# Ion Heating by Nonlinear Landau Damping of High-n Toroidal Alfvén Eigenmodes in ITER

Plasma Laboratory for Advanced REsearch

**Jaemin Seo**, Y.-S. Na* and T.S. Hahm

*Department of Nuclear Engineering, Seoul National University, Seoul 151-744, Korea*
*ysna@snu.ac.kr

## Abstract

Bulk ion heating from nonlinear Landau damping of high-n Toroidal Alfvén Eigenmodes (TAEs) excited by energetic ions is studied. Based on the nonlinear saturation level of high-n TAEs which is confirmed by numerical studies of a wave-kinetic equation incorporating the ion Compton scattering-induced spectral transfer and the particle trapping by the wave, we assess potentially beneficial effect of bulk ion heating, so-called alpha channeling for ITER DT plasmas using an integrated simulation. The result indicates that, in its optimistic limit, the anomalous ion heating due to high-n TAEs can compensate the heating reduction due to energetic particle loss.

## Motivations

- For high-n TAEs ($n \gtrsim 10$) in ITER, the nonlinear mode interaction such as ion Compton scattering (ICS, or nonlinear Landau damping) can be a dominant mechanism for the saturation of TAEs [1,2,3].
- Previous analytic studies derived the saturation level of the modes by ICS [1,3] and the consequent bulk ion heating rate [2].
- We need to investigate how the multiple TAEs evolve dynamically and how significant the ion heating will be in ITER, which can be a candidate for the **alpha-channeling**.

## 2. Nonlinear evolution of high-n TAEs

- **Wave-kinetic equation** [1,2]

$$\frac{\partial}{\partial t}E_\omega = 2\gamma_L(\omega)E_\omega - \sum_{\omega'} M_{\omega,\omega'}E_{\omega'}E_\omega \qquad (1)$$

$$\frac{\partial}{\partial t}E_{ion} \simeq \sum_{\omega=\omega_1}^{\omega_M}\sum_{\omega'=\omega_1}^{\omega}\frac{\omega-\omega'}{\omega}M_{\omega,\omega'}E_{\omega'}E_\omega \qquad (2)$$

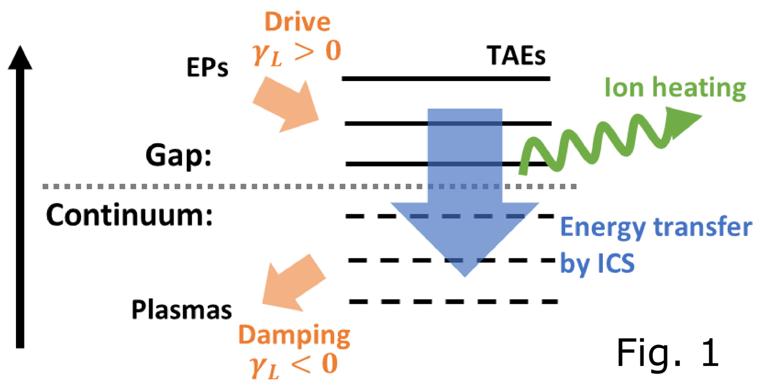


Fig. 1

- $\gamma_L > 0$ modes in the gap grows linearly and transfer the energy to lower $\omega$ modes by ICS.
- $\gamma_L < 0$ modes near the lower continuum are linearly stable, but are driven nonlinearly by the energy transfer.
- This system exhibits a typical predator-prey (PP) behavior.

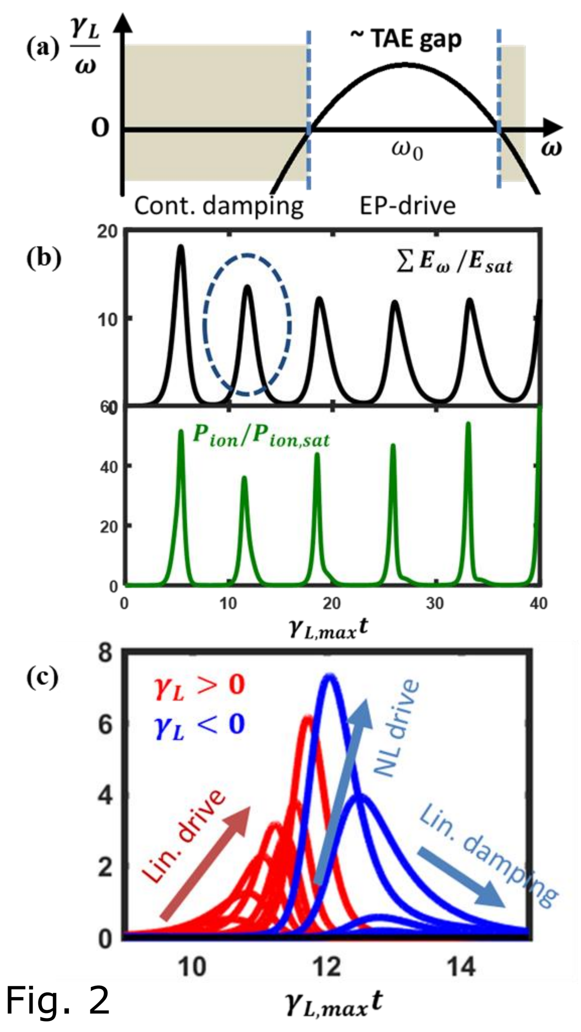


Fig. 2

- **PP oscillation of TAEs by ICS**
  - For a parabolic shape of the linear growth rate curve, Eq. (1) and (2) result in the PP oscillation of the multiple TAEs (Fig. 2 (b)).
  - The nonlinear transfer can sufficiently drive the linearly stable modes such as kinetic TAEs (Fig. 2 (c)).
  - The transient peak level of the total mode energy during the bursty behavior is much larger than the previously expected NL saturation level.

- Initially, the modes near the center of the gap are amplified.
- Then, the downward transfer by ICS excites the stable modes near the gap boundary.
- Finally, the low-$\omega$ modes are damped by the continuum.

- Since the gap structure varies radially, the mode amplitude evolves in real space as well (Fig. 3 (b)).
- It can lead to EP avalanches [4] which induce performance degradation and a wall damage.

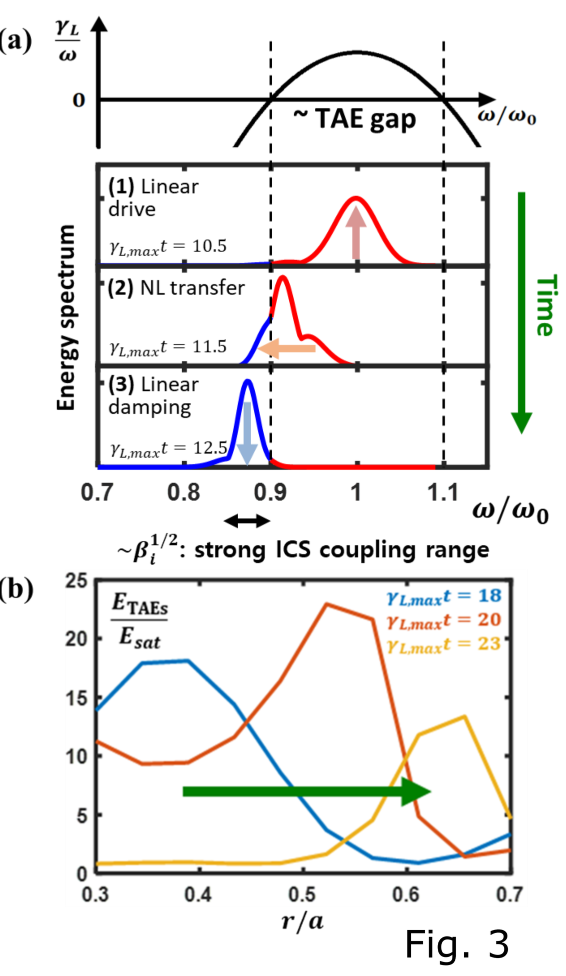


Fig. 3

- **Mode saturation by considering the wave-trapping effect** [5]

$$\gamma_{eff} = \gamma_f(\delta B) - \gamma_d \qquad (3)$$

$$\gamma_f(\delta B) = \min\left[1, G\omega_0^2\frac{v_{d0}v_0^3 m^3 g(m)}{\omega_b^3(\delta B)\, v_A^3}\right]\gamma_{f0} \qquad (4)$$

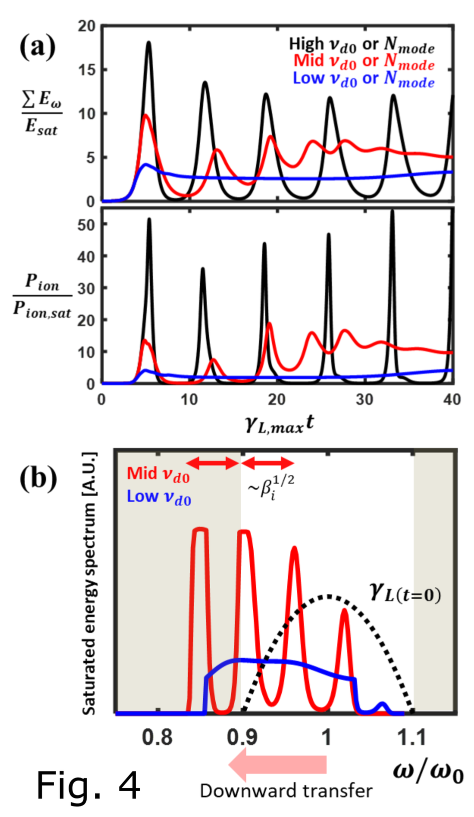


Fig. 4

- When we take the wave-trapping effect into account, the system saturates after decaying oscillations (Fig. 4 (a)).
- The levels normalized to the analytic estimations converge into $O(1)$.
- The saturated energy spectrum (Fig. 4 (b)) shows different characteristics according to $v_{d0}$, but both are shifted downwards from the original linear growth curve.

## 3. Alpha-channeling via high-n TAEs in ITER

- **EP transport and energy channeling by TAEs**

$$\frac{\Delta E}{\Delta P_\phi} \simeq \frac{\omega}{n} = const. \qquad (5)$$

$$P_{EP\to TAE} \equiv n_{EP}\left\langle -\frac{dE}{dt}\right\rangle_{EP} = n_{EP}\frac{\omega}{n}\left\langle -\frac{dP_\phi}{dt}\right\rangle_{EP} = \frac{\omega}{n}\frac{ZeBr}{q}\Gamma_{EP} \qquad (6)$$

EP transport via ICS [3]

- From the EP flux by [3], we can estimate the EP energy transfer to TAEs.

$$P_{TAE\to ion} = \begin{cases} P_{EP\to TAE} & \text{for } \gamma_L \ll \gamma_f \sim \gamma_d \quad \text{(optimistic)} \\ (\sqrt{2\pi}v_{ti}/v_A)P_{EP\to TAE} & \text{for } \gamma_L \sim \gamma_f \sim \sum_{\omega'} M_{\omega,\omega'}E_{\omega'} \quad \text{(conservative)} \end{cases}$$

- **Integrated simulation in ITER burning plasma**

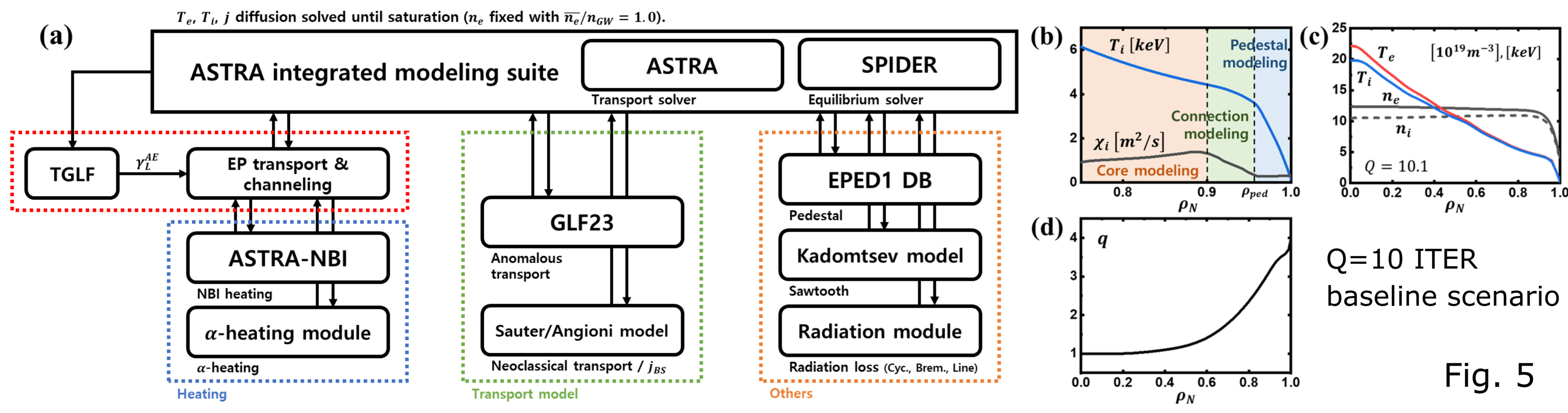


Fig. 5

Self-consistent simulation

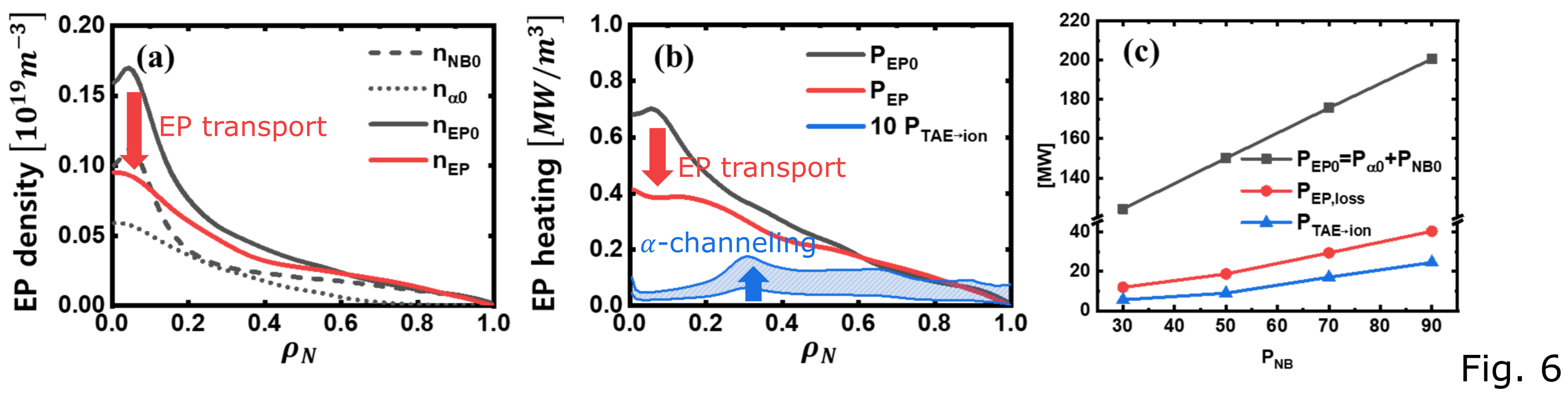


Fig. 6

- The EPs are transported by TAEs, and the central plasma heating by EP drops about 1/3.
- The ICS of high-n TAEs induces additional ion heating (alpha-channeling, Fig 6 (b)).
- The ion heating by alpha-channeling can compensate the collisional ion heating loss by the EP transport ($P_{TAE\to ion}/P_{EP,loss} > f_{i,coll} \sim 0.3$).

Tab. 1

| [MW] | $P_{abs} = P_\alpha + P_{NB} - P_{EP,loss}$ | $P_{abs,elec}$ | $P_{abs,ion}$ | $Q = P_{fus}/P_{in}$ |
|---|---|---|---|---|
| Case 1: Reference ($P_{EP,loss} = 0$) | 150.1 | 109.3 | 40.8 | 10.1 |
| Case 2: EP transport | 121.7 | 91.0 | 30.7 | 8.79 |
| Case 3: EP transport + channeling | 128.5 | 87.4 | 41.2 | 9.64 |

- In Case 1, the EP energy is transferred to plasmas by coll. slowing down only ($Q \approx 10.1$).
- Considering the EP transport (Case 2), the reduced plasma heating by EPs decreases $T_i$ and so does alpha heating further ($Q \approx 8.79$ with 25% reduction of ion heating).
- In Case 3, the ion heating fraction becomes higher by alpha-channeling, which compensates the ion heating loss by the EP transport ($Q \approx 9.64$).
- The alpha-channeling by TAEs is ~10MW, which is as influential as a single ICRH antenna.

## Conclusion

- The NL evolution of high-n TAEs induced by ICS is investigated.
- The ICS shows that the modes evolve with PP bursts that can cause EP avalanches.
- If we consider a weak effect of particle trapping, the system becomes saturated.
- The ion heating during the spectral transfer, responsible for alpha-channeling, is modeled for the predictive simulation.
- With the integrated modeling, it is found that the ion heating by the channeling can compensate the heating loss by the EP transport in the optimistic limit.
- It is still necessary to consider various factors such as GAM coupling [6], CAE-induced channeling [7] and cyclotron resonance of alpha particles [8] in the future.

## Acknowledgments

The authors also gratefully acknowledge The Research Institute of Energy and Resources and The Institute of Engineering Research at Seoul National University. This research was supported by R&D Program of "Development of Electromagnetic Gyrokinetic Model Describing Trapped Particles in Magnetic Field(code No. IN2104)" through the Korea Institute of Fusion Energy(KFE) funded by the Government funds, Republic of Korea.

## References

[1] HAHM, T.S. and CHEN, L., *Phys Rev. Lett* **74** (1995) 266
[2] HAHM, T.S. *Plasma Sci. Technol.* **17** (2015) 534
[3] QIU, Z., et al., *Nucl. Fusion* **59** (2019) 066024
[4] HAHM, T.S. and DIAMOND, P.H. *J. Korean Phys. Soc.* **73** (2018) 747
[5] BERK, H.L. and BREIZMAN, B.N. *Phys. Fluids B* **2** (1990) 2246
[6] QIU, Z., et al., *Nucl. Fusion* **59** (2019) 066031
[7] GORELENKOV, N.N., et al., *Plasma Phys. Control. Fusion* **52** (2010) 055014
[8] WHITE, R.B., et al., *Phys. Plasmas* **28** (2021) 012503