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BEAM ION LOSS DUE TO FAST FREQUENCY CHIRPING INSTABSILITIES IN DIII-D

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This is a preprint of a paper to be presented at the Forty-First European Physical Society Conf. on Plasma Physics, June 23–27, 2014 in Berlin, Germany and to be published in the *Proceedings.*

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Beam Ion Losses Due to Fast Frequency Chirping Instabilities in DIII-D

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Fast frequency-chirping instabilities in the Alfvén eigenmode (AE) frequency range are observed to generate beam ion losses in DIII-D [1] plasmas with little to no other coherent loss flux. The appearance of beam ion losses suggests that the chirping modes warrant improved understanding as a potential energetic ion loss mechanism in ITER. Furthermore, predictive modeling of plasma performance in ITER and future reactors is improved by the inclusion of the fundamental effects leading to nonlinear mode saturation and evolution.

These fast frequency chirping AEs are produced across a select range of DIII-D parameter space. The shots begin with typical DIII-D AE spectral behavior featuring (slow) frequency changes determined by plasma equilibrium, density, and q-profile evolution. Example time evolution from a single-null plasma shape in shot 152828 is shown in Fig. 1. Fast frequency chirping events appear strongly beginning at $t \approx 955$ ms as indicated by the dashed green vertical line. The two dashed blue vertical lines represent the times (940 and 970 ms) for which simulations of the modes are produced with the Landau-fluid code TAEFL [2].

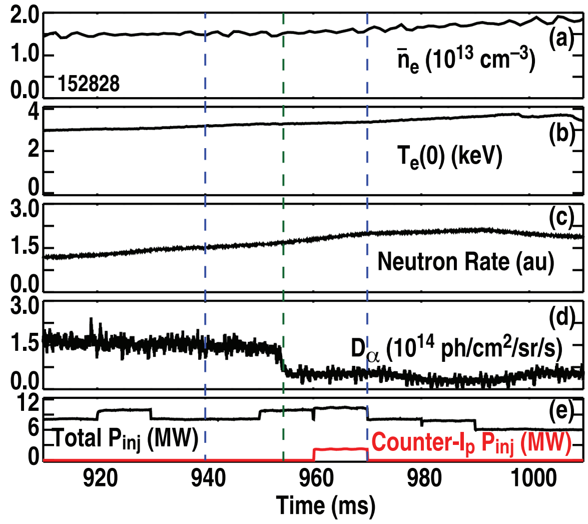

Figure 1: Time series data from shot 152828 including (a) line-averaged density, (b) central electron temperature, (c) neutron rate, (d) D_α emission, and (e) injected neutral beam power.

Figure 2 illustrates the changes in AE behavior throughout shot 152828. Density fluctuations are shown in Fig. 2(a). Frequency chirping events become evident after 955 ms and appear as the downward sweeping bursts. These events occur within 1-2 ms and this is much faster than the tens of milliseconds over which the equilibrium may change. TAEFL calculations of the mode structure before and after $t = 955$ ms is shown in Fig. 2(b). The onset of chirping coincides with a wider radial mode structure. TAEFL reproduces the observed mode frequency ($f \approx 60$ kHz) for the case of a toroidal Alfvén eigenmode with toroidal mode number of $n = 1$.

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Coherent fast ion losses are observed within a subset of the shots that exhibit chirping AEs. While there are no definitive observations of fast ion losses in shot 152828, the widened mode structure coinciding with the chirping behavior is conceptually interesting because it implies that the modes are more capable of interacting with fast ions near loss boundaries that occur at larger radii. An example of fast ion losses from another chirping shot is given in Fig. 3 for shot 152818. Figure 3(a) is a spectrogram of losses as measured by a fast ion loss detector (FILD) located on the outer midplane. The data for this figure are from the fast-sampled photomultiplier of the FILD, while the three vertical lines overlaid on the plot indicate the camera acquisitions that are used to determine these losses occur for ions of $E \approx 81.1$ keV and $v_{||}/v = 0.6$, where $v_{||}$ is the ion velocity along the background magnetic field and v is the total ion velocity. Two spikes in power at all frequencies represent the turn-on (960 ms) and turn-off (970 ms) of a counter-I_p neutral beam that initializes the detection of lost ions. The loss spectrogram compares well with that of the magnetics shown in Fig. 3(b). Magnetics measurements indicate that the loss frequencies correspond to $n = 2$ and 3 modes in this shot. The loss spectrum also features higher frequencies that appear to be harmonics of the $n = 2$ and $n = 3$ modes, e.g., the $f = 105$ kHz feature at $t = 961$ ms. As these harmonics do not appear in the magnetics spectrogram, it is possible that this represents a single-pass AE-ion interaction as recently observed in other DIII-D experiments [3].

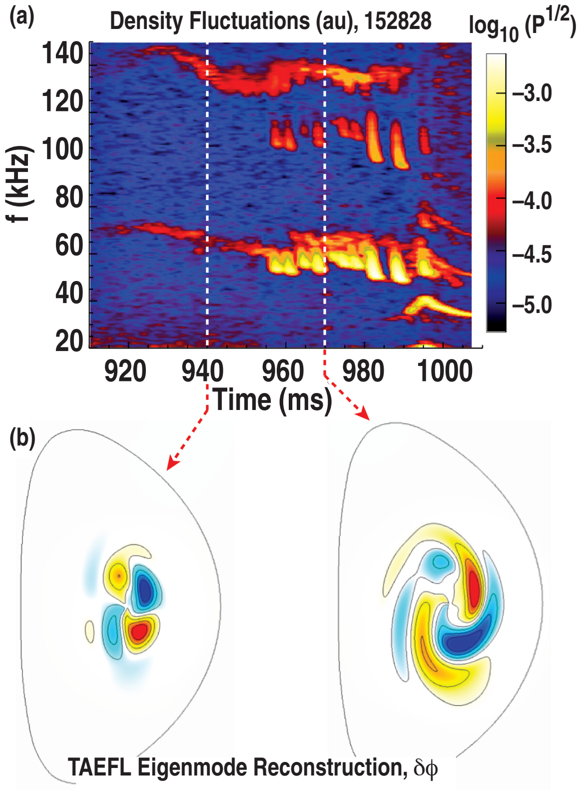

Figure 2: (a) Density fluctuations indicating the presence of strongly frequency chirping modes for $t > 955$ ms. (b) TAEFL calculations of the eigenmode structure at $t = 940$ ms and $t = 970$ ms. The last closed flux surface is shown for perspective (the minor radius is $a = 60$ cm).

Direct measurements of the chirping AEs in shot 152818 indicate that the eigenmodes extend beyond mid-radius. These results are shown in Fig. 4 at $t = 960$ ms just as the first coherent losses are observed. Figure 4(a) is a contour of fluctuation amplitude spectra for density obtained from a beam emission spectroscopy (BES) diagnostic as a function of radial position. In this contour the dark band occurring near $f = 60$ kHz and at $\rho > 0.35$ (ρ is the normalized square-root of the toroidal flux) represents the mode for which coherent losses are observed. Radial profiles of the fluctuations at this frequency are shown in Fig. 4(b) for both the density fluctuations of BES and the electron temperature fluctuations as measured by the electron cyclotron emission (ECE) system. The temperature fluctuation profile confirms the radially extended nature of the AE during this time.

The measured radial extent of the mode is combined with the lost ion information in Fig. 5. The plasma equilibrium at $t = 960$ ms is plotted with the radial region of $0.4 \leq \rho \leq 0.6$ highlighted in orange as a representation of the approximate radial extent (or its measured minimum outer extent) of the chirping AE that produced the measured losses. The loss orbit is traced backward from the position of the FILD near the outer midplane ($\times$-symbol) through most of a poloidal orbit. This orbit is found to be radially adjacent to the AE. As the losses are measured following the beginning of counter-I_p beam injection [see Fig. 3(a)] we conclude that the loss process involves counter-I_p passing ions that are placed on trapped orbits (that connect to the outer wall) through the radial transport induced by the chirping mode. It is also interesting to note that the losses corresponding to the $n = 3$ mode at $f = 70$ kHz are observed even after the counter-I_p beam turns off at 970 ms. This supports the assessment that counter-passing orbits (i.e., confined orbits) are the original source of the eventual losses. Contributing further to the intrigue of this case, however, is that the apparent harmonics of the $n = 3$ loss that are observed near $f = 140$ kHz are only observed during the period of counter-I_p beam injection. An explanation for this situation is that the beam prompt-losses are

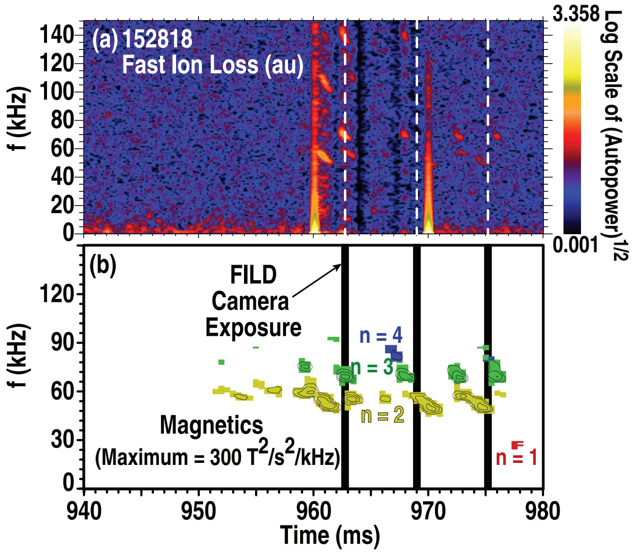

Figure 3: Spectrograms of (a) fast ion loss and (b) magnetic fluctuations for shot 152818. Vertical lines indicate the acquisitions of camera data from the FILD.

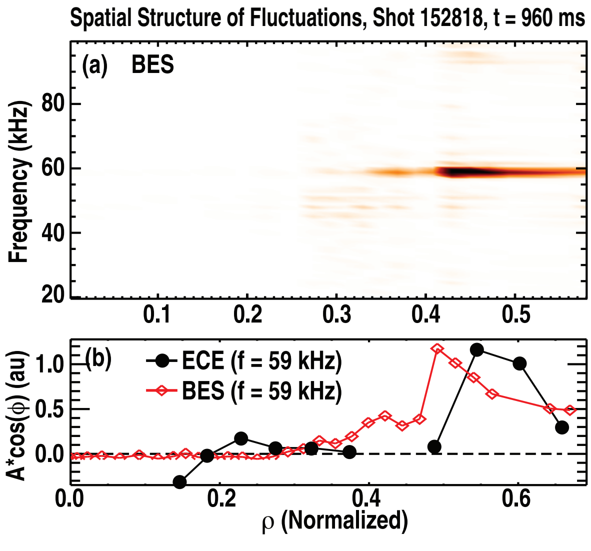

Figure 4: (a) Amplitude spectra (au) as a function of position for BES channels in shot 152818 at 960 ms. (b) Spatial profiles of fluctuation amplitude from the BES system (⋄-symbols) and ECE chords (•-symbols).

subject to the non-linear loss process similar to that described in [3] (which is limited in time to the on-period of the source beam), and that this occurs in addition to the more standard process of the mode pushing ions across the passing-trapped boundary (which can extend beyond beam turn off as it takes some milliseconds for the ions to slow down appreciably below their injection energy).

In conclusion, a series of shots at DIII-D exhibit fast frequency chirping events of AEs. Present experimental results demonstrate that chirping modes can produce coherent energetic ion losses. Including these losses in the simulations will refine the theory-experiment comparison of wave-particle interactions. The conditions that lead to chirping beam ion losses will be investigated with orbit following codes using measured mode structure and plasma equilibria as inputs.

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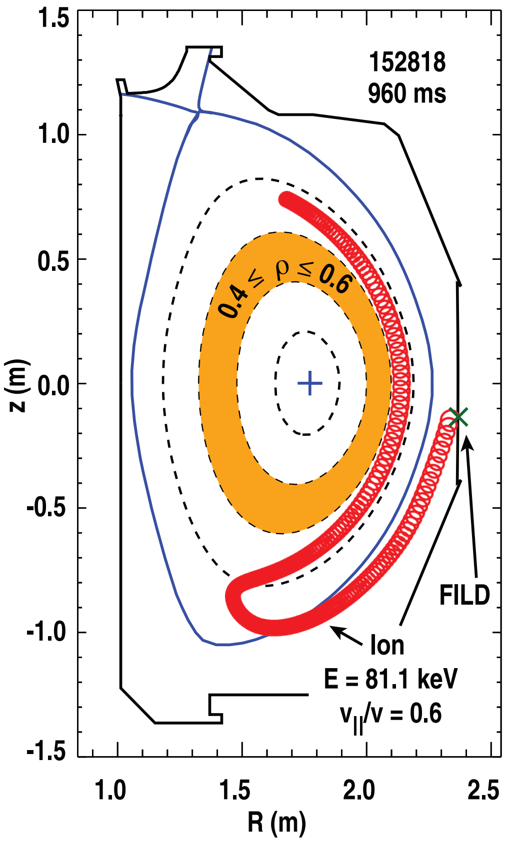

Figure 5: Magnetic equilibrium from shot 152818 at 960 ms. A back traced ion orbit using the FILD-measured $E = 81.1\,\mathrm{keV}$ and $v_{\|}/v = 0.6$ properties is shown.

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