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

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ABSTRACT

- The key result of the present work is the 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).
- State-of-the-art global GENE simulations reveal that the F-ATB is characterized by a full suppression of the turbulent transport - caused by strongly sheared, axisymmetric E × B flows - and an increase of the neoclassical counterpart.
- The trigger mechanism is a mainly electrostatic resonant interaction between supra-thermal particles, generated via ion-cyclotron-resonance heating, and plasma micro-turbulence.
- These findings are obtained by realistic simulations of the ASDEX Upgrade discharge #36637 - properly designed to maximized the beneficial role of the wave-particle resonance interaction - which exhibits the expected properties of improved confinement produced by energetic particles.

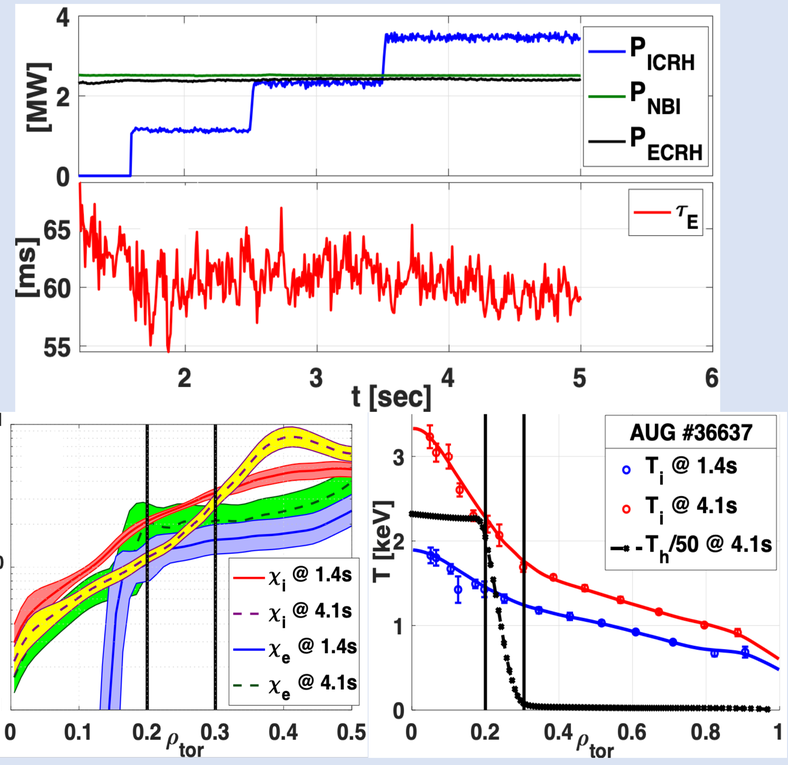

Fig.3. Time history of a) injected power and b) confinement time for the ASDEX Upgrade discharge #36637; c) Radial profile of the ion and electron thermal conductivities; d) Temperature profiles of the main ions.

Turbulence suppression by fast ions: wave-particle resonance

- Energetic particles can resonate with the background instabilities when Ion-scale frequency matches fast ions drift frequency.
- Significant energy exchanged if $|R/L_{T,f}| \gg |R/L_{n,f}|$.
- Depending on the phase—space localization of the resonance, wave-particle resonance can lead to stabilization or destabilization of ITGs.

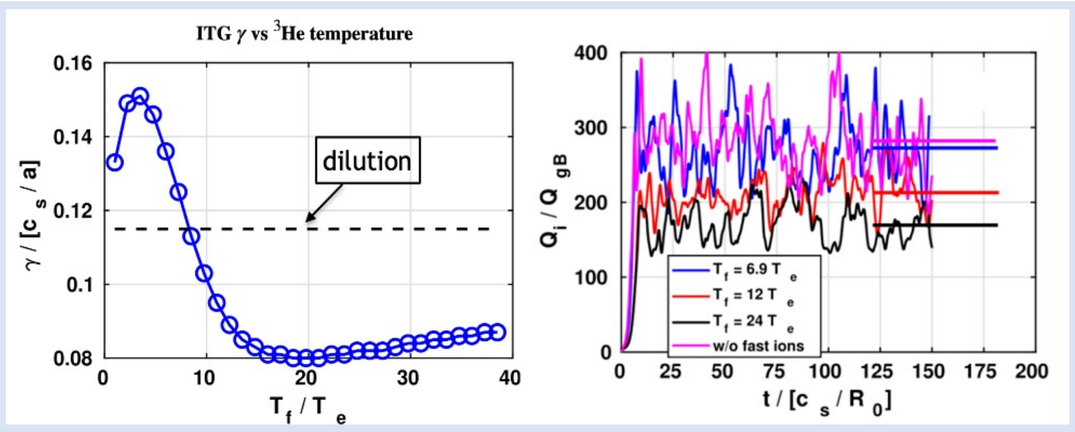

Fig.1. a) Growth rates and b) thermal ion heat fluxes as a function of the ratio between fast ion to electron temperatures

Profile optimization with GENE and TORIC/SSFPQL for AUG

To ultimately trigger a transport barrier via the wave-particle resonant interaction the following constraint needs to be fulfilled:

- Ratio T_f/T_e has to be designed to fully suppress ITG micro-instabilities in a narrow core region.
- Large energetic particle charge concentration.
- Large $R/L_{T,f}$ in the region where T_f/T_e is optimal.
- Both stabilizing and de-stabilization regions are essential for the transport barrier formation.

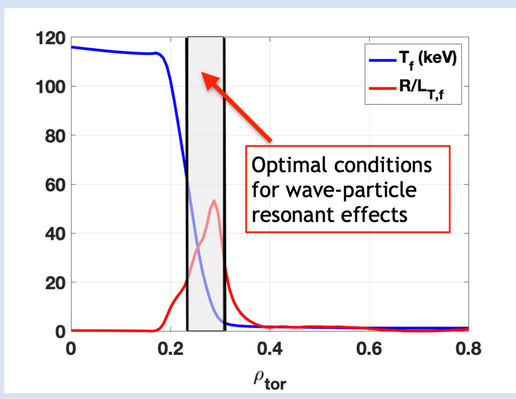

Fig.2. Optimized fast particle profile via GENE and TORIC/SSFPQL simulations. The vertical black lines delimit the gray region where the wave-particle resonant interaction is maximized.

Experimental results at AUG for optimized discharge

The ASDEX Upgrade H-mode discharge #36637 was the result of a careful optimization procedure based on theoretical predictions.

- A deuterium plasma is heated with 2.5MW of NBI, 2.5MW of ECRH.
- The ICRH power is increased with four phases at constant power.
- Small degradation of energy confinement time by increasing external ICRF power.
- Steepening of main ion temperature profile in the region of larger fast ion logarithmic temperature profile

Global GENE simulations

- Internal "anomalous" transport barrier observed in radially global electromagnetic GENE simulations.
- Localised E x B shearing layers in the v_{ExB} observed at the radial boundaries of the transport barrier.
- Excellent agreement with power balance only

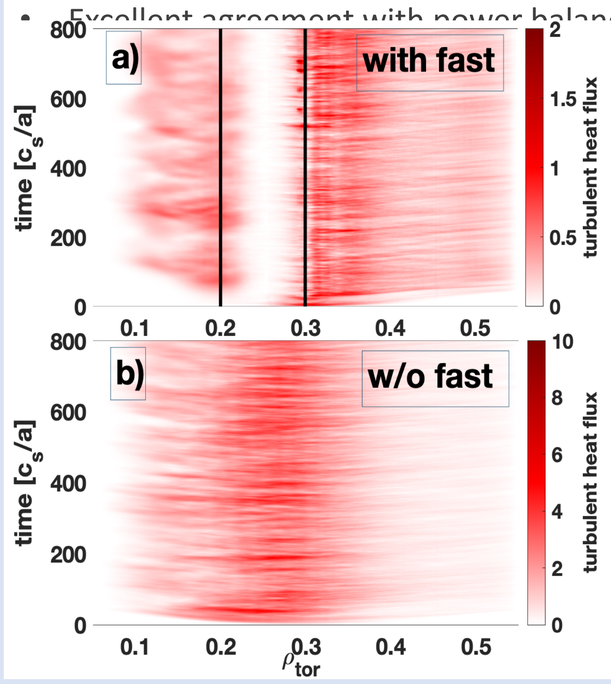

Fig.4. Time evolution of the total ion heat flux for simulations with/without fast ions

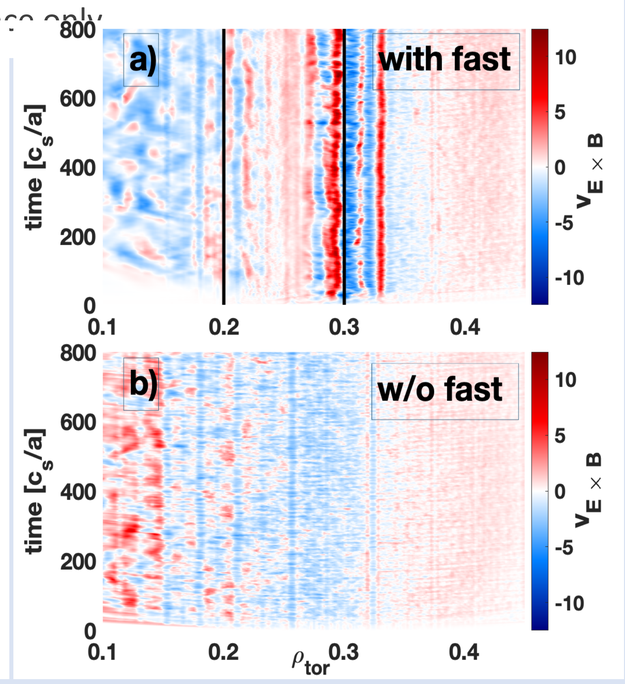

Fig.5. Time evolution of v_{ExB} with/without fast ions

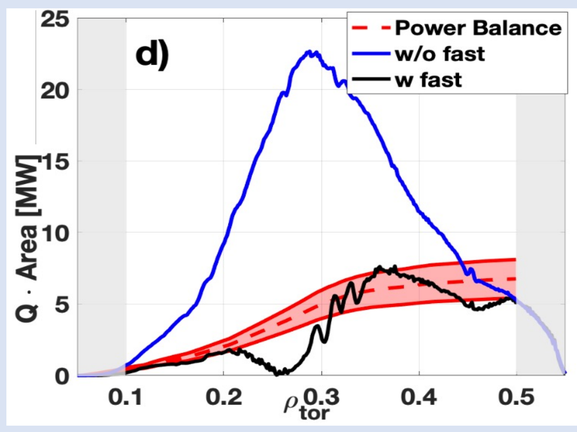

Fig.6. Comparison of total (ion + electrons + fast ion) heat flux with the volume average of the injected sources computed by ASTRA,

CONCLUSION

- Theoretical prediction and observation of the formation of a new type of transport barrier 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.

ACKNOWLEDGEMENTS / REFERENCES

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