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Gyrokinetic simulations on the formation of Internal Transport Barrier in HL-2A tokamak plasmas

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HPC workshop 2023

Background

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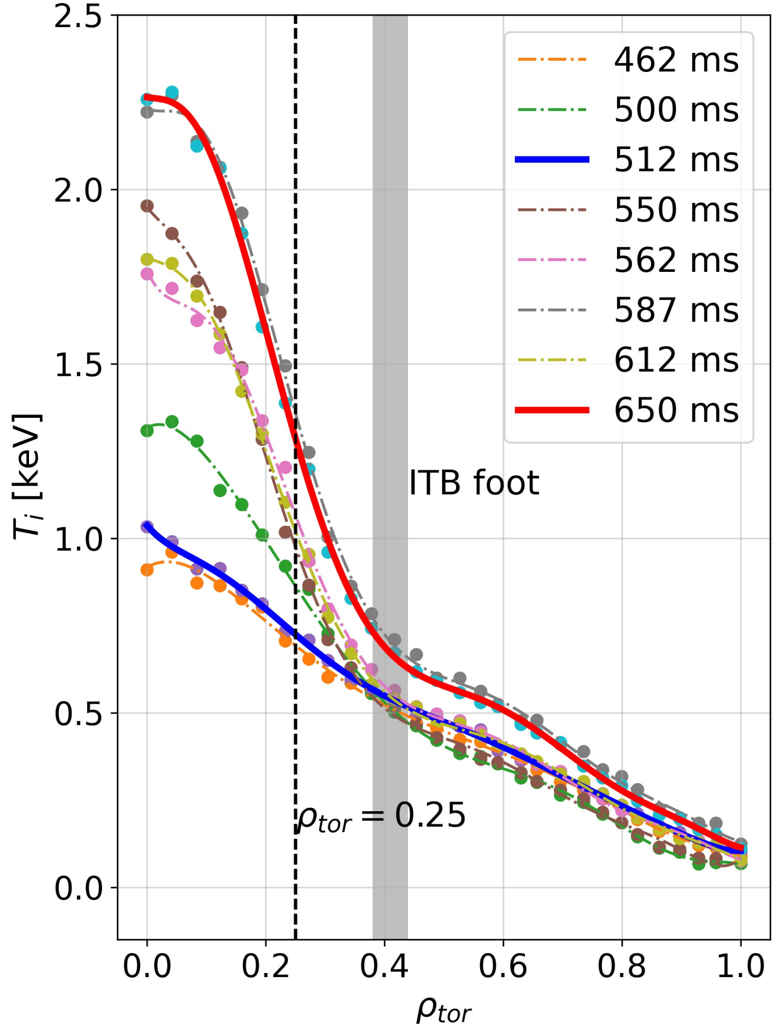
❑ Internal transport Barrier (ITB)

- localized region with high ∇T or ∇n
- indicating good confinement in Tokamak
- generated when heat flux is suppressed

❑ Mechanisms for ITB

≈ methods to suppress the **micro-instabilities**



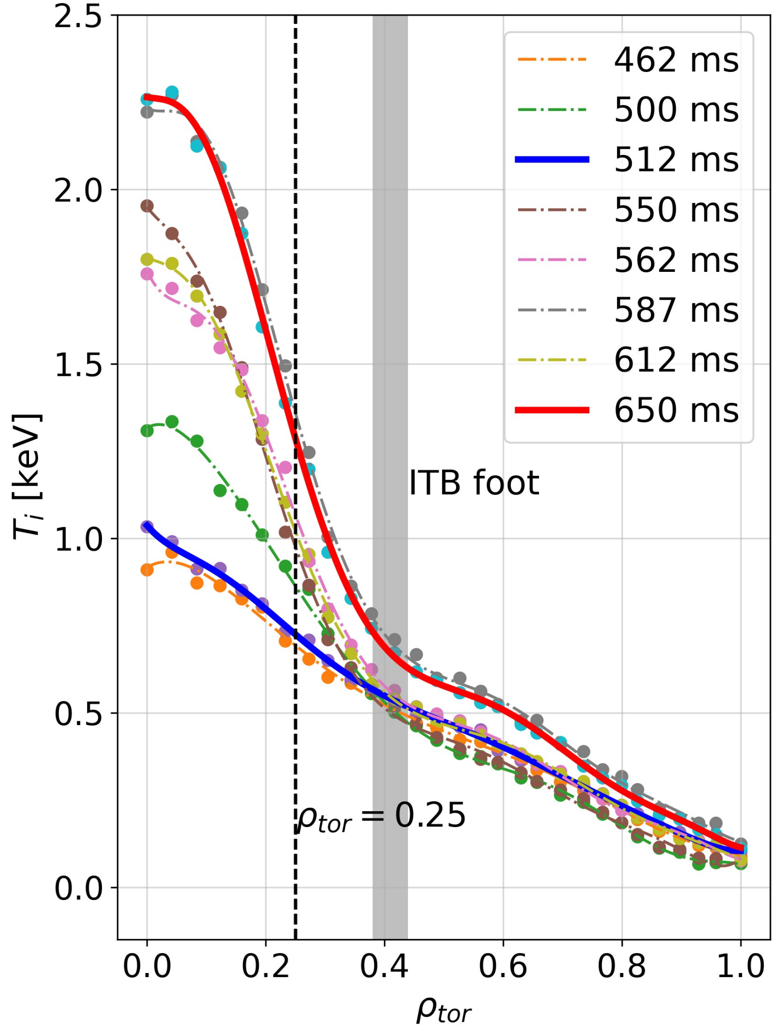
Background

❑ Internal transport Barrier (ITB)

- localized region with high ∇T or ∇n
- indicating good confinement in Tokamak
- generated when heat flux is suppressed

❑ Mechanisms for ITB

- Zonal Flow (ZF), $E \times B$ shear ($\gamma_{\mathrm{E\times B}}$)
- Effects of Fast Ion (FI)
- β-stabilization ($\beta = 8\pi \mathrm{p}/\mathrm{B}^2$)



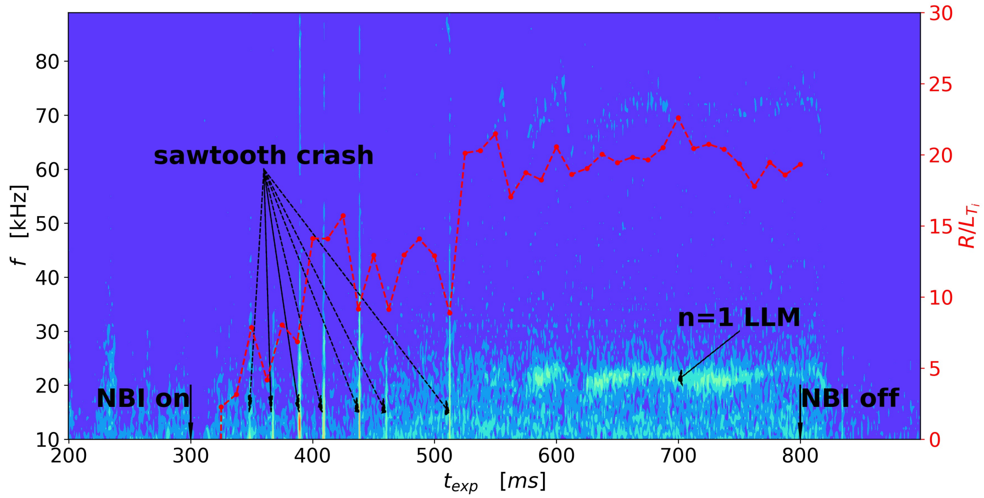
Background

❑ Characteristic of ITB in HL-2A tokamak:

- High power Neutral Beam Injection (NBI)

$\Rightarrow$ large n_{fi}
increased β
plasmas rotation and $\gamma_{E\times B}$

- Coexistence with n=1 Long-Lived Mode (LLM)



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❑ Characteristic of ITB in HL-2A tokamak:

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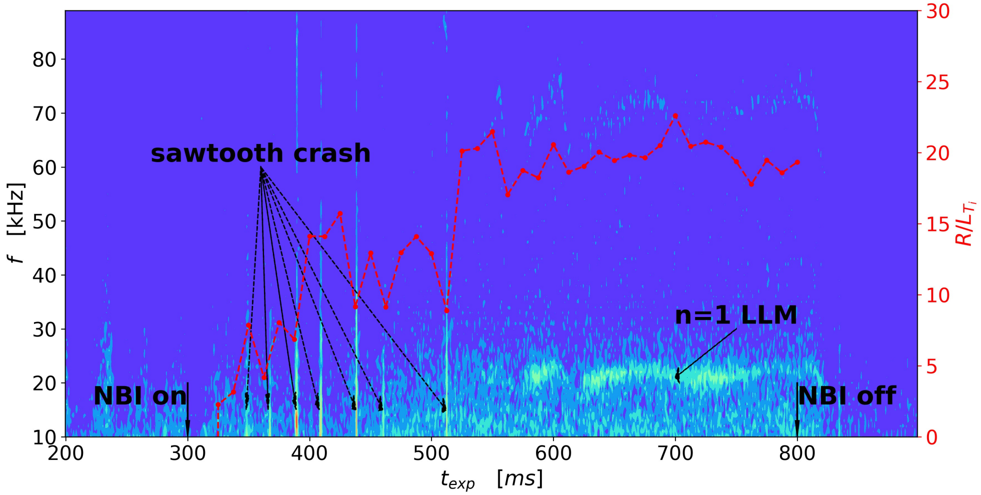

- Coexistence with n=1 Long-Lived Mode (LLM)

Which one is the main cause of ITB triggering in HL-2A? FI, β, $\gamma_{E\times B}$ or LLM?

Are they effective throughout the whole process of ITB formation?

Outline

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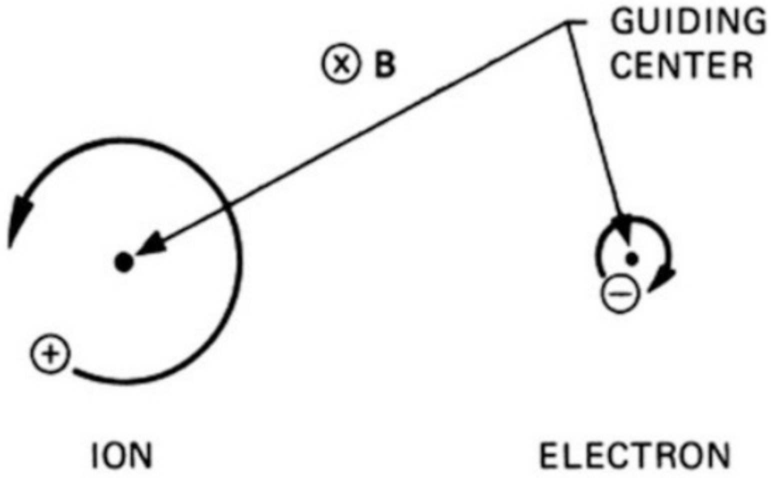
- Introduction and Simulation setup
- Instabilities analyses
- Transport reduction in non-linear simulations
- A new ITB self-sustainment mechanism
- Summary

Turbulence analyses

❑Gyrokinetic Simulation

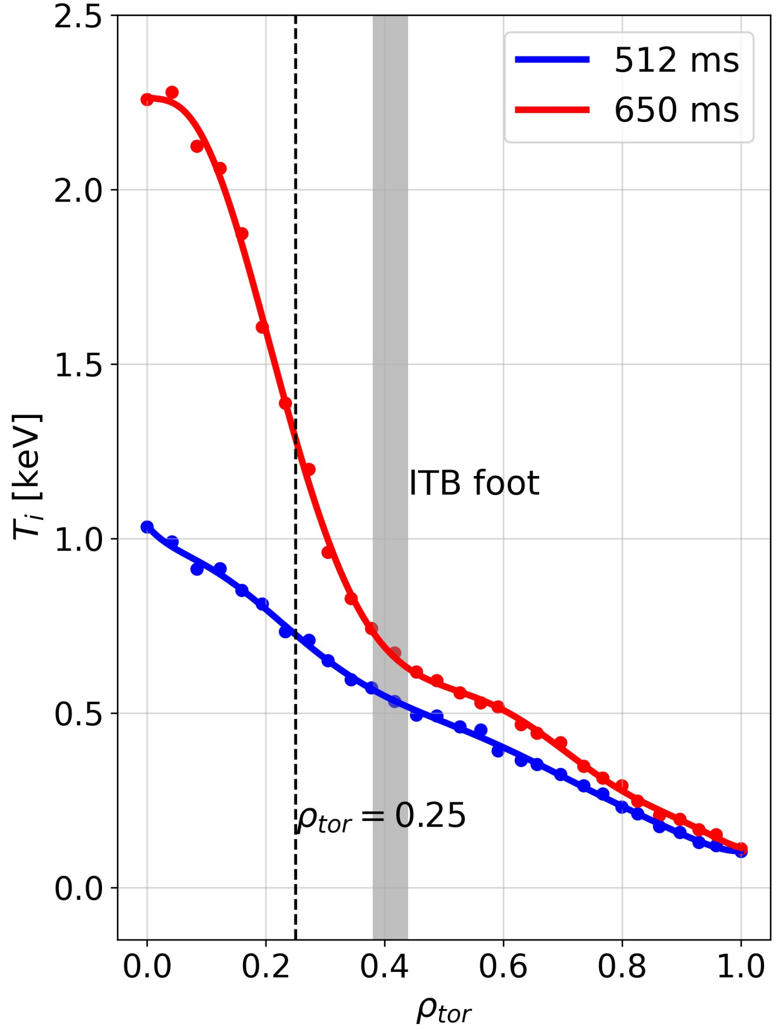
- Turbulence and transport analyzed by performing **Gyrokinetic simulations**
- **5-dimensional** simulation averaging out the particle dynamic associated with the gyro-motions
- Solving the 5D gyrokinetic **Vlasov equation** and the coupled **Maxwell equations**



Turbulence analyses

❑ Simulation parameters

- GENE code [Jenko2000]
- realistic parameters taken at the ITB-triggering (510 ms) and fully formed ITB (650 ms)
- n_{fi}, β, and $\gamma_{E\times B}$, scanned to provide indications for ITB formation [Lin2023nf]



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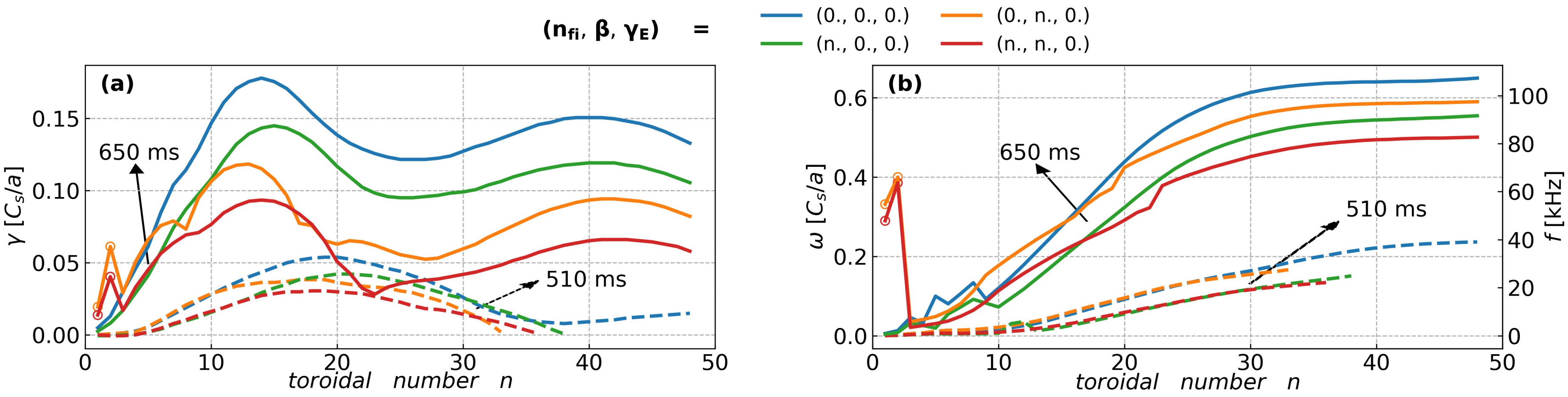
Instabilities in linear simulations

❑**Linearly dominant modes**:

- **ion-temperature-gradient (ITG) modes**, electrostatic (**ES**) mode excited by ∇T_i and stabilized by fast ion dilution [Tardini2007] and β effects [Weiland1992]



Instabilities in linear simulations

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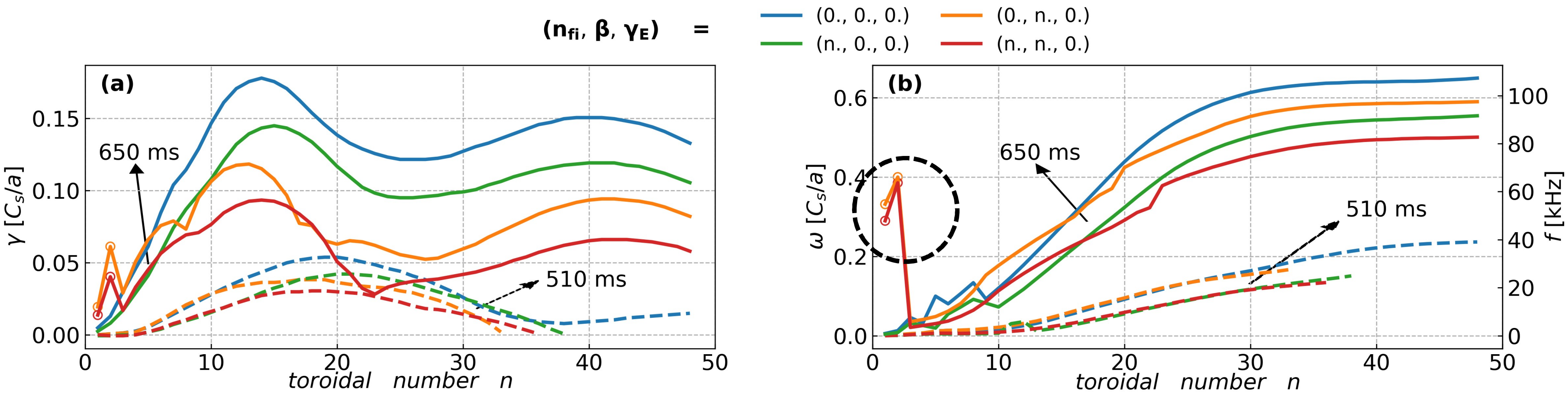
❑Linearly dominant modes:

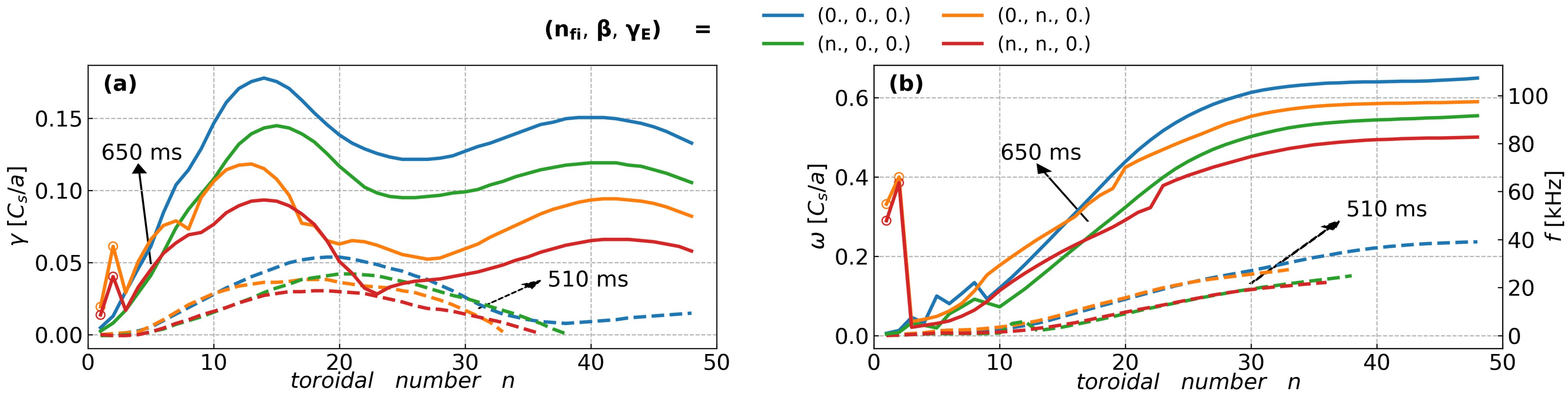
- ***β*-induced Alfvenic (BAE) modes**; as identified in [Lin2023cpb], it is an electromagnetic (**EM**) mode destabilized by ∇T_i in the condition of finite-β



Instabilities in linear simulations

❑ Comments of linear simulations:

- $\gamma_{E\times B}$ is not included; $E \times B$ algorithm not compatible in linear simulation
- Modes are decoupled; zonal mode is stable



Instabilities in non-linear simulations

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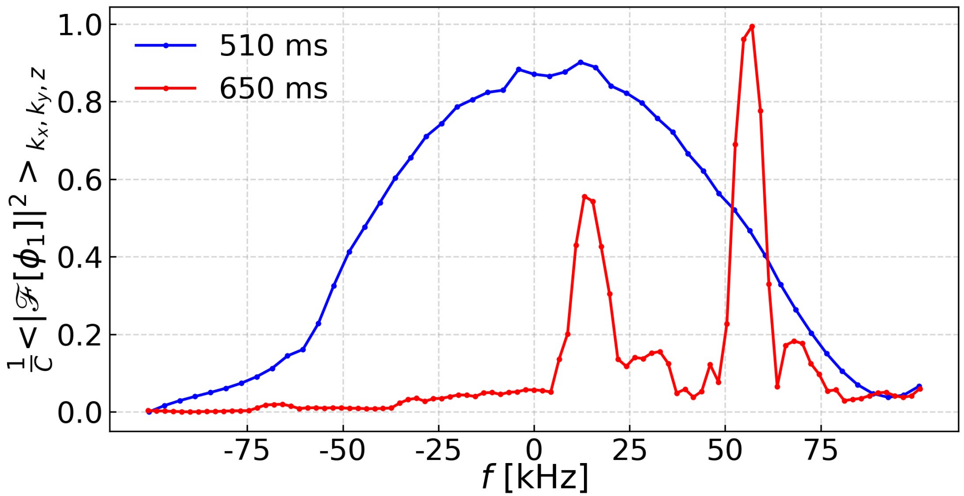
❑Non-linearly dominant modes:

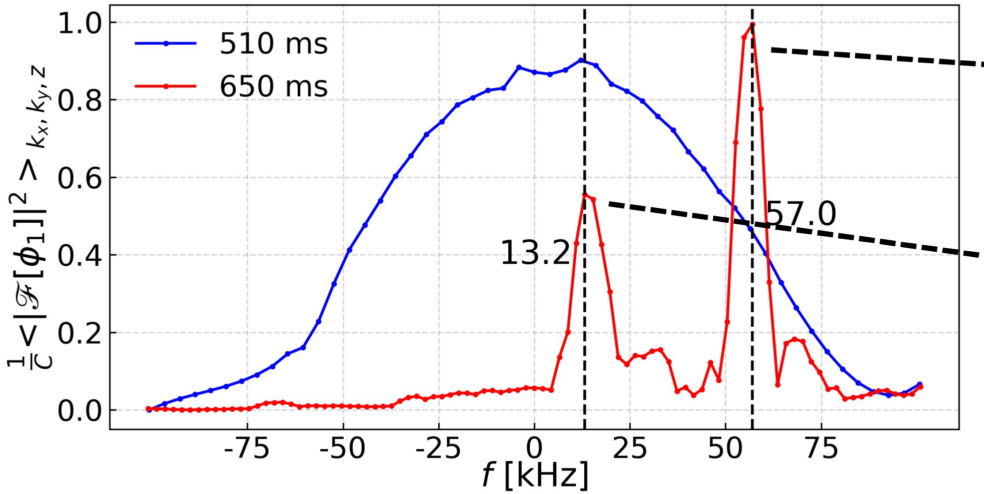
- **Zonal Flow (ZF)** (mode with $n = 0$ and $\omega = 0$, too dominant to plot in the following figures)
- Two high frequency modes at 650 ms whereas none at 510 ms

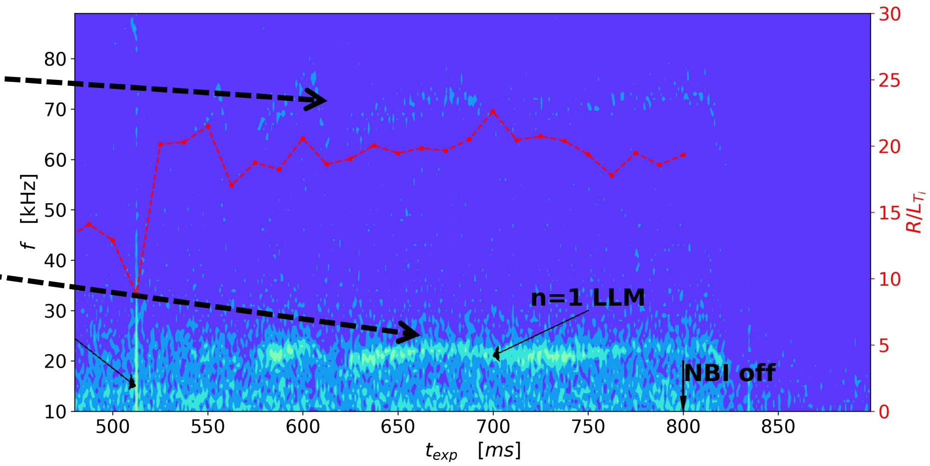


Instabilities in non-linear simulations

❑Non-linearly dominant modes:

- $f = f_{lab} - nf_{tor}$; $f_{tor} \approx 7$ kHz
- $n = 1$ LLM and $n = 2$ BAE; (inconsistence in amplitude may result from the local assumption)

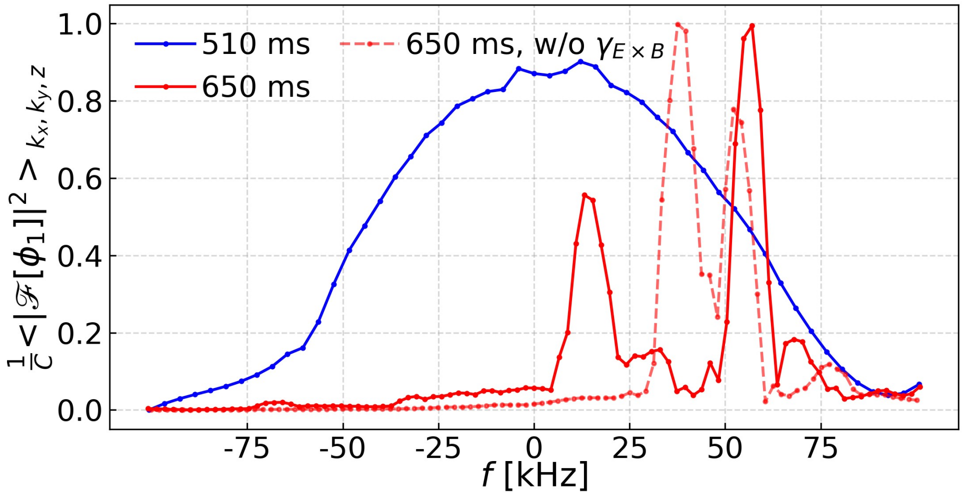


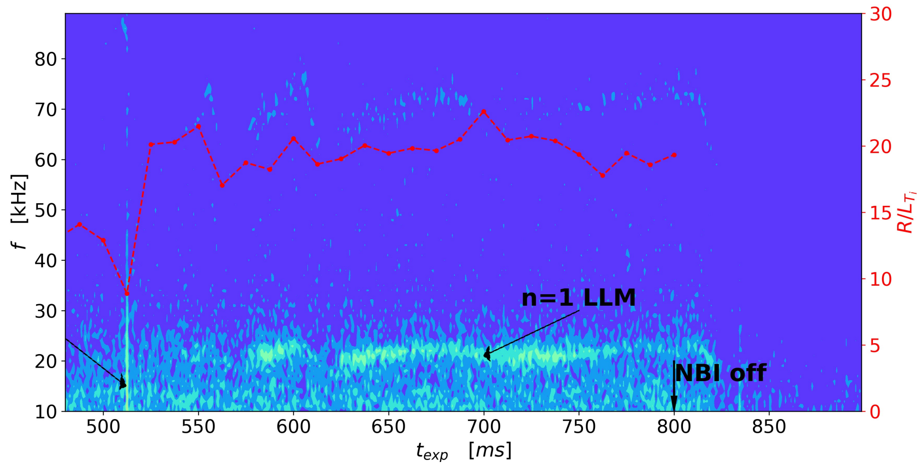


Instabilities in non-linear simulations

❑Non-linearly dominant modes:

- The free energy of low-n modes derive from ITB-generated
- LLM is sensitive to $\gamma_{E\times B}$





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Ion heat flux driven by Instabilities

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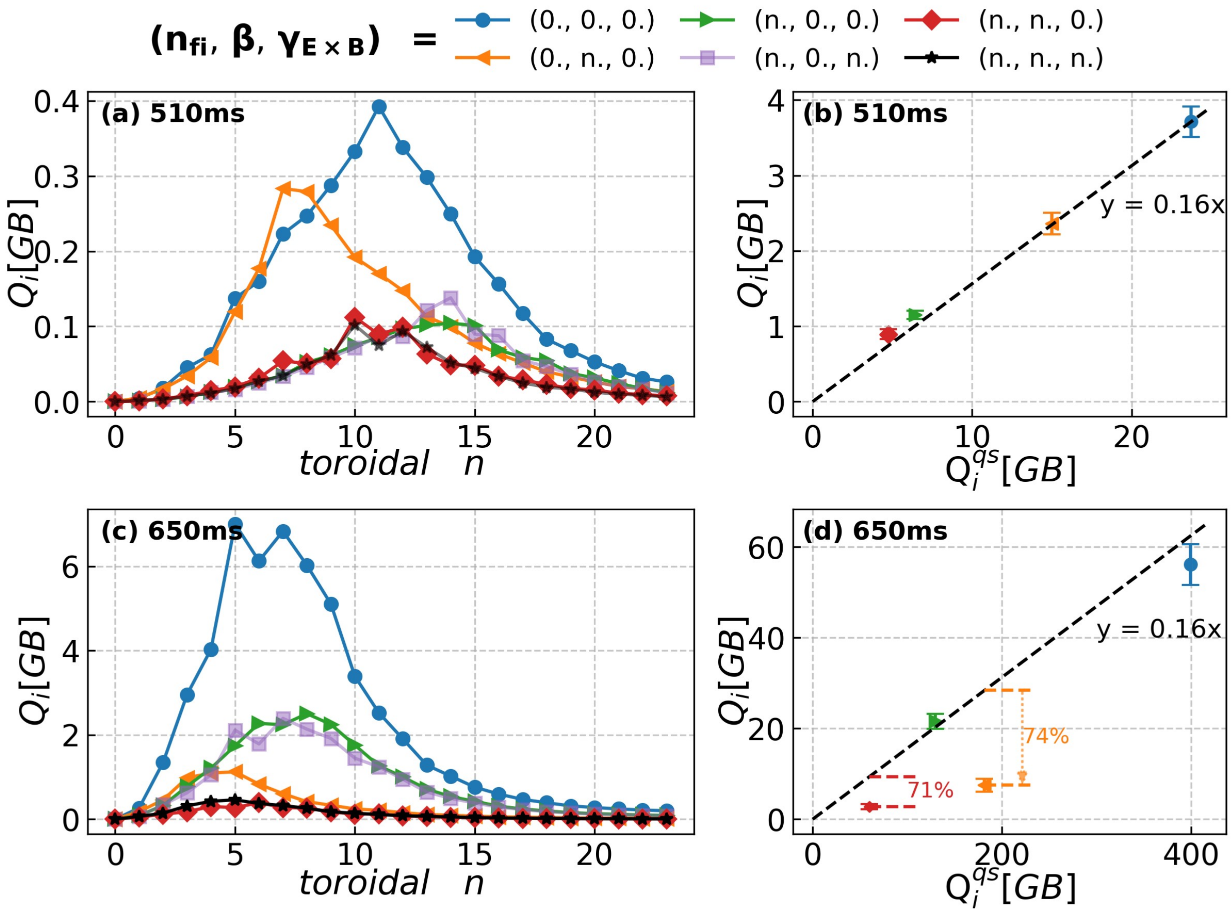
❑Spectra of ion heat flux

- Left: nonlinear flux spectra
- Right: total flux and quasi-linear flux (dashed line)



Ion heat flux driven by Instabilities

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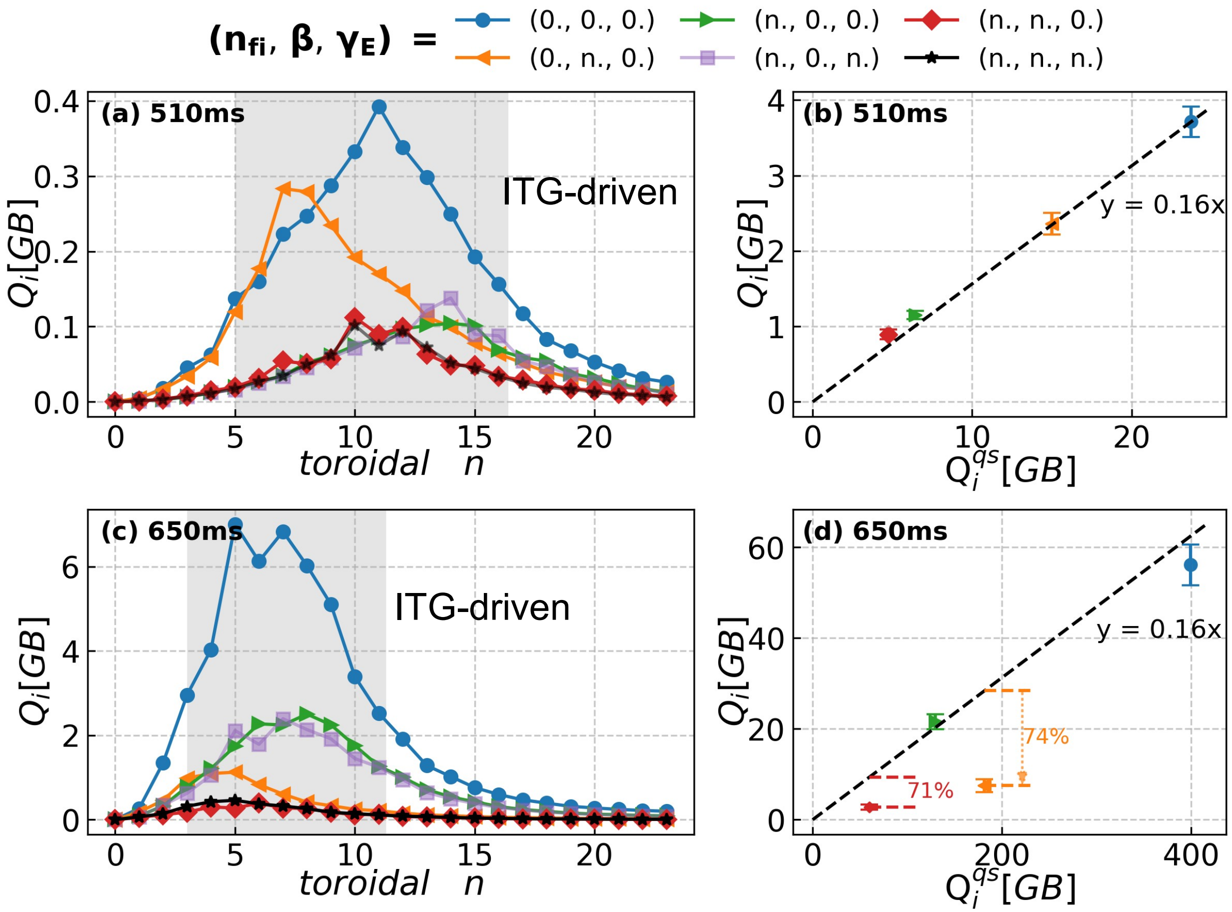
❑ Spectra of ion heat flux

- ITG modes are responsible for most of the flux
- The low-n EM modes (LLM and BAE) make little contribution directly to the flux in spite of their dominant amplitudes



Ion heat flux driven by Instabilities

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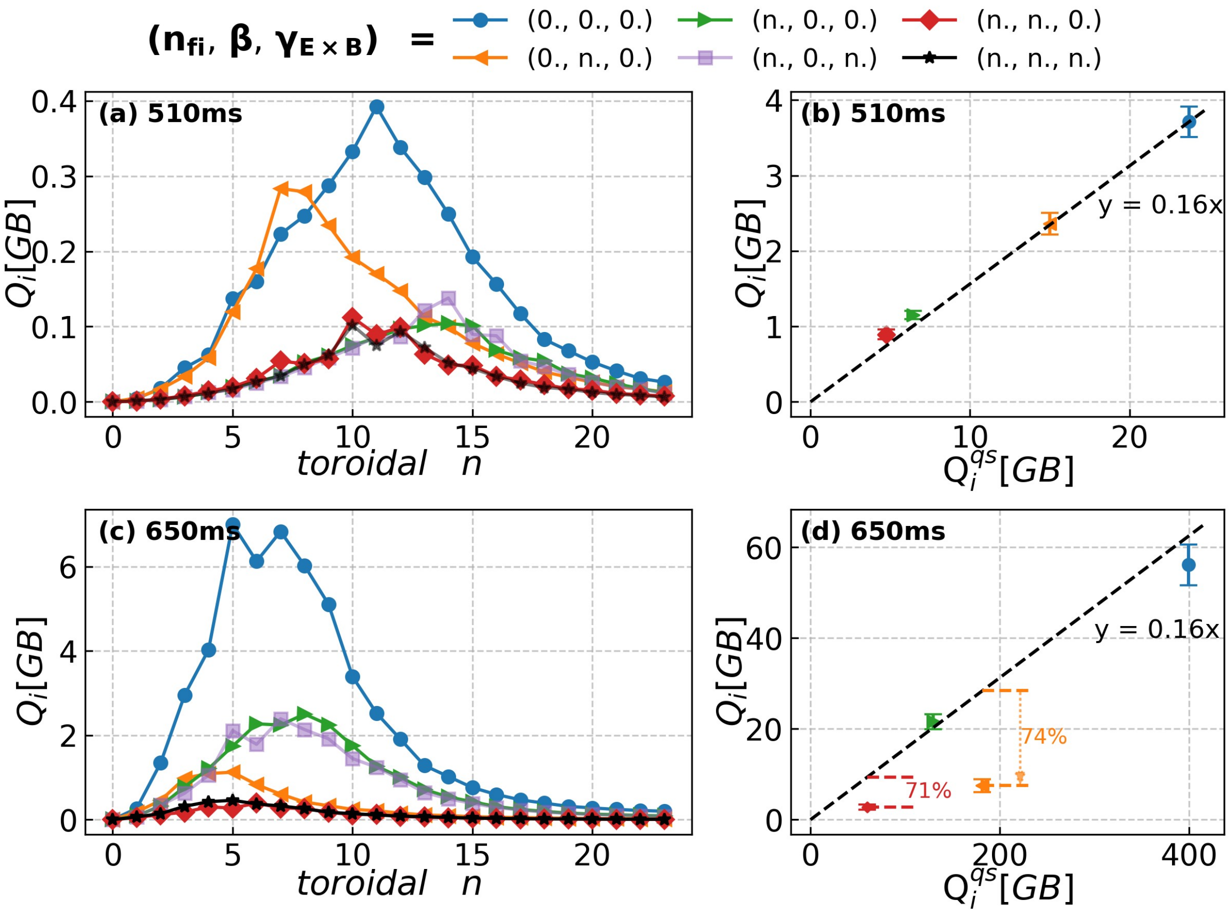
❑ Spectra of ion heat flux

- At 510 ms, the dilution effect of fast ion reduced the flux by linearly stabilizing ITG
- At 650 ms, the flux is reduced mostly by the nonlinear effects of β
- $\mathrm{E} \times \mathrm{B}$ shearing makes little difference



Ion heat flux driven by Instabilities

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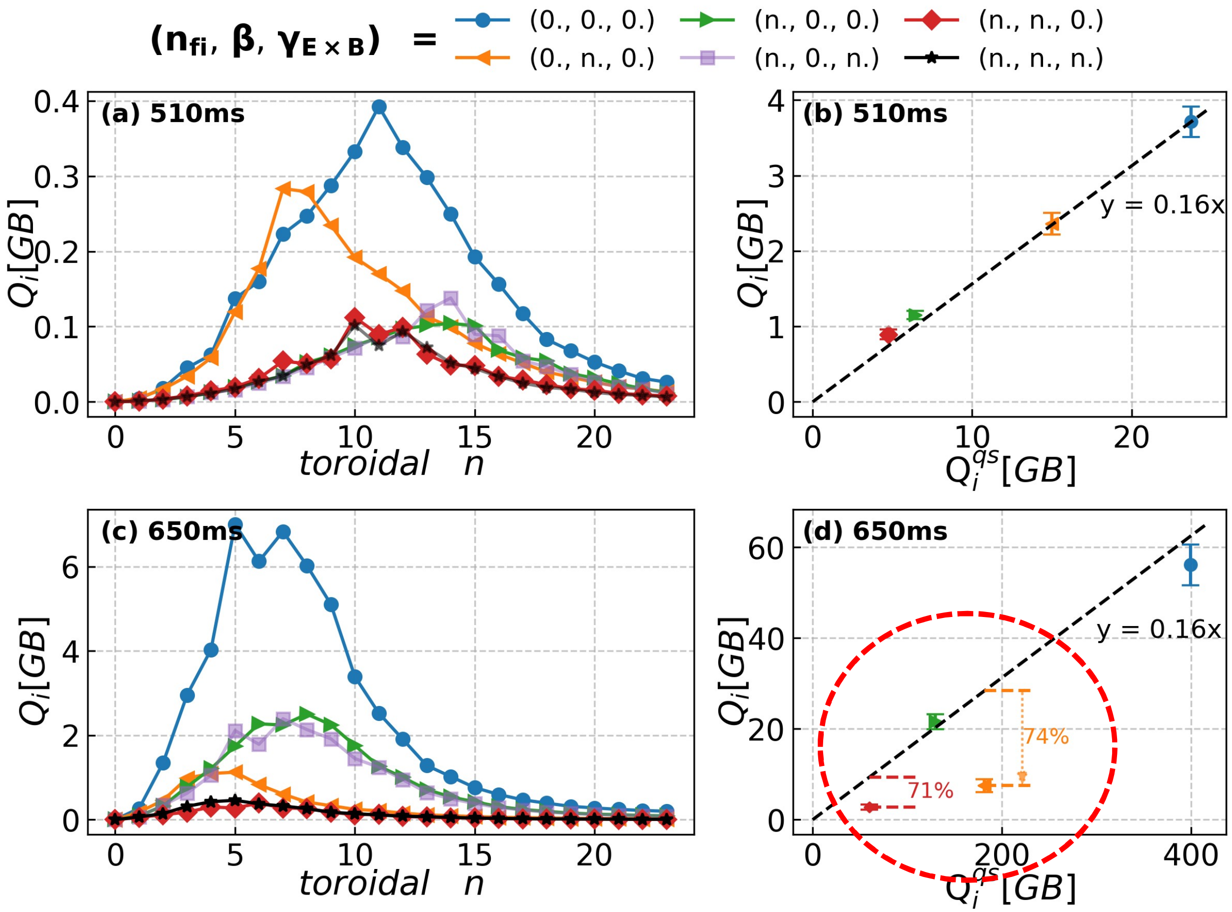
❑Spectra of ion heat flux

- At 510 ms, the dilution effect of fast ion reduced the flux by linearly stabilizing ITG
- At 650 ms, the flux is reduced mostly by the nonlinear effects of β
- $\mathrm{E} \times \mathrm{B}$ shearing makes little difference
- **The deviations from quasi-linear prediction indicate the role of ZF and the couplings between modes in reducing the flux.**



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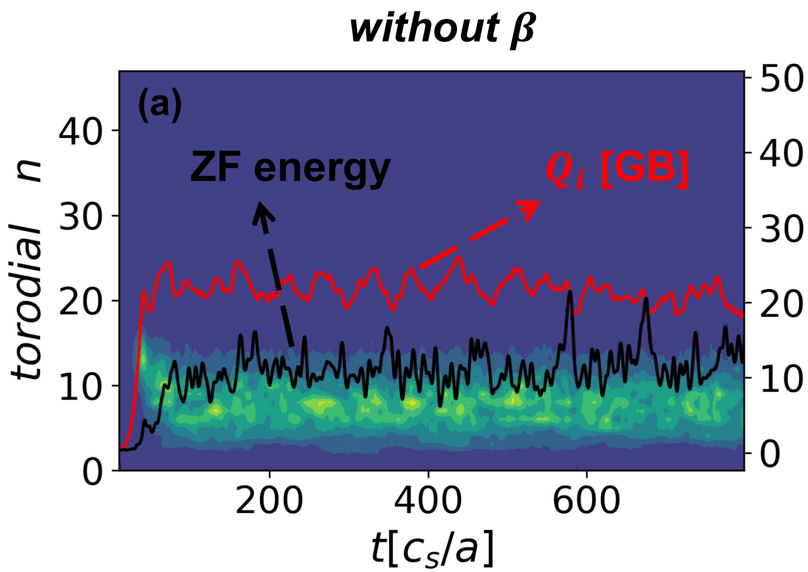
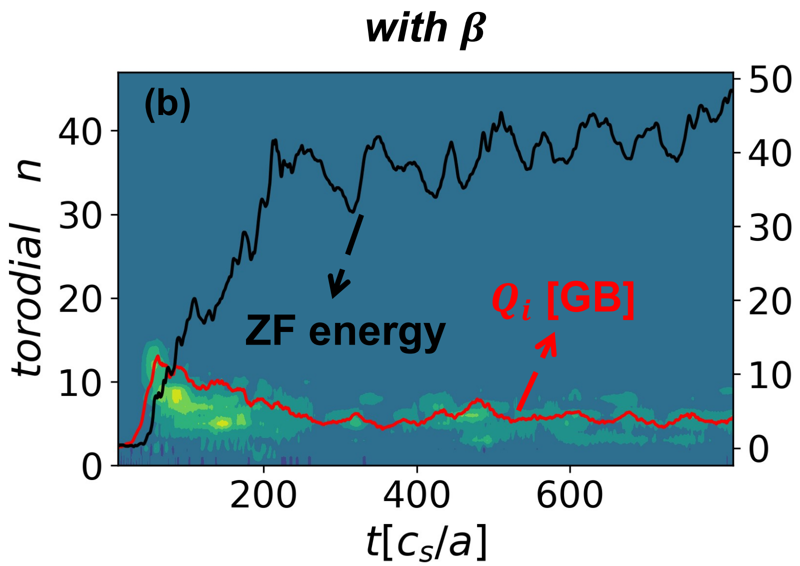
❑Correlations between ZF and ion heat flux

- In the condition of finite-β, ZF develop in a much larger amplitude, reducing drastically the heat flux.
- ZF growth is the key factor of the sustaining of ITB at 650 ms.





Zonal flow and ion heat flux

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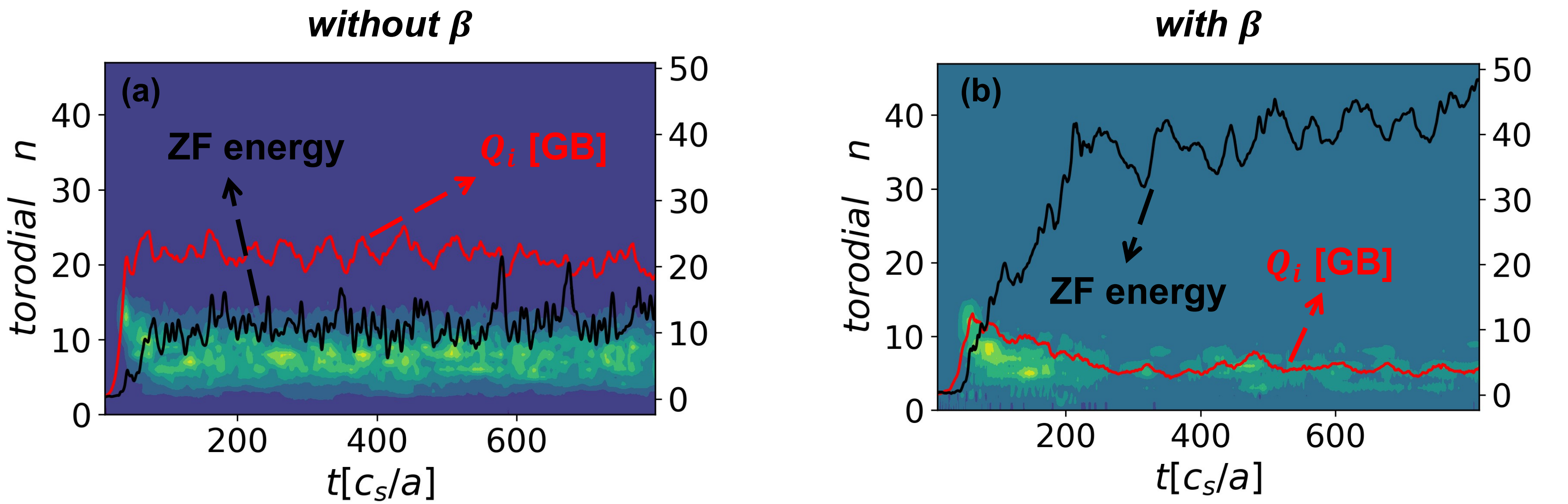
❑ Correlations between ZF and ion heat flux

But what's the cause of zonal flow growth in the condition of finite-β?



Cause of zonal flow growth

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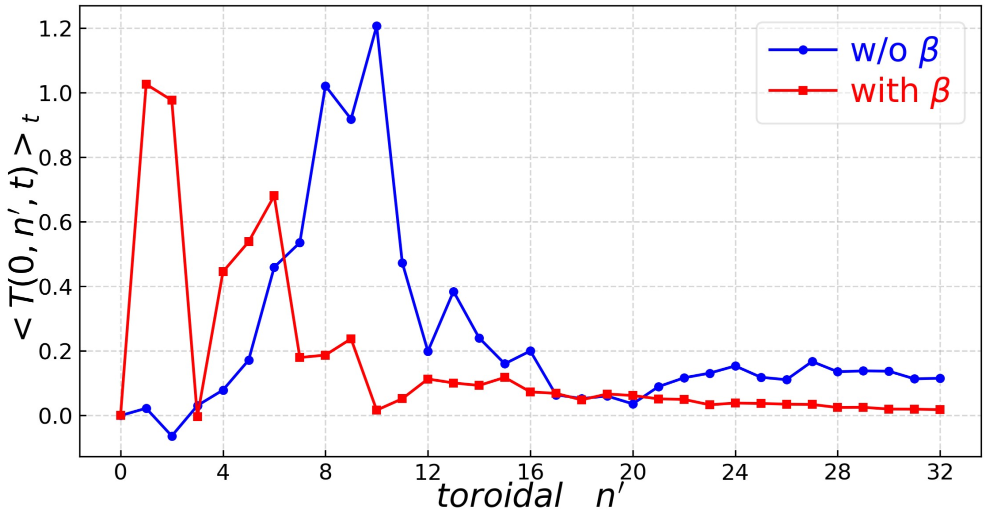
❑Energy source of ZF

$$\frac{dE_n}{dt}|_{NL} = \sum_{n'} T(n,n',t) \propto Re \sum_{n',n'_x,n_x} (n'_x n - n' n_x) \int J dz\, M \bar{\phi}_1^*|_k \chi_1|_{k'} g_1|_{k-k'}$$

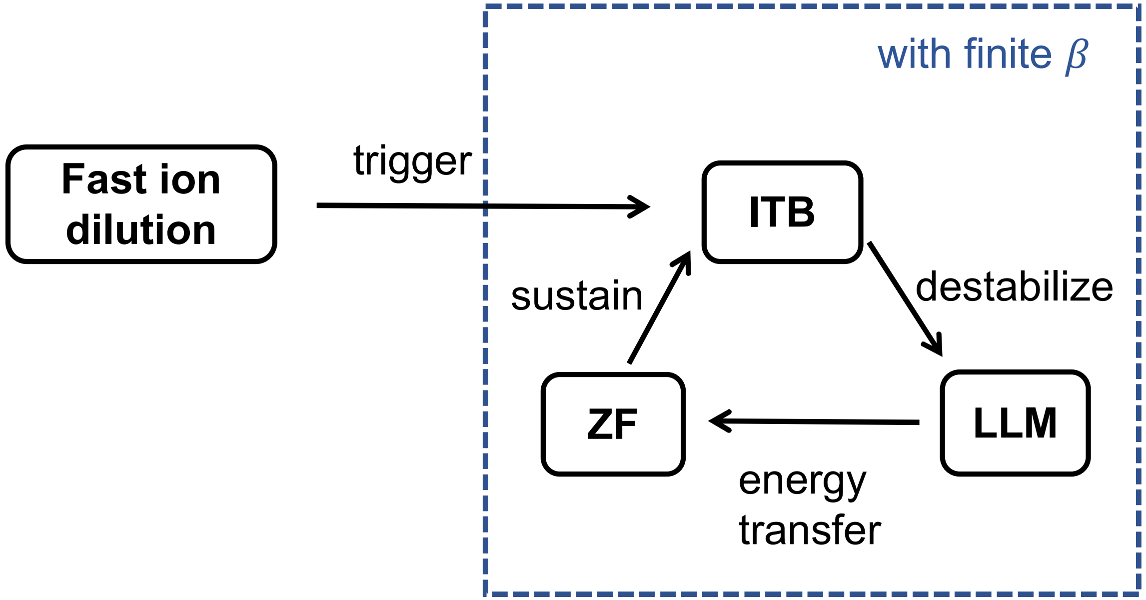
❑Spectra of the ZF energy source

- Without finite β, ZF energies are mostly fed by ITG modes.
- With finite β, the n=1 LLM and n=2 BAE make the most contribution to ZF energy.



A new ITB self-sustainment Mechanism

❑Chart of ITB formation



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Summary

- The triggering of ITB is caused by the dilution effect of fast ions arising from NBI.
- After the triggering of ITB, the dilution effect alone, however, is incapable to sustain the ITB. Instead, the effects of finite-β are indispensable.
- $\mathrm{E} \times \mathrm{B}$ shear is not found to play a role in any stage of ITB formation.
- A new self-sustainment mechanism of ITB is proposed in which ITB is sustained by the growth of ZF which live on the LLM destabilized by ITB itself.
- The full ITB formation in HL-2A tokamak is thus characterized as self-organized system.

Thank you for listening!

Reference

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