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Alfvén Mode Chirping

R.B. White[1], V.N. Duarte[1], N.N. Gorelenkov[1], A. Bierwage[2], E.D. Fredrickson[1], M. Podestà[1], H.L. Berk[3]
[1]PPPL, Princeton / USA, [2]QST / Japan, [3]IFS, Univ. of Texas, Austin / USA
E-mail: rwhite@pppl.gov

ABSTRACT

- Using the ORBIT code [1,2], we study 3 stages of nonlinear frequency chirping of an energetic particle (EP)-driven Alfvén mode in realistic tokamak geometry:
  (1) Birth of a primordial hole-clump pair triggered by a symmetry-breaking perturbation and propagation of convective hole/clump wave fronts;
  (2) Accumulation of hole/clump fragments into larger structures;
  (3) Detachment and long-range propagation of solitary hole/clump vortices.
- Particular attention is paid to the **effect of beating** – namely, field amplitude pulsations and phase jumps – caused by the presence of multiple phase space structures that interact simultaneously with the same Alfvén mode.
- Here we show some results from our detailed study of chirping & beating [2,3].

BACKGROUND

- Complex frequency modulation – "chirping" – of a resonantly driven mode is a nonlinear phenomenon seen in many systems subject to drive and damping.
- Alfvén mode chirping driven by EPs (beam ions, RF-heated ions, fusion products, etc.) is routinely observed in magnetically confined fusion (MCF) experiments. It is also expected to occur in future reactors, such as ITER [4].
- **Chirping is important because it is a signature of enhanced EP transport.**
- Theories of chirping usually focus on the interaction of the Alfvén mode with only one resonant structure in EP phase space at a time.
  In reality, chirps often occur in groups of two or more, which implies the existence of multiple resonant pump waves in EP phase space density.
- **An Alfvén mode driven by multiple EP pump waves is subject to beating** [5].
- Although amplitude pulsations and phase jumps of a beating Alfvén mode are routinely observed in experiments and simulations, the role that beating plays in the dynamics has, to our knowledge, not been investigated in detail before.

METHODS

ORBIT is a Hamiltonian guiding center (g.c.) orbit-following code with a reduced (semi-perturbative) model for the evolution of resonantly driven modes with fixed radial profile. **Ideal MHD displacement:**

$$\tilde{\boldsymbol{\xi}}(\psi_\mathrm{P},\vartheta,\zeta,t)=\sum_{l=1}^{N_\mathrm{mode}}A_k(t)\sum_m\hat{\boldsymbol{\xi}}_{k,m}(\psi_\mathrm{P})e^{i\Theta_{k,m}(t)},$$

$$\Theta_{k,m}(t)=n_k\zeta-m\vartheta-\omega_{0k}t-\phi_k(t);$$

FIELD EQUATIONS:

Ampli-tude:
$$\frac{\mathrm{d}A}{\mathrm{d}t}=-\Omega_\mathrm{c}\frac{v_{\mathrm{A}0}^2}{\omega_0^2}\int\mathrm{d}\boldsymbol{Z}_\mathrm{gc}\delta f\frac{\boldsymbol{v}_\mathrm{gc}\cdot\boldsymbol{E}_\perp}{A}-\gamma_\mathrm{d}A,$$

Phase:
$$A\frac{\mathrm{d}\phi}{\mathrm{d}t}=-\Omega_\mathrm{c}\frac{v_{\mathrm{A}0}^2}{\omega_0^3}\int\mathrm{d}\boldsymbol{Z}_\mathrm{gc}\delta f\frac{\boldsymbol{v}_\mathrm{gc}\cdot\partial_t\boldsymbol{E}_\perp}{A};$$

PARTICLE EQUATIONS:

Position in g.c. phase space:
$$\dot{\vartheta}=\partial_{P_\vartheta}H,\quad\dot{P}_\vartheta=-\partial_\vartheta H,$$
$$\dot{\zeta}=\partial_{P_\zeta}H,\quad\dot{P}_\zeta=-\partial_\zeta H,$$

Hamiltonian & momenta:
$$H=\frac{(\rho_\parallel-\alpha)^2B^2}{2}+\mu B+\Phi,$$
$$P_\zeta=g\rho_\parallel-\Psi_\mathrm{P},\quad P_\vartheta=I\rho_\parallel+\Psi.$$

FIG.1: ***(a)*** *Pulsations of mode amplitude A(t).*
(b) *Phase ϕ(t) jumps by ±π during amplitude minima.*
(c) *DMUSIC spectrogram of signal s(t) = A(t) × sin(-ω₀t – ϕ(t)).*
Nonadiabatic onset of chirping is staircase-like. Tanh(γt/2) curve fits trend, as predicted by Zonca & Chen [ZC] "relay runner" model [6].

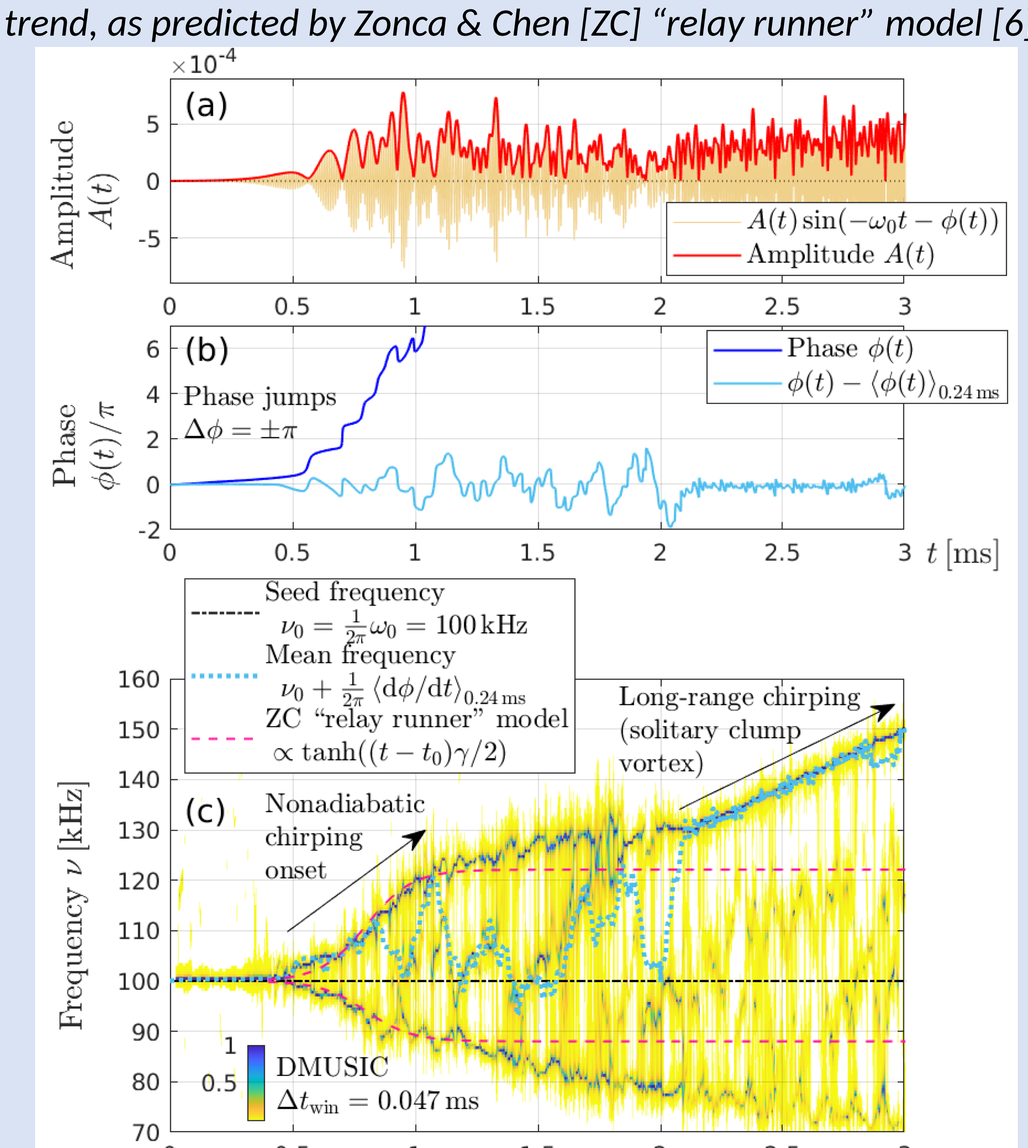
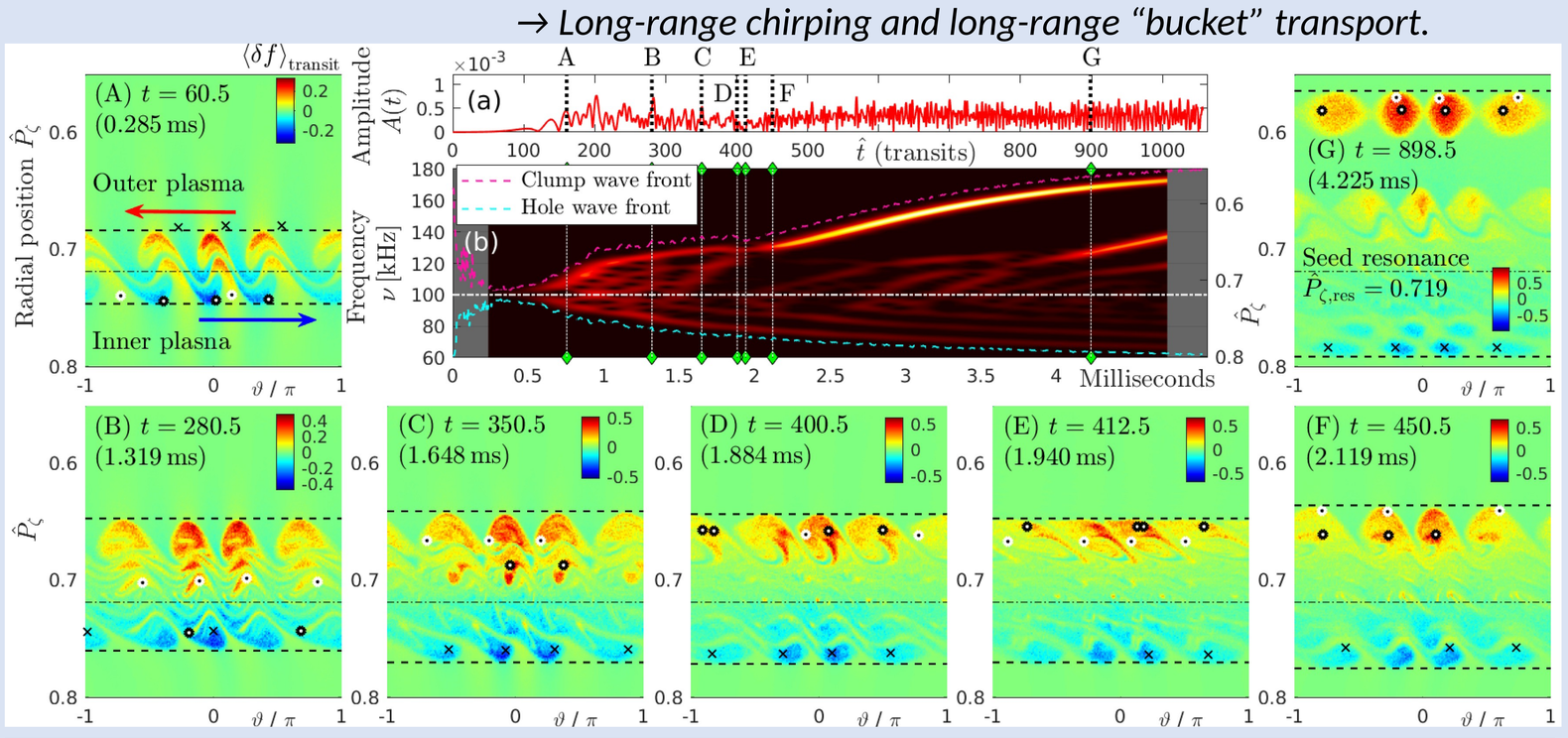


FIG.2: ***(a)*** *Amplitude evolution.* ***(b)*** *FFT spectrogram of signal s(t).*
Snapshots of δf-weighted Poincaré plots:
(A) *Primordial hole-clump wave pair (here at time of 3rd pulse)*
(B-F) *Formation (and temporary disintegration) of a large clump.*
(G) *Solitary clump vortex after detachment from turbulent belt.*
→ Long-range chirping and long-range "bucket" transport.



RESULTS & CONCLUSION

- Beating is found to be a mechanism that drives the evolution of EP phase space structures:
  → Pulsed propagation of hole and clump wave fronts → Staircase-like chirping [Fig.1].
  → May inhibit early detachment of solitary phase space vortices, but facilitates aggregation of larger structures [Fig.2]. Underlying feedback loops are discussed in Ref. [3].
- It is remarkable that detached vortices remain robust and, on average, maintain their concentric nested layers while being visibly perturbed by the field's continued beating [3].

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