levels which might have a significant role in the light shift of the $22p$ level due to the 1.06-μm laser field are $6s$, $7s$, $4d$, and $5d$. These are far from being resonantly coupled to the $22p$ level, at least 1700 cm^{-1} away. Their relative positions are such that their combined effects are partially cancelled. A rough evaluation showed that under these conditions the $5d$ level, which is expected to be responsible for the largest effect, contributes to the shift of the $22p$ level an amount of approximately 3×10^{-3} MHz/MW$\cdot$cm^{-2}. This is at least 4 orders of magnitude less than the measured shift, and is thus completely negligible.

With respect to the shift $\Delta\nu_g$ of the ground state, since it cannot be measured alone the best procedure is to calculate it as carefully and precisely possible. A calculation based on Fig. 1 has been carried out.[6] The result is $\Delta\nu_g = -26.3$ MHz/MW$\cdot$cm^{-2}. The dashed line in Fig. 3 corresponds to the sum of the two calculated shifts $\Delta\nu_e + \Delta\nu_g$, whereas the straight line corresponds to a least-squares fit on the measured shifts. Agreement between experimental and theoretical results is satisfactory.

To conclude, this experiment provides clear evidence for the shift of a Rydberg level, due to an intense and strongly nonresonant em field. It is of interest to note that in a pure quantum treatment, radiative corrections can be interpreted as the sum of spontaneous and stimulated radiative corrections. The net effect of spontaneous radiative corrections due to vacuum fluctuations is well known to be responsible for the Lamb shift. In the same spirit, the light shifts which have been studied in our experiment can perhaps be viewed as resulting from the stimulated radiative corrections induced by an intense and nonresonant em field.

We thank Professor Cl. Cohen-Tannoudji for many helpful discussions concerning both the experiment and its interpretation. We are indebted to Dr. M. Aymar and Dr. M. Crance for their calculation of the shift of the ground state.

This work was supported in part by the Durection des Recherches, Etudes et Techniques under Grant No. 80/654. The Laboratiore Aimé Cotton is a laboratoire associé à l'Université Paris-Sud.

---

[1] T. F. Gallagher and W. E. Cooke, Phys. Rev. Lett. 42, 835 (1979).

[2] J. W. Farley and W. H. Wing, Phys. Rev. A 23, 2397 (1981).

[3] P. Avan, C. Cohen-Tannoudji, J. Dupont-Roc, and C. Fabre, J. Phys. (Paris) 37, 993 (1976).

[4] S. Liberman and J. Pinard, Phys. Rev. A 20, 507 (1979).

[5] S. Liberman and J. Pinard, Opt. Commun. 20, 344 (1977).

[6] M. Aymar and M. Crance, private communication.

Study of High-Beta Magnetohydrodynamic Modes and Fast-Ion Losses in PDX

K. McGuire, R. Goldston, M. Bell, M. Bitter, K. Bol, K. Brau, D. Buchenauer, T. Crowley, S. Davis,
F. Dylla, H. Eubank, H. Fishman, R. Fonck, B. Grek, R. Grimm, R. Hawryluk, H. Hsuan, R. Hulse,
R. Izzo, R. Kaita, S. Kaye, H. Kugel, D. Johnson, J. Manickam, D. Manos, D. Mansfield,
E. Mazzucato, R. McCann, D. McCune, D. Monticello, R. Motley, D. Mueller,
K. Oasa,[a] M. Okabayashi, K. Owens, W. Park, M. Reusch, N. Sauthoff,
G. Schmidt, S. Sesnic, J. Strachan, C. Surko,[b] R. Slusher,[b]
H. Takahashi, F. Tenney, P. Thomas,[c] H. Towner,
J. Valley,[b] and R. White
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544

(Received 29 September 1982)

Strong magnetohydrodynamic activity has been observed in PDX neutral-beam–heated discharges. It occurs for $\beta_T q \geqslant 0.045$ 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 bursts of oscillations of $\leqslant 1$ msec duration at 1–6-msec intervals. The magnetohydrodynamic activity has been dubbed the "fishbone instability" from its characteristic signature on the Mirnov coils.

PACS numbers: 52.55.Gb, 52.35.Py

On the PDX tokamak, large-amplitude magnetohydrodynamic (MHD) fluctuations have been observed during plasma heating by injection of high-power neutral beams. The bursts of MHD activity are associated with losses of the energetic beam ions, which are injected nearly perpendicularly in PDX. The losses degrade the efficiency of plasma heating and could have serious consequences for neutral-beam and other auxiliary heating methods in the regime of high $\beta_T q$ (volume-averaged toroidal beta times the safety factor) which will be necessary for fusion reactor operation.

An x-ray imaging system consisting of 57 detectors and an array of 16 magnetic pickup coils (Mirnov coils) were used to determine the mode structure of the MHD fluctuations. Beam-ion slowing-down spectra and the loss of fast ions were obtained from fast charge-exchange and neutron detectors. Microwave and CO_2-laser scattering systems observed density fluctuations during the burst of MHD, which were dominated by the 5–15-kHz frequency of the fishbone oscillations. Data acquisition was by a 60-channel CAMAC system with a sampling frequency up to 1 MHz.

MHD stability during near perpendicular injection (14° from perpendicular at $R = 143$ cm) of up to 7.2 MW of neutral beam power has been studied in the PDX tokamak.[1] The PDX machine typically runs 1-sec discharges with $B_\varphi \leq 2.4$ T, $I_p \leq 500$ kA, $a \leq 44$ cm, and $R \approx 143$ cm. The data discussed in this Letter were obtained with circular cross-section discharges with a water-cooled carbon rail limiter.

The main MHD activity observed on the soft-x-ray array is an $m = 0$, $n = 0$ (m and n are the poloidal and toroidal mode numbers) sawtooth with an $m = 1$, $n = 1$ precursor mode. In Ohmic plasmas the sawtooth oscillations are not correlated with the signals from the Mirnov coils. But for low-power neutral-beam injection (1–3 MW), when $\beta_T q \approx 0.025$, the $m = 1$ mode observed on the soft-x-ray signal in the plasma core has the same frequency as that on the Mirnov coils, the coherence being strongest at the fall of the sawtooth. These coupled modes are very similar to the oscillations observed on the ISX-B and JFT-2 tokamaks[2] which have tangential beam injection.

The normal structure of the sawtooth oscillations changes with coinjection of 4–6 MW of beam power at low toroidal field ($B_T < 1.5$ T). 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 linear rise of the $m = 0$, $n = 0$ sawtooth. These bursts of $m = 1$ oscillations are coherent with bursts observed on the Mirnov coils (Fig. 1) and we have chosen to call the instabilities "fishbone" oscillations because of their characteristic signals on the Mirnov coils. By use of Fourier decomposition of the signals, each significant frequency component is found to be rotating in the ion diamagnetic drift direction (this can also be interpreted as the beam injection and fast-ion precession direction). The mode structure is complex, appearing to be a spectrum of modes with $m \geq 2$.[2,3] The oscillation frequency within a fishbone is ~10 kHz, but precursors at 50–150 kHz are sometimes observed.

The MHD activity near the $q = 1$ surface during fishbone activity is also observed on other diagnostics. The 2-mm microwave interferometer through the central chord shows $\delta\bar{n}_e/\bar{n}_e = 4\%$, which is consistent with $\delta n_e/n_e = 5\%–10\%$ observed by CO_2 laser and microwave scattering. The radial wavelength of the $m = 1$ mode estimated from CO_2 scattering is > 5 cm. The Ti XIX radiation from the plasma core shows the same behavior as the central x-ray channels. Near the plasma edge, the fishbone activity is quite different. The signal observed with the ultrasoft-x-ray detectors exhibits an inverted sawtooth-type oscillation with each fishbone event. Similar temporal behavior is detected on C III radiation and L_α hydrogen radiation.

When the fishbone activity is very strong, typically at low toroidal field and high beam power, the central soft-x-ray signal during a fishbone shows a decrease like a short-period, low-amplitude, sawtooth oscillation.[3] The sawtooth inversion radius for these fishbones is at $r \simeq 20$ cm and the inverse sawtooth pattern propagates to the plasma boundary. The long-period, large-amplitude sawtooth oscillations observed at lower beam power begin to disappear. With strong fishbone activity, the antiparallel ion distribution at $E = 5–10$ keV measured by active charge exchange shows strong sawtoothlike behavior. The radial pattern is similar to that of the x rays, showing activity out to the plasma boundary. Hence, these strong fishbones must to some degree enhance thermal energy transport.

A simple empirical scaling of the fishbone period, $\tau_{\rm fb}$, with toroidal field is observed: $\tau_{\rm fb} \propto B_T$ for I_p ~300 kA, $R/a = 143/42$ cm, with B_T between 0.7 and 1.7 T, and four D^0 beams injecting into an H^+ plasma. The growth rate of the fast $m = 1$ mode oscillation during the fishbone is about 7 times larger at 0.7 T than at 1.7 T. Thus for high beam power and low toroidal field (high $\beta_T q$) the period between fishbones is short and the growth rate is large. It is also in this regime that we observe saturation in the curve of plasma

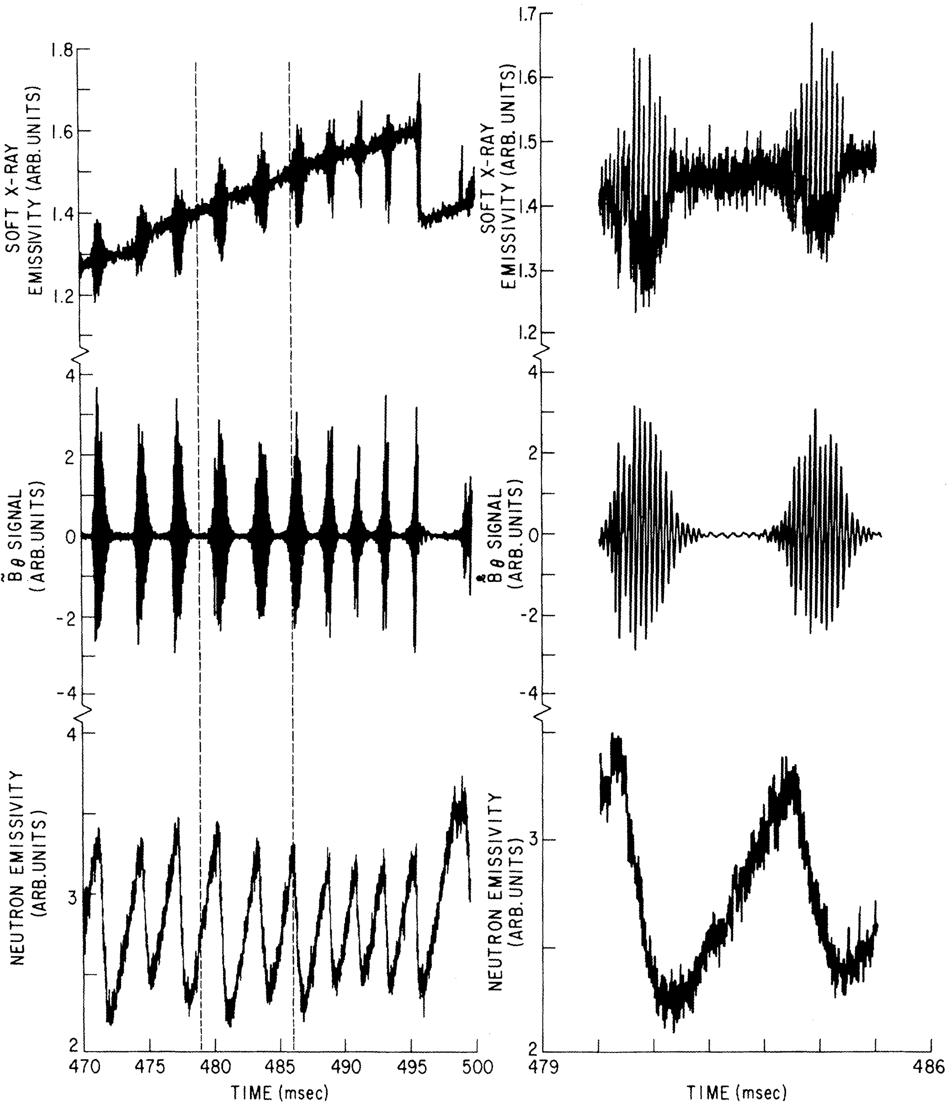

FIG. 1. The time evolution of the soft–x-ray emission along a central chord, the $\dot{B}_\theta$ signal from a coil near the outer wall of the vacuum vessel, and the fast neutron flux. Expansion of the data near two "fishbones" is also shown.

energy (or β_T) versus injected power.

The scaling of the frequency of the $m=1$ mode during the fishbone has been studied as a function of the beam injection energy ($E_{\rm inj}$), the absorbed beam power ($P_{\rm abs}$), the plasma current (I_p), and the toroidal field strength (B_T). A linear dependence on $E_{\rm inj}$ and an inverse dependence on I_p are found, with little or no dependence on $P_{\rm abs}$ or B_T (i.e., $f \sim E_{\rm inj}/I_p$). Interpreted as a toroidally propagating mode, the phase velocity of the $m=1$ mode is in general significantly greater than the plasma toroidal rotation velocity at a similar minor radius as measured from the Doppler shift of Ti XVII forbidden-line radiation.[4] The observed mode frequency is comparable to the precession frequency of deeply trapped energetic particles at about the beam injection energy. The precession frequency for fast ions has a dependence $v_\varphi \propto E_{\rm inj}/I_p$. This result suggests that a resonance may exist between the MHD mode and the beam ions, which could enhance the loss of beam particles. It is also possible that such a resonance could contribute to the instability. This resonance between the MHD mode and the beam ions could be less severe for tangential beam injection, for which there are fewer deeply trapped fast ions.

Large bursts of charge-exchange neutral efflux are observed which are correlated with the fishbone activity. These bursts are peaked in the perpendicular direction and modulated at the 5–

20-kHz frequency of the $m = 1$ mode. At low fishbone amplitudes, the energy range of this enhanced neutral efflux is between $E_{\rm inj}/2$ and $E_{\rm inj}$ (≤ 50 keV), while at high amplitudes, it extends from thermal energies up to $1.5E_{\rm inj}$. At the lower 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 shows a broad band of rf noise up to 500 MHz, which appears only during the fishbone bursts. Thus lower-hybrid waves, high-harmonic 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 $E_{\rm inj}/2$ to $E_{\rm inj}$ (see Fig. 2). 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 $E_{\rm inj}/2$, however, while strong spikes are observed at high fishbone levels, we have not been able to identify a region in velocity space which is depleted just after the fishbone. In the angular scan range available, from near perpendicular to parallel in the counter direction, the charge-exchange spikes and the depletion occur primarily at near-perpendicular angles. Because the enhanced charge-exchange flux occurs in a limited angular and energy range, we can eliminate the possibility that these increases are due to change in the neutral density in the plasma core. From the large relative amplitude of the charge-exchange bursts, increases up to 2 orders of magnitude, it is clear that fast ions are being displaced from the central region of the plasma to the periphery, and probably beyond.

Rapid decreases in the neutron emission by as much as 40% are observed at each burst of MHD activity (Fig. 1). These decays may be similar to fast decays in the neutron emission (described as "fast-ion disruptions") in high-power deuterium beam injection on the Princeton Large Torus, which has tangential beam injection.[5]

If a periodic loss of fast ions with $E > 35$ keV and $|V_\parallel/V| \leq 0.125$ is employed in Fokker-Planck[6] and Monte Carlo beam-orbit codes,[7] then reasonable matches to the overall depletion of the slowing-down spectrum, the rapid depletion after each burst, and the neutron modulation can be obtained. The code calculations indicate that 20%–40% of the beam heating power can be lost by this process.

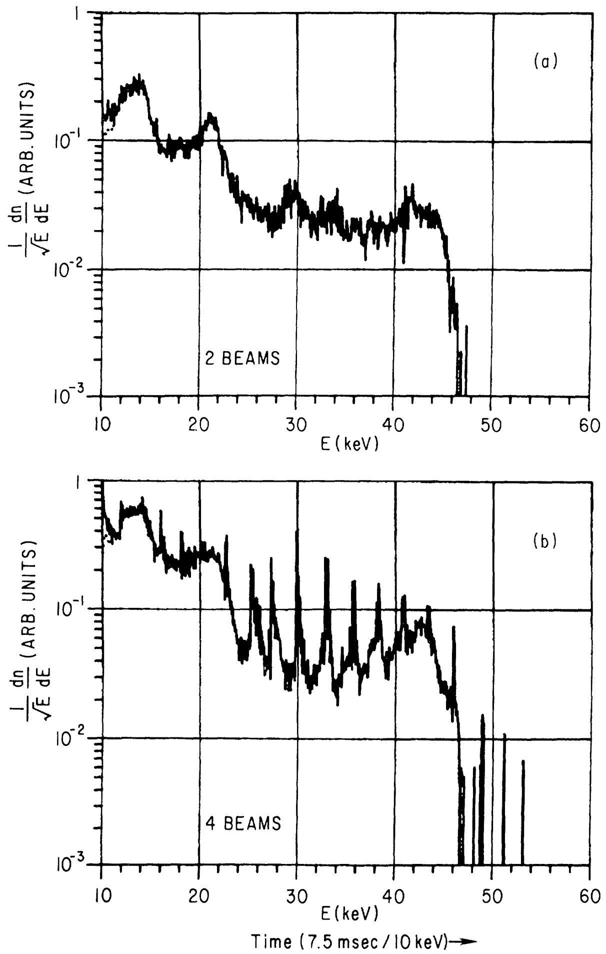

FIG. 2. Charge-exchange spectra in the counter-near-perpendicular direction of the slowing-down beam ions for (a) two-beam no-fishbone discharge, compared with (b) four-beam severe-fishbone discharge. The depletion of beam ions from just below $E_{\rm inj}$ down to $E_{\rm inj}/2$ is very evident. Note that these spectra were obtained by sweeping the energy analyzer in time, so that fishbone spikes appear to be localized in energy; in fact they are localized in time. The signal integration time is 100 μsec for both spectra.

A counterinjection experiment was run to look for changes in confinement and MHD activity. No fishbone activity was observed and a β_T of 2.7% was obtained at $B_T = 0.9$ T with $q_\psi = 2.0$. Despite substantial core radiation and orbit losses calculated to be ~50%, this is nearly the same β_T as achieved with coinjection at the same beam power. This result suggests questions about the effects of radial electric fields on thermal plasma confinement. The sawtooth activity at high beam power in the coinjection and counterinjection cases was also very different. In the counterinjection case the fall of the sawtooth extended over 2 msec, while with coinjection it occurred typically over a period of 100 μsec. The absence of fishbone oscillations in the counterinjection cases may be due to the opposite directions of plasma rotation and beam-ion precession. More critical may be the broader beam-ion-density profile and the less anisotropic distribution which arise from finite banana-width effects. However, the $q(r)$ profile shape and, specifically, a higher $q(0)$ may also play an important role in the enhanced stability of the counterinjection cases. For although the $T_e(r)$ profiles with counterinjection were very similar to those observed with coinjection, visible bremsstrahlung measurements indicate that in the counterinjection case $Z_{\rm eff}(r)$ was peaked on axis, and thus the $q(r)$ profiles were different.

In summary, at high values of $\beta_T q$ in PDX a loss of fast ions is seen simultaneously with large MHD (fishbone) activity. Modeling of charge-exchange measurements and neutron modulation indicates that 20%–40% of the beam heating is lost during periods of fishbone activity. This can serve to explain the observed limit to $\beta_T q$ in PDX[3]; however, an additional deterioration of thermal confinement cannot be ruled out. From the soft-x-ray measurements this high-beta activity is identified as an $m=1$ mode, rotating in the ion diamagnetic direction. With near perpendicular counterinjection in PDX, high beta values were obtained without fishbone activity. How the beam ions and MHD activity interact, and the role of the q profile in the fishbone instability, are the subject of continuing investigation. Stability calculations for ballooning and pressure-driven internal modes are being carried out at present and compared with experimental results.

We wish to express our appreciation to the Neutral Beam technical group for operating and maintaining the PDX beam system, to the technicians and engineers who keep PDX operating, and for the continuing support by Dr. H. P. Furth, Dr. P. H. Rutherford, and Dr. D. M. Meade. The PDX project is supported by the U. S. Department of Energy under Contract No. DE-AC02-CHO-3073.

(a)Permanent address: Japan Atomic Energy Research Institute, Tokai, Japan.

(b)Permanent address: Bell Laboratories, Murray Hill, New Jersey 07974.

(c)Permanent address: JET-Joint Undertaking, Abingdon, United Kingdom.

[1] D. Meade *et al.*, in *Proceedings of the Eighth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium, 1980* (International Atomic Energy Agency, Vienna, 1981), Vol. 1, p. 665; R. J. Hawryluk *et al.*, Phys. Rev. Lett. 49, 326 (1982).

[2] J. L. Dunlap *et al.*, Phys. Rev. Lett. 46, 538 (1982); S. Yamamoto *et al.*, Nucl. Fusion 21, 993 (1981).

[3] D. Johnson *et al.*, in Proceedings of the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1982 (to be published).

[4] S. Suckewer *et al.*, Nucl. Fusion 21, 1301 (1981).

[5] Princeton Plasma Physics Laboratory Annual Report No. PPPL-Q-38, 1980 (unpublished).

[6] J. D. Strachan *et al.*, Nucl. Fusion 21, 67 (1981).

[7] R. J. Goldston *et al.*, J. Comput. Phys. 43, 61 (1981).