Wave driven fast ion loss in the National Spherical Torus Experiment

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Will fast ion driven instabilities be important in the CTF/NSO?

- Fast ion instabilities can raise ignition threshold in fusion reactors;
  - Fast ion losses, first wall damage
  - "alpha-channeling"
- ST's, with intrinsic low field, are particularly susceptible to fast ion driven instabilities.
- Need to understand instability drive, loss mechanisms.
- Results may also be important for CAT reactors.

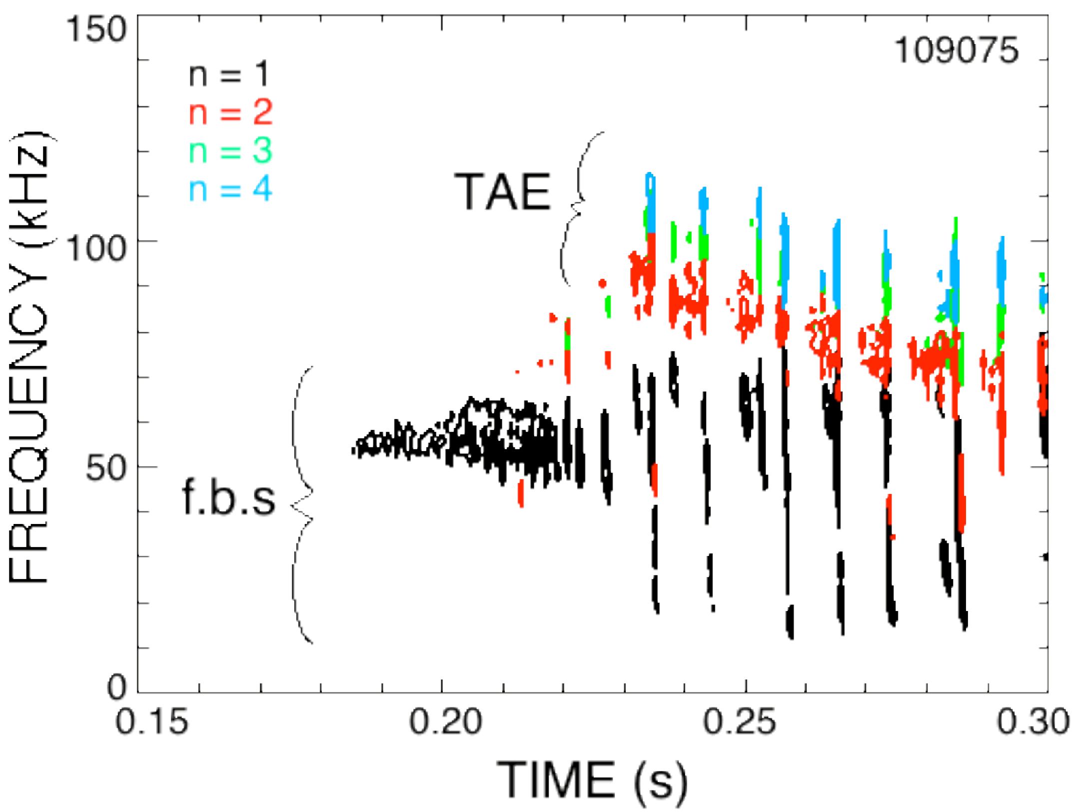
Fast ion loss parameters

- $V_{fi}/V_{Alfvén}$;
  - How much, if any of energy in fast ion distribution available to drive waves.
  - Fusion □'s are all at full energy, only fraction of beam power at full energy.
- □$_{fi}/a_{plasma}$;
  - Measure of mode structure, effectiveness at causing fast ion losses.
- Compact, low field reactors in the worst corner…

TAE and fishbone-like modes are common on NSTX

NSTX

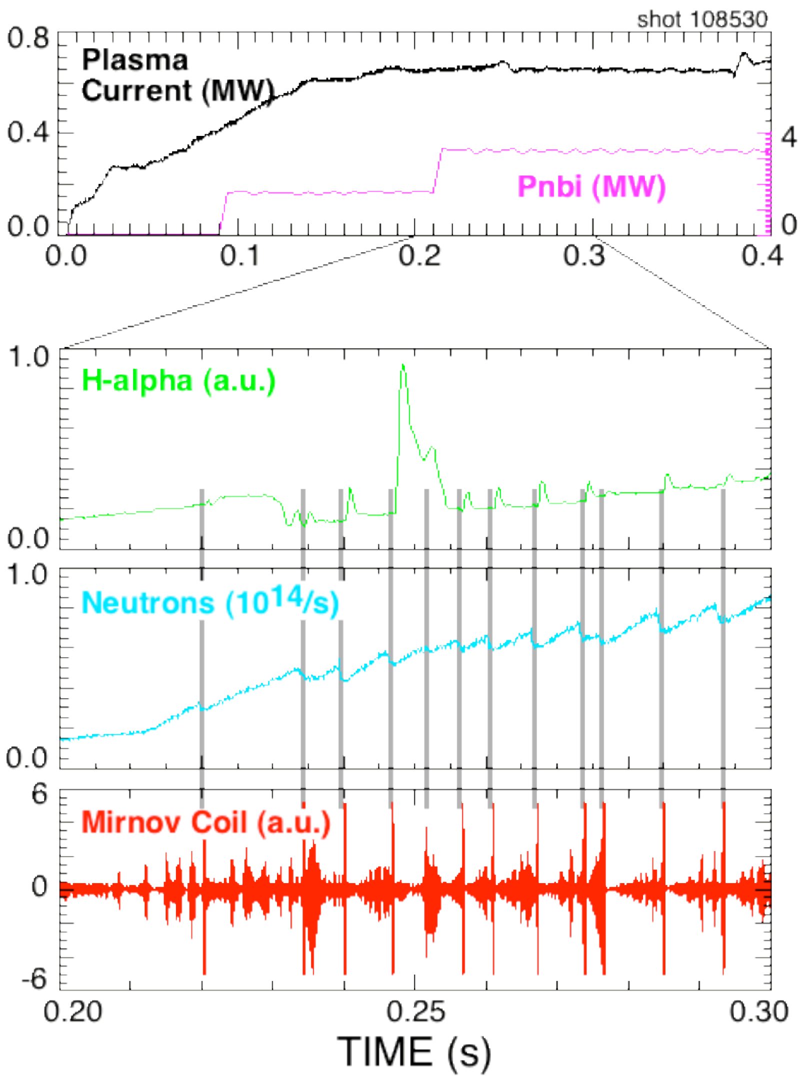
- Non-chirping, high frequency modes classified "TAE".
- Variety of chirping modes classified as "fishbones".



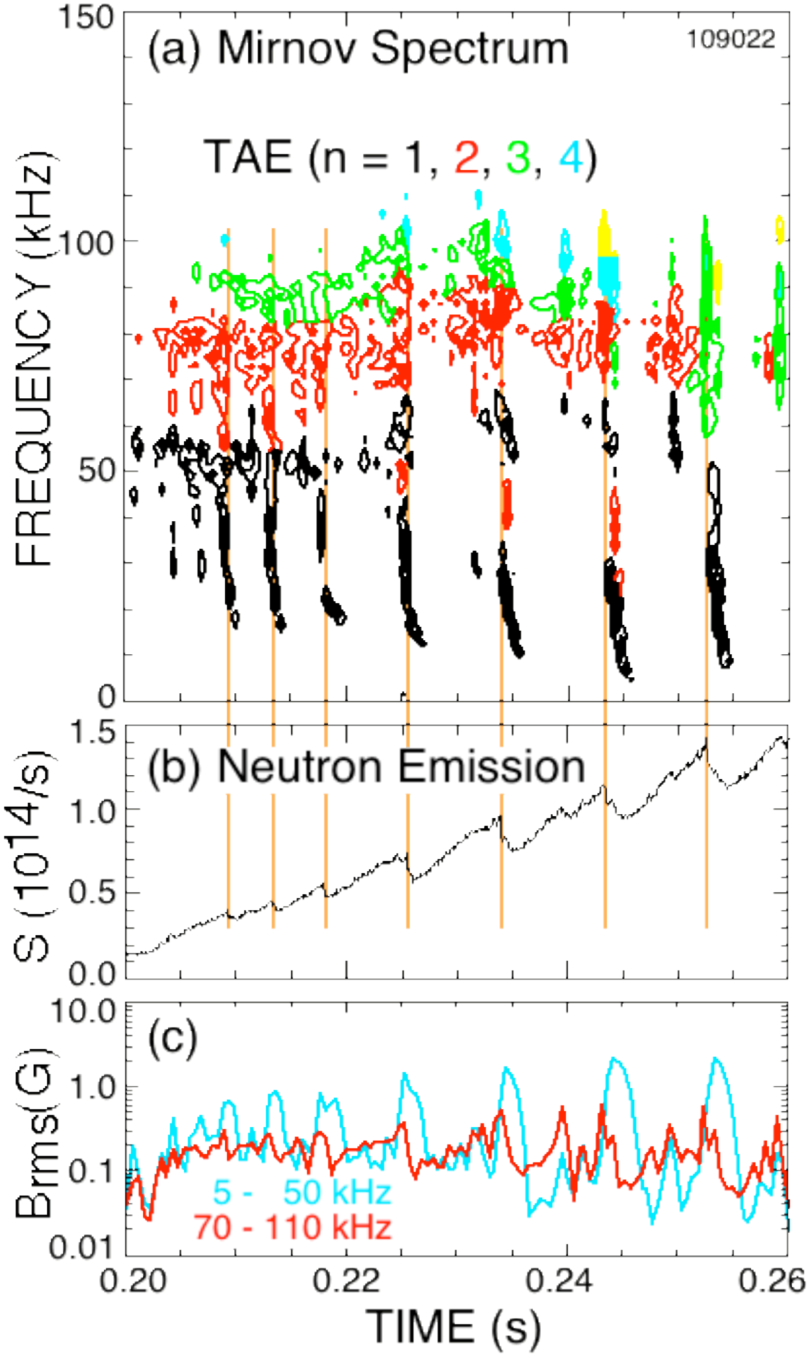
- The "TAE" have toroidal mode numbers $2 < n < 6$.
- The "TAE" can be bursting or quasi-steady state.
- The "fishbones" can have $n > 5$.

Neutron rate drops, D_α bursts imply fast ion loss

NSTX



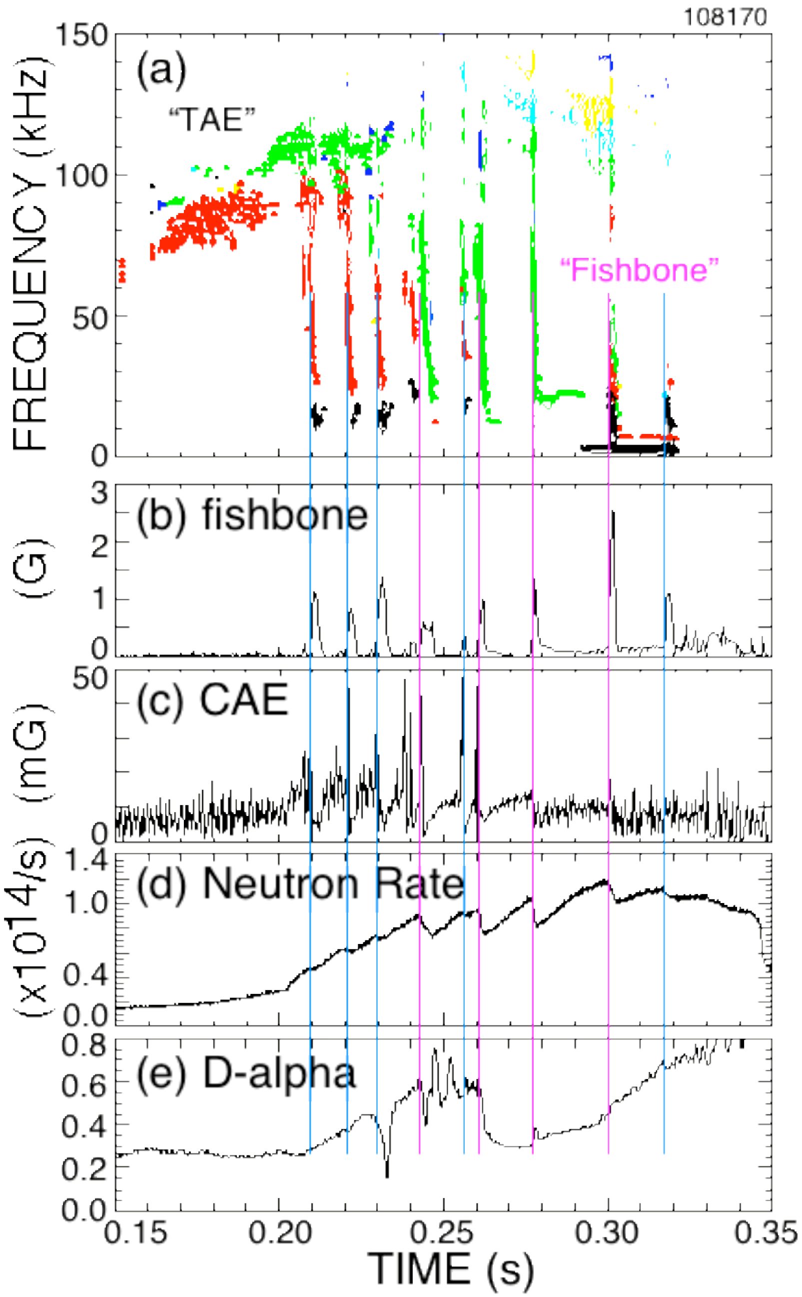
- Neutrons are beam-target; drops mean fast ion loss
  - $\Delta S \propto \Delta n_{fi}$
- D_α bursts probably due to fast ions hitting wall or divertor plates
  - Can be confused with ELMs
- In L-mode, sometimes correlated with D_α drops.
- Loss also seen in iFLIP, redistribution in NPA.



TAE/fishbones synergistic?

- Correlation of f.b. and TAE bursts suggests coupling.
- Attribution of cause of fast ion losses difficult to make.
- TAE bursts cause initial, fast drop, fishbones later, slower drop.
- Neutron drops related to loss of fastest ions; slower ions may also be lost.

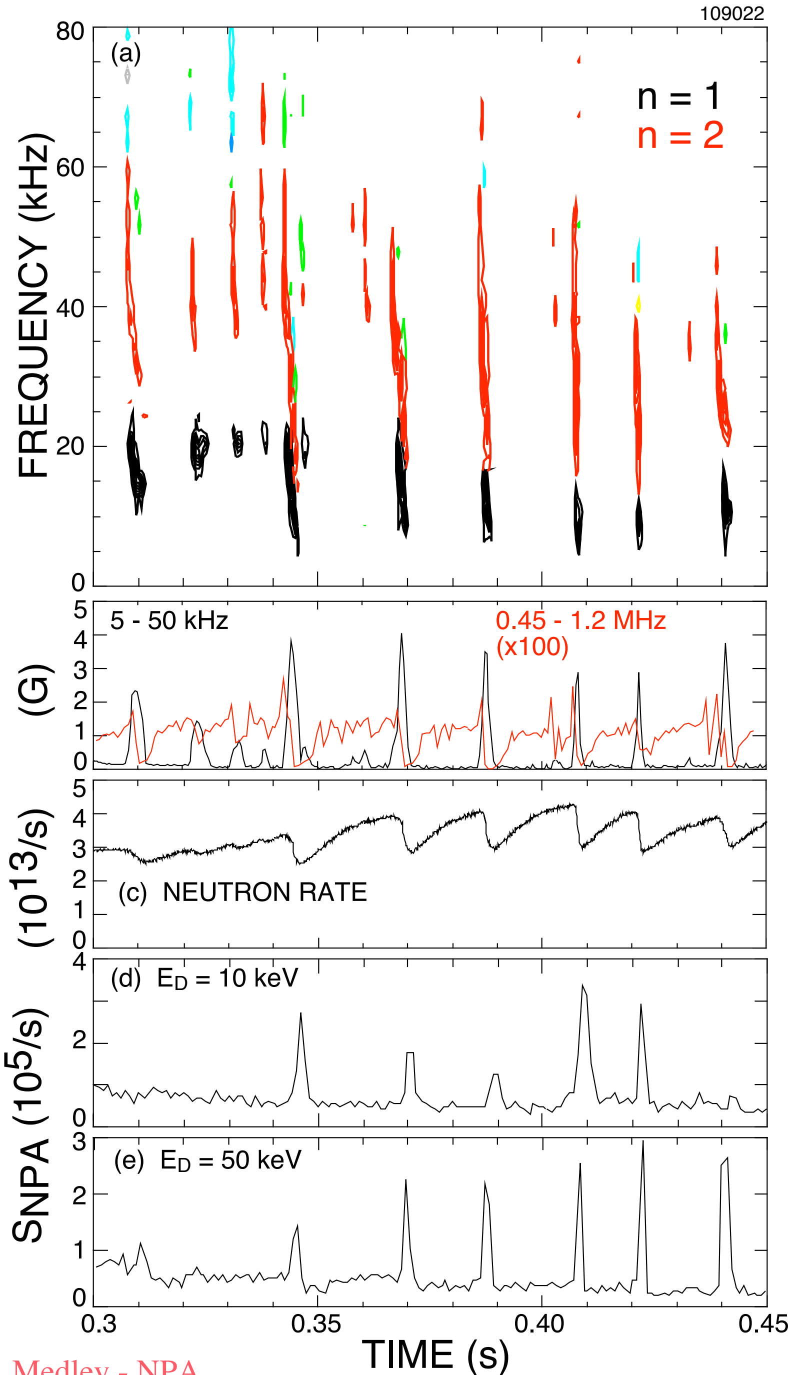
Ip = 0.8 MA, Pbeam = 3.4 MW



Large fast ion losses with "pure" fishbones

NSTX

- Up to 20% drops in the neutron rate, with f.b. periods of ≈ 10 ms; steady-state reduction in fast ion population of ≈50%.
- Why do some fishbones cause neutron drops, others no drop?
- Even no-drop f.b.'s affect CAE.
- Or do CAE trigger f.b.'s?
- Correlation of fishbones with H-mode transitions?



S. Medley - NPA

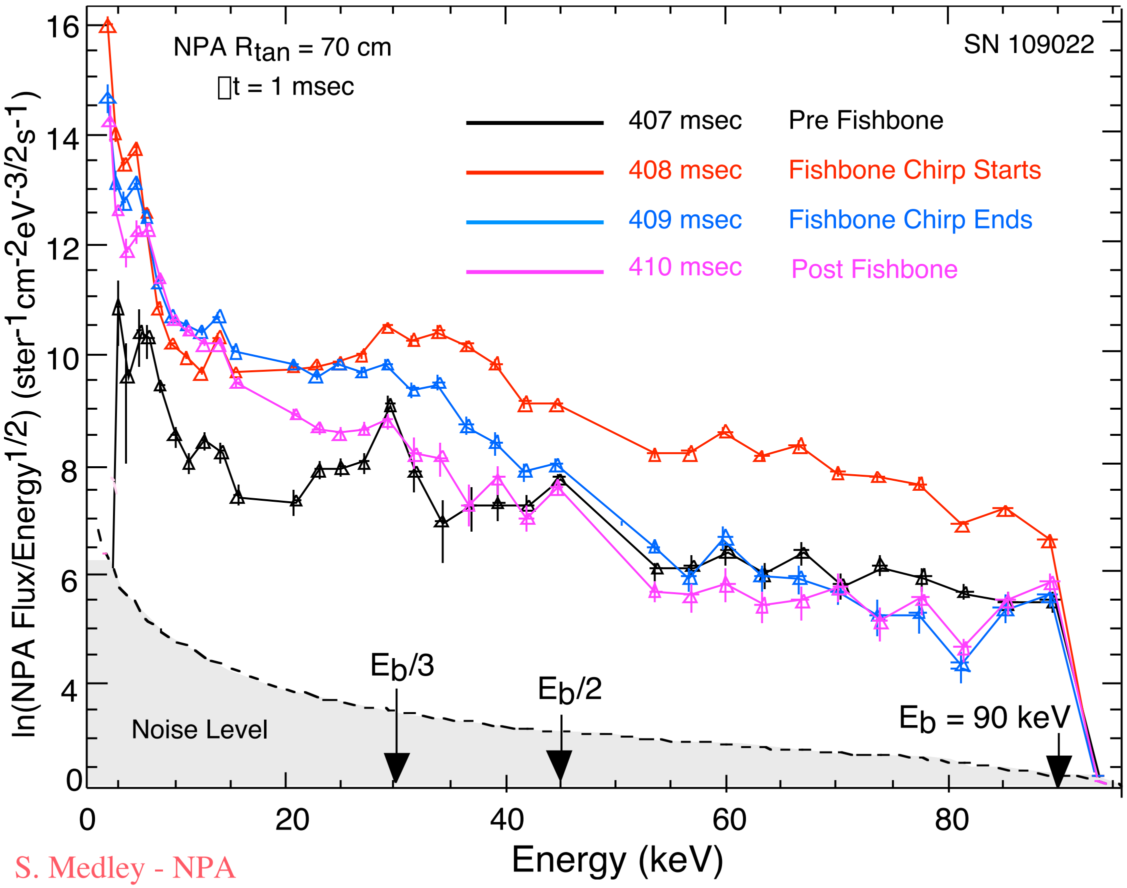
Strong chirping most effective in transporting fast ions

NSTX

- In this case, multiple modes also seem to co-exist.
- Lack of neutron drop may mean loss of lower energy ions; but not according to NPA.
- It would be very nice to have good internal data.

Redistribution energy dependent, as seen on NPA spectra

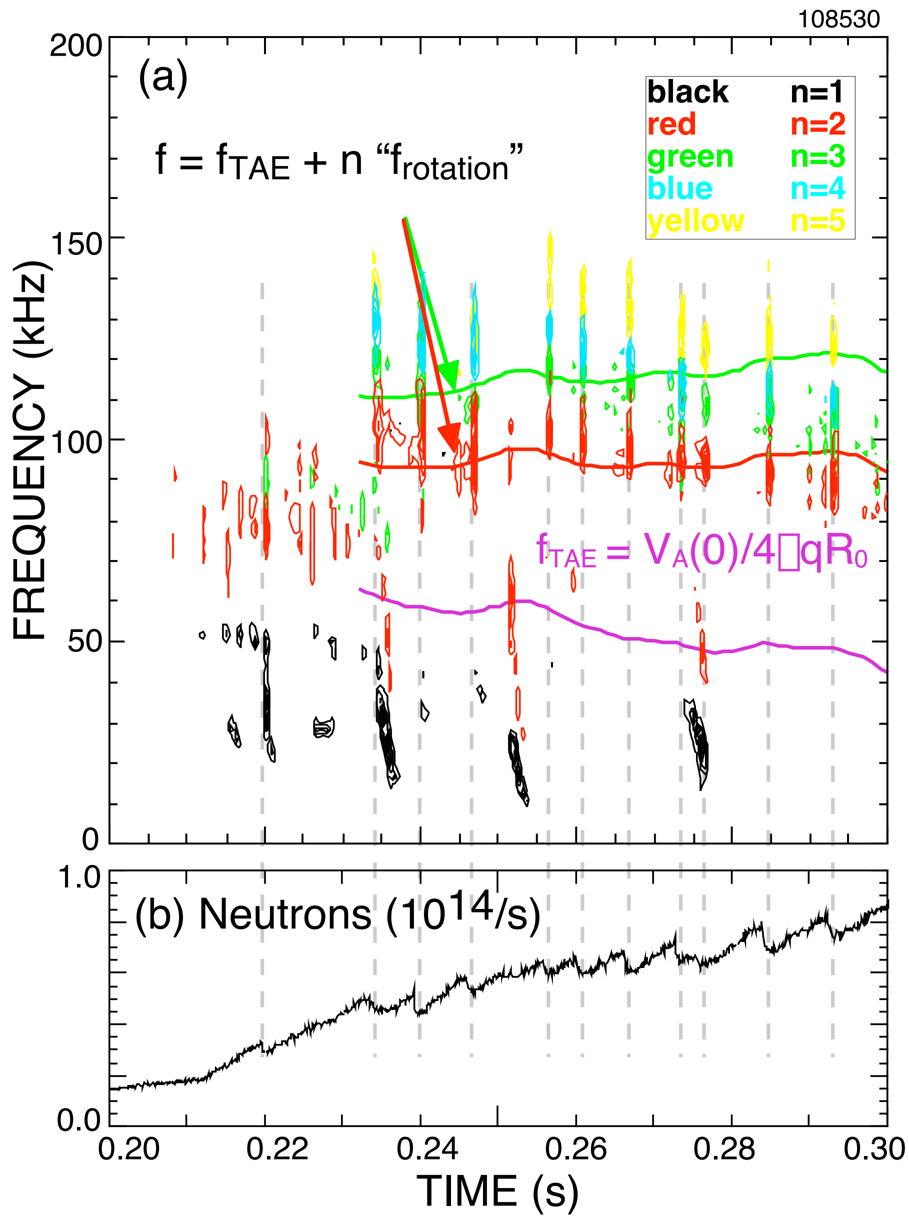
S. Medley



S. Medley - NPA

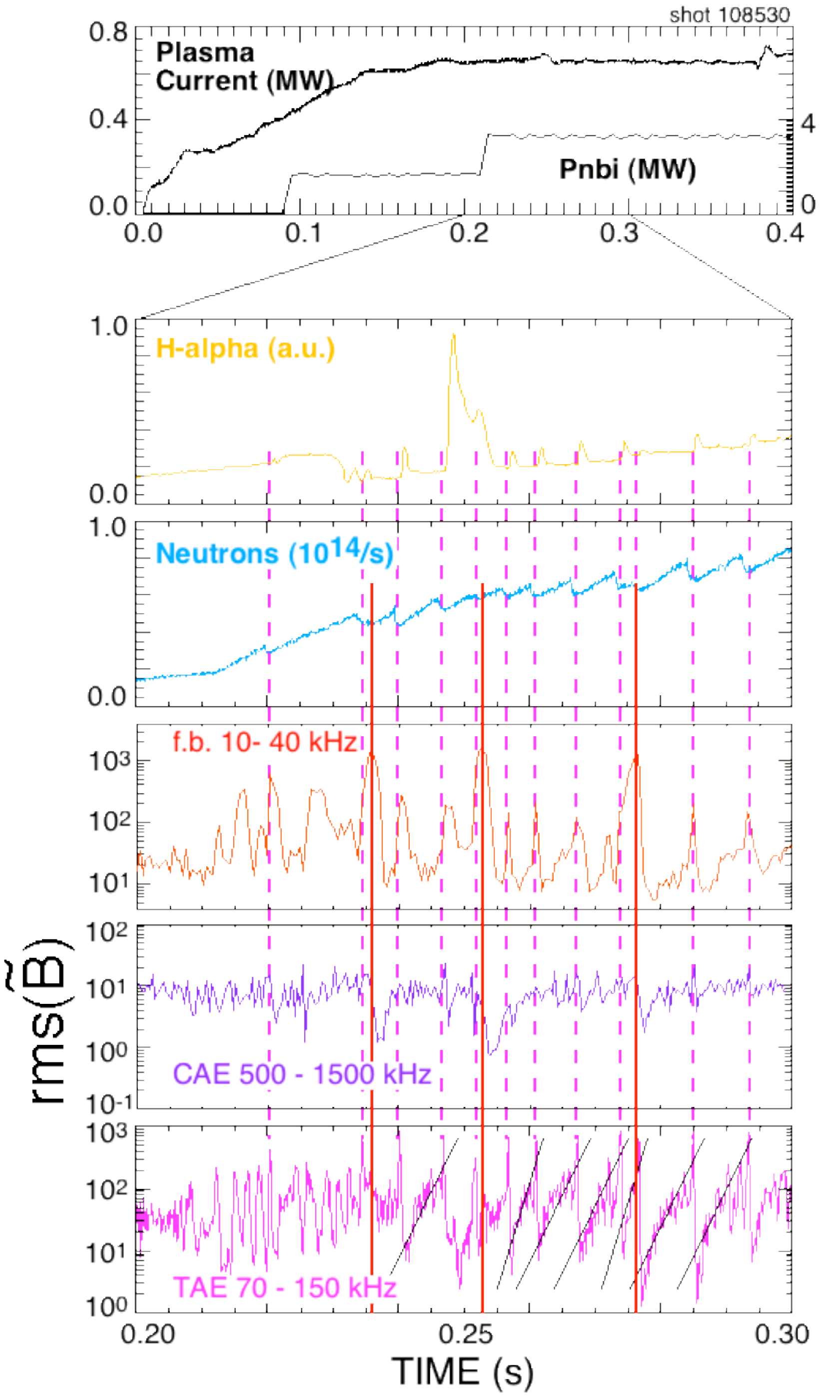
- Energetic ions are lost during fishbone.
- Lower energy ion population increases (at this tangency radius).

Similarly, TAE alone can also cause large fast ion loss



NSTX

- Neutron drops ≈ 10-15 %.
- Period is again ≈ 10 ms.
- In steady-state, predicted reduction in fast ion beta of 40 %.
- TAE have strong bursting character with multiple modes present.



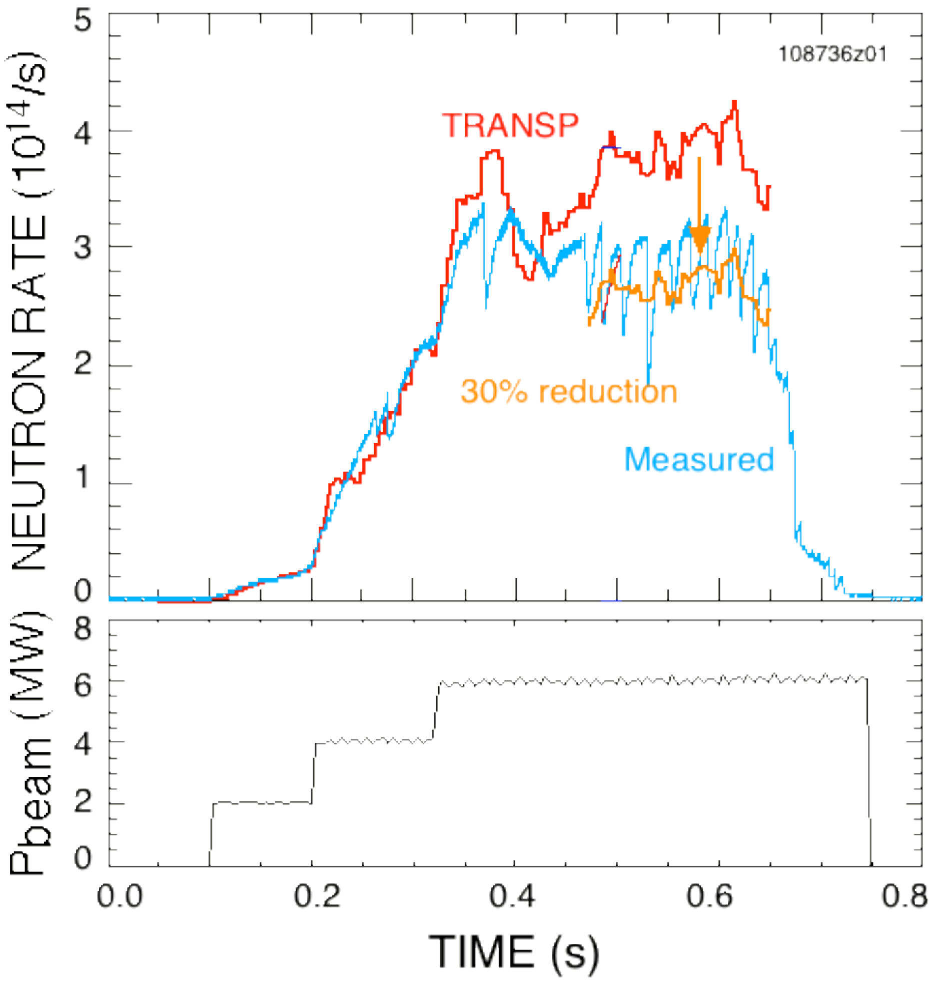
TAE, f.b. and CAE/GAE interact

NSTX

- TAE bursts precede fishbones.
- TAE-induced fast-ion losses don't affect CAE.
- Fishbone-induced bursts cause drops in CAE amplitude, small effect on neutron rate.

"Small" losses can add up

NSTX



- Fast ion population is modeled as constant source and exponential decay, $S(t) = S_0(1\text{-}e^{t/\tau})$.
- 20% drops every 18 ms with $\tau_s \approx 36$ ms means average drop of 30%.
- Lots swept under rug, but coincidently the prediction is pretty good…

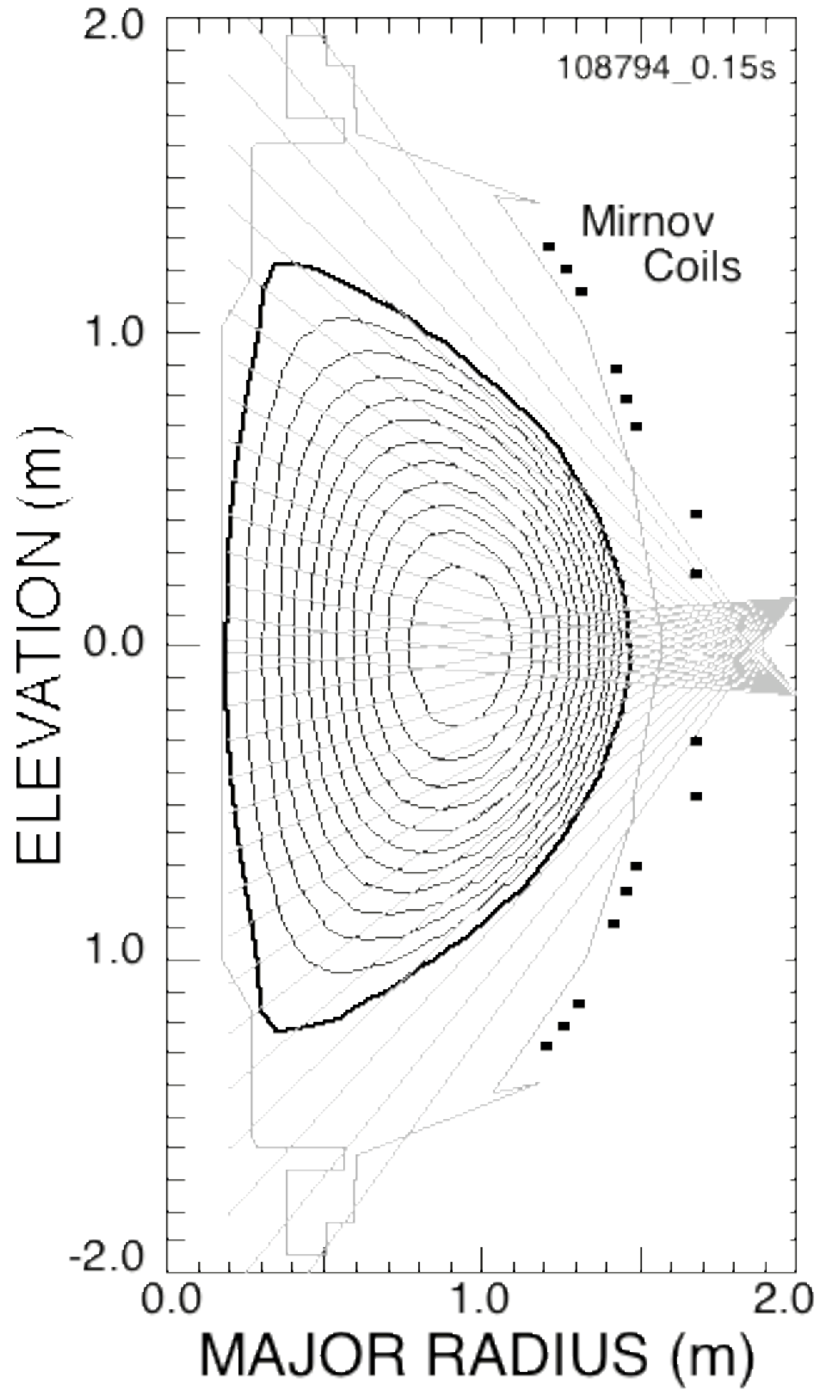
Theoretical modeling

- TAE modes:
  - Some work done with Nova-k (G. Kramer)
  - G. Fu has some preliminary results using M3D non-linear code.
- Fishbones:
  - R. White, L. Chen analytic theory, fast ion modeling.
  - G. Fu can potentially address with M3D
- Fast ion distributions from TRANSP…

Principal diagnostics of mode structure are Mirnov arrays, soft x-ray cameras

NSTX

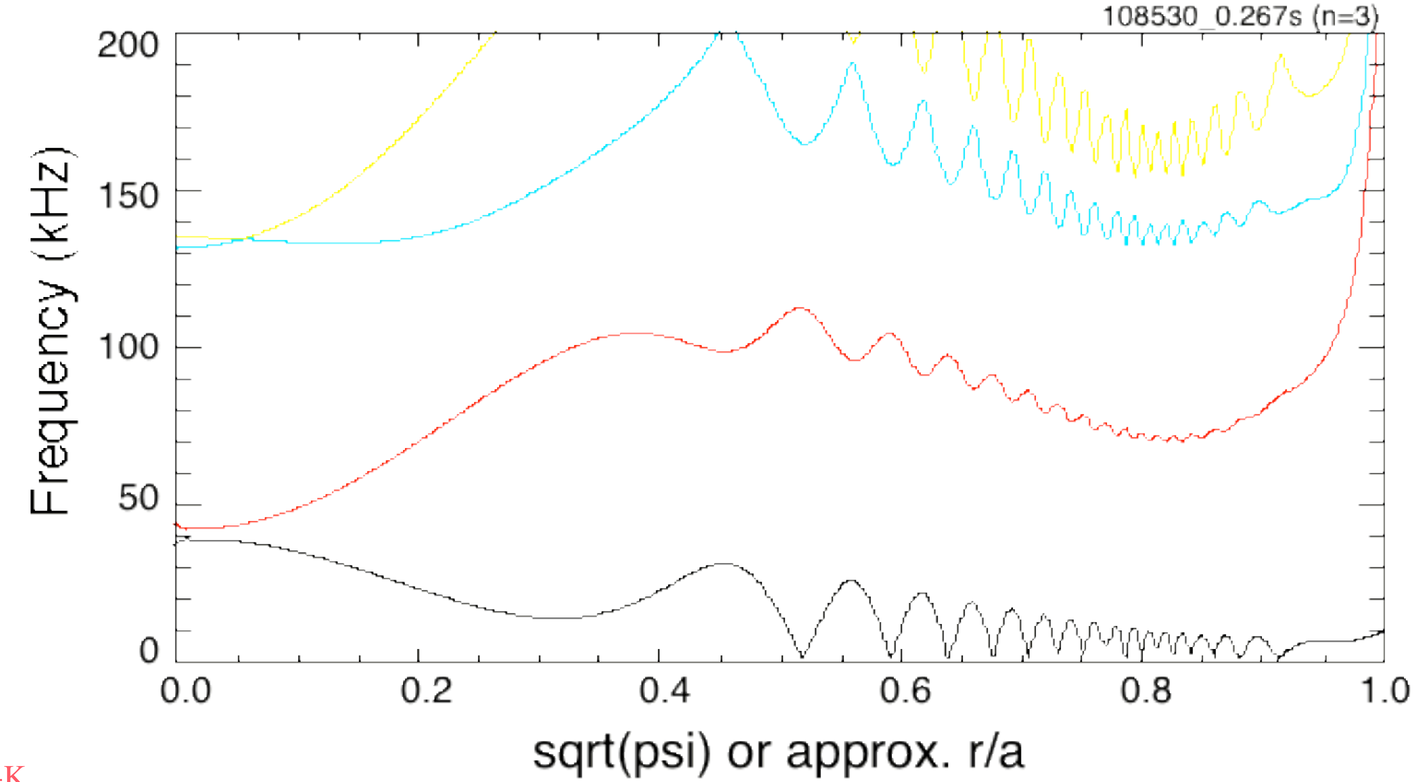
- Mirnov coils have limited poloidal coverage; plasma-coil separation varies significantly.
- Soft x-ray data dependent on plasma conditions; H-modes are bad.



ST's have large gaps due to low aspect ratio

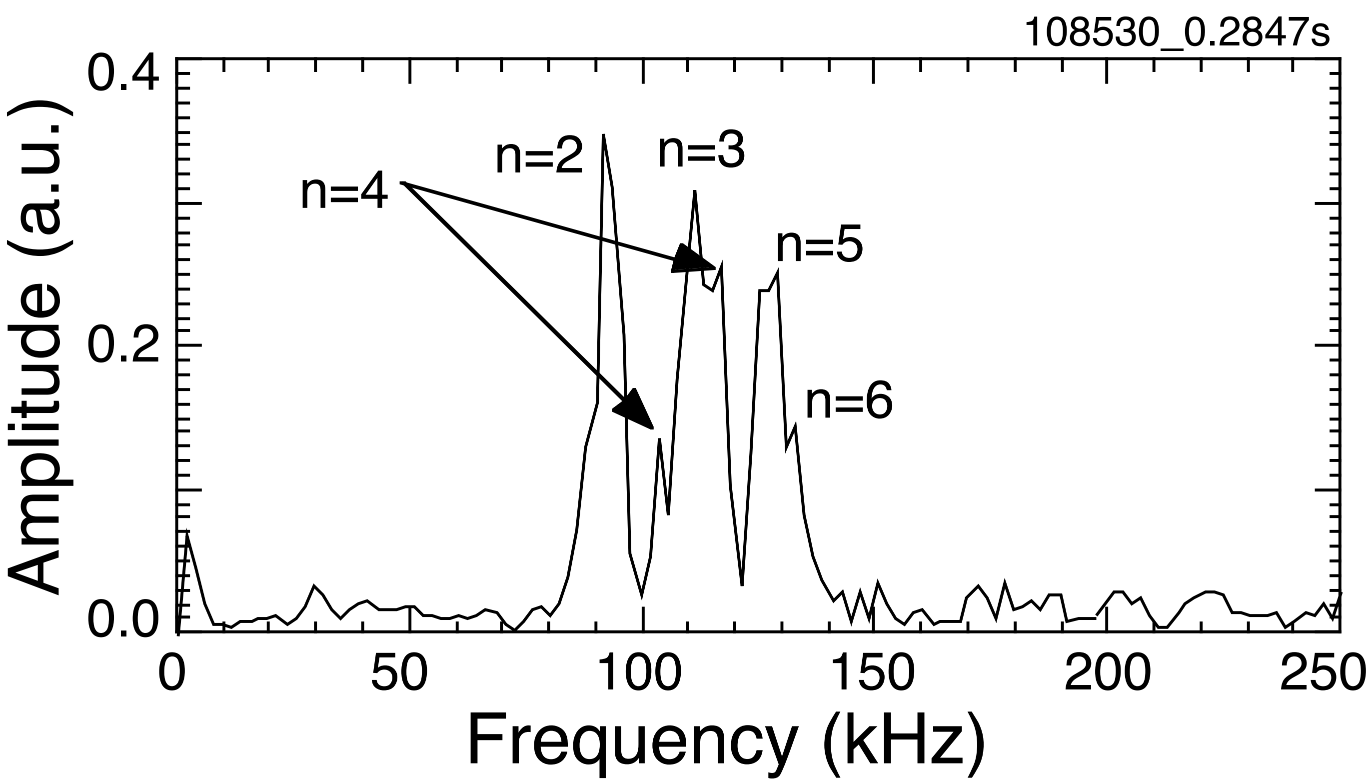
NSTX

- Gaps extend to very low frequencies; no separation in frequency space for fishbones and TAE.

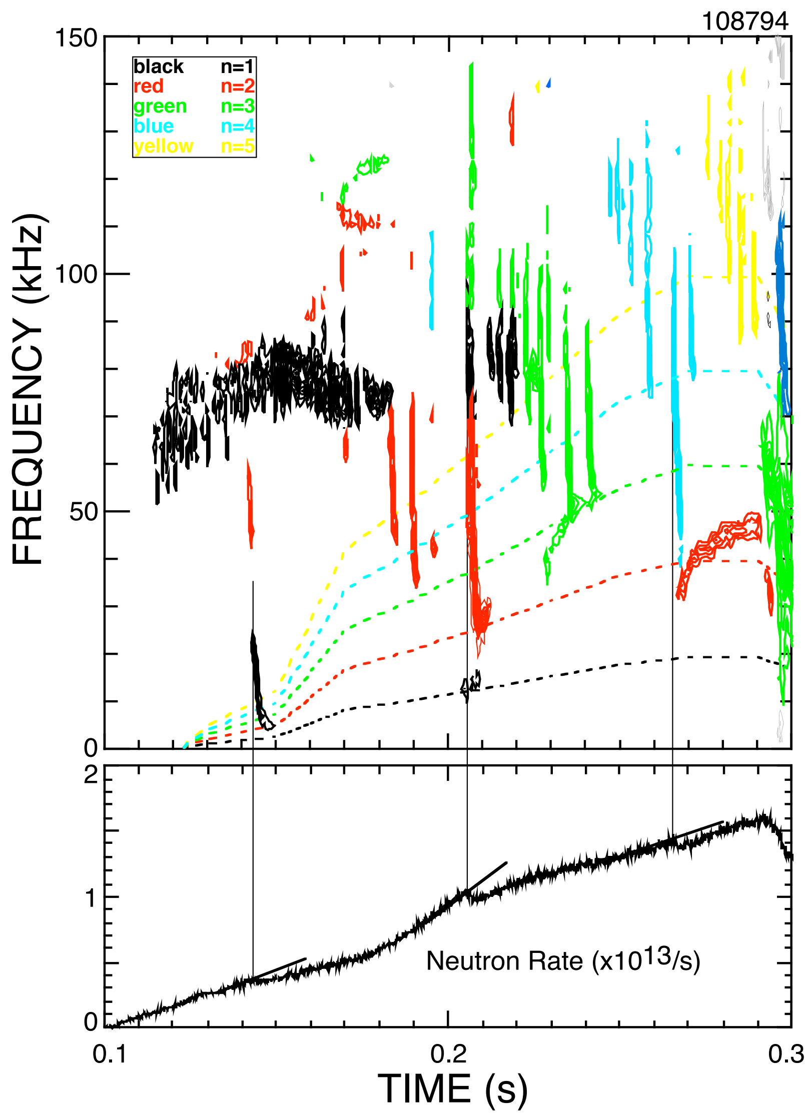


Often many modes are present simultaneously

- Largest amplitude (on Mirnov) at lower n, but higher m's should have faster fall-off from plasma edge.

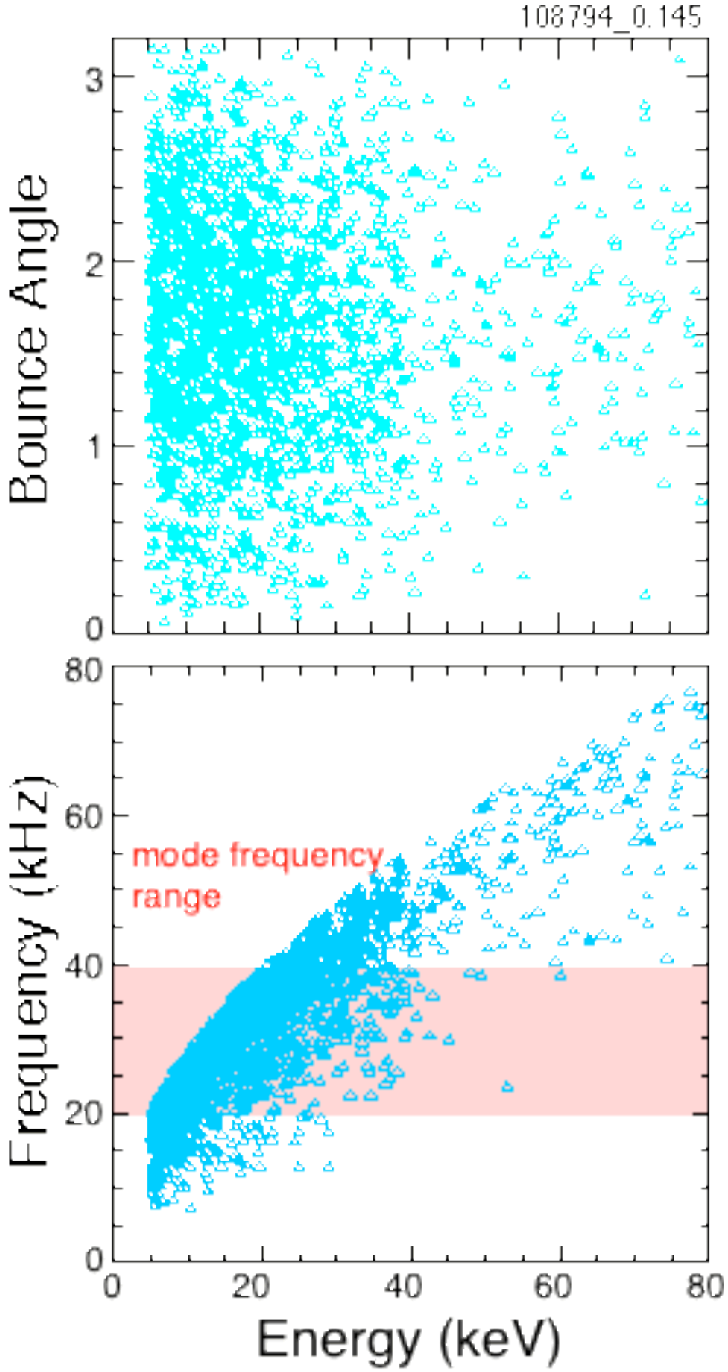


"Not your typical fishbones…"



- Retain strong frequency chirping and periodic bursting character.
- Toroidal mode numbers up to n=5 have been seen.
- Often with q(0) > 1 and m >1
- Onset frequency well above precession drift frequency.
  - Probably bounce resonance*

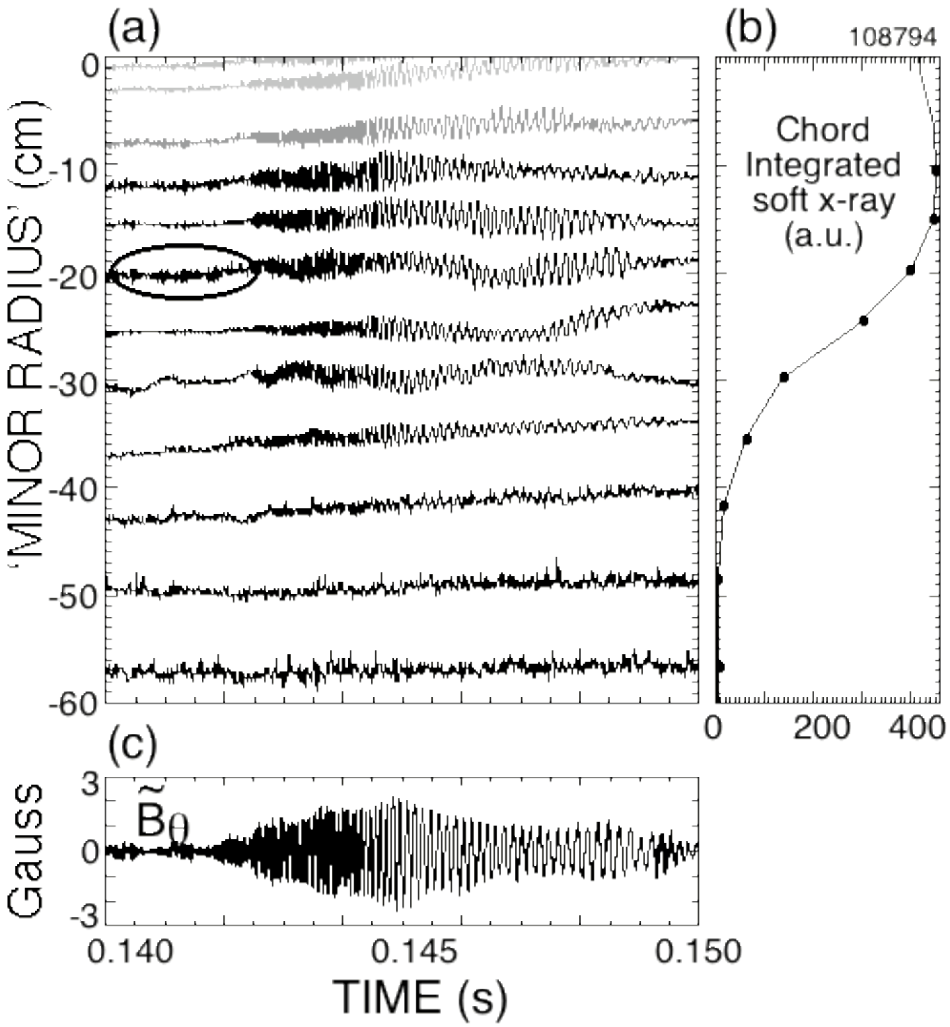
*Fredrickson, Chen, White, submitted to Nucl. Fusion



Bounce-resonance, as well as precession, can drive f.b.'s

- For effective drive, need large average bounce angle…
- …and bounce frequency in reasonable range.
- For most conventional, beam heated tokamaks, this is not the case.
- However, ITER may be a different story.

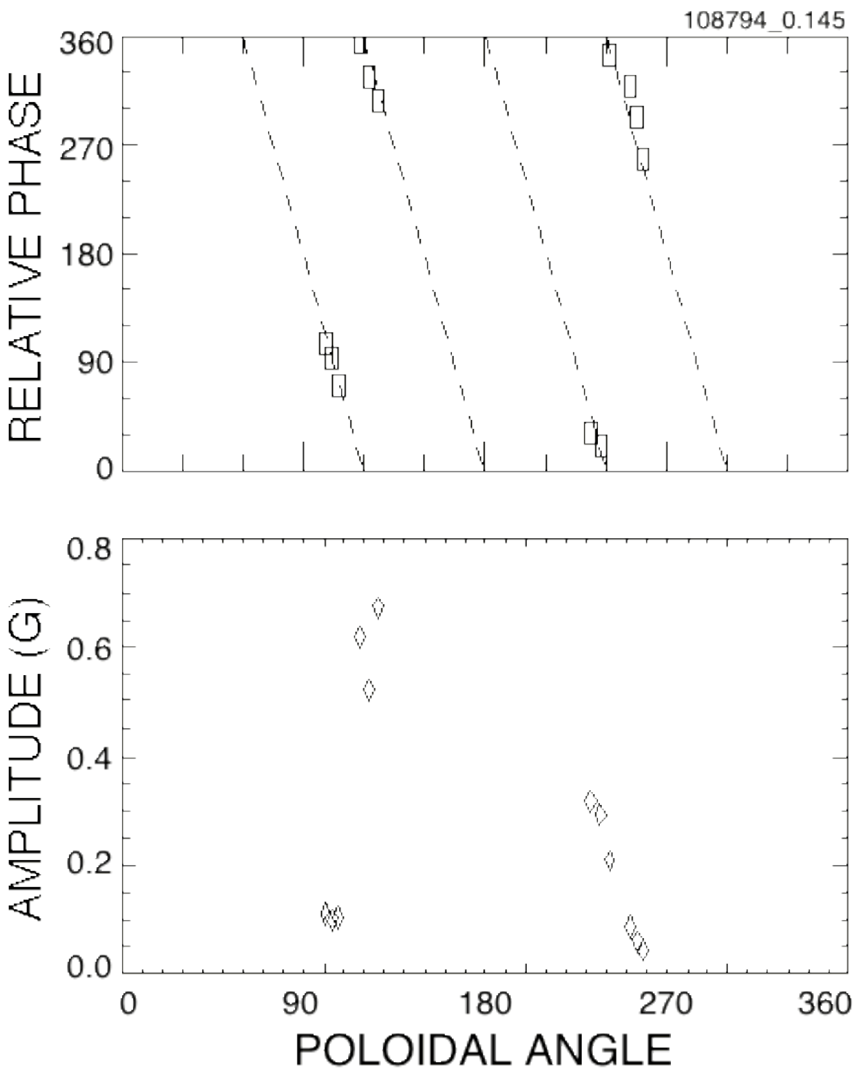
Mode amplitude typically largest near core, data limited.



- Data acquisition rate ≈ 200 kHz.
- Horizontally viewing camera.
- High frequency f.b.s also seen; much weaker.
- No obvious phase inversion; no island?
- Signal low near edge.

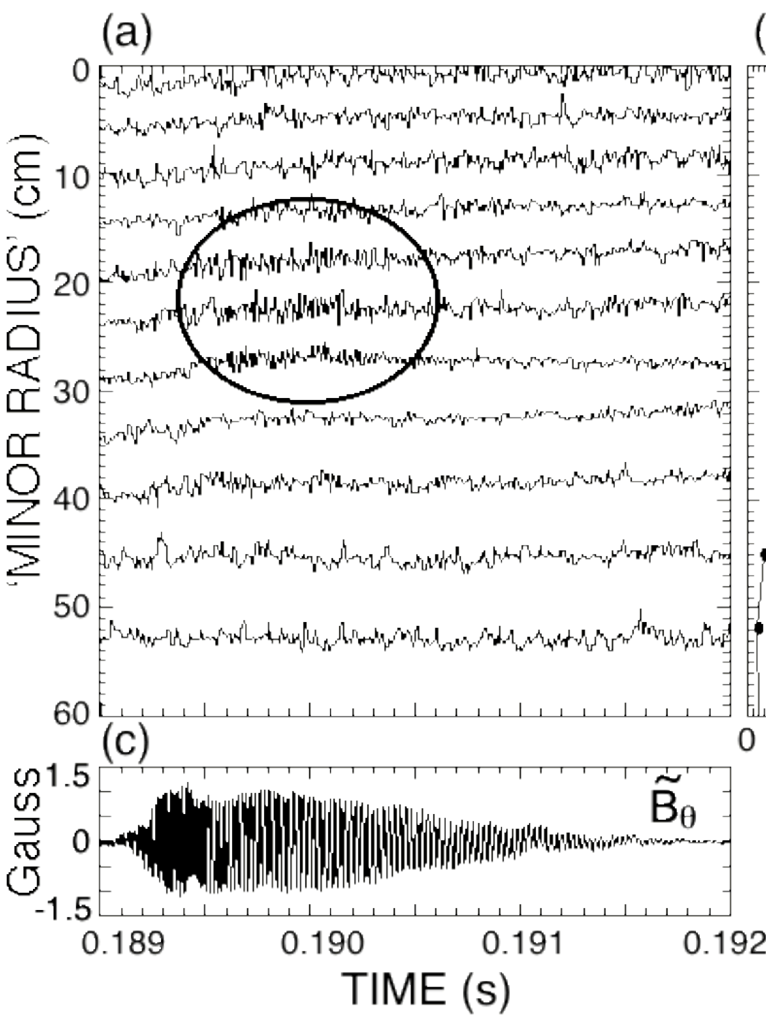
Soft x-ray data from JHU cameras.

Fishbones appear to be strongly ballooning?



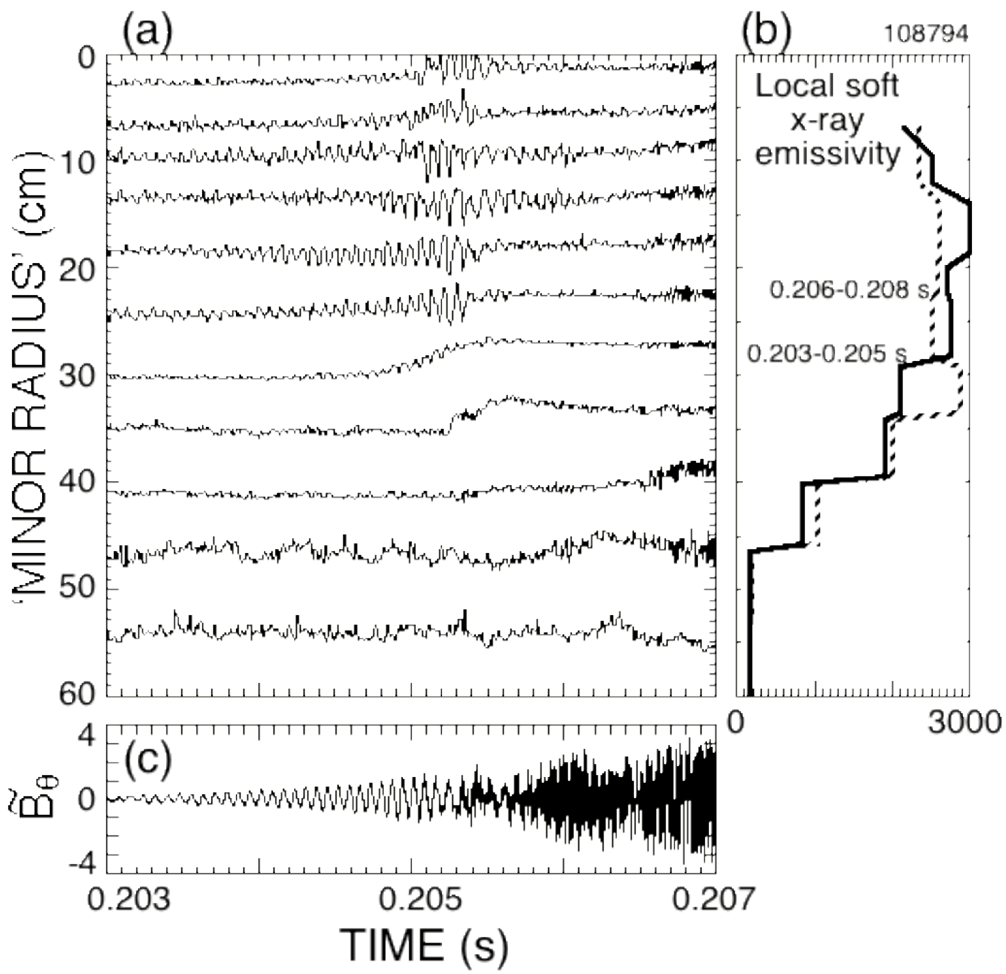
- Interpretation a little tricky due to varying plasma-coil separation.
- Outboard poloidal wavelength reasonably long.
- Inboard wavelength irrelevant?

Radial structure can differ?



- This is an n=2 fishbone vs. n=1 for first case.
- Similar amplitude on Mirnov coils (still ballooning, $m_{eff} \approx 7$).
- Mode appears to be weaker on soft x-rays.
- Soft x-ray signal level similar (only 40-50 ms later).
- Neutron drop similar.

Mini-reconnection events combined with fishbones



- Does not appear to be a sawtooth; q greater than 1 at this time.
- Precursor is n=1.
- Event followed immediately by fishbone.
- Redistribution of fast ions triggers fishbone?

Summary

NSTX

- "Collective" fast ion losses seen on NSTX
  - "fishbone" induced losses of up to 20% and new fishbone physics
  - TAE induced losses of 10-15% per burst
  - Coupled TAE/fishbone induced losses
- Losses are significant, either because they may:
  - Raising ignition threshold
  - Increase first wall power loading
- Need physics basis to extrapolate to NSST or ITER