Parametric Study of Linear Stability of Toroidal Alfvén Eigenmode in JET and KSTAR

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❖ *Main results are highlighted in red boxes.*

1. Abstract

- In JET, beam damping of TAE (driven by ICRH) is general when NBI is on, while the beam in other devices such as KSTAR usually drives the modes.
- Parametric study was conducted to understand the mode destabilizing criteria by the beam using the analytic expressions for (γ/ω) of TAEs.
- The parametric dependence of the beam-TAE stability with the parameter Δ_b/Δ_m shows good agreement with KSTAR experiments.
- TAE growth rate by ICRH was derived for modelling ICRH-driven TAE in JET.
- The linear stability of TAE was calculated using the analytic expressions in #92416 in JET, noting that the strong beam interaction with the modes requires rather high plasma density for the resonance condition $v_{b\parallel} = v_A/3$, as well as enough β_b.
- Alpha particle effect on TAEs was predicted for the future DT campaign in JET.

2. TAE interaction with beam ions

- **Parametric dependence on the linear growth rate of TAE by beam ions**

- NBI has a damping effect of TAE in JET ($\gamma_{NB}^{drive} < \gamma_{NB}^{damp}$) while driving in other devices ($\gamma_{NB}^{drive} > \gamma_{NB}^{damp}$) in spite of its same resonance condition $v_\parallel = v_A/|2s-1|$.

(FOW effect)

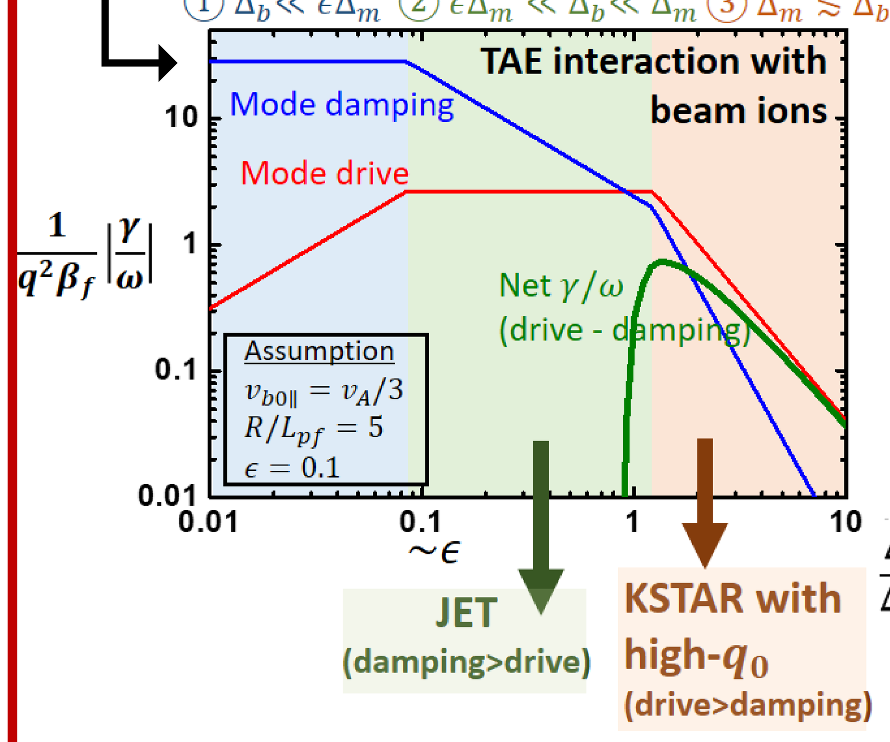
$$\left.\begin{aligned}\left(\frac{\gamma}{\omega}\right)_{NB}^{drive} &= -q^2\beta_b \frac{\omega_{*b}}{\omega}(1+\cos^2\theta_0)^2 \\ \left(\frac{\gamma}{\omega}\right)_{NB}^{damp} &= -3q^2\beta_b(1+\cos^2\theta_0)^2/y_s^2\end{aligned}\right\} \times \begin{cases} \frac{3\pi}{4} y_s^4 \eta(1-y_s) & \Delta_b \ll \Delta_m^{(i)} \left(\simeq \epsilon\Delta_m^{(o)}\right) \\ \frac{4\Delta_m^{(i)}}{\Delta_{bo}} y_s^3\eta(1-y_s) & \Delta_m^{(i)} \ll \Delta_b \ll \Delta_m^{(o)} \\ \frac{24\Delta_m^{(i)}\Delta_m^{(o)2}}{\Delta_{bo}^3} y_s\eta(1-y_s) & \Delta_b \gg \Delta_m^{(o)} \end{cases} \quad [1]$$

with $y_s = v_A/|2s-1|v_0\cos\theta_0$ the resonance parameter.

$$\left(* \frac{\omega_*}{\omega} \simeq \left(\frac{2}{9}\frac{R}{L_{pf}}\right)\frac{\Delta_b}{\Delta_m^{(o)}} \sim \frac{\Delta_b}{\Delta_m^{(o)}}\right) \quad [2]$$

- γ/ω has **different scaling dependence of Δ_b/Δ_m** w.r.t the orbit width regime [1].
- **Δ_b/Δ_m-dependence in drive and damping is also different** $\left(\because \frac{drive}{damping} \sim \frac{\omega_*}{\omega} \propto \frac{\Delta_b}{\Delta_m}\right)$.

① $\Delta_b \ll \epsilon\Delta_m$ ② $\epsilon\Delta_m \ll \Delta_b \ll \Delta_m$ ③ $\Delta_m \lesssim \Delta_b$



- Therefore, not only Δ_b/Δ_m causes the FOW correction, but also it determines which effect is dominant between drive and damping.
- For high-Δ_b/Δ_m, TAE drive > damping and for low-Δ_b/Δ_m, drive < damping.
- Here, Δ_b/Δ_m ($\propto q^2$) is strongly affected by q.

In **JET**, which shows beam damping generally, Δ_b/Δ_m is quite low due to the large r and B_0!

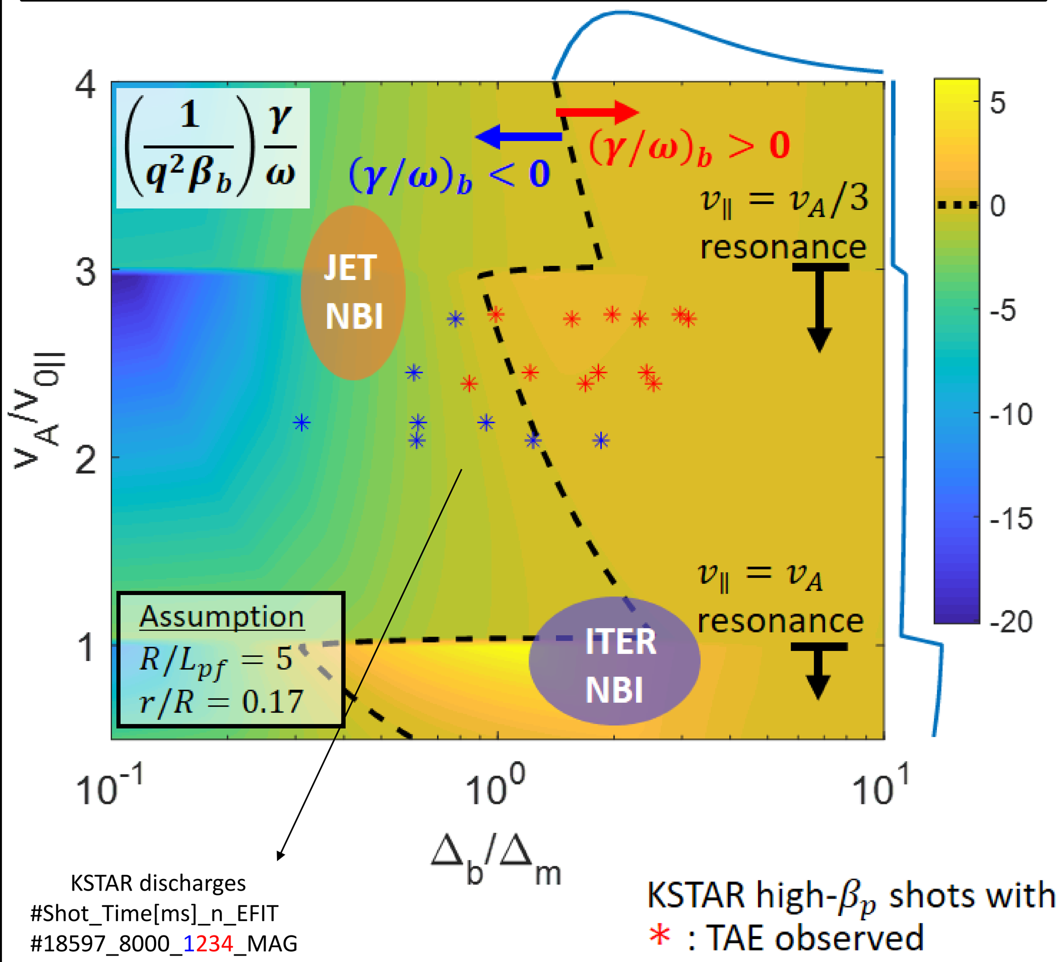
($n = 5, q = 2, E_{NB} = 100\ keV, a = 1\ m, B = 3.4\ T$)
$\rightarrow \Delta_b/\Delta_m \simeq 0.38$ **(TAE damping by NBI)**

In **KSTAR**, which often shows beam drive in high-q_0 ($q_0 \sim 3$) discharges (but not in low-q_0's), Δ_b/Δ_m is quite high.

($n = 3, q = 3, E_{NB} = 100\ keV, a = 0.5\ m, B = 1.8\ T$)
$\rightarrow \Delta_b/\Delta_m \simeq 1.9$ **(TAE drive by NBI)**

- **2D parametric scan with KSTAR discharges**

$$\left(\frac{\gamma}{\omega}\right)_f = q^2\beta_f\left[\left|\frac{\omega_{*f}}{\omega}\right|(\dots)_{drive} - (\dots)_{damp}\right] = q^2\beta_f F\left(\frac{\Delta_b}{\Delta_m}, \frac{v_A}{v_{0\parallel}}\right)$$



KSTAR high-β_p shots with
* : TAE observed
* : TAE not observed

: #21695 is aimed to enhance continuum damping by adjusting q profile by ECCD [3]. But this effect was not considered here.

- Since q, v_A are not significantly varying with radius in the core region, TAE stability by NBI can be simply checked only with 0D parameters, $q \simeq q_0$ and $v_A \simeq B_0/\sqrt{\mu_0 \bar{n}_i M_D}$.
- TAE is driven by sideband resonance with the beam ($v_\parallel = v_A/3$) in the cases with high Δ_b/Δ_m. $\rightarrow \Delta_b/\Delta_m$ determines whether beam drives TAE or not.
- It shows quite good agreements with experiments about NBI destabilizing criteria even without considering other damping mechanisms. $\rightarrow$ NBI contribution dominant in KSTAR?

3. Linear stability analysis with time-evolution in JET

- **TAE modelling with JINTRAC for JET application**

$$\left.\frac{\gamma}{\omega}\right|_{n,m} = \left(\frac{\gamma}{\omega}\right)_{RF} + \left(\frac{\gamma}{\omega}\right)_{NB} + \left(\frac{\gamma}{\omega}\right)_i [4] + \left(\frac{\gamma}{\omega}\right)_e [5] \qquad \left(\text{at } q = \frac{m+0.5}{n}\right)$$

From EP profile by PION-PENCIL — From plasma profile — ← JINTRAC [6]

* Equilibrium from EFIT with Faraday constraint (EFTF)
* n_e, T_e: fitted from HRTS, T_i: TRAU by M. Fitzgerald
* Flat q profile at core → continuum damping was not considered.

- **Modelling of the TAE interaction with ICRH fast ions**

- In JET, TAEs are usually driven by ICRH fast ions, showing different properties from NBI-driven modes in other devices.
- For the deeply trapped ICRH ions, $\Delta_b \sim qv/\sqrt{\epsilon}\omega_c \gg \Delta_m$, so nonlocal theory with $\omega - s\omega_b - \omega_P = 0$ condition should be adopted [1].

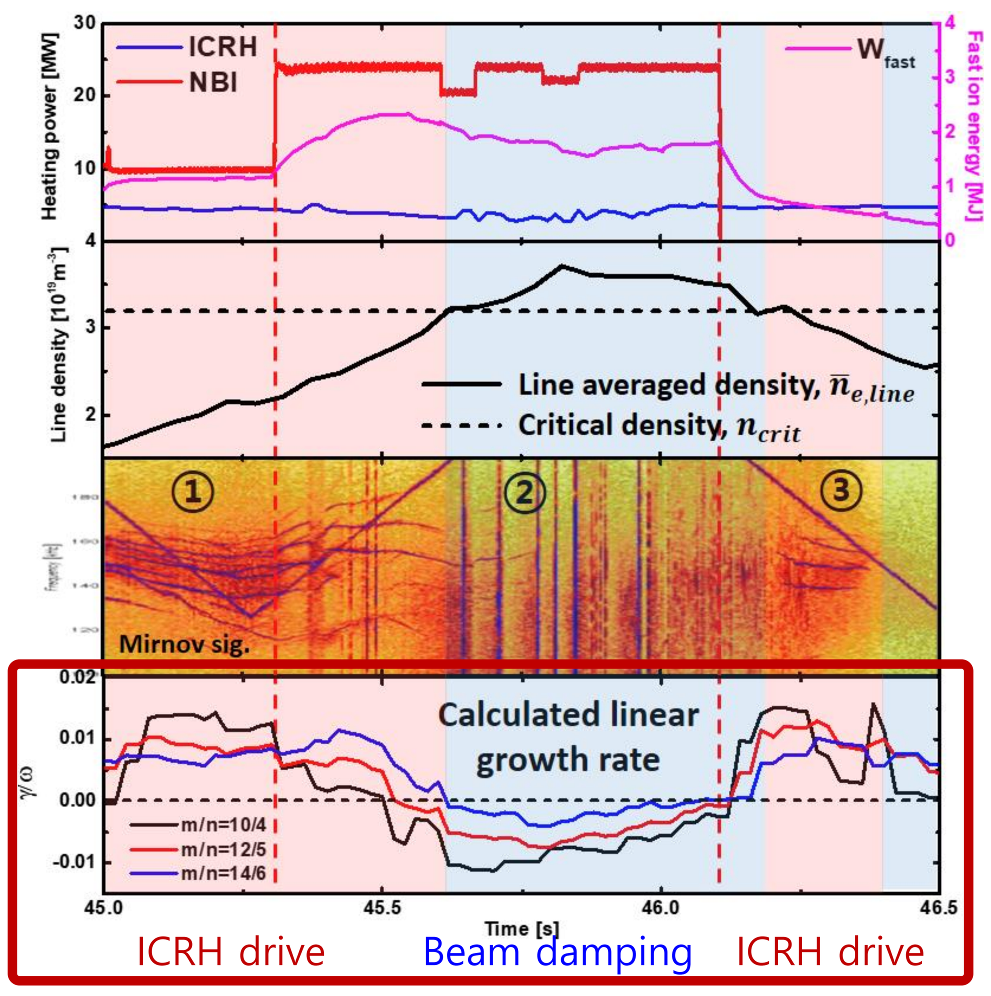
$$\frac{\gamma}{\omega} \simeq \frac{256\pi\mu_0\sqrt{2\epsilon}q^3 nM_f v_1^6}{B_0^2 r\omega_c D_1} J_0^2\left(\frac{mv_1}{r\omega_c}\right)\int_0^{\kappa_{max}^2} \kappa^2 d\kappa^2 \frac{\Delta_m^{(i)}\Delta_m^{(o)2}}{\Delta_{b,t}^3}\left(\frac{\omega}{\omega_*} - 1\right)\left.\frac{\partial f_0}{\partial r}\right|_{v=v_1} [1]$$

$$f_0 = \frac{n_f}{T_\perp\sqrt{T_\parallel}}\left(\frac{M_f}{2\pi}\right)^{\frac{3}{2}}\exp\left[-\frac{M_f v_\parallel^2}{2T_\parallel}\right]\exp\left[-\frac{M_f v_\perp^2}{2T_\perp}\right]$$: **bi-Maxwellian** assumed for ICRH fast ions

$$\Rightarrow \begin{cases} \left(\frac{\gamma}{\omega}\right)_{RF}^{drive} = -nq^3\frac{\partial\beta_f}{\partial r} J_0^2\left(\frac{mv_1}{r\omega_c}\right)\frac{\Delta_m^i\Delta_m^{o\,2}}{\zeta_t^3}\frac{v_1}{D_1 r\omega_c} F_{rf}\left(\frac{v_1}{v_{T\perp}}, \frac{v_1}{v_{T\parallel}}\right) \\ \left(\frac{\gamma}{\omega}\right)_{RF}^{damp} = -q\beta_f J_0^2\left(\frac{mv_1}{r\omega_c}\right)\frac{\Delta_m^i\Delta_m^{o\,2}}{\zeta_t^3}\frac{\sqrt{\epsilon}v_A}{D_1 R_0 v_1} G_{rf}\left(\frac{v_1}{v_{T\perp}}, \frac{v_1}{v_{T\parallel}}\right) \end{cases}$$

- Here, $\left|\frac{drive}{damp}\right| \sim \frac{nq^2}{L_{pf}}\frac{R_0 v_1^2}{r\omega_c\sqrt{\epsilon}v_A} \sim \frac{1}{\epsilon^{3/2}}\frac{\Delta_{b,t}}{\Delta_m^{(o)}} \gg 1$, indicating that the ICRH fast ions are destabilizing TAEs rather than damping, in agreement with the observations of ICRH-driven TAEs in JET.

- **Time-evolution of linear stability of TAE in #92416**

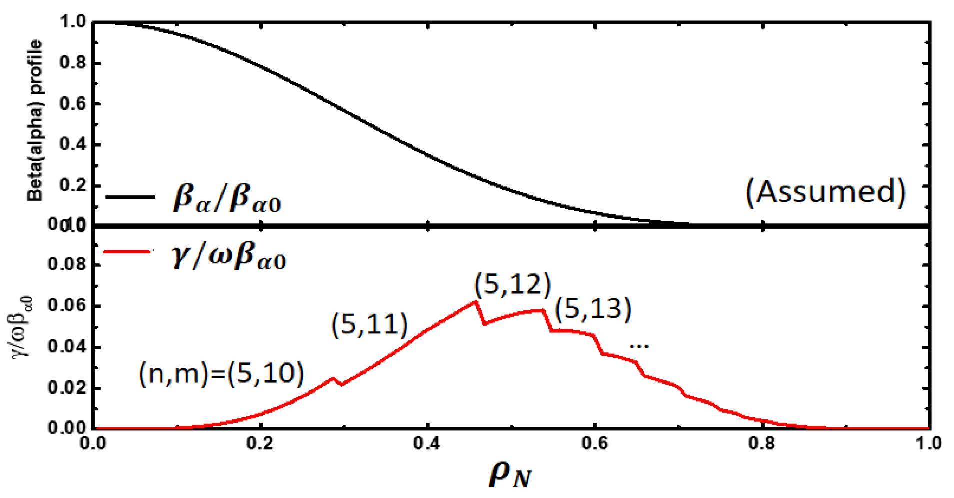


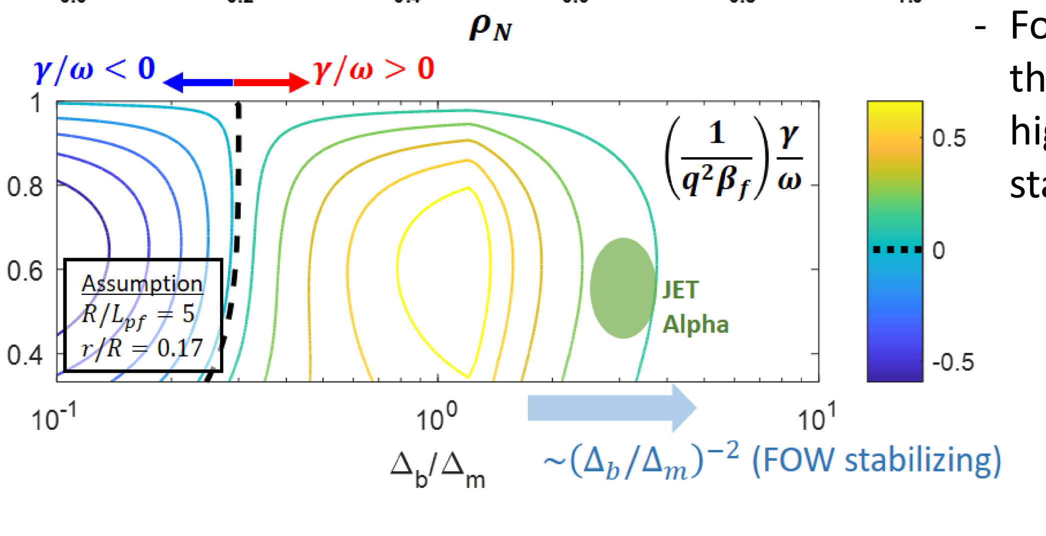
* $q_0 \simeq 2.1$ in the entire time domain.

① TAE is driven by ICRH fast ions.
② TAE is damped by increased β_{NB}.
③ Afterglow TAE after beam off.

- After increase of P_{NB} at 45.3 s, TAE is still undamped for ~300 ms, while the beam is absorbed enough in ~200 ms ($\tau_{thermalise} \simeq 150$ ms).
- To satisfy the beam resonance condition ($v_b = v_A/3$), plasma density must exceed the critical value, $n_{crit} = B_0^2/3\mu_0 M_i v_0^2$.
- As the density exceeds this critical value, TAE disappears by the beam damping.
- (γ/ω)-calculation well catches the stability of TAEs in spite of its simplicity so can be used for fast prediction.

- **Prediction of alpha particle contribution to TAE for DT scenarios**





- Assuming a core peaked alpha profile for DT, it shows relatively low TAE drive comparing with ICRH case (This plasma will be run without ICRH to ensure we can observe the effect of alpha particles).
- For $\beta_{\alpha 0} \sim 0.1\%$ [7], $\gamma/\omega < 0.01$ %.
- For alpha particles, Δ_b is much greater than the mode width Δ_m due to their high velocity, causing strong FOW stabilizing effect [1].

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4. Summary

- The effect of Δ_b/Δ_m on the linear growth rate of TAE by beam ions was analyzed to understand the beam-destabilizing criteria of the modes.
- The modelling of ICRH-driven TAE was conducted for describing the net linear stability of TAE in JET.
- Linear growth rate in time-evolving plasma in JET was calculated and shows good agreement with the experiments, noting that high plasma density is required for the beam resonance condition.