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MODE PARTICLE RESONANCES DURING NEAR-TANGENTIAL NEUTRAL BEAM INJECTION IN LARGE TOKAMAKS

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ABSTRACT

Coherent magnetohydrodynamic modes have been observed during neutral beam injection in TFTR and JET. Periodic bursts of oscillations were detected with several plasma diagnostics, and Fokker-Planck calculations show that the populations of trapped particles in both tokamaks are sufficient to account for fishbone destabilization. Estimates of mode parameters are in reasonable agreement with the experiments, and they indicate that the fishbone mode may continue to affect the performance of intensely heated tokamaks.

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The fishbone instability, named because of its characteristic signature on the Mirnov coil signals, was first identified during near-perpendicular neutral beam injection in the Poloidal Divertor Experiment (PDX), in plasmas with high values of poloidal beta.[1] The instability was also observed in subsequent experiments with near-perpendicular injection in the Princeton Beta Experiment (PBX),[2] and a theory for explaining the fishbone mechanism has been successfully developed.[3-6]

Since the model predicted that mode-induced particle losses would be most significant with near-perpendicular injection and for high toroidal precession frequency, fishbones were not expected to be excited in tokamaks like the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET), where the beamlines are oriented in near-tangential directions, and the precession rates are significantly lower, due to larger field strength and major radius. However, an $m = 1$, $n = 1$ internal mode, very reminiscent of fishbones, was observed in several low-q(a) discharges (toroidal field = 2.88 T and $\beta_{total}q = 0.02$) in TFTR.[7] When the toroidal field was raised to 4.8 T, the plasma beta dropped by about a factor of three, and the mode was no longer seen. This is consistent with the mode being destabilized only in the vicinity of the internal kink threshold.

These plasmas, as shown in Fig. 1, are characterized by repetitive bursts in the Mirnov coil signal (dB_p/dt) associated with fishbones. These are correlated with spikes in the fast charge-exchange (C-X) neutral flux, but only approaching the injection energy (~ 90 keV). The C-X data in Fig. 1 were obtained with the neutral particle analyzer sightline at a tangency radius (R_{tan}) of 91 cm. The bursts were less pronounced as the analyzer sightline became increasingly tangential, and hence less sensitive to the population of trapped beam ions. C-X measurements with higher time resolution also show that the spikes have an internal frequency[1] of about 5 kHz, which is the same as that of both the Mirnov and soft X-ray (SXR) diode fluctuations. Unlike the results from near-perpendicular injection in PDX and PBX, the instability is benign at the levels observed to date in that there are no visible fluctuations in the neutron emission, I_n, at least beyond the 3% level. Nearly all of these observations have also been made in similar beam-heated plasmas ($\beta_{total}q = 0.01$) in JET.[8,9] The TFTR and JET parameters were used as input for a bounce-averaged Fokker-Planck code,[10,11] and the calculations indicated trapped beam ion fractions that were sufficient for a noticeable mode-particle resonance.

Although the induced resonant loss of high energy particles in the presence of a magnetic perturbation with a real frequency is easily simulated for high-beta plasma equilibria with a shaped cross section,[1,2] the theory of trapped particle destabilization of the internal kink mode has been completed only for circular, large aspect ratio equilibria.[4,5] Within this approximation, a variational principle yields the mode dispersion relation which possesses, in addition to the usual magnetohydrodynamic (MHD) branch, a trapped particle branch. This branch has a threshold in trapped particle beta, β_T, and a real frequency given by an average over the trapped particle distribution of toroidal precession frequency, ω_d. For a model slowing-down distribution, the threshold is given by

$$\beta_{crit} = \frac{\langle\omega_d\rangle}{\pi\tilde{\omega}_A} \quad , \tag{1}$$

where

$$\tilde{\omega}_A = \frac{v_A}{\sqrt{3}Rrq'} \tag{2}$$

with v_A being the Alfvén velocity, R and r the major and minor radii, respectively, and

$$q' = \frac{dq}{dr} \qquad , \qquad (3)$$

where q is the safety factor, and $\tilde{\omega}_A$ is evaluated at the q = 1 surface. Although the theory of mode destabilization has not been formally generalized beyond the treatment of the m = 1, n = 1 mode, the relative amplitudes of the higher m modes and the simulated mode-particle coupling indicate that they all couple to the beam ions as well.[3] This is consistent with the experimental observation of fishbones in TFTR during tangential injection, where most of the beam ions near the injection energy were not close to the magnetic axis, and in our simulations, mode-particle coupling over the whole plasma with all modes was assumed. The mode frequency is given by the average precession rate $\langle\omega_d\rangle$, and the growth rate for the mode is given by

$$\gamma = \langle\omega_d\rangle \left(\frac{\beta_T}{\beta_{crit}} - 1\right) , \qquad (4)$$

where β_T is the trapped beam particle beta.

The fishbone cycle has been simulated for various trapped particle distributions, and consists of a gradual increase in β_T, at a rate given by the beam injection parameters, followed by a burst of mode activity with a loss which, for PDX parameters, consisted of typically 30% of the trapped particles. Thus the theory predicts mode frequency and threshold, as well as burst period and the distribution of the resonantly ejected particles. The estimates for these quantities for the plasma parameters observed during fishbone bursts in PDX, TFTR, and JET are given in Table I, along with the experimental parameters describing the discharges. The fraction of beam particles in trapped orbits, and the injection rate $d\beta_T/dt$ for the trapped particles, were obtained using the Fokker-Planck code.[10,11] The estimates for the fishbone threshold and mode frequency are only approximate, as they depend on the particle distribution in energy and radius and the q profile, and these are not accurately known. The threshold and mode frequency, furthermore, are also affected by the fishbone bursts themselves. Since most of the beam ions are trapped in the outer two-thirds (in minor radius) of the TFTR plasma, and beam ions affected by the fishbone instability were observed up to a tangency radius of 148 cm, we assumed an average pitch angle of about 0.5. The mean precession frequency $\langle\omega_d\rangle$ for our estimates is thus

$$\langle\omega_d\rangle = \frac{E}{2mR\omega_c} \quad , \tag{5}$$

with E, m, and ω_c being the injection energy, mass, and gyrofrequency, respectively. This expression gives the mode frequency, and together with the shear Alfvén frequency, provides the fishbone threshold. Because of the lack of precision with which the relevant parameters are known, this procedure is more a consistency check than an exact prediction. The shear Alfvén frequency was found by taking the q = 1 surface to be at one-third of the minor radius, and assuming $q'r_s = 0.5$.

The fraction of trapped particles lost during a fishbone burst can be estimated from the simulation results for PDX.[4] The fishbone cycle consists of a constant increase in β_T, given by the injection rate. When β_T exceeds β_{crit}, the mode amplitude A grows according to Eq. (4) with the dependence

$$A \sim e^{ct^2} \quad , \tag{6}$$

where

$$c = \langle\omega_d\rangle \frac{1}{\beta_{crit}} \frac{d\beta}{dt} \tag{7}$$

and β_T equaling β_{crit} at $t = 0$. This behavior of the mode makes its effect negligible until it is large enough to eject particles, at which point they are lost in a time short compared to the burst period. Thus the number of trapped particles lost in each burst is determined by the mode growth time ($1/\sqrt{c}$) and the deposition rate through

$$\Delta\beta_T \sim \frac{d\beta_T}{dt} \left[\frac{1}{c} \ln \left(\frac{A_{max}}{A_{min}}\right)\right]^{1/2} \quad . \tag{8}$$

The fishbone cycle consists of periodic motion in the (A, β_T) plane, given by the equations

$$\frac{dA}{dt} = A\langle\omega_d\rangle \left(\frac{\beta_T}{\beta_{crit}} - 1\right) \tag{9}$$

$$\frac{d\beta_T}{dt} = S - L(A, \beta_T) \quad , \tag{10}$$

where S is the constant beam source, and L is the loss rate. Without attempting to model the loss, we simply note that the trajectories in this plane are defined by the values of the maximum amplitude (A_{max}) and β_{crit}, and the integrals of Eq. (9) and (10). These quantities are only algebraic functions of machine parameters. The value of A_{max} can be readily estimated, and the result is confirmed by the actual simulations.[3] Because of its explosive behavior [Eq. (6)], A(t) grows until it resonantly ejects large numbers of trapped particles. Since the toroidal precession rate is proportional to the energy, the effective width of the resonance becomes very large when the radial displacement, due to the mode in one period, is comparable to the minor radius. The radial motion[3] is linear in ω_d and A, that is, dr/a varies as $\omega_d tA$. If dr/a and $\omega_d t$ are required to be on the order of unity, we find A_{max} to be approximately independent of particle energy and machine parameters. We thus neglect the weak dependence on A_{max}/A_{min} in Eq. (8), and express $\Delta\beta_T$ as

$$\Delta\beta_T \sim \frac{d\beta_T}{dt}\frac{1}{\sqrt{c}} \quad . \tag{11}$$

The simulation of PDX fishbones gave a loss rate of approximately 30% of the trapped particles per burst. By substituting values from PDX and TFTR, we find that $c_{PDX}/c_{TFTR} = 16$. This gives a loss rate of 7% of the trapped particles per burst for TFTR, or about 1% of the total beam particles. Using this result, we also calculate the burst period Δt according to the relation

$$f\beta_{crit} = \frac{d\beta_T}{dt}\,\Delta t \tag{12}$$

with f being the fraction of trapped particles lost. For TFTR, we find Δt = 21 msec, which falls within the range of observed fishbone periods. A similar calculation for JET gives the results in Table I, which are consistent with experiment within the accuracy with which the parameters are known.

Note that the scaling results obtained in this work imply that the relatively benign behavior of the fishbone mode in these devices is due to the relatively slow beam injection rate (in terms of dβ/dt) compared to that in PDX. The future TFTR program involves balanced injection with neutral beams which are still more tangential than perpendicular, and simulations assuming a very pessimistic case with 30 MW of beam power in a low-q(a) plasma suggest at most a three-fold increase in $d\beta/dt$ over the levels in the current study. Deuterium-tritium "Q ~ 1" experiments will also be performed at much higher toroidal fields and plasma currents, so fishbones (according to Eq. (11)) are not expected to be detrimental under planned TFTR operating conditions.

The very modest 1% loss of beam particles for TFTR at the present injection rate is consistent with the negligible change in the neutron emission when the fishbones occur. It should be noted, however, that the fishbone oscillations are predicted to limit the trapped particle population to a value corresponding to a β_{crit} [as defined in Eq. (1)] of approximately 3×10^{-3}. Since the passing beam particles are not affected, this does not seriously limit the effectiveness of beam heating.

It has been pointed out that for large tokamaks, modifications of the fishbone threshold due to resistive effects can inhibit this mode,[13] provided that the resistive growth time $\omega_R = S^{-1/3}\omega_A$, where S is the magnetic Reynolds number, is greater than the mode frequency $\langle\omega_d\rangle$. For the beam injection energies used, however, we find ω_R to be close to $\langle\omega_d\rangle$, which is nearly the same situation that prevailed in PDX, so resistive effects do not modify the mode.

To conclude, we have found that the fractions of trapped particles produced in the beam injection geometries used in TFTR and JET are sufficient to induce fishbone bursts, and estimates that are governed by the constraints of the fishbone model for mode frequency, burst period, and fractions of particles ejected are reasonably consistent with experimental observations. Because relatively few beam particles are participating in the mode, and the injection rate is lower, the bursts are not as violent as in PDX, and their effect on the neutron emission is significantly less. The possibility of fishbones in large tokamaks, however, suggests that care should be taken in choosing operating regimes (e.g., avoiding high $\beta_{total}q$) for them to prevent instabilities associated with trapped ion populations.

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TABLE I. Observed mode characteristics, calculated mode properties, and typical experimental plasma parameters used to compute them for PDX,[1] TFTR, and JET.[9]

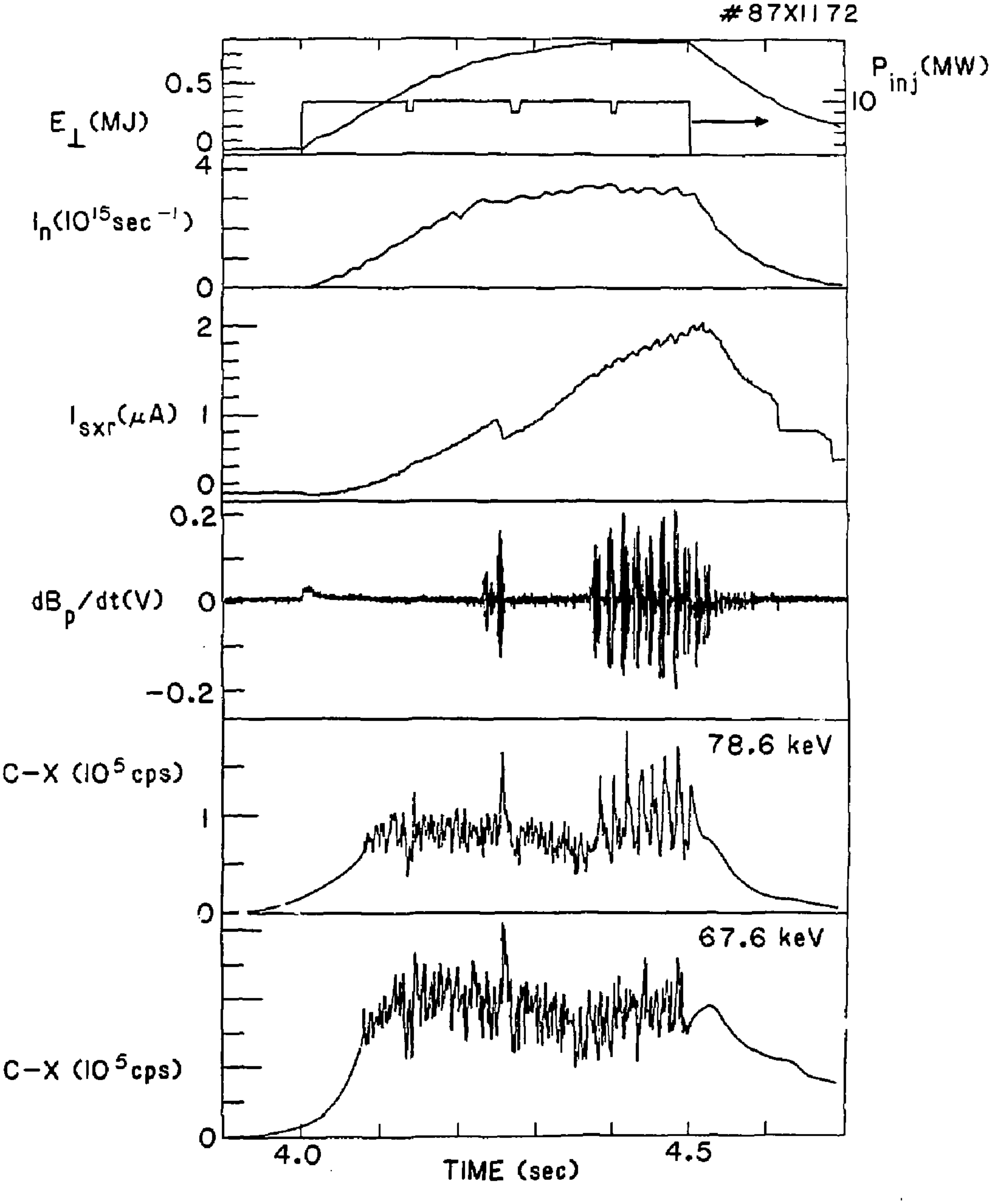
OBSERVED MODE CHARACTERISTICS	PDX	TFTR	JET
Mode Frequency Range (kHz)	10 - 20	4 - 6	5 - 10
Burst Period Range(msec)	1 - 6	13 - 30	5 - 40

EXPERIMENTAL PLASMA PARAMETERS	PDX	TFTR	JET
Minor Radius (m)	0.4	0.79	1.2
Major Radius (m)	1.43	2.45	2.97
Toroidal Field (T)	1.0	2.88	2.15
Plasma Current (MA)	0.3	0.9	2.0
$T_e(0)$ (keV)	1.1	3.7	6.0
$T_i(0)$ (keV)	2.1	13.4	5.0
$n_e(0)$ $(10^{13}cm^{-3})$	5	3.5	3.0
Co-perpendicular Beam Power (MW)	4	0	0
Co-tangential Beam Power (MW)	0	5.2	5.0
Counter-tangential Beam Power (MW)	0	4.6	0
Beam Injection Energy (keV)	50	95	70

CALCULATED MODE PROPERTIES	PDX	TFTR	JET
Fraction of Beam Trapped(%)	63	14	47
Shear Alfvén ω_A (sec^{-1})	1.6×10^7	4×10^6	3×10^6
Precession Rate $\langle\omega_d\rangle(sec^{-1})$	1.2×10^5	4×10^4	3×10^4
Fishbone Threshold β_{crit}	2.5×10^{-3}	3×10^{-3}	2×10^{-3}
Injection Rate $d\beta_T/dt(sec^{-1})$	0.44	0.01	0.04
Total Beam Ions Lost per Burst (%)	19	1	11
Mode Frequency (kHz)	20	6	5
Burst Period (msec)	3	21	12

FIGURE CAPTION

1. TFTR plasma characteristics for a representative discharge containing an n = 1 bursting mode (approximately 5 MW co plus 5 MW counter, I_p = 0.9 MA, $q_{cylindrical}$ = 4.1, and $\beta_{poloidal}$ = 1.2). Beginning from the top, the figure shows the perpendicular stored energy, beam power, neutron emissivity, soft X-ray signal, Mirnov coil signal, and the charge-exchange (C-X) flux at the two energies indicated. The C-X data before 4.08 sec and after 4.5 sec were obtained at a much lower sampling rate. Only the beam heating phase (4.0 - 4.5 sec) is shown, and the event at 4.25 sec is a sawtooth oscillation.



#87X1172
0.5
0
E⊥(MJ)
P_inj(MW)
10
4
I_n(10^15 sec^-1)
0
2
1
0
I_sxr(μA)
0.2
0
-0.2
dB_p/dt(V)
78.6 keV
C-X (10^5 cps)
1
0
67.6 keV
C-X (10^5 cps)
0
4.0
4.5
TIME (sec)

Fig. 1

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