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[1]University of California-Irvine, Irvine, California
[2]Max-Planck-Institut für Plasmaphysik, Garching D-85748, Germany
[3]University of Wisconsin-Madison, Madison, Wisconsin
[4]Oak Ridge National Laboratory, Oak Ridge, Tennessee
[5]Princeton Plasma Physics Laboratory, Princeton, New Jersey
[6]University of California-Los Angeles, Los Angeles, California
[7]University of California-San Diego, San Diego, California

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Utilizing an array of new diagnostics and simulation/modeling techniques, recent DIII-D experiments have elucidated a variety of energetic ion transport behaviors in the presence of instabilities ranging from large-scale sawteeth to fine spatial scale microturbulence. Important new insights include: microturbulence can significantly contribute to the removal of alpha ash while having little effect on fusion alphas; sawteeth such as those of the ITER baseline scenario cause major redistribution of the energetic ion population; and high levels of transport induced by Alfvén eigenmodes are due to the integrated effect of a large number of simultaneous modes. Developing validated predictive models for the nonlinear interaction of energetic particles with plasma instabilities is vital for extrapolation to ITER and future devices since adequate confinement of the 3.5 MeV fusion born alpha particles, such that their energy is deposited to the background plasma, is required in order to maintain a burning plasma state. Further, once these particles have deposited their energy, the challenge is to remove this alpha ash before it begins to absorb energy intended for the deuterium/tritium fuel.

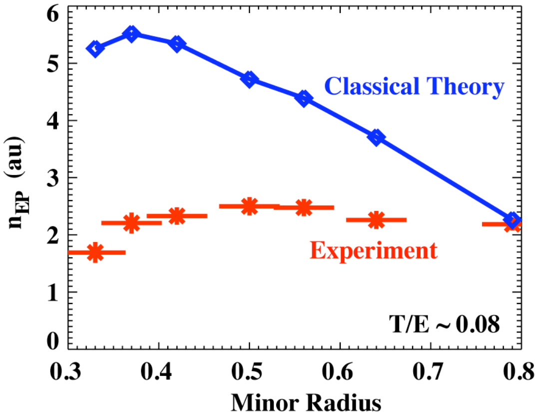

Fig. 1. Deviation of energetic ion profile from classical predictions due to microturbulence induced transport in off-axis beam heated discharges.

Energetic ions are better confined than thermal particles, in part, because the large orbits of energetic ions allow them to average over microturbulence such as the ion temperature gradient (ITG) mode and trapped electron mode (TEM); however, experiments on the DIII-D tokamak [1,2] with neutral beam injection and MHD quiescent plasmas, indicate differences between the measured energetic ion confinement and the predictions of classical (i.e., collision dominated) theory. Figure 1 shows the radial profile of energetic ion density as determined from radiance measurements using a fast ion D_α (FIDA) system. The experimental profile (red, asterisks) shows a significant depletion of core energetic ion density compared to the expectation from classical theory (blue, diamonds). This result agrees with recent theoretical and simulation work showing [3-5] energetic particles with beam energy in DIII-D are susceptible to microturbulence-induced transport. The transport enhancement due to microturbulence for beam ions is theoretically expected to scale as T/E, where T is the plasma temperature and E is the energy of the energetic ions. The consequence for ITER operation is that fusion alphas ($T/E << 1$) should experience little to no transport enhancement and that alpha ash ($T/E \sim 1$) will be strongly affected and therefore more easily extracted from the plasma. Microturbulence in the form of ITG and TEM is most likely to interact with energetic ions due to their comparatively long wavelengths. These turbulent modes are studied experimentally using beam emission spectroscopy (BES) and Doppler backscattering (DBS) to quantify density fluctuation activity in the low through intermediate-k range that corresponds to these modes. The difference between experimental observations and classical theory is most pronounced in cases featuring higher plasma temperature and lower energetic ion energy. These trends support the theoretical scaling with T/E.

In large-scale simulations that are the first of their kind, the gyrokinetic toroidal code [6] (GTC) is used to simulate both the microturbulence and the energetic ion response taking experimentally measured plasma profiles as input parameters. Values for the energetic ion diffusivity obtained from GTC simulations are provided to TRANSP, which then calculates the resulting energetic ion profiles for comparison with experimental measurements, where agreement with many of the major trends was found. Additional modeling using TGYRO/TGLF

[7,8] with measured plasma profiles reproduces the theoretically expected trend of increased energetic ion transport for larger values of *T/E*.

Energetic ion loss is observed during sawtooth crashes using the newly commissioned fast-ion loss detector (FILD) at DIII-D. The FILD is a scintillator-based loss detector that provides large bandwidth information on the gyroradius and pitch angle ($v_{\|}/v$) of ions that reach its position near the outer wall. As shown in Fig. 2, bursts of loss are observed during large amplitude sawtooth crashes. Imaging of the pitch and energy resolving FILD scintillator shows that these losses occur at low pitch angles across a range of energies. Supporting these loss measurements, dramatic 2D images of fast ion D_α emission show large redistribution of core fast ion profiles during sawtooth crashes. Furthermore, various plasma shapes, which exhibit different crash mechanisms, were investigated and FIDA measurements of fast ion transport support theoretical predictions which indicate a correlation between the time duration of the reconnection event and the impact on the fast ion profile.

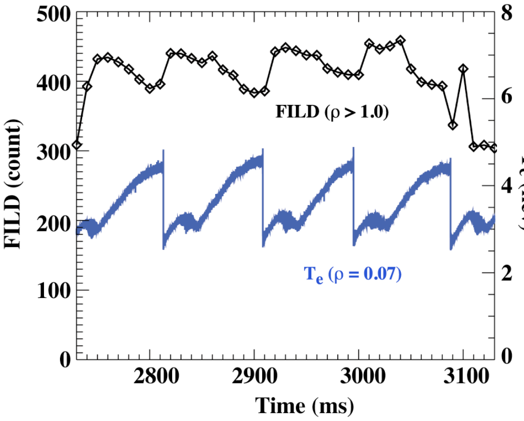

Fig. 2. Ion losses measured by the FILD at the outer wall shortly after sawtooth crash events are observed in the core electron temperature.

In reversed shear plasmas with many small amplitude ($\delta B/B \sim 2\text{x}10^{-4}$) toroidal and reversed-shear Alfvén eigenmodes, the central fast-ion profile flattens. Initial calculations failed to reproduce the experimental results [9] but new calculations that utilize hundreds of harmonics and include the inductive electric field predict diffusive fast-ion transport at the observed level [10]. New FIDA and FILD measurements under these conditions will be reported.

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