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Measurements of beam-ion confinement during tangential beam-driven instabilities in a bean tokamak experiment

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During tangential injection of neutral beams into low-density tokamak plasmas with $\beta > 1\%$, instabilities are observed that degrade the confinement of beam ions. Neutron, charge-exchange, and diamagnetic loop measurements are examined in order to identify the mechanism or mechanisms responsible for the beam-ion transport. The data suggest a resonant interaction between the instabilities and the parallel energetic beam ions. Evidence for some nonresonant transport also exists.

I. INTRODUCTION

During tangential neutral beam injection into low-density, high-beta plasmas in the Princeton Beta Experiment (PBX),¹ two instabilities were observed that removed energetic beam ions from the plasma center. The more prominent of the instabilities (dominant frequency $F = 20$ – 30 kHz) had been observed earlier on the ISX-B² and PLT³ tokamaks but without extensive documentation of the fast-ion loss. This low-frequency MHD burst¹ has features similar to the sawtooth instability observed in low- β plasmas⁴ and the fishbone instability observed during perpendicular neutral beam injection.⁵ A possibly related instability was observed on the JFT-2 tokamak.⁶ The second, higher frequency ($F = 120$ – 210 kHz) instability was observed for the first time during tangential injection in PBX.¹

In this paper, neutron, charge-exchange, and diamagnetic loop measurements are studied in an attempt to discover the physical mechanisms affecting beam-ion confinement during these tangential beam-driven instabilities. A companion paper¹ described the instabilities and discussed their impact on the flow of beam power to the plasma. The present paper begins with a description of the diagnostics and a discussion of their interpretation (Sec. II). Next, the instabilities are summarized (Sec. III A) and the charge-exchange (Sec. III B) and diamagnetic loop (Sec. III C) data are presented. Hard x-ray measurements are also examined to gauge the effect of the instabilities on runaway electron confinement (Sec. III D). In Sec. IV, the data are compared with previous observations during the fishbone (Sec. IV A) and the sawtooth (Sec. IV B) instabilities and with mode-particle pumping theory⁷ (Sec. IV C). It is concluded (Sec. V) that some resonant transport of beam ions probably occurs.

II. APPARATUS

A. Plasma conditions and instrumentation

The measurements were performed in low-density ($\bar{n}_e = 1.7 \times 10^{13} \text{ cm}^{-3}$), weakly indented (12%) deuterium PBX plasmas ($Z_{\text{eff}} \approx 4.5$) during coinjection of ~ 2.7 MW of deuterium neutral beams. The plasma current ($I_p \approx 240$ kA) was fairly constant during the beam pulse and the toroidal field ($B_t = 0.84$ T) was low. The central electron and ion

temperatures were 0.9 keV and 2 keV, respectively. The toroidal plasma rotation was large [$v_\phi(0) \approx 2.4 \times 10^7 \text{ cm/sec}$].

The primary diagnostics for studies of beam-ion loss were a Mirnov coil, a neutron scintillator, a neutral particle analyzer, and a diamagnetic loop. The $\bar{B}_\theta$ coil was situated at $R \approx 205$ cm, $z = 0$ cm, approximately 56 cm from the magnetic axis and 7 cm inside the vacuum vessel wall. The frequency response of the coil was flat up to 40 kHz, then decreased with frequency, reaching the 13 db level at 250 kHz.

Neutron measurements were made primarily with an uncollimated plastic scintillator mounted between toroidal field coils just outside the vacuum vessel.³ The frequency response of the detector was limited by the electronics to ~ 23 kHz (3 dB point). The absolute magnitude (factor-of-2 accuracy) and linearity of the neutron flux measurements were established by calibrating relative to BF_3 proportional counters.³ The measurements were also corroborated by measurements with an adjacent $\text{ZnS}(^6\text{Li})$ scintillator that is ~ 30 times less sensitive to hard x rays than the plastic scintillator.⁸ Occasionally, hard x-ray bursts were observed on the plastic scintillator. The hard x rays have energies $\gtrsim 1$ MeV (to penetrate the vacuum vessel) and presumably originate in runaway electron collisions with vacuum vessel hardware. Normally, however, the hard x-ray contribution to the scintillator signal was negligible.

Charge-exchange measurements were made with a compact analyzer⁹ that views cocirculating ions in the horizontal midplane. The line of sight of the analyzer was variable from a tangency radius of $R_{\text{tan}} = 160$ cm to 58 cm. (The angle of beam injection was $R_{\text{tan}} = 130$ cm and the magnetic axis was $R_0 \approx 149$ cm.) The electrostatic deflection plates could be swept to measure the neutral spectrum, or set at a fixed energy (with a resolution of approximately 1.4 keV at 45 keV) for measurements at high time resolution. The integration time of the detector and associated electronics was ~ 30 μsec .

Measurements of the effect of the instabilities on the perpendicular energy of the plasma were made with a high-resolution diamagnetic loop. The diamagnetic and compensation loops were both mounted inside the vacuum vessel and were thus free from shielding effects of the vessel eddy currents. The frequency response of the loop, relative to its low-frequency value, was ~ 0.5 at $f = 10$ kHz and ~ 0.43 for

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$f > 30$ kHz. The displaced toroidal flux, $\Delta\Phi_t$ (so-called “diamagnetic flux”) measured by the loop is related to the poloidal β in the perpendicular direction $\beta_{\perp}$ by¹⁰

$$\beta_{\perp} = S_1 - \Delta\Phi_t / \Phi_p, \quad (1)$$

where $\Phi_p \equiv (\mu_0 I_p)^2 / 8\pi B_{\phi 0}$ is the paramagnetic flux and $B_{\phi 0}$ is the toroidal field on axis. The term S_1 is an integral of poloidal magnetic field components on a surface that encloses the plasma ($S_1 = 1$ for a cylindrical plasma of circular cross section when the surface is chosen to be the plasma boundary). In general, $\beta_{\perp}$ changes when either $\Delta\Phi_t$, S_1 , or Φ_p changes. For the instabilities studied here, changes in Φ_p can be excluded. Changes in S_1 on a millisecond time scale are possible, however. In our interpretation of the data (Sec. III C), we have assumed that the change in $\beta_{\perp}$ is caused solely by changes in $\Delta\Phi_t$.

Except where noted, all of the data discussed here were archived together by fast transient digitizers at 500 kHz.

B. Interpretation

The neutron and charge-exchange measurements are interpreted as monitors of beam-ion loss from the center of the plasma. For PBX plasmas with $D^0 \rightarrow D^+$ tangential neutral beam injection, calculations¹¹ indicate that beam-plasma reactions constitute $> 85\%$ of the total neutron emission. The calculations indicate that most of the reactions occur in the center of the plasma where the density and temperature are high ($\sim 90\%$ inside $r/a = 0.5$); this expectation has been verified experimentally on PLT.¹² In general, small gradual drops in neutron emission I_n can be explained by changes in the density and temperature of the background plasma,¹³ but sudden drops imply either rapid deceleration of the injected beam ions or radial redistribution of the beam ions to a region of lower deuterium density. Adopting the interpretation used to analyze the neutron emission during the fishbone instability,³ the instantaneous energetic beam-ion confinement time τ_B is

$$\tau_B(t) = I_n(t) / [\dot{I}_n(t_0) - \dot{I}_n(t)], \quad (2)$$

where $\dot{I}_n$ is the derivative of the neutron emission and $\dot{I}_n(t_0)$ is the slope of the emission in a quiescent portion of the discharge just before or after an MHD burst. The effect of a typical low-frequency instability on the neutron flux is shown in Fig. 1(a), together with the quantities used to analyze the signal. The slope of the neutron emission $\dot{I}_n(t)$ was found by performing a least squares fit to the 49 neutron data points around the time t ; this procedure limited the temporal resolution of the τ_B measurement to $\sim 50 \mu\text{sec}$ (the nominal frequency response of the detector electronics). The instantaneous loss rate of the beam ions τ_B^{-1} was then found through substitution into Eq. (2). Another useful quantity derived from the signal is the normalized drop in neutron emission $\Delta I_n / I_n$ [Fig. 1(a)], which is approximately the fraction of energetic beam ions lost at the instability.³

The effect of a typical low-frequency event on the parallel charge-exchange flux is shown in Fig. 1(b). For this analyzer setting ($E = 35$ keV; $R_{\text{tan}} = 160$ cm), the flux first increases at the instability and then falls below its initial level after the burst [Fig. 1(b)]. In general, the passive charge-

FIG. 1. (a) Time evolution of the neutron emission at a typical instability for the discharge shown in Fig. 2, illustrating the quantities used to analyze the neutron data. The instantaneous beam-ion loss rate τ_B^{-1} is inferred from the slope of the emission before and during the instability [Eq. (2)]. The fractional change in the number of energetic ions is found from the total drop in neutron emission $\Delta I_n / I_n$. Also shown is the gradual change in emission associated with a normal sawtooth,¹³ as calculated by Fokker-Planck simulation¹⁴ for PBX parameters. (b) Time evolution of the 35 keV neutral flux, showing the quantities used to analyze the charge-exchange data. The quiescent flux F_q is the average flux prior to the MHD burst. The net flux at the burst $\bar{F}_b$ is found by integrating the signal around the time of the peak mode amplitude t_p . The depletion of the flux ΔF is found by comparing the average flux after the burst to the flux prior to the burst. The absolute value of the charge-exchange flux is arbitrary but the relative value of the flux is used consistently throughout the paper.

exchange flux at a given tangency radius can change because of pitch-angle scattering, energy diffusion, transport, or variations in neutral density. Variations in neutral density are not a likely explanation for the flux changes at MHD bursts, since the relative change in signal is a strong function of analyzer energy (Sec. III B). Moreover, the increase in H_α emission at MHD bursts in these L-mode¹⁵ plasmas was very small [$\Delta H_\alpha / H_\alpha = (5 \pm 3)\%$]. As will be discussed in Sec. III, there is little evidence for appreciable pitch-angle scattering at the MHD bursts. The most likely explanation for the charge-exchange bursts is that ions are expelled from the center of the plasma (a low neutral density region) to the plasma edge (where the charge-exchange probability is an

order of magnitude higher). In some cases, energy diffusion may also play a role in the observations.

Figure 1(b) illustrates the quantities used to analyze the neutral flux F . The quiescent flux F_q is the average flux before an MHD burst. The average flux associated with the burst $\bar{F}_b$ is found by integrating the signal around the time of peak magnetic oscillations t_p ,

$$\bar{F}_b \equiv \int_{t_p - 0.5 \text{ msec}}^{t_p + 0.5 \text{ msec}} (F - F_q) dt. \quad (3)$$

The integration window was chosen to span the duration of the MHD burst [typical growth rate $\approx (0.1 \text{ msec})^{-1}$]. If the burst is caused by radial transport of the beam ions, $\bar{F}_b$ is related to the number of beam ions that move outward to a region with higher neutral density. After the burst, the flux drops an amount $\Delta F = F_{\text{after}} - F_q$. If the neutral density and beam-ion profiles are similar before and after the burst, $\Delta F/F_q$ is approximately the fraction of beam ions removed from the sightline at the measured energy.

III. RESULTS

A. Description of instabilities

During tangential coinjection of 2.7 MW of $\sim 43 \text{ keV}$ deuterium neutrals into low-density, weakly indented, deuterium PBX plasmas with toroidal $\beta > 1\%$, repetitive bursts of MHD activity are observed with Mirnov coils, neutron scintillators, soft x-ray detectors, a neutral analyzer, and a diamagnetic loop.¹⁶ In the present paper, the mechanism of the beam-ion loss is investigated; in a companion paper,¹ the instabilities were described. In summary, two types of bursts are observed: bursts dominated by large amplitude [$\tilde{B}_\theta/B_\theta = O(10^{-3}-10^{-2})$], low-frequency ($F = 20-30 \text{ kHz}$) magnetic oscillations, and events with smaller amplitude [$\tilde{B}_\theta/B_\theta = O(10^{-4}-10^{-3})$, including frequency-response correction], high-frequency ($F = 120-210 \text{ kHz}$) bursts. As shown in Fig. 2, the low-frequency events are associated with $\sim 20\%$ drops in neutron emission and relatively large charge-exchange bursts, while the high-frequency events (indicated by dashed vertical lines) correlate with small discontinuities in the slope of the neutron emission ($\Delta I_n/I_n \sim 2\%$) and smaller charge-exchange bursts. The low-frequency mode has a dominant $m = 1, n = 1$ structure that rotates with a velocity near the central plasma rotation velocity. The mode amplitude usually (but not always) decays coincidentally with a soft x-ray sawtooth (fractional drop in amplitude $\Delta A/A \sim 5\%$). Some power at higher frequencies ($F > 120 \text{ kHz}$) is always present at low-frequency events. In contrast, high-frequency bursts often occur without any appreciable change in the magnitude of low-frequency ($< 50 \text{ kHz}$) MHD activity.

To study systematically the fast-ion behavior during the tangential instabilities a data base was formed of approximately 450 events. All instabilities that met these criteria were included.

(1) Only tangential deuterium beams were injected (no perpendicular beams) into a deuterium plasma with weak indentation ($< 14\%$). Strongly indented plasmas were excluded to avoid possible stabilization of the instabilities by beam shaping.¹⁷

FIG. 2. Time evolution of $\tilde{B}_\theta$ (in volts), I_n , and 35 keV neutral flux ($R_{\text{tan}} = 160 \text{ cm}$) during injection of two deuterium neutral beams ($E_{\text{inj}} = 39.5$ and 44.2 keV ; $P_B = 2.7 \text{ MW}$) into a deuterium plasma ($I_p = 240 \text{ kA}$; $B_t = 0.84 \text{ T}$; $\bar{n}_e = 1.7 \times 10^{13} \text{ cm}^{-3}$). The dotted lines indicate high-frequency bursts (120–220 kHz) found by filtering the Mirnov signal.

(2) The instability was a discrete burst. Occasionally, virtually continuous MHD activity occurred that suppressed the level of the neutron emission. These instabilities were excluded because the quantities used to analyze the neutron and charge-exchange data (Fig. 1) are only well defined for a discrete burst.

(3) The plasma was not rapidly changing. Neutron drops and charge-exchange bursts were sometimes observed as the plasma evolved toward a major disruption, but these instabilities¹⁸ seem different from the two instabilities studied here.

(4) The neutron signal was free from contamination by hard x rays.

(5) The data were digitized at a sufficiently fast rate (typically 500 kHz).

Application of these criteria restricted the data so that

98% of the events in the data base were from three days of low-density ($\bar{n}_e \lesssim 2.7 \times 10^{13} \text{ cm}^{-3}$), low-toroidal-field ($B_t \approx 9 \text{ kG}$), low-current ($I_p \approx 230 \text{ kA}$) operation. Approximately 15% of the instabilities in the data base occurred when one tangential beam was injected ($P_b \approx 1.3 \text{ MW}$) while the remainder occurred during injection of two beams ($P_b \approx 2.6 \text{ MW}$).

B. Neutron and charge-exchange data

An example of the time evolution of the neutron and charge-exchange signals during a low-frequency event that had a high-frequency precursor is shown in Fig. 3. The event begins with a high-frequency burst at 532.75 msec [Fig. 3(c)]. The burst correlates with jumps in the energetic-ion loss rate τ_B^{-1} and the flux of 35 keV neutrals [Fig. 3(b)]. After the burst, the amplitude of low-frequency oscillations grows [Fig. 3(a)]. As the oscillations approach their maximum amplitude, the high-frequency oscillations grow rapidly. The mode decays rapidly from its peak amplitude, al-

FIG. 3. Time evolution of the filtered Mirnov signal (a) and (c) and τ_B^{-1} and 35 keV neutral flux (b) at a low-frequency event with a high-frequency precursor (dotted lines) for the discharge shown in Fig. 2.

though successor oscillations persist for $\sim 0.5 \text{ msec}$. The energetic-ion loss rate and charge-exchange flux peak approximately $70 \mu\text{sec}$ after the peak in the magnetic oscillations, and then decay to their initial levels in $\sim 0.5 \text{ msec}$. Following the burst, the neutral flux continues to fall to a level $\sim 20\%$ lower than before the burst (Fig. 2).

At a pure high-frequency event, the amplitude of low-frequency magnetic oscillations changes very little [Fig. 4(a)]. Jumps in the energetic-ion loss rate τ_B^{-1} and the flux of 35 keV neutrals [Fig. 4(b)] are coincident with the high-frequency burst [Fig. 4(c)]. At this event, the energetic-ion loss rate peaked approximately $170 \mu\text{sec}$ after the peak in the magnetic oscillations, and the neutral flux returned to near its initial level in $\sim 0.5 \text{ msec}$.

The time evolution of the parallel charge-exchange flux ($R_{\text{tan}} = 160 \text{ cm}$) during low-frequency events is quite different for neutrals of different energies (Fig. 5). The data in Fig. 5 were obtained by varying the energy setting of the charge-exchanger analyzer in a sequence of similar dis-

FIG. 4. Time evolution of the filtered Mirnov signal (a) and (c) and τ_B^{-1} and parallel ($R_{\text{tan}} = 160 \text{ cm}$) 35 keV neutral flux (b) at a high-frequency event. ($E_{\text{inj}} = 46.4, 47.8$; $P_b = 2.83 \text{ MW}$; $I_p = 230 \text{ kA}$; $B_t = 0.84 \text{ T}$.)

FIG. 5. Time evolution of τ_B^{-1} and 25 keV (a), 35 keV (b), and 45 keV (c) neutral flux at low-frequency events. $R_{tan} = 160$ cm; $P_B \approx 2.6$ MW; $I_p \approx 230$ kA; $B_z \approx 0.84$ T; $\bar{n}_e \approx 1.7 \times 10^{13}$ cm $^{-3}$. The energies of the injected neutrals were 43.0 and 44.2 keV (a), 44.5 and 39.5 keV (b), and 42.6 and 43.8 keV (c). The line labeled "sawtooth" is the evolution of the flux predicted by Fokker-Planck simulation of the charge-exchange signal¹⁴ assuming a 0.1 keV sawtooth in the electron temperature.

charges. For neutrals at 35 keV (~ 7 keV below the injection energy), the time evolution of the flux follows fairly closely the loss rate of central energetic ions measured by the neutrons [Figs. 5(b) and 3(b)]. At 25 keV (~ 18 keV below the injection energy), the neutral flux peaks near the peak of the energetic-ion loss rate but remains elevated after the mode has decayed [Fig. 5(a)]. Following the burst, the flux decays in ~ 2 msec to its initial level. At 45 keV ($1\text{--}3$ keV above the injection energy), the flux drops precipitously at the time of peak mode amplitude, and stays suppressed for several milliseconds [Fig. 5(c)].

The abrupt drop in parallel charge-exchange flux near E_{inj} [Fig. 5(c)] could be caused either by the sudden loss of ions near E_{inj} or by their deceleration, but cannot be ex-

plained by changes in background plasma parameters. Since there are very few ions more than a few keV above E_{inj} in the plasma (roughly, $f_b \approx f_b(E_{inj}) \exp [-(E - E_{inj})/T_e]$ in a classical plasma), if most of the ions near E_{inj} lose $\gtrsim 1$ keV of energy, the flux near E_{inj} drops precipitously. In contrast, analytical estimates¹⁴ and numerical simulation of the charge-exchange signal¹⁴ indicate that a sudden drop in electron temperature at the MHD burst produces a much slower [$O(1$ msec)] change in 45 keV flux than observed experimentally [Fig. 5(c)]. Since the 45 keV flux dropped in 0.1 msec, the change in signal must indicate a direct effect of the instability on the beam-ion distribution function. Pitch-angle scattering of the parallel ions is not a likely explanation for the sudden drop since, if the beam ions were given more perpendicular velocity, an increase in the flux of neutrals

FIG. 6. (a) Average flux just before an MHD burst versus energy for various analyzer angles. The perpendicular data are from a vertically viewing analyzer (ODE).⁹ (b) Neutral burst at low-frequency events (normalized to the fractional loss of energetic ions $\Delta I_n/I_n$) versus energy for various analyzer angles [same symbols as in (a)]. Negative values of $\bar{F}_b$ mean the average flux during the burst was less than the flux prior to the burst. The curves are guides to the eye and the error bars represent the standard deviation of several bursts.

with larger $v_{\perp}$ and $E \approx E_{inj}$ is expected, and such a jump is not observed. Probably, the drop near E_{inj} implies either rapid deceleration of some of the 45 keV beam ions in the charge-exchange sightline or loss of these ions.

A possible explanation for the gradual decay in 25 keV flux following the MHD burst [Fig. 5(a)] is that some higher energy beam ions move outward at the instability, then lose energy collisionally following the burst, leading to an enhancement of the number of 25 keV ions near the edge. Alternatively, some ions above 25 keV may be decelerated by the instability, then lose energy collisionally, which would also result in an increase in the 25 keV signal.

The trends illustrated in Fig. 5 are generally observed in our set of data. The results of a discharge-to-discharge scan in analyzer angle and energy during similar plasma conditions are summarized in Fig. 6. The flux prior to a burst is largest for the most parallel observation angle ($R_{tan} = 160$ cm) and falls off fairly sharply as the analyzer is turned to view in a more perpendicular direction (i.e., smaller tangency radius) [Fig. 6(a)]. The change in flux at an MHD burst ($\bar{F}_b$) is largest for the angle and energy at which the largest flux prior to the burst occurs [Fig. 6(b)]. To reduce scatter in the data associated with variations in the severity of the MHD event, the neutral burst $\bar{F}_b$ in Fig. 6(b) is normalized to the number of beam ions lost, $\Delta I_n/I_n$. Slightly above the injection energy, the average flux at a burst is less than the quiescent level for $R_{tan} = 160$ cm [cf., Fig. 5(c)]. The instability affects beam ions detected at $R_{tan} = 100$ cm, but for more perpendicular viewing angles, the effect of the instability on the neutral flux is negligible. No neutrals are observed ≥ 10 keV above the injection energy. The data shown in Fig. 6 suggest that it is the ions in the most densely populated portion of phase space that are most strongly affected by the instability. It also appears that ions with larger $v_{\parallel}/v$ are more strongly affected by the instability than more perpendicular ions. In Fig. 7, the change in flux at an MHD burst $\bar{F}_b$ is plotted versus tangency radius for the $E = 35$ keV data. The

FIG. 7. Relative change in charge-exchange flux $\bar{F}_b/F_q$ at low-frequency events (normalized to the fractional loss of energetic ions $\Delta I_n/I_n$) versus the tangency radius of the neutral particle analyzer. $E = 35$ keV. The error bars are the standard deviation of several bursts.

FIG. 8. Delay of the neutral flux Δt_{cx} [Eq. (4)] versus energy for low-frequency events. The error bars are the standard deviation of several bursts.

charge-exchange burst is normalized both to the severity of the MHD burst ($\Delta I_n/I_n$) and to the quiescent neutral flux level (F_q). The data indicate that the relative amplitude of the burst $\bar{F}_b/F_q$, is largest for the most parallel orientation.

The tendency for low-energy neutrals to escape later than neutrals at the injection energy is shown in Fig. 8. The flux delay Δt_{cx} is the delay of the signal with respect to the time of maximum amplitude of the instability t_p ,

$$\Delta t_{cx} \equiv \frac{\int (t - t_p) (F - F_q) dt}{\left| \int (F - F_q) dt \right|}. \quad (4)$$

The quantity Δt_{cx} is the average time of arrival of the charge-exchange burst. The upper limit of the integral in Eq. (4) was generally extended to the time when the flux F returns to

FIG. 9. Depletion of the flux $\Delta F/F_q$ following low-frequency events (normalized to the fractional loss of energetic ions $\Delta I_n/I_n$) versus energy. The error bars are the standard deviation of several bursts.

FIG. 10. Spectrum of neutrals at the angle of beam injection ($R_{\text{tan}} = 130$ cm) during injection of two parallel beams ($E_{\text{inj}} = 41.7, 43.9$ keV) into a discharge with strong low- and high-frequency bursts (solid) and during injection of one beam ($E_{\text{inj}} = 45.1$ keV) into a similar plasma with infrequent bursts (dotted). Since the spectra are obtained by sweeping the voltage of the analyzer deflection plates in time, the MHD bursts appear as periodic bursts in the spectrum; in reality, the bursts are localized in time rather than in energy.

its quiescent level; if another burst intervened before $F \approx F_q$ that datum was rejected. Figure 8 indicates that, although the magnitude of the burst F_b is sensitive to analyzer angle (Fig. 6), most of the flux escapes at the same time for different orientations (between $R_{\text{tan}} = 100$ cm and $R_{\text{tan}} = 160$ cm). The trends shown in Fig. 5 hold for all parallel orientations: the flux near E_{inj} decreases through the MHD burst, the flux at 35 keV peaks near the peak of the MHD burst, and the flux at 25 keV persists considerably longer than the MHD burst.

The low-frequency events appear to reduce the number of ions near the injection energy preferentially. Figure 9 shows the *reduction* in flux *after* the MHD burst ΔF as a function of analyzer energy. Just above the injection energy E_{inj} , the flux of parallel ions typically falls a factor of 2 after a burst. For neutrals ~ 7 keV below the injection energy, the drop in flux $\Delta F/F_q$ nearly equals the drop in neutron emission $\Delta I_n/I_n$. For neutrals ~ 9 keV below E_{inj} , no significant drop in flux was observed after an MHD burst. For lower energies ($E - E_{\text{inj}} \approx -18$ keV), the neutral burst was delayed with respect to the MHD burst [Figs. 5(a) and 8], and the flux gradually decayed in ~ 2 msec to the initial level ($\Delta F \lesssim 0$).

The neutral spectrum also suggests that ions near the injection energy are affected preferentially. Comparison of the neutral spectrum at the angle of beam injection ($R_{\text{tan}} = 130$ cm) for two-beam and one-beam operation in otherwise similar plasmas shows that the ratio of neutrals around E_{inj} to neutrals around $E_{\text{inj}}/2$ is smaller for the two-beam plasma than for the one-beam plasma (Fig. 10). This change may merely reflect a change in neutral density or beam-ion deposition profile with two-beam operation. On

FIG. 11. Spectrum of parallel ($R_{\text{tan}} = 160$ cm) neutrals during injection of two parallel beams ($E_{\text{inj}} = 46.5, 46.8$ keV) into a discharge with repetitive high-frequency bursts.

the other hand, since the most obvious difference between the two plasmas is the increased severity of the instabilities during two-beam operation, the distorted spectra may be further evidence that ions near the injection energy are more strongly affected by the low-frequency bursts than lower energy ions.

The best data on the energy dependence of beam-ion transport during pure high-frequency events is from a discharge that had repetitive bursts of high-frequency events (separated by ~ 0.8 msec) but no low-frequency events. The neutral spectrum at the most parallel viewing angle ($R_{\text{tan}} = 160$ cm) for this discharge is shown in Fig. 11. Since the spectrum is obtained by sweeping the energy of the analyzer in time, the repetitive MHD bursts appear as periodic bumps in the spectrum. Comparison of the magnitude of the bumps with the level between bursts indicates that, as was observed for the low-frequency events (Fig. 6), $\bar{F}_b/F_q$ is largest ~ 7 keV below the injection energy. Another similarity is that no burst is observed near the injection energy. These similarities are consistent with the hypothesis that high-frequency instabilities affect the transport of beam ions at low-frequency events as well as at pure high-frequency bursts.

It appears that the behavior of parallel neutrals ($R_{\text{tan}} = 130$ – 160 cm) at $E = 35$ keV is representative of the behavior of most of the energetic ions. These parallel orientations see the largest flux both in the quiescent plasma and at MHD bursts (Figs. 6 and 7). At $E = 35$ keV, the time evolution of the neutral flux for $R_{\text{tan}} = 130$ cm and $R_{\text{tan}} = 160$ cm follows closely the time evolution of the energetic-ion loss rate τ_B^{-1} inferred from the neutrons [Figs. 3(b) and 5(b)]. Moreover, the reduction in flux after a burst $\Delta F/F_q$ is close to the drop in neutron emission $\Delta I_n/I_n$ for these settings (Fig. 9). A study of the correlation of the magnitude of the charge-exchange burst at $R_{\text{tan}} = 160$ cm and $E = 35$ keV with the drop in neutron emission (Fig. 12) shows that the neutral flux scales approximately linearly with the fraction of energetic beam ions lost from the plasma center ($\Delta I_n/I_n$), although there is significant scatter in the data (correlation coefficient $R^2 = 0.52$). The ratio of $\bar{F}_b$ to

FIG. 12. Burst of parallel ($R_{\text{tan}} = 160$ cm) 35 keV neutral flux versus the total energetic-ion loss $\Delta I_n/I_n$. The error bars are the standard deviation of many bursts.

$\Delta I_n/I_n$ tends to be $\sim 30\%$ higher for high-frequency events. In general, if the direction of beam-ion losses depends strongly on mode amplitude, the charge-exchange burst will not scale linearly with the average beam-ion loss measured by the neutrons. For example, if vertical losses increase more strongly with mode amplitude than horizontal losses, the charge-exchange flux in the horizontal midplane will increase slowly with $\Delta I_n/I_n$. The fact that the ratio of neutral burst to neutron drop is approximately independent of mode amplitude suggests that the fraction of lost beam ions that moved radially outward was approximately constant for all of the events studied here.

The correlation of the neutron and charge-exchange data with mode amplitude is studied in Fig. 13. In Fig. 13(a), the peak loss rate of the energetic ions τ_B^{-1} is plotted versus the peak mode amplitude $\tilde{B}_\theta/B_\theta$ found after digitally filtering the Mirnov signal. For pure high-frequency events, τ_B^{-1} correlates weakly with the amplitude of low-frequency oscillations [Fig. 13(a)]. For low-frequency events ($\tilde{B}_\theta/B_\theta > 10^{-3}$), however, τ_B^{-1} scales approximately linearly with low-frequency mode amplitude. For comparison, perpendicular beams alone were injected into similar plasmas.¹ Measurements taken during this comparison allow us to relate the loss rate during fishbones⁵ to the loss rate during parallel injection. For $\tilde{B}_\theta/B_\theta \sim 10^{-2}$, τ_B^{-1} is ~ 2.5 times higher during parallel injection than during fishbones. Since the fishbone instability lasted longer than the parallel instability, however, the total beam-ion loss $\Delta I_n/I_n$ was comparable for the two cases. The dependence of charge-exchange flux on mode amplitude follows similar trends although the scatter is larger. The largest flux of parallel neutrals at $E = 35$ keV and $R_{\text{tan}} = 160$ cm occurs for large-amplitude ($\tilde{B}_\theta/B_\theta > 2 \times 10^{-3}$) low-frequency events [Fig. 13(b)]. Smaller bursts are observed at small-amplitude ($\tilde{B}_\theta/B_\theta \lesssim 2 \times 10^{-3}$), low-frequency events and at high-frequency events [Fig. 13(b)].

For high-frequency events, the dependence of beam-ion losses on mode amplitude is obscured by the frequency response of the Mirnov coil (Sec. II A) and by the relatively small change in neutron signal. Focusing on two discharges

FIG. 13. (a) Peak value of τ_B^{-1} versus peak value of the filtered Mirnov signal (4–50 kHz). The solid point is the peak value τ_B^{-1} measured during perpendicular injection in PBX. (b) Neutral burst $\bar{F}_b/\bar{F}_q$ versus peak value of the filtered Mirnov signal (4–50 kHz) for $R_{\text{tan}} = 160$ cm and $E = 35$ keV. The error bars are the standard deviation of many bursts.

that had no low-frequency events and repetitive, relatively large, high-frequency events with a well-defined, dominant frequency alleviates some of these diagnostic difficulties. For these plasmas, a roughly linear correlation of beam-ion

FIG. 14. Peak value of τ_B^{-1} versus peak value of the filtered Mirnov signal (120–220 kHz) in two discharges with large, repetitive high-frequency bursts and no low-frequency events. The bursts had prominent peaks in the Fourier spectrum at approximately 125 kHz for one of the discharges and at ~ 148 kHz for the other discharge. The error bar indicates the typical accuracy.

losses on mode amplitude is observed (Fig. 14). During low-frequency events, the amplitude of $\tilde{B}_\theta/B_\theta$ in the high-frequency band is 3–10 times larger than for these pure high-frequency bursts, so it is possible that high-frequency instabilities account for the larger beam-ion losses observed at low-frequency events.

At low-frequency instabilities, $\tilde{B}_\theta$ usually decays quickly at a sawtoothlike crash but sometimes the mode decays more slowly (in a manner similar to a fishbone).⁵ Events that decay quickly usually exhibit a sudden change δB_θ in the poloidal field measured at the Mirnov coil, while $\delta B_\theta \approx 0$ for fishbonelike events. A study of events with $\tilde{B}_\theta/B_\theta \approx 10^{-2}$ indicates that the fraction of energetic ions lost from the center ($\Delta I_n/I_n$) is independent of the value of δB_θ . Apparently, a sawtoothlike crash is not required for beam-ion transport.

C. Diamagnetic loop data

After a low-frequency event with $\Delta I_n/I_n = 0.27$, the displaced toroidal flux $\Delta\Phi_t$ gradually fell $45 \mu\text{Wb}$ in approximately 2.0 msec [Fig. 15(a)], then gradually recovered. The paramagnetic flux for this discharge was 4.3 mWb and hence the drop in displaced toroidal flux represents a drop in

β_{p1} of 0.010 (out of the total β_{p1} of 0.98). The smooth evolution of the signal was temporarily interrupted by a high-frequency burst that resulted in a transient increase in $\Delta\Phi_t$ [Fig. 15(a)]. Scarcely any drop in $\Delta\Phi_t$ occurred until well after $\tilde{B}_\theta$ had decayed. This is in contrast to the behavior at a fishbone during perpendicular injection under similar conditions, where $\Delta\Phi_t$ dropped $100 \mu\text{Wb}$ in ~ 0.5 msec, then quickly began to recover [Fig. 15(b)]. At a fishbone, the time evolution of $\Delta\Phi_t$ is similar to the evolution of I_n but, for parallel injection, the temporal behavior is quite different (Fig. 15).

These trends are generally observed in our study of low-density PBX plasmas during parallel and perpendicular injection. For fishbones, $\Delta\beta_1/\beta_1$ scales linearly with the fraction of energetic ions lost [Fig. 16(a)]. For tangential instabilities, $\Delta\beta_1/\beta_1$ also increases linearly with the loss of beam ions, but the magnitude of the drop in $\Delta\beta_1/\beta_1$ is approximately three times smaller for parallel injection than for perpendicular injection [Fig. 16(b)]. Transient jumps in $\Delta\Phi_t$ are observed at most high-frequency bursts during tangential injection.

Comparison of these results with calculations of the expected drop in β_1 indicates that both the fishbones and the

FIG. 15. Time evolution of the neutron emission and the displaced toroidal flux during tangential (a) and perpendicular (b) injection into plasmas with tangential beam-driven and fishbone instabilities, respectively. The diamagnetic loop signal was archived separately from the neutron signal so the precise temporal relationship of the two signals is uncertain to ~ 0.1 msec. The simulation in (a) assumes that beam ions with $v_{||}/v > 0.85$ and $E > 35$ keV are lost instantly at the tangential low-frequency event, and the simulation in (b) assumes that 50% of the beam ions with $E > 25$ keV that are trapped in the bad curvature region are lost at the fishbone in the perpendicular case. The line marked "thermal response" is the change in $\Delta\Phi_t$ associated with modulation of the flow of beam power to the thermal plasma [Eq. (7)]. The theoretical predictions for $\Delta\beta_1$ are related to $\Delta\Phi_t$ through Eq. (1).

FIG. 16. (a) Reduction in $\beta_{\perp}$ inferred from the change in diamagnetic flux [Eq. (1)] versus reduction in the number of energetic ions $\Delta I_n/I_n$ for fishbones in low-density PBX plasmas under constant conditions.¹ The line is the expected change in $\beta_{\perp}$ associated with the loss of beam ions [Eq. (5)]. (b) Reduction in $\beta_{\perp}$ inferred from the change in diamagnetic flux versus $\Delta I_n/I_n$ for tangential low-frequency events. Also shown is the expected change in $\beta_{\perp}$ associated with modulation of the power flow to the plasma [Eq. (7)]. The other two lines are the predictions of the Fokker-Planck simulations assuming that beam ions with $E > 35$ keV and $v_{||}/v > 0.85$ are lost (upper line) and with $E > 25$ keV and $v_{||}/v > 0.93$ are lost (middle line). All of the theoretical predictions are uncertain to approximately 35%. The error bars are the standard deviation of many bursts.

tangential low-frequency events expel energetic beam ions, with little direct effect on the thermal plasma. For injection into these low-density plasmas, the beam ions constitute a significant fraction of the total plasma pressure ($\geq 30\%$). The drop in $\beta_{\perp}$ associated with the loss of beam ions is expected to be proportional to the number of beam ions lost ($\Delta I_n/I_n$) and to the fraction of $\beta_{\perp}$ contributed by the beam ions ($\beta_{\perp}^{\text{beam}}/\beta_{\perp}$),

$$\frac{\Delta \beta_{\perp}}{\beta_{\perp}} = k \left(\frac{\beta_{\perp}^{\text{beam}}}{\beta_{\perp}} \right) \left(\frac{\Delta I_n}{I_n} \right), \quad (5)$$

where k is a constant of proportionality that depends on the energy of the escaping beam ions. If ions of all energies are lost, $k = 1$. If only ions near the injection energy are lost, the neutron emission changes more than W_{beam} (W_{beam} is the total beam-ion energy), since the ions with a larger fusion cross section are lost preferentially. This proportionality factor k is plotted in Fig. 17 as a function of the minimum

FIG. 17. Proportionality factor k that relates the drop in neutron emission to the drop in $W_{\perp}$ versus minimum energy of the beam ion losses. The line is from the expression,

$$k \equiv \frac{\int_{E_{\text{min}}}^{E_{\text{inj}}} E_{\perp} f_b(v) dv}{\int_{E_{\text{min}}}^{E_{\text{inj}}} E_{\perp} f_b(v) dv} \frac{\int_{E_{\text{min}}}^{E_{\text{inj}}} \sigma v f_b(v) dv}{\int_{E_{\text{min}}}^{E_{\text{inj}}} \sigma v f_b(v) dv},$$

where σ is the fusion cross section and f_b is the beam distribution function (assumed $\propto v^{-3}$). The circles are inferred from the Fokker-Planck simulations with $\Delta I_n/I_n \approx 20\%$. For very weak losses, k approaches the plotted line, while for very strong losses ($\Delta I_n/I_n \rightarrow 1$), $k \rightarrow 1$.

energy of the lost beam ions E_{min} . For fishbones, beam-ion losses are thought to occur primarily above $E_{\text{min}} = 35$ keV,⁵ so $k \approx 0.4$ and Eq. (5) gives the expected drop in $\beta_{\perp}$ associated with the loss of beam ions as $(\Delta \beta_{\perp}/\beta_{\perp}) \approx 0.14(\Delta I_n/I_n)$, where $(\beta_{\perp}^{\text{beam}}/\beta_{\perp}) \approx 0.3$ is estimated from transport analysis.¹¹ This prediction agrees well with the data [Fig. 16(a)], implying that virtually all of the measured drop in $\beta_{\perp}$ is caused by the loss of beam ions. The time evolution of the neutron emission and diamagnetic flux also agree well with a Fokker-Planck simulation¹⁴ of the beam distribution that assumes that 50% of all beam ions that are above 25 keV and are trapped in the bad curvature region are lost at each fishbone [Fig. 15(b)]. The only significant discrepancy between simulation and experiment is an artifact of the assumption that the fishbone is virtually instantaneous while, in actuality, the instability is of finite duration [Fig. 15(b)].

For tangential injection, the expected drop in $\beta_{\perp}$ associated with a loss of energetic ions is smaller than for perpendicular injection because the perpendicular energy of the energetic ions is smaller. Some sudden drop still is expected, however, because most tangentially injected ions have some perpendicular energy [$E_{\perp}/E = \sqrt{1 - (v_{||}/v)^2}$]. The magnitude of the predicted drop depends on the assumed pitch-angle loss boundary $v_{||}/v$. If beam ions with $v_{||}/v > 0.85$ and $E > 35$ keV are assumed lost in the Fokker-Planck simulation, the predicted magnitude of $\Delta \beta_{\perp}/\beta_{\perp}$ exceeds experiment by a factor of 2 [Fig. 16(b)]. If, however, the simulation assumes only very parallel ions are lost ($v_{||}/v > 0.93$, $E > 25$ keV), the magnitude of the drop is in reasonable agreement with experiment [Fig. 16(b)]. With either assumption, however, the predicted time evolution of the displaced toroidal flux agrees poorly with experiment [Fig. 15(a)]. In

these simulations, the fraction of ions in the “loss cone” that were expelled from the plasma was adjusted to match the measured drop in neutron emission.

The loss of beam ions can indirectly affect $\beta_\perp$ by modulating the power flow to the thermal plasma. To evaluate this effect, we consider a zero-dimensional model for the plasma energy W_{thermal} ,

$$\frac{dW_{\text{thermal}}}{dt} = -\frac{W_{\text{thermal}}}{\tau_E} + \frac{W_{\text{beam}}}{\tau_{\text{beam}}}, \quad (6)$$

where τ_E is the energy confinement time and τ_{beam} is the time constant for the beam ions to transfer their energy to the plasma. From the shape of the neutron signal, we approximate W_{beam} by a sawtooth waveform of period T and find (assuming τ_E and τ_{beam} are constant in time)

$$\frac{\Delta W_{\text{thermal}}}{W_{\text{thermal}}} \approx \frac{k}{8} \frac{T}{\tau_E} \left[\left(\frac{2t}{T} - 1 \right)^2 - 1 \right] \frac{\Delta I_n}{I_n}, \quad (7)$$

where $0 < t < T$ and k is the proportionality factor that relates drops in neutron emission to changes in beam energy (Fig. 17). The time evolution predicted by Eq. (7) agrees fairly well with the evolution of the experimental trace [Fig. 15(a)], but the magnitude of the prediction underestimates the observed drop in $\Delta\beta_\perp/\beta_\perp$ by about a factor of 2 [Fig. 16(b)].

It appears that a combination of effects are required to explain the diamagnetic flux during tangential injection. The lack of a detectable sudden drop in $\Delta\Phi_i$ suggests that beam ions are not completely expelled from the plasma at the burst, but the sudden drop in neutron emission means that beam ions must move to (at least) the low-density edge of the plasma. Even if the beam ions do not strike the vessel walls, since beam ions in the edge plasma thermalize quickly, the relatively small magnitude of $\Delta\beta_\perp/\beta_\perp$ still suggests that only beam ions with large $v_\parallel/v$ are affected by the instability. Alternatively, a small amount of pitch-angle scattering by confined ions may compensate for the reduction in $\beta_\perp$ associated with parallel ions that are lost. The similarity between the time evolution of the diamagnetic flux and the predicted time evolution associated with fluctuations in thermal energy suggests that this effect is at least partially responsible for the observed variation in $\Delta\beta_\perp/\beta_\perp$.

Whatever the explanation for the time evolution of the diamagnetic flux during tangential injection, the very small magnitude of the drop in $\beta_\perp$ and the fact that most of the drop can be accounted for by measured beam-ion losses [Fig. 16(b)] indicates that thermal losses at low-frequency bursts are $O(0.1\%)$ which is two orders of magnitude smaller than the beam-ion losses. This conclusion is supported by soft x-ray (SXR) and Thomson scattering measurements. The largest drops in central soft x-ray (SXR) emission at low-frequency events are $\Delta A/A \sim 5\%$; however, some events with $\Delta I_n/I_n > 15\%$ have no detectable drop in SXR signal. Since the SXR measurements are sensitive to impurity concentrations and radial profiles as well as to electron temperature, a small drop in SXR emission probably indicates small electron losses but does not exclude the possibility of larger losses. Comparison of Thomson scattering profiles taken at different times with respect to the sawtooth-

like crash in a sequence of discharges with strong tangential instabilities suggests that the drop in central electron temperature is $\Delta T_e/T_e \lesssim 10\%$ with no appreciable reduction in T_e for $r/a \gtrsim 0.5$. The diamagnetic, SXR, and Thomson scattering data all suggest that direct thermal losses at these instabilities are much smaller than beam-ion losses.

D. Hard x-ray data

On some discharges, a burst of hard x rays was observed by the plastic scintillator at low-frequency events (Fig. 18). The burst is presumably bremsstrahlung from runaway electrons that strike vacuum vessel hardware and serves as a useful diagnostic of runaway electron confinement. The amplitude of the burst usually dropped 20%–50% on successive low-frequency events of equal amplitude. Since most of the runaways probably are created before the beam pulse,

FIG. 18. Time evolution of the Mirnov (a) and (c) and the plastic scintillator (b) signals at a low-frequency event that had hard x rays.

this reduction in signal on successive bursts suggests that 20%–50% of the runaways are lost at a large amplitude ($\tilde{B}_\theta/B_\theta \approx 10^{-2}$) event. An x-ray burst of this magnitude is too large to be explained by shifts in the position of the plasma¹⁹ or by modification of the runaways' drift orbit because of flattening of the current profile.²⁰ These bursts are probably caused by runaway transport at the low-frequency events.

In contrast to the signals observed following sawteeth in low- β PLT discharges, which peaked 1–5 msec after the sawtooth crash,²¹ the x-ray bursts at PBX low-frequency events peak only ($45 \pm 25 \mu\text{sec}$) after the mode reaches its peak amplitude (Fig. 18). In all of the approximately 25 events observed, the x-ray burst does not begin until after high-frequency activity appears in the 120–220 kHz frequency band (Fig. 18). No hard x rays have been observed at pure high-frequency events. This behavior contrasts with the behavior of the fast ions, which are lost at pure high-frequency events and are lost before the high-frequency activity at low-frequency events becomes large (Fig. 3). Some x-ray bursts have been observed when the mode decayed relatively slowly ($\delta B_\theta \approx 0$), indicating that a sudden sawtoothlike crash is not required for runaway transport.

IV. DISCUSSION

A. Comparison with fishbones

There are many similarities and some differences between the neutron and charge-exchange data during tangential beam-driven instabilities and perpendicular beam-driven instabilities. The behavior of the neutron emission at a low-frequency tangential event is similar to the behavior at a "classic" (~ 20 kHz) fishbone.³ For the largest fishbones observed on PDX, the neutron flux was modulated $\sim 5\%$ at the frequency of the magnetic oscillations,³ but this modulation, if it occurs for parallel injection, would be obscured in our measurements by poorer counting statistics and more electronic attenuation (at frequencies above 20 kHz). For a given amplitude burst, $\tilde{B}_\theta/B_\theta$, the magnitude of the drop in neutron emission $\Delta I_n/I_n$ is comparable for fishbones and tangential low-frequency events. The rate of fall of the neutrons is ~ 2.5 times faster for parallel events than for most PDX fishbones [Fig. 13(a)], but comparably large values of τ_B^{-1} were observed in PDX at high- β sawteeth.³ For both fishbones³ and low-frequency tangential events (Fig. 3), the energetic-ion loss rate τ_B^{-1} peaks $\sim 100 \mu\text{sec}$ after the peak of the magnetic oscillations.

High-frequency (~ 80 kHz) bursts with $\tilde{B}_\theta/B_\theta \sim 10^{-4}$ were also observed during perpendicular injection on PDX.³ These events had a peak neutron loss rate $\tau_B^{-1} \approx 0.1$ kHz, which is similar to the observations during tangential high-frequency events in PBX [Fig. 13(a)]. The loss rate peaks $81 \pm 55 \mu\text{sec}$ after the peak of the high-frequency oscillations for tangential injection, which is consistent with the PDX observation.³

The most obvious difference in the beam-ion data between tangential low-frequency events and fishbones is the weak ($\lesssim 1\%$) modulation of the charge-exchange flux at the mode frequency for tangential injection. For fishbones, the flux was strongly modulated at the mode frequency.⁹ It

should be noted, however, that modulation of the flux at frequencies ≥ 30 kHz could not be resolved with our analyzer. In other regards, the charge-exchange flux at tangential low-frequency events is similar to the flux at fishbones. As with fishbones,^{5,22} the charge-exchange bursts and depletion of the neutral spectrum are largest near the pitch angle of beam injection (Fig. 6). In addition, the bursts are largest ~ 10 keV below the injection energy and are small near E_{inj} (Fig. 6), as with fishbones.⁹ Neutrals with energies ~ 20 keV below the injection energy escape later than higher energy neutrals for both tangential events and fishbones.

In contrast to fishbones,^{5,9} neutrals well above the injection energy are not observed during tangential injection. This is probably because the radio-frequency instability that is thought to accelerate the ions²³ is absent during tangential injection.¹ The rf instability, in turn, is probably absent because the trapped beam ions posited to destabilize the rf²⁴ are absent for tangential injection.

On PDX, hard x-ray bursts were not observed with the plastic scintillators unless edge relaxation phenomena²⁵ (ERP) were coincident with the fishbone.³ In PBX, however, hard x-ray bursts similar to the one shown in Fig. 18 have been seen at fishbones that do not have a concurrent ERP. Differences between PBX and PDX include reconfiguration of the internal vacuum vessel hardware, which may change the location of the x-ray emission relative to the detector, and more plasma shaping, which may modify the electron dynamics. As during the tangential low-frequency instability, the hard x-rays during PBX fishbones begin after high-frequency activity appears, peak near the time of peak mode amplitude, and have a markedly different time history through the event than τ_B^{-1} or the charge-exchange flux.

As for fishbones,⁵ the data indicate that direct thermal electron and ion transport at tangential low-frequency events is small relative to beam-ion transport. The diamagnetic loop measurements indicate that thermal losses at both fishbones and tangential low-frequency events are two orders of magnitude smaller than beam-ion losses (Sec. III C).

B. Comparison with sawteeth

At low- β sawteeth during tangential $D^0 \rightarrow D^+$ injection into PLT, the drop in neutron emission was small ($\Delta I_n/I_n \lesssim 3\%$) and the emission decayed in 0.1–0.5 msec.¹³ These observations could be explained either with or without invoking a spatial redistribution of the fast-ion population.¹³ These sawteeth are completely different in their effect on the neutrons than the instabilities discussed here [Fig. 1(a)]. At higher β in PLT ($\beta q \sim 2\%$), drops as large as $\Delta I_n/I_n \approx 50\%$ were observed.³ These events probably were a manifestation of the low-frequency instability discussed here.

Radial transport of parallel ions at low- β sawteeth has been observed previously on the PDX tokamak²⁶ using spatially resolved charge-exchange measurements. Also, during tangential beam injection on PLT, bursts in the flux of 17 keV neutrals at sawteeth were observed in both the perpendicular and in the parallel direction.²⁶ These measurements indicate that some radial transport is normally associated with a sawtooth event. The significant aspect of the events

studied here is the relatively large number of beam ions ($\sim 20\%$) lost from the center, which results in a measurable loss of beam power from the plasma.¹

C. Comparison with mode-particle pumping theory

The data (Sec. III) suggest that a physical mechanism exists that affects full energy beam ions more strongly than other particles. Six features of the data suggest that full energy beam ions with large $v_{\parallel}/v$ are more strongly affected by the instabilities than other beam ions.

(1) The relative magnitude of the charge-exchange burst is largest for the most tangential orientation of the neutral analyzer (Fig. 7).

(2) The depletion of the charge-exchange flux following a burst is largest near E_{inj} (Fig. 9).

(3) The slope of the neutral spectrum is modified near E_{inj} when strong instabilities are present (Fig. 10).

(4) The charge-exchange flux near E_{inj} drops suddenly at the peak of the instability [Fig. 5(c)].

(5) The diamagnetic flux does not drop suddenly at the MHD burst [Fig. 15(a)] and the magnitude of the reduction in $\beta_{\perp}$ is small [Fig. 16(b)].

(6) The frequency of the high-frequency bursts and the peaks in the high-frequency part of the spectrum during low-frequency events never exceed the circulation frequency of full-energy beam ions (~ 220 kHz).¹

In Ref. 7, White *et al.* developed a theory to treat resonant transport of perpendicular beam ions during the fishbone instability. They found that, for trapped ions, radial transport depends on a resonance between the toroidal precession motion of the ions and the instabilities. White *et al.* also considered resonant transport of circulating beam ions and found that, for modes with $n = 1$, the radial transport of circulating ions should be an order of magnitude smaller than for trapped ions.⁷ Generalizing their theory to include modes with $n > 1$ (experimentally, the structure of the high-frequency modes is uncertain but it seems plausible to postulate $n > 1$), we find a new condition for resonant interaction of passing particles with a mode,

$$N = (\omega/\omega_c)q - nq + m, \quad (8)$$

where ω and ω_c are the mode and circulation frequency (in the laboratory frame), respectively, q is the safety factor, m and n are the poloidal and toroidal mode numbers, and N is an integer. The average radial motion $\langle \psi \rangle$ is given by Eq. (32) of Ref. 7:

$$\langle \psi \rangle \simeq - \sum_m \cos(\delta_{nm}) \frac{N\omega_c \alpha_{nm}}{\epsilon(1 - nq/m)} J_N \left(\frac{mqv_d}{\omega_c r_0} \right), \quad (9)$$

where α_{nm} is proportional to the mode amplitude, δ_{nm} is the mode phase, ϵ is the inverse aspect ratio, r_0 is the mode rational surface, and v_d is the vertical drift velocity of the resonant ions. The argument of the Bessel function J_N is approximately $m/3$ for PBX conditions. Equation (9) implies that if the resonance condition [Eq. (8)] is satisfied and the mode amplitude α_{nm} is comparable to the fishbone mode amplitude, the radial motion of passing particles will be comparable to the radial motion of trapped particles at a

fishbone. Experimentally, the amplitude of the high-frequency modes at low-frequency events is uncertain but the data suggest that the mode amplitude could be as large as at a fishbone. For radial transport across the plasma to occur, the radial motion associated with different modes must add constructively, as it was postulated that they do for fishbones. Multiple peaks in the high-frequency part of the magnetic spectrum were sometimes observed (e.g., Fig. 1 of Ref. 1) but it is not known if these high- n modes, if they exist at all, add constructively.

The mode-particle pumping theory predicts that resonant beam ions decelerate.⁷ Deceleration of parallel beam ions is a likely explanation for the sudden drop in charge-exchange flux near E_{inj} [Fig. 5(c)].

Equation (9) predicts that radial transport is linearly proportional to mode amplitude. Experimentally, the beam-ion losses do scale roughly linearly with high-frequency mode amplitude (Fig. 14) where reliable data are available. The energetic-ion losses also scale linearly with low-frequency mode amplitude [Fig. 13(a)] but this agreement may be fortuitous, since, in the mode-particle pumping theory, the low-frequency mode does not play an important role in beam-ion transport.

Although the data are consistent with resonant transport of the beam ions, the evidence is not strong enough to exclude significant transport by other mechanisms. Although the losses of thermal particles at the instabilities are small, the losses of runaway electrons are comparable to the beam-ion losses. If the beam ions are resonant with a mode, runaway electrons with $v_{\parallel}^{\text{runaway}} \gg v_{\parallel}^{\text{beam}}$ cannot satisfy the resonance condition. Since runaways are lost nonresonantly at the MHD bursts, some of the beam-ion transport could be caused by the same mechanism responsible for the runaway transport. Perhaps parallel transport along perturbed magnetic field lines plays a role in both runaway-electron and beam-ion losses. The differing time evolution of the runaway and beam-ion losses suggests that the physical mechanism responsible for runaway transport is not the only mechanism affecting beam-ion confinement, however. Moreover, since hard x-ray bursts are also observed during fishbones and beam-ion transport probably is dominated by mode-particle pumping during fishbones,^{3,5,9} the observation of runaway transport does not exclude the possibility of resonant beam-ion transport.

V. CONCLUSION

Both neutron and charge-exchange measurements indicate the transport of beam ions from the plasma center during tangential beam-driven instabilities. Apart from the absence of appreciable modulation in the charge-exchange flux, the neutron and charge-exchange measurements resemble measurements at instabilities during fishbones in PDX. The beam ions are affected much more strongly by these instabilities than by low- β sawteeth. The charge-exchange signal depends strongly on energy and the beam-ion losses are two orders of magnitude greater than the thermal losses, suggesting that mode-particle pumping may be responsible for some of the beam-ion transport.

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