Effects of MHD instabilities on Neutral Beam current drive

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Neutral beam injection (NBI) is one of the primary tools foreseen to heat and inject torque in future fusion reactors such as ITER and a Fusion Nuclear Science Facility. In addition, tailored deposition of NB fast ions can be used to vary the radial profile of non-inductive current, thus providing a means to act on the safety factor profile. As a drawback, NB fast ions provide the drive for energetic particle-driven plasma instabilities such as Alfvénic (AEs), kink-like and so-called Energetic Particle modes. Those instabilities, in turn, redistribute fast ions in space and energy, thus affecting the control capabilities and overall efficiency of NB-driven current. Experiments on the NSTX tokamak are performed to understand and quantify the effects of AEs and other MHD instabilities on NB current drive efficiency as a function of NBI parameters and amount of MHD activity. A preliminary interpretation is that TAEs mainly affect strongly co-passing fast ions with large parallel velocity, which are the most effective in driving current, leaving other portions of the fast ion distribution nearly unperturbed. Clearly, this type of effect cannot be correctly modeled by ad-hoc diffusion models with no phase-space selectivity.

NSTX scenarios with unstable toroidicity-induced AEs (TAEs) and low-frequency, kink-like modes confirm that instabilities can indeed reduce the NB-driven current density and modify its profile over most of the plasma radius. Figure 1 shows results for a discharge at B_t~0.5 T, with TAEs driven unstable by fast ions from NBI. A lower frequency, kink-like mode also becomes unstable after t~280 ms. TAE modes manifest as large amplitude (maximum dB/B~10^{-3}) intermittent bursts, or *avalanches*, which cause substantial drops in the measured neutron rate. The latter is indicative of redistribution of fast ions in both radius and energy [2].

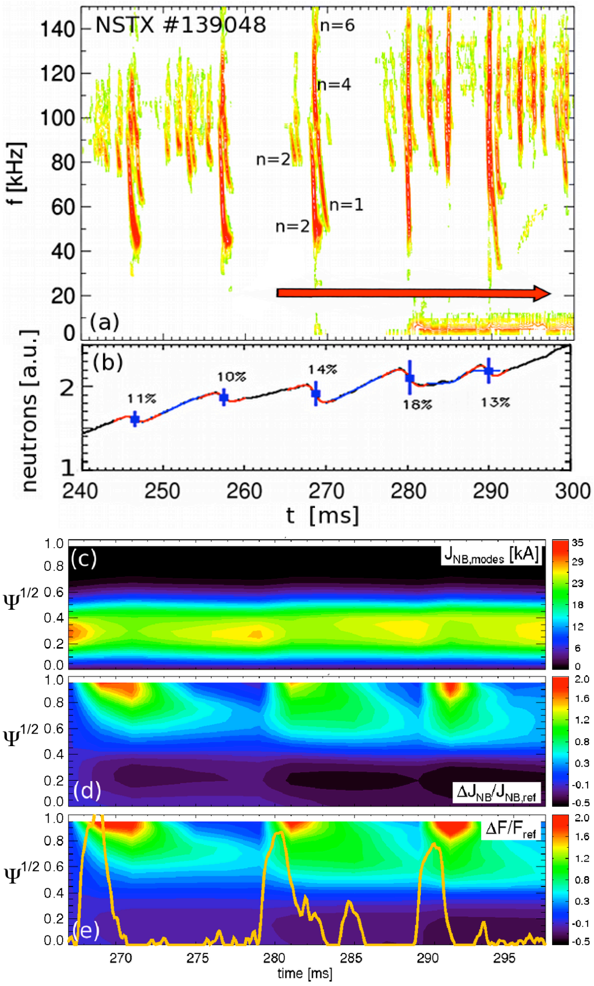

Fig. 1: (a) Spectrum of TAE and kink-like activity for NSTX discharge no. 139048. Red arrow shows the time of interest. (b) Measured neutron rate showing significant drops caused by TAEs. (c) Simulated evolution of NB-driven current. (d-e) Changes of NB-driven current and fast ion density relative to the case with no instabilities. Solid line in (e) shows the total TAE mode amplitude.

The effects of instabilities are first simulated via the transport code TRANSP [1] by assuming an ad-hoc, radially uniform fast ion diffusivity $D_b(t)$. A net redistribution of NB-driven current is observed when instabilities are accounted for. However, one of the main uncertainties in this analysis is to quantify the relative contribution of each class of instabilities (TAE vs. kink-like modes) in NB-driven current modifications. This can not be properly taken into account by simple modeling with an ad-hoc $D_b(t)$.

In order to obtain more accurate results, experiments are interpreted through new numerical tools aimed at improved modeling of NB current drive in the presence of instabilities. In particular, a new fast ion

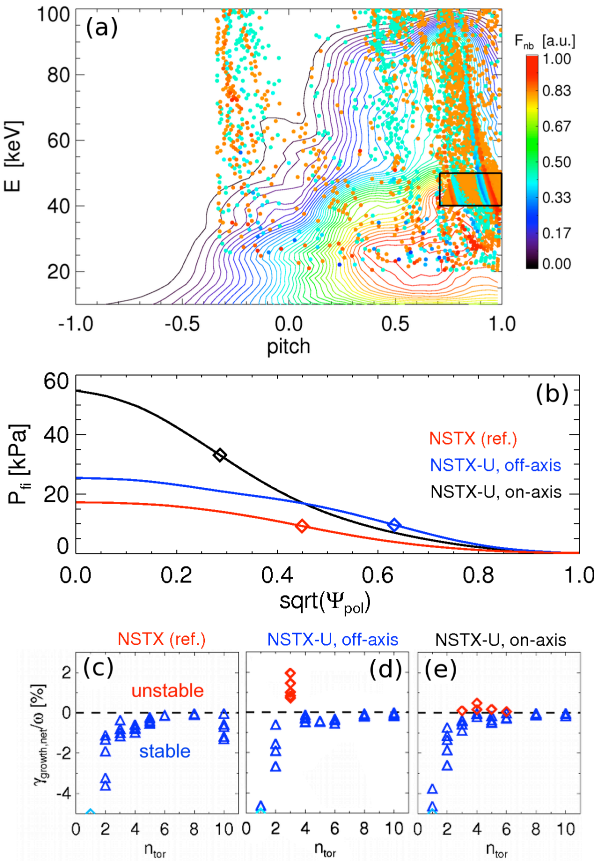

Fig. 2: (a) Fast ion distribution vs energy and pitch (ratio of parallel to total velocity). Red (blue) dots represent resonant particles which gain (lose) energy, as calculated by the ORBIT code. The rectangle delimits a region with enhanced resolution, showing the large number of possible resonances. (b) Fast ion pressure for a reference NSTX scenario and for NSTX-U projections with different NBI geometries. (c-e) NOVA-K stability results for the 5 least stable TAEs with toroidal mode number n=1-10.

transport model [3] has been developed for TRANSP. Contrary to the ad-hoc fast ion diffusion model, the new model accounts for particle's transport *in phase space*, as required to model resonant AE perturbations consistently. The model is based on a probability distribution function that contains information on fast ion energy and toroidal angular momentum modifications caused by instabilities [3]. For the cases discussed herein, the probability function is obtained through the orbit-following code ORBIT [6]. An example of initial simulations for the NSTX scenario in Fig. 1(a-b) is given in Figs. 1(c-e). The temporal evolution of the total TAE mode amplitude is inferred from the neutron rate variations induced by TAE bursts. It can be seen (Fig. 1d) that TAE avalanches induce rapid drops of up to ~50% in the NB driven current in the core, and even larger (relative) changes toward the plasma edge. Perturbations of the current profile persist for a considerable fraction of the beam ion slowing down time, which is ~15-20 ms for this case. The rate of recovery is mainly determined by the NB injection rate.

Interestingly, relative changes in the core fast ion content appear smaller than for the NB driven current (Fig. 1d). A preliminary interpretation is that TAEs mainly affect strongly co-passing fast ions with large parallel velocity (cf. Fig. 2a), which are the most effective in driving parallel current, leaving other portions of the fast ion distribution nearly unperturbed. Clearly, this type of effect cannot be correctly modeled by an ad-hoc diffusion with no selectivity in energy and pitch, whereas it is captured by the new model.

The improved TRANSP modeling is then used to make predictions of NB-CD performance for scenarios on the NSTX-U [5] device. NSTX-U will feature a new set of more tangential NB injectors to complement the existing (more perpendicular) ones, which results in a large variety of achievable fast ion profiles, see Fig. 2b. Linear stability analysis through the ideal MHD stability NOVA-K indicates that TAEs can be, in fact, unstable for high NB power NSTX-U discharges [6], see Fig. 2(c-e). Predicting their actual saturation level is, however, challenging. Instead, a parametric study is performed. TAE amplitude and regime (including stationary vs. bursting activity) are varied, and the resulting effects on NB current drive efficiency quantified through the improved TRANSP modeling.

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