Turbulence suppression due to energetic particles: From first principles to gyrokinetic simulations and experimental observations

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with

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IPP ASDEX Upgrade

Overview

Novel type of ITB induced by ion-cyclotron-resonance-heating (ICRH) fast ions predicted-first theoretically and observed at ASDEX Upgrade (AUG)

- Theoretical model: wave-particle resonant interaction between fast ions and ITG.
- How to design an optimised discharge at ASDEX Upgrade?
- Experimental evidence: improved confinement!
- Radially global GENE turbulence simulations: transport barrier
- Transport barrier trigger mechanism
- Conclusions

Turbulence stabilising mechanism by fast ions: wave-particle resonance effect

- Ion-scale frequency (positive defined for ion mode) ω_k → fast ions drift frequency (due to inhomogeneity of B_0) $\omega_{d,f}$

Resonant interaction (quasi-linear, electrostatic effect):

1. energetic particles can resonate with the background instabilities if

$$\omega_k \approx \omega_{d,f}$$

$\omega_{d,f}$ is controlled by T_f

2. significant effect only if

$$\left|\frac{R}{L_{n,f}}\right| \ll \left|\frac{R}{L_{T,f}}\right|$$

Condition typically matched by ICRH fast ions

- Depending on the phase-space localisation of the resonance, this effect might be destabilising as well

[1] A. Di Siena et al., Nucl. Fusion ***58*** *054002 (2018).*

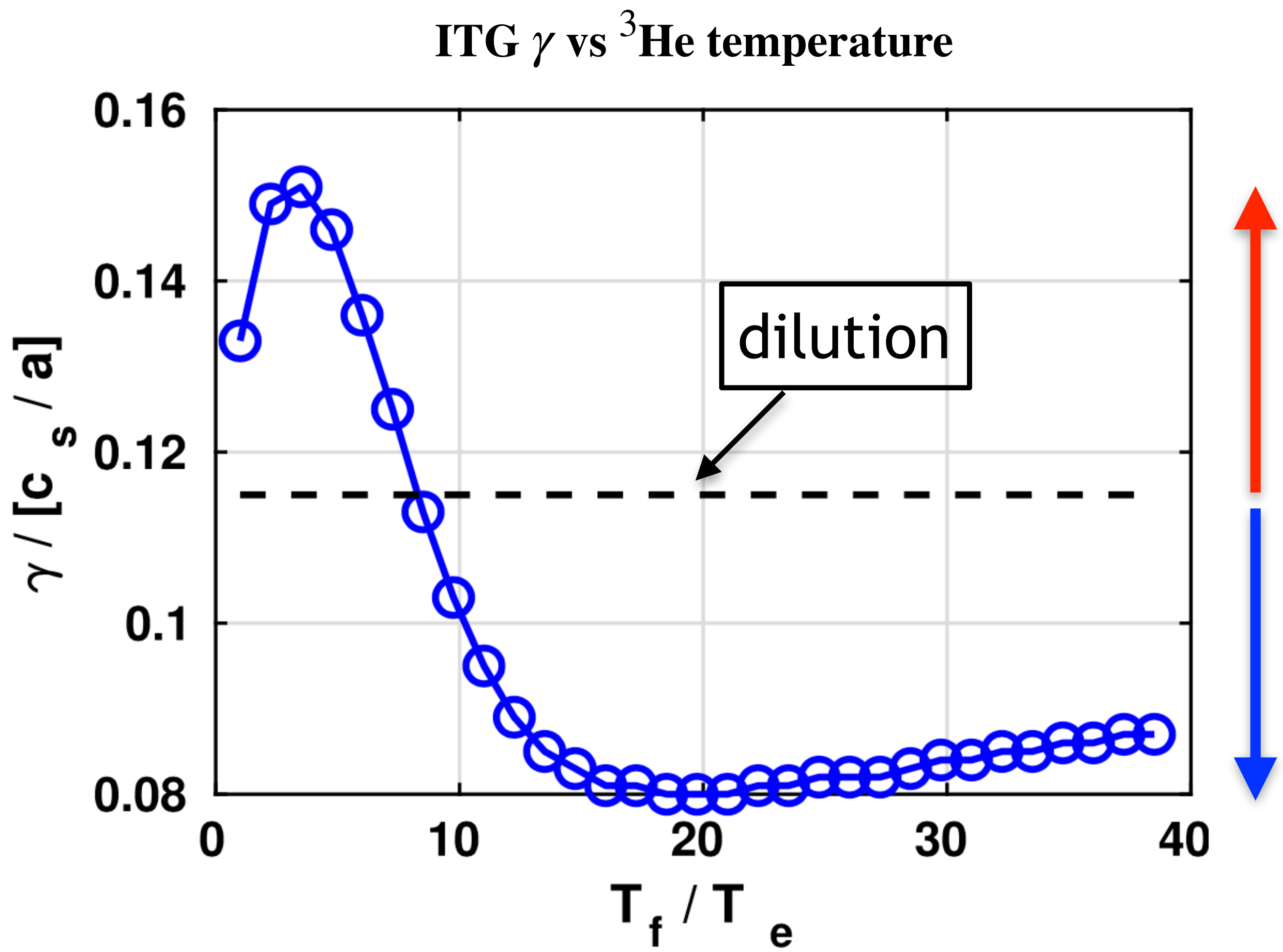
[2] A. Di Siena et al., Phys. Plasmas ***26*** *052504 (2019).*

[3] A. Di Siena et al., Phys, Rev. Lett. ***125*** *105002 (2020).*

[4] A. Di Siena et al., submitted to publication https://arxiv.org/abs/2010.14839

Turbulence stabilising mechanism by fast ions: wave-particle resonance effect

- $T_f/T_e < 7$ leads to a linear ITG destabilisation $\rightarrow \omega_k = \omega_{d,f}$ (positive drive region)
- Optimal stabilisation for ^{3}He at $T_f/T_e \sim 20 \rightarrow \omega_k = \omega_{d,f}$ (negative drive region)



- Depending on the wave-number selected the "sweet-spot" in T_f/T_e for maximum stabilisation changes.

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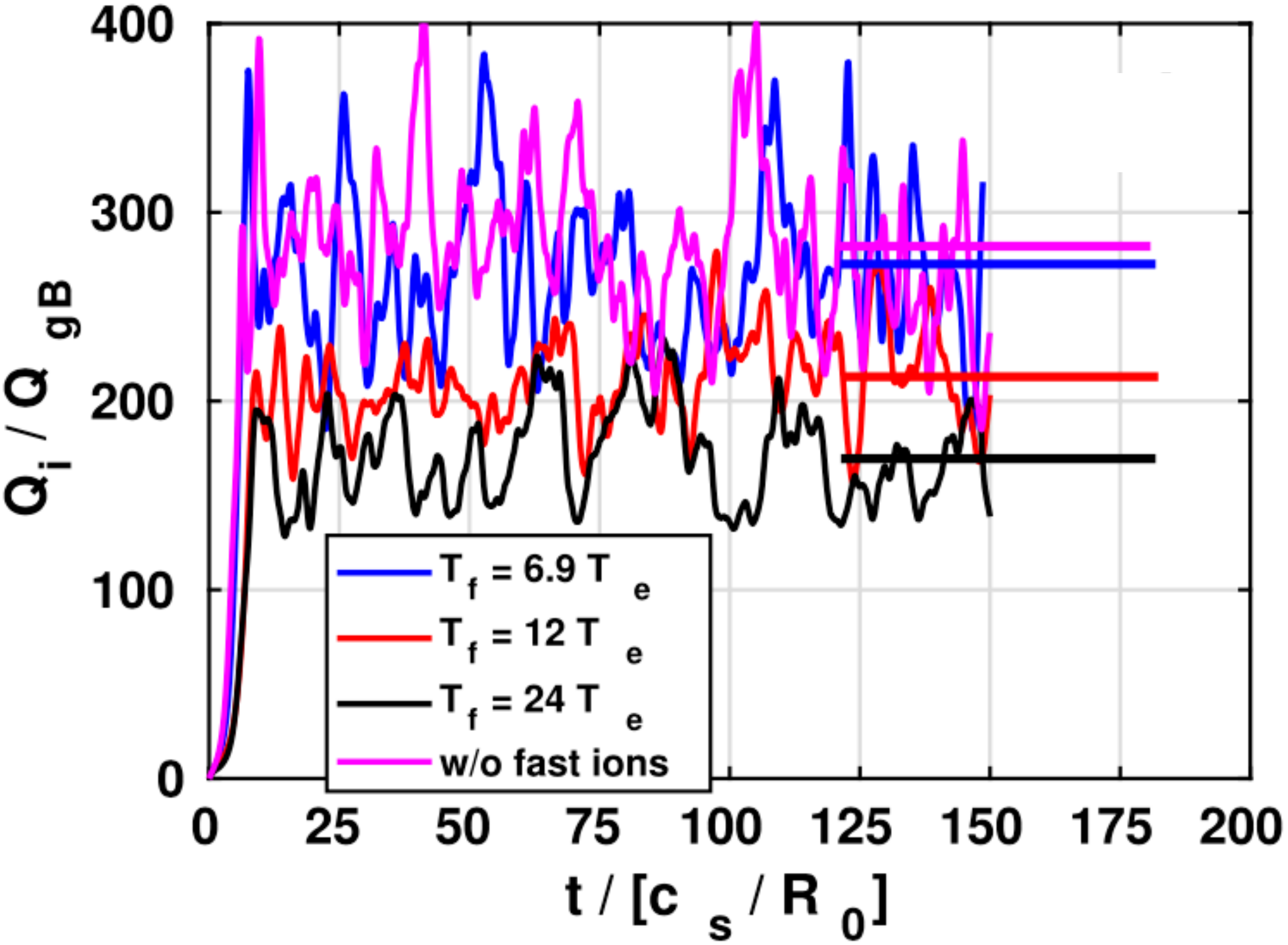

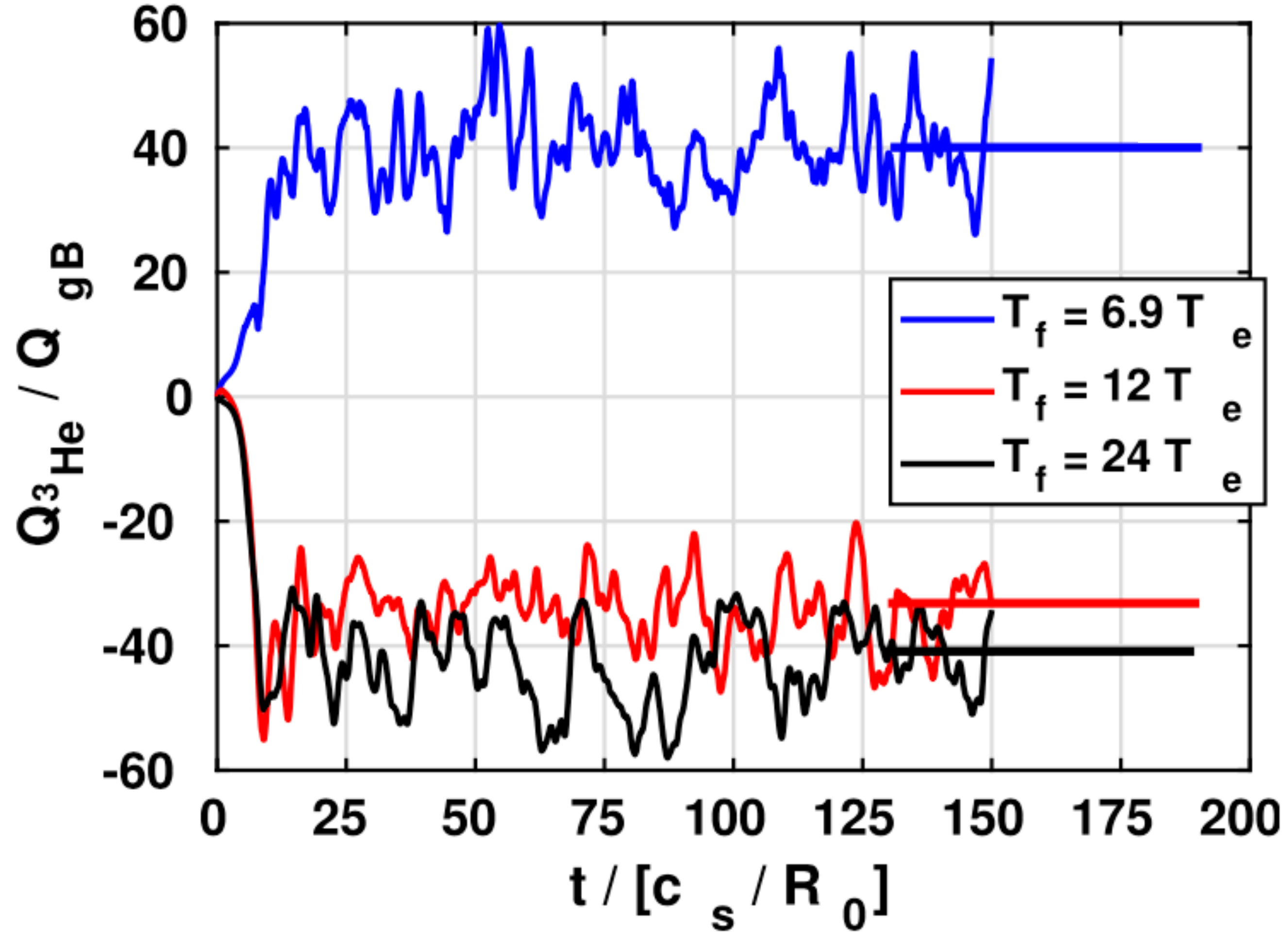

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How to design experimental profiles maximising this resonance effect with TORIC/SSFPQL and GENE?

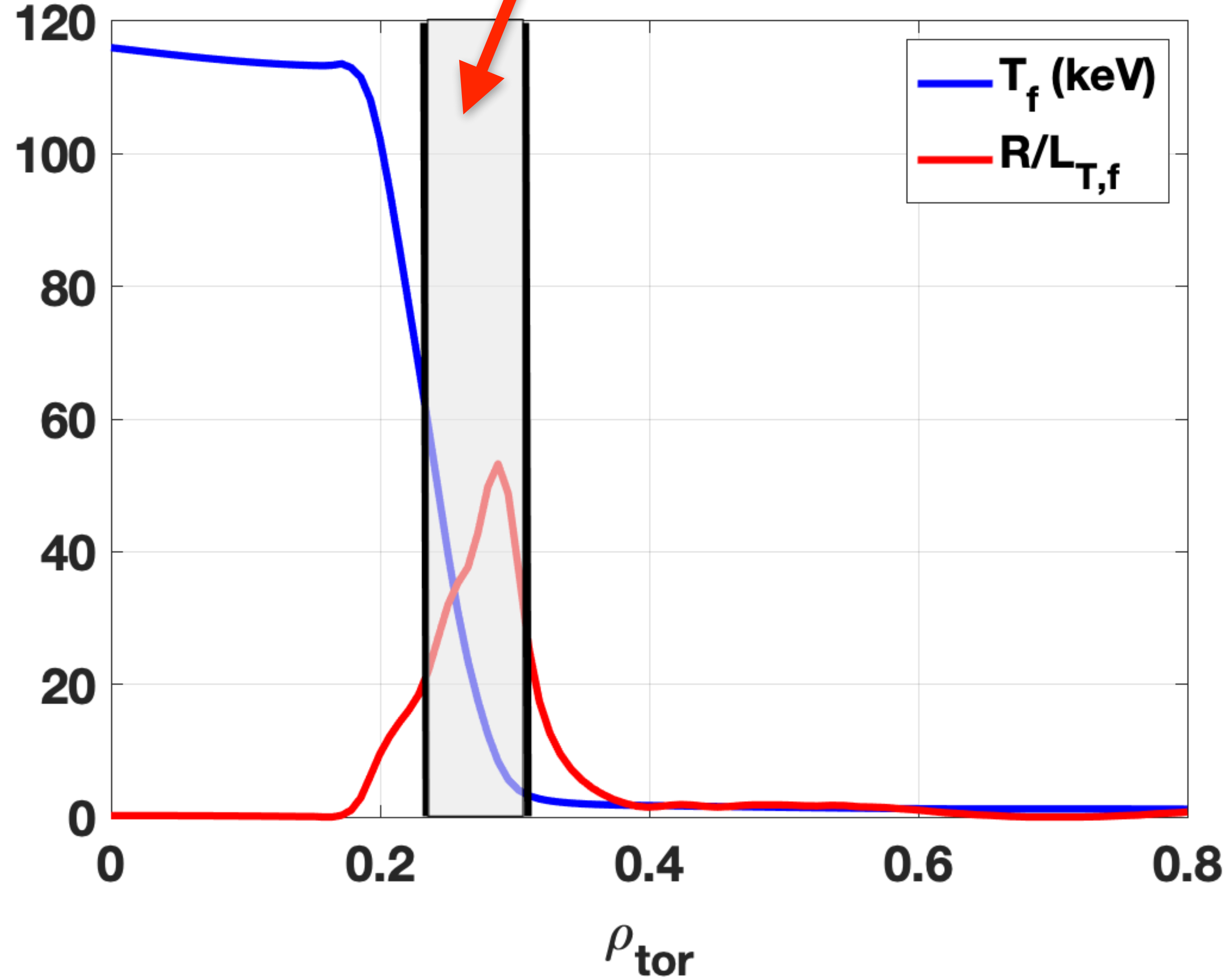
- Energetic particle temperature profile is designed to suppress almost totally the ITG micro-instabilities in a narrow layer

- Large energetic particle charge concentration are required

- Large temperature gradients in the region where T_f/T_e is optimal

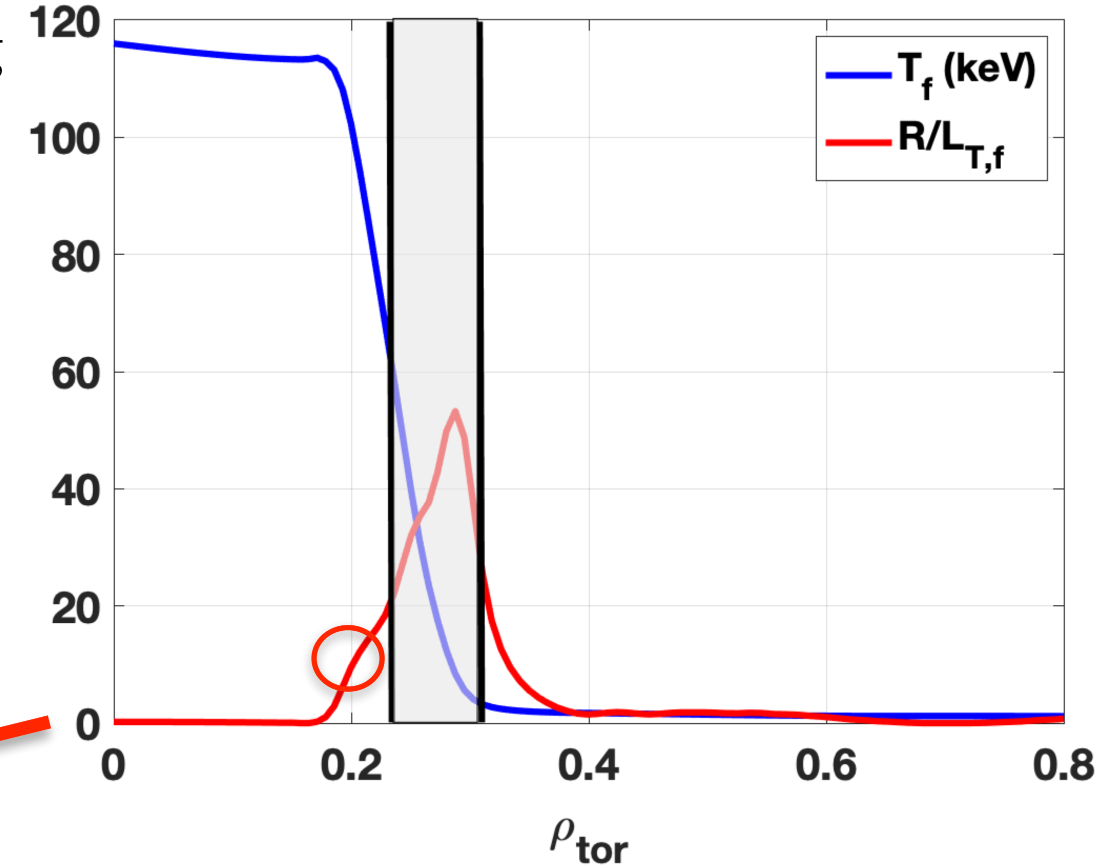
- Both stabilising and de-stabilisation regions are essential for the transport barrier formation (shown later)

Optimal conditions for wave-particle resonant effects

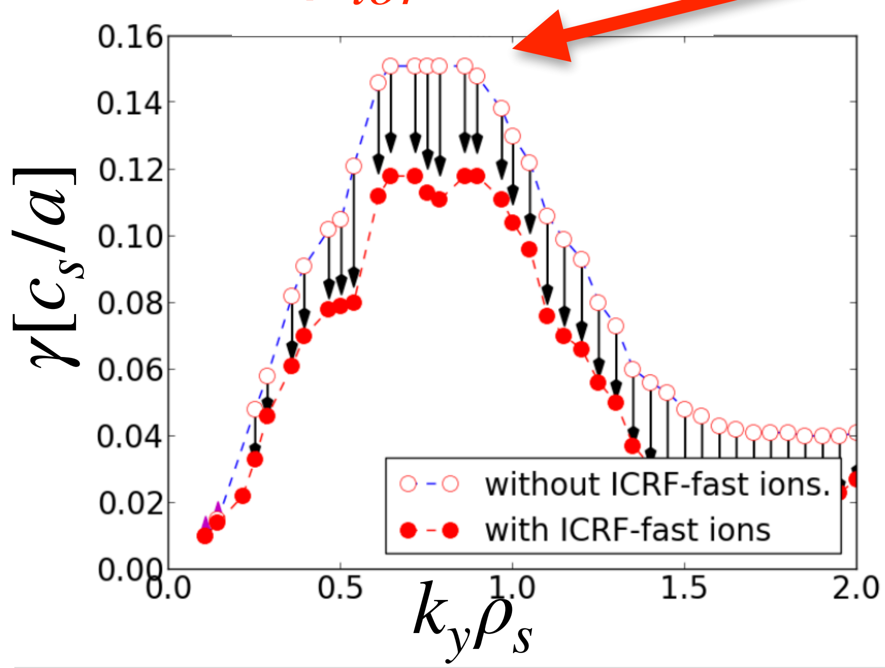


Microinstability characterisation

- $\rho_{tor} = 0.2$: large T_f; small R/L_{T_f}: no significant stabilising effect expected/observed.



$\rho_{tor} = 0.2$



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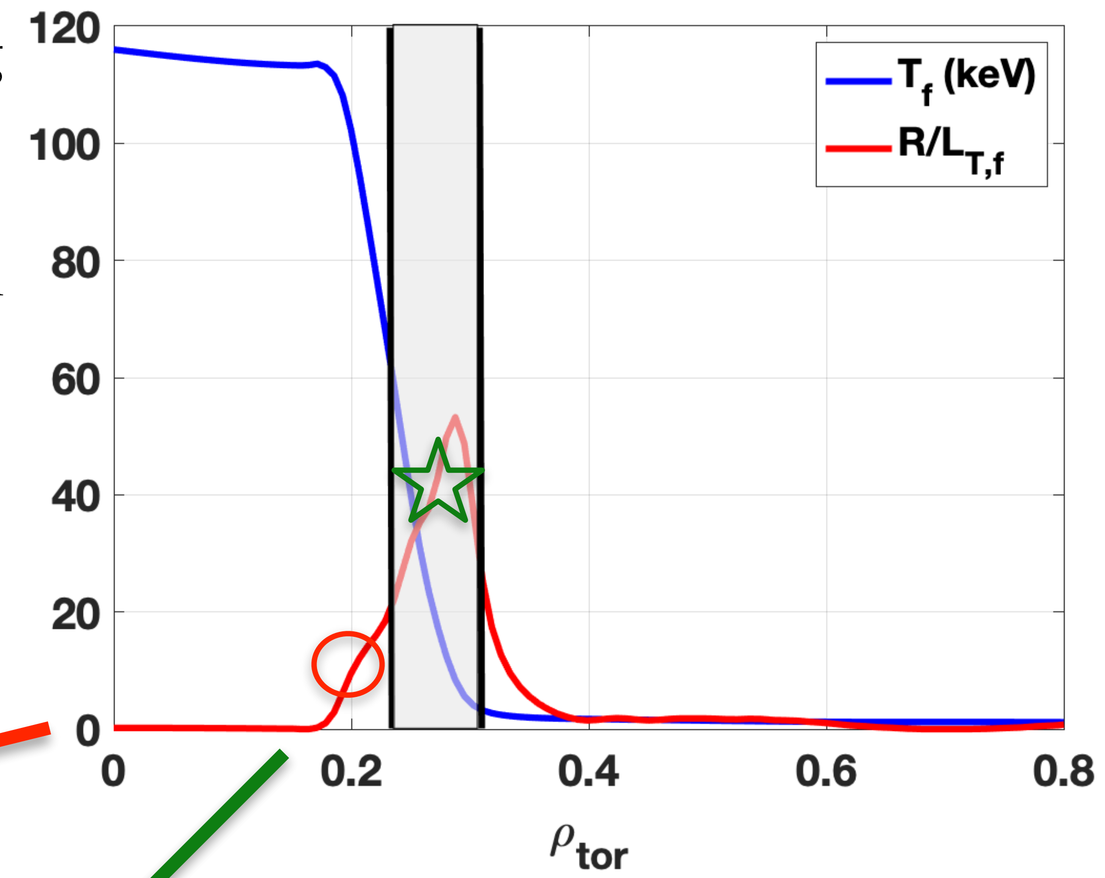
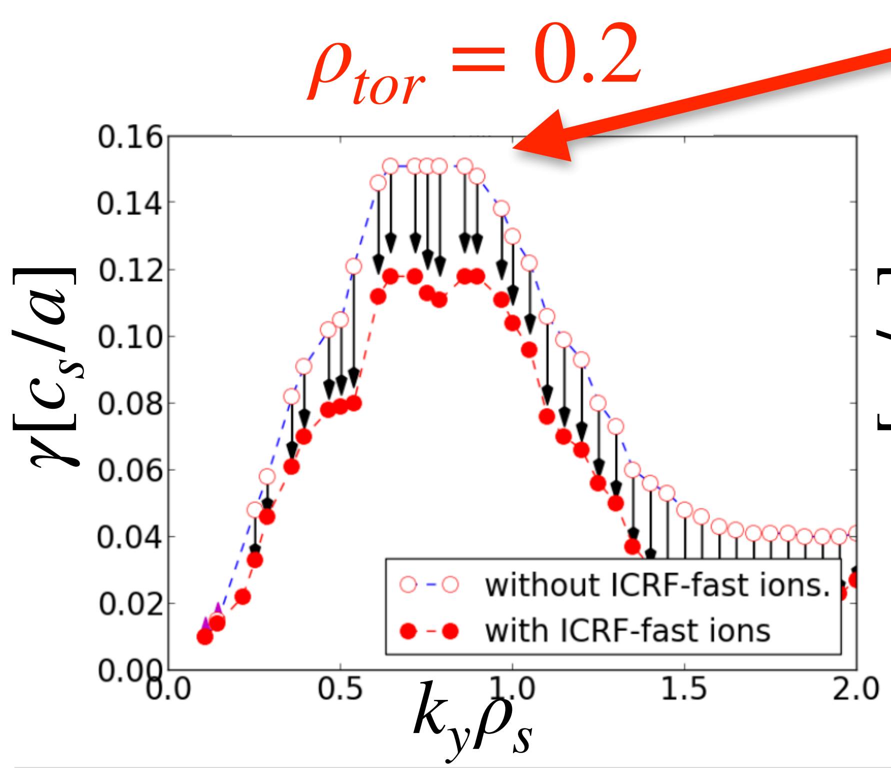
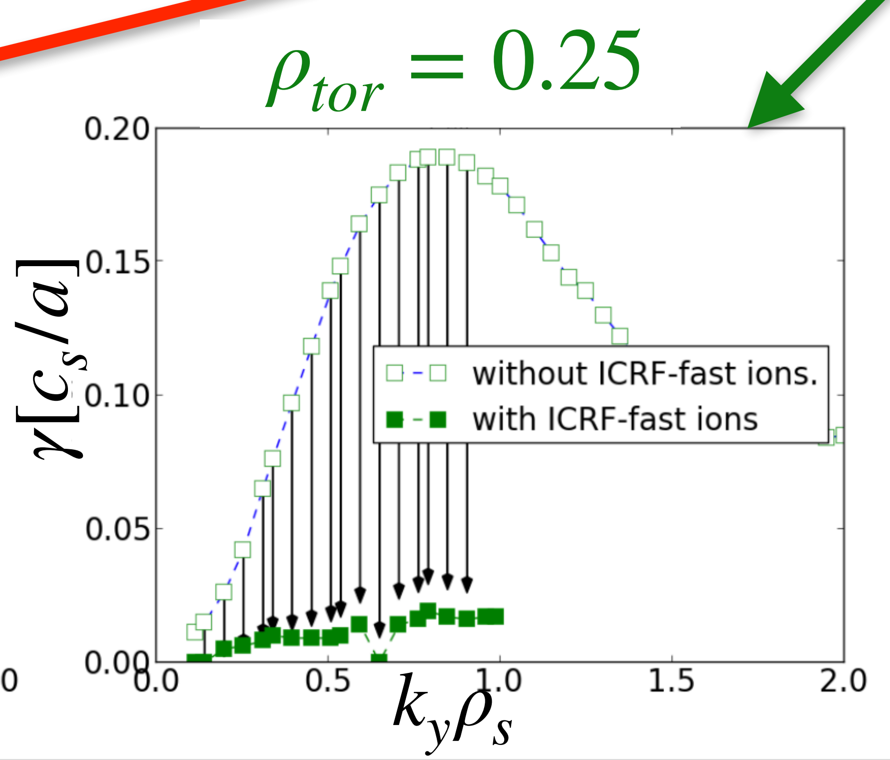
- $\rho_{tor} = 0.25$: optimal T_f; large R/L_{T_f}; substantial stabilising effect expected/observed.







Microinstability characterisation

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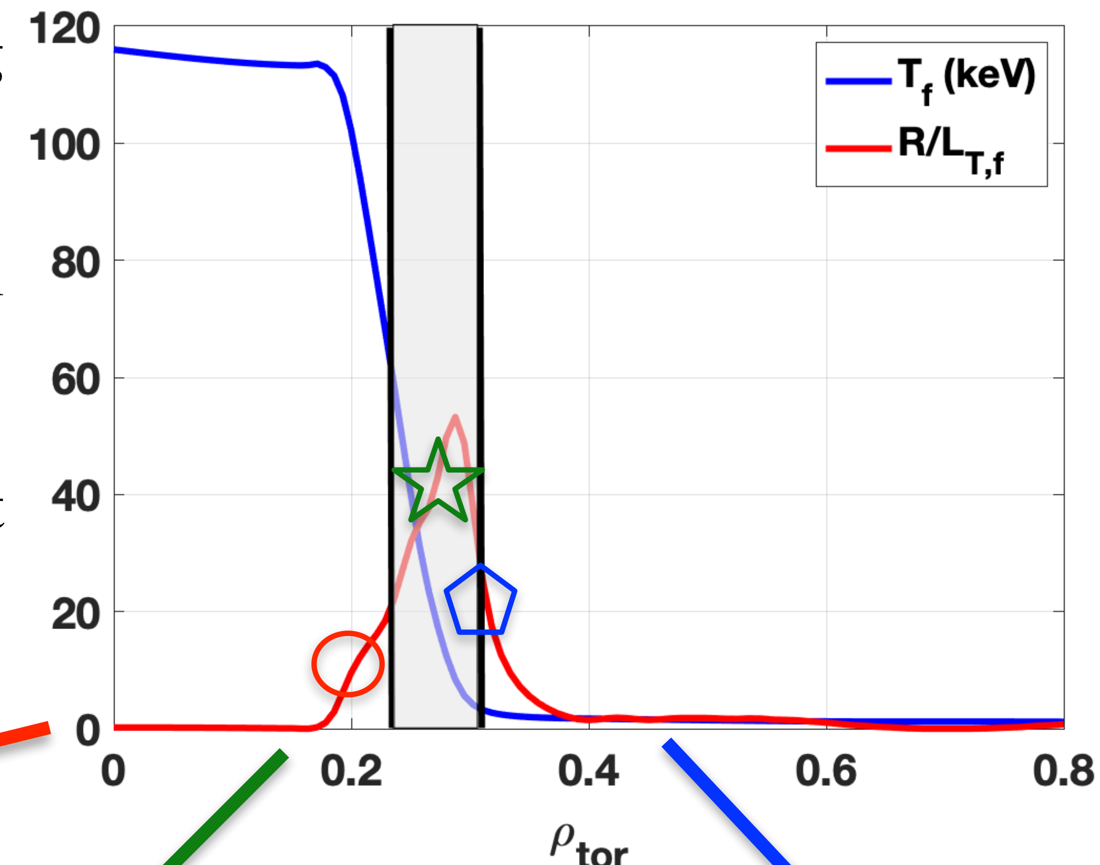
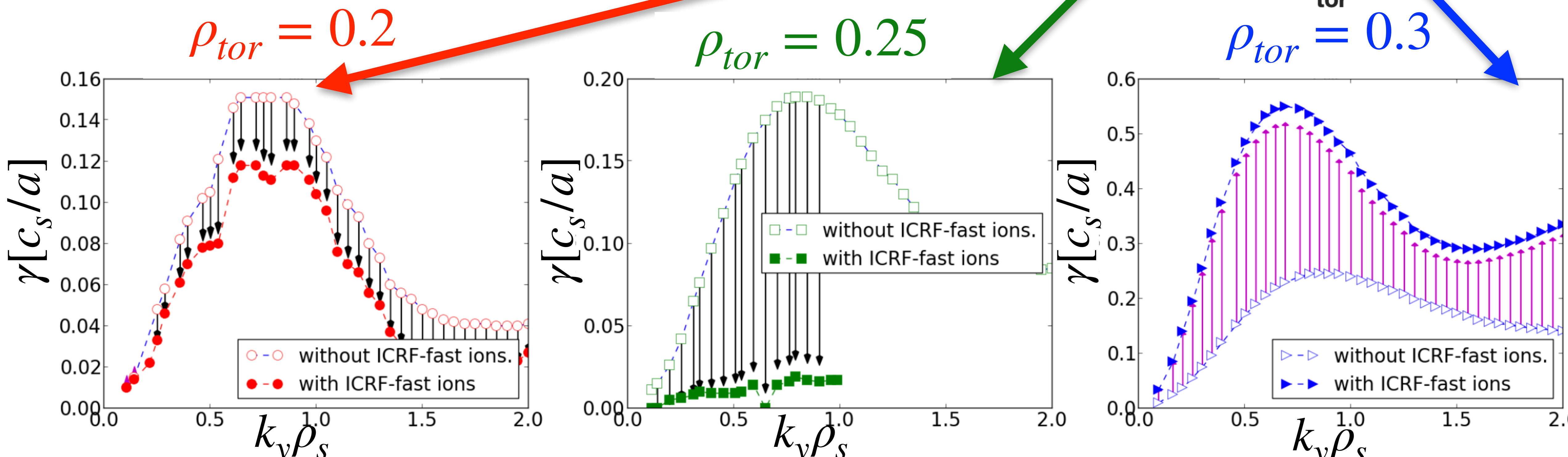
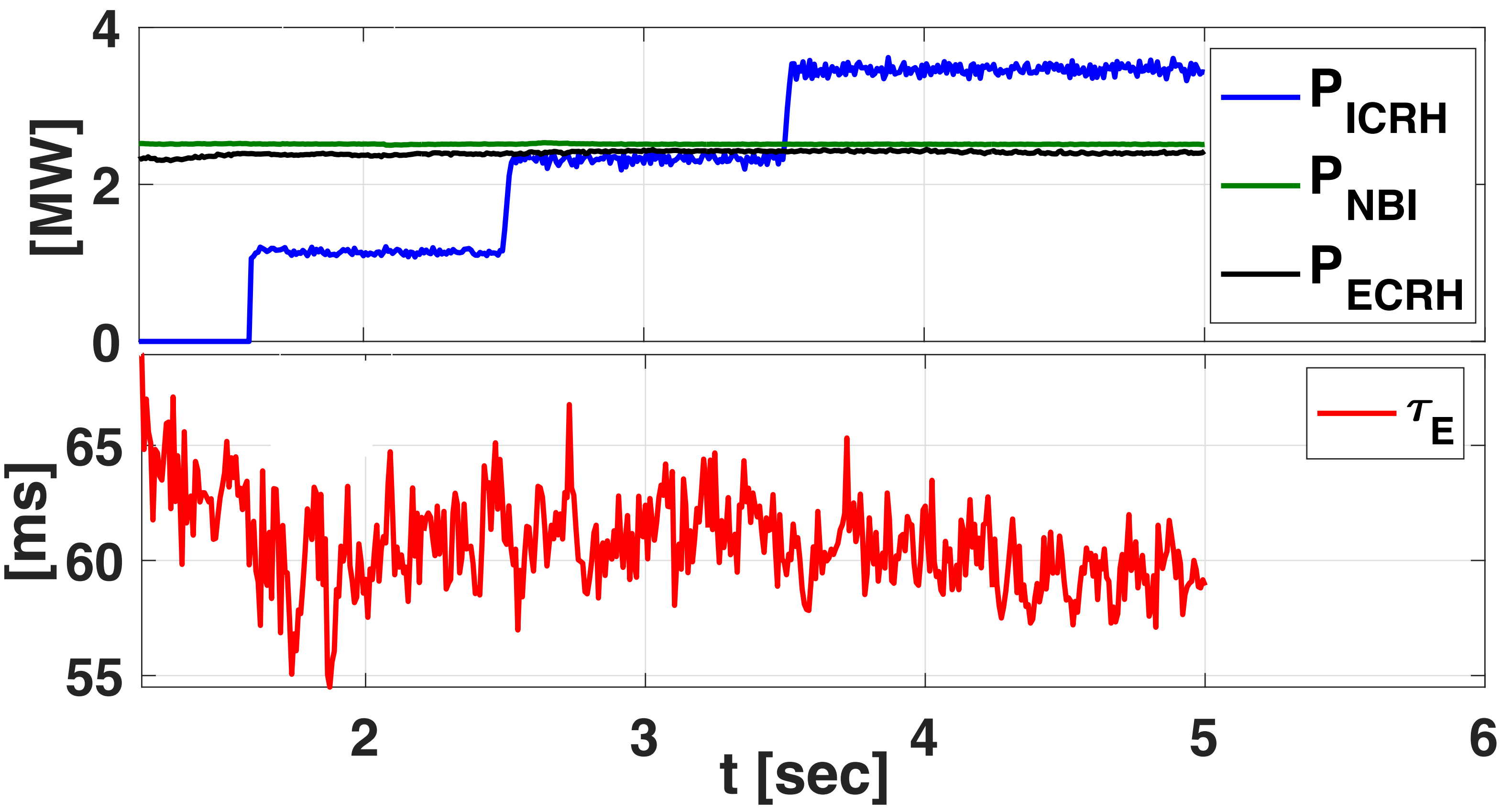
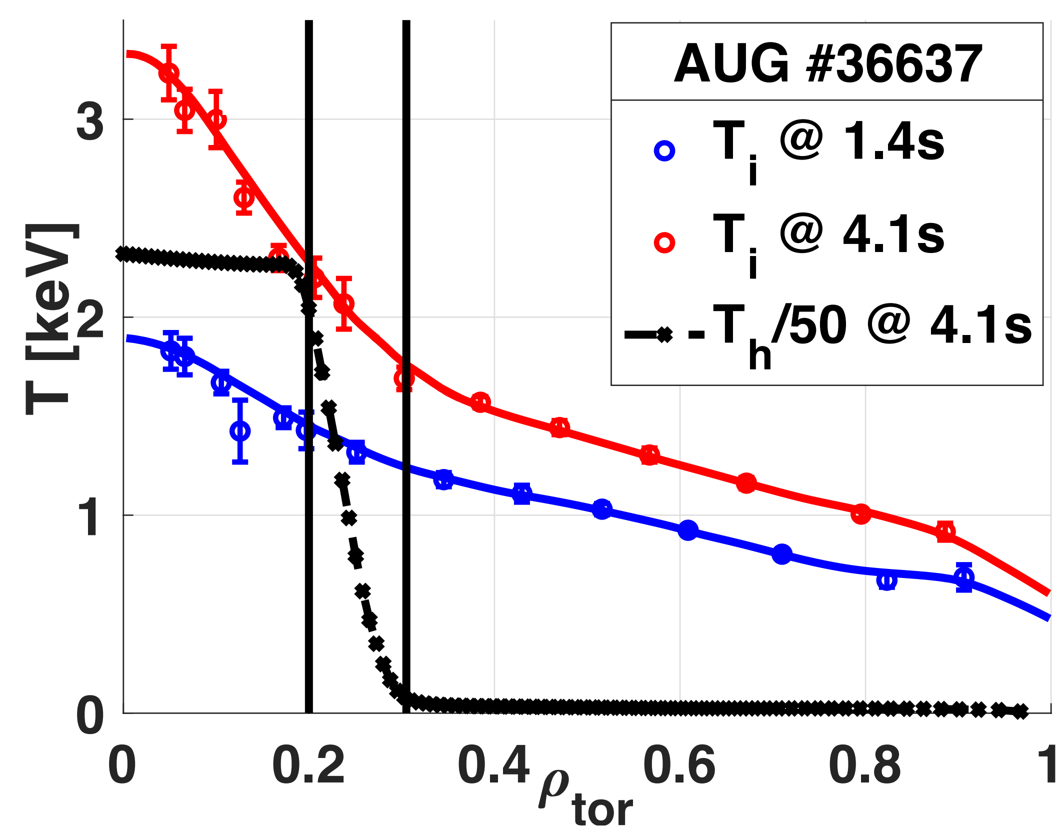
- $\rho_{tor} = 0.25$: optimal T_f; large R/L_{T_f}; substantial stabilising effect expected/observed.
- $\rho_{tor} = 0.3$: small T_f; large R/L_{T_f}; destabilising effect expected/observed.





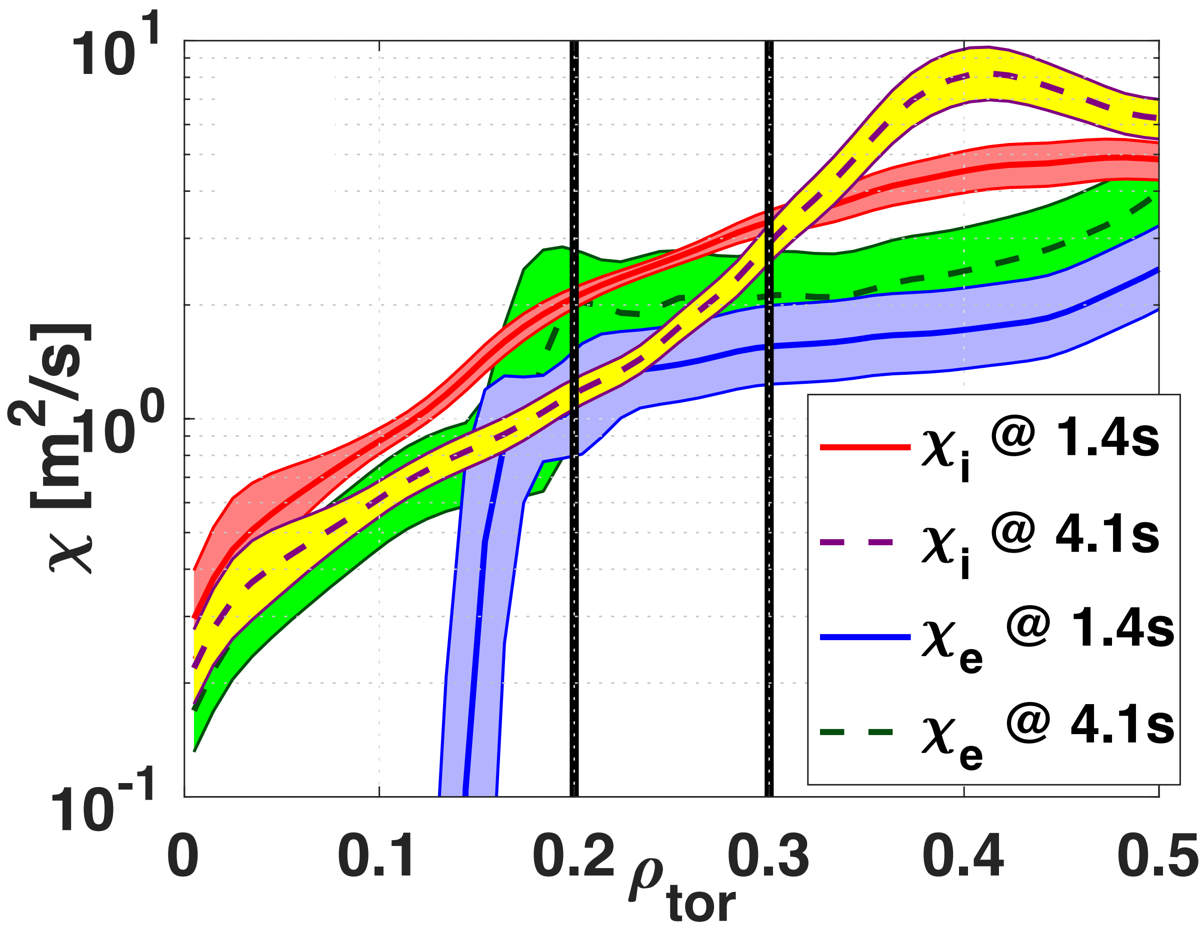
Time traces AUG#36637





- Very small degradation of energy confinement time observed by increasing external ICRF power; in H-mode plasmas expected $\tau_e \sim P^{-0.67}$
- Significant steepening of main ion temperature profile in the region of larger fast ion logarithmic temperature profile

Power balance computed by ASTRA

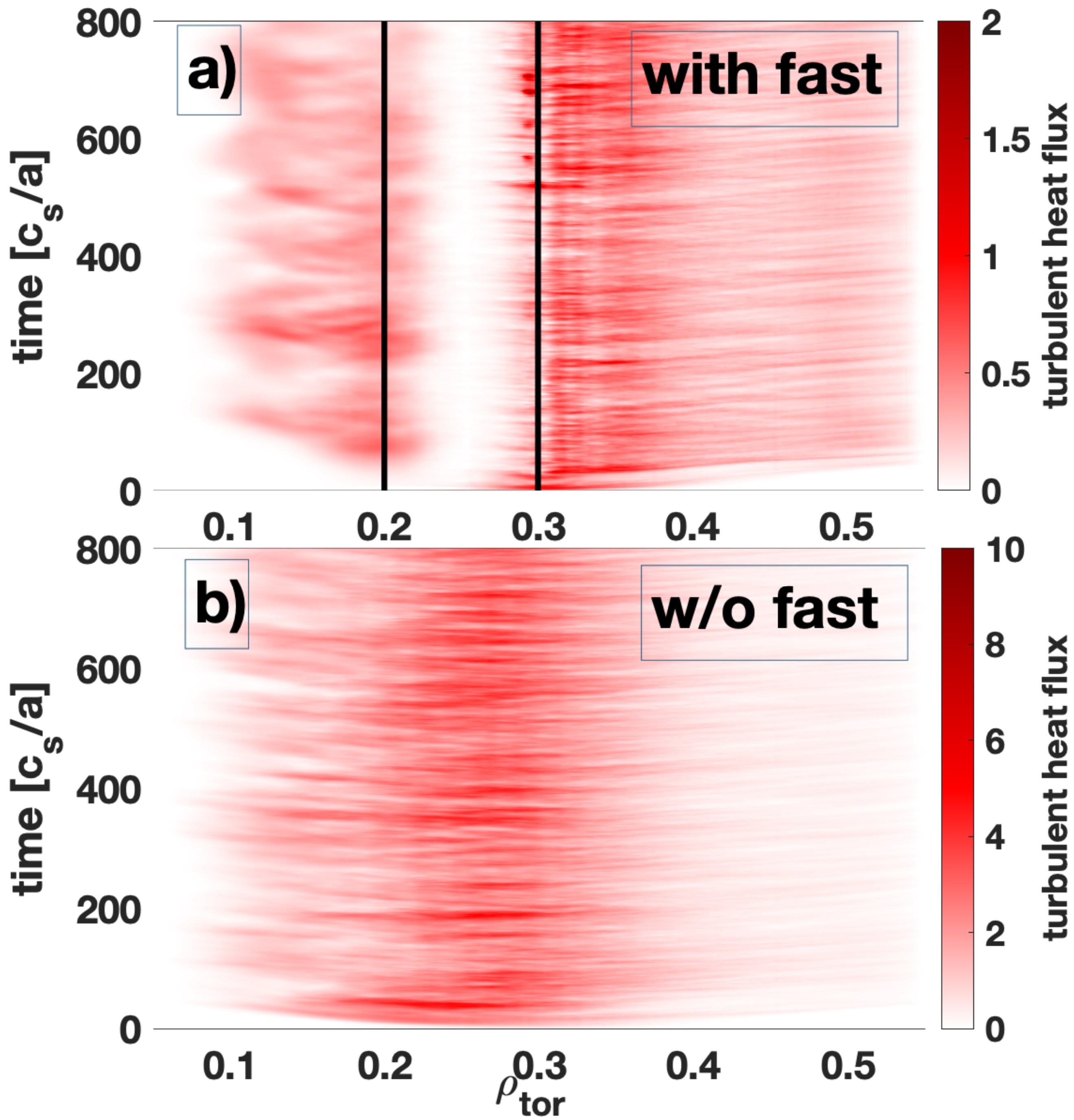


- Ion conductivity at $t = 4.1s$ is reduced by $\sim 50\,\%$ despite the $\sim 40\,\%$ increase of the auxiliary heating.
- Electron conductivity remains at similar levels.

Beneficial effect of ICRF observed at AUG

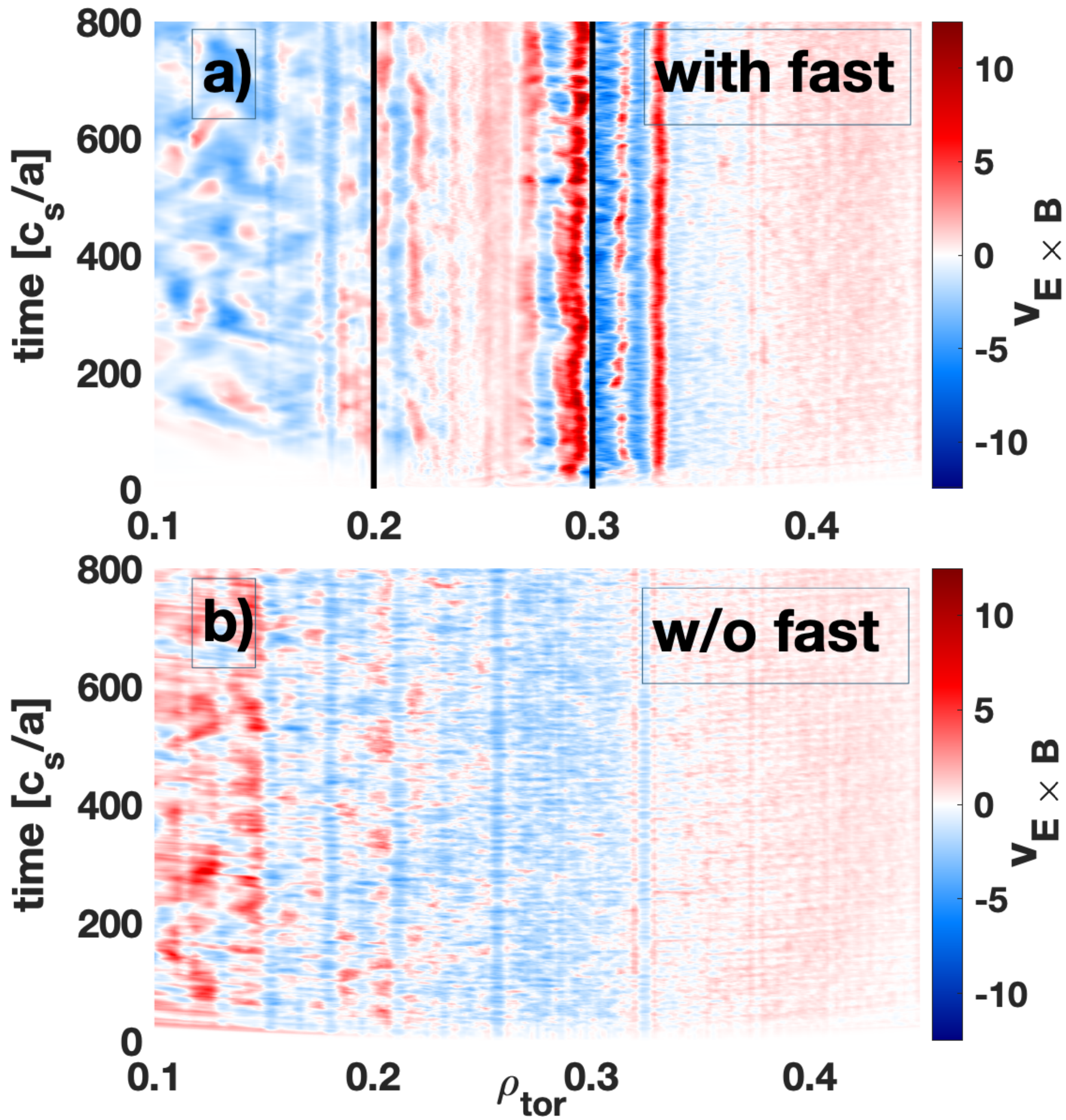
Radial profiles of overall heat fluxes

- Internal “anomalous” transport barrier observed in radially global electromagnetic GENE simulations by looking at the overall (thermal + fast) ion heat flux



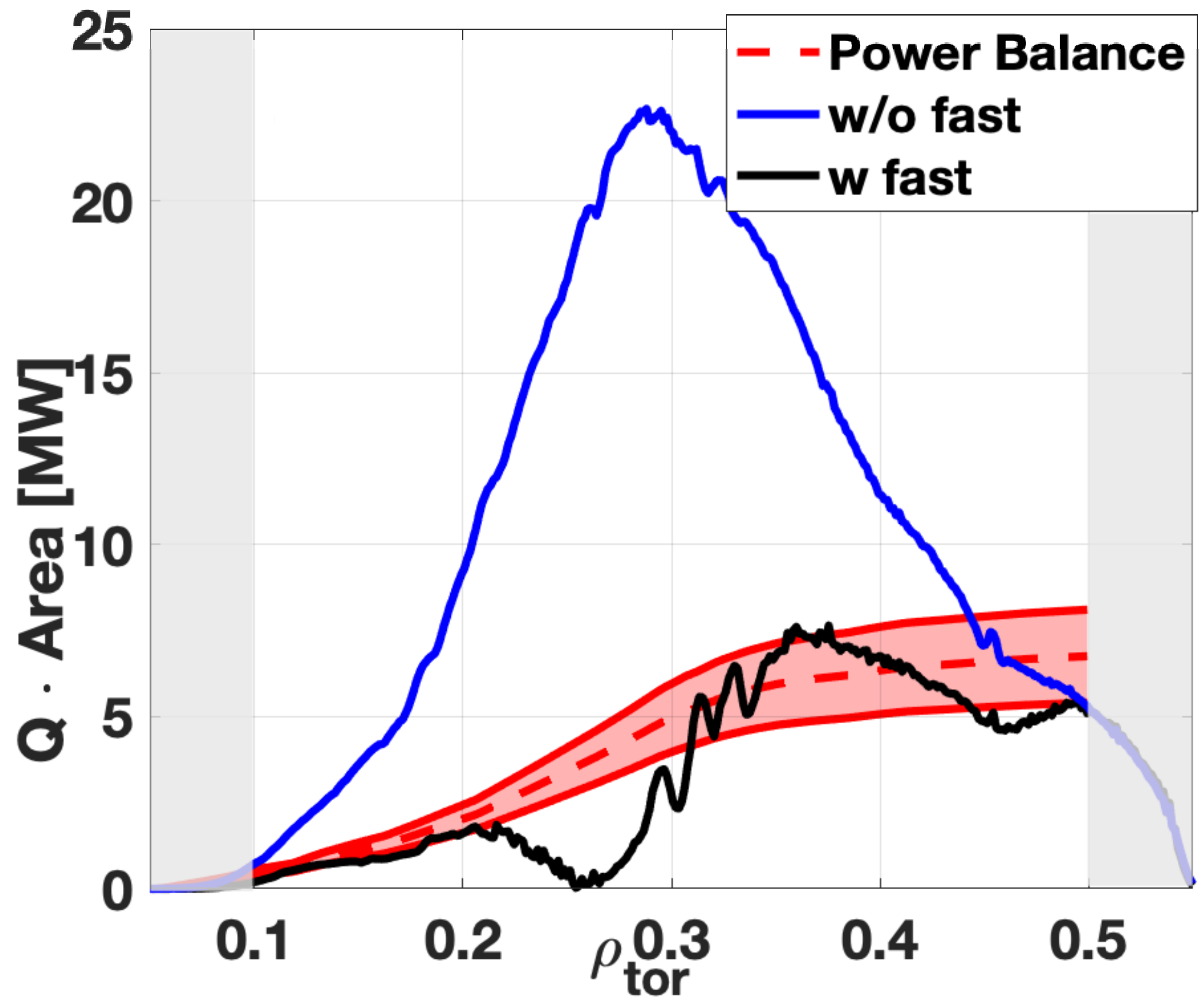
Radial profile of $v_{E\times B_0}$

- Localised $E \times B_0$ shearing layers in the $v_{E\times B_0} = \partial_x \phi_1 / \rho_{tor} B_0$ observed at the radial boundaries of the transport barrier



Comparison with experimental power balance

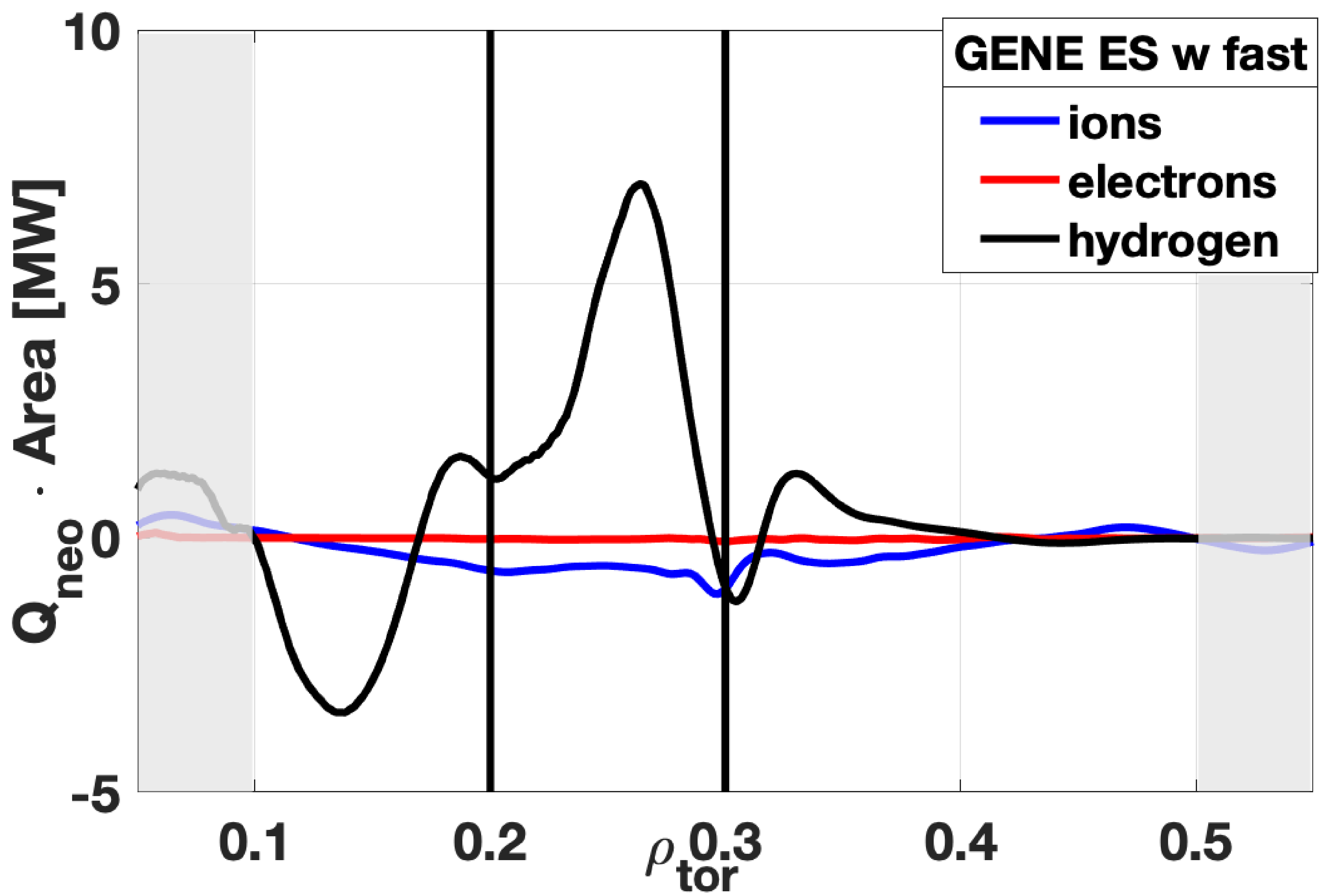
- Excellent agreement between GENE and the volume integral of the injected sources computed by ASTRA.



- GENE correctly reproduce experimental fluxes only when supra-thermal particles are retained.

Neoclassical fluxes

- Neoclassical transport increases to the turbulent levels as the turbulent heat flux drops in the F-ATB region.

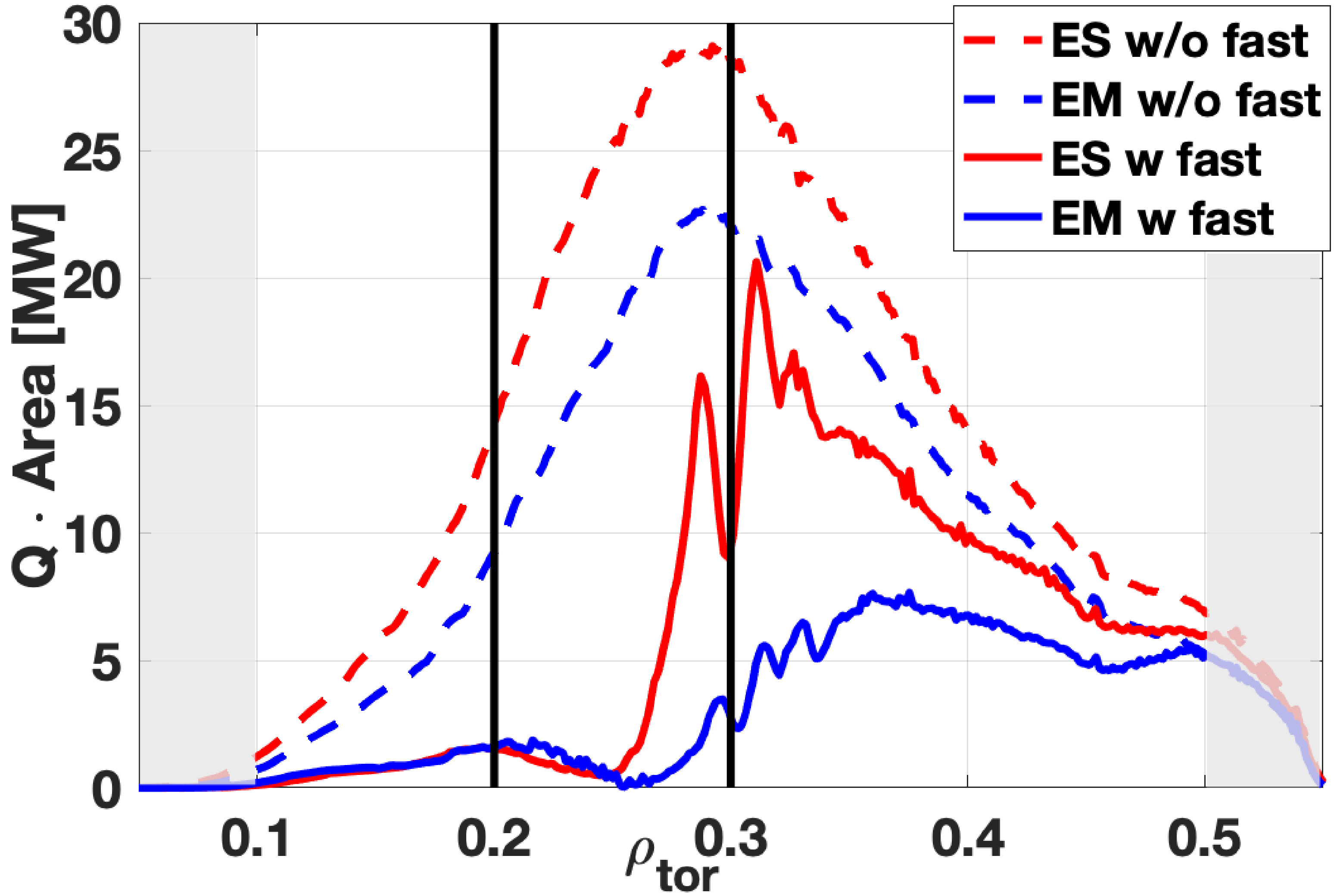


- Dominant neoclassical contribution given by the supra-thermal particles.

Electrostatic vs electromagnetic simulations

- Localised turbulence suppression, characteristic of the F-ATB, is largely observed also by neglecting the EM fluctuations → ES trigger mechanism.

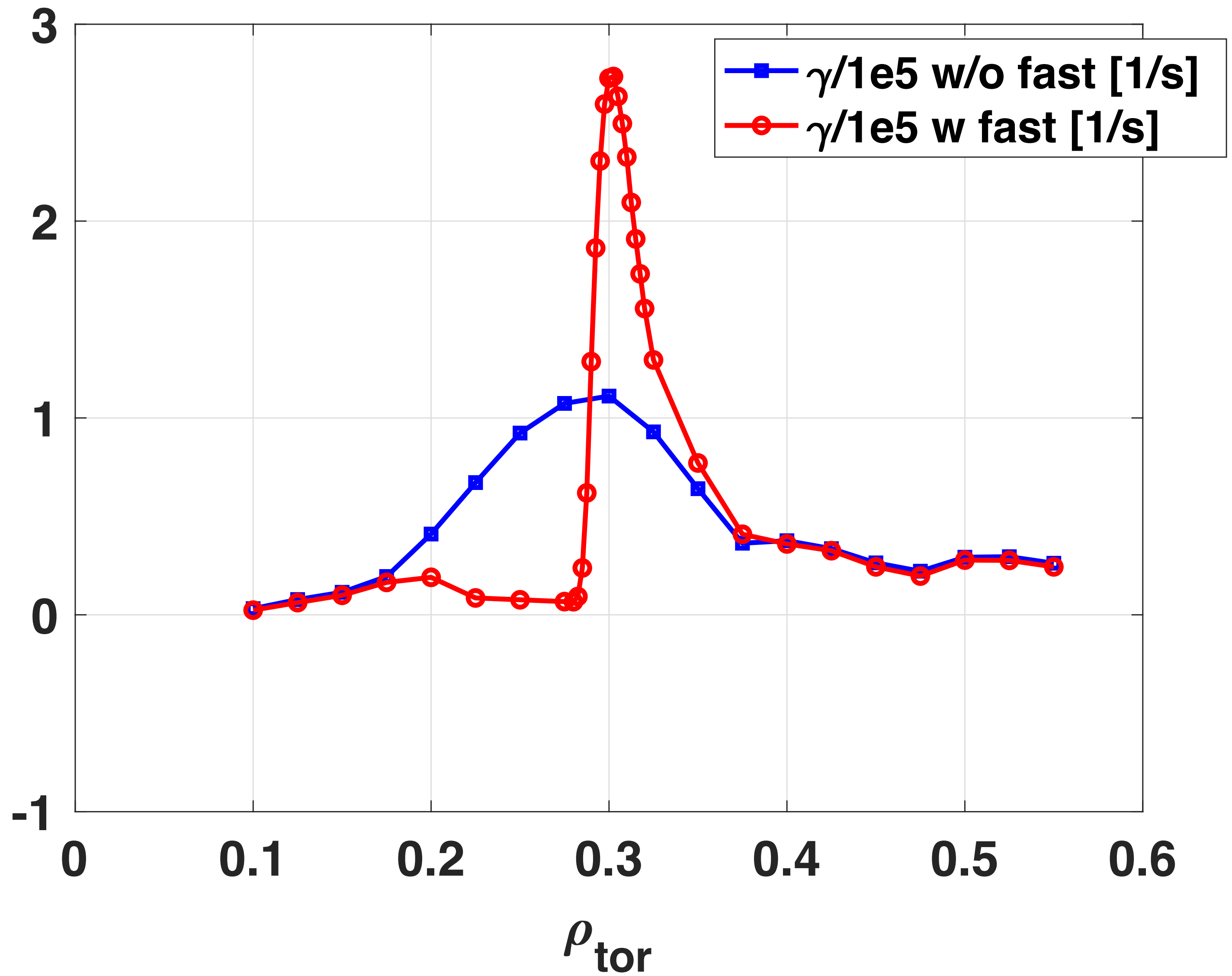
- Electromagnetic effects leads to a turbulence stabilisation in $\rho_{tor} = [0.3 - 0.5]$.



- These findings cannot be explained by transport barrier trigger mechanisms known in literature.

F-ATB trigger mechanism: wave-particle resonant interaction between ITGs and fast ions (ICRH)

- Dominant ITG linear growth rate (n = 21) exhibits almost full suppression in $\rho_{tor} = [0.2 - 0.25]$: fast ion contribution to ITG mode dominated by stabilising velocity space regions.



- Local changes in fast ion temperature and density profiles → effect of supra-thermal particles on plasma turbulence turns from stabilising to destabilising in $\rho_{tor} = [0.25 - 0.3]$.

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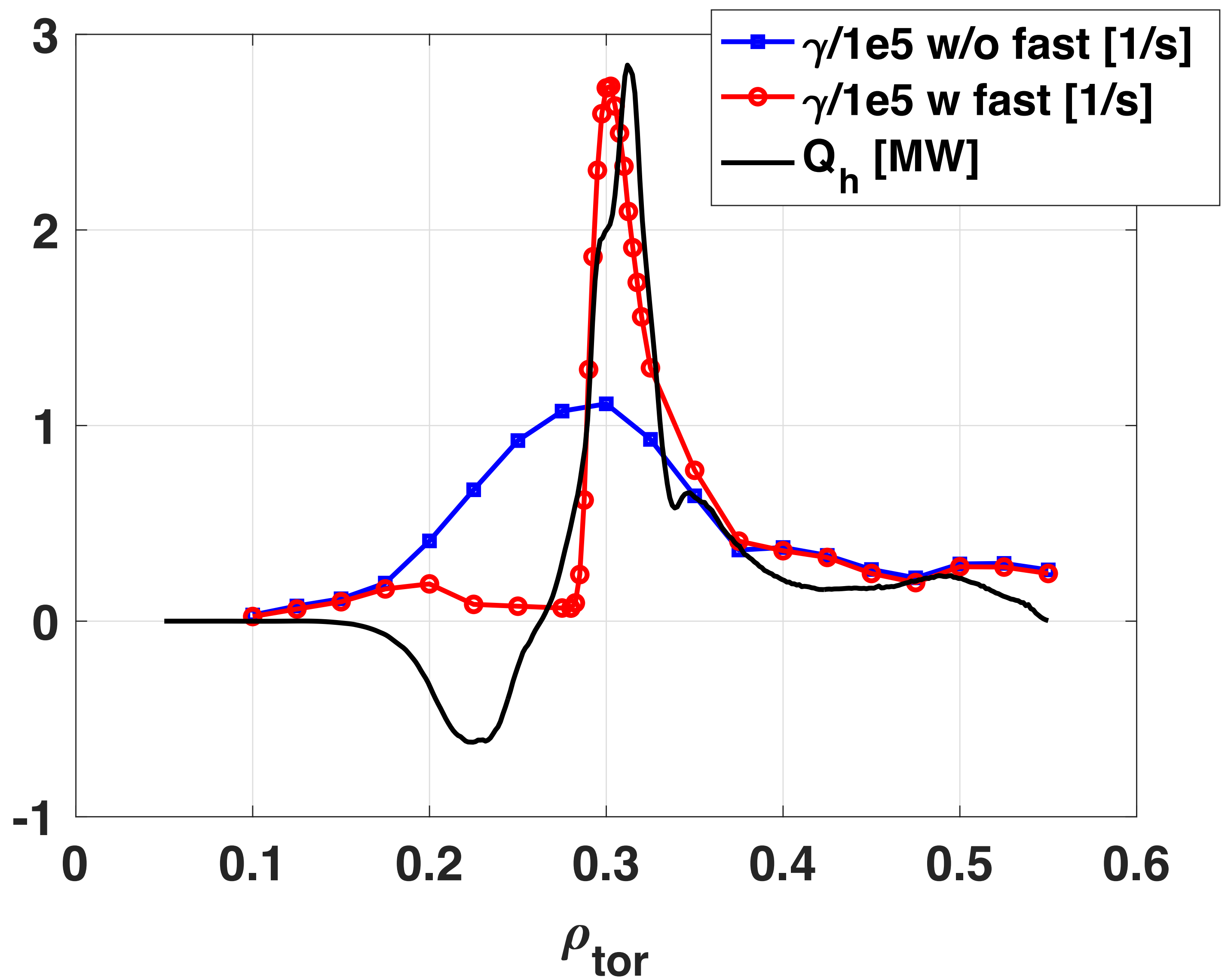

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Conclusions

- Theoretical prediction and observation of the formation of a new type of transport barrier in fusion plasmas, called F-ATB (fast ion-induced anomalous transport barrier)
- Existence of the F-ATB demonstrated via global gyrokinetic simulations with realistic ion-to-electron mass ratio, collisions, and fast ions modelled with realistic background distributions.
- Trigger mechanism: electrostatic resonant interaction between supra-thermal particles and plasma micro-turbulence.
- Experimental evidence at ASDEX Upgrade on a properly designed scenario to maximise fast ion effects on turbulence in a narrow radial region.

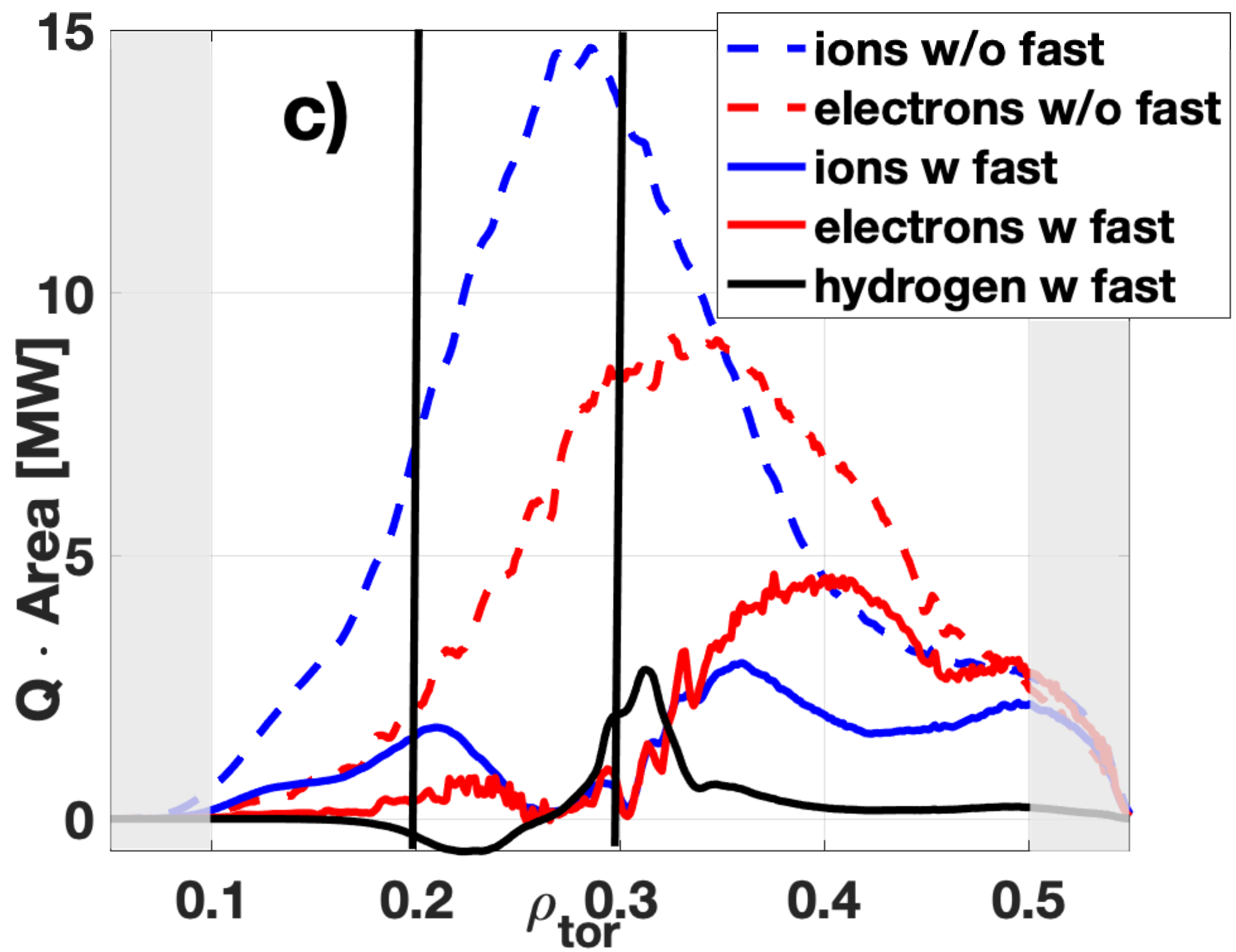
Next steps:

- Additional dedicated experiments on ASDEX Upgrade to explore further this ion confinement improvement with ICRH.
- Investigate the possible role of the F-ATB on SPARC.

Backup slides

Single species heat flux contributions

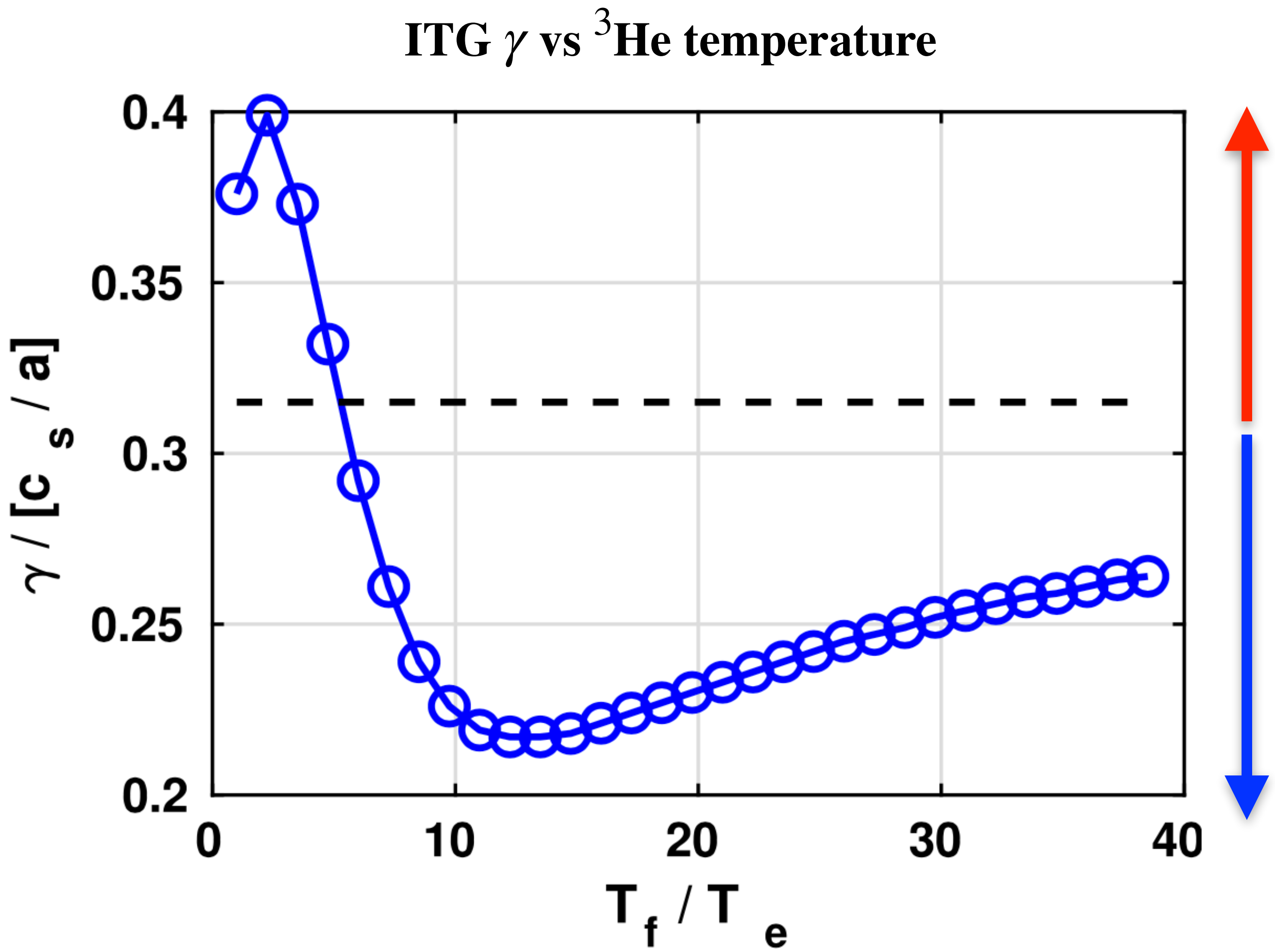
- A full turbulence suppression of the overall heat transport observed within the F-ATB (fast ion induced anomalous transport barrier).

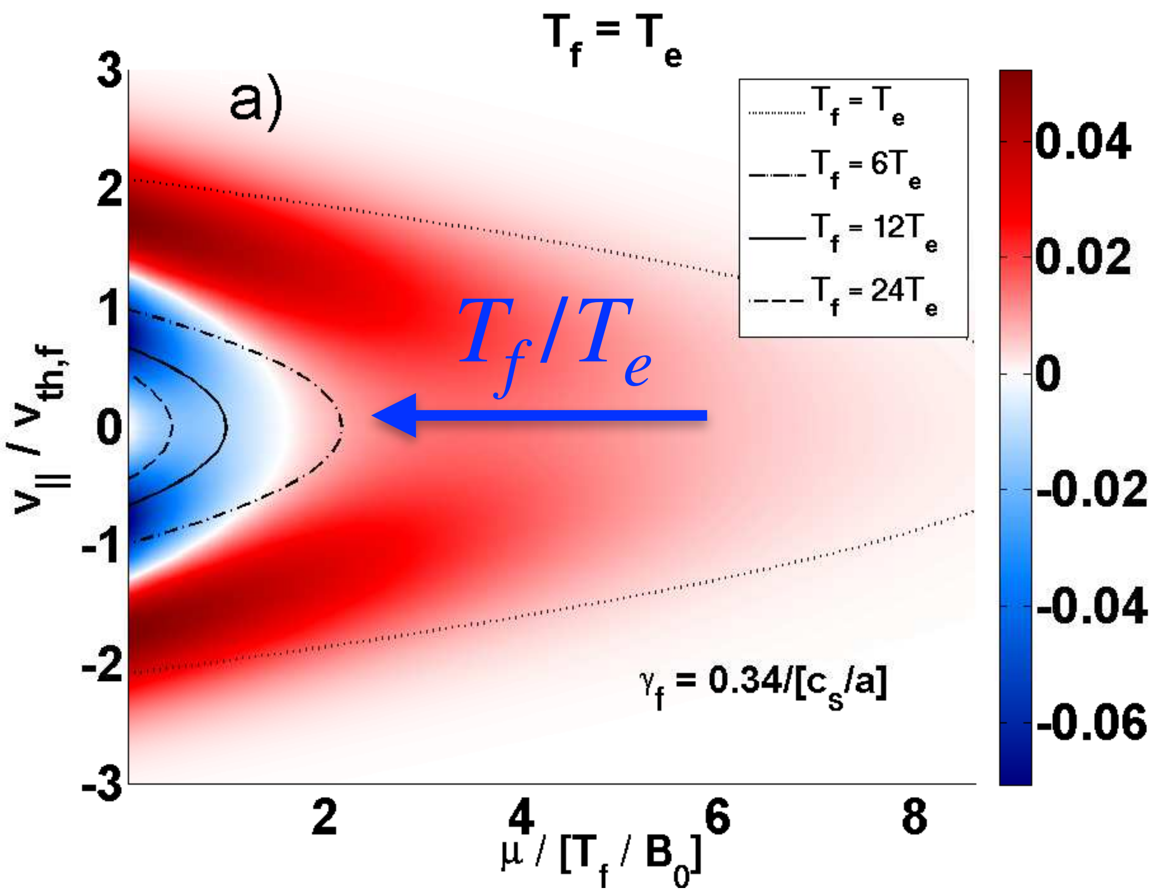


- Turbulence reduction extends to $\rho_{tor} \sim 0.1$ consistently with modifications in χ_i due to the rump-up of the ICRF power.

Turbulence stabilising mechanism by fast ions: wave-particle resonance effect

- $T_f/T_e < 4$ leads to a linear ITG destabilisation $\rightarrow \omega_k = \omega_{d,f}$ (positive drive region)
- Optimal stabilisation for ^{3}He at $T_f/T_e \sim 12 \rightarrow \omega_k = \omega_{d,f}$ (negative drive region)





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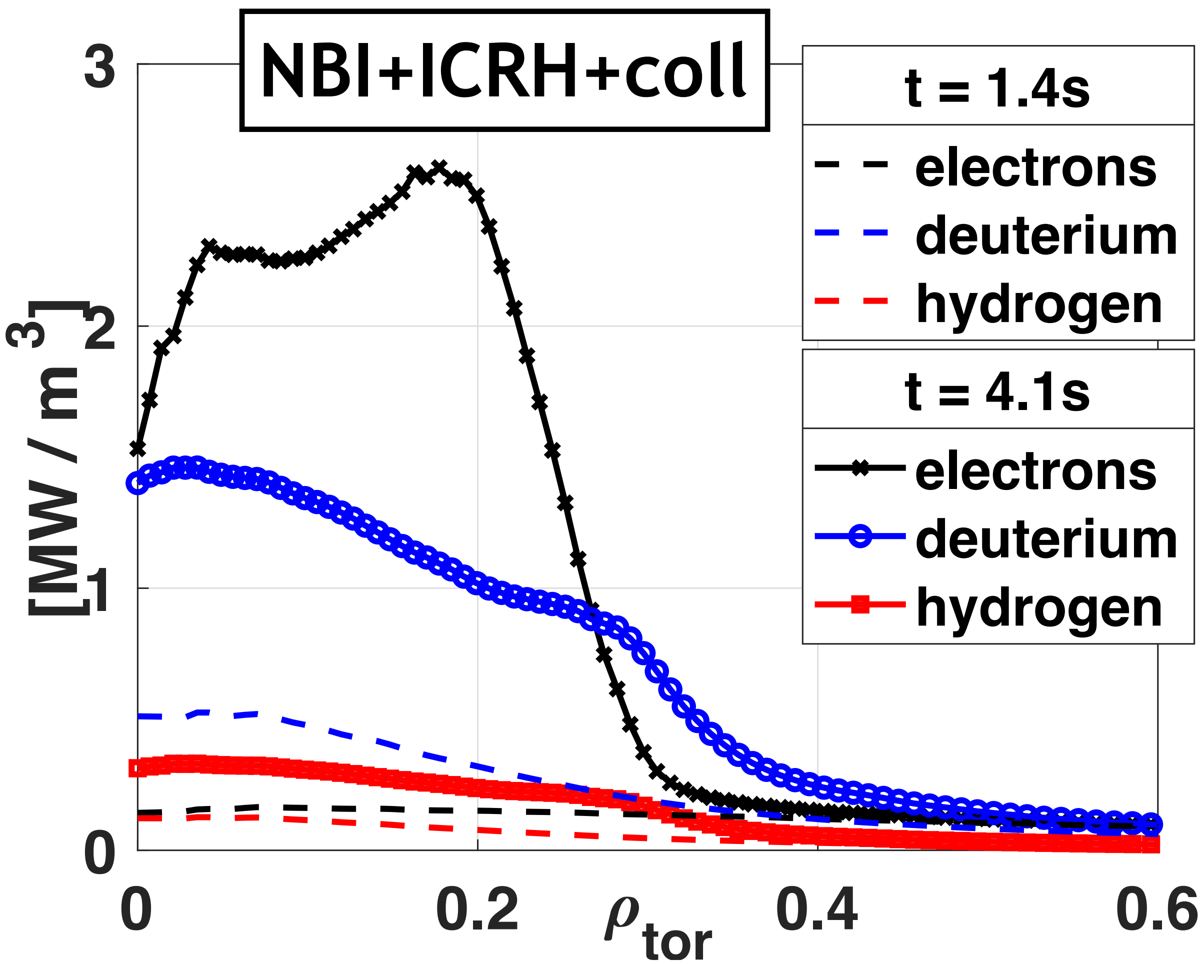
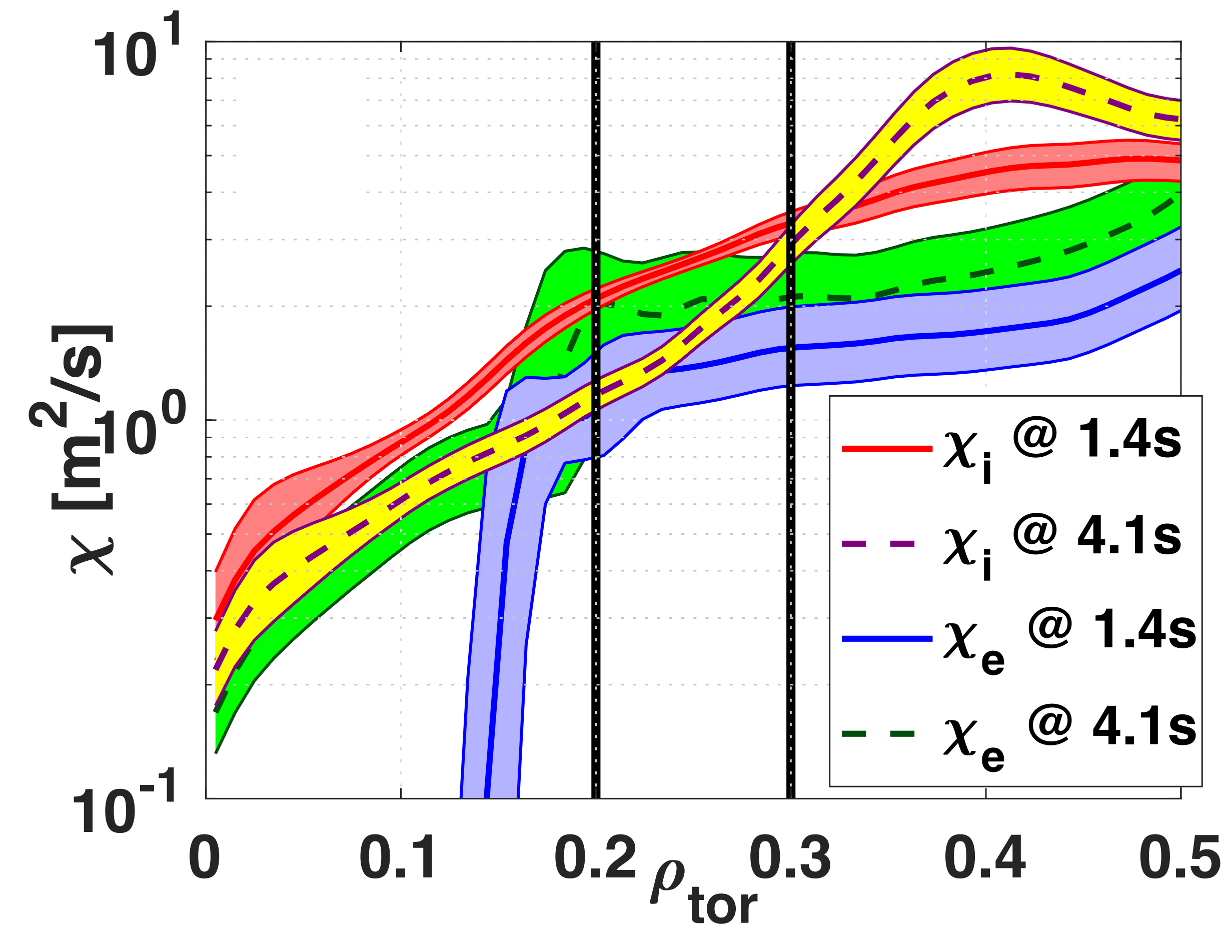
Power balance computed by ASTRA

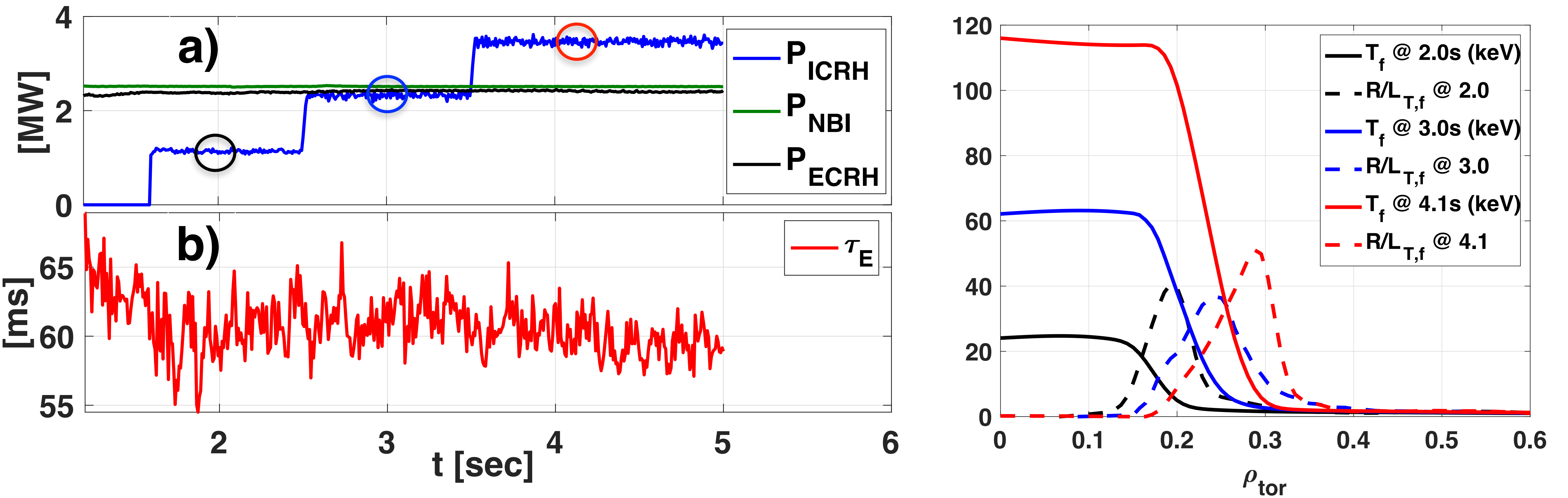




- NBI + ICRH power mostly absorbed by electrons.
- Ion conductivity at $t = 4.1s$ is reduced by $\sim 50\,\%$ despite the $\sim 40\,\%$ increase of the auxiliary heating.
- Electron conductivity remains at similar levels.

Beneficial effect of ICRF observed at AUG

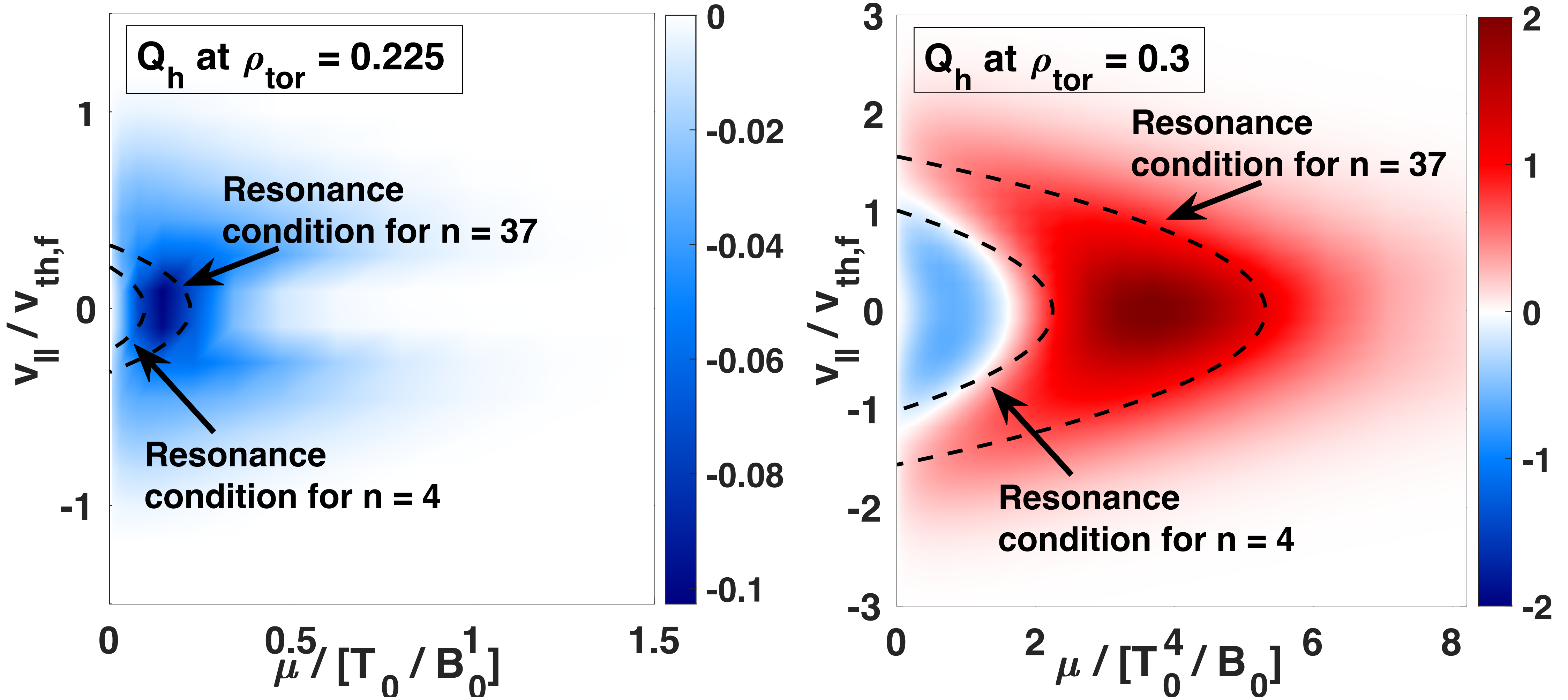
Fast ion profiles AUG#36637



- $t = 2.0s \rightarrow T_f$ is too small, despite the large $R/L_{T,f}$
- $t = 3.0s \rightarrow T_f \sim 50keV$ reached only where $R/L_{T,f}$ is small (~ 10)
- $t = 4.1s \rightarrow T_f \sim 50keV$ close to the peak of $R/L_{T,f}$ (largest effect)

Velocity space structures

- Phase-space structure of fast ion heat flux exhibits only negative values at $\rho_{tor} = 0.225 \rightarrow$ localised where the resonance condition of the most relevant modes is matched.



- Wave-particle resonance enhances the turbulence drive at $\rho_{tor} = 0.3 \rightarrow$ largest heat flux contribution lies within the largest phase-space region.