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Turbulent transport at the pedestal top of small-ELM plasmas at JET: key mechanisms and their impact

M. Dicorato

M. Muraglia, Y. Camenen, J. Garcia, X. Garbet, D. R. Hatch, G. Merlo, E. de la Luna, Ž. Štancar, L. Garzotti, V.K. Zotta, F. Rimini, D. Frigione, and JET Contributors

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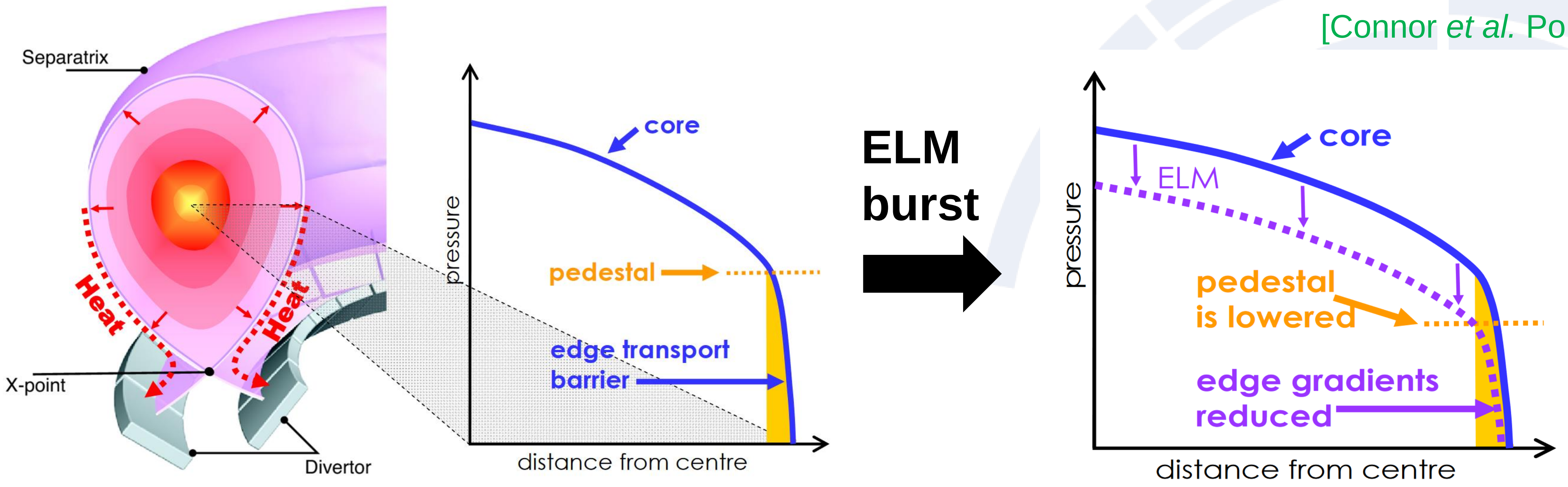
Pedestal in H-mode plasma regime

[Connor *et al.* PoP2008]



H-mode plasma regime [Wagner *et al.* PRL1982]

I. Formation of an edge transport barrier leading to a "**pedestal**"
II. Edge dynamics regulated by edge-localized modes (**ELMs**) determining release of energy and particles [Zohm PPCF1996]

Transport in the pedestal

Pedestal structure set by different *time-scales* process [Snyder *et al*. NF2011, Groebner and Saarelma PPCF2023]

I. MHD stability for **ELMs** onset

II. Transport mechanisms [Kotschenreuther *et al*. NF2019]

→ Instability: **EM** – kinetic-ballooning modes (**KBM**), micro-tearing modes (**MTM**);
ES – ion&electron-temperature gradient (**ITG/ETG**) modes, trapped-electron modes (**TEM**) [Hatch *et al*. NF2015, NF2016, NF2017, NF2019]

→ Turbulence saturation: $\boldsymbol{E} \times \boldsymbol{B}$ **shearing** (equilibrium and self-regulation), electromagnetic effects [Scott PPCF2007], …

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In this work, **JET-Be/W** plasmas in *different* **ELMy** regimes with *different* **pedestal structures** [Garcia *et al*. PoP2022]
⇒ **I.** Drastic change in **stability**
⇒ **II. Saturation mechanisms** identified

Method: local gyrokinetic simulations **GENE** [Jenko *et al*. PoP2000]

Experimental setup [Garcia *et al*. PoP2022, de la Luna *et al.* submitted]

Baseline scenario: $q_{95} = 3.2,\ H_{98} \sim 1$

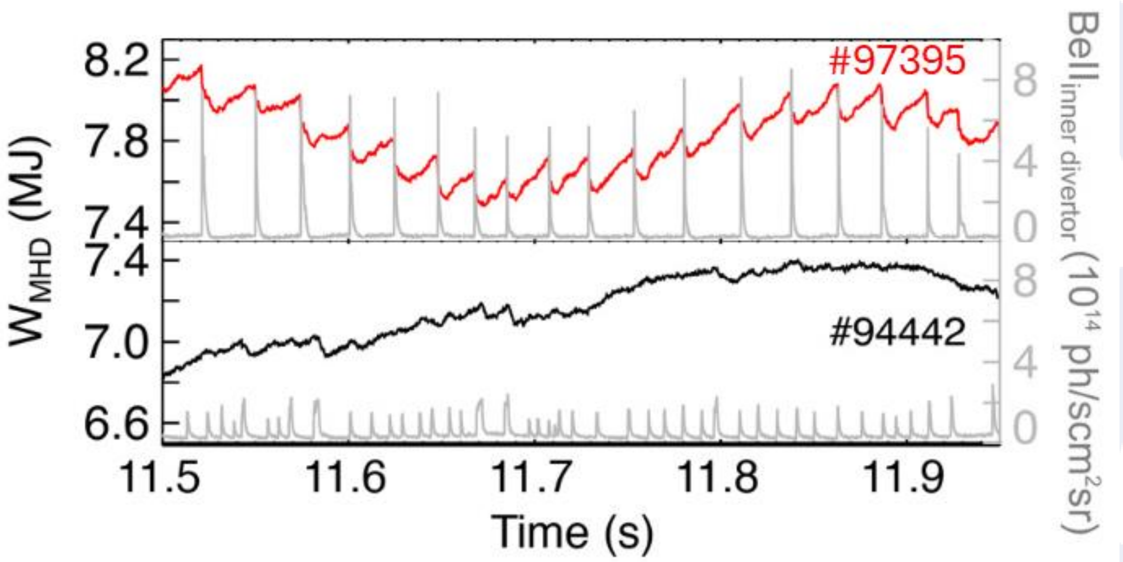
Deuterium plasmas with different P_{NBI} and

$$\boldsymbol{I_p} = 3\ MA\ \ \boldsymbol{B_t} = 2.8\ T\ \ \boldsymbol{P_{ICRH}} = 4\ MW$$

- **Type-I ELMs #97395 –** $P_{tot} = 32\ MW$
  → **with** *low* gas puffing

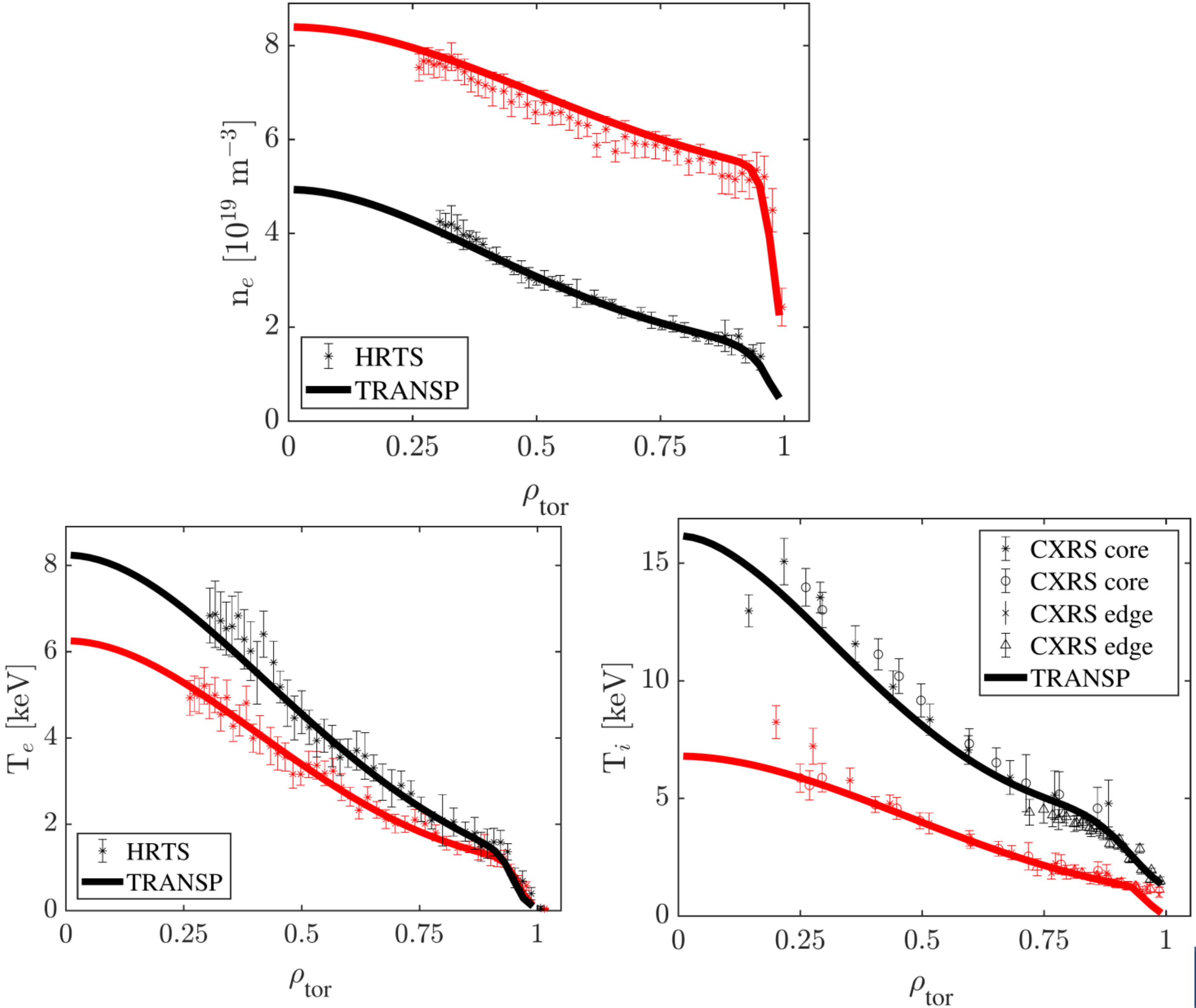
- **Small-ELMs #94442 –** $P_{tot} = 21\ MW$
  → **without** gas puffing

→ Particle source key parameter to access
Baseline small-ELMs regimes



Pedestals in JET: type-I ELMs vs. small-ELMs [Garcia *et al.* PoP2022]

Type-I ELMs: #97395 | small-ELMs: #94442



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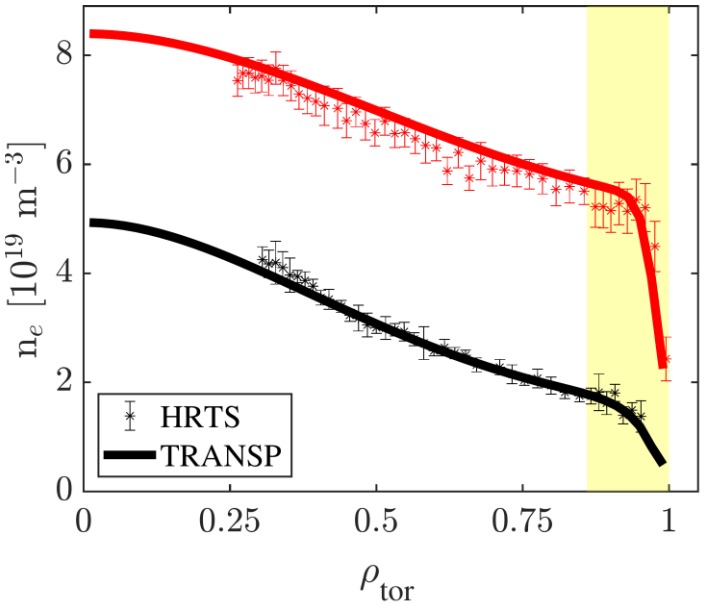

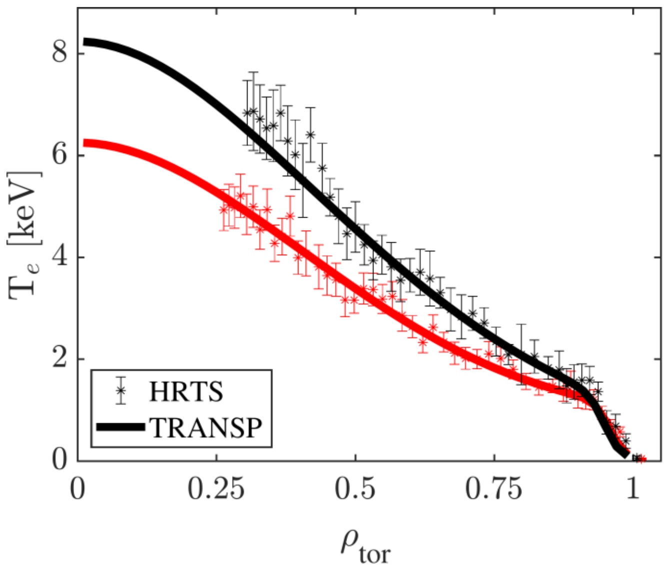

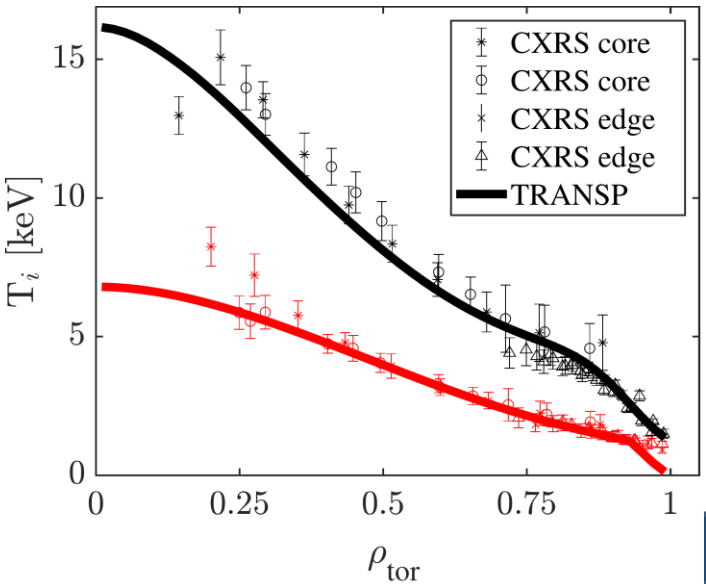

- **Density**

→ **type-I ELMs** has higher pedestal w.r.t. **small-ELMs** with wider and lower pedestals

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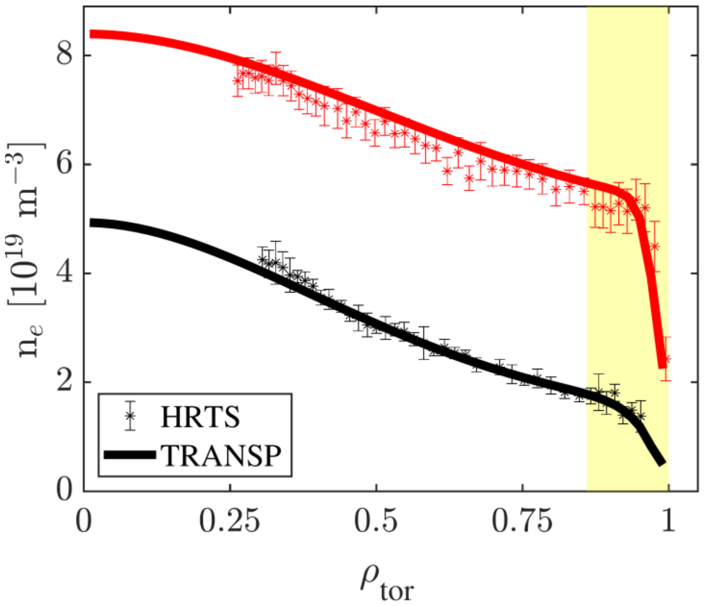

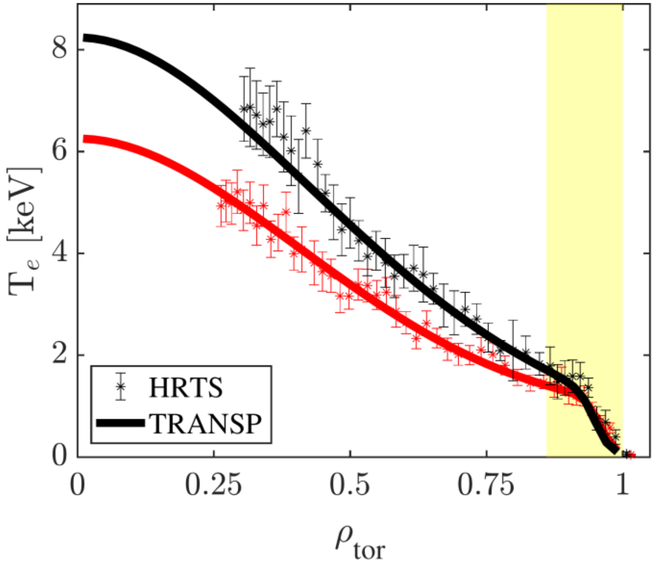

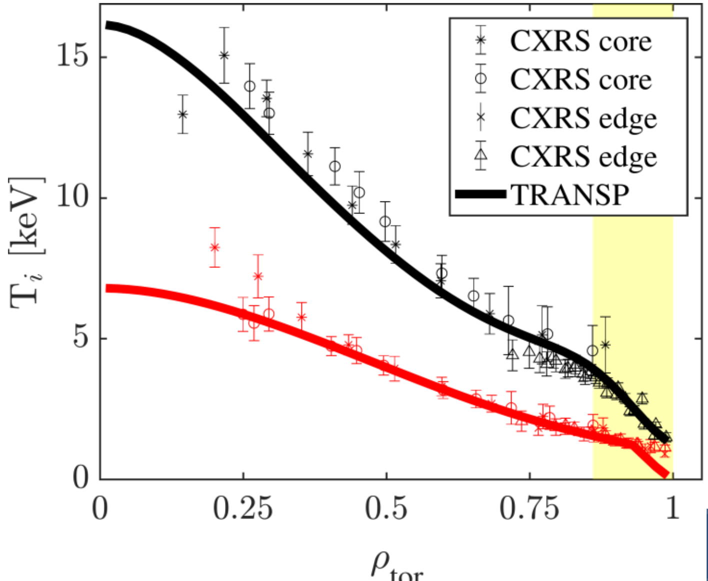

- **Density**
→ **type-I ELMs** has higher pedestal w.r.t. **small-ELMs** with wider and lower pedestals

- **Temperature**
→ electron pedestals are similar; ion pedestals are higher in **small-ELMs** regime

Baseline **JET-Be/W** shots in *different* **ELMy** regimes
→ *Different* **pedestal structures**

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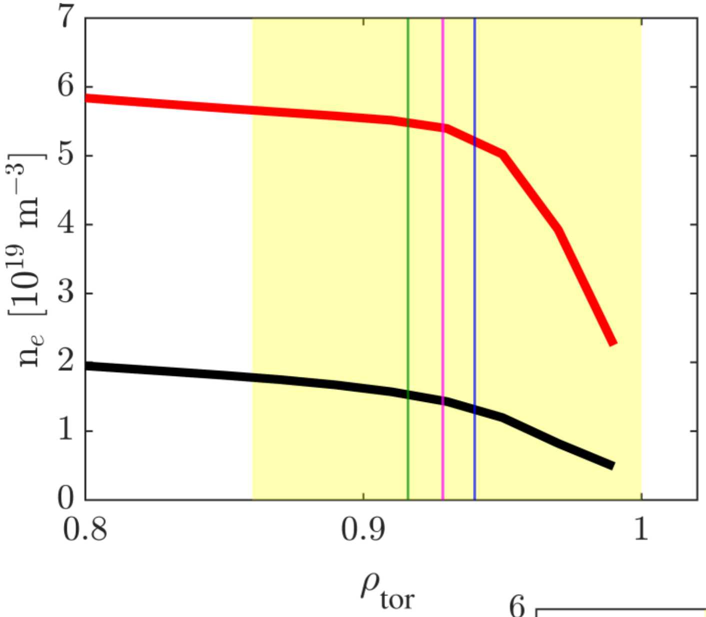

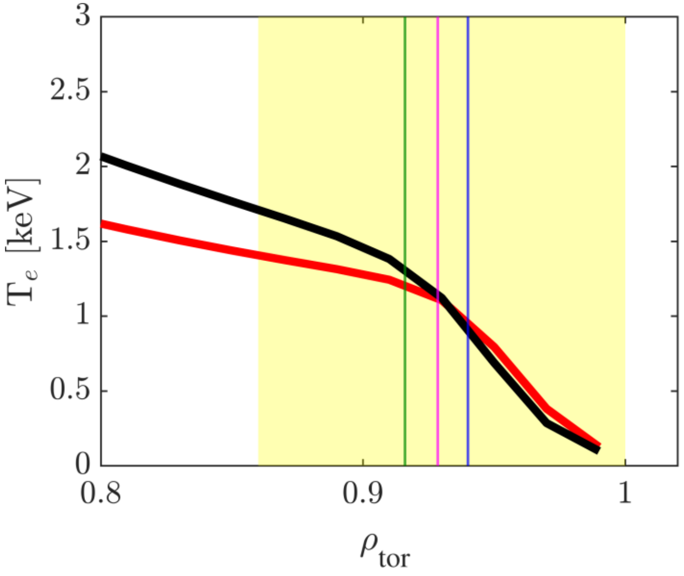

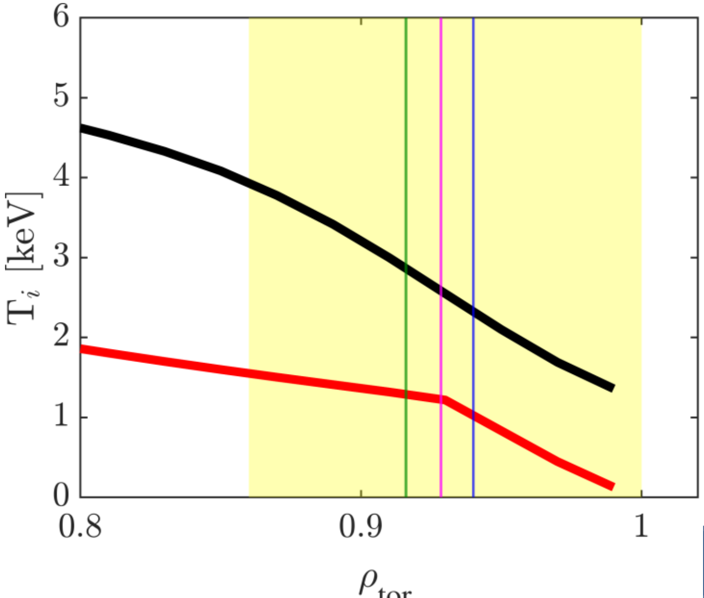

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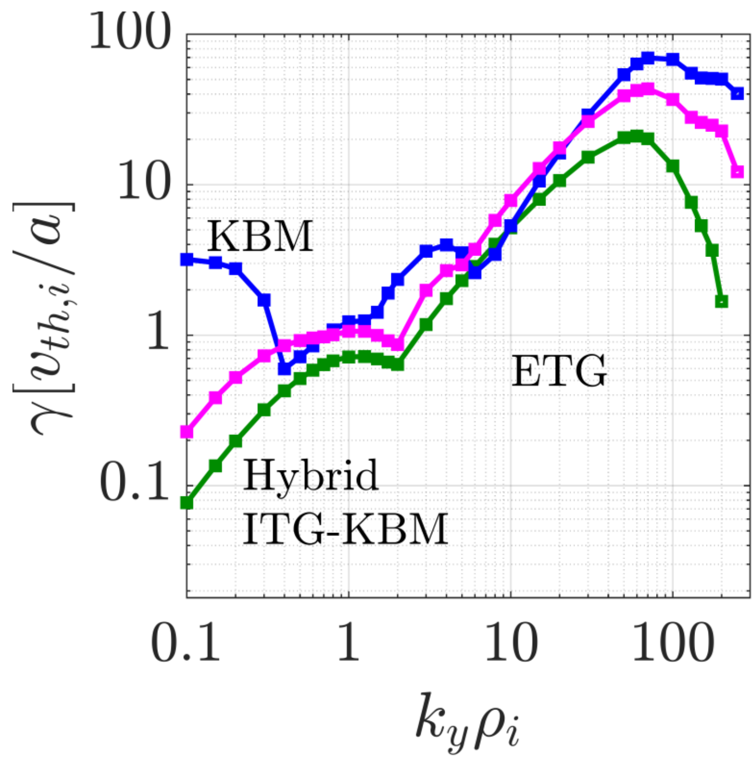
Baseline **JET-Be/W** shots in *different* **ELMy** regimes
→ *Different* **pedestal structures**

$r = 0.91$	$r_{top} = 0.93$	$r = 0.94$

Stability of JET pedestals

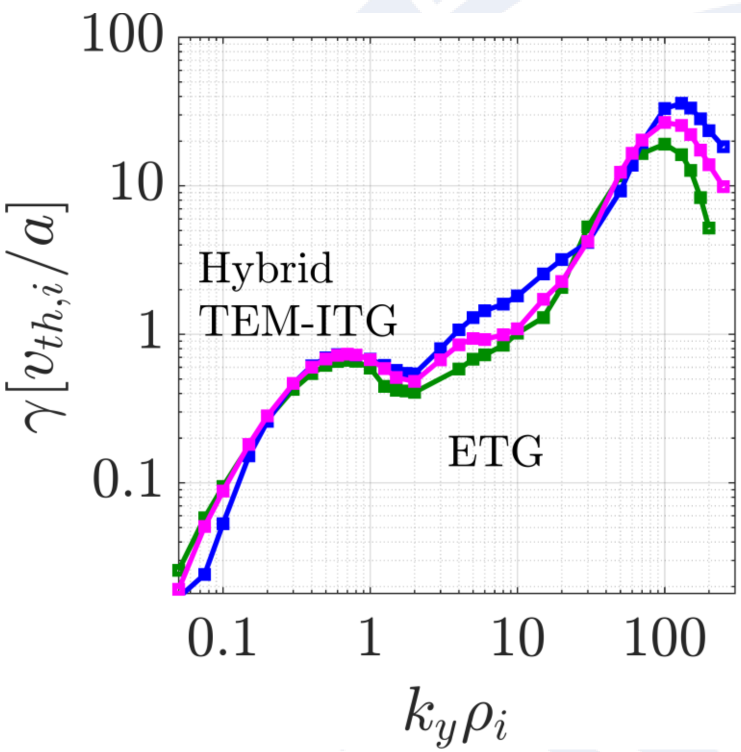
Type-I ELMs: #97395



<u>Ion-scale</u>

hybrid **ITG-KBM** and **KBM**

small-ELMs: #94442



<u>Ion-scale</u>

hybrid **TEM-ITG** w/o **KBM**

⇒ lower β_e [Dicorato *et al*. JPCS2022]

<u>Electron-scale:</u> **ETG** [Parisi *et al*. NF2020, NF2022]

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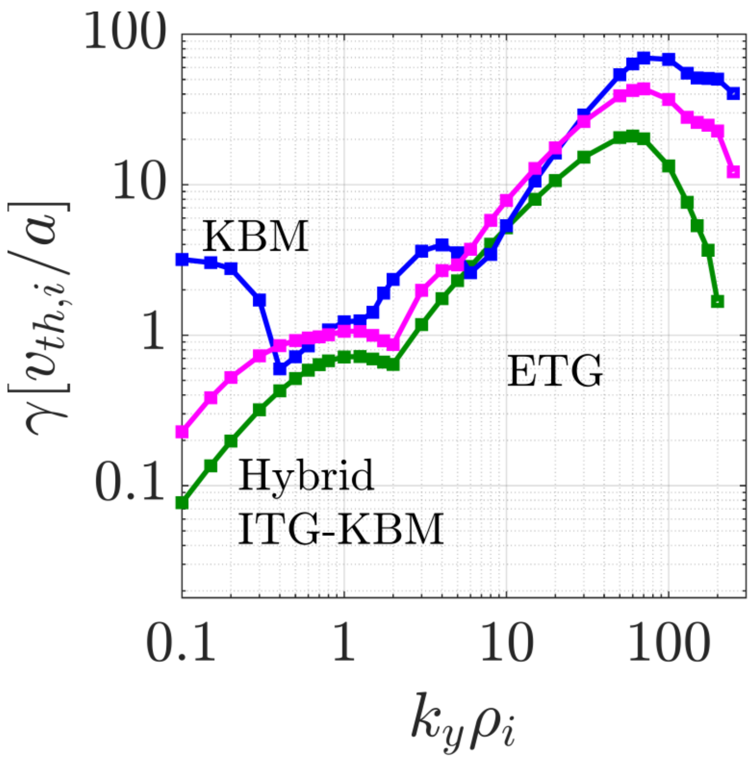

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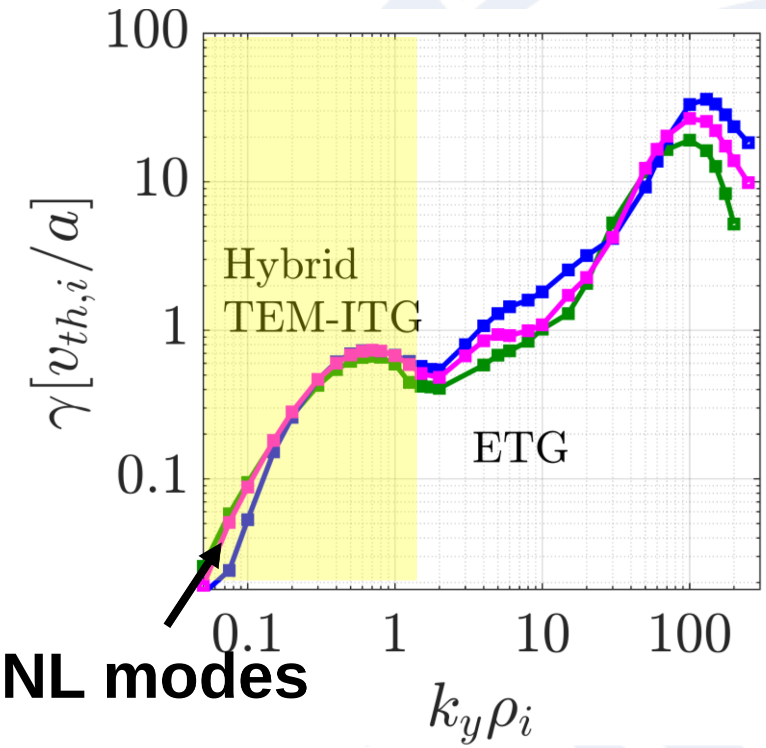

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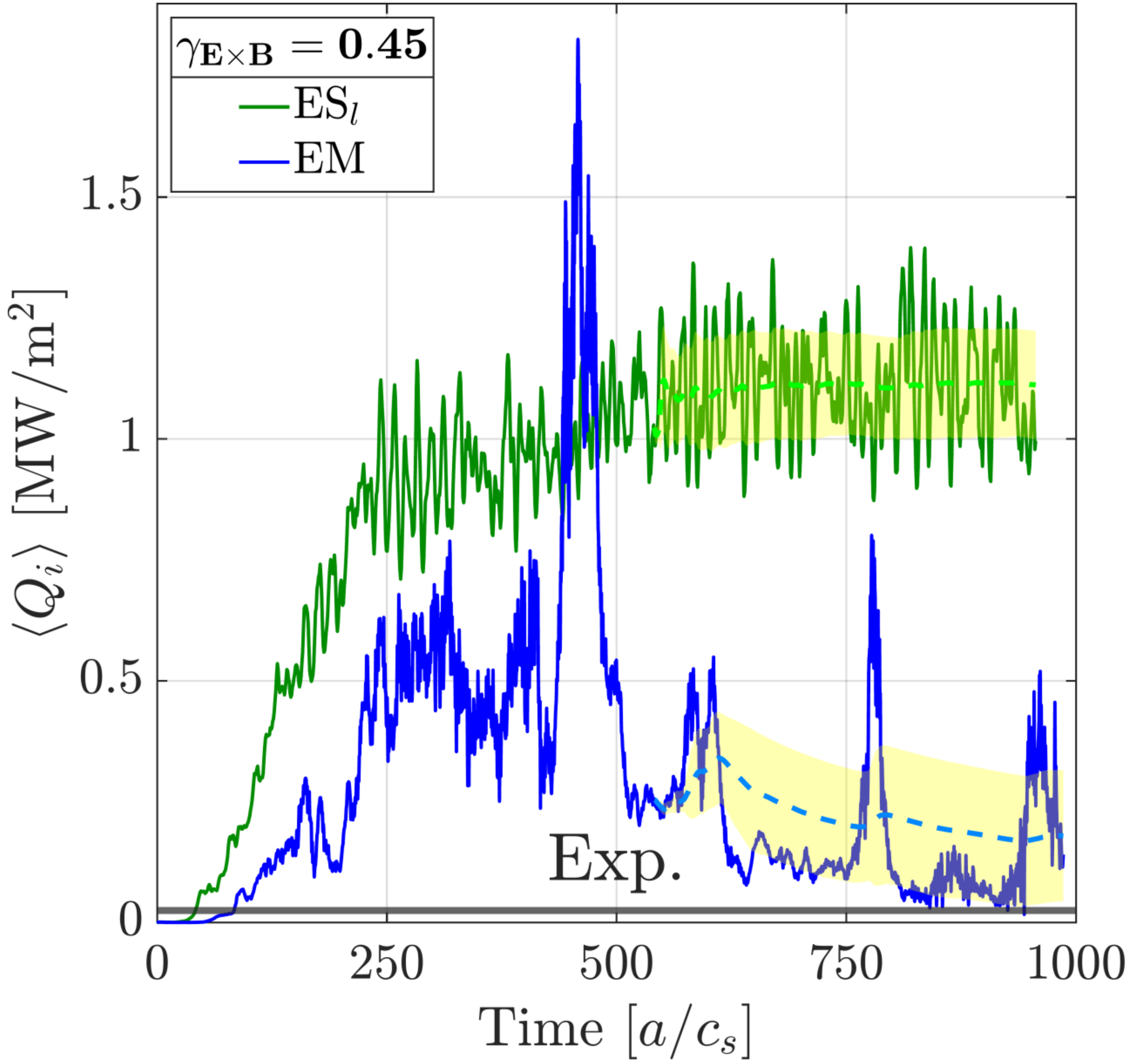
Small-ELMs – Non-linear Electromagnetic stabilization

r_{top}



Electrostatic vs. Electromagnetic

- **Equilibrium** $\boldsymbol{\gamma_{E\times B}}$: toroidal rotation + ∇p

  $\rightarrow$ nominal: $\boldsymbol{\gamma_{E\times B}} = 0.45$

- Heat flux, mainly $\boldsymbol{E} \times \boldsymbol{B}$ advection

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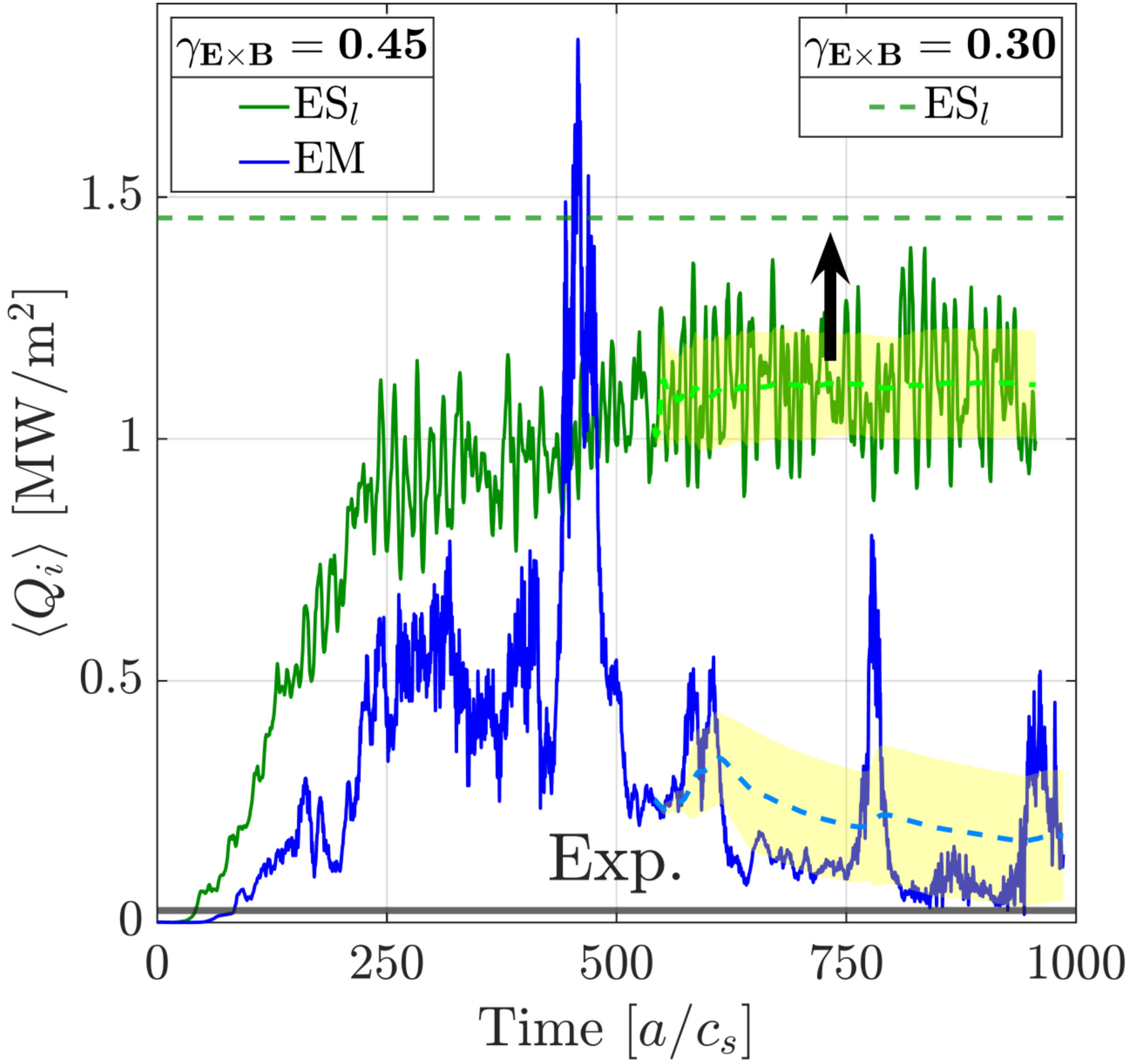

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Reducing the equilibrium $\boldsymbol{\gamma_{E\times B}}$ by 30%

$\Rightarrow$ **ES** increases

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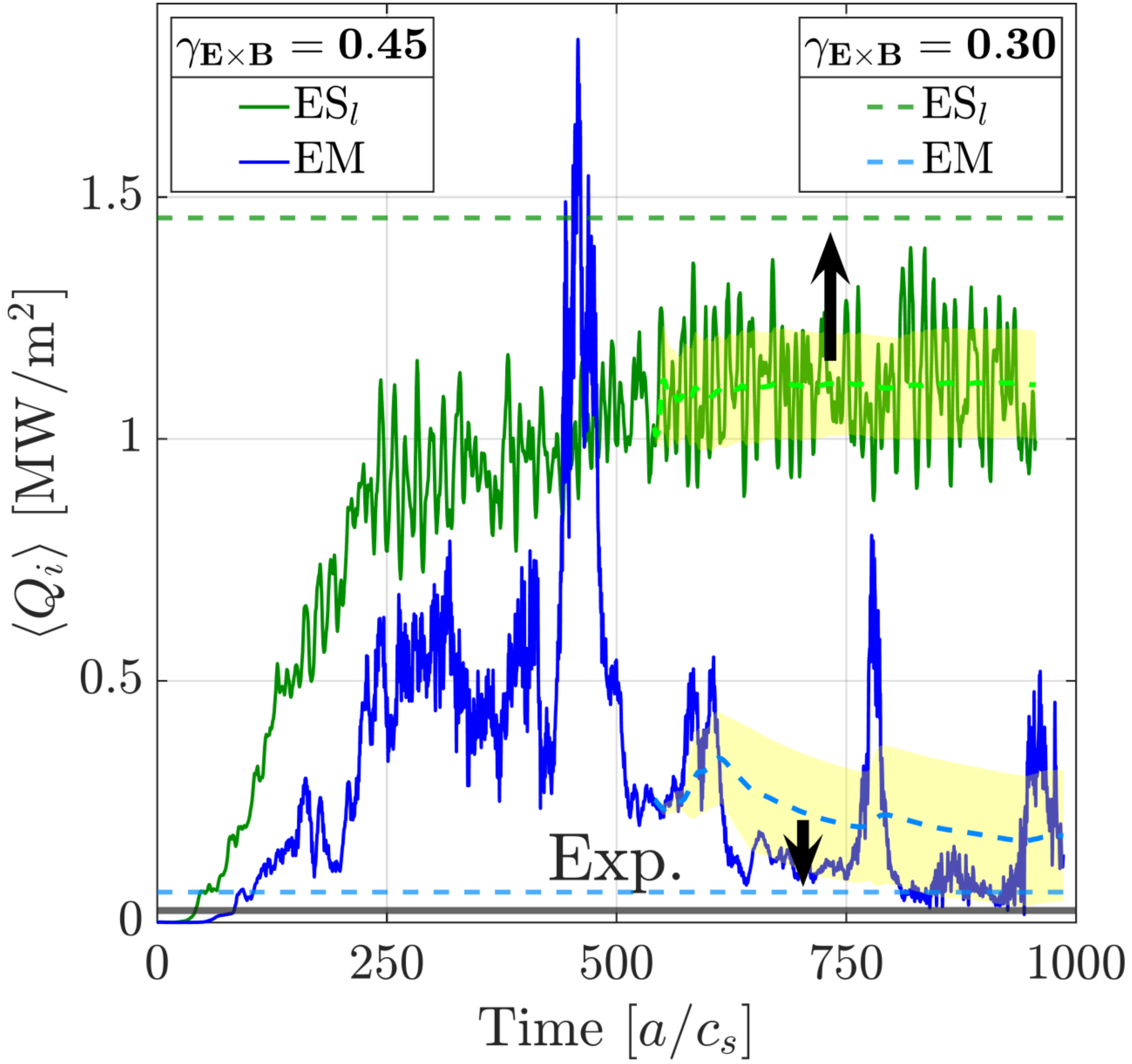

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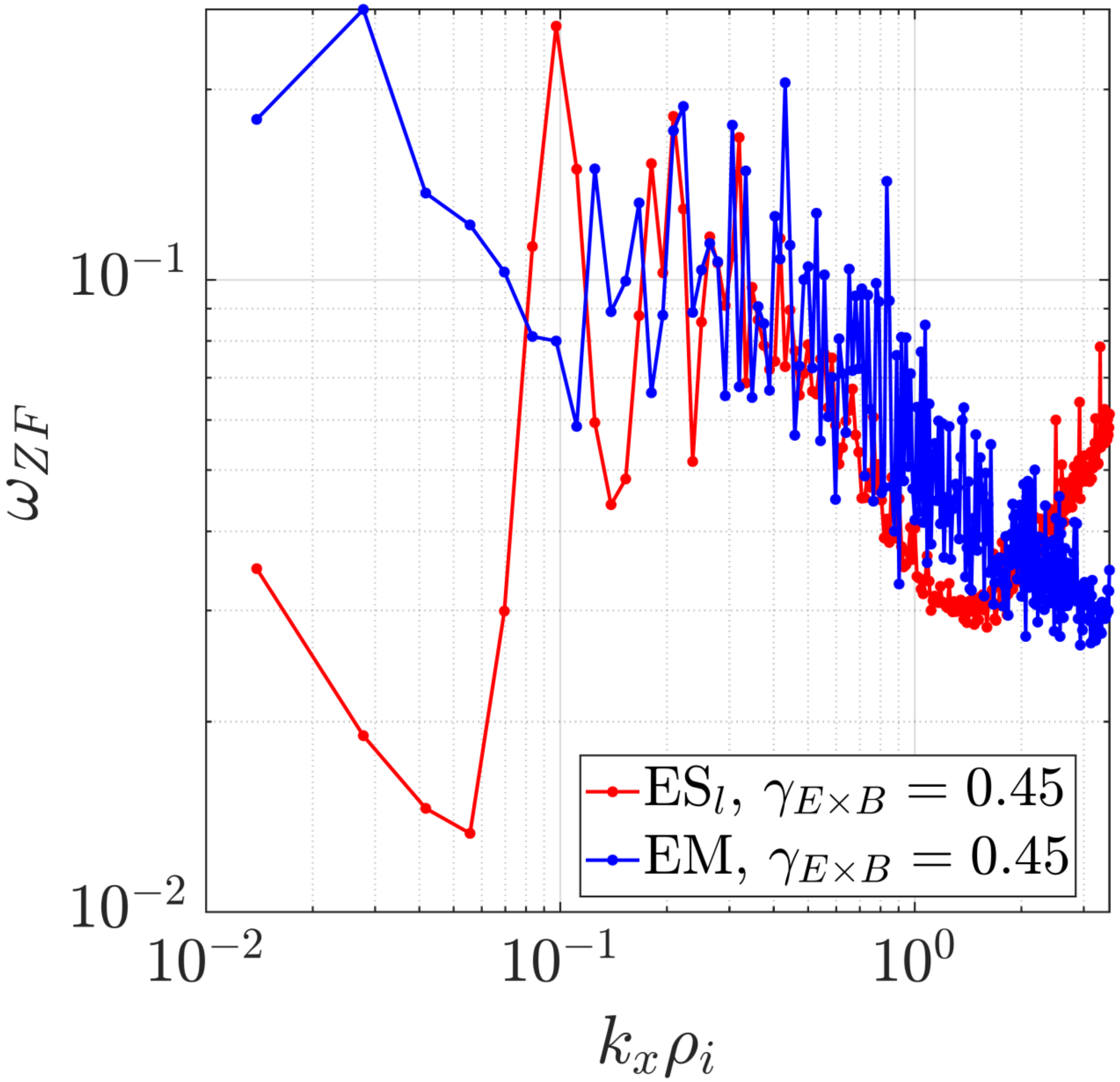
Reducing the equilibrium $\gamma_{E\times B}$ by 30%

$\Rightarrow$ **ES** increases

$\Rightarrow$ **EM decreases!**

Interplay $\gamma_{E\times B}$ + EM stabilization
$\Rightarrow$ *decisive* for reaching experimental transport level

Small-ELMs – Electromagnetic enhanced Zonal Flows

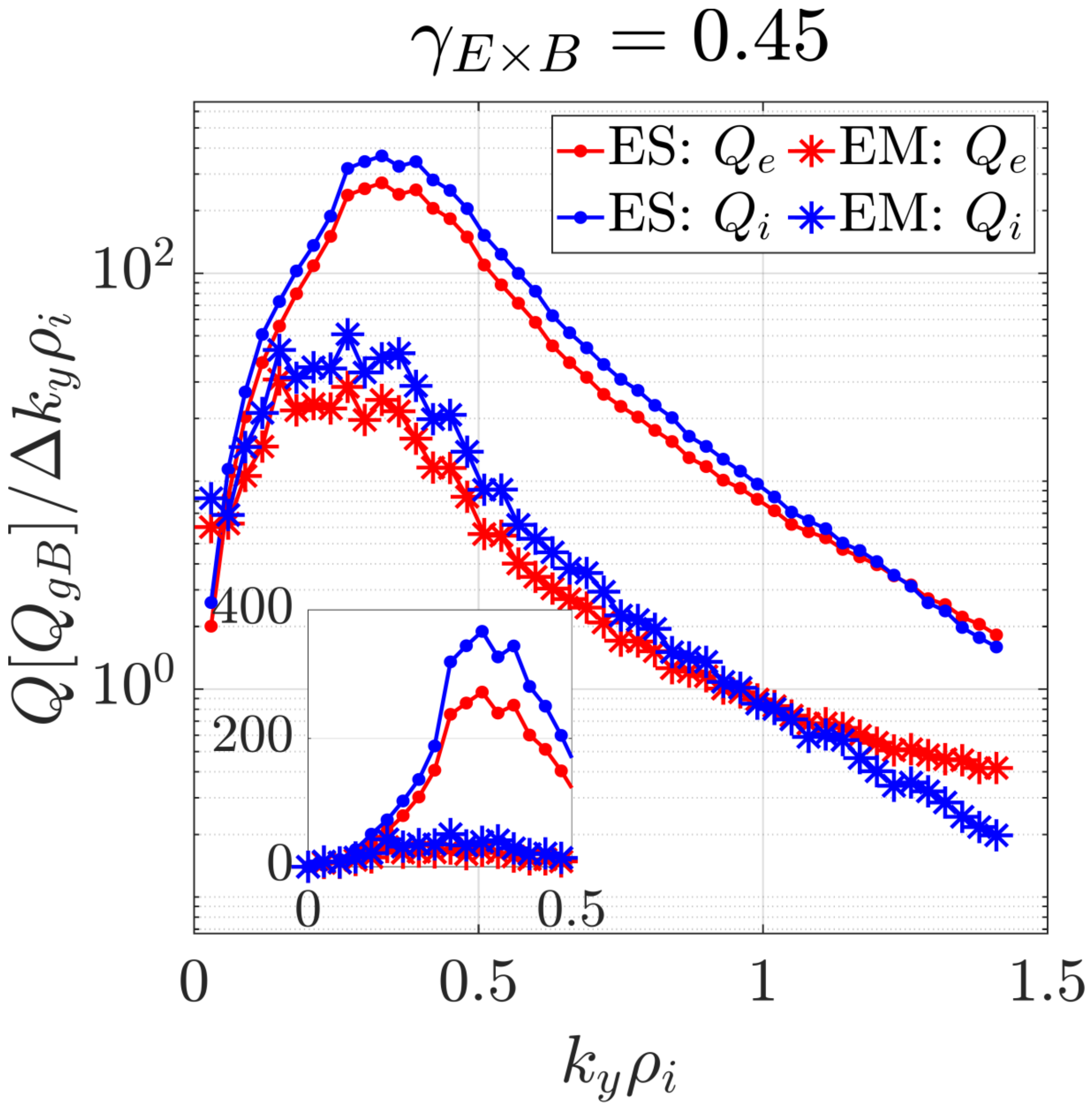


- **Zonal flows (ZFs)** $\phi_{k_x,k_y=0}$
  → Turbulence **self-regulation** mechanism

- Associated **shearing rate**
  $$\omega_{ZF}(k_x) = \langle -k_x^2 |\phi_{k_x,k_y=0}| \rangle_t$$

Electrostatic vs. **Electromagnetic**
→ Large scale **ZFs** activity **enhanced** in **EM** simulation
⇒ suggested as **mechanism** contributing to **EM stabilization**

Small-ELMs – Heat fluxes spectra ES vs. EM



Electron and ion heat flux spectra

- **ES** – heat flux peak at $\boldsymbol{k_y\rho_i \sim 0.4}$
- **EM** – heat flux peak *slightly* shifted to lower $k_y\rho_i$

Electrostatic vs. **Electromagnetic**
⇒ *strong* flux reduction starting at
$\boldsymbol{k_y\rho_i \sim 0.2}$

Conclusions

- Stability: differences at **JET-Be/W**

→ **type-I ELMs: KBM** unstable [Dicorato *et al*. JPCS2022]

→ **small-ELMs: hybrid ITG-TEM** (w/o KBM)

- Ion-scale turbulence: **saturation level** determined by **electromagnetic stabilization + equilibrium $\boldsymbol{E} \times \boldsymbol{B}$ shearing** [Dicorato *et al*. to be submitted PPCF]

⇒ suggested as leading mechanisms regulating ion temperature

→ *Opposite* role of equilibrium $\boldsymbol{E} \times \boldsymbol{B}$ **shearing** in electrostatic and electromagnetic turbulence regime

Perspective work: nonlinear electromagnetic stabilization, global and multi-scale simulations

EUROfusion

Thank you!

M. Dicorato

mattia.dicorato@univ-amu.fr

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Authors list and affiliations

M. Dicorato[1,2], M. Muraglia[1], Y. Camenen[1], J. Garcia[2], X. Garbet[2,3], D. R. Hatch[4], G. Merlo[5], E. de la Luna[6], Ž. Štancar[7], L. Garzotti[7], V.K. Zotta[8], F. Rimini[7], D. Frigione[9], and JET Contributors[*]

[1]Aix-Marseille Université, CNRS, PIIM UMR7345, Marseille, France
[2]CEA, IRFM, Saint-Paul-lez-Durance, F-13108, France
[3]School of Physical and Mathematical Sciences, Nanyang Technological University, 637371, Singapore
[4]Institute for Fusion Studies, University of Texas at Austin, Austin, TX 78712, USA
[5]Oden Institute for Computational Engineering and Sciences, University of Texas at Austin, Austin, TX, 78712, USA
[6]Laboratorio Nacional de Fusión, CIEMAT, 28040 Madrid, Spain
[7]United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon OX14 3DB, UK
[8]Department of Astronautical, Electrical and Energy Engineering, Sapienza University of Rome, Via Eudossiana 18, Rome, 00184, Italy
[9]University of Rome Tor Vergata, Via del Politecnico 1, Rome, 00133, Italy
[*]See the author list of “Overview of T and D-T results in JET with ITER-like wall” by C.F. Maggi et al to be published in Nuclear Fusion special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference (London, UK, 16–21 October 2023)

Simulations Input Parameters at r_{top}

	ρ_{tor}	T_e/T_i	n_D/n_e	Z_{eff}	$1/L_n$	$1/L_{T_i}$	$1/L_{T_e}$	q	$\hat{s}$	β_e
#97395	0.93	0.93	0.92	1.4	2	10	10	3.1	2.0	3×10^{-3}
#96994	0.91	0.52	0.88	2.4	5.7	6.2	15	3.0	1.63	3×10^{-3}
#94442	0.92	0.44	0.88	3.1	6.2	8.8	15	3.1	2.21	1.8×10^{-3}

Table 1: $1/L_n = \mathrm{d}(\log(n))/\mathrm{d}\rho_{tor}$, $1/L_{T_i} = \mathrm{d}(\log(T))/\mathrm{d}\rho_{tor}$

- **Characterization of turbulent transport in different plasma regimes**

$\Rightarrow$ different pedestal turbulence due to:

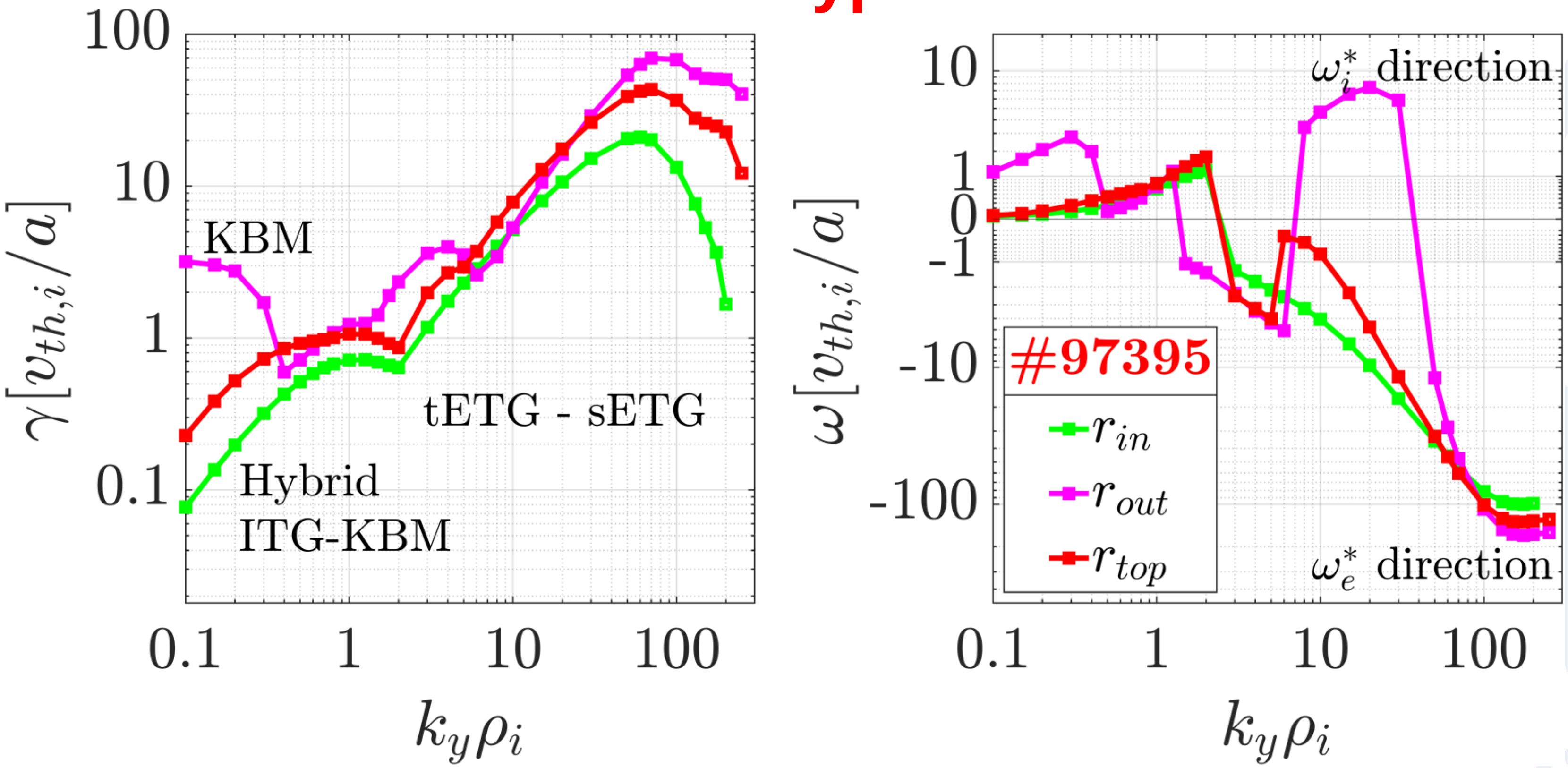
– different T_e/T_i $\rightarrow$ destabilizing parameter for **ITG**

– **Higher** logarithmic density gradient in **BSE** (due to lower density) $\rightarrow$ driving the **TEM**

– **Different** β_e $\rightarrow$ electromagnetic effects

Micro-instabilities in JET pedestals (1/2)

#97395 – Type-I ELM



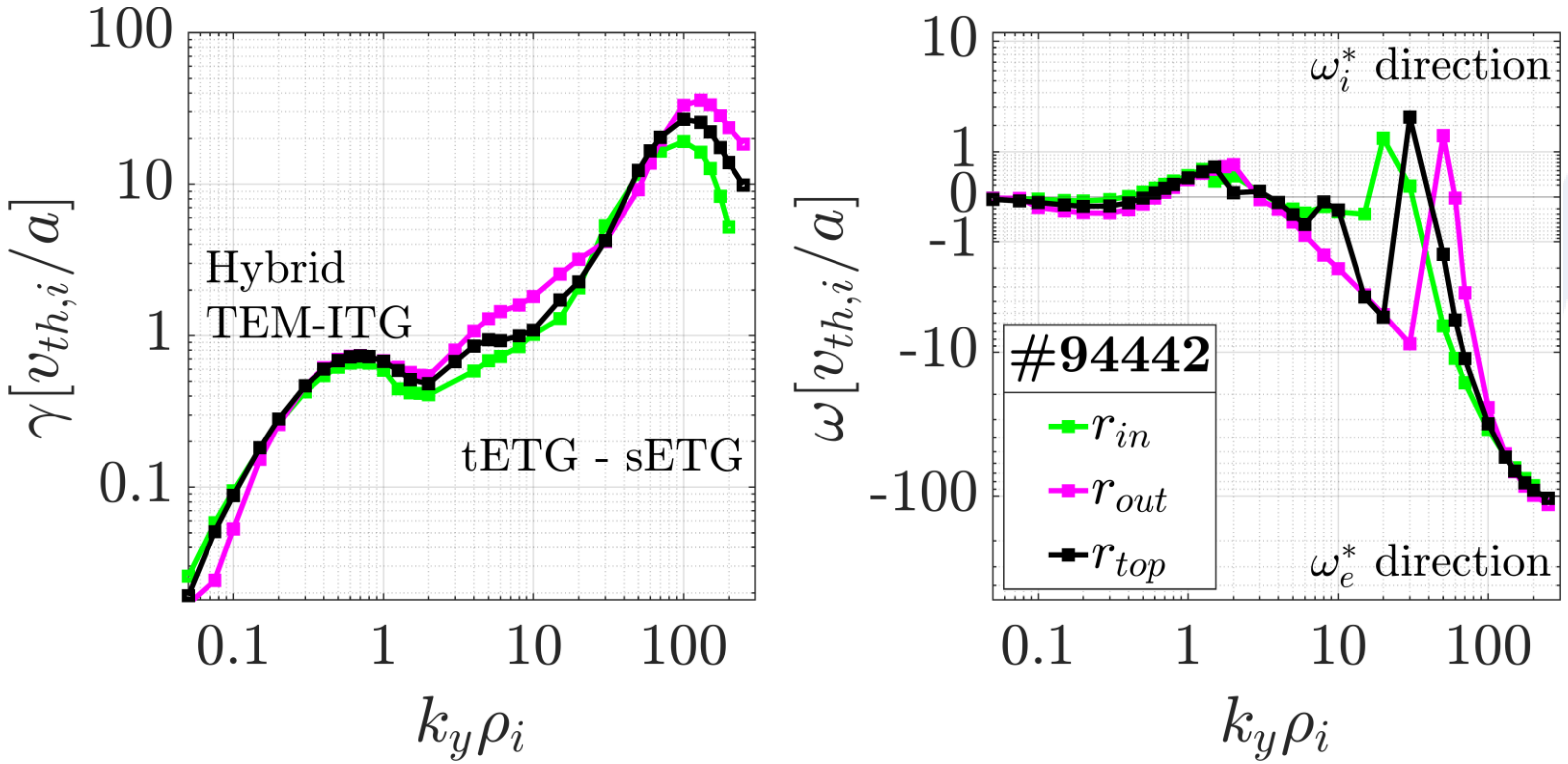
r_{in}	r_{top}	r_{out}
0.91	0.93	0.94

γ = growth rate
ω = real frequency
$k_y\rho_i$ = binormal wave-number

- <u>Ion-scale</u> up to $k_y\rho_i \sim 1.5$: hybrid **ITG-KBM** and **KBM**
- <u>Electron-scale:</u> toroidal and slab **ETG** [Parisi *et al*. NF2020, NF2022]

Micro-instabilities in JET pedestals (2/2)

#94442 – small-ELM

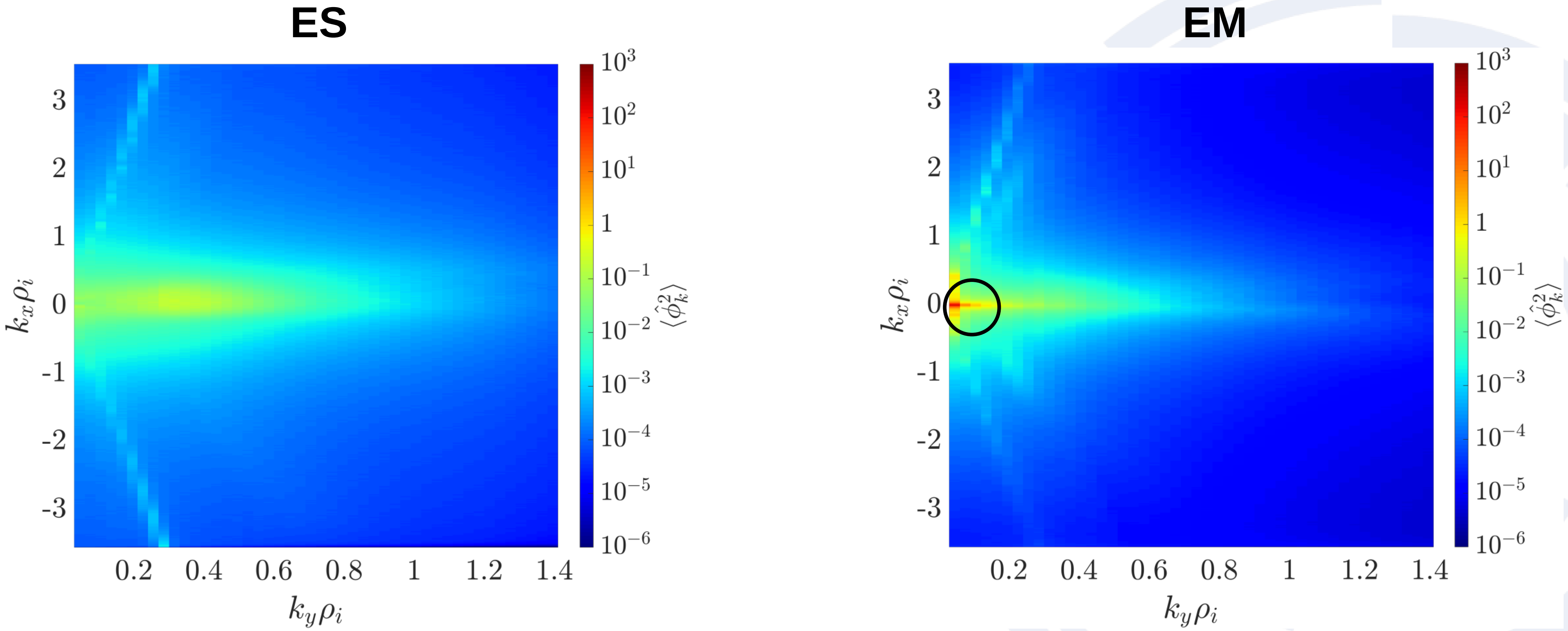


r_{in}	r_{top}	r_{out}
0.91	0.93	0.94

- Ion-scale up to $k_y\rho_i \sim 1.5$: hybrid **TEM-ITG**

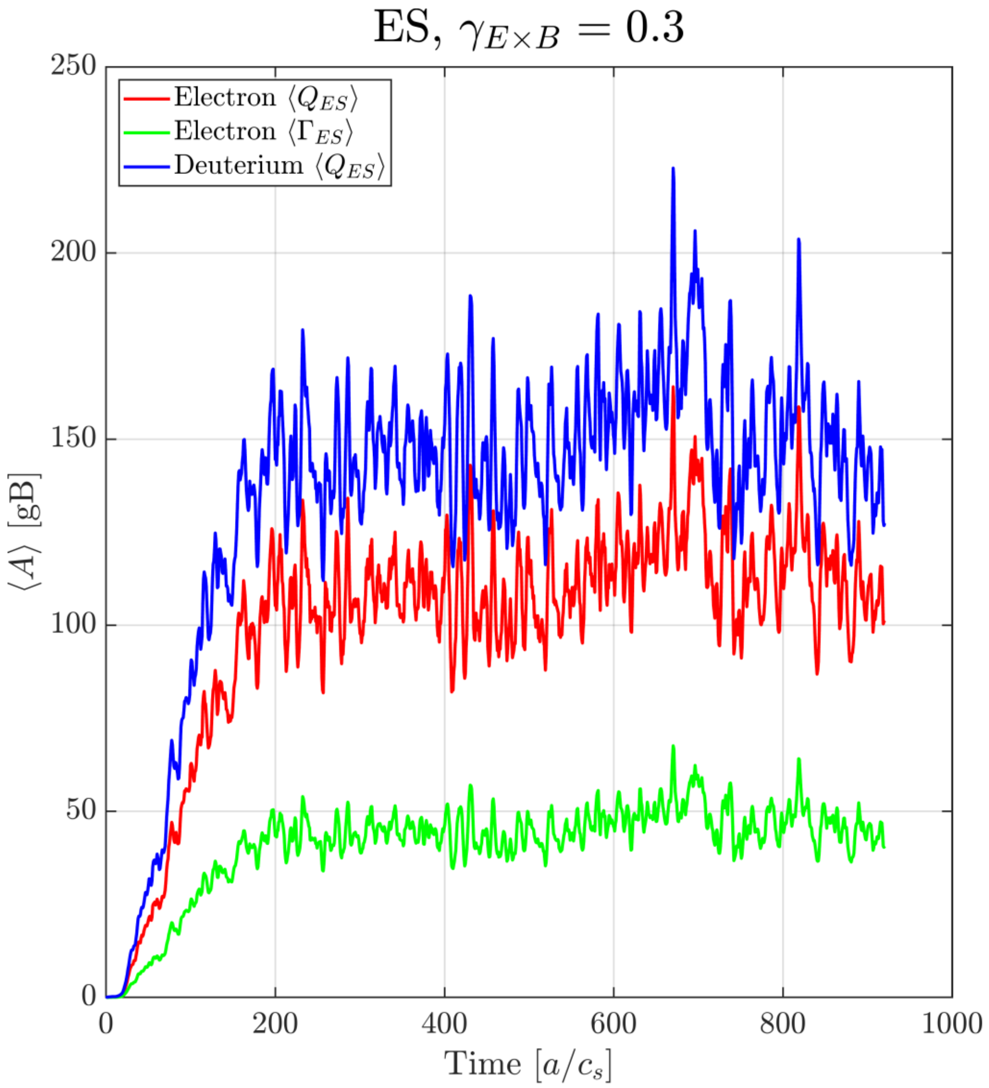
  → **no KBM** due to **lower pressure** ⇒ lower β_e [Dicorato *et al*. JPCS2022]
- Electron-scale: toroidal and slab **ETG**

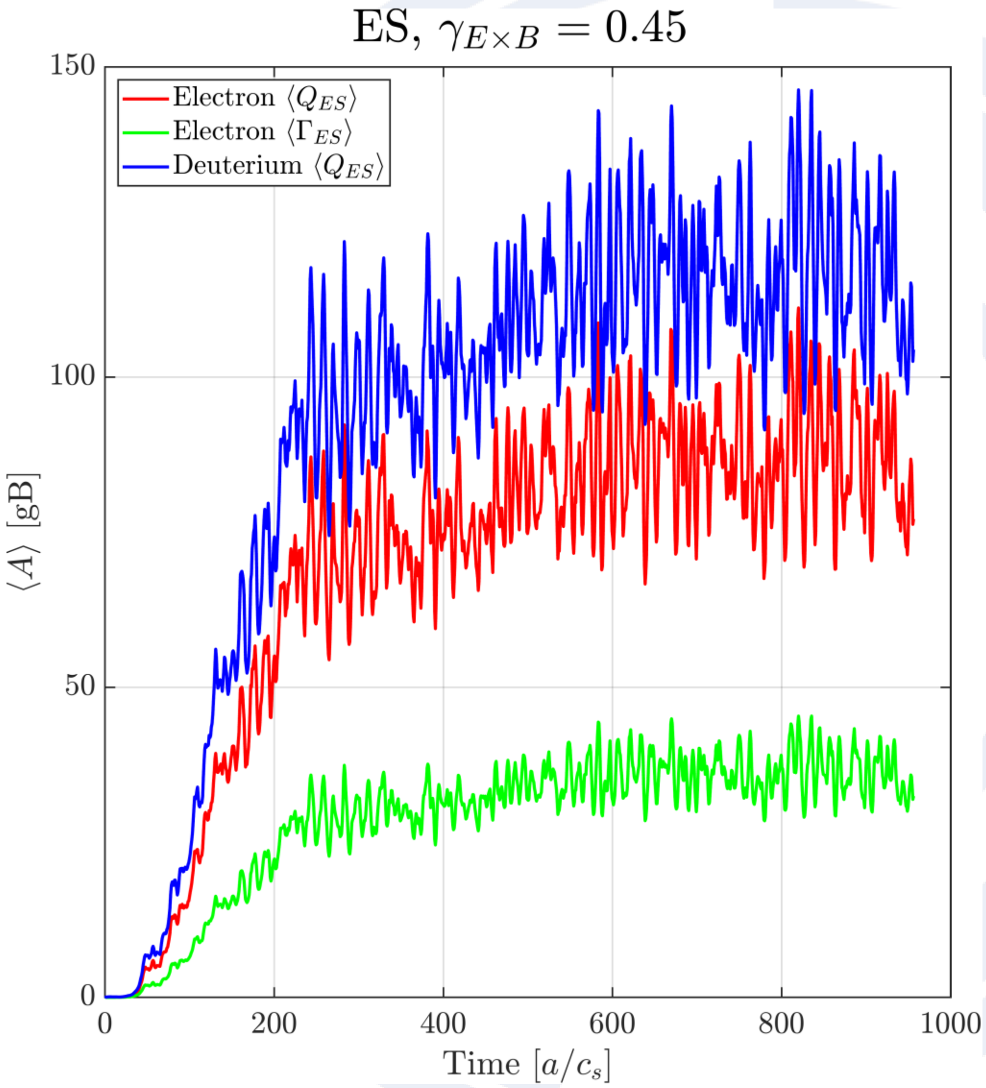
Small-ELM – Turbulence spectra $<\phi^2(k_x, k_y)>_t$



Electromagnetic effects (nominal β_e) determine different **turbulence regime**
$\Rightarrow$ low-k_x low-k_y modes *strongly* enhanced

Small-ELM – Turbulent Fluxes: ES, $E \times B$ shear





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