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IN THE PRINCETON BETA EXPERIMENT

By

W.W. Heidbrink et al.

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PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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TANGENTIAL NEUTRAL-BEAM-DRIVEN INSTABILITIES IN THE PRINCETON BETA EXPERIMENT

W.W. Heidbrink, K. Bol, D. Buchenauer,^a R. Fonck, G. Gammel,
K. Ida,^b R. Kaita, S. Kaye, H. Kugel, B. LeBlanc, W. Morris,^c
M. Okabayashi, E. Powell, S. Sesnic, H. Takahashi

*Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544*

ABSTRACT

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 predominately 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.

MASTER

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 PDX¹ and Doublet III² 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 beam ions³ and showed that a resonance between the mode rotation and the toroidal precession of the beam ions should eject the resonant ions.⁴ Many groups had studied tangential neutral beam injection and, although repetitive instabilities at toroidal $\beta = 0.5$ –3% had been observed on the ISX-B,⁵ JFT-2,⁶ and PLT⁷ 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), 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 ($\bar{n}_e \gtrsim 4 \times 10^{13} \text{ cm}^{-3}$), two-beam, bean-shaped PBX plasmas were less susceptible to fishbone instabilities than typical PDX plasmas,⁹ making comparison of plasma stability with high-power perpendicular and tangential neutral beam injection difficult. By operating at low densities ($\bar{n}_e \lesssim 2.5 \times 10^{13} \text{ cm}^{-3}$) 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, the beam-ion losses from the plasma center are comparable in both cases.

In these experiments, 2.7 MW of 44 keV deuterium neutrals were co-injected with a tangency radius of $R_{tan} = 130 \text{ cm}$ into a deuterium plasma with $Z_{eff} \simeq 4.5$. The outer flux surfaces of the plasma had a weakly indented (12%) bean shape (elongation = 1.4; $a_{mid} = 38 \text{ cm}$; $R_0 = 149 \text{ cm}$). Reducing the indentation to 5% did not appreciably alter the virulence of the instabilities discussed here. The plasma current ($I_p = 240 \text{ kA}$) was fairly constant during the beam pulse and the toroidal field was kept low ($B_t = 0.84 \text{ T}$) to increase β ($\beta_{\perp} = 1.3\%$). The electron temperature and density measured by Thomson scattering were $T_e(0) = 0.9 \text{ keV}$, $\langle T_e \rangle = 0.4 \text{ keV}$, $n_e(0) = 3.1 \times 10^{13} \text{ cm}^{-3}$, and $\bar{n}_e = 1.7 \times 10^{13} \text{ cm}^{-3}$. The central ion temperature (2 keV) and toroidal plasma rotation ($v_{\phi}(0) \simeq 2.4 \times 10^7 \text{ cm/sec}$) were measured using 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 20–30 kHz occurred approximately every 5 msec and smaller bursts with typical frequencies

between 150-200 kHz occurred approximately every 2 msec. The neutron emission I_n dropped $\sim 20\%$ at the low frequency bursts and $\sim 2\%$ 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 decrease of the neutron emission is greatest (Fig. 1b).

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 PBX 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 analyzer¹⁰ that views co-circulating 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 due to 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. 1b evolve similarly in time, suggesting that both diagnostics monitor central beam-ion confinement. In contrast to fishbones,¹⁰ the CX flux (Fig. 1b) is only weakly modulated at the mode frequency ($\dot{A}/A \lesssim 1\%$); 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 instability studied on ISX-

B^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 SXR and $\dot{B}_r$ arrays, respectively). On large events ($\bar{B}_\theta/B_\theta \simeq 10^{-2}$ at the outer wall; $\Delta I_n/I_n \gtrsim 20\%$), the X-ray oscillations are jagged and non-sinusoidal ($\bar{A}/\bar{A} \sim 0.5$) and are seen out to $z = 32$ cm. The mode usually decays rapidly from its maximum amplitude ($\tau_d \simeq 50 \mu\text{sec}$), 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 ($\tau_d \sim 300 \mu\text{sec}$) and no "sawtooth" drop is observed on the X-rays. The rate of decay of the mode does not correlate with $\Delta I_n/I_n$. Some power between 120-220 kHz is always observed at low frequency events.

The frequency of the low frequency mode behaves differently than the frequency of the fishbone. For fishbones, the mode frequency at peak amplitude exceeds the frequency of toroidal rotation of the bulk plasma at the center of the discharge by a factor of two or more.¹ For parallel injection, the mode frequency never exceeds the measured central rotation frequency by more than 10%. In addition, while the internal oscillations of a fishbone typically slow down by a factor of two,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.

Less is known about the high frequency events. The growth rate of these modes is typically $(100\text{--}150 \mu\text{sec})^{-1}$ and the decay rate is $(100\text{--}200 \mu\text{sec})^{-1}$. The peak mode amplitude at the wall is $\bar{B}_\theta/B_\theta = O(10^{-4})$. The power spectrum of a high frequency event often has no identifiable peaks below 100 kHz. For events that do have an identifiable low frequency peak, the frequency of the high frequency mode is independent of the lower frequency. High frequency events have not been observed at frequencies higher than the circulation frequency of the injected beam ions (220 kHz).

During fishbones, neutral bursts $\gtrsim 5$ keV above the injection energy were observed¹⁰ and strong ion cyclotron instabilities were present.¹¹ Both are absent during parallel injection. This observation supports the hypothesis¹¹ 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.

A direct comparison of the severity of beam-ion loss for parallel and perpendicular injection was achieved by injecting two parallel beams (2.7 MW) and two perpendicular beams (2.8 MW) into the same discharge on successive shots. Except for the neu-

tron yield (a factor of two lower for parallel injection), the plasma rotation (a factor of four 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.) Using the average beam-ion confinement time $\langle\tau_B\rangle$ deduced from the neutron emission⁷ [roughly, $\langle\tau_B\rangle \sim (\text{period between events})/(\Delta I_n/I_n)$], 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 $\langle\tau_B\rangle \lesssim \tau_e$ (Fig. 2), the losses have a deleterious effect on the power balance of the plasma. Under these conditions, an independent estimate of beam-ion 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 sightline. 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 ($R_{tan} = 160$ 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 existence of oscillations at $\lesssim 220$ kHz suggests a resonant interaction between the circulating beam ions and the wave. 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 $\bar{n}_e = 1.7 \times 10^{13} \text{ cm}^{-3}$ to $\bar{n}_e = 2.7 \times 10^{13} \text{ cm}^{-3}$, 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_i^2 than with the plasma β . Alternatively, beam-driven currents or ion-streaming instabilities may destabilize the modes.

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- ^a Permanent address: Sandia National Laboratory, Livermore California 94550
- ^b Permanent address: Institute of Plasma Physics, Nagoya University, Nagoya, Japan
- ^c Permanent address: Balliol College, University of Oxford, United Kingdom
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Figure Captions

Fig. 1 Mirnov trace and power spectrum, CX flux from co-circulating ($R_{tan} = 160$ 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.

Fig. 2 $\langle \tau_B \rangle$ versus normalized perpendicular beta ($\beta_c \equiv \mu_0 I_p / a_{mid} \langle B_t \rangle$)¹² for tangential $D^0 - D^-$ injection into PBX plasmas with indentation $< 14\%$ and $\bar{n}_e \leq 4.5 \times 10^{13} \text{ cm}^{-3}$. 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 data⁷ and τ_s is the beam slowing-down time for PBX conditions.

Fig. 1

Fig. 2

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