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Tangential Neutral-Beam–Driven Instabilities in the Princeton Beta Experiment

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During tangential neutral-beam injection into the PBX tokamak, bursts of two types of instabilities are observed. One instability occurs in the frequency range 120–210 kHz and the other oscillates predominantly near the frequency of bulk plasma rotation (20–30 kHz). Both instabilities correlate with drops in neutron emission and bursts in charge-exchange neutral flux, indicating that beam ions are removed from the center of the plasma by the instabilities. The central losses are comparable to the losses induced by the fishbone instability during perpendicular injection.

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For efficient heating of a tokamak with neutral beams, the injected beam ions must remain confined long enough to transfer their energy to the plasma. Injection of neutral beams nearly perpendicular to the toroidal axis of the poloidal-divertor experiment (PDX)[1] and Doublet III[2] tokamaks resulted in instabilities ("fishbones") that degraded the confinement of the beam ions. Theorists suggested that the fishbone was an internal kink mode destabilized by the trapped perpendicular beam ions[3] and showed that a resonance between the mode rotation and the toroidal precession of the trapped beam ions should eject the resonant ions.[4] The theories predicted that circulating beam ions arising from tangential neutral-beam injection would not resonantly destabilize the internal kink[3] and that, should a kink still appear, the loss of circulating ions should be several times smaller than for perpendicular injection.[4] Many groups had studied tangential neutral-beam injection and, although repetitive instabilities at toroidal $\beta=(0.5\text{–}3)\%$ had been observed on the ISX-*B*,[5] JFT-2,[6] and PLT[7] tokamaks, measurements of beam-ion loss during tangential injection had not been well documented. So, when the PDX tokamak was converted into the Princeton beta experiment (PBX) tokamak, two of the four perpendicular neutral-beam injectors were reoriented to inject tangentially in the hope of reducing beam-ion losses.[8] At normal operating densities ($\bar{n}_e \gtrsim 4\times10^{13}$ cm^{-3}), two-beam, bean-shaped PBX plasmas were less suceptible to fishbone instabilities than typical PDX plasmas,[9] making comparison of plasma stability with high-power perpendicular and tangential neutral-beam injection difficult. By operation at low densities ($\bar{n}_e \lesssim 2.5\times10^{13}$ cm^{-3}) with weak plasma shaping, a regime was found where two perpendicular beams excited strong fishbones.[9] Using this regime to compare perpendicular and parallel injection, we have found that although there are differences between perpendicular and parallel instabilities (Sect. I), the beam-ion losses from the plasma center are comparable in both cases (Sect. II).

I. Description of instabilities.—In these experiments, 2.7 MW of 44-keV deuterium neutrals were coinjected with a tangency radius of $R_{tan}=130$ cm into a deuterium plasma with $Z_{eff}\simeq4.5$ The outer flux surfaces of the plasma had a weakly indented (12%) bean shape (elongation = 1.4; $a_{mid}=38$ cm; $R_0=149$ cm). Reducing the indentation to 5% did not appreciably alter the virulence of the instabilities discussed here. The plasma current ($I_p=240$ kA) was fairly constant during the beam pulse and the toroidal field was kept low ($B_t=0.84$ T) to increase β ($\beta_\perp=1.3\%$). The electron temperature and density measured by Thomson scattering were $T_e(0)=0.9$ keV, $\langle T_e\rangle=0.4$ keV, $n_e(0)=3.1\times10^{13}$ cm^{-3}, and $\bar{n}_e=1.7\times10^{13}$ cm^{-3}. The central ion temperature (2 keV) and toroidal plasma rotation [$v_\phi(0)\simeq2.4\times10^7$ cm/sec] were measured by means of charge-exchange recombination spectroscopy.

Under these conditions, repetitive bursts of activity were observed with Mirnov coils, soft-x-ray detectors, neutron scintillators, a fast neutral analyzer, and a diamagnetic loop (Fig. 5 of Ref. 9). Large bursts with dominant internal fluctuation frequencies between 20 and 30 kHz occurred approximately every 5 msec and smaller bursts with typical frequencies between 150 and 200 kHz occurred approximately every 2 msec. The neutron emission I_n dropped $\sim20\%$ at the low-frequency bursts and $\sim2\%$ at the high-frequency events. Data from a low-frequency event that had a high-frequency precursor (which is usually, but not always observed) are shown in Fig. 1. At 501.7 msec, high-frequency activity is observed with a Mirnov coil at the outer midplane. The burst correlates with an increase in charge-exchange (CX) flux and a 2% reduction in neutron emission. At the end of the high-frequency burst, the amplitude of low-frequency oscillations grows. As the low-frequency oscillations approach their maximum amplitude, high-frequency oscillations in the frequency range 140–220 kHz reappear. About 0.1 msec after the mode reaches its maximum amplitude, the CX flux peaks and the rate of

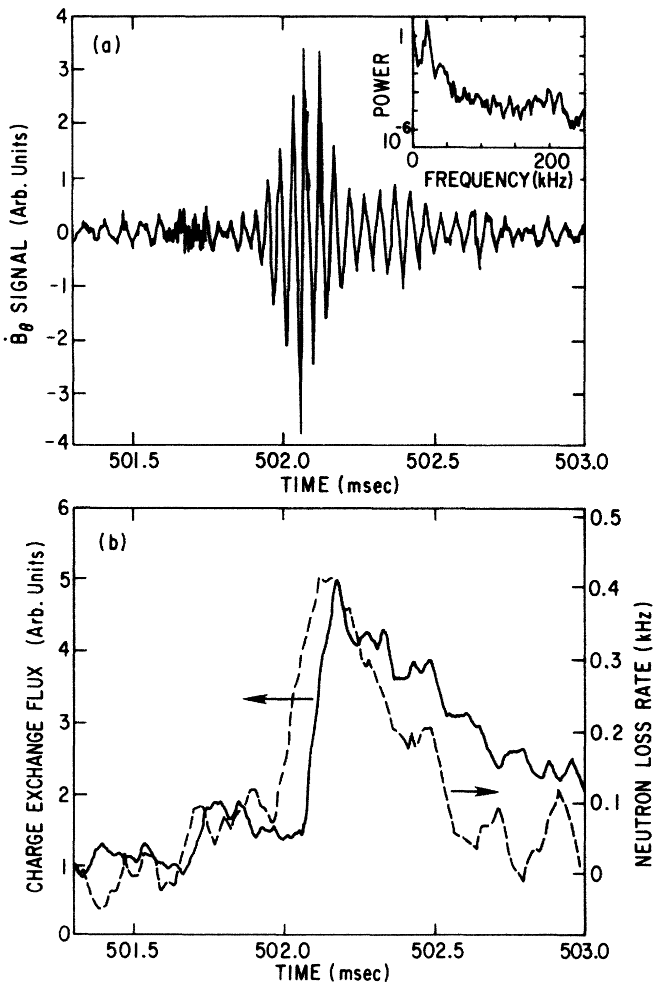

FIG. 1. Mirnov trace and power spectrum, CX flux from cocirculating ($R_{tan} = 160$ cm) 35-keV beam ions, and neutron loss rate τ_B^{-1} for a moderate-amplitude ($\Delta I_n / I_n = 14\%$), low-frequency event.

decrease of the neutron emission is greatest [Fig. 1(b)].

The neutron and CX measurements indicate that beam ions are removed from the center of the plasma by the instability. Calculations show that the neutron emission for tangential $D^0 \rightarrow D^+$ injection into the PBX plasma is dominated by beam-plasma reactions near the center of the plasma. In general, rapid reductions in neutron emission indicate either rapid deceleration of some of the beam ions or the expulsion of beam ions from the center of the plasma to a region of lower deuterium density. Following Strachan *et al.*,[7] we interpret the drops in neutron emission as due to the escape of beam ions from the plasma center and relate the slope of the neutron emission to the beam-ion confinement time

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

where $\dot{I}_n(t_0)$ is the slope of the neutron emission before the instability. The CX data are from a compact analyzer[10] that views cocirculating ions in the horizontal midplane along a variable line of sight. In general, CX bursts do not necessarily imply radial transport of beam ions since the flux can change as a result of scattering in velocity space or changes in neutral density profile. Variations in neutral density profile are not a likely explanation for the bursts since the relative change in signal is a strong function of analyzer energy. Scattering in velocity space cannot be excluded but, from a scan of analyzer angle, there is no evidence for appreciable pitch-angle scattering. The most likely explanation for the bursts is that beam ions are expelled from the center of the plasma (a low-neutral-density region) to the plasma edge (where the CX probability is an order of magnitude higher). The neutron and CX measurements in Fig. 1(b) evolve similarly in time, suggesting that both diagnostics monitor central beam-ion confinement. In contrast to fishbones,[10] the CX flux [Fig. 1(b)] is only weakly modulated at the mode frequency ($\tilde{A}/A \lesssim 1\%$); modulations in flux $\gtrsim 30$ kHz were beyond the bandwidth of the electronics for both the neutron and the neutral detectors.

The low-frequency mode seems similar in structure to the "sawtooth" instability studied on the ISX-*B* tokamak[5] and to the fishbone instability.[1] The instability rotates in the direction of the injected beam and plasma current with a $m=1$, $n=1$ structure (identified with soft-x-ray and $\dot{B}_r$ arrays, respectively). On large events ($\tilde{B}_\theta / B_\theta \simeq 10^{-2}$ at the outer wall; $\Delta I_n / I_n \gtrsim 20\%$), the x-ray oscillations are jagged and nonsinusoidal ($\tilde{A}/\bar{A} \sim 0.5$) and are seen out to $z = 32$ cm. The mode usually decays rapidly from its maximum amplitude ($\tau_d \simeq 50$ μsec), although successor oscillations often persist for ~ 0.5 msec. On events that rapidly decay, the central soft x rays typically drop 5% and the amplitude outside $z = 20$ cm increases, as in a sawtooth. Other times (as in Fig. 1), the mode decays more slowly ($\tau_d \sim 300$ μsec) and no sawtooth drop is observed on the x rays. The rate of decay of the mode does not correlate with $\Delta I_n / I_n$, implying that a sawtooth crash is not required for beam-ion transport.

Some power between 120 and 220 kHz is always observed at low-frequency events. In contrast, high-frequency events often occur without significant low-frequency activity. High-frequency events have not been observed at frequencies higher than the circulation frequency of the injected beam ions (220 kHz). This suggests that a resonant interaction between the circulating beam ions and the high-frequency waves may be responsible for beam-ion transport in both the low-frequency and the high-frequency events.

The frequency of the low-frequency mode behaves differently than the frequency of the fishbone. For fishbones, the observation[1] that the mode frequency was close to the frequency of beam-ion precession but exceeded the frequency of rotation of the bulk plasma by a factor of 3 provided strong evidence for destabilization of the mode by the beam ions. For parallel injection, however, the frequency of the low-frequency mode never exceeds the measured central toroidal rotation frequency by more than 10%. In addition, while the internal oscillations of a fishbone typically slow down by a factor of 2,[10] the mode frequency during parallel injection only falls $(19 \pm 7)\%$ for large-amplitude, low-frequency events. The frequency reduction is even less for small-amplitude events. These results suggest that the low-frequency mode may be stationary in the plasma frame and may not be destabilized directly by the beam ions.

During fishbones, neutral bursts $\gtrsim 5$ keV above the injection energy were observed[10] and strong ion-cyclotron instabilities were present.[11] Both are absent during parallel injection. This observation supports the hypothesis[12] that the high-energy perpendicular ions seen during fishbones are accelerated by an ion-cyclotron instability destabilized by escaping perpendicular beam ions at the plasma edge.

Phenomenologically, the instabilities observed during parallel and perpendicular injection are similar (Table I). The principal differences are that parallel instabilities always have 120–220 kHz activity, that the low-frequency parallel mode may be stationary in the plasma frame, and that the CX flux is not strongly modulated at ~ 25 kHz.

II. Evaluation of beam-power loss.—A direct comparison of the severity of beam-ion loss for parallel and perpendicular injection was achieved by injection of two parallel beams (2.7 MW) and two perpendicular beams (2.8 MW) into the same discharge on successive shots. Except for the neutron yield (a factor of 2 lower for parallel injection), the plasma rotation (a factor of 4 higher), and the perpendicular beta (35% lower), the discharge parameters were similar for the two cases. (The magnitude of the neutron emission is reduced for tangential injection because the plasma rotation reduces the relative velocity between beam and target ions by 12%, yielding a $\sim 100\%$ reduction in fusion reactivity.) With use of the average beam-ion confinement time $\langle \tau_B \rangle$ deduced from the neutron emission[7] [roughly, $\langle \tau_B \rangle \sim$ (period between events)/$(\Delta I_n / I_n)$], it is found that the central losses were just as severe for parallel injection as for perpendicular injection (Fig. 2). Parallel beams alone were rarely used on PBX and most of the available data are from the low-density, low-indentation discharges specifically created for the study reported here. Comparison of all of the available PBX data during $D^0 \rightarrow D^+$ tangential injection to the PDX data compiled by Strachan *et al.*[7] indicates that the losses were generally comparable to the losses observed during fishbones on PDX (Fig. 2).

When $\langle \tau_B \rangle \lesssim \tau_s$ (Fig. 2), the losses have a deleterious effect on the power balance of the plasma. Under these conditions, an independent estimate of beam-ion

TABLE I. Comparison of instabilities during tangential and perpendicular (Refs. 1 and 7) neutral-beam injection.

Quantity	Tangential	Perpendicular
	Low frequency burst	
$\tilde{B}_\theta / B_\theta$	$\sim 10^{-2}$	$\sim 10^{-2}$
Mode freq.	$\simeq$ rotation freq.	$>$rotation freq.
Growth rate	$\sim (100\ \mu\text{sec})^{-1}$	$\sim (150\ \mu\text{sec})^{-1}$
Decay rate	$\sim (50\ \mu\text{sec})^{-1}$ [a]	$\sim (400\ \mu\text{sec})^{-1}$ [b]
Structure	$m=1, n=1$	$m=1, n=1$
80–220 kHz activity	always concurrent	sometimes concurrent
rf activity	never concurrent	always concurrent
Largest CX burst	$\parallel$ ions near E_{inj}	$\perp$ ions near E_{inj}
CX modulation	weak at ~ 25 kHz	strong at ~ 15 kHz
Max. CX energy	$\lesssim 1.1 E_{\text{inj}}$	$\gtrsim 2 E_{\text{inj}}$
Neutrons	$\Delta I_n / I_n \simeq 20\%$	$\Delta I_n / I_n \simeq 20\%$
Diamagnetic loop	$\Delta\beta_\perp / \beta_\perp \simeq 0.4\%$	$\Delta\beta_\perp / \beta_\perp \simeq 2\%$
	High frequency burst	
$\tilde{B}_\theta / B_\theta$	$\sim 10^{-4}$	$\sim 10^{-4}$
Frequency	~ 150 kHz	~ 80 kHz
Growth rate	$\sim (125\ \mu\text{sec})^{-1}$	$\sim (200\ \mu\text{sec})^{-1}$
Decay rate	$\sim (150\ \mu\text{sec})^{-1}$	$\sim (800\ \mu\text{sec})^{-1}$
Neutrons	$\Delta I_n / I_n = (1\text{–}6)\%$	$\Delta I_n / I_n \sim 3\%$

[a]Usually (when the mode decays with a "sawtooth crash"); $\sim (200\ \mu\text{sec})^{-1}$ occasionally.
[b]Usually; occasionally $\sim (50\ \mu\text{sec})^{-1}$ (when the mode decays with a "sawtooth crash").

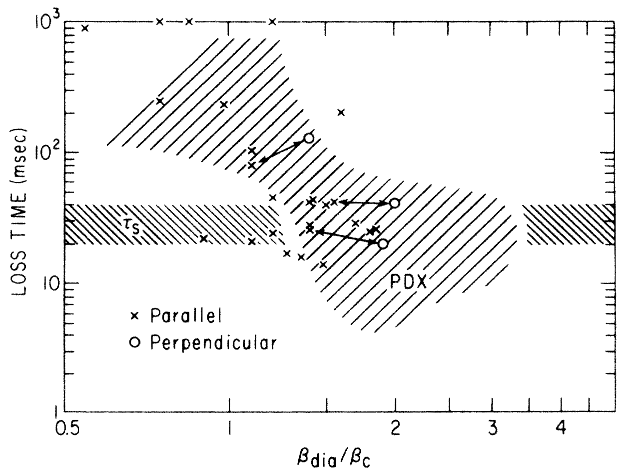

FIG. 2. $\langle \tau_B \rangle$ vs normalized perpendicular beta ($\beta_c \equiv \mu_0 I_p / a_{\rm mid} \langle B_t \rangle$) (Ref. 13) for tangential $D^0 \rightarrow D^+$ injection into PBX plasmas with indentation < 14% and $\bar{n}_e \leq 4.5 \times 10^{13}$ cm^{-3}. The circles with arrows are the results of the direct comparison between perpendicular and parallel injection at different values of $\bar{n}_e$ and P_b. The hatched region represents the PDX fishbone data (Ref. 7) and τ_s is the beam slowing-down time for PBX conditions.

losses can be obtained from transport analysis.[1] Since thermal particles appear to be weakly affected by the instabilities ($\beta_\perp$ drops $\simeq 0.4\%$ at the burst when $\Delta I_n / I_n \gtrsim 20\%$), the analysis assumes that some parallel beam ions are lost at instabilities but that the thermal transport coefficients are unaffected by the MHD activity. When $\sim 20\%$ of the beam energy is assumed lost, reasonable agreement with the measured thermal content of the plasma is obtained.

Another indication of severe beam-ion losses is that, between bursts, the CX flux is reduced, suggesting depletion of beam ions from the sight line. This reduction is evidenced both by distortion of the neutral spectrum as the beam power is increased and by the fact that, following a strong burst, the CX flux F is less than it was prior to the burst. Angular and energy scans show that the flux at the time of the instabilities is biggest for the same viewing angle ($R_{\rm tan} = 160$ cm) and energy ($E = 35$ keV) that measures the biggest flux between bursts. For this energy and viewing angle, the reduction in flux after a burst ($\Delta F / F = 0.22 \pm 0.05$) nearly equals the observed reduction in neutron emission ($\Delta I_n / I_n = 0.21 \pm 0.02$).

In conclusion, neutron, power-balance, and CX measurements all indicate a substantial loss of beam power during tangential injection. The repetitive nature of the instabilities suggests that the beam β may play an important role in the destabilization of the instabilities.[9] This conjecture is supported by the observation that when the density was increased from $\bar{n}_e = 1.7 \times 10^3$ cm^{-3} to $\bar{n}_e = 2.7 \times 10^{13}$ cm^{-3} (which reduces the beam β by reducing τ_s), the high-frequency events disappeared, the period between low-frequency events increased to ~ 10 msec, and the sawtooth inversion radius shrank to ~ 12 cm. Also, we find that $\langle \tau_B \rangle$ correlates more strongly with P_b / B_t^2 than with the plasma β. Alternatively, beam-driven currents or ion-streaming instabilities may destabilize the modes. If the instabilities are destabilized by beam β, then they may have serious consequences for the achievement of high Q [$Q \equiv$ (fusion power)/(input power)] in larger beam-heated tokamaks. For example, in the tokamak fusion test reactor (TFTR) at $Q = 1$, it is estimated that $\beta / \beta_c \gtrsim 2$, which exceeds the value in our PBX experiment (Fig. 2), and so the Q achieved in TFTR may be limited by beam-ion losses.

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