Modeling Fast Ion Transport in TAE Avalanches in NSTX

E. D. Fredrickson, M. Podesta[1], N. A. Crocker[2], D. Darrow, N. N. Gorelenkov,
S. Kubota[2], F. M. Levinton[3], D. Liu[1], S. S. Medley, H. Yuh[3], R. E. Bell

Princeton Plasma Physics Laboratory, Princeton New Jersey 08543
[1]*Univ. of Caliifornia., Irvine, CA 92697*
[2]*Univ. of California, Los Angeles, CA 90095*
[3]*Nova Photonics, Princeton, NJ 08543*

Toroidal Alfvén eigenmodes (TAE) cause fast ion transport that increases non-linearly with mode amplitude in NSTX. Moreover, multiple modes can interact synergistically, as in an "avalanche event" [1], causing substantial fast ion transport and loss. Interaction of multiple modes on ITER in a similar manner could redistribute or cause the loss of fusion αs. Fast ion losses are of concern regarding the ignition threshold and transient heat loads on plasma facing components (PFCs), and the energetic alphas can bury themselves in PFCs, causing blistering and greatly enhancing the rate of erosion.

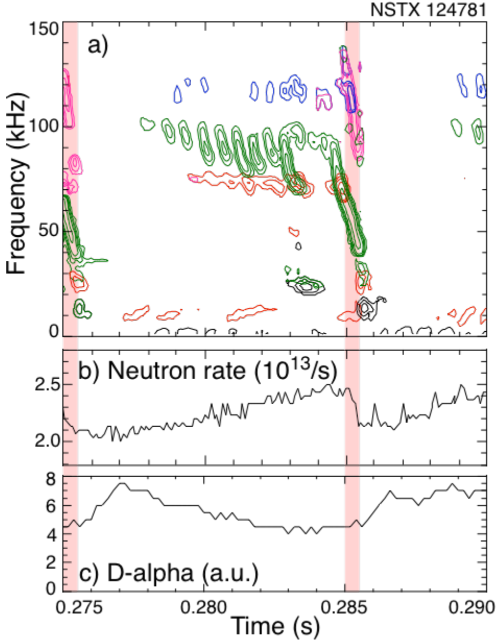

Fig. 1. a). Spectrogram showing TAE; black, red, green, blue, magenta correspond to n = 1, 2, 3, 4, 6, respectively, b) neutron rate, c) D-alpha emission.

The observation of TAE avalanches on NSTX (Fig. 1) offers the opportunity to benchmark ideal stability and fast ion transport codes in low aspect ratio geometry. One consequence of the low aspect ratio of NSTX is that the core rotation frequency (≈ 30kHz) and the TAE frequencies (≈ 50 to 80 kHz) are comparable. The sheared rotation affects the TAE gap structure as shown in Fig. 2 where the continua calculated for n = 3, with and without Doppler corrections (using a version of NOVA developed by G. Kramer [2]). are compared. The curves in blue show the gap structure neglecting rotational shear. The curves in red show the same gap structure including the effects of rotational shear. The red dotted line indicates the Doppler frequency correction for the n = 3 mode. The rotational shear has the effect of closing the gap, meaning that TAE in NSTX will have significant continuum interactions.

Multiple modes are seen during TAE avalanche events. In the example studied here, four modes are present during the final, large TAE burst (Fig. 1a). Here, the colors of the contours indicate the toroidal mode numbers, with black, red, green, blue and magenta representing, respectively, n = 1, 2, 3, 4 and 6. Coincident with the large TAE bursts are drops in the neutron rate of 10 to 15% (Fig. 1b) and bursts of D_α light indicating that fast ions lost to the wall are enhancing deuterium recycling. Measurements with Neutral Particle Analyzer diagnostics indicate that the fast ion losses occur over a broad range of energies.

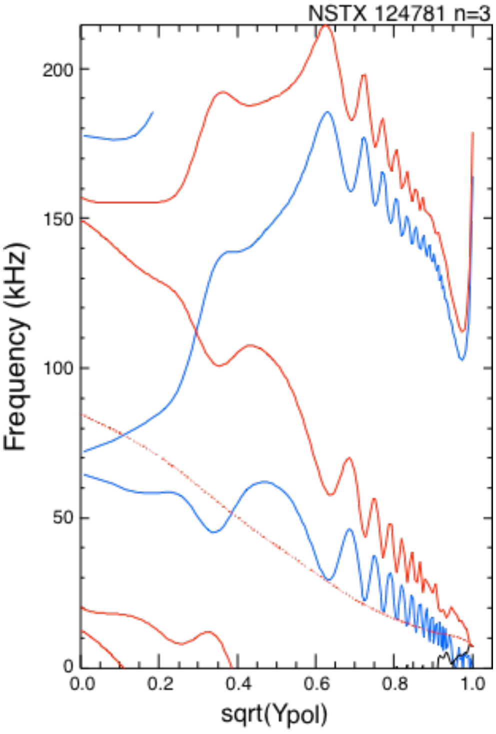

Fig. 2. Alfvén continue for n = 3 without Doppler corrections (blue) and with first order Doppler corrections (red).

Detailed measurements of the equilibrium are used in the NOVA code to calculate the Toroidal Alfvén Eigenmodes. Simulations done with NOVA, for equilibria with and without the local Doppler correction due to the sheared rotation, find multiple solutions in the TAE gap. Identification of the best fit to the measured fluctuations is based on measurements of the mode profile with the five channel reflectometer diagnostic, and, to a lesser extent, based on comparison of simulated and measured mode frequencies. The latter approach has significant uncertainties due to the strongly sheared toroidal rotation.

The density perturbations from NOVA are compared to the reflectometer data by simulating the reflectometer response. NOVA calculates density fluctuations from both the displacement and compressional terms. The magnitude of the compressional density fluctuation can be significant; for the n = 3 mode it is about 50% of the displacement term. The compressional terms add to the displacement terms on the inboard side and subtract on the outboard side. Thus, the compressional terms reduce the density fluctuations, for a given mode amplitude, on the outboard side by roughly a factor of two. The radial structure is unchanged within the uncertainties of the reflectometer fluctuation profile. In the ORBIT simulations described below, the scale factors determined by matching the density fluctuations determined from only the displacement term are scaled by a factor of two.

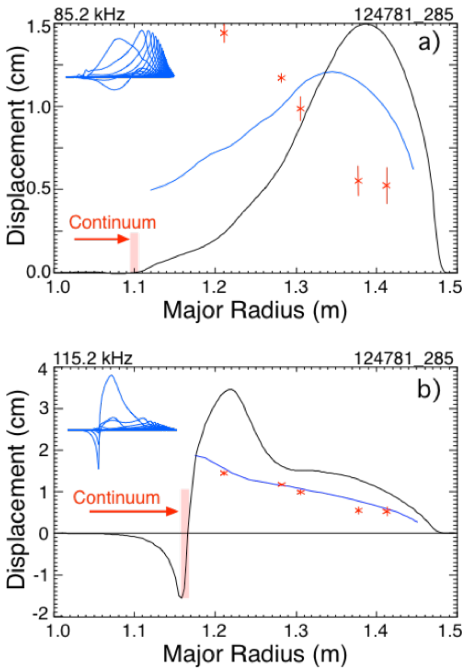

Fig. 3. Simulated reflectometer response (solid blue line) compared with reflectometer data (red points) for n=3 modes. Black curve is actual displacement.

NOVA is a linear code, thus, to simulate the effect of modes on fast ion transport, both the time-dependent mode amplitudes and frequencies must be taken from the experimental measurements. To properly scale the mode amplitudes, the NOVA eigenmodes are used to simulate the reflectometer response and that is compared with the measurements from a five channel reflectometer array. In Fig. 3 the shapes of two of the n = 3 NOVA eigenfunctions (poloidal harmonics shown in the blue inset) are used to find the displacement on the outboard midplane (solid black line). This displacement is used to simulate the reflectometer response (blue curve), which is compared with measurements from the array of five reflectometers (red points). The error bars on the reflectometer data result from analysis done at multiple times within the burst (all profiles from the growing mode are normalized to the peak amplitude). The small size of the error bars reflects the observation that the mode structure doesn't change substantially as the mode grows. This supports the assumption that the linear NOVA eigenmode is a reasonable approximation to the saturated TAE. With this analysis, the NOVA eigenmodes in closest agreement with the reflectometer data can be selected and scaled in amplitude to simulate how the TAE affect fast ion transport with the ORBIT code.

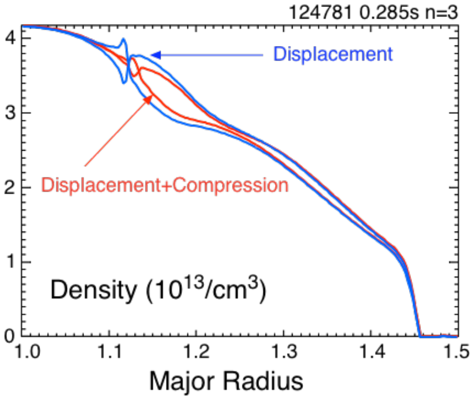

Fig. 4. Perturbed density profiles showing peak density perturbation from n = 3 mode.

The NOVA eigenfunctions which best fit the reflectometer data (*e.g.*, the mode shown in Fig. 3b, not 3a) for the three dominant modes, the n = 2, 3 and 4), are used in the ORBIT code to simulate the effect on fast ion transport. The measured amplitude and frequency evolutions for the final one ms avalanche burst, seen at 0.285s in Fig. 1, are used to scale the linear NOVA eigenmodes in an ORBIT simulation. The unperturbed fast ion distribution is calculated with the TRANSP Monte Carlo beam deposition code and used as input to ORBIT.

The amplitude of the density fluctuations from the n = 3 mode reaches ≈ 15% at the end of the burst. The simulated perturbed density profile is shown in Fig. 4, for both the assumptions that the density fluctuations are from displacement (blue) and for combined shear and compression terms (red curves). The peak amplitude of this mode is quite large.

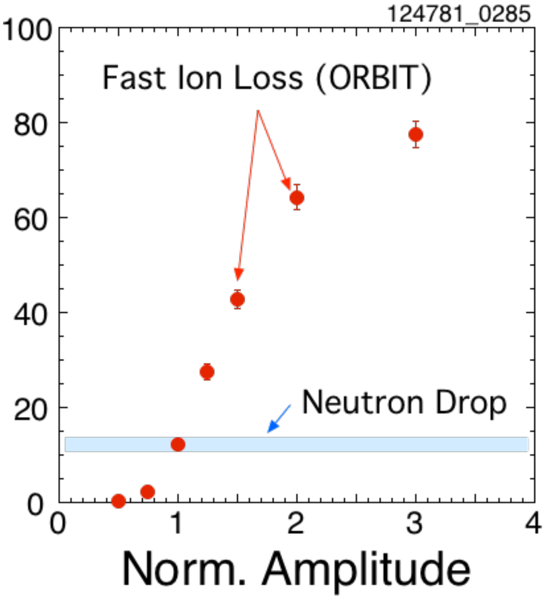

Fig. 5. Fast ion losses vs. amplitude normalized to experimental amplitude. Blue bar indicates drop in experimental neutron rate, roughly equal to the percent loss of fast ions.

ORBIT simulations were run for a range of mode amplitudes. In Fig. 5 are shown the predicted fast ion losses as the mode amplitudes are increased. The loss shows a strong, non-linear onset. For a normalized mode amplitude of one, that is, for the experimentally measured mode amplitude evolution, the predicted fast ion loss is ≈ 12%, in good agreement with the drop in neutron rate of ≈ 12%. Simulations with only the n = 3 mode find losses of 6.9% and with only the n = 2 and 4 modes find negligible losses. Thus, there is an apparently synergistic interaction of the three modes in the TAE-induced losses, consistent with the avalanche interpretation.

Simulations of individual modes during a TAE avalanche event in NSTX have found modes reasonably matching the mode structure as measured with an array of five reflectometers. Using the NOVA eigenmodes scaled to the experimental amplitudes and frequencies in the ORBIT code, simulations of the 1 ms burst have found good agreement between predicted losses and the observed drop in the neutron rate. Simulations where the amplitude was scaled indicate a threshold, rather than linear response of the loss rate, consistent with the assumption that these are avalanche events.

Work supported by U.S. DOE Contracts DE-AC02-09CH11466, DE-FG03-99ER54527, DE-FG02-06ER54867, and DE-FG02-99ER54527.

[1] H. L. Berk, B. N. Breizman, M. Pekker, Phys. Plasmas **2**, 3007 (1995)
[2] G. J. Kramer, et al., Phys. Plasmas **13** (2006) 056104.