Non-linear dynamics of toroidicity-induced Alfvén eigenmodes on NSTX

M. Podestà[1], E. D. Fredrickson[1], N. Gorelenkov[1], R. White[1], R. E. Bell[1], B. LeBlanc[1], W. W. Heidbrink[2], N. Crocker[3], S. Kubota[3], H. Yuh[4]

[1]Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ-08543
email: mpodesta@pppl.gov
[2]University of California, Irvine, CA-99297
[3]University of California, Los Angeles, CA-90095
[4]Nova Photonics, Princeton, NJ-08543

The non-linear dynamics resulting from the coupling of multiple toroidicity-induced Alfvén eigenmodes (TAEs) is believed to be one of the main loss mechanisms for fast ions in ITER. Major consequences of enhanced losses are decreased fusion efficiency and possible damage to in-vessel structures. It is therefore important to understand this phenomenon in order to limit its effects or avoid it. Bursts of TAE activity are commonly observed in neutral beam-heated plasmas on the National Spherical Torus Experiment (NSTX), with a prompt depletion of up to 30% of the confined fast ion population associated with single events. TAE bursts are thought to be triggered by an enhanced coupling between unstable modes. The experimental results are qualitatively consistent with a quadratic non-linearity acting on TAEs with consecutive toroidal numbers and causing an explosive growth of the modes.

NSTX operates at toroidal field B_{tor}=3.5-5.5kG, with typical density 3-10×$10^{19}m^{-3}$ and temperature ~1keV. Neutral beam (NB) injection is the primary system for heating and current drive. The total available power is P_{NB}=7MW at injection energy 60keV<E_{inj}<90keV. The resulting fast ion population is super-Alfvénic with velocities $1<v_{fast}/v_{Alfvén}<5$. This results in a strong drive for TAEs with toroidal mode number up to n=8 and frequency 60<f<250kHz. An example is shown in Fig.1a for a L-mode deuterium plasma with ~1.5MW of injected NB power. Weak amplitude variations of the TAEs, measured by Mirnov coils, correlate with frequency variations <10kHz. Eventually, the modes exhibit larger bursts in amplitude and frequency down-chirps >10kHz, which lead to a so-called TAE *avalanche* [1]. Avalanches cause fast ion losses up to ~30% over ~1ms, as inferred from the volume-integrated neutron rate [2], cf. Fig.1b. The drop in the neutron rate vs. mode amplitude, integrated over 15<f<250kHz, is illustrated in Fig.1c for a set of similar discharges. As expected, the losses increase with the mode amplitude. In addition, activity with n=1 and f~25kHz, i.e. well below the TAE gap, is detected during TAE bursts. This fluctuation has duration comparable with that of the avalanches. The temporal correlation with TAE bursts suggests that the n=1 fluctuation may have a role in the fast ion loss process. Because of its limitations in temporal

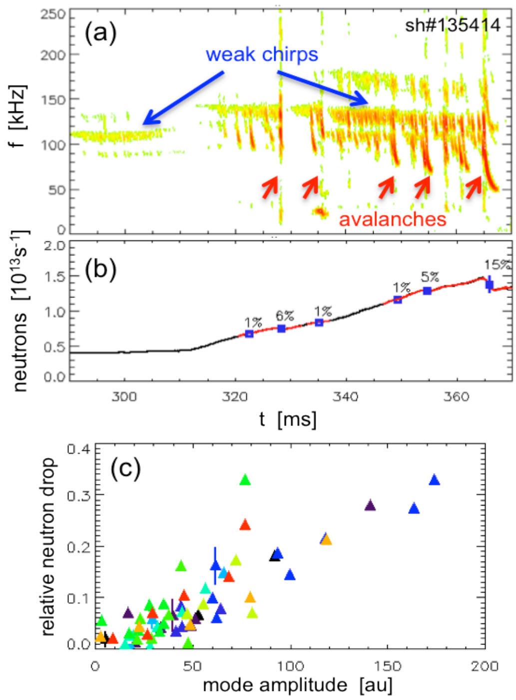

Fig. 1: (a) Frequency spectrum vs. time showing TAE activity between 60kHz and 250kHz. (b) Measured neutron rate and relative neutron drop caused by TAE bursts. (c) Relative neutron drop vs. mode amplitude integrated over f=15-250kHz. Colors indicate different discharges.

resolution and the lack of statistics, Fourier analysis cannot be used to study the mode coupling process during single events. An analysis in the time domain is instead done.

First, the matching conditions for mode-mode coupling are investigated. Signals are band-pass filtered around the modes' frequency to obtain the time derivative of fluctuations, $s'_n(t)$, for each mode number n. The B-field signals, $s_n(t)$, are calculated by integrating $s'_n(t)$ via software. The evolution of frequency and real amplitude of the modes, f_n and A_n, are then reconstructed. Fig.3a shows the results of this analysis for a TAE burst at t~328.2ms. The frequency f_1 overlaps with the difference f_4-f_3 and, later in time, with f_3-f_2. The matching conditions for mode-mode coupling are thus satisfied. As a second step, the data is compared with a simple model based on bilinear interactions between modes. One expects that $A'_1 \sim c_{(n+1,n)} A_{n+1} A_n \exp(i\phi)$, where the right-hand side is filtered around the n=1 frequency and the prime indicates time derivative. $c_{(n+1,n)}$ is a coupling coefficient and ϕ is a phase shift term. The measured $s'_1(t)$ and reconstructed signals shown in Fig.3b are consistent with this model for the couples n=(4,3) and n=(3,2) and a phase shift of 180°. The n=1 oscillation amplitude grows at the same rate as the (4,3) and (3,2) bilinear terms, then decays when the frequency match condition is no longer satisfied and the amplitude of (at least one of) the higher n modes vanishes. A similar temporal evolution, but with a phase shift ϕ~90°, is observed for fluctuations with frequency higher than that of the dominant n=3,4 modes, cf. Fig.3c.

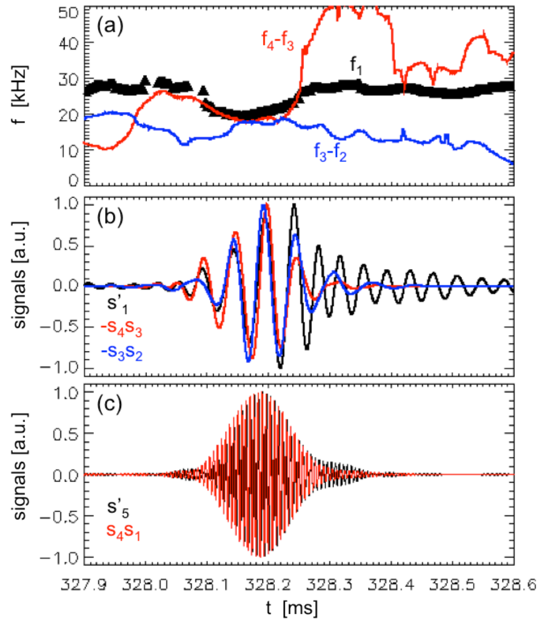

Fig. 3: (a) Evolution of n=1 frequency and difference frequency between n=(4,3) and n=(3,2) modes for the discharge shown in Fig.1a. (b) n=1 signal as measured and reconstructed from a simple model based on a bilinear interaction between n=(4,3) and n=(3,2) modes. (c) Measured and reconstructed n=5 signal at ~150kHz for the sum interaction n=(4,1).

These features, along with the absence of detectable density fluctuations from reflectometry measurements, suggest that the n=1 activity actually represents a forced oscillation of the magnetic field with perpendicular wave-number close to zero, driven by the enhanced TAE amplitude. The n=1 oscillation would then mediate the non-linear coupling between the primary TAEs. This mechanism is then different from other mode coupling processes previously observed on NSTX [3]. The evolution of the non-linear system can also destabilize otherwise stable modes with higher n's (Fig.3c). During this process, the amplitude of the TAEs grows by more than one order of magnitude over a few hundred microseconds. The effective growth rate is >10%, i.e. much larger than the typical linear growth rate of $O(1\%)$ calculated through the NOVA-K code for TAEs on NSTX.

Work supported by U.S. DOE Contract DE-AC02-09CH11466.

References:

[1] E. D. Fredrickson *et al.*, Phys. Plasmas **16** 122505 (2009)
[2] M. Podestà *et al.*, Phys. Plasmas **16** 056104 (2009)
[3] N. Crocker *et al.*, Phys. Rev. Lett. **97** 045002 (2006)