MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Impact of fast ions and fishbones on core turbulence at rational surfaces via global GENE simulations

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EUROfusion

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Introduction and motivations

In tokamak plasmas, **turbulence suppression** is essential to reach reactor-relevant scenarios (high T and n) and increase the plasma confinement time.

Many factors influence the suppression. Among these:

Rational surfaces

- Zonal flow (ZF) generation by turbulence **self-interaction** [Volčocas 24, Di Giannatale 25]
- **Fishbone** destabilization (kink-mode ↔ fast ions) [Brochard 25]

Fast ions physics

Great importance to describe **heating** and predict **burning plasma** scenarios.

- **ZF generation** by **EP modes** [Chen 12]
- Thermal profiles **dilution** [Tardini 07]
- **Quasi-resonant** effect [Di Siena 21]
- **Zonal flow enhancement** [Hahm 23, Choi 24]

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Interplay studied via **GENE** simulations

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Presentation outline

- Tools: the GENE code
- Plasma profiles and setup
- Low T_f values
    - Linear fast ions physics
    - Turbulence analysis
- High T_f values
    - Linear FB destabilization
    - Turbulence analysis
- Conclusions

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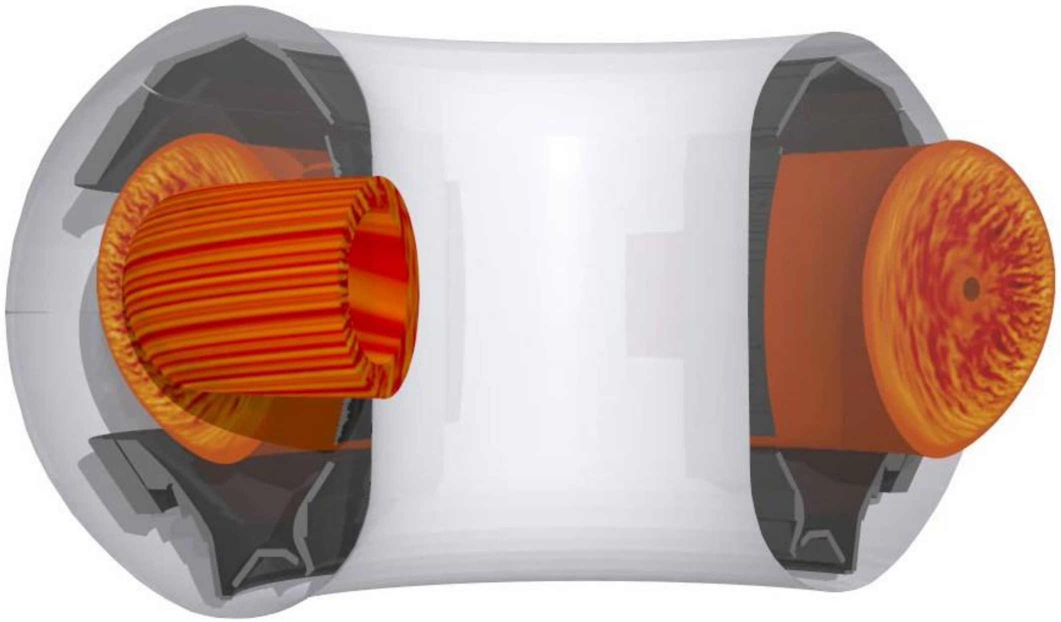
Tools: the GENE code

All results described are obtained via the eulerian δf gyrokinetic code **GENE** [Jenko 00, Görler 11].

- Solves the perturbed **Vlasov-Maxwell system** in the $(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}, \boldsymbol{v}_{||}, \boldsymbol{\mu})$ phase space
- Field aligned coordinates: x radial, y binormal coordinate and z follows $\boldsymbol{B}$
- Electrostatic and electromagnetic paradigm.
- Flux-tube and global approach
- Linear (single-mode) and non-linear simulations

All simulations reported are performed in a **global**, **electromagnetic** setup



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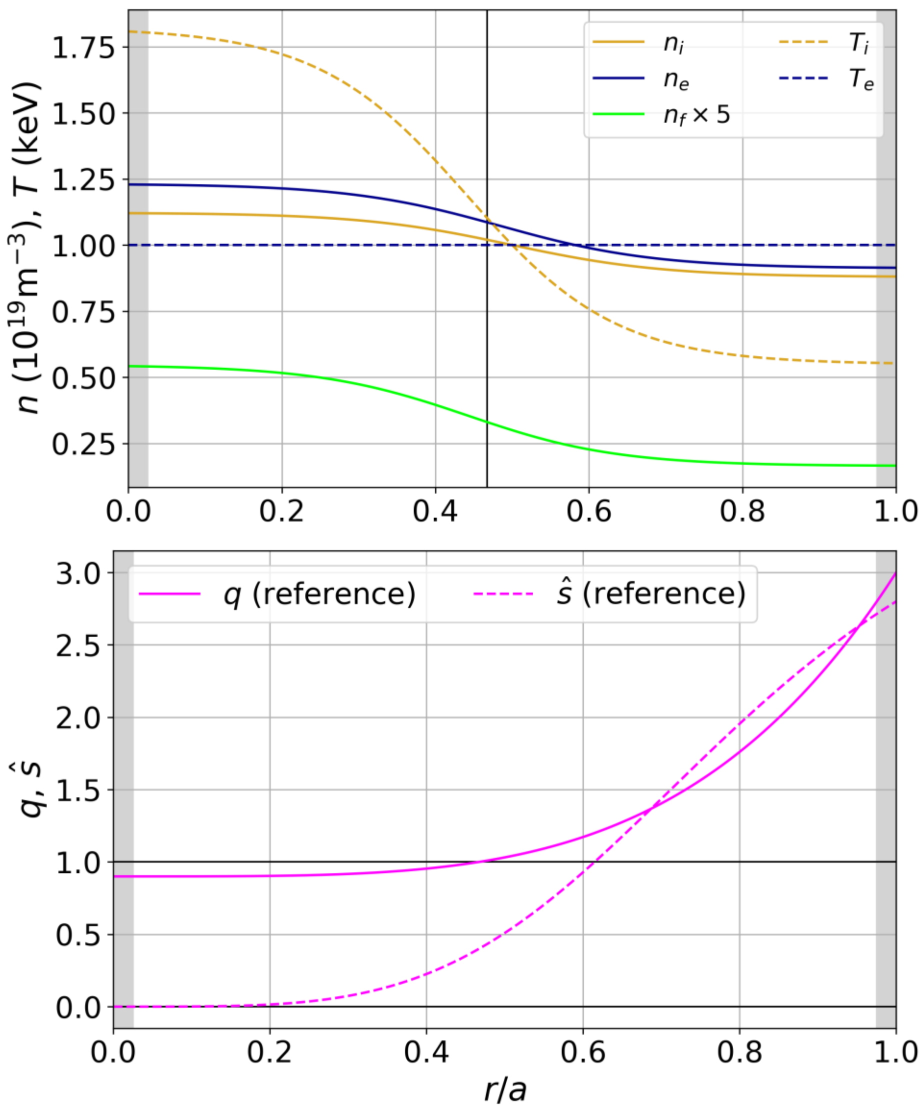
Plasma profiles and setup

Analytical n, T and q profiles are designed to **maximize the impact of fast ions at q = 1**.

- $n_i = n_e - n_f$
- Flat T_e and T_f profiles. a/L_{T_i} and a/L_n peak at q = 1
- β_e = 0.075%, ρ^* = 0.006, B_T = 1 T
  Concentric geometry with ε = 0.1



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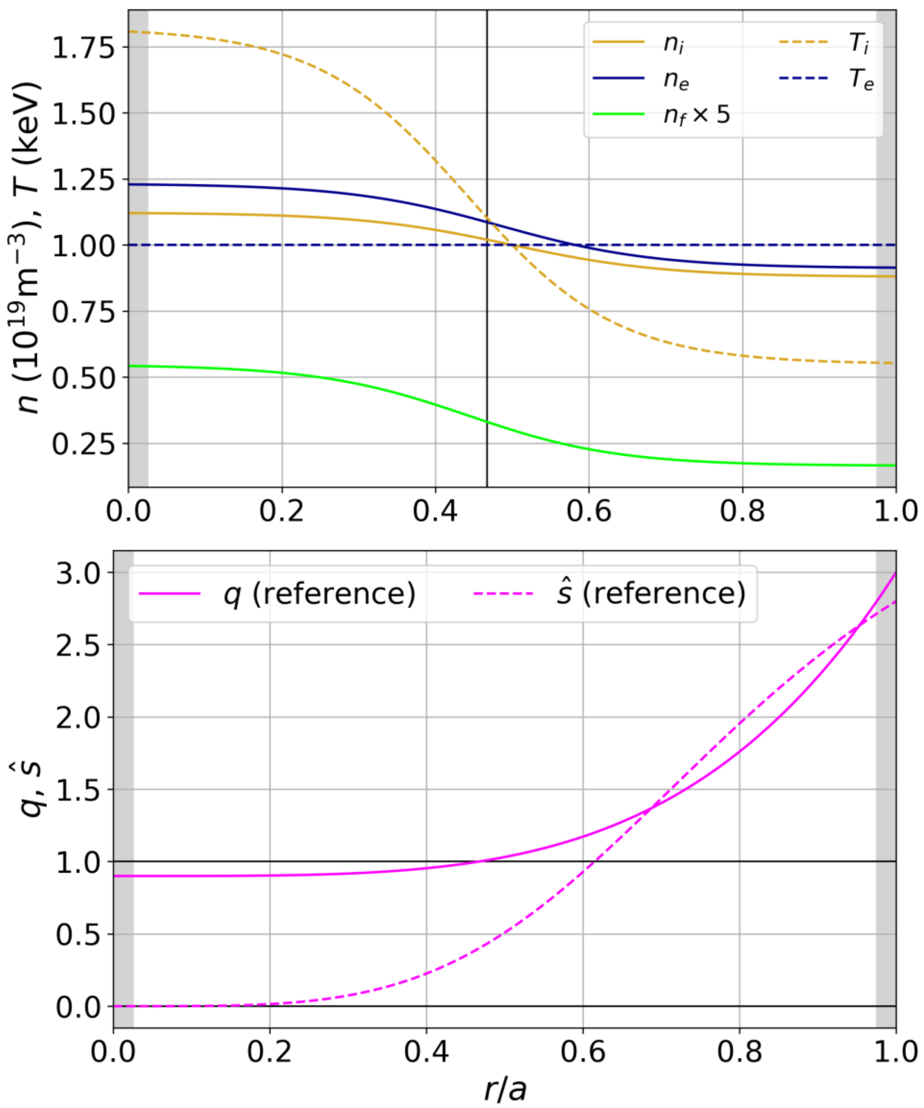

- **Ion temperature gradient** (ITG) **mode** is the dominant instability
- No **$n \neq 1$** EP-driven mode
- The **n = 1 FB** appears for $T_f \gtrsim$ 40 keV

A scan in T_f is perfomed in the setup

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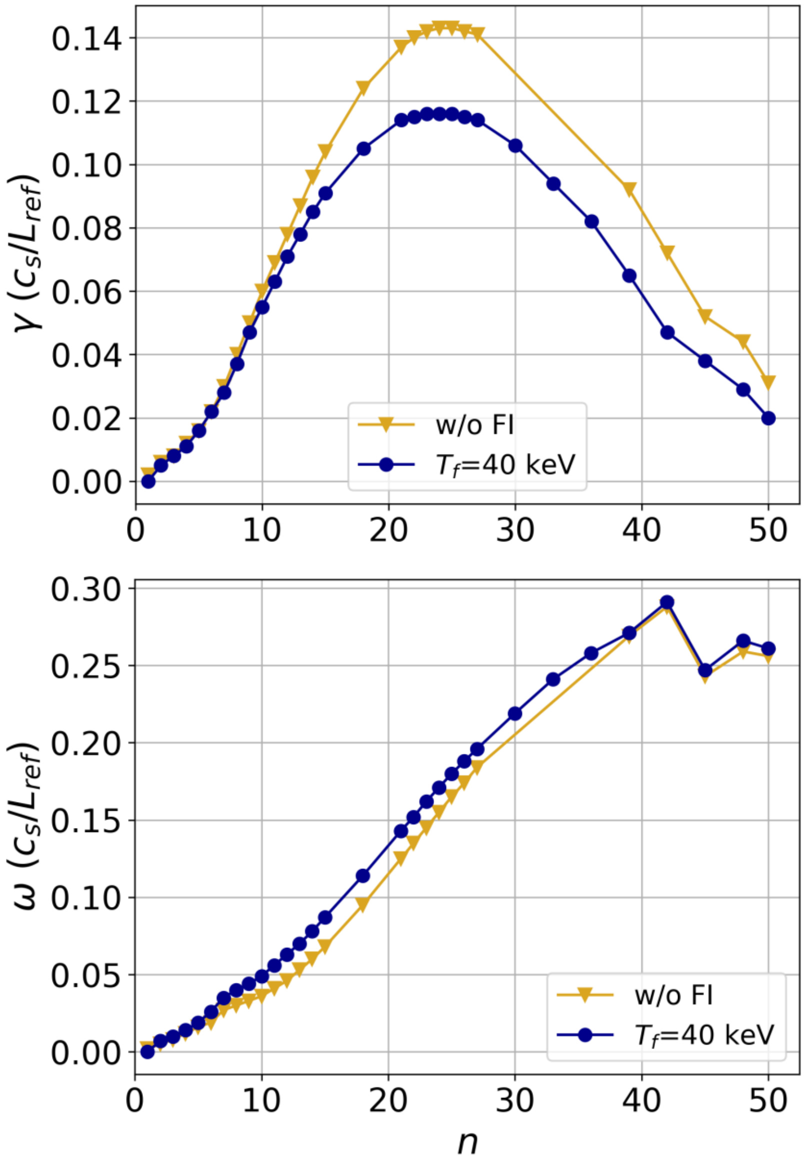
Low T_f values – Linear fast ions physics

- Inclusion of FI (T_f = 40 keV) leads to a **stabilization** of the ITG (ω > 0) branch



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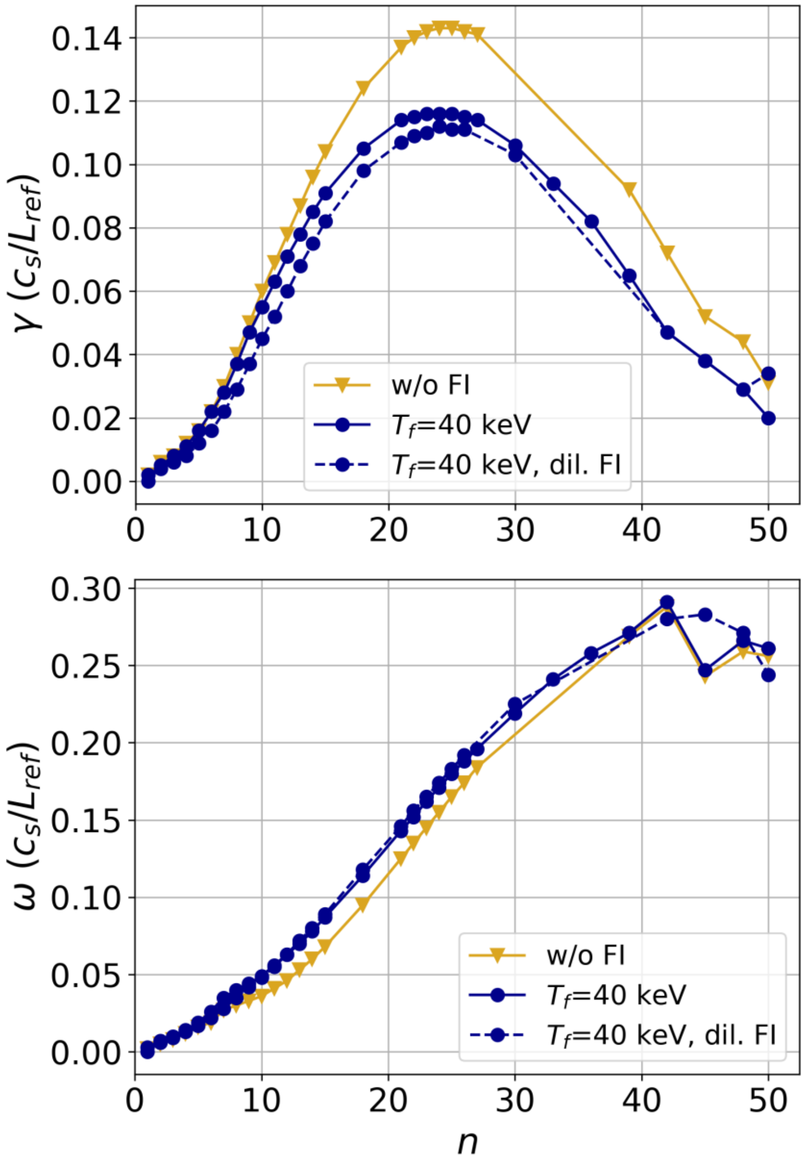

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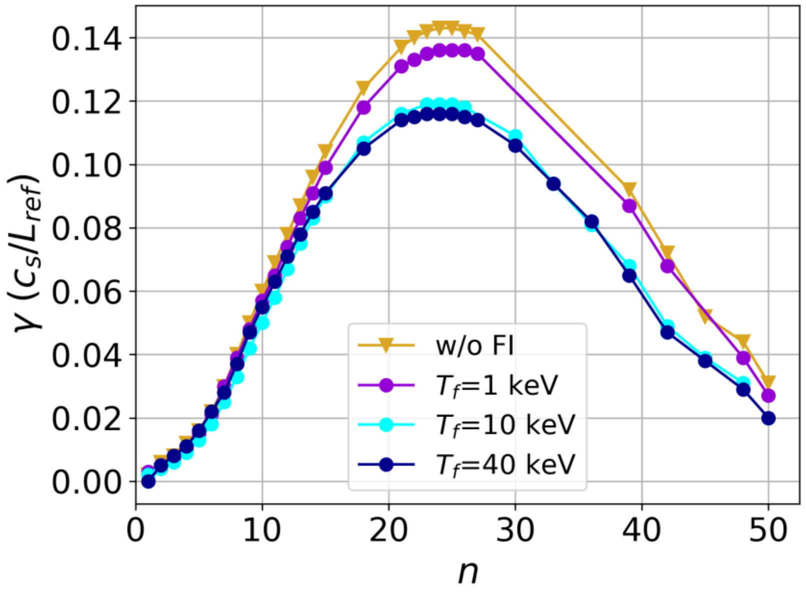
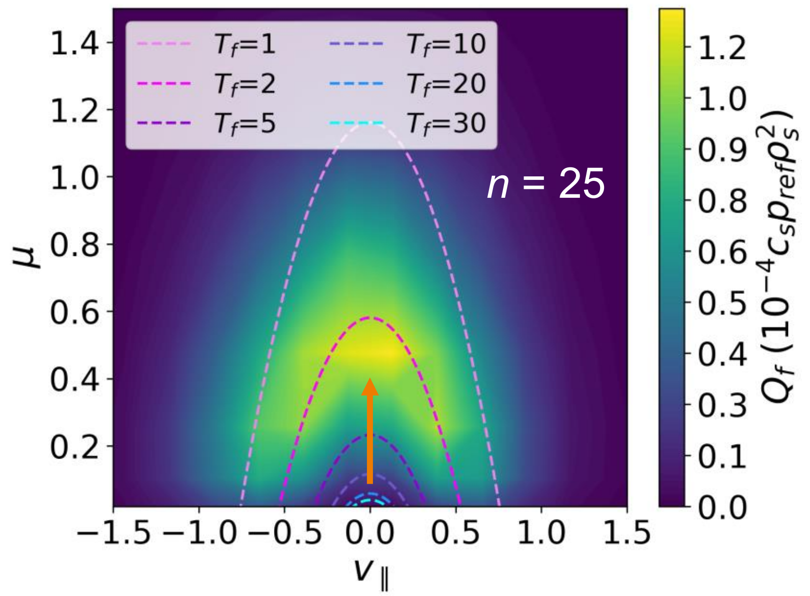


- Lowering T_f, an increase in γ is observed
- ITG / FI **quasi-resonant interaction** ($\omega_{d,f} = \omega_{ITG}$) is maximized for $T_f \approx 2$ keV [Di Siena 21]

Lowering T_f (**orange** arrow) we increase the energy exchanged between FI and wave

ITG gets destabilized



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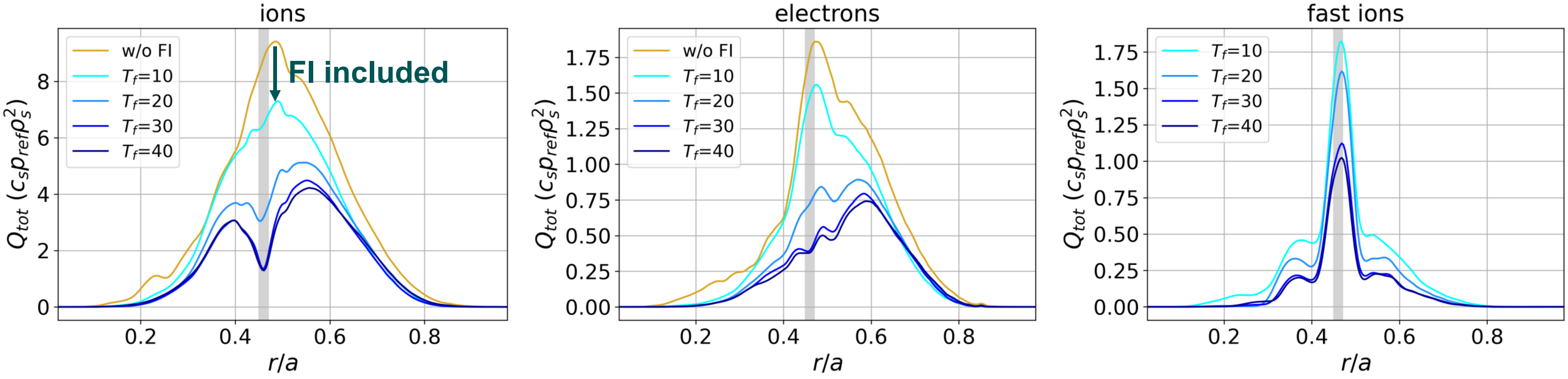
Low T_f values – Turbulence analysis

Nonlinear simulations are performed including modes n **= (0,1,…,47)** at different T_f **≤ 40 keV**.

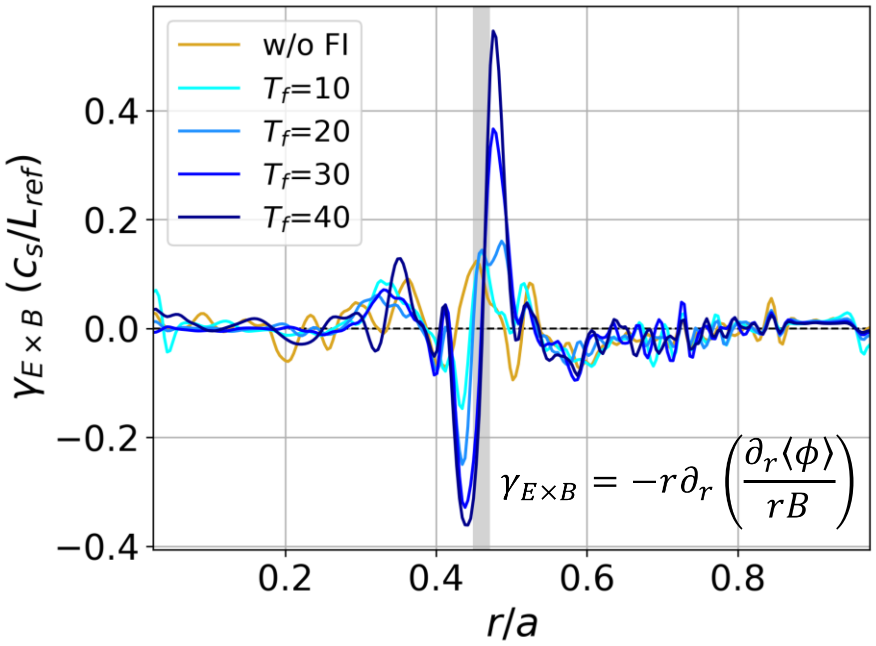


- The quasi-resonant effect explains the **global decrease in heat fluxes** with **increasing T_f**
- A pronounced reduction of fluxes is observed at q **= 1** (**gray** region). This stabilization increases with T_f

Low T_f values – Turbulence analysis

Nonlinear simulations are performed including modes $\boldsymbol{n}$ **= (0,1,…,47)** at different $\boldsymbol{T_f}$ **≤ 40 keV**.

- The stabilization at q = 1 is linked to the generation of an $\boldsymbol{n}$ **= 0 shearing structure**



- $\boldsymbol{\gamma_{E\times B}}$ **>** $\boldsymbol{\gamma_{ITG}}$ for the T_f values where the stabilization is observed
- The shearing structure is strongly localized at $\boldsymbol{q}$ **= 1**

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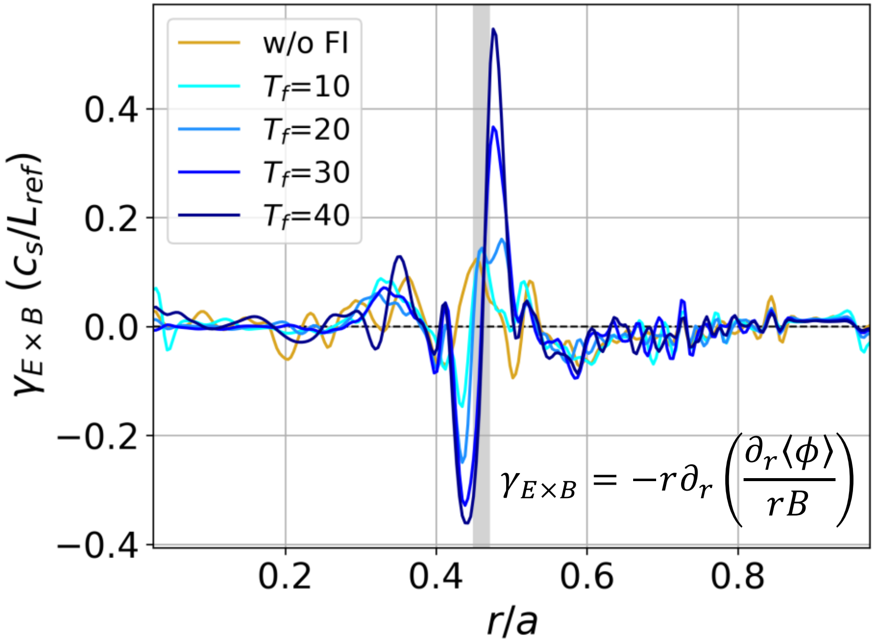
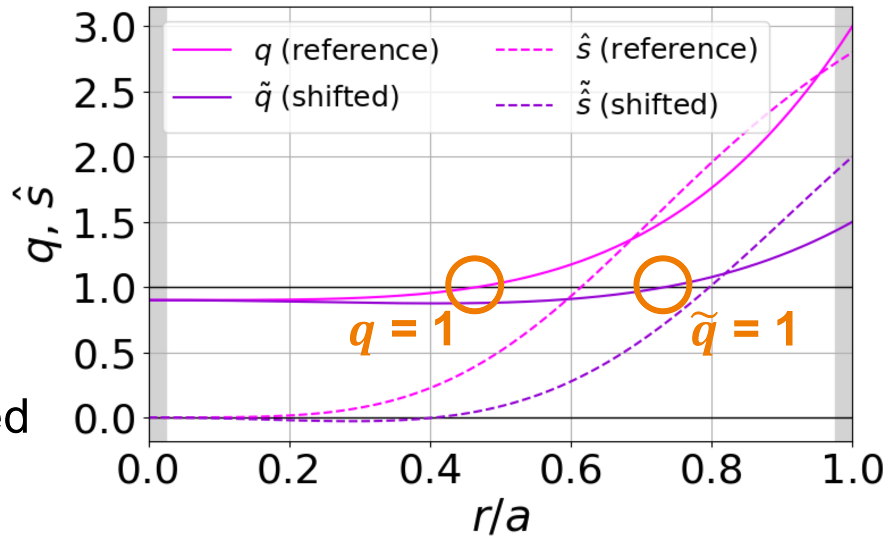


- **$\gamma_{E\times B}$ > γ_{ITG}** for the T_f values where the stabilization is observed
- The shearing structure is strongly localized at **q = 1**



- A run with **shifted $\tilde{q}$** ($r_{q=1}$ = 0.47 → $r_{\tilde{q}=1}$ = 0.75) is performed

Low T_f values – Turbulence analysis

Nonlinear simulations are performed including modes **n = (0,1,…,47)** at different **T_f ≤ 40 keV**.

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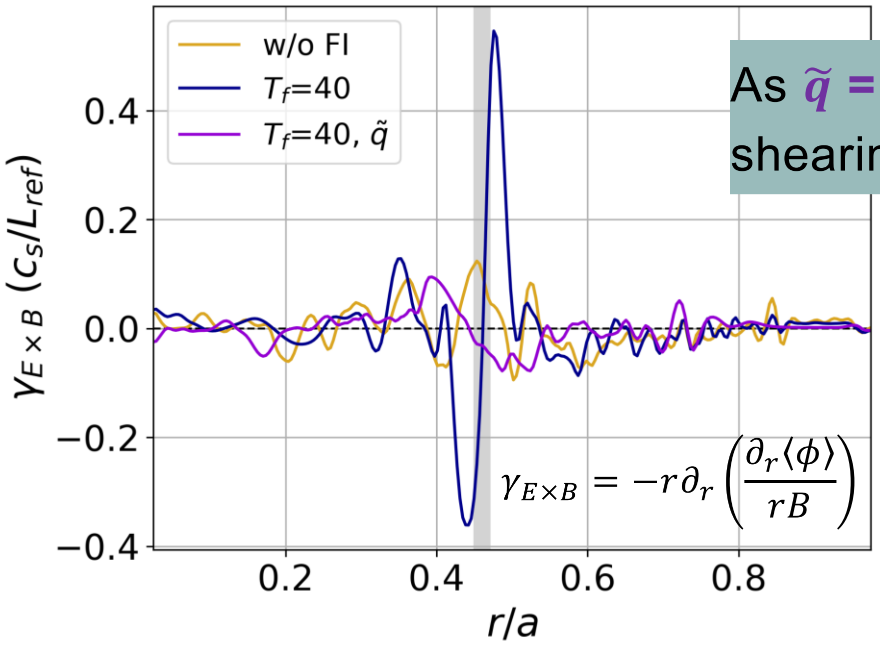
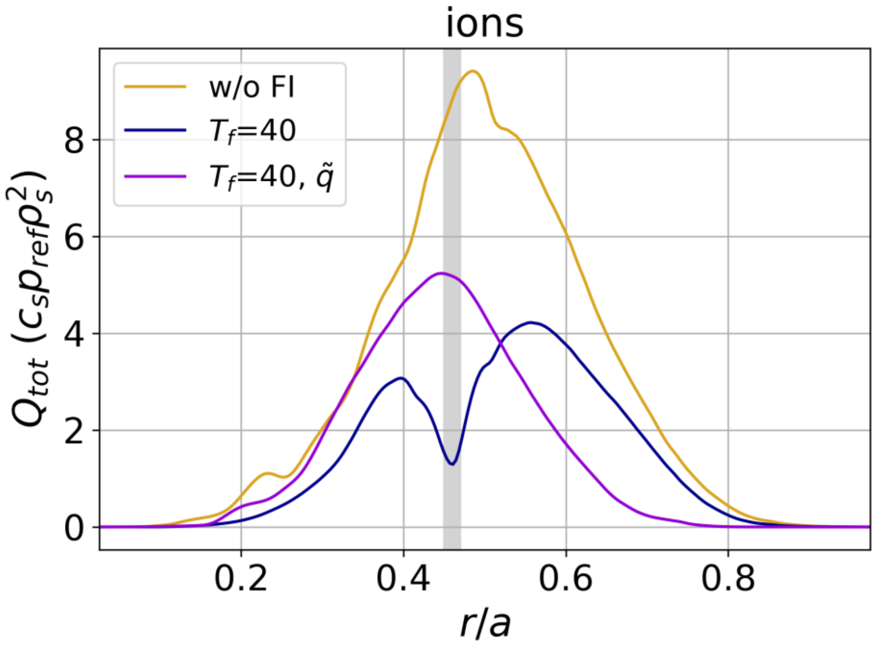


As **$\tilde{q}$ = 1 is shifted**, the shearing layer disappears

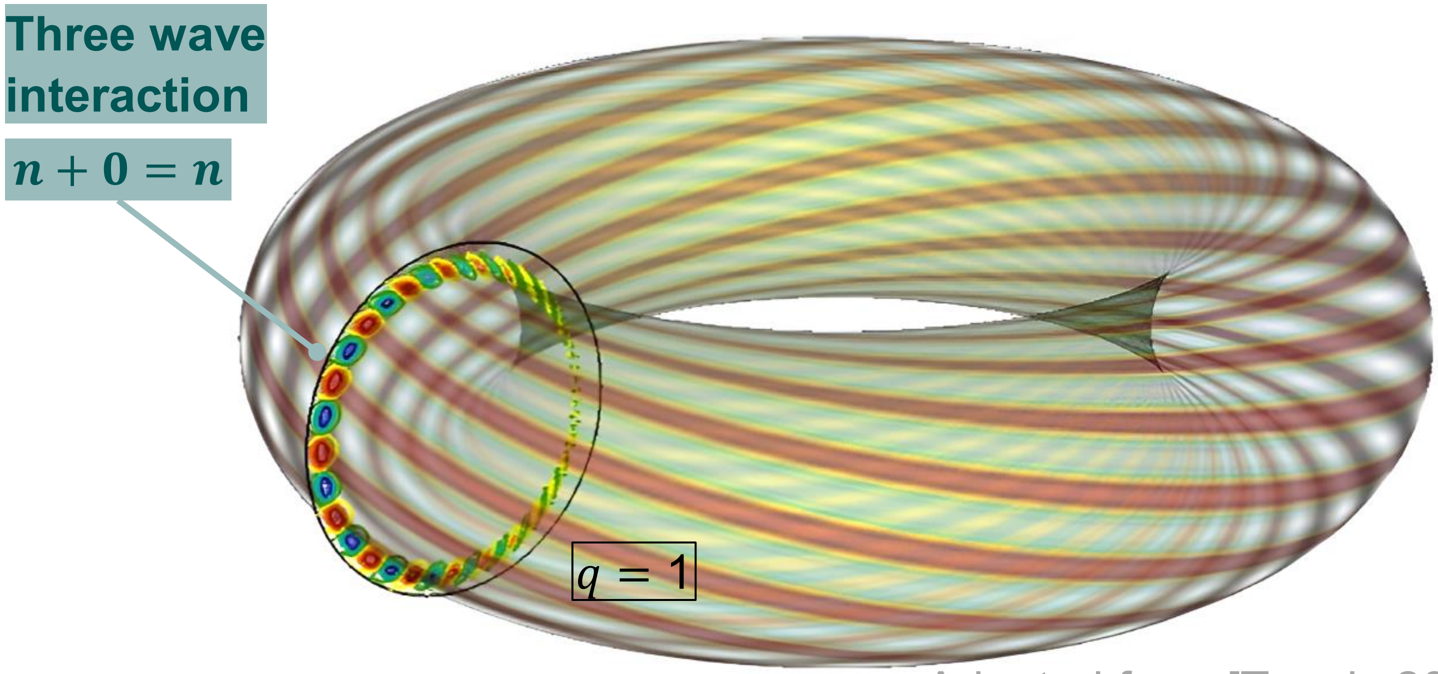


Maximum of the gradients (ITG drive) coincides with q = 1 → $\gamma_{E\times B}$ generation → Q_{tot} reduction

How do we explain this?

Low T_f values – ZF through turbulence self-interaction

Turbulent eddy self interaction – The mode n interacts with itself to generate the n = 0 ZF by «biting its own tail» after traveling around the torus. This process efficiency is maximized on **lower order rational surfaces** [Volčocas 24, Di Giannatale 25].



Adapted from [Tzanis 20]

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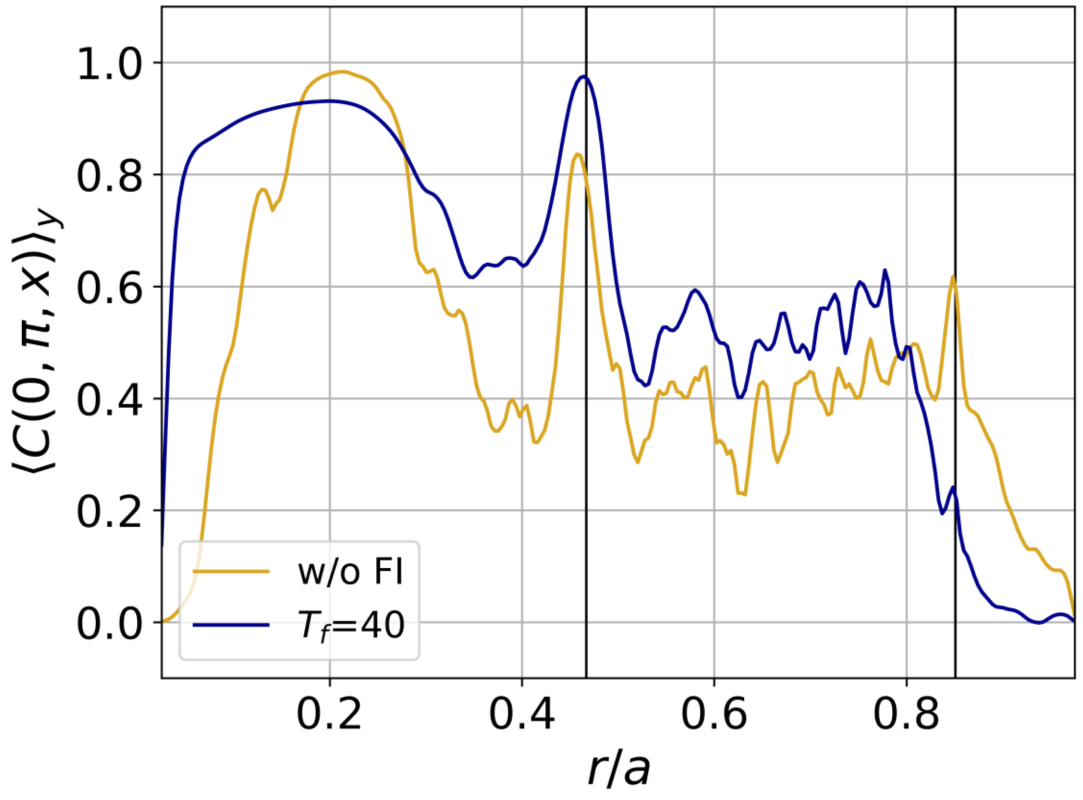
Correlation between z = -π and $z = 0$: how much does the eddy «sense» itself along the field line?

$$C(\boldsymbol{x}_1, \boldsymbol{x}_2) = \frac{\langle \phi_{NZ}(\boldsymbol{x}_1)\phi_{NZ}(\boldsymbol{x}_2)\rangle_t}{\sqrt{\langle \phi_{NZ}^2(\boldsymbol{x}_1)\rangle_t \langle \phi_{NZ}^2(\boldsymbol{x}_2)\rangle_t}}$$

- $\langle C\rangle_y$ peaks at q = 1 , q = 2 and where $\hat{s} \approx 0$ ($l_{||} \sim \hat{s}^{-1}$), both with and w/o FI



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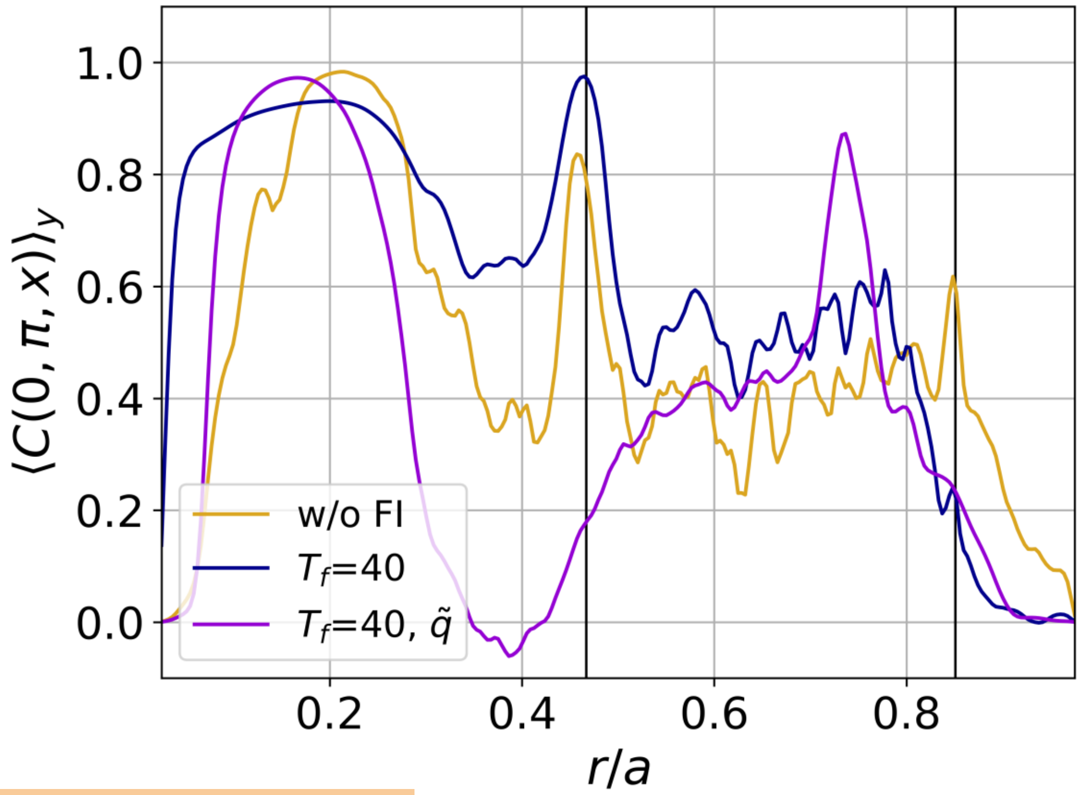
- $\langle C \rangle_y$ peaks at q = 1 , q = 2 and where $\hat{s} \approx 0$ ($l_{||} \sim \hat{s}^{-1}$), both with and w/o FI
- When $\tilde{q}$ **= 1 is shifted**, also $\langle C \rangle_y$ peak moves

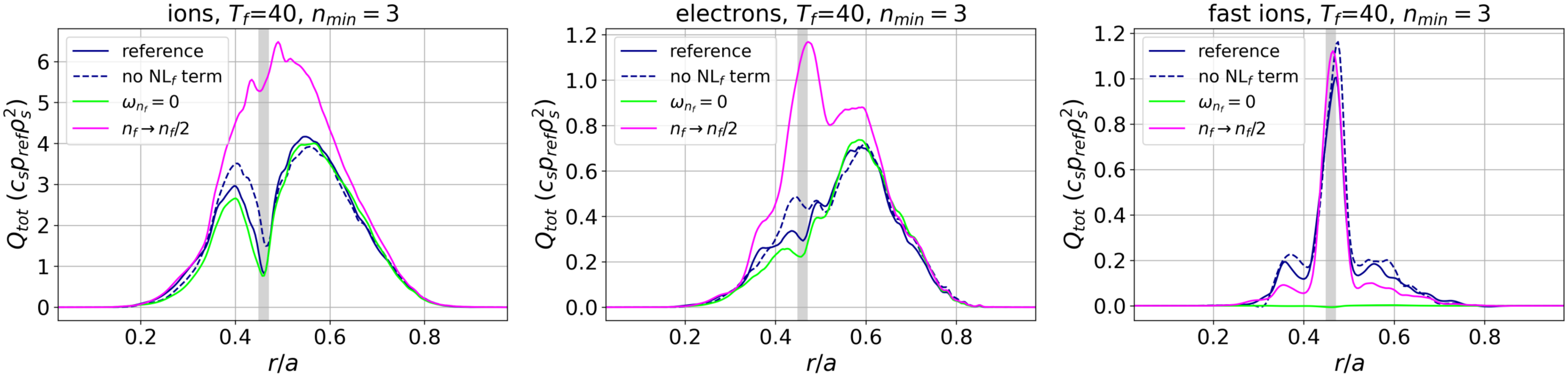


We have self-interaction at q = 1. How do **fast ions** enter the picture?

Low T_f values – FI enhancement of ZF generation

The role fast ions play in the nonlinear zonal flow physics is investigated.

- NL term ($\propto \vec{v}_{\bar{\xi}}$) is removed from FI Vlasov equation → no effect
- n_f **profile is flattened** → no effect
- n_f **is halved** → stabilization vanishes → hint of a **threshold in FI density**



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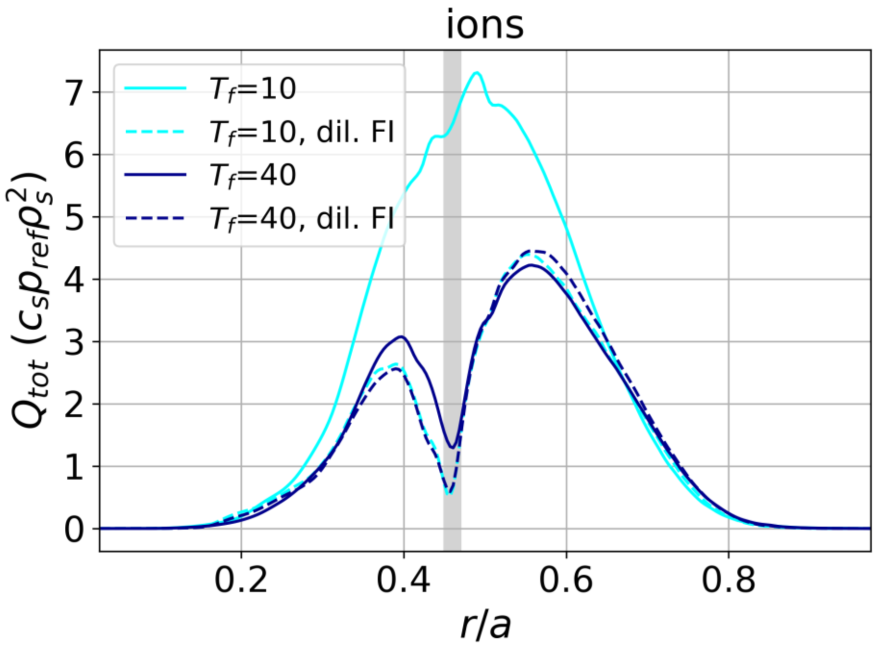
FI dilution effect on ZF generation – For, $k_y^2\rho_s^2 \ll k_y^2\rho_{T_f}^2$, FI considered a passive species in the turbulence + zonal flow system → **ZF destabilization threshold scales as $(1 - n_f/n_e)$** → Higher n_f enhances the ZF trigger [Hahm 23, Choi 24].

- FI set as a **dilution species** → Stabilization at q = 1 recovered independently on T_f



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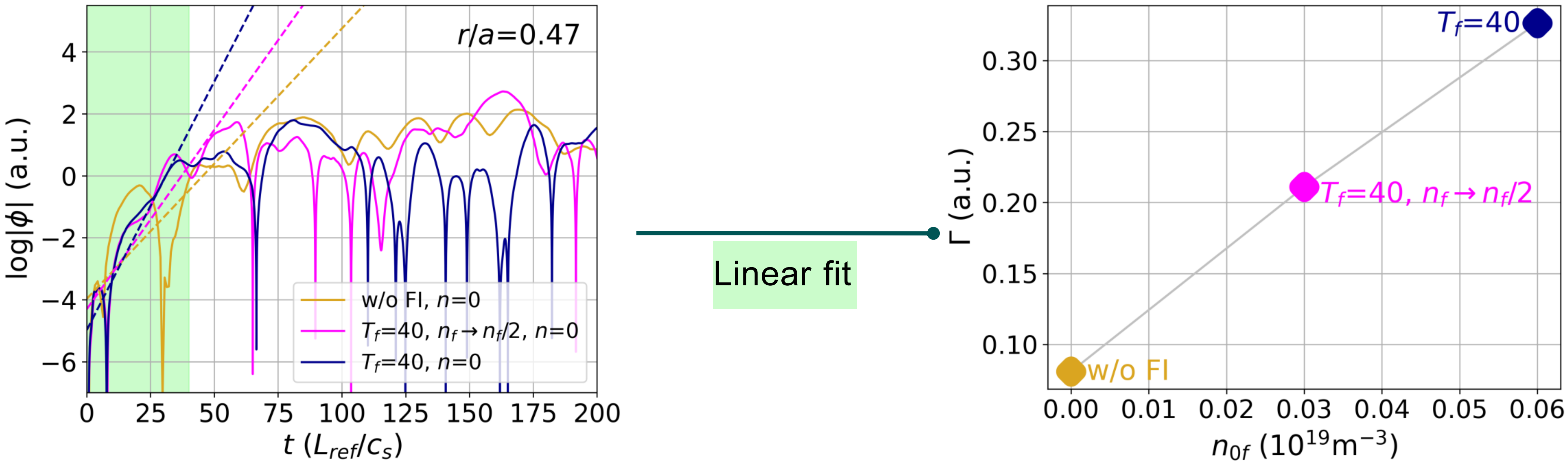
- ZF growth rate scales as n_f in the linear phase



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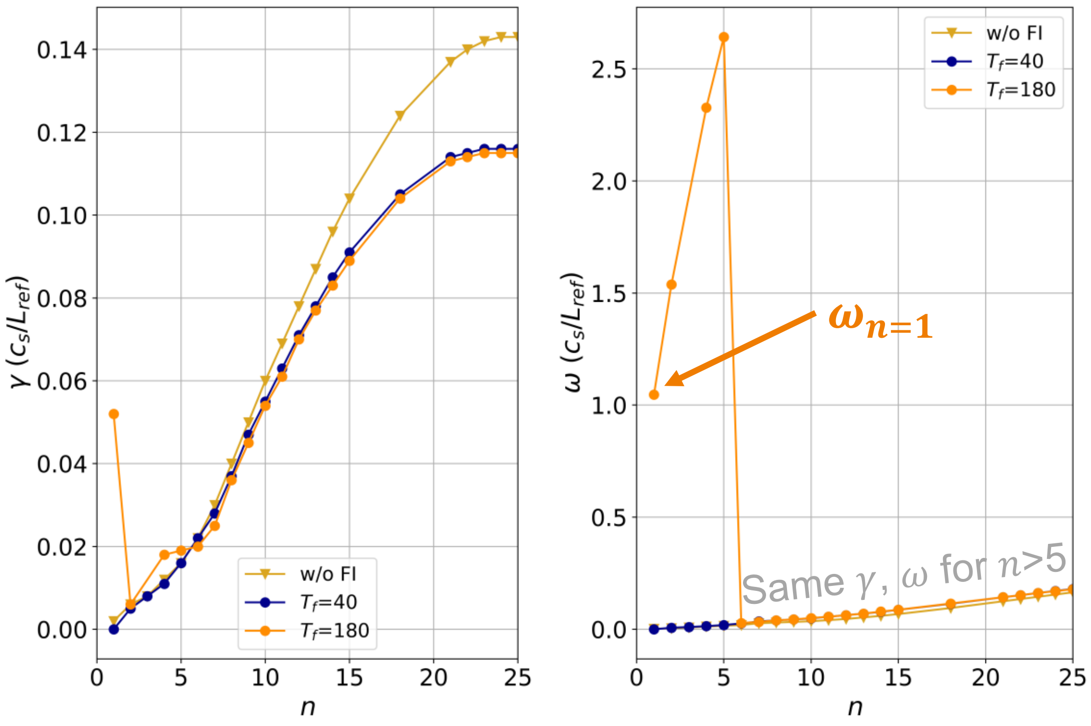
High T_f values – Linear FB destabilization

A case with $\boldsymbol{T_f}$ **= 180 keV** is now considered.

- The $\boldsymbol{n}$ **= 1** mode is destabilized around $\boldsymbol{q}$ **= 1**



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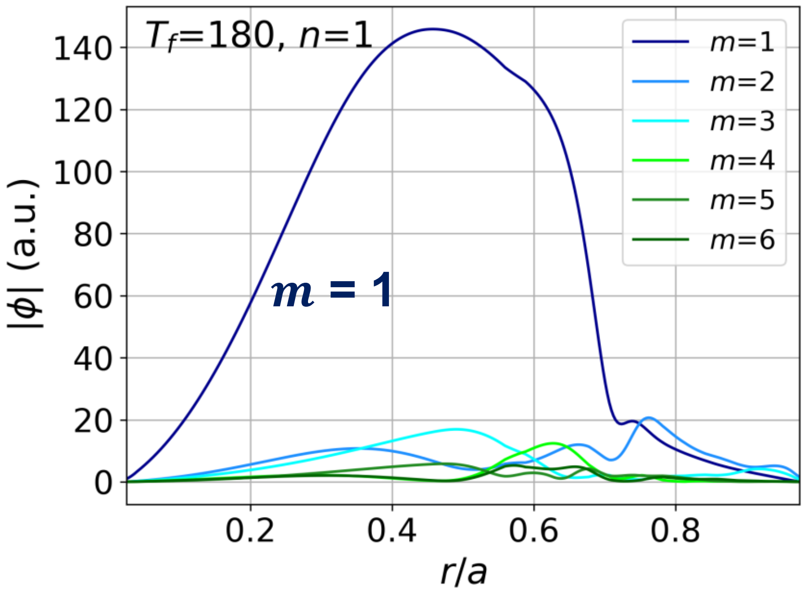
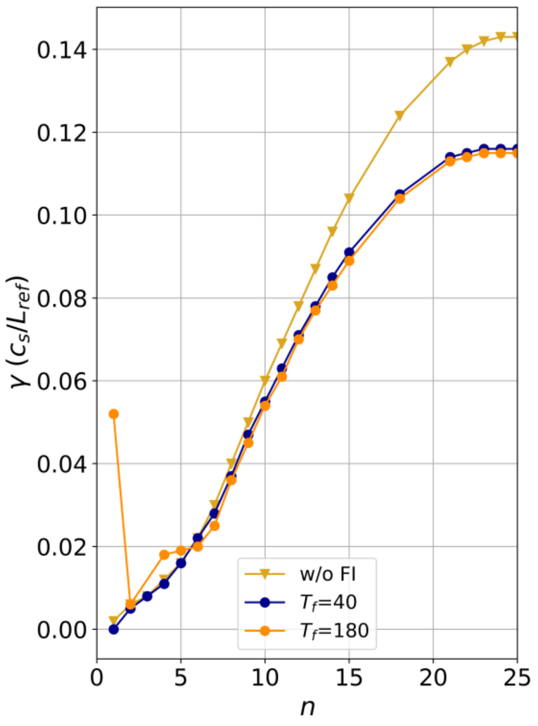
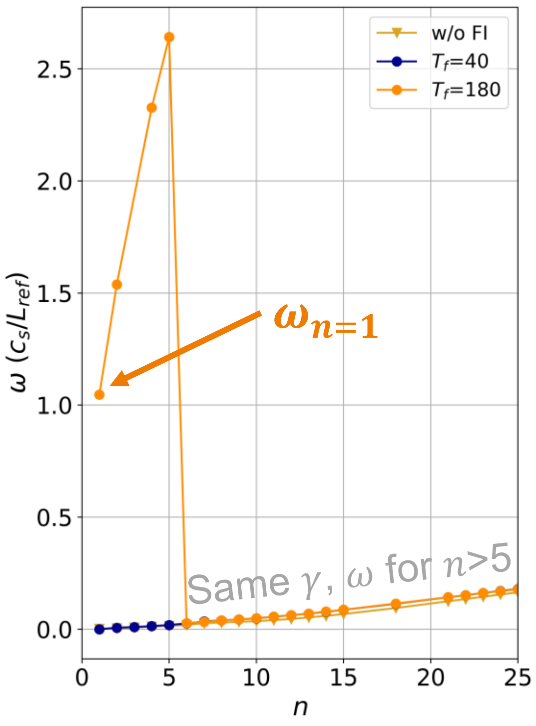
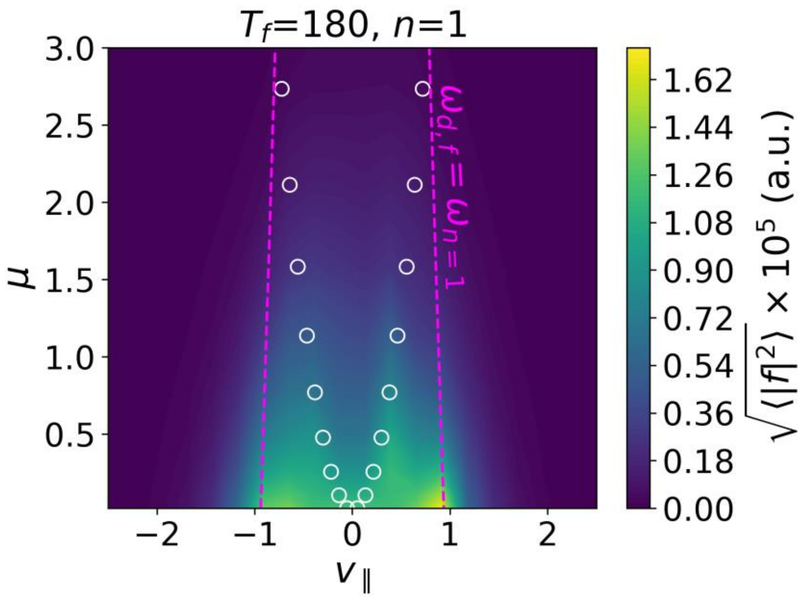
- The n **= 1** mode is destabilized around q **= 1**
- Dominant m **= 1** contribution in the $|\phi|$ envelope
- High-frequency mode resonates with **passing FI precessional frequency** [Brochard 19]









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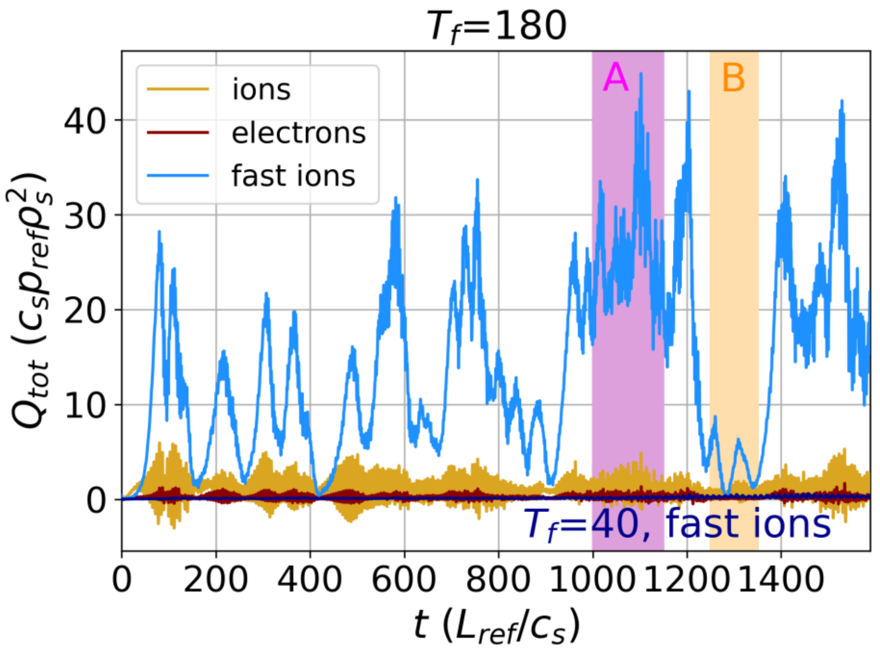
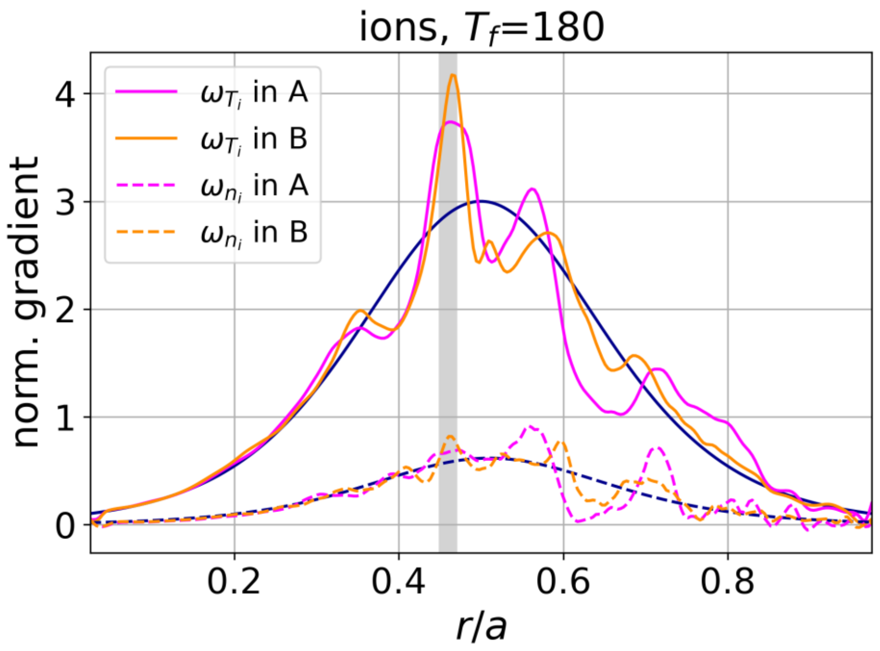
A nonlinear simulation is perfromed and compared with the «low T_f» ones.

- Phases with **high Q_{tot}** (**A**) alternate to phases with **low Q_{tot}** (**B**)





- A strong flattening (decr. ω_{n_i,T_i}) of the thermal profiles is detected during **phase A**

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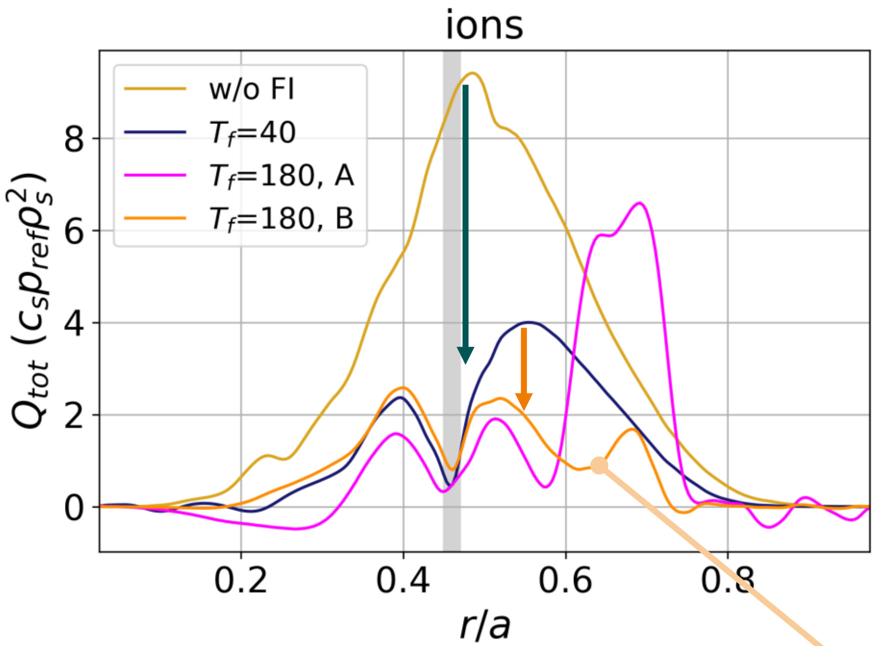
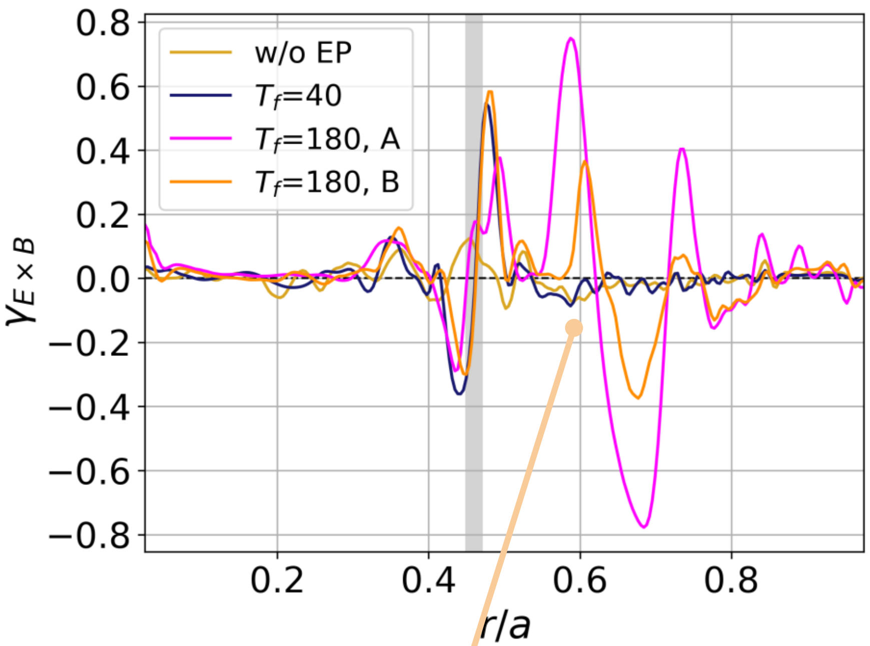




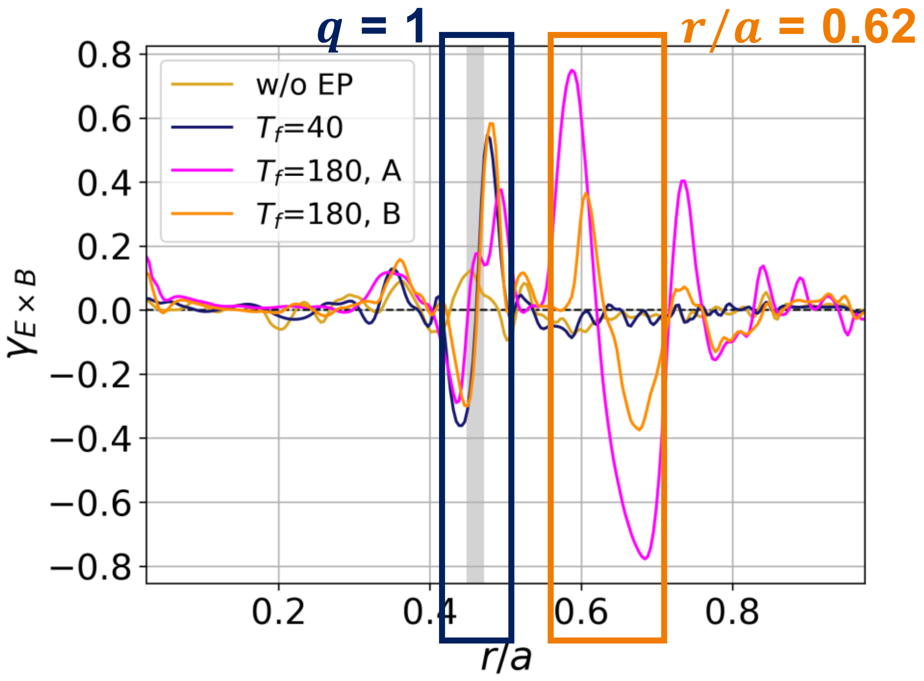
90% stabilization at q **= 1** due to ZF from eddy self-interaction (same Q_{tot} and $\gamma_{E\times B}$)

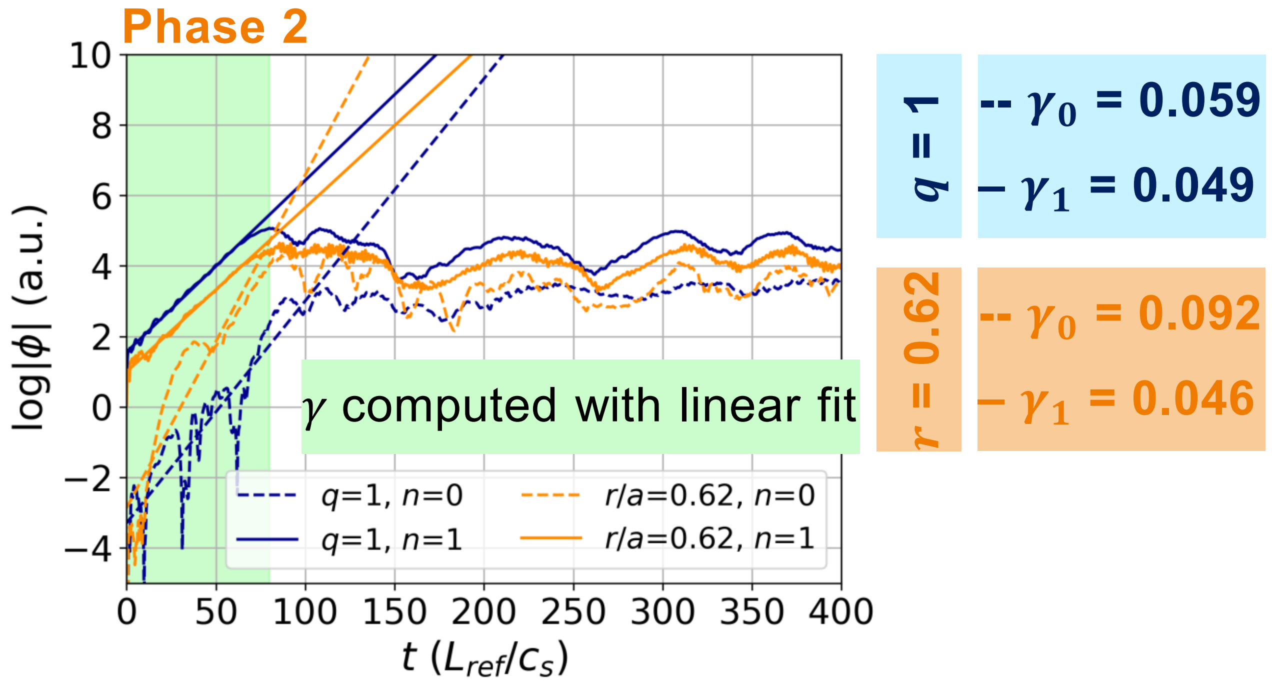
50% stabilization at $r/a \approx$ **0.62** due to **new shearing layer** generation. Q_{tot} increase in **A** at $r/a \approx$ **0.7**.

High T_f values – ZF generation by FB mode

The zonal mode characteristics are studied for the T_f = 180 keV setup.

- Around $r/a \approx 0.62$, $\gamma_0 = 2\gamma_1$ holds. This is not true at q = 1 (where the mechanism for ZF generation is different)





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Conclusions

- The influence of **fast ions** in a setup where thermal gradients peak at q = 1 has been investigated
- **Zonal-flow generation via turbulence self-interaction** has been studied. This effect is independent on fast ions
- **ZF enhancement via FI dilution** is very efficient in reducing turbulent fluxes
- When a **FB** is destabilized, fluxes are further reduced via **beat-driven ZF**

Interaction between FI and rational surfaces is a fundamental topic for the study of turbulence suppression

…Future work

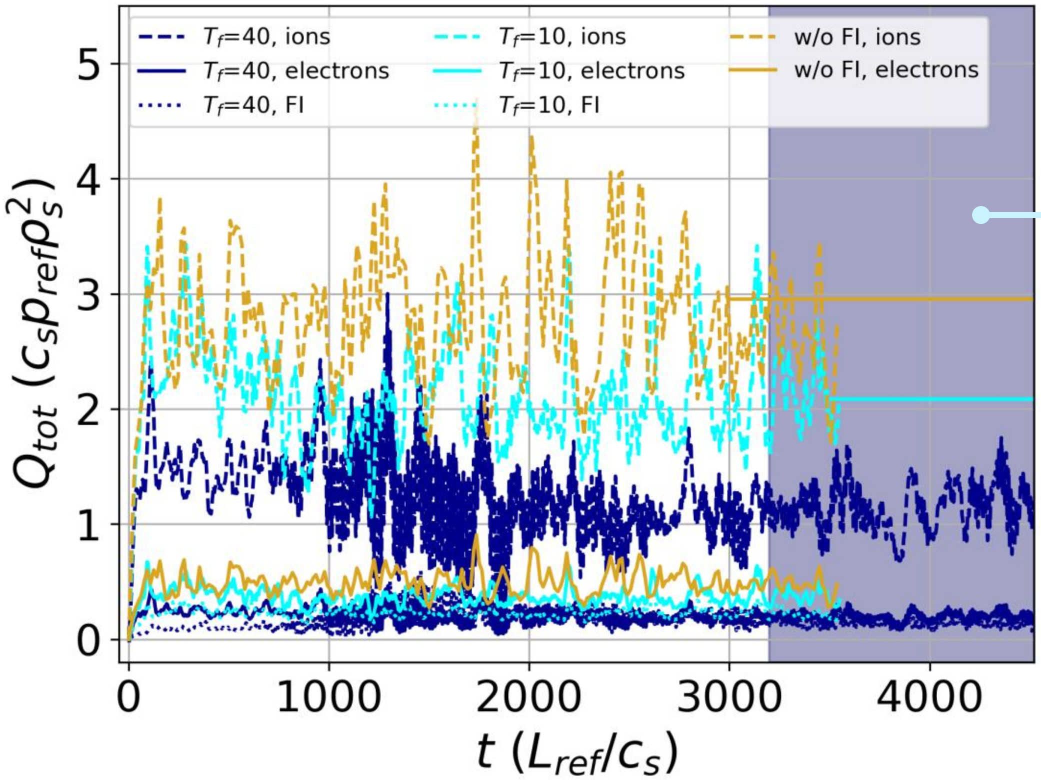
- Modeling of an **AUG** scenario with strong FB activity is ongoing
- Comparison between GENE and **ORB5** [Lanti 20] for this case

Thank you for your attention!

Low T_f values – Nonlinear simulations time traces

Backup

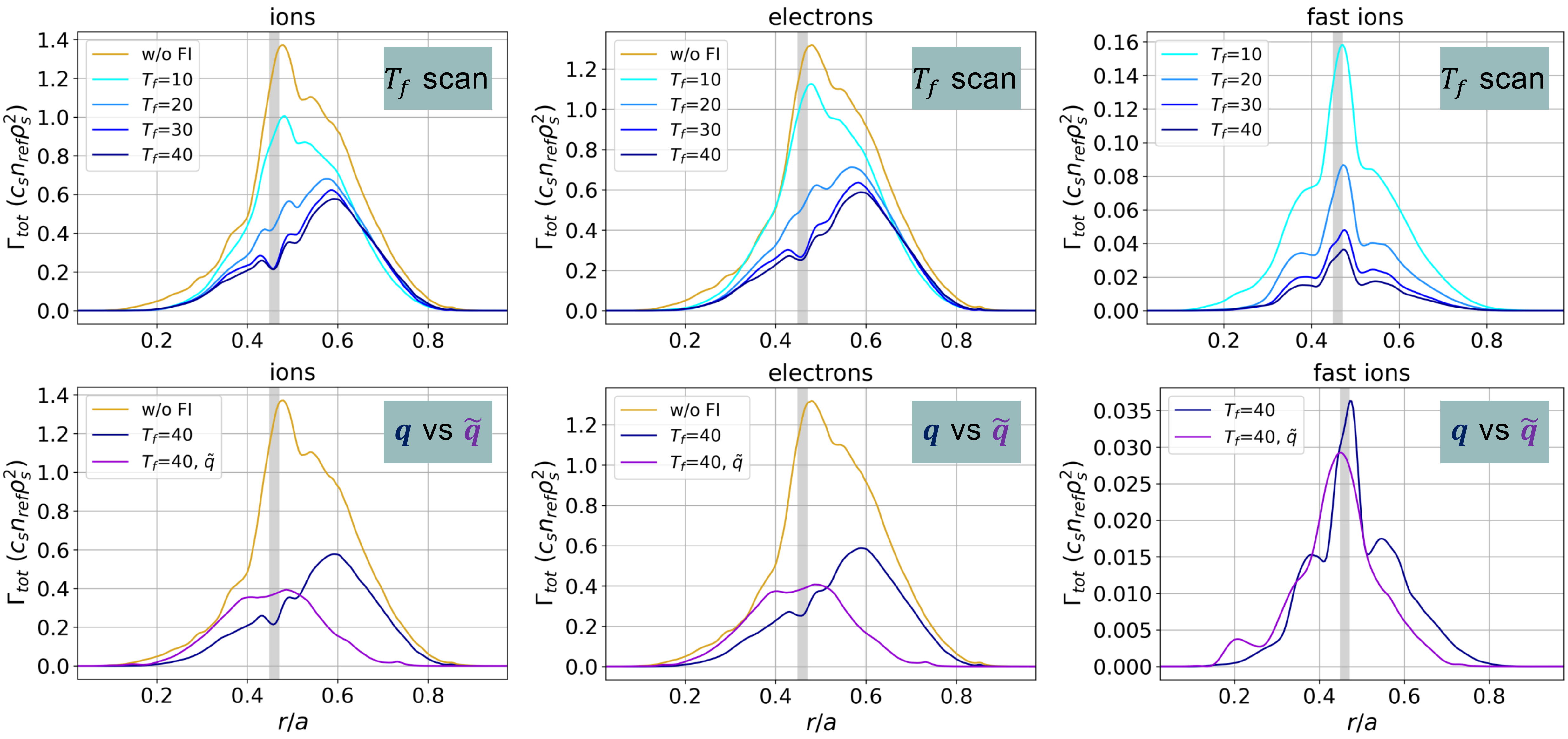
All analyzed quantities are time-averaged in an interval in which turbulence is saturated.



T_f = 40 quantities averaged here

Low T_f values – Particle fluxes

Backup

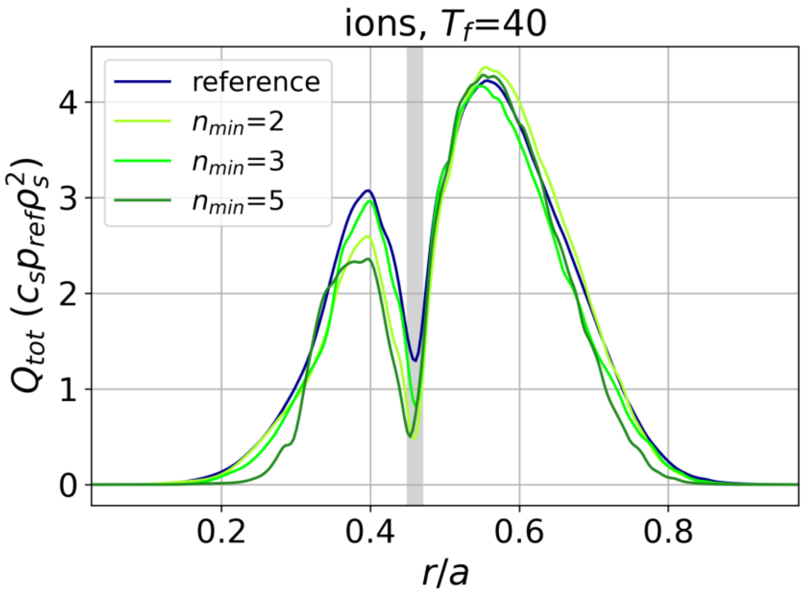


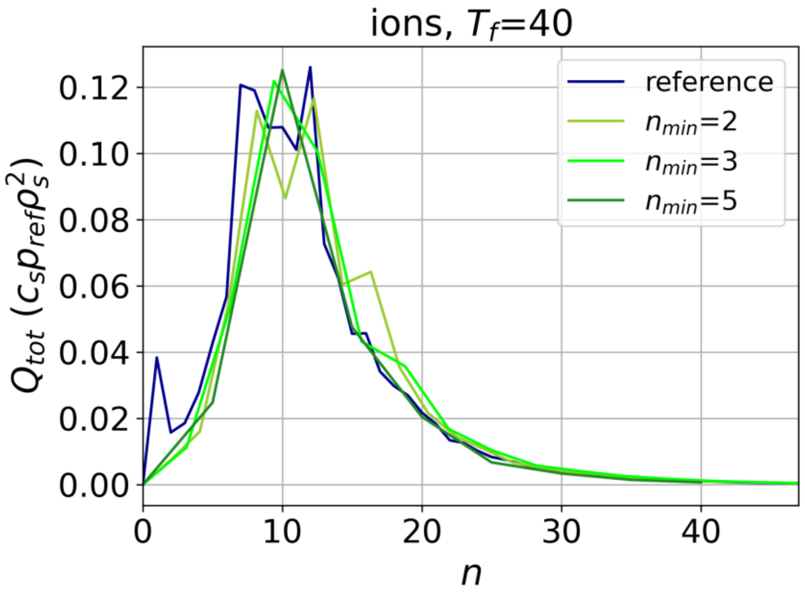
Low T_f values – Different n_{min} runs

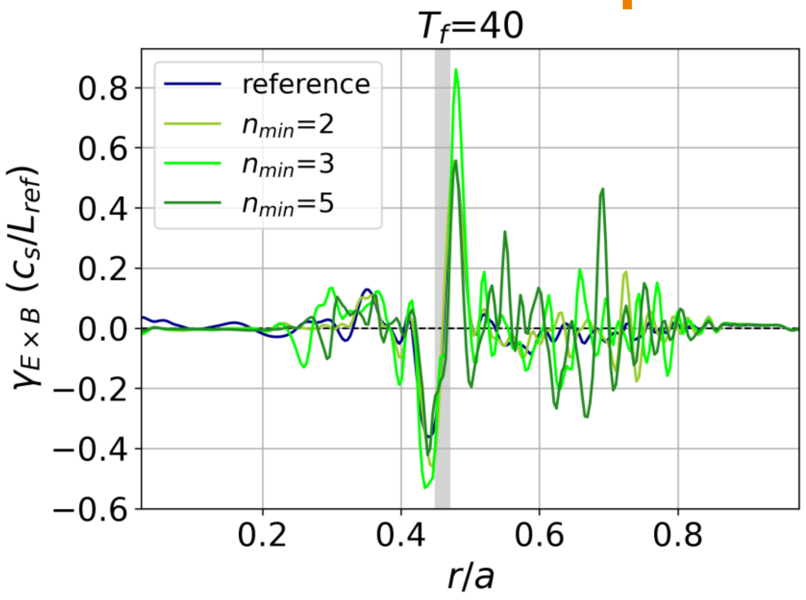
Backup

Runs with $n_{min} \in \{1,2,3,5\}$ are performed.

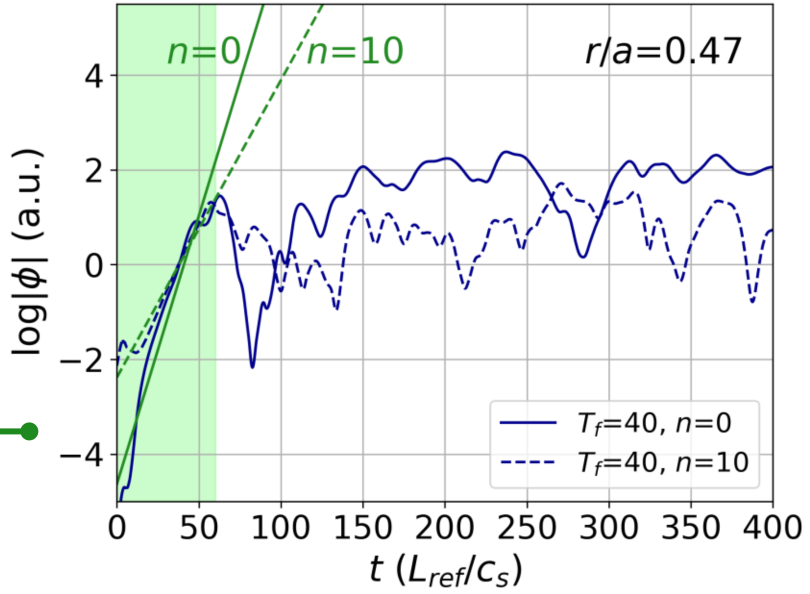
Modes included are $n = (n_{min}, 2n_{min}, \dots, (n_{k_y}-1)n_{min})$.







- We confirm that low-n modes do not contribute to the physics
- For n_{min} = 5: n = 10 is enough to trigger the self-interaction ZF
  At q = 1 we have $\gamma_0 \approx 2\gamma_{10}$



Low T_f values – General picture

Backup

Reference setup w/o FI

- ITG-dominated
- ZF generation via **turbulence self-interaction** at lower order rational surfaces (q = 1)

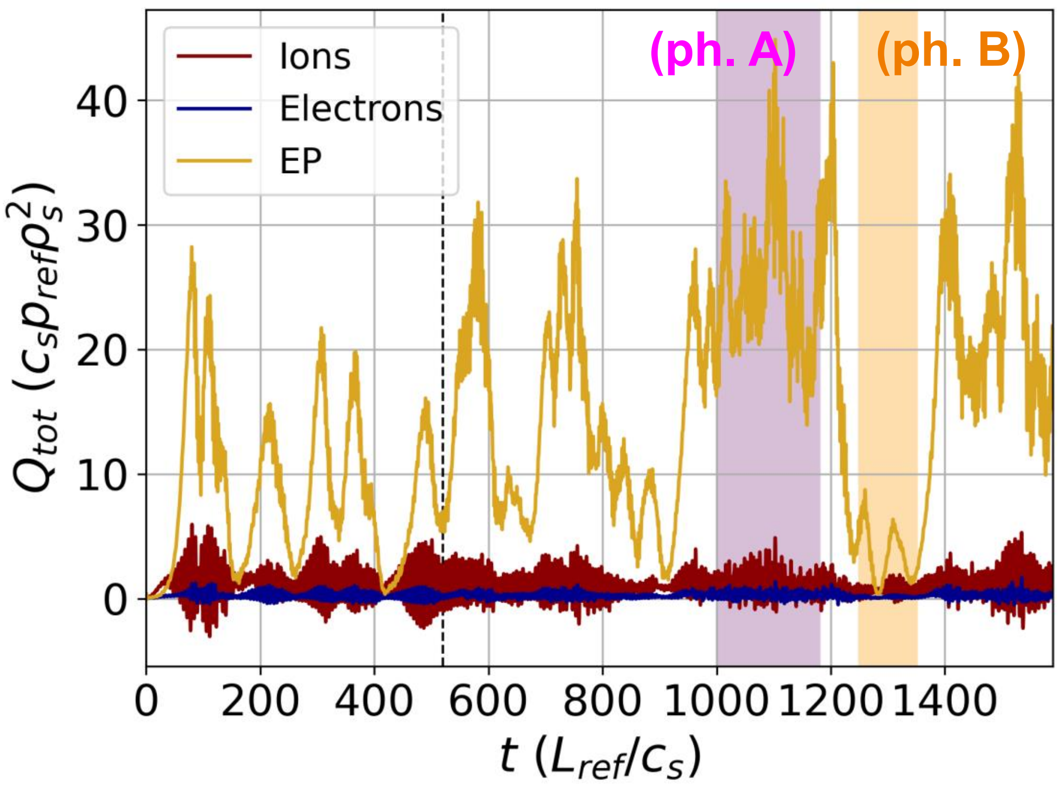
With FI

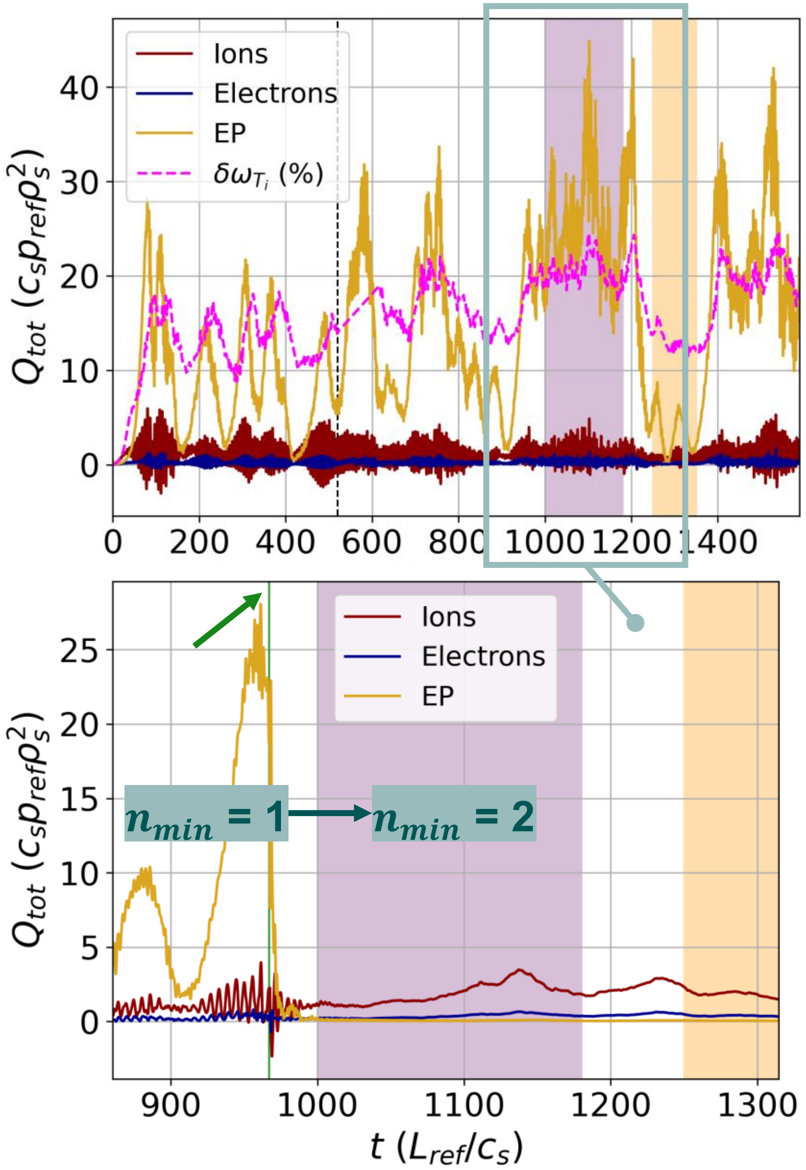
- Dilution of thermal profiles – $\boldsymbol{\gamma\downarrow}$ with FI
- Quasi-resonant effect – $\boldsymbol{\gamma\downarrow}$ as T_f increases
- ZF enhancement – $\boldsymbol{\gamma_{E\times B}\uparrow}$ as T_f increases ($k_y^2\rho_s^2 \ll k_y^2\rho_{T_f}^2$)

ZF threshold reduction by FI is a very efficient way to suppress turbulence via shearing

High T_f values – Nonlinear simulations time traces

Backup





- Dashed vertical line: outer buffer region increased from $\Delta r/a$ = 0.025 to $\Delta r/a$ = 0.05
- $\delta\omega_{T_i} = \langle |\omega_{T_i} - \omega_{T_i0}|/\omega_{T_i0} \rangle_{r/a}$

High T_f values – Heat and particle fluxes

Backup