Energetic Ion Transport in Tokamak Plasmas Dominated by Microturbulence, Alfvénic Activity, or Applied Magnetic Perturbations

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The confinement of energetic particles in tokamaks is a fundamental aspect of magnetic confinement fusion since fusion products (i.e., alpha-particles) must transfer their energy to the thermal plasma in order to maintain a burning scenario. This places a great value on the development of energetic ion transport models that can be used to predict the performance of ITER plasmas. Experiments conducted on the DIII-D tokamak [1] use both on-axis and off-axis neutral beam injection (NBI) to investigate the comparative importance of different energetic ion transport mechanisms. These mechanisms span a wide parameter range, including the small scales of microturbulence, the intermediate scales of Alfvénic instabilities, and larger scales of applied magnetic perturbations. It is found that energetic ion transport due to Alfvén eigenmodes (AEs) and applied 3D magnetic perturbations is of greater concern for ITER than that due to microturbulence.

Energetic ion transport due to microturbulence is investigated [2] by varying relevant parameters such as the value of E_b/T_e, with E_b the energetic ion energy and T_e the electron temperature, through the use of electron cyclotron heating and the mixtures of on-axis and off-axis NBI. This transport effect is modeled using numerical [3] and analytic [4] methods to calculate the expected energetic ion diffusivity due to microturbulence across a range of plasmas featuring NBI as the energetic ion source. The use of off-axis NBI deposits beam ions near the normalized toroidal flux surface of $\rho = 0.5$. This mid-radius deposition places the energetic ions in a region of significant microturbulence fluctuation amplitude. In high-performance plasmas that utilize off-

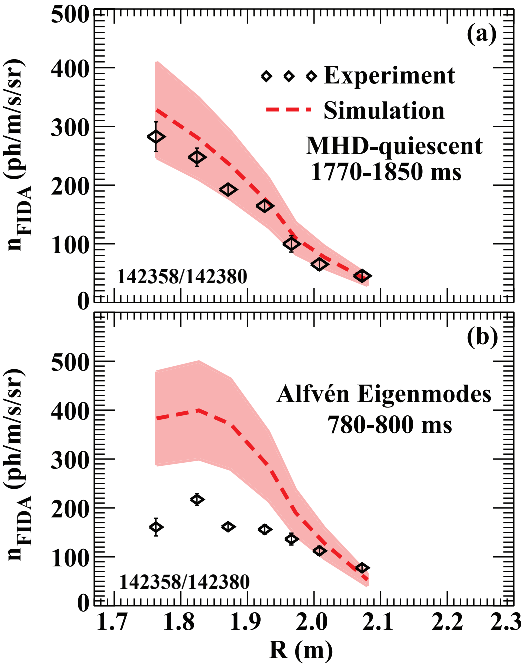

Figure 1: Measured energetic ion density profiles compared with classical transport simulations demonstrate agreement during (a) MHD-quiescent periods dominated by microturbulence, while enhanced transport is observed during (b) periods of strong AE activity.

axis NBI to maintain steady-state scenarios with $q_{min} > 2$, the modeled beam current drive is accurately described by theory without invoking a transport enhancement due to microturbulence [5].

Figure 1 shows a comparison between measured energetic ion profiles and the results from a synthetic diagnostic [6] simulation in which transport is assumed to be entirely classical (i.e., no turbulence-induced diffusion is included). Figure 1(a) presents an MHD-quiescent time period in which no energetic ion-driven modes are observed. During this time, the measured and simulated profiles agree. As shown in Fig. 1(b), however, the experimentally measured profile is considerably flatter than the simulated profile over time periods for which there is noticeable Alfvénic activity. Throughout all of the L-mode plasmas studied, any transport enhancement due to microturbulence is too small to measure.

In plasmas that are strongly unstable to AEs such as the toroidal (TAE) and the reversed-shear (RSAE) AEs, different NBI combinations are used to alter the classically expected gradient of energetic ion beta ($\nabla\beta_f$) [7]. In the plasma core, off-axis NBI reduces $\nabla\beta_f$ and, consequently, the amplitude of AE activity is reduced. To quantify the effect on stability, electron cyclotron emission (ECE) spectra are analyzed in different regions of the plasma. Figure 2(a) shows the magnitude of coherent AE activity for ECE signals near q_{min}. Off-axis NBI reduces the amplitude of core-localized RSAEs an order of magnitude. Data from inside q_{min} show that core TAEs are also strongly stabilized. In contrast, at larger minor radius, the fast-ion gradient is similar for on- and off-axis injection and switching the angle of injection has a weaker effect on the stability of TAEs. These trends are qualitatively consistent with linear stability calculations that use the classically-expected fast-ion profile.

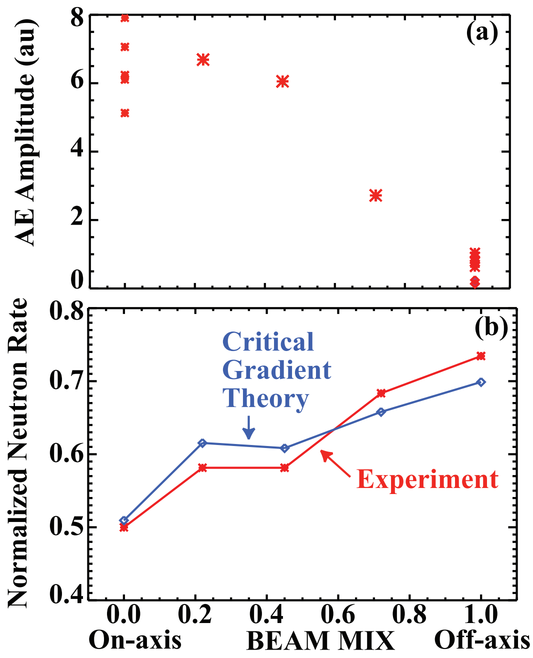

Figure 2: (a) Summed amplitude of coherent AE activity $\sum \delta T_e/T_e$ vs. the fraction of off-axis beam power for channels near q_{min} ($R \simeq$ 194-202 cm). The "beam mix" is the ratio of off-axis to total power. (b) Measured (*) and predicted (◇) neutron rate vs. beam mix. The measurements are time-averages that are normalized by the classically expected rate. The theoretical points are also time-averages and have been divided by a factor of 1.32 to facilitate comparison.

Nevertheless, FIDA measurements show that the actual fast-ion profile is insensitive to the angle of beam injection. Apparently, in this regime with many small-amplitude AEs, the fast-ion transport is stiff, causing the profile to "clamp" in proximity to the marginally stable profile. A comparison of the measured neutron rate with the predictions of an infinitely-stiff transport model [8] is shown in Fig. 2(b). Although the details of the profiles differ from measured profiles, the volume-averaged neutron prediction is in excellent agreement with experiment, suggesting that a "critical gradient" model can describe fast-ion transport in this regime.

Enhanced losses of energetic ions have also been observed in plasmas with applied magnetic perturbations [9]. An example of this increased loss is shown in Fig. 3, where measured energetic ion losses [10] are seen to oscillate in-phase with the current waveform during application of a rotating $n = 2$ perturbation with peak $\delta B/B \approx 10^{-3}$ in the plasma. The observed prompt loss modulation amplitude and phase with respect to the I-coil current is a complicated combination of several factors including the toroidally localized beam deposition profile, FILD location, $n = 2$ field structure, and orbit topologies determined by the injection geometry and magnetic equilibrium. The measured energies, pitch angles, and rapid decay of the losses after beam turn-off indicate that these ions result from changes in the NBI prompt-loss. Beam deposition and full orbit modeling using M3D-C1 [11] calculations of the perturbed kinetic profiles and fields show modulation of prompt-loss as observed. Modeling indicates that two mechanisms contribute to the increased losses: magnetic perturbations inside the last closed flux surface that affect the number of prompt-loss ions, and changes in neutral beam deposition resulting from density perturbations. Of these two, the effect of the magnetic field perturbation plays the greater role in modulating prompt-loss.

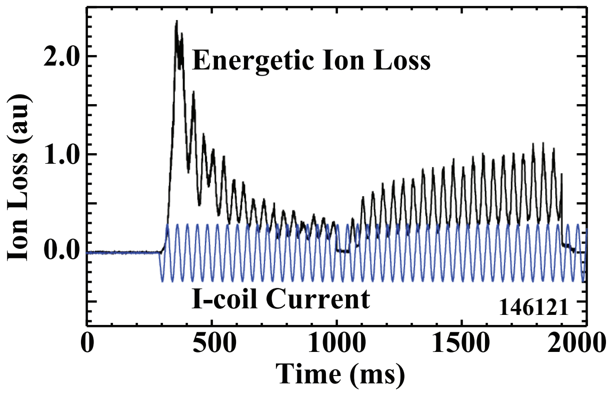

Figure 3: Energetic ion losses are enhanced by applied magnetic perturbations and oscillate in-phase with the coil current.

Energetic ion transport in the presence of various perturbations and instabilities is investigated with a diagnostic suite in DIII-D neutral beam heated plasmas. Together, these studies suggest that energetic ion transport in ITER will be dominated by MHD over microturbulence, and that NBI prompt-losses may be enhanced by the application of magnetic perturbations, causing increased heat load to the first wall.

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