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Theory and observation of frequency splitting and sweeping in tokamaks

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Frequency splitting and frequency sweeping ("chirping") of high frequency MHD modes are widely observed in tokamak plasmas [1,2]. Here we consider observations of frequency splitting on JET (see for example Fig. 1) and chirping on MAST (Fig. 3), and show how these may be modelled by the Berk-Breizman augmentation of the Vlasov-Maxwell equations (henceforth "the VM(BB) system") [3–5]. The VM(BB) system models the coupling between energetic particles and the wave modes they excite, based on the one-dimensional electrostatic bump-on-tail problem with particle distribution relaxation and background electric field damping. We cast the model as the follows [7], in terms of the particle distribution $f(x, v, t)$ and the electric field $E(x, t)$:

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} + E\frac{\partial f}{\partial v} = -\nu_a \left(f - F_0\right) \tag{1}$$

$$\frac{\partial E}{\partial t} + \int v \left(f - f_0\right) dv = -\gamma_d E \tag{2}$$

Here F_0 denotes the combined particle source and loss function, ν_a the particle relaxation rate, γ_d the combined effect of all background damping mechanisms that act on the electric field, and f_0 the spatial mean of f. Spatial lengths are normalised to the Debye length λ_D; velocities to the thermal speed v_{the}; time to the inverse plasma frequency $\omega_p^{-1} \equiv \lambda_D/v_{the}$; and E to $m_e v_{the}^2/e\lambda_D$.

A code has recently been developed [6] that allows direct numerical solutions of the fully nonlinear VM(BB) system across the entirety of (γ_d, ν_a) parameter space for any $F_0(v)$. Application of this code [7] for a particular $F_0(v)$ shows how the behaviour of the VM(BB) system depends on its parameters. We can take a cut through (γ_d, ν_a) parameter space and observe how the behaviour of the system varies as we travel along this line. Consider the line $\gamma_d = 1.0$: for each value of ν_a, we extract the extreme values achieved by the electric field energy (excluding the initial transient phase), and plot in Fig. 2 these extrema as a function of ν_a. For example, sinusoidal behaviour at a particular ν_a would contribute two points to the plot. Provided the underlying period varies slowly with ν_a, an abrupt splitting of an observed extremum into two branches implies a period doubling bifurcation at that parameter value. Figure 2 demonstrates how the VM(BB) system naturally generates frequency splitting phenomenology as seen experimentally in Fig. 1.

Fig. 3, Fig. 4 exhibits repeated bursts whose frequency undergoes almost-symmetric up-down chirping. Direct measurements of the spatially averaged distribution function $f_0(v)$, linked to corresponding instants during the evolution of a single burst, are shown in Fig. 5, which demonstrates the central role of hole-clump pair formation and evolution. This is entirely responsible for the chirping seen in Fig. 4, which suggests that this may be the mechanism underlying the phenomenology observed in the real tokamak plasma (Fig. 3).

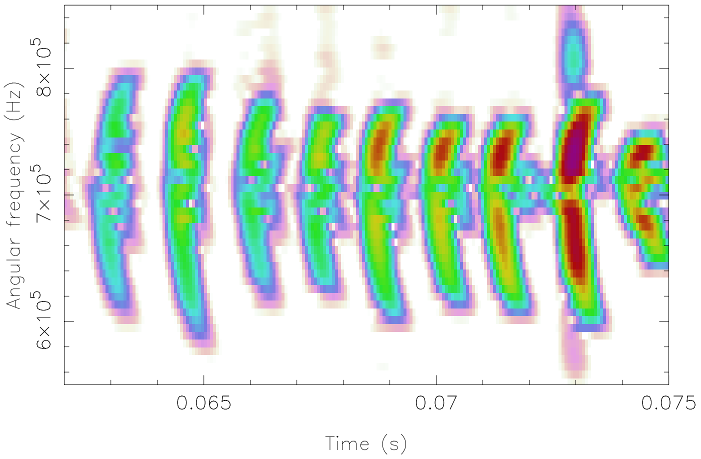

Figure 3: Experimental observation of frequency chirping in nine successive bursts of TAE activity. Magnitude of MHD activity measured in neutral beam-heated MAST pulse 5568 during a 13ms interval, showing frequency in the range 80-120kHz.

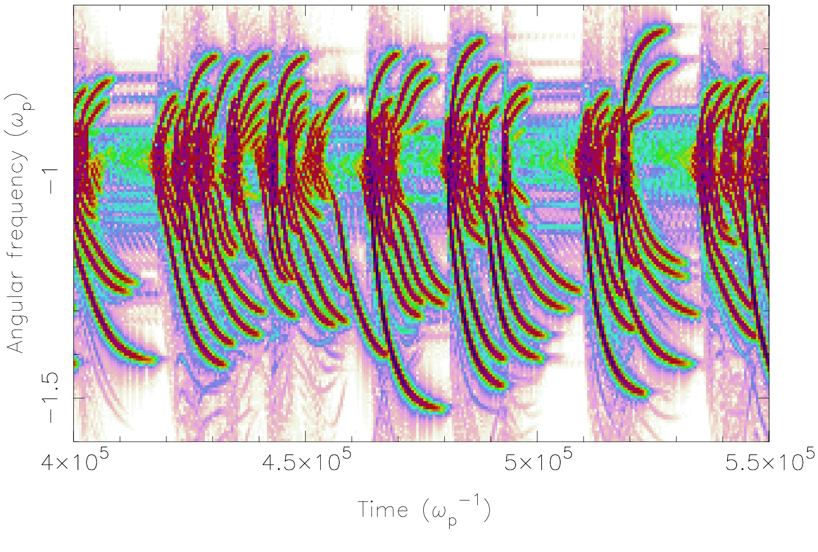

Figure 4: Frequency chirping in successive bursts of activity from the fully nonlinear VM(BB) model. Dimensionless time and frequency are normalised by ω_p. The plot shows mode amplitude on a logarithmic colour scale.

Our novel splitting and sweeping results provide fresh evidence of the range of tokamak phenomenology that is captured by the fully nonlinear VM(BB) model.

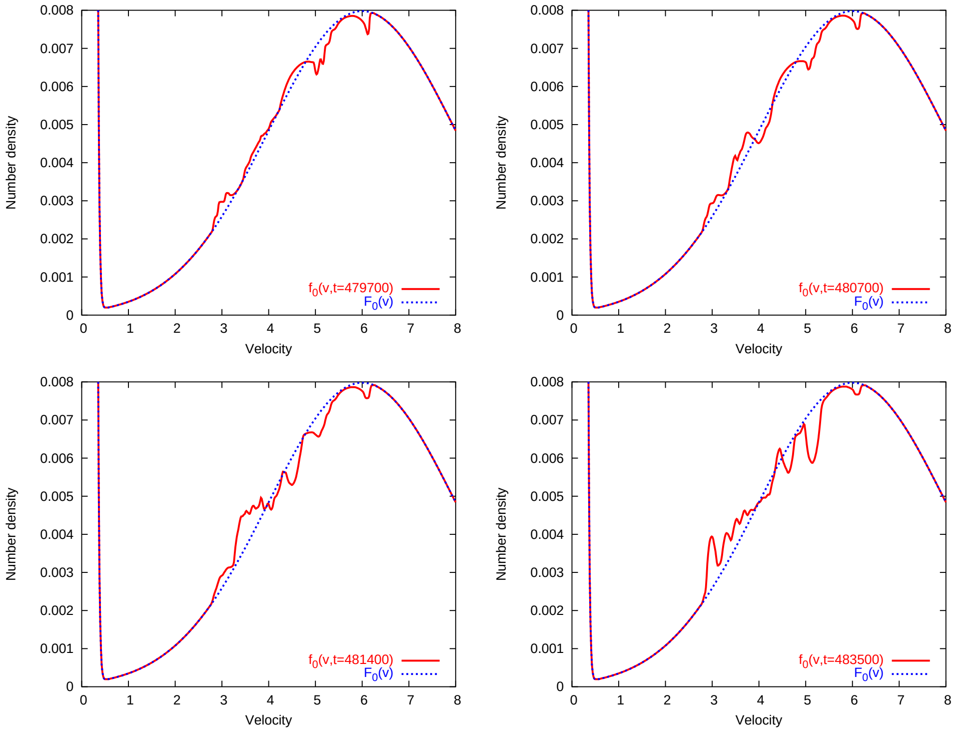

Figure 5: Hole-clump pair formation and evolution shown at four different times during the simulation whose spectrogram is shown in Fig. 4. Available as a movie [9].

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