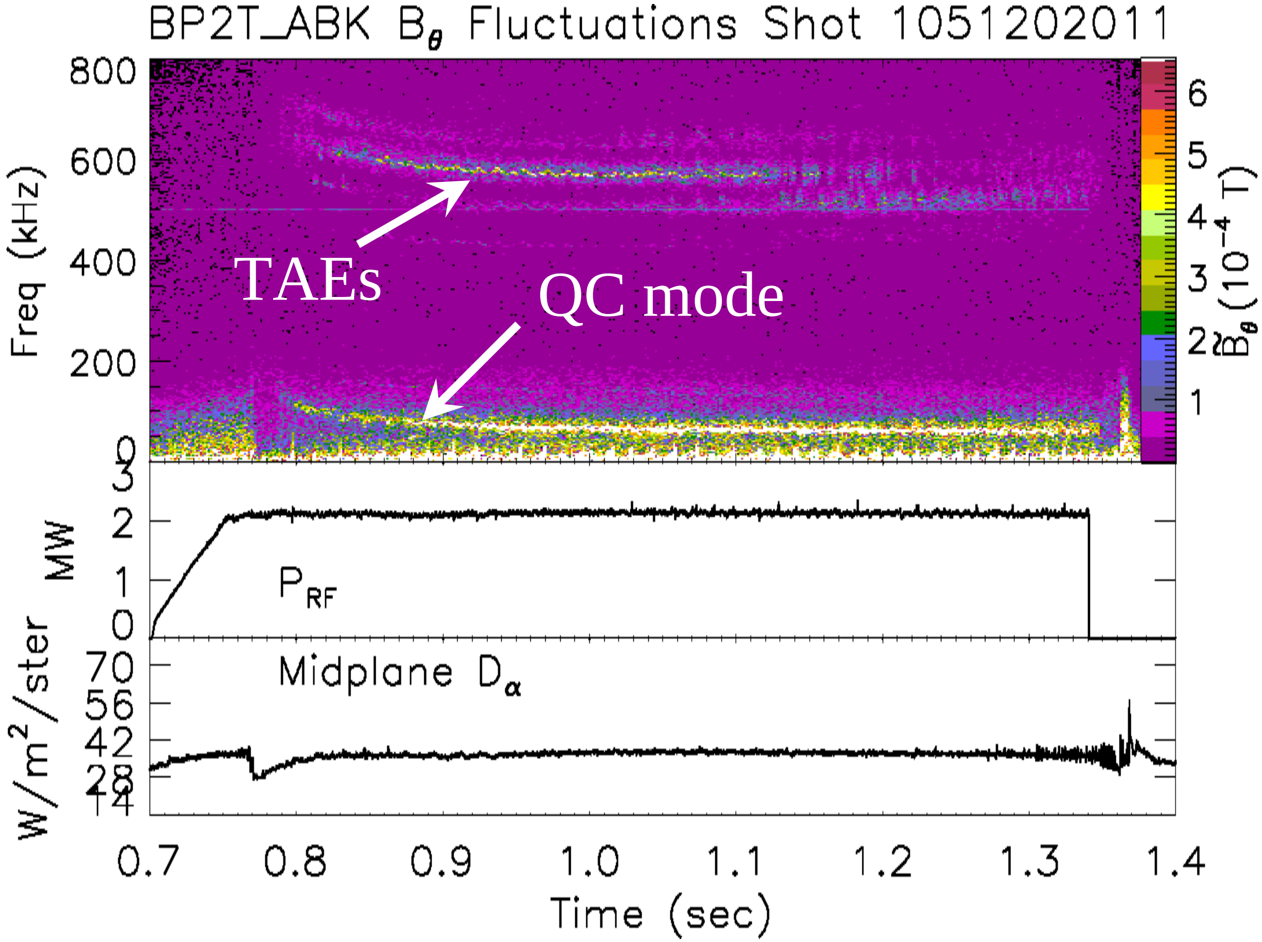
A Comparison of Alfvén Eigenmode Stability in L- and H-mode

J A Snipes, E Edlund, N N Gorelenkov[†],
M Porkolab, V Tang[#]

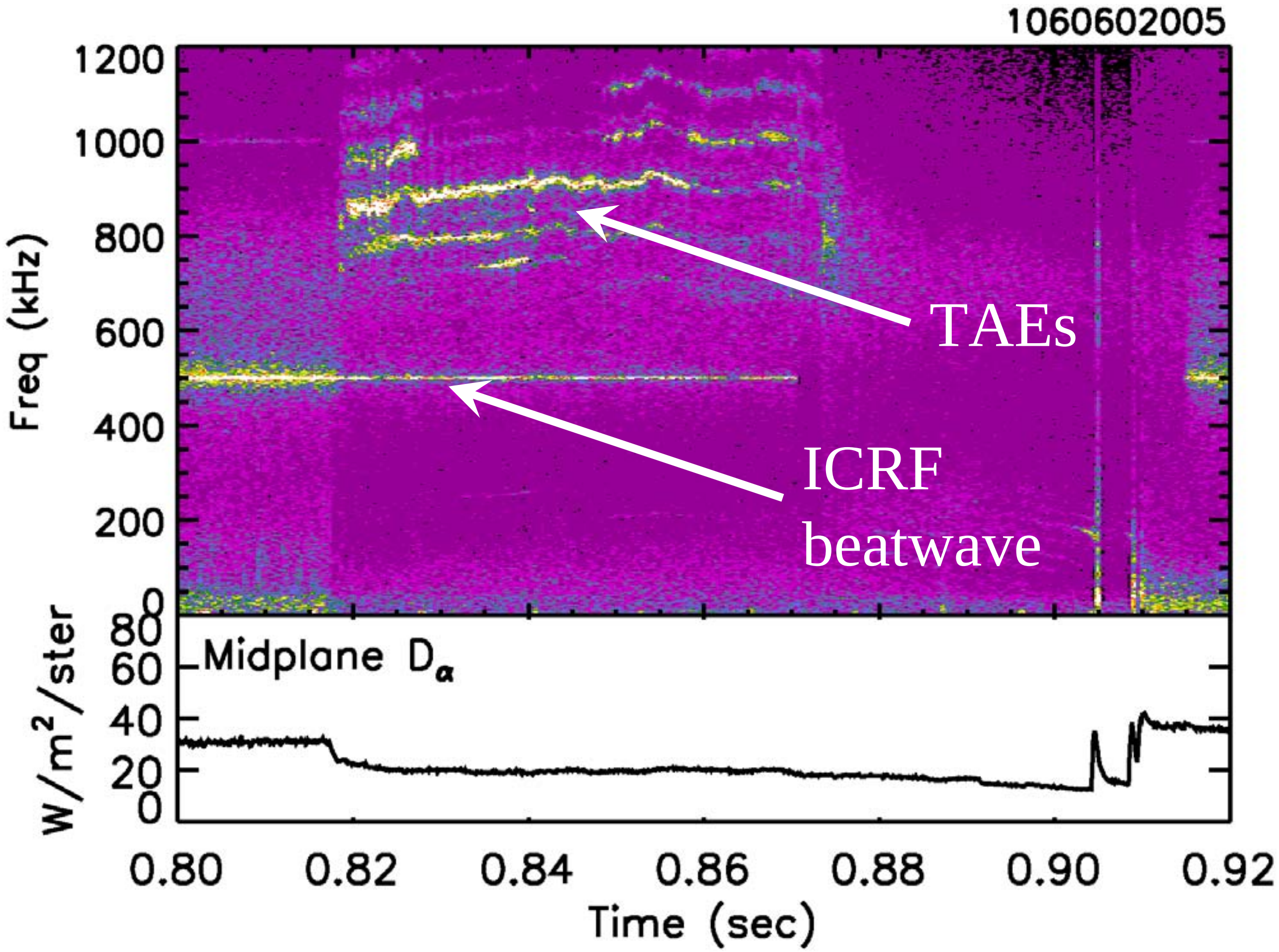
MIT Plasma Science and Fusion Center, Cambridge, MA USA
[†]Princeton Plasma Physics Laboratory, Princeton, NJ USA
[#]present address Lawrence Livermore National Laboratory, Livermore, CA USA

Unstable High Frequency TAEs in EDA H-mode



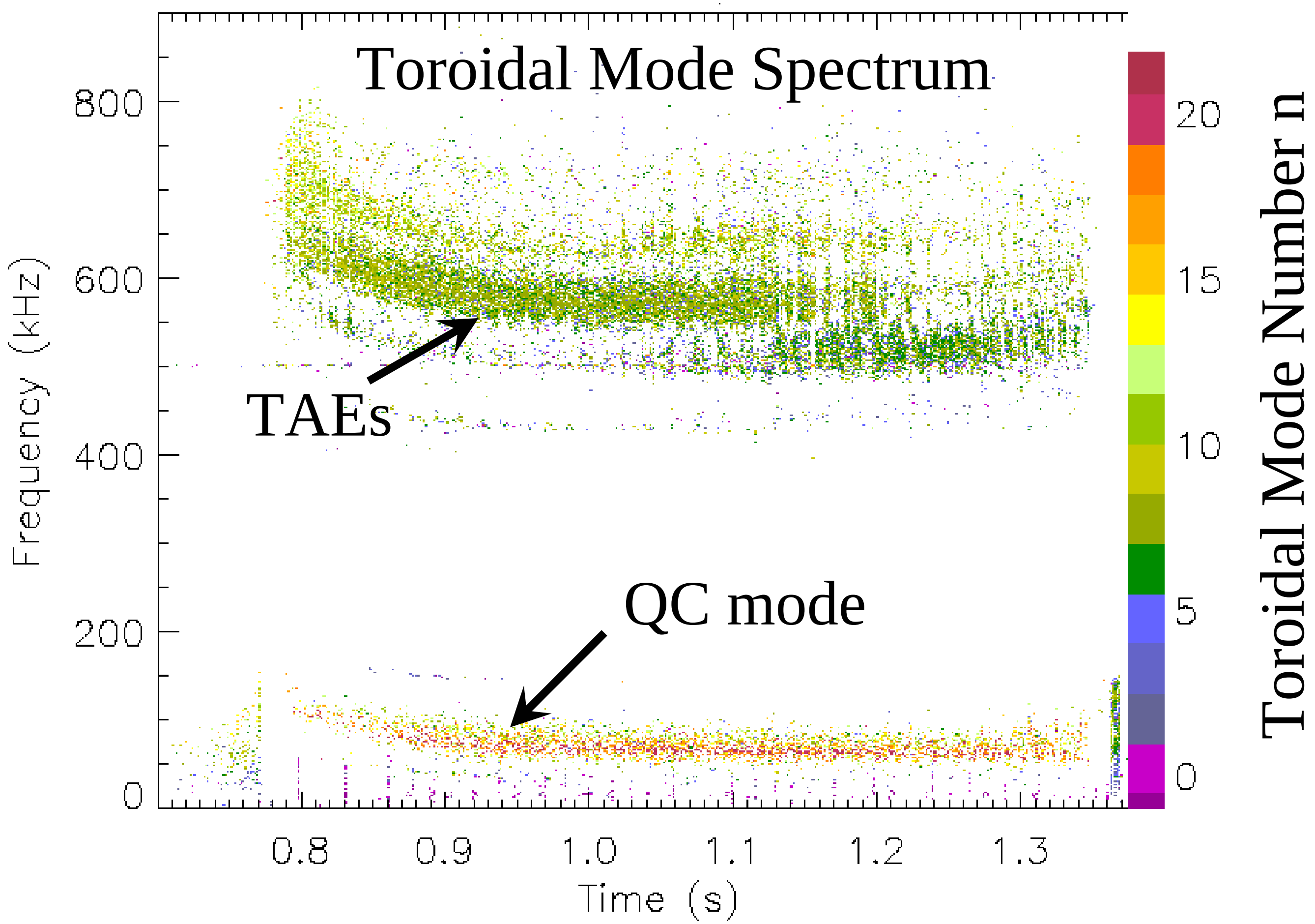
- Toroidal Alfvén Eigenmodes with f_{TAE} ~ 600 kHz correlate with QCM
- These TAEs only occur in ICRF heated H-mode not in L-mode

Unstable TAEs in ELM-free H-mode



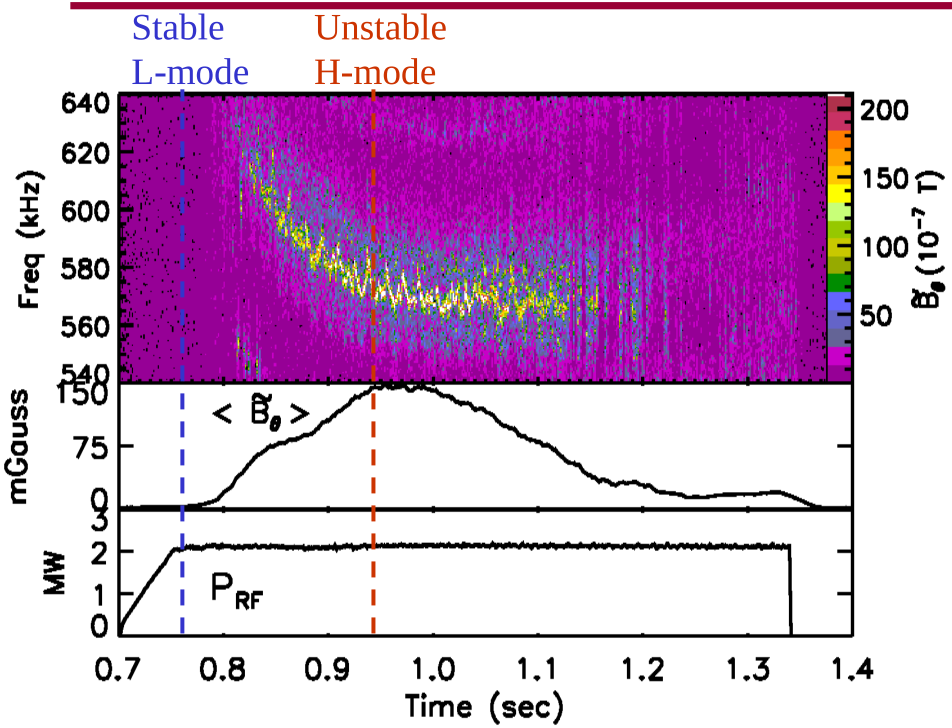
- In low density ($\bar{n}_e \sim 1.5 - 2 \times 10^{20}$ m^{-3}) ELM-free ICRF H-modes high frequency TAEs are sometimes observed without the QC mode

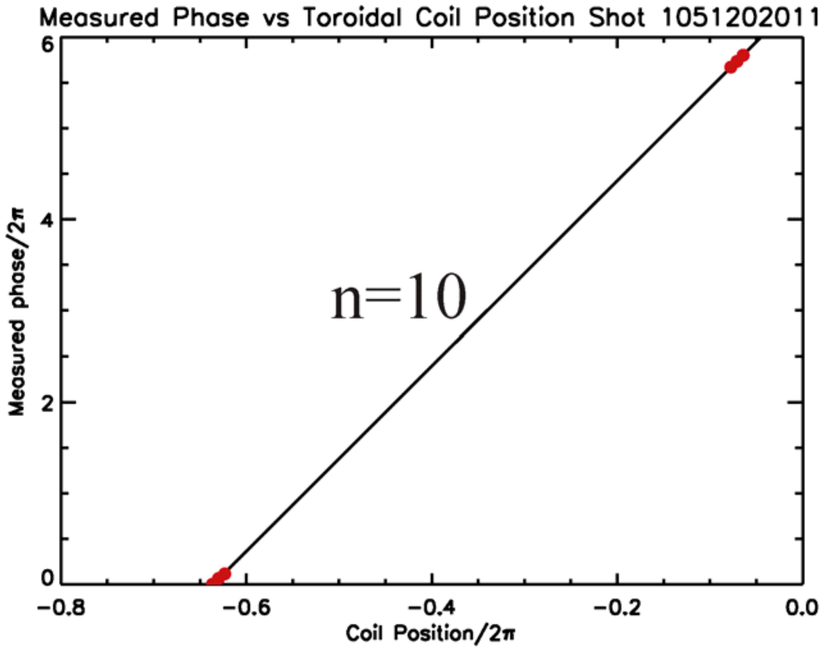
QC and TAEs Rotate Together with High n



- The QC mode and the TAEs all rotate in the electron direction
- These TAEs have toroidal mode numbers 6 ≤ n ≤ 11

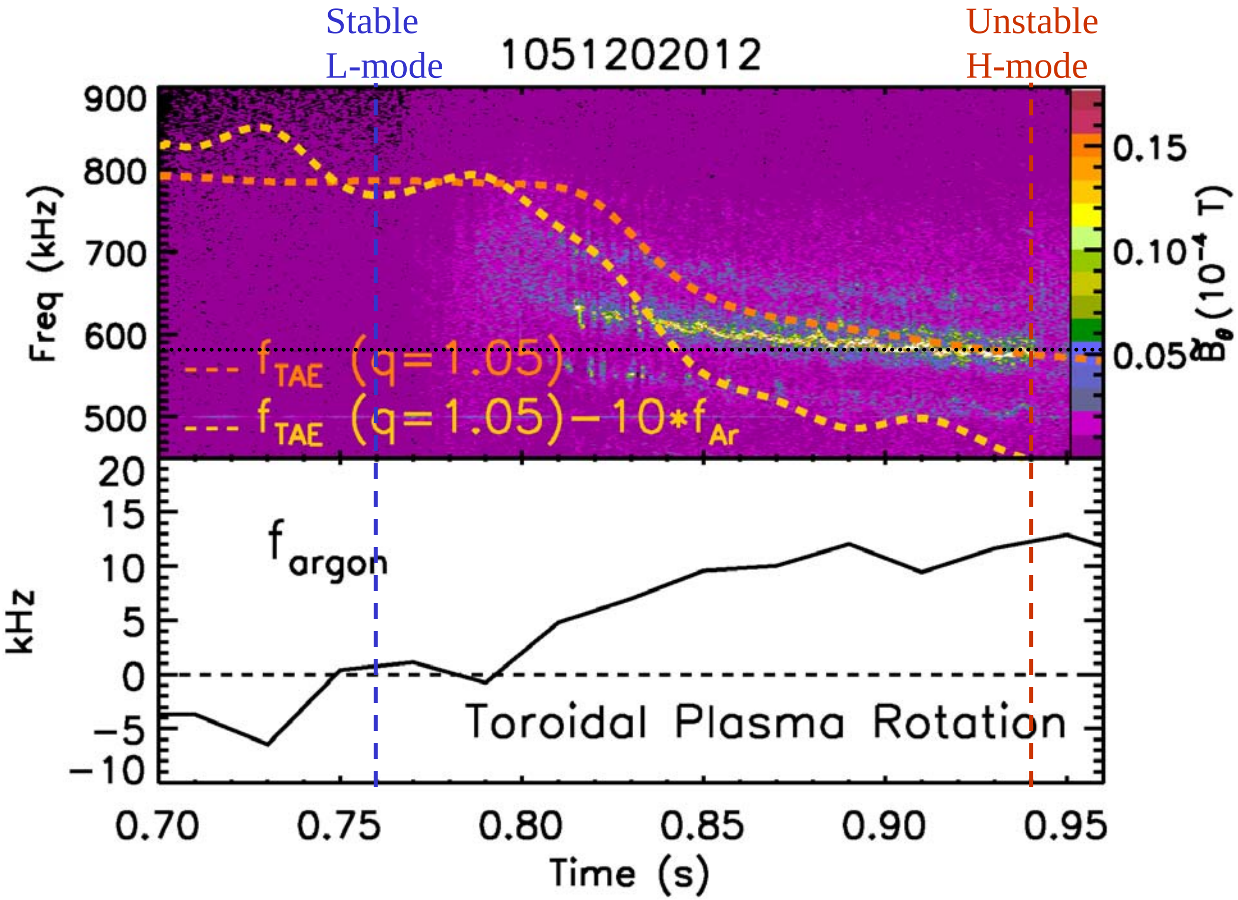
Choose Dominant Mode for Stability Analysis





- Dominant TAE peaks at about t = 0.94 s with $f_{measured}$ ~ 580 kHz, n = 10
- Choose this mode for stability analysis using the NOVA-K code and compare with the L-mode time at t = 0.76 s where the mode is stable

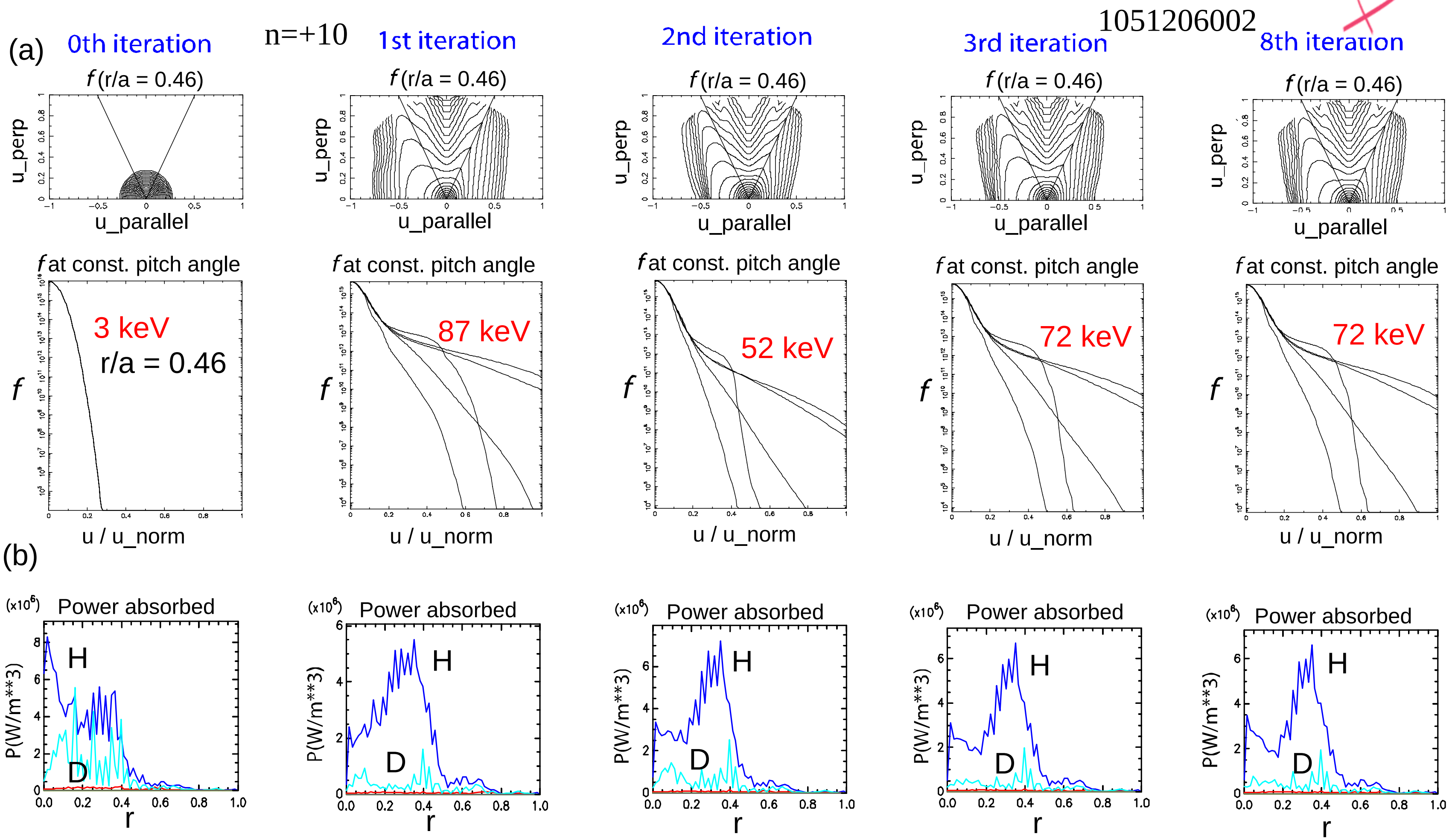
Determine Mode Frequency in the Plasma Frame



- Plasma rotation in the next shot, which was nearly identical, had f_{argon} ~ 12.5 kHz at t=0.94 s in H-mode
- Doppler shift of ~ +125 kHz for n = -10
- In the plasma frame f_{TAE} ~ 580 + 125 kHz ~ 705 kHz for n= - 10
- For n=+10 rotating in the ion direction, the mode frequency in the plasma frame would be f_{TAE} ~ 580 – 125 kHz ~ 455 kHz at t=0.94 s
- At t=0.76 s, plasma rotation ~ 0 ➔ mode frequency f_{TAE} ~ 800 kHz

AORSA/CQL3D Finds Off-Axis Fast Ion Profile

Alcator C-Mod



P(H) = 0.459 MW = 76 %

P(H) = 0.499 MW = 83%

P(H) = 0.518 MW = 86%

P(H) = 0.526 MW = 87%

P(H) = 0.522 MW = 87%

- Iterated self-consistent ICRF distribution function

E. F. Jaeger,
R. Harvey,
RF SCIDAC

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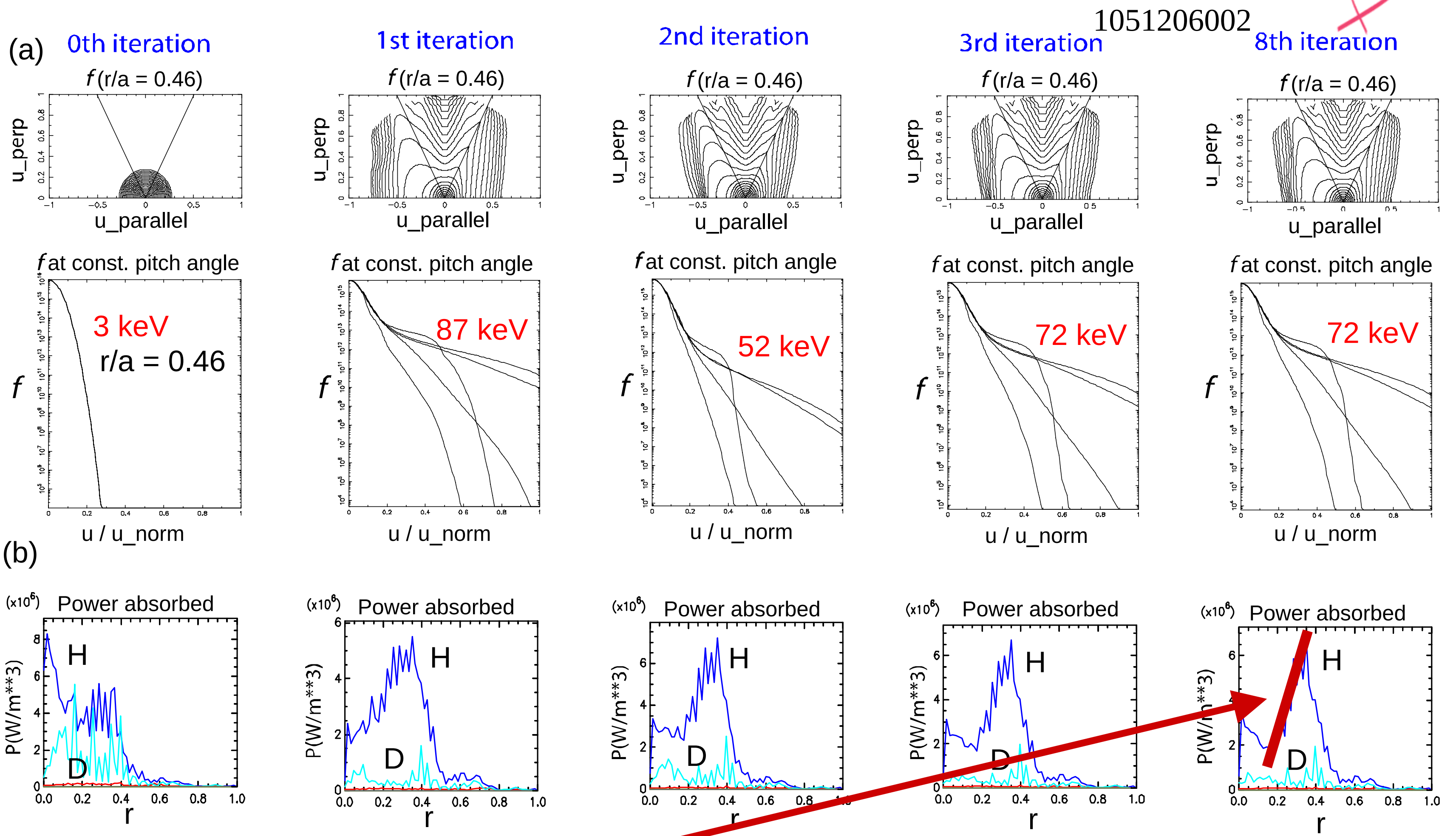

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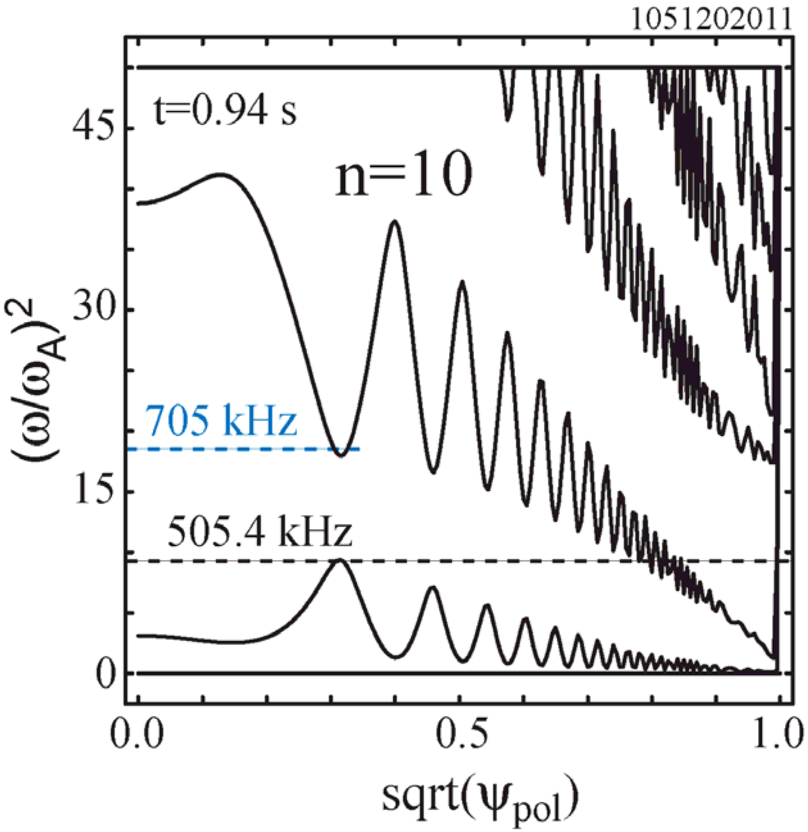
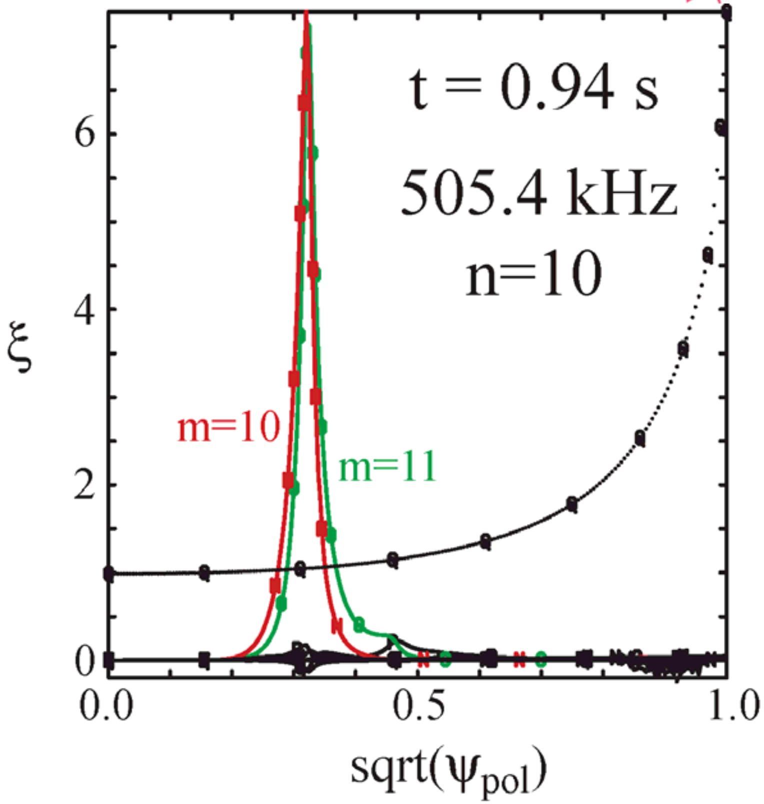
- Positive gradient in fast ion beta could drive TAE in the electron direction

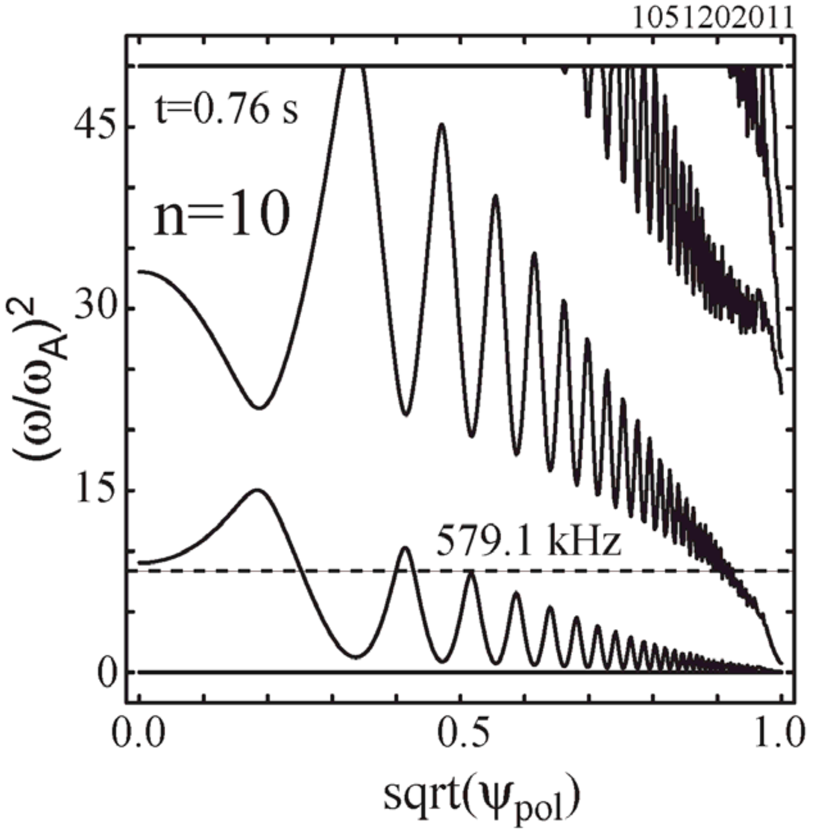
NOVA-K Finds Core Localized n=10 Mode in H-mode

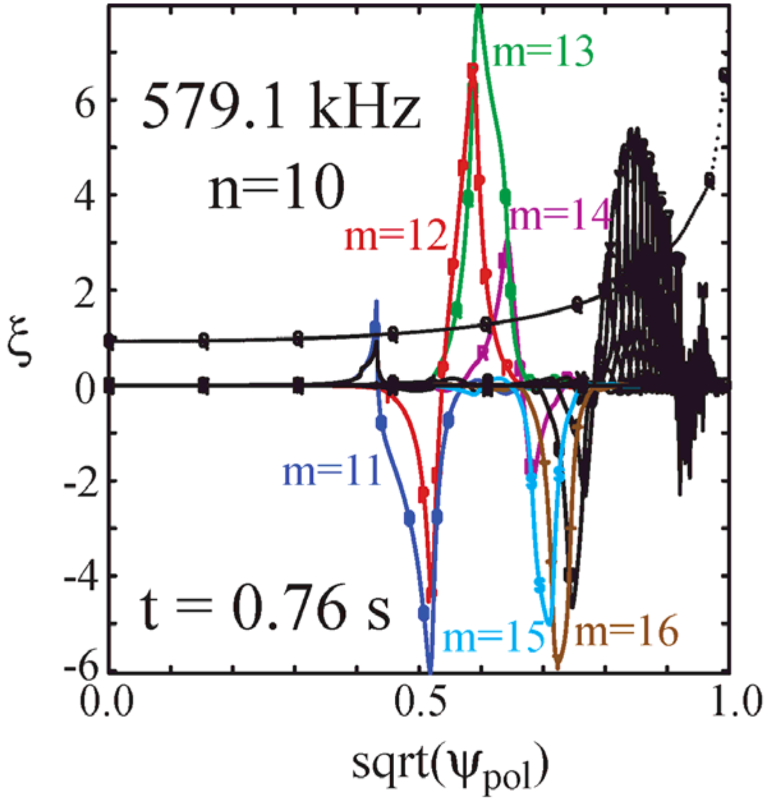




- NOVA-K finds a core localized n=10 mode at 505.4 kHz (bottom of gap)
- Measured mode frequency with Doppler shift ~705 kHz at the top of gap
- No mode found by NOVA near the top of the TAE gap

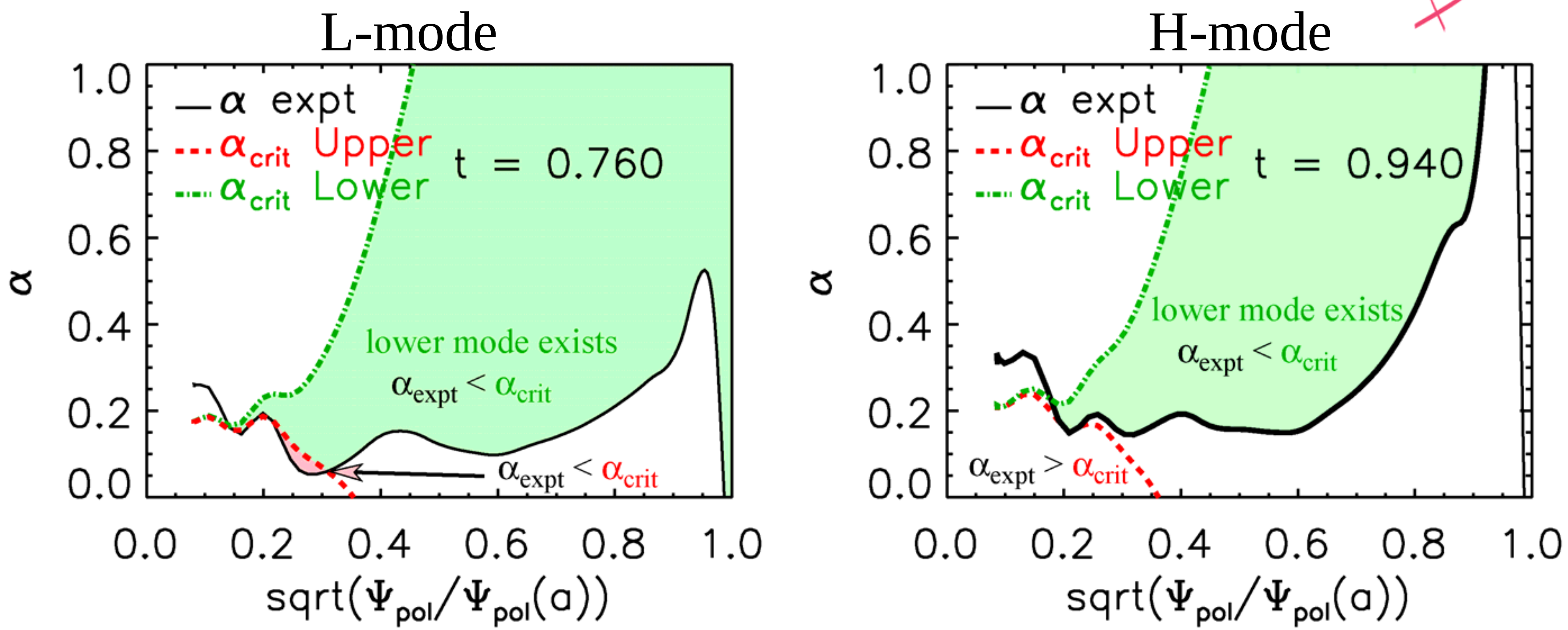
NOVA-K Finds Broader n=10 Mode in L-mode





- NOVA-K finds broad n=10 modes at 579.1 kHz and 644 kHz
- No modes were found throughout the rest of the gap

Why NOVA Does not Find Modes Near the Top of the Gap



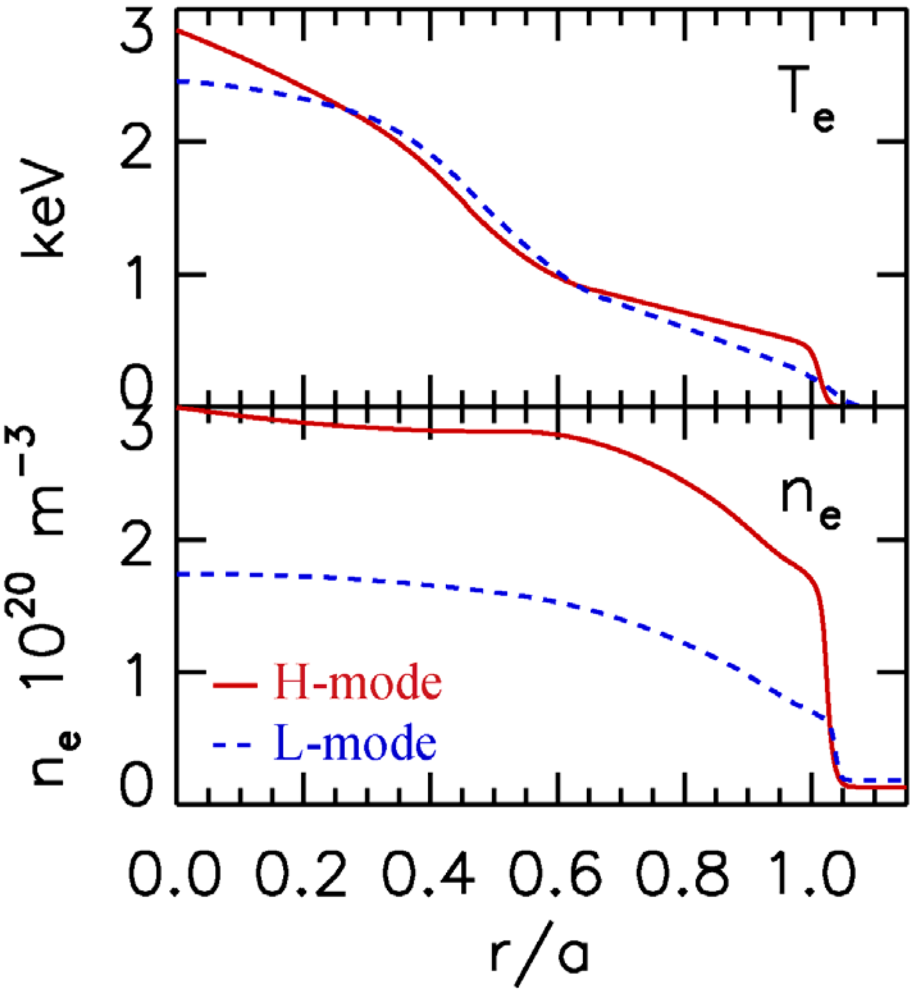
$$\underset{upper}{\alpha_{crit}} = -s^2 + \varepsilon + 2\Delta' \qquad \underset{lower}{\alpha_{crit}} = s^2 + \varepsilon + 2\Delta' \qquad \alpha = -Rq^2\beta'$$

$$\Delta' = (\varepsilon + \alpha)/4$$

Berk, et al, PoP (1995) **2** 3401

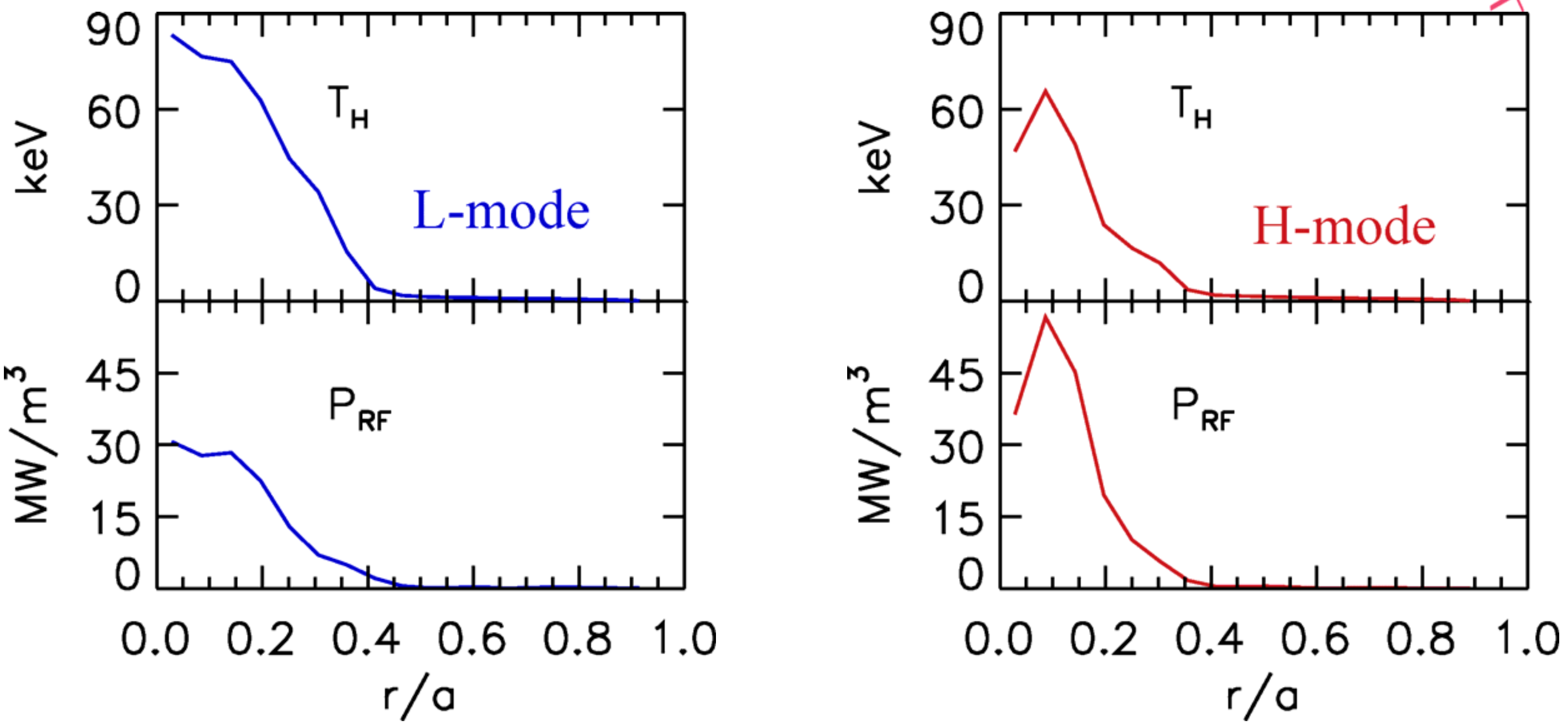
- Core TAE existence criteria require $\alpha_{expt} < \alpha_{crit}$ for modes to exist
- Upper gap criterion not satisfied (barely in L-mode) ➔ need lower shear

Temperature and Density Profiles in L- and H-mode



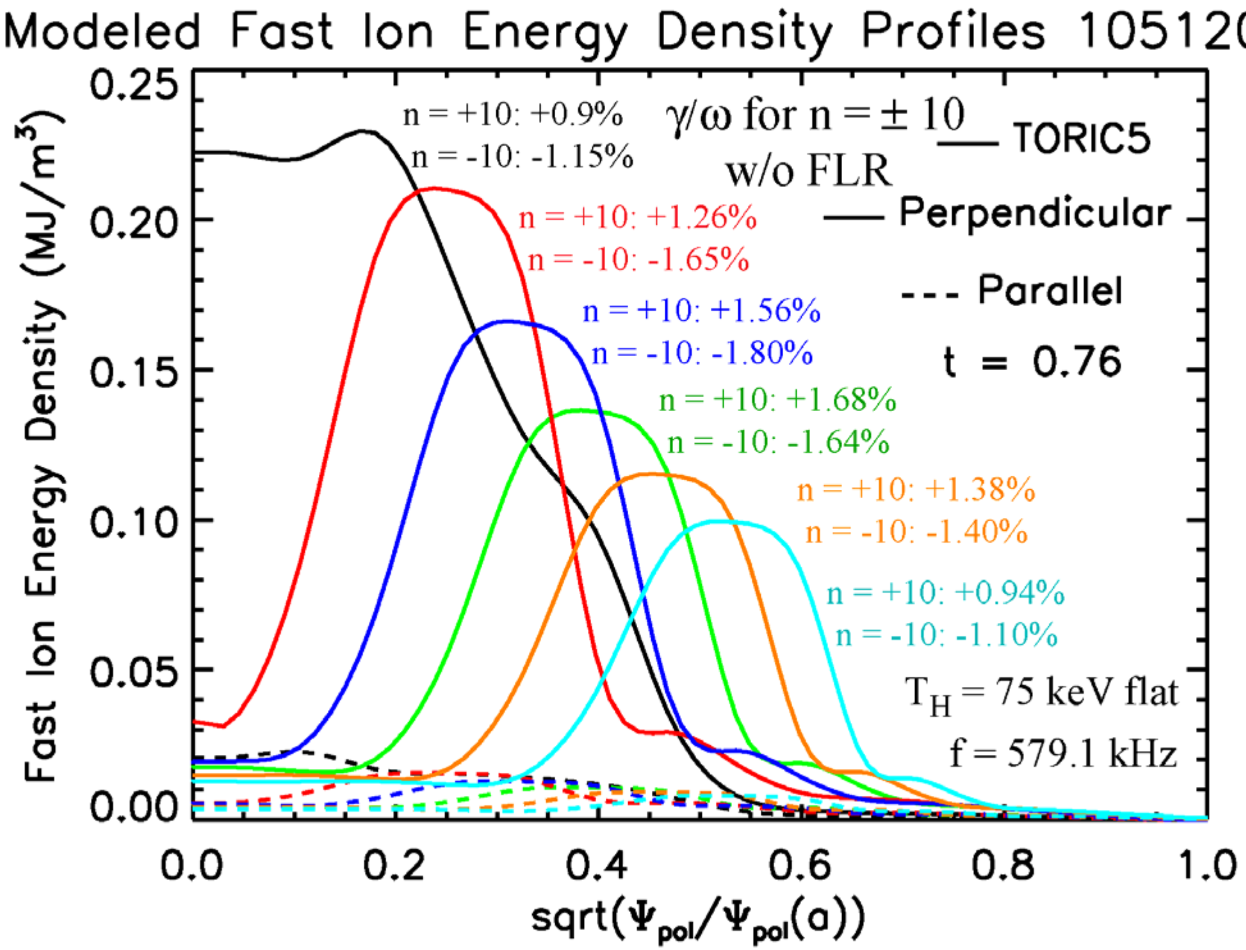
- Stability calculations depend on input temperature and density profiles
- H-mode has a more peaked temperature and a steep pedestal compared to L-mode
- Density profiles are nearly flat
- H-mode density is nearly twice the L-mode density with a large steep pedestal
- TRANSP H minority density assumed proportional to $n_e(r)$

TRANSP/TORIC5 Finds Peaked Fast Ion Profiles



- Transient L-mode effective fast ion temperature profile is broad with an on-axis maximum T_H ~ 75 keV
- Steeper H-mode profile peaked just off-axis with peak T_H ~ 55 keV

L-mode Found Stable to TAEs for n = ±10



γ/ω_{tot} = drive - damping

$\gamma/\omega_{drive} \leq 1.68\%$ for +n

$\gamma/\omega_{drive} \leq -1.1\%$ for -n

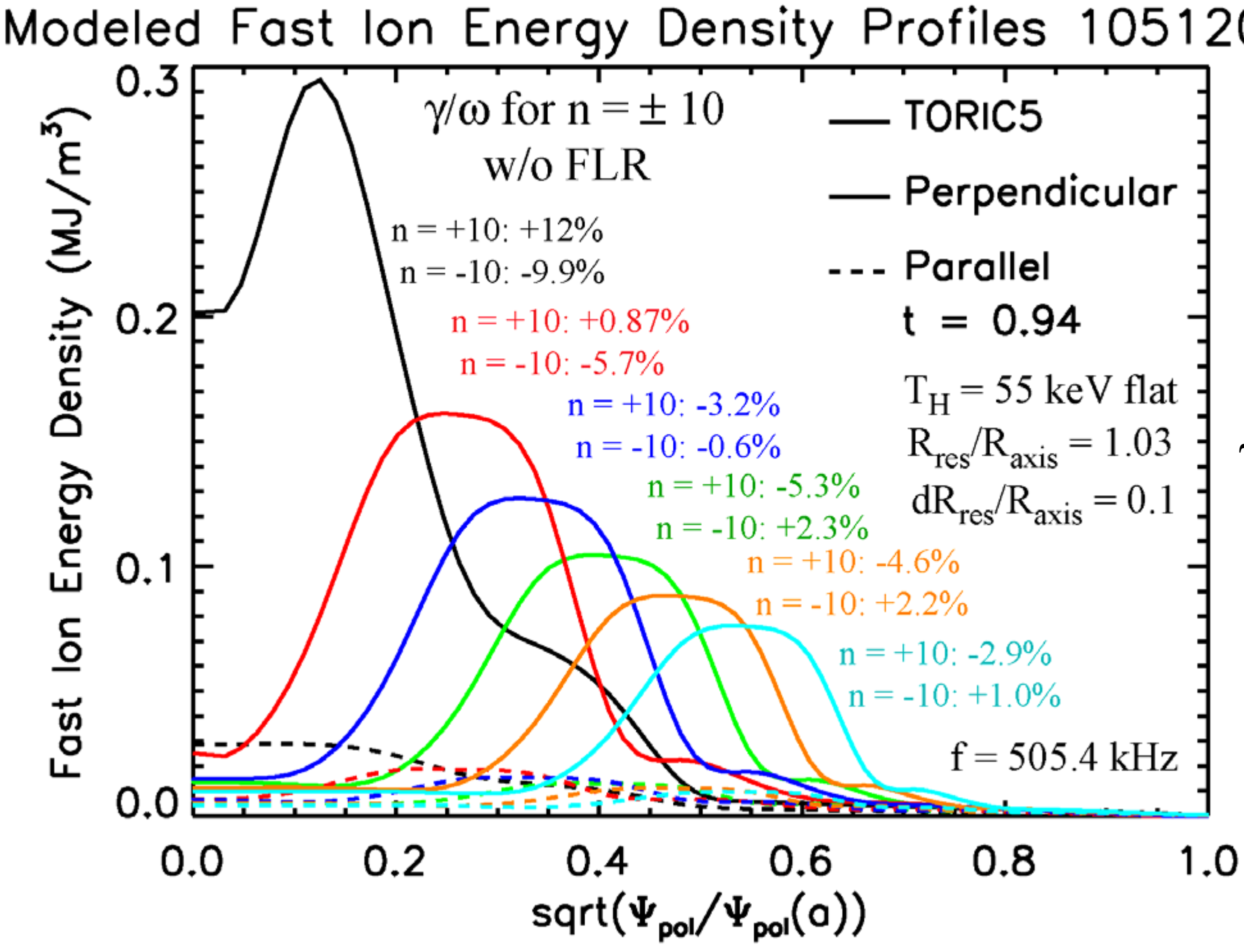
$\gamma/\omega_{damp} \sim -7\%$ radiative

$\gamma/\omega_{damp} \sim -0.6\%$ cont.

$\gamma/\omega_{tot} \leq -5\%$ stable

- TAE growth rate largest for off-axis fast ion profile shape (green +n)
- L-mode remains robustly stable to TAEs with ≤ -5% damping rate agrees with stable mode in the experiment

H-mode Found Unstable to TAEs for n = ±10 w/o FLR



γ/ω_{tot} = drive - damping

$\gamma/\omega_{drive} \leq 12\%$ for +n

$\gamma/\omega_{drive} \leq 2.3\%$ for -n

$\gamma/\omega_{damp} \sim -0.7\%$ radiative

$\gamma/\omega_{tot} \leq 11.3\%$ for +n

$\leq 1.6\%$ for –n

Unstable for ±n

- TAE growth rate largest for off-axis fast ion profile for –n (green)
- TAE growth rate largest for peaked fast ion profile for +n (black). Small damping leads to unstable modes for ±n without FLR effects included

Check Fast Ion Distribution Effects on TAE Growth Rate

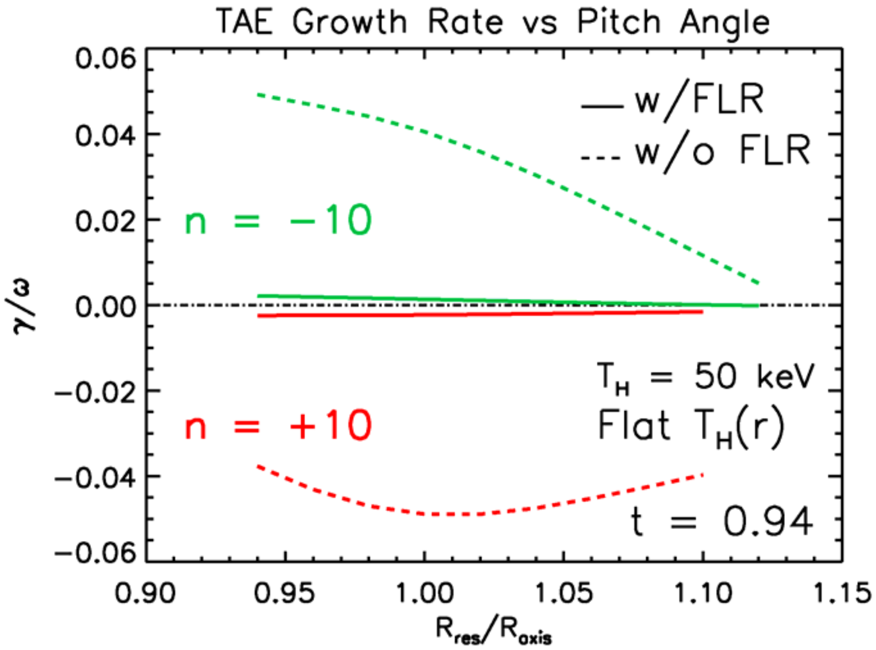
- Maxwellian and pitch angle distribution in Nova-K:

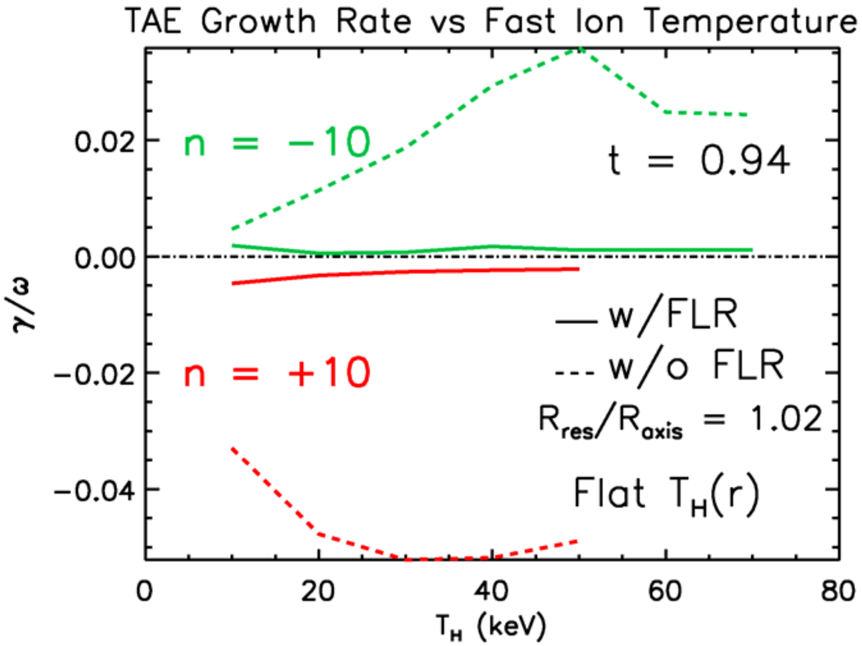
$$f \propto \exp[-\frac{E}{T_H} - (p - \frac{R_{res}}{R_{axis}})^2 / (\frac{dR}{R_{axis}})^2]$$

where $E = \frac{1}{2}mv^2$, T_H is the fast ion temperature, $p=\mu B_{axis}/E$, and μ is the magnetic moment $\mu = 1/2mv_\perp^2/B$

- Varied R_{res}/R_{axis} and T_H to look for changes in the growth rate
- NOVA-K normally assumes flat $T_H(r)$ profile then calculates $n_H(r)$ to match the input fast ion pressure profile
- Instead modified NOVA-K to use an input $T_H(r)$ profile and calculate the $n_H(r)$ profile to match the input fast ion pressure profile in better agreement with ICRF modeling of the fast ion profiles
- Compare growth rates with and without finite Larmor radius effects

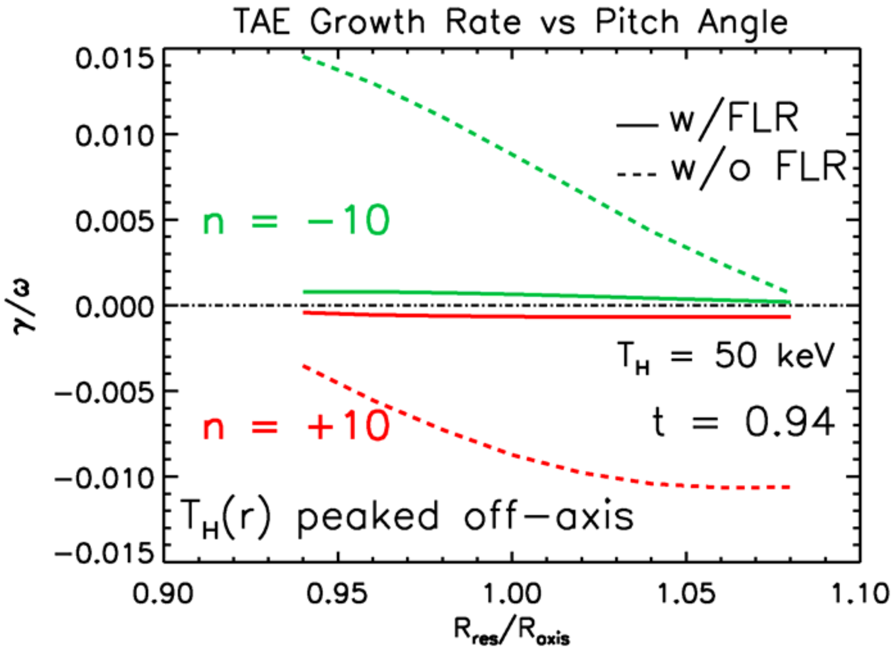
TAE Growth Rate Peaks at 50 keV for Flat T_H w/o FLR

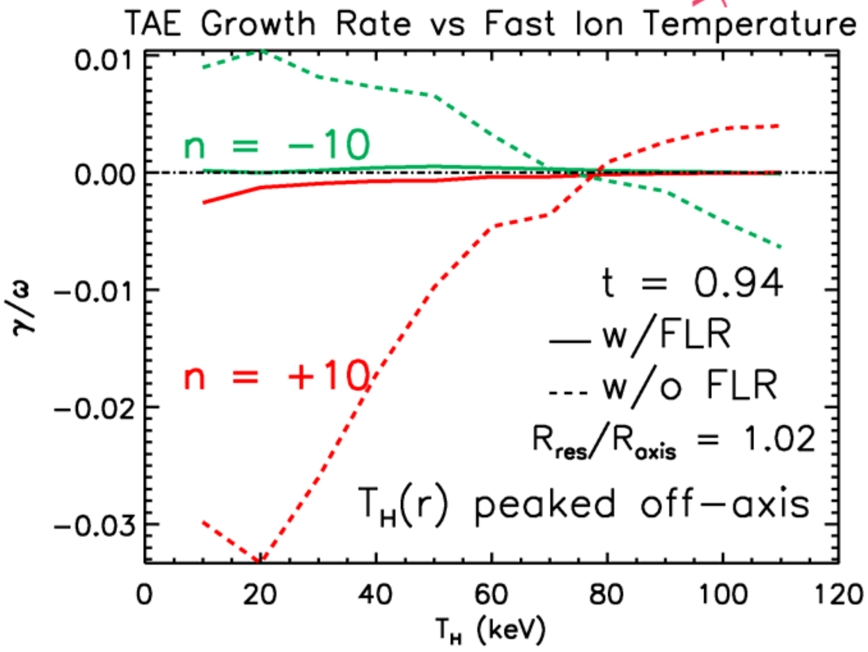




- TAE growth rate peaks for inboard R_{res}/R_{axis} at 50 keV for n = -10 assuming a flat $T_H(r)$ profile and a fast ion pressure profile peaked off-axis at $\mathrm{sqrt}(\Psi_{pol}/\Psi_{pol}(a)) \sim 0.3$ for the H-mode time at t = 0.94 s
- For this profile n = +10 remains stable in H-mode even w/o FLR effects
- FLR effects dominate the growth rates reducing them to near zero

TAE Growth Rate Peaks at 20 keV with $T_H(r)$ w/o FLR





- TAE growth rate peaks for inboard R_{res}/R_{axis} at 20 keV for n = -10 assuming a shaped $T_H(r)$ profile and a fast ion pressure profile peaked off-axis at sqrt($\Psi_{pol}/\Psi_{pol}(a)$) ~ 0.3 for the H-mode time at t = 0.94 s
- n = +10 remains stable except for higher T_H > 80 keV w/o FLR effects
- FLR effects dominate the growth rates again reducing them to near zero

Conclusions

- TAEs are often unstable in H-mode but not in corresponding lower density L-mode plasmas with the same ICRF input power
- These modes are observed to always rotate in the electron direction suggesting a hollow fast ion profile as found with AORSA/CQL3D in other discharges
- TRANSP/TORIC5 fast ion profiles are peaked near the axis which would only excite TAEs rotating in the ion direction
- NOVA-K modeling finds a core localized n=10 mode in H-mode at the bottom of the TAE gap but no mode near the top of the gap where the observed mode appears, suggesting lower shear may be required to satisfy $\alpha < \alpha_{crit}$ criterion
- NOVA-K modeling of the L-mode gives robustly stable growth rates for all conditions with substantial radiative damping in agreement with stable modes in the experiment
- H-mode found unstable to TAEs with larger growth rates for off-axis fast ion profiles for –n and larger growth rates for peaked fast ion profiles for +n

Conclusions (continued)

- Modified NOVA-K to use input shape of $T_H(r)$ rather than a flat profile
- Varied the pitch angle (R_{res}/R_{axis}) and peak T_H and found growth rates for –n peak for inboard resonance locations without FLR effects
- Growth rates for –n peak at 50 keV assuming a flat $T_H(r)$ but only at 20 keV assuming an off-axis peaked $T_H(r)$ profile without FLR effects
- Growth rates decrease by more than an order of magnitude when FLR effects are included making the modes stable for all conditions with minimal damping
- To properly model the mode in the experiment, a lower shear than provided by the standard EFIT equilibrium may allow a core TAE near the upper end of the gap to help match the observed mode frequency
- Lower shear should also reduce damping and increase drive to better match the unstable mode found in the experiment when FLR effects are included