Effects of MHD instabilities on Neutral Beam current drive

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Abstract:
Neutral beam injection (NBI) is one of the primary tools foreseen for heating, current drive (CD) and q-profile control in future fusion reactors such as ITER and a Fusion Nuclear Science Facility. However, fast ions from NBI may also provide the drive for energetic particle-driven instabilities (e.g. Alfvénic modes - AEs), which in turn redistribute fast ions in both space and energy, thus hampering the control capabilities and overall efficiency of NB-driven current. Based on experiments on the NSTX tokamak [M. Ono *et al.*, Nucl. Fusion **40** (2000) 557], the effects of AEs and other low-frequency MHD instabilities on NB current drive efficiency are investigated. It is found that instabilities do indeed reduce the NB-driven current density over most of the plasma radius by up to $\sim 50\%$. A new fast ion transport model, which accounts for particle transport in phase space as required for resonant AE perturbations, is utilized to obtain consistent simulations of NB-CD. Predictions for the NSTX-Upgrade device, which features an expanded set of NB injectors, are finally discussed for projected scenarios with different levels of MHD activity.

1 Introduction and experimental scenario

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.

NSTX scenarios with unstable toroidicity-induced AEs (TAEs) and low-frequency, kink-like modes are analyzed to investigate MHD effects on NB-driven current. Figure 1 summarizes the main properties of instabilities for a particular H-mode discharge with toroidal field $B_t \sim 0.5$ T. A number of TAEs with toroidal mode number $n = 2-6$ are destabilized by NB ions. Their mode structure is computed through the NOVA-K

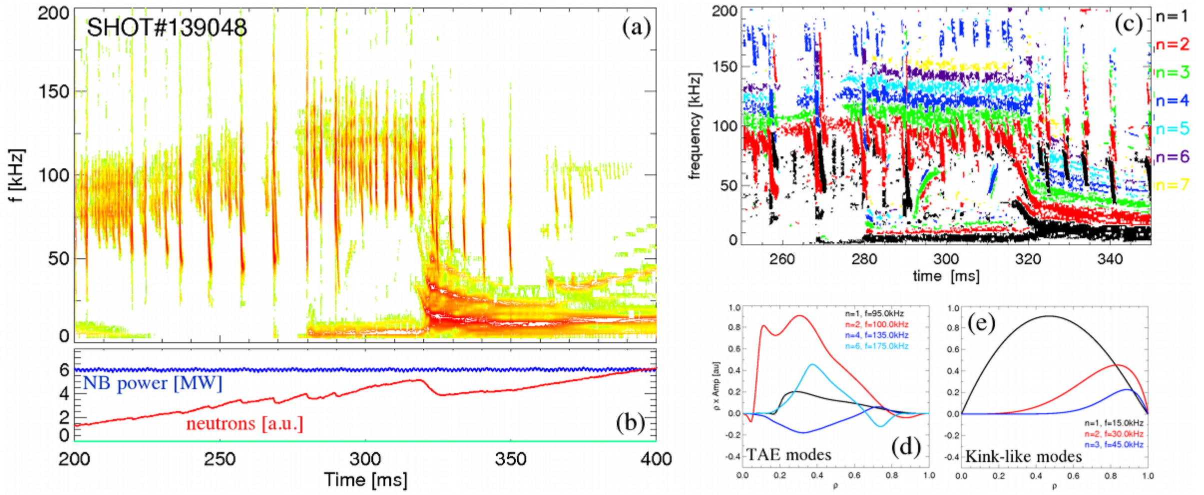

FIG. 1: Experimental scenario from NSTX #139048. (a) Spectrum from Mirnov coils vs. time. (b) Traces of NB power and neutron rate. Note the neutron drops coinciding with enhanced mode activity in (a). (c) Mode number spectrum, showing dominant TAEs with $n = 2 - 5$. (d) Mode structure from NOVA-K for the most unstable TAEs in (a) around $t \approx 260$ ms. (e) Mode structure of kink-like modes from a simple model.

code [1][2]. The details of the analysis are found in Refs. [3][4]. A lower frequency, kink-like mode also becomes strongly unstable after $t = 320$ ms. TAE modes manifest as large amplitude (peak $\delta B/B \sim 10^{-3}$), intermittent bursts - or *avalanches* - which cause substantial drops in the measured neutron rate. Neutron drops are indicative of redistribution of fast ions in both radius and energy [3][4].

2 Analysis methods

Quantitative simulations of NB-CD in the presence of MHD instabilities is inherently related to the modeling of the fast ion evolution under the effects of the modes. In this work, the TRANSP code [5] and its modules are the main tools for a consistent analysis of NB-driven current which takes into account NB deposition and thermal plasma evolution. Two methods are used. The first method, described in Sec. 2.1, is commonly used to model the fast ion evolution when mechanisms other than "classical" conspire to enhance the fast ion diffusivity. The second method, described in Ref. [6] and summarized in Sec. 2.2, is presently under implementation in the TRANSP code and is aimed at a more consistent characterization of the effects of instabilities on fast ion evolution.

2.1 TRANSP analysis with *effective* fast ion diffusivity

The NUBEAM module [7][8] implemented in TRANSP models fast ion dynamic in tokamaks based on classical physics. In addition, NUBEAM has options to model fast ion transport mechanisms different from classical through *ad-hoc* diffusivity and convection terms, which result in a radial fast ion flux proportional to the local fast ion density

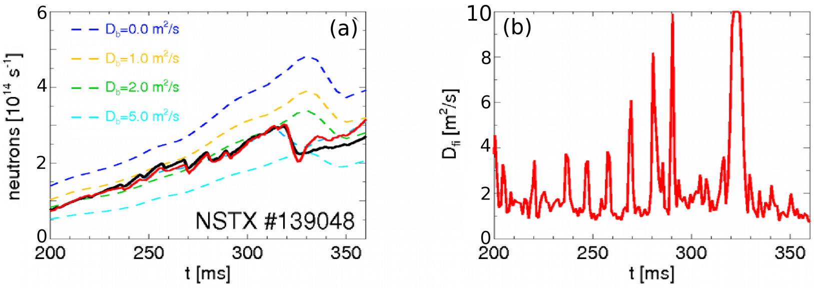

FIG. 2: TRANSP analysis with fast ion diffusivity $D_{fi}(t)$. (a) Measured neutron rate (thick, black) compared to predictions with different levels of diffusivity. The thick, red curve shows the inferred $D_{fi}(t)$ assumed to match the experimental value. (b) $D_{fi}(t)$ coefficient corresponding to the thick, red curve of simulated neutron rate in (a).

gradient and density. Although these non-classical transport models in NUBEAM do not contain the physics of resonant interaction between instabilities and fast ions, they are widely used and do indeed capture, although empirically, some of the major effects of instabilities on fast ion evolution, see for instance Refs. [9][10]. A metric that is commonly used to set the level of additional fast ion diffusivity, D_{fi}, is the agreement between measured and simulated neutron rate. Typically, $D_{fi}(t)$ is adjusted until a satisfactory agreement is found, see Fig. 2. (Here and in the following a D_{fi} uniform in radius and phase space is used). TRANSP simulations with the adjusted $D_{fi}(t)$ are then used to compute the NB-driven current.

2.2 *Kick model* for consistent phase space evolution

The main limitation of TRANSP simulations with an ad-hoc $D_{fi}(t)$ is that wave-particle interaction is treated in a very rough manner, since all fast ions are subject to the same diffusion rate. Even if modifications of fast ion profile or NB-driven current are inferred from the model, uncertainties remain to quantify the relative contribution of each class of instabilities (TAE vs. kink-like modes). This can not be properly taken into account by simple modeling with an ad-hoc $D_{fi}(t)$.

Instabilities such as TAEs act on fast ions through specific mechanisms. Consider a particle orbiting in the presence of a single mode with toroidal mode number n and frequency $\omega = 2\pi f$. Based on the guiding center Hamiltonian formulation, a precise relationship exists between mutual variations of energy and toroidal angular momentum (E and P_ζ) [11][12]:

$$\omega P_\zeta - nE = const. \rightarrow \Delta P_\zeta / \Delta E = n/\omega \quad (1)$$

This sets a constraint for the allowed trajectories in the (E, P_ζ) space. If a finite mode frequency width is assumed and if more than one mode are present, ΔE and ΔP_ζ can depart from the ideal (linear) relation of Eq. 1. The main ingredient of the newly developed *kick* model [6] is the probability $p(\Delta E, \Delta P_\zeta | E, P_\zeta, \mu)$ that a particle characterized by the constant of motions (P_ζ, E, μ), experiences E and P_ζ variations of magnitude ΔE and ΔP_ζ (μ is the magnetic moment). Variations are consistent with Eq. 1 in the presence

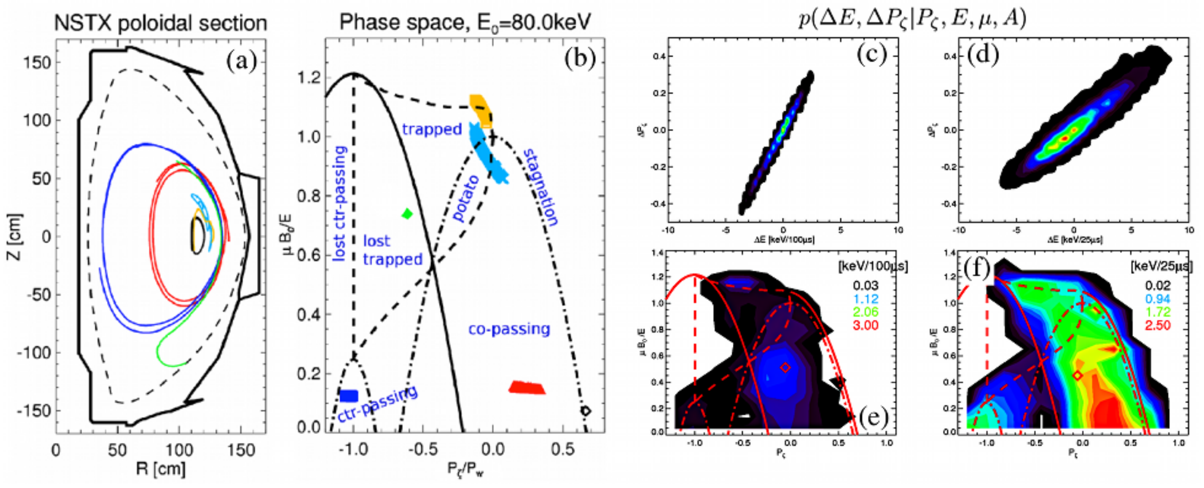

FIG. 3: (a) Representative fast ion orbits in NSTX for particles with $E = 80$ keV but different values of pitch, P_ζ and μ. (b) Same orbits represented in phase space. Orbit classification follows Ref. [11]. Right panels show the probability $p(\Delta E, \Delta P_\zeta)$ resulting from (c) a kink-like mode and (b) TAEs for particles with $E = 80$ keV, $P_\zeta \approx 0$ and $\mu B_0/E \approx 0.5$. (e-f) Rms energy kicks for kinks and TAEs for $E \approx 80$ keV.

of a mode with amplitude A_{mode}. In practice, $p(\Delta E, \Delta P_\zeta)$ can be computed via particle following codes such ORBIT [13] or directly from theory. Note that the probability is computed in phase space, therefore it represents the average effects of the modes on the entire particle orbit instead of at each point in space. It is assumed that μ is conserved, which is a reasonable assumption for low-frequency Alfvénic modes with $\omega \ll \omega_{ci}$ (ω_{ci} being the ion cyclotron resonance frequency), such as TAEs.

3 NB-CD modifications by MHD

The effects of instabilities are first simulated via the transport code TRANSP by assuming an ad-hoc, radially uniform fast ion diffusivity $D_b(t)$, cf. Fig. 2b. A net redistribution of NB-driven current is observed when instabilities are accounted for, see below. To obtain more accurate results, experiments are interpreted through the new *kick* model. The simulation procedure is explained in detail in Ref. [6]. At present, it has been implemented in a *stand-alone* version of the NUBEAM module of TRANSP. Implementation and validation for the full time-dependent TRANSP code is under way. An example of initial simulations for the NSTX scenario described in Fig. 1 is given in Fig. 4 for a time window in which only TAE modes are observed. The temporal evolution of the total TAE mode amplitude is inferred from the neutron rate variations induced by TAE bursts. Here and in the following, A_{mode} for TAEs is scaled to match the measured mode activity level [4].

It can be seen that TAE avalanches induce a rapid decrease of fast ion content and NB-driven current. Drops of up to $\approx 50\%$ are computed for 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 $\sim 15-20$ ms for this case. The rate of recovery is mainly determined by the

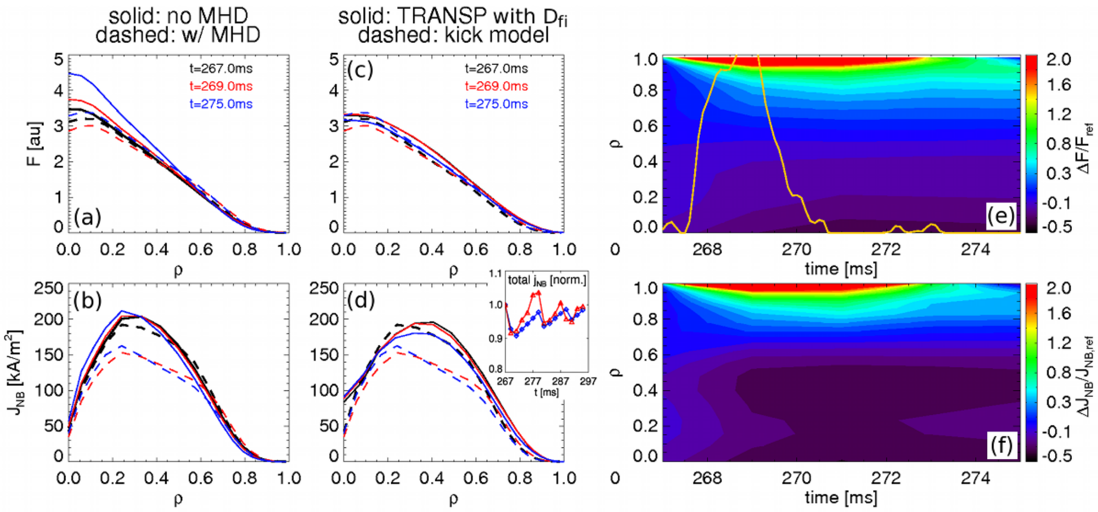

FIG. 4: Effects of bursting TAEs on fast ion and NB-driven current profiles (ρ: normalized radius). (a) Fast ion profile before, just after and 10 ms after a TAE burst, computed through the kick model. (b) Same as in (a) for the NB-driven current profile. Solid (dashed) lines in (a-b) refer to simulations without (with) enhanced transport from TAEs. (c-d) Comparison between F_{nb} and J_{nb} computed through kick and ad-hoc D_{fi} models. The inset in (d) shows the time evolution of the total, normalized NB-driven current. (e-f) Relative variation of $F_{nb}(\rho)$ and $J_{nb}(\rho)$, normalized to the no-modes reference case. The solid line in (e) shows $A_{mode}(t)$.

NB injection rate. Results obtained from TRANSP with $D_{fi}(t) \neq 0$ and from the kick model are compared in Figs. 4c-d. Drops in the fast ion density are comparable, whereas the ad-hoc D_{fi} model underestimates the NB-driven current redistribution. This suggests that the F_{nb} evolution is rather different in the two cases, as expected from the different approaches underlying the two fast ion transport models used in the simulations.

Later in the discharge, a kink-like mode and its harmonics are also destabilized. Results from modeling with the *kick* model are shown in Fig. 5. TAE mode amplitude is scaled to match the measured level. The normalized kink amplitude from Mirnov coils is then scaled to match the neutron rate. As for the previous example, $p(\Delta E, \Delta P_\zeta)$ is computed through ORBIT [13]. Simulations are performed for TAEs-only, kink-only and TAEs plus kink cases. Because of the different mode structure (Figs. 1d-e) and interaction with fast ions (Figs. 3c-f), the two type of instabilities have a different effect on J_{nb}, and especially on its profile. When both instabilities are included, the local drop in J_{nb} exceeds 40% with respect to the no-MHD case, providing an estimate of the rather dramatic effects of instabilities on the overall NB-CD efficiency. Redistribution of fast ions is also significant and mostly affects high energy fast ions, $E \geq 50$ keV (Figs. 5e-g).

An interesting result from the examples discussed above is that relative changes in the core fast ion content appear smaller than for the NB driven current (Fig. 4a-b). Analysis of the inferred phase space modifications (Fig. 6) indicates that TAEs mainly affect strongly co-passing fast ions with large parallel velocity, 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.

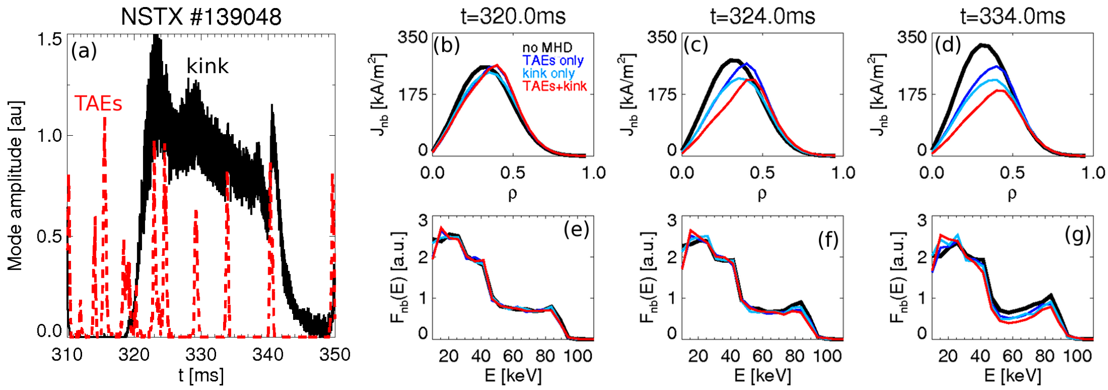

FIG. 5: Modifications of NB-driven current by TAEs and kink-like modes. (a) Normalized mode amplitude evolution. (b-d) $J_{nb}(\rho)$ at three different times assuming different instabilities acting on fast ions. Thick black profiles refer to the no-mode case. (e-g) Variations of the fast ion energy distribution around $\rho = 0.5$ for the cases in (b-d).

4 Projection to NSTX-Upgrade scenarios

Besides the analysis of actual discharges, the new modeling tool is also suitable for scenario predictions and development. To this end, a procedure is developed and tested to make initial predictions of NB-CD performance for scenarios on the NSTX-U [14] 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. Extensive scenario predictions have been performed in the past to explore the achievable plasma regimes and configurations [15]. In this Section, a specific scenario with $B_t = 0.8$ T is investigated as an example of the predictive capability of the new model. Three NB sources are used to heat the plasma and drive non-inductive current. The mostly tangentially-aimed sources result in a peaked fast ion pressure profile, whose maximum value attains three times the pressure measured on a comparison NSTX discharge, cf. profiles in Fig. 7a-c. The fraction of NB-driven current is about 30% of the total current.

Linear stability analysis through NOVA-K indicates that TAEs can be, in fact, unstable for high NB power NSTX-U discharges [16], including the discharge discussed herein (Fig. 7d-e). The spectrum of most unstable modes with $n = 2-6$ from NOVA-K analysis is used as input for the following analysis. Mode structures are shown in Fig. 7f. Mode amplitudes are scaled to mimic discharges with stationary TAE activity.

Predicting the actual mode saturation level is challenging. Instead, a parametric study is performed. TAE amplitude is varied, and the resulting effects on NB current drive efficiency are quantified through modeling. Initial results are shown in Fig. 7g-l. As for typical NSTX scenarios, a plethora of TAE resonances is observed. Resonances are dense in phase space regions populated by co-passing fast ions, although trapped particles can also be affected at high energy (cf. Fig. 15 in Ref. [16]). First, TRANSP modeling with ad-hoc D_{fi} is used, see Fig. 7g-h. For values $0 < D_{fi} < 2$ m^2/s, typical of NSTX plasmas, the effects on *total* J_{nb} are quantified as $\lesssim 15\%$ of the classical J_{nb} value. Similar values are obtained when an avalanching scenario is simulated. The relatively small drop in J_{nb} even for the highest diffusivity may appear surprising. In fact, this is explained by

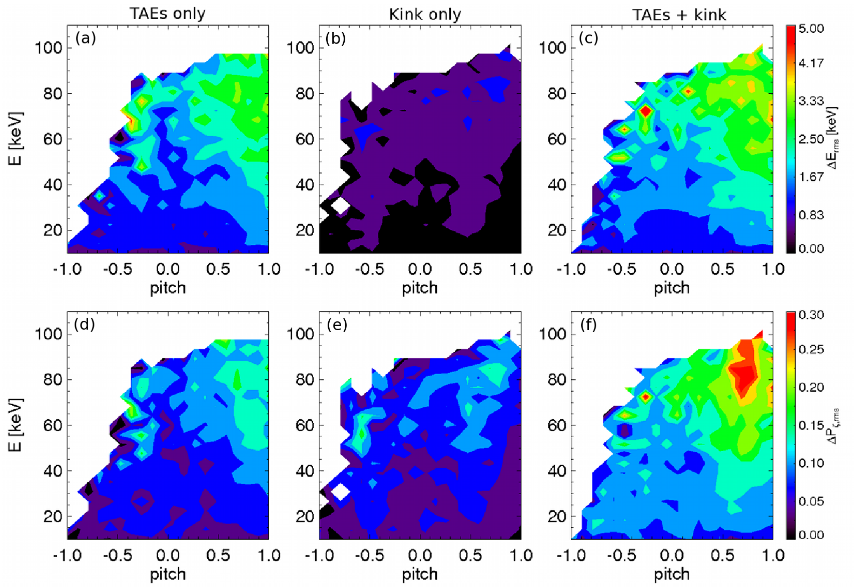

FIG. 6: Detail of the phase space dependence of E and P_ζ variations computed by the kick model for the cases show in Fig. 5c-f. Variations are computed as the rms values ΔE_{rms}, $\Delta P_{\zeta,rms}$ for the original fast ion distribution $F_{nb}(E,p)$ around $\rho = 0.5$.

the centrally-peaked J_{nb} profile. As shown in Fig. 7h, current is redistributed from the core to larger radii, but the majority of current is still driven in the core, inside $\rho \sim 0.75$.

The kick model is then applied for different values of mode amplitude, $0 < \delta B/B < 10^{-4}$. For a direct comparison with TRANSP data, results are shown as a function of an *effective diffusivity* D_{eff}, which corresponds to the D_{fi} value from TRANSP simulations required to cause a comparable drop in the neutron rate. The simulated effects on J_{nb} are shown in Figs. 7i-l. The drop in *total* NB-driven current is comparable for the two transport models. However, the modified $J_{nb}(r)$ profiles are substantially different. The kick model predicts more localized variations at the lower diffusivity for small mode amplitude, caused by the localization of the modes around $\rho \approx 0.5$. At higher D_{eff} (i.e., larger mode amplitude) perturbations of J_{nb} propagate to the plasma center, but the relative, local effects are still considerably smaller than when the ad-hoc D_{fi} is used.

Clearly, these results depend on the specific prediction for the TAE mode structure [16] and plasma profiles [15], hence for the probability $p(\Delta E, \Delta P_\zeta)$ used in the kick model. Although linear stability is used here to select the unstable spectrum, in practice non-linear TAE physics can result in a different spectrum, including coupling to - and destabilization of - otherwise stable modes [17]. For instance, when the broader mode structures from #139048 (Fig. 1) are used instead of those from #133964, a drop in the central $J_{nb}(r)$ is observed, see dashed curve in Fig. 7l. Besides the reliability of linear TAE stability calculations to quantitatively predict spectrum and saturated amplitude of TAEs, a main conclusion of the present work is that TRANSP analysis with an *ad-hoc* D_{fi} provides reasonable estimates for global quantities (neutron rate, total current), but may fail when estimated quantities depend strongly on fast ion phase space details (e.g., J_{nb} profile).

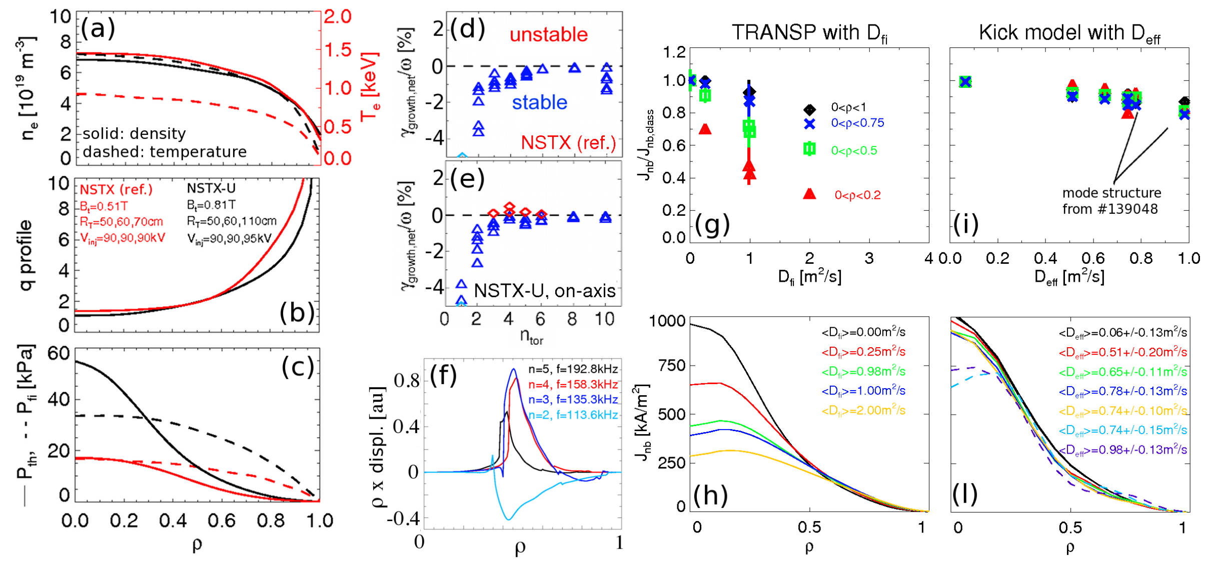

FIG. 7: (a-b) Predicted NSTX-U scenario with on-axis NBI and reference NSTX scenario, shot #133964. (d-e) NOVA-K linear stability analysis for the two cases and (f) Structure of most unstable modes for the NSTX-U case. (g-h) Relative current variations and profile modifications from TRANSP analysis with D_{fi}. (i-l) Same as in (g-h) computed through the kick model. The dashed curve in (l) refers to simulations using the broader mode structures from Fig. 1d.

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