Example of BAAEs in DIII-D and the evaluation of the chirping criterion

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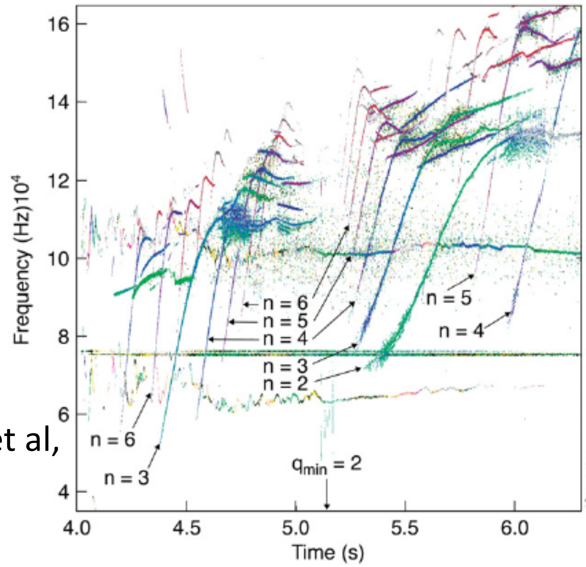
Two types of frequency shift observed experimentally

Frequency sweeping

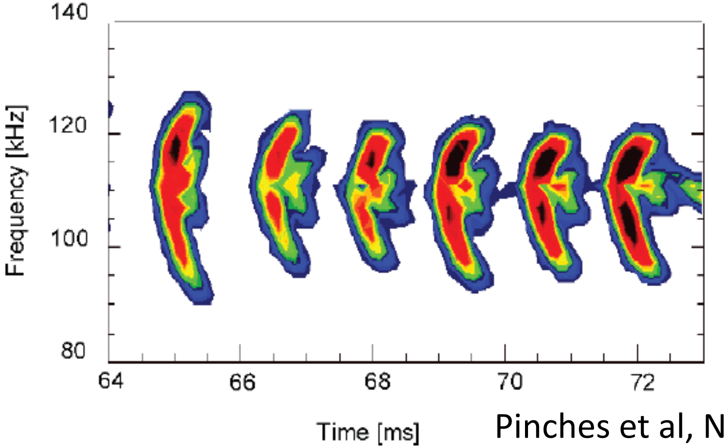
- frequency shift due to time-dependent background equilibrium
- MHD eigenmode
- timescale: ~100ms



Sharapov et al, PoP 2006

Frequency chirping

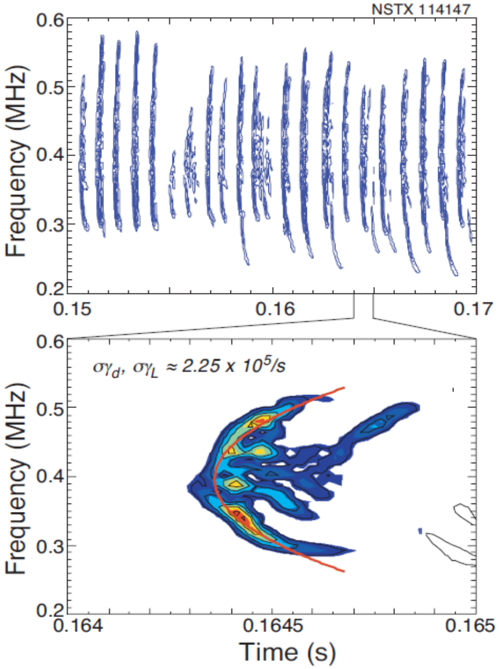
- frequency shift due to trapped particles
- does not exist without resonant particles
- timescale: ~1ms



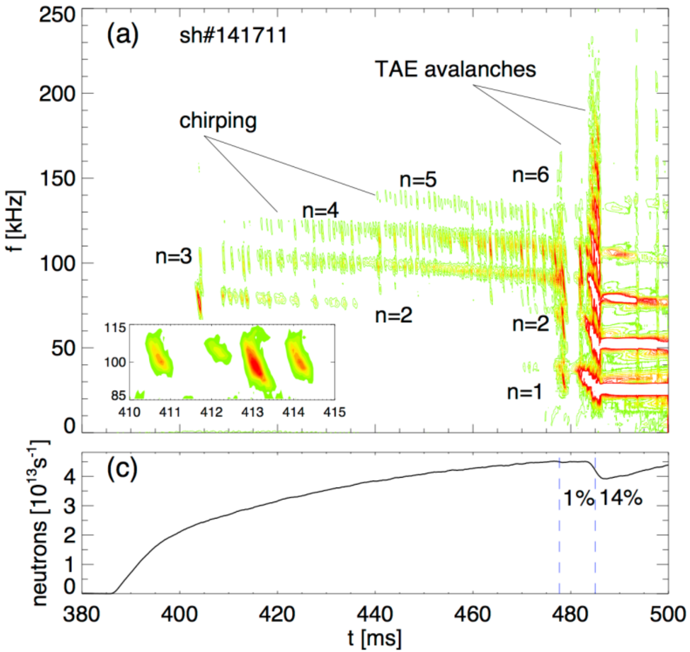
Pinches et al, NF 2004

Chirping modes can degrade the confinement of energetic particles

GAE/CAE
Fredrickson et al, PoP 2006.



TAE Podestà et al, NF 2012



Up to 40% of injected beam is observed to be lost in DIII-D and NSTX

Chirping is ubiquitous in NSTX but rare in DIII-D. Why??

Outline

- **Theory of nonlinear instability near theshold**
- BAAE identification
- Chirping criterion analysis via TRANSP to infer scattering rates

Nonlinear dynamics of driven kinetic systems close to threshold

Starting point: **kinetic equation** plus **wave power balance**

Assumptions:

- Perturbative procedure for $\omega_b \ll \gamma$
- Truncation at third order due to closeness to marginal stability

Cubic equation: lowest-order nonlinear correction to the evolution of mode amplitude A:

$$\frac{dA}{dt} = A - \int_0^{t/2} d\tau \tau^2 A(t-\tau) \int_0^{t-2\tau} d\tau_1 e^{-\nu_{scatt}^3 \tau^2 (2\tau/3+\tau_1) + i\nu_{drag}^2 \tau(\tau+\tau_1)} A(t-\tau-\tau_1) A^*(t-2\tau-\tau_1)$$

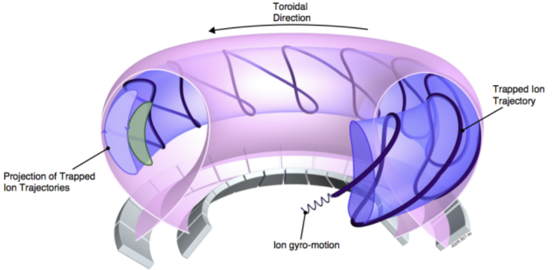
stabilizing

destabilizing (makes integral sign flip)

- If nonlinearity is weak: linear stability, solution saturates at a low level and f merely flattens (system not allowed to further evolve nonlinearly).
- If solution of cubic equation explodes: system enters a strong nonlinear phase with large mode amplitude and can be driven unstable (precursor of chirping modes).

Berk, Breizman and Pekker, PRL 1996 Lilley, Breizman and Sharapov, PRL 2009

Generalization to tokamak geometry: cubic equation with collisional coefficients varying along resonances and particle orbits



Action-angle formalism for the general problem, with a similar perturbative approach employed before, leads to the **generalized criterion for existence of steady-state solutions** (no chirping):

$$\sum_{l,\sigma_\parallel}\underline{\int dP_\varphi \int d\mu}\, \frac{\tau_b}{\nu_{drag}^4}|V_l|^4 \left|\frac{\partial\Omega_l}{\partial I}\right| \frac{\partial F}{\partial I} Int \boxed{>0}$$

>0: steady state solution

<0: chirping may happen

$$Int \equiv -Re\int_0^\infty dz \frac{z}{-\frac{\nu_{diff}^3}{\nu_{drag}^3}z + i} exp\left[-2\frac{\nu_{diff}^3}{\nu_{drag}^3}z^3/3 + iz^2\right]$$

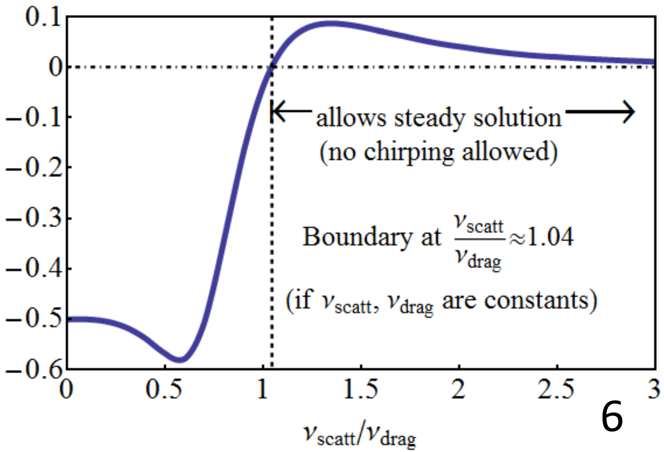
Phase space integration

Eigenstructure information:

$$q\int dt \mathbf{v}_{dr}\cdot\delta\mathbf{E}e^{i\omega t}$$

Resonance surfaces:

$$\Omega\left(\mathcal{E}, P_\varphi, \mu\right) = 0$$



Criterion was incorporated into NOVA-K: nonlinear prediction from linear physics elements

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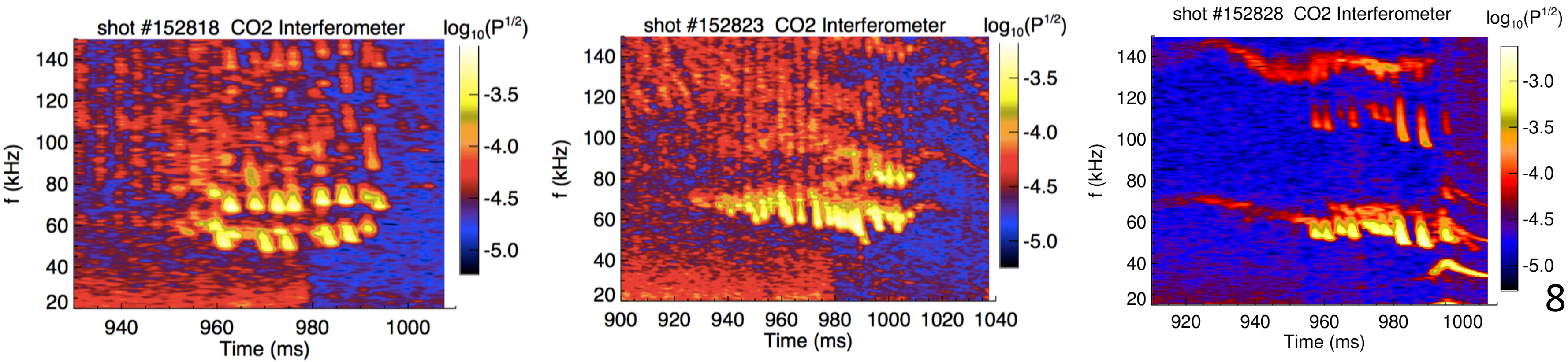
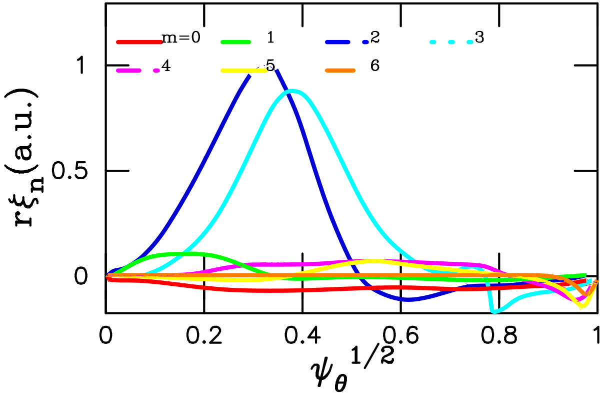
Common features observed in the DIII-D chirping BAAE discharges

- high ion temperature (8-13 keV on axis)
- q_{min} ~1.6-2.1
- strong toroidal rotation (35-50 kHz on axis)
- BAAEs appear to be located close to q_{min}
- the emergence of chirping correlates with a marked drop in the microturbulence level

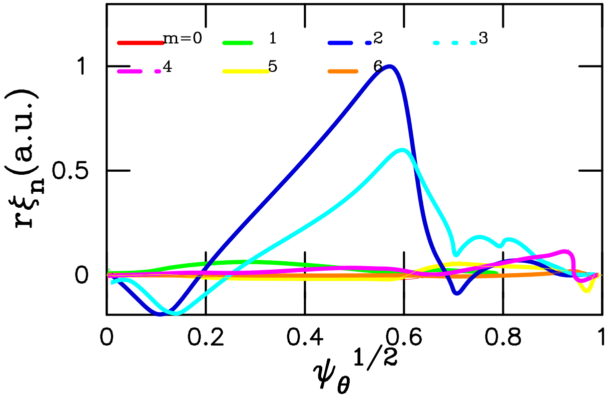


NOVA identification of n=1 BAAE in DIII-D via best match of frequency and of ECE data for mode structure

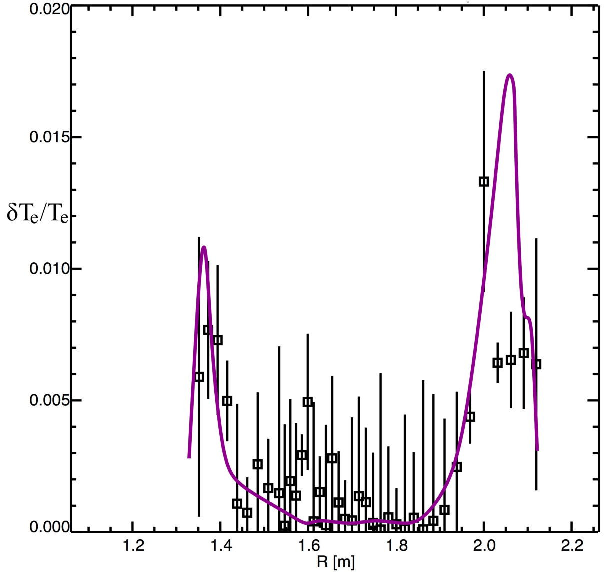
NOVA, t=900ms



NOVA, t=970ms



NOVA (magenta) vs ECE (black) for DIII-D pulse 152828 at t=970ms

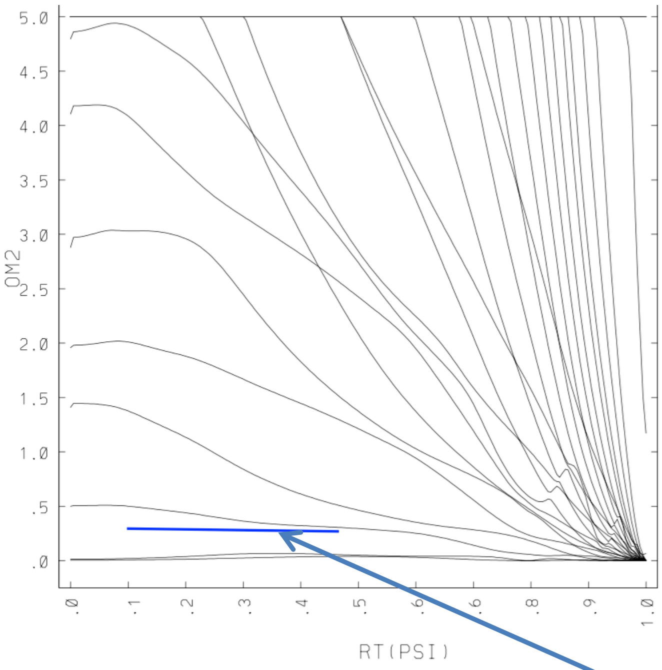


$$\frac{\delta T_e}{T_e} = -(\gamma - 1)\nabla \cdot \boldsymbol{\xi} - \frac{\nabla T_e}{T_e} \cdot \xi$$

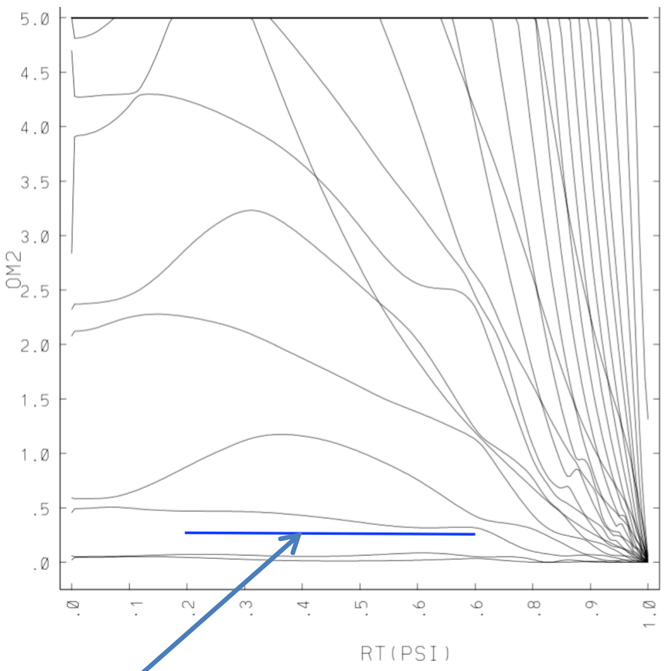
Changes in mode structure with time are accounted for in the chirping criterion

NOVA calculations including the modes acoustic component

t=900ms



t=970ms



location of the chirping BAAE
(DIII-D shot 152828)

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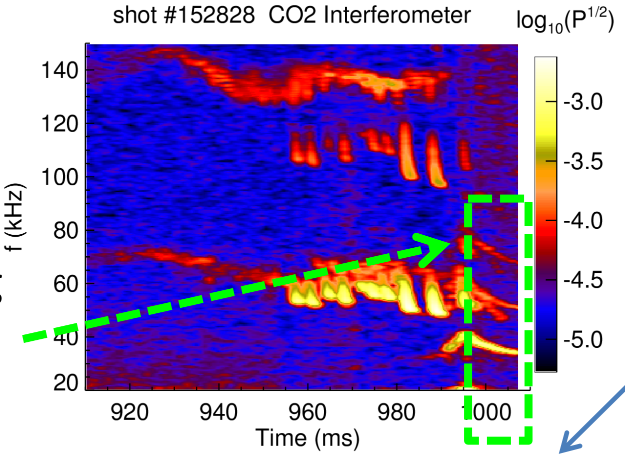
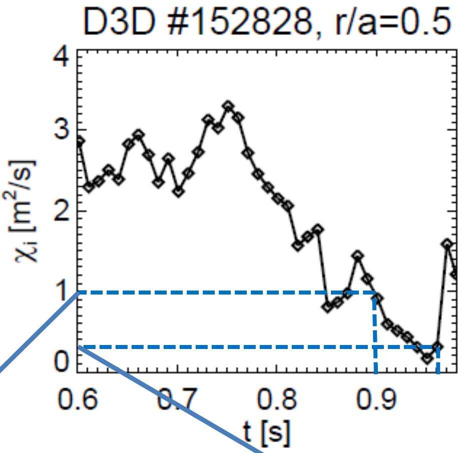
Characterization of a rarely observed chirping mode in DIII-D



End of chirping correlates with onset of NTM

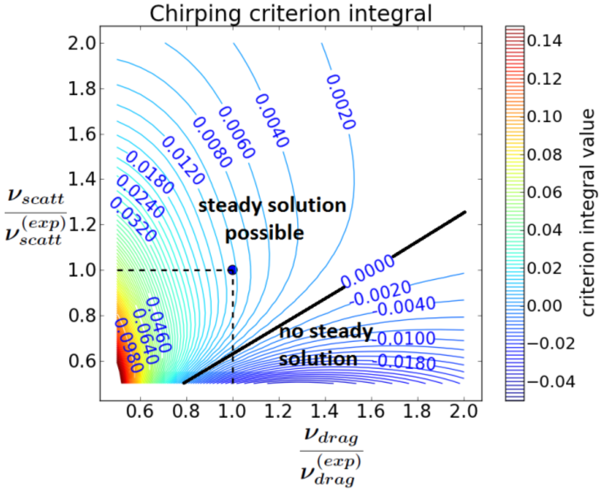


TRANSP run
Diffusivity vs time

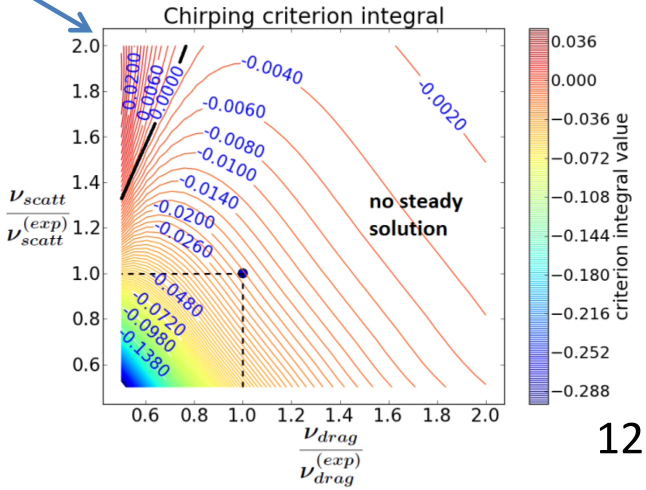
Diffusivity drop due to L→H mode transition

Strong rotation shear was observed

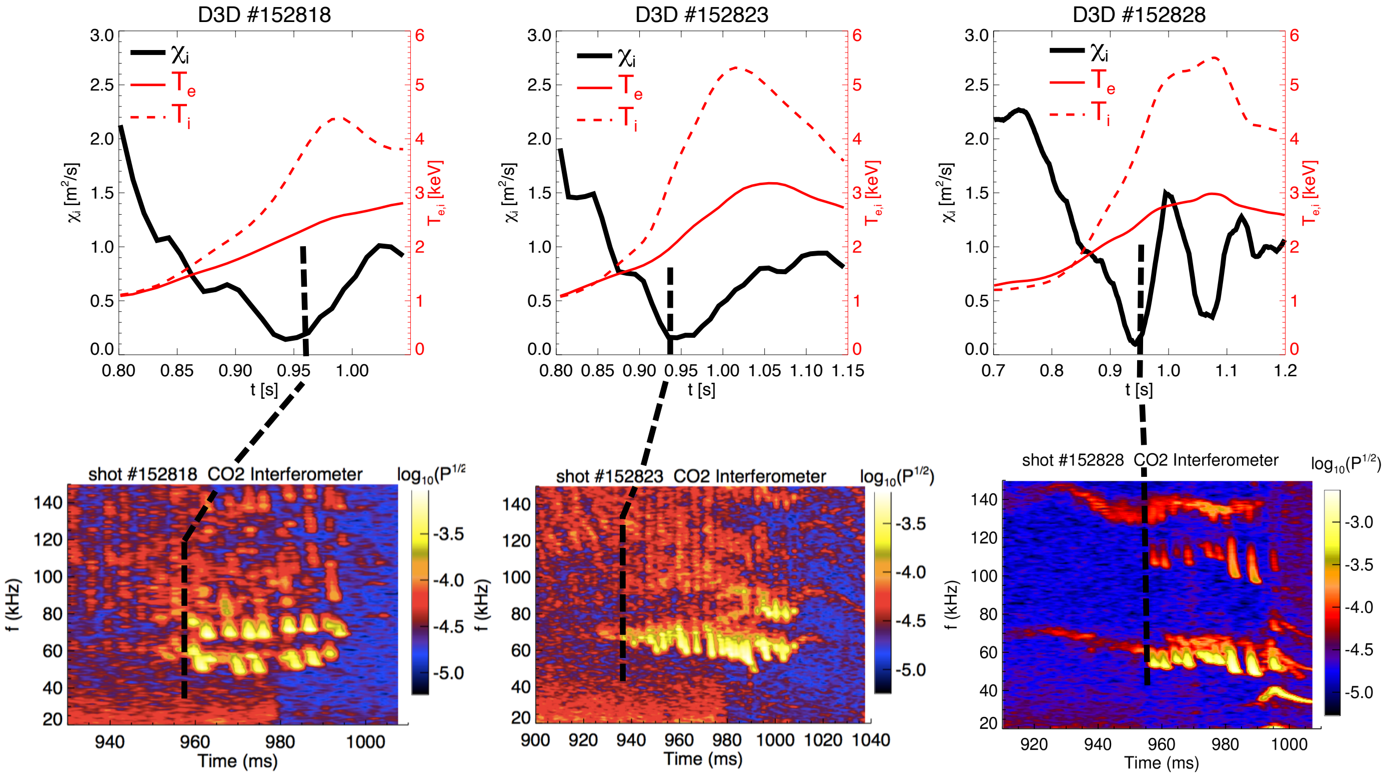
Before chirping, at 900ms: D~1m^2/s



During chirping, at 960ms: D~0.2m^2/s



Correlation between chirping onset and a marked reduction of the turbulent activity in DIII-D



- The thermal ion heat conductivity is used as a proxy for the fast ion anomalous transport
- This observation motivated DIII-D experiments with negative triangularity that showed more prevalent chirping under lower turbulence

TRANSP values taken near the mode peak

Ion temperature was quite high in these shots (~12keV on axis)

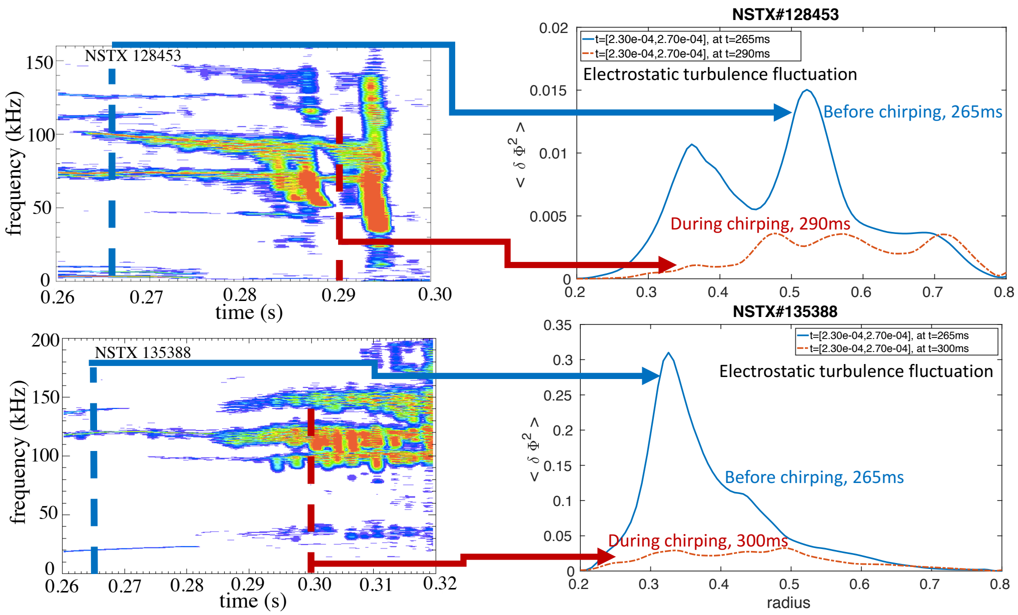
Duarte et al, NF 2017.

Summary

- Chirping BAAEs have been observed and categorized in DIII-D.
- The level of micro-turbulence appears as a plausible candidate for changing the BAAE spectral character.

Recent outcome

- This chirping study motivated dedicated shots in DIII-D under negative triangularity [Van Zeeland, IAEA oral 2017]. Chirping was observed to be more prevalent in less turbulent scenarios.
- Nonlinear gyrokinetic GTS simulations have been employed to infer turbulence levels in NSTX.
- Predictive studies of the likely Alfvénic spectral behavior in ITER has been recently performed [Duarte, APS oral 2018, NF 2018].



Complementary material

Ion and electron density, temperature, and their gradients for the DIII-D shots with transition to chirping