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THE FISHBONE INSTABILITY IN THE DIII-D TOKAMAK

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ABSTRACT. Although most DIII-D plasmas are stable to the fishbone instability, fishbones are sometimes observed when $\beta_p \geq 1.5$ and $\bar{n}_e \lesssim 5 \times 10^{13} \text{ cm}^{-3}$. These bursts are usually of minor significance operationally; however, under one condition, over 50% of the beam power was lost. The angle of beam injection has little effect on the virulence of the instability, suggesting that the fishbone instability in DIII-D is the ion diamagnetic branch of the internal kink.

1. INTRODUCTION

During perpendicular neutral beam injection into the poloidal divertor experiment (PDX), a repetitive instability called the 'fishbone' instability was observed [1]. Like precursors to the sawtooth instability [2], the fishbone was an $n = 1$, $m = 1$ mode, but the $m = 0$ reduction in soft X-ray emission was smaller and the concurrent $m \geq 2$ magnetic oscillations were measured with Mirnov coils [1]. The mode frequency was higher than at a sawtooth [1] and 'whistled down' during a burst from an initial value of $f \approx 22 \text{ kHz}$ to a final value of $f \approx 11 \text{ kHz}$ [3]. Fishbones were observed in PDX whenever the product of toroidal beta and safety factor exceeded a critical value ($\beta_T q \geq 2.5\%$) [4]. Since the instability ejected large numbers of fast ions [1, 3–10] it limited the maximum β achievable in PDX [4].

Two main theoretical interpretations of the fishbone instability have been advanced. Chen et al. [11] discovered that beam ions trapped within the $q = 1$ radius can kinetically destabilize a branch of the internal kink mode with frequency $\omega \approx \omega_p$, where ω_p is the precession frequency of the resonant beam ions; they suggested that fishbones occur when the pressure of these hot, trapped beam ions ($\beta_{h,i}$) is sufficiently high. Later, Coppi et al. [12] extended the analysis of Chen et al. to include the effect of finite diamagnetic frequency ω_{*i} , where

$$\omega_{*i} = \frac{k_\theta c}{eBn} \frac{dp_{i\perp}}{dr} \quad (1)$$

is evaluated at the $q = 1$ radius. In addition to the kinetically destabilized mode found earlier, they found an $n = 1$, $m = 1$ internal mode that is destabilized at lower values of hot ion pressure. For this mode, destabilization is due to an effective ion viscosity associated with momentum transfer within the ion population. Coppi et al. suggested that it is this branch of the internal kink with $\omega \approx \omega_{*i}$ that is the experimentally observed fishbone and emphasized the importance of the poloidal beta β_p in determining stability. Recent work [13–15] has shown that these two distinct branches exist for $\hat{\omega}_{*i} \equiv \omega_{*i}/\omega_p < 0.5$ but that the branches merge for $\hat{\omega}_{*i} > 0.5$.

The experimentally observed fishbone instability has not yet been conclusively identified in terms of the proposed theoretical models. Both interpretations agree with most but not all of the data. Observations that fit within the framework of the trapped particle precession theory include:

- In PDX, the observed frequency was roughly ω_p [1]. The expected scaling of mode frequency with beam energy and plasma current (E/I_p) was sometimes observed [16].
- The observation that faster beam ions were expelled first [6] explained the 'whistling down' of the mode

frequency [1], since the resonant precession frequency fell with time.

- Using the reduction in $\beta_{h,i}$ inferred from neutron measurements, the full PDX fishbone cycle was modelled successfully [5].
- The improved fishbone stability of Doublet III relative to PDX [17] was attributed to the more tangential orientation of the beam injectors.
- The improved fishbone stability of PBX relative to PDX was attributed to a reduction in δW_{MHD} [18].
- Fishbone bursts on JET [19]*, TFTR [20], and JT-60 [21] are at frequencies that are consistent with the fast ion precession frequency.

Some observations are problematic for the trapped particle precession theory, however.

- Studies of fishbones in divertor plasmas in Doublet III [17] and PDX [16] found that the mode frequency did not correlate with E/I_p , but perhaps the discrepancy was due to the neglect of plasma rotation in the scaling studies [16].
- In PDX, the observed frequency coincided with beam ions at $R \approx R_0 + a$ rather than those within the $q = 1$ radius [16]. Proponents of the trapped particle precession frequency have suggested that trapped ions outside the $q = 1$ surface may also resonate with the internal kink [20], although this has not yet been shown theoretically.
- In PDX, kink instabilities during parallel injection were just as virulent as the fishbones during perpendicular injection even though the perpendicular β was much smaller [22, 23].

The ion diamagnetic theory of the fishbone instability is also consistent with most experimental observations:

- In PDX and Doublet III, the observed mode frequency was roughly ω_{*i} .
- The predicted threshold in β_p was observed [16].
- The weak beam angle dependence observed in PBX [22] is expected.

On the other hand, the observation that the mode frequency ‘whistled down’ a factor of two in PDX [1] is problematic for the ion diamagnetic theory since it seems unlikely that $dp_{i\perp}/dr$ dropped by 50% at a burst. Some correlation of frequency change Δf with mode amplitude was observed [16], however, so perhaps the frequency whistle was due to a local flattening of the pressure profile.

* Note added in proof: Reference [19] reports that the fishbone frequency in JET can be substantially lower than ω_p .

Our study of the fishbone instability in DIII-D is motivated by two questions: “Can DIII-D data help establish the correct theoretical identification of the fishbone instability?” and “Can the deleterious effects of the fishbone instability be avoided in high beta plasma operation?” Our answers to these questions are: (1) fishbones in DIII-D are probably the ion diamagnetic branch of the internal kink and (2) DIII-D high beta plasmas are rarely afflicted by fishbones.

2. EXPERIMENT

The DIII-D tokamak [24] is well suited for high beta studies and has obtained the highest values of β_T ($\approx 9.3\%$) of any large tokamak [25]. It has a small aspect ratio ($R_0/a = 167 \text{ cm}/64 \text{ cm} = 2.6$), a relatively modest toroidal field capability ($B_T \leq 2.1 \text{ T}$), and an extremely flexible set of field shaping coils. Most of the discharges studied here were expanded boundary, single-null divertor discharges with elongation $\kappa = 1.6$ –2, triangularity $\delta = (R_0 - R(z_{\text{max}}))/a \approx 0.4$, and indentation ≈ 0 . Neutral beams ($E_{\text{inj}} \approx 75 \text{ keV}$; $P_b \leq 18 \text{ MW}$) were injected in the direction of the plasma current at two angles that are intermediate between perpendicular and tangential (63° and 45° at R_0 ; $R_{\text{tan}} = 110 \text{ cm}$ and $R_{\text{tan}} = 74 \text{ cm}$). Both $\text{H}^0 \rightarrow \text{D}^+$ and $\text{D}^0 \rightarrow \text{D}^+$ neutral beam injection have been employed extensively; most plasmas were in the H-mode [26].

When observed, fishbones in DIII-D are similar to the instability observed on PDX. Figure 1 shows an example from one of the discharges with fishbone bursts. As often observed on PDX at modest beam power [16], a brief quiescent period follows the sawtooth at 2747 ms. Then, as the sawtooth cycle advances, fishbone bursts begin. After a few bursts, a fishbone culminates in a sawtooth [evidenced by the abrupt decay of $m = 1$ oscillations and the drop in soft X-ray (SXR) emission], and the cycle repeats. The fishbone growth rate tends to increase as the cycle progresses, a trend also observed in PDX [16].

Figure 2 shows the internal structure of one of the bursts. As in PDX, the growth rate of the burst ($\approx 4 \text{ kHz}$) tends to be somewhat larger than the decay rate (except when the burst terminates in a sawtooth). The mode frequency of $f \approx 11 \text{ kHz}$ exceeds the frequency of central plasma rotation ($f_{\text{rot}} \approx 8 \text{ kHz}$) measured by charge exchange recombination (CER) of helium (Table I). The frequency decreases through a burst approximately 20%. Mode analysis of data from a poloidal SXR array yields $m = 1$, while toroidal and

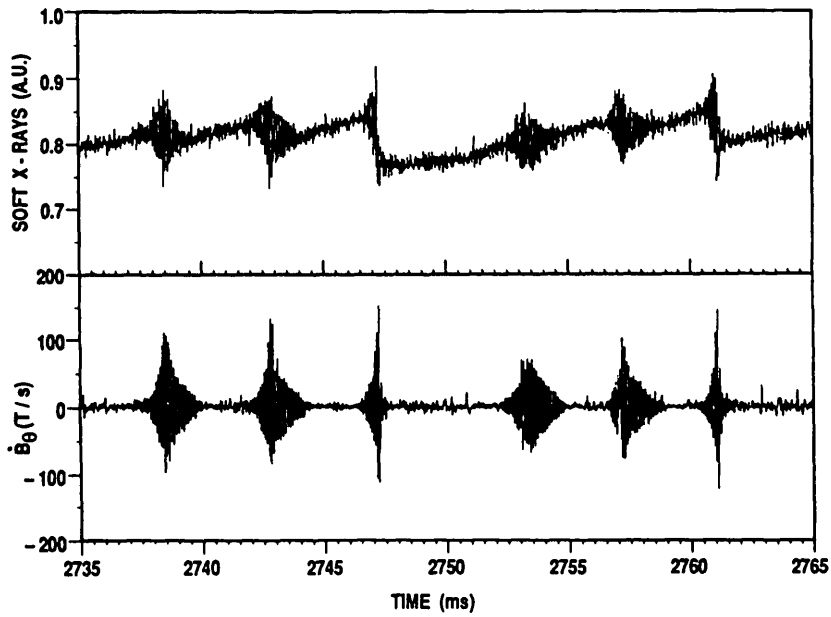


FIG. 1. Fishbone bursts detected by a magnetic probe (at the midplane by the outer wall) and a central soft X-ray detector. $B_T = 0.9$ T; $I_p = 0.45$ MA; $\bar{n}_e = 3.5 \times 10^{13}$ cm $^{-3}$; $H^0 - D^+$; $P_b \approx 10$ MW; single-null divertor with $\kappa = 1.8$; $\beta_p = 2.1$; $\beta_T = 2.5\%$; $T_i(0) \approx 1.5$ keV; soft X-ray inversion radius = 23 cm.

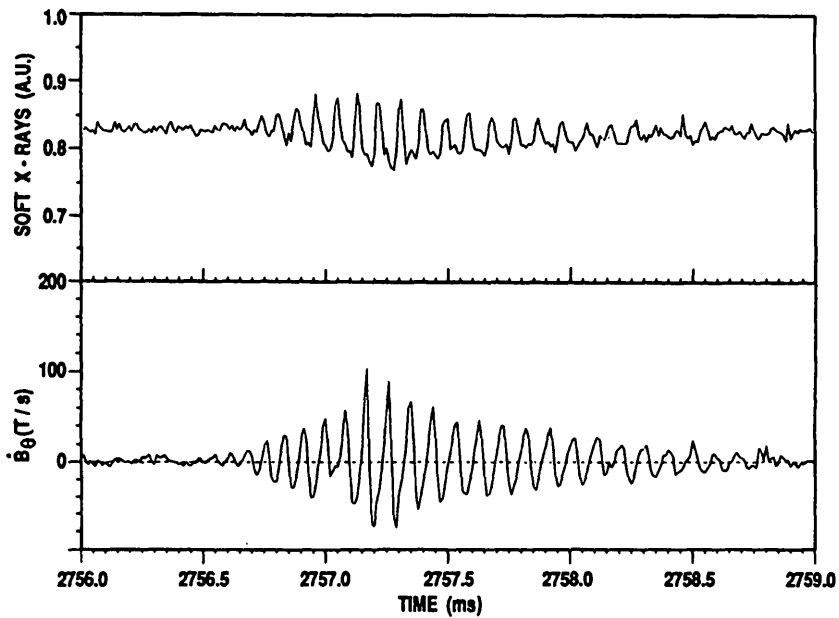


FIG. 2. Internal structure of one of the fishbones in Fig. 1.

TABLE I. COMPARISON OF EXPERIMENTAL AND THEORETICAL FREQUENCIES (kHz)

| Shot | I_p (MA) | f | f_{rot}^a | $f - f_{rot}$ | f_{*1}^a | f_p^b |
|---|------------|----------------|---------------|---------------|---------------|---------------|
| 60443 ($H^0 \rightarrow D^+$) | 0.45 | 10.8 ± 0.2 | 6.0 ± 1.3 | 4.8 ± 1.3 | 2.4 ± 0.9 | 8 ± 1 |
| 62901 ($D^0 \rightarrow D^+$) | 1.02 | 13.2 ± 0.2 | 11 ± 2 | 2 ± 2 | 6.5 ± 2.5 | 1.8 ± 0.5 |
| Left only ($D^0 \rightarrow D^+$) | 0.68 | 18.5 ± 0.2 | 18 ± 3 | 0 ± 3 | N/A | 1.4 ± 0.3 |
| Right only ($D^0 \rightarrow D^+$) | 0.68 | 13.8 ± 0.2 | 10 ± 2 | 2 ± 2 | 6.3 ± 2.5 | 2.7 ± 0.5 |

^a Evaluated at the $q = 1$ radius.

^b Averaged over the full trapped beam ion distribution.

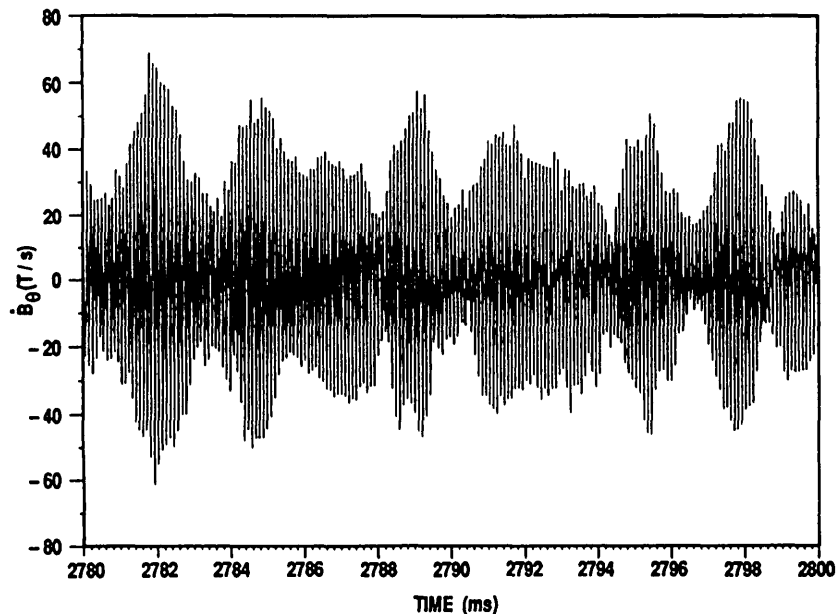


FIG. 3. Run-on fishbones in a discharge in the same sequence as the discharge in Fig. 1. $B_t = 0.9$ T; $I_p = 0.53$ MA; $\bar{n}_e = 4.3 \times 10^{13}$ cm⁻³; $H^0 \rightarrow D^+$; $P_b \approx 10$ MW; single-null divertor with $\kappa = 1.9$; $\beta_p = 1.8$; $\beta_T = 2.9\%$.

poloidal arrays of magnetic probes find $n = 1$, $m \geq 2$ symmetry. In summary, the mode structure, frequency behaviour, growth rate, and relationship to the sawtooth cycle all support identification of these bursts with the fishbone instability observed in PDX.

When discrete bursts are observed at $\beta_p \approx 2$ (Fig. 1), 'run-on' fishbones characterized by modulated, continuous activity (Fig. 3) are observed at slightly lower values of β_p . In PDX, a similar behaviour was observed

near the threshold for fishbone instability [16]. In a few other discharges, the extended precursors to a sawtooth crash also resemble run-on fishbones (Fig. 4), although the precursors may be an instability different from the fishbone.

When large fishbones occur during $D^0 \rightarrow D^+$ injection, neutron scintillators [3] measure coincident reductions in neutron emission (Fig. 5). Generally, the loss of beam power associated with fishbone bursts is

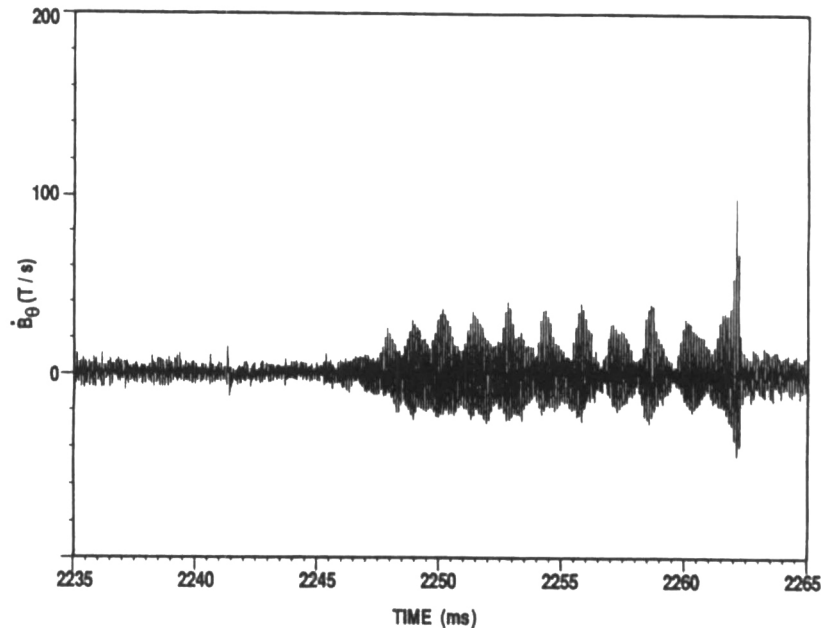


FIG. 4. Run-on fishbones before a sawtooth. $B_T = 0.9$ T; $I_p = 1.0$ MA; $\bar{n}_e = 6.5 \times 10^{13}$ cm $^{-3}$; $H^0 - D^+$; $P_b \approx 7$ MW; single-null divertor with $\kappa = 1.9$; $\beta_p = 0.7$; $\beta_T = 4.0\%$.

negligible ($< 1\%$) but, on one day, large fishbones resulted in appreciable losses. At the burst at 1739 ms shown in Fig. 5, the neutron emission I_n dropped 20% in 1.2 ms, indicating that approximately 20% of the full energy beam ions were lost from the plasma centre to the plasma edge [3]. The magnetic perturbation measured at the outer midplane wall was $\tilde{B}_\theta/B_\theta = 2.5\%$ at this burst. In PDX, magnetic perturbations of 1% at the outer wall (the wall conforms to the plasma more closely in DIII-D than it typically did in PDX) produced comparable neutron behaviour [3]. In DIII-D, magnetic perturbations of $\tilde{B}_\theta/B_\theta \approx 4 \times 10^{-4}$ correlate with $\sim 1\%$ drops in neutron emission; a similar threshold was observed in PDX [3]. Another signature of PDX fishbones were coincident bursts of fast ions measured with sensitive neutral particle analysers [1, 6, 8, 10]. Increases in neutral flux associated with DIII-D fishbones (if any) are below the sensitivity of the E||B charge exchange diagnostic [27]. Since the diamagnetic loop is mounted outside the vacuum vessel in DIII-D, reductions in diamagnetic flux associated with fishbones [23] are also too rapid to be detected.

The most severe losses yet observed occurred during intense $D^0 \rightarrow D^+$ injection ($P_b \approx 13$ MW) into a low current ($I_p = 0.75$ MA), low density ($\bar{n}_e \approx 3 \times 10^{13}$ cm $^{-3}$), low field ($B_t = 0.8$ T) double-null divertor, H-mode plasma. Fishbones in this $\beta_p \approx 1.5$ plasma caused 13% drops in neutron emission every 5 ms. These data

imply that the confinement time for a typical beam ion [3] was only 38 ms, which is considerably shorter than the classical deceleration time [28] of $\nu_E^{-1} = 84$ ms for 75 keV beam ions in this $T_e = 1.8$ keV plasma. Thus, the neutron data suggest [4] that as little as one-third of the beam power was deposited in the plasma for this condition.

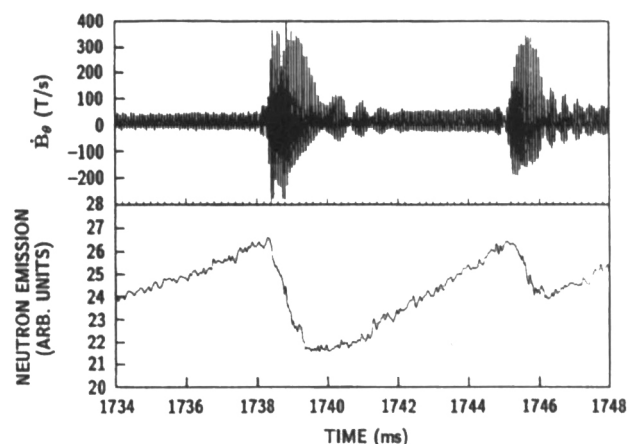


FIG. 5. Time evolution of the signals from a Mirnov coil and from a plastic scintillator in a $D^0 - D^+$, double-null divertor discharge with $I_p = 0.7$ MA, $\bar{n}_e = 2.8 \times 10^{13}$ cm $^{-3}$, $B = 0.8$ T, $P_b \approx 8.8$ MW, $\beta_p = 1.5$ and $\beta = 4.8\%$. The large, rapid drops in neutron emission indicate that beam ions are lost from the centre of the plasma at the fishbone bursts.

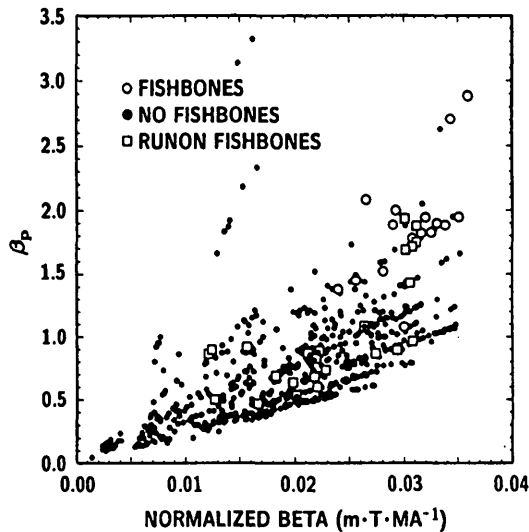


FIG. 6. Position of fishbones (open circles) and run-on fishbones (squares) in parameter space. The run-on fishbones include both sawtooth precursors (Fig. 4) and continuous activity (Fig. 3). Beta is determined from magnetic measurements.

On DIII-D, plasma parameters for 'good' discharges are routinely entered into databases for subsequent study. For this study, all high beta discharges before March 1989 in the DIII-D 'stability' and 'confinement' databases were examined for evidence of fishbone instability. These databases include plasmas with $I_p = 0.3\text{--}2.2$ MA, $B_T = 0.6\text{--}2.2$ T, and $\bar{n}_e = 0.1\text{--}1.2 \times 10^{14}$ cm $^{-3}$. Of the 718 time slices with suitable magnetic probe data, only 21 plasmas with discrete fishbone bursts were found. Twenty-nine plasmas had run-on fishbones; approximately half of these were extended sawtooth precursors similar to the one shown in Fig. 4, and the rest were modulated, semi-continuous $n = 1$ activities similar to those in Fig. 3. For the plasmas with discrete or run-on fishbones, the frequency of the mode was obtained from the fast Fourier transform of a magnetic probe signal.

Fishbones are only observed in DIII-D when both the poloidal beta β_p and the normalized beta [$\beta_N \equiv \beta_T(aB/I)$] are large (Fig. 6). In Fig. 6, fishbones were absent in the very high β_p ($\beta_p > 3$) current drive discharges [29]. These plasmas had $q_{95} > 20$ (q_{95} is the safety factor at the flux surface that encloses 95% of the poloidal flux), so it is unlikely that the $q = 1$ surface was in the plasma. At the other extreme, fishbones were also absent in the many high β_N discharges with $\beta_T > 7\%$, since $\beta_p \leq 1.2$. Even when β_p and β_N are both large, fishbones do not always occur. One high β_p point without fishbones in Fig. 6 occurs for $\beta_p \approx 2.6$ and $\beta_N \approx 3.2\% \cdot \text{m} \cdot \text{T} \cdot \text{MA}^{-1}$. This high β_p

plasma initially did not have fishbones, but broke into fishbone bursts about 50 ms later, following a 30% rise in central SXR emission. Near $\beta_p \approx 2$, some $H^0 - D^+$ discharges exhibit fishbone bursts while others are stable. $D^0 - D^+$ discharges tend to have fishbones at slightly lower values of β_p (≥ 1.5) than $H^0 - D^+$ discharges. Near the stability boundary, visible bremsstrahlung measurements suggest that stable discharges tend to have somewhat lower values of Z_{eff} than the unstable discharges. In several high β_p plasmas (including the one shown in Fig. 1), the fishbones suddenly disappeared when a continuous $n = 2$ oscillation appeared. Run-on fishbones and extended sawtooth precursors have been observed over a wide range of parameters, perhaps indicating that the extended precursors are a different instability. The dependence of fishbone stability on β_p (or related quantities) is the strongest dependence in our dataset.

Statistically, fishbones are more likely to occur in DIII-D when the density is not very high (Fig. 7). In DIII-D H-mode operation, the steady state density depends approximately linearly on the plasma current [30], so the density dependence in our dataset may merely reflect an underlying dependence on β_p . Another possibility is that reduced density increases the fast ion pressure by increasing the slowing-down time, but the presence of fishbone activity correlates more weakly with $P_0 W / \bar{n}_e^2 B^2$ (which is roughly proportional to β_{beam})

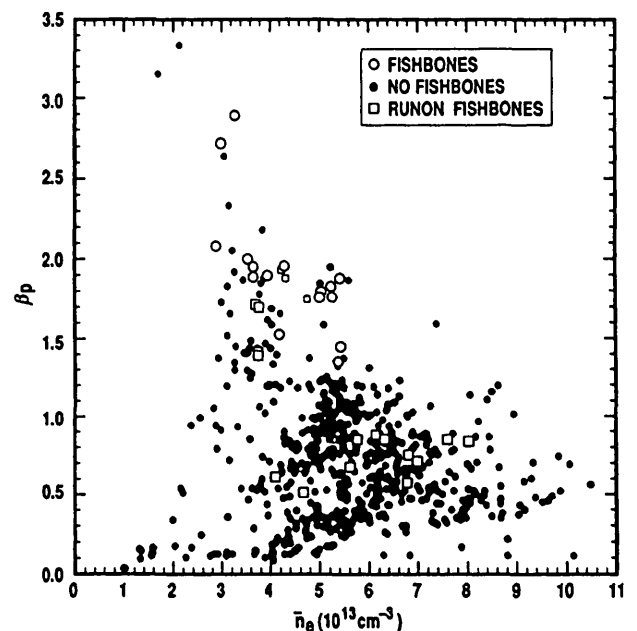


FIG. 7. Dependence of fishbones (open circles) and run-on fishbones (squares) on line average density and poloidal beta.

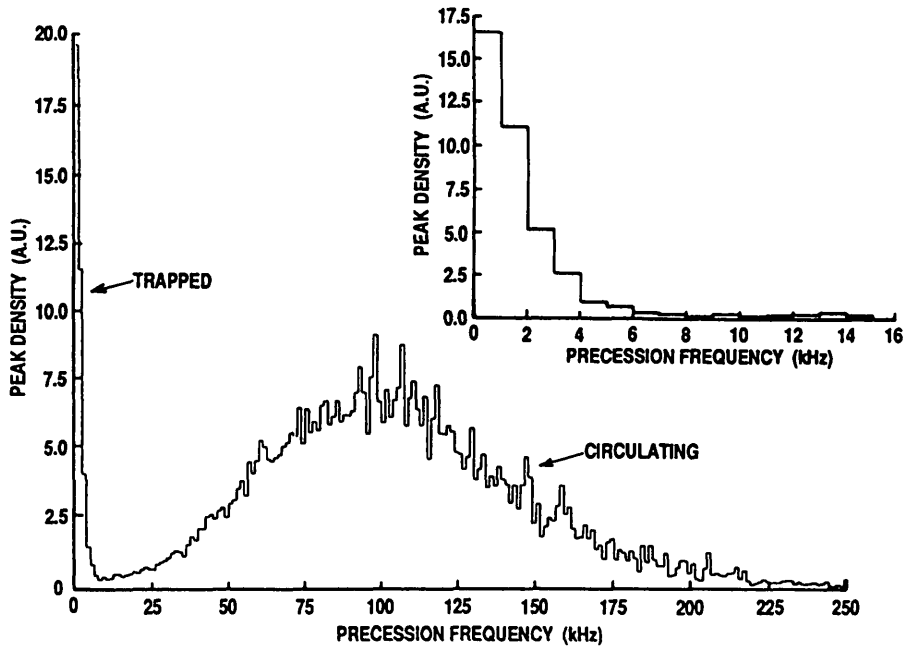


FIG. 8. Circulation frequency for deuterium beam ions in DIII-D (shot 62901) calculated by the Monte Carlo code MCGO. All beam ions are included in the histogram. The insert is a detail of the trapped particle population.

than with n_e , so this explanation seems unlikely. The beam beta in a typical discharge with weak fishbones (shot 62901 in Table I) was 0.8%. In the discharges with strong fishbones (e.g., Fig. 5), β_{beam} is calculated (neglecting the effect of the fishbones) to be 2.3% on average and 18% on axis. The beam beta in PBX discharges with moderately severe fishbones (20% drops in neutron emission) was only 0.4% [23]; however, the fraction of the pressure contributed by beam ions is similar in the two devices.

In DIII-D, most beam ions circulate rather than execute banana orbits. Figure 8 shows a histogram of the circulation frequency (for passing particles) or the toroidal precession frequency (for trapped particles) of the beam ions in a typical $D^0 - D^+$ discharge with fishbones (shot 62901). The calculation was performed by the Monte Carlo code MCGO [31], which calculates the beam deposition from the actual beam geometry and measured density profiles, uses the magnetic field inferred from magnetic measurements [32] in its calculation of beam orbits, and employs measured T_e , n_e and Z_{eff} profiles in its calculations of Coulomb scattering. The calculation was corroborated by a Lorentz orbit code [33] that employs DIII-D magnetic fields [32]. When the calculation is restricted to ions born within the $q = 1$ surface, the peak near the origin in Fig. 8 disappears, indicating that trapped beam ions within

the $q = 1$ surface constitute a very small fraction [$O(1\%)$] of the total beam ion population in DIII-D.

The observed mode frequency f is compared with the diamagnetic frequency f_i and with the precession frequency f_p for several discharges in Table I. The diamagnetic frequency f_i is calculated by substituting experimental data into Eq. (1); the experimental uncertainty is rather large because only the T_i profile in dp_{\perp}/dr was measured. The precession frequency given in Table I is the average value for the full trapped ion population including ions outside the $q = 1$ surface (Fig. 8). Also included in Table I is the plasma rotation frequency (measured by CER) at the putative $q = 1$ radius (inferred from the SXR inversion radius). For comparison with theory, which assumes a reference frame where $E_r = 0$, the plasma rotation frequency f_{rot} is subtracted from the observed mode frequency f [21]. The data in Table I are from shot 60443 (shown in Fig. 1), from shot 62901 (single-null divertor, $I_p = 1.0$ MA, $B_T = 1.7$ T, $\bar{n}_e = 5.6 \times 10^{13}$ cm $^{-3}$, $P_b = 10.5$ MW, $D^0 - D^+$), and from the two discharges documented in Fig. 9.

Fishbones in DIII-D occur for $0.3 < \hat{\omega}_{*i} \equiv \omega_{*i}/\omega_p < 3.6$ (Table I). The experimentally observed mode frequency $f - f_{\text{rot}}$ is comparable to f_i and f_p in all cases, but does not agree consistently with either frequency (Table I). Not enough ion temperature and

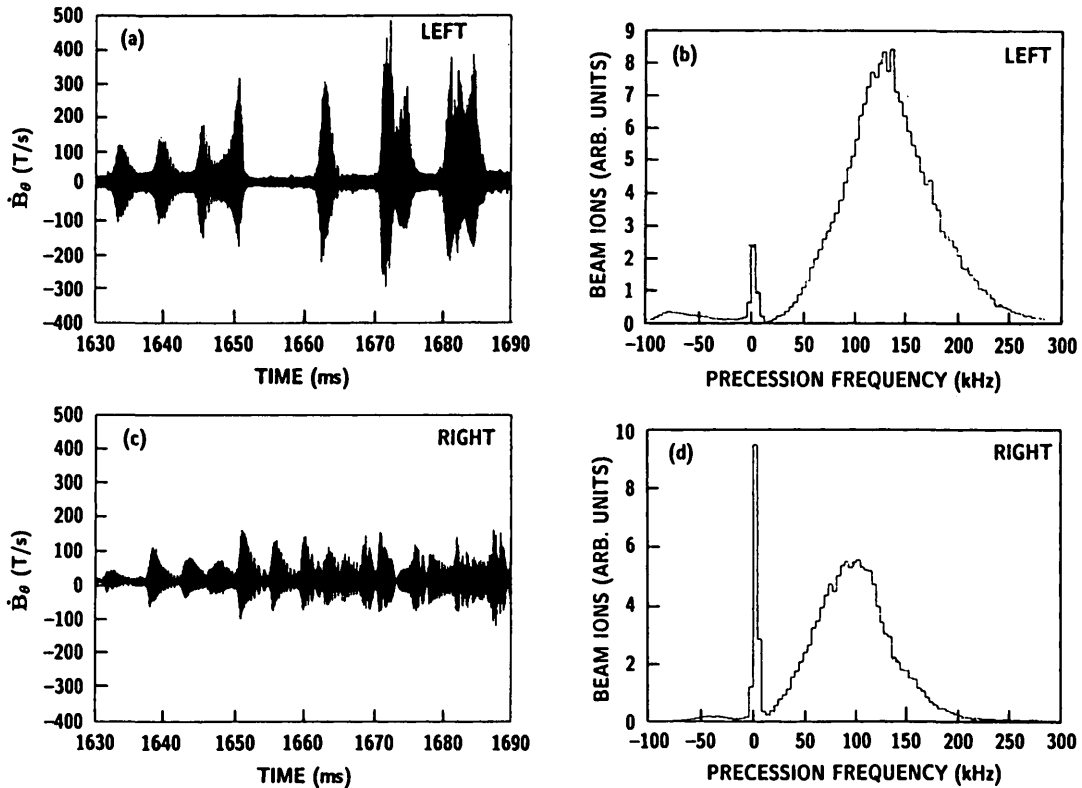


FIG. 9. Comparison of the fishbone activity in two similar discharges ($I_p = 0.7$ MA, $B = 0.7$ T, $P_b \approx 8$ MW) with different angles of beam injection.

(a) Mirnov trace with left beams only ($\bar{n}_e = 3.0 \times 10^{13}$ cm $^{-3}$, $\beta_p = 1.3$; $f \approx 18$ kHz).

(b) Calculation of the distribution as a function of circulation or toroidal precession frequency for the left beam case.

(c) Mirnov trace with right beams only ($\bar{n}_e = 2.4 \times 10^{13}$ cm $^{-3}$, $\beta_p = 1.3$; $f \approx 13$ kHz).

(d) Calculation of the beam distribution as a function of circulation or toroidal precession frequency for the right beam case.

This example shows that fishbone activity can be more severe with fewer trapped particles. For other similar discharges in this sequence, the fishbone activity was slightly less severe with left beams than with right beams.

plasma rotation data are available to establish statistically which theory agrees better with experiment. Since, in analytic theory [34], the precession frequency varies inversely with the poloidal field, one might expect the mode frequency to vary with the plasma current. No correlation of f with I_p is observed in our dataset, but it should be noted that the rotation velocity and beam deposition also depend on I_p (because of the correlation of density with current in our dataset), so the actual dependence of the mode frequency on f_p could easily be obscured. The internal frequency f also does not correlate with q_{95} , \bar{n}_e , P_b/\bar{n}_e , β_T or β_p .

On the day when strong fishbones were observed (Fig. 5), a study of the dependence of fishbone stability on beam injection angle was performed. First, 'left' beams alone ($R_{\text{tan}} = 110$ cm) were injected into high beta discharges with $\beta_p \approx 1.5$ and $\bar{n}_e \approx 2.3 \times 10^{13}$ cm $^{-3}$; on a subsequent discharge, 'right' beams alone ($R_{\text{tan}} = 74$ cm) were employed. Comparison of the time

evolution of the discharges indicates that the macroscopic plasma parameters (except plasma rotation) were quite similar in the two cases. Monte Carlo calculations predict strongly peaked beam deposition profiles in both cases. The computed number of trapped beam ions is five times smaller for the case of left beams (Fig. 9(b)) than for the right beams (Fig. 9(d)), however, so one might expect a change in fishbone stability with beam injection angle. Experimentally, however, the fishbone activity was just as strong for left beams (Fig. 9(a)) as for right beams (Fig. 9(c)), indicating that the fraction of trapped ions has little effect on fishbone stability in DIII-D. To within 10%, the reduction in neutron emission for a given value of \bar{B}_θ/B_θ was also independent of the beam injection angle in these discharges.

In summary, the fishbone instability is definitely observed in DIII-D, but the stability threshold is more diffuse than in PDX. High β_p and low-to-moderate density are necessary but not sufficient for instability.

The loss of energy associated with the instability is usually negligible but, under one condition, large losses were observed. The severity of the fishbone activity is unaffected by changes in the beam injection angle between $R_{\text{tan}} = 110$ cm and $R_{\text{tan}} = 74$ cm.

3. DISCUSSION

Much of the improved stability of DIII-D relative to PDX is attributable to the beneficial effects of plasma shaping on kink stability. The PDX group encountered fishbones whenever $\beta_{\text{t}q}$ exceeded 2.5% [4], but, in DIII-D, discharges with $\beta_{\text{t}q_{95}} > 20\%$ are stable to fishbones. Troyon et al. [35] showed that in shaped plasmas $\beta_{\text{N}} \equiv \beta_{\text{t}aB}/I_{\text{p}}$ is a more relevant measure of external kink stability than $\beta_{\text{t}q}$. In terms of β_{N} , the stability threshold for fishbones in DIII-D is only about twice as large as in PDX. Thus, one reason DIII-D can obtain high β_{t} discharges without fishbone instabilities is that the machine can operate at large values of I_{p}/aB .

Chen's hypothesis that the fishbone is driven by trapped beam ions within the $q = 1$ surface [11] does not seem to apply in DIII-D. The observed mode frequency does not correlate with E/I_{p} (although the dependence could be masked by variations in rotation frequency). Little dependence of fishbone stability on β_{beam} is observed. The severity of the fishbones is unaffected by changes in the fraction of trapped particles caused by variation in the angle of beam injection. These results are really not very surprising. When initially ionized in DIII-D, only beam ions in the outer part of the plasma execute banana orbits, so most beam ions must pitch angle scatter or diffuse radially to become trapped ions. Consequently, the calculated number of trapped beam ions within the $q = 1$ radius is only $\sim 1\%$ of the total beam ion population. Trapped beam ions within the $q = 1$ surface constitute a relatively weak source of free energy.

Though unlikely, the possibility that trapped beam ions drive the DIII-D fishbone cannot, however, be rigorously excluded. Kaita et al. [20] have suggested that trapped ions outside the $q = 1$ surface may resonate with harmonics of the internal kink. The average precession frequency f_{p} of all the beam ions does not agree very well with the observed mode frequency $f - f_{\text{rot}}$ (Table I), but perhaps the agreement could be improved with a different spatial average of the beam population. If one includes beam ions outside the $q = 1$ surface, $\beta_{\text{h,t}}$ in the discharge of Fig. 1 is approximately three times the theoretical threshold

[11], so the observation of fishbones is not unexpected. For deuterium injection, $\beta_{\text{h,t}}$ tends to be larger than for hydrogen injection because the beam power is larger, pitch angle scattering is more important (W_{crit} is larger), and the slowing-down time is larger; this may explain the tendency for fishbones to occur at somewhat lower values of β_{p} for $\text{D}^0 \rightarrow \text{D}^+$ than for $\text{H}^0 \rightarrow \text{D}^+$.

Although fishbones in DIII-D may be the trapped particle branch of the internal kink, it seems more likely that they are predominantly the ion diamagnetic branch. The observed mode frequency $f - f_{\text{rot}}$ does not agree very well with f_{i} (Table I), but the discrepancies are within experimental error. The weak dependence of fishbone severity on injection angle and the weak dependence of f on E/I_{p} are predicted by the ion diamagnetic theory. This theory also successfully predicts that β_{p} is the dominant factor in determining stability.

Zhang et al. [13] have suggested that one difference between PDX and Doublet III is the lower value of the ratio $\hat{\omega}_{\text{i}}^* \equiv \omega_{\text{s,i}}/(\omega_{\text{p}})$ in Doublet III. As indicated in Table I, $\hat{\omega}_{\text{i}}^*$ ranges from small values (< 0.5) to large values (> 1) in DIII-D, so it seems unlikely that this parameter alone accounts for the enhanced stability of DIII-D.

It should be noted that recent theoretical work [13–15] predicts that the trapped particle branch and the ion diamagnetic branch merge for $\hat{\omega}_{\text{s,i}} > 0.5$, so identification of the dominant branch may not be possible for many of the DIII-D data. Perhaps this explains why the observed mode frequency does not agree particularly well with either $f_{\text{s,i}}$ or f_{p} . Another caveat in the comparison between experiment and theory is that the resistivity is sufficiently large that the criteria for ideal theory [36] are only marginally satisfied.

White et al. [5] proposed that the mechanism of beam-ion transport in the presence of the fishbone instability is a resonant interaction between the trapped ion precessional drift and the mode. This theory was consistent with all experimental measurements of fast-ion transport at fishbones in PDX [3, 6–10] and could even be reconciled with the fast-ion losses observed during tangential injection in PBX [23]. White's theory does not agree well with the DIII-D data, however. In contrast to the predictions of Fig. 4 of Ref. [5], the magnitude of the fast-ion loss is independent of the ratio of trapped to circulating ions, and the losses can exceed the computed number of trapped ions. Perhaps the (as yet undetermined) mechanism responsible for fast-ion transport at sawteeth [3, 10, 37] also accounts for the beam-ion transport at fishbones in DIII-D.

4. CONCLUSIONS

Although DIII-D operates at the highest values of β_t of any large tokamak, the fishbone instability is rarely observed. Operation at large values of normalized beta ($\approx 0.035 \text{ m} \cdot \text{T} \cdot \text{MA}^{-1}$) without fishbone activity is possible. At low values of I_p/aB ($\beta_p \geq 1.5$), fishbones are sometimes observed, and the loss of beam power associated with the fishbones can be considerable ($\approx 2/3$ lost under one condition).

The frequency of fishbone oscillations is roughly consistent with both the precession frequency of trapped beam ions and the ion diamagnetic frequency. The virulence of the instability seems independent of the number of trapped beam ions, however, suggesting that the ion diamagnetic branch is primarily responsible for fishbones in DIII-D.

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