Fast Ion Induced Shearing of 2D Alfvén Eigenmodes Measured by Electron Cyclotron Emission Imaging

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Abstract. Two-dimensional images of electron temperature perturbations are obtained with Electron Cyclotron Emission Imaging (ECEI) on the DIII-D tokamak and compared to Alfvén eigenmode structures obtained by numerical modeling using both ideal MHD and hybrid MHD-gyrofluid codes. While many features of the observations are found to be in excellent agreement with simulations using an ideal MHD code (NOVA), other characteristics distinctly reveal the influence of fast ions on the mode structures. These features are found to be well described by the non-perturbative hybrid MHD-gyrofluid model TAEFL.

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A host of fast ion driven instabilities may be excited by fusion-born alpha particles [1,2] in future devices such as ITER [3], as well as by confined fast ions created during neutral beam injection and RF heating in contemporary machines [1,4]. These instabilities have been shown to affect the energetic particle population leading to enhanced transport, losses, and modification of the pressure and current profiles [1]. These issues are critical not only to the performance of future burning plasma experiments, but also to the survivability of first wall components [3–5]. As a result, the detailed validation of models for these instabilities remains an important issue in tokamak physics. Recent developments in Electron Cyclotron Emission Imaging (ECEI) diagnostics have demonstrated a capability to identify and image a variety of these modes [6]. This letter presents the first unambiguous measurements of theoretically predicted shearing due to fast ion effects on 2D Alfvén eigenmode structures. Modeling in the non-perturbative code TAEFL [7,8] suggests the inclusion of fast ion dynamics, particularly fast ion diamagnetic shear, is prerequisite for adequately predicting the mode structure, growth rate, and nonlinear evolution, all of which are important ingredients in modeling fast-ion interactions and losses.

The early injection of tangential neutral beam power during the current ramp phase of plasma discharges on DIII-D slows the penetration of the inductively driven current and generates an off-axis minimum in the q profile, resulting in the excitation of reversed shear induced Alfvén eigenmodes (RSAEs) [9] in addition to toroidicity induced modes (TAEs). In the experiment described in this letter, 7.1 MW of deuterium beam power at a full energy of 80 keV is injected in the direction of plasma current. The ECEI diagnostic system, described in Refs. [10–14], is configured with a viewing window encompassing the location of the minimum in the safety factor ($q_{\min}$). The relevant portion of the diagnostic coverage ranges from a major radius of 1.93 m to 2.08 m (normalized minor radius of 0.325 to 0.62) with a total vertical coverage of 0.56 m. A single detector array is composed of 160 channels, 8 radial and 20 vertical, each with a resolution of 0.01 m radial by 0.025 m vertical. A composite spectrum of the relevant modes in this view is given in Fig. 1. The modes are observed in the lab frame to oscillate with a frequency $f = f_{MHD} + n f_{rot}$, where n and f_{rot} are the toroidal mode number and rotation frequency of the plasma, respectively. The MHD frequency, f_{MHD}, is approximated for TAEs by $f_{TAE} \approx V_A / 4\pi q R$, where V_A is the Alfvén velocity and R is the tokamak major radius. This frequency varies slowly as the plasma current is ramped up, whereas RSAEs chirp rapidly upward in frequency with a small reduction in $q_{\min}$. The corresponding approximate expression applicable to an RSAE, characterized by a single dominant poloidal mode number m, is given by $f_{RSAE} \approx [(m - n q_{\min}) V_A]/(2\pi q_{\min})$.

The multitude of modes resolved allows for the application of a technique known as MHD (or Alfvén eigenmode) spectroscopy [15,16], where the value of $q_{\min}$ is obtained by fitting a simple model to the observed power spectra and the appearance of RSAEs, which correspond to temporal crossings of rational q values. An RSAE is excited initially at the location of $q_{\min}$, and so the peak of this mode also provides the radial location of the q-profile minimum. Parameters obtained in this way, along with data from the motional Stark effect (MSE) diagnostic and thermal pressure data, are used as constraints to form an optimized EFIT [17] magnetic equilibrium reconstruction. This equilibrium, along with measured profiles of density, Z_{eff}, and temperature, serve as inputs to both linear eigenmode solvers discussed in this letter.

The ideal MHD code NOVA [18,19] is used to simulate 2D structures of the shear Alfvén eigenmodes which may be excited in the plasma. For low frequency modes, compressibility does not affect the electron temperature perturbation [20] and so the radial displacement of a magnetic field line, ξ_r, may be converted to fluctuation in electron temperature, T_e, for direct comparison with ECEI data through the relation, $\delta T_e = -\xi_r \cdot \partial T_e / \partial r$. The 2D nature of the diagnostic technique allows for the identification of each poloidal harmonic and its corresponding amplitude, making ECEI a powerful tool for the validation of eigenmode solving codes.

Detailed 2D structure of three separate RSAEs measured by ECEI and compared to NOVA simulations are shown in Fig. 2. The modes shown in Fig. 2(a) and (c) are n = 3 and n = 2 RSAEs with single maxima in their radial amplitude eigenfunction. Figure 2(b) shows a second n = 3 RSAE, characterized by a node in its radial eigenmode envelope and downshifted in frequency by approximately 5 kHz from the corresponding fundamental RSAE. It is identified as the first radial harmonic [9]. The node position is constrained to a flux surface and therefore reveals exactly the shape of the plasma flux surface. This provides a potentially powerful constraint for equilibrium reconstructions.

The electron temperature fluctuation amplitude of these modes averages 0.5%, or approximately 2.5 eV. This is significantly less than the statistical noise limit of the diagnostic, which is 2.4% for the video bandwidth setting used in this experiment (200 kHz). Therefore, singular value decomposition (SVD) [21] and Fourier decomposition are applied to the data in order to remove uncorrelated noise and isolate the oscillatory behavior of interest [6]. Figure 2 shows the real part of selected Fourier components, $|A|\cos\alpha$, where A is the amplitude of the fluctuation and α is the phase.

The distribution of the mode in both the radial and poloidal angle coordinates agree in all three cases. The predicted mode frequencies are also in good agreement, deviating by approximately 4-8%, which is consistent with previously reported comparisons between NOVA and experiments on DIII-D [22].

Not captured by NOVA are important features which represent the influence of the fast ions on RSAE and TAE mode structure, an interaction excluded by the ideal MHD approximation and perturbative methods. Therefore, the non-perturbative hybrid MHD-gyrofluid model TAEFL is used to reproduce these effects [7,8]. This code employs a reduced MHD model for the background plasma, while the energetic particle population is represented by a gyrofluid model with Landau closure. The evolution of scalar fields in this model is solved by a 3D initial value code which includes $E \times B$ and fast ion diamagnetic flows. Alfvén eigenmodes are destabilized by inverse Landau damping and mode structures are allowed to evolve freely to a limit of saturation and even decorrelation [23]. The predicted influence of the fast ion population on mode structure is illustrated in Fig. 3, where a solution obtained using the ideal MHD approximation is compared to that which results from TAEFL.

Figure 4 compares experimentally obtained mode structures with those destabilized in TAEFL at corresponding toroidal mode number, n. Excellent agreement is obtained with the radial localization and extent of the mode observed with ECEI. Each RSAE structure is dominated by a single poloidal mode number, m, which is positively identified in each case. The most notable feature of the modes shown is a distinct poloidal shearing or spiraling that is not captured by ideal MHD models. This mode shear occurs such that regions at greater minor radius (observed on the outboard midplane) are shifted in the ion diamagnetic drift direction. For modes localized near $q_{\min}$, the phenomenon is characterized by bean-shaped oscillation maxima and minima, as the degree of shear is not observed to be constant with radius. Global TAEs and coupled modes spanning the entire viewing region often exhibit an extended spiral mode structure. Careful examination of the phase structure of the modes shown in Fig. 2 reveals that they also exhibit this characteristic. The observation of this shearing through localized, 2D measurement with ECEI unambiguously identifies the origin of a radial phase ramp observed in 1D ECE radiometer measurements [9] and eliminates the possibility that this phase variation is the result of radial propagation of the mode.

The inclusion of plasma compressibility results in an upward shift of the Alfvén continuum at $q_{\min}$ [24]. Therefore, the omission of this effect in the TAEFL model contributes to a discrepancy in mode frequency on the order of the geodesic acoustic frequency [25,26]. However, this limitation does not restrict the ability of the model to produce mode shearing consistent with experimental observations. While both $E \times B$ and diamagnetic flows are included in the model, tests with and without $E \times B$ flow indicate that it has little effect on mode structure for the radial electric fields characteristic of the discharges discussed here. In contrast, mode structure is found to be sensitive to diamagnetic shear imposed on the fast ion population, highlighting the importance of non-perturbative effects. A manipulation of the fast ion pressure profile, and therefore the fast ion diamagnetic shear, results in a modification of the Alfvén eigenmode shear or mode spiraling. This is a clear demonstration of the influence of the fast ion population in perturbing the mode structure. Because these effects are reproduced while retaining the generality of an isotropic fast ion velocity distribution, their consequences should be considered in devices such as ITER, where beam ions no longer dominate in destabilization.

In summary, it has been demonstrated that fast ion dynamics produce measurable modifications to the 2D structure of Alfvén eigenmodes derived from electron temperature perturbations obtained with ECEI on the DIII-D tokamak. The most prominent of these, mode shearing resulting in a radial spiral mode structure, has been predicted by non-perturbative modeling. Quantifying both the magnitude and the distribution of this shear may yet prove a useful method of diagnosing fast ion pressure profiles. Further, modifications to Alfvén eigenmode structures, such as changes in radial correlation lengths and relative phasing of the mode, are expected to have consequences on linear growth rates, nonlinear dynamics, fast ion losses, and transport. These effects have yet to be evaluated through comparative studies utilizing orbit following codes and are therefore topics that warrant further investigation.

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Figure Captions

FIG. 1. (COLOR) A composite spectrogram shows the many RSAEs and TAEs excited during the current ramp phase of discharge #14211 and captured by the ECEI diagnostic. Many RSAEs, or Alfvén cascades, are excited simultaneously at rational crossings of $q_{\min}$. The vertical dashed lines identify the passing of $q_{\min} = 4$ at $t \sim 525$ ms and $q_{\min} = 3$ at $t \sim 800$ ms.

FIG. 2. (Color On-line ONLY) Eigenmode structures for three RSAEs excited near $t = 550$ ms are captured with ECEI and compared to simulated mode structures obtained with NOVA. The excitation frequencies and simulation times from NOVA are given in the figure and found to be in good agreement with those of the corresponding modes observed experimentally, which were (a) $f = 70.8$ kHz, $t = 551.1$ ms, (b) $f = 67.3$ kHz, $t = 554.2$ ms, and (c) $f = 73.2$ kHz, $t = 570.6$ ms. The color bar given is applicable to the measured data from ECEI, while simulated modes are plotted on a normalized scale. The modes in (a) and (c) show a "fundamental" radial mode structure with a single maximum in the radial mode envelope. The mode shown in (b) exhibits a radial null in the fluctuation amplitude and is identified as the first radial harmonic of the $n = 3$ mode shown in (a).

FIG. 3. (COLOR) Simulations using TAEFL illustrate that mode structures are strongly influenced by the fast ion population. In (a), a structure with no shearing is obtained by retaining only the conventional ideal MHD symmetry. Non-perturbative coupling to the experimentally measured fast ion pressure profile results in the $n = 4$ RSAE predicted at 44.6 kHz by TAEFL and shown in (b). By systematically varying the fast ion density and, correspondingly, the eigenmode drive, the zero growth rate frequency (ideal MHD frequency) is estimated to be 41.6 kHz.

FIG. 4. (COLOR) Imaging of RSAEs near $t = 725$ ms reveals shearing of the Alfvén eigenmode structure which cannot be described by the ideal MHD approximation. In the (a) $n = 3$ and (b) $n = 4$ modes shown, the fluctuation phase reveals an outward spiraling, or poloidal shearing, of the mode in the ion diamagnetic drift direction. This behavior is well represented in the non-perturbative code TAEFL, where the effect of fast ion dynamics is included in the 2D eigenmode structure. A discrepancy in mode frequency arises from the omission of compressibility in the simulation model and is found to be consistent with the geodesic acoustic shift of the Alfvén continuum.

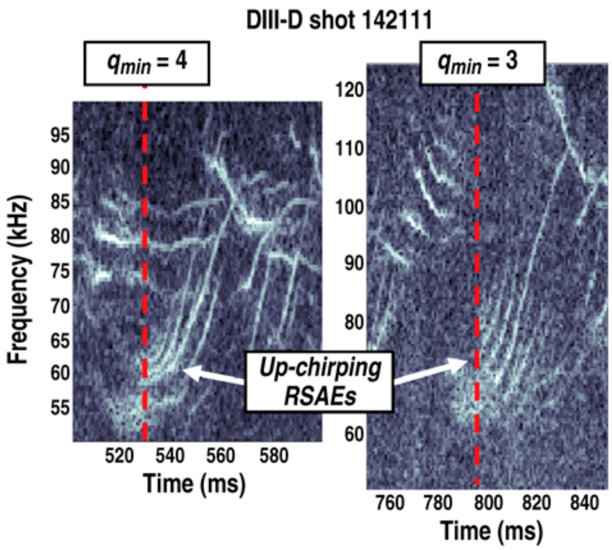

Fig. 1, B.J. Tobias (COLOR)

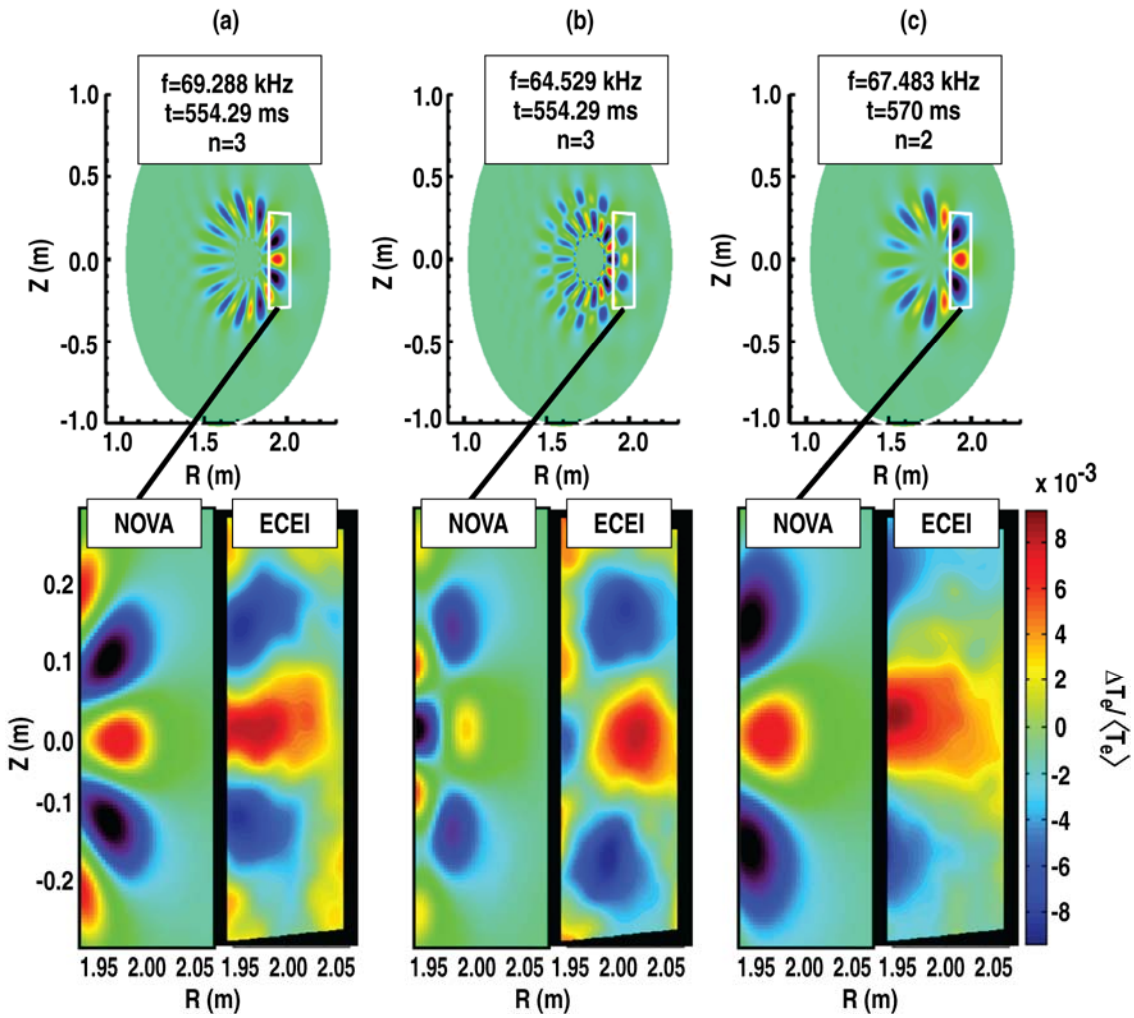

Fig. 2, B.J. Tobias (Color On-Line ONLY)

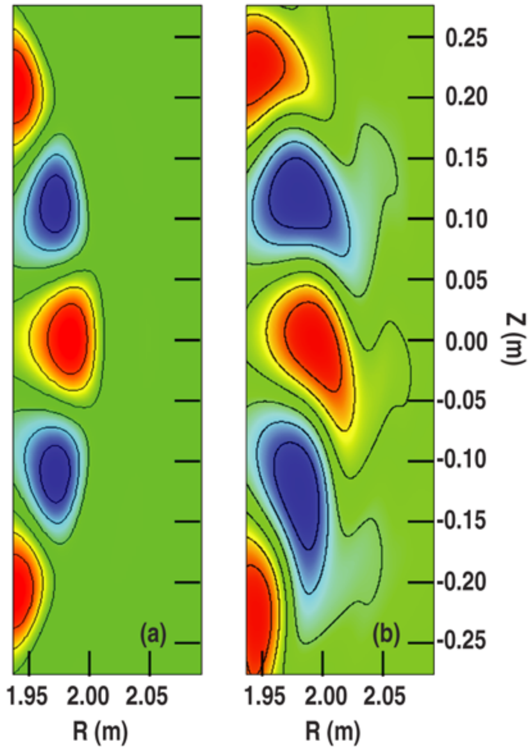

Fig. 3, B.J. Tobias (COLOR)

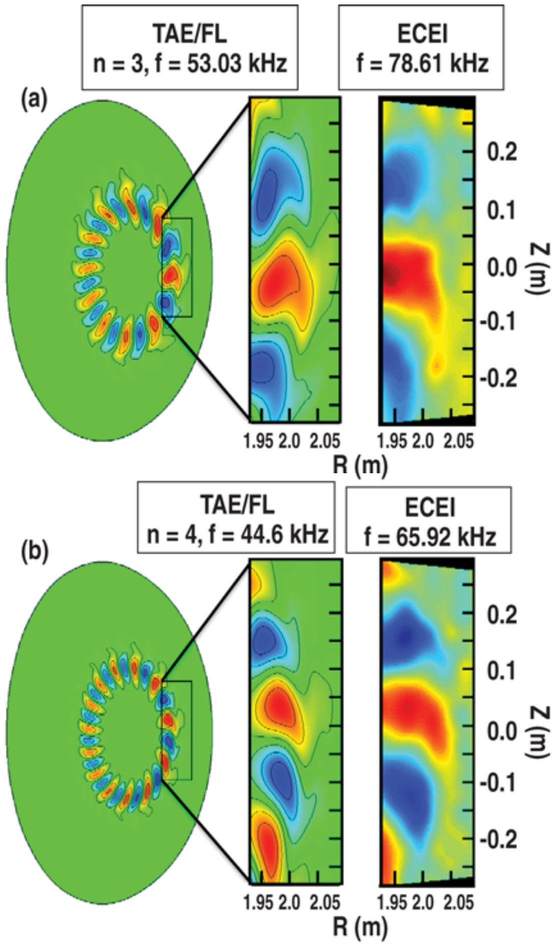

Fig. 4, B.J. Tobias (COLOR)