Experimental study of Reversed Shear Alfvén Eigenmodes During ICRF Minority Heating and Relationship to Sawtooth Crash Phenomena in Alcator C-Mod

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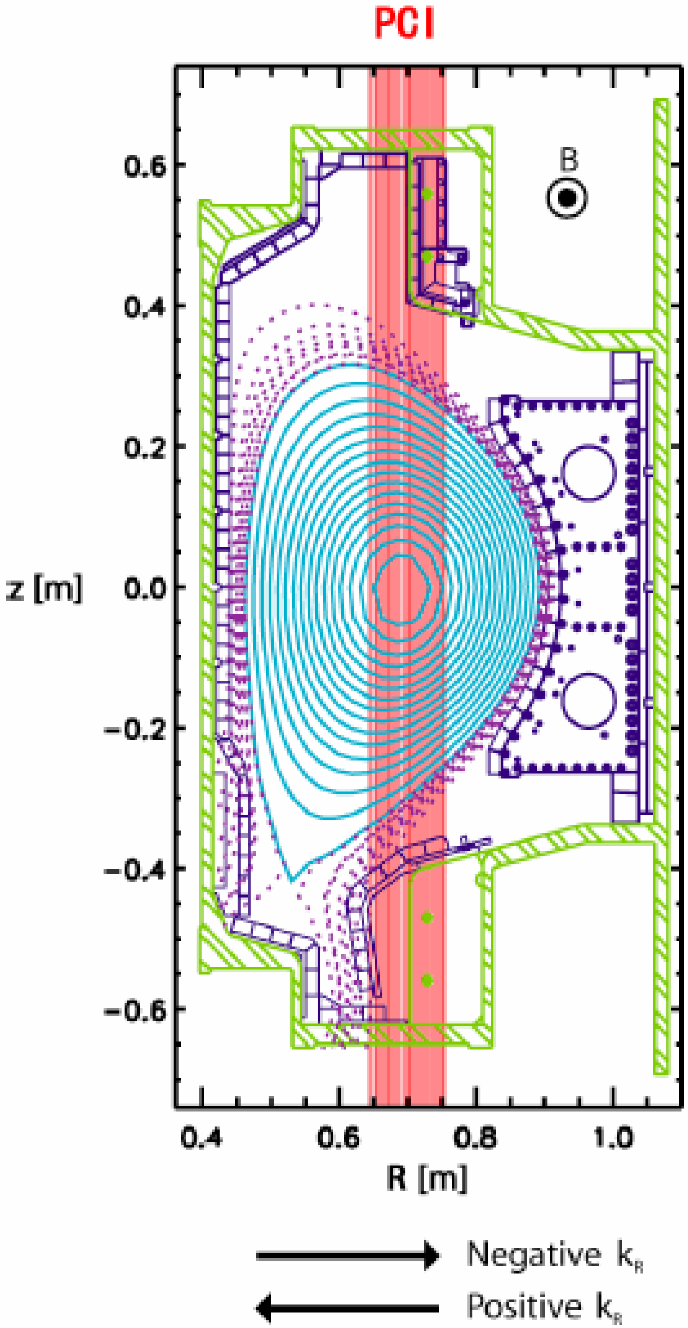
PCI System in C-Mod



PCI measures electron density fluctuations along 32 vertical chords.

Wave number Range:	Localization
$0.5cm^{-1} < \lvert k_R \rvert < 55\ cm^{-1}$	60cm<R<79cm
Frequency Range	**Laser**
2kHz~5MHz	60 Watt CO_2 CW
tunable 50 or 80 MHz	λ =10.6 μ m
(Heterodyned)	TEM_{00}

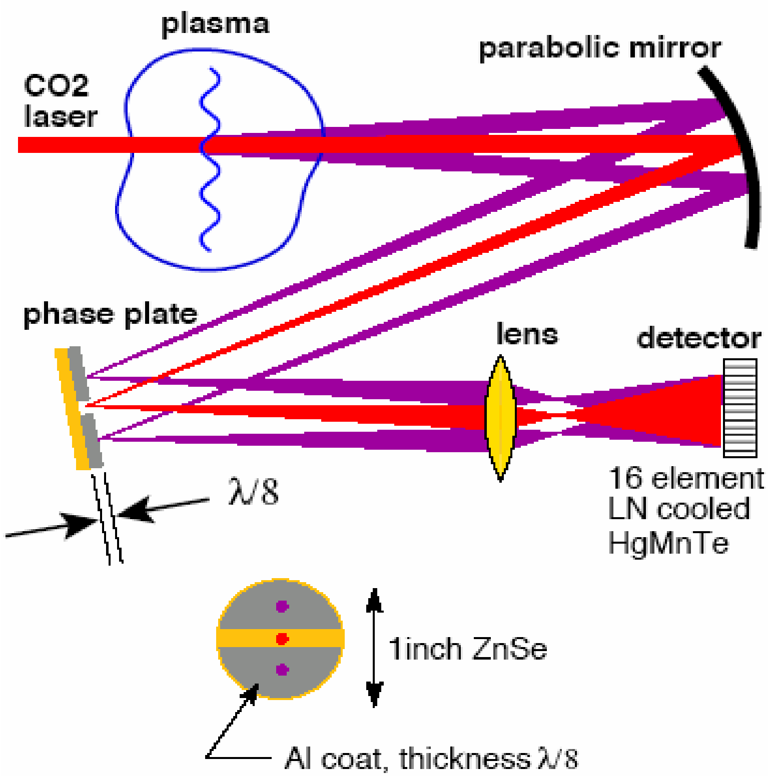
- A masking phase plate system has been installed to localize short wavelength fluctuations along the laser beam.
- Optional optics configurations are available for optimizing turbulence measurements in different wavenumber ranges.

Principle of Phase Contrast Imaging (PCI)

Zernike, PCI Microscope, 1930s, Nobel Prize

H. Weisen, first application to tokamak plasmas, 1980s

Density perturbations imaged on detector



- Before phase plate: $E_0(1 + i\Delta\phi)$
- After phase plate $E_0(i + i\Delta\phi)$
- $I \propto |E|^2 = E_0^2(1 + 2\Delta\phi)$

Phase Change represents plasma density

- Index of refraction for laser
  $N = (1 - \omega_{pe}^2/\omega^2)^{\frac{1}{2}} \simeq 1 - \omega_{pe}^2/2\omega^2$
- Phase shift depends on density
  $\Delta\phi(R) \simeq \int (N-1)dz \propto \int \tilde{n}(R,z)dz$
- Each detector channel i maps to a "radius" R_i ($\perp$ to beam).
  Each signal is $s_i = \int \tilde{n}(R_i, z)dz$

Dispersion Relation (approximate)*

$$\omega^2 \approx \underbrace{\frac{V_A^2}{R_0^2}\left(n-\frac{m}{q_{\min}}\right)^2}_{①} + \underbrace{\frac{2T_e}{M_i R_0^2}\left(1+\frac{7}{4}\frac{T_i}{T_e}\right)}_{②}$$

$$-\underbrace{\frac{2}{M_i R_0^2} r \frac{d}{dr}\left(T_e+T_i\right)}_{③} - \underbrace{\frac{\omega\omega_{c,H}}{m}\frac{q_0}{r_0^2 q_0''}\frac{r_0}{n_e}\frac{d}{dr}\langle n_H \rangle}_{④}$$

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① ~ 0 – 500 kHz

② ~ 150 kHz at 3keV

③ ~ 100 kHz at 3keV taking $r/L_{te} \sim 1$

⇨ $\Delta f \sim$ 20kHz

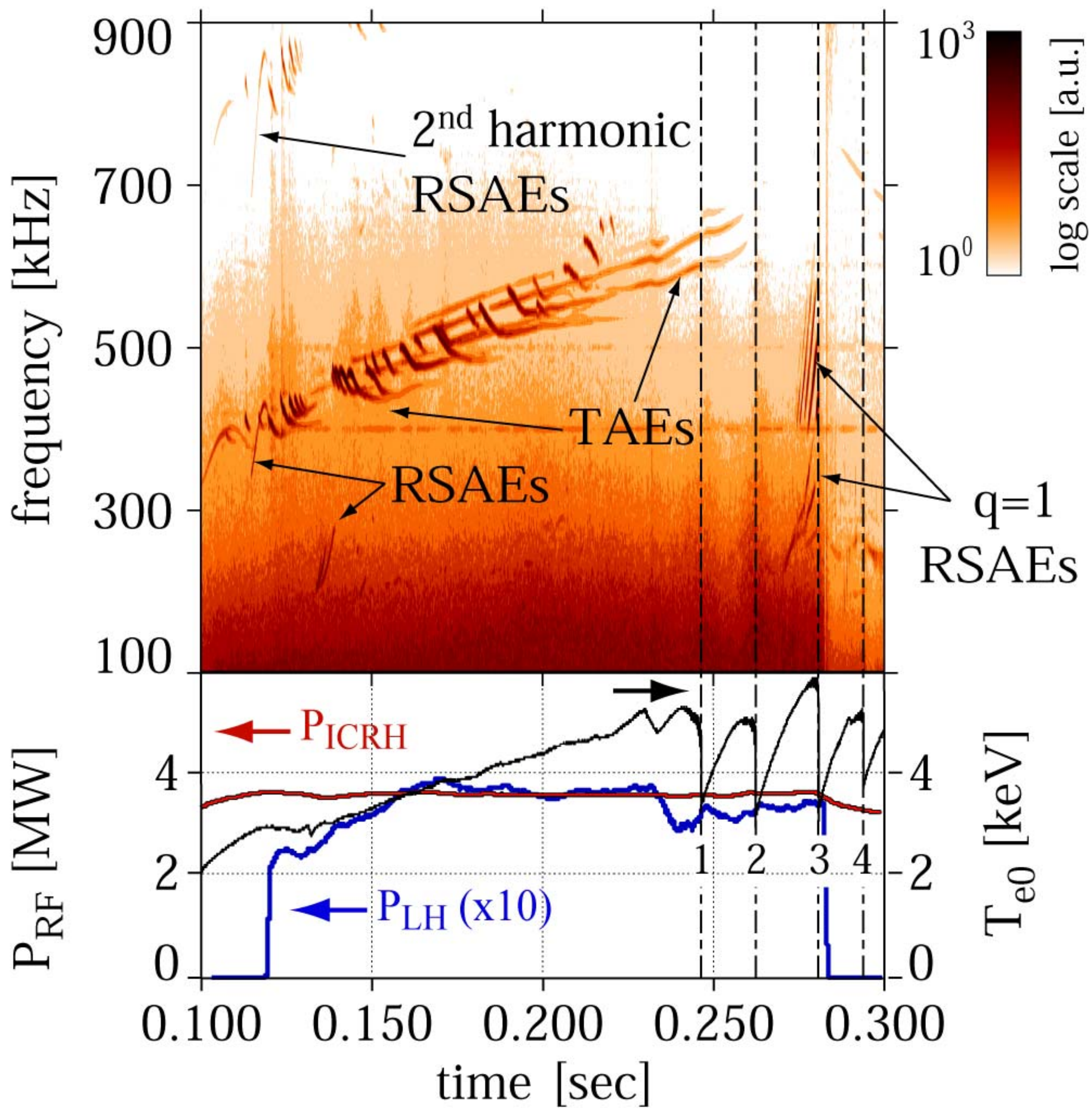
④ ~ 50 kHz for m~4 $r/L_{n,H} \sim 1/10$ $n_H/n_e \sim 0.01$

⇨ $\Delta f \sim$ 10kHz

*Breizman, Pekker, and Sharapov, Physics of Plasmas **12** (2005).

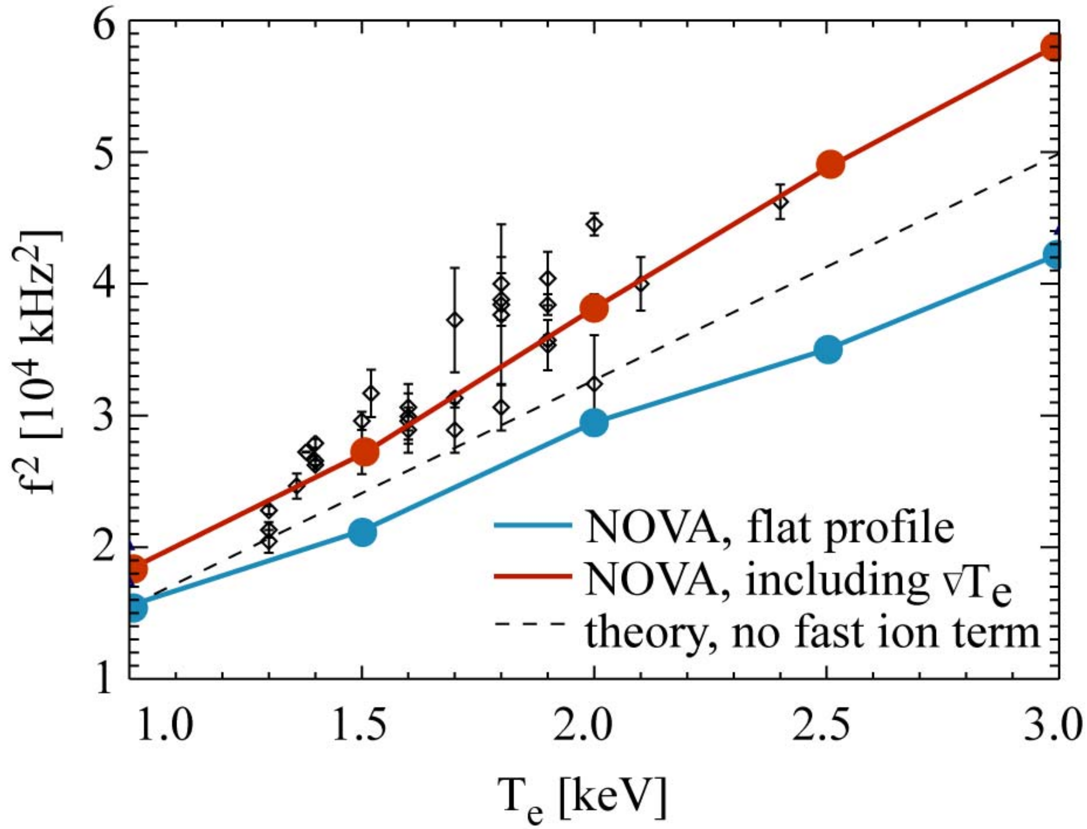
Experiments designed to study RSAEs during the current ramp phase

- Use a low-density target plasma
  $n_{e0} \approx 1.5\ 10^{20}\ m^{-3}$
  $n_{e,avg} \approx 1.0\ 10^{20}\ m^{-3}$
- Early ICRH brings temperature to the 3-6 keV range
- Recent experiments show a new lower threshold for RSAE excitation at about 0.8 MW ICRH power



T_e Scaling

- Expect a scaling of initial frequency given by $f^2 \propto T_e$
- NOVA results underpredict frequencies when a flat T_e profile is used
- Much better agreement with experimental trend when the T_e gradient is included

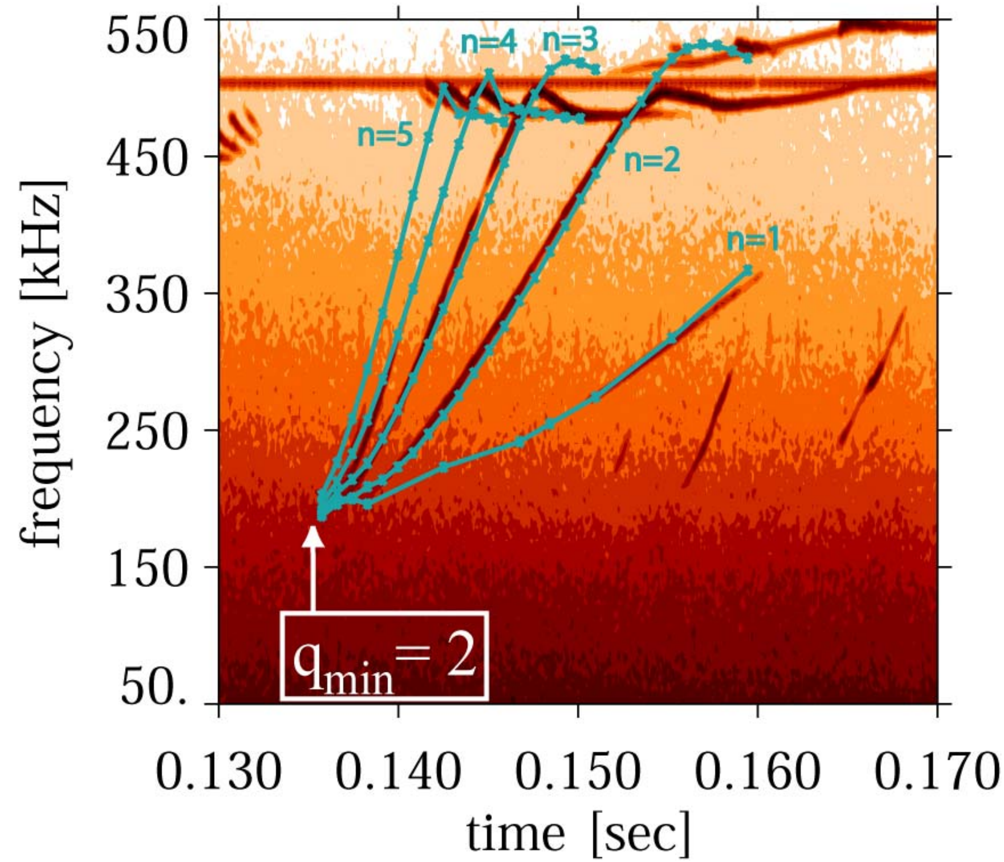


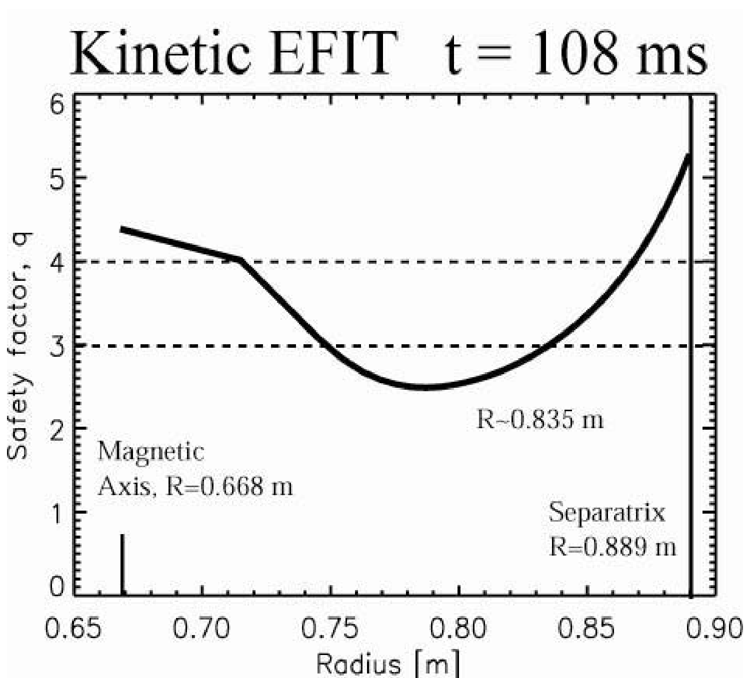
- The remaining scatter may be due suggesting that contributions from fast particles are playing a role in the dispersion relation.

see Gorelenkov *et al*, PPCF **48**, 1255 (2006).

Observations of RSAEs during the current ramp

- "Grand Cascade" structure exists as q_{min} passes through integer values
- Mode numbers have been inferred from ratio of slopes of modes and comparison to NOVA modeling



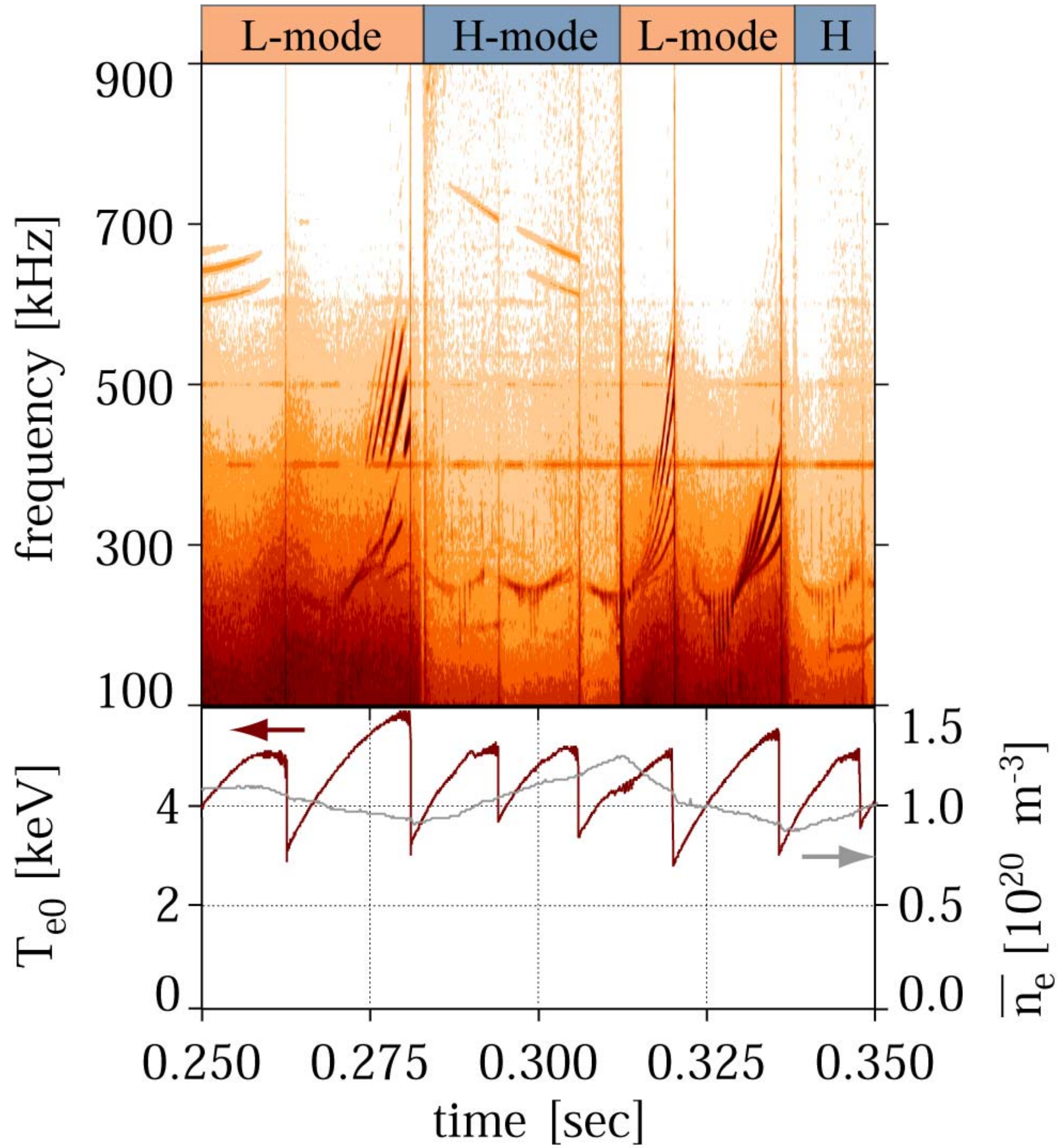


- Results of q-profile evolution in agreement with kinetic EFIT modeling,

  In, Hubbard, Hutchinson, NF **40**, 1463 (2000).

Observations of RSAEs during the current flattop

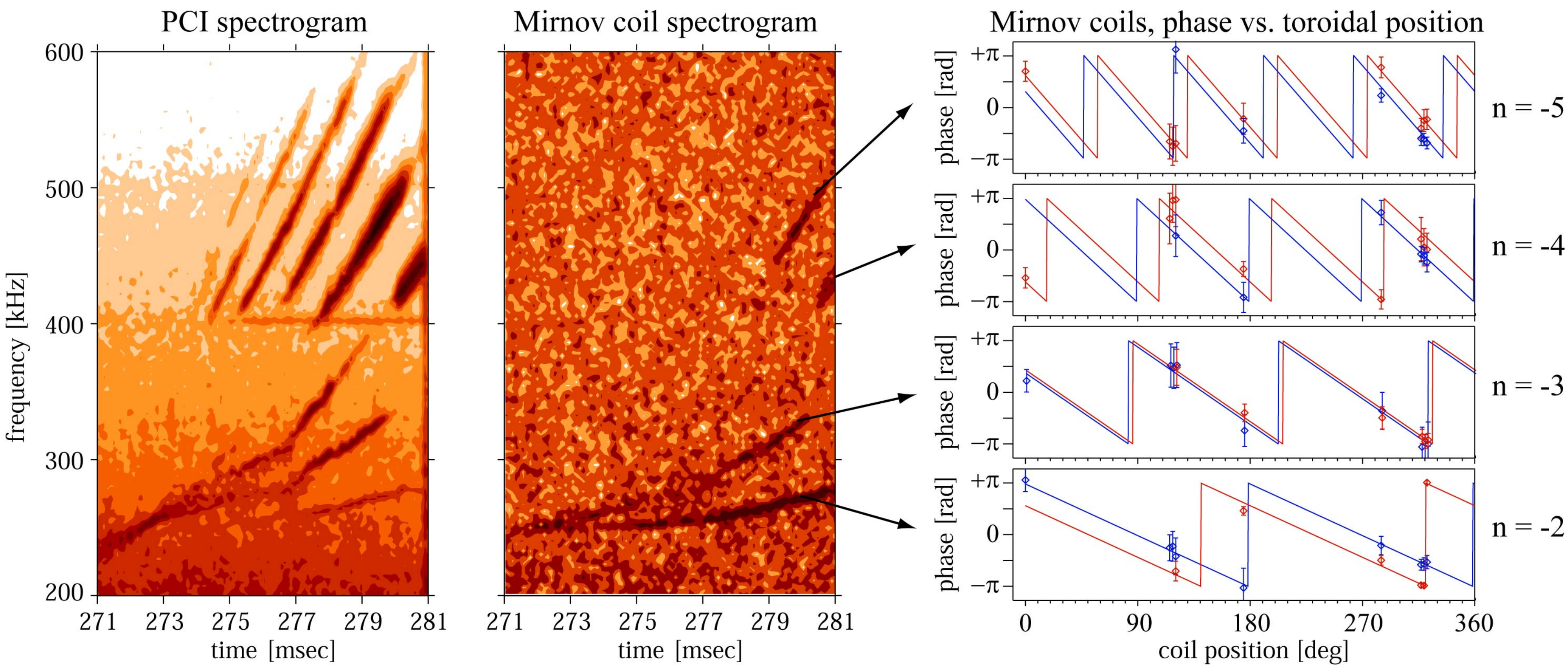
- Modes exhibit frequency up-chirp prior to the sawtooth crash
- RSAE-like spectral pattern
- Initial frequency scales well with $T_e^{1/2}$
- Strongly excited in L-mode, weakly excited in H-mode (low density)
- Low n mode numbers measured by magnetics



Mode numbers measured with Mirnov coils

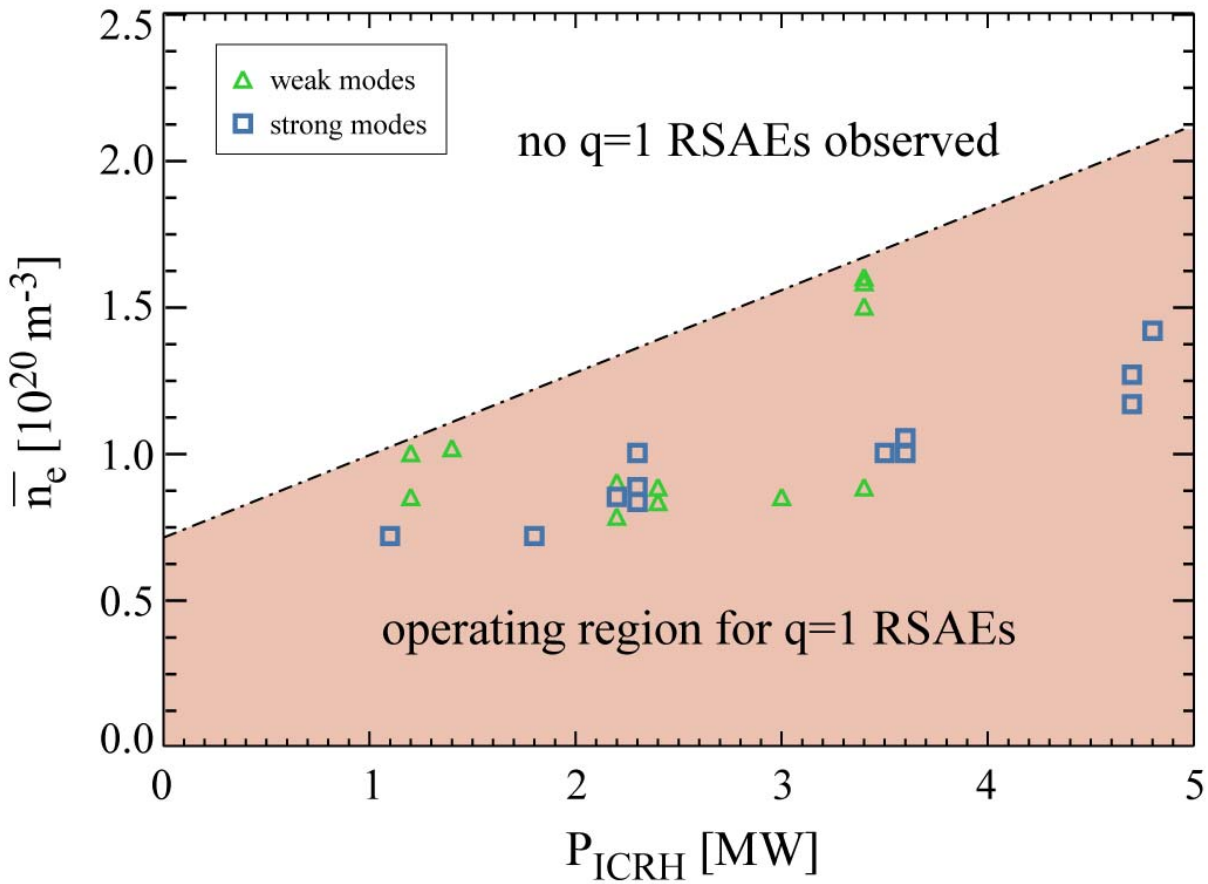
- A few shots had RSAEs strong enough to register signal on the Mirnov coils

- Phase analysis shows low n modes, ion diamagnetic direction, as expected from ramp-up experiments



Conditions under which q=1 RSAEs are observed

- Many cases exist with weak or moderate q=1 RSAE excitation
- Observed in relatively low density operation, similar to RSAEs during the ramp-up
- Shown to be excited more easily with larger I_p (flatter central q profile) and at higher B_t (more peaked fast ion pressure)

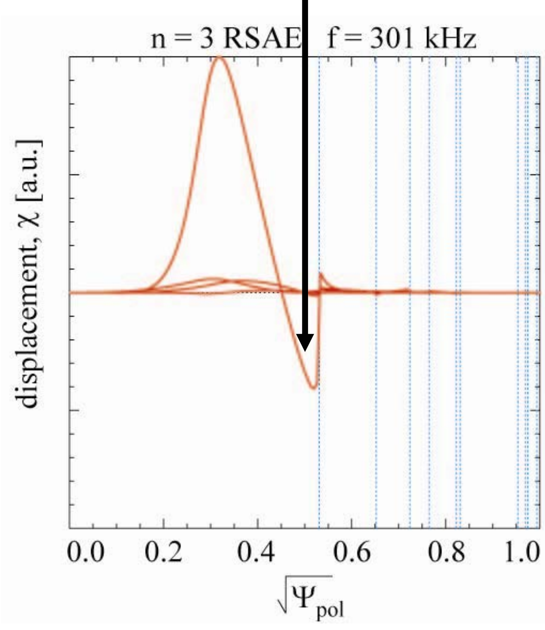


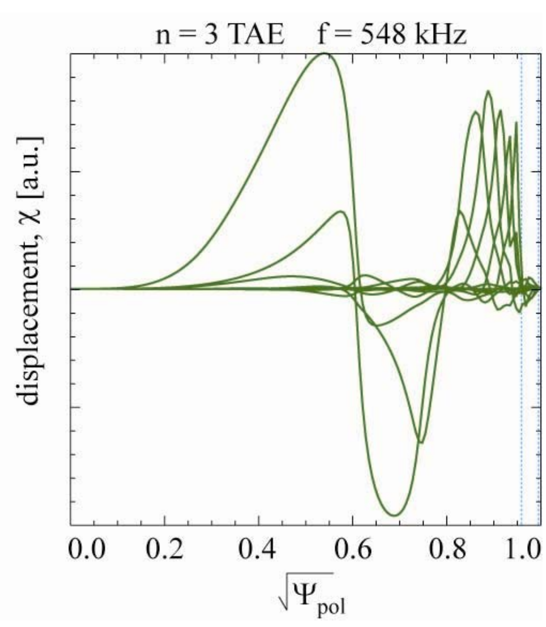
- Lazarus *et al.* report reversed shear in DIII-D during sawteeth in strongly shaped plasmas.

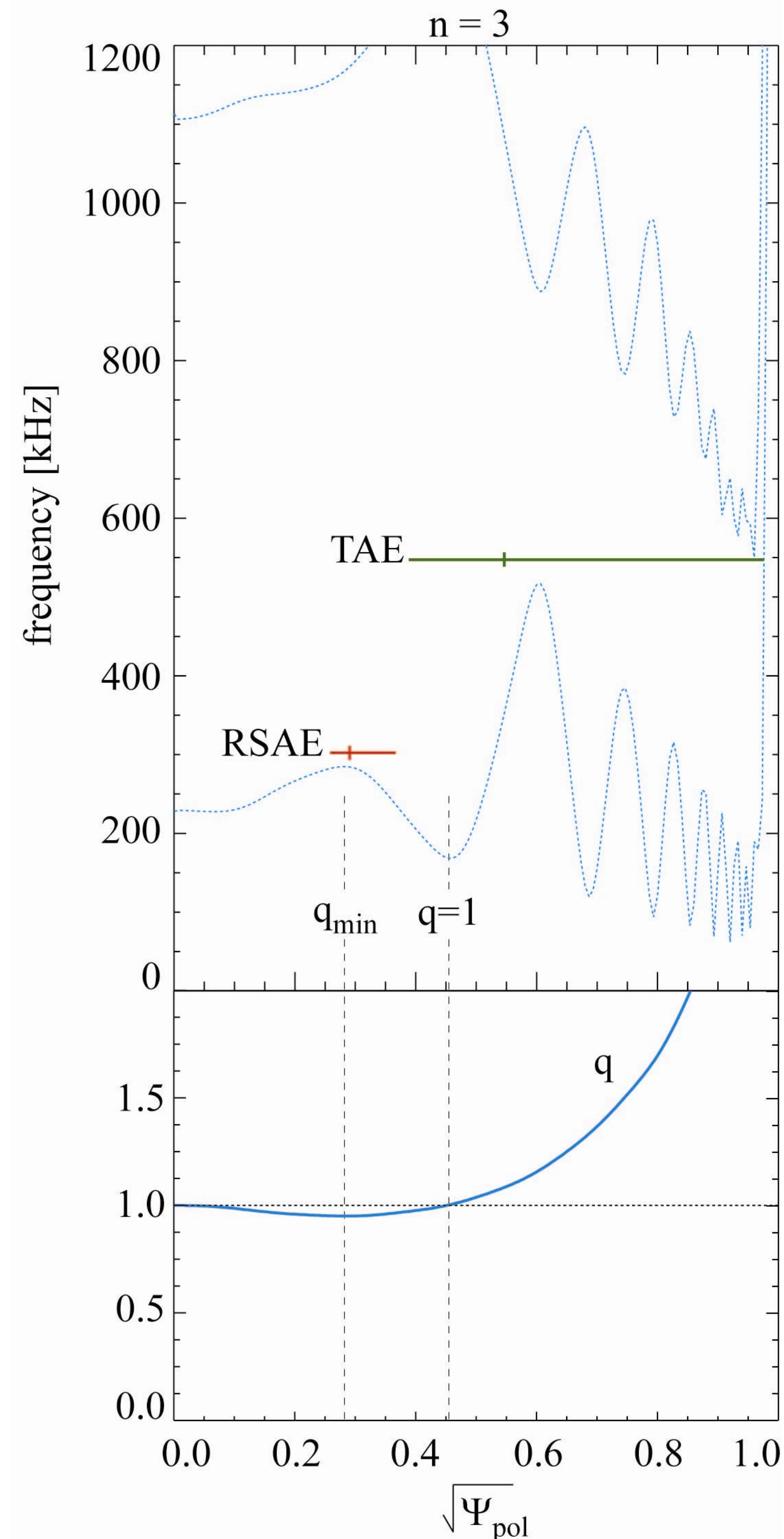
Lazarus *et al*, PoP **14**, 055701 (2007).

NOVA finds q=1 RSAEs

- Must assume some amount of reversed shear
- RSAEs show significant continuum interaction, damping rates probably not reliable
- Large spike in RSAEs near q=1 is robust to variations in equilibrium

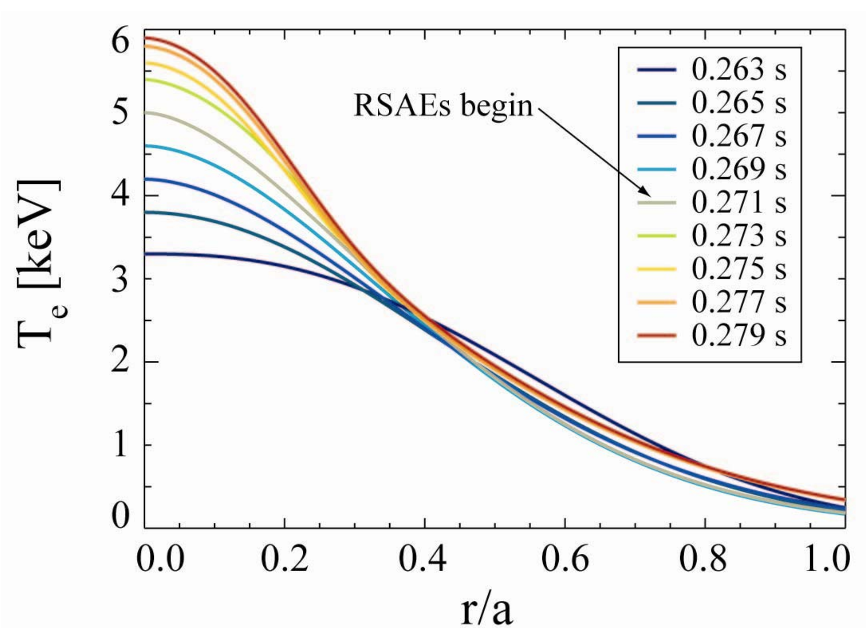


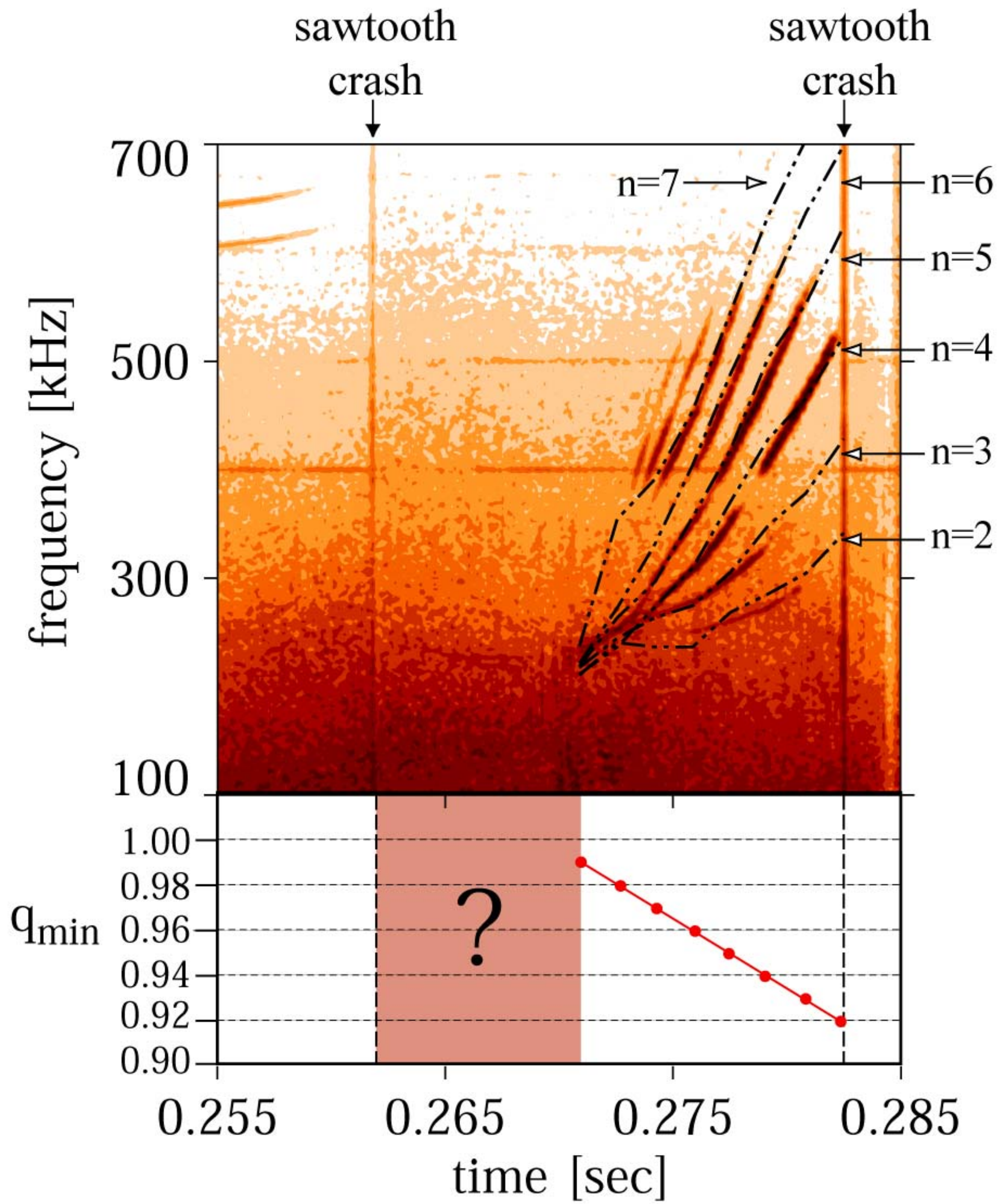




MHD Spectroscopy

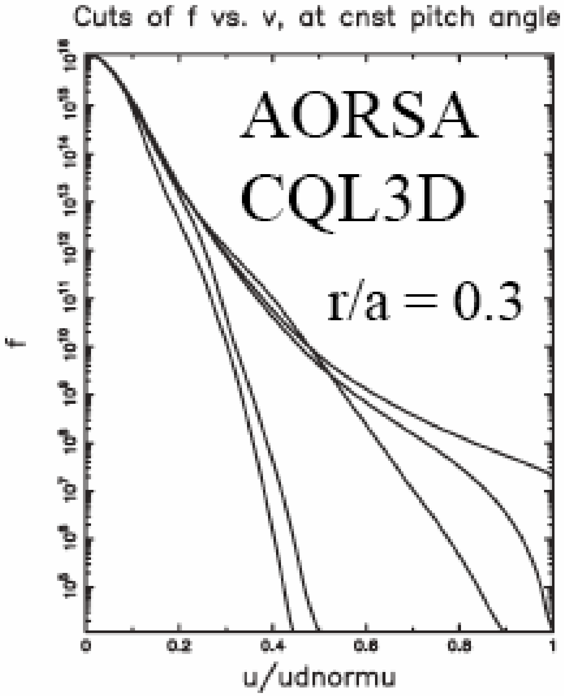
- Comparison of PCI and NOVA results can be used to determine q_{min}
- Value of q_{min} immediately after the crash has not been determined, but is expected to be ≥ 1.0

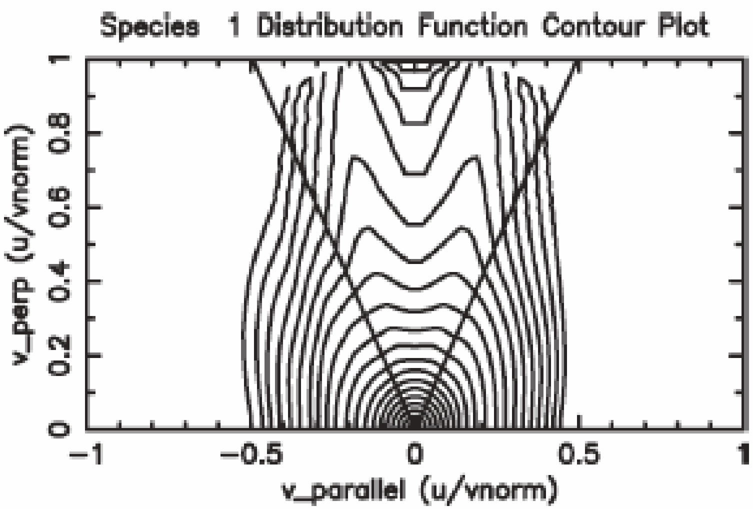




NOVA-K Will Use AORSA/CQL3D ICRF Distribution Function

Alcator C-Mod





- Maxwellian and pitch angle distribution in Nova-K:

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

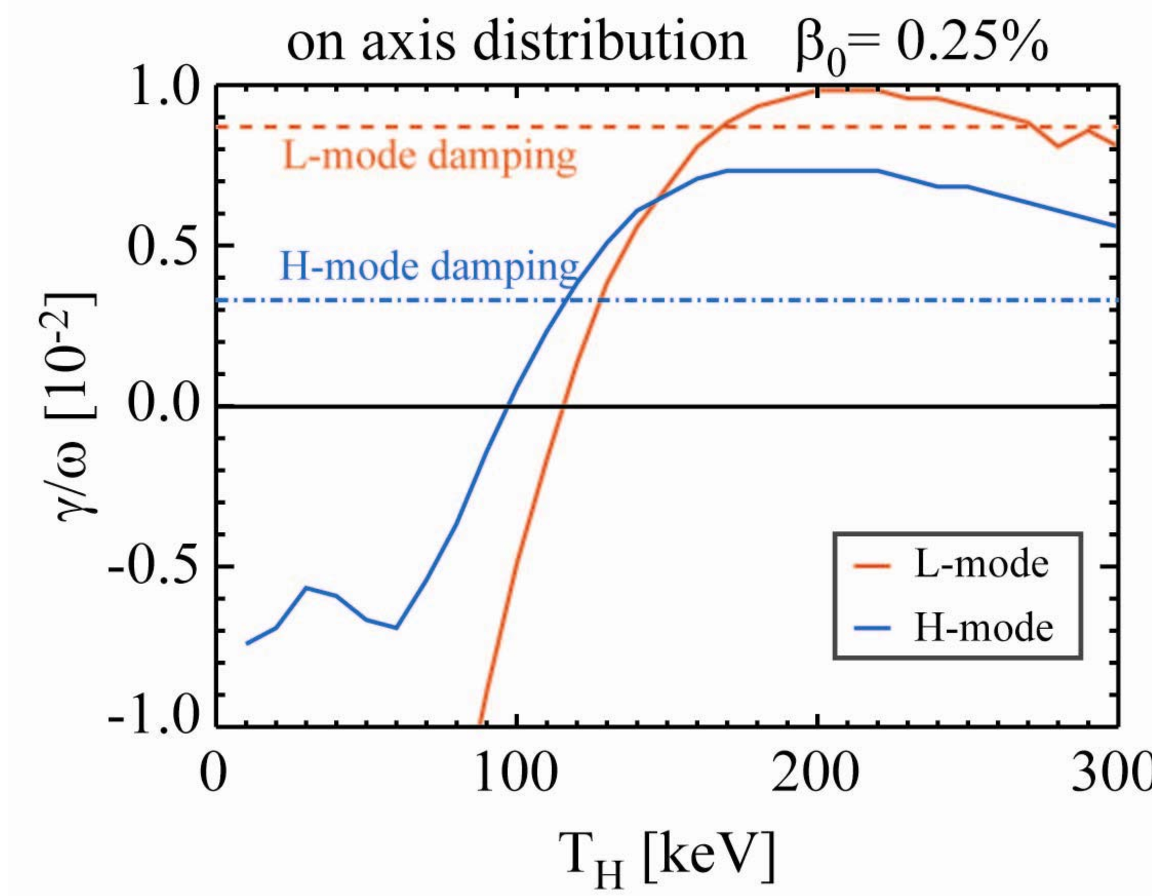
where $E = \frac{1}{2}mv^2$, T_H is the fast ion temperature, $p = \mu B_{axis}/E$, and μ is the magnetic moment

$$\mu = \frac{1}{2} m v_{\perp}^2 / B$$

- To be compared to analytic spline fits to the self consistently calculated non-Maxwellian distribution function calculated with AORSA/CQL3D

Growth Rate Calculations from NOVA

- Experiments show strong excitation in L-mode, weak or absent excitation in H-mode phase
- Experimental density and temperature profiles used in NOVA
- Fast ion population modeled with on-axis and off-axis peaked profiles for a range of tail temperatures taking $\int \beta_H dV$ = constant

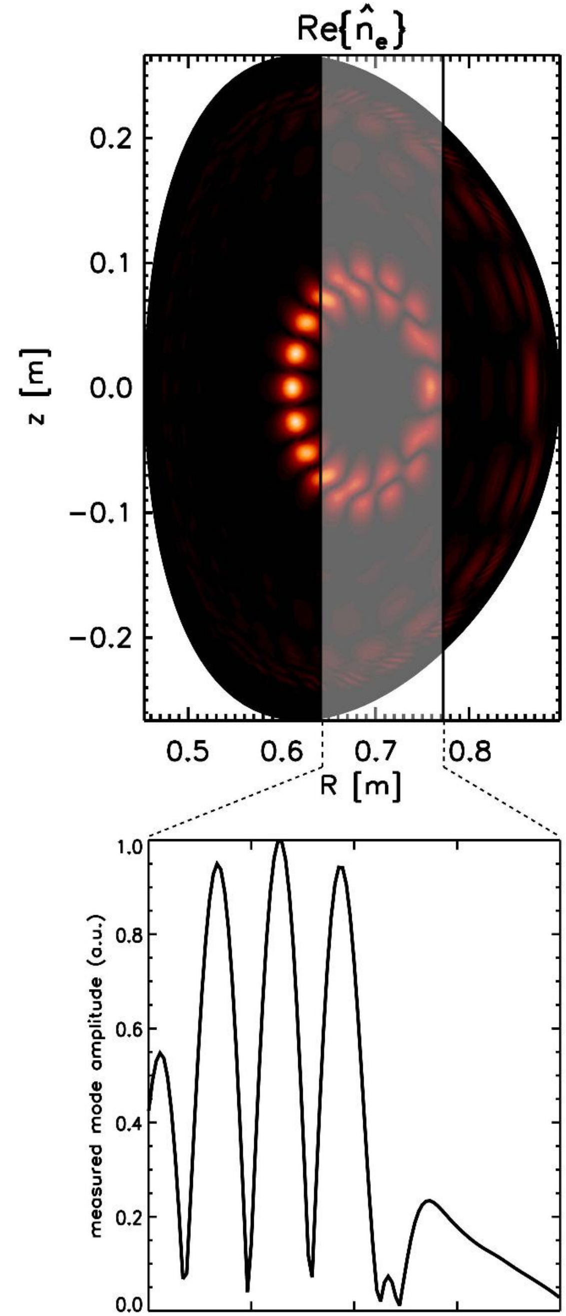


- Results

  L-mode: larger growth rates and larger damping

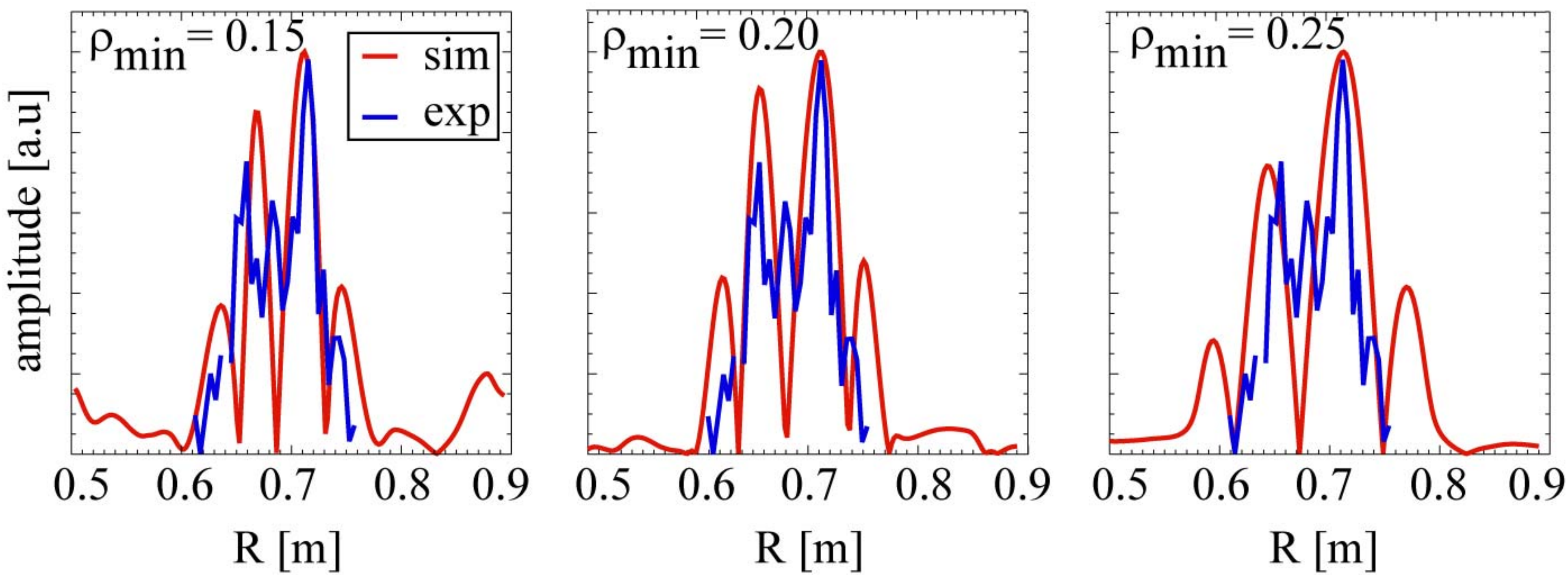
Synthetic PCI Diagnostic

- Numeric outputs from NOVA are transformed to rectangular coordinates and line-integrated
- Positive and negative density fluctuations may cancel
- Integrated structures with multiple peaks can form, even from a radial structure with no nodes
- The results are sensitive to the values of q_{min} and r_{min} and somewhat dependent on q_0



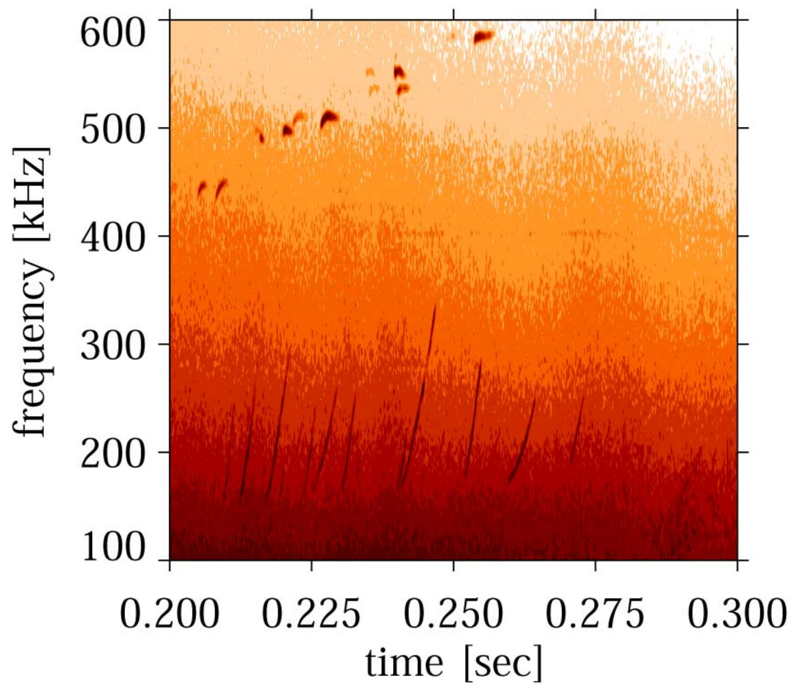
Synthetic PCI results

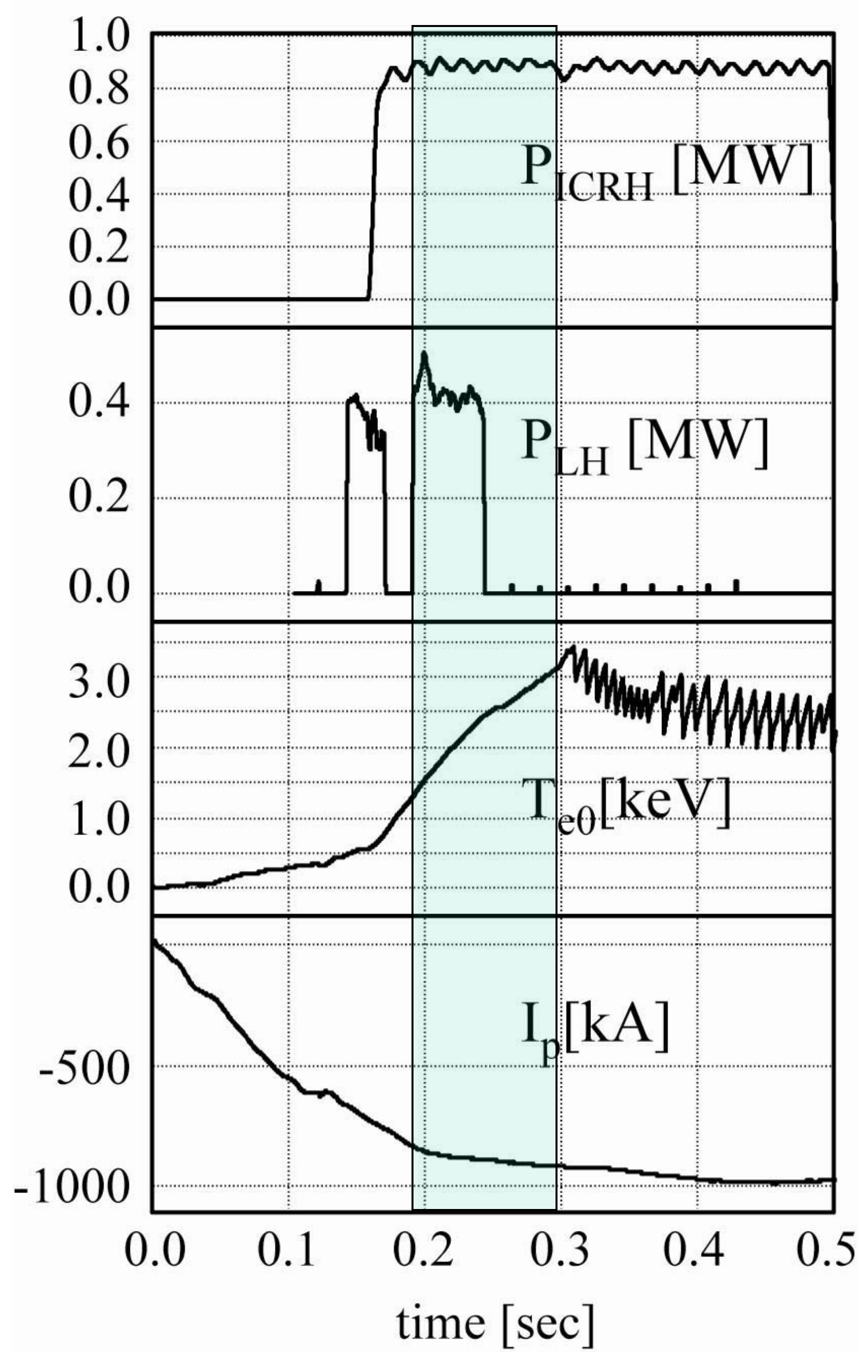
- Mode structures from NOVA can be compared to PCI data through the use of a "Synthetic PCI"
- Main parameter to scan is r_{min}, i.e. $q(r_{min}) = q_{min}$
- Results show qualitative agreement, suggesting $\rho_{min} \approx 0.20$ more work needed



Experiments with LHCD during the Current Ramp

- Application of early LHCD has extended the presence of RSAEs by nearly 100 msec
- Use high $n_{||} \approx 3$ LH waves for current drive, absoprtion at $T_e \approx 3$ keV, need higher T_e for off-axis LHCD





Conclusions

- RSAEs observed during the current ramp and now in the sawtoothing phase
- The observed characteristics of the q=1 RSAEs fit all expectations (low n, rate of chirping, initial frequency)
- From the frequency spectra of these modes q_{min} prior to the sawtooth crash has been determined to be about 0.92
- Growth rate calculations show that the L-mode RSAEs have larger growth rates
- Damping rate calculations for these modes show that the H-mode RSAES should have a net instability greater than L-mode – suggests the need for proper continuum damping calculations