Fast Particle Destabilization of TAE Type Modes in NSTX, JT-60U and Proposed Burning Plasma Devices.[1]

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Abstract. The properties of fast ion driven TAEs are studied in National Spherical Torus Experiment (NSTX), JT-60U, and proposed DT burning plasma experiments in International Tokamak Experimental Reactor (ITER), FIRE, and IGNITOR, and JET DT operation. Unstable TAEs have been observed in NSTX and JT-60U experiments to cause significant fast ion loss. Theoretical studies employing the global kinetic-MHD stability codes, NOVA/NOVA-K code, and a high-n non-perturbative HINST code have been performed, and the analysis explains well the experimental results. For the proposed DT burning plasma experiments TAEs are expected to be unstable in ITER and FIRE.

1. Introduction

Of major importance in burning plasma studies is the fast ion confinement. In burning plasmas 3.5 MeV α-particles and other fast ions transfer their energy to the background plasma. Collective instabilities destabilized by fast ion pressure gradient can cause premature loss of fast ions from the confinement system. Theory and experiment have confirmed that large amplitude Toroidicity-Induced Alfvén Eigenmodes (TAEs) [1–3] can lead to expulsion of fast ions, degrade ignition margin and produce localized heating or damage on plasma facing components. The TAE frequency is $\omega \sim V_A/2qR$, where V_A is the Alfvén velocity, q is the safety factor, R is the major radius. TAEs can resonate with energetic particles with $V_h \sim V_A$ and can be destabilized by the energetic particle phase space gradient (pressure gradient and positive energy gradient). For a slowing-down energy distribution, fast particles can drive TAEs if $nq(V_h/V_A) \geq (rL_p/R\rho_h)$, where n is the toroidal mode number, r is the minor radius, and ρ_h, L_p are the hot ion gyroradius and pressure gradient scale length, respectively. Thus, the device size, which determines L_p/ρ_h and aspect ratio, is an important parameter in determining the unstable TAE spectrum. However, TAEs can be unstable only if the fast particle drive overcomes damping effects of bulk electron and ion Landau damping, radiation and continuum damping.

In the paper we address the properties of fast ion driven TAE type modes in NSTX and JT-60U and in the proposed burning plasma experiments of ITER, FIRE, IGNITOR, and JET-DT operation. For NSTX we present TAE results observed even for a modest NBI power and compare the experimental results with theoretical analysis. For JT-60U we present theoretical interpretation for TAEs destabilized by NNBI fast ions in normal shear discharges. For the proposed burning plasma experiments we present TAE stability analysis and summarize the parameter domain where TAEs are expected to be unstable due to α-particles produced in D-T fusion reaction. The stability of TAE-type modes is analyzed by employing global kinetic-MHD stability codes, NOVA/NOVA-K codes [4], and a high-n non-perturbative HINST code [5].

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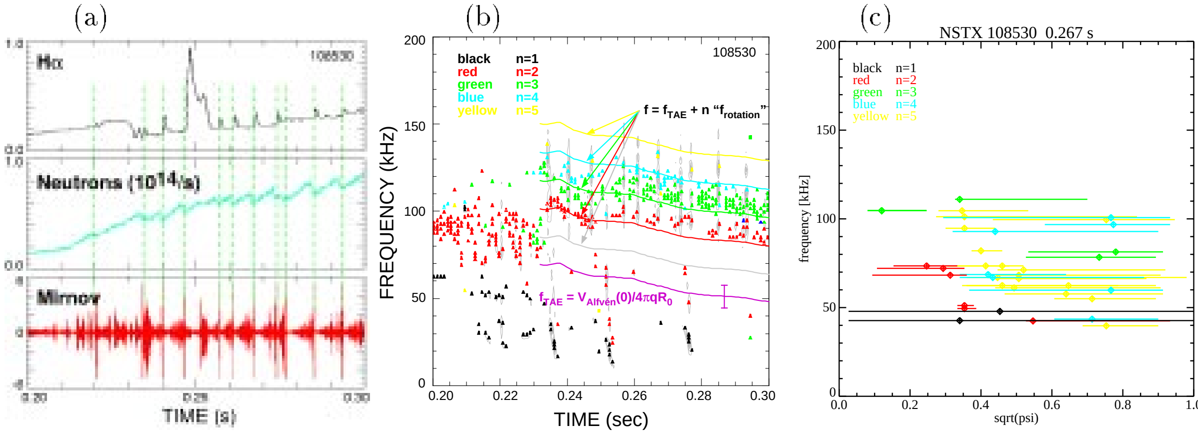

FIG. 1: (a) and (b) show TAE activities observed in the NSTX shot 108530, and (c) shows TAE spectrum at 0.267 sec computed by the NOVA/NOVA-K codes.

2. TAEs in NSTX

TAE modes have been observed in NSTX even for modest NBI power. Because of low aspect ratio the toroidal coupling effect is strong. The Alfvén continuum gap is wide open across the minor radius and a broad spectrum of TAEs can exist [6] for each toroidal mode number n. A variety of modes in the frequency range from 20 to 150 kHz with toroidal mode numbers from $n = 1$ to $n = 6$ are commonly seen in beam heated discharges. FIG. 1(a) shows the Mirnov magnetic field fluctuation and corresponding total neutron count rate and H_α signal in the NSTX shot 108530. FIG. 1(b) shows a broad spectrum of TAEs observed with several frequencies for each n. The plasma parameters for this shot are $B_0 = 0.434T$, $R = 87cm$, $a = 63cm$, ellipticity $\epsilon = 1.74$, triangularity $\delta = 0.5$, and the deuterium neutral beam is injected co-tangentially to the plasma current (but counter to the toroidal field) with an injection energy of 80 keV. At 0.09 sec the beam source A is injected with 1.6 MW power, and at 0.21 sec a second beam B is injected and the total NBI power is 3.2 MW and the steady state plasma current is about 0.65 MA. In addition to the more commonly observed quasi-continuous TAEs, bursting TAEs (indicated by vertical dashed lines in FIG. 1(b)) are also observed after the beam B is injected at 0.21 sec. These bursting modes are associated with fast neutron drops, H_α micro-bursts, and $5 - 10\%$ fast ions hitting the wall. Each burst consists of multiple modes with n range from 2 - 5 with a dominant mode being $n = 2$ or 3. From the bursting mode amplitude modulation one sees beating of multiple modes, but the bursting fluctuation is dominated by a single frequency mode with mode growth and decay times approximately 50 - 100 μs. The TAEs are most commonly present in the early phase of the discharge, during the current ramp and when the density is low ($2-3\times10^{13}cm^{-3}$ on axis). The higher n modes are generally associated with higher frequencies, possibly related to increased Doppler shift due to plasma rotation. However, the mode spacing is not nearly as uniform.

FIG. 1(c) shows a very rich TAE frequency spectrum and the radial extent (half width) of TAEs for $n = 1 - 5$ modes computed by the NOVA/NOVA-K code. The NSTX equilibrium is constructed with plasma profiles modeled by the TRANSP code at 0.267 sec, $q_a = 11.4$, $n_e(0) = 2.54 \times 10^{13}cm^3$, $\beta(0) = 21.4\%$, $\langle\beta\rangle \sim 2.88\%$. Note that for each n there are multiple TAEs. Only TAEs with frequency residing in the TAE continuum gap are chosen so that they do not suffer continuum damping. Higher frequency EAEs are excluded in the plot. Also, we restrict TAEs with peak amplitude located at radial location $r/a \leq 0.8$. Because the plasma toroidal rotation velocity is significant with $V_{rot}(0) \simeq 170\ km/s$ at 0.27 sec and has a peak profile, the frequencies shown in FIG. 1(c) are the NOVA computed TAE frequencies Doppler-shifted by $f = f_{TAE} + nf_{rot}$, where

f_{rot} is weighted by the square of the mode amplitude and is averaged over the mode half width. With $V_{rot} = 100km/s$ and $R = 1m$, we have $f_{rot} \simeq 16kHz$. These $n = 1 - 5$ TAEs with peak amplitude located inside $r/a \leq 0.5$ can be destabilized by NBI ions, in good agreement with the NSTX experimental results shown in FIG. 1(b). The calculated linear growth rates are about 10% of the real frequency for $\beta_h(0) \simeq 13\%$.

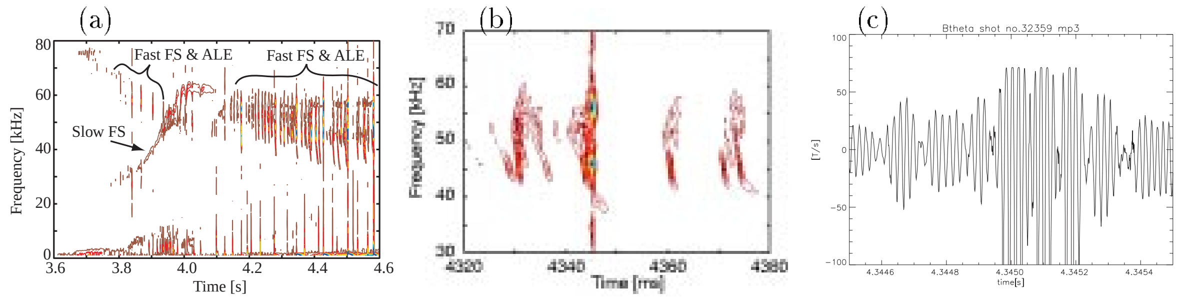

FIG. 2: TAEs observed in the JT-60U shot E32359.

3. TAEs in JT-60U

In JT-60U experiments, very rich TAE-type mode activities have been observed [7, 8]. In the Negative-ion-based Neutral Beam Injection (NNBI) (injection energy at $\leq 400keV$) experiments with normal magnetic shear, three types of modes have been found as shown in FIG. 2 for the E32359 shot. The NNB fast ion parameters are $V_b/V_A \leq 1.5$, $0.1\% \leq \langle\beta_h\rangle \leq 1\%$, which are similar to α-particle parameters in ITER with $V_\alpha/V_A \leq 1.5$, $\langle\beta_\alpha\rangle \sim 0.2\%$. The first type is the quasi-continuous modes that can last through out NNB injection and is explained as TAEs with frequency variation due to variation of the profiles of magnetic safety factor and plasma density. The second type is slow frequency upward sweeping modes that last for 100s of $msec$ (from 3.8 to 4 sec in FIG. 2(a)) and is explained as resonant TAE (RTAE) [9]. These modes are RTAEs because their frequencies at the initial chirping stage are inside the Alfvén continuum and they occur when the fast particle drive is strong, so that these modes can overcome the continuum damping. The reason for the slow frequency chirping is the evolution of the fast particle pressure profile and corresponding shift of the RTAE radial location accompanied by the change in the mode frequency during the fast particle pressure buildup. Similar slow frequency chirping modes were also modeled by the HINST code to explain the observed changes of the mode frequency in TFTR. The third type is bursting modes (or called the Abrupt Large-amplitude Events (ALE) [8]) that last typically less than 0.5 $msec$, which are much shorter than the time scale of equilibrium profile evolution. The bursting mode frequency remains almost unchanged during bursting, but the amplitude varies very fast in a few wave periods as shown in FIG. 2(c), which is caused by the change in the fast particle velocity and/or spatial distribution during the nonlinear phase. We construct a JT-60U equilibrium at 4.3 sec with $R = 3.37m$, $a = 83cm$, $\epsilon = 1.49$, $\delta = 0.15$, $B_0 = 1.2T$, $q_a = 4.7$, $n_e(0) = 2 \times 10^{13}cm^3$, and $\langle\beta\rangle = 0.74\%$. The NOVA/NOVA-K code calculation gives $71kHz$ for an $n = 1$ TAE, $66kHz$ for an $n = 2$ TAE. If we include the downward Doppler frequency shift due to the plasma rotation (assuming $V_{rot} \simeq 150km/s$) resulting from the co-tangential (to both the plasma current and toroidal field) injection of NNB and PNB to the plasma current and the toroidal field, the computed TAE frequencies are consistent with the observed mode frequencies for $n = 1$ and 2 TAE modes.

Significant fast ion loss has been found during the presence of bursting modes, in particular, during ALEs. The fast ion loss was seen indirectly in both drop in neutron emission rate and enhancement of neutral particle flux measured by the neutral particle analyzer (CX-NPA). Because about 90% of neutron emission rate is from beam-target reaction in the NNB experiments, the sudden drop in neutron emission rate during bursting modes can only be caused by either rapid deceleration of NNB ions or by a radial transport of the beam ions to a lower background density region. But, the beam ion slowing-down time in the plasma core region is about $0.5sec$, which is much longer than the time scale of neutron emission rate drop. Moreover, from the energy spectra of the fast neutral flux, the peak flux enhancement is at about $260keV$, which is the energy of beam ions resonating with the bursting modes. These lead to the conclusion that lost fast ions are ejected while resonating with bursting modes. Moreover, the neutron flux signals increase in the peripheral region ($r/a \geq 0.48$) and decrease in the central region ($r/a \leq 0.34$) during the occurrence of ALE bursting modes, which suggests that ALE bursting modes cause a large radial transport of fast ions.

Tokamak	R,m	a,m	B_0, T	$n_{e0}, \frac{10^{14}}{cm^3}$	T_{i0}, keV	σ	$\beta_{\alpha 0}, \%$	$-R\nabla\beta_\alpha, \%$	V_h/V_{A0}	$a/\rho_{\alpha 0}$
ITER-FEAT	6.2	2	5.3	1	19.3	0.78	0.7	5	1.8	39.1
FIRE	2.14	0.6	10	4.9	11.9	0.825	0.28	1.3	2.1	22.14
IGNITOR	1.32	0.48	13.1	9.4	9.9	0.91	0.2	0.8	2.21	23.2
JET-DT	2.92	0.94	3.82	0.45	23	0.795	0.4	2.3	1.66	13.25

TABLE I: KEY PLASMA PARAMETERS FOR BURNING PLASMA DEVICES.

4. TAEs in Proposed Burning Plasma Experiments

The TRANSP code is employed to model plasma conditions for the proposed burning plasma experiments of ITER, FIRE, IGNITOR and JET-DT operation. Despite noticeable difference in the device size, most dimensionless plasma parameters appear to be quite similar for these burning plasmas as seen from TABLE I, where $\sigma = (n_D + n_T)/n_e$ is the plasma ion depletion factor, $\rho_{\alpha 0}$ is the alpha gyroradius at the birth energy with B_0. The HINST [5] is used to analyze the local TAE stability. As expected, TAEs can be driven by α-particles for all these burning plasma experiments with growth rate on the order of a few percent of frequency [10]. The mode spectrum and their radial location are different for different machine sizes. For FIRE, IGNITOR and JET-DT the unstable spectrum is in the range of $1 \leq n \leq 10$. For ITER the of unstable spectrum has higher n with $5 \leq n \leq 12$ due to a larger value of $|(\rho_{\alpha 0}/a)R\nabla\beta_\alpha|$.

FIG. 3 shows the frequency and growth rate versus the normalized toroidal flux $\sqrt{\Phi/\Phi_0}$ for (a) $n = 10$ TAEs in ITER, (b) $n = 7$ TAEs in FIRE, and (c) $n = 5$ TAEs in JET, where TRANSP generated q-profile as well as the model q-profile, but otherwise parameters obtained from TRANSP was used. Note that the IGNITOR case is not shown because TAEs turn out to be robustly stable, though sometimes close to the marginal stability, because of weak α drive due to low β_α and strong trapped electron collisional damping due to high density. For ITER, from FIG. 3(a), the instability region lies within $0.35 < \sqrt{\Phi/\Phi_0} < 0.7$, which is primarily due to the lower damping at $\sqrt{\Phi/\Phi_0} \sim 0.5$. Note that in ITER high energy D beams at $1MeV$ energy are planned for better penetration into the plasma, and they can provide additional instability drive for TAEs for a wide range of n-values due to the large value of $\omega_{*\alpha}$ term and the strong anisotropy of the beam ion velocity space distribution. From the global NOVA-K code calculation, the unstable TAE spectrum expand towards higher n-values due to 1 MeV beam ions, and the beam ion TAE drive is similar to the alpha drive. For lower energy beam ions the drive will be weaker and at 500 keV energy the beam ion drive is reduced by one half.

For FIRE, with the TRANSP calculated central value of $\beta_{\alpha 0} = 0.28\%$, the radial span of the TAE unstable region lies within $0.5 < \sqrt{\Phi/\Phi_0} < 0.65$ and the growth rate sharply

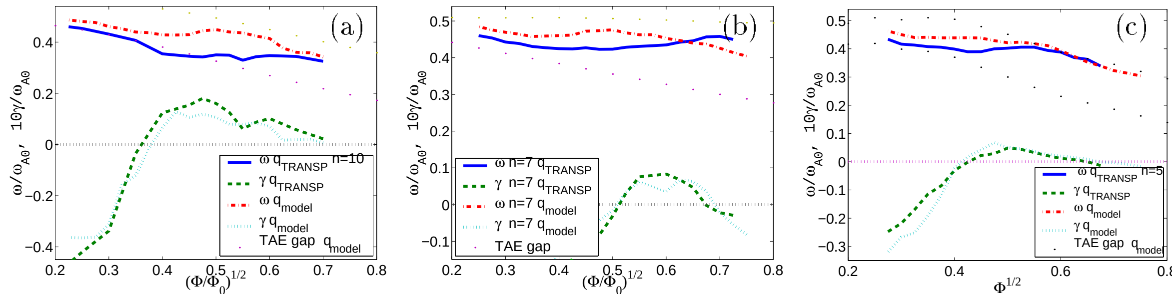

FIG. 3: TAE eigenfrequency and growth rate as functions of the minor radius in (a) ITER ($n = 10$), (b) FIRE ($n = 7$), and (c) JET ($n = 5$) for TRANSP and a model q-profiles.

decreases outside that region as shown in FIG. 3(b). For JET-DT plasmas the maximum growth rate, without NBI ions, is rather low at $n \simeq 6$ as shown in FIG. 3(c), which is close to what was predicted in other studies [11]. Including NBI fast ions, an additional strong stabilizing effect is present due to beam ion Landau damping. We computed the TAE growth rate for a deuterium NBI beta $\beta_b(0) = 0.6\%$ at 100 keV injection energy, we found at $\sqrt{\Phi/\Phi_0} = 0.5$ the $n = 5$ TAE is stabilized primarily due to damping on beam ions, consistent with the previous study [11].

Finally, because TAEs typically have a global structure, a more accurate stability calculation will require taking an appropriate average over the minor radius. The nonlocal calculation has been performed with the NOVA/NOVA-K codes, and TAEs are usually found to be more stable than from the HINST code. However, for ITER and FIRE TAEs are still expected to be unstable.

5. Summary

In summary, we have performed studies of TAEs for presently operating devices, NSTX and JT-60U, as well as for the proposed DT burning plasma experiments of ITER, FIRE, IGNITOR and JET-DT operation. For NSTX and JT-60U bursting type TAEs are found to cause significant fast ion loss. Theoretical investigations yield TAE frequencies and stability, consistent with experimental observations. For the proposed DT burning plasma experiments, the global and local calculations predict that TAEs would be unstable for ITER and FIRE.

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