

FISHBONE MODES IN JET OPTIMISED SHEAR PULSES

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1. Introduction

In the JET ‘Optimised Shear’ regime [1], a combination of Lower Hybrid current drive, and Ion Cyclotron and Neutral Beam heating is used during the current rise phase to control the plasma current profile in the central region (giving $q_0 \sim 1.5$). This gives rise to very good core confinement, with a transport barrier being established at mid-radius ($q \sim 2$). The resulting pressure profiles can be strongly peaked ($P_0 / \langle P \rangle \sim 7$) and in combination with a predicted low or slightly reversed magnetic shear in the core region drive MHD instabilities. In the moderate frequency range (~ 10 -40 kHz) several types of related MHD events are observed:

- Pressure-driven infernal or double kink modes which grow to a large amplitude, lock and cause disruptions [2]
- Bursts of $n=1$ modes, at ~ 10 -15 kHz, which cause a rapid collapse of the internal transport barrier, which in turn triggers an H-mode transition
- Fishbone-like oscillation bursts which show a rapid frequency decrease from ~ 50 -30 kHz to 30-15 kHz, and occur in nearly all Optimised Shear pulses

As discussed below, analysis of experimental SXR and ECE data shows all these modes have a similar eigenmode structure but differ in frequency behaviour and consequences. An examination of the fishbone type bursts is the subject of this paper. Fishbone modes were first identified as being caused by a resonant exchange of energy from trapped fast particles to an $m=n=1$ internal kink mode in the PDX tokamak [3]. The $m=1$ fishbone has also been identified in several other tokamaks, e.g. DIII-D [4] and JET [5]. Recently it has been shown theoretically for reversed shear configurations (with $q_{\min} > 1$) that fishbone-type modes driven by a resonance with the banana precession frequency may occur [6]. In particular a dominantly $m=2$ fishbone mode may occur in this case and, as discussed below, this has many of the characteristics of the modes observed in JET, where a significant trapped fast particle population is induced by the ICRH.

2. Experimental Results

Fishbone-like bursts occur in nearly all Optimised Shear plasmas; an example of a series of such bursts for a D-T plasma is shown in Fig. 1. A common feature of these bursts is that they are composed of several harmonics, $n=1,2,3\dots$, and indeed in some cases the $n=2$ harmonic can be dominant. Generally these fishbone bursts are benign - this was also found to be the case for $m=1$ fishbones in JET which had no obvious effect on neutron yields, in contrast to the results found for PDX. In a small subset of cases in Optimised Shear plasmas a large fishbone mode, giving rise to $\sim 7\text{cm}$ displacements near the transport barrier ($q\sim 2$), can cause a temporary confinement degradation and a transition from L to H-mode (which is not necessarily desirable) - an example of such behaviour is shown in Fig. 2.

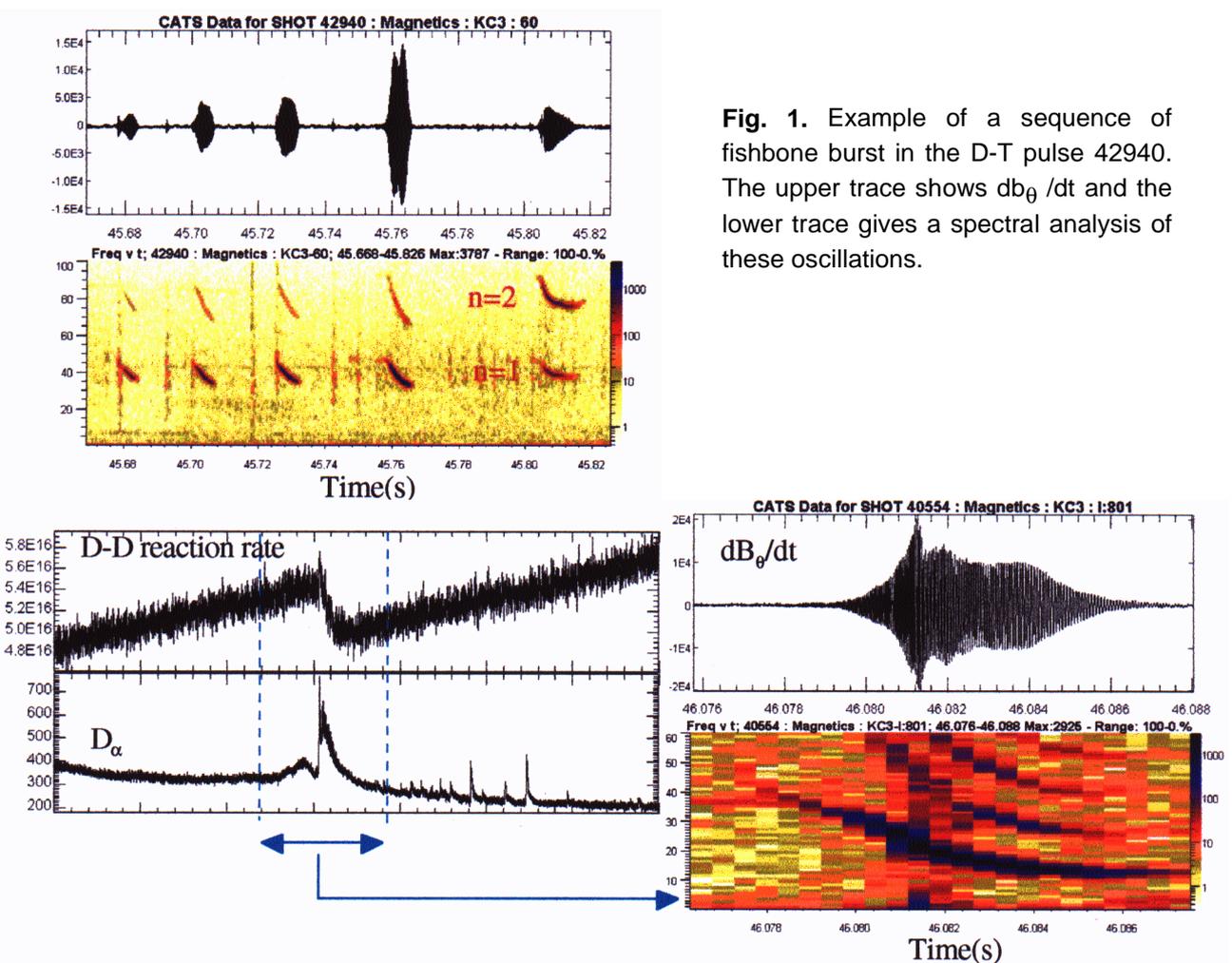


Fig. 1. Example of a sequence of fishbone burst in the D-T pulse 42940. The upper trace shows dB_θ/dt and the lower trace gives a spectral analysis of these oscillations.

Fig. 2. Example of a deuterium pulse in which there is a temporary decrease in D-D reaction rate and an H-mode transition due to a fishbone mode. The right-hand traces show the fishbone mode while the left-hand traces show the effect of this mode on the neutron yield and D_α .

The radial displacement due to the fishbone mode can be inferred from SXR tomography or from ECE measurements, the results being in good agreement. Figure 3 shows a comparison

of the radial displacement, inferred from ECE measurements, for a disruption precursor and a fishbone mode. It can be seen that within experimental errors they have a common radial structure.

In these Optimised Shear plasmas the plasma rotation velocity, measured by charge exchange spectroscopy, is typically $\sim 30\text{kHz}$ in the core decreasing rapidly across the transport barrier to $\sim 10\text{kHz}$. Thus, the fishbones typically originate at a frequency of $\sim 20\text{--}30\text{kHz}$ above the local plasma rotation velocity.

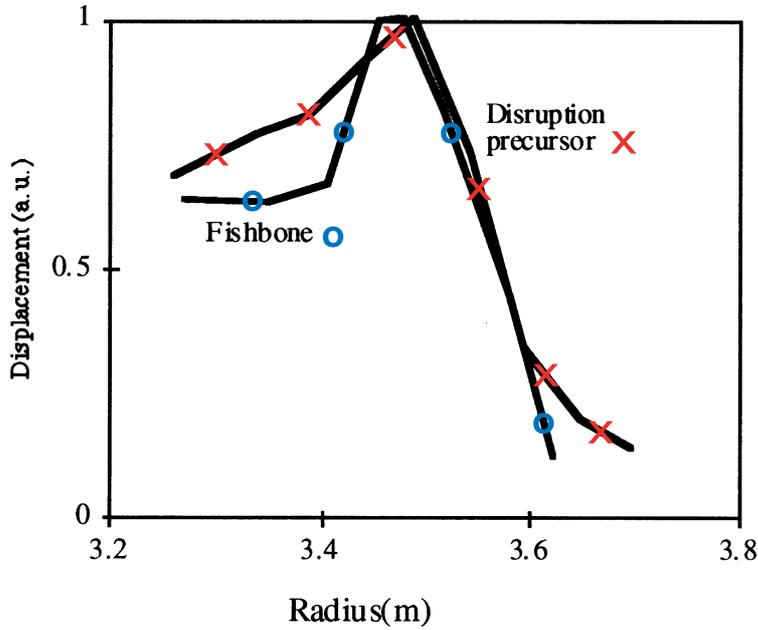


Fig. 3. Comparison of radial displacement in outboard midplane for a disruption precursor (pulse 42735) with a fishbone burst (pulse 40554). The magnetic axis is at $\sim 3.2\text{m}$.

3. Theory

For these Optimised Shear plasmas, TRANSP simulations indicate a low magnetic shear in the core with $q_0 \sim 1.5$. MHD calculations show that the strong pressure gradient near $q=2$ can drive an ideal instability for such equilibria, with the observed fishbone mode structure (dominantly $m=2$, see Fig 3 of [2]), unstable (or nearly unstable). Optimised Shear plasmas typically contain about 1 MJ of fast ions accelerated by the $\sim 5\text{MW}$ of ICRH. These ions have a strongly anisotropic velocity distribution and are able to resonantly destabilise the $m=2$ fishbone mode.

It has been demonstrated theoretically [6] that, in discharges with a non-monotonic q -profile and a minimum q just below 2, fast ions can affect $m/n = 2/1$ modes in a similar way to the ordinary $m/n = 1/1$ mode in discharges with $q_0 < 1$. In particular, phenomena analogous to sawtooth stabilisation and fishbone excitation are predicted. (Off-axis sawteeth have been observed in TFTR and Tore Supra in the region of the $q=2$ surface). The excitation of fishbones is possible by resonance with the fast-ion precession drift at the frequency

$$\omega_D \sim \frac{E}{ZeB_0 R_0^2} \sim 2\pi \frac{E}{1\text{MeV}} 35\text{kHz},$$

where E is the fast-ion kinetic energy. The ICRH ions are thus in resonance with the observed mode. The dispersion relation is of a similar form to that governing $m=n=1$ internal fishbones,

$$\frac{\omega}{i\omega_A} + \delta W_{MHD} + \delta W_h = 0,$$

where the bulk plasma energy δW_{MHD} and fast-ion energy $\delta W_h \propto \frac{1}{2} \int \xi_{\perp}^* \cdot \nabla(\delta \mathbf{P}_h) dV$, (with $\delta \mathbf{P}_h$ the perturbation of the fast-ion pressure tensor) have been suitably normalised, and δW_h has a resonant character. For example, for a slowing-down distribution of trapped fast ions, injected with the energy E_{\max} , with turning points at $\theta=\pi/2$,

$$\begin{aligned} \delta W_h &\propto \hat{\omega} \ln(1 - \hat{\omega}^{-1}) && \text{(banana width} < \text{mode width} < r) \\ \delta W_h &\propto 1 - \hat{\omega}^{1/2} \ln \frac{1 + \hat{\omega}^{1/2}}{1 - \hat{\omega}^{1/2}} && \text{(mode width} < \text{banana width} < r) \end{aligned}$$

with $\hat{\omega} \equiv \omega/\omega_D(E_{\max})$. As $\hat{\omega} \rightarrow 1$ from below, $\text{Re } dW_h$ becomes infinitely negative, indicating resonant destabilisation of the mode. The strength of the interaction, but not its character, is reduced by orbit-width effects. The instability is driven by the fast-ion pressure gradient, and can be excited if the fall in fast-ion beta over the thickness of the mode exceeds a threshold, which for JET parameters becomes

$$\Delta\beta_h^{threshold} = \frac{4\epsilon}{3\pi^2} \frac{s\sqrt{1+2q^2}}{q^2 ZeB_{\theta} R c_A} E = 2 \cdot 10^{-3} \frac{sE}{1\text{MeV}}$$

where $s = d \ln q / d \ln r$ is the magnetic shear, c_A the Alfvén speed and E the fast-ion energy. This excitation threshold is easily overcome by the ICRH ions. The frequency change of the mode is likely to be caused by nonlinear evolution of the fast-ion distribution function due to the wave-particle interaction. It should be noted that although this theory is for non-monotone q -profiles, equivalent results are expected for internal modes occurring in low shear regions.

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