A historical overview of the impact of fast ions and EM effects on turbulence

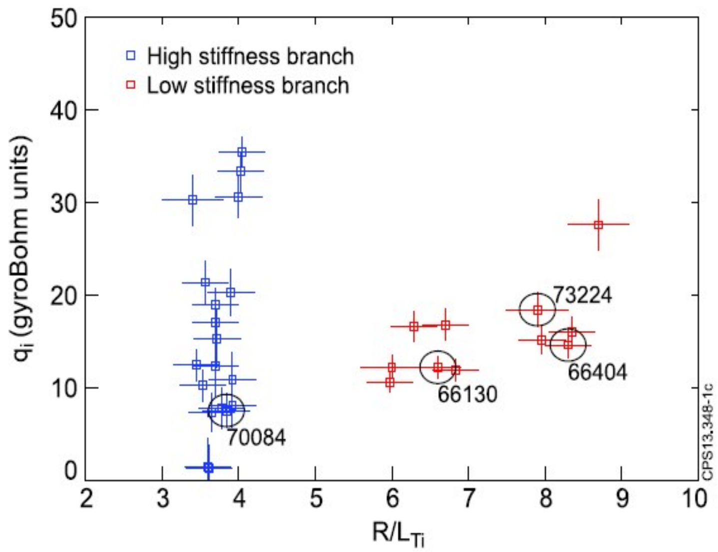
Jeronimo Garcia

Note

- Fast ions can interact with turbulence/transport in many different ways
    - Dilution
    - Magnetic geometry change
    - Linear resonance
    - Non-linear effects
- **Stronger impact of alpha particles on turbulence likely have non-linear origin**
- **Talk heavily based on JET experimental and modelling results**

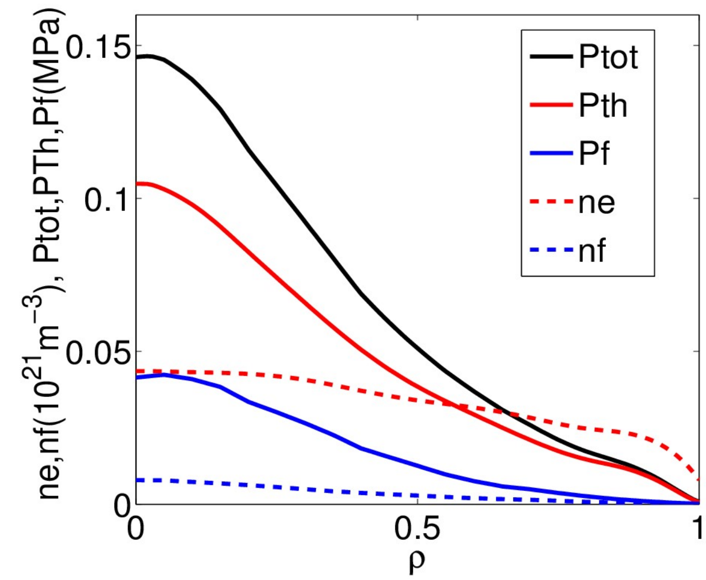
The origins: L and H-mode plasmas

L mode: 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)

H mode: high beta plasma

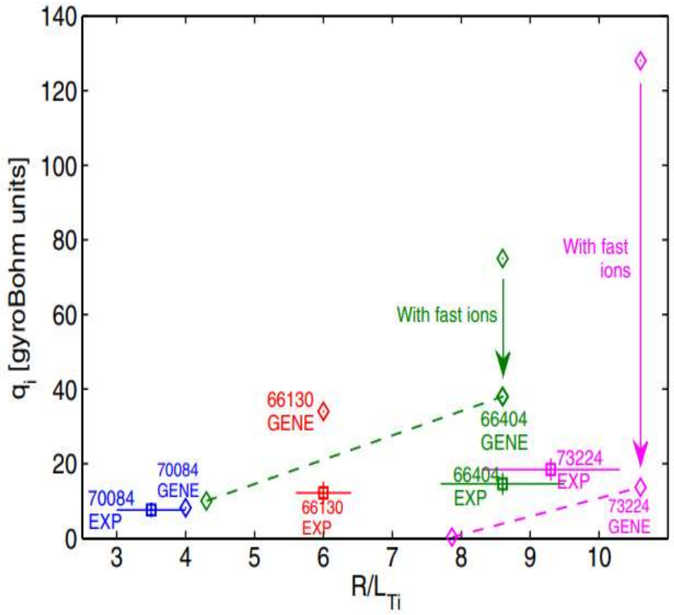


J. Garcia and G. Giruzzi PRL **104**, 205003 (2010)

J. Garcia *et al* 2013 *Nucl. Fusion* **53** 043023

- **New findings challenging mean ExB shearing as route to low turbulence/transport**

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



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

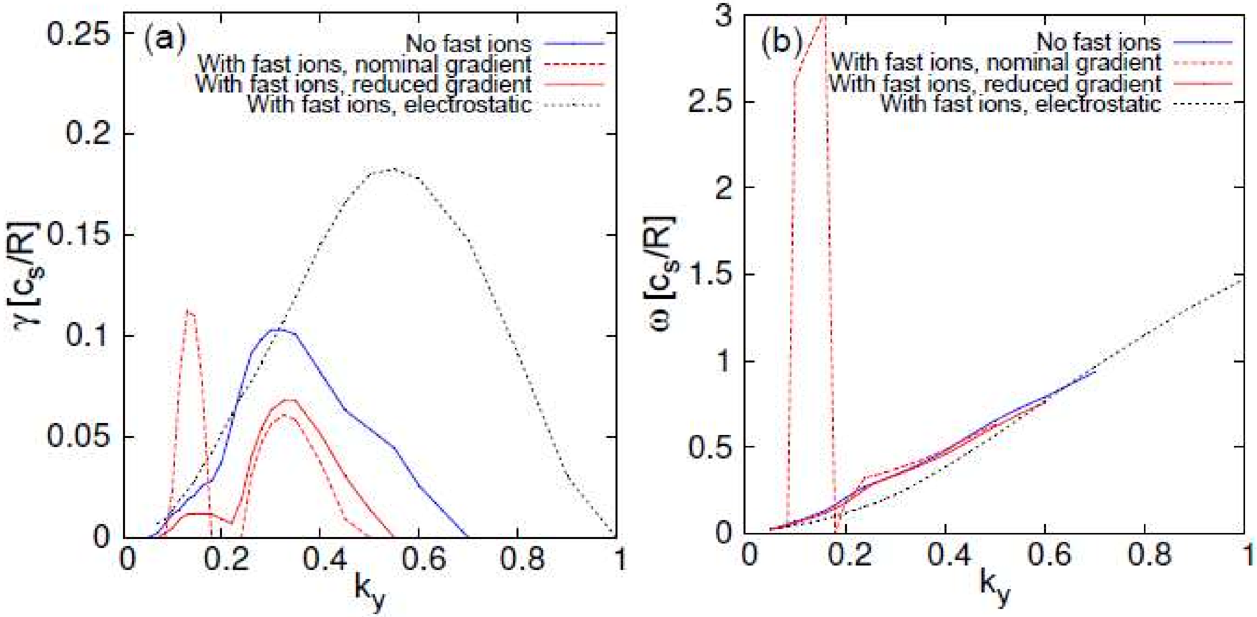
- Inclusion of fast ions yields strongly reduced fluxes and low stiffness, but only in nonlinear electromagnetic simulations!
- The nonlinear electromagnetic stabilization is greater than the linear stabilization!
- Agreement between EXP and NL simulations drop to within $\approx \times 2$

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

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

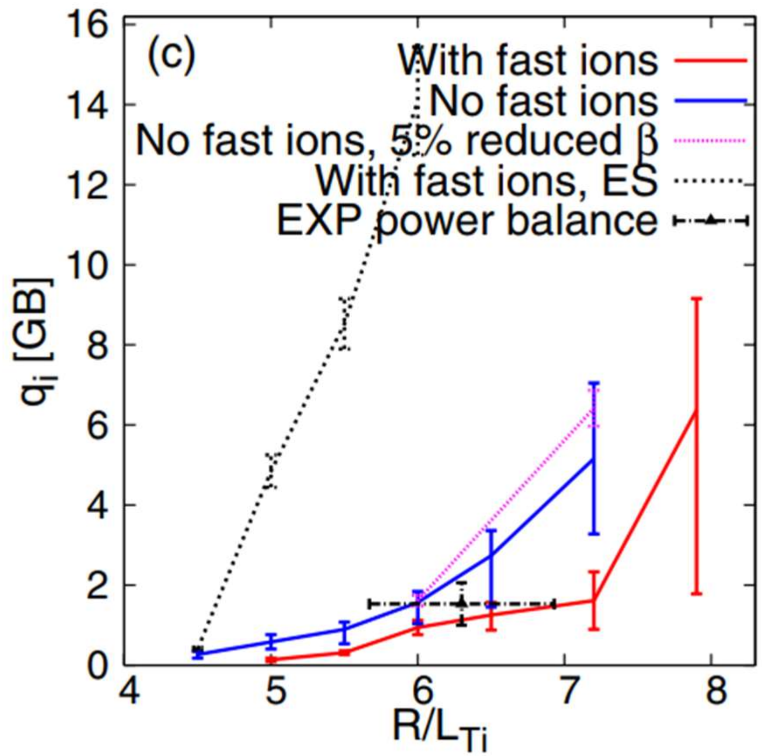
J. Garcia et al 2015 Nucl. Fusion 55 053007

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 $k_y < 0.2$, not detected in experiment
- Fast ion mode stabilized by $\approx 30\%$ reduction of fast ion gradient. Likely coupled with KBM branch, thus referred to BAE/KBM.

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

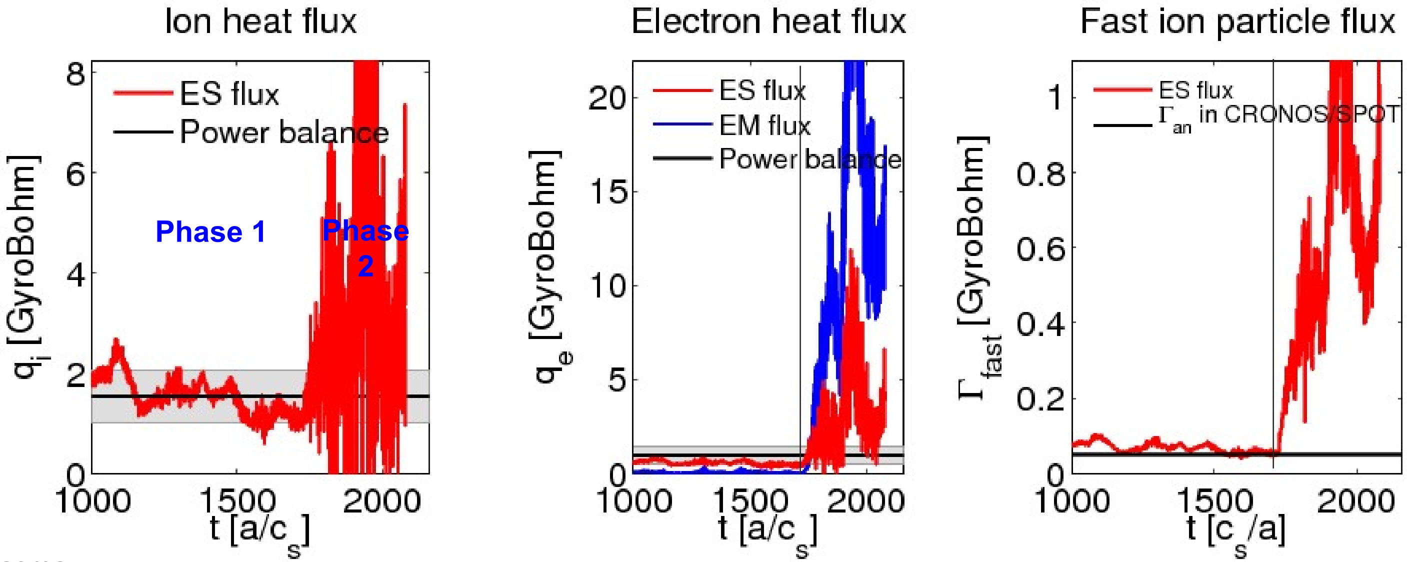


J. Garcia et al 2015 Nucl. Fusion 55 053007

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

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?

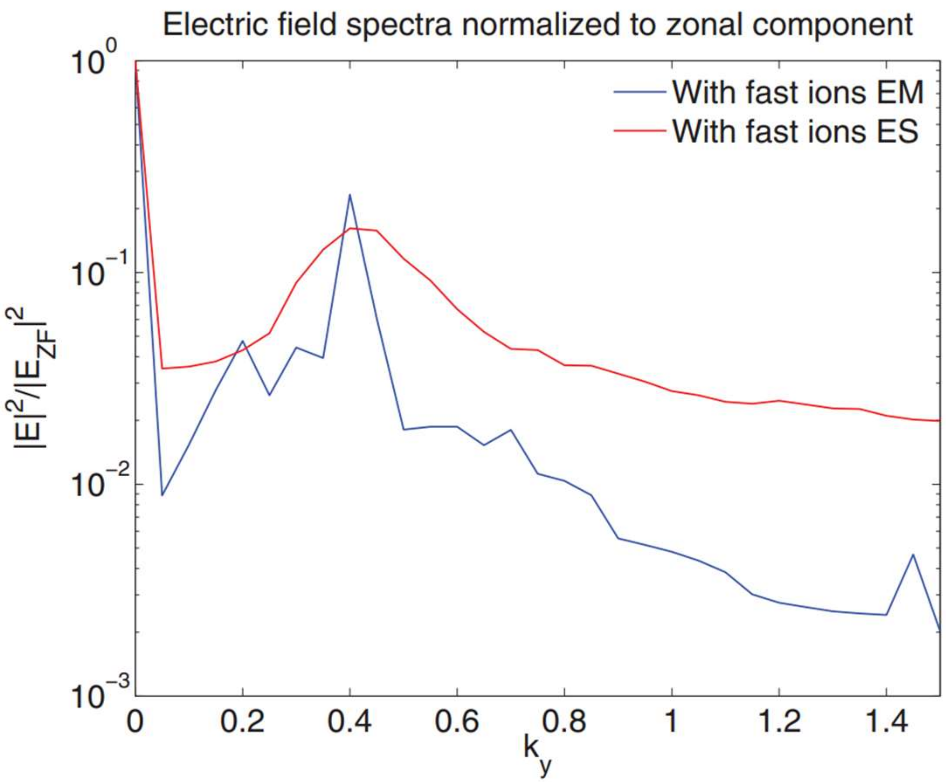


J Citrin et al 2015 Plasma Phys. Control. Fusion 57 014032

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?

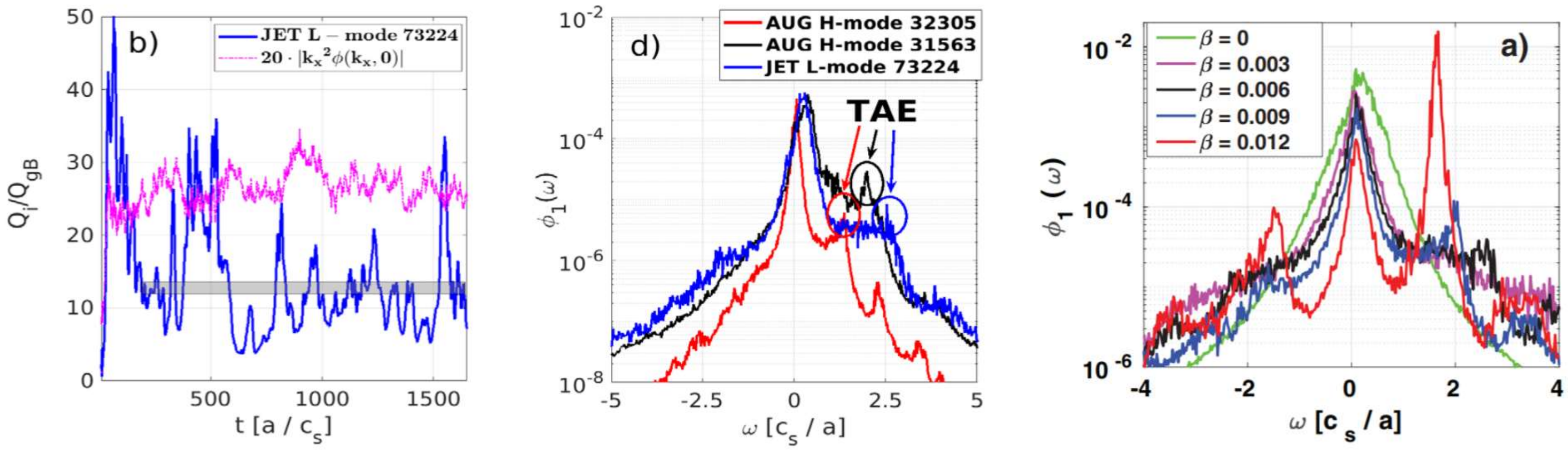
The impact of Zonal flows



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

- Strong impact of zonal flows in EM gyrokinetic simulations with FI
- Significantly stronger than in ES simulations with FI
- Extended studies were necessary

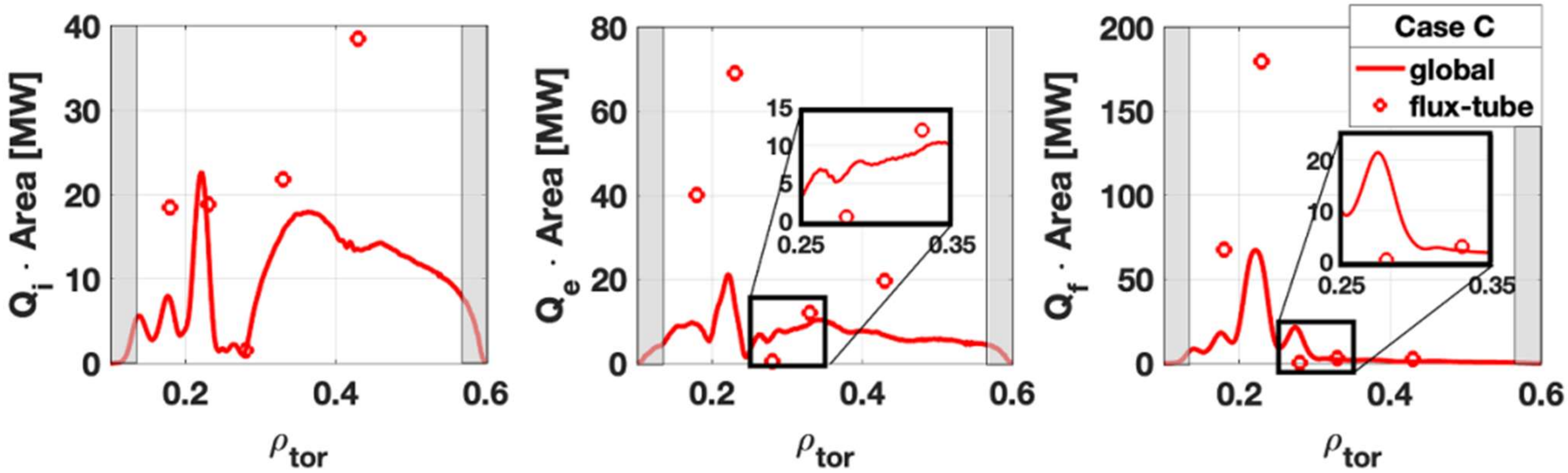
TAE and zonal flows behind transport reduction



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, as predicted [Chang & Zonca PRL 12]
- Increase in ZF levels strongly suppresses heat/particle fluxes and reduce the TAE drive
- Drawback: no TAE modes ever detected in such experiments

Local vs Global simulations

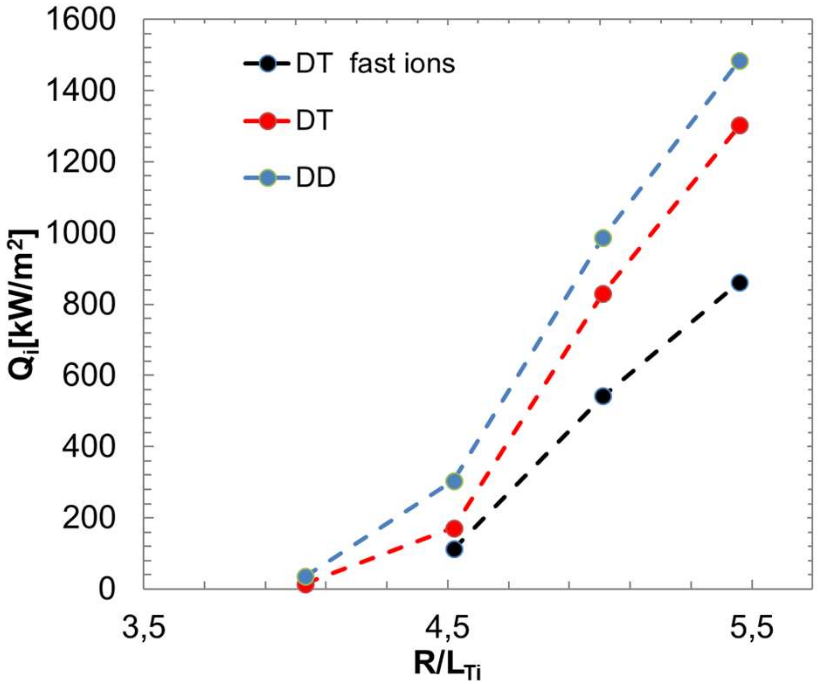


A. Di Siena et al 2023 Nucl. Fusion 63 106012

- Comparisons between local and global simulations performed with JET cases with GENE code
- AITG/KBM modes destabilized in the code
- Differences between local and global simulations are amplified when increasing AITG/KBM intensity

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 D
- MeV alpha particle impact on ITG turbulence can be significant
- How to 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

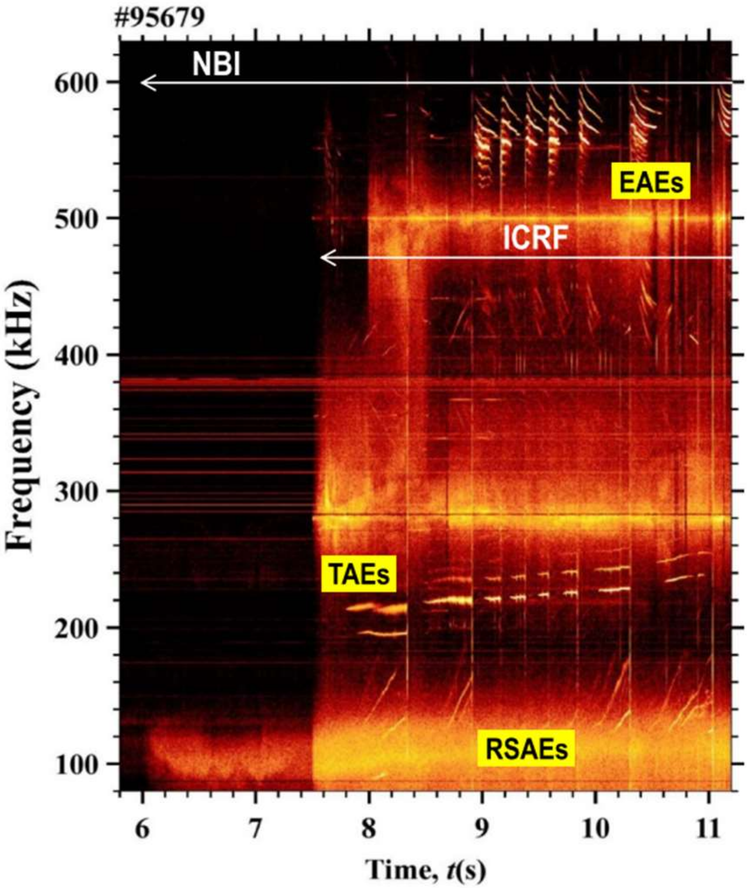
Case Study	Species	T_i/T_e	n_{FI}/n_e [%]	T_{FI}/T_e	β_e [%]
JET #73224 – [Citrin PRL(2013),Di Siena NF(2019)]	$D - {}^3He$	**1**	**6 – 7**	**9.8 – 6.9**	**0.33**
JET #90672 – [Bonanomi NF(2018)]	${}^3He$	**0.8**	**9**	**12**	**0.4**
JET #75225 – [Citrin PPCF(2015),Garcia NF(2015)]	D	**1.6**	**12**	**7.3**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

JET plasmas close to ITER conditions

Case Study	Species	T_i/T_e	n_{FI}/n_e [%]	T_{FI}/T_e	β_e [%]
ITER Hybrid Scenario – [Garcia PoP(2018)]	^{4}He	**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

Alfven waves destabilized in JET with ICRF

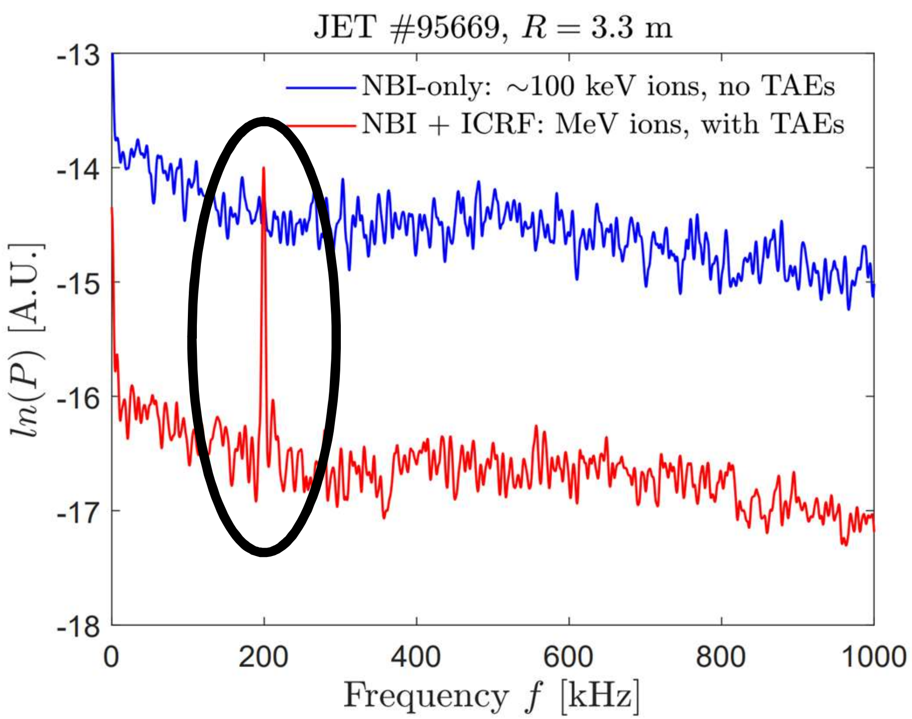


[M. Nocente NF(20)][Y. Kazakov PoP(21)][M. Dreval NF(22)]

- New experiments performed at JET in D-(D_{nbi})-^{3}He plasmas
- Heating mechanisms: NBI and ICRF
- Alfven waves in the range of 100-600kHz
- Fluctuations not detected in only NBI phase

Strong decrease of density fluctuations in the presence of MeV ions

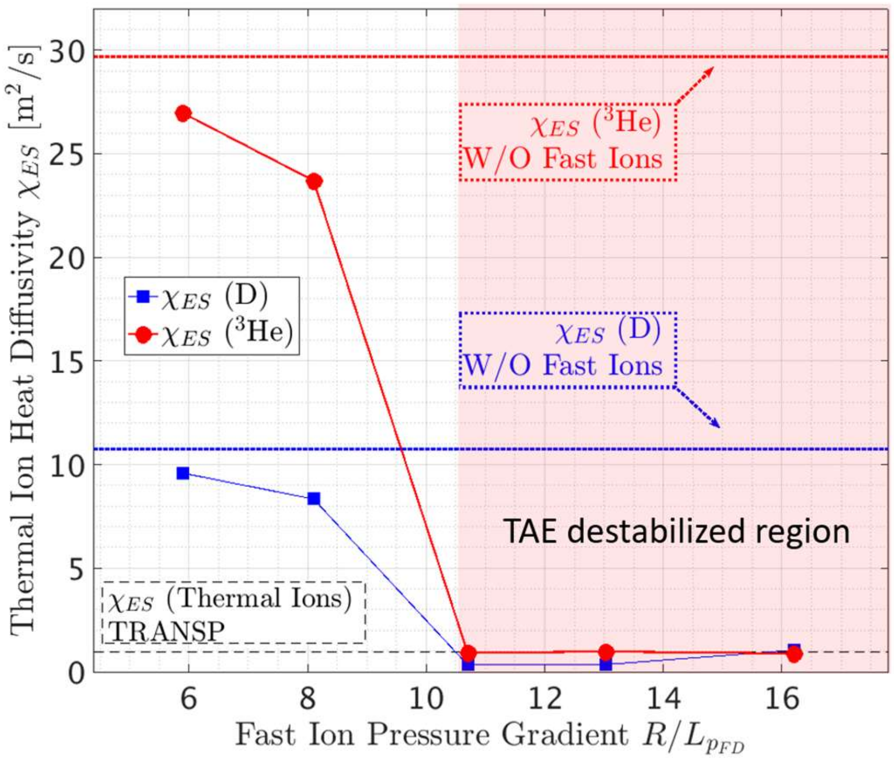
Reflectometry measurements



[S. Mazzi Nat. Phys.(22)]

- **Plasma density fluctuations spectrum→ turbulence intensity**
- **Compared to NBI, fluctuations reduction in the presence of MeV ions**
- **Unexpectedly, Alfven waves and reduced turbulence coexist**

Suppression of Thermal Electrostatic Fluxes in the Presence of FI-driven Modes



[S. Mazzi Nat. Phys.(22)]

➢ $R/L_{p_{FD}} = 10.7$:

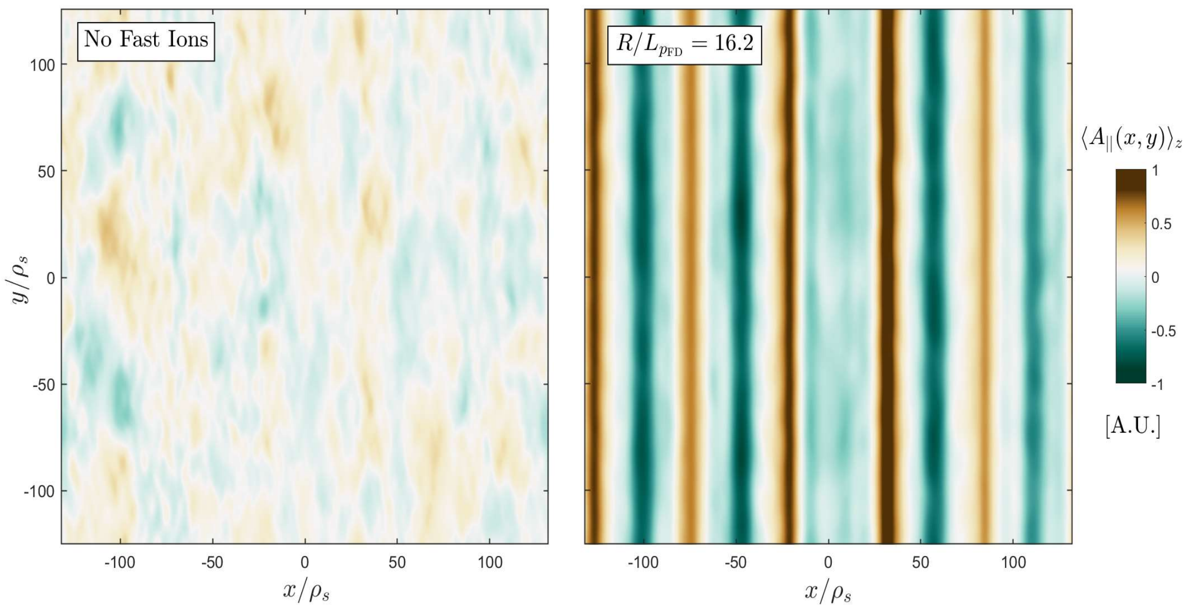
Linear marginal stability → Nonlinear destabilization of FI-modes reminiscent of mode-mode coupling [Di Siena NF(2019)]

➢ $R/L_{p_{FD}} = 16.2$:

Suppression of turbulence with fully destabilized TAE, good agreement with power balance from TRANSP

Mitigation of EM Transport by Zonal Fields

- Strong FI driver → Large-amplitude fluctuations of perturbed fields (Φ & $A_{||}$) at low-k_y [Gorelenkov NF(2010)]
- ES fluxes suppressed → Electromagnetic (EM) transport dominates



- Low thermal velocity for thermal ions → Low thermal ion magnetic flux ($\mathrm{E}_{\mathrm{EM},s} \propto v_{th,s} A_{||}$)
- $A_{||}$ zonal structures appear when FI-modes unstable
- Electron magnetic flux expected to explode [Citrin NF(2015)] → Mitigation by Zonal fields

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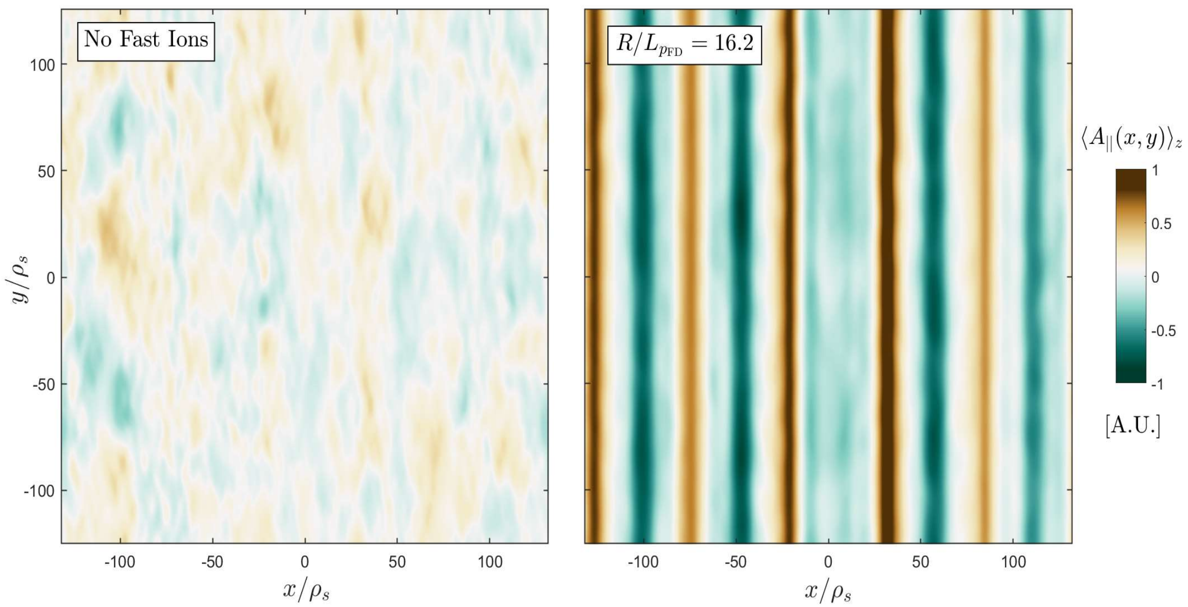

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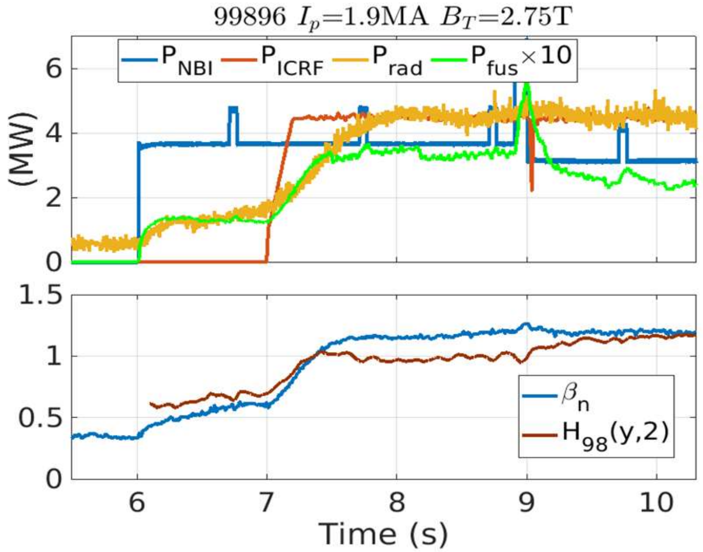
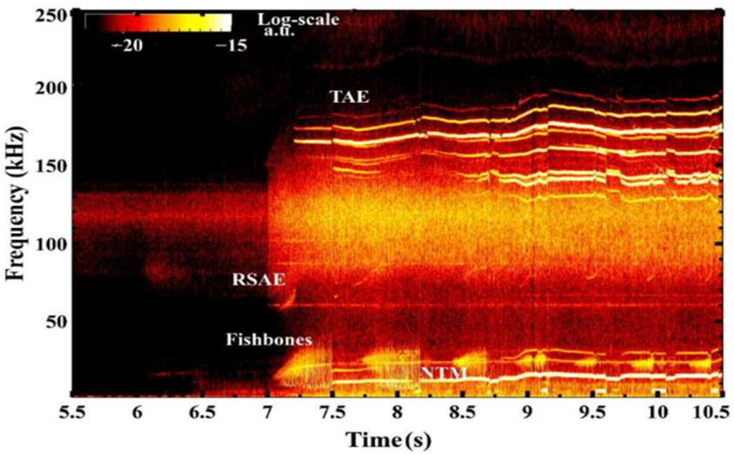
- Can this local simulation provide the correct physics answer? → J. Ruiz this workshop

Exploration of core burning plasmas characteristics





[J.Garcia IAEA23]

[J. Garcia, Y. Kazakov arXiv:2309.11964]

- **DT plasmas explored in core ITER relevant conditions:**
  - High heating fraction to electrons (~60%) (1% H minority)
  - Low input torque
  - Destabilized fast ion modes

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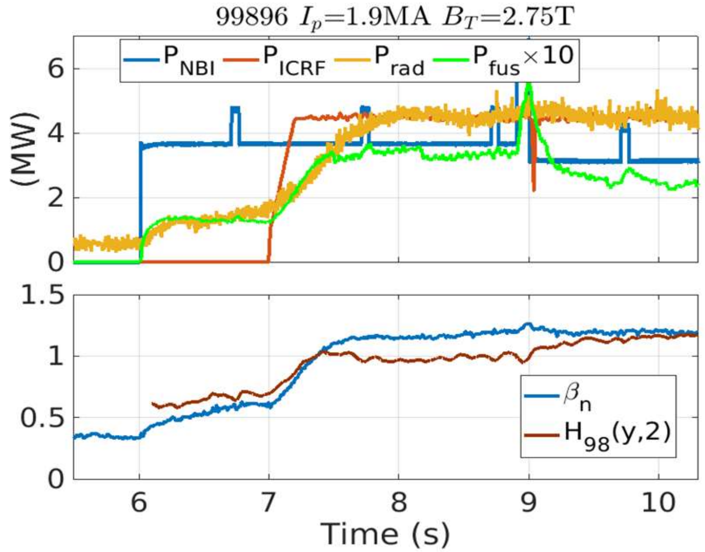

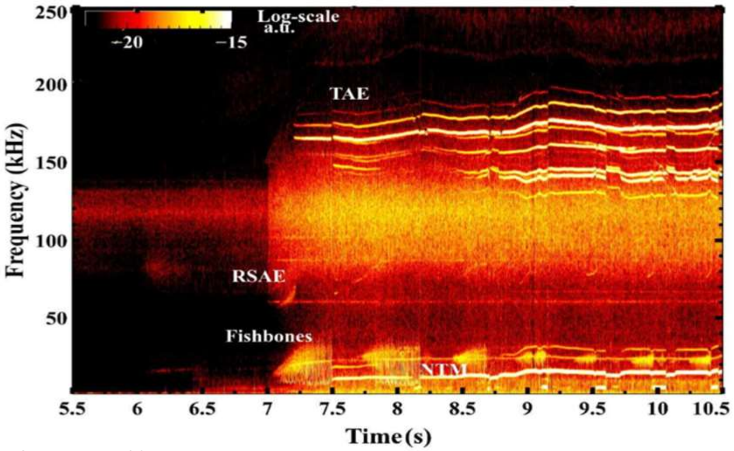

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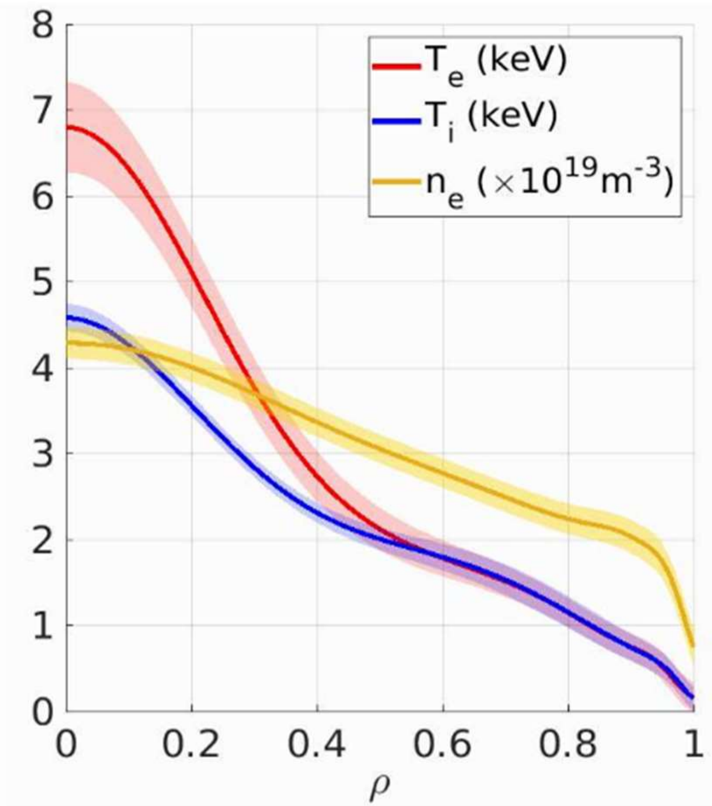
  - High heating fraction to electrons (~60%) (1% H minority)
  - Low input torque
  - Destabilized fast ion modes
- High confinement obtained: $H_{98}(y,2)\geq 1$
  - Low core transport: $Q_{e,i}$~0.5GB
  - 15% better confinement in DT than D

High core electron heating with ICRF



- High electron heating and low torque: T_e/T_i~1.4, M_{ach}=0.12

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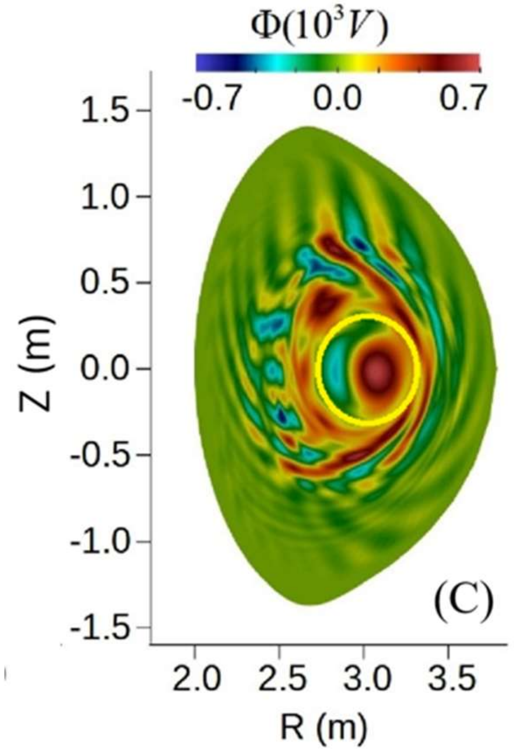
Fast ion perturbations simulated

Non-linear global gyrofluid simulations with FAR3d code



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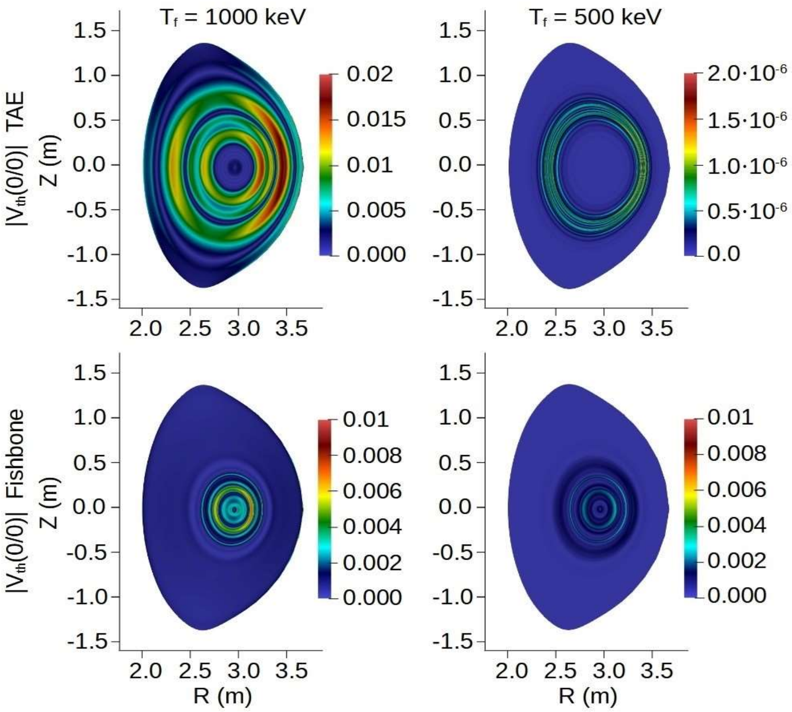
- High electron heating and low torque: T_e/T_i~1.4, M_{ach}=0.12
- Core fast ions perturbations reproduced considering ICRF accelerated ions

Zonal activity induced by perturbations

Non-linear global gyrofluid simulations with FAR3d code



[J.Garcia IAEA23]

[J. Garcia, Y. Kazakov arXiv:2309.11964]

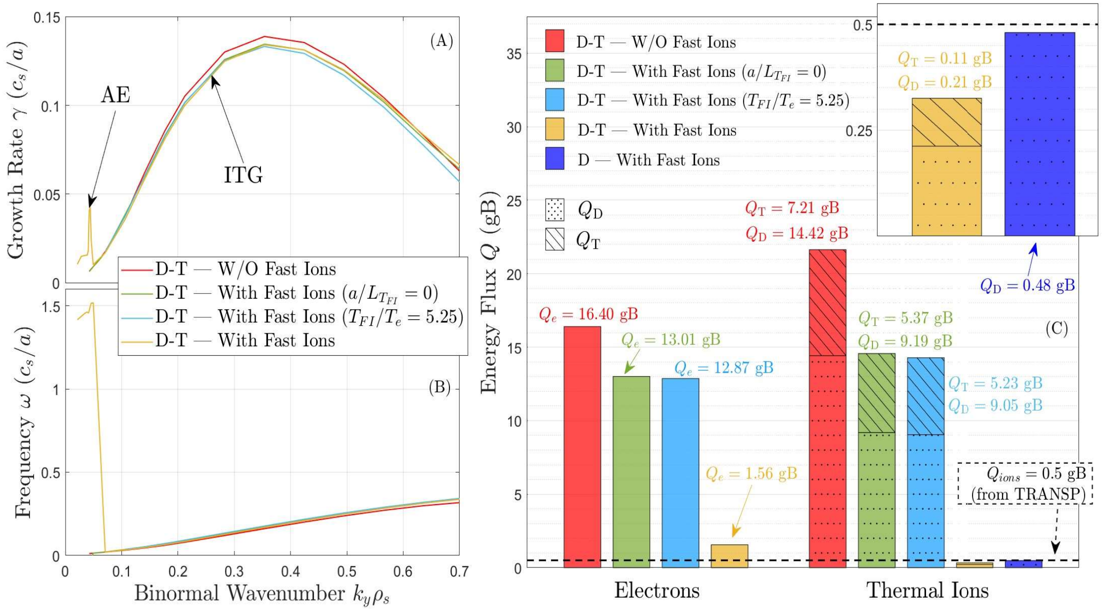
- High electron heating and low torque: T_e/T_i~1.4, M_{ach}=0.12
- Core fast ions perturbations reproduced considering ICRF accelerated ions
- Fishbone and TAE generate zonal structures
- Zonal activity leads to reduced ion thermal transport
- No evidence of T_i clamping at 90% of electron heating

Role of EP modes on improved confinement

[J.Garcia IAEA23]

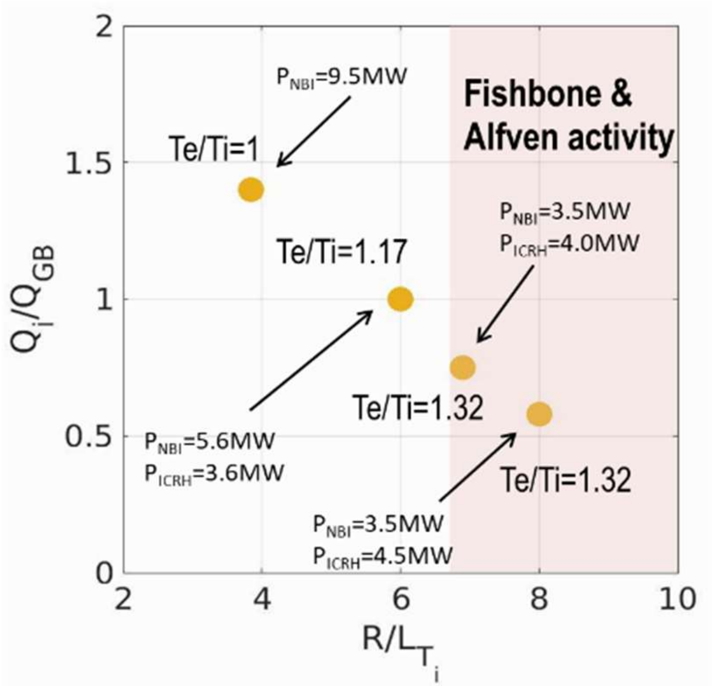
[J. Garcia, Y. Kazakov arXiv:2309.11964]

gyrokinetic simulations with CGYRO code



- CGYRO simulations show importance of highly energetic ions to reduce turbulence
- Key role of energetic ion modes rather than energetic ions themselves (as found in D-^{3}He [S. Mazzi Nat.Phys. 21])
- Global simulations with CGYRO do not seem to change the main results (work ongoing)

Why this topic is important?

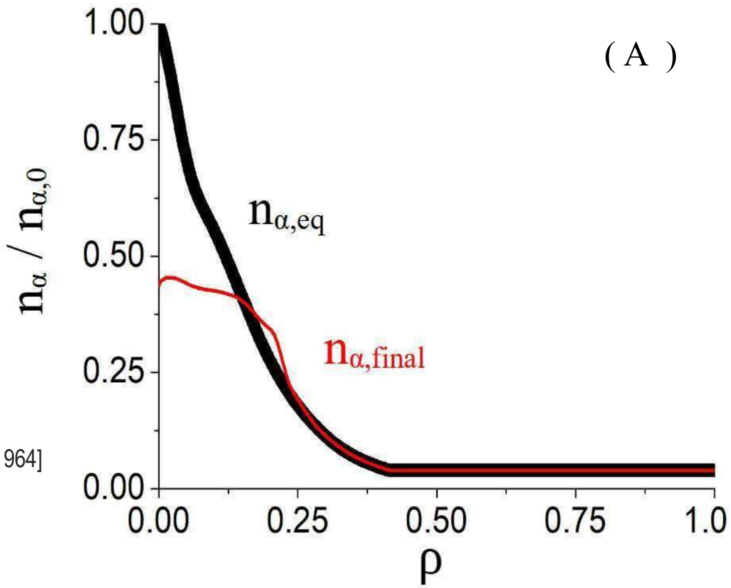


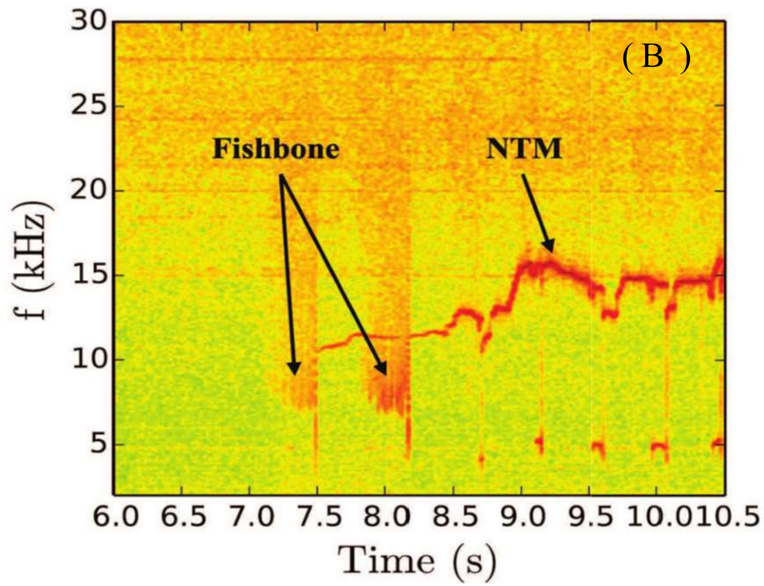
- Evidence of improved core confinement in the presence of Fishbone and Alfven activity
- **Better confinement at higher Te/Ti and electron heating than with ion heating**

[J.Garcia IAEA23]

[J. Garcia, Y. Kazakov arXiv:2309.11964]

Alpha particle losses





[J.Garcia IAEA23]

[J. Garcia, Y. Kazakov arXiv:2309.11964]

- Strong alpha particle losses in the presence of fishbone predicted by FAR3D→ Confirmed in experiment
- No ICRH FI losses detected
- Real impact of FI modes on plasma is much more complex than just confinement

Conclusions

- Extensive experimental and numerical results showing improved confinement in the presence of fast ions
- In particular when FI destabilize FI modes
- Interplay between FI, Fi modes and Zonal flows and Zonal fields numerically identified with several codes → Solid result
- Experimental evidence recently obtained→ J. Ruiz this workshop
- Direct evidence of the impact of alpha particles rather than ICRH FI is necessary→ A. di Siena this workshop
- Further numerical, theoretical and experimental work is necessary to understand this topic→ Shutdown of JET is a drawback (but a lot of data available!)

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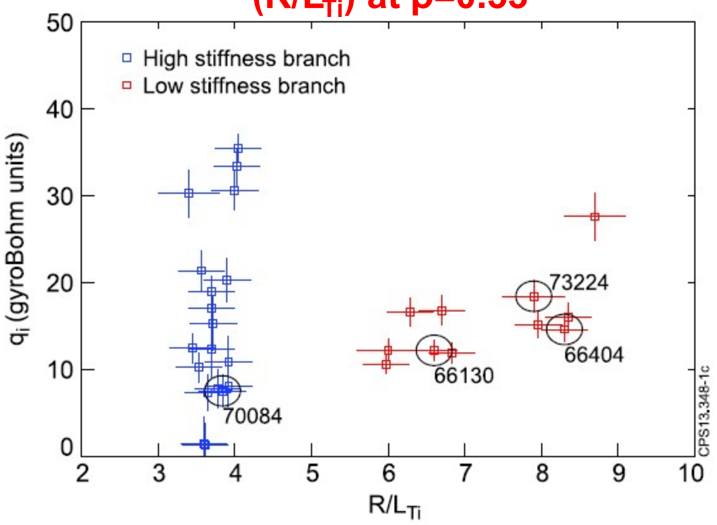
The origins: L-mode plasmas

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

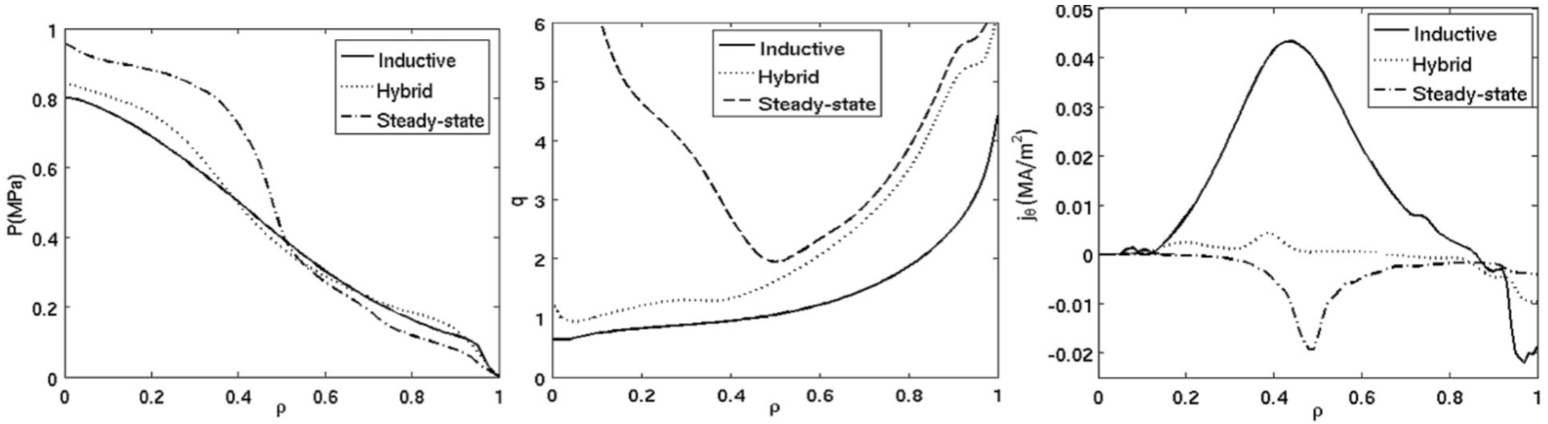


[1] P. Mantica et al., Phys. Rev. Lett. **102**, 175002 (2009); [2] P. Mantica et al., Phys. Rev. Lett. **107**, 135004 (2011)

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 origins: magnetism behaviour in H-mode



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

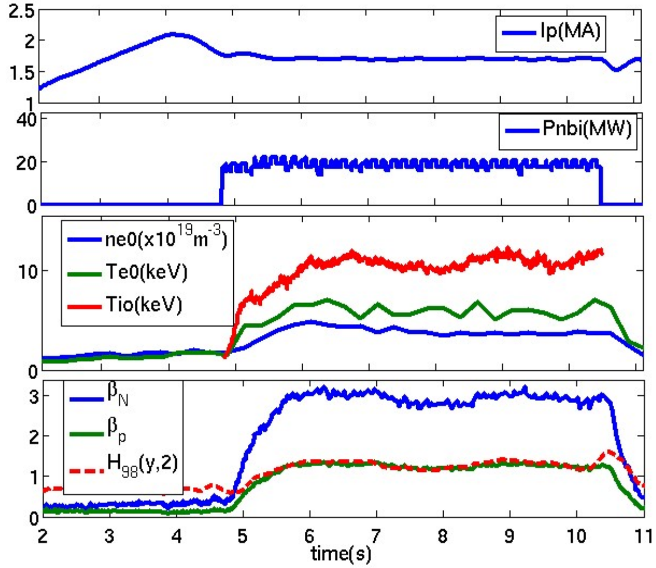
E. Solano and R. Hazeltine 2012 Nucl. Fusion **52** 114017

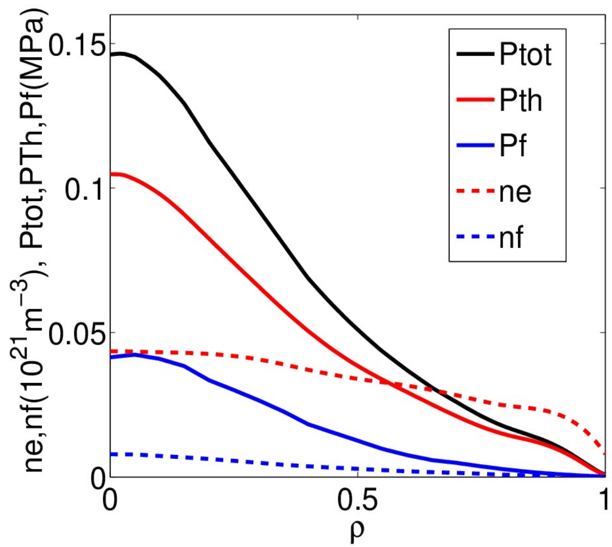
Emilia R Solano 2004 Plasma Phys. Control. Fusion **46** L7

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 origins: magnetism behaviour in H-mode





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

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_p
- Indication of strong EM effects: $\beta_p(r/L_\perp)^2$