EUROfusion

Fast ions as a source of transport suppression in JET plasmas

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Outline

- The origins
- The initial HPC analyses: non-linear electromagnetic and fast ions effects
- Experimental validation
- Searching for physical mechanisms
- Closing the loop→ ITER
- Conclusions

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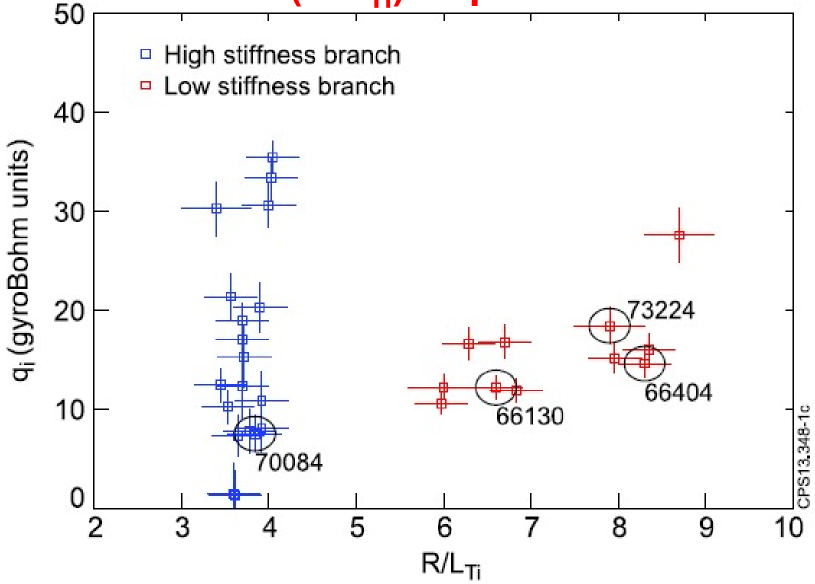
The origins: L-mode plasmas

Ion heat flux (q_i) vs logarithmic ion gradient (R/L_{Ti}) at ρ=0.33

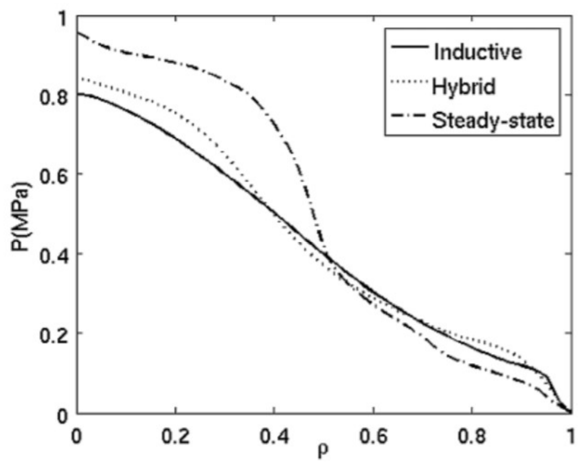


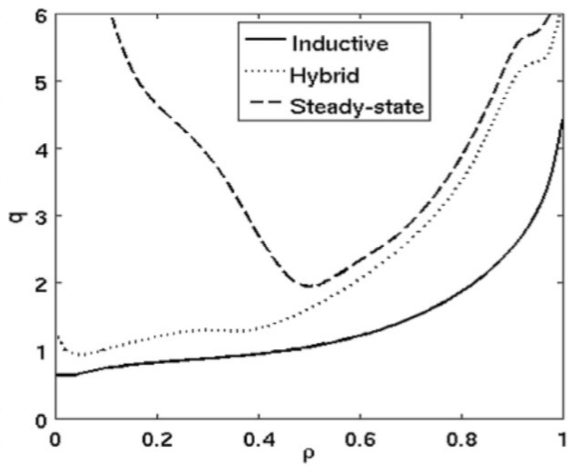
[1] P. Mantica et al., Phys. Rev. Lett. **102**, 175002 (2009); [2] P. Mantica et al., Phys. Rev. Lett. **107**, 135004 (2011)

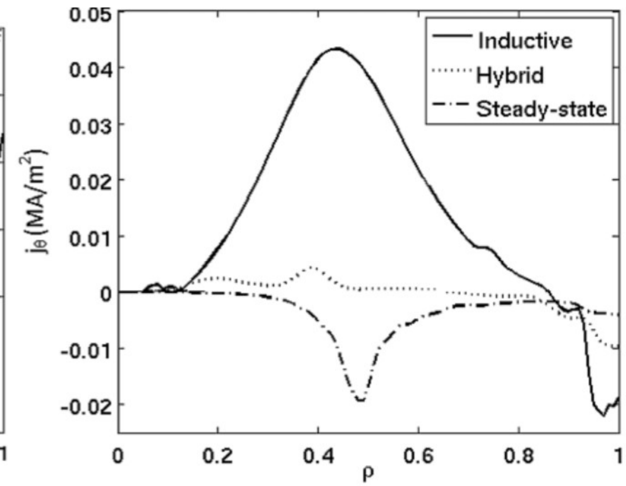
Main observation: Significant reduction of ion temperature profile stiffness, defined as the local normalized q_i gradient with respect to R/L_{ti}, when NBI and ICRH combined

- JET data-set in L-mode was a challenge for theoretical understanding of ion temperature gradient (ITG) turbulence, primarily responsible for ion heat transport [1,2]
- ExB shearing thought to be primarily responsible for transport reduction

The orirings: magnetism behaviour in H-mode







Emilia R Solano 2004 Plasma Phys. Control. Fusion 46 L7

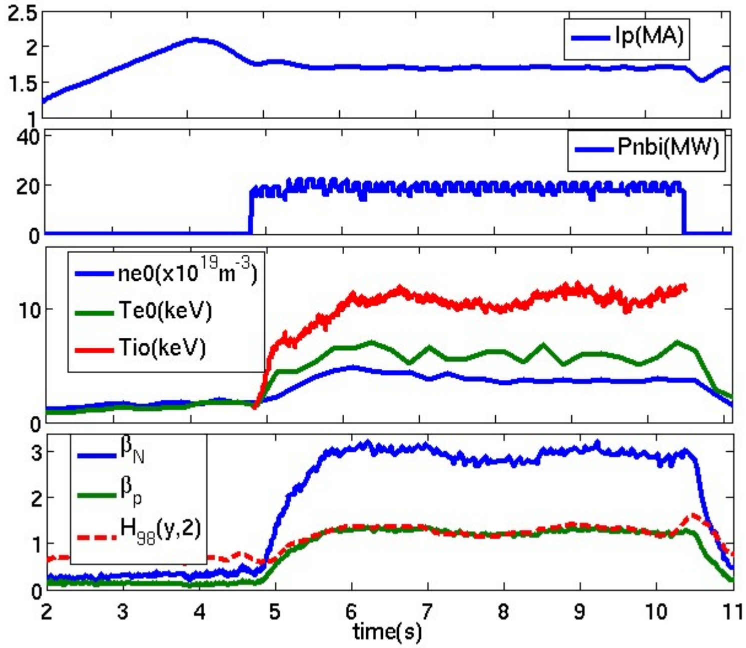
J. Garcia and G. Giruzzi PRL 104, 205003 (2010)

E. Solano and R. Hazeltine 2012 Nucl. Fusion 52 114017

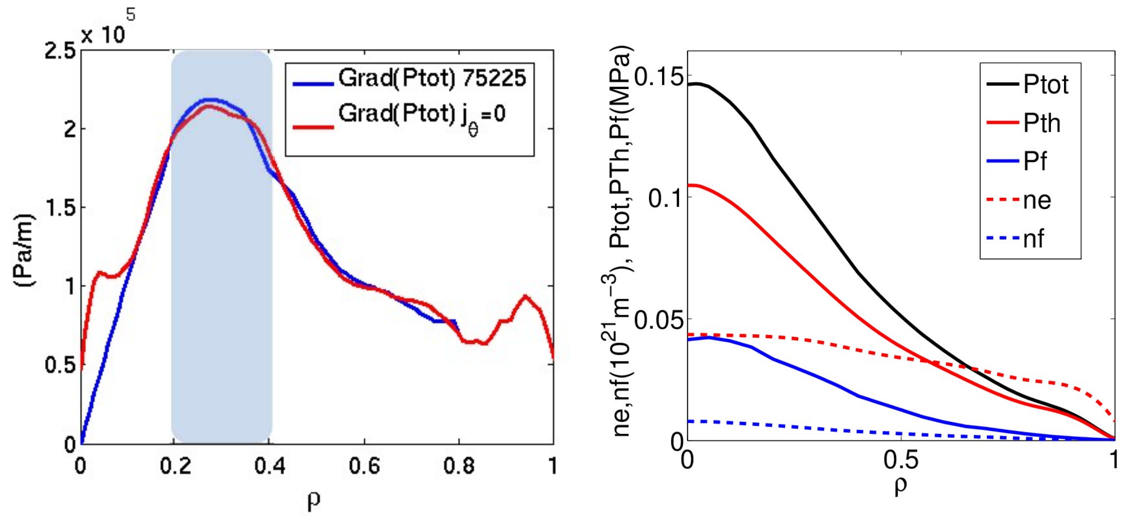
Main observation

- Stationary high confinement scenarios show different type of magnetism characteristics
- Reversal from paramagnetic to diamagnetic→ Role of poloidal current profile and β_p

The orirings: magnetism behaviour in H-mode



J Hobirk et al 2012 Plasma Phys. Control. Fusion 54 095001



J. Garcia and G. Giruzzi Nucl. Fusion **53** (2013) 043023

Main observation

- High pressure gradient necessary to attain diamagnetism at ρ=0.2-0.4
- Hybrid scenarios with peaked core ion temperature profile have a significant fast ions content which highly increases core pressure gradient and β

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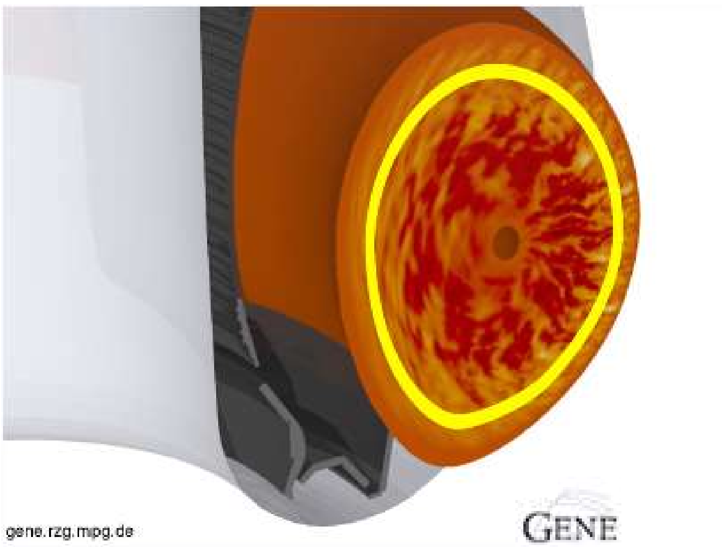
The GENE code: an essential tool



F. Jenko, W. Dorland, M. Kotschenreuther, and B.N. Rogers, Phys. Plasmas **7**, 1904 (2000); see http://gene.rzg.mpg.de for code details and access

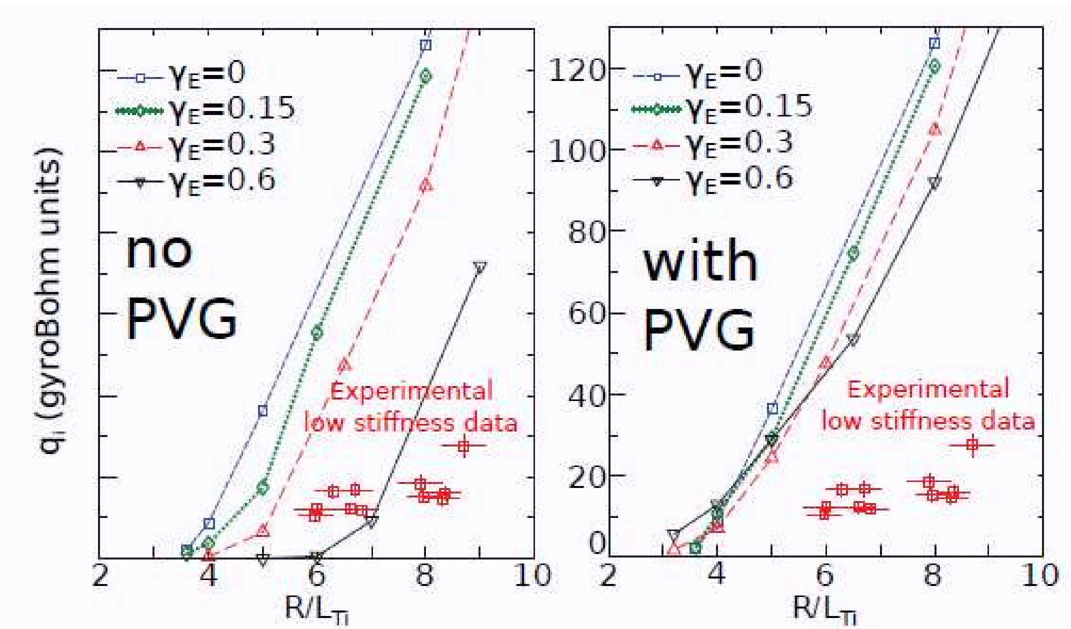
GENE is a Eulerian gyrokinetic code:

- Kinetic treatment for each species (including fast ions)
- Electromagnetic fluctuations
- Linearised Landau-Boltzmann and Sugama-type collisional operators
- External ExB shear flows
- Initial value or eigenvalue solvers
- Realistic equlibrium
- Supports local (flux-tube) and global (full-torus), gradient- and flux-driven simulations
- Both Maxwellian and realistic non – Maxwellian background distributions

L mode: Flow shear does not explain observations

Simulation of low rotation JET discharge 70084 at $\rho = 0.33$

Increase flow shear and see if low stiffness can be reached



Stabilizing perpendicular flow shear rate (toroidal rotation)

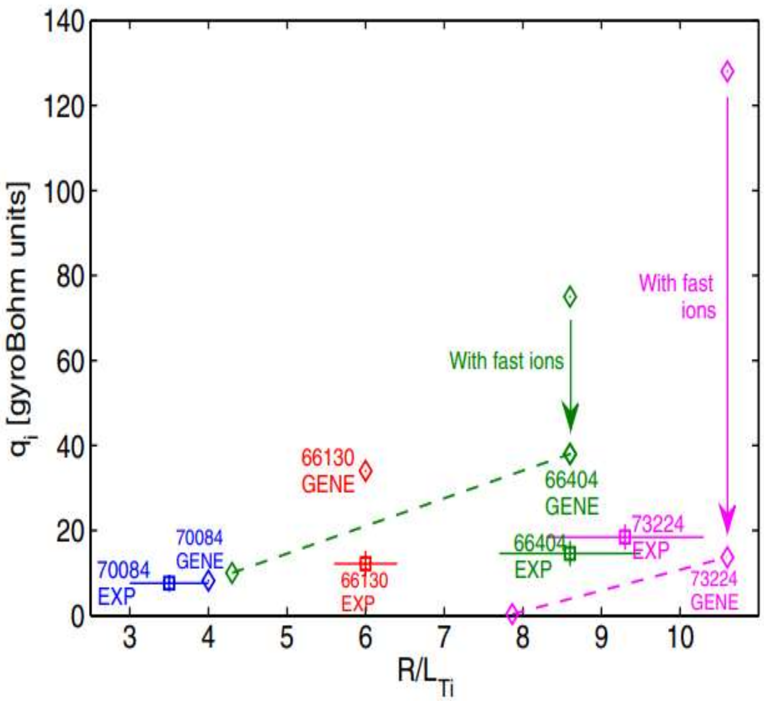
$$\gamma_E \equiv (r/q)(d\Omega/dr)/(c_s/R)$$

- Compare stiffness for various γ_E, with and without PVG term
- Experimental "high rotation" value is $\gamma_E = 0.3\ c_s/R$

- With PVG, stiffness only slightly reduced near threshold.
- With no PVG, classic "Waltz-rule" threshold shift recovered

Experimental observations cannot be explained by flow shear

L mode: Experimental ion heat flux reached when including fast ions in EM simulations



J. Citrin et al. PRL 111, 155001 (2013)

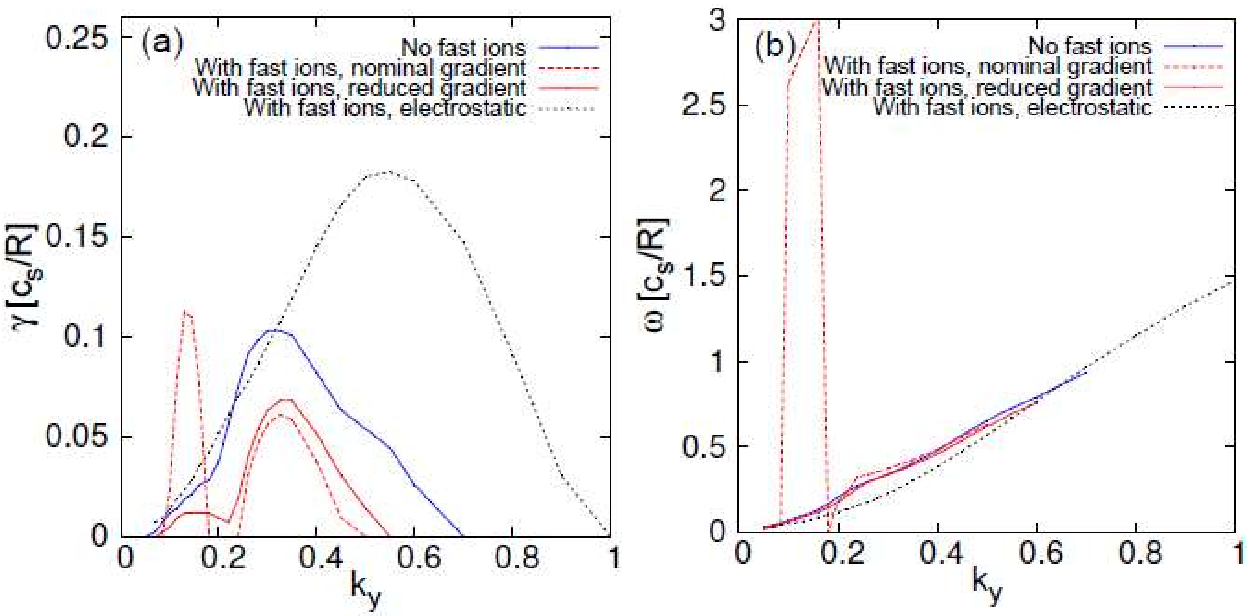
- Inclusion of fast ions yields strongly reduced fluxes and low stiffness, but only in nonlinear electromagnetic simulations!
- The nonlinear electromagnetic stabilization is greater than the linear stabilization!
- Agreement between EXP and NL simulations drop to within $\approx \times 2$

Stabilization by electromagnetic effects: Suprathermal pressure gradients adds to the total β'. Can significantly stabilize turbulence.

Hybrid H-mode scenario: mild linear impact of fast ions and electromagnetic effects

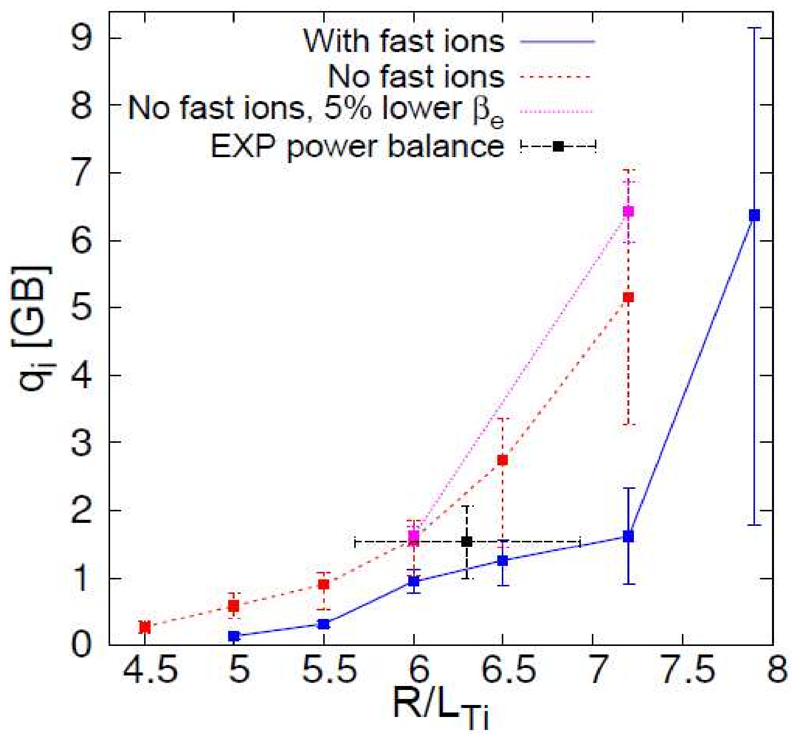
J. Garcia et al 2015 Nucl. Fusion 55 053007

J Citrin et al 2015 Plasma Phys. Control. Fusion 57 014032



- Significant EM-stabilization of ITG modes. Enhanced by fast ions.
- With nominal fast ion pressure, fast ion modes at $k_y < 0.2$, <u>not detected in experiment</u>
- Fast ion mode (consistent with beta induced Alfven Eigenmode – BAE) stabilized by $\approx 30\%$ reduction of fast ion gradient. Likely coupled with KBM branch, thus referred to BAE/KBM.

Hybrid H-mode scenario : strong non-linear impact of fast ions and electromagnetic effects



J. Garcia et al 2015 Nucl. Fusion 55 053007

- 10-20% increase of R/L_{Ti} for the same heat flux with fast ions
- Fast ions change the threshold
- EM-effects + fast ions are key factor for obtaining experimental heat fluxes
- Fluxes calculated with reduced fast ion pressure gradient.
- Slightly fast ion transport necessary

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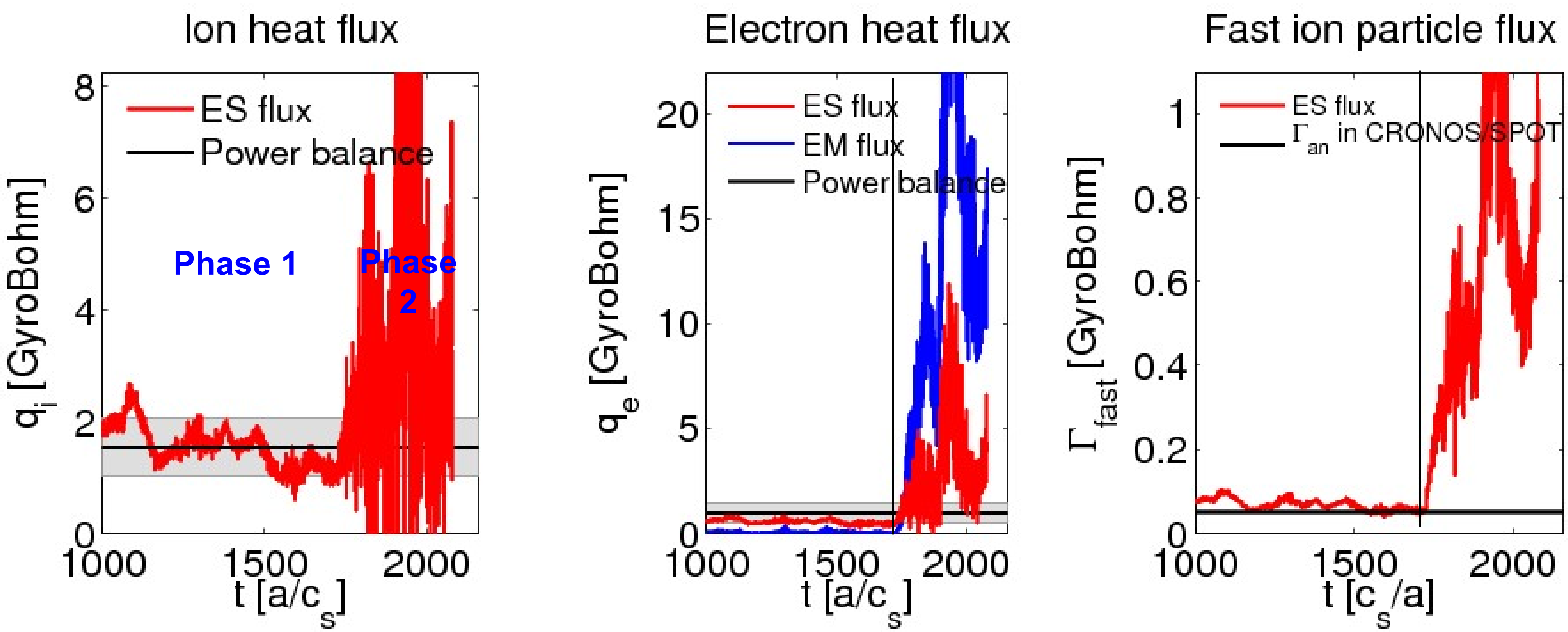
With fast ion mode in NL simulation, fluxes far above power balance levels

What happens nonlinearly if we allow the BAE/KBM mode to be unstable?



J Citrin et al 2015 Plasma Phys. Control. Fusion 57 014032

Phase 1: With 30% reduced fast ion pressure (no BAE/KBM mode)

Phase 2: increase to nominal fast ion pressure and restart simulation

- System with fast ion mode has fluxes clearly above power balance values. Limit cycles? Robustly maintained below limit?

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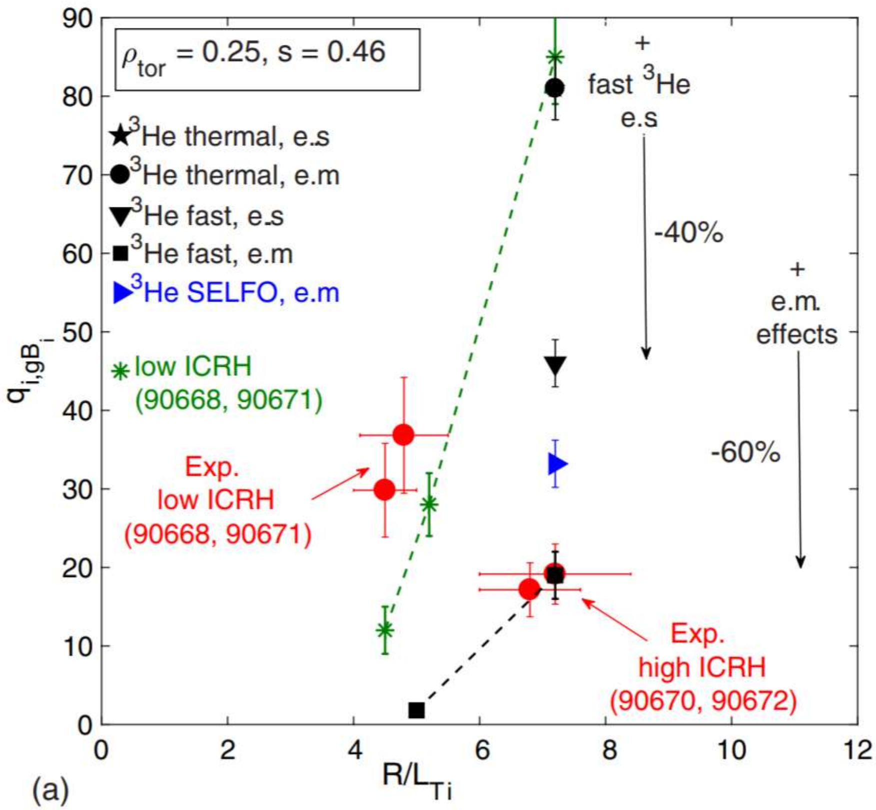
Experiments validate HPC results!



N. Bonanomi et al 2018 Nucl. Fusion 58 056025

- How to experimentally validate HPC results?
- New experiment performed at JET with mostly ICRH heating→ low rotation
- **Previous HPC results confirmed:** heat flux reduction obtained in presence of fast ions and low rotation

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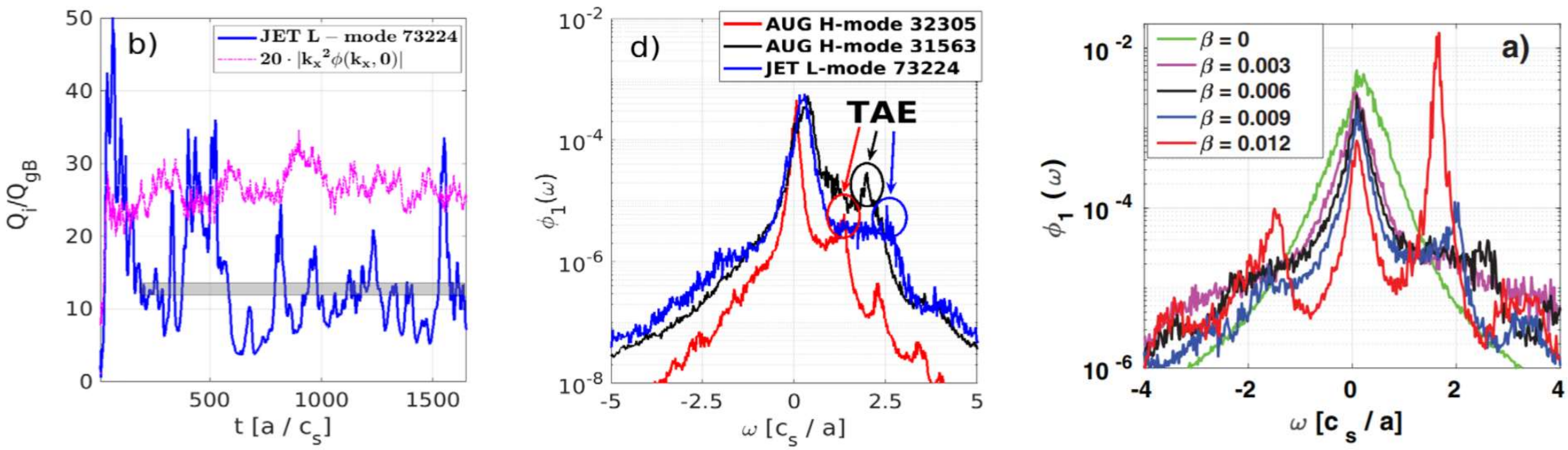
TAE and zonal flows behind transport reduction



A. Di Siena et al 2019 Nucl. Fusion 59 124001

- Transport reduction by fast ions analyzed in JET L-mode plasmas
- Linearly marginally stable TAE modes nonlinearly excited by ITG to TAE spatio-temporal scales.
- Fast ion modes furthermore start to increasingly affect the ZF levels
- Increase in ZF levels strongly suppresses heat/particle fluxes and reduce the TAE drive
- Drawback: no TAE modes ever detected in such experiments

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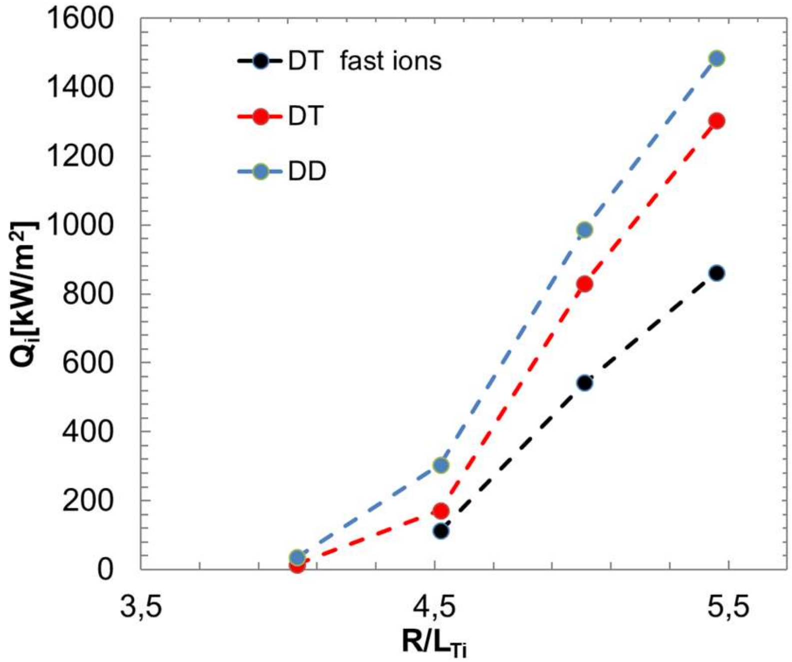
Role of alphas in ITER: transport suppression

ITER hybrid scenario



J. Garcia et al., Phys. Plasmas 25, 055902 (2018)

- DT plasmas in ITER can be different to DD
- MeV alpha particle impact on ITG turbulence can be significant
- How to experimentally validate such results?
- ITER relevant plasmas need:
    - Electron heating
    - MeV ions
    - Ti~Te
    - Low rotation
    - Alfvén modes destabilization?

Previous experimental condition quite far from ITER

- Stabilizing fast ion effect → BUT way less energetic particles than DT fusion born alpha particles modelled [Citrin PRL(2013), Garcia NF(2015), Bonanomi NF(2018), Di Siena NF(2019)]
- How to asses the impact of alpha particles on turbulence/transport in ITER and DEMO conditions?
- 2 steps programme at JET: Highly energetic MeV studies in D and DT campaign in 2021

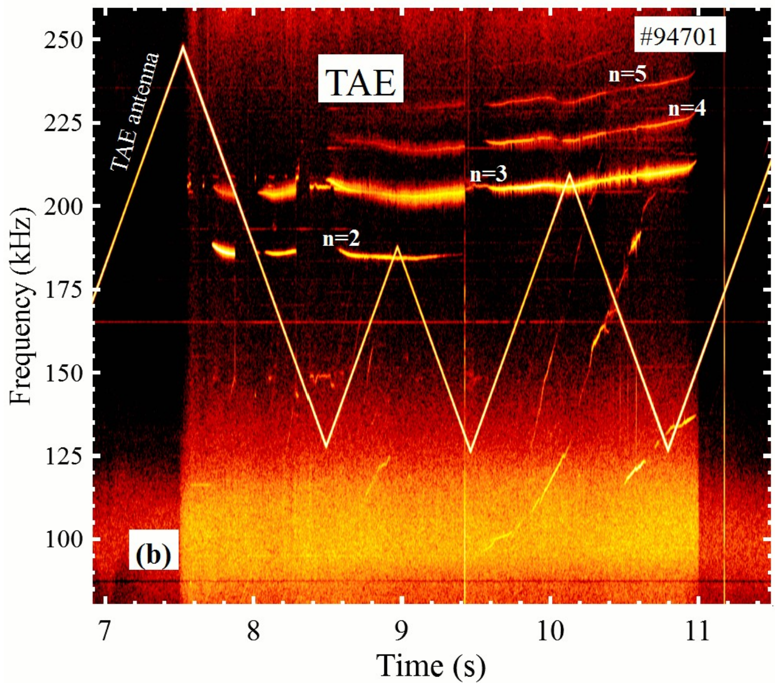
Case Study	Species	T_i/T_e	n_{FI}/n_e [%]	T_{FI}/T_e	β_e [%]
JET #73224 – [Citrin PRL(2013),Di Siena NF(2019)]	$D - {}^3He$	**1**	**6 – 7**	**9.8 – 6.9**	**0.33**
JET #90672 – [Bonanomi NF(2018)]	${}^3He$	**0.8**	**9**	**12**	**0.4**
JET #75225 – [Citrin PPCF(2015),Garcia NF(2015)]	D	**1.6**	**12**	**7.3**	**1.8**
ITER Hybrid Scenario – [Garcia PoP(2018)]	${}^4He$	**1**	**0.9**	**41.3**	**1.25**

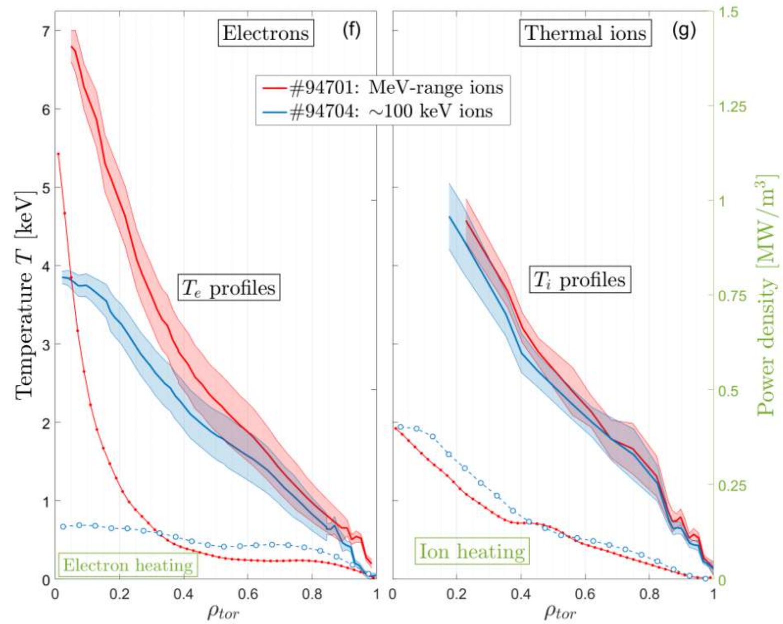
JET plasmas close to ITER conditions: new experiment

Case Study	Species	T_i/T_e	n_{FI}/n_e [%]	T_{FI}/T_e	β_e [%]
ITER Hybrid Scenario – [Garcia PoP(2018)]	^4He	**1**	**0.9**	**41.3**	**1.25**
JET #94701 – 3 ions scheme	D	**1**	**3**	**33.6**	**0.68**

- ICRH 3 ions scheme [Y. Kazakov et al., Nature Phys **13,** 973–978 (2017)] in D-^{3}He provide MeV ions and mostly electron heating

JET plasmas close to ITER conditions: strong transport effects

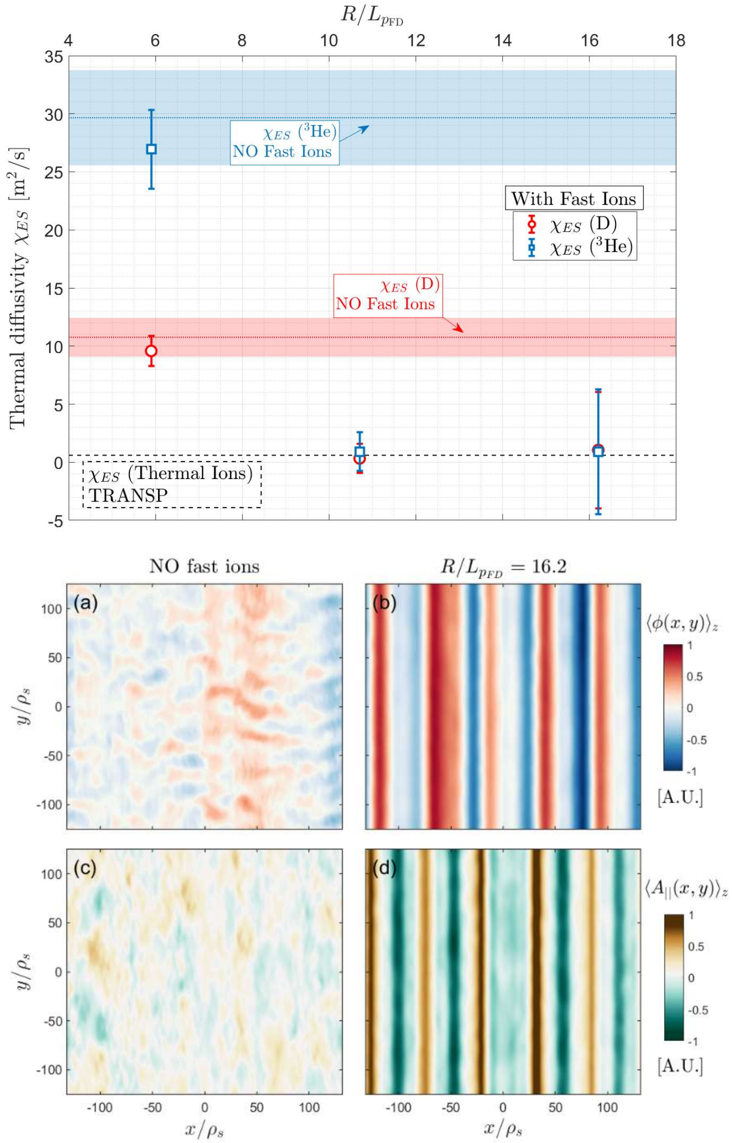




Ye.O. Kazakov et al 2020 Nucl. Fusion 60 112013
M. Nocente et al 2020 Nucl. Fusion 60 124006
V. Kiptily submitted to PRL

- Strong AE activity obtained
- Plasmas with ICRH electron heating have higher Ti than NBI plasmas at the same total power and density
- Improved confinement with electron heating and AE activity

JET plasmas close to ITER conditions: turbulent transport suppression



S. Mazzi et al submitted to Nat. Physics

- GENE simulations: MeV ions completely supress ion electrostatic transport
- Only in the presence of marginally or even fully developed AE
- Fast ions energy is channelled through zonal activity to thermal ions
- AE fluctuations do not lead to explosion of electromagnetic transport→ zonal fields
- Similar effect expected with α's in DT?
- DT campaign in 2021

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- Fast ions impact on turbulence at JET has been a story of success!
- HPC has driven research towards new discoveries
- Fast ions can significantly reduced or even supress turbulence
- Gyrokinetic theory has been proven to be correct in its domain of applicability
- Interplay between experiments, modelling and HPC is essential to understand and predict future plasmas
- Expected that alpha particles from DT reactions to play a role on transport/turbulence: come to JET-DT and let's check!