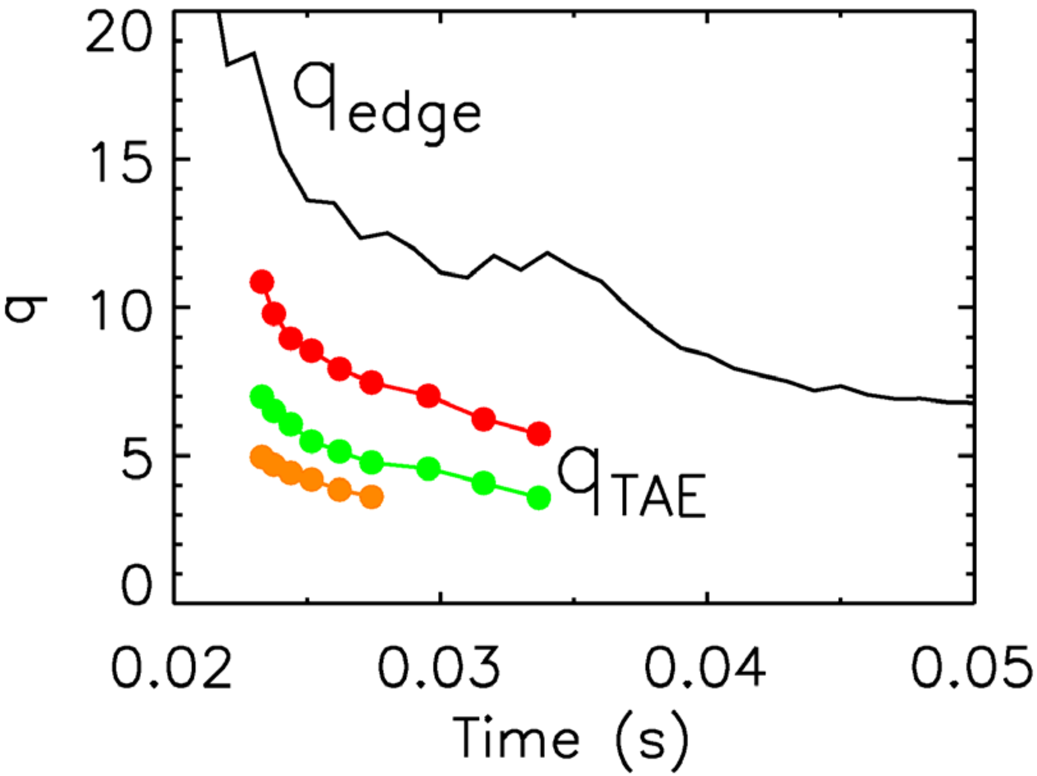
Mode Frequencies Scale as TAEs for Intermediate q Values



- Now suppose f_ϕ is small and each frequency band has its own q value. Then the mode frequencies fit well to q values between ~11 and 3.5
- Why are there simultaneous bursts at these particular q values?

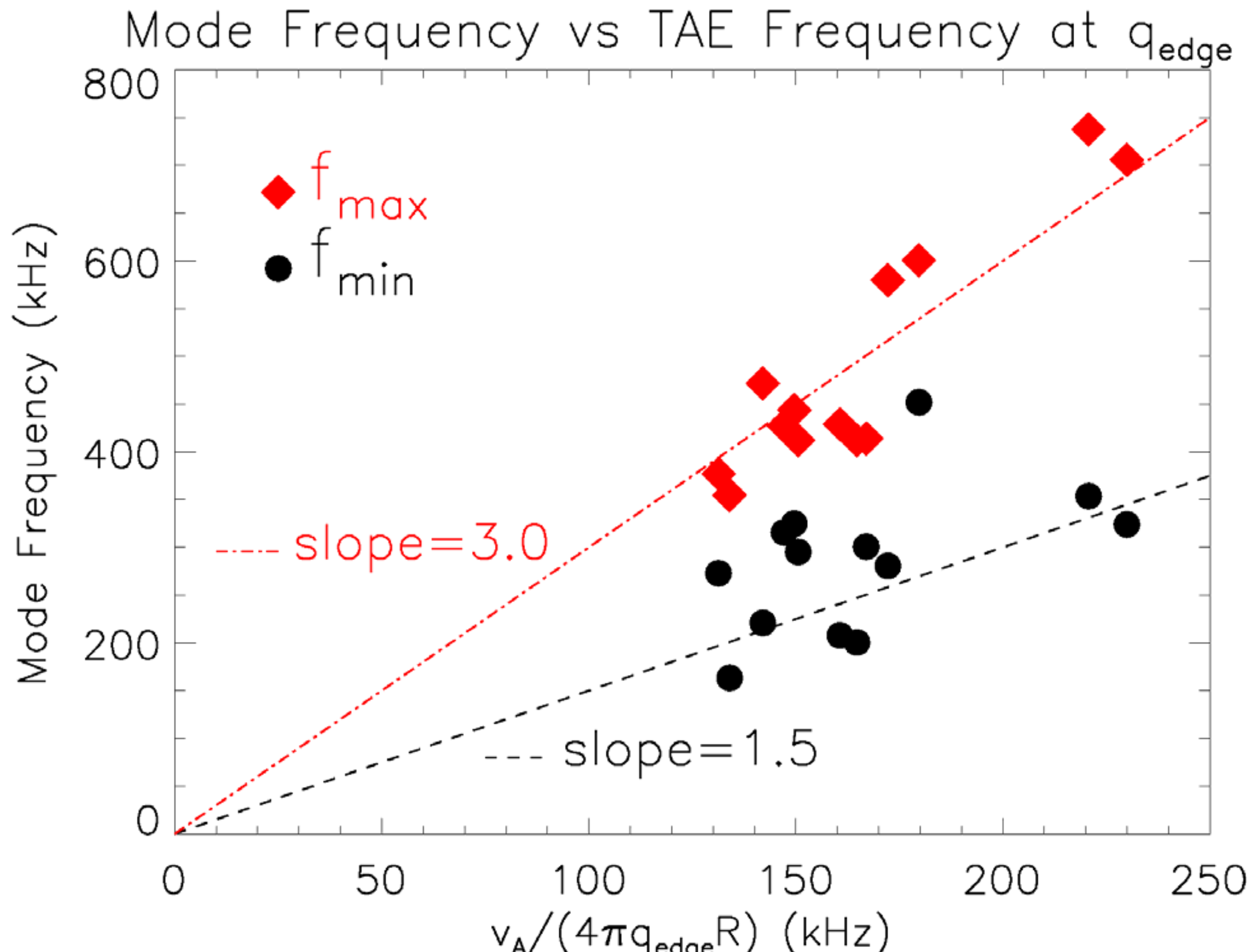
Resonant q Values Track Edge q Time Evolution

Edge q and TAE q Time Evolution



- Early TAEs have resonant q from 11 to 3.5 before 0.035 s
- Resonant q values track edge q time evolution and indicate resonances are deep inside the plasma
- Lower q surfaces may not have yet entered the plasma

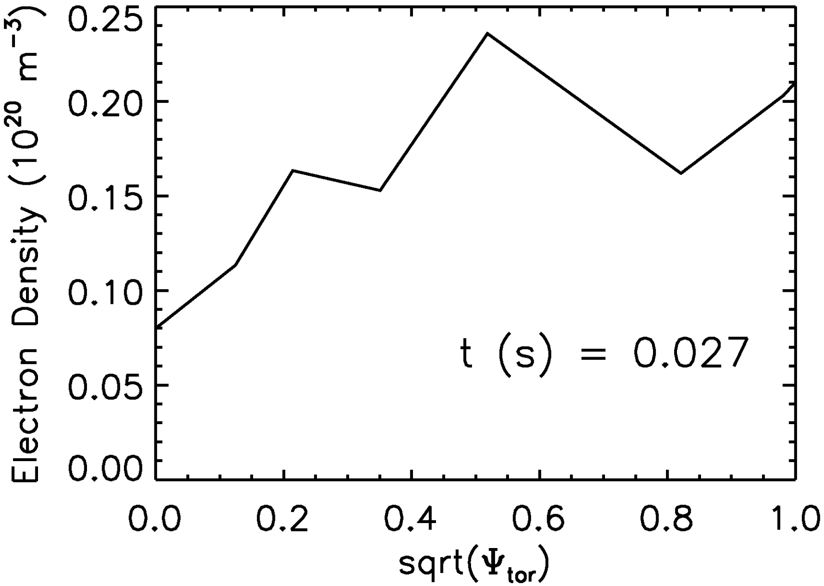
Mode Frequency Proportional to TAE Frequency



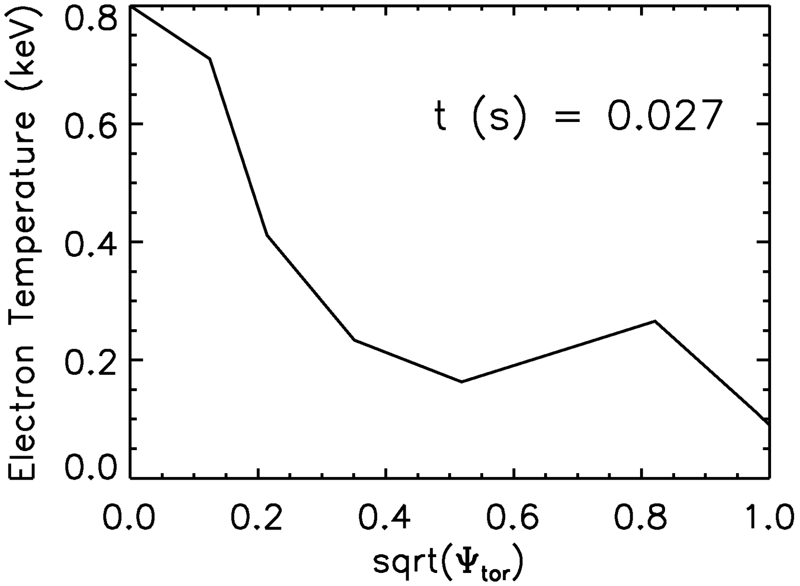
- Minimum mode frequencies scale approximately as f_{TAE} at $q_{edge}/1.5$
- Maximum mode frequencies scale approximately as f_{TAE} at $q_{edge}/3.0$

Hollow Density and Peaked Temperature Profile

Electron Density



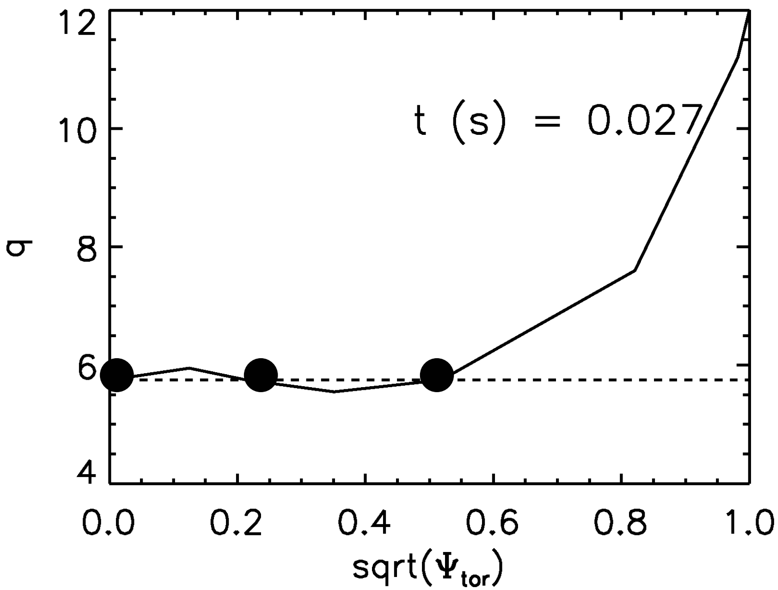
Electron Temperature



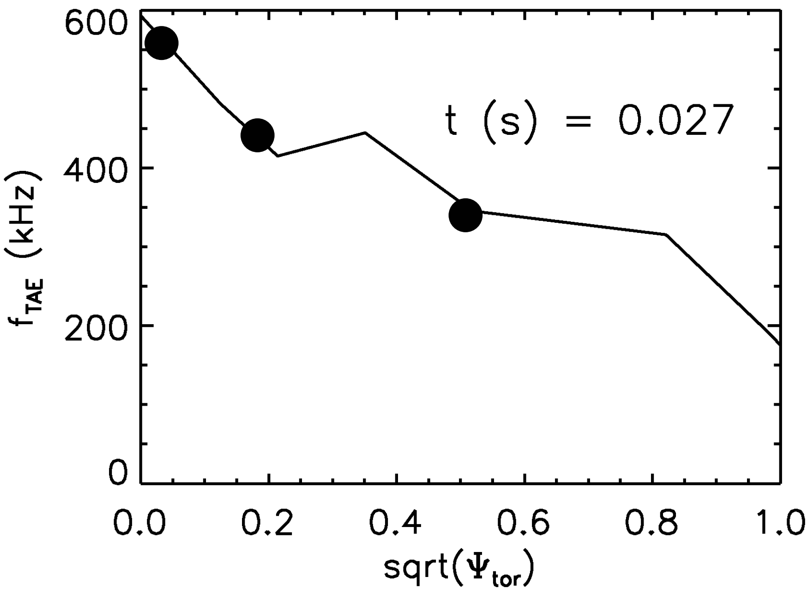
- Measured profiles from Thomson scattering show a very hollow electron density and peaked electron temperature profile
- A hollow density profile could account for nearly a factor of two change in TAE frequency across the profile at the same resonant q

Hollow Density and Peaked Temperature Profile

Invented q Profile

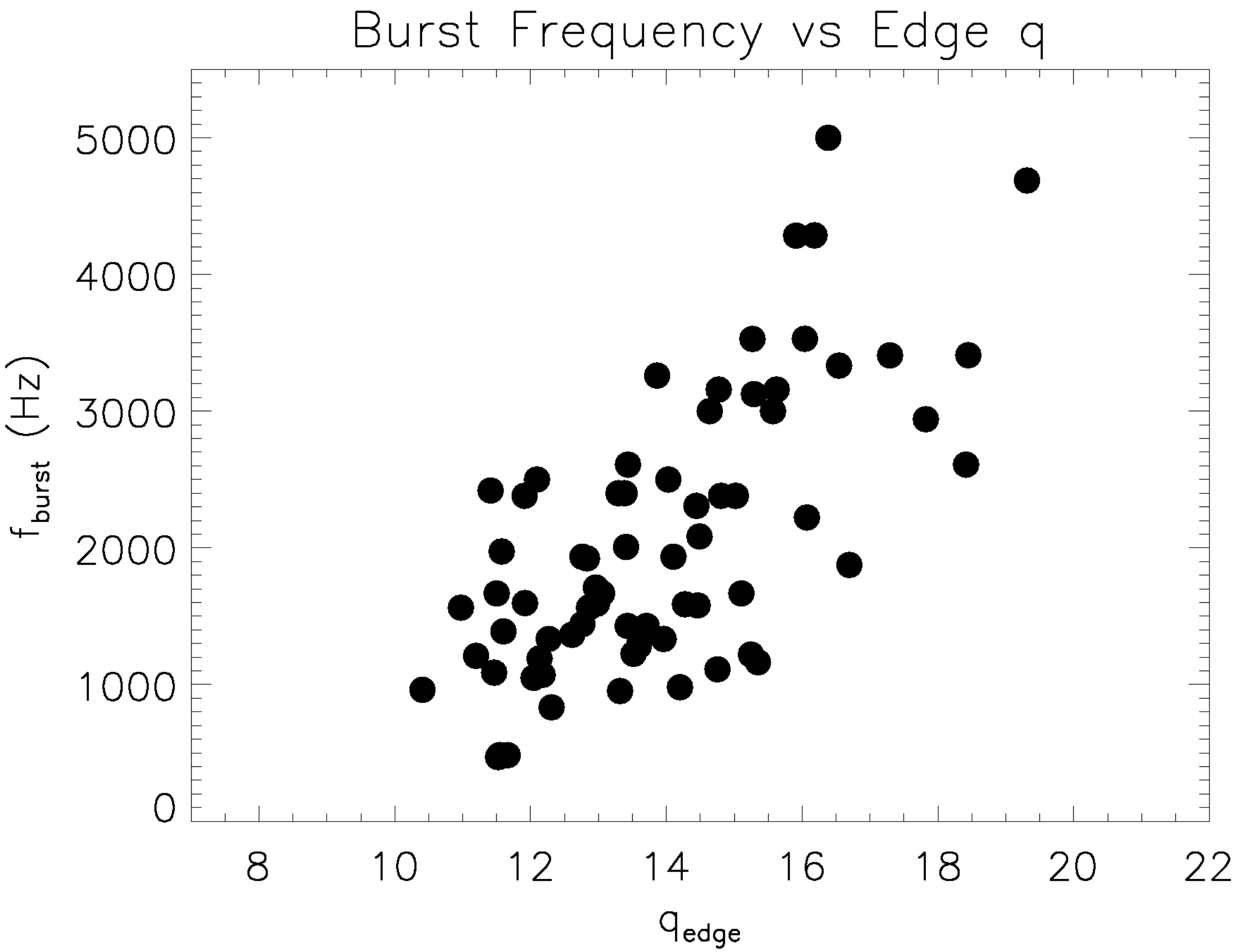


Resulting TAE Freq Profile



- Assuming a reversed shear q profile the measured hollow density profile can provide nearly a factor of two change in TAE frequency
- The measured TAE frequencies can be modeled with this q profile within the errors on the density profile
- The three freq bands then correspond to the same rational q surface

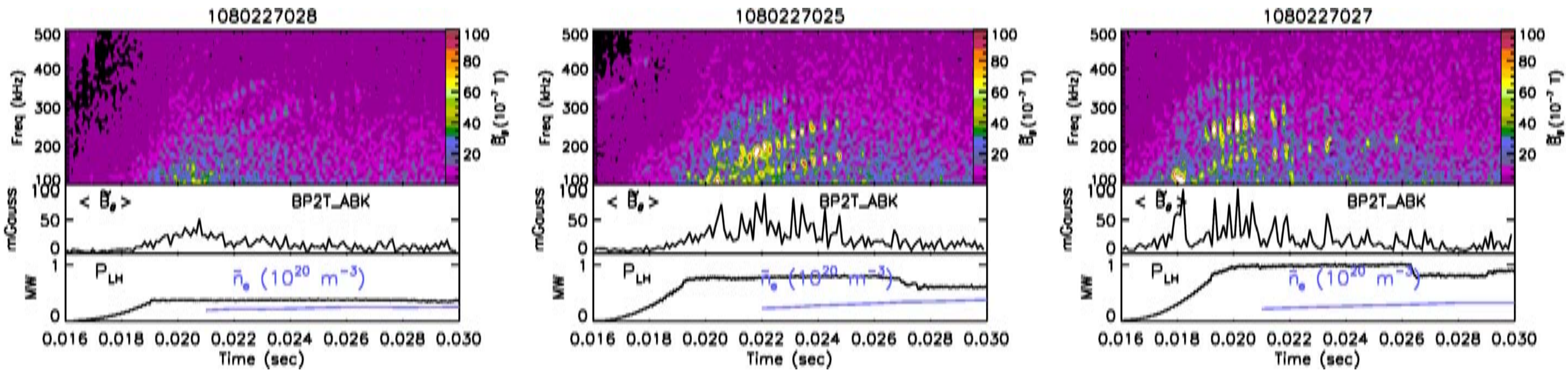
Frequency of Bursts Decreases with Decreasing Edge q



- Frequency of bursts decreases with decreasing edge q
- There are fewer low order rational surfaces at lower q

Mode Amplitude Increases with LHCD Power

$P_{LH} = 0.4$ MW　　$P_{LH} = 0.8$ MW　　$P_{LH} = 1.0$ MW

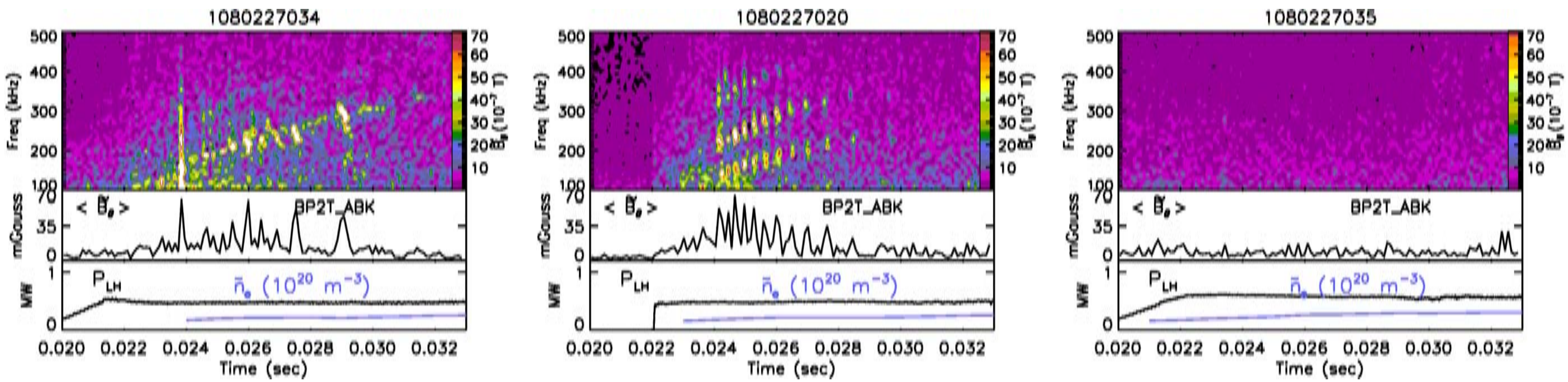


- Mode amplitude increases with increasing P_{LH}
- Modes are absent with $P_{LH} = 0.2$ MW
- Indicates fast electron drive increases with lower hybrid power as expected

Eigenmode Stability Depends Strongly on LHCD Phase

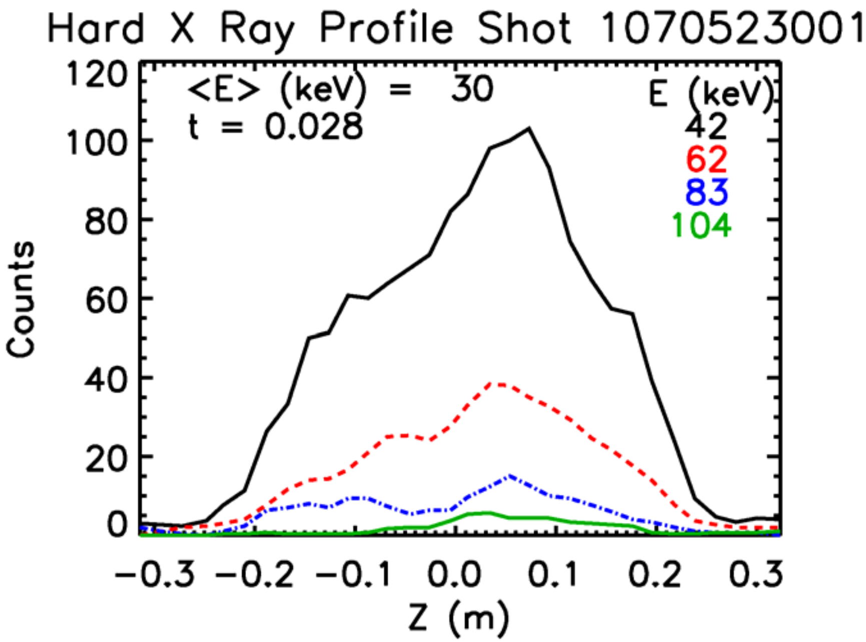
Alcator C-Mod

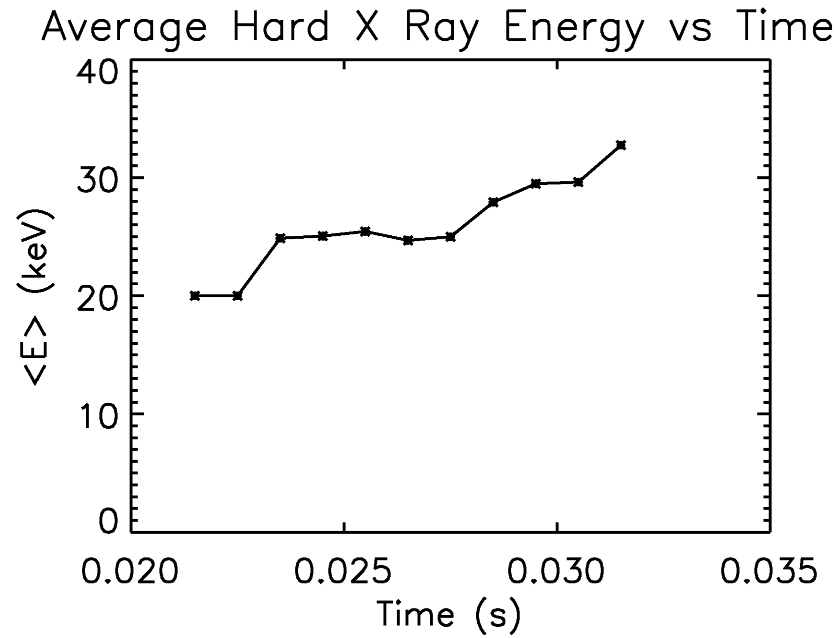
$\varphi_{LH} = 60°$ $\varphi_{LH} = 90°$ $\varphi_{LH} = 120°$



- Modes are strongest at 90° phasing ($n_{||} \approx 2.3$)
- Some modes are visible at 60 ° phasing ($n_{||} \approx 1.55$)
- Modes are absent at 120 ° phasing ($n_{||} \approx 3.09$) where current drive is weak and the electron distribution function is less energetic

Average Hard X Ray Photon Energy Exceeds 30 keV



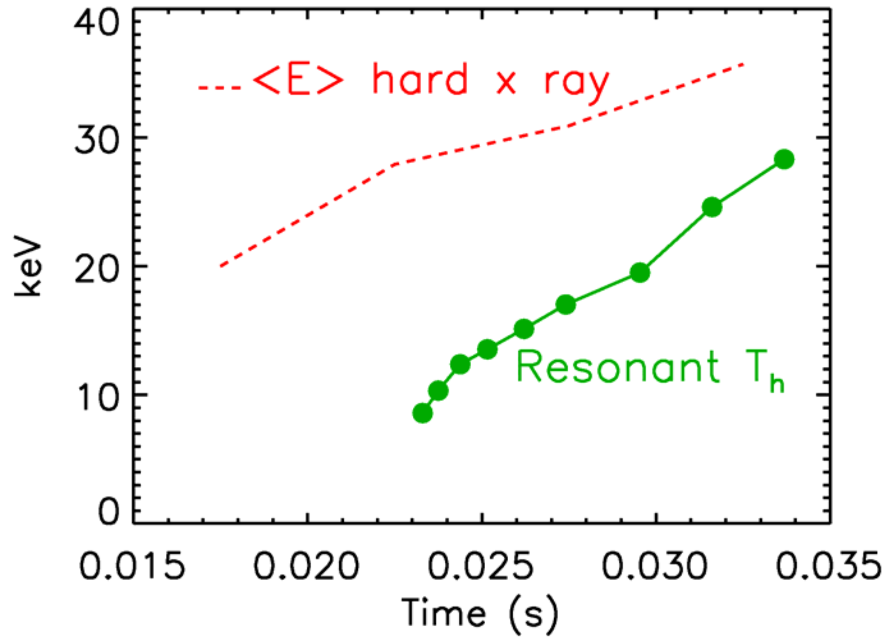


- Radially viewing hard x ray camera shows a broad profile with significant counts out to at least 80 keV photon energy
- Average hard x ray photon energy increases from 20 – 35 keV during the high frequency modes

High Frequency Mode Satisfies Resonance Condition

- Precession drift resonance condition for deeply trapped particles maximizes the fast electron drive when $\omega \approx \omega_d$ so that [4] $T_h(\text{keV}) \sim 2.52\, f_{mode}(\text{kHz})\, B(\text{T})\, r_s\, R_0/(nq)$
- Using r_s=0.1 m, the n=2 frequencies in the shot of interest give T_h comparable to the measured hard x ray photon energy vs time
- This resonance condition may also explain why the modes go away despite continued LH heating, since lower q requires higher fast electron energies to continue to drive the modes unstable
- Constrains the fast electron distribution function

Precession Drift Resonance and <E> Hard X Ray



[4] F Zonca *et al*, *Nucl Fus* **47** (2007) 1588

A High Perpendicular Temperature Results from Pitch Angle Scattering of the Parallel LHRF-Generated Electron Tail

- From Fuchs *et al.*, Physics of Fluids **28**, 3619 (1985) Eq. (37):

$$\frac{T_\perp}{T_e} \approx \frac{(\alpha_i\text{-}1)(\mathrm{v}_2^{\alpha_i+1} - \mathrm{v}_1^{\alpha_i+1})\mathrm{v}_1^{2-\alpha_i} - \mathrm{v}_1^2(\mathrm{v}_2 - \mathrm{v}_1)(\alpha_i^2 - 1)}{2(\mathrm{v}_2 - \mathrm{v}_1)(\alpha_i^2 - 1) - (\alpha_i + 1)\mathrm{v}_1^{2-\alpha_i}(\mathrm{v}_2^{\alpha_i-1} - \mathrm{v}_1^{\alpha_i-1})}$$

$$\alpha_i = (2 + 2Z_i)/(2 + Z_i) = 5/3 \text{ for } Z_i = 4$$

$$\mathrm{v}_1 = \mathrm{v}_{//_1}/\mathrm{v}_{te} \approx 3.5 \text{ (Quasi-linear ELD limit)}$$

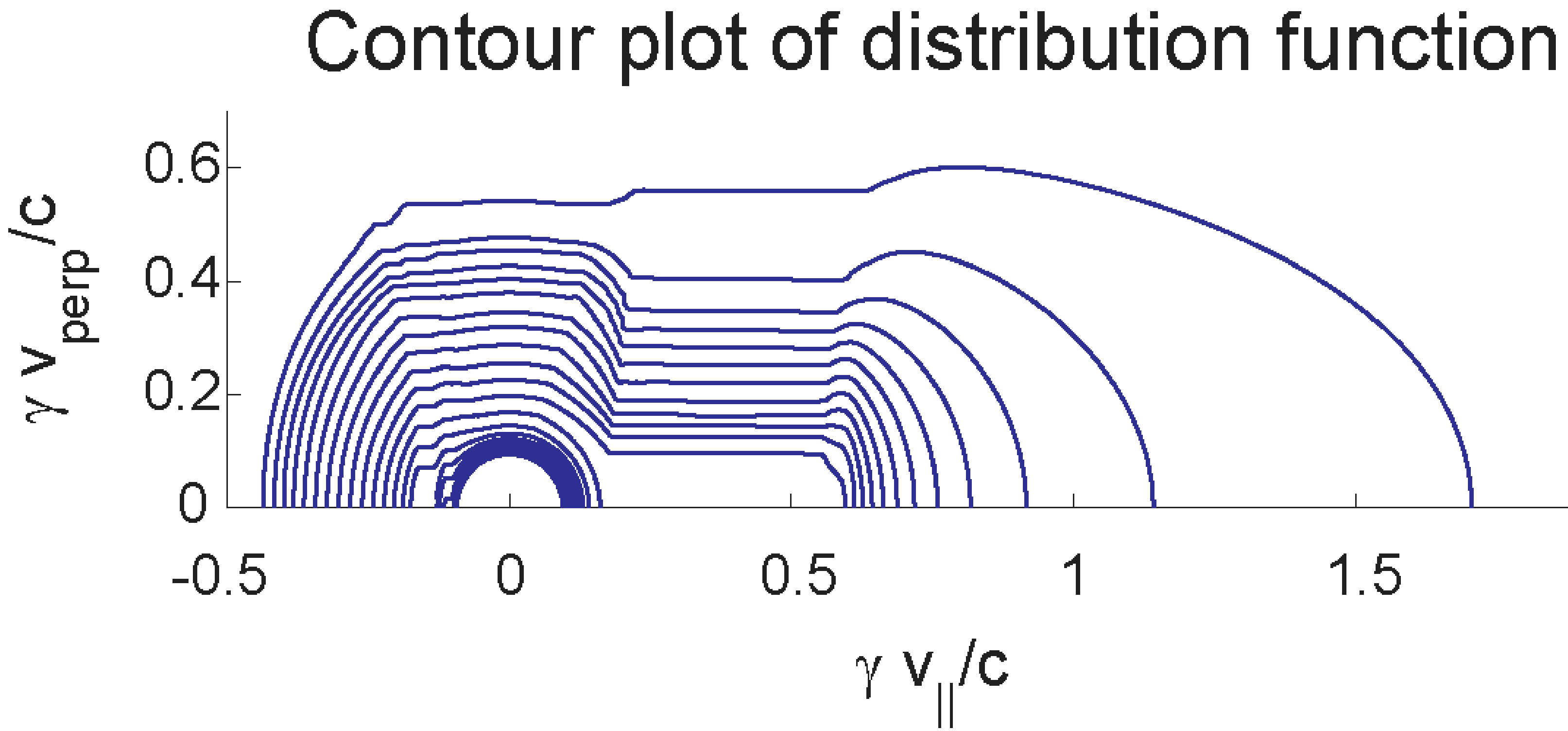
$$\mathrm{v}_2 = \mathrm{v}_{//_2}/\mathrm{v}_{te} \approx 24.8 \text{ for } (c/\mathrm{v}_{//_2}) = n_{//_{acc}} \approx 1.3 \ \& \ T_e \approx 0.5 \text{ keV}$$

$$\mathrm{v}_{te} = (T_e/m_e)^{1/2}$$

$$\Rightarrow \frac{T_\perp}{T_e} \approx 95$$

➔ $T_\perp$ ~ 47 keV consistent with precession drift resonance for the highest frequency n=3 modes

Fokker-Planck Simulations Show Large $T_{e\perp}$ from Pitch Angle Scattering



- Fokker-Planck simulations show a large $T_{e\perp}$ from pitch angle scattering
- These trapped electrons can then provide the necessary drive for TAEs since $\gamma\, v_\perp/c = 0.3$ ➔ $T_{e\perp} = 47$ keV matches the highest freq n=3 modes

Conclusions

- 300 – 400 kW of LHCD in the early current rise drives a substantial fast electron tail with $E_{x\ ray}$ > 30 keV that excites fast electron driven Toroidal Alfvén Eigenmodes
- These TAEs have resonant q values from ~ 11 to 5.5 and burst at low order rational q values and provide a measure of the q profile evolution
- A toroidal field scan from 4.5 to 6.3 T shows that the mode frequencies scale as the TAE frequency
- The observed factor of two range in TAE frequencies may be explained by a hollow density profile and a reversed shear q profile that crosses a given rational q surface three times

Further Conclusions

- These modes require P_{LH} > 0.2 MW and the mode amplitude increases with increasing P_{LH}
- The modes were strongest at 90° phasing ($n_{||} \approx 2.3$), weaker at 60° phasing ($n_{||} \approx 1.5$), and disappeared at 120° phasing ($n_{||} \approx 3$) as expected from LH wave velocity and absorption effects
- The measured hard x ray photon average energy is comparable to the fast electron energy required to satisfy the precession drift resonance condition for fast electron driven TAEs
- Analytic and numerical calculations of the $T_{e\perp}$ from pitch angle scattering are consistent with the electron energy required to match the precession drift resonance condition for deeply trapped electrons