Comparative Study of Rapidly Chirping Beam-Ion Driven Instabilities in NSTX and DIII-D

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ABSTRACT. Beam-driven instabilities with frequencies of the order of 100 kHz are common in both NSTX and DIII-D. In NSTX, the frequency often changes appreciably ($\Delta f/f >$ 10%) in milliseconds, while rapid frequency chirping is rare in DIII-D. The origin of this difference is investigated. One hypothesis is that rapid chirping is associated with strong shear in the characteristic orbital frequencies of the fast ions, such as $d\omega_b/dr$. (ω_b is the bounce frequency of trapped beam ions.) Another possibility is that linewidths are broad in NSTX because many TAEs are simultaneously desta-

bilized in the wide spectral gap. A third possibility is that nonlinear saturation of the Alfvén instabilities shows more variety in a spherical tokamak because the transport of beam ions is reduced.

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Motivation

- An unstable mode isn't necessarily deleterious– it all depends how it saturates. (For example, Alfvén modes can be beneficial–see QP1.046 in this session.)
- Simplified models of nonlinear saturation have had several successes for modes in the TAE band of frequencies [1, 2, 3] but understanding is still incomplete.
- Beam-driven modes in MAST and NSTX often chirp rapidly in frequency. This phenomenon is occasionally observed in DIII-D but it is rare [4].
- An Alfvén similarity experiment between NSTX and DIII-D with closely matched parameters was recently completed [5]. Can a comparative study shed light on the mechanisms that control chirping?

Hypotheses: What Causes Chirping?

Spatial dependence of orbital motion Early theories of the fishbone instability suggested that the mode chirps because the beam-ion precession frequency decreases with radius [6]. As the beam ions move out radially, the mode manages to preserve the resonance. A "relay runner" model may explain how this occurs [7].

Doppler shift effects Initial analysis of DIII-D data suggested that chirping occurs for particular values of the toroidal rotation frequency [4] but subsequent data contradicted this hypothesis [8]. Another idea is that, as the mode amplitude grows, magnetic interaction with the vessel or with uncorrected error fields exerts a torque on the mode, causing it to slow down.

Phase-space hole According to a theory by Berk *et al.* [9], frequency sweeping is determined by a competition between three different rates: the fast-particle drive, γ_L, the damping due to background dissipation, γ_d, and the effective collision rate for scattering out of resonance in phase space, ν_{eff}. Frequency sweeping occurs when $\gamma_L \gtrsim \gamma_d$ but $\nu_{eff} < \gamma_d$. In an experiment involving hot electrons [10], the occurrence of chirping was controlled by increasing ν_{eff}. Recent comparisons of this theory with chirping Alfvén modes observed in JT-60U and MAST are promising [11].

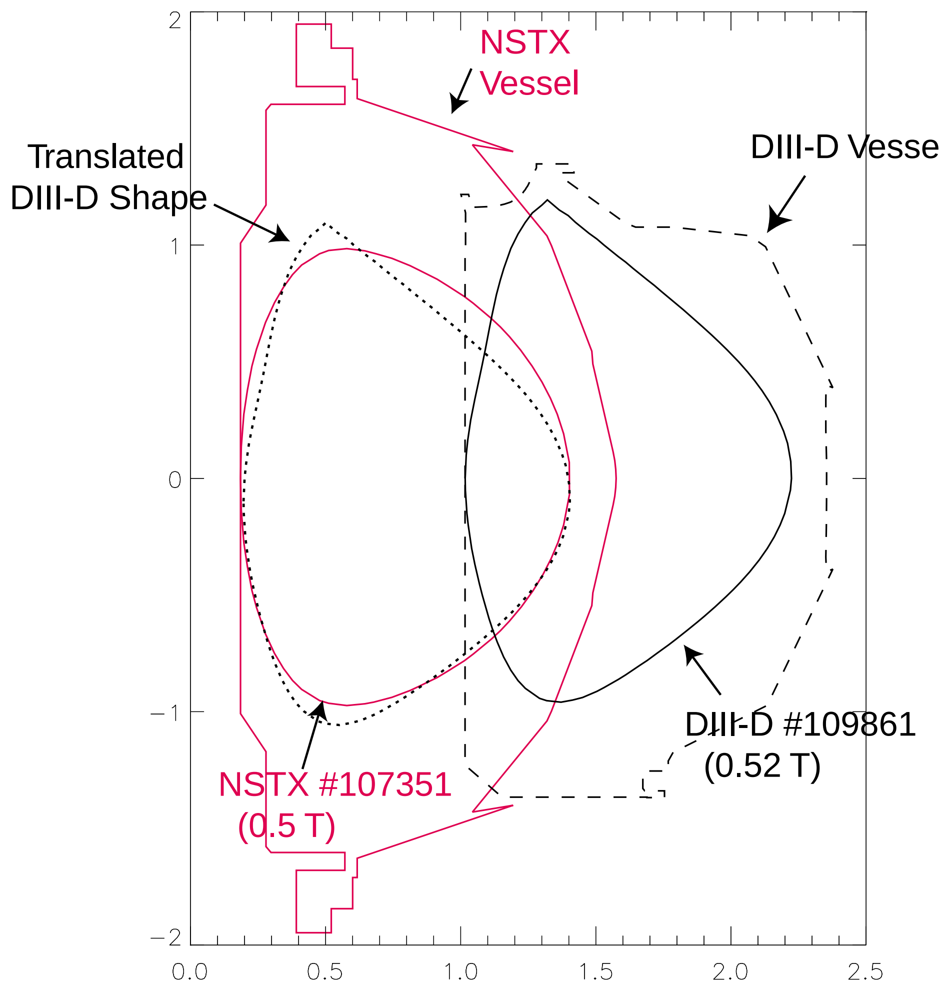
Wide spectral gap The gaps in the Alfvén continuum are very wide in a ST and different poloidal numbers are more strongly coupled than in DIII-D. Perhaps the linewidth is broad in NSTX because several TAEs are simultaneously destabilized.

Different beam-ion transport Differences in radial transport of the beam ions may account for the difference (perhaps acting as a different ν_{eff} in the Berk-Breizman model).

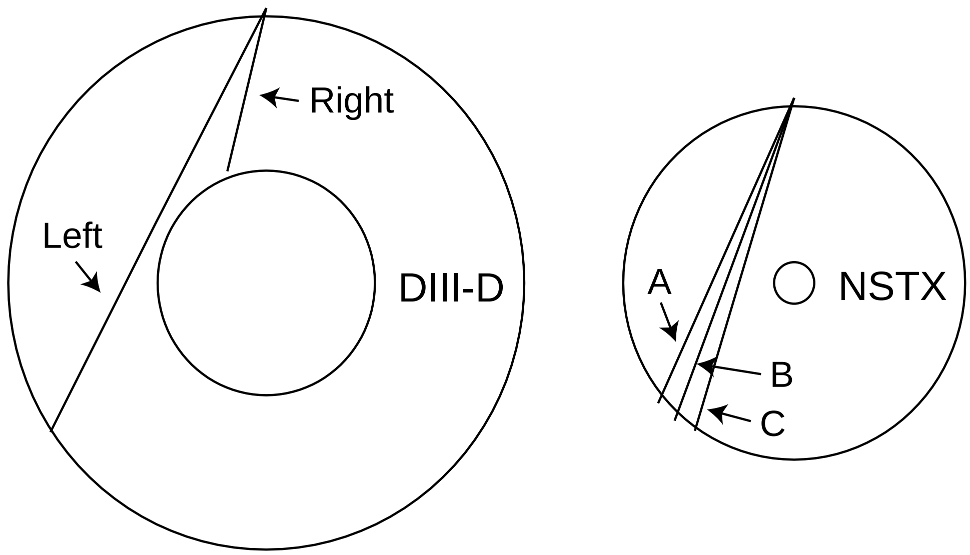
More toroidal harmonics Chirping modes usually have a dominant toroidal mode number; in DIII-D, steady modes often consist of a "cluster" of different n numbers. Perhaps the resonances in phase space are more likely to occur in DIII-D, causing the saturation mechanism to be an "avalanche" [12].

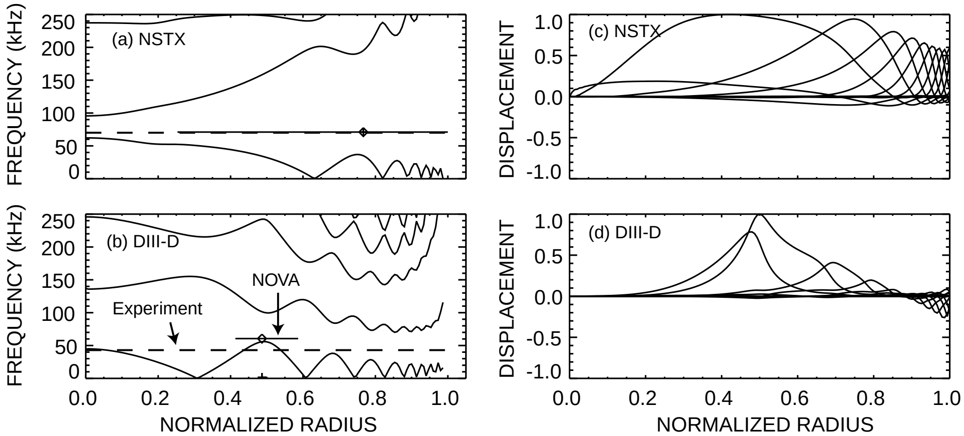
Alfven Mode Similarity Experiment

Goals: Match NSTX field and shape to study R dependence.
(The beams are similar, so this matches v_b/v_A.)
Measure stability threshold.
Measure most unstable toroidal mode number n.

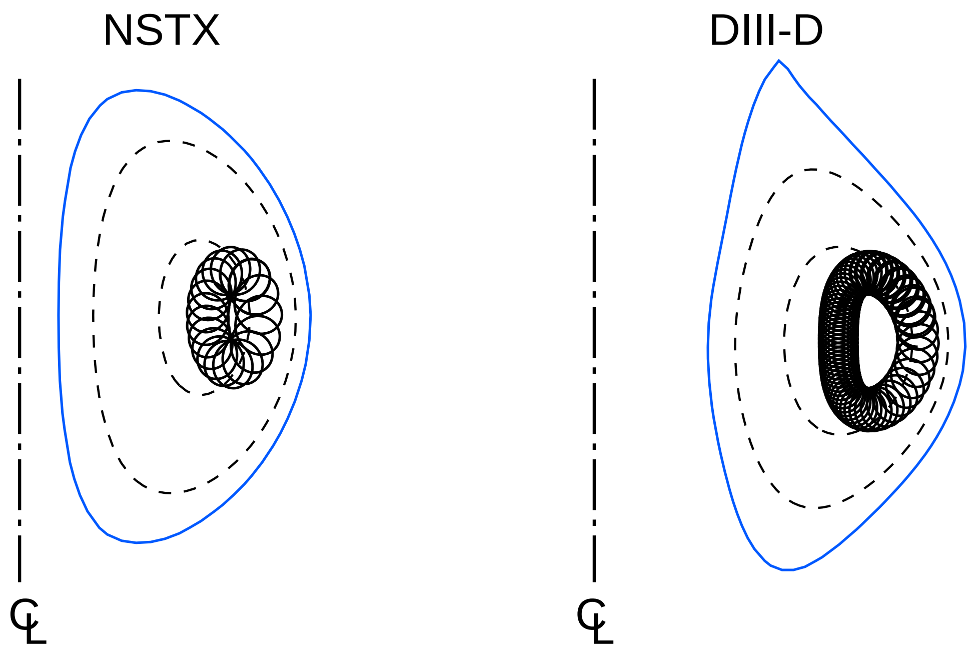


Different Beam Combinations Match Average Pitch or Trapped/Passing Fraction
(80 keV deuterium beams in both devices)

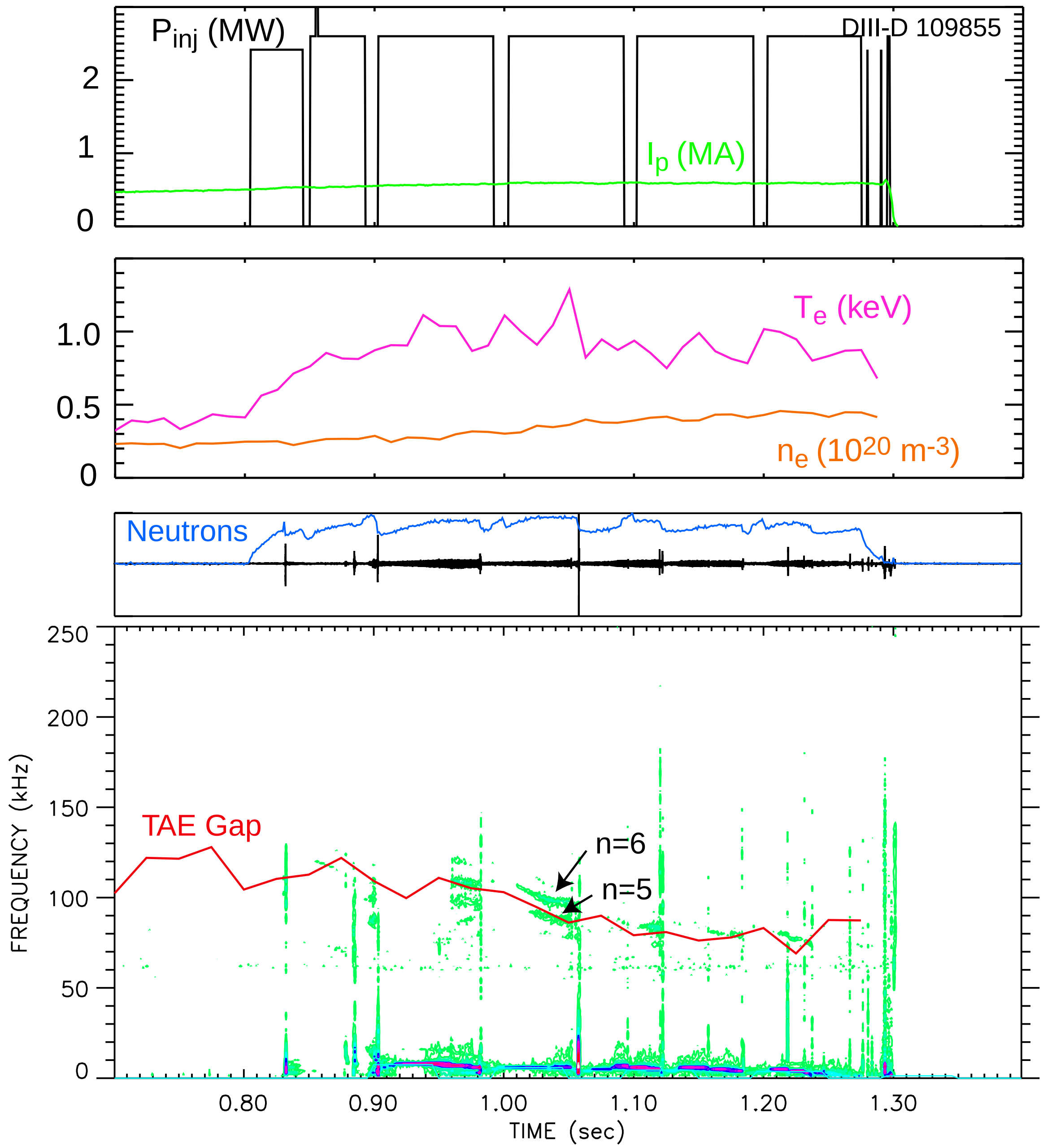



(a) NSTX
FREQUENCY (kHz)
(b) DIII-D
NOVA
Experiment
NORMALIZED RADIUS
(c) NSTX
DISPLACEMENT
(d) DIII-D
NORMALIZED RADIUS

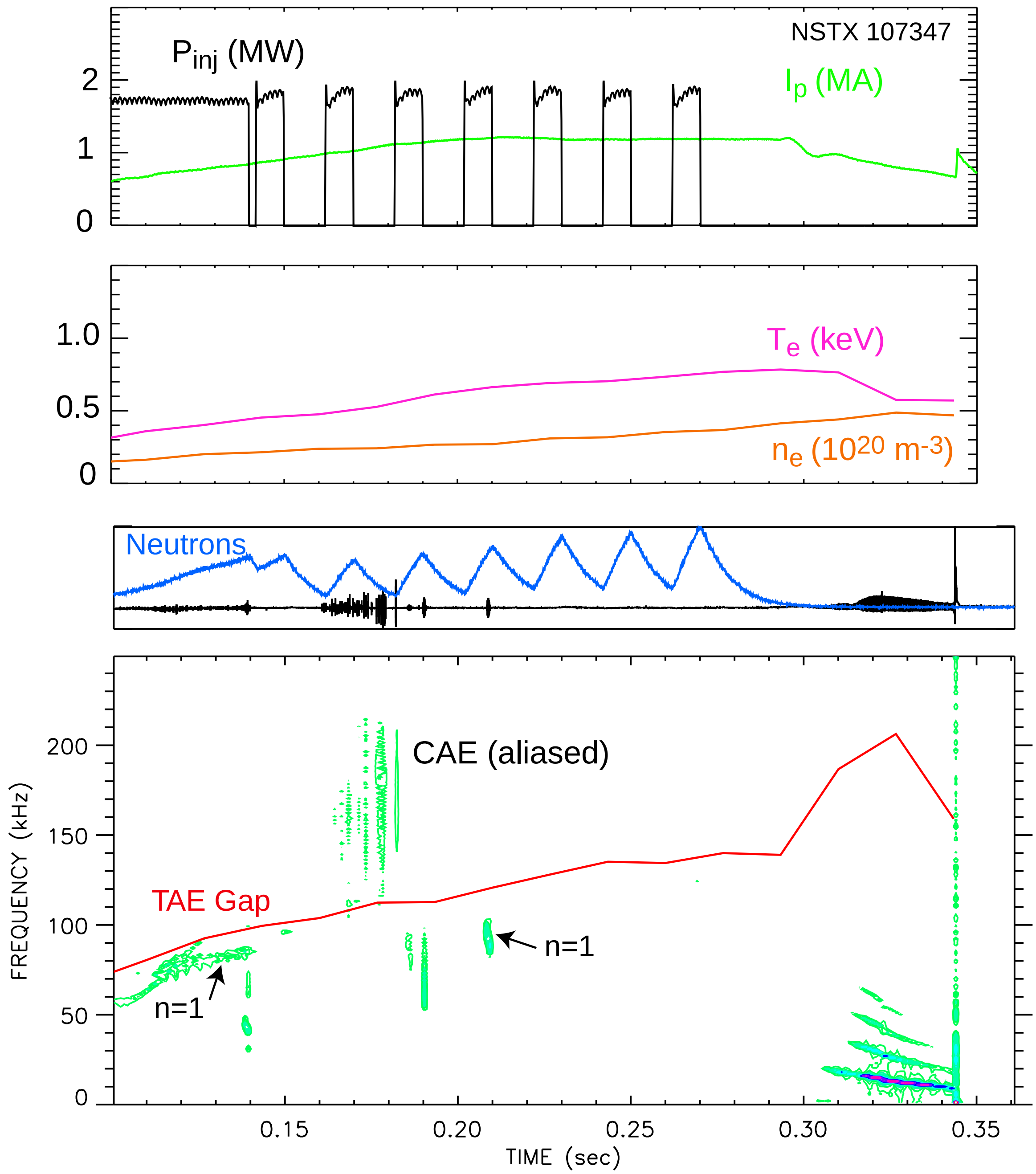
Beam-ion Orbits Span Most of the Plasma



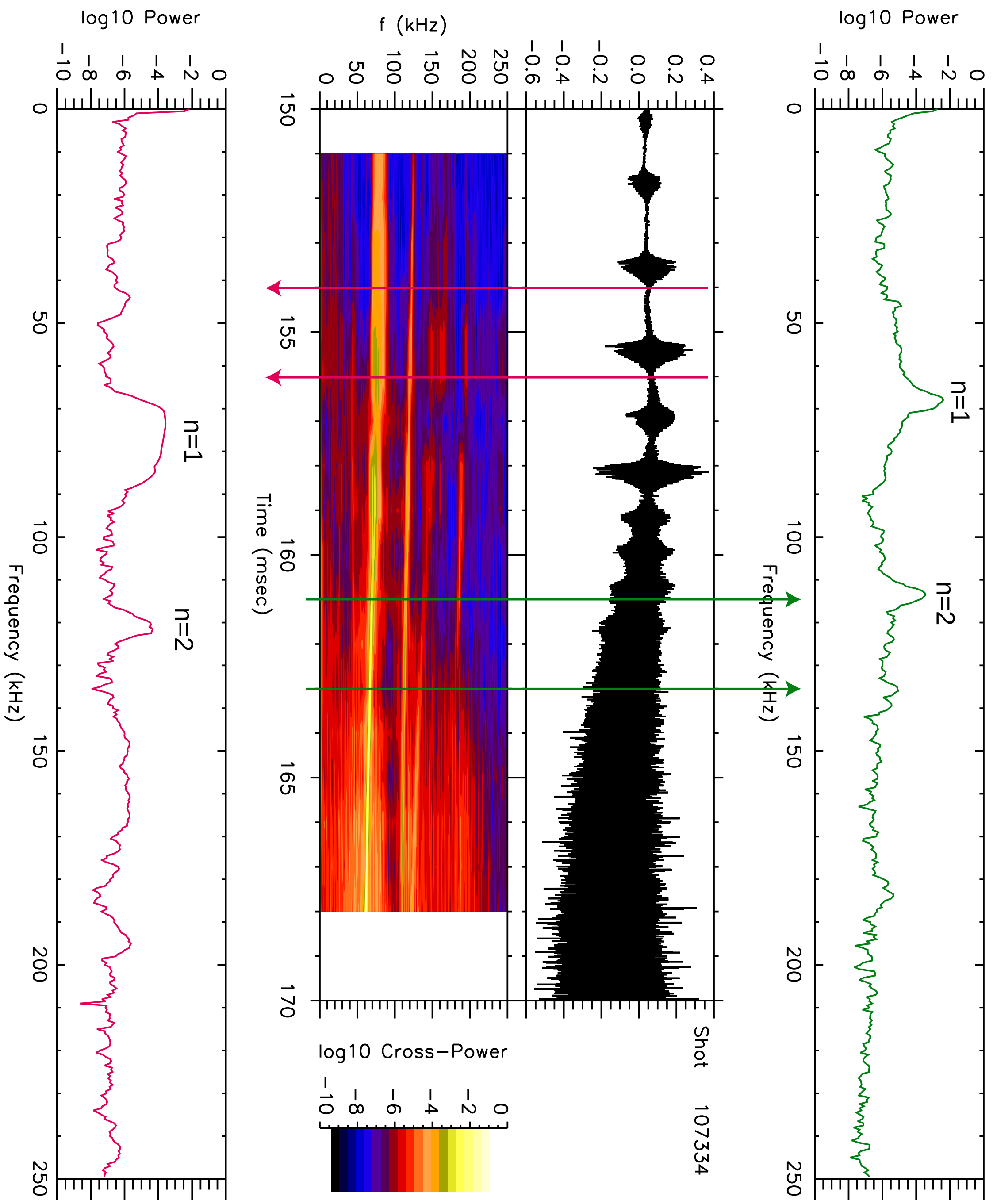
A typical 0.6 T DIII-D Discharge

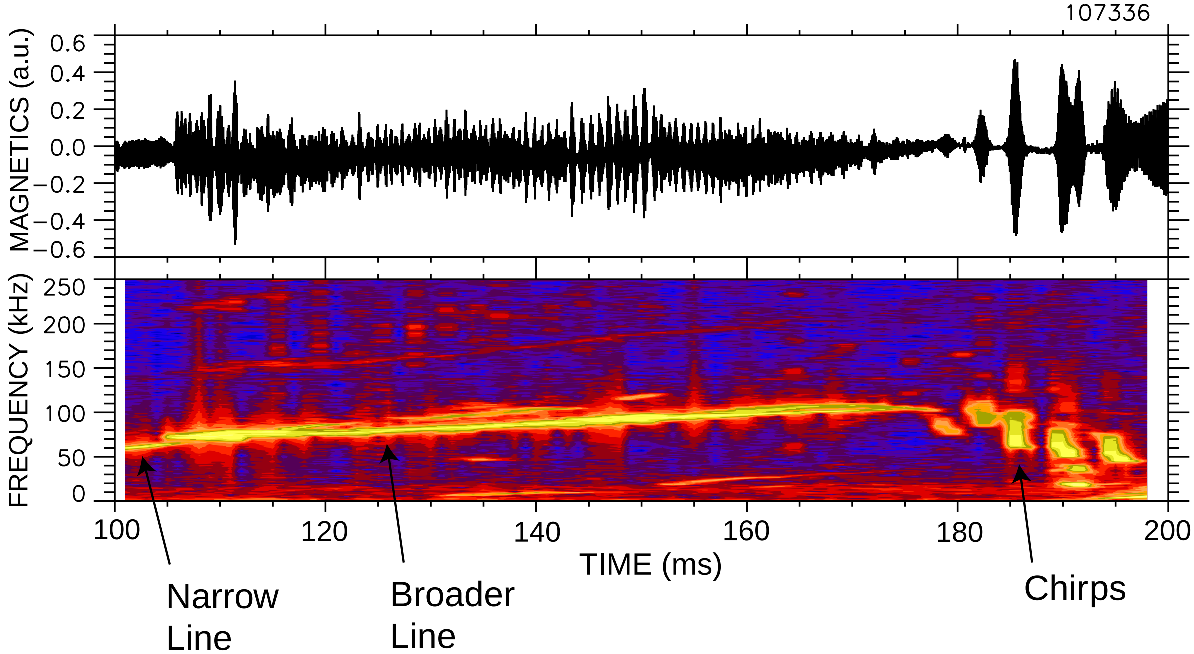


A typical NSTX Discharge



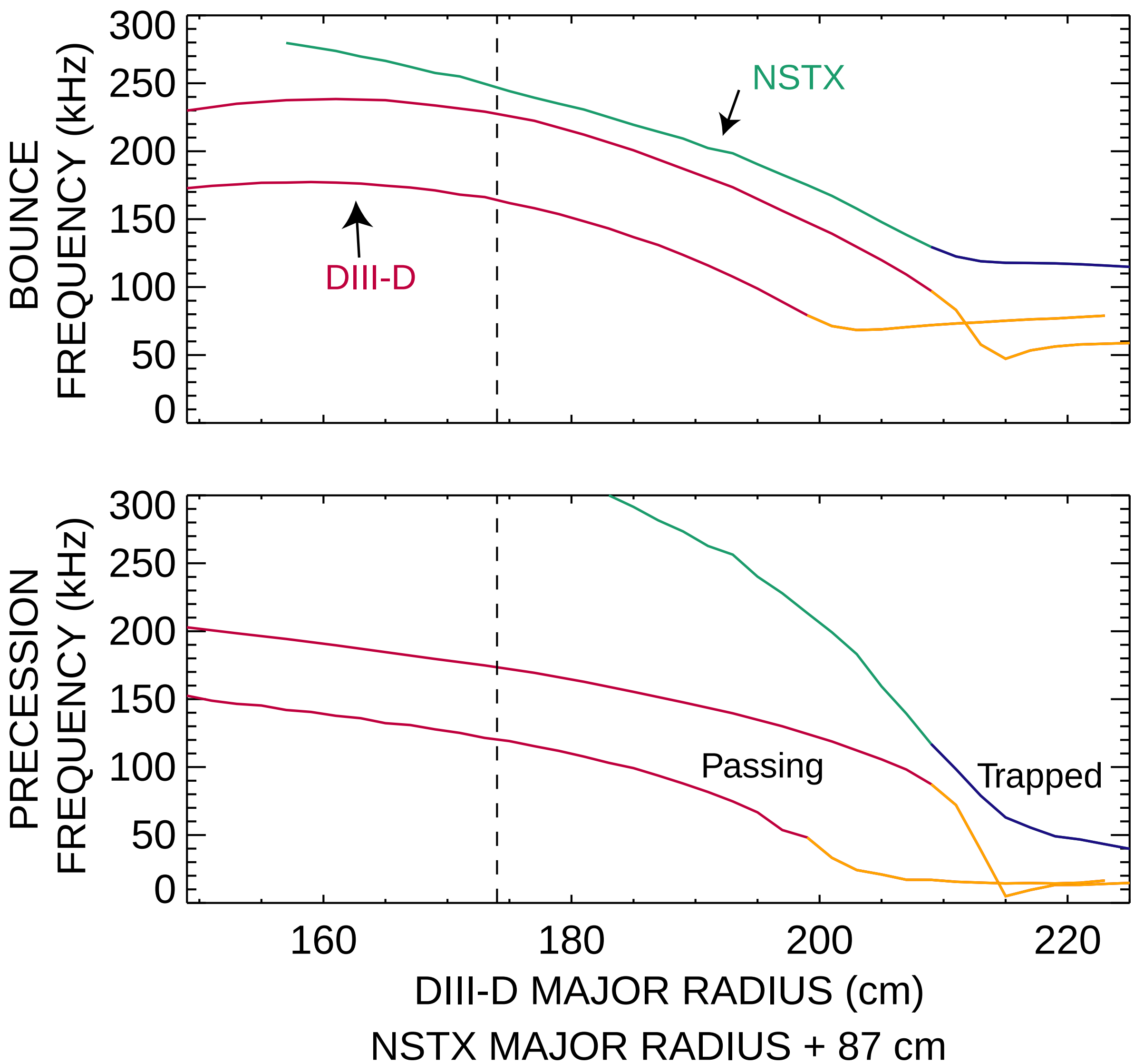
Broad & Narrow Features Have Similar Frequencies



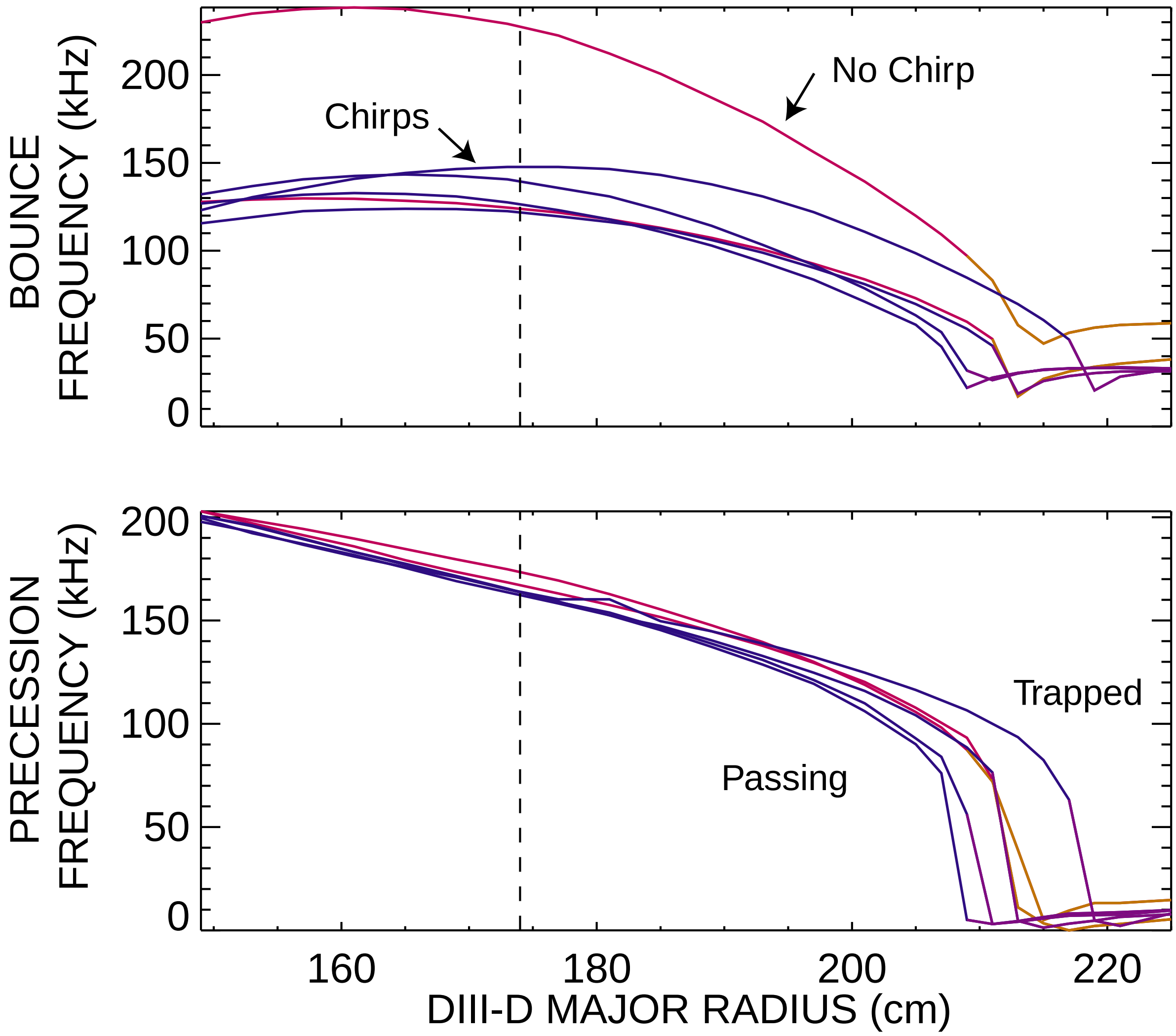


107336
MAGNETICS (a.u.)
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
FREQUENCY (kHz)
250
200
150
100
50
0
100
120
140
160
180
200
TIME (ms)
Narrow Line
Broader Line
Chirps

Orbital Frequency Hypothesis: NSTX Similar to DIII-D



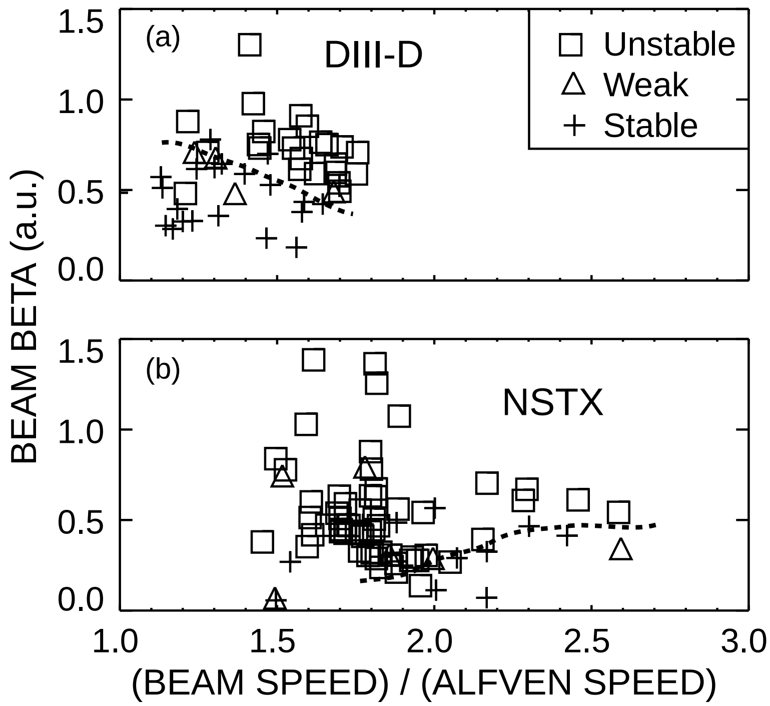
Orbital Frequency Hypothesis: DIII-D Chirping and Steady Modes are Similar



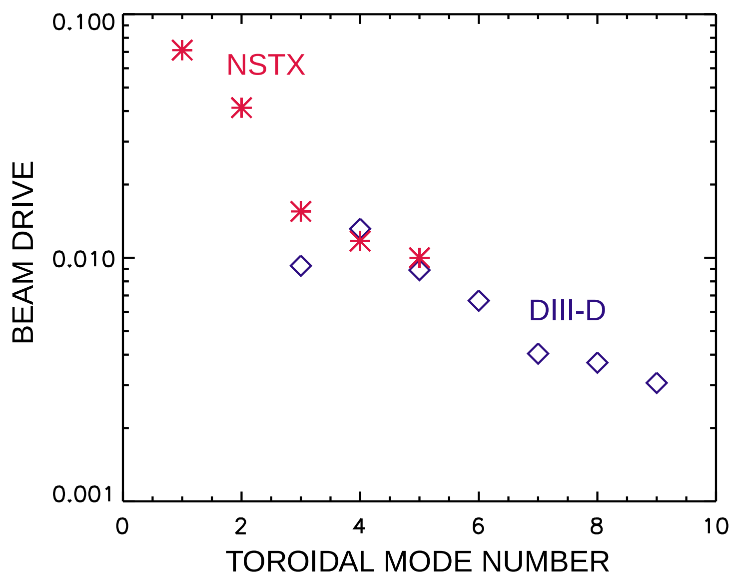
Berk-Breizman Hypothesis: Some Rates are Uncertain

- Z_{eff} in NSTX is usually larger than in DIII-D $\rightarrow$ if ν_{eff} is caused by pitch-angle scattering, makes chirping less likely.
- Stability study suggests marginal stability in NSTX occurs at slightly lower values of beam beta; also NOVA-K finds stronger drive in NSTX $\rightarrow$ larger value of γ_L/γ_d favors chirping.
- The relative value of the damping rate is uncertain both experimentally and theoretically.

Larger γ_L in NSTX?



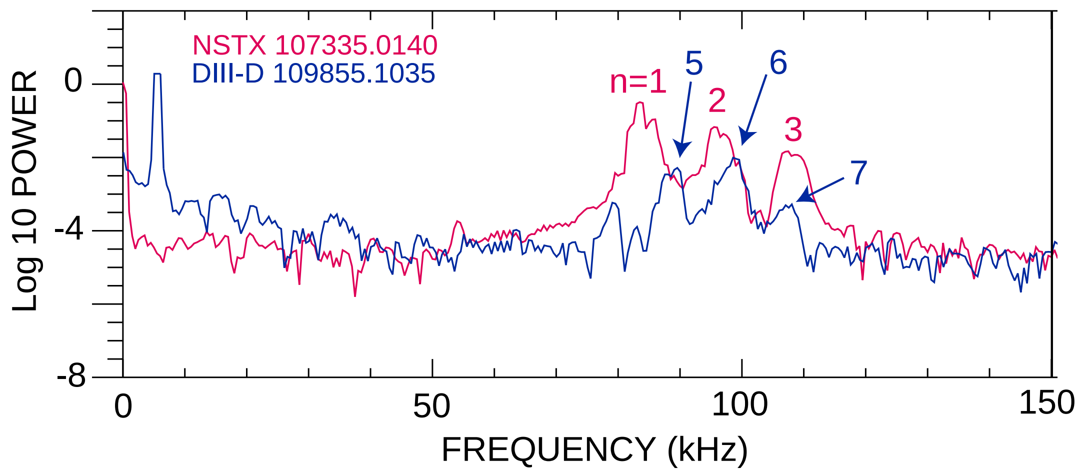
NOVA-K Calculation of γ_L



Beam Transport Hypothesis is Plausible

- Reductions in the neutron rate that correlate with Alfvén activity occur less often in NSTX than in DIII-D.
- In particular, in the similarity experiment, the neutron rate was unaffected by Alfvén activity in NSTX but was $\sim 15\%$ lower than the classical rate in DIII-D.
- In earlier work, a semi-empirical preadator-prey model that attributes mode saturation to beam-ion losses agreed well with the TAE data [1].
- For a given mode amplitude at the wall, steady TAE modes in DIII-D cause ten times larger drops in the neutron rate than chirping modes [4].
- DIII-D plasmas with effective transport generally have multiple modes. Is this always the case? (Needs further analysis.)

Multiple unstable toroidal modes are common in DIII-D



Conclusions: What Causes Chirping?

Spatial dependence of orbital motion Probably not

Doppler shift effects Excluded

Phase-space hole Maybe–needs better analysis or more clever experiments

Wide spectral gap Not evaluated here (but seems unlikely–the DIII-D gaps are already quite wide).

Different beam-ion transport Empirical results OK–needs rigorous study

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