Some characteristics of co-propagating CAEs

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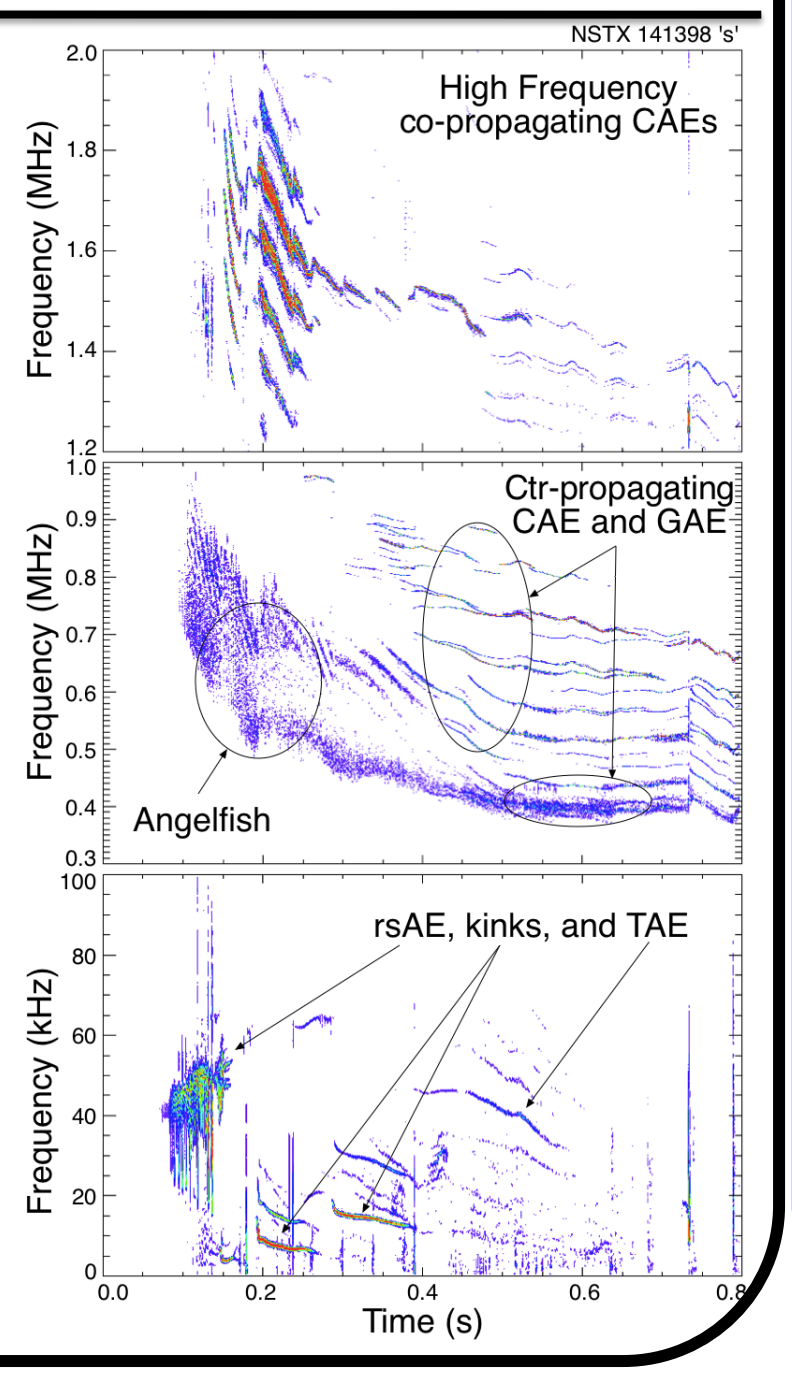
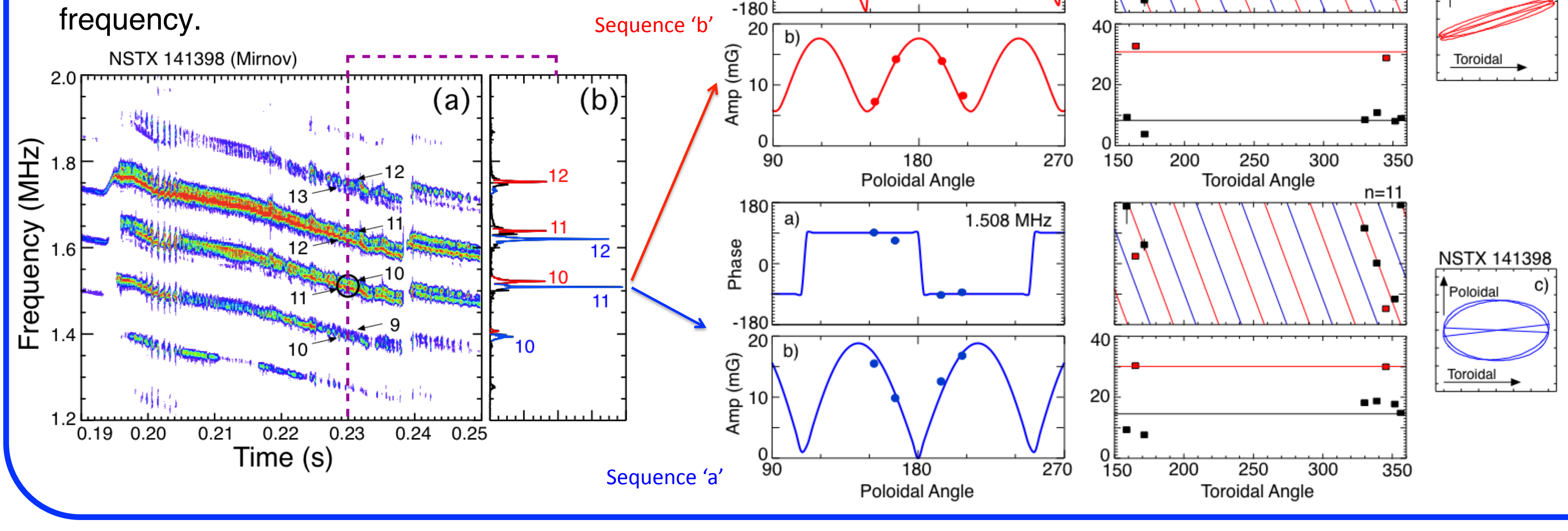
Fast ions excite a broad spectrum of modes on NSTX

- 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 typically have one or more sequences modes nearly equally spaced in frequency

- The Poloidal structure and polarization of hfCAE two bands is qualitatively different.
- The toroidal mode numbers increase with frequency.



Sequence ‘b’ is a mix of poloidally standing and propagating waves,

Has anti-nodes on the midplane

Modes 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.

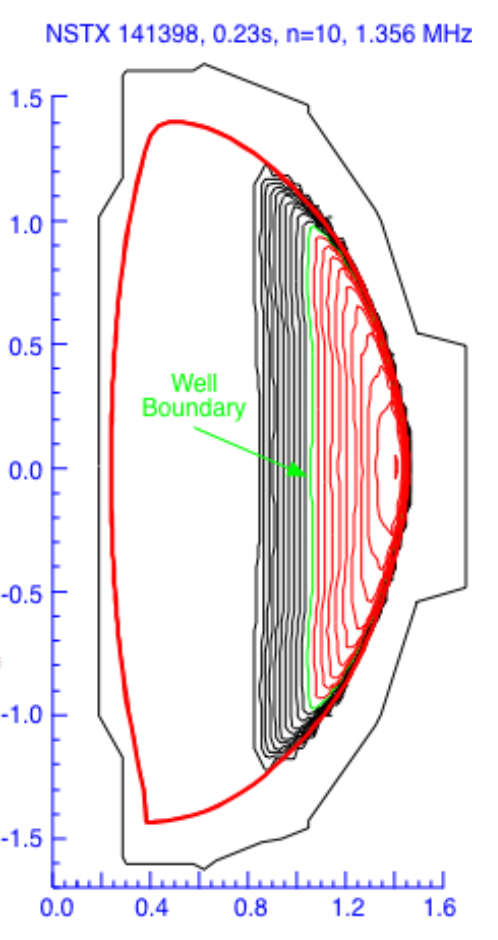
A simple dispersion relation for the CAE is modeled as an off-axis well

- The simple Alfvén wave dispersion relation in cylindrical coordinates can be separated to get the perpendicular part:

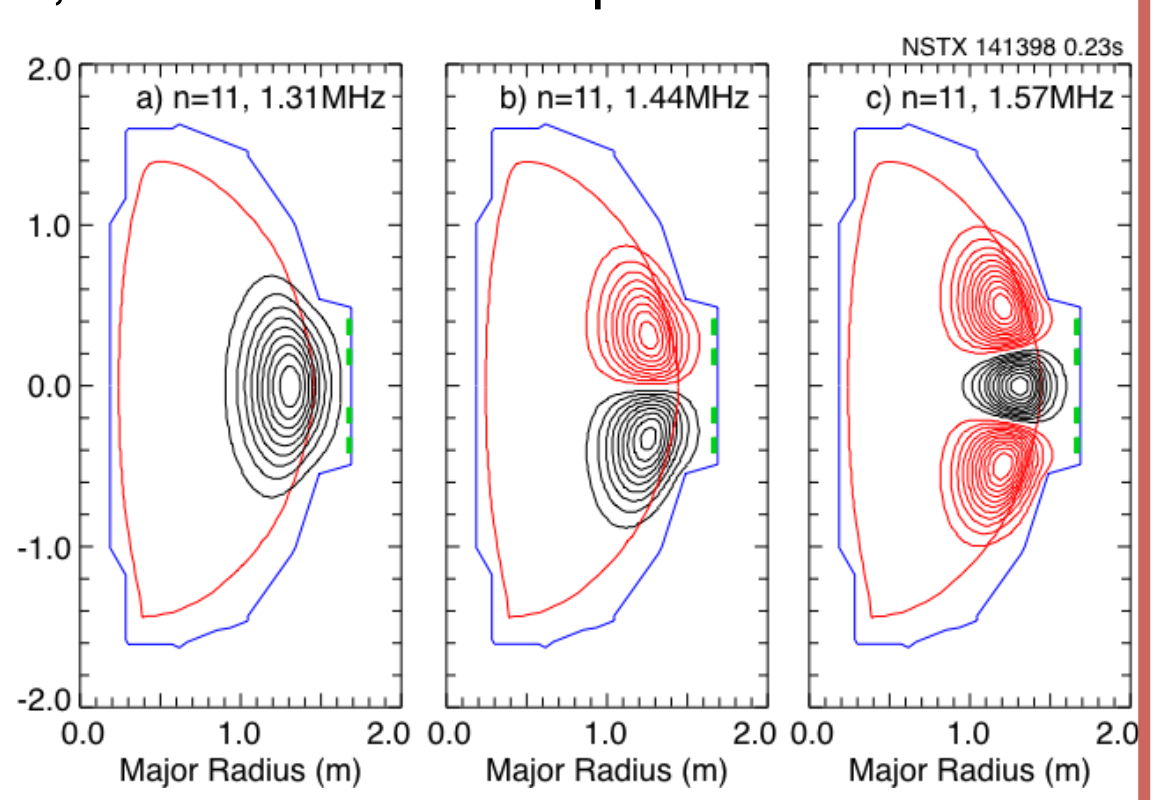
$$V_{Alfvén}^2 \nabla^2 E_\perp = -\omega^2 E_\perp$$

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

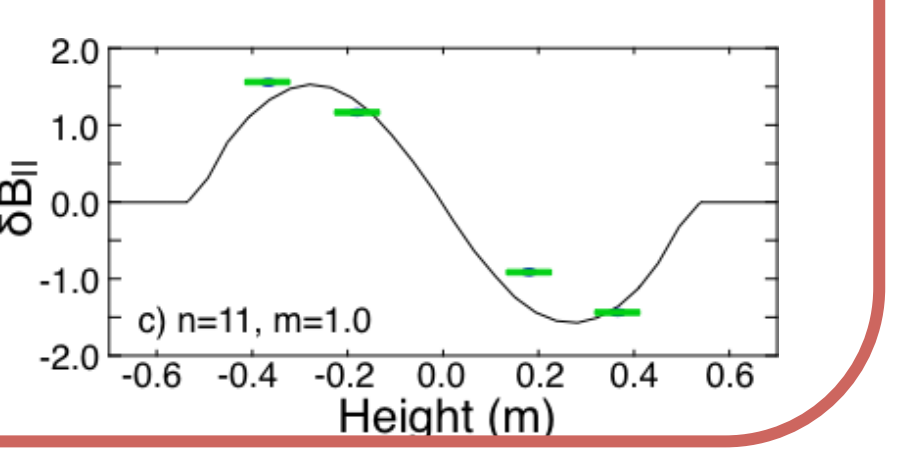
- After separation the dispersion relation is a 2-D wave equation with a well.
- Eigenmodes/eigenvalues for the 2-D equation can be found with a numerical code.



- The solutions have nodes or anti-nodes on the midplane, consistent with experimentt.

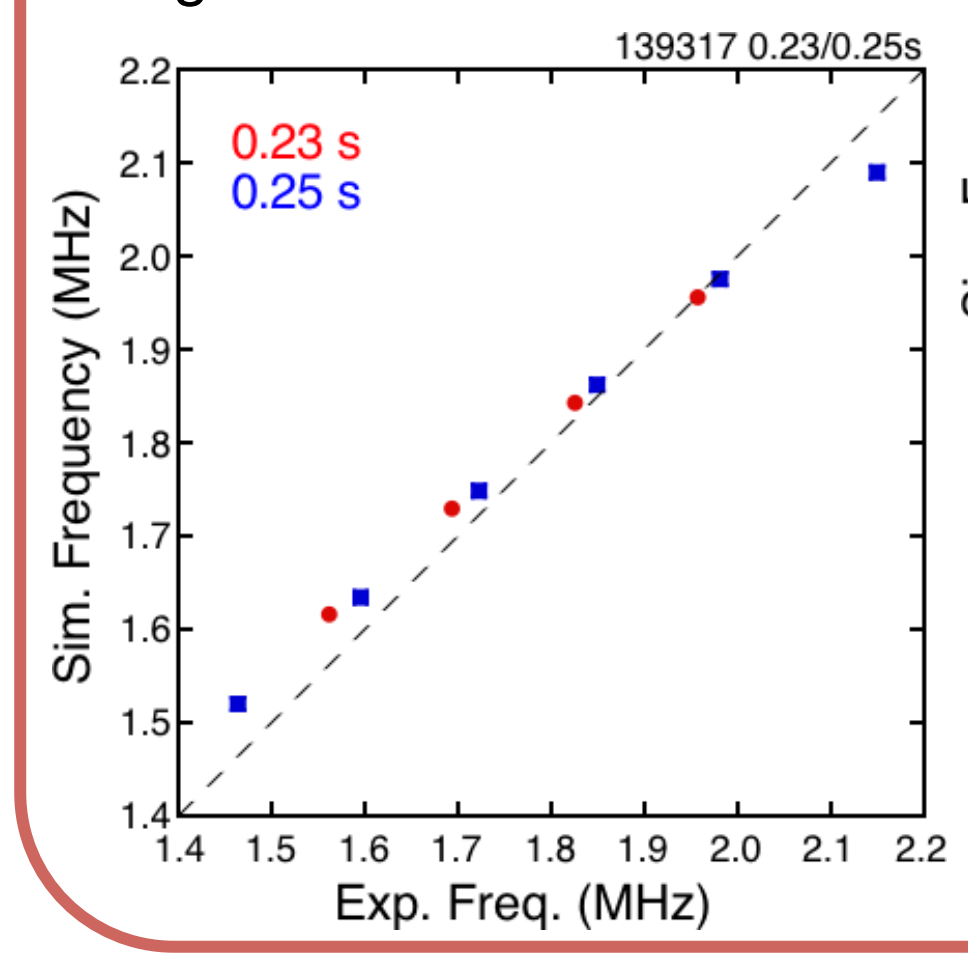


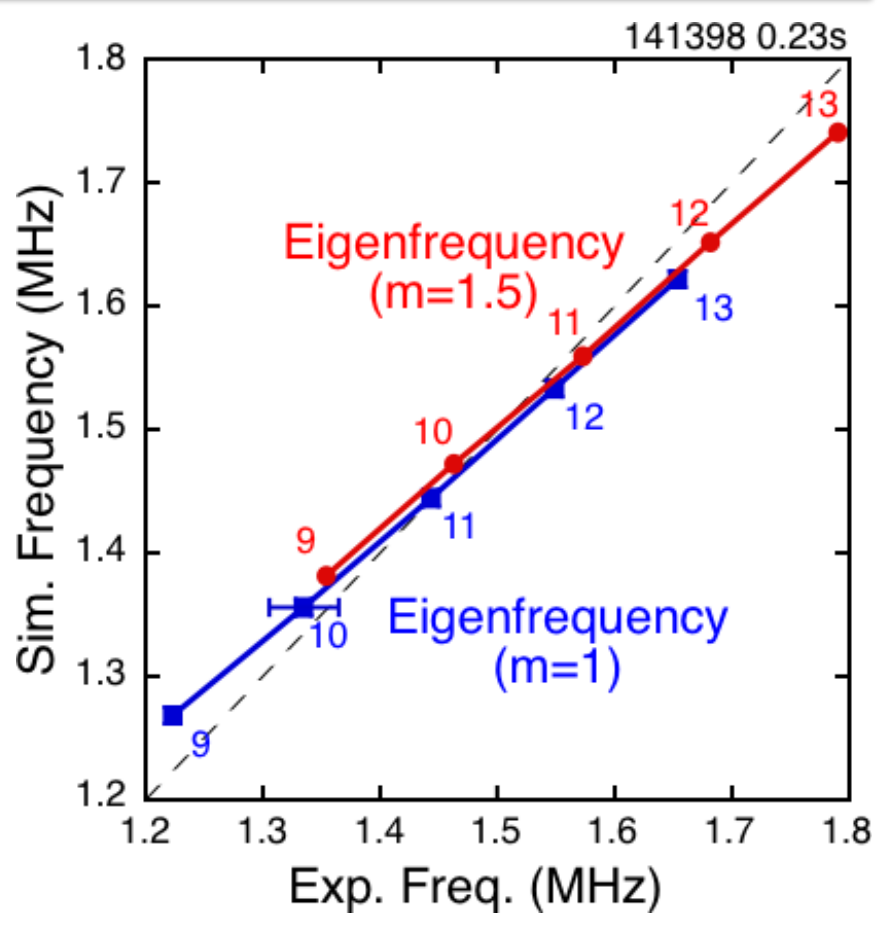
- Eigenfunction shape fits experimental data for m=1.0 eigenfunction, others less well.



Solution of simple dispersion relation matches experimental frequencies

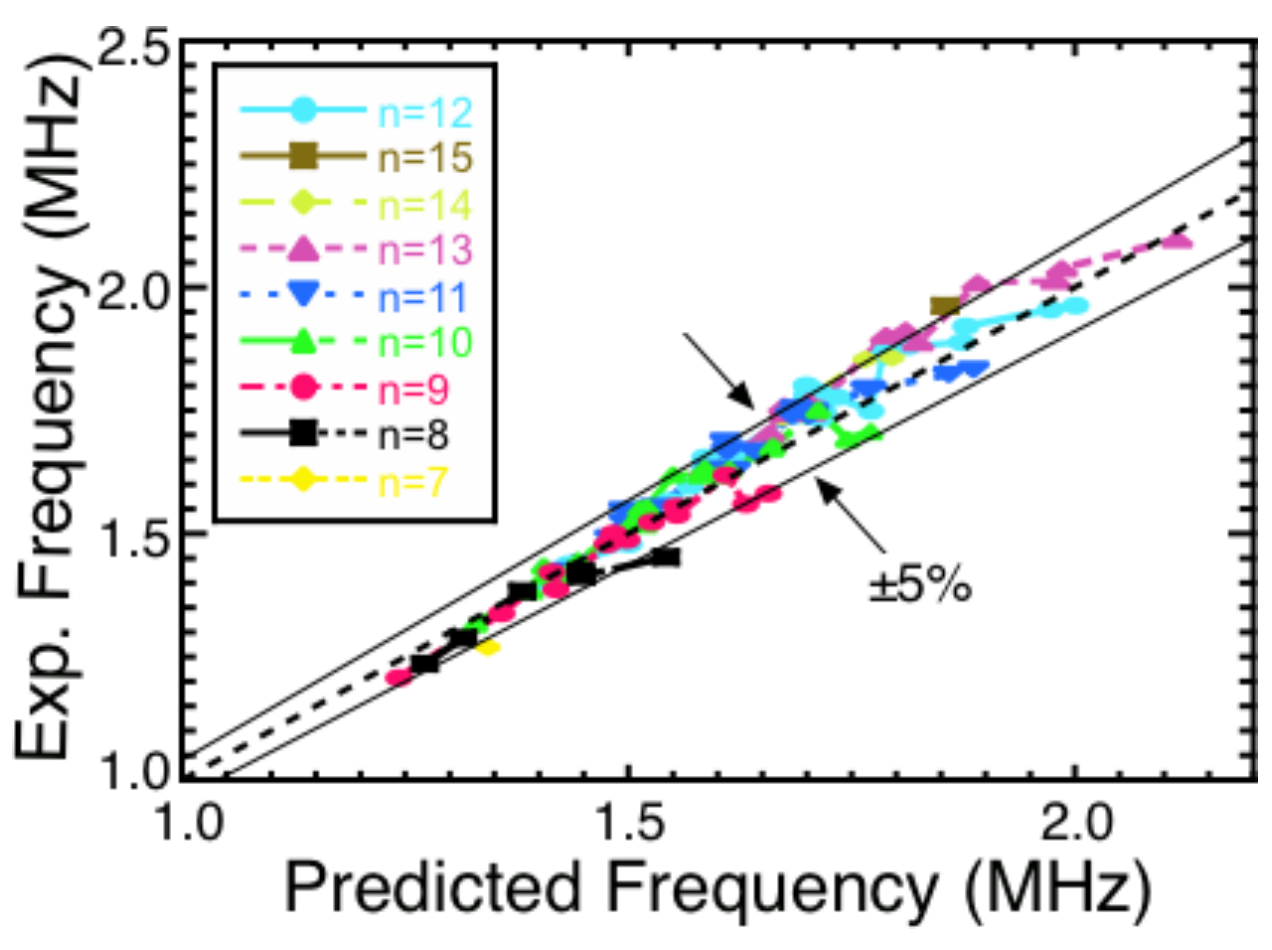
- Frequency variation with toroidal and poloidal mode numbers in good agreement.



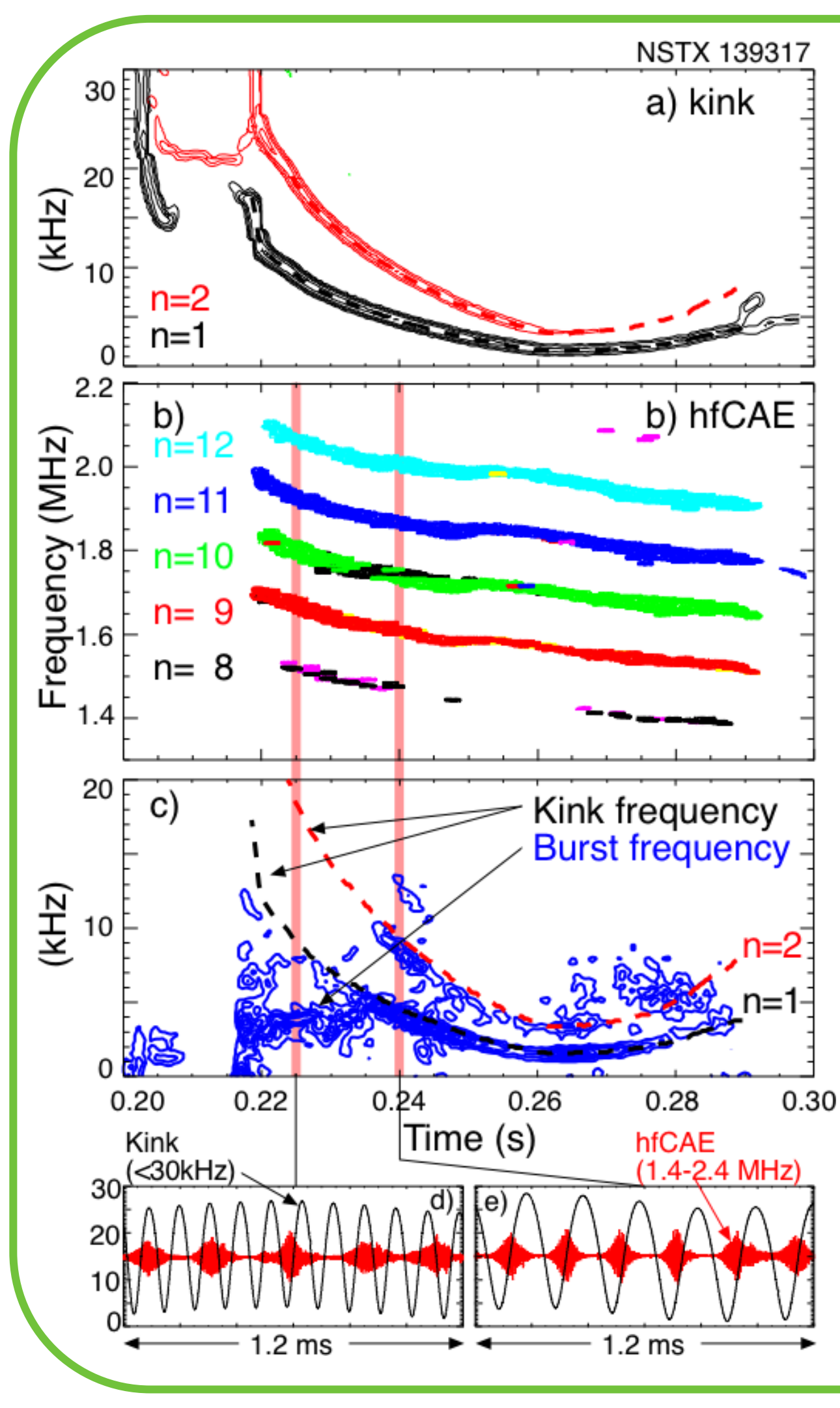


- Frequency variation in time is also well reproduced by this simple model.

Good agreement found for range of shots, mode numbers

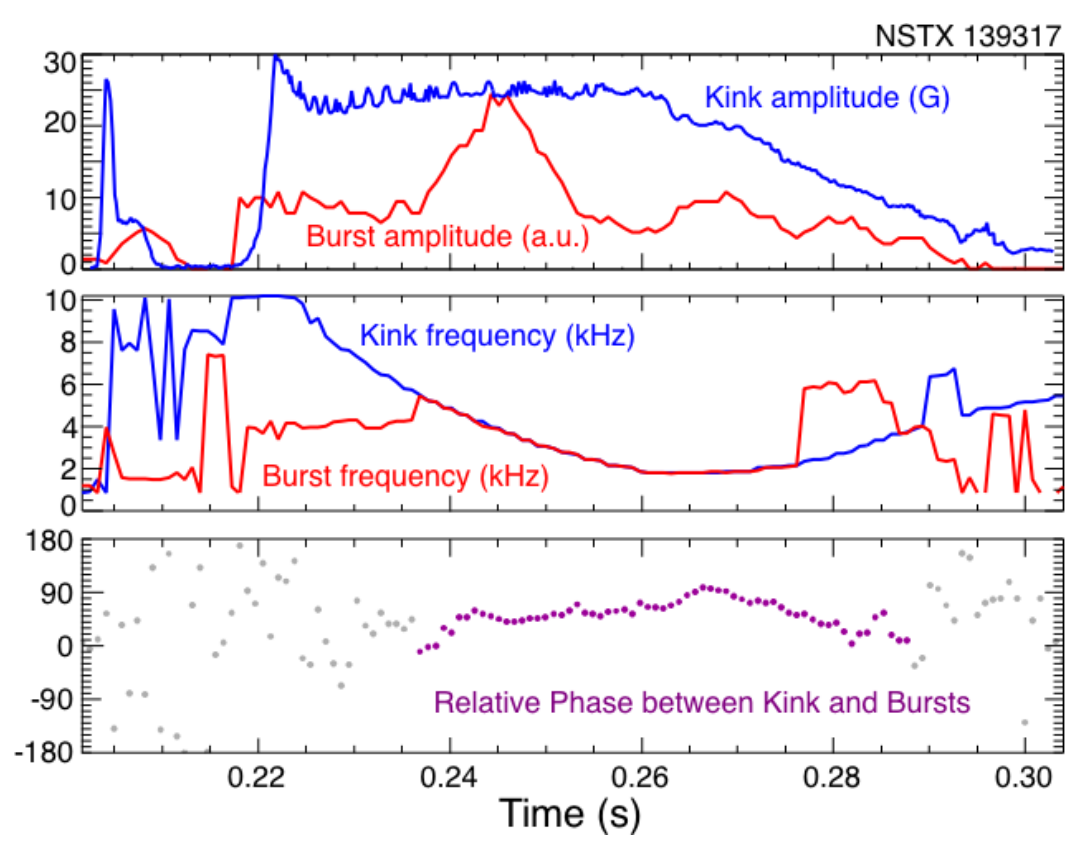


- Predicted frequencies for hfCAE in a range of shots is also well reproduced by this simple model.



Like most fast-ion modes on NSTX, the hfCAE are a sequence of short bursts

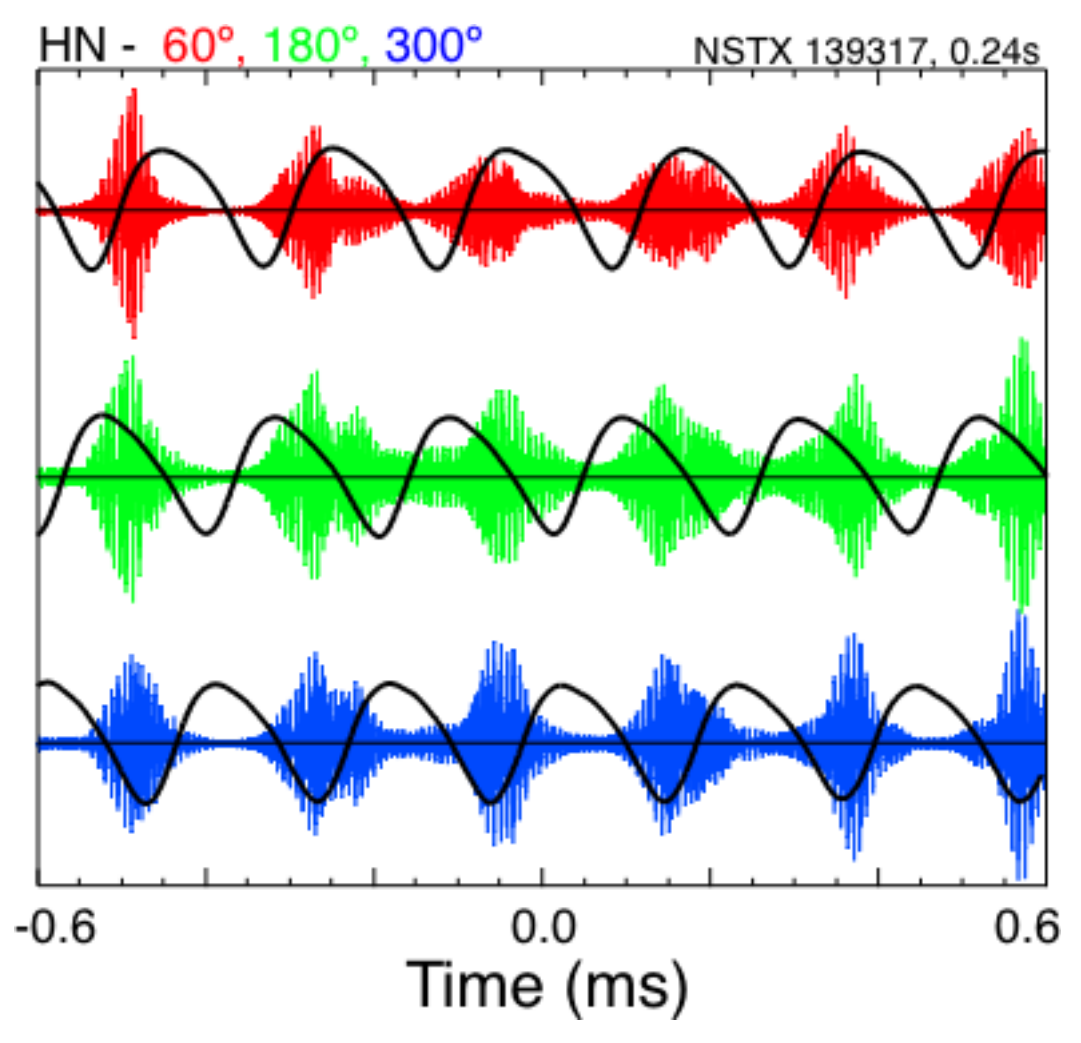
- The initial hfCAE burst frequency is 3 – 5 kHz, uncorrelated with the kink mode.
- After 0.235 seconds, hfCAE burst frequency matches kink frequency.
- The phase is nearly constant for > 40ms, although it wanders over a range of about 90º.
- Strong correlation implies direct modulation of CAE stability by kink.
- Implies that kink interaction with another asymmetry modulates hfCAE stability.
- Could be error field, NBI angle or vacuum vessel asymmetries.



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

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

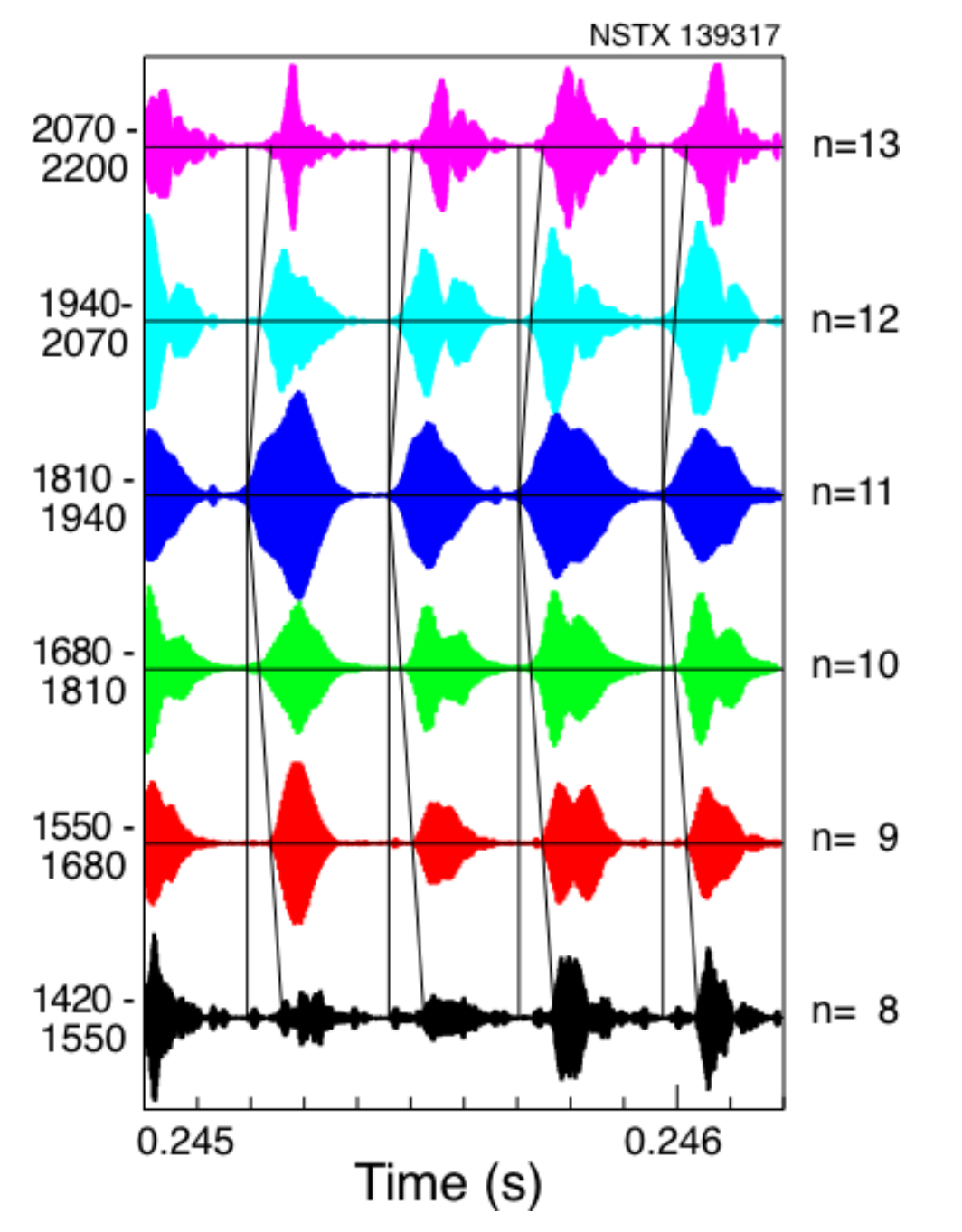
- Mode amplitude is modulated globally, by the kink plus non-axisymmetric perturbation?
- Need axi-symmetry breaking mechanism, *e.g.*, error field, first wall?

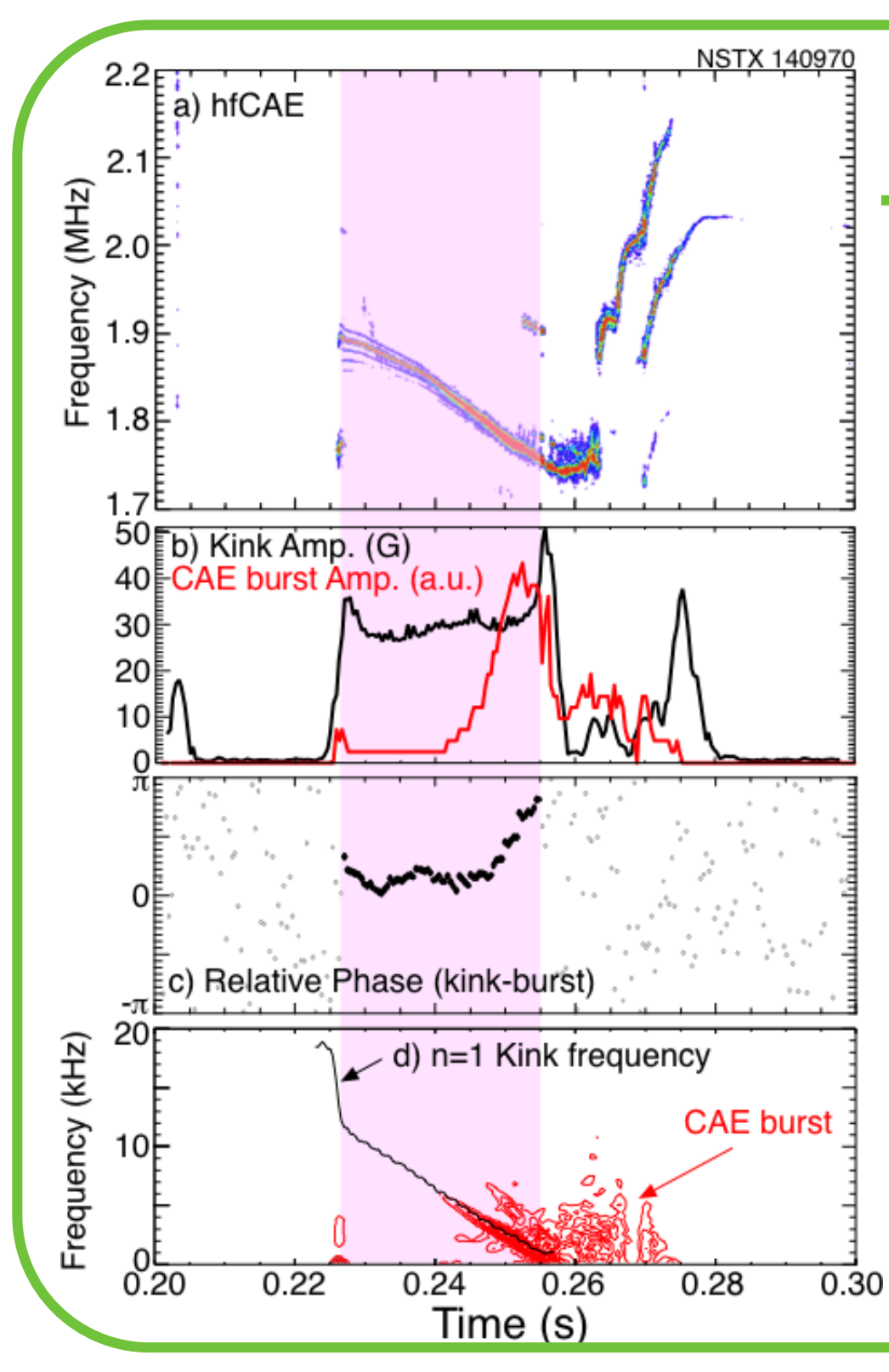


- Filtered bursts are shown at three toroidal locations, separated by 120º, scaled for aesthetics.
- Similar synchronous behavior seen poloidally.

Initially individual hfCAEs burst nearly synchronously...

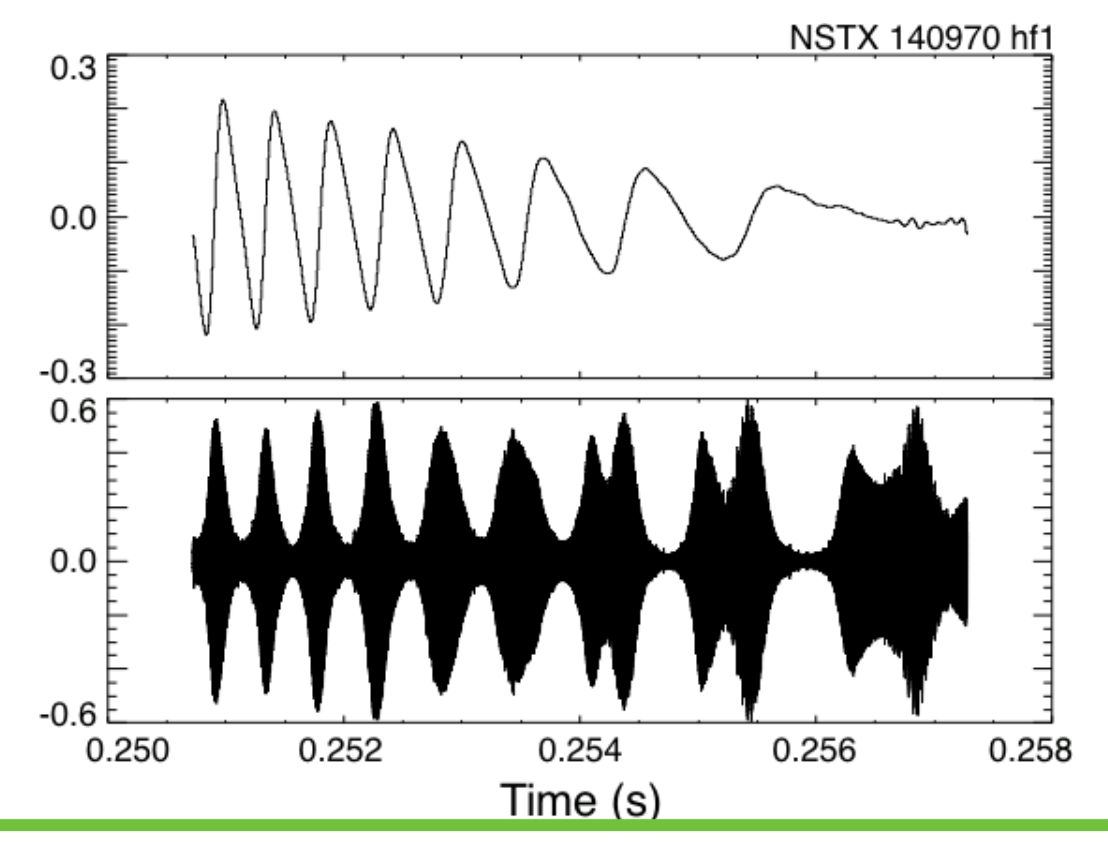
- Burst modulation is initially nearly 100%
- Driving mode appears to be the n=11 mode, with other bursts starting later
- Delay of burst growth appears to increase with frequency or n-separation.



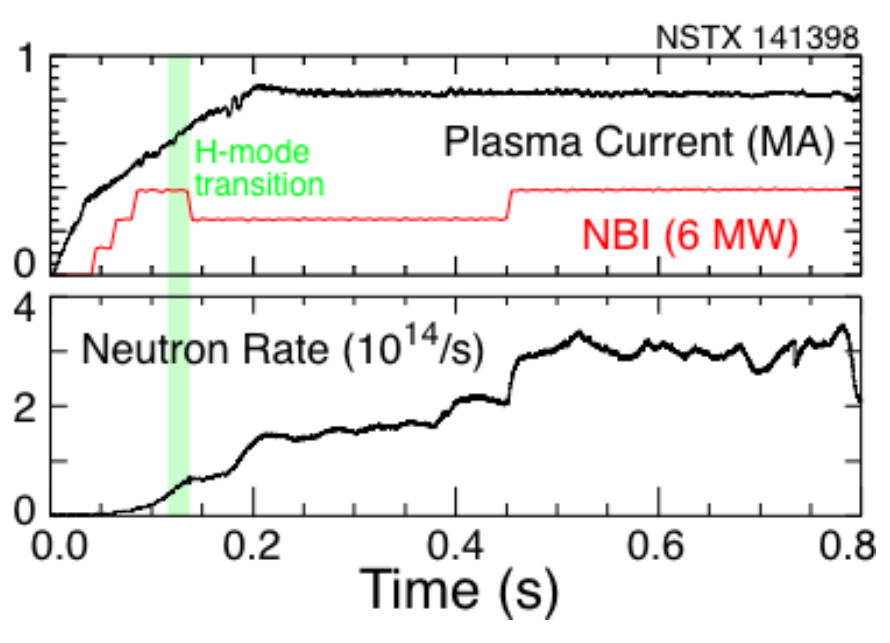


Modulation of hfCAE burst frequency seen to frequencies below 1 kHz

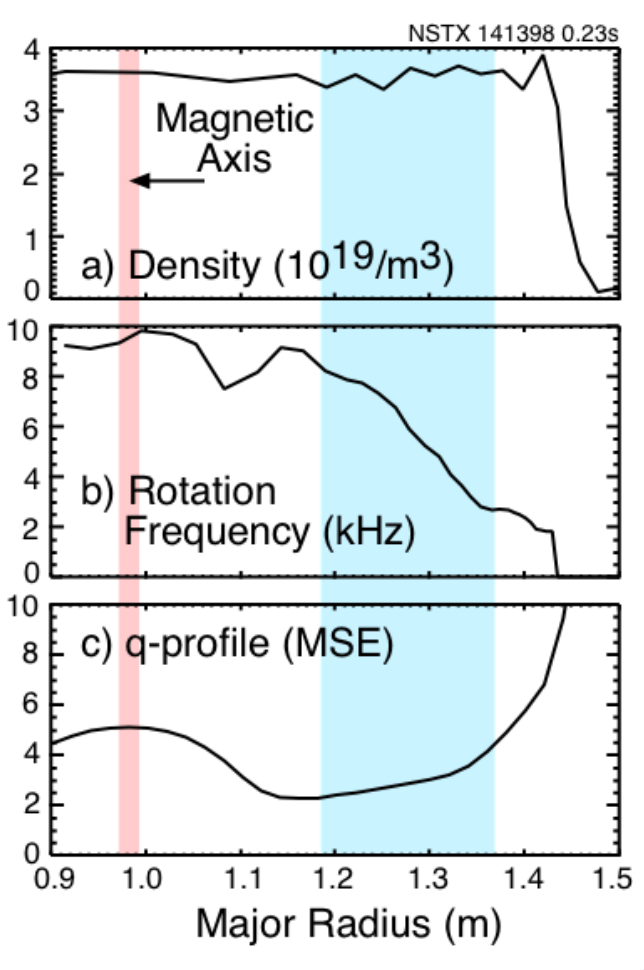
- At lowest frequency, natural burst frequency begins to appear with double bursts in each kink period.
- Mode amplitude stays high as burst frequency drops towards zero.



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



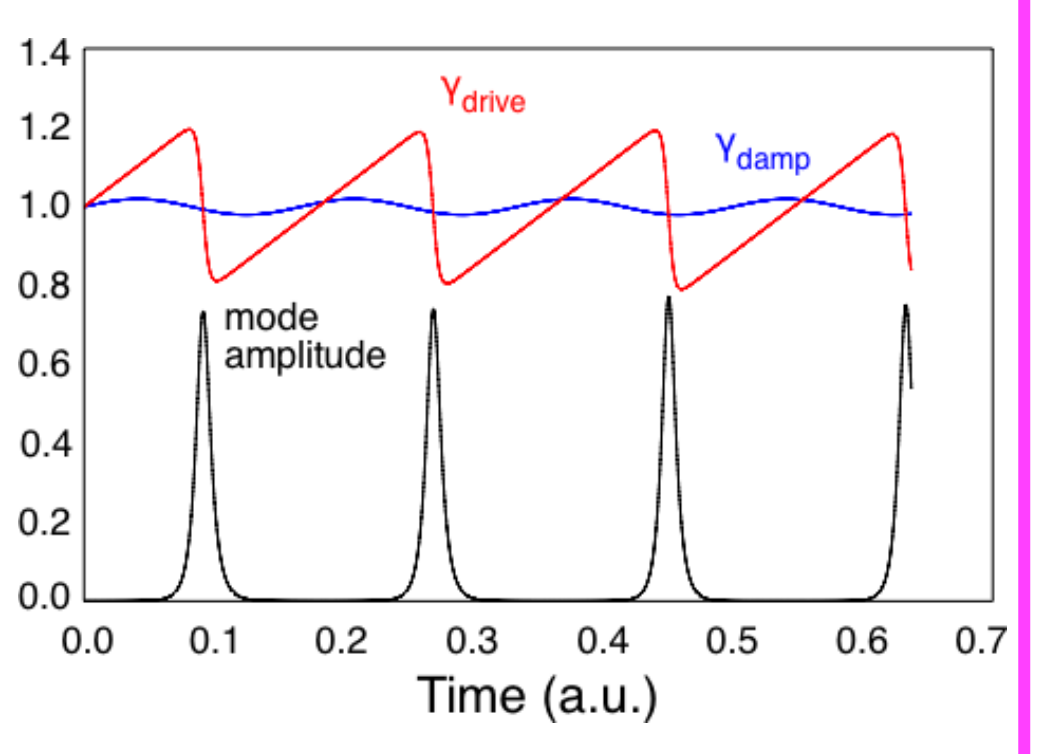
- hfCAE show up shortly after current ramp ends.
- Density is very flat in core.



- 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.

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 resonant loss, proportional to A.



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

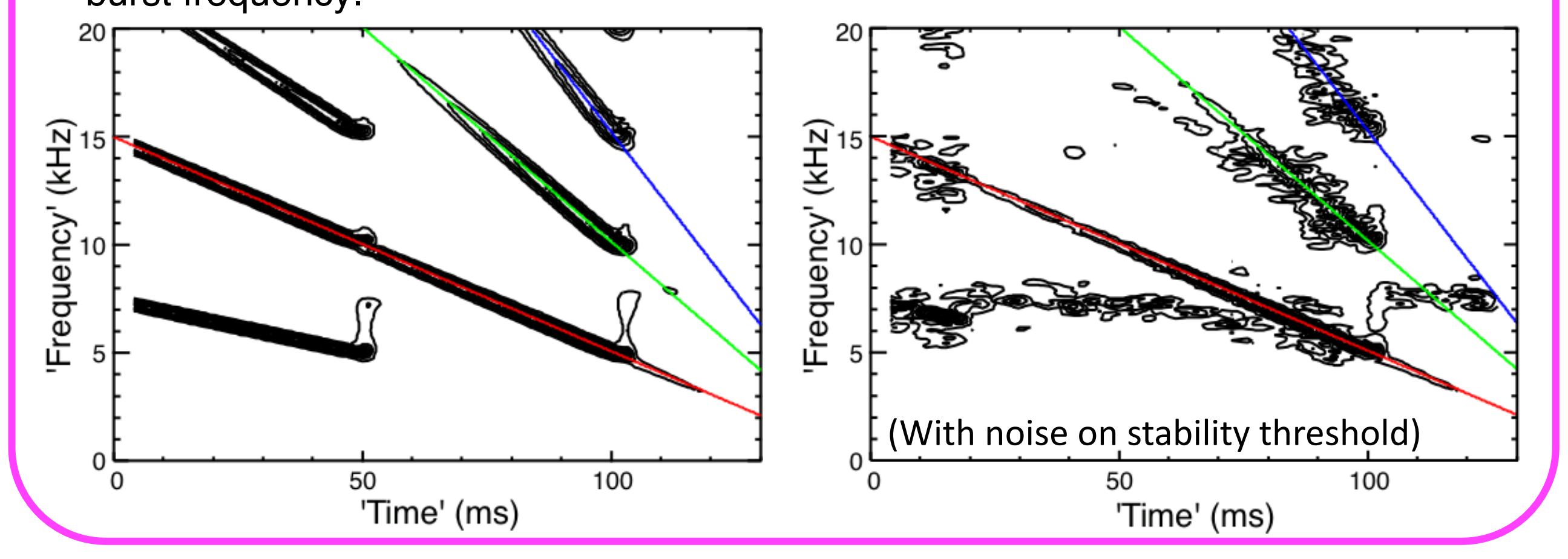
$$\frac{\partial \beta_{fast}}{\partial t} = s - \varepsilon A$$

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

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

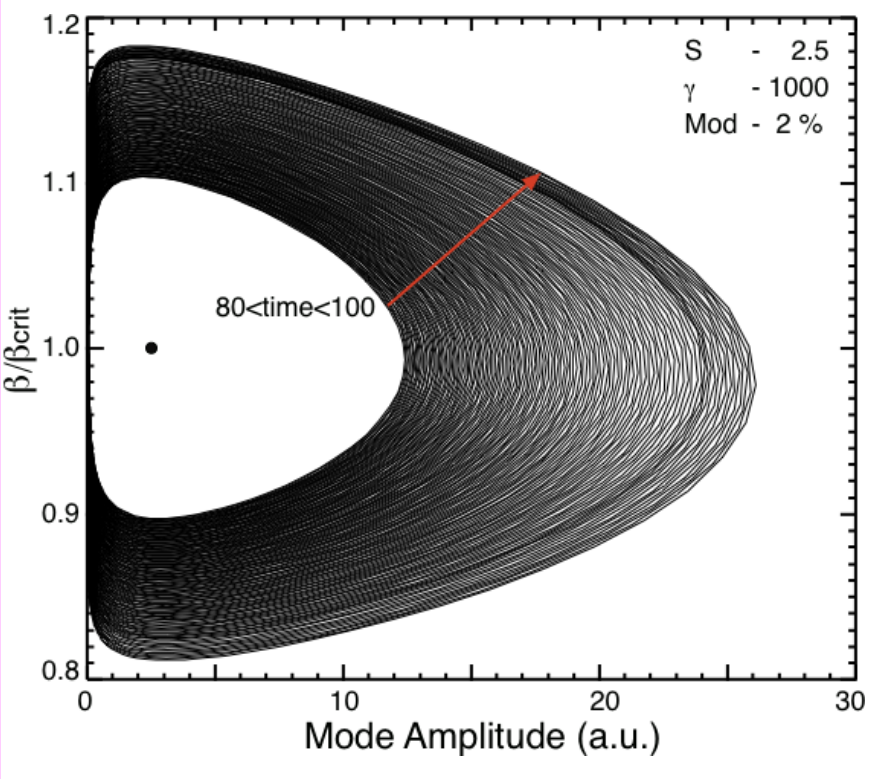
Simulation with damping modulated by 2% captures burst frequency

- Source, damping, drive, fast ion loss dependence on mode amplitude adjusted to give ‘natural’ burst frequency of ≈7 kHz, but only in ‘noisy’ system.
- With modulation frequency higher than natural burst frequency, burst frequency is modulated at the kink frequency and its harmonics.
- Frequency-capture becomes weaker as modulation frequency drops below natural burst frequency.

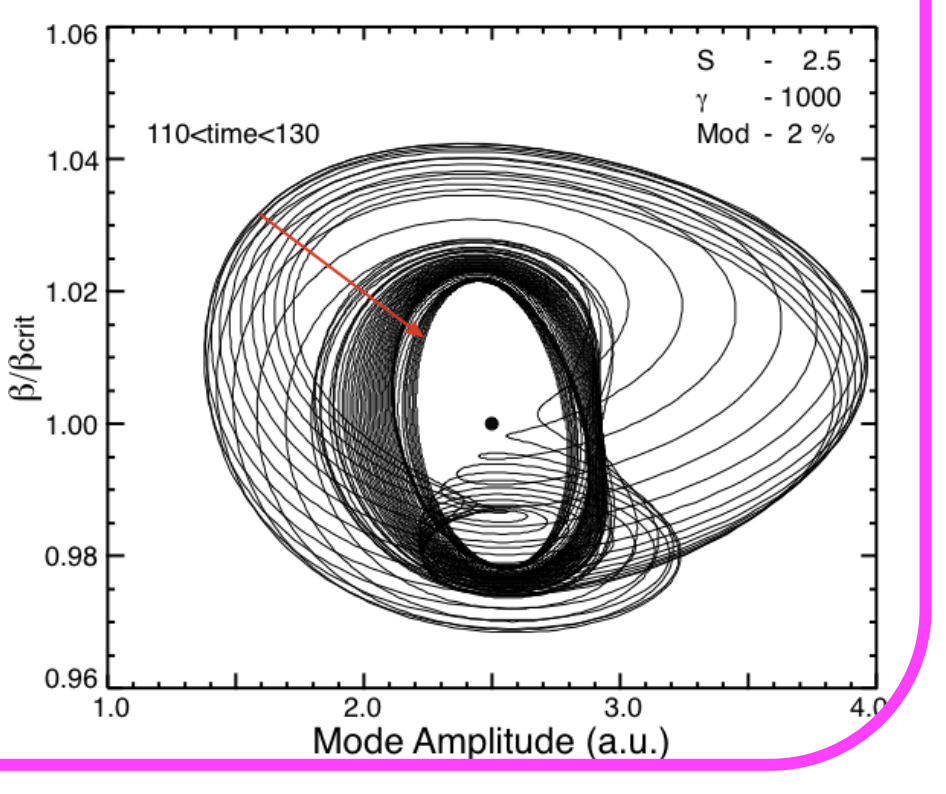


(With noise on stability threshold)

Predator-prey equations have a cyclic simple attractor solution (and a trivial point solution)



- Attractor is not strange; figure shows evolution of attractor as ‘kink frequency’ is swept towards natural resonant frequency.
- Mode amplitude increases as frequency drops.
- Below the natural resonant frequency, mode amplitude modulation is no longer 100%; in apparent contrast with experimental observation.



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.