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: \( \sim 100\text{ms} \)

**Frequency chirping**
- frequency shift due to trapped particles
- does not exist without resonant particles
- timescale: \( \sim 1\text{ms} \)

Sharapov et al., PoP 2006

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 threshold

• 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 $A$:

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

- 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):

\[
\sum \int dP_{\varphi} \int d\mu \frac{\tau}{v_{\text{drag}}^4} |V_i|^4 \left| \frac{\partial \Omega_i}{\partial I} \right| \frac{\partial F}{\partial I} \text{Int} > 0
\]

Phase space integration

Eigenstructure information:

\[
q \int dt v_{\text{drag}} \cdot \delta E e^{i\omega t}
\]

Resonance surfaces:

\[
\Omega (E, P_{\varphi}, \mu) = 0
\]

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

>0: steady state solution

<0: chirping may happen
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Common features observed in the DIII-D chirping BAAE discharges

- high ion temperature (8-13 keV on axis)
- $q_{\text{min}} \approx 1.6-2.1$
- strong toroidal rotation (35-50 kHz on axis)
- BAAEs appear to be located close to $q_{\text{min}}$
- 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

Changes in mode structure with time are accounted for in the chirping criterion
NOVA calculations including the modes acoustic component

location of the chirping BAAE (DIII-D shot 152828)
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Characterization of a rarely observed chirping mode in DIII-D

Before chirping, at 900ms:
D~1m²/s

During chirping, at 960ms:
D~0.2m²/s

End of chirping correlates with onset of NTM

Diffusivity drop due to L→H mode transition

Strong rotation shear was observed
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.
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