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FAST ION PHYSICS ENABLED BY OFF-AXIS NEUTRAL BEAM INJECTION

by
W.W. HEIDBRINK and the DIII-D TEAM

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Fast Ion Physics Enabled by Off-Axis Neutral Beam Injection EX-W

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Off-axis injection of neutral beams into DIII-D has provided new insights into fast-ion instabilities that may impact alpha-particle and neutral-beam confinement in ITER. The most dramatic effect of off-axis injection is stabilization of reversed shear Alfvén eigenmodes (RSAE) (Fig. 1), which are fast-ion driven instabilities that are localized near the minimum of the q profile (at $\rho_{q_{min}}$). The enhanced stability for off-axis injection is attributed to flattening of the fast-ion gradient $\nabla\beta_f$ near $\rho_{q_{min}}$ that drives the modes unstable. Since off-axis beam deposition peaks near $\rho_{q_{min}}$, switching between on-axis sources that inject at the midplane and off-axis sources that aim below the midplane has a large local effect on $\nabla\beta_f$. In contrast, at larger minor radius, the fast-ion gradient is similar for on- and off-axis injection. As a result, switching the angle of injection has little effect on the stability of toroidal Alfvén eigenmodes (TAE) that appear in the outer portion of the plasma.

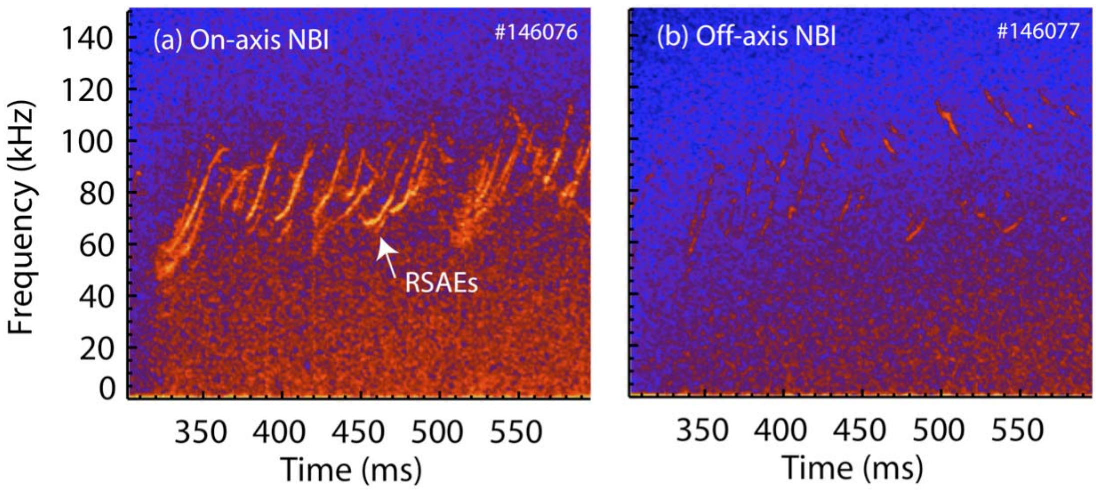

Fig. 1. Cross-power of two ECE channels located near $\rho_{q_{min}}$. RSAE activity is (a) strong during on-axis injection but (b) virtually absent during off-axis injection.

To validate off-axis beam performance, individual sources inject sequentially into low-power plasmas that are optimized for accurate fast-ion D-alpha (FIDA), neutral-particle analyzer (NPA), and neutron measurements. As expected, the fast-ion profile is broader with off-axis injection than with on-axis injection. The number of trapped fast ions in the core depends sensitively on the pitch of the magnetic field lines. Separate control of $\nabla\beta_f$ and of the trapped/passing fraction is a powerful tool in fast-ion instability studies.

Two-dimensional measurements of RSAE mode structure with an electron cyclotron emission imaging (ECE-I) diagnostic show that the phase of the eigenfunction varies with radius [1]. This phase variation is not present in the ideal MHD model but does appear in gyrokinetic and gyrofluid calculations. The phase variation was originally attributed to symmetry breaking associated with the fast-ion gradient [1] but the recent comparisons of on- and off-axis injection show that the phase variation is insensitive to $\nabla\beta_f$.

Plasmas with weakly reversed q profiles are unstable to beta-induced Alfvén-acoustic eigenmodes (BAAE). Like RSAEs and TAEs, these lower-frequency modes cause transport that flattens the fast-ion profile. Thus, they also are of concern for ITER. Measurements of the eigenfunction show that, like the RSAE, the BAAE is dominated by a single poloidal harmonic (Fig. 2). Surprisingly, switching between on- and off-axis injection has little effect on mode stability, although it does alter the mode frequency. Theoretically, one might anticipate large ion Landau damping of these low frequency modes but, in another surprise, BAAEs are unstable even when $T_i \gtrsim T_e$.

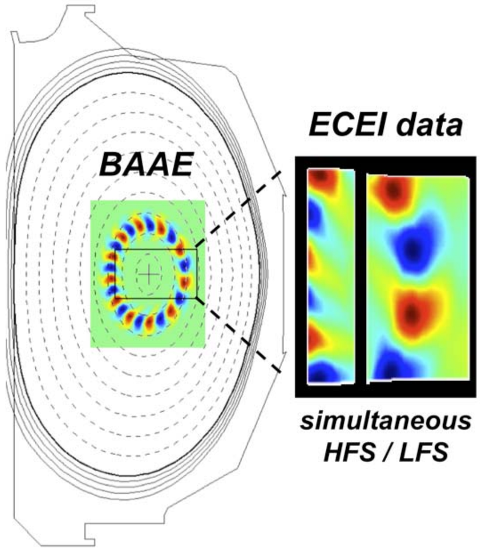

Fig. 2. ECE-I measurement of the mode structure of a 15.6 kHz BAAE. Imaging arrays on both the high-field and low-field side demonstrate that, like the RSAE, the BAAE is essentially a cylindrical mode

Off-axis fishbones are modes that are driven unstable by resonance with the precessional motion of trapped fast ions [2]. The fishbones expel trapped ions in a “beacon” with a definite phase relationship relative to the mode. Seven types of loss detectors measure the beacon. The non-ambipolar fast-ion losses cause a sudden change in toroidal rotation frequency across the entire plasma. Substitution of off-axis beams for on-axis beams varies the $\nabla\beta_f$ profile and trapped/passing fraction to study the effect on stability.

Another concern for ITER is the possibility that microturbulence will cause appreciable transport of alphas and neutral-beam ions. Previous FIDA measurements showed evidence of anomalous beam-ion transport of off-axis beams in small, vertically-shifted, DIII-D plasmas [3]. The new off-axis beam capability has enabled new experiments in full-size plasmas with full radial coverage and the entire suite of microturbulence diagnostics. Preliminary analysis suggests that departures from classical confinement are observed in some H-mode plasmas. Another study shows that both ion-temperature gradient (ITG) and trapped electron mode (TEM) turbulence can impact fast-ion confinement.

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