STUDY OF HIGH-BETA PRESSURE-DRIVEN MODES IN PDX*

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* This work supported by the United States Department of Energy Contract
No. DE-AC02-CHO-3073.

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Abstract

A new pressure driven instability has been observed in PDX neutral beam heated discharges. It occurs for $\langle \beta_T \rangle q > 0.045$ and is associated with a significant loss of fast ions and a drop in neutron emission. As much as 20-40% of the beam heating power may be lost. The instability occurs in repetitive oscillatory bursts of < 1 msec duration at 1 - 6 msec intervals. It has been dubbed the "fishbone" instability from its characteristic signature on the Mirnov coils. From the soft x-ray detector array, it is identified as an $m = 1$ mode; the Mirnov coil signals are synchronous with it but indicate $m > 2$. The oscillation frequency within a fishbone burst is ~ 10 kHz, but precursors at 50 - 150 kHz are sometimes observed. Much higher frequency oscillations, up to ~ 500 MHz, have been observed as well.

1. Basic Observations of MHD Activity

Under normal conditions in PDX ($I_p > 300$ kA, $B_T > 1.2T$), very little MHD activity is detected by a Mirnov coil. When detectable magnetic perturbations do occur, the mode is usually an $m = 2$, $n = 1$ which rotates in the electron diamagnetic direction. The main type of MHD activity observed on the soft x-ray array is an $m = 0$, $n = 0$ sawtooth oscillation with an $m = 1$, $n = 1$ precursor mode. The sawtooth period in an ohmic plasma can vary from 5 to 10 msec; with neutral beam injection, the period can extend to 50 msec.

The radii of the $q = 1$ surface for a $q_{sh}(a) \sim 3^*$ discharge are ≈ 8 and ≈ 16 cm for ohmic and neutral beam heated discharges respectively. The sawtooth oscillations observed in the ohmic plasma are not correlated with the

*We define $q_{sh}(a) = q_{cy1}(a) \{1 + (a/R_0)^2 (1 + (\beta_p + l_i/2)^2/2)\}$, the lowest order correction to the cylindrical aperture safety factor.

signals from the Mirnov coils. Table 1 contains information on typical MHD activity for both ohmic neutral beam heated discharges. For low power neutral beam injection (1 - 2 beams), the $m = 1$ mode observed on the soft x-ray signal in the plasma core couples to the Mirnov coils. This coupling is strongest at the fall of the sawtooth oscillation. The oscillation on the Mirnov coil is in phase with $m = 1$ mode in the plasma core. The frequency of the oscillations is about 5-10 times greater than in an ohmic plasma and the mode rotates in the ion diamagnetic direction [1].

When continuous $m = 2$ activity is present in ohmic or neutral beam heated low- q discharges, the global confinement time is about half that of a sawtooth type. When the $m = 2$ activity grows in amplitude a clear decrease in the $\beta_p \propto I_i/2$ signal is observed. The $m = 2$ $n = 1$ activity also modulates the neutron emission and the charge-exchange flux. The fast ion slowing-down spectrum is modulated in amplitude but does not change in shape with the $m = 2$ activity present. Discharges which have continuous $m = 2$, $n = 1$ mode activity present, are not used in our scaling studies and are not further discussed in this paper.

2. Fishbone MHD Activity

The normal structure of the sawtooth oscillations changes with injection of 3 - 4 beams at low toroidal field. Instead of a single growing envelope of $m = 1$ before the fall of the sawtooth, many bursts of $m = 1$ localized near the $q = 1$ surface appear in the soft x-ray signal during the rise of the $m = 0$, $n = 0$ part. These bursts of $m = 1$ oscillations are very clearly observed on the Mirnov coils (Fig. 1). Using Fourier decomposition of the signals, these oscillations are found to be rotating in the ion diamagnetic drift direction (in the beam injection direction). The mode number is difficult to identify,

but it appears that the oscillations are due to a spectrum of modes with $m > 2$ [2,3].

The MHD activity near the $q = 1$ surface is also observed on various diagnostics. The 2mm microwave interferometer through the central chord shows $\delta \bar{n}_e / \bar{n}_e = 4\%$, which is consistent with the observation of $\delta n_e / n_e = 5-10\%$ observed by CO_2 laser and microwave scattering. The radial wavelength estimated from CO_2 scattering is > 5 cm. The Ti XIX radiation from the plasma core shows the same behaviour as the central x-ray channels.

At the plasma edge, the fishbone activity is completely different. The signal observed with the ultra-soft x-ray detectors exhibits an inverted sawtooth-type oscillation when the fishbone activity is present. Similar time behavior is detected on CIII radiation and L_α hydrogen radiation.

At the onset of a single fishbone, a higher frequency 50-150 kHz precursor oscillation was observed. From the Mirnov coils and the soft x-ray system a clear identification of the mode number cannot be made. However, the mode appears to come from a region around the $q = 1$ surface. This high frequency fluctuation has a $\tilde{B}_\theta / B_\theta$ amplitude which is about 10 times larger in a 250 kA than in a 400 kA discharge.

When the fishbone activity is very strong, typically at low toroidal field and high beam power, the central soft x-ray signal shows a decrease like a low amplitude sawtooth oscillation. The inversion radius is determined to be $r = 20$ cm and the inverse sawtooth pattern extends to the plasma boundary. The long period, large amplitude sawtooth oscillations observed at lower beam power begin to disappear. Under these conditions the parallel ion distribution function at $E = 5-10$ keV measured by active charge-exchange, also shows strong sawtooth-like oscillation correlated with fishbones. These also extend out to the plasma boundary with an inversion point similar to that seen

in the x-ray signal. This evident field ergodicity or reconnection at each fishbone must to some degree enhance thermal energy transport.

3. Scaling of the Fishbone Activity

A simple empirical scaling of the fishbone period, τ_{fb} , with toroidal field is observed, $\tau_{fb} \propto B_T$ for constant current ($I_p \sim 300$ kA), $R/a = 143/42$ cm, B_T between 0.7 and 1.7T, and four D^0 beams injecting into an H^+ plasma (Fig. 2a). The variation of τ_{fb} with beam power and plasma current is weak. At a toroidal field of 2T, the fishbone activity is very weak, even with four beams, and the soft x-ray signal is more like the classic sawtooth oscillation. The growth rate of the fast $m = 1$ mode oscillation during the fishbone is about 7 times faster at 0.7T than at 1.7T (Fig. 2b). Thus for high beam power, and low toroidal field (and thus high $\langle\beta_T\rangle q$) the period between fishbones is short and the growth rate is fast.

The scaling of the frequency of the $m = 1$ mode during the fishbone has been studied as a function of the beam injection energy (E_{inj}), the absorbed beam power (P_{abs}), the plasma current, and the toroidal field strength. A linear dependence on E_{inj} (Fig. 3a) and an inverse dependence on I_p (Fig. 3b) are found, with little or no dependences on P_{abs} or B_T . The toroidal rotation frequency of the $m = 1$ mode scales approximately as $v_\phi = 94 E_{inj} \text{ (keV)} / I_p \text{ (kA)}$ kHz. where $v_\phi = 2\pi R_O V_\phi \text{ (Hz)}$ cm/sec for an $n = 1$ mode.

This mode rotation velocity is in general significantly greater than the near-central plasma toroidal rotation velocity as measured from the Doppler shift of TiXVII forbidden-line radiation. In addition, the inverse current dependence of the mode rotation speed disagrees with the measured plasma rotation scaling. On the other hand, the observed mode rotation frequency is very similar to the precession frequency of deeply trapped energetic particles

at about $0.6 \times$ the beam injection energy. The precession frequency for fast ions can be estimated by:

$$\begin{aligned} \nu_{\phi} &= v_b^2 / (4\pi R_o^2 \Omega_{ci}) \cdot (B_T/B_0) \\ &= 162 E_{inj}(\text{keV}) / I_p(\text{kA}) \text{ KHz} . \end{aligned}$$

This result suggests that a resonance may exist between the MHD mode and the beam ions which could account for the loss of beam particles. It is also possible that such a resonance could contribute to the instability.

4. Fast Ion Effects and Fishbone Model

Large bursts of charge-exchange neutral efflux are observed which are clearly correlated with the fishbone activity. These are strongly peaked in the perpendicular direction and modulated at the 5 - 20 kHz of the $m = 1$ mode. At low fishbone amplitudes, the energy range of these neutrals is $E_{inj}/2$ to E_{inj} (50 keV), while at high amplitudes, it extends from thermal energies up to $1.5 E_{inj}$. At low particle energies, the background species neutrals are seen to contribute to the spikes. The presence of particles at energies as high as 75-80 keV indicates that a strong accelerating mechanism is present in the plasma. An electrostatic probe in the shadow of the limiter was used to detect frequencies up to 1 GHz. The result shows a broad band of RF noise up to 500 MHz, which appears only during the fishbone bursts. Thus lower hybrid waves, ion cyclotron waves, or the MHD activity itself could be responsible for the acceleration of the beam particles.

The slowing-down spectra of the beam particles show significant depletion in the range from $E_{inj}/2$ to E_{inj} (see Fig.4). At energies above ~ 35 keV, the spectrum is clearly depleted from its original level after each fishbone and begins to recover between events. At energies below $E_{inj}/2$, however, while strong spikes are observed at high fishbone levels, we have not been able to identify a region of the angular spectrum which is depleted just after the fishbone. In the angular scan range available, from counter-near-perpendicular to counter-parallel, the charge-exchange spikes and the depletion are seen to occur primarily at the near-perpendicular angles.

Rapid decreases in the neutron emission are observed at each burst of MHD activity (Fig.1). The neutron signal can decrease by as much as 40% during a fishbone burst. Observations of fast neutron decays have been described as "fast ion disruptions" on PLT, which has tangential neutral beam injection [4].

In order to estimate the loss in heating power which accompanies the observed loss of fast ions, a numerical "fishbone model" was used in the Monte Carlo beam orbit section of the kinetic code [5]. A perpendicular loss cone for particles with $E > 35\text{keV}$ and $|V_{\parallel}/V| < 0.125$ in the horizontal midplane was switched on for 0.4 msec every 3 msec to reproduce the envelope and period of the fishbone structure for a typical 1.0 T discharge. The model gives a reasonable match with the observed rapid depletion of near-perpendicular fast ions after each fishbone, the overall slowing-down spectrum and the neutron modulation. The model was used to analyze the 1.0 T power scan which showed moderate $\langle \beta_T^{dia} \rangle$ saturation versus power and moderate fishbone activity [2]. Figure 5a shows a comparison of the experimental betas and those calculated in the kinetic code both with and without the fishbone model losses. Figure 5b shows the corresponding change in the thermal confinement and the net heating

power to the electrons and ions. In this case the conclusion is that the observed saturation of heating could indeed be due to loss of fast ions.

5. Stability Calculations

A theoretical study of MHD activity in PDX high beta discharges has been made using a full non-linear, 3-D resistive code, H.I.B., which utilises a large aspect ratio expansion [6]. For the large sawtooth type activity with $\langle \beta_T \rangle q < .025$ (see Table 1), good agreement is found between the calculated and the observed soft x-ray and Mirnov coil signals. The non-linearity of the modes and the proper treatment of the vacuum region were found to be essential for these good comparisons. The results indicate that the modes observed at these large amplitude sawteeth are due to a non-linear free boundary resistive mode with a strong $m = 1$ kink component.

The critical $\langle \beta_T \rangle$ for ideal internal modes calculated by the PEST code [7] tends to decrease monotonically as the edge q increases [2]. The critical beta for ballooning modes (infinite n) is close to the experimentally achievable maximum beta. Furthermore, the critical beta of the ideal internal $n = 1$ mode is close to the onset of the fishbone activity. The potential significance of the internal $n = 1$ mode was discussed theoretically in [8] and some experimental indications were presented by the JFT-2 group [9].

6. Co- and Counter-Injection Comparison

A short counter injection experiment was run to study the effect of the fast ion precession being in the opposite direction to the plasma rotation. The results were very encouraging: no fishbone activity was observed and $\langle \beta_T \rangle$ of 2.7% was obtained at $B_T = 0.9$ T and $q_{gh} = 2.0$. The sawtooth activity in the co- and counter-injection cases was very different. In the counter-

TABLE 1
MHD ACTIVITY IN PDX WITH NEUTRAL BEAM INJECTION

	NORMAL DISCHARGE			m = 2 DISCHARGES	
	OH	1-2 BEAMS	3-4 BEAMS	OH	WITH NEUTRAL BEAMS
ACTIVITY OBSERVED ON SOFT X-RAY SIGNAL
$\langle \beta \rangle_{\psi}$ RANGE	~.01	~.025	.045	~.01	~.025
X-RAYS MIRNOV COIL	SAWTEETH AND m=1 VERY LOW LEVEL OF MHD ACTIVITY	LARGE SAWTEETH COUPLING TO MIRNOV COIL AT FALL OF SAWTOOTH m ≥ 2	FISHBONE ACTIVITY STRONG COUPLING OF m=1 TO MIRNOV COIL, m ≥ 2	m=2 MODE m=2	SAWTEETH THEN m=2 LARGE m=2
NEUTRON EMISSION		DECREASE (FAST ION DISRUPTION)	DECREASE ~40%		m=2 OSCILLATIONS OBSERVED ON NEUTRON EMISSION
CHARGE EXCHANGE FLUX		SAWTEETH OBSERVED ON CHARGE EXCHANGE AND SPIKE AT DROP OF SAWTOOTH	LARGE BURST OF CHARGE EXCHANGE DURING FISHBONE AND DEPLETION IN SLOWING DOWN SPECTRUM		m=2 ACTIVITY ON CHARGE EXCHANGE FLUX. NO DEPLETION OF THE FAST-ION SLOW- ING DOWN SPECTRA
CONCLUSIONS	NO TRANSPORT EFFECTS.	NO CLEAR GLOBAL TRANSPORT EFFECTS OBSERVED	A LOSS OF FAST IONS FROM THE PLASMA. A DROP IN THE CALCULATED T _E .	DECREASE IN CON- FINEMENT TIME IS OBSERVED WHEN m=2 ACTIVITY IS PRESENT	CONFINEMENT TIME IS $\frac{1}{2} \rightarrow \frac{2}{3}$ THE CONFINEMENT WITH SAWTEETH OR FISHBONES

injection case the fall of the sawtooth extended over 2 msec, while with co-injection it occurred typically over a period of 100 μ sec at high beam power.

Transport analysis of discharges with four beam counter-injection, which takes into account classical bad-orbit losses, gives an energy confinement time for the thermal plasma of 35 msec, as compared to 15 - 20 msec for similar co-injected plasmas, even in the absence of fishbones at the two beam level (Fig. 5). Furthermore, the central radiation level is much higher than with co-injection, comparable to the local input power to the electrons. Accumulation of high Z impurities is seen in the center of the discharge. Laser ablation experiments showed long central impurity confinement times.

The absence of fishbone oscillations in the counter-injection cases may indeed be due to the opposite directions of plasma rotation and beam ion precession. On the other hand, the $T_e(r)$ profiles with counter-injection were very similar to those observed with co-injection, but there are indications that $Z_{eff}(r)$ was peaked on axis. This suggests that the $q(r)$ profile shape and, specifically, a higher $q(0)$ may play an important role in the enhanced stability of the counter-injection cases.

The relatively high thermal confinement of the counter-injected plasmas, and the observed impurity accumulation, may be related to the negative potential developed in the plasma with counter-injection [10]. Monte-Carlo beam thermalization calculations taking into account a ± 6 kV central potential (corresponding to $V_\phi(0) = cE_r/B_0 \approx \pm 2 \times 10^7$ cm/sec) have been made. The effects of a positive potential (co-rotation) on co-injection heating are found to be negligible, while the presence of a negative potential (counter-rotation) is calculated to improve counter-injection heating efficiency by only $\sim 15\%$. The rotation speeds taken in these calculations are higher than the experimental conditions.

7. Conclusions

The observation of a $\langle \beta_T \rangle q^{1.15}$ limit in PDX [2] can be explained by a loss of fast ions due to the fishbone activity, although an additional deterioration of thermal confinement cannot be ruled out. By modeling the charge-exchange measurements of the fast ions and the neutron emissivity, code results indicate that 20 - 40% of the beam heating can be lost due to fishbone activity. From the soft x-ray system this high beta activity is identified as an $m = 1$ mode, rotating in the ion diamagnetic direction. Stability calculations with PEST suggest that pressure-driven (possibly non-ideal) internal modes may be responsible for the fishbone activity. With perpendicular counter-injection in PDX high beta values with good energy confinement (although substantial beam orbit losses) were obtained without fishbone activity present. The mechanism of interaction of the beam ions and MHD activity, as well as the role of the q profile in the fishbone instability, are the subject of continuing investigation.

Acknowledgments

We wish to express our appreciation for the efforts by M. Williams, T. Kozub, and the neutral beam technical group in operating and maintaining the PDX beam system, to the technicians and engineers who keep PDX operating, and for the continuing support by Drs. H.P. Furth, P.H. Rutherford, and especially, D.M. Meade.

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Figure Captions

Fig. 1 Shows the time evolution of the soft x-ray emission from a central channel, the $\dot{B}_\theta$ signal from a coil near the outer wall of the vacuum vessel and analog output from a fast neutron detector. Expansion of the data from 479 to 496 msec is also shown.

Fig. 2 (a) Variation of the fishbone oscillation period with toroidal field strength for circular plasmas. (b) Dependence of the growth rate γ of the fishbone oscillation on toroidal field, where $1/\gamma$ is defined here as the time between the half and full amplitude of the burst.

Fig. 3 (a) Dependence of the toroidal rotation frequency of the fishbone $m = 1$ mode on the plasma current, I_p . (b) Variation of the toroidal rotation frequency (in kHz) with injection energy (E_{inj}) of the neutral beams for $I_p = 250 - 290$ kA and $R/a = 143/42$ cm. The numbers close to the data points indicate the beam power injected in MW.

Fig. 4 Charge-exchange spectra in the counter-near-perpendicular direction of the slowing down beam ions for a two-beam no fishbone discharge, overlaid with a four beam severe fishbone discharge. The depletion of beam ions from just below E_{inj} down to $E_{inj}/2$ is very evident. Note that these spectra were obtained by sweeping the energy analyzer in time, so fishbone spikes appear to be localized in energy, while in fact they are not, but rather they are localized in time.

Fig. 5 (a) Shows a comparison of the experimental beta's and those calculated in the kinetic code with and without the fishbone model losses. (b) Shows the corresponding change in the thermal confinement and the net heating power to the electrons and ions.

Fig. 1

(a)

(b)

Fig. 2

Fig. 3

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Fig. 5