Fast-ion energy loss during TAE avalanches in the National Spherical Torus Experiment

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The ability to predict the fast ion confinement, distribution and energy transfer rate to the thermal plasma is important for optimizing the performance of ITER and other tokamaks. For example, the presence of TAE or other MHD could redistribute fast beam ions in minor radius or energy, impairing the accurate modeling of beam driven currents that ITER and Spherical Tokamaks rely upon. Fast ions on NSTX are also known to be redistributed by low frequency MHD (kinks, NTMs), energetic particle modes and TAE avalanches, affecting the beam-driven current profile [1]. Drops in the neutron rate correlated with bursts of TAE activity are seen in NSTX (*cf.,* Figs. 1b&c), are further evidence that the TAE significantly affect the fast ion population. In this paper we report that modeling of the effect of TAE on fast ions finds that diffusion of fast ions in phase space, resulting in a net drop in fast ion energy, explains the bulk of the observed neutron rate drop, without the need for significant fast ion losses.

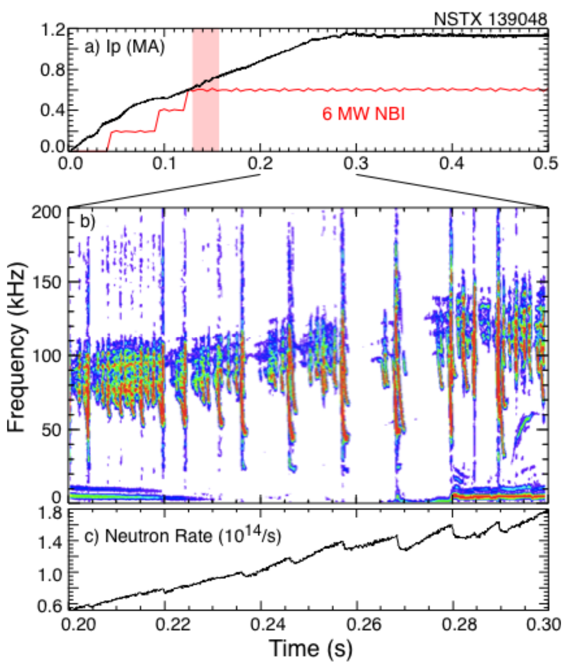

Fig. 1. a) Plasma current and NBI heating profiles, red bar indicates H-mode transition time, b) spectrogram of magnetic fluctuations show TAE bursts, c) neutron rate with drops at TAE bursts.

The linear ideal stability code, NOVA, and the particle following code ORBIT were used previously to model the redistribution of fast ions by avalanches in an NSTX L-mode plasma [2]. The peaked L-mode density profile meant good measurements of the TAE amplitudes were possible with an array of reflectometers. The measured mode amplitude evolution was used to scale the NOVA linear eigenmodes in the ORBIT simulations. Here we extend that approach to a relatively low-density H-mode plasma with weak core density peaking, allowing mode amplitude measurements with several reflectometer channels. The unexpected result of this work is that very few fast ions are predicted to be lost in simulations which use the measured mode amplitudes, but the drop in the neutron rate can be nearly entirely accounted for by the predicted loss of energy from the fast ion population. Further, the lost energy from the fast ion population was roughly consistent with estimates of the energy lost from the TAE to the thermal plasma through damping.

In Fig. 1 is shown an overview of the plasma conditions for the TAE avalanche being modeled here. The plasma current is ramped up to 0.8MA in the first 0.2s of the discharge as seen in Fig. 1a. The neutral beam power is injected early to aid in the current ramp with beam-driven current and to promote an early H-mode transition. Strong TAE bursts consisting of multiple modes begin around 0.15s and persist to ≈0.3s (Fig. 1b). Each burst is correlated with a drop in the neutron rate of 5-15% (Fig. 1c). Bursts of D_α light also accompany each TAE burst, indicating that some fast ions are lost. The TAE burst at 0.268s is analyzed in detail as described below.

The spectrogram of a Mirnov coil signal of the TAE avalanche at 0.268 s is shown in Fig. 2a. There are four important modes in this avalanche burst. The avalanche begins with the strong growth of an n=2 TAE (red) which triggers n=4 (blue) and n=6 (magenta) modes, and then an n=1 TAE (black). The amplitude evolution of these four modes, as measured with three internal reflectometer channels, are shown in Fig. 2b. In both Figs. 2a and 2b, the solid curves are analytic approximations to the frequency and amplitude evolutions which are used in the ORBIT code simulations described below.

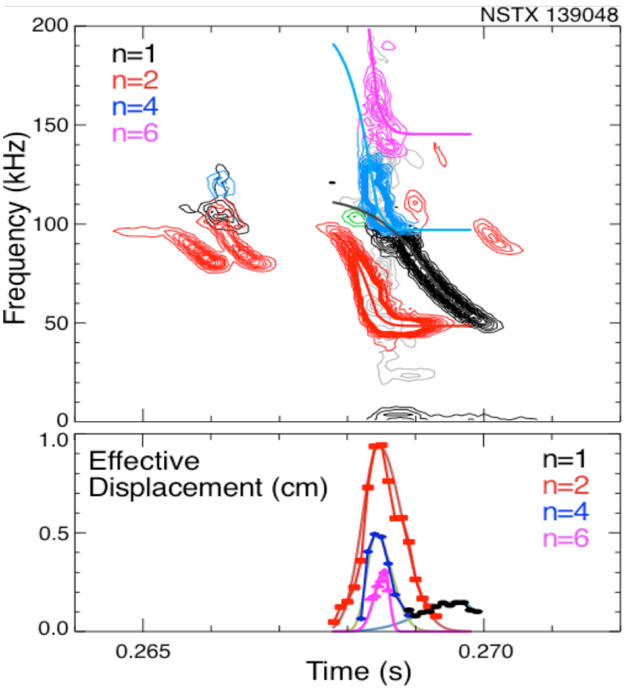

Fig. 2. a) Spectrogram of a Mirnov coil where contours are color-coded to indicate the toroidal mode numbers, as indicated in the legend, b) the peak mode amplitude evolution for each mode from the reflectometer array.

The NOVA code uses the plasma equilibrium as reconstructed using magnetic field pitch angle measured with a Motional Stark Effect diagnostic to calculate linear eigenmodes for each of the four dominant modes in Fig. 2 used in the ORBIT simulation. As NOVA is a linear code, we scale the eigenmodes so that the simulated reflectometer response matches the amplitude of the reflectometer signals. The experimental frequency evolution, with strong frequency chirping, are also used in ORBIT. Since, within experimental uncertainty, the mode structure is not changed during the burst, use of the linear mode structure is justified. Pitch angle scattering and slowing down are not included in the ORBIT simulations as the timescale is too short for these terms to be important.

Simulations with ORBIT find very small fast ion losses at the nominal measured mode amplitudes, however, there is a drop in energy of the fast ion population of ≈ 5.4% caused by the modes. Simulations done with the mode amplitude scaled by factors ranging from 0.1 up to 2.5 find the threshold for onset of significant fast ion losses during the 2 ms long burst is about the measured mode amplitude (Fig. 3, blue dots).

The effect of the TAE on the neutron rate was estimated by calculating the change in fusion rate using the modified fast ion distribution, equilibrium ion density profile and energy-dependence of the fusion cross-section. The neutron production in this discharge is approximately 75% from beam-target reactions and 25% from beam-beam (from TRANSP). The change in the beam-target reaction rate can be estimated as the change in $\Sigma\sigma(E_n)n_{ion}v_n$, where the sum is over the fast ion population. This sum is done over the sample distribution of fast ions used in the ORBIT simulation. The estimate of the beam-beam fusion rate is more difficult as the fusion cross-section will depend on the velocities of both fast ions. To estimate the change in the beam-beam fusion rate, a linear dependence of the fusion cross-section was used, motivated by the roughly linear dependence of the fusion rate on temperature for a Maxwellian fast-ion distribution with a temperature of ≈ 50 keV [3].

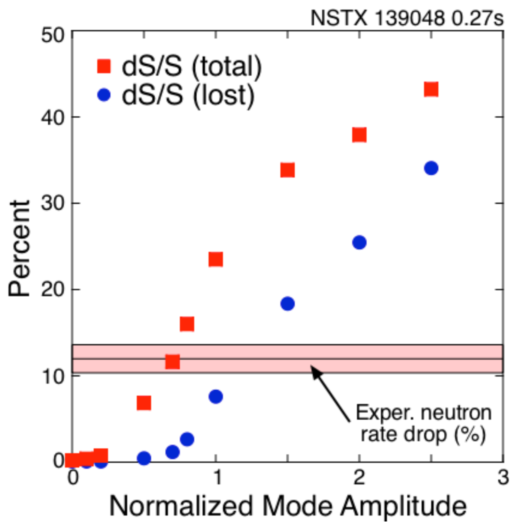

Fig. 3. Simulated beam-target neutron rate drop due to fast ion losses (blue), stochastic cooling of fast ion distribution and losses (red).

The total neutron rate change *vs.* mode amplitude, (from the energy change, fast ion redistribution and fast ion losses) is shown as the red squares in Fig. 3. The blue points show change in neutron rate from fast ion losses only. While ORBIT and NOVA do not self-consistently model the mode growth and fast ion transport, it might be assumed that the energy lost from the fast-ion distribution would transfer to the thermal plasma by damping of the TAE. The time dependent change in β_{fast} is correlated with the growth of the TAE burst (Fig. 4). An estimate of the wave energy in the TAE burst is comparable to the decrement of energy in the fast-ion population at the observed mode amplitude.

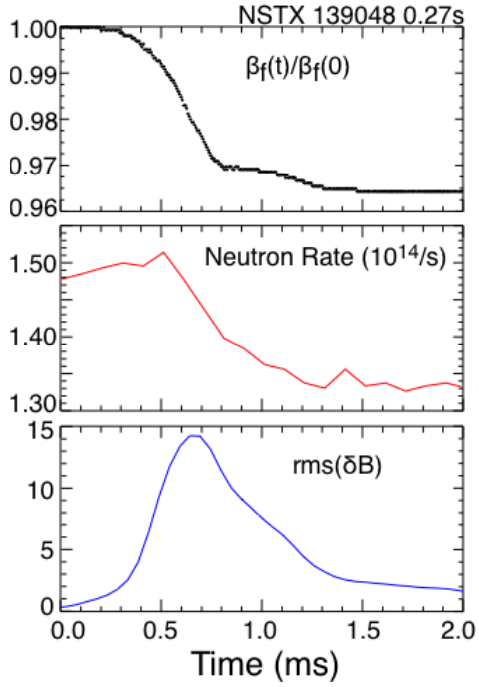

Fig. 4. a) Time dependence of change in β_{fast} in ORBIT simulation, b) experimental neutron rate through burst, c) experimental rms magnetic fluctuation amplitude at plasma edge.

The histograms of beam-ion energy shown in Fig. 5 illustrate the effect of the TAE burst on the fast ion energy. The black curve shows the initial fast ion energy distribution used in ORBIT. The red curve shows the fast ion energy distribution at the end of the 2ms TAE burst as simulated with ORBIT, where the mode amplitudes were scaled (by a factor of 0.7) so as to match the measured change in neutron rate. The net loss in energy of the fast ion distribution is only about 3.6% of the initial energy in the fast ion population. The redistribution from higher energies to lower is seen more clearly from the ORBIT simulation using the nominal measured mode amplitudes as shown by the green curve. Here the estimated drop in neutron rate is ≈23%, roughly twice the measured neutron rate drop. However, the green curve is clearly lower than the black curve for most energies above 20 keV. The distribution function used here was cut-off below 20 keV to speed the ORBIT simulations. However, simulations with the energy distribution extending down to 5 keV also found about a 3.6% drop in total fast ion energy.

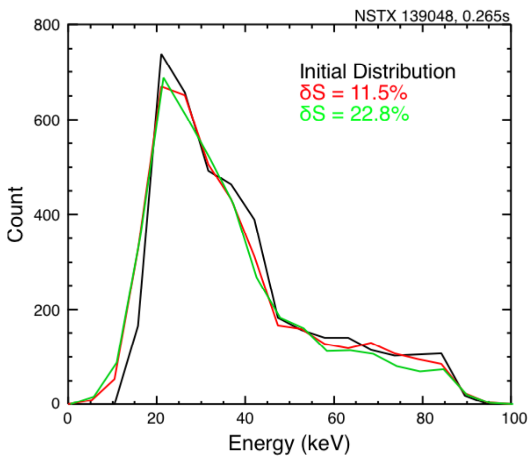

Fig. 5. Histograms of the fast ion energies at; the start of the ORBIT simulations (black curve), then end of an ORBIT simulation with experimental mode amplitudes (green curve) and with mode amplitudes scaled by 0.7 to match measured neutron rate decrease (red).

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