Fast ions as a tool for turbulent transport suppression on JET

J. Garcia[1] and JET contributors*

1 CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.

*See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France,10-15 May 2021)

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Acknowledgments

N. Bonanomi[1], J. Citrin[2], T. Goerler[1], Y. Kazakov[3], J. Ongena[3], P. Mantica[4], S. Mazzi[6], A. Di Siena[7]

[1]Max-Planck-Institut f¨ur Plasmaphysik, D-85748 Garching, Germany

[2]DIFFER — Dutch Institute for Fundamental Energy Research, Eindhoven, The Netherlands

[3]Laboratory for Plasma Physics, LPP-ERM/KMS, EUROfusion Consortium member, TEC Partner, Brussels, Belgium

[4] Istituto per la Scienza e Tecnologia dei Plasmi, CNR, via Cozzi 53, 20125 Milan, Italy

[5] Aix-Marseille Université, CNRS PIIM, UMR 7345 Marseille, France

[6] The University of Texas at Austin, 201 E 24th St, 78712 Austin, TX, USA

Outline

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

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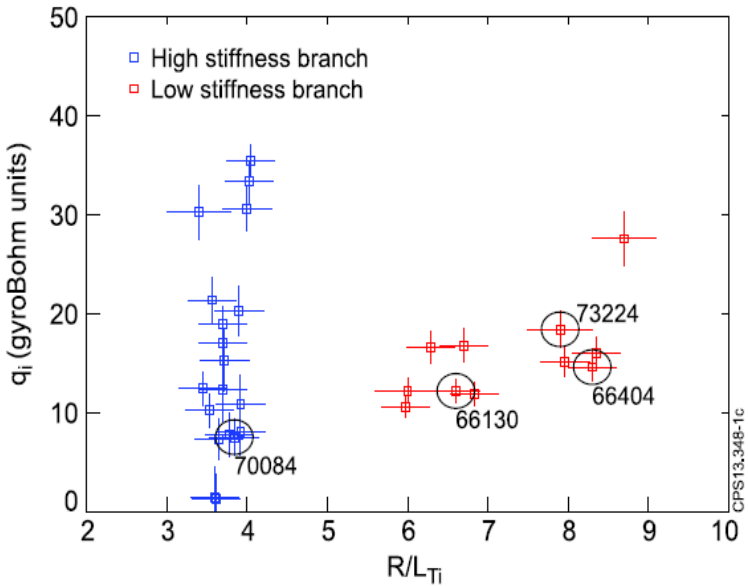
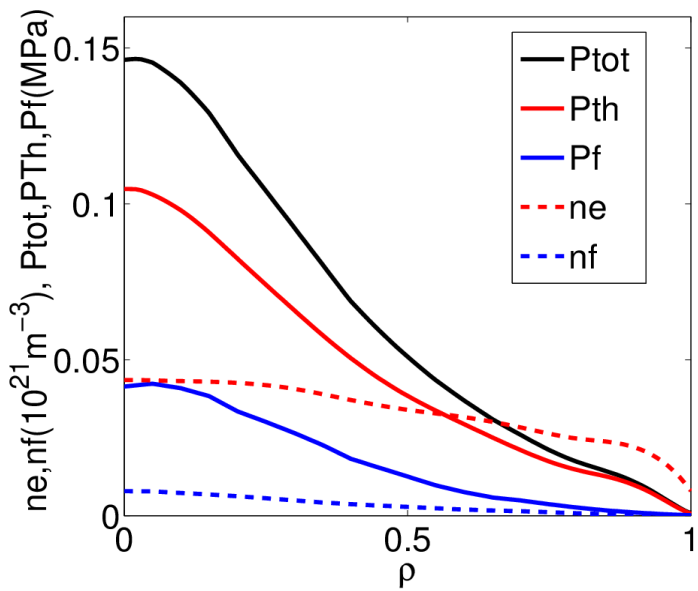
High fast ion fraction in low transport L and H-mode



P. Mantica et al., Phys. Rev. Lett. **102**, 175002 (2009)
P. Mantica et al., Phys. Rev. Lett. **107**, 135004 (2011)



J. Garcia and G. Giruzzi PRL **104**, 205003 (2010)
J Hobirk et al 2012 Plasma Phys. Control. Fusion **54** 095001
J. Garcia and G. Giruzzi Nucl. Fusion **53** (2013) 043023

- JET data-set in L-mode was a challenge for theoretical understanding of ion temperature gradient (ITG) turbulence
- Hybrid scenarios with peaked core ion temperature profile and good confinement have a significant fast ions content which highly increases core pressure gradient and β

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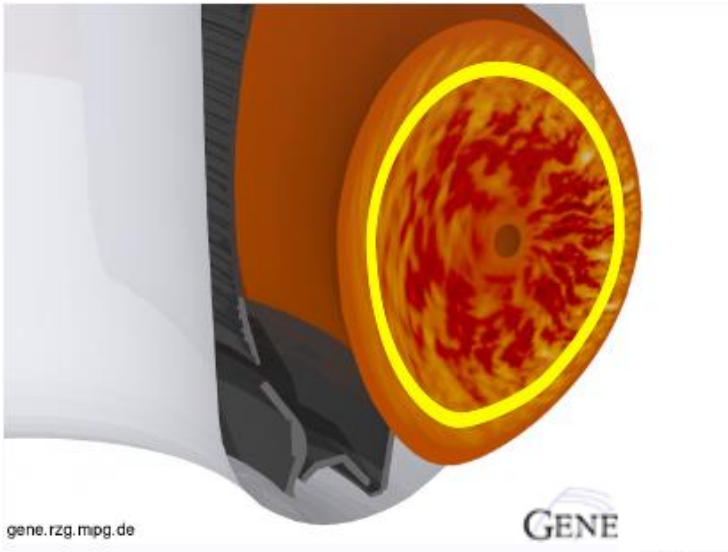
The GENE code: an essential tool

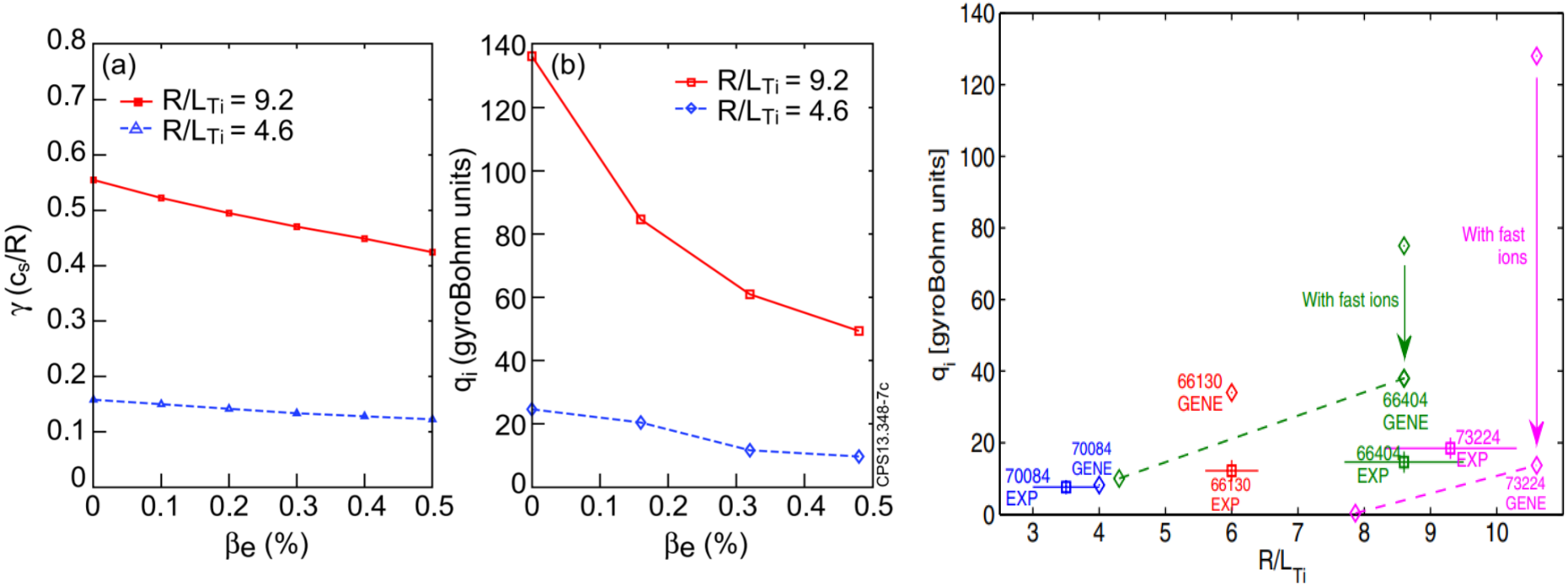


F. Jenko, W. Dorland, M. Kotschenreuther, and B.N. Rogers, Phys. Plasmas **7**, 1904 (2000); see http://gene.rzg.mpg.de for code details and access

GENE is a Eulerian gyrokinetic code:

- Kinetic treatment for each species (including fast ions)
- Electromagnetic fluctuations
- Collisions
- External ExB shear flows
- Realistic equilibrium
- Local (flux-tube)
- Both Maxwellian and realistic non – Maxwellian background distributions
- Sophisticated integrated modelling for the calculation of input data

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



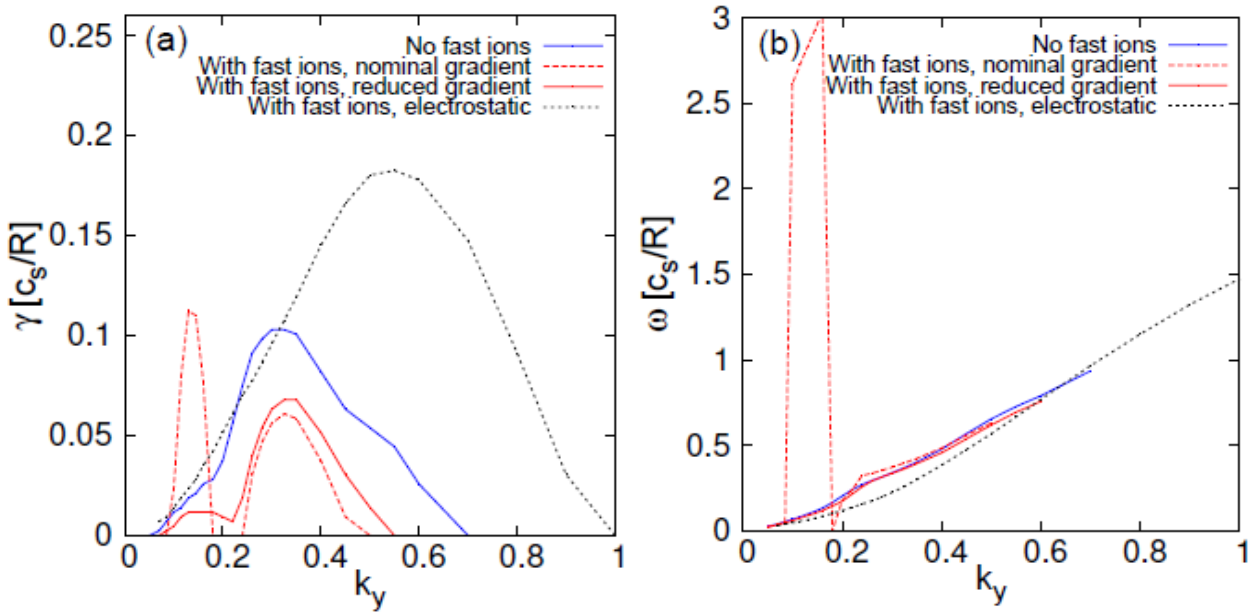
J. Citrin et al. PRL 111, 155001 (2013)

- The nonlinear electromagnetic stabilization is greater than the linear stabilization!
- Inclusion of fast ions yields strongly reduced fluxes and low stiffness, but only in nonlinear electromagnetic simulations!

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

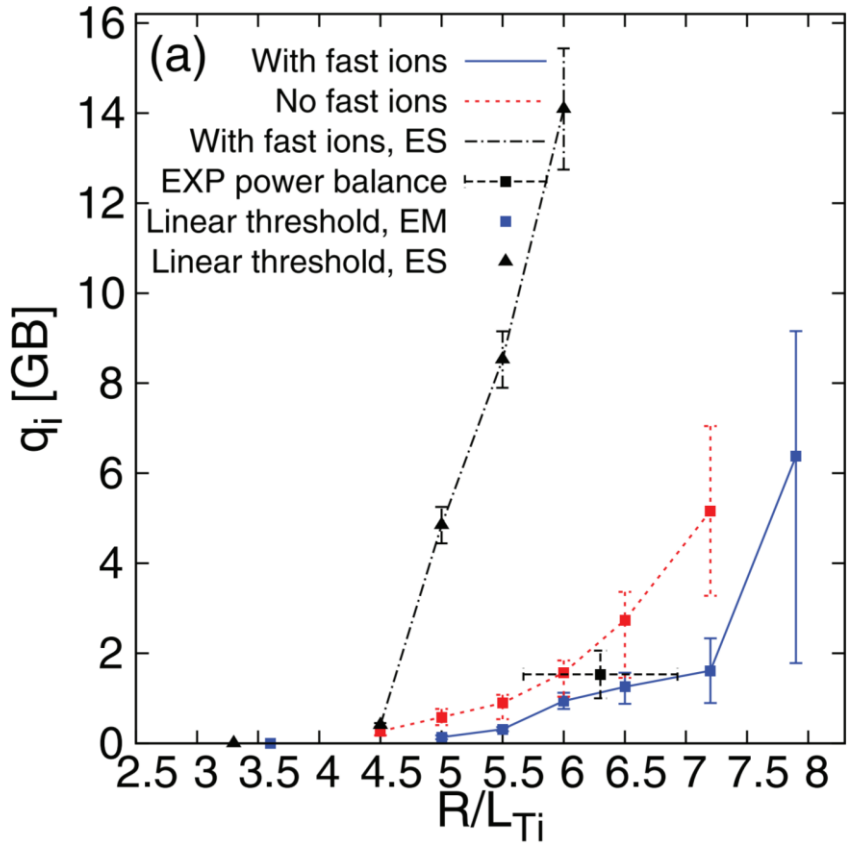
J. Garcia et al 2015 Nucl. Fusion 55 053007

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 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



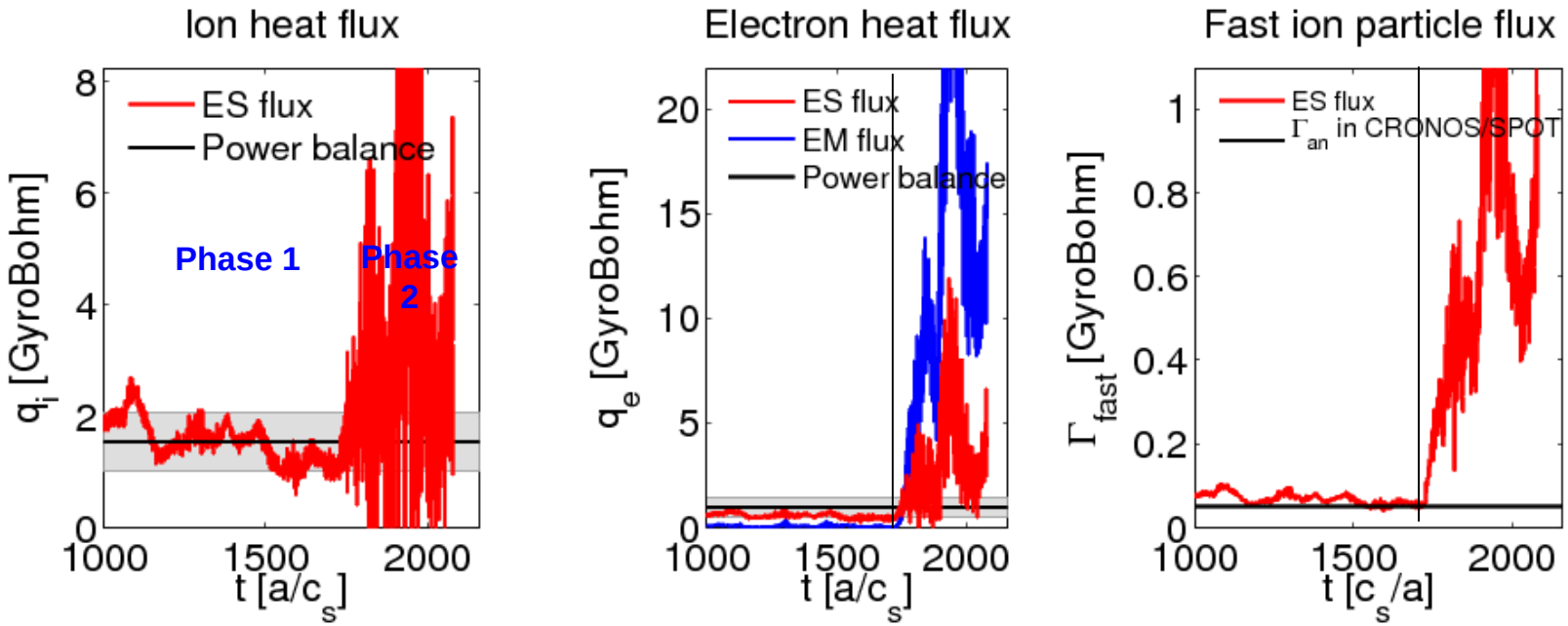
J. Garcia et al 2015 Nucl. Fusion 55 053007

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

- 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?

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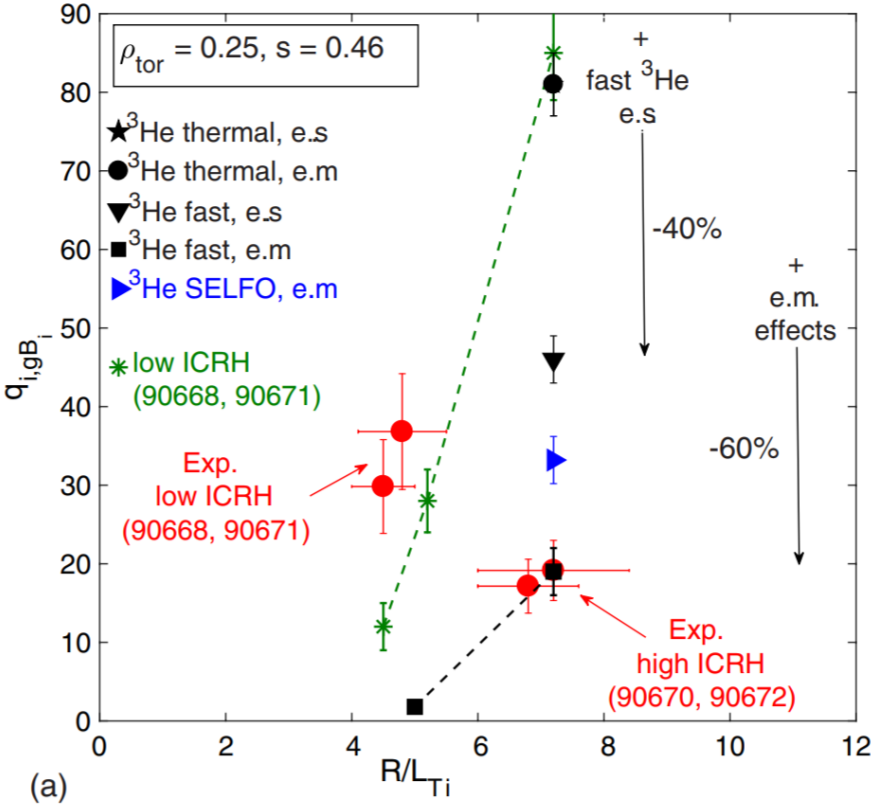
Experiments validate HPC results!



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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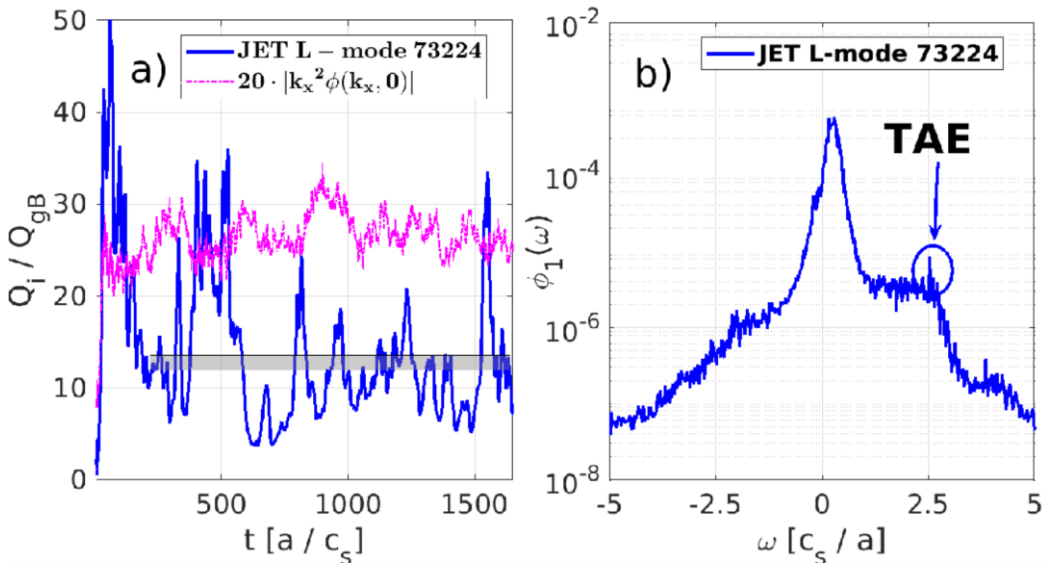
TAE and zonal flows behind transport reduction



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
- Increase in ZF levels strongly suppresses heat/particle fluxes and reduce the TAE drive
- Drawback: no TAE modes ever detected in such experiments→ Only marginally stable TAE modes possible?
- Non-linear electromagnetic effects without fast ions have similar non-linear behavior [GG Whelan PRL 2018]

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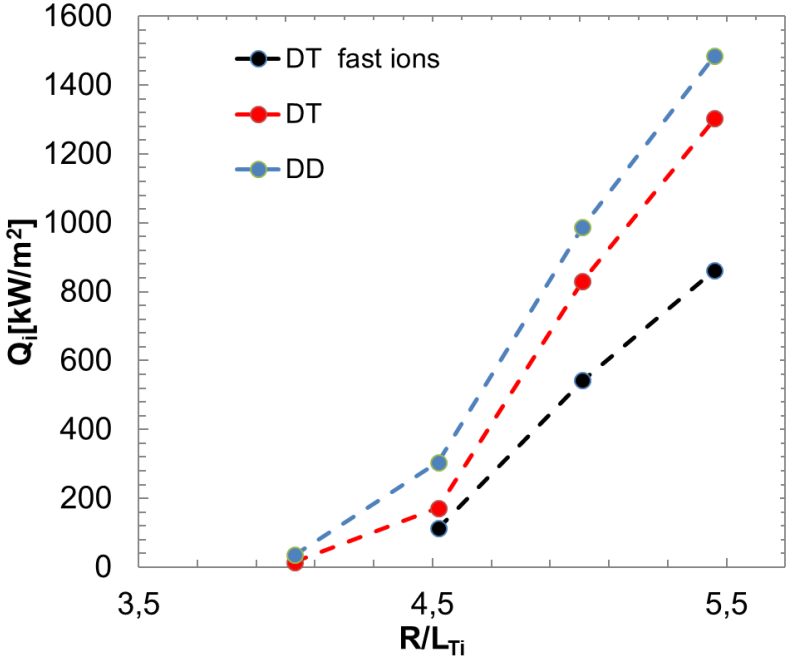
Role of alphas in ITER: transport suppression

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 – ^{3}He	**1**	**6 – 7**	**9.8 – 6.9**	**0.33**
JET #90672 – [Bonanomi NF(2018)]	^{3}He	**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)]	^{4}He	**1**	**0.9**	**41.3**	**1.25**

JET plasmas close to ITER conditions: new experiment

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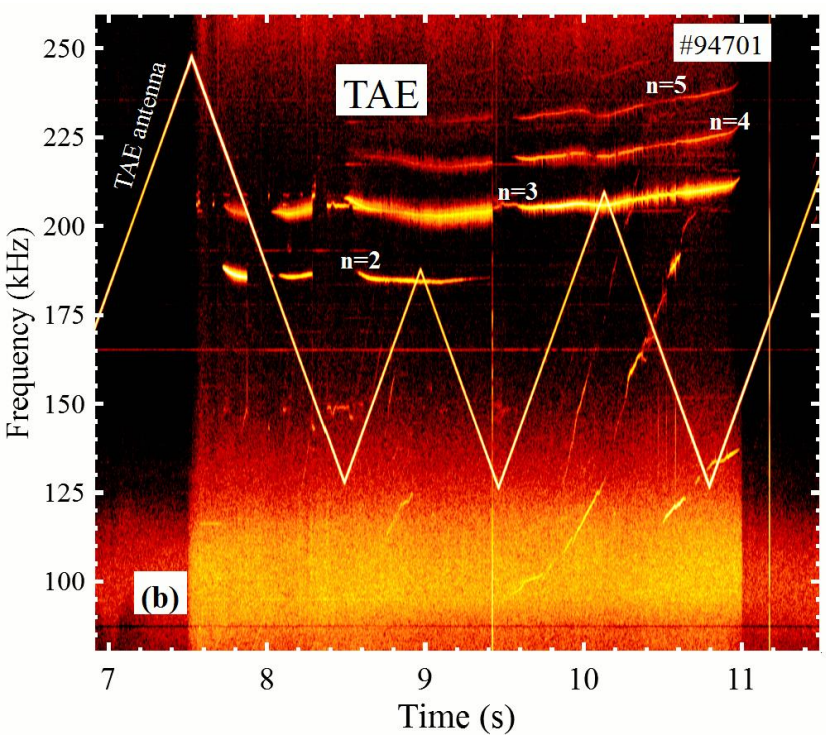
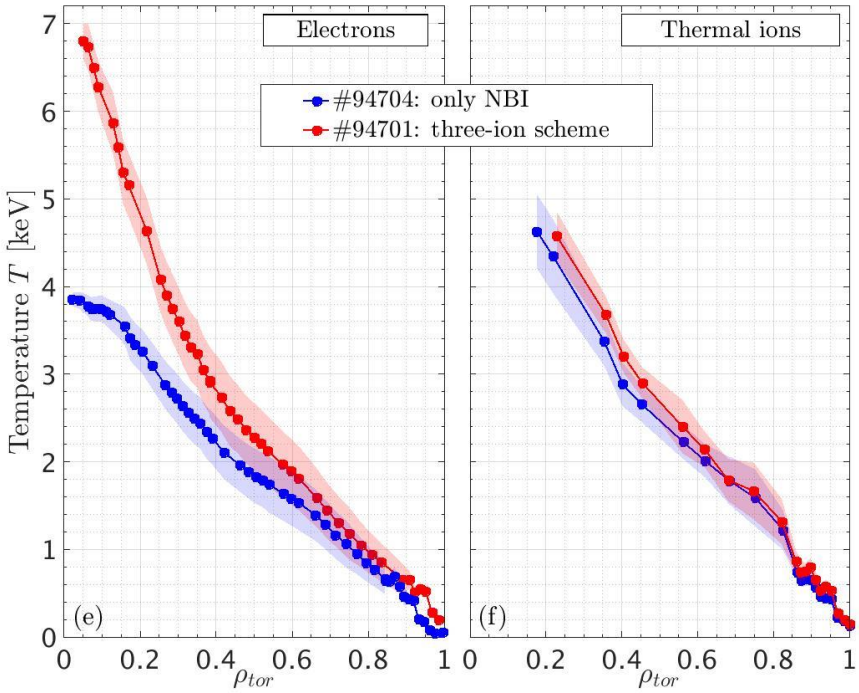
ITER Hybrid Scenario – [Garcia PoP(2018)]	^{4}He	**1**	**0.9**	**41.3**	**1.25**
JET #94701 – 3 ions scheme	D	**1**	**3**	**33.6**	**0.68**

- 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

JET plasmas close to ITER conditions: strong transport effects

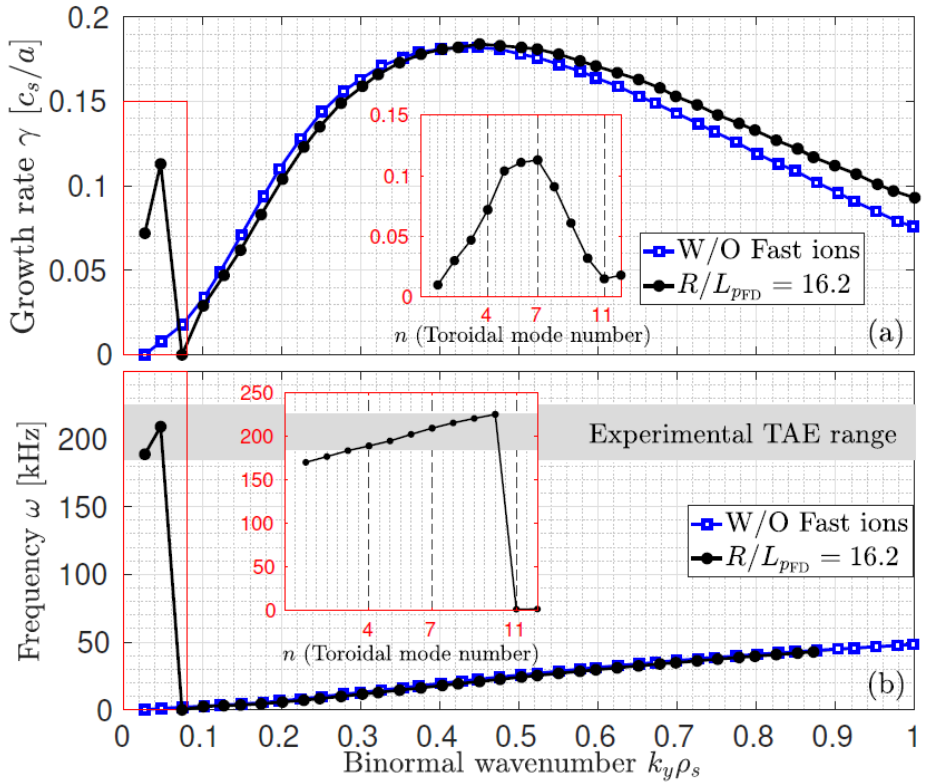




Y. Kazakov NF 2020
M. Nocente NF 2020
V. Kiptily NF 2021

- 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 #94701 → GENE Linear Analysis

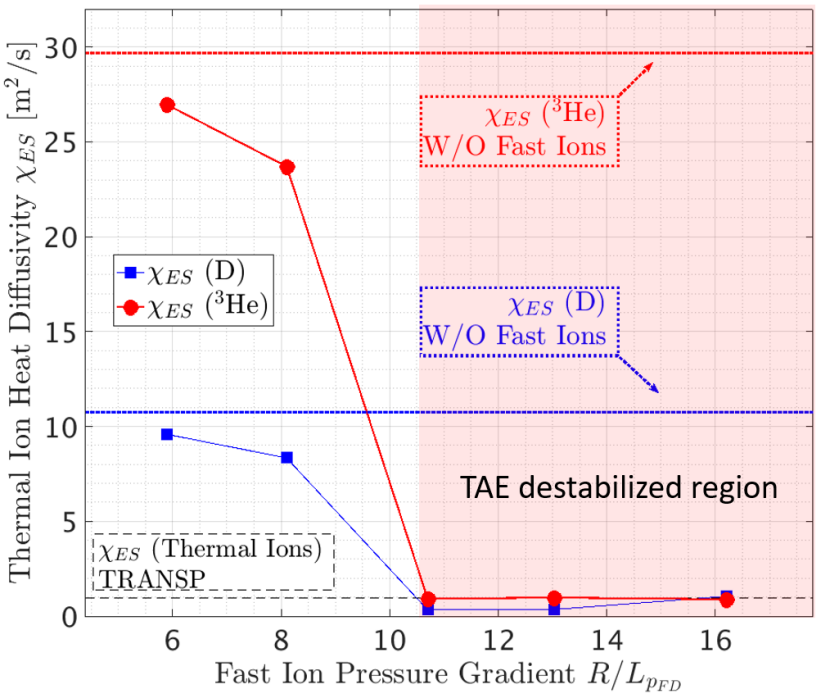


[Mazzi et al. *APS 2020*]
[Mazzi et al. *Submitted.*]

- Unstable modes:
  - ITG → Dominant ion-scale instability
  - FI-driven modes → Low-k_y when $R/L_{p_{FD}}$ > threshold and TAE frequency range

- Unlike previous studies [Garcia NF(2015)], no linear fast-ion effect on ITG → Large T_{FD}/T_i [Di Siena NF(2018)]

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



[Mazzi et al. *APS 2020*]
[Mazzi et al. *Submitted.*]

- $R/L_{p_{FD}} = 10.7$:

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

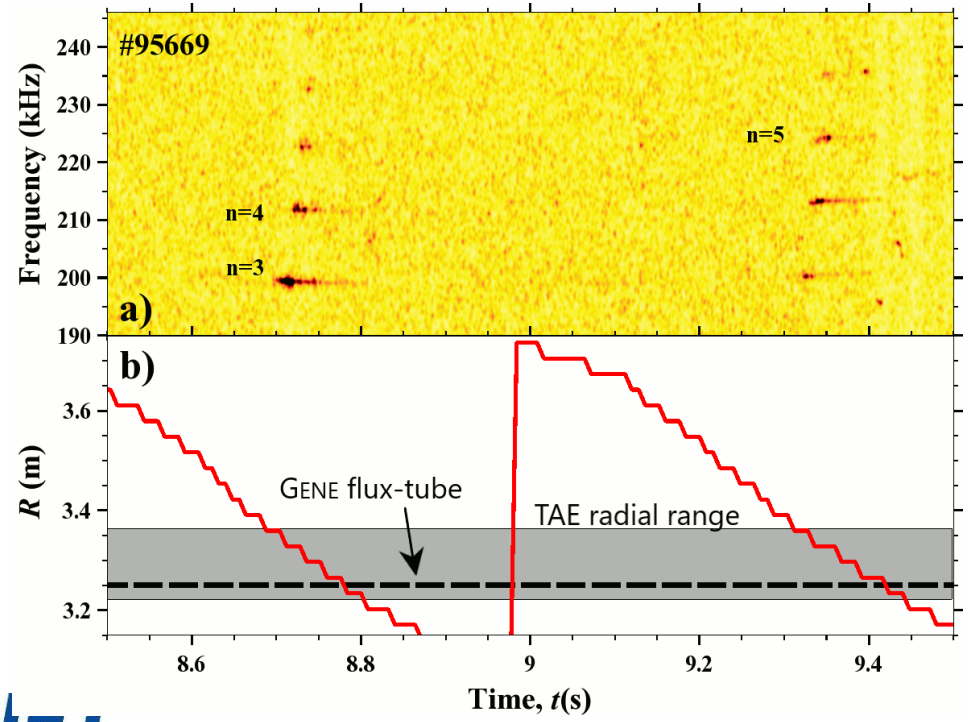
- $R/L_{p_{FD}} = 16.2$:

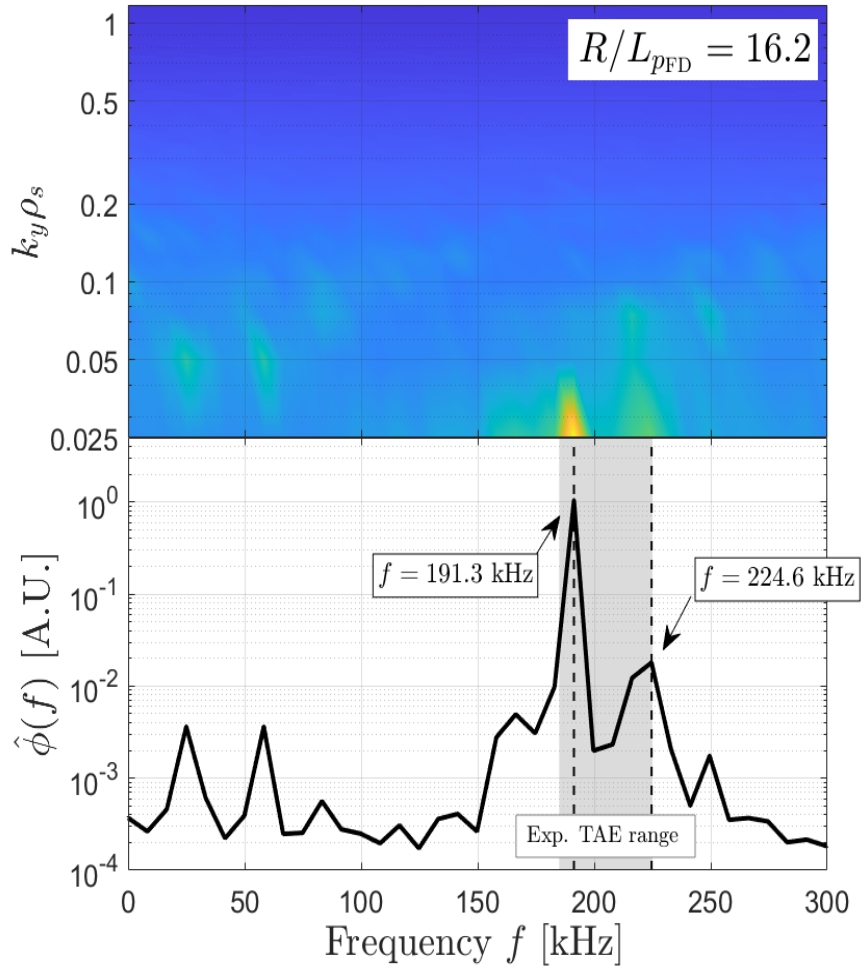
  Suppression of turbulence with fully destabilized TAE, good agreement with power balance from TRANSP

Unlike previous studies: suppression beyond FI-modes threshold → Good experimental agreement!

FI-Mode Identification → TAEs

- Linear simulations → TAE experimental range
- Detected mode frequencies close to Alfvén continuum toroidicity-induced gaps (for $n = 4$ & 7)
- Nonlinear Φ fluctuations for $R/L_{p_{FD}} = 16.2$ (and 10.7) → TAE experimental range
- TAE radial localization by **X-mode reflectometer** → Agreement with GENE radial domain

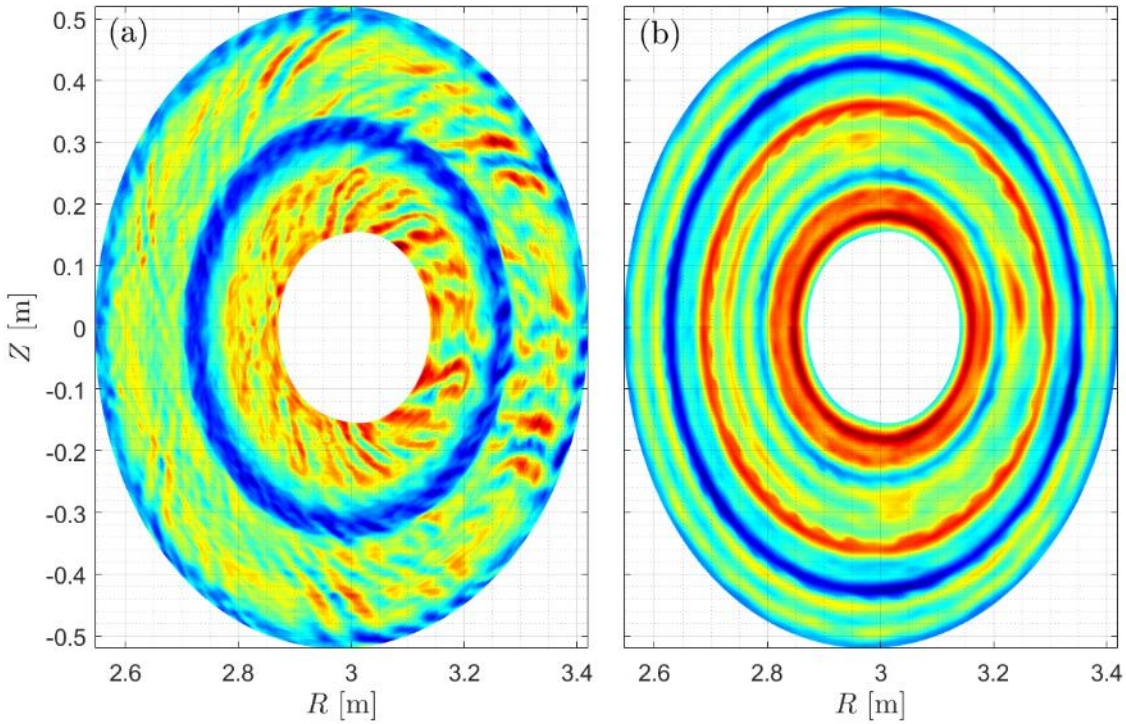




Suppression by Zonal Flows

[Mazzi et al. *APS 2020*]

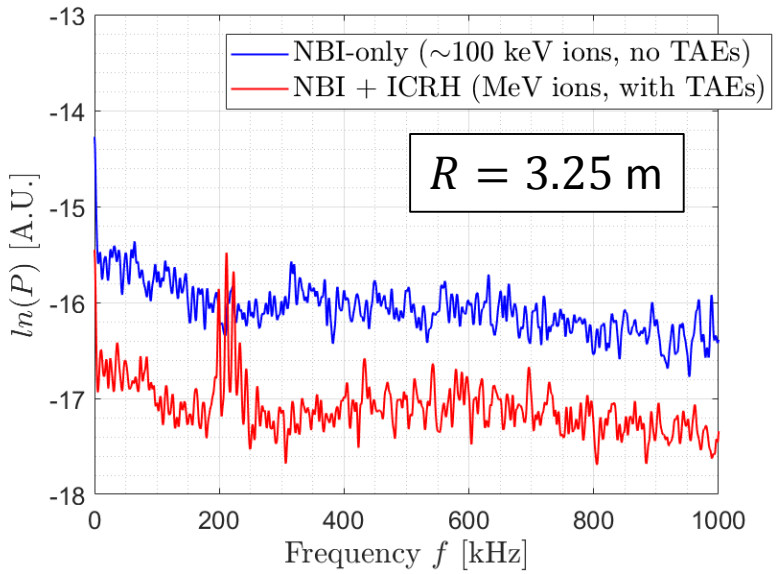
[Mazzi et al. *Submitted*]

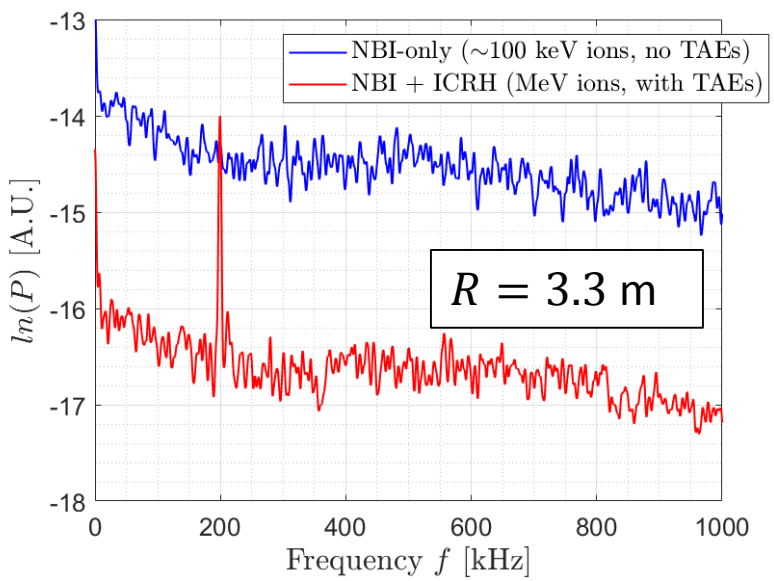


- **No Fast Ions** : small-scale turbulent eddies radially elongated → ITG turbulence
- $R/L_{p_{FD}} = 16.2$: vertical ('poloidal') structures → Zonal Flow activity

ES flux reduction obtained only when TAEs unstable → TAEs nonlinearly trigger Zonal Flows

Density Fluctuation Measurements → Turbulence Reduction with TAEs



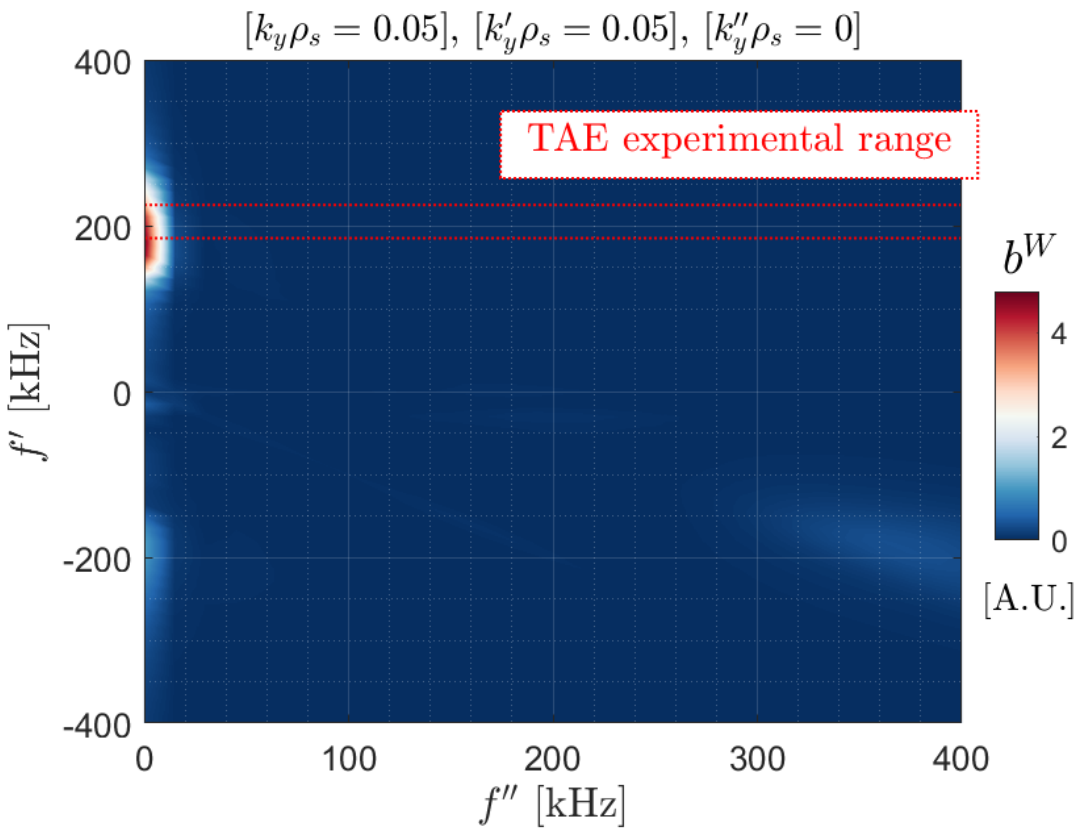


- TAE radially localized with X-Mode Reflectometer: $3.22\ \text{m} < R < 3.36\ \text{m}$
- Inspecting density fluctuation levels with X-Mode Reflectometer in pulse #95569:
  - ➢ <u>Lower amplitude for $f < 100$ kHz with 3-ion scheme</u>
  - ➢ <u>TAE-induced fluctuations for $f \approx 200$ kHz</u>

Measured reduction of density fluctuations when FI-driven TAEs are unstable

Bispectral Analysis → Spatio-Temporal Coupling Between TAE and ZF scales

- Bispectral analysis: Wavelet decomposition [Van Milligen PRL(1995),Zarzoso NF(2017)] of Φ
- Investigating coupling between <u>most destabilized TAE & Zonal modes</u> [Qiu PoP(2016),Todo NF(2010)]
- Nonlinear coupling exists → ZF enhance due to energy transfer from TAE spatio-temporal scales



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Conclusions

- Interplay between experiments, modelling and HPC is essential to understand and predict future plasmas
- Fast ions can reduce or even supress turbulence in plasmas with significant EM effects
- First time experimental evidence supports fluctuations reduction in the presence TAE destabilized by FI
- Expect that alpha particles from DT reactions play a strong role on transport/turbulence
- Will ITER work in DT with very low or even absent core turbulent transport?

Outlook: Still plenty of work to do…

- The validity of the local GK approximation for the interplay between ITG and AE.
- Use of turbulence measurement characteristics for GK simulation validation
- Electron transport in the presence of FI, notably when AE are destabilized.
- Flux driven GK simulations including all the transport requirements
- The role of alpha particles in the so called anomalous ion heating identified in the first DT campaign at JET [Testa NF 2012]

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Ongoing JET-DT campaign is the right test bed for such topics!!