Effect of Internal Magnetic Structure on Energetic Ion Confinement in Tokamaks

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For the tokamak magnetic confinement concept, theory has predicted a distinct relationship between the plasma shape, the internal magnetic structure, and the presence or absence of fast ion losses in the presence of plasma instabilities. We have, for the first time, carried out measurements of the magnetic safety factor profile, $q(r)$, in plasmas unstable to a specific instability, the so-called "fishbone" mode. The experimental equilibria reconstructed from these data have been used to demonstrate that when the plasma is unstable to fishbones, the fast ion confinement properties depend strongly on the radius of the magnetic surface where $q(r)=1$.

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Auxiliary heating techniques for achieving high temperatures in tokamak plasmas are particularly sensitive to the confinement of the fast ions on which they depend. Magnetohydrodynamic (MHD) instabilities like the so-called "fishbone" mode [1], for example, are known to cause fast ion losses, and theoretical predictions have related these losses to the internal magnetic geometry of the plasma [2-5]. The magnetic safety factor profile, or $q(r)$, is essential for the unique determination of this geometry, and with the motional Stark effect diagnostic on PBX-M [6], q profiles can be measured in hot, dense thermonuclear plasmas. In addition, PBX-M has the ability to change the internal magnetic geometry through plasma shaping [7]. The cause and control of fast ion losses is a critical issue for controlled nuclear fusion. This is investigated in plasmas of different shapes, but with nearly identical MHD behavior and kinetic stability. The presence or absence of fast ion losses is correlated with the measured locations of the $q(r)=1$ surfaces.

Fishbones have been attributed to a resonance between a population of high energy, toroidally precessing ions and an unstable (or marginally stable) internal kink mode [2-5], or, alternatively, a coupling of the hot ions, through viscous damping in the bulk plasma, to an MHD mode at the ion diamagnetic drift frequency of the thermal ions [8]. The relatively cold background plasma is described by an MHD model. The stability analysis is done via the energy principle [9]. The procedure is to add to the contribution of $\delta W_{\rm MHD}$ from the background plasma terms due to the kinetic, δW_k, and inertial, δ_I, terms, leading to a variational dispersion relation, $D(\xi)=\delta W_{\rm MHD}+\delta W_k+\delta_I=0$ [5]. In this dispersion relation, the inertial term resolves the singularity in the displacement $\xi(\mathbf{r})$, and its contribution is important only in a small domain. The kinetic term arises from the hot trapped particle population. The size of this population is characterized by the hot particle beta, β_h. For even modest values of β_h ($\sim 10^{-3}$), the δW_k term can destabilize a marginally stable internal kink mode ($\delta W_{\rm MHD}\gtrsim 0$). The resulting mode has a frequency $\omega\sim\omega_d$, where ω_d is the toroidal precession frequency of the hot trapped particles. Such a mode is observed experimentally [10].

The onset conditions for the fishbone mode have been calculated for a slowing-down distribution of hot particles produced by neutral beam injection [5]. The threshold condition corresponding to the fishbone modes observed on PDX, PBX, and PBX-M is found to be $\beta_{{\rm crit},h}=\langle\omega_d\rangle/\pi\omega_A$, where $\omega_A=v_A/\sqrt{3}Rr_sq'$ is the shear Alfvén frequency evaluated at $q(r_s)=1$ [the magnetic safety factor $q(r)=\oint dl\,B_T/2\pi RB_p$, where B_T and B_p are the toroidal and poloidal components of the magnetic field]. r_sq' is the magnetic shear at the rational surface [11].

The dependence of the instability on q can be seen clearly from the above expressions. In addition, the mode structure depends on the radial location of the rational surfaces. A measurement of $q(r)$ would thus provide important confirmation of the mode-hot-ion resonance model. To date, such measurements have never been made in plasmas specifically tailored to excite fishbones. Using the neutral probe beam q profile diagnostic available on PBX-M, we have obtained the necessary information to compute a plasma equilibrium that accurately models the experiment. We can use this to determine the plasma's stability, and study the predicted dependence of the mode-hot-ion resonance associated with the fishbone instability. This paper describes experiments in which the fishbone mode was excited and measured on PBX-M and q profile and fast ion measurements were made. These experiments provide the first comparison between the theoretically predicted dependence of the mode on the internal magnetic structure of the plasma and actual experimental measurements of $q(r)$.

The fishbone experiments were conducted in low field, low current, bean-shaped plasmas (see Table I). At 400 ms into the discharge, the plasma shape relaxed from a bean-shaped condition, with elongated internal flux surfaces, to a more D-shaped condition, with relatively circular internal surfaces. At the time of the relaxation, the

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TABLE I. A summary of the plasma parameters for the early, late, and enhanced loss cases described in the text.

Plasma parameters	Early (no FI loss)	Late (FI loss)	Enhanced FI loss
Toroidal field, $B_T(0)$	10 kG	10 kG	10 kG
Plasma current, I_p	200 kA	190 kA	160 kA
Electron density, $n_e(0)$	3.5×10^{13} cm^{-3}	5.5×10^{13} cm^{-3}	5.5×10^{13} cm^{-3}
Electron temperature, $T_e(0)$	1.4 keV	1.2 keV	1.2 keV
Major radius, R_0	171 cm	169 cm	172 cm
Minor radius, a	29 cm	26 cm	27 cm
Central elongation, $\kappa(0)$	1.40	1.35	1.25
Total beta, β	2.5%	2.5%	2.3%
Poloidal beta, β_p	2.2	2.3	2.6

amplitude of the fast ion losses—as seen by a perpendicularly viewing, multichannel, charge exchange analyzer of the Fast Ion Diagnostic Experiment (FIDE) [12] —increased sharply. A drop in neutron emission associated with the fishbone mode [1] is seen during both the early, bean-shaped and the later, D-shaped phases. Figure 1 shows the Mirnov loop signal from a coil on the outboard midplane and the fast ion signal seen by the FIDE analyzer near the NBI energy for the earlier bean-shaped, fast ion loss-free phase. Coherent fishbone oscillations are clearly seen on the Mirnov trace, and they are indeed correlated with changes in core reactivity as indicated by the neutron measurements. However, we see no evidence of fast ion expulsion associated with these fishbones at the early time.

Figure 2, similar to Fig. 1, shows the signal from the midplane Mirnov loop and the perpendicular fast ion losses seen by the FIDE analyzer during the later D-shaped, fast ion loss phase. As in the early, fast ion loss-free phase, coherent fishbone oscillations are clearly seen on the Mirnov trace. However, there are now also coherent bursts of fast ion losses associated with the fishbones. The similarity in the Mirnov data and in the basic plasma conditions (low density, high β, high β_p) indicates that during both the early and late phases, conditions are such that an MHD fishbone mode is destabilized; however, differences in the plasma equilibrium have developed during the relaxtion at $t=400$ ms causing the observed change in the fast ion loss behavior.

To determine the $q(r)$ profile during each phase, two magnetic field pitch angle ($\gamma_p(r)=\arctan[B_p(r)/B_T(r)]$) measurements were made [13]. Briefly, the motion of a neutral hydrogen probe beam across the tokamak's magnetic field creates an electric field in the rest frame of the beam. This Stark splits the $H\alpha$ emission from the beam, and by measuring its polarization, the magnetic field pitch angle is obtained. The $q(\psi)$ (ψ is the magnetic flux coordinate) and $q(r)$ profiles obtained from the γ_p data [14] for the early (fast ion loss-free) phase and the late phase are shown in Fig. 3. Comparing these results, we begin to see the equilibrium changes believed responsible for the differences in the observed fast ion losses. At the late time, the q profile becomes broader. In particular, the radius of the $q=1$ surface increases (see Table II). The $q(\psi)$ profile shows this more clearly, since the motion of the magnetic axis R_0 is suppressed by the use of the flux ψ as the independent variable.

The observations indicate that as the q profile broadens and flattens, the radius of the $q(r)=1$ surface increases. Consequently, the strength of the fast ion losses rises. This was particularly evident in several low current discharges, which showed considerably enhanced fast ion losses during the late phase of the discharge. The strength of these losses increased by roughly a factor of 5 over the previously described losses. The Mirnov data suggest that, for these enhanced loss cases, a similar mode-hot-ion resonance is present in the core, but again the details of the equilibrium determine the degree of fast

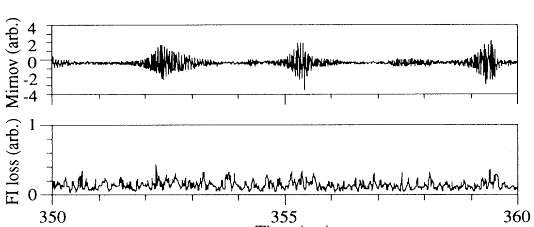

FIG. 1. The midplane Mirnov coil and perpendicular fast ion (FI) loss data for the fast ion loss-free phase of the shaped, fishboning plasma case.

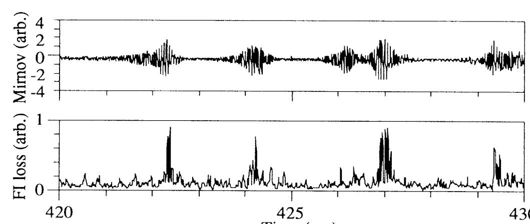

FIG. 2. The midplane Mirnov and FI loss data for the late, fast ion loss phase of the shaped, fishboning plasma case. This shows a series of fishbone oscillations, including the coherent fast ion losses that appear at the late time.

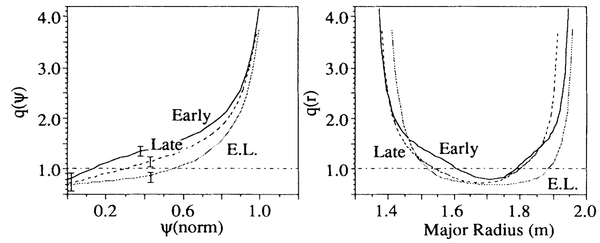

FIG. 3. A comparison between the $q(\psi)$ and $q(r)$ profiles for the early, late, and enhanced loss (EL) phases of the shaped, fishboning plasmas. The uncertainty in q both on and off axis are shown.

ion losses. To understand this, the pitch angle data were used in an equilibrium reconstruction for one of the enhanced loss shots. As shown in Fig. 3, the $q(\psi)$ and $q(r)$ profiles for the enhanced loss case are substantially broader and more U shaped than in the conventional late case.

We compared these results with the fast ion losses predicted by the White-Chen fishbone model by using the guiding center code ORBIT, developed by White and Chance [15]. The code studies the fast ion losses resulting from a perturbation of the axisymmetric equilibrium magnetic field due to the MHD modes of the mode-hot-ion resonance. Previous fast ion loss studies employing ORBIT have used analytic equilibria, or numerical equilibria in which one or more of the quantities $p(\psi)$, $q(\psi)$, or $g(\psi)$ had an assumed analytic form [2,15]. With the magnetic pitch angle data from our fishbone experiments and the resulting equilibrium reconstructions they provide, we have for the first time compared the predictions of the White-Chen model for fast ion losses with the observed losses and accurate equilibrium information in each of our experimental conditions.

The fast ion loss calculations made by using ORBIT require the equilibrium information discussed above as well as amplitudes of each poloidal and toroidal (m,n) component of the MHD activity. To obtain the amplitudes of each (m,n) component, we incorporated both our measured Mirnov data and stability results from the PEST ideal MHD stability code [16]. Using PEST, we found that the fast ion loss-free phase of the shaped, fishboning plasmas was unstable to the internal kink. From this analysis, we determined the maximum amplitude of each (m,n) mode measured at the plasma edge. For the late, fast ion loss phase of the shaped, fishboning plasmas, we carried out stability analyses for both the conventional and enhanced loss cases. The PEST results for each case indicate that the plasmas were unstable to the internal kink as in the earlier time. The broad, flat q profile in the later cases, however, leads to a significantly larger radial extent for the internal kink activity.

The basic fluid stability conditions for driving fishbones exist in the core at both the early and late times. The predominant MHD modes found by PEST and our Mirnov measurements for the early and late phases were quite similar: The basic character of the MHD activity seen in the Mirnov data was essentially unchanged by the shape relaxation at $t = 400$ ms, the mode analysis of the Mirnov data showed that the predominant (m,n) contributions to the MHD activity at the early and late times were $m=1, n=1$ and $m=2, n=1$, and the frequencies at the early and late times differed only slightly.

The differences in the measured fast ion behavior for each phase were also not due to gross dissimilarities in kinetic stability. The properties of the fast ion loss-free and fast ion loss periods were examined using the kinetic dispersion relation solver CHEN [5], developed by White and Chen and modified for this work to allow more accurate reconstruction of the experimentally determined q profile. Each of our cases was found to be unstable to the fishbone mode according to these calculations.

The calculations support the conclusion that, in all cases, the fishbone mode is being excited in the core, but a broadened q profile is required to couple the mode sufficiently to the plasma edge for fast ion losses to occur. To verify this relationship, we used our experimental equilibria, the measured neutral beam parameters, and the MHD mode amplitudes described above to obtain the calculated fast ion losses with the ORBIT code. Table II summarizes the observed and calculated mode properties for the fishbone observations in each of our three cases. The observed and calculated mode frequencies are in agreement. Note that the fishbone threshold suggests

TABLE II. A summary of the observed and calculated fishbone properties for each phase of the shaped, fishboning plasmas.

Mode characteristics	Early	Late	Enhanced loss
Observed mode frequency (kHz)	15–25	10–20	10–20
Fraction of beam trapped (%)	64	82	79
Fraction of beam trapped, $q<1$ (%)	8	21	42
Radius of the $q=1$ surface, $r(q=1)/a$	0.32	0.49	0.71
Shear Alfvén frequency, ω_A (sec^{-1})	3.8×10^6	2.6×10^6	1.8×10^6
Precession frequency $\langle\omega_d\rangle$ (sec^{-1})	8.8×10^4	9.3×10^4	1.0×10^5
Fishbone beta threshold, $\beta_{h,\mathrm{crit}}$	7.4×10^{-3}	1.1×10^{-2}	1.8×10^{-2}
Calculated mode frequency (kHz)	14	15	16

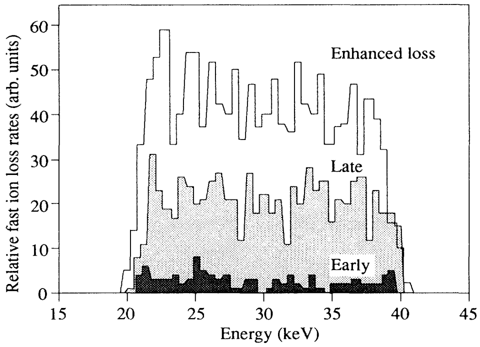

FIG. 4. The energy distribution of the predicted fast ion losses for each of the shaped, fishboning plasma cases. The magnitude of the losses for each case are in good agreement with the experimental observations.

that the early, fast ion loss-free case is at least as unstable as at the later times. The fraction of fast ions trapped within the kink resonance at $q=1$ seems to confirm the relationship between q profile width and observed losses.

The results of our ORBIT calculations for the fast ion losses predicted for each of our cases are shown in Fig. 4. The plots show the energy distribution of exiting particles for the early, late, and enhanced loss cases. From the figure, we see that the magnitude of fast ion losses in the conventional late case is about 7 times greater than in the early case. This agrees with our experimental observations, where in the early case, we could discern no fast ion losses above the noise. The magnitude of the measured fast ion losses for the enhanced loss case shows an increase of two to three over the conventional late case. Comparing the relative amplitude of the losses for the conventional and enhanced loss cases, we find that our results obtained from the White-Chen model, as plotted in Fig. 4, substantially agree with the experimentally observed variation in fast ion losses.

We have observed that in plasmas exhibiting a high-beta ("fishbone") instability, the details of the equilibria—specifically the location of the $q(r)=1$ surface in our case—can greatly affect the confinement of fast ions. While our results suggest that plasmas of different shapes may not differ in their stability against such modes, the influence of shape on the q profile itself determines whether or not the fast ion losses actually occur. This can have important implications in the operation of a burning plasma experiment or a fusion test reactor, in which the loss of high energy particles, either from auxiliary heating or from fusion products themselves, could greatly affect the performance of the device [17].

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