Fishbone Generation of Sheared Flows and the Creation of Transport Barriers

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Introduction

Recent observations indicate that the formation of internal transport barriers (ITBs) in ASDEX Upgrade are always preceded by fishbones [1], i.e. oscillations of the internal kink driven by the fast ion population. In this work the time evolution of such a mode is prescribed and its effect upon the fast ion population and background plasma investigated.

The key result of this work is that for fishbones that repeat on a timescale faster than the poloidal damping timescale, a sufficiently sheared flow can be build up that leads to the suppression of the plasma turbulence and the creation of a local transport barrier. For the ASDEX Upgrade parameters consider here, the relevant timescale is given by the effective collision timescale, $\tau_{\rm eff} \sim \mathcal{O}(1)$ ms.

The mechanism by which this happens may be summarized as follows: The fast ions resonantly interact with the kink distortion of the magnetic field and are radially expelled leading to a radial current, or equivalently, an electric field. This produces a sheared $\mathbf{E}\times\mathbf{B}$ flow which if sufficiently large to overcome the growth rate of the turbulent eddies ($\omega_{\mathbf{E}\times\mathbf{B}} > \gamma_{\rm max}$) can lead to their destruction and to a region of reduced radial transport [2].

Fishbone Simulations

The time evolution of the fast ion radial current is calculated using the HAGIS code [3] which evolves the distribution of energetic ions as they interact with the prescribed kink mode shown in Fig.1. The equilibrium configuration employed is a reconstruction of ASDEX Upgrade discharge 13921 and the radial structure of the mode (including absolute amplitude) is matched to the experimental electron cyclotron emission (ECE) data. The frequency evolution is chosen to match the Mirnov coil data corrected for the toroidal rotation frequency of the plasma (~ 10 kHz) obtained from charge exchange measurements. The velocity distribution of the fast ions is specified as a slowing down distribution from the injection energy of 60 keV with a volume averaged fast particle beta value matched to the calculated value, $\langle\beta_f\rangle = 0.36\%$.

The evolution of the $\mathbf{E}\times\mathbf{B}$ and poloidal rotation frequencies and the $\mathbf{E}\times\mathbf{B}$ shearing rate,

$$\omega_E = \frac{\langle E_r^* \rangle}{\langle RB_p\rangle}, \quad \omega_p = \frac{\langle RB_t\rangle\langle V_p\rangle}{\langle B_p\rangle\langle R^2\rangle} \quad \text{and} \quad \omega_{\mathbf{E}\times\mathbf{B}} = \frac{1}{q}\left|\frac{\partial \omega_E}{\partial \hat{r}}\right|,$$

follow from the following pair of coupled differential equations [4]:

$$\frac{\partial \omega_p}{\partial t} = \frac{\partial \omega_E}{\partial t} + \frac{\langle J^{\psi_p}(t)\rangle}{m_i n_i \langle R^2\rangle}, \tag{1a}$$

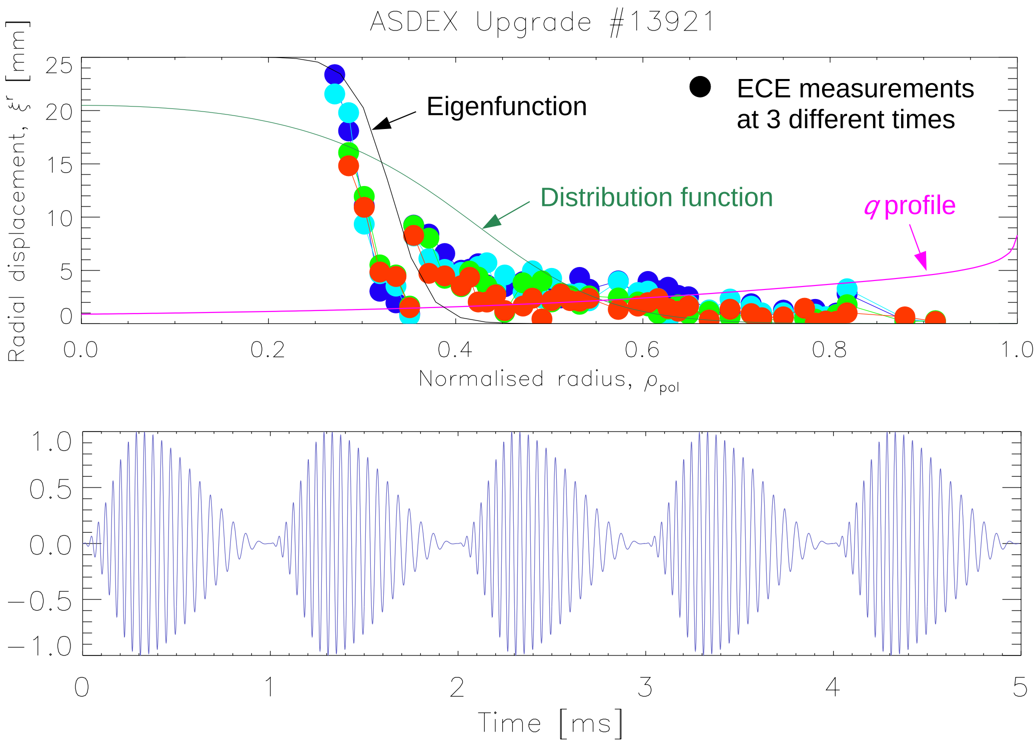

Figure 1: Details of eigenmode structure and evolution of $m = 1$, $n = 1$ internal kink modeled with linear frequency chirps (27.5 → 20 kHz) using the HAGIS code.

$$\frac{\partial \omega_p}{\partial t} = \left[1 - \frac{\epsilon^2}{q^2}\left(\frac{1+\kappa^2}{2} + 2q^2\right)\right]\frac{\partial \omega_E}{\partial t} - \frac{\mu_i}{m_i n_i}\omega_p, \tag{1b}$$

where $J^{\psi_p}(t)$ is the time dependent fast ion radial current, E_r^* is the effective radial electric field $E_r^* = E_r - \nabla_r p_i/(e_i n_i)$ and $\langle \ldots \rangle$ denotes flux surface averages. Neutral friction, Reynold's stress, Stringer spin up and toroidal damping have all been neglected. The latter implies that ω_E never attains a saturated value in these fishbone simulations, therefore the growth rate comparisons are made with the poloidal shearing rate. For the deuterium plasma under consideration the normalised viscosity is approximated by,

$$\frac{\mu_i}{m_i n_i} \approx 220\sqrt{\epsilon}\frac{n_i[10^{19}\mathrm{m}^{-3}]}{T_i[\mathrm{keV}]^{3/2}}.$$

It should be noted that $\omega_{\mathbf{E}\times\mathbf{B}}$ is associated with the effective electric field, E^*, implying that an increase in the pressure gradient as for instance due to the formation of a transport barrier, will change the electric field and can then sustain the barrier.

The timescale upon which the poloidal flow is damped is given by the effective collision frequency,

$$\nu_{\mathrm{eff}} = \frac{q^2}{\epsilon^2}\frac{2}{1+\kappa^2+4q^2}\frac{\mu_i}{m_i n_i}$$

where the complicated pre-factor accounts for the generation of the Pfirsh-Schlüter flow.

The result of modelling the experimentally observed fishbone bursts is shown in Fig. 2. It is observed that the number of fast ions radially expelled decreases for successive fishbones.

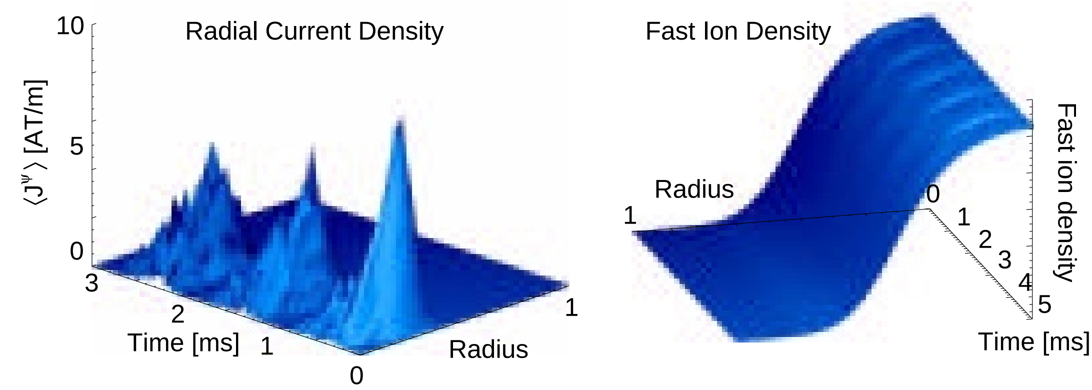

Figure 2: Time dependent radial fast ion current density and the corresponding variation of fast ion radial distribution function arising from fishbone bursts every 1 ms.

This is due to the fact that in the simulations no allowance is made for a source of fast ions with the result that there is no replenishment of resonant ions and hence fishbones subsequent to the first are weaker.

Having calculated $J^{\psi_p}(t)$ it is possible to integrate equations (1) to obtain the poloidal rotation and shearing rates as shown in Fig. 3. In order to proceed to longer timescales,

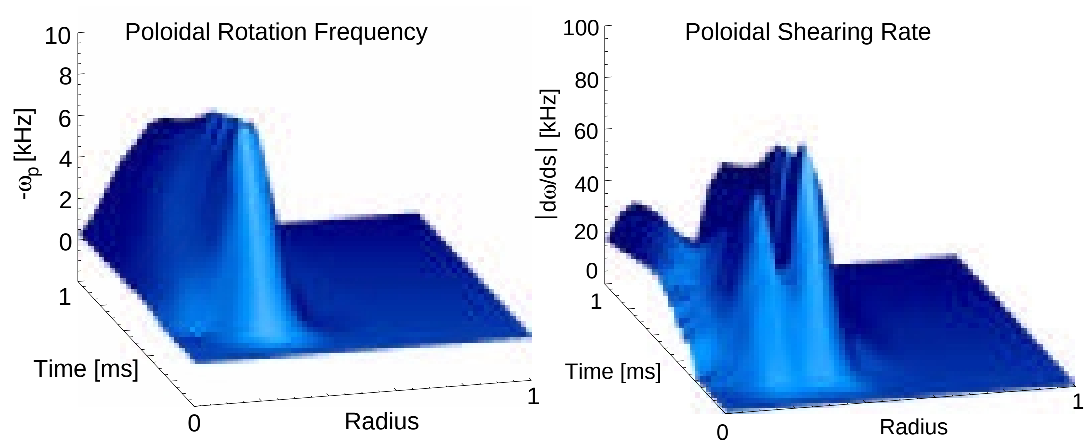

Figure 3: Calculation of the poloidal rotation arising from the HAGIS simulation of a fishbone burst and the corresponding poloidal shearing rate.

the assumption is made that the source of fast ions from neutral beam refuelling allows a steady-state to be achieved with the radial current generated by each fishbone equal in magnitude to that of the first fishbone shown in Fig. 2.

Making a fit to this time dependent radial current and simulating many fishbones with a repetition frequency of 1 ms, a saturated poloidal rotation frequency is obtained as shown in Fig. 4. Scaling the poloidal shearing rate obtained after one fishbone from Fig. 3 in accordance with this saturated value gives shearing rates which are comparable with the calculated ITG growth rates, $\gamma_{\rm ITG} \sim \mathcal{O}(10^2)$ kHz [5].

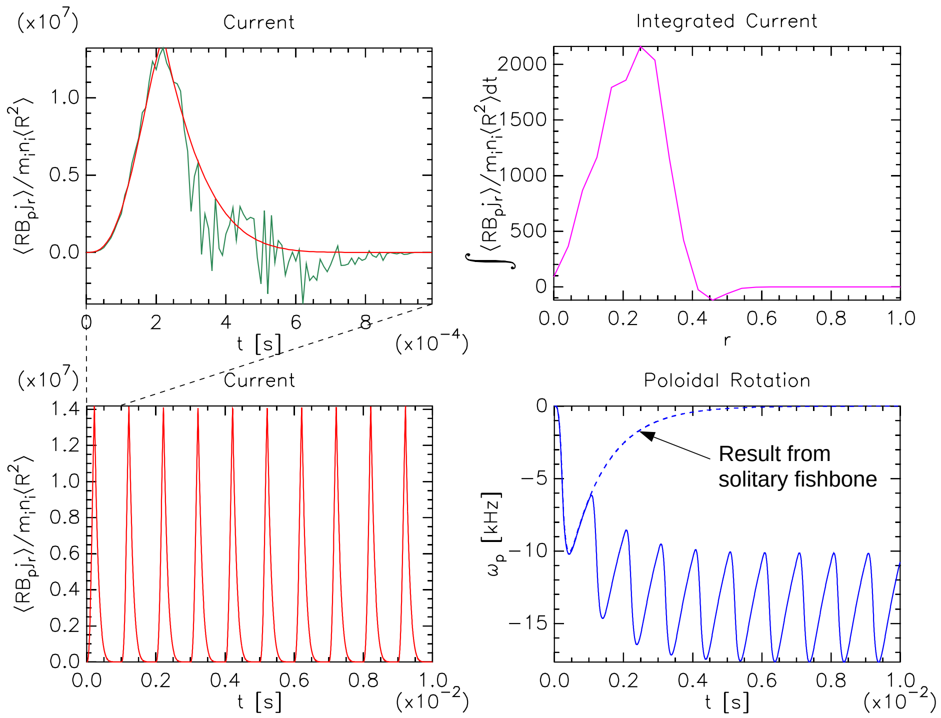

Figure 4: Radial current arising from HAGIS simulations and the fit used for the long timescale calculation of the poloidal rotation frequency, ω_p. The dotted line shows ω_p for a solitary fishbone burst.

Conclusions and Future Work

This work demonstrates how the radial current of fast ions expelled by fishbones can lead to the generation of sheared flows. A comparison of the shearing rate calculated for ASDEX Upgrade parameters indicates that fishbones with a sufficiently high repetition frequency ($\tau_{\rm fb} \sim 1/\nu_{\rm eff}$), give shearing rates comparable with estimates of the linear growth rates of ITG modes. Fishbones thus pose as a suitable candidate for the triggering of internal transport barriers.

The work described here is of a preliminary nature with the dependency upon many of the parameters in the simulation still to be investigated. A more rigorous treatment, including such effects as particle sources, will form the basis of future work.

References

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