Evidence for Fast-Ion Transport by Microturbulence

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Cross-field diffusion of energetic ions by microturbulence is measured during neutral-beam injection into the DIII-D tokamak. Fast-ion D_α, neutron, and motional Stark effect measurements diagnose the fast-ion distribution function. As expected for transport by plasma turbulence, anomalies relative to the classical prediction are greatest in high temperature plasmas, at low fast-ion energy, and at larger minor radius. Theoretical estimates of fast-ion diffusion are comparable to experimental levels.

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Neutral-beam injection is the most common form of auxiliary heating in magnetic fusion experiments. Accordingly, knowledge of the fast-ion distribution function undergirds most studies of fusion plasmas. Beam ions supply energy, momentum, and particles, so knowledge of these sources is essential in plasma transport studies. The pressure and current from fast ions are exploited to avoid instabilities and improve confinement.

Fusion reactions and rf heating also produce fast ions. Based on calculations dating back to 1979 [1], the conventional wisdom is that, in the absence of long-wavelength MHD instabilities, fast-ion confinement is much *better* than thermal-ion confinement. In particular, it is generally assumed that the alpha particles and high-energy neutral-beam ions that will heat ITER will be well confined unless they drive Alfvén waves unstable [2]. Theoretically, the reason for this expectation is that the large orbits of fast ions phase average over electrostatic turbulence with decorrelation lengths on the scale of the thermal-ion gyroradius. The effectiveness of phase averaging increases with the ratio of fast-ion energy E to plasma temperature T. For example, Ref. [3] predicts that, in the high-energy limit, the diffusivity of passing fast ions D_B is proportional to $(E/T)^{-3/2}$, while Ref. [4] predicts $(E/T)^{-1}$ scaling for electrostatic turbulence and no reduction for electromagnetic microturbulence. Other authors stress that the Kubo number (ratio of decorrelation time to fast-ion time of flight) is a crucial parameter and that phase averaging may not occur at all [5]. A compilation of data [6] in the large energy regime ($E/T \gg 10$) confirms the conventional wisdom, but some anomalies at smaller E/T have been reported [7,8].

This Letter reports the first clear evidence of fast-ion transport by microturbulence in the $E/T \lesssim 10$ regime. The transport depends strongly on energy and temperature, as predicted by most theories. Quantitative consistency with the expected transport levels is observed.

The measurements are performed in the DIII-D tokamak during experiments designed to study off-axis neutral-beam current drive (NBCD) by ~80 keV deuterium neutral beams that are injected in the direction of the plasma current [9,10]. Analysis is performed during the steady-state portion of the discharge in four discharges with injected beam power of $P_B = 3.1$, 5.0, 5.7, and 7.2 MW. The primary diagnostic is a vertical array of fast-ion D-alpha (FIDA) detectors that measure the spectra of light from fast ions that charge exchange with one of the heating beams [11]. Spatially resolved information about the fast-ion distribution function is also available from reconstructions of the driven current and pressure based on a 64-channel motional Stark effect diagnostic [12]. The neutron rate is primarily from beam-plasma reactions in these discharges, so the volume-averaged 2.5 MeV neutron rate is also sensitive to the fast-ion distribution function. Low-frequency MHD and fast-ion driven instabilities can cause fast-ion transport in DIII-D [13,14], but the observed fluctuations on the internal diagnostics are small or nonexistent for the discharges in this power scan.

The NUBEAM module of the TRANSP code [15] calculates beam deposition, Coulomb scattering, orbits, neoclassical transport, and charge-exchange losses to predict the fast-ion distribution function. In these "classical" simulations, no additional fast-ion transport is assumed. In the simulations that estimate transport by microturbulence, a spatially variable energy-dependent fast-ion diffusion coefficient is employed using the algorithm described below. The NBCD profile and neutron rate are calculated by the TRANSP code, while the FIDA prediction is derived from a post processor [11] that uses the NUBEAM distribution function as input.

In contrast to earlier results in lower temperature plasmas [16], the classical prediction is inconsistent with both the FIDA wavelength spectra and the radial profile (Fig. 1). The spectra in Fig. 1 are from the blueshifted side of the cold D_α line, so ions that approach the lens with higher velocities appear at shorter wavelengths. Data from central channels typically agree well with classical theory at moderate beam power [Fig. 1(a)]; at larger radius, anomalies appear at smaller Doppler shift even at modest beam power

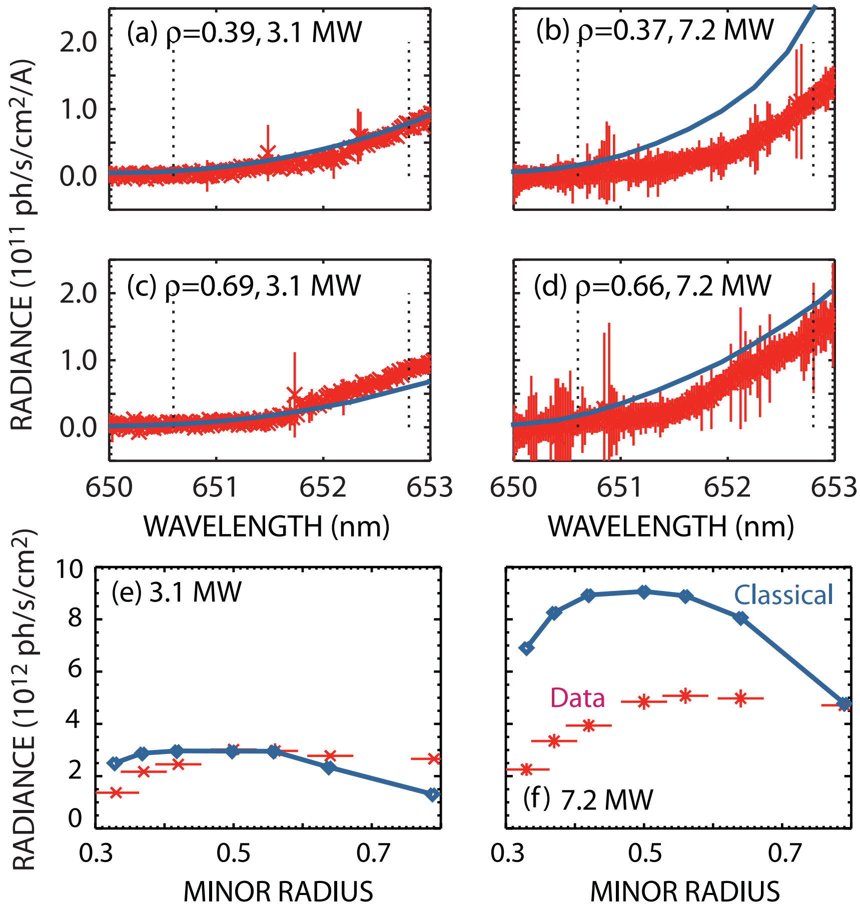

FIG. 1 (color online). (a)–(d) Blueshifted FIDA spectra for two radii and two beam powers. The solid lines are the classical predictions. The dotted vertical lines indicate the spectral band used for the radial profiles. The minor radius ρ is the normalized square root of the toroidal flux. (e), (f) Radial profile of the FIDA radiance at moderate and high beam power.

[Fig. 1(c)]. At higher power, the measured radiance is smaller than predicted for central channels [Fig. 1(b)], while the spectral shape is discrepant at larger radius [Fig. 1(d)]. Figures 1(e) and 1(f) show the radial profiles derived by integrating the spectra over wavelength. A large discrepancy is observed at high power, especially near the axis. Detailed analysis shows that, at moderate power and high fast-ion energy, the spectra are consistent with classical theory at all radii (reduced chi-squared $\tilde{\chi}^2 \lesssim 1$) but inconsistent at low fast-ion energy and large minor radius. At high power, the spectra are inconsistent with classical theory in all energy bands at all radii. Uncertainties in background subtraction generally dominate the experimental uncertainty for FIDA measurements but are small in these discharges with steady conditions that persist for seconds. A sensitivity analysis [9] shows that uncertainties in the classical prediction associated with uncertainties in the plasma parameters are also much smaller than the discrepancies.

Like the FIDA data, profiles of the NBCD are consistent with classical theory at moderate power [10] but, as shown in Fig. 2, disagree with theory at high power. Because the area of the plasma increases with minor radius, the classical prediction in Fig. 2 overestimates the total beam-driven current by 29%.

The discrepancy between classical theory and experiment increases with increasing beam power for three in-

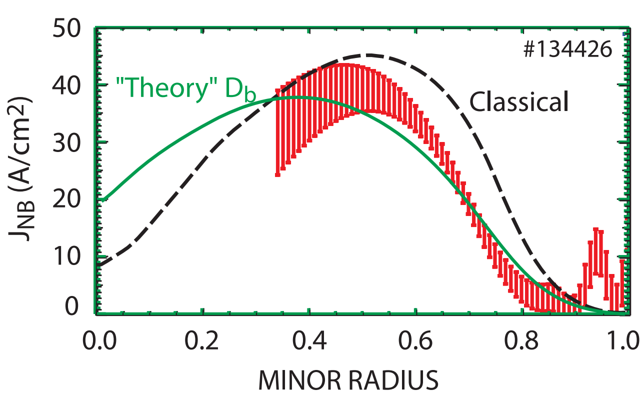

FIG. 2 (color online). Measured beam-driven current (symbols), classical prediction (dashed line), and theory-based prediction (solid line) versus ρ for the 7.2 MW discharge.

dependent measurements: FIDA, NBCD, and the neutrons [Fig. 3(b)]. The underlying reason for the increasing discrepancy is that the temperature increases with beam power [Fig. 3(a)]. Analysis of data from many discharges shows a consistent correlation of the FIDA discrepancy with increasing temperature T_i (also T_e) [9].

The hypothesis that microturbulence is responsible for the discrepancies is consistent with the observed parametric dependencies. (1) The discrepancies increase with increasing temperature because E/T is smaller. (2) The discrepancies are larger at low Doppler shift than at large Doppler shift because E/T is smaller. (3) The discrepancies are more evident at large minor radius because the fluctuations are stronger at larger ρ, as evidenced by the increase of the thermal-ion heat diffusivity χ_i with minor radius (Fig. 4). (4) The discrepancies do not depend strongly on injection angle [9], which is consistent with a mechanism that affects all fast ions and depends relatively weakly on the ratio of trapped-to-passing ions.

Theoretical calculations using a gyro-Landau-fluid model [17] predict that drift waves caused by the ion temperature gradient (ITG) instability are unstable at $\rho = 0.6$ in these discharges. Experimentally, the ion thermal diffusivity χ_i is five times larger than the neoclassical value at this radius, and the beam-emission spectroscopy diagnostic [18] measures large broadband density fluctuations with frequencies of $\lesssim 250$ kHz, consistent with the hypothesis that ITG turbulence is responsible for the fast-ion transport.

To quantitatively estimate the effect of microturbulence on the fast-ion signals, the "anomalous" fast-ion diffusion D_B in NUBEAM is assumed to vary with energy and space as $D_B = c(E/T)D_i$ (Fig. 4). Here, $c(E/T)$ is the functional dependence of D_B on E/T for ITG turbulence shown in Fig. 3 of Ref. [3] and D_i is the thermal-ion diffusivity profile assumed to approximately equal χ_i; also, $T \simeq T_i$ is used. A comparison of experiment with simulations that use this theory-based D_B is shown in Fig. 3(c). For the neutrons and the NBCD, the discrepancy between theory and experiment is eliminated. For FIDA, the predicted spectra and radial profiles still differ from experiment but the discrepancy is reduced. Thus, the expected transport by microturbulence is the correct order of magnitude to explain most of the observations. Future work will attempt to improve the agreement by simulating measured fluctuations with a gyrokinetic code, calculating the effect of the microturbulence on the fast ions, and predicting the resulting fast-ion signals.

In conclusion, most previous measurements of fast-ion transport in the absence of long-wavelength MHD were made in the regime $E/T \gg 10$ [6], where turbulence by microturbulence should be negligible. In the present experiments with $E/T \lesssim 10$, three independent diagnostic techniques indicate that the fast-ion distribution function differs from classical theory. The parametric dependencies on T, E, and radius are qualitatively consistent with theories that predict significant reductions in transport when E/T increases from $\sim 5 \rightarrow 15$. The inferred transport rates are compatible with rough estimates of the expected levels. The lack of appreciable anomalies at large values of E/T confirms that alphas in ITER will not suffer appreciable transport for most of the slowing-down process [19]; however, appreciable transport at lower energies will be important in limiting the accumulation of alpha ash. In current experiments, this transport mechanism cannot be ignored in hot high-performance plasmas with moderate values of E/T. Future work should focus on detailed confirmation and refutation of the various theoretical predictions.

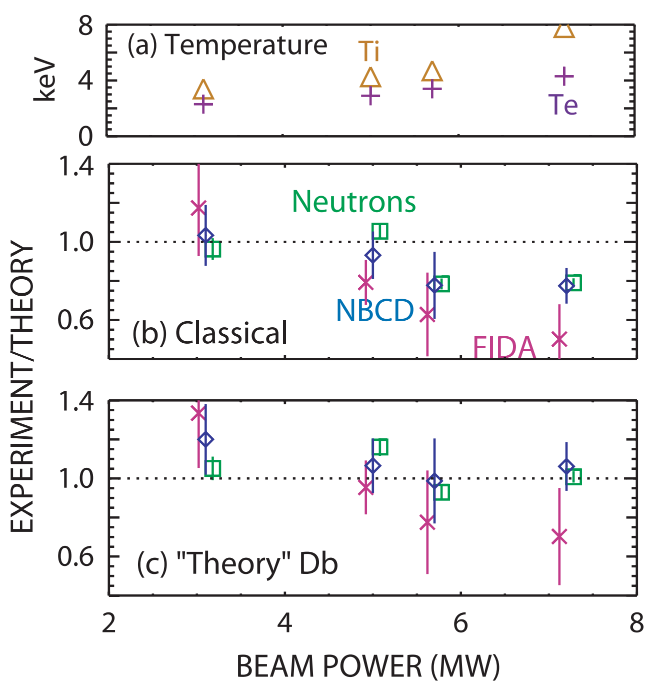

FIG. 3 (color online). (a) Central temperature versus P_B. (b), (c) Measured neutron rate (□), total beam-driven current (◇), and FIDA radiance from $E_\lambda = 20$–60 keV at $\rho \simeq 0.5$ (×) divided by the classical prediction (b) and by the theory-based prediction (c) versus P_B.

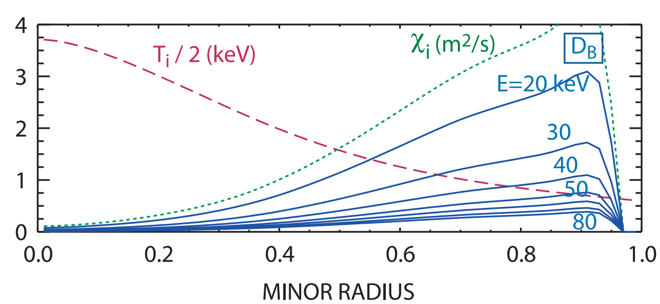

FIG. 4 (color online). T_i (dashed line), χ_i (dotted line), and $D_B(E, \rho)$ (solid line) used by NUBEAM versus ρ for the 7.2 MW discharge.

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