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Hole-clump Pair Suppression with HHFW on NSTX

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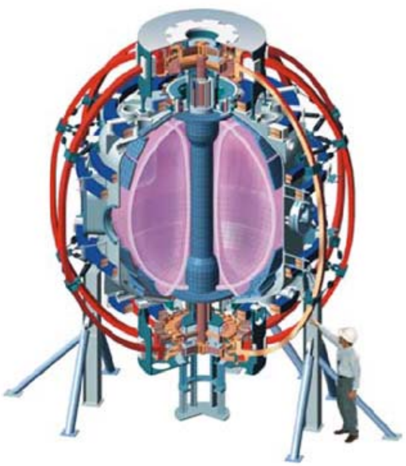

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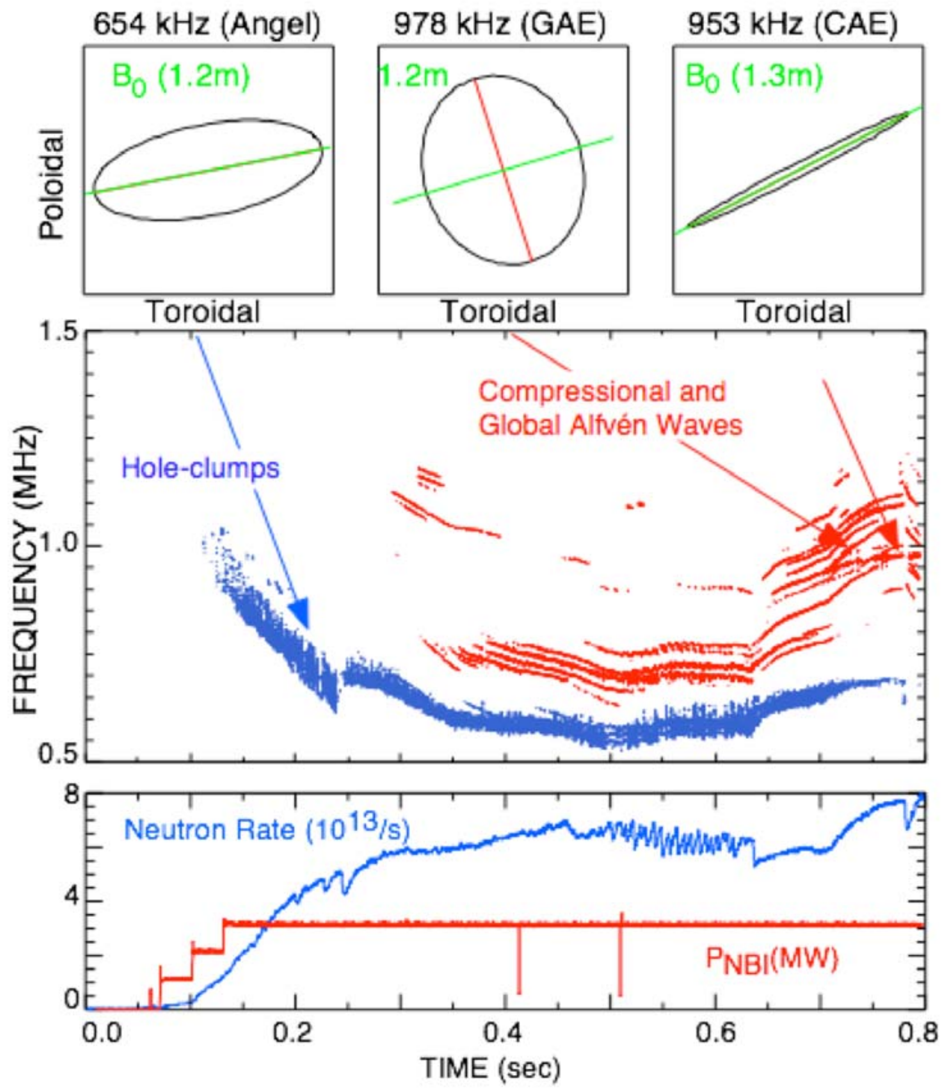
Study of hole-clumps addresses important area of physics for ITER

NSTX

- MHD-induced fast-ion losses can raise ignition threshold, damage plasma facing components.
- Non-linear behavior of modes controlled by γ_L, γ_D and fast ion phase space diffusivity, ν_{eff}.
- Simultaneous up-down frequency chirping (hole-clumps) one manifestation of non-linear behavior.
- Hole-clumps give insight on instability drive, damping, and ν_{eff}.
  - Non-linear physics of mode saturation; vital for predicting impact on fast ion confinement
- Heating the fast ion population, e.g., with HHFW, increases ν_{eff}, provides a window on fast ion distribution.

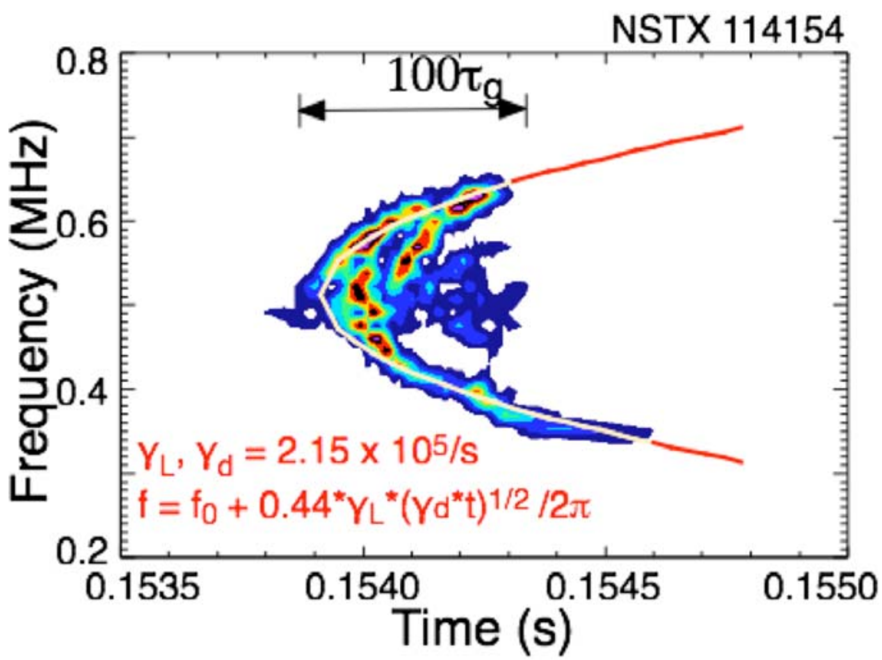
Hole-clumps common on NSTX



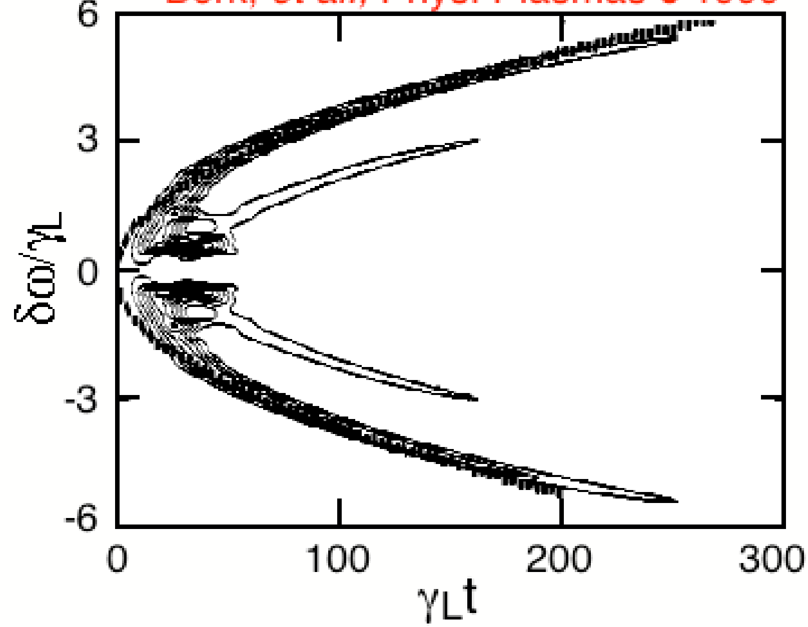
- Higher frequency modes are GAE and CAE, excited through Doppler-shifted ion cyclotron resonance.
- Modes commonly exhibit chirping (hole-clump) behavior.
- Modes have mixed polarization; CAE *or* GAE

Single bursts have frequency chirping like hole-clumps

- Red curve is single parameter fit to frequency evolution using model of hole-clump pair creation*.
- This system is much more complex, Doppler-shifted cyclotron resonances, possibly other multiple resonances.



Berk, *et al.*, Phys. Plasmas **6** 1999

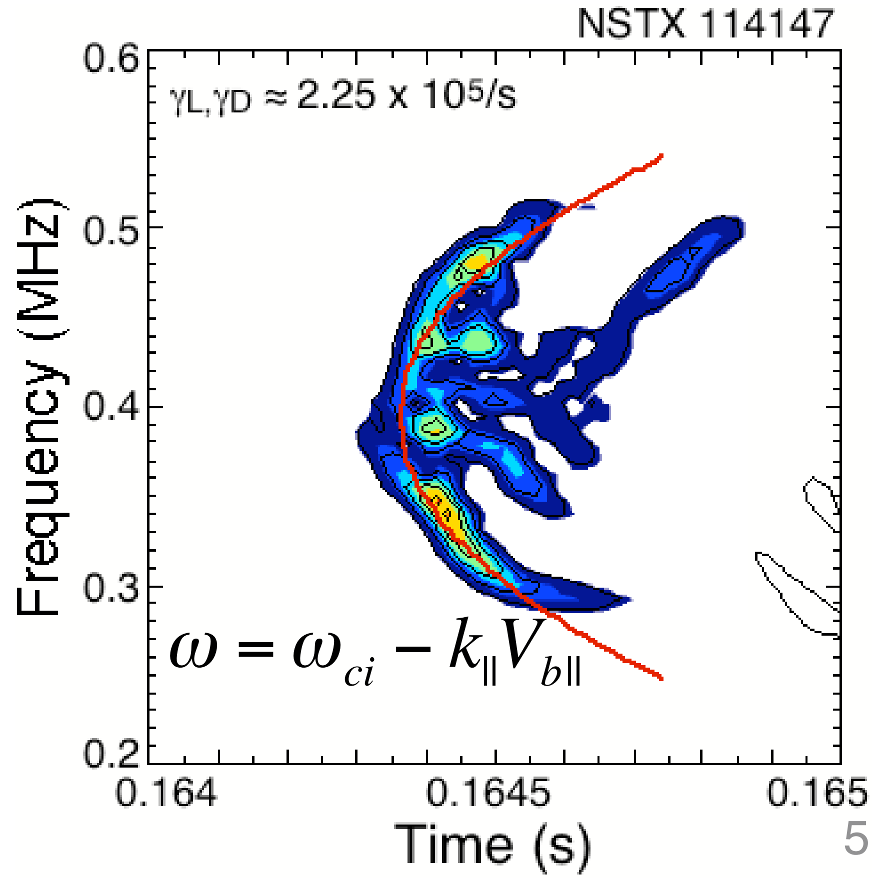


*H.L. Berk, B.N. Breizman, N.V. Petviashvili, Phys. Lett. A **234** (1997) 213.

Angelfish frequency is consistent with either GAE or CAE

- Both up and down chirp modes are n = 5.
- Growth rate, $\gamma_L/\omega \approx$ 5.3% in agreement with Nova $\gamma_L/\omega \approx$ 4%.

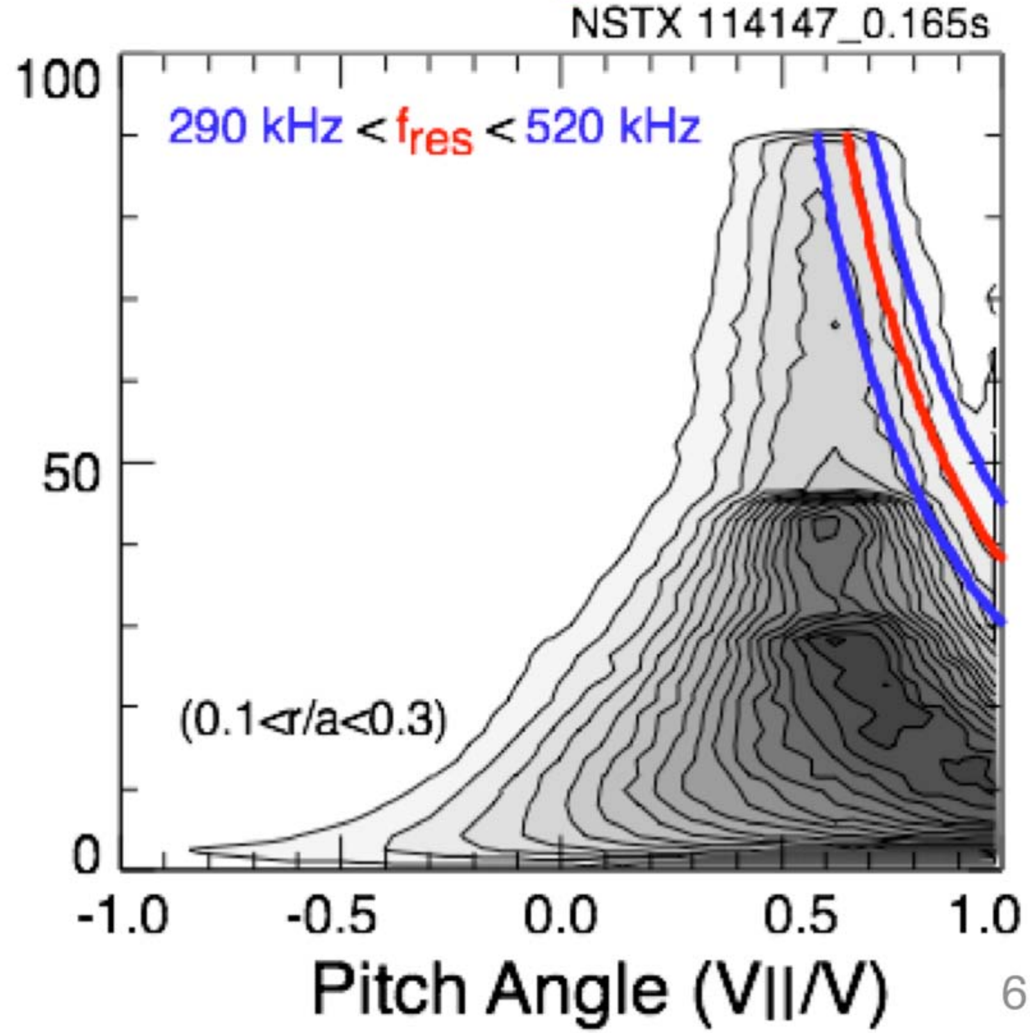
- Mode $k_{//}$ can be estimated from dispersion relation and toroidal mode number.
- If $\omega_{GAE} \approx k_{//} V_{Alfvén}$;
  $V_{Alfvén} \approx 7.2 \times 10^6$ m/s,
  $k_{//} \approx 4.5$ m^{-1}
- If $\omega_{CAE} \approx k_{\perp} V_{Alfvén}$;
  $V_{Alfvén} \approx 6.1 \times 10^6$ m/s,
  $k_{\perp} \approx 4.2$ m^{-1}, $k_{//} \approx 3.2$ m^{-1}



Perpendicular fast ion "bump-on-tail" near axis (GAE)

$$\omega = \omega_{ci} - k_{\parallel} V_{b\parallel}$$

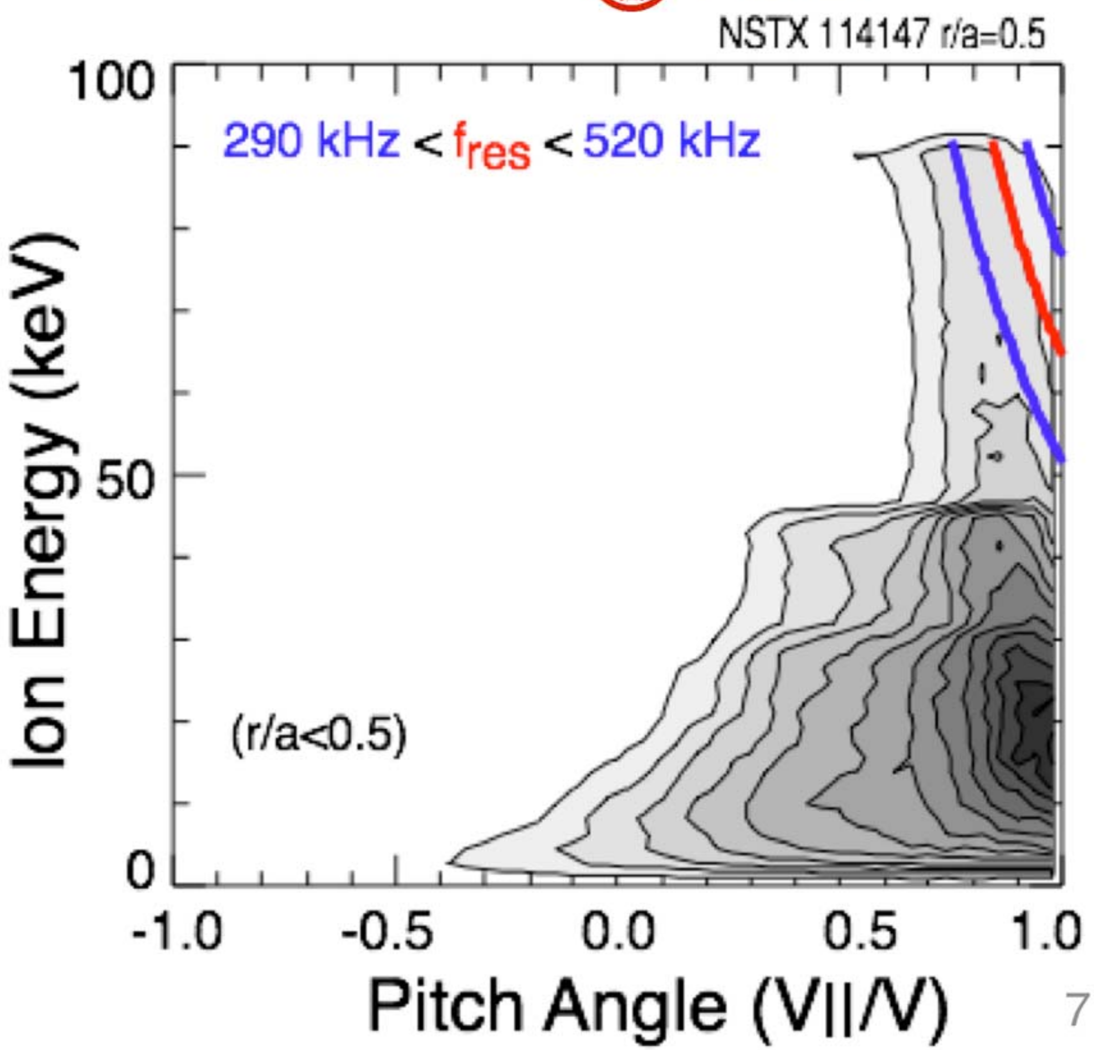
- The mode and ion cyclotron frequency are known, $k_{//} \approx 4.5\ m^{-1}$ deduced from GAE dispersion relation.
- The lines indicate fast ions that satisfy the resonance condition initial and extremes of frequency chirps.



CAE localized further out, mode driven at higher pitch angle

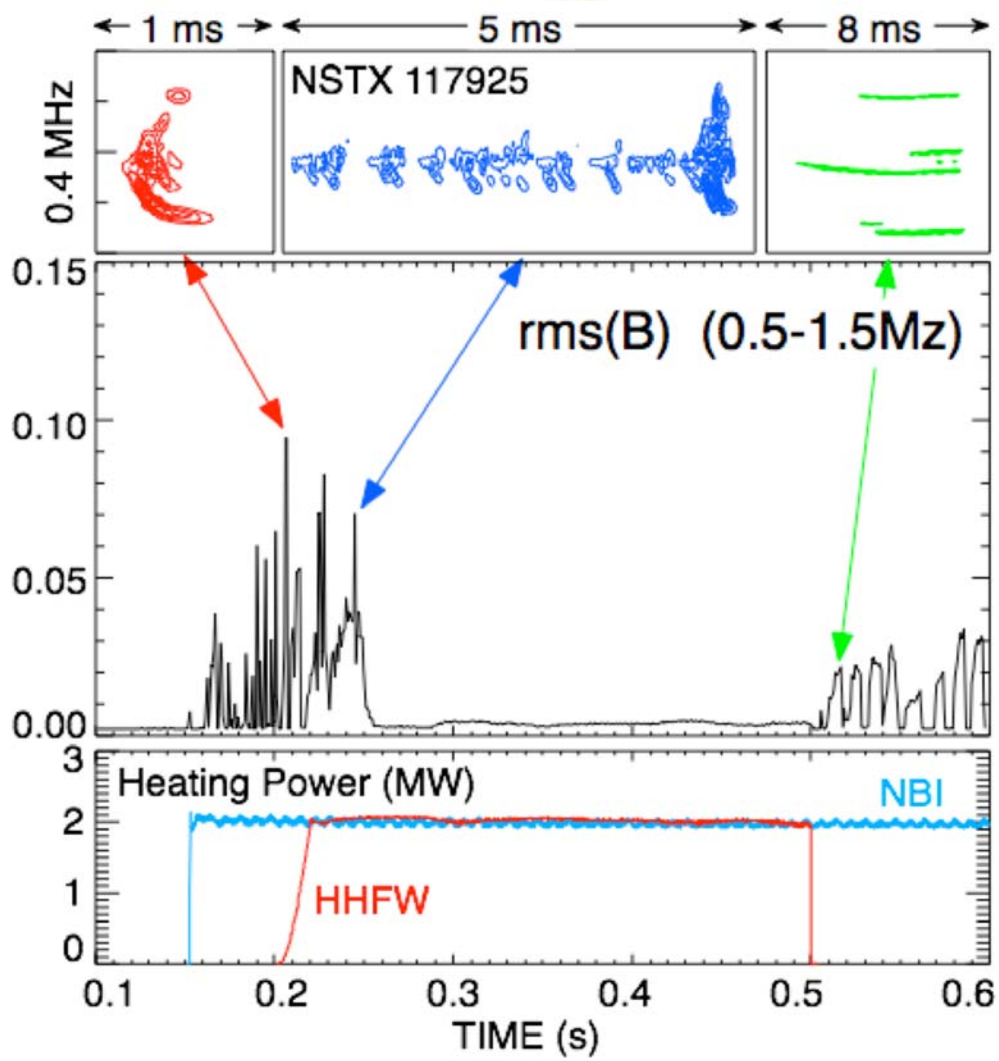
$$\omega = \omega_{ci} - k_{\|} V_{b\|}$$

- Bump-on-tail is at higher pitch angle further out.
- Lower $k_{//}$ ($\approx 3.2\ m^{-1}$) needed to satisfy resonance condition.
- Resonance located on peak gradient in perpendicular "bump-on-tail".



Approximately 2 MW of HHFW can suppress Hole-clumps

- The Angels become weaker and shorter when the RF turns on, mixed with intermittent larger chirps/bursts).
- Then there is a period with no mode activity.
- After RF, the modes reappear, but are no longer chirping - HHFW suppresses mode drive?



≈ 2 MW HHFW marginal for Hole-clump stabilization

- Condition for HHFW to affect hole-clumps[1]:
  - $(\delta E/E)^2 > (\omega_b/\omega)^2 \approx (\gamma/2\omega)^2$
- Growth rate estimates[2] from slowing down distribution as calculated in TRANSP for the CAE is $\gamma/\omega \approx 0.04$; from the frequency sweep $\gamma/\omega \approx 0.053$:
  - $(\gamma/2\omega)^2 \approx 4 - 7 \times 10^{-4}$
- Stochastic diffusion (heating) from HHFW estimated from NPA data[1] to be 2×10^4 keV^2/s:
  - $\delta E^2 \approx D_E t \approx 2 \times 10^4$ keV^2/s $\times 2 \times 10^{-4}$s ≈ 4 keV^2
  - $(\delta E/E)^2 \approx 5 \times 10^{-4}$

[1]W W Heidbrink, et al., PPCF **48** (2006) 1347., [2]Berk, et al., IAEA, Chengdu, China, 2006

Summary

- Bursting/chirping modes seen in CAE/GAE frequency range.
- Frequency chirps fit Berk-Breizman-Petviashvilli hole-clump model, growth rate in agreement with Nova for CAE;
  - $\gamma/\omega \approx 0.04$ vs. 0.053.
- Both CAE/GAE modes satisfy perpendicular bump-on-tail resonance condition with $k_{||}$ derived from dispersion relation.
- Range of frequency chirps matches extent of bump-on-tail.
- 2 MW HHFW is some cases suppresses frequency chirps.
- Estimates suggest that HHFW power threshold is > 2 MW to affect hole-clump frequency chirps.

Hole-Clump simulations have secondary (satellite) modes

- Perturbations in distribution function drive mode frequency off resonance, triggers bifurcation.
- Subsequent perturbations trigger satellite modes.

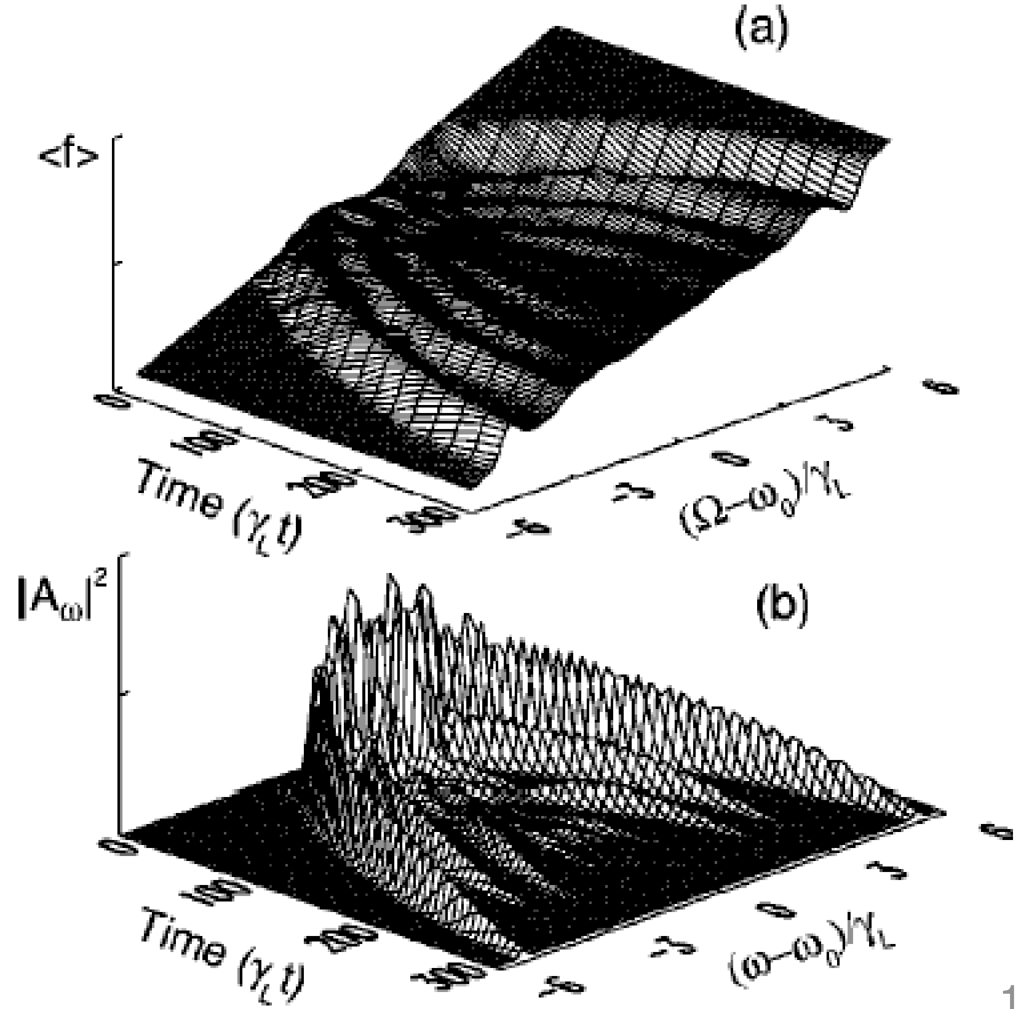


Fig. 3, H. L. Berk, B. N. Breizman, *et al.*, Phys. Plasmas **6**, 3102