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EUROfusion

Gyrokinetic and quasi-linear simulations of JET plasmas in view of DT operation

A. Mariani*, N. Bonanomi, D. Brioschi, P. Mantica, T. Tala, and J. Garcia

*Istituto per la Scienza e Tecnologia dei Plasmi, CNR, Milano, Italy

alberto.mariani@istp.cnr.it

JET

ISTITUTO
PER LA SCIENZA
E TECNOLOGIA
DEI PLASMI

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- **Isotope dependence of the heat and particle transport** when changing the main ion from deuterium to tritium: impact on temperature and density peaking.
- **Effect of Electron Temperature Gradient modes (ETGs) on the electron heat transport**: important for future reactors in conditions of dominant electron heating.

Need of High Performance Computing

Gyrokinetic simulations: modelling of **micro-turbulence** (spatial scales: ~ion-electron Larmor radii)

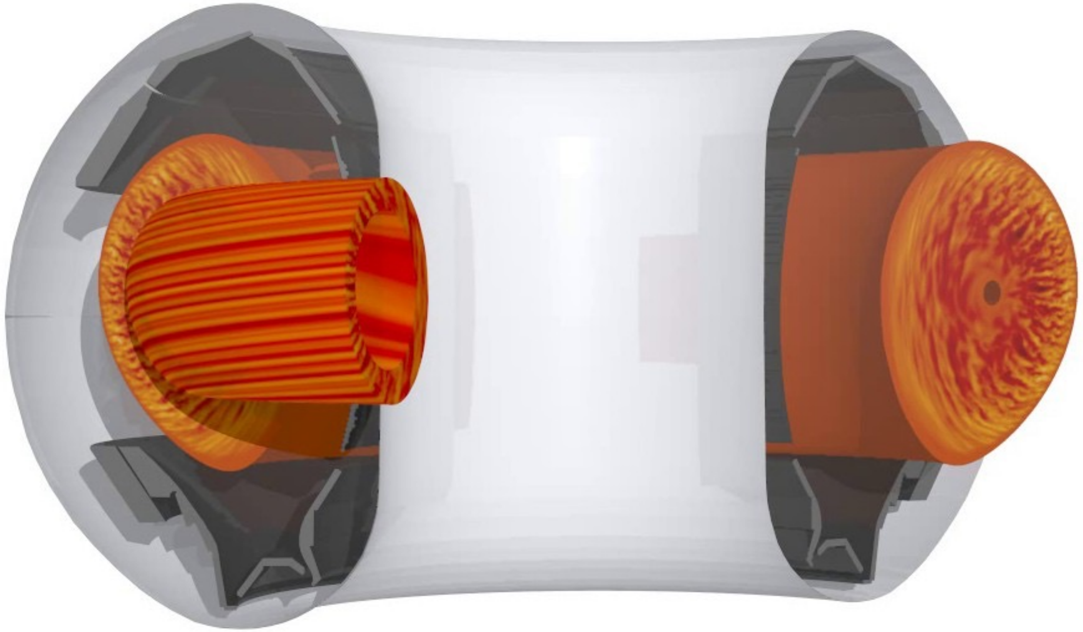
Based on the **gyrokinetic equations**:
evolution of the particles distribution functions in a reduced 5D phase space (dependence on the gyration around the magnetic field: removed)

Very expensive calculations:

1 (linear) < CPU hours < 10^7 (nonlinear multi-scale)

Simulations: performed on
Marconi-CINECA cluster (Italy)

GENE code [Jenko F. *et al.* PoP 2000]



(from http://genecode.org)

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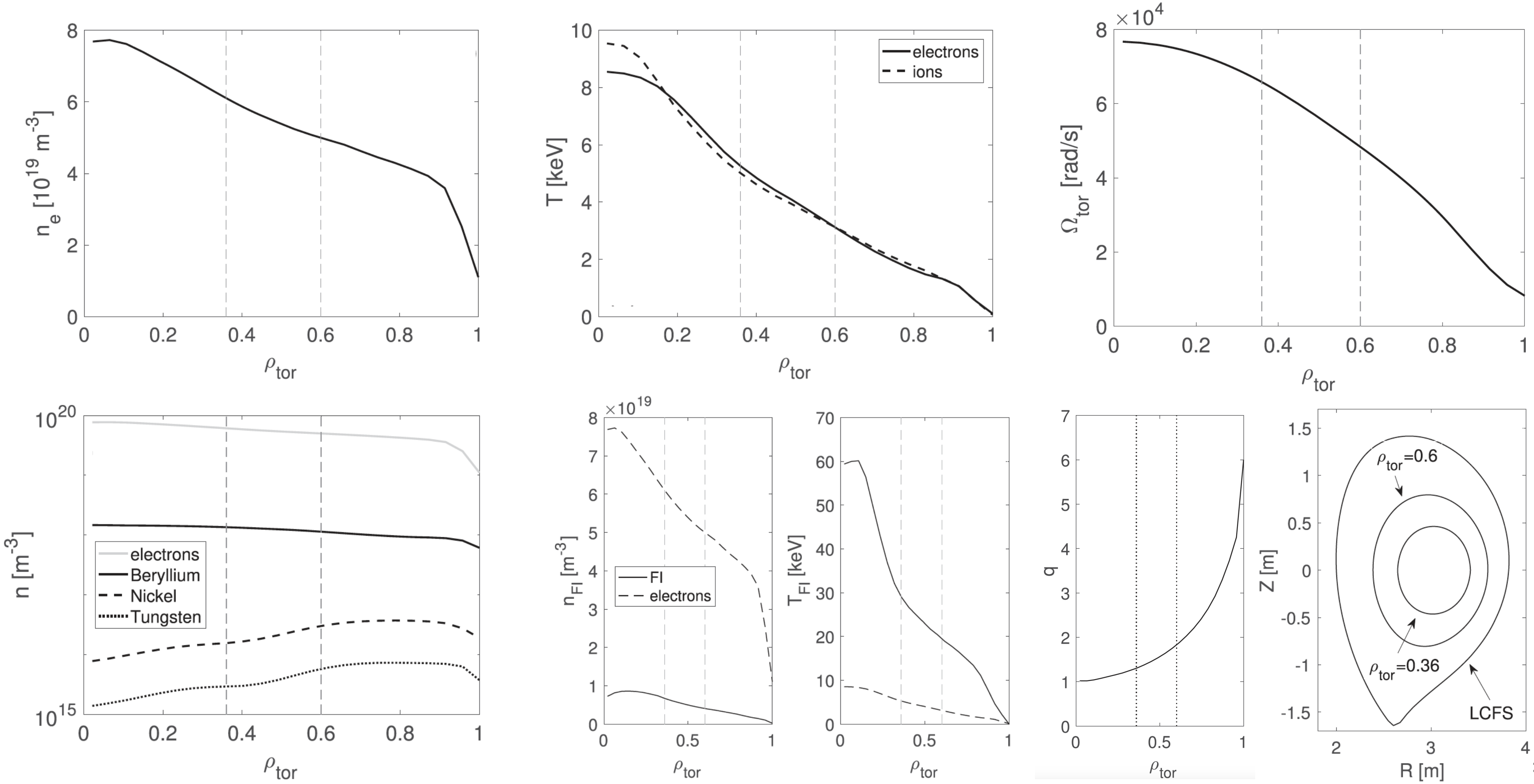
4. Gyrokinetic modelling of the isotope effect on the core ion temperature stiffness, comparing recent JET tritium discharges with older deuterium ones (ongoing work).

1st topic

Benchmark of quasi-linear models against gyrokinetic single scale simulations in deuterium and tritium plasmas for a JET high beta hybrid discharge [A. Mariani et al., 2021 Nucl. Fusion 61, 066032]

JET high-β hybrid pulse parameters

- High performance high-β JET hybrid pulse #94875 with deuterium;
- Confronting the results obtained using the two models QuaLiKiz and TGLF with GENE, also artificially changing the mass of the main ion to T, to investigate the isotope effect.



Plasma profiles: from the end of a JETTO predictive simulation.

Numerical simulations

Gyrokinetic analysis of the heat transport
at fixed radii $\rho_{tor} = 0.36, 0.6$ (flux-tube simulations)

Table 1. Reference parameters at the end of the JETTO-QuaLiKiz simulation ($t = 49.2$ s), at the two radii of analysis $\rho_{tor} = 0.36$ and $\rho_{tor} = 0.6$, for both D and T simulations. Only γ_E is adapted in T multiplying it by $\sqrt{3/2}$, as explained in the text.

El.-ions, q:	R/L_{ne}	R/L_{Te}	R/L_{Ti}	T_i/T_e	q	$\hat{s}$
$\rho_{tor} = 0.36$	2.97	6.42	6.25	0.95	1.26	0.47
$\rho_{tor} = 0.6$	2.31	9.93	7.95	1.00	1.83	1.41
Impurities:	n_{Be}/n_e	n_{Ni}/n_e	n_W/n_e	R/L_{nBe}	R/L_{nNi}	R/L_{nW}
$\rho_{tor} = 0.36$	2.21×10^{-2}	2.57×10^{-4}	4.81×10^{-5}	1.64	−3.73	−1.69
$\rho_{tor} = 0.6$	2.28×10^{-2}	6.02×10^{-4}	1.15×10^{-4}	3.44	−9.05	−10.82
FI, β_e, $E \times B$:	n_{FI}/n_e	R/L_{nFI}	R/L_{TFI}	T_{FI}/T_e	β_e	$\gamma_E[c_s/R]$
$\rho_{tor} = 0.36$	0.11	6.24	6.58	5.50	1.75×10^{-2}	0.11 (D)
$\rho_{tor} = 0.6$	0.08	6.84	5.61	6.24	8.49×10^{-3}	0.23 (D)

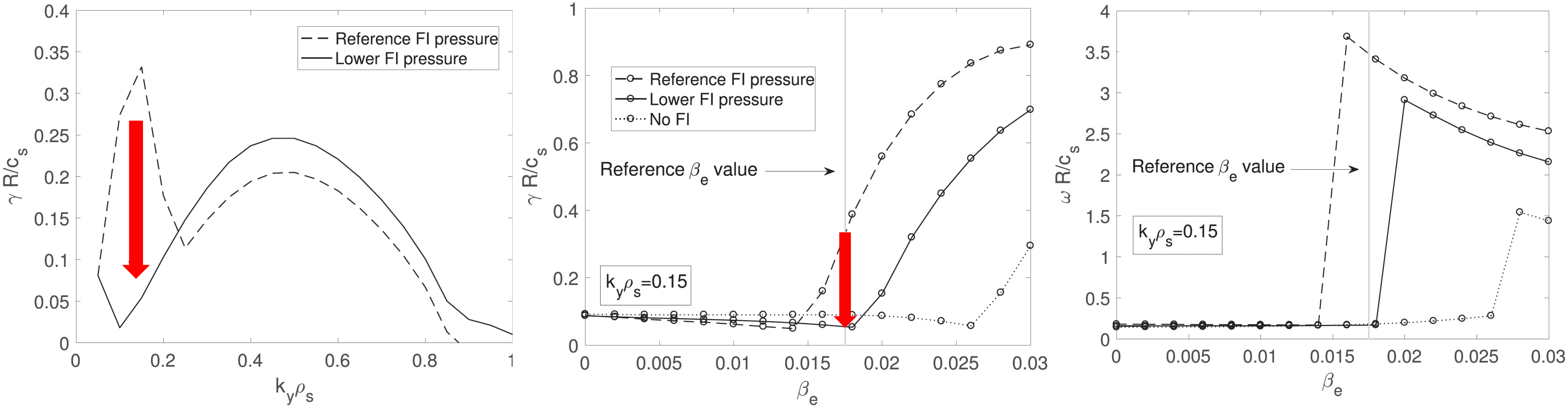
GENE simulations:

- Geometry: s-α (to compare with QuaLiKiz) and Miller (to compare with TGLF);
- Collisions: Landau self adjoint operator;
- Electrostatic and electromagnetic runs, compared;
- Impurities: beryllium, nickel+tungsten (lumped, conserving neutrality and effective charge Z_{eff});
- Fast ions (both due to NBI and ICRH);
- Rotation: $E \times B$ shear and parallel flow shear:

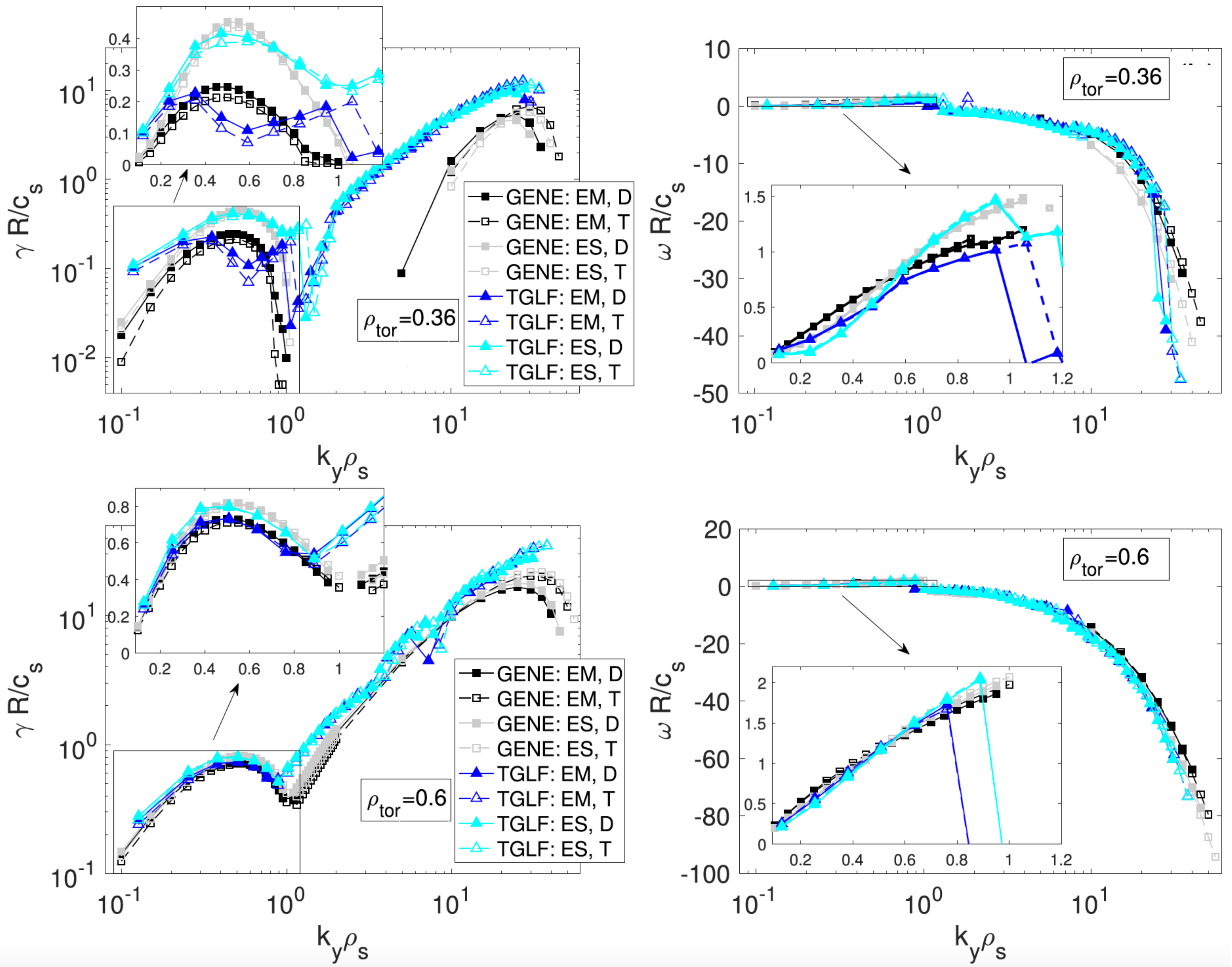
Fast ions

FI pressure: tuned within error bars to stabilize low-k electromagnetic modes, that produce unphysically large fluxes in the nonlinear simulations

Low-k electromagnetic modes: β induced Alfvén eigenmodes (BAE), likely coupled with kinetic ballooning modes (KBM): similar large positive frequencies (following GENE sign conventions), ballooning parity and a β_e threshold.



Linear growth rates and frequencies of unstable modes



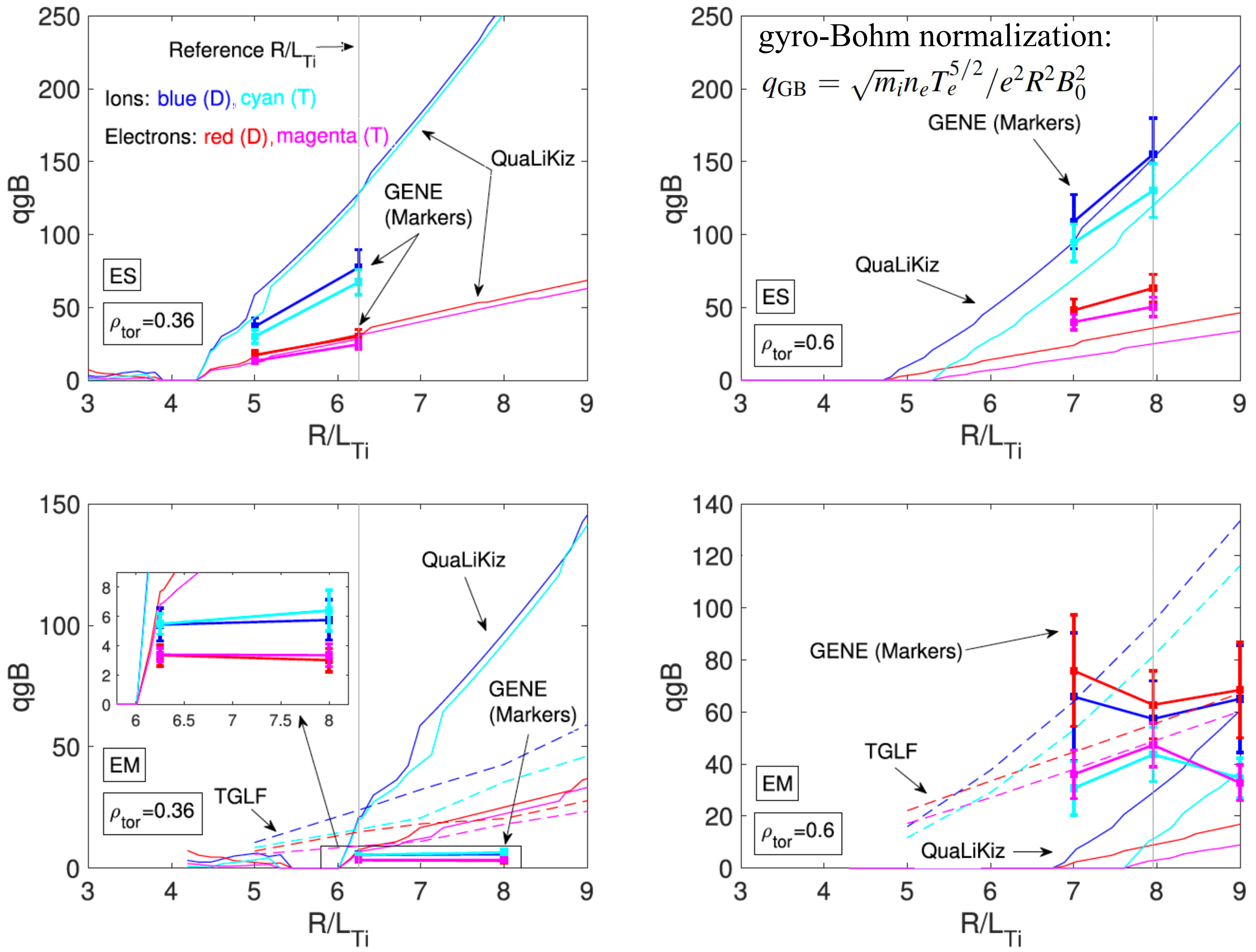
GENE-TGLF: good agreement

ITG micro-instability at ion-scales. ETG should not contribute to nonlinear fluxes according to $\gamma/k_\perp$ quasi-linear criterion ($(\gamma/k_y)^{max}_{ETG} > (\gamma/k_y)^{max}_{ITG}$ for ETG relevance)

Strong EM stabilization at $\rho_{tor} = 0.36$, due to almost double β_e at $\rho_{tor} = 0.36$ compared to $\rho_{tor} = 0.6$, together with a more efficient β_e stabilization at $\rho_{tor} = 0.36$;

Slightly smaller growth rates are found in T with respect to D at $\rho_{tor} = 0.36$ in the EM regime

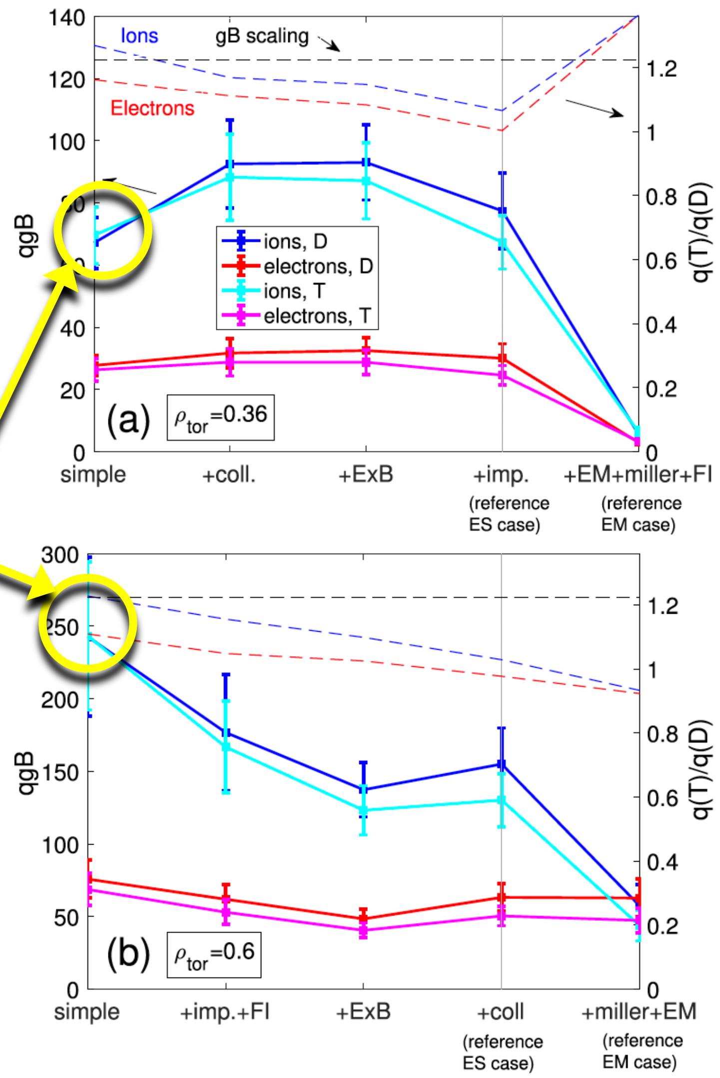
Nonlinear/quasi-linear heat fluxes



- Very strong EM stabilization at ρ_{tor} = 0.36, even without FI, compared to ρ_{tor} = 0.6, where a milder EM stabilisation is seen, almost only acting on ions;
- Negligible anti-gB effect at ρ_{tor} = 0.36, which increases with increasing radius and is not small at ρ_{tor} = 0.6 for the EM case.
- Difficulties for QL modes to reproduce the nonlinear GK results.

Physics ingredients affecting anti-gB behaviour (GENE)

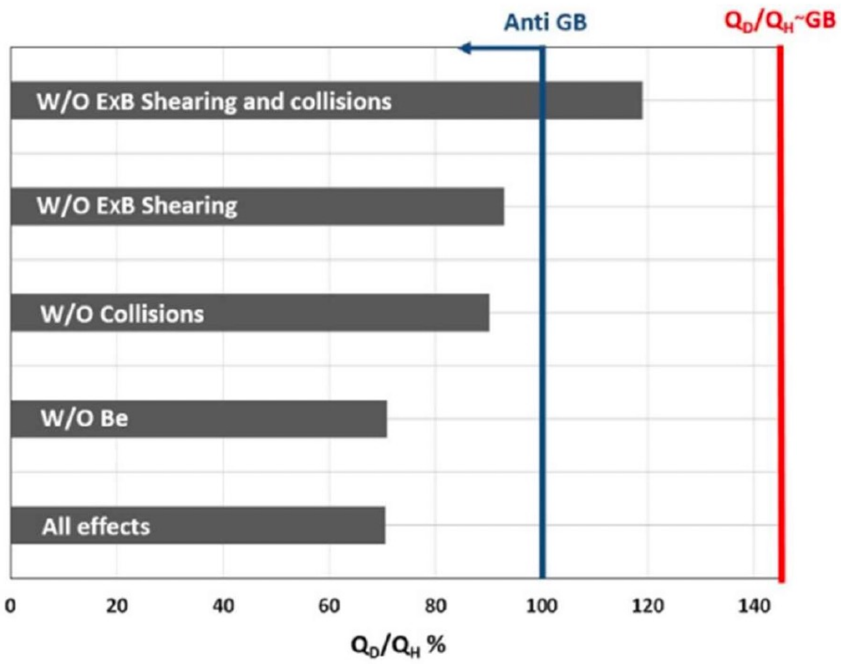
gB behaviour only appears for the ions when removing impurities, collisions, FI, rotation shear and shaping



Consistent with the recent literature: different physics ingredients can break gB scaling

GENE

- Several physics mechanisms found to break GB scaling:
  - EM effects
  - ExB shearing
  - Collisionality
  - Kinetic electrons
  - Non pure ITG turbulence
  - Zonal flows



[Garcia NF19] [Mantica PPCF20] [Garcia PPCF22]

2nd topic

Gyrokinetic and transport modelling of a couple of JET deuterium and tritium L-mode plasmas constituting a dimensionless isotope mass scaling experiment [T. Tala et al., 2023 Nucl. Fusion 63, 112012]

Dimensionless isotope mass scaling experiment

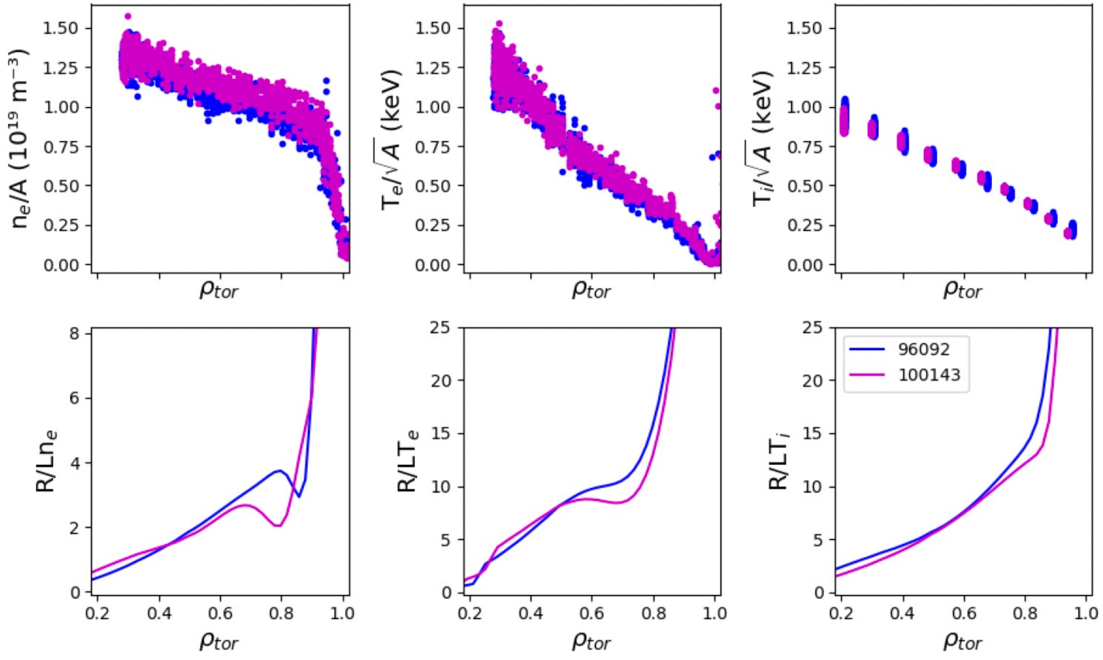


Figure 5: Isotope mass scaled electron density (top left), electron temperature (top middle) and ion temperature (top right) profiles for the Deuterium discharge (96092) and the Tritium discharge (100143). The corresponding inverse gradient lengths calculated from the real (not scaled) profiles normalised with R are shown on the bottom row, respectively.

- **Dimensionless isotope mass scaling experiment** between pure **deuterium** and pure **tritium** plasmas;
- L-mode with dominant electron heating (NBI+ohmic) conditions;
- Matching: $\rho*$, $\nu*$, β_n, q and T_e/T_i;
- 28% higher scaled energy confinement time is found in favour of the tritium plasma;
- Pulses:
- 96092: **deuterium**
- 100143: **tritium**
- **GENE: gyrokinetic analysis** of the heat and particle transport at fixed radius $\rho_{tor} = 0.6$.

GENE main input parameters at $\rho_{tor} = 0.6$

	D: 96092	T: 100143
R/L_n	1.83	1.68 (−8%)
R/L_{Te}	7.11	6.43 (−10%)
R/L_{Ti}	5.48	5.39 (−2%)
T_e/T_i	1.15	1.16 (+1%)
$\bar{\nu}_c$ $(\bar{\nu}_c = R\nu_{ei}/c_s)$	0.83	0.99 (+19%)
β_e $[10^{-3}]$	1.31	1.46 (+11%)
q	1.51	1.49 (−1%)
$\hat{s}$	1.07	1.15 (+7%)

In addition to the reference cases 96092 (D) and 100143 (T), a third numerical case has been considered (TN: Tritium numerical)

→ single out the **effect of the isotope mass alone** on the results.

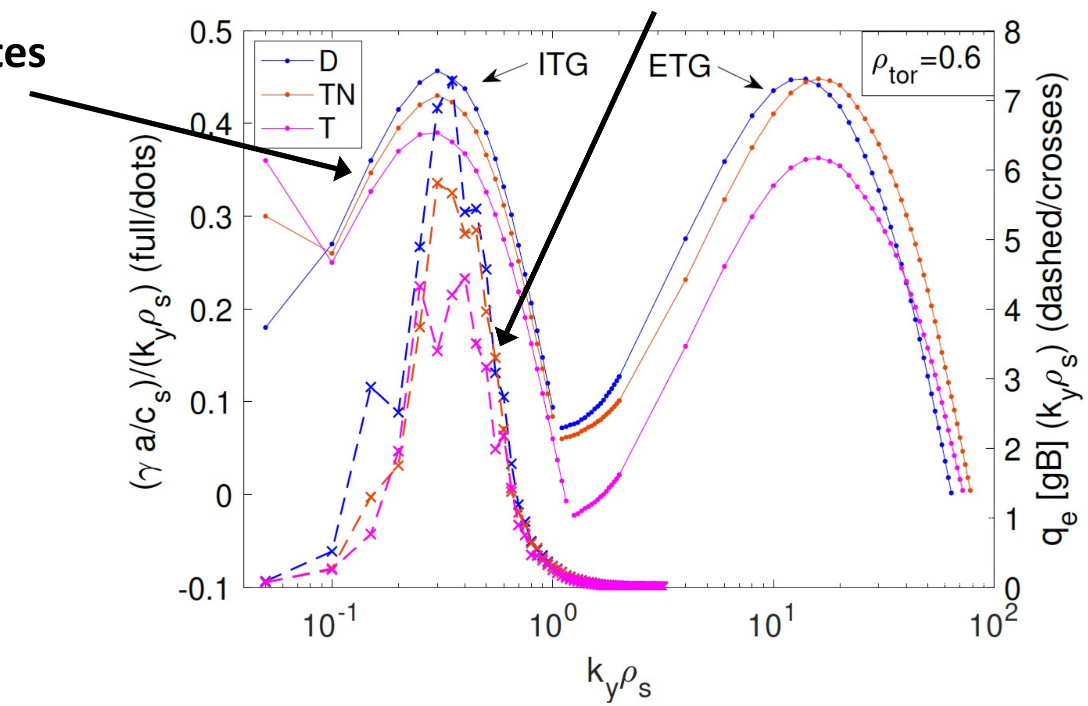
TN: obtained by considering all the parameters of the 96092 (D) pulse, only changing the isotope mass from Deuterium to Tritium in the GENE simulations.

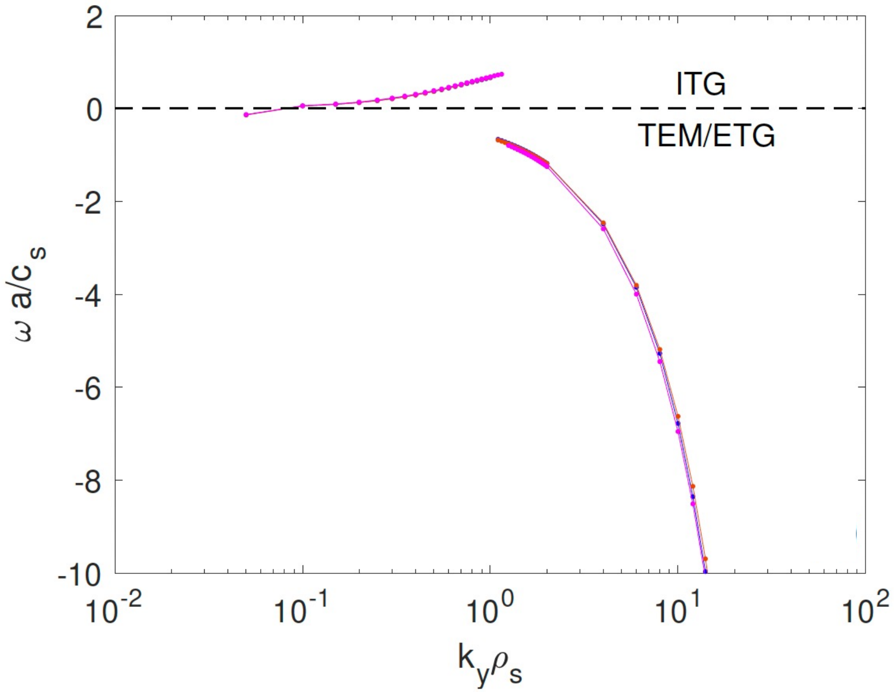
GENE linear eigenvalues and nonlinear q_e spectra

Nonlinear q_e spectra

Frequencies

Growth rates

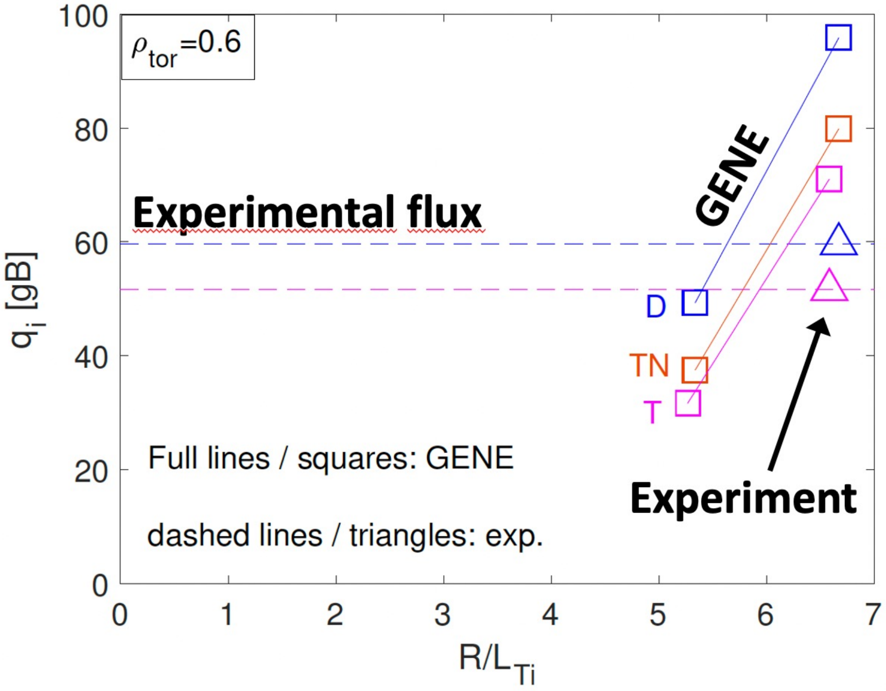




- Micro-instability regime: **ITG** (ion-scales); **ETG** (electron scales). ETGs could potentially impact the nonlinear fluxes, based on $\gamma/k_\perp$ quasi-linear rule of thumb (**not guaranteed**).
- **Small** but non negligible **direct isotope effect** (only change isotope mass): $D \longrightarrow TN$ ($\mathbf{-6\%}$ on γ_{max});
- **Larger indirect isotope effect** (due to other different parameters): $TN \longrightarrow T$ ($\mathbf{-12\%}$ on γ_{max});
- q_e shows the **same trend** as the growth rates.

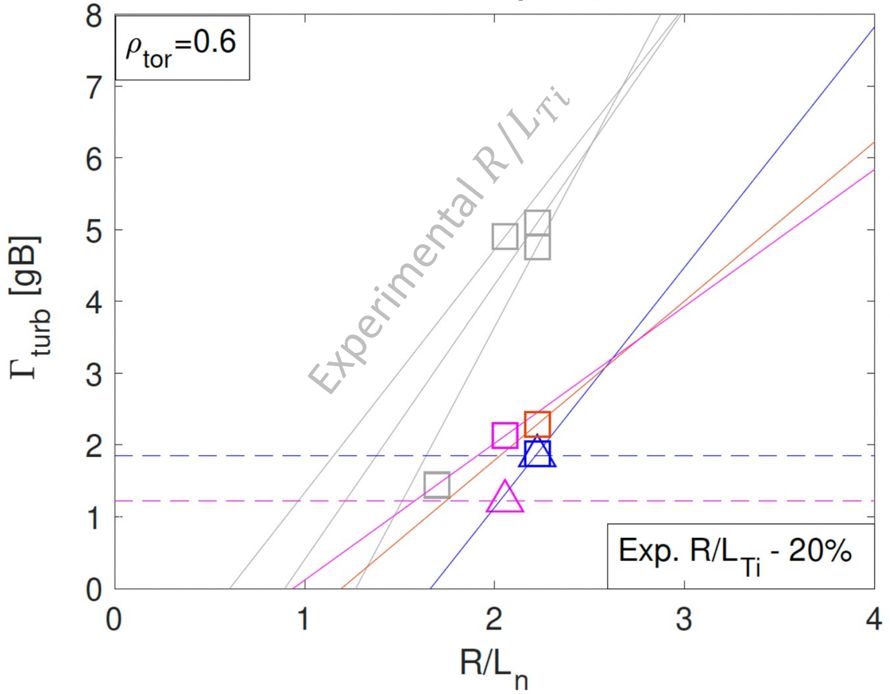
GENE nonlinear fluxes

Heat fluxes:



Particle fluxes:

Experimental R/L_{Ti} -20% :



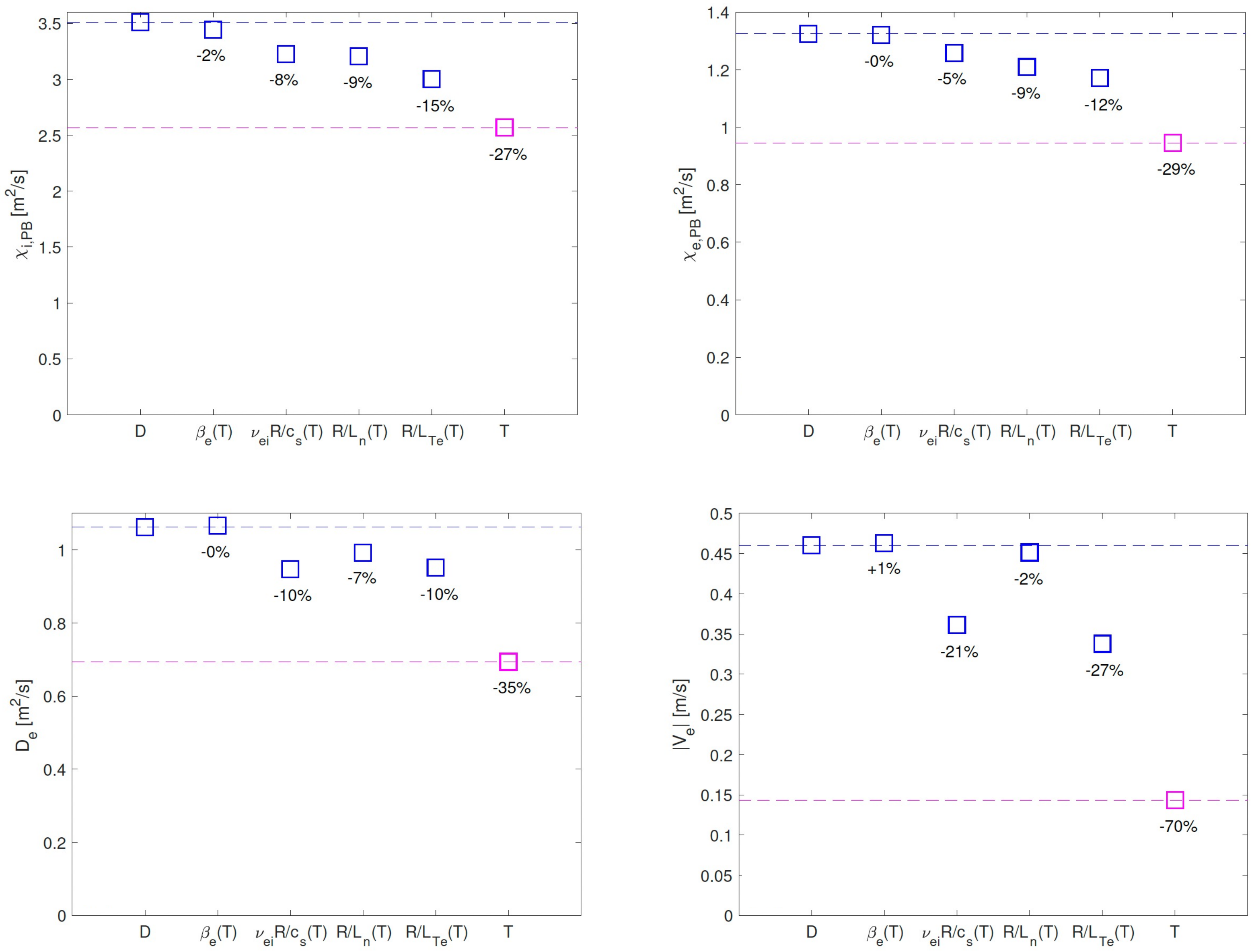
- Possible to **match the experiment** by reducing R/L_{Ti} within $\pm 20\%$ error bars;
- **Direct anti-gB effect on heat fluxes**: $D \longrightarrow TN$ $(\sim -20\%) \longrightarrow$ **same fluxes in physical units**;
- **Decreasing density peaking with increasing isotope mass** $\longrightarrow$ expected in collisional ITG-dominant turbulence [C. Angioni et al., PoP 2018].

Transport coefficients (GENE)

	D	TN	T
Experimental R/L_{Ti}:			
$\chi_{e,PB}$ $[m^2/s]$	1.32	1.36 (+3%)	0.94 (-29%)
$\chi_{i,PB}$ $[m^2/s]$	3.51	3.58 (+2%)	2.57 (-27%)
D_e $[m^2/s]$	1.06	1.00 (-6%)	0.69 (-35%)
$\|V_e\|$ $[m/s]$ $(V_e < 0)$	0.46	0.31 (-33%)	0.14 (-70%)
Experimental R/L_{Ti}-20%:			
$\chi_{e,PB}$ $[m^2/s]$	0.84	0.76 (-9%)	0.51 (-39%)
$\chi_{i,PB}$ $[m^2/s]$	1.80	1.68 (-7%)	1.14 (-37%)
D_e $[m^2/s]$	0.71	0.58 (-18%)	0.39 (-45%)
$\|V_e\|$ $[m/s]$ $(V_e < 0)$	0.40	0.24 (-40%)	0.12 (-70%)

$D \longrightarrow T$ **: reduction of the transport coefficients** $\chi_{e,PB}$, $\chi_{i,PB}$, D_e, $|V_e|$, i.e. isotope scaling with smaller transport in T $\longrightarrow$ **partly coming** directly **by changing the mass** in the GENE simulations ($D \longrightarrow TN$) and **partly coming from the small differences between the pulses** in GENE input ($TN \longrightarrow T$), such as R/L_n (8% difference), R/L_{Te} (10% difference), ν_c (19% difference), β_e (11% difference) and $\hat{s}$ (7% difference).

GENE: effect of the single parameters on the reduced transport in T w.r.t. D

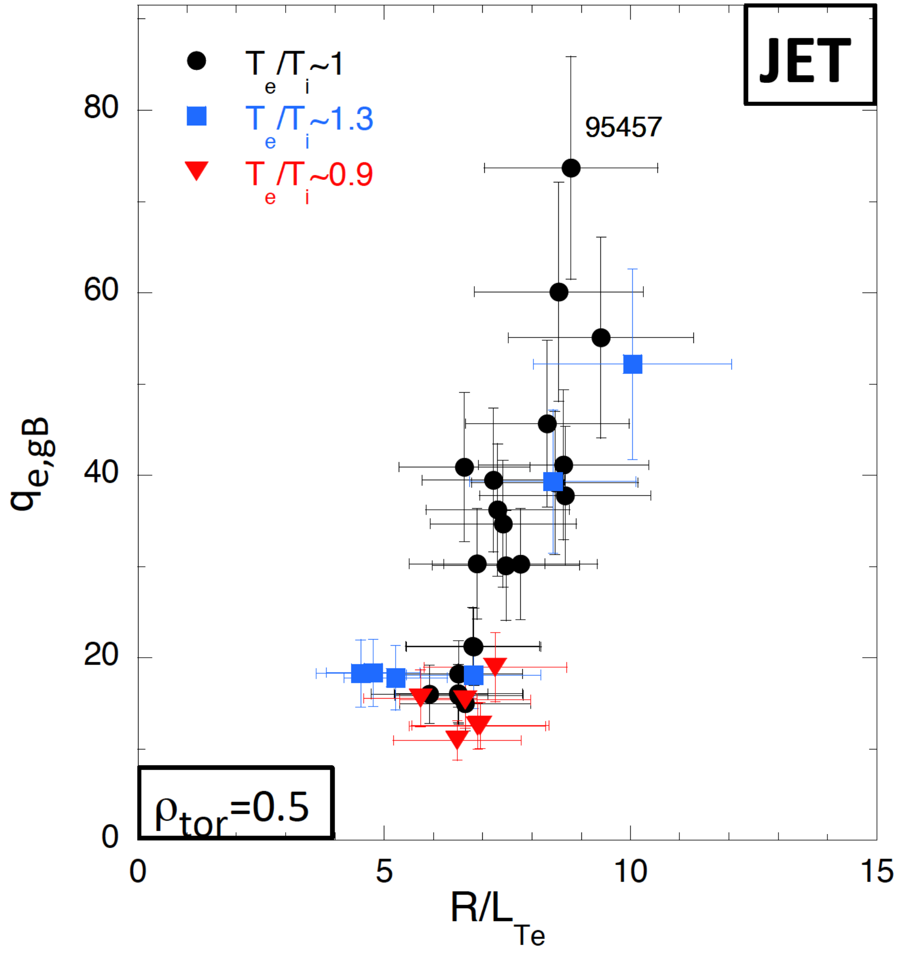


- Repeating the nonlinear D run, changing one by one the parameters (only one at a time), taking them from T;
- **There is not a single parameter** ⟶ explains the lower transport levels in T plasma as compared to the D one; **more than one parameter contributes.**

3rd topic

Gyrokinetic simulations of multi-scale electron heat transport in JET
[A. Mariani et al., 2021 Nucl. Fusion 61, 116071]

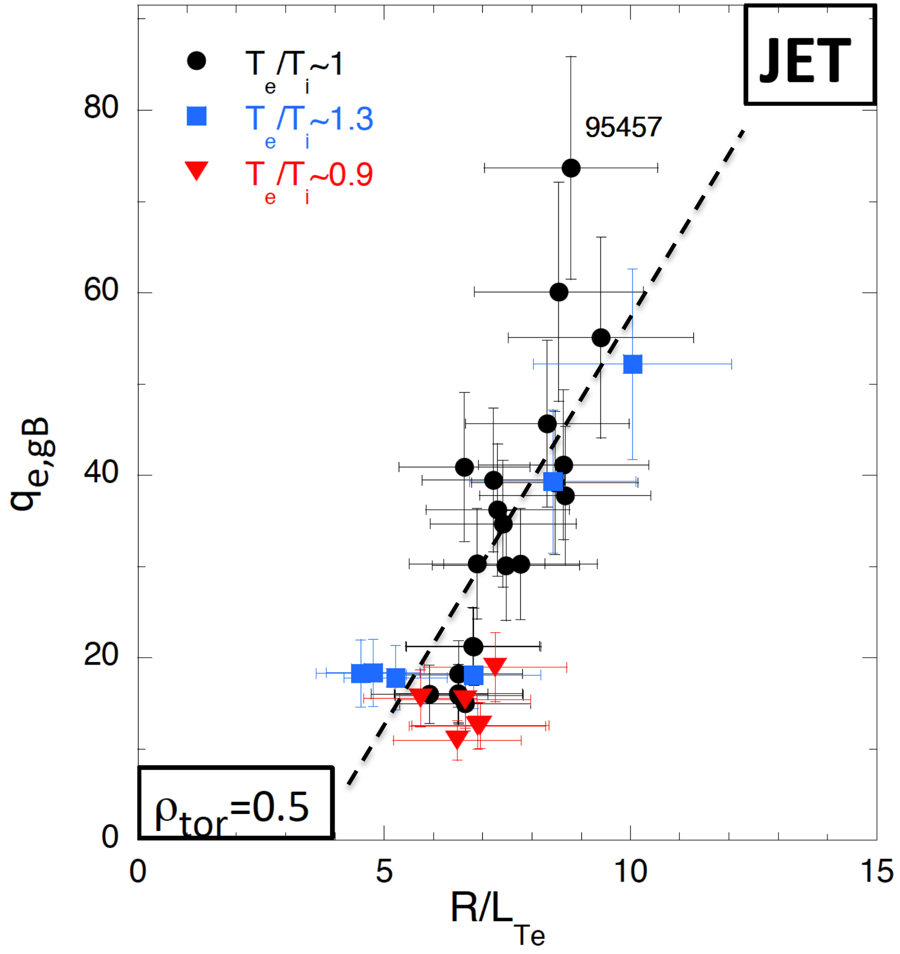
Experiments at JET with ETG favourable conditions



[Mantica. P. et al., Nucl. Fusion 61 (2021) 096014]

- L-modes and H-modes, B_0 = 3.3 T , I_p = 2 MA;
- Heat flux scan: vary ICRH power (<6 MW, H minority to mainly heat electrons) deposition;
- ICH only steady (no RF modulation ⟶ no perturbative analysis);
- NBI(<20 MW) to have a T_e/T_i range.

Outline



[Mantica. P. et al., Nucl. Fusion 61 (2021) 096014]

Only steady state: TEM-compatible

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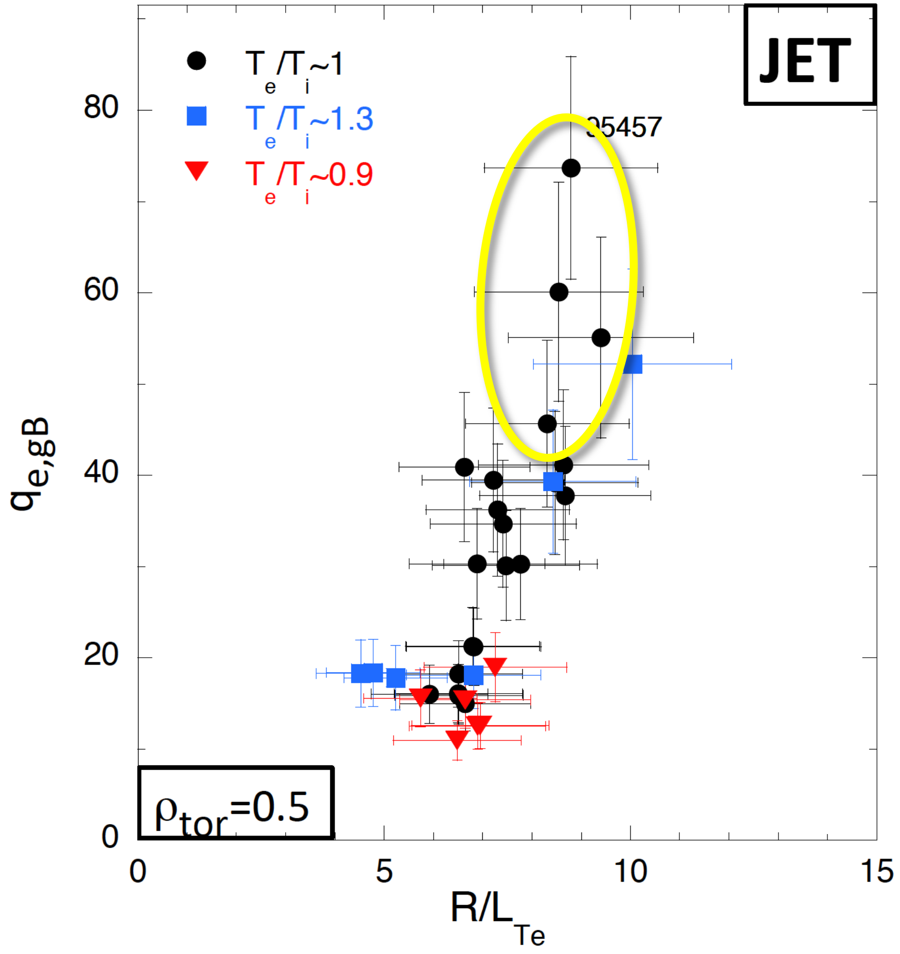
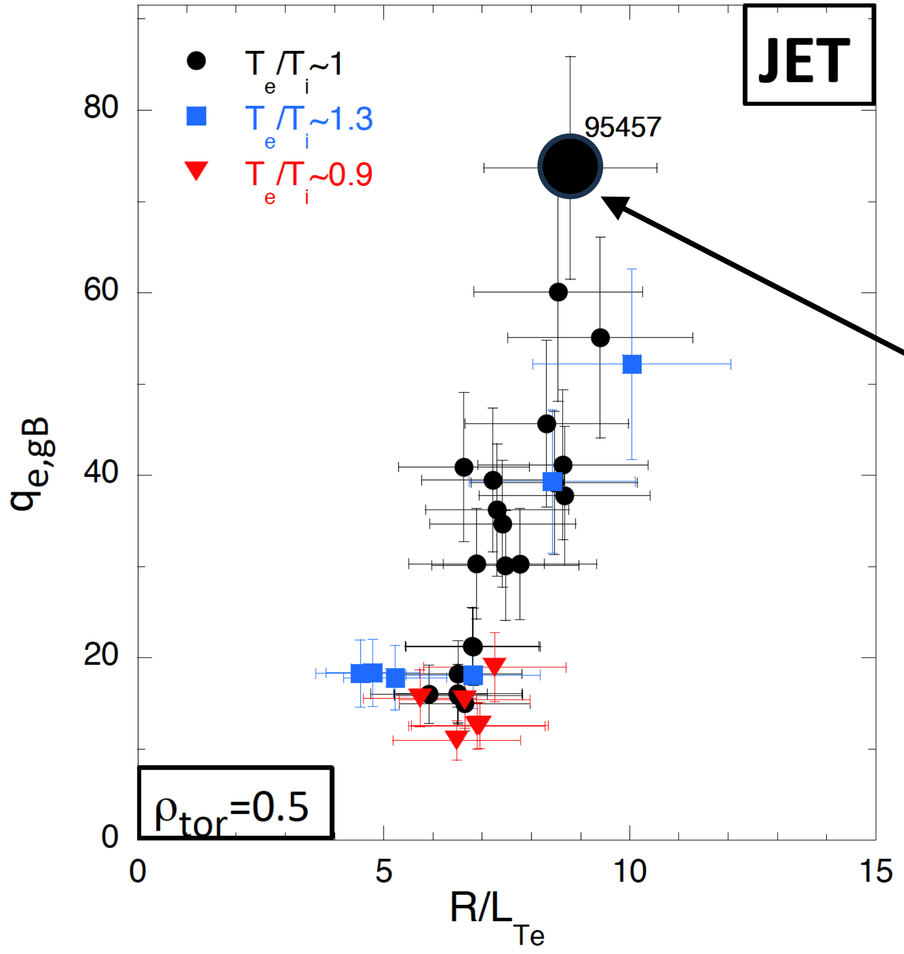


[Mantica. P. et al., Nucl. Fusion 61 (2021) 096014]

Only steady state: TEM-compatible **except for highest $q_{e,gB}$ points with $T_e \sim T_i$ (ETG wall?)**.

(consistent with theory: ETGs are expected to impact q_e when $T_e \sim T_i$ and R/L_{Te} is sufficiently large)

Outline



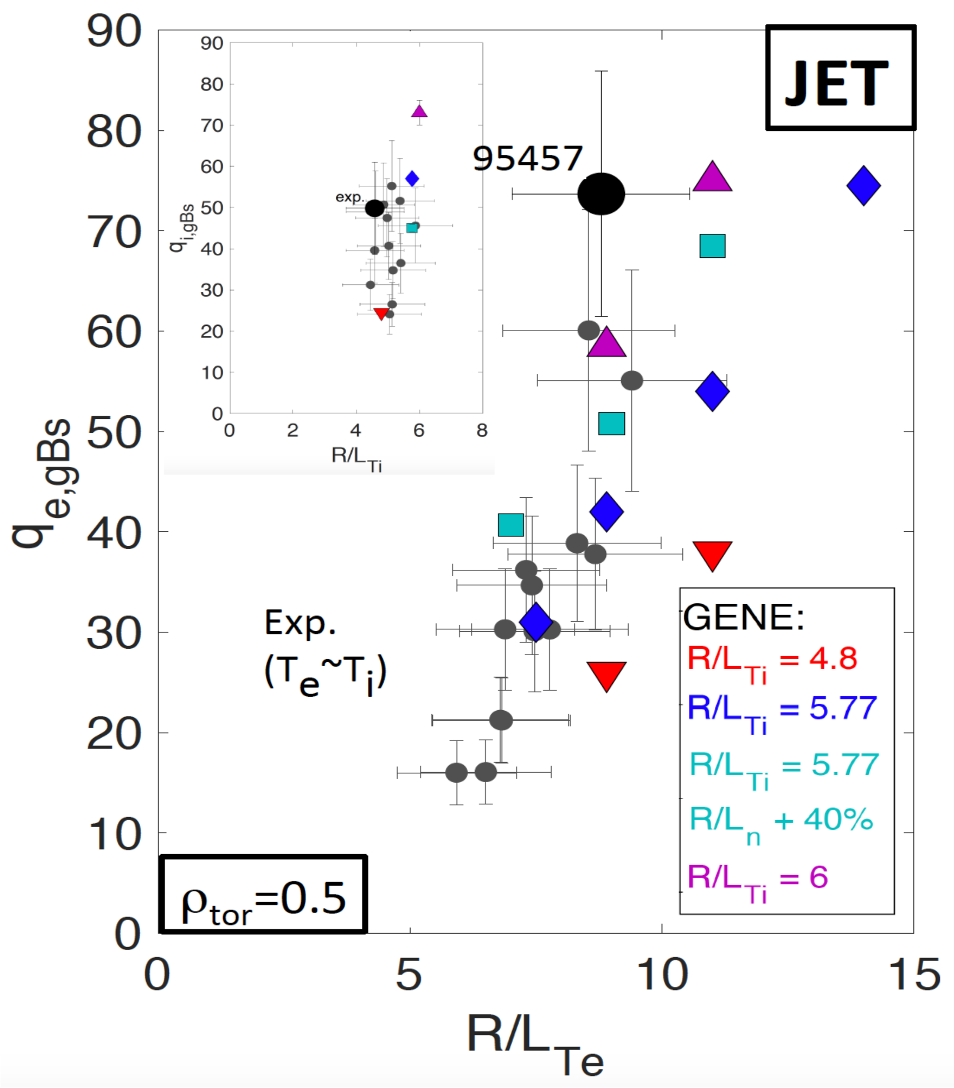
[Mantica. P. et al., Nucl. Fusion 61 (2021) 096014]

Test the presence of an ETG wall:
GENE simulations for the JET pulse with largest $q_{e,gB}$

GENE simulations

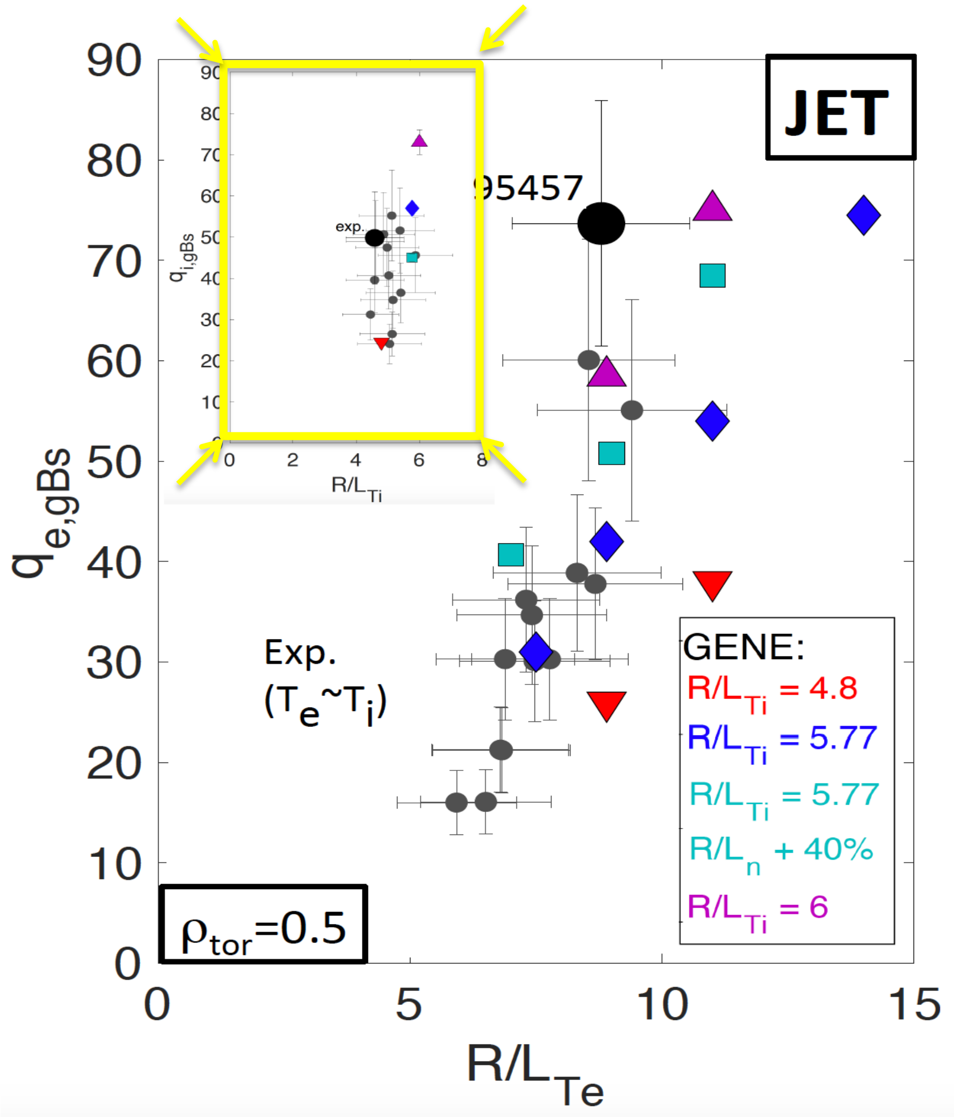
- Flux-tube (radially local) version of GENE;
- Nonlinear ion-scale and **nonlinear multi-scale (~20M CPU hours)**;
- real electron/ion mass ratio is kept also in the nonlinear multi-scale runs;
- Realistic geometries: magnetic equilibria from EFIT [Brix M. et al., Rev. Sci. Instrum. 79 (2008)];
- Collisions;
- Finite-beta (electromagnetic) effects;
- Impurities: lumped in a single effective species;

Nonlinear ion-scale simulations



- GENE: compared with experiment (sensitivity to R/L_{Ti} and R/L_{ne} is tested: colored markers);

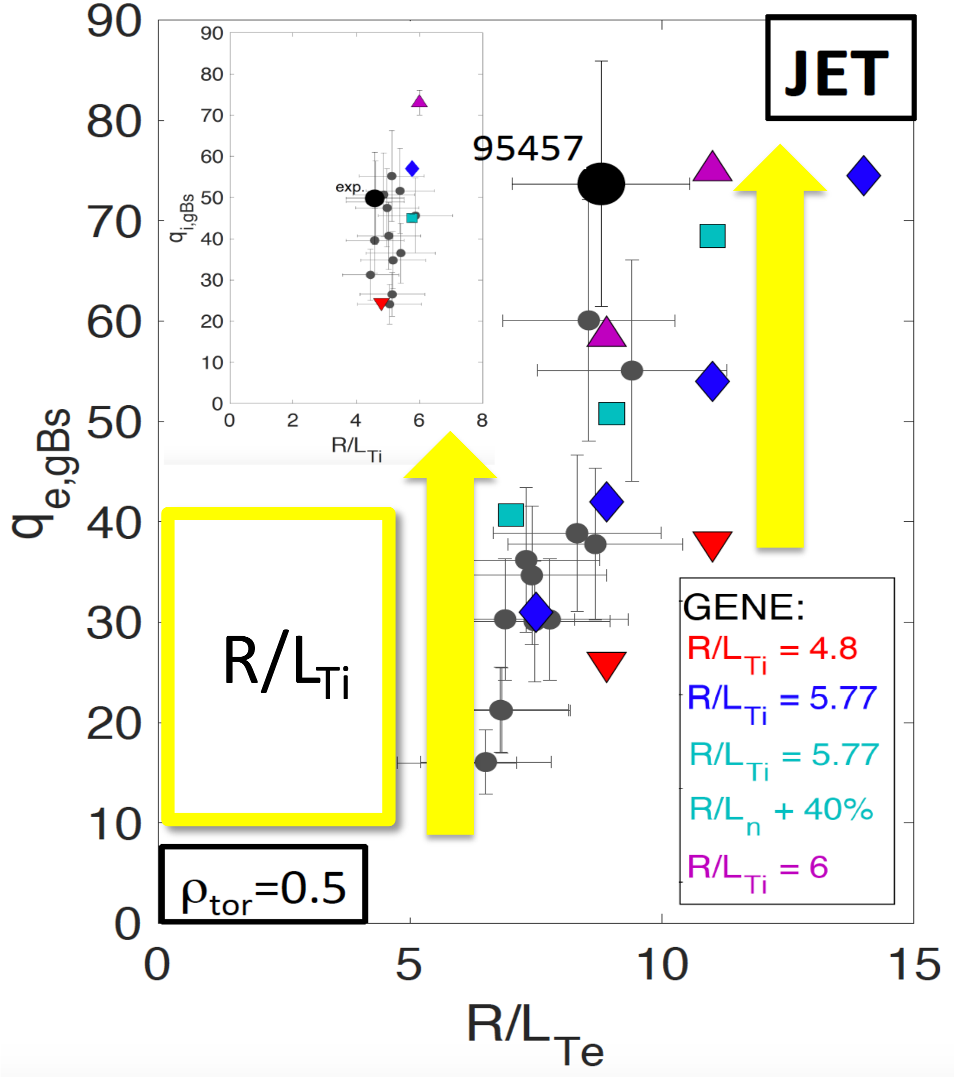
Nonlinear ion-scale simulations



- GENE: compared with experiment (sensitivity to R/L_{Ti} and R/L_{ne} is tested: colored markers);

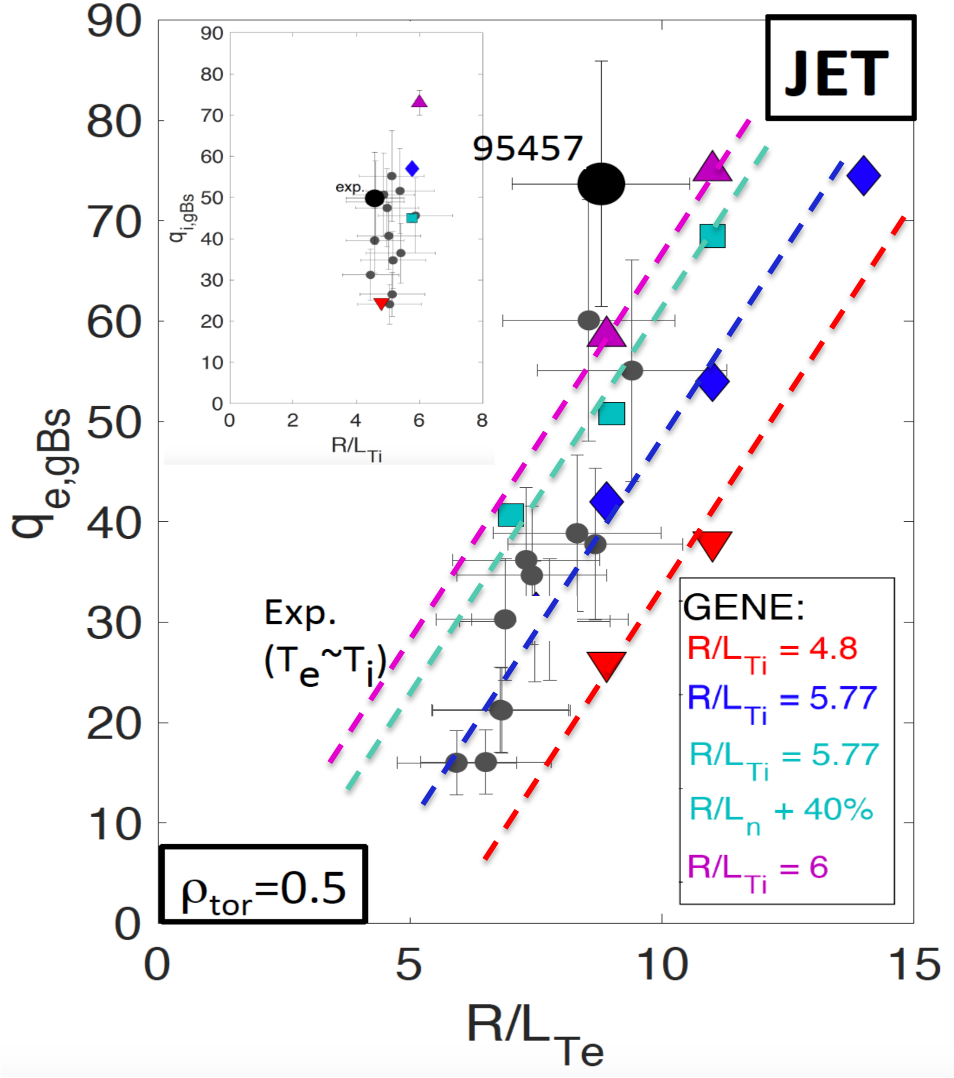
- Ions are very stiff

Nonlinear ion-scale simulations



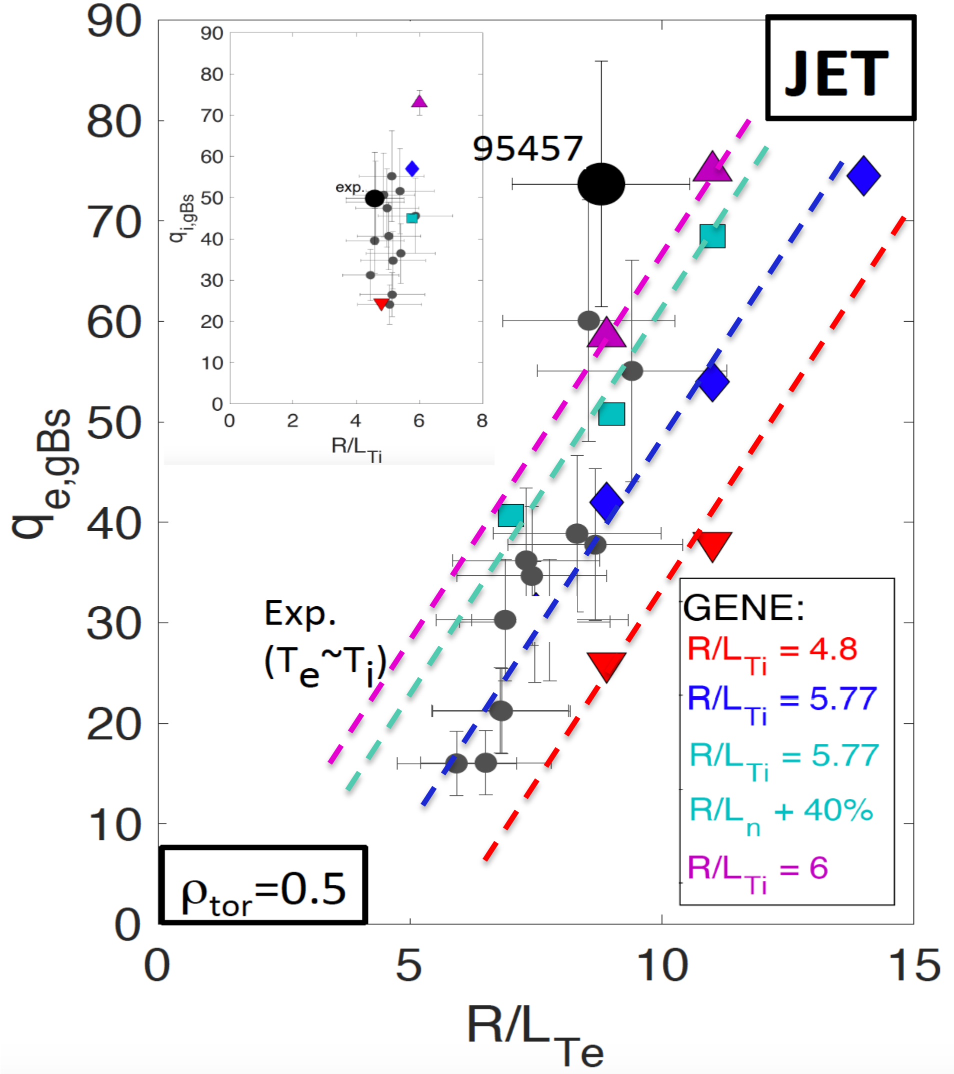
- GENE: compared with experiment (sensitivity to R/L_{Ti} and R/L_{ne} is tested: colored markers);
- Ions are very stiff and R/L_{Ti} also impacts q_e;

Nonlinear ion-scale simulations



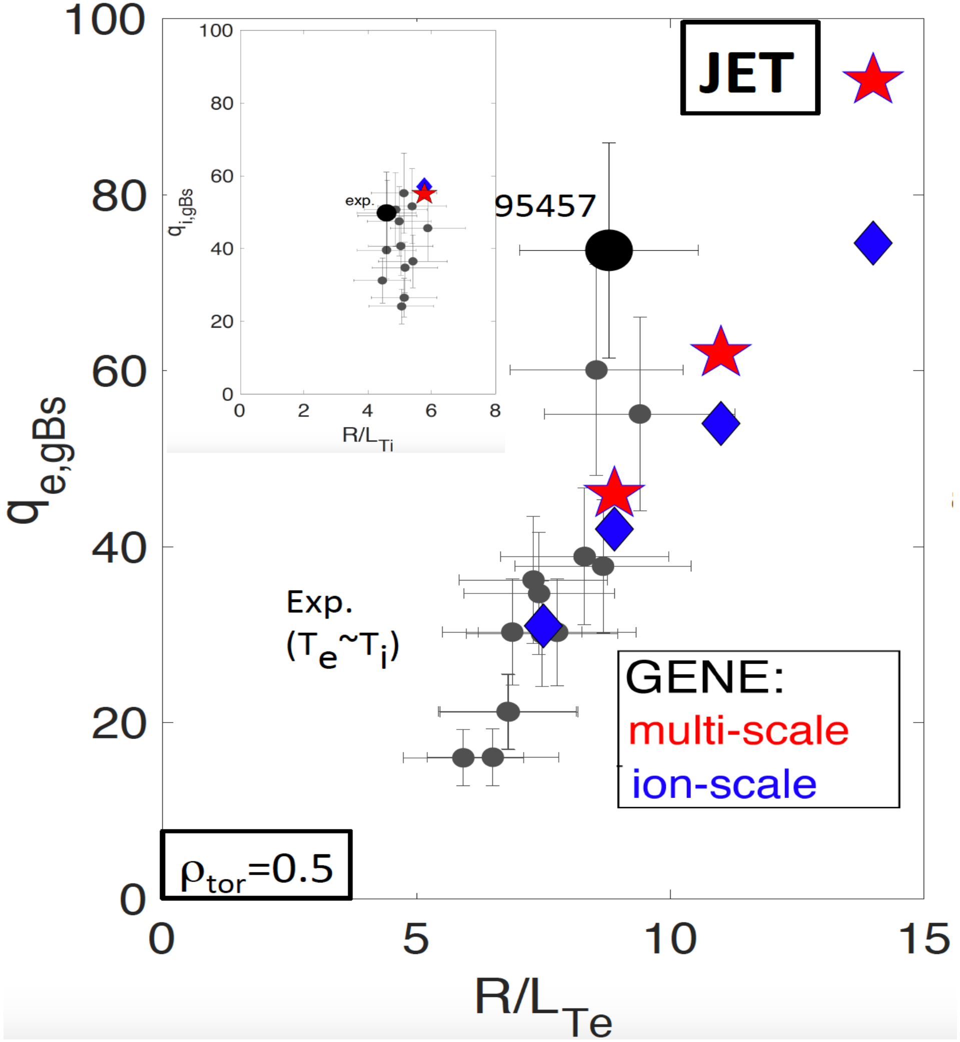
- GENE: compared with experiment (sensitivity to R/L_{Ti} and R/L_{ne} is tested: colored markers);
- Ions are very stiff and R/L_{Ti} also impacts q_e;
- However: they do not impact the stiffness;

Nonlinear ion-scale simulations

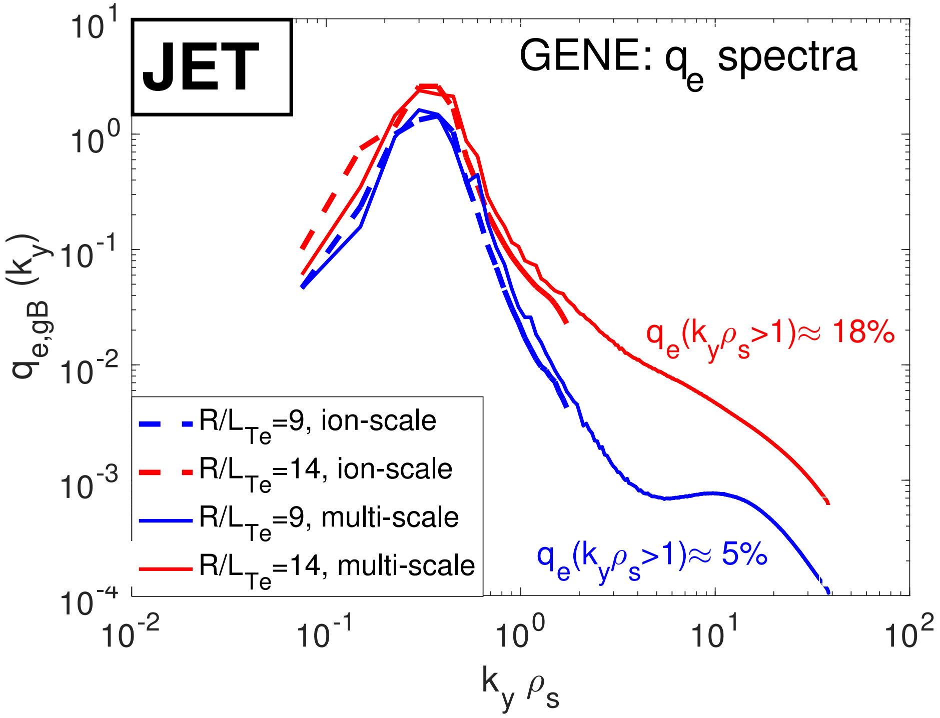


- GENE: compared with experiment (sensitivity to R/L_{Ti} and R/L_{ne} is tested: colored markers);
- Ions are very stiff and R/L_{Ti} also impacts q_e;
- However: they do not impact the stiffness;
- **Possible to match $q_{e,gB}$ but not the stiffness with ion-scale runs.**

Nonlinear multi-scale simulations



Electron heat flux spectra:



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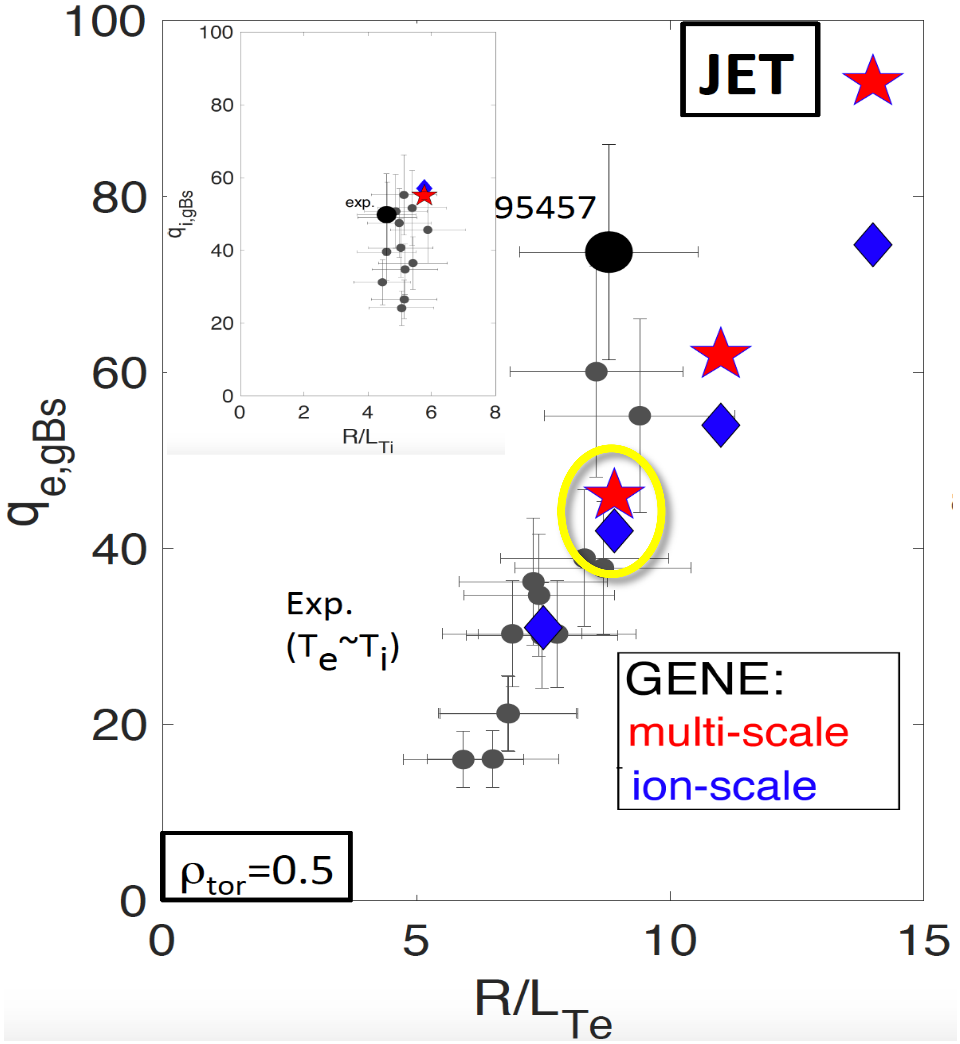
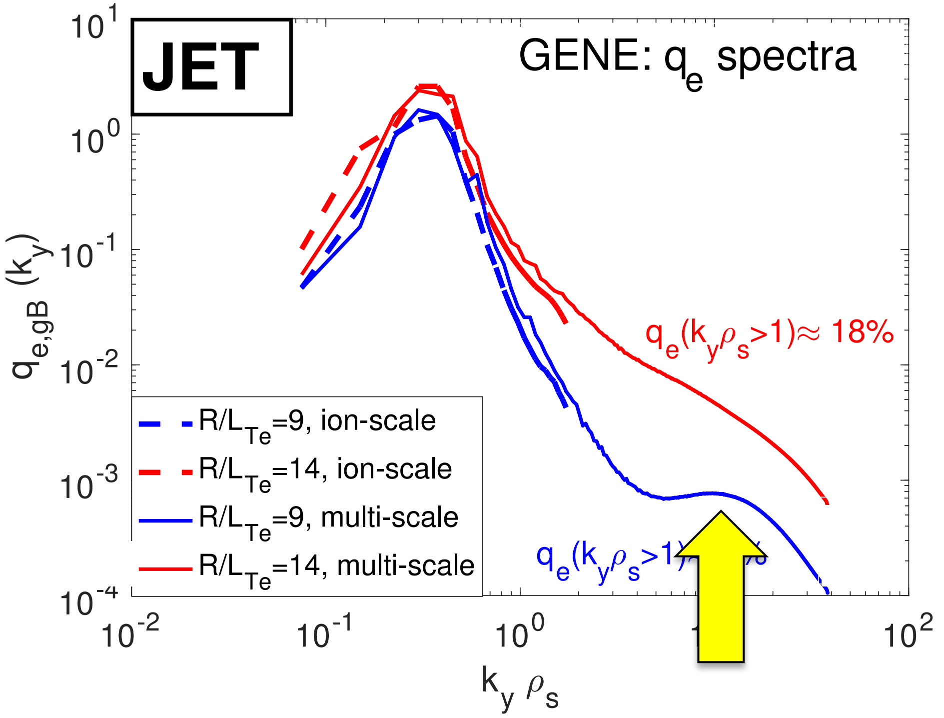
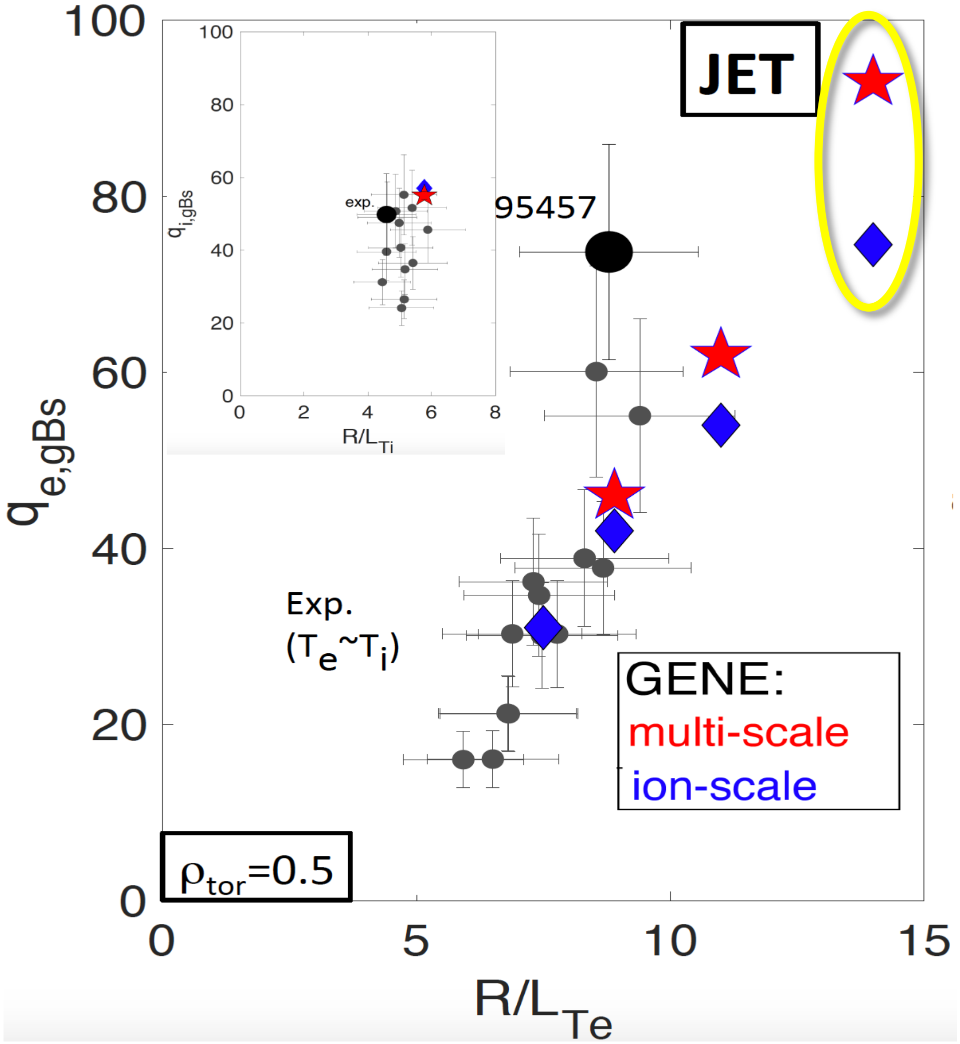


Electron heat flux spectra:

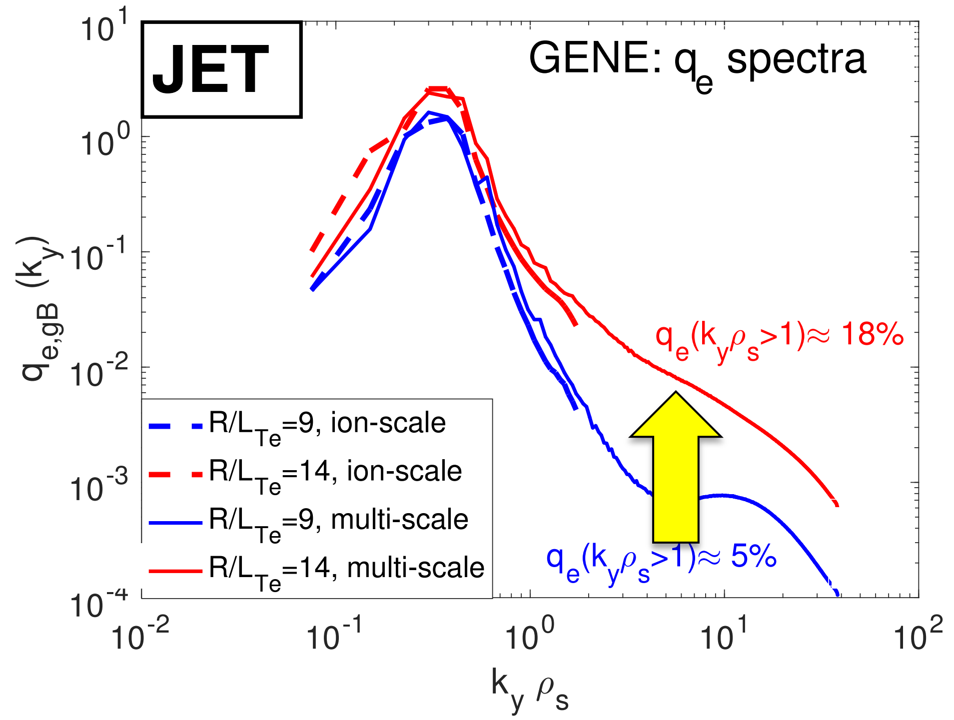


- Impact of ETGs on q_e: negligible (~5%) at exp. R/L_{Te}=9

Nonlinear multi-scale simulations

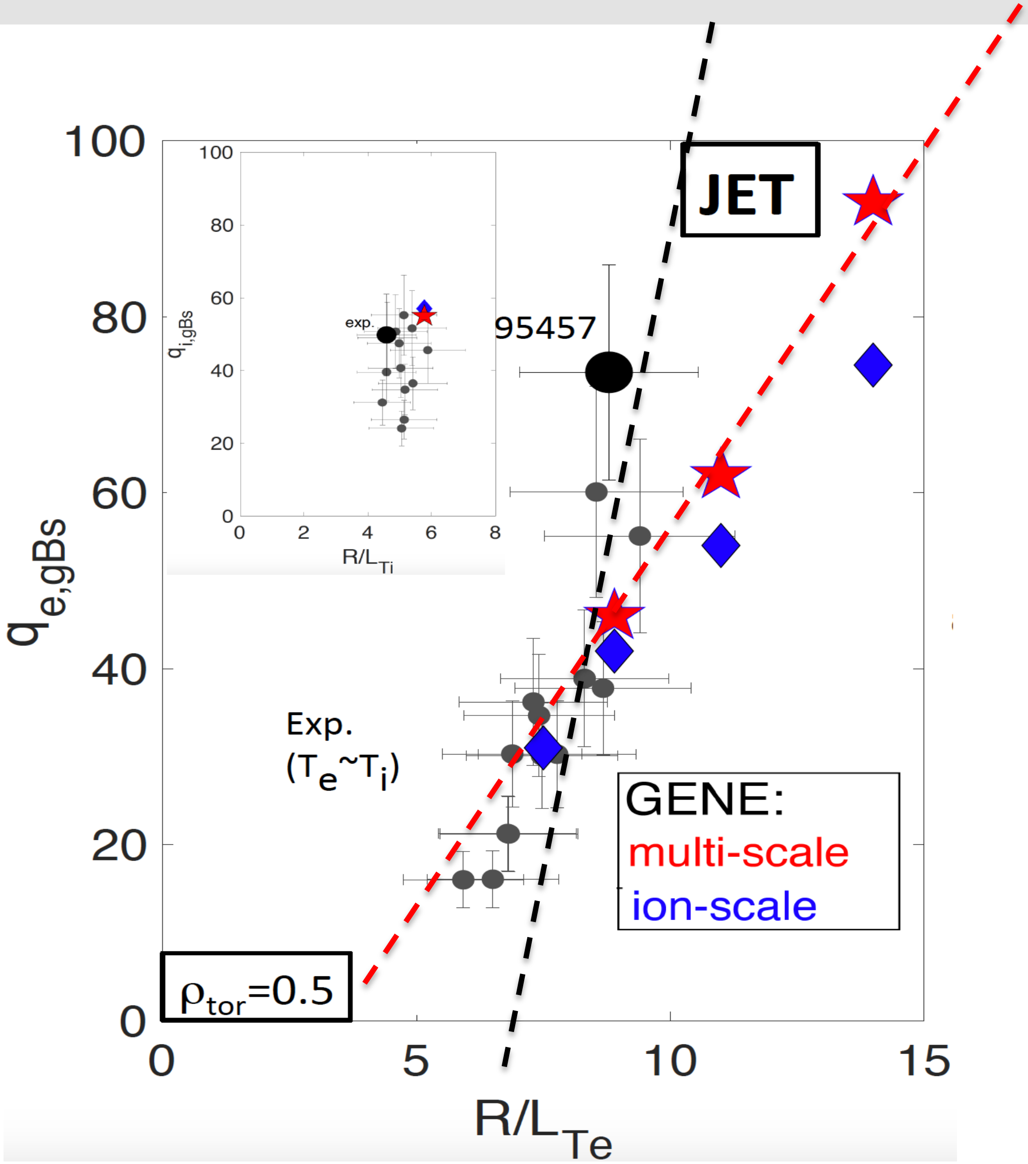


Electron heat flux spectra:

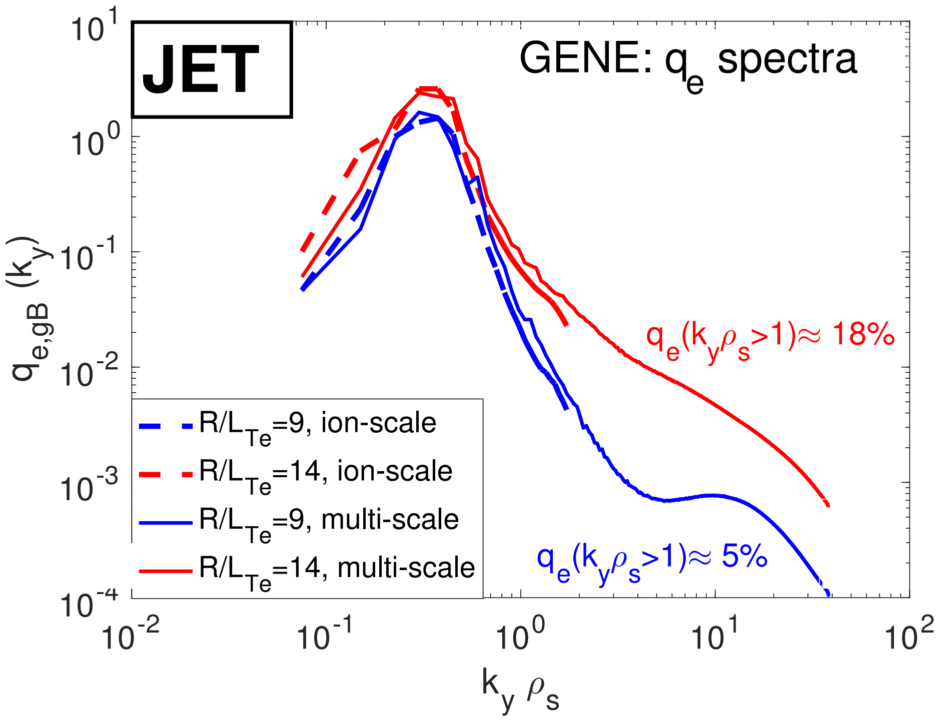


- Impact of ETGs on q_e: negligible (~5%) at exp. R/L_{Te}=9, **moderate** (~18%) at **R/L_{Te}=14**;

Nonlinear multi-scale simulations



Electron heat flux spectra:



- Impact of ETGs on q_e: negligible (~5%) at exp. R/L_{Te}=9, **moderate** (~18%) at **R/L_{Te}=14**;
- Multi-scale stiffness: **moderate**, it **still does not explain the exp. Stiffness.**

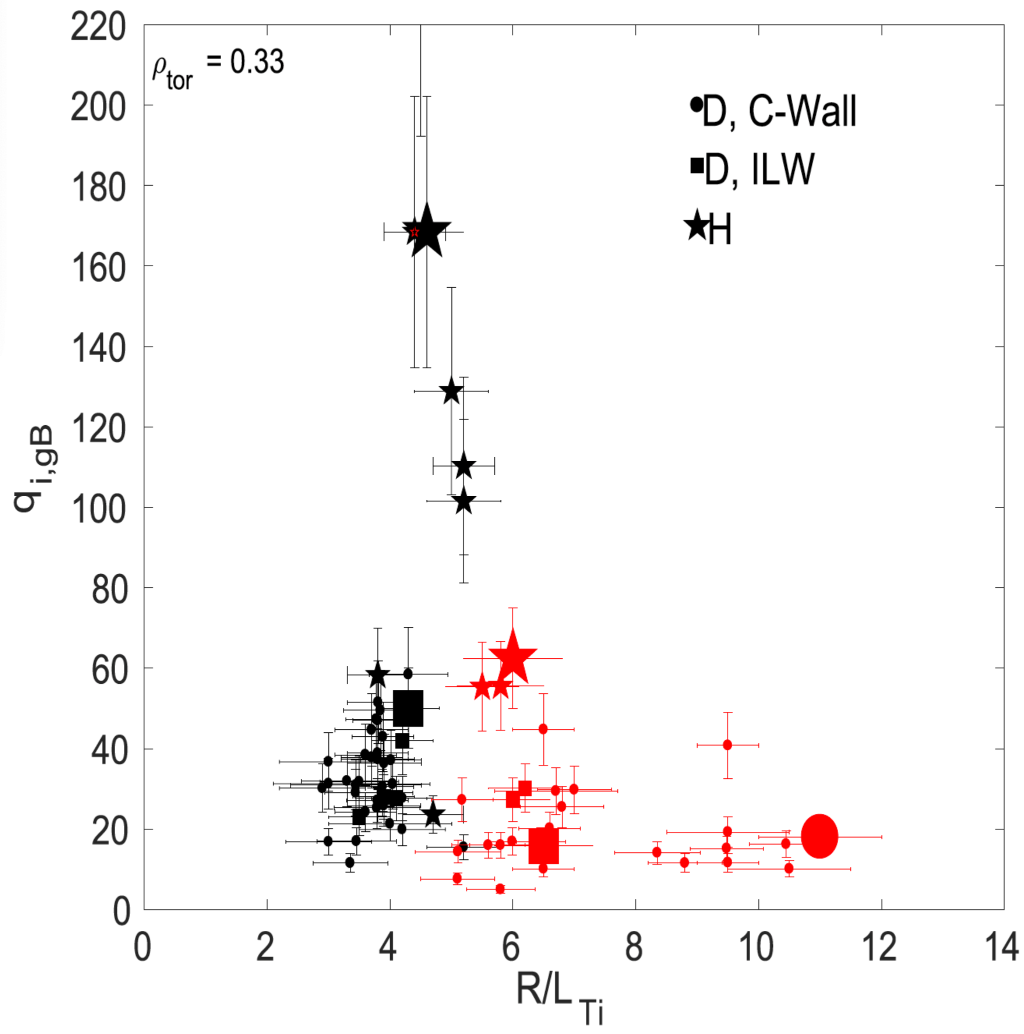
4th topic

Gyrokinetic modelling of the isotope effect on the core ion temperature stiffness, comparing recent JET tritium discharges with older deuterium ones (ongoing work).

Previous work: comparing H and D in the inner core

[N. Bonanomi et al., Nucl. Fusion 59 (2019) 096030]

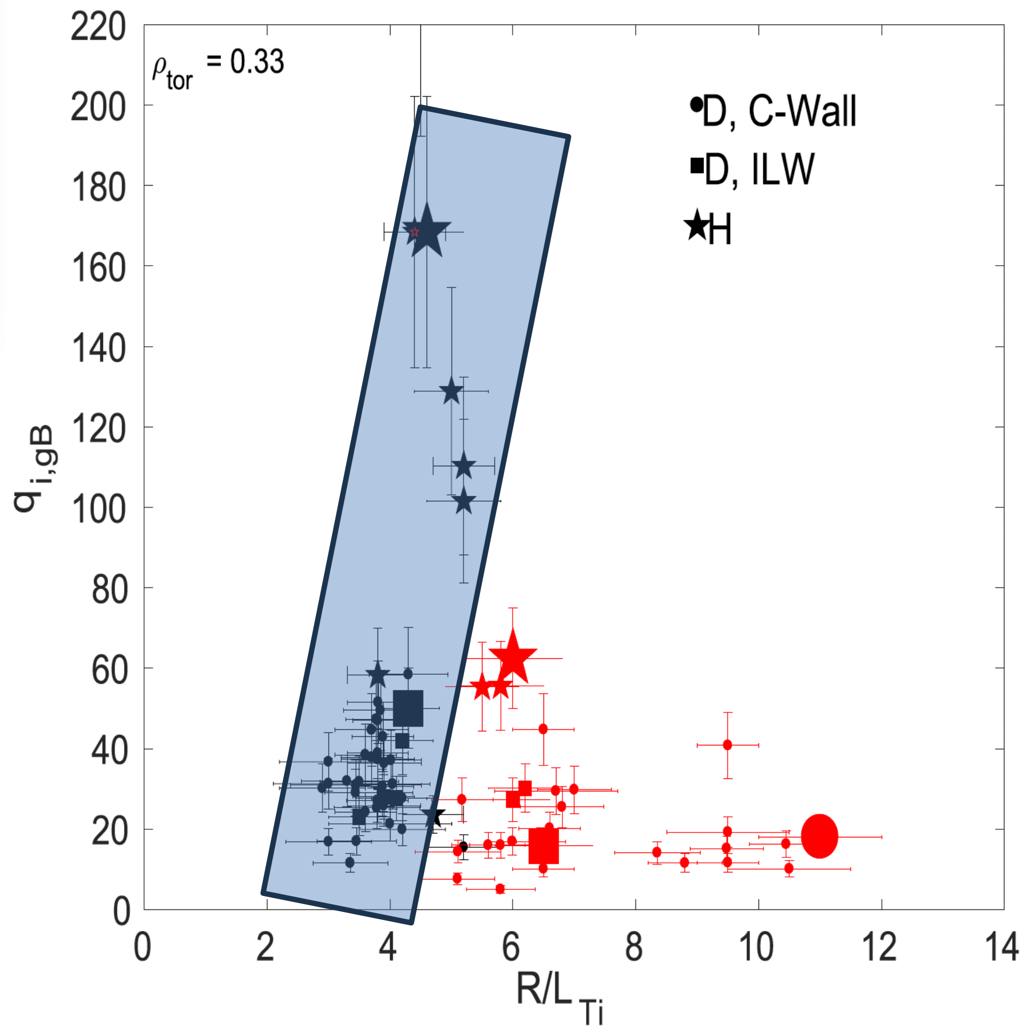
- Hydrogen and deuterium JET L-modes:



Previous work: comparing H and D in the inner core

[N. Bonanomi et al., Nucl. Fusion 59 (2019) 096030]

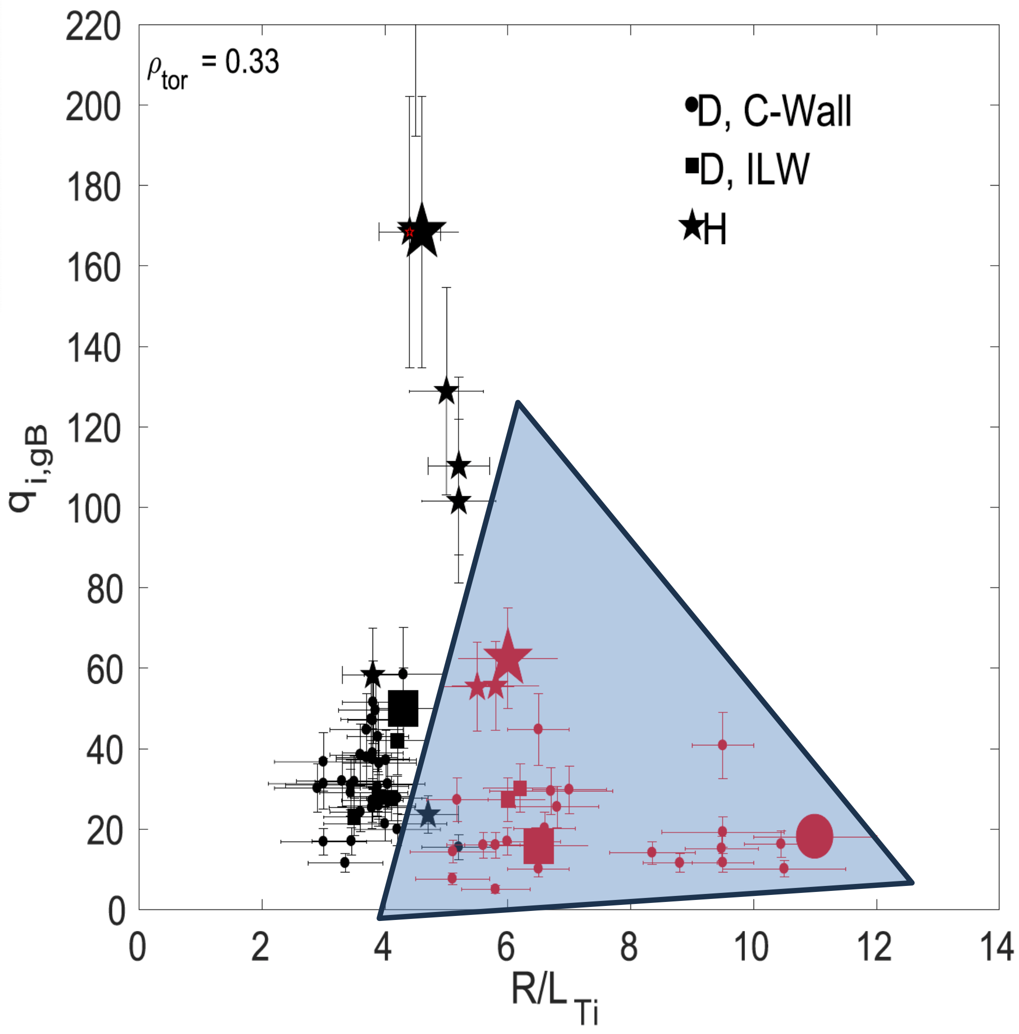
- Hydrogen and deuterium JET L-modes:
- Lower NBI power



Previous work: comparing H and D in the inner core

[N. Bonanomi et al., Nucl. Fusion 59 (2019) 096030]

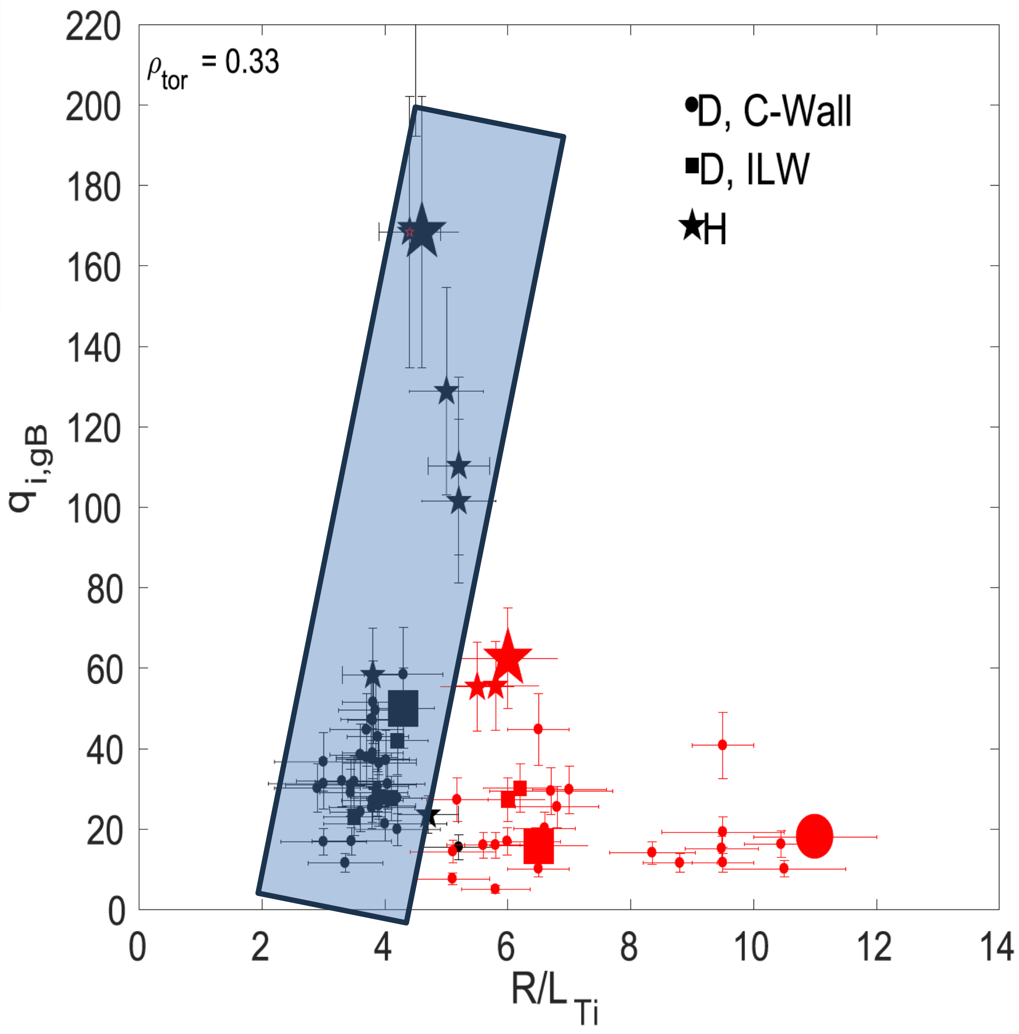
- Hydrogen and deuterium JET L-modes:
- Lower NBI power ⟷ higher NBI power;



Previous work: comparing H and D in the inner core

[N. Bonanomi et al., Nucl. Fusion 59 (2019) 096030]

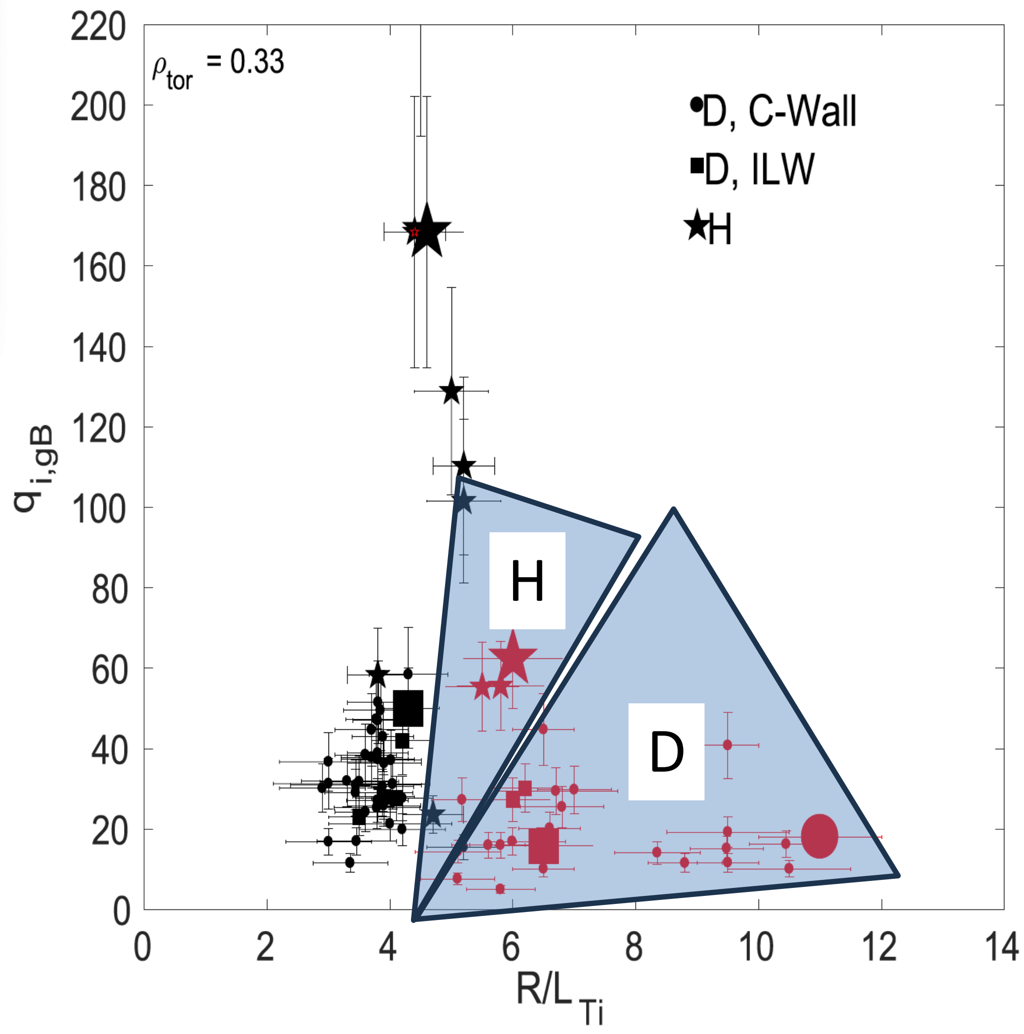
- Hydrogen and deuterium JET L-modes:
- Lower NBI power ⟷ higher NBI power;
- Lower NBI power: impossible to detect a isotope effect within error bars;



Previous work: comparing H and D in the inner core

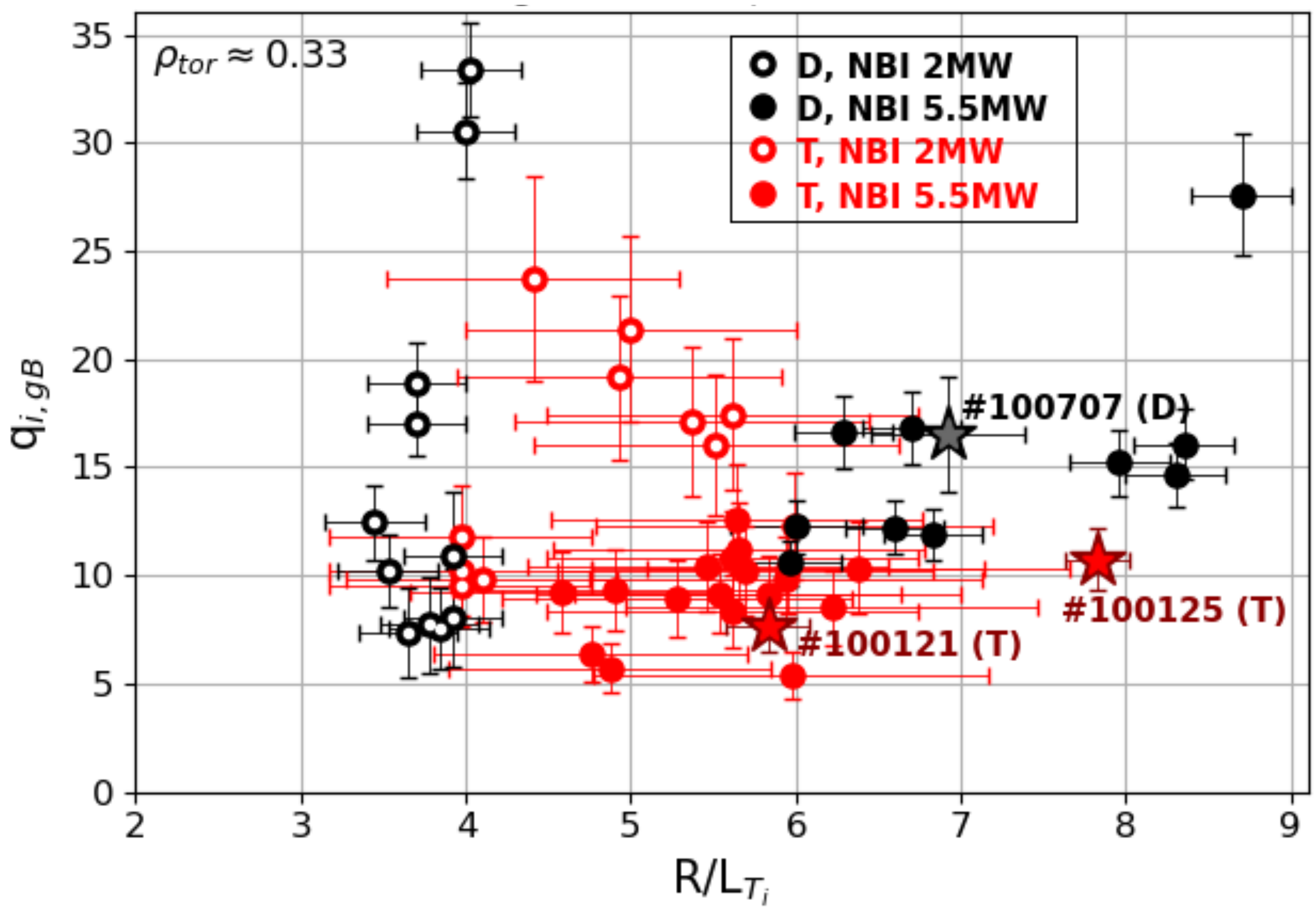
[N. Bonanomi et al., Nucl. Fusion 59 (2019) 096030]

- Hydrogen and deuterium JET L-modes:
- Lower NBI power ⟷ higher NBI power;
- Lower NBI power: impossible to detect a isotope effect within error bars;
- Higher NBI power: **lower stiffness** (higher T_i peaking) **in D**, **explained by GENE:** larger effect of nonlinear FI stabilization in D, due to lower FI pressure in H compared with D (different heating power settings and schemes in H and D).



Isotope dependence of D and T ion stiffness in JET

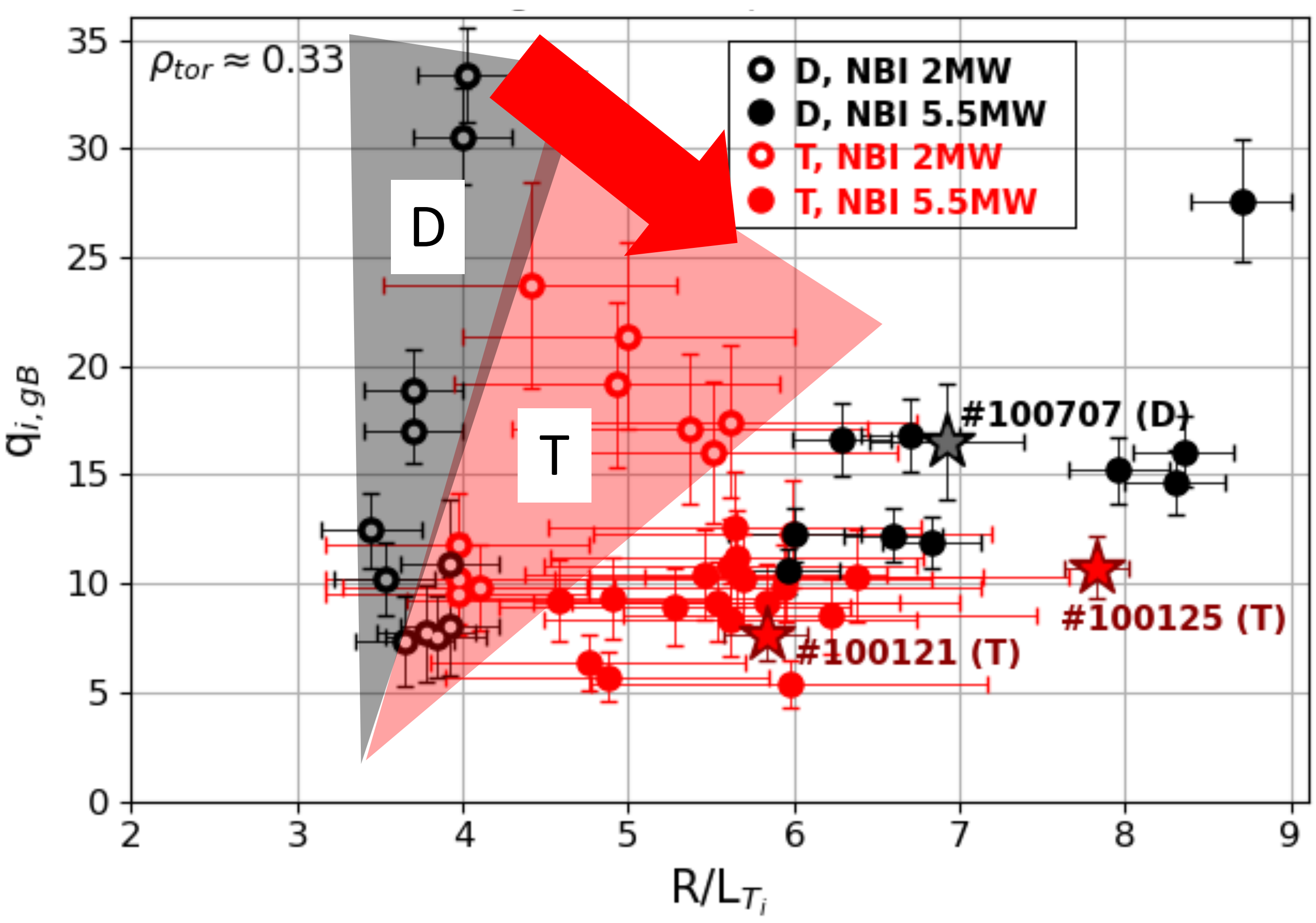
We want to repeat this analysis, comparing the D pulses with recent dedicated ones in T



Outline

Lower NBI power:

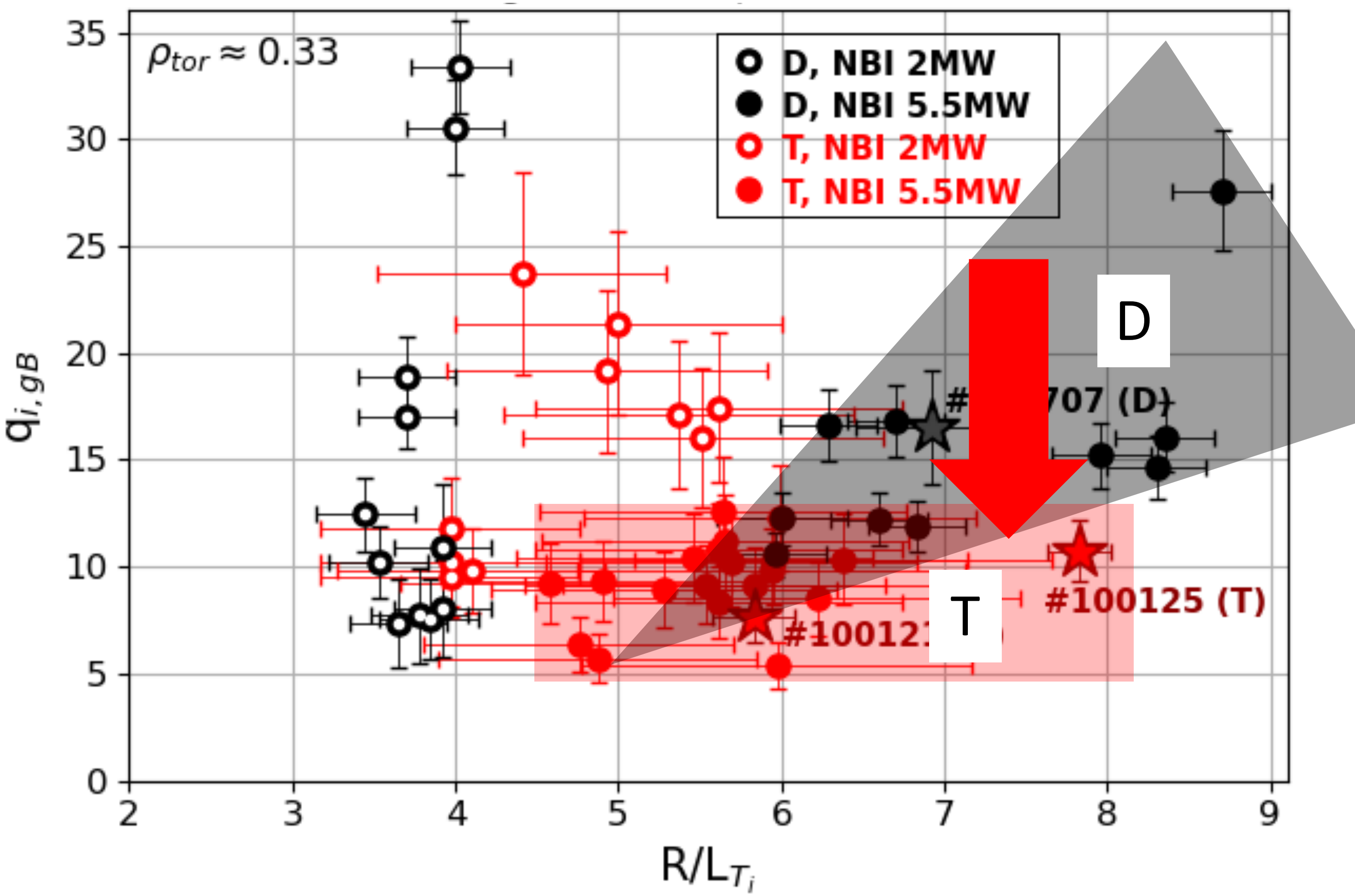
Comparing D and T,
Differently from H-D analysis, the stiffness in T seems lower than in D, outside experimental uncertainties



Outline

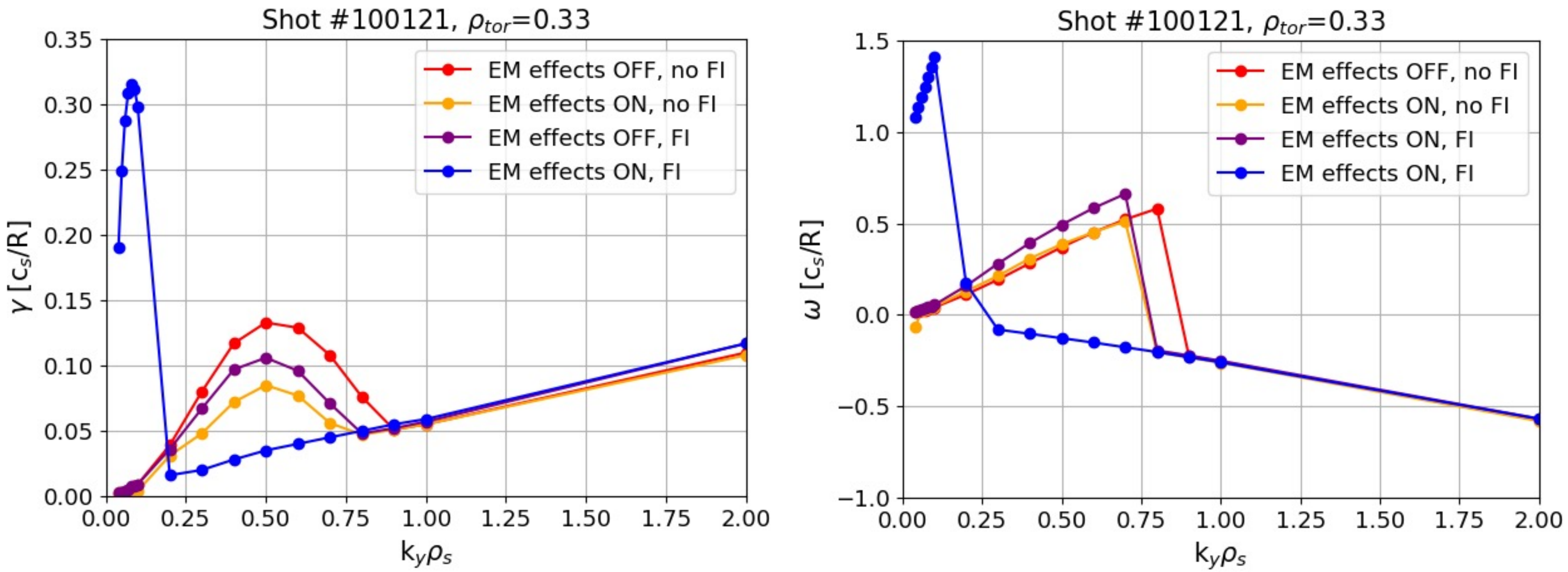
Higher NBI power:

stiffness in T seems lower than in D, with very small stiffness in T



Preliminary linear simulations at $\rho_{tor} = 0.33$

GENE linear simulations for high NBI power JET T pulse #100121:



- Large EM stabilization of ITGs;
- Large FI ES and EM stabilizing effect on ITGs;
- Possible role of FI in explaining the lower stiffness in T compared with D.

Conclusion

- An extensive modelling work has been performed at JET in view of DT operation, and it is going on, investigating plasma conditions of interest for fusion reactor operation;

- The heat and particle transport has been modelled, interpreting JET discharges, learning physics mechanisms that will be important in reactor relevant conditions.

In particular:

- High-β regime: accounting for EM stabilization of micro-turbulence, correctly including the contribution of fast ions (from ICRH and/or NBI), is necessary to reproduce the experimental flux levels;

- Isotope effect: different physics ingredients can introduce a beneficial effect of increasing the isotope mass, differently from the simple gyro-Bohm scaling, and they have to be included in a consistent way to make reliable predictions.

- Ion-electron multi-scale transport and effect of ETGs on electron heat transport: the underlying theory is still under development, and the database of available nonlinear gyrokinetic multi-scale simulations has to be considerably expanded (this needs consistent numerical resources).

- All these mechanisms are sometimes only partially included, or even completely missing, in the actual quasi-linear models that are used to predict the profiles of future plasmas, therefore a massive work is needed to fill this gap.