Fast ion transport by toroidicity-induced Alfvén eigenmodes on NSTX

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Introduction and experimental setup. Toroidicity-induced Alfvén eigenmodes (TAEs) can redistribute fast ions in velocity and real space, thus degrading fusion and current drive efficiency in devices such as ITER. TAEs naturally occur in beam-heated plasmas of NSTX [1], a spherical tokamak with major and minor radius of 0.8 m and 0.65 m. For the present study, a L-mode helium plasma with n_0=3.2x10^{19} m^{-3}, $T_{e,0}$=1.3 keV and lower-single-null configuration is investigated (Fig. 1). Up to 2.7 MW of neutral beam (NB) power is injected by three sources (Fig.1-d), with maximum acceleration voltage of 90 kV. Beam ions velocity is $v_f \leq 5 \times v_A$ (v_A: Alfvén velocity). The q-profile is slightly reversed. Space and energy resolved measurements of fast-ion dynamics are available from a number of diagnostics. Two Fast-Ion D-alpha (FIDA) systems [2], based on active charge-exchange recombination spectroscopy, measure the radial profile of confined fast ions, n_f(R,t). One instrument (s-FIDA) measures the spectrum of Doppler-shifted emission from recombining fast ions, with time resolution of 10 ms. A second system (f-FIDA) integrates the fast ion signal through a bandpass filter. Its time resolution is 20 μs. FIDA systems are complemented by neutral particle analyzers (NPA), neutron detectors and a scintillator-based fast-ion loss probe (sFLIP), measuring fast ions lost from the plasma [3]. Data on TAE fluctuations are gathered from Mirnov coils. A multi-channel reflectometer is used to infer the radial structure of instabilities.

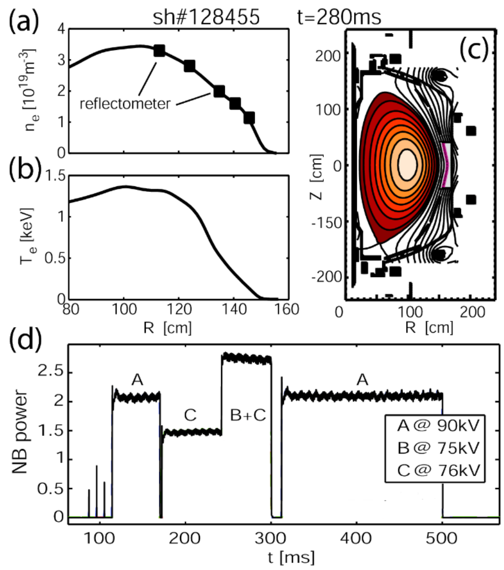


Fig. 1: Shot#128455. (a,b) Electron density and temperature. Squares indicates the position of reflectometer measurements. (c) Magnetic surfaces. (d) NB waveform.

TAE-induced fast ion losses. For the discharge discussed here, TAEs are destabilized when the injected NB power exceeds 1.4 MW (Fig. 2), with a beam extraction energy of 75 keV. Modest changes

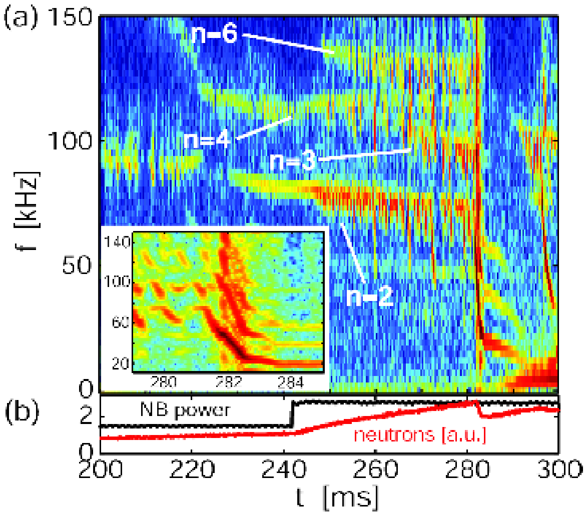


Fig. 2: (a) B-dot spectrogram from Mirnov coils showing the evolution of TAEs with n=2-6. An avalanche occurring at t=282ms is detailed in the inset. (b) Waveforms of NB power and neutron rate.

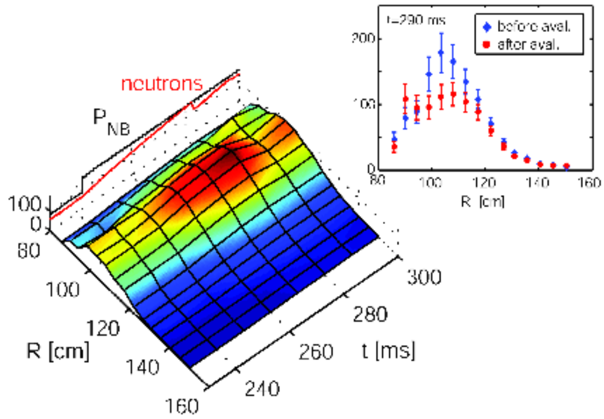


Fig. 3: Fast-ion density measured by s-FIDA. Note the decrease after t=280 ms, caused by a TAE avalanche. The inset details the fast ion profiles measured before/after the avalanche, showing that a depletion in n_f occurs over a broad spatial region.

in $n_f(R)$ are observed during this initial phase, characterized by multiple quasi-stationary modes [4]. The injected neutral beam power is then increased to ~2.7 MW at t=240 ms. Other TAEs with toroidal mode numbers n=2− 6 are destabilized. For t>250 ms, the modes show a bursty character, and finally at t=282 ms they terminate in an *avalanche*. The latter appears as a rapid frequency down-chirp of all the observed TAEs, accompanied by a prompt increase in the modes' amplitude. At the same time, a rapid decrease of ~35% in the volume-integrated neutron rate is measured. A clear decrease in n_f correlates with the avalanche, see Fig. 3. The fast ion radial profile remains peaked at the magnetic axis. No clear evidence of spatial fast ion redistribution within the plasma volume is observed. Energy spectra measured by s-FIDA and by a four-channel solid-state NPA (ssNPA) show a depletion of fast ions with energy >20 keV. However, sFLIP data indicates that only ions close to the injection energy hit the detector during this event. The range of pitch angles and energy of the lost fast ions vary from shot to shot. The discrepancy between FIDA, ssNPA and sFLIP will be investigated in more detail in future works. Further information on the fast ion dynamic on time-scales ~50 μs is added by f-FIDA data (Fig. 4), showing a correlation between internal fast ion measurements at R=120 cm and MHD activity measured by Mirnov coils at the plasma edge. (No clear fluctuations are observed in the f-FIDA data from R=100 cm). Similar features are observed in the total sFLIP signal, which is integrated over energy and pitch of the lost fast ions. These results suggest a direct coupling between internal fluctuations and the resulting fast ion losses.

Qualitatively, similar features are observed in a number of discharges. The average neutron drop associated with a single avalanche is 10-15%. The general picture derived from these

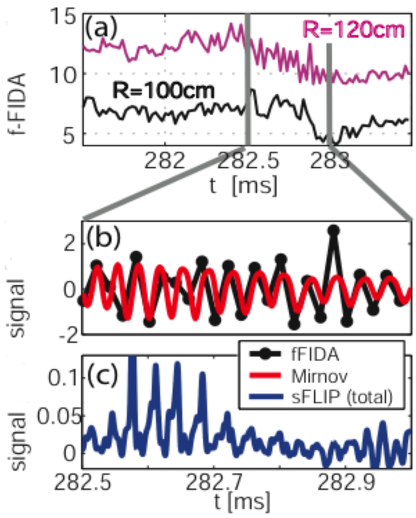
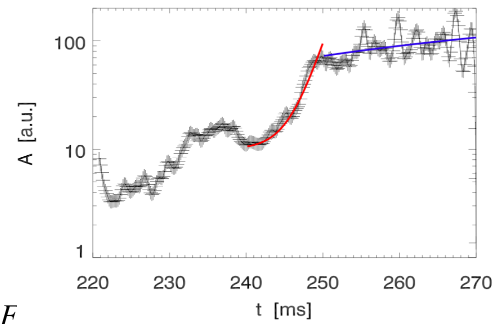


Fig. 4: Correlation between two f-FIDA channels at R=100, 120 cm (a), low-frequency MHD from Mirnov coils (b) and the total sFLIP signal (c). (Signals in arbitrary units).

experiments is that TAEs are gradually driven more unstable by the build-up of the fast ion population and by an increase in the radial gradient of $n_f(R,t)$. Eventually, TAEs collapse into an avalanche and a fraction of fast ions is expelled from the plasma. This triggers a relaxation of the gradient, and of the drive for TAEs [4].

TAE dynamics and NOVA-K modeling. In order to explore the conditions leading to avalanches, hence to fast ion losses, the evolution of the dominant n=2 mode is investigated. Referring to the Fourier spectrogram in Fig. 2, the mode is destabilized at t≈225 ms, then it is driven more strongly unstable by a second NB source, for t>240 ms. Between 250 ms and 280 ms the mode shows large bursts in amplitude, accompanied by frequency down-chirping. Both features are reminiscent of a weakly turbulent dynamics, where drive and damping of the mode compete in modifying the fast ion distribution around the resonance in velocity space [5]. The interpretation of the experimental data on the basis of weak turbulence theories requires an accurate quantitative knowledge of drive and damping rates. As a first check, the stability of the n=2 mode is calculated through the linear MHD stability code NOVA-K [6]. First, the "measured" mode is selected among the many solutions found by NOVA-K (Fig. 6). This is done on the basis of (i) the consistency of NOVA-K results with the measured frequency from 225 ms to 250 ms data, and (ii) from three reflectometer channels, showing two inversions in the sign of the eigenfunction. Then, the linear growth and damping rates, γ_L and γ_D, are calculated for t=225 ms, when the n=2 TAE is destabilized. At this time, NOVA-K calculation should find a marginally unstable growth rate with $\gamma_L \simeq \gamma_D$. For the selected mode (f=61.8kHz in the plasma frame, Fig. 6-c), we obtain γ_L/ω=2.17% and γ_D/ω=2.22%. According to NOVA-K, the mode should be stable, which is contrary to the experimental observations. For t=245 ms we find γ_L/ω=2.03% and γ_D/ω=2%. Despite the build-up of the fast ion density (and



F [illegible] mode at f~75kHz (Fig. 2). Note the initial exponential growth (red line) as the second NB source turns on at 240 ms, followed by a more turbulent behavior with steady increase in amplitude (blue line).

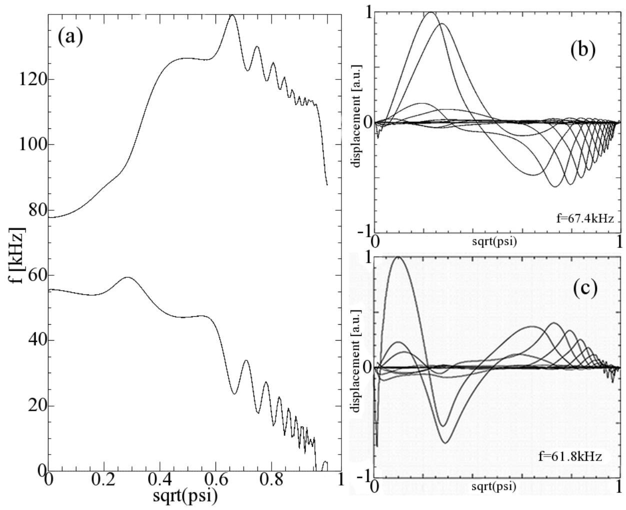


Fig. 6: (a) NOVA-K results for the Alfvén continuum at t=225 ms and predicted structure for two n=2 modes (b-c). The one in (c) is the best guess for the measured mode at f~75kHz, based on frequency and reflectometer data.

gradient), the drive would instead be *reduced*, but the damping is also reduced: the mode is predicted to be marginally unstable. Note that the other mode whose frequency is compatible with the measured frequency (Fig. 6-b) is stable at all times. NOVA-K results are therefore compatible with the experiment, although several issues must be still verified. Firstly, the fast ion distribution is modeled in NOVA-K as a slowing-down distribution, which is not correct for transient phases, such as at t=245 ms. Spatially averaged energy and pitch parameters are used, whereas in practice they vary in the radial direction. The presence of three energy components, leading to three different sources, is ignored. Secondly, plasma rotation was set to zero for the current analysis; the impact on the final stability results has not been investigated in detail. Thirdly, for these simulations the damping term is dominated by Landau damping on main plasma, contaminants and electrons (in order of relevance). Other contributions, such as electron collisional and radiative damping, are not included as their treatment in NOVA-K is not adequate for highly-shaped, low-aspect ratio devices such as NSTX, usually characterized by a large fast ion Larmor radius. Note that these additional terms would increase the damping rate even further. Finally, an unusual species mix was used in this experiment, with helium as main species and deuterium and carbon as minority species. It should also be mentioned that the signal-to-noise ratio in the reflectometer data is poor for t<280 ms, leading to uncertainties in the mode identification. Future work will investigate all these issues, including the accuracy of the numerical predictions, in order to proceed with a quantitative comparison with the experimental data.

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