Some characteristics of co-propagating CAEs

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NSTX-U

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For the NSTX Team

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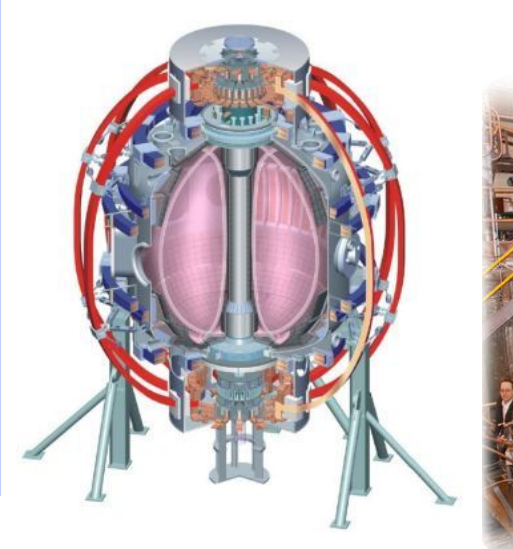

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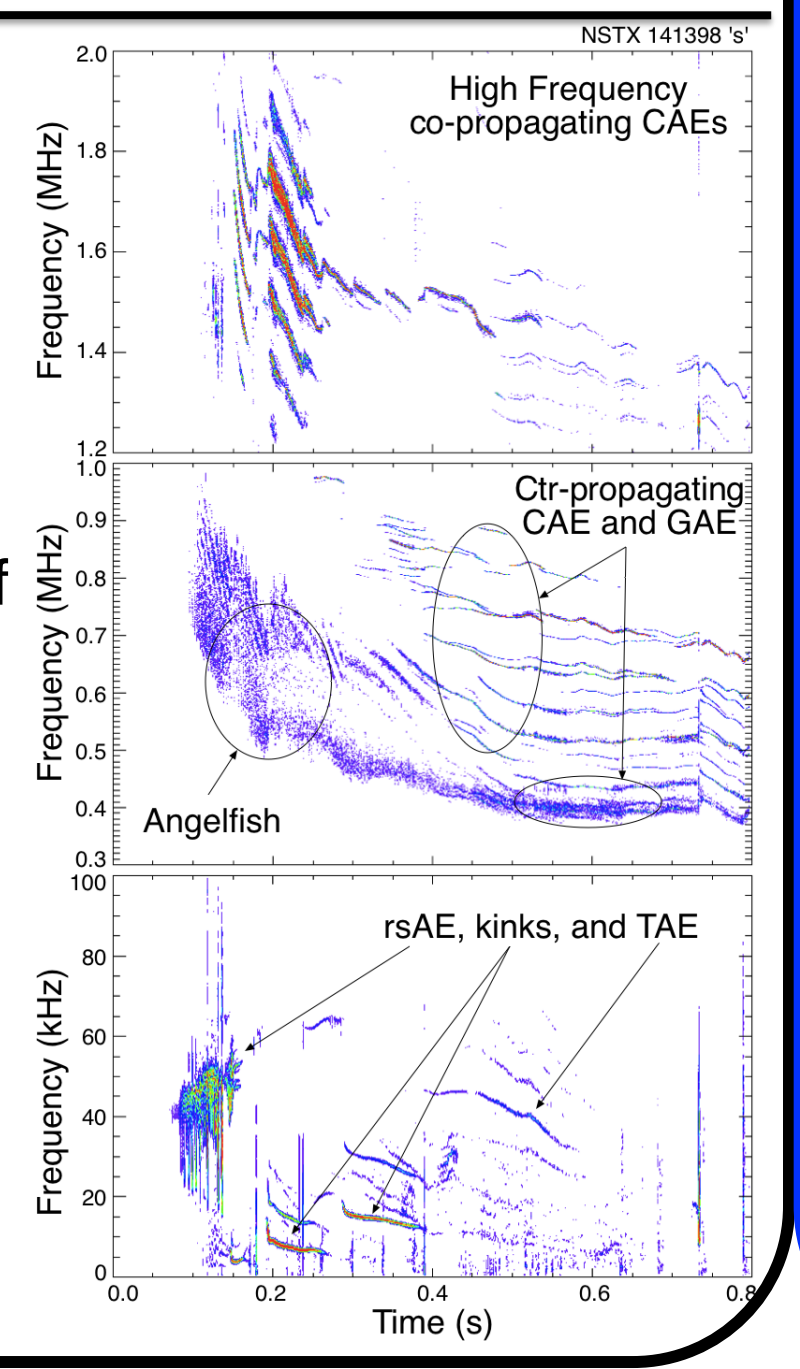
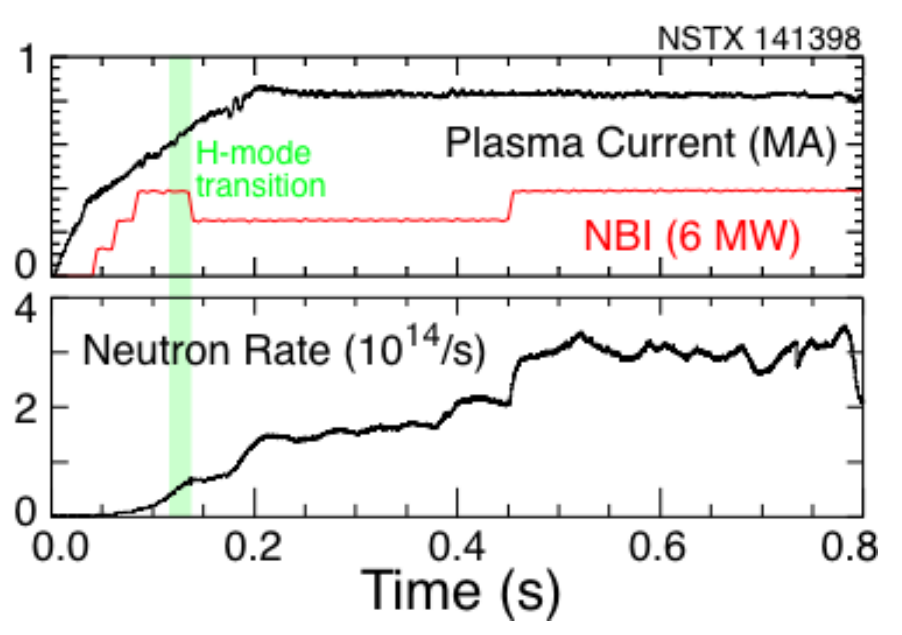
Fast ions excite a broad spectrum of modes on NSTX

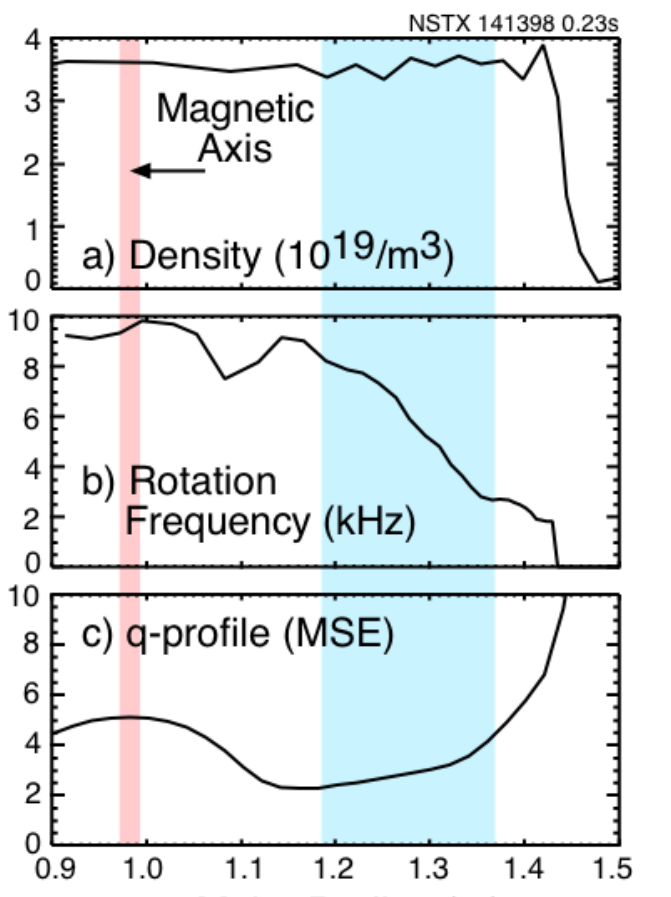
- Co-propagating Compressional Alfvén Eigenmodes are seen with frequencies between roughly 1.2MHz and 2.5MHz (hfCAE).
- At somewhat lower frequencies, 0.3MHz to ≈1.5MHz are a mix of counter propagating Global and Compressional Alfvén Eigenmodes.
- At lower frequencies, less than ≈250kHz are the more common energetic particle modes (e.g., fishbones) and a variety of Alfvén modes like TAE, rsAE, BAAE, and BAE.



The hfCAE have only been seen in H-modes with flat or hollow density profiles



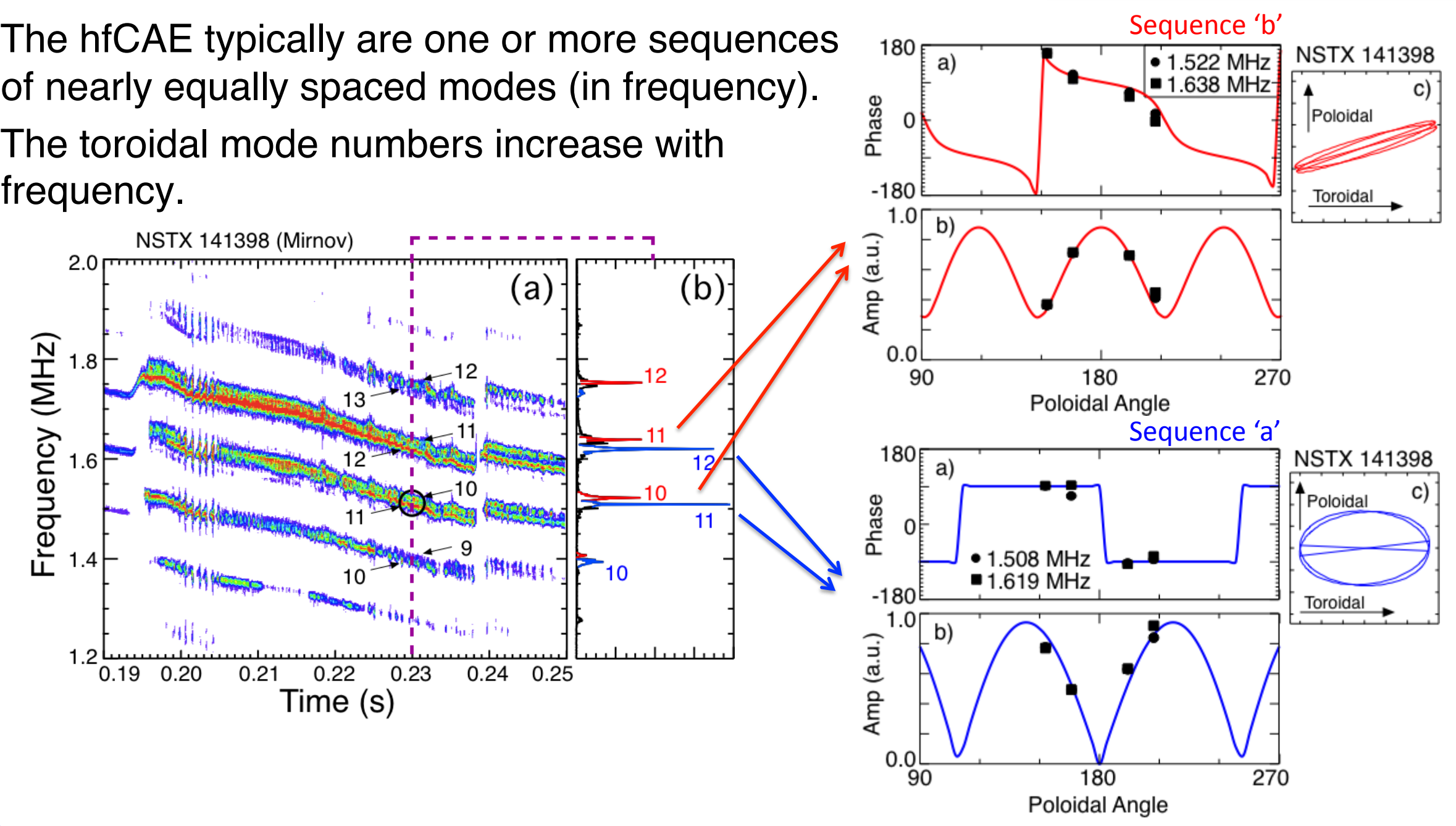
- hfCAE show up shortly after current ramp ends.
- Density is very flat in core.



- hfCAE are believed to peak in blue region.
- Plasma rotation is sheared, but relatively low for this shot.
- Average rotation frequency over mode region is about 5 kHz.
- Magnetic shear is low, but shouldn't be important.

Poloidal structure and polarization of hfCAE two bands is qualitatively different

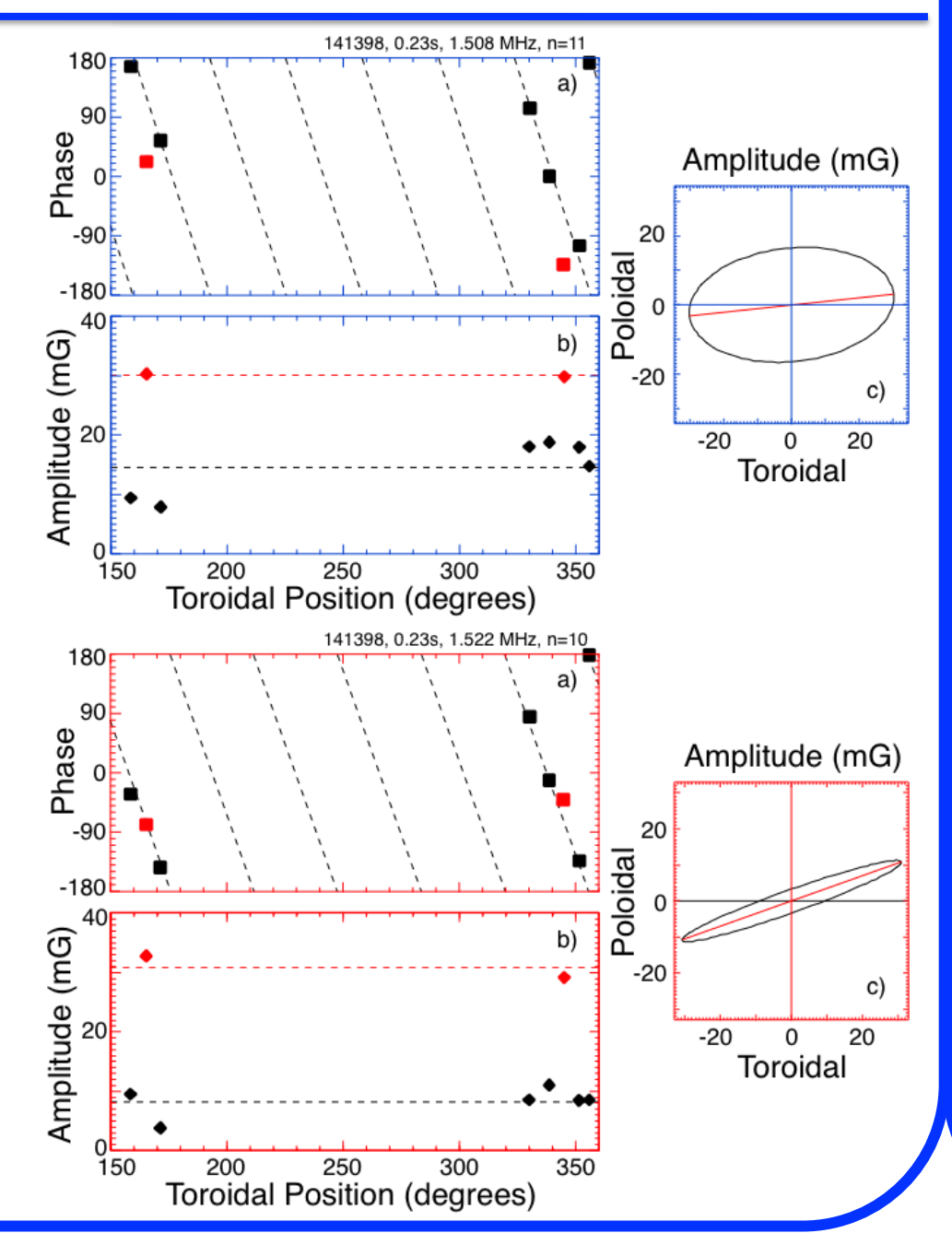
- The hfCAE typically are one or more sequences of nearly equally spaced modes (in frequency).
- The toroidal mode numbers increase with frequency.



- Sequence 'b' is a mix of poloidally standing and propagating waves,
- Have anti-nodes on the midplane
- Nodes almost purely compressional.
- Sequence 'a' has a nearly standing wave structure in the poloidal direction
- Has node on the midplane
- Modes are elliptically polarized, but still dominantly compressional.

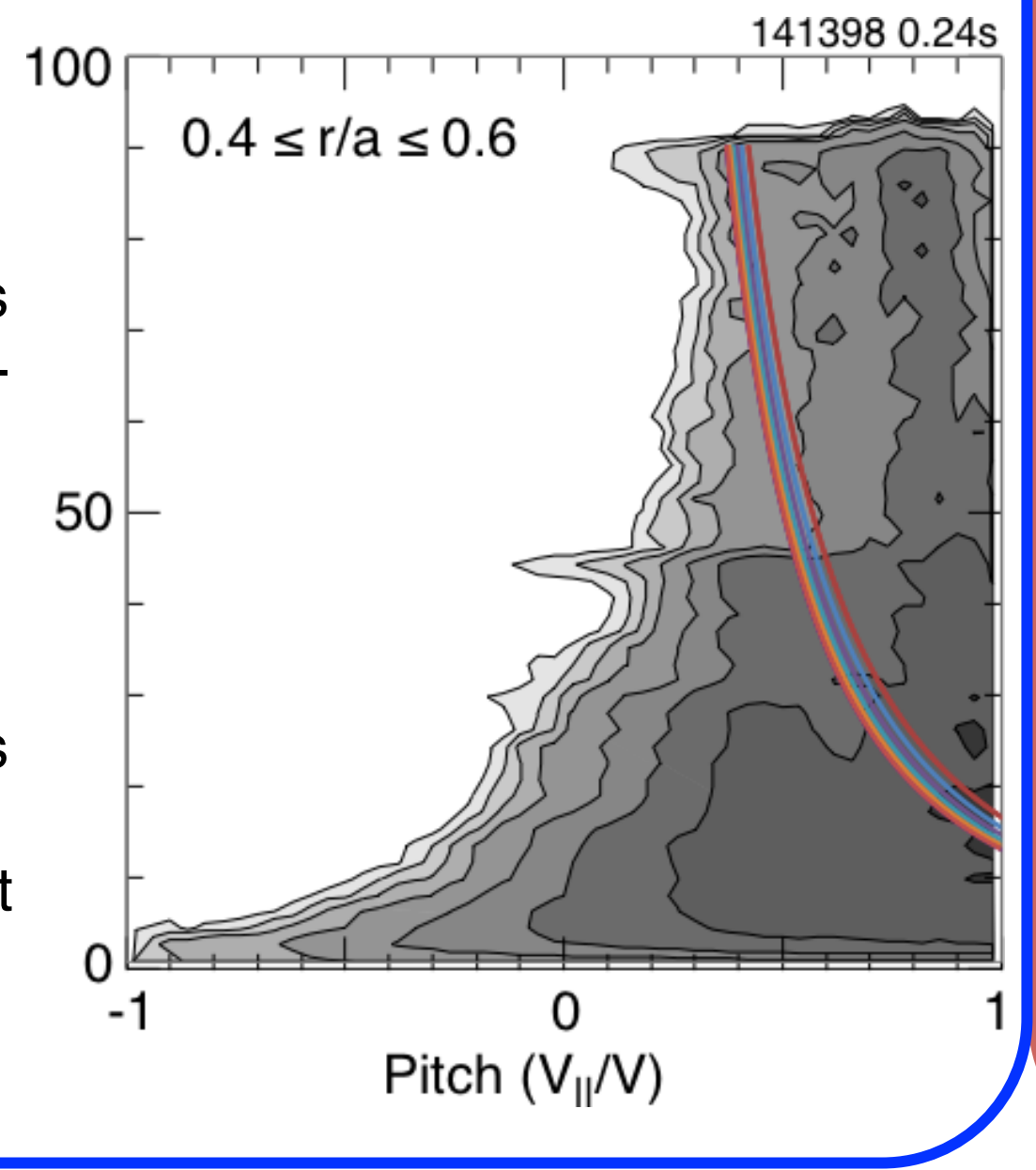
Toroidal array of poloidal and toroidal Mirnov coils measure polarization and mode number

- The two modes near 1.5 MHz are shown here.
- Red points are measurements from toroidally oriented coils.
- Both sequences have larger toroidal magnetic fluctuations than poloidal.
- All mode in sequence show similar polarization, either elliptical or compressional.



Fast ions satisfying simple resonance condition don't obviously form bump-on-tail

- Each colored line in figure is for different mode.
- Fast ion distribution is representative of mid-radius (unperturbed).
- Resonance condition is: $k_{||} V_{beam} = \omega_{mode}$.
- Fast ion distribution is perturbed by kink-like mode; mayb sufficient to form some type of bump-on-tail.



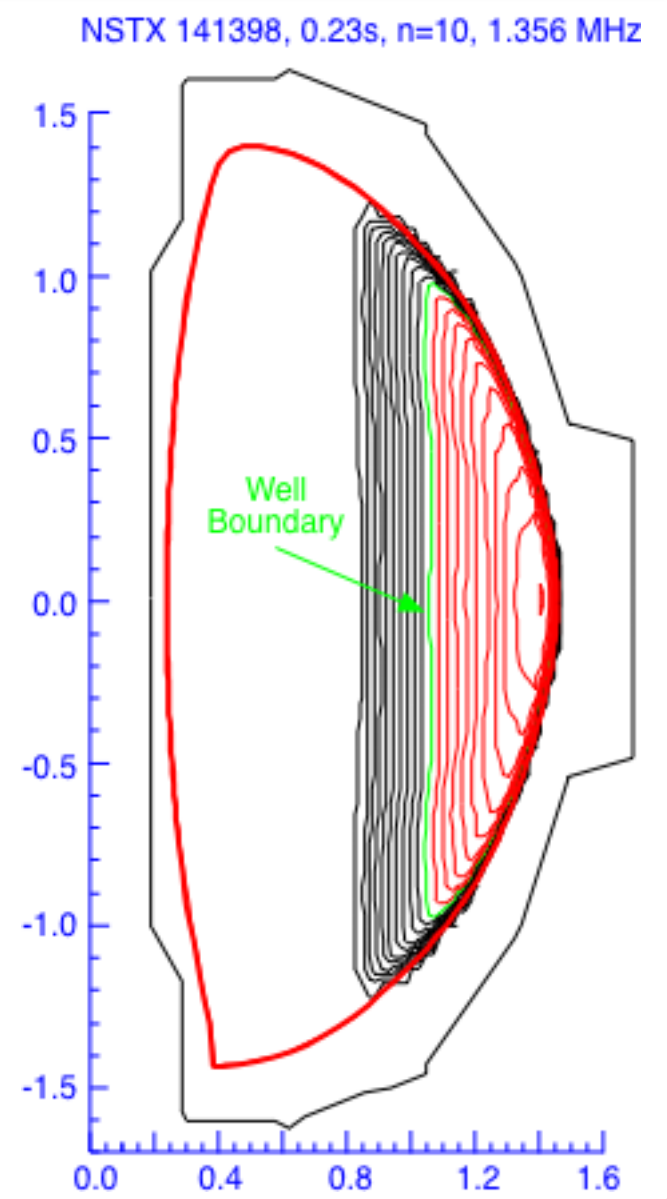
A simple dispersion relation for the CAE is modeled as an off-axis well, localized at large R

- The simple Alfvén wave dispersion relation in cylindrical coordinates can be separated:

$$V_{Alfvén}^2 \nabla^2 E_\perp = -\omega^2 E_\perp$$

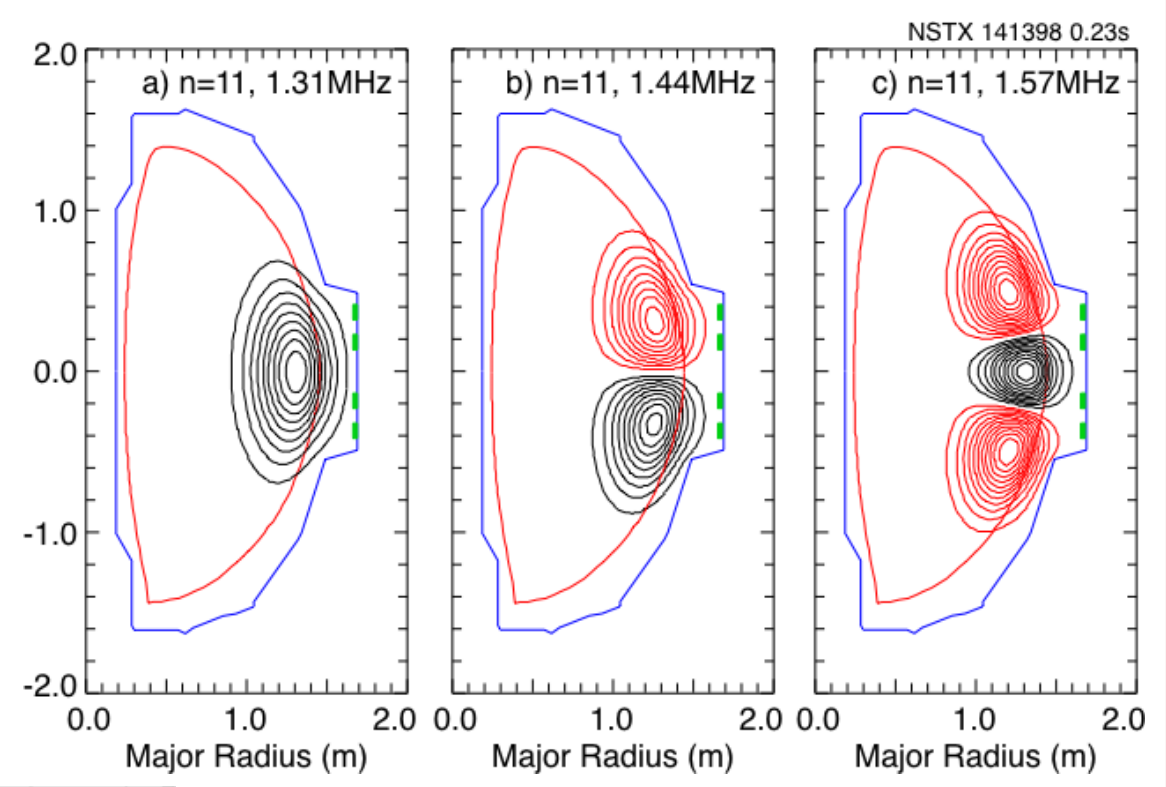
$$\left[\frac{1}{R}\frac{\partial}{\partial R}R\frac{\partial}{\partial R}+\frac{\partial^2}{\partial z^2}-\left(\frac{n^2}{R^2}-\frac{\omega^2}{V_{Alfvén}^2}\right)\right]E_\perp = 0$$

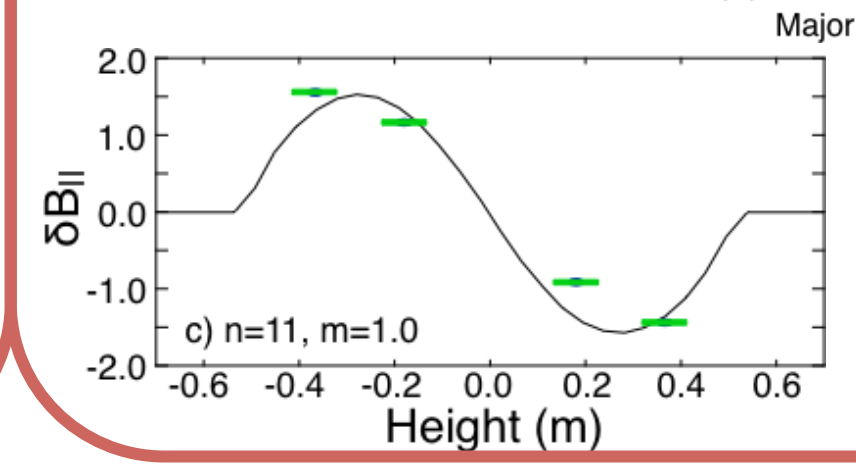
- After separation the dispersion relation is a 2-D wave equation with a well.
- Eigenmodes/eigenvalues for the 2-D equation can be found with a numerical code.



Here, all solutions are deeply trapped, poloidally, that is with standing wave solutions

- The solutions oscillate between nodes and anti-nodes on the midplane.
- Eigenfunction shape fits experimental data for m=1.0 eigenfunction, others less well.

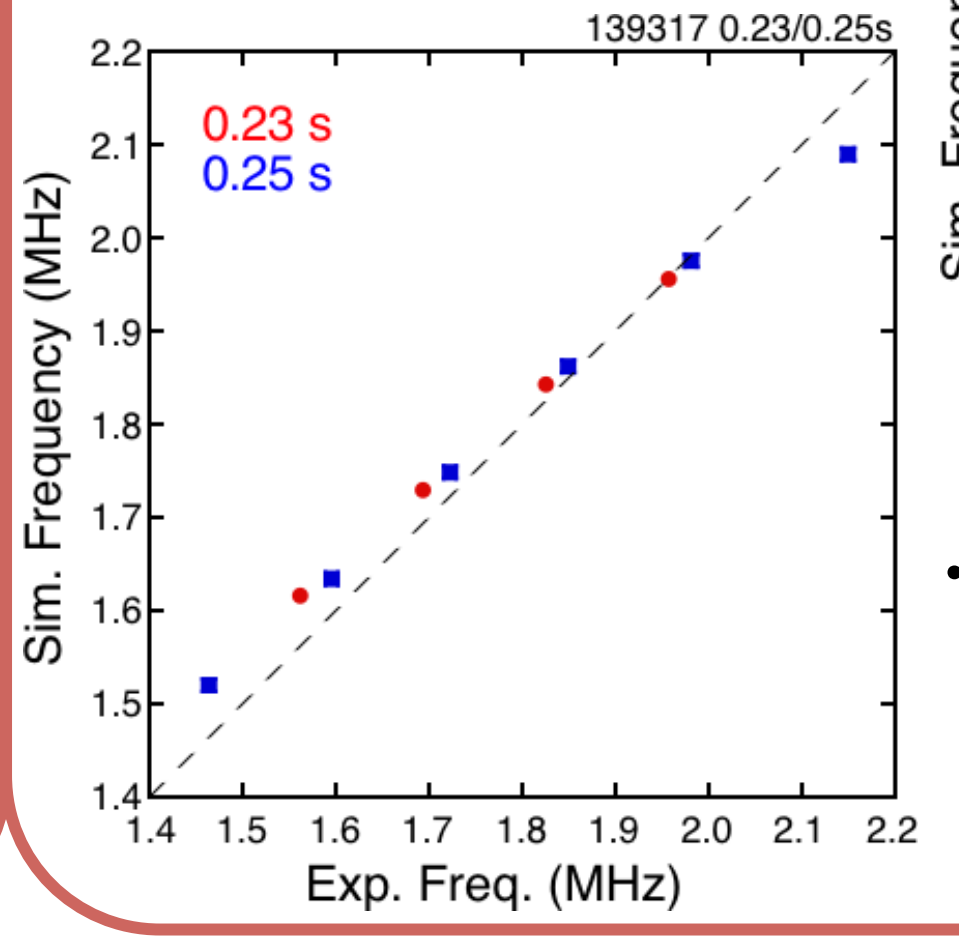


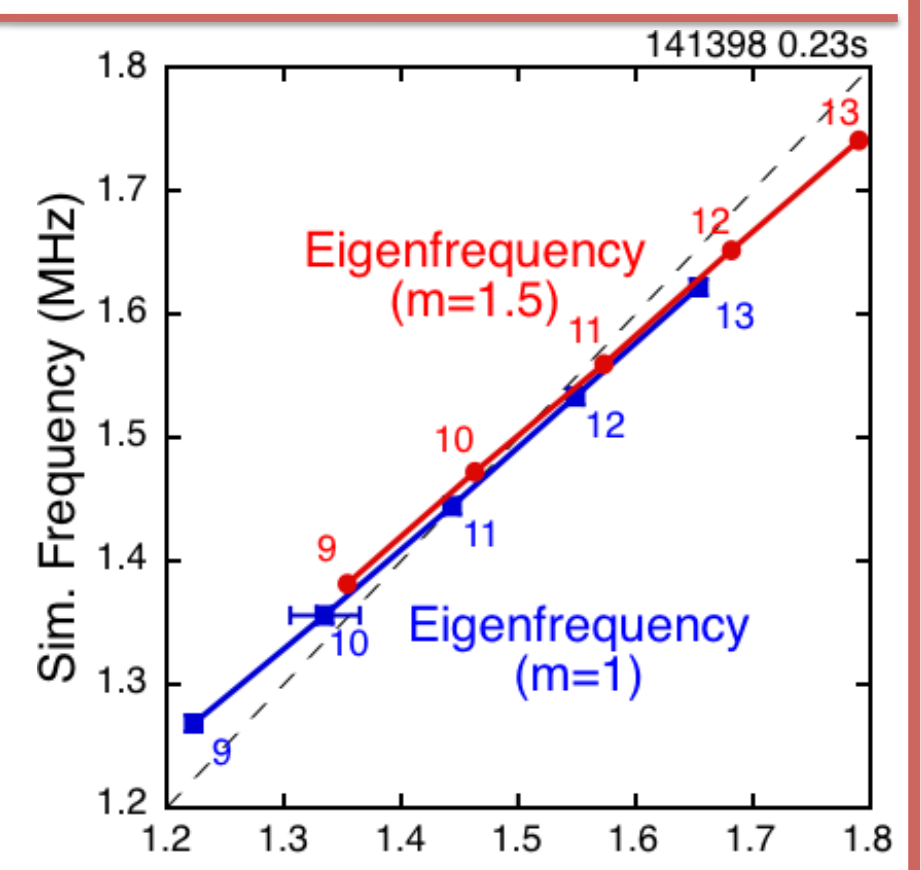


- Vertical wavelength in simulation shorter than in experiment.

Solution of simple dispersion relation matches experimental frequencies

- Frequency variation with toroidal an poloidal mode numbers in good agreement.

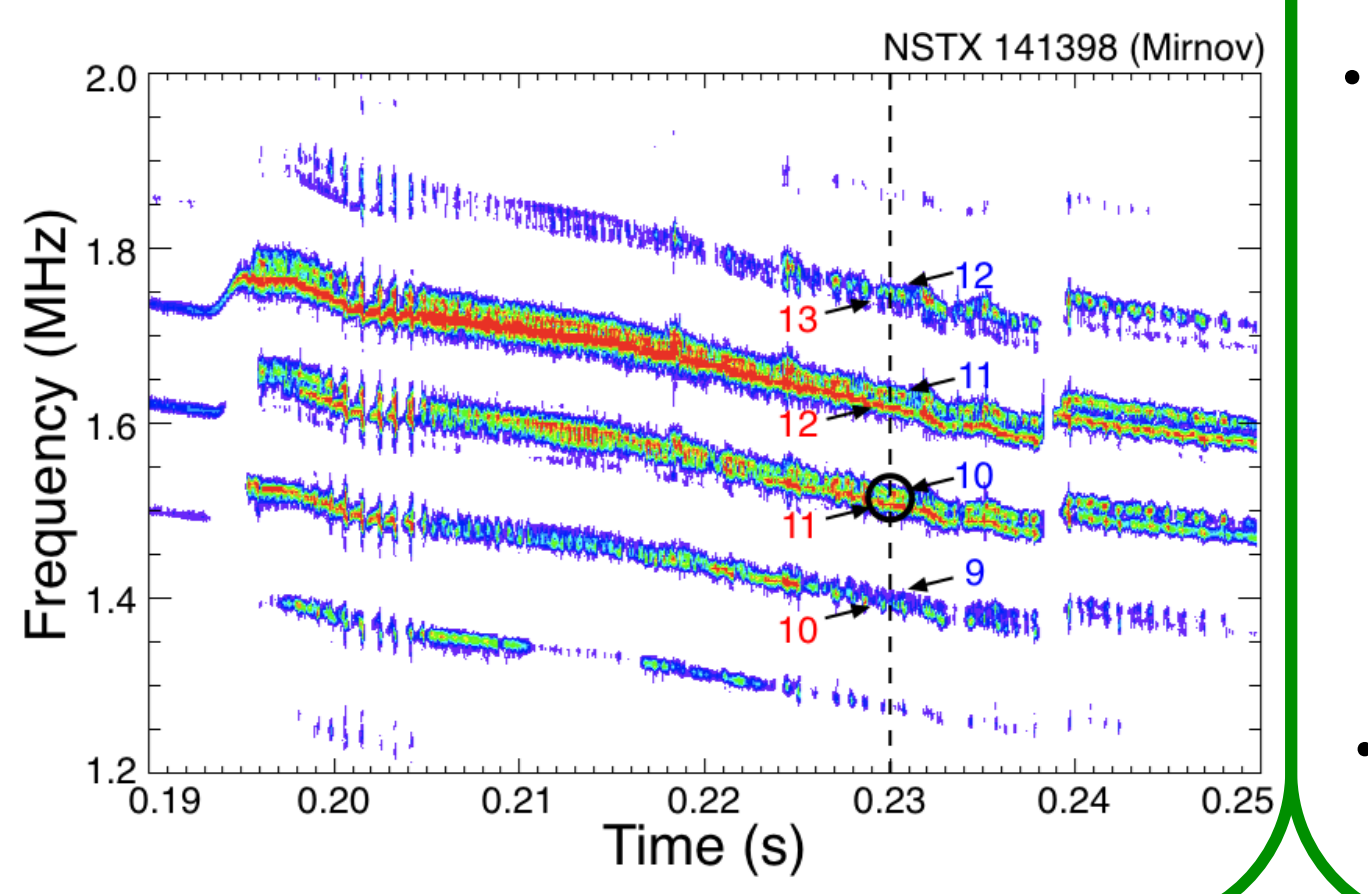




- Frequency variation in time, and between shots is also well reproduced by this simple model.

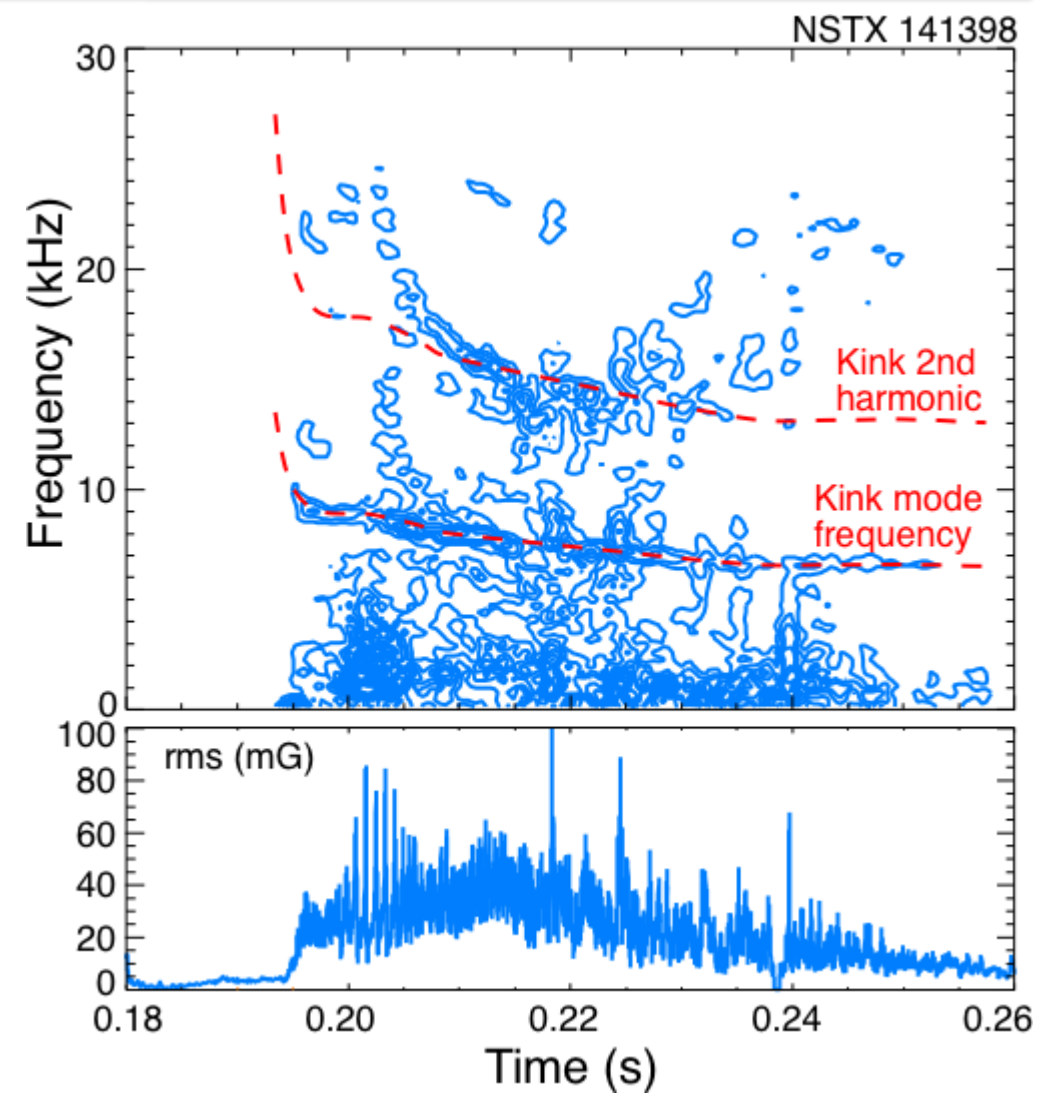
The hfCAE are, like most fast-ion modes on NSTX, a sequence of short bursts

- The strong bursts in the beginning occur simultaneously for all modes.
- This is preceded and followed by the more typical, short period bursting barely visible in this spectrogram
- Burst of the multiple modes are correlated; possibly through some non-linear coupling mechanism.



A spectrogram of the rms hfCAE amplitude shows the frequency of the bursts

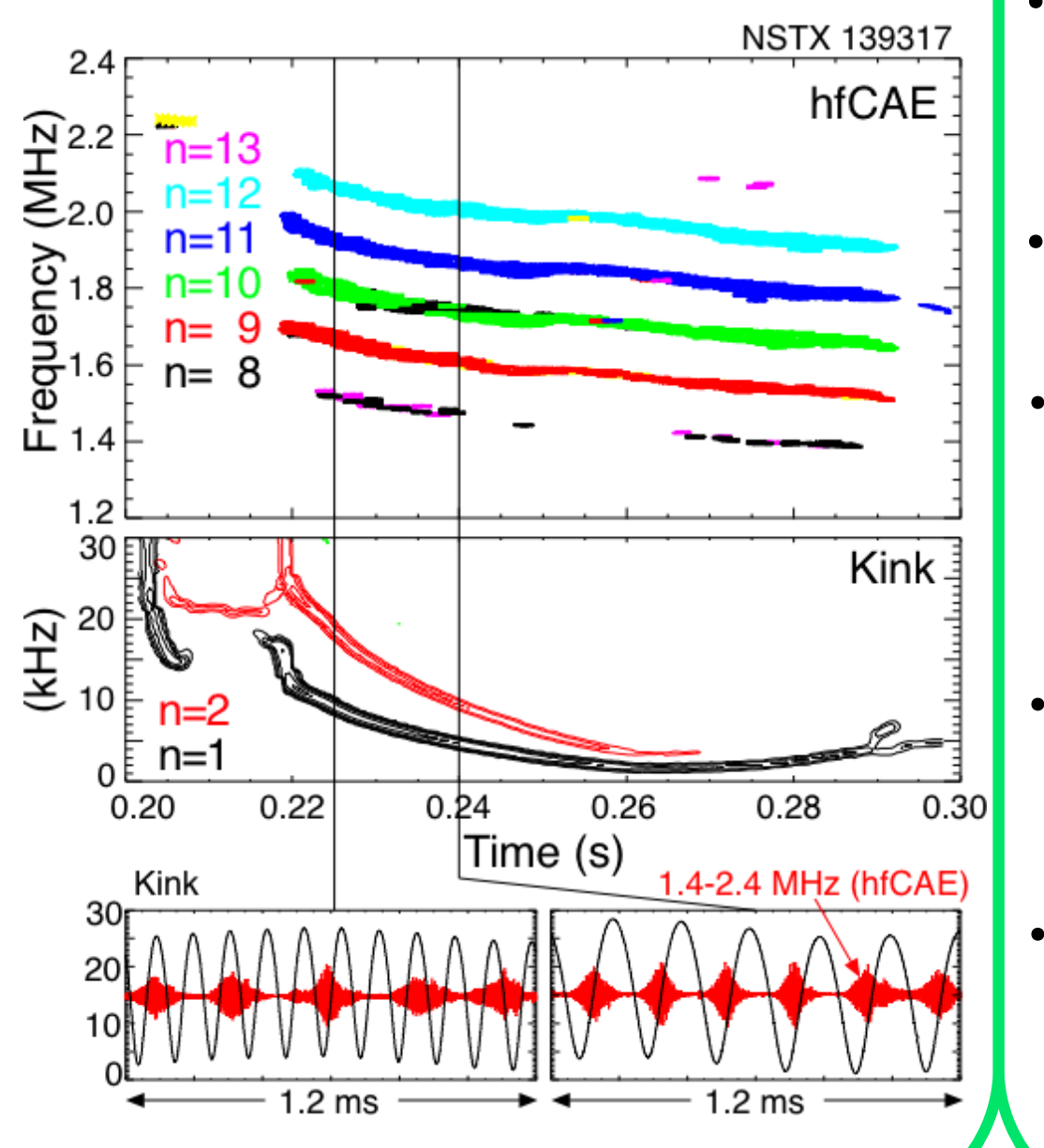
- RMS of mode amplitude in lower figure, spectrogram of rms is above.
- Most of the spectral power is in low frequencies, but there is a modulation of the burst frequency at the frequency of the kink mode (red dashes).



- The effect in this example is weak; there are clearer examples.

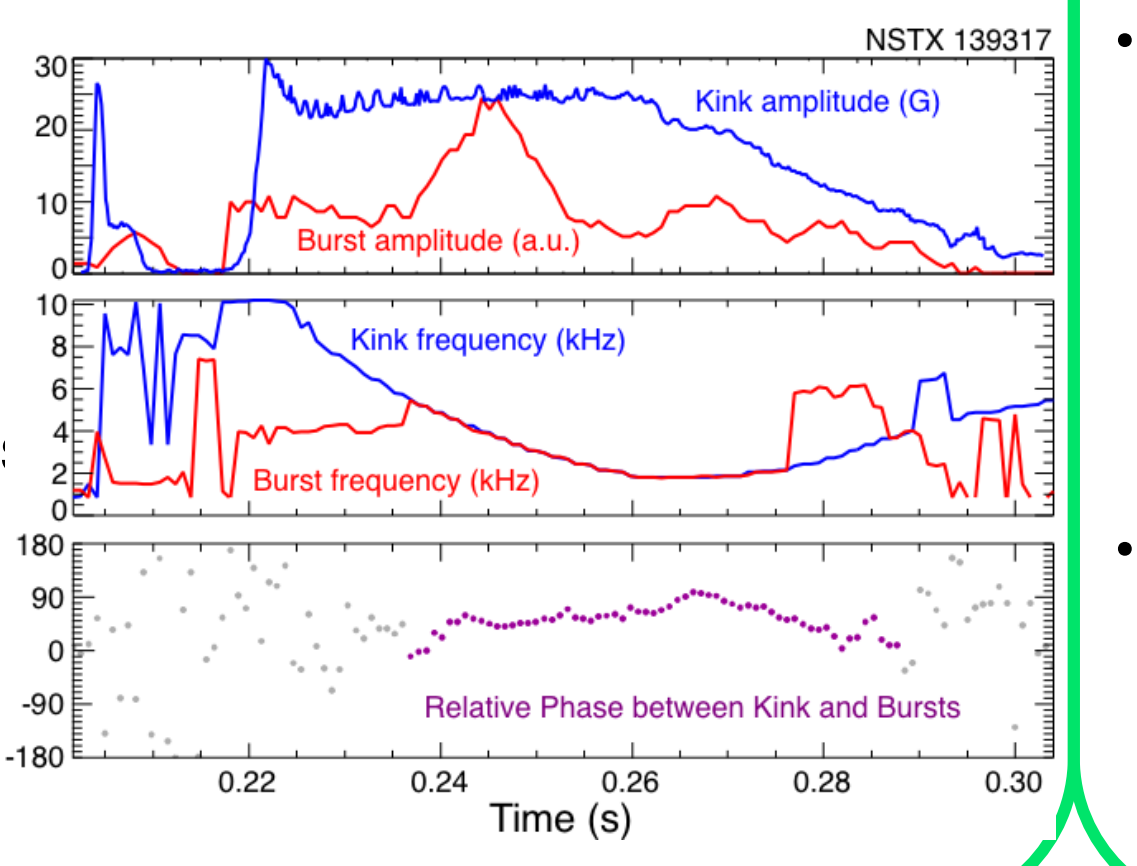
The onset of phase locking can be seen very clearly by overlaying hfCAE bursts and kink

- In lower panels hfCAE bursts are at first uncorrelated with kink.
- Later, when kink frequency drops near 'natural' CAE burst frequency, bursts are strictly phase locked with kink.
- Earlier, weak modulation of burst frequency can be seen in shape of CAE bursts.



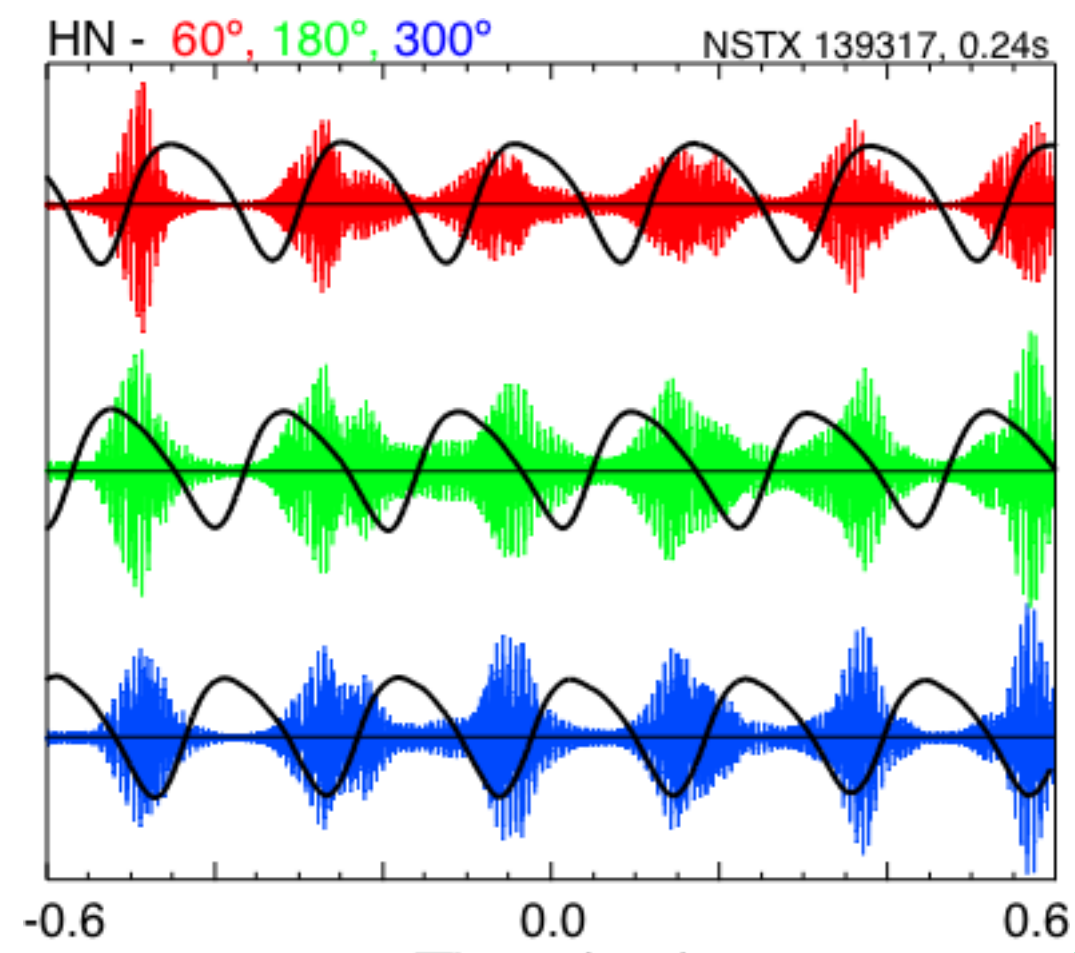
Strong correlation of CAE bursts with kink suggest that CAE stability is modulated by kink.

- The strong correlation between the CAE burst frequency and the n=1 kink mode are seen by comparing the relative phase.
- The phase is nearly constant for > 40ms, although it wanders over a range of about 90°.
- Strong correlation implies direct modulation of CAE stability by kink.
- There is no shift of the relative phase of bursts with toroidal angle.
- Is interaction between rotating kink and stationary error field responsible?



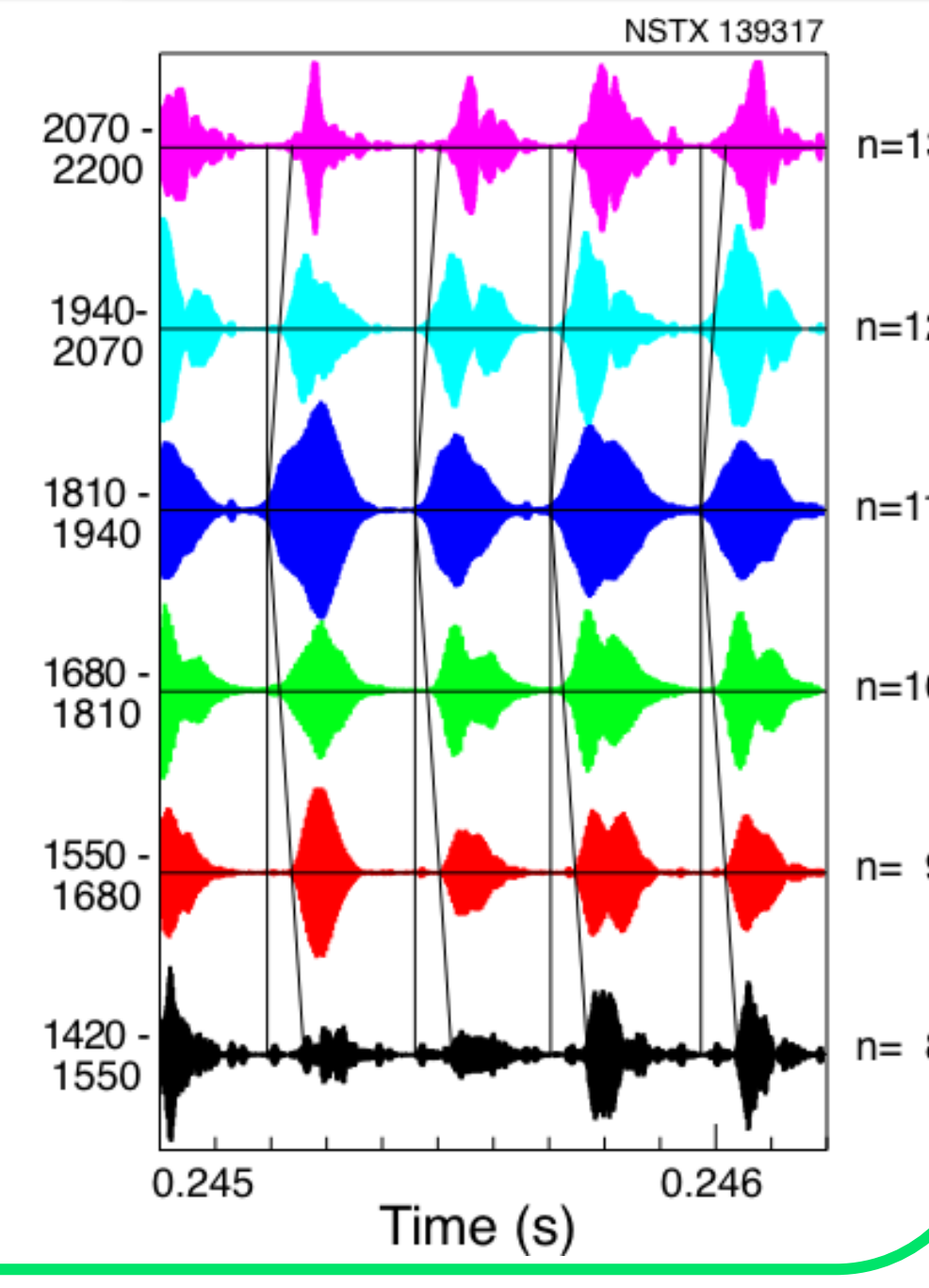
Bursts are not entrained in kink, as was previously seen with TAE

- Mode amplitude is modulated globally, by the kink plus non-axisymmetric perturbation?
- Need axi-symmetry breaking mechanism, *e.g.*, error field, first wall?
- Filtered bursts are shown at three toroidal locations, separated by 120°, scaled for aesthetics.
- Similar synchronous behavior seen poloidally.



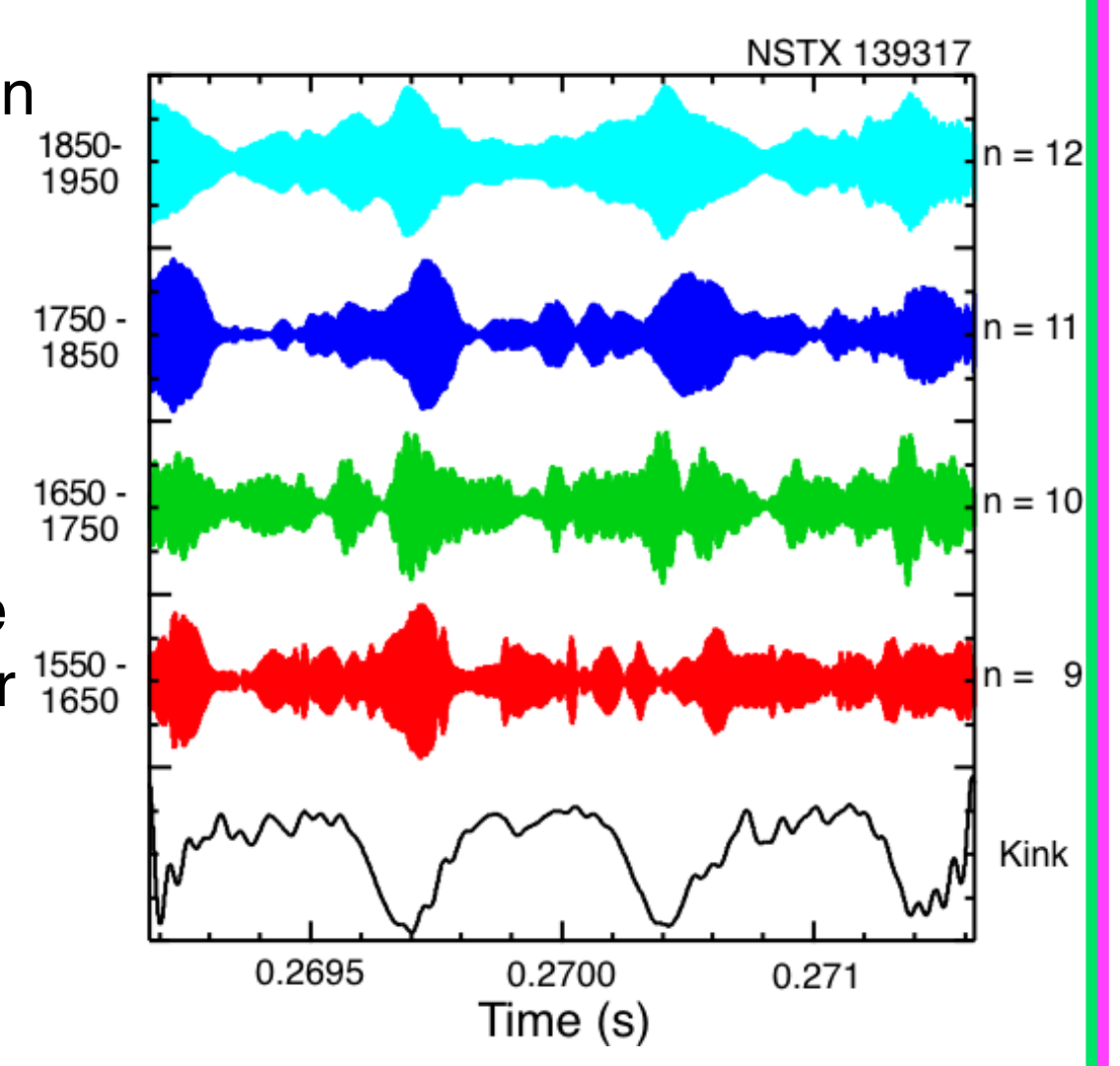
Initially hfCAEs burst nearly synchronously...

- Burst modulation is initially nearly 100%
- Driving mode appears to be the n=11 mode, with other bursts starting later
- Delay of burst growth appears to increase with frequency or n-separation.
- Behavior has some characteristics of avalanching (micro-avalanches?)



...later, hfCAE bursts are less well defined

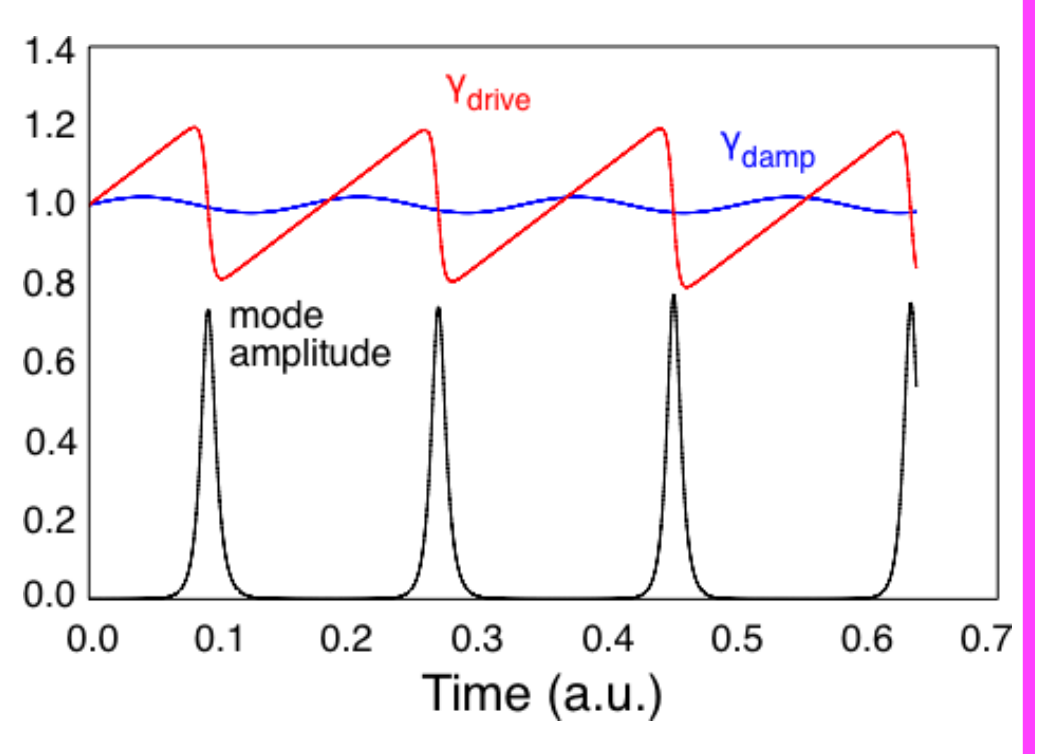
- Significant modulation at kink frequency, but...
- ...bursts of different modes are less correlated, and...
- mode amplitudes are modulated on shorter timescales.
- Kink amplitude is decreasing, but still large.



- Signifcant modulation at kink frequency, but..

Burst-frequency capture by kink seen in modified Predator-Prey type model

- Fast-ion mode drive replenished with NBI and fast ion diffusion.
- Mode causes redistribution, drop in drive.
- Assume stochastic loss, proportional to A^2.



$$\gamma_{drive} \propto \beta_{fast}$$

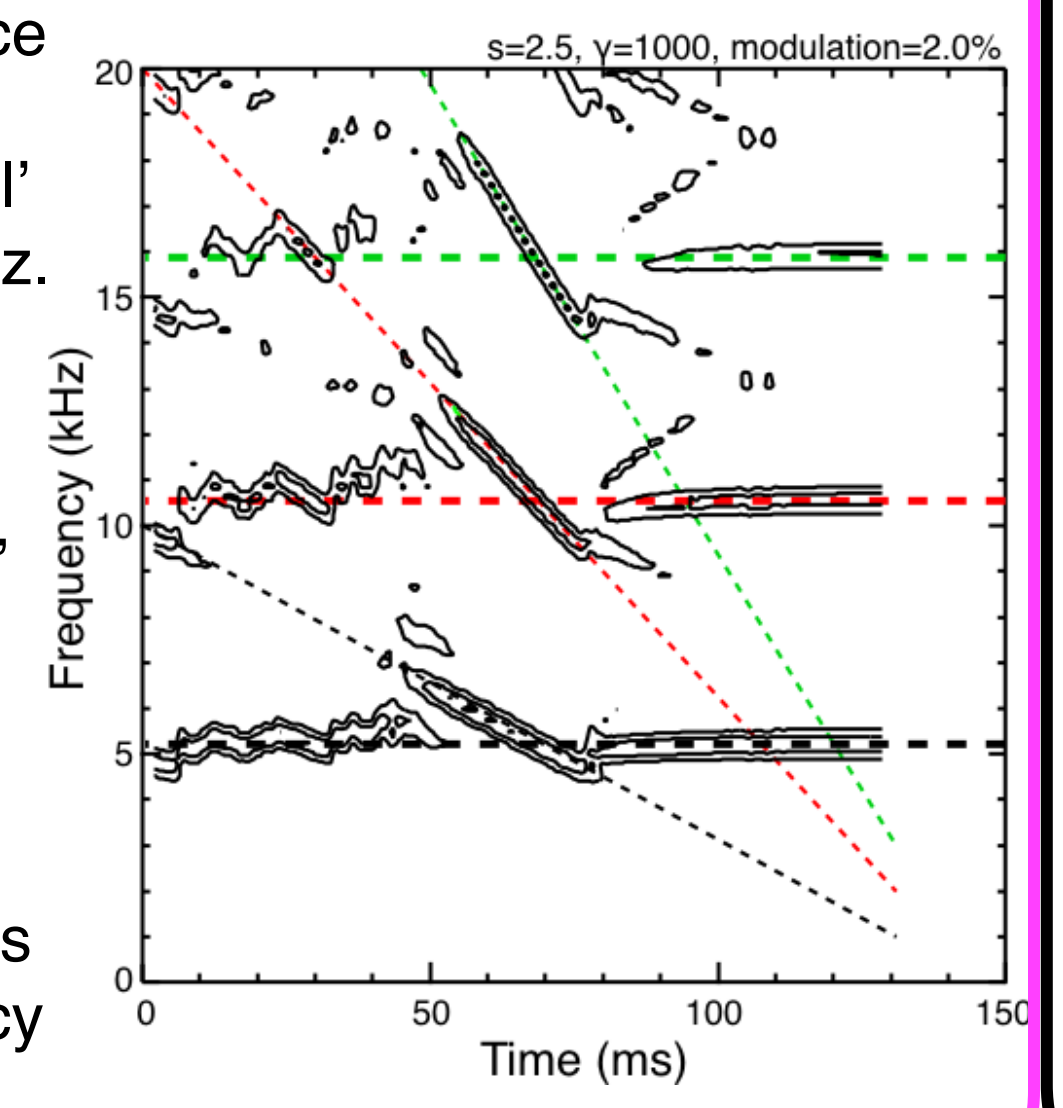
$$\frac{\partial \beta_{fast}}{\partial t} = s - \varepsilon A^2$$

$$\frac{1}{A}\frac{\partial A}{\partial t} = \gamma_{drive} - \gamma_{damp}(1+\delta \sin(\omega_{kink} t))$$

- Mode grows when $\gamma_{drive} > \gamma_{damp}$.
- Modulate γ_{damp} by 2% at f_{kink}.
- s = source, A = mode amplitude

Simulation with damping modulated by 2% captures burst frequency

- Source, damping, drive, fast ion loss dependence on mode amplitude adjusted to give 'natural' burst frequency of 5 kHz.
- With modulation frequency higher than natural burst frequency, burst frequency is modulated at kink frequency, and harmonics.
- Frequency-capture ends for modulation frequency slightly below natural burst frequency.



Summary of observations

- High frequency, co-propagating Compressional Alfvén Eigenmodes are seen coincident with the onset of a low frequency kink mode.
- Mode frequencies, mode structures in good agreement with simple predictions of 3-D dispersion relation.
- High frequency CAE are globally bursting modes.
- Bursts of individual hfCAE are synchronized with each other.
- hfCAE bursts can become synchronized with kink mode.
- Burst frequency capture by the kink can be modeled with a modified predator-prey type model.
- Frequency capture can happen with as little as a 2% modulation of the CAE damping rate by the kink.