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Suppression of ion-scale turbulent transport by MeV-range fast ions at JET

Motivations & Background

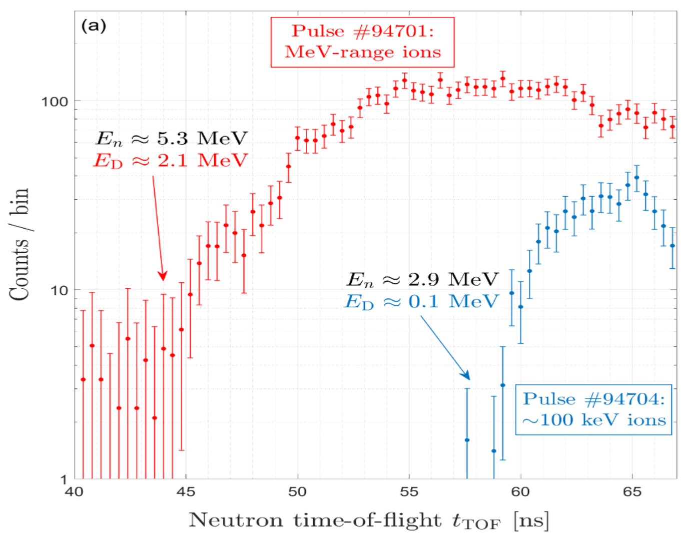
- Well-established beneficial impact of fast ions on Ion-Temperature-Gradient (ITG) turbulence:
  - **Experimentally**: ✓ Improvement of ion confinement in JET L-mode plasmas and subsequently observed in several other devices (also H-mode plasmas)
  - **Numerically**: ✓ Stabilization of ITG turbulent transport due to Fast-Ion-triggered complex mechanism involving enhanced zonal flows [Citrin2013,Zarzoso2013,DiSiena2019] and possible linear resonant mechanisms [DiSiena2018,DiSienaEPS2021] found by gyrokinetic simulations

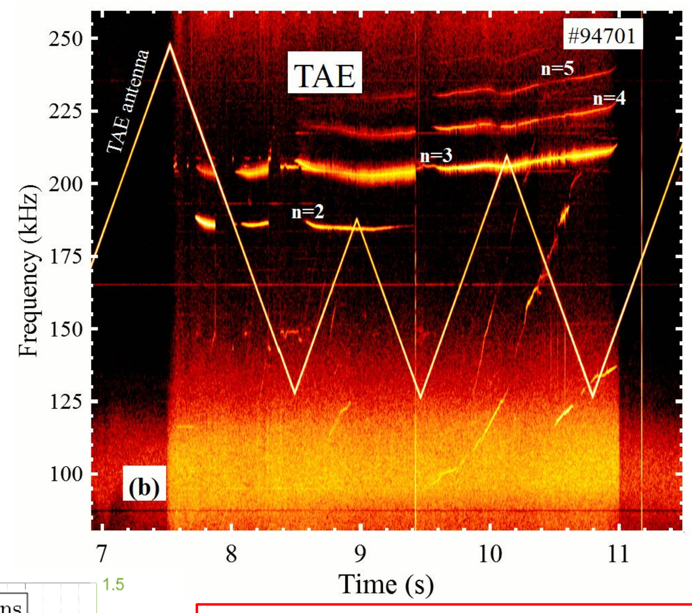
Open question: What will happen in alpha heated plasmas? → Need for ITER-relevant conditions!

Filling the gap towards ITER: 3-ion scheme at JET

- 3-ion heating scheme (ICRH + NBI) applied at JET: generated strong MeV Deuterium tail → Mimicking alphas' energy

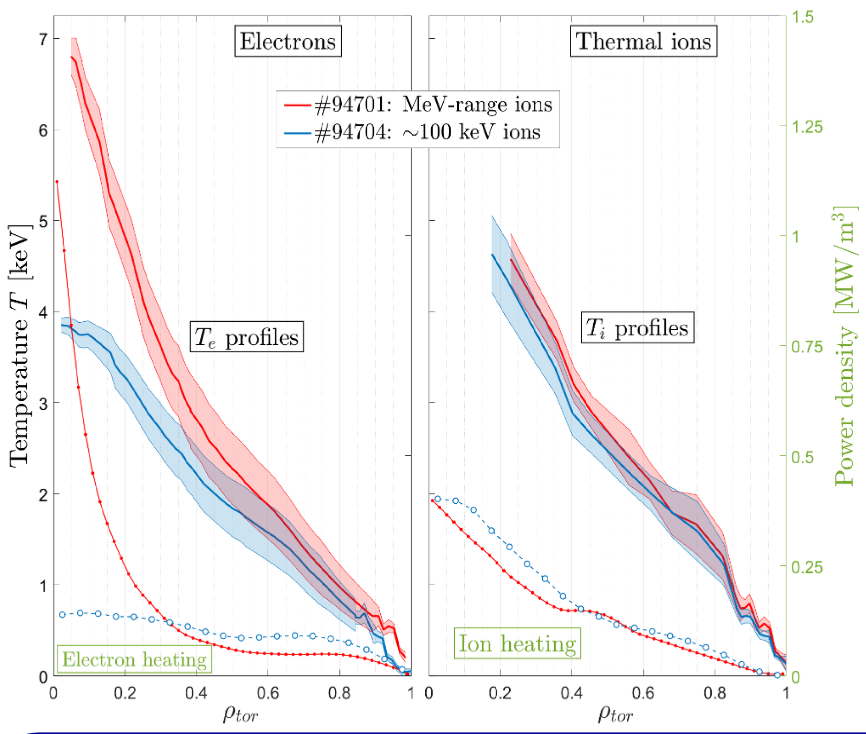
MeV ions effects
- ➢ Destabilizing Alfvén Eigenmodes (AEs)
- ➢ Strong fast-ion to electron heating



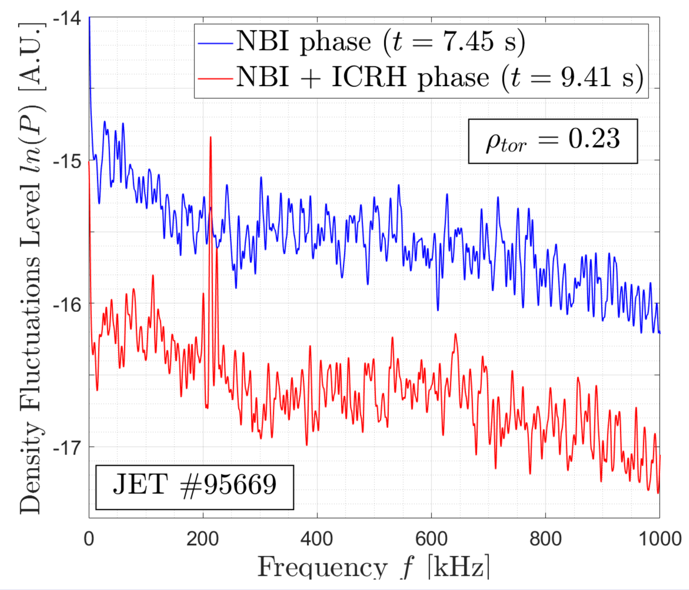


Usually thought to be detrimental for the ion confinement…

[Nocente2020]
[Sahlberg2020]
[Kazakov2021]
[KazakovEPS2021]
[ŠtancarEPS2021]
[Mazzi2020]



… However, diverse experimental indicators show an improved ion confinement and turbulence reduction!



Novelty of the study

- ✓ For the first time: impact of alpha-like fast ions on microturbulence from experimental data
- ✓ Fast ion characteristics closer to alpha modeling of ITER Hybrid Scenario [Garcia2018]
- ✓ Dominant electron heating ($E_{fast} \gg E_{crit}$)
- ✓ Low NBI → Lacking stabilizing ITG mechanisms: ratio T_i/T_e & $E \times B$ shearing
- ✓ Rich variety of AEs unstable

	Previous studies	This study	ITER (alphas)
Fast-ion energies (NBI, ICRH)	O(100keV)	MeV-range	MeV-range
Fast-ion heating channel (collisional)	Ion	Electron	Electron
Destabilized TAEs	No	Yes	(Potentially) Yes

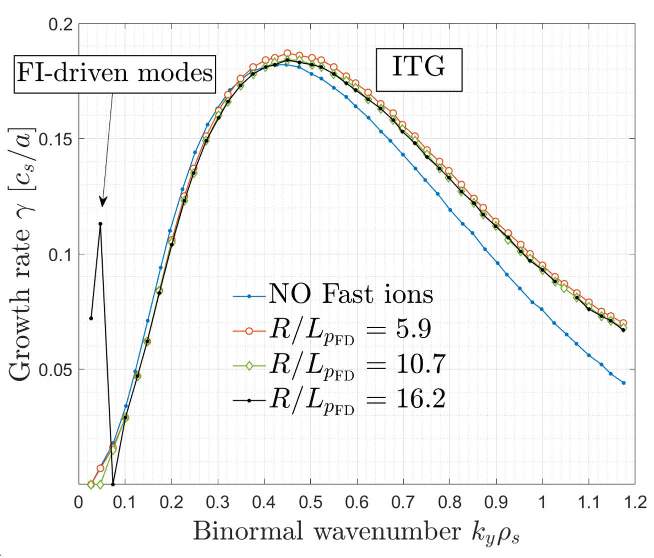
Numerical tools for Modelling JET L-mode #94701

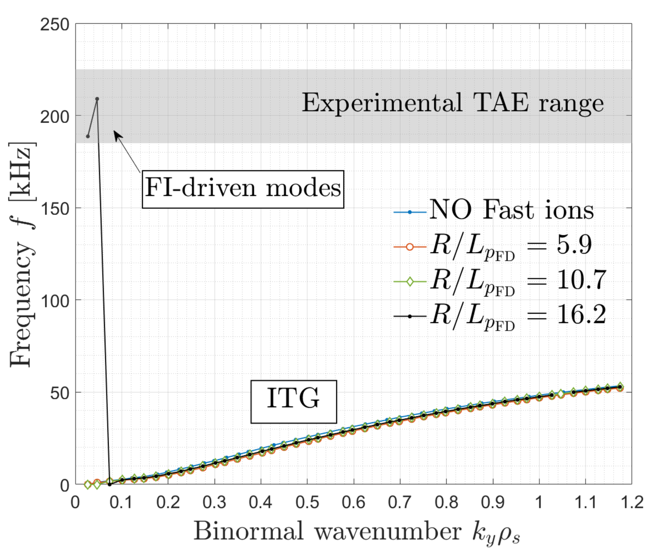
- GENE [Jenko2000] flux-tube simulations
- Integrated modelling: TRANSP
- @ $\rho_{tor} = 0.23$
  - ✓ Reliable exp. measurements
  - ✓ Strong presence of fast ions & TAEs
- $q = 1.1$ & $\hat{s} = 0.63$ (from MHD markers)

- Including:
  - ✓ Kinetic electrons
  - ✓ Electromagnetic ($\delta B_{||}$ & $\delta B_{\perp}$)
  - ✓ Collisions
  - ✓ Realistic geometry
- Equivalent Maxwellian fast-ion distribution function

Very demanding setup:
$(n_x = 256, n_y = 48,$
$n_z = 32, n_{v_{||}} = 48,$
$n_\mu = 64)$
with $k_{y,min} = 0.025$

Linear stability analysis

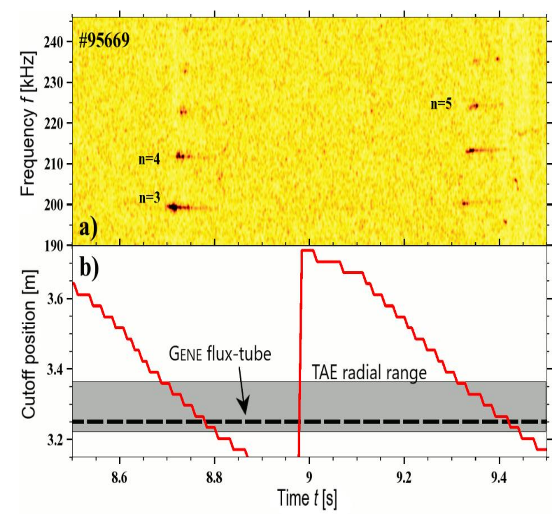




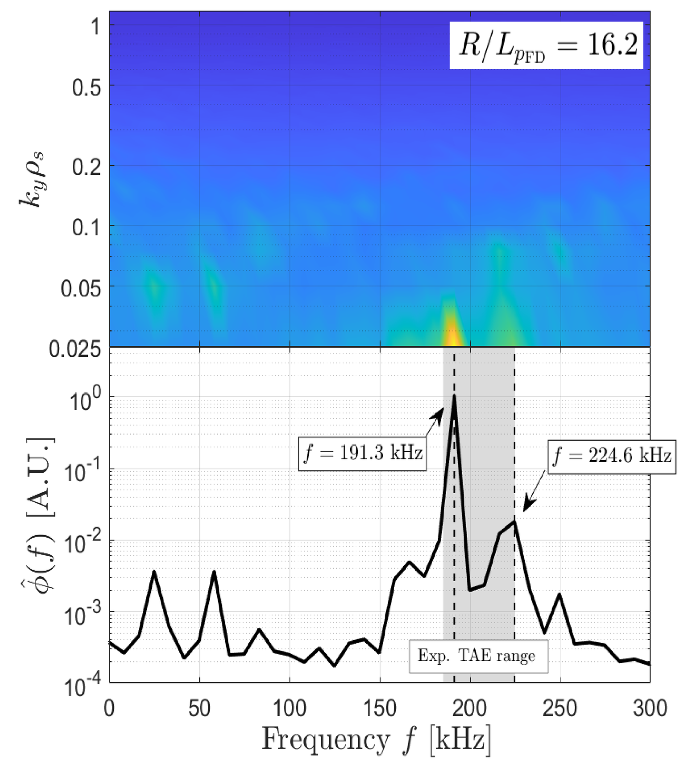
Unstable modes:
- ➢ ITG → Dominant ion-scale instability
- ➢ FI-driven modes → Low-k_y when $R/L_{p_{FD}}$ > threshold & TAE frequency range

- Unlike previous studies [DiSiena2018] no linear fast-ion effect on ITG

Fast Ion mode identification: TAEs



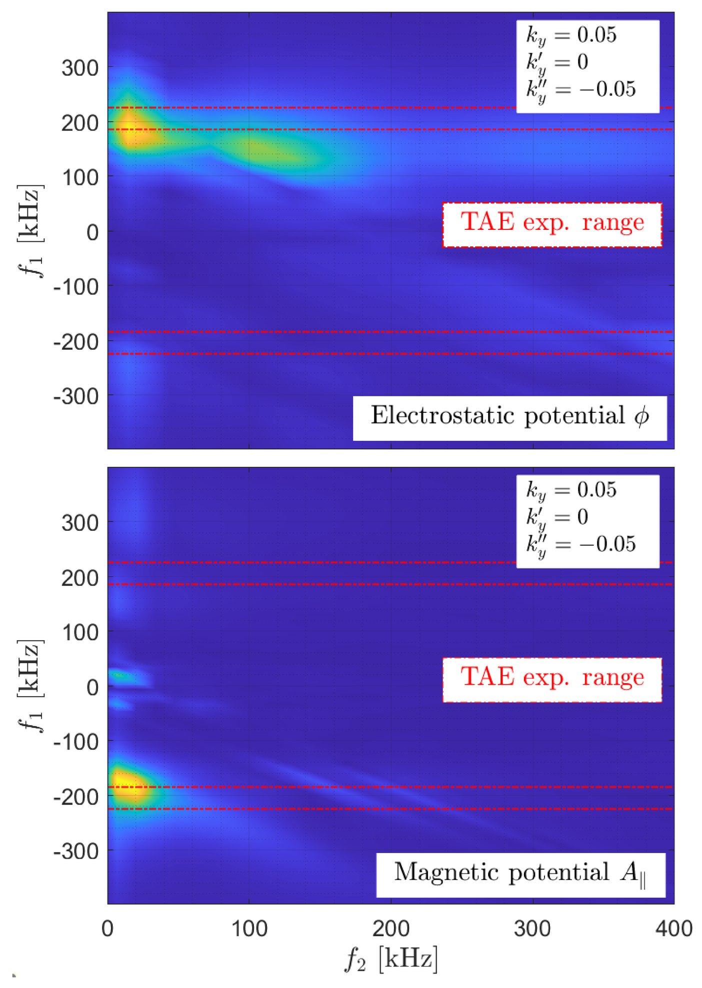
- Linear simulations → TAE experimental range
- Detected mode frequencies close to Alfvén continuum toroidicity-induced gaps (for $n = 4$ & 7)
- Nonlinear Φ fluctuations for $R/L_{p_{FD}} = 16.2$ → TAE experimental range



- TAE radial localization by **X-mode reflectometer** → Agreement with GENE radial domain

The unstable mode in numerical analyses has been identified as fast-ion driven TAE

Ion-scale turbulence suppression via complex mechanism



- Bispectral analysis: Wavelet decomposition [Meneveau1991,Hudgins1993] of both Φ & $A_{||}$ (Ξ refers to Φ & $A_{||}$)

$$W_{\Xi_{k_x,k_y}}(\omega,t) = \int_R \Xi_{k_x,k_y}(\tau)\Psi_\omega(\tau - t)d\tau$$

- Morlet wavelet function: $\Psi_\omega(t) = \sqrt{\frac{\omega}{2\pi}}e^{i\omega t}e^{-\frac{1}{2}\left(\frac{\omega t}{2\pi}\right)^2}$
- Wavelet bispectrum is defined as:

$$b^W(\omega_1,\omega_2) = \int dt \left(W_{\Xi_{k_x,k_y}}(\omega,t)\right)^{cc} \sum_{k_x} W_{\Xi_{k'_x,k'_y}}(\omega_1,t) W_{\Xi_{k''_x,k''_y}}(\omega_2,t)$$

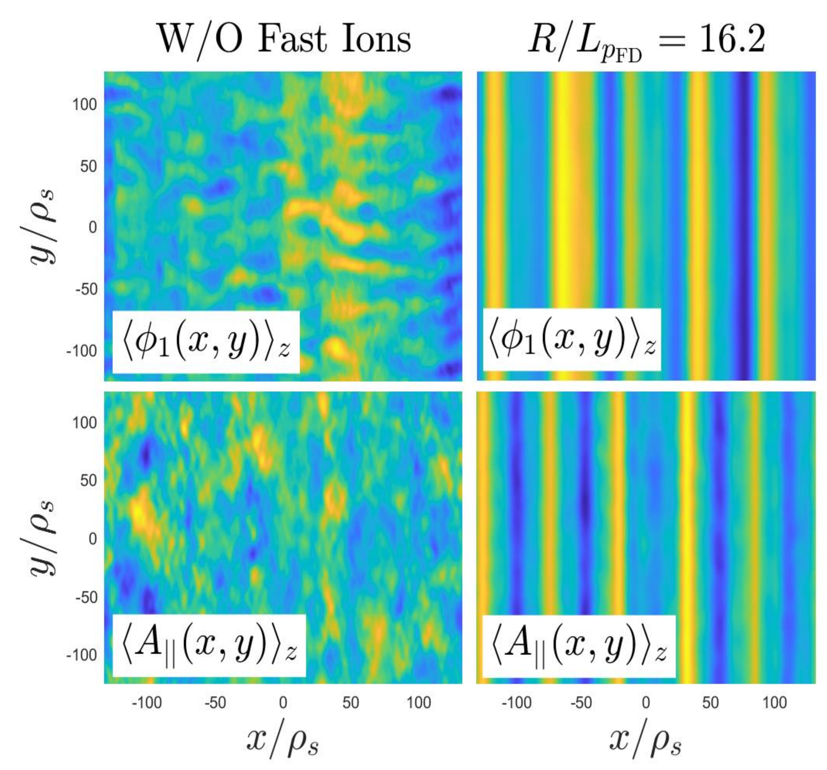
- Analyzed triplets:
  - ➢ $(k_y, k_x) = (k_{y,TAE}, k_{x,TAE})$
  - ➢ $(k'_y, k'_x) = (0, a)$
  - ➢ $(k''_y, k''_x) = (-k_{y,TAE}, -a)$

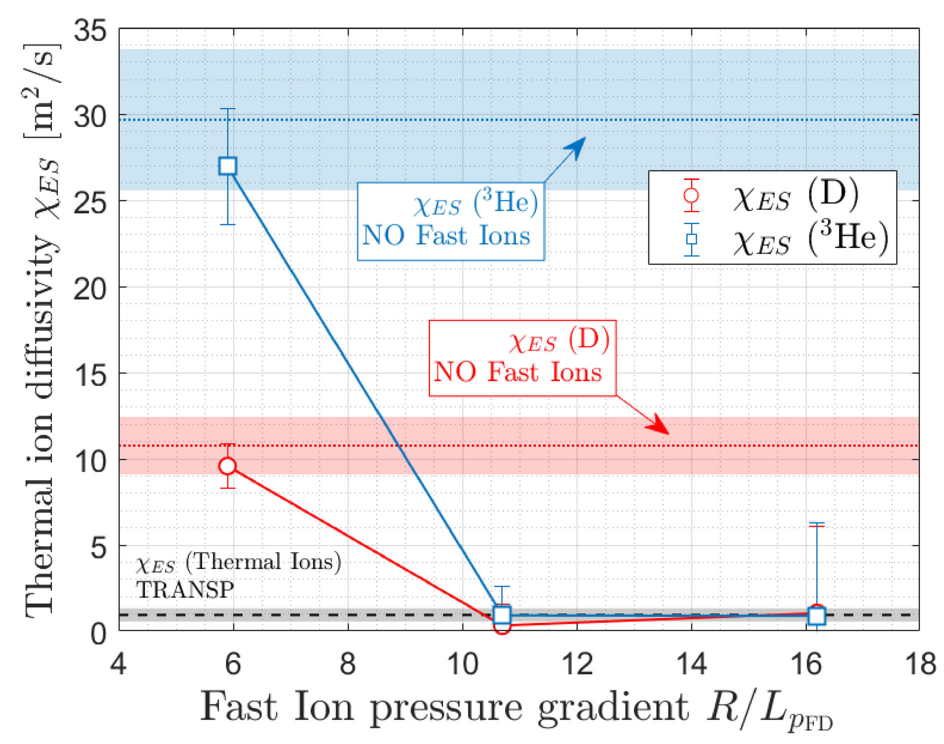
Strong spatio-temporal nonlinear coupling between TAE and Zonal modes

[Qiu2016,Todo2010]

- Electrostatic fluxes of thermal species are suppressed only when TAEs are driven unstable → Nonlinearly triggered Zonal Flows act as a strong suppression mechanism of ion-scale turbulence
- Good agreement with the TRANSP power balances [Mazzi2020]

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

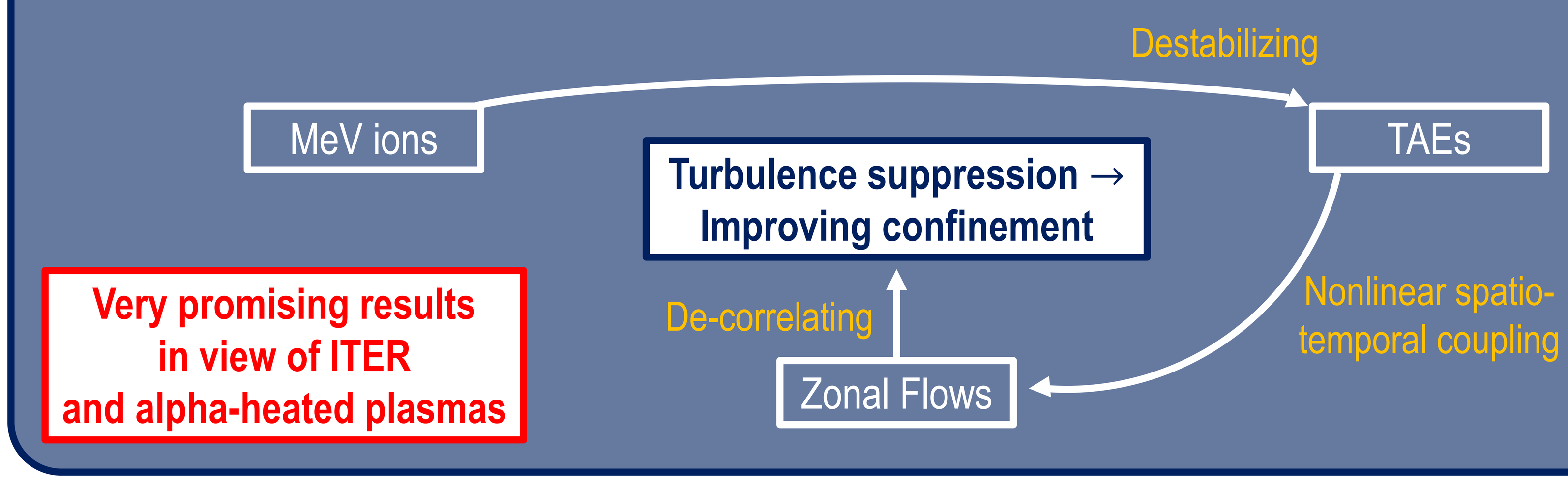




- Although strong magnetic flutter and dominant electron heating → Electron confinement do not degrade ($\chi^{el}_{EM} = 3.1\ \mathrm{m}^2/\mathrm{s}$)
- Concurrently with electromagnetic transport mitigation: onset of Zonal Field structures

Conclusions

Towards the frontier of the fusion experiments in present fusion devices → Crucial predictions for ITER



References

[Citrin2013]: J. Citrin *et al.*, *Phys. Rev. Lett.* 111(15), 155001 (2013)
[DiSiena2018]: A. Di Siena *et al.*, *Nucl. Fusion* 58(5), 054002 (2018)
[DiSiena2019]: A. Di Siena *et al.*, *Nucl. Fusion* 59 (12), 124001 (2019)
[DiSienaEPS2021]: A. Di Siena *et al.*, this conference – I3.105
[Garcia2018]: J. Garcia *et al.*, *Phys. Plasmas* 25(5), 055902 (2018)
[Hudgins1993]: L. Hudgins *et al.*, *Phys. Rev. Lett.* 71(20), 3279 (1993)
[Jenko2000]: Jenko *et al.*, *Phys. Plasmas* 7(5), 1904-1910 (2000)
[Kazakov2021]: Y. Kazakov *et al.*, *Phys. Plasmas* 28(2), 020501 (2021)
[KazakovEPS2021]: Y. Kazakov *et al.*, this conference – I3.104
[Mazzi2020]: S. Mazzi *et al.*, *Submitted to Nat. Phys.* (2020)
[Meneveau1991]: C. Meneveau, *J. Fluid Mech.* 232, 469-520 (1991)
[Nocente2020]: M. Nocente *et al.*, *Nucl. Fusion* 60(12),124006 (2020)
[Qiu2016]: Z. Qiu *et al.*, *Phys. Plasmas* 23(9), 090702 (2016)
[Sahlberg2021]: A. Sahlberg *et al.*, *Nucl. Fusion* 61(3) 036025 (2021)
[ŠtancarEPS2021]: Ž. Štancar *et al.*, this conference – O4.108
[Todo2010]: Y. Todo *et al.*, *Nucl. Fusion* 50(8), 084016 (2010)
[Zarzoso2013]: D. Zarzoso *et al.*, *Phys. Rev. Lett.* 110, 125002 (2013)

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