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Measurements of classical deceleration of beam ions in the DIII-D tokamak

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Studies of the slowing down of short pulses of deuterium beam ions in the DIII-D tokamak [Nucl. Fusion **28**, 1897 (1988)] are extended to the regime where ion drag dominates electron drag. The deceleration of the beam ions is consistent with Sivukhin's classical theory [*Reviews of Plasma Physics* (Consultants Bureau, New York, 1966), Vol. 4, p. 93] to within 25%.

The deceleration of test particles through Coulomb collisions is a fundamental process in plasma physics. For such a fundamental topic, there have been relatively few direct experimental tests of the theory.¹ In tokamak research, energy transfer is almost invariably assumed to be classical. Transport coefficients inferred from neutral-beam heating experiments are determined by assuming that the beam power is partitioned classically between electrons and ions. Conceivably, however, other processes such as enhanced scattering associated with plasma turbulence² or the excitation of beam-driven instabilities³ could lead to enhanced deceleration rates and might partition the energy differently between electrons and ions. The goal of the present research is to confirm that classical drag dominates beam deceleration in a tokamak plasma when the density of fast ions is well below the threshold for collective instability.

The experiment reported here is an extension of an earlier study.⁴ Both studies use the same diagnostic technique. Short (2 msec) pulses of deuterium neutral beams are injected into deuterium plasmas in the DIII-D tokamak.⁵ After ionization, the beam ions produce 2.5 MeV neutrons in beam-plasma fusion reactions. Because the $d(d,n)^3\text{He}$ fusion cross section falls rapidly with decreasing energy, the neutron emission decays as the beam ions decelerate so the decay time of the neutron emission is simply related to the beam-ion slowing-down time. In the previous study, the neutron decay time τ_n was found to agree with classical theory (to within 30%) for an order of magnitude variation in τ_n .⁴ The study was restricted to the regime $E_b > E_{\text{crit}}$, where E_b is the beam energy and E_{crit} is the critical energy at which ion drag equals electron drag. The present work extends the previous study into the regime where beam ions slow down primarily upon thermal ions ($E_b < E_{\text{crit}}$). In both experiments, the beam velocity is intermediate between the ion and electron thermal velocities ($v_e \gg v_b \gg v_i$). For comparison with

classical theory, short beam pulses are superior to neutron measurements following beam heating,^{6,7} because the beam ions are nearly monoenergetic and because the background plasma parameters are barely perturbed by the beam pulse.

The regime $E_b < E_{\text{crit}}$ was accessed by reducing the beam voltage from 76 to 39 kV and by employing electron cyclotron heating (ECH) to raise the electron temperature (which raises E_{crit}). The neutral-beam accelerating voltage rose in approximately 0.15 msec (to within 2 kV of its final value) and turned off following the 2 msec pulse in <0.05 msec. Approximately 1.5 MW were injected at 76 kV and 0.4 MW at 39 kV. Inside launch ECH with primarily extraordinary mode polarization (>1 MW for 500 msec) was used to heat the electrons. The plasma density ($\bar{n}_e = 1.1\text{--}4.5 \times 10^{13} \text{ cm}^{-3}$), toroidal field ($B_t = 1.7\text{--}2.0 \text{ T}$), and plasma current ($I_p = 0.6\text{--}1.2 \text{ MA}$) were selected for good ECH heating. The ionic composition was primarily deuterium (spectroscopic measurements found <1% hydrogen) but Z_{eff} (from visible bremsstrahlung) was 2 to 4 (presumably, principally carbon impurity). (Theoretically, τ_n is practically independent of Z_{eff} for fully stripped impurities in deuterium.) The plasma was run in the single-null divertor configuration. The electron temperature (0.9–2.5 keV) was measured using the electron cyclotron emission (ECE) profile diagnostic⁸ corroborated by Thomson scattering.⁹ Within ~15% errors, the measurements were consistent. Electron density was measured by four CO₂ interferometer chords. The Thomson scattering density measurements were typically 20% lower than the density inferred from the CO₂ measurements. The perturbations in T_e and $\bar{n}_e$ associated with the beam pulse were undetectable. The fast-ion density was well below the thresholds for beam driven instabilities ($n_b/n_e < 0.1\%$). The neutron emission was measured using an uncollimated plastic scintillator with a temporal resolution of <0.1 msec.^{6,10}

FIG. 1. Experimentally measured decay time τ_n versus the prediction of classical theory. The theory is uncertain to 20% because of uncertainties in beam deposition and in electron density and temperature. Also, the neglect of velocity space diffusion results in a 10%–25% underestimate of the theoretical decay time. The error in τ_n is typically 2 msec but is larger in some cases. The line indicates agreement between experiment and theory.

The neutron emission generally rose linearly during the 2 msec beam pulse, then decayed exponentially following the pulse (Fig. 1 of Ref. 4). For beam-plasma emission, the jump in neutron emission ΔI_n is expected to depend linearly on the number of injected beam ions N_b , the fusion reactivity σv , and the central deuterium density n_d .⁴ Experimentally, ΔI_n did scale roughly linearly with $N_b \sigma v n_d$, where N_b was estimated from the beam current and pulse duration, σv was evaluated at the injection energy, and n_d was assumed proportional to $\bar{n}_e$. At the lowest beam voltages, the beam-plasma emission was only two to three times larger than the thermonuclear emission, so the accuracy of determination of τ_n was typically 15%. At the highest voltages, the signal was an order of magnitude larger and τ_n could be measured to 5% accuracy.

The data are in good agreement with theory (Fig. 1). As expected, low voltage pulses tend to decay more quickly (due to a reduction in τ_s and to the steeper fusion cross section at low E_b). The classical prediction was calculated numerically using fits to the experimentally measured profiles with the code developed previously.⁴ The code uses Sivukhin's formula for $\langle dW/dt \rangle$ (Ref. 11) to calculate the deceleration of a monoenergetic beam (the fast ions are assumed to remain a δ function distribution as they slow down). The fusion reactivity is evaluated at the energy of the fast ions since corrections associated with plasma ion temperature and rotation are negligible in these slowly rotating, low ion temperature ($T_i < 1$ keV) plasmas. For $E_b < E_{\text{crit}}$, the neglect of energy diffusion is a poorer assumption than for $E_b > E_{\text{crit}}$; estimates⁴ indicate the approximation results in a $\sim 20\%$ underestimate of τ_n for the low voltage cases. This error is comparable to the errors associated with uncertainties in the profiles of T_e , n_e , and beam deposition (the beam deposition was estimated from numerical calculations). The small contribution of half-energy ions to the neutron emission was included in the calculation.

FIG. 2. Ratio of experimental τ_n to calculated decay time versus the ratio of beam voltage to critical energy. Here, $E_{\text{crit}} = 30T_e$,¹¹ where T_e is the central electron temperature measured by ECE. Also, $E_b = 39$ –76 kV; $T_e = 0.9$ –2.5 eV. The line indicates agreement between theory and experiment.

The ratio of experimentally measured decay time to calculated decay time is plotted versus E_b/E_{crit} in Fig. 2. No systematic variation is observed as the beam ions switch from slowing primarily upon electrons to slowing primarily upon ions. Systematic dependencies upon E_b , T_e , and $\bar{n}_e$ are also absent.

In conclusion, beam ions in the regime $v_e \gg v_b \gg v_i$ and $n_b/n_e < 0.1\%$ decelerate classically in the DIII-D tokamak. The $\sim 25\%$ agreement between theory and experiment for the range $0.5 < E_b/E_{\text{crit}} < 2.4$ suggests that the distribution of beam power between ions and electrons is classical.

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