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トカマクプラズマにおける非線形周波数チャーピングの物理
Physics of Nonlinear Frequency Chirping in a Tokamak Plasma

ビアワーゲ・アンドレアス [1]，ホワイト・ロスコー [2]
Andreas Bierwage[1] and Roscoe B. White[2]

量子科学技術研究開発機構 六ヶ所核融合研究所 [1]，プリンストンプラズマ物理学研究所 [2]
National Institutes of Quantum and Radiological Science and Technology (QST),
Rokkasho Fusion Institute, Aomori, Japan[1],
Princeton Plasma Physics Laboratory (PPPL), Princeton NJ, USA[2]

In axisymmetric tokamak plasmas, collisionless long-range transport of energetic ions interacting with waves can occur due to (i) crossing the passing-trapped boundary, (ii) resonance overlap, and (iii) phase space vortex propagation. The latter is often observed in the form of rapid frequency chirping, and it is the subject of the present numerical study.

We employ the Hamiltonian guiding center (GC) orbit following code Orbit [1] with a reduced δf model for nonlinear interactions between fast ions and ideal electromagnetic modes in toroidal geometry [2]. This model strikes a compromise between the highly simplified 1-D bump-on-tail paradigm [3] and the complete 4-D problem tackled by self-consistent gyrokinetic or hybrid models [4]: While simulation particles in Orbit are pushed in realistic magnetic geometry with all relevant aspects of GC motion retained[*1], the field dynamics are reduced to the evolution of an amplitude $A(t)$ and phase $\phi(t)$, subject to constant damping $\gamma_{\rm d}$ and initially uniform phase space gradients. Fixing the radial profile $\hat{\Phi}(r)$ of the fluctuating field prevents spatial corrugation, making the model resilient to particle noise and reducing the dynamic complexity of the system. The result is a computationally efficient and numerically accurate model, that has the potential to enhance our qualitative understanding of frequency chirping and particle transport in realistic geometry, albeit quantitative predictions remain out of scope.[*2]

The concrete motivation for the present study was the observation of rapid field amplitude pulsations and phase jumps in experiments and simulations (e.g., see Ref. [6] for JT-60U). This phenomenon is seen whenever there are multiple chirps occurring at the same time at different frequencies. The pulsations and phase jumps can be readily explained by the beating of multiple modes [6]. At first glance, it might be surprising that such beating can be reproduced with reduced models that evolve only a *single mode*, such as the well-studied 1-D bump-on-tail paradigm [3] and recent Orbit simulations for tokamamk geometry [7]. The situation becomes clearer if one distinguishes between the *field mode*, which, in our simulations, takes the form

$$\Phi(r,\vartheta,\zeta,t) = A(t)\hat{\Phi}(r)\sin(n\zeta - m\vartheta - \omega_0 t - \phi(t)),$$

and *phase space modes* — a.k.a. holes and clumps — of the combined field+particle system.[*3] As an analogy, one might think of the holes and clumps as different players in an orchestra, whose collective music is recorded on a single sound track $\Phi(t)$.

[*1] Polarization drift and ponderomotive force are ignored. All other aspects of GC motion are retained to the extent permitted by a Hamiltonian formulation in Boozer coordinates (which requires neglecting the field component δ in Eq. (2.26) of Ref. [5] arising from the coordinates' nonorthogonality). The model is appropriate for fast ions interacting with shear Alfvén modes.

[*2] Quantitative predictions may become feasible through systematic extensions; e.g., independent modelets at different radii, and a damping rate $\gamma_{\rm d}(r,\omega,A)$ that depends on radius, frequency and amplitude, mimicking the effect of continuum damping and fluid nonlinearities. Collisions and sources also need to be considered.

[*3] When the field mode appears, it creates radially extended modulations of phase space density (primordial hole-clump pairs) that undergo poloidal shearing. Around a resonance (dashed line in Fig. 1(c)), clumps/holes move down/up-hill, and their frequencies shift up/down. When the field mode is damped, holes & clumps can escape and form independent waves — *phase space modes* — whose oscillations are superimposed in the velocity-space integrals governing the evolution of $A(t)$ and $\phi(t)$ [2]. This temporal interference is observed as amplitude modulations & phase jumps.

We may then ask about the resulting feedback: How is the performance of each player perturbed by the signals made by other players? This question arises from the anticipation that the robustness of coherent phase space structures depends on the local quality of resonant particle trapping in the fluctuating field $\Phi(r,\vartheta,\zeta,t)$. While the contributions of all players are superimposed linearly when they drive the field fluctuations, we expect the feedback to be nonlinear when dynamic time scales overlap: phase space shearing & wave breaking, amplitude & phase modulations, field damping ... Thus motivated, our recent studies focused on question like these:

1. What do the field mode dynamics look like on different time scales? Alfvén wave spectrograms are usually computed with t windows as long as a millisecond, since FFT is of little use on shorter scales. Here, we employ the DMUSIC algorithm [8] in order to visualize spectral dynamics down to the 0.1 ms scale of the above-mentioned amplitude modulations. Our hope is that high-resolution spectrograms as in Fig. 1(b) will enable us to anticipate the underlying dynamics without having to compute phase space plots, like the δf contours in Fig. 1(c,d).

2. What form does the start of a chirp take? Near marginal stability, collisionless chirps were predicted to pitch-fork ($\dot{\phi} \propto \sqrt{t}$ [3]) in the adiabatic regime, whose onset time (if any) may vary from case to case. Our paper will discuss several different examples for realistic tokamak geometry. The case in Fig. 1(b) has a time-dependence of the form $\dot{\phi} \propto \tanh(t)$, indicating a long-lasting nonadiabatic phase [9, 10] dominated by wave breaking as seen in Fig. 1(c).

3. What causes the emission of solitary phase space vortices? Fig. 1(b) shows a strong upward chirp that is launched around $t \approx 1.5$ ms and connected with the emission of the massive solitary clump seen at the top of Fig. 1(d). We are investigating how the solitary clump detaches from the wave-breaking domain and drifts outward.

In the present case, the emission of solitary clumps seems to be of probabilistic nature and ultimately connected to how they are fueled by clumplets that are scraped off by the holes uphill and travel downhill through the wave breaking domain as indicated schematically by the meandering lines in Fig. 1(d).

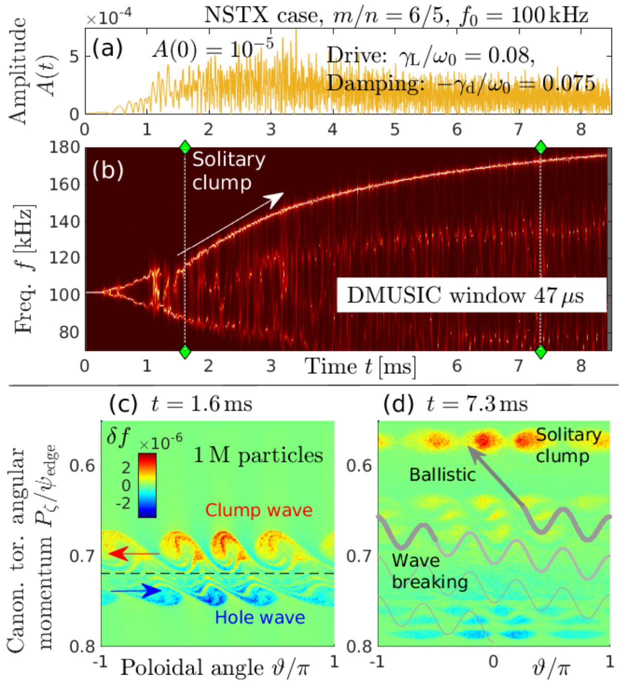

Fig. 1: DMUSIC spectrogram & snapshots of propagating phase space modes (a.k.a. holes & clumps).

Clarifying this process may yield useful insight into the transport of fast ions during Alfvénic chirping.[*4]

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[*4] The radially propagating micro-structures seen in recent ORBIT simulations (Fig. 11 in Ref. [7]) may not contribute to transport. They seem to be the result of phase mixing of density modulations whose origin may be partly physical (incomplete mode-orbit overlap due to magnetic drifts) and partly numerical (curable with a quiet start accounting for drifts and mirror forces [11]). Note also that ORBIT is not a conservative solver; the Liouville theorem may be violated on multi-ms scales.