Turbulent Dynamics of Tokamak Plasmas (TDoTP)

UK Atomic Energy Authority

Turbulent transport in the core of high-β spherical tokamaks and predictions for STEP

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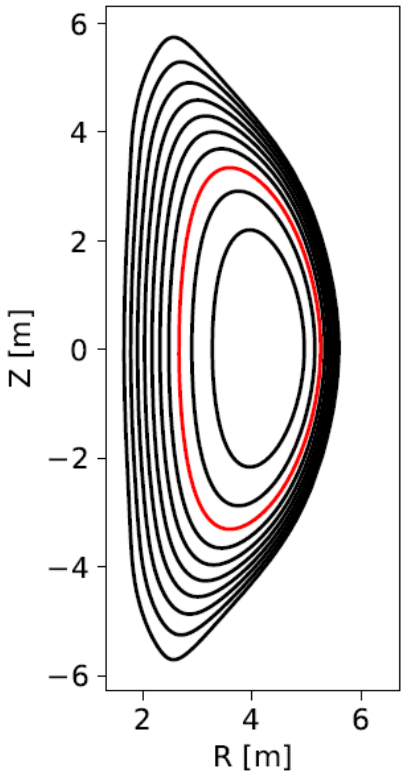
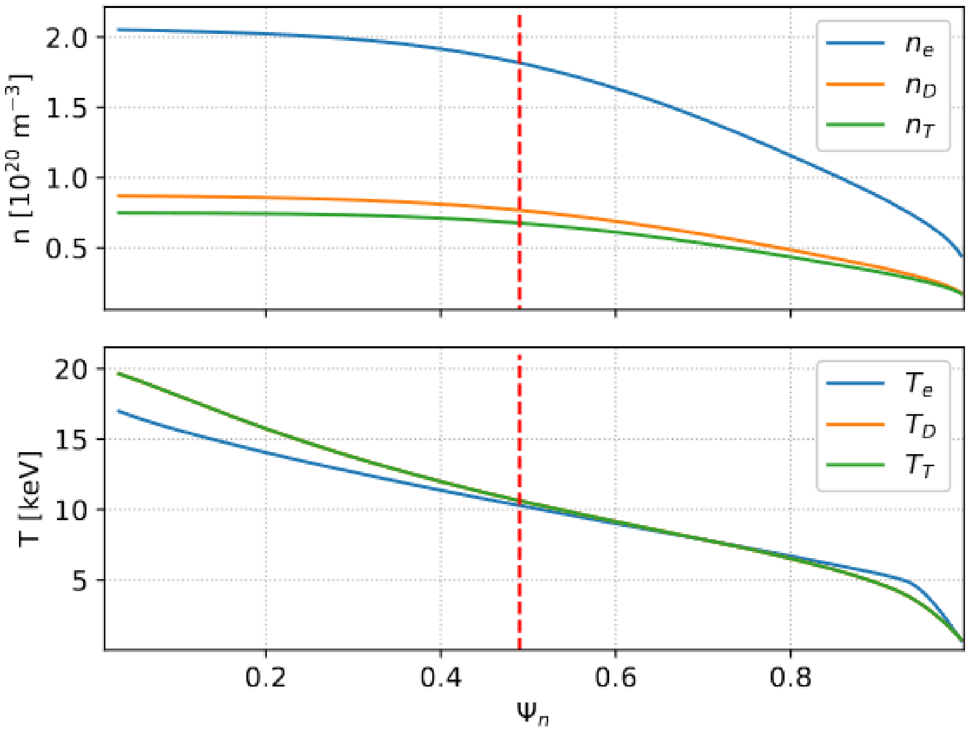
Outline

- The STEP flat top operating point
- Gyrokinetic linear analysis: mode characterisation and sensitivity
- Gyrokinetic nonlinear analysis: turbulent transport prediction
    - Effect of equilibrium flow shear
    - Sensitivity study
- Conclusions

STEP reference case: GK analysis at $\Psi_n = 0.5$





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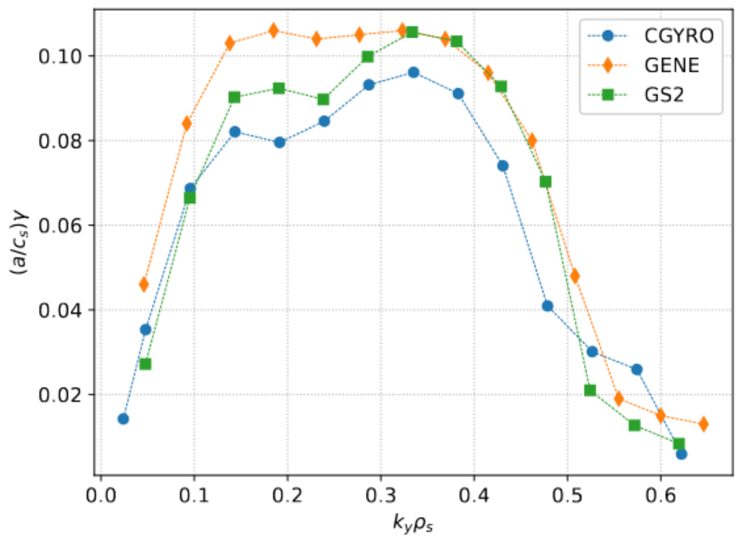
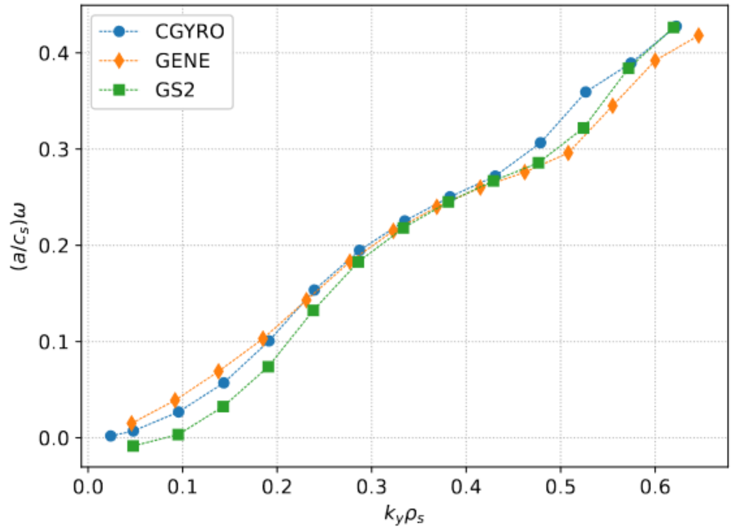
r [m]	1.3	a/L_{n_T}	0.99
R [m]	4.0	a/L_{T_e}	1.58
A_{surf} [m^2]	370	a/L_{T_D}	1.82
P_{surf} [MW]	400	a/L_{T_T}	1.82

- Linear results in D. Kennedy, M. Giacomin *et al*, submitted to Nucl. Fusion (arXiv:2307.01670).
- Nonlinear results in M. Giacomin, D. Kennedy *et al*, submitted to Nucl. Fusion (arXiv:2307.01670).

Gyrokinetic linear analysis

- Linear simulations carried out with CGYRO, GENE and GS2 show relatively good agreement.
- Three species are included: electron, deuterium and tritium.
- Effect of impurities on growth rate is relatively weak. Effect of fast α particles is currently being investigated.
- Mode unstable at very low k_y (toroidal mode number $n > 2$).
- No instability at electron scale.

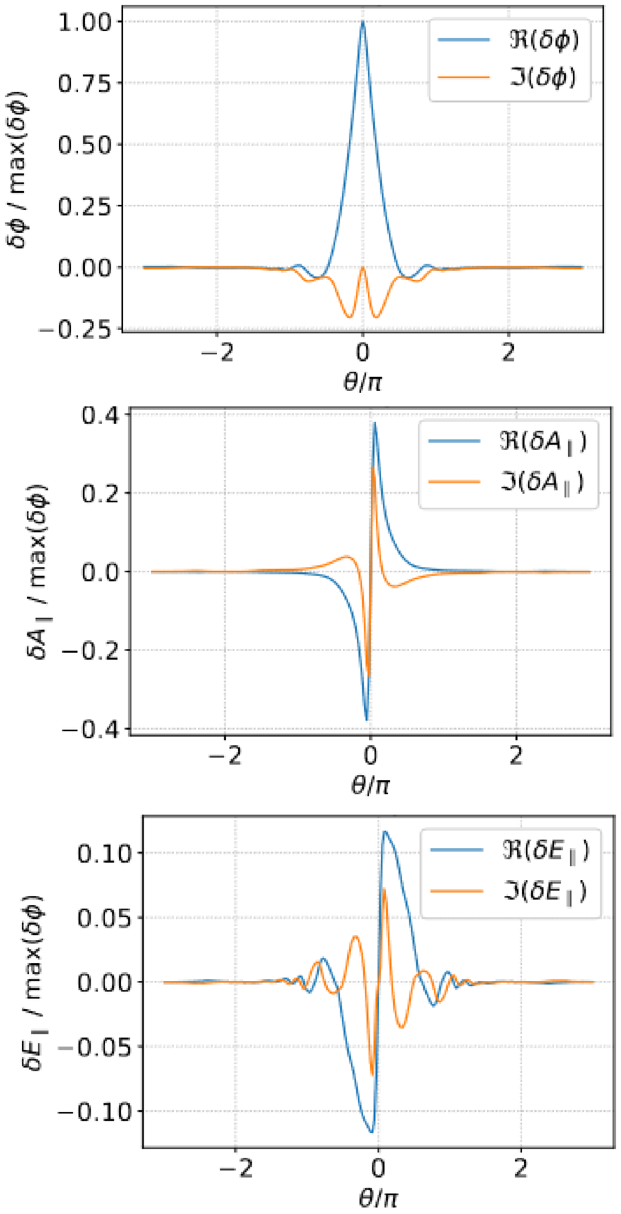




Properties of the dominant mode

- Mode frequency in the ion direction.
- Electromagnetic ($|\delta A_\parallel| \simeq |\delta\phi/c_s|$).
- Twisting parity.
- MHD-like ($|a\delta E_\parallel| \ll |\delta\phi|$).

Kinetic Ballooning Mode (KBM)



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- Mode frequency in the ion direction.
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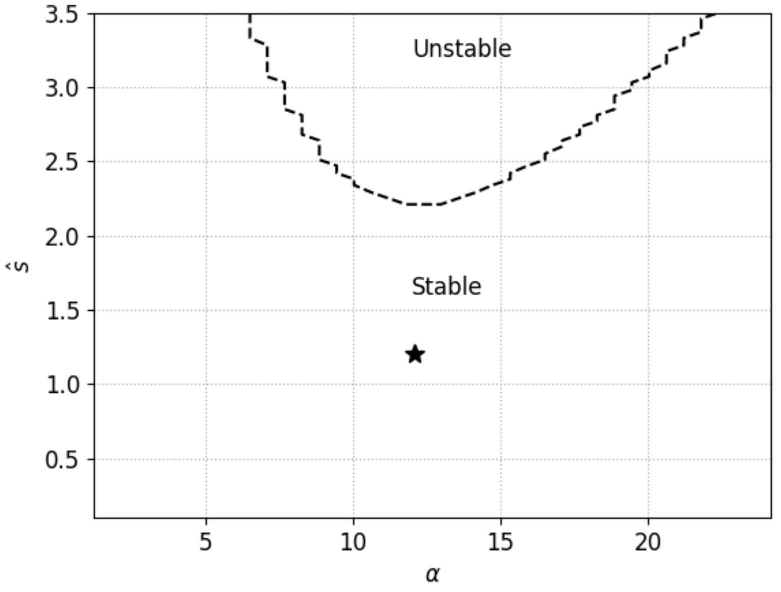
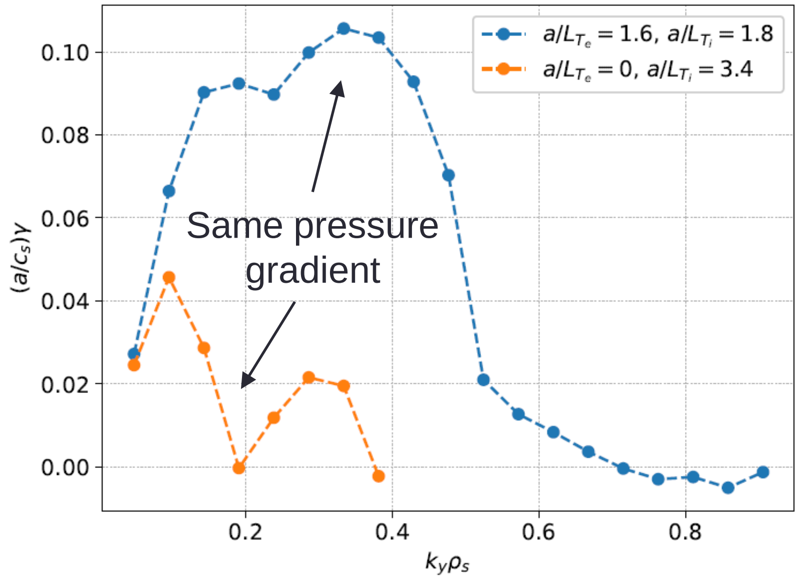
- MHD-like ($|a\delta E_{\parallel}| \ll |\delta\phi|$).
- Below the ideal MHD ballooning limit.
- Stronger sensitivity to a/L_{T_e} than to a/L_{T_i}.
- $\delta B_{\parallel}$ is essential for this instability.





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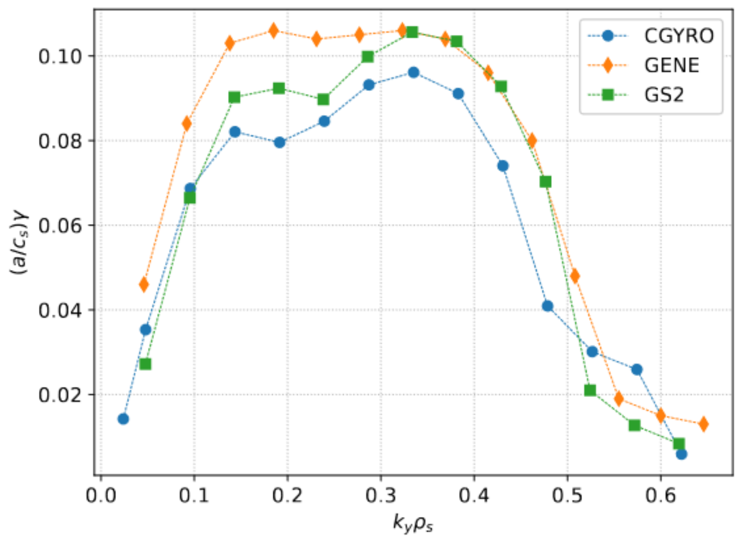
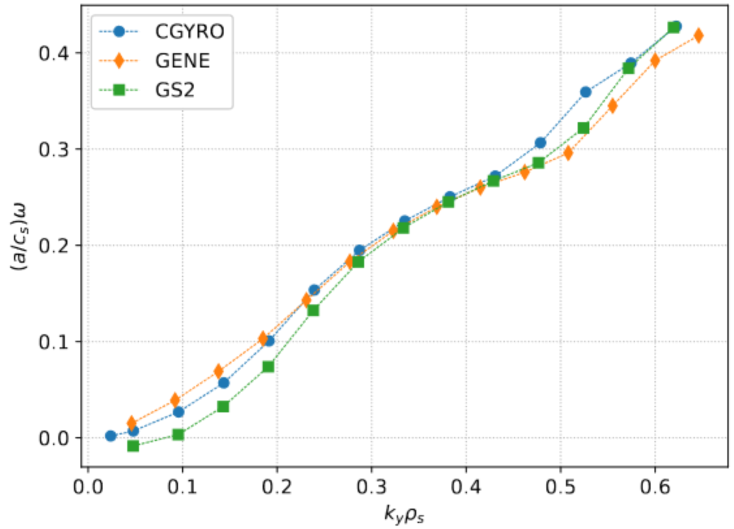
We can label this mode as hybrid KBM

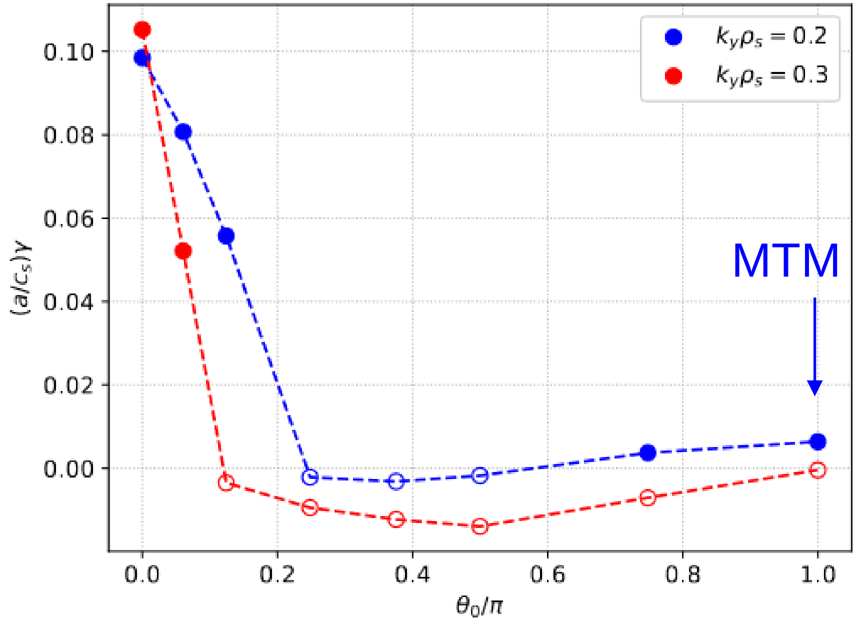




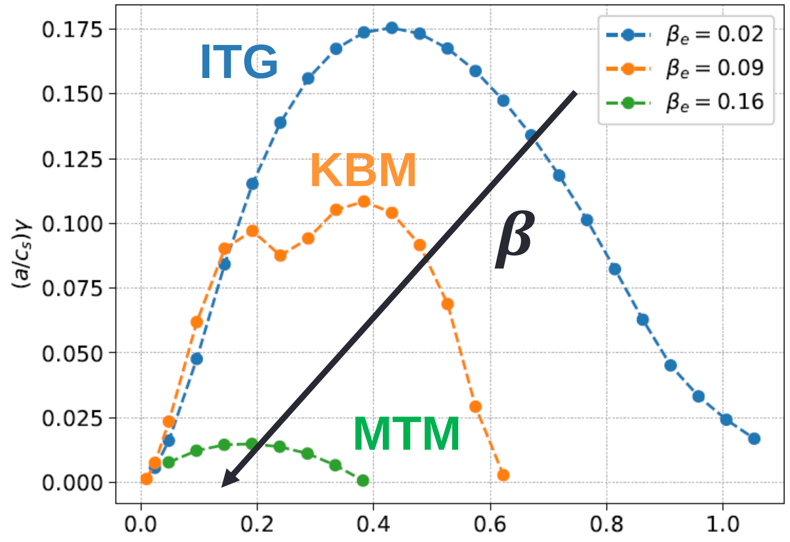
High sensitivity to θ_0 and β'

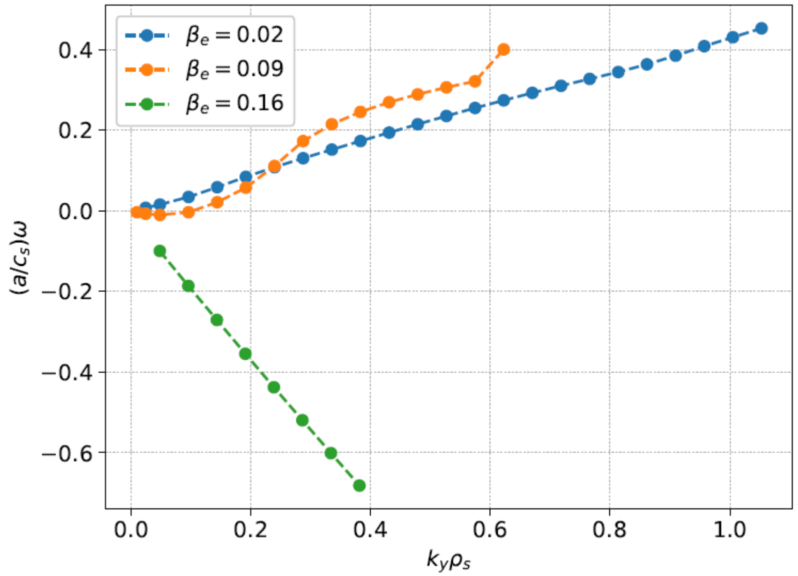
- The hybrid KBM is suppressed at $\theta_0 > 0$: possible important effect of equilibrium flow shear.
- Suppression of hybrid KBMs and transition to a MTM instability at high β' .

θ_0 sensitivity



β scan where β' is varied consistently





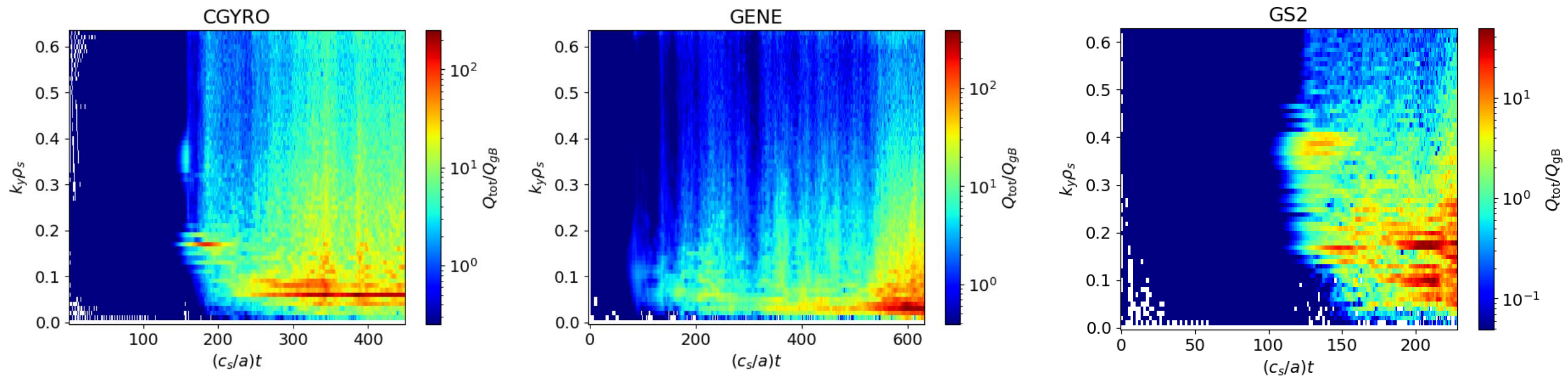
Nonlinear gyrokinetic analysis

- High β and unstable modes at low k_y make local nonlinear simulations challenging.
- Three well established GK codes are used: CGYRO, GENE and GS2.
- Each nonlinear simulation requires more than 10^5 core-hours.
- Pyrokinetics library (https://github.com/pyro-kinetics/pyrokinetics) greatly helps conversion between different input files: aiming to standardize GK analysis.
- The goal of this first nonlinear GK analysis is to assess turbulent transport in this new STEP regime and evaluate potential challenges*.

*First attempts to perform nonlinear gyrokinetic simulations in a regime close to STEP revealed saturation issues (D. Dickinson *et al*, Joint Varenna-Lausanne International Workshop 2022, https://doi.org/10.5281/zenodo.7961621).

Saturation at large heat flux largely driven by low k_y modes

Simulations without equilibrium flow shear

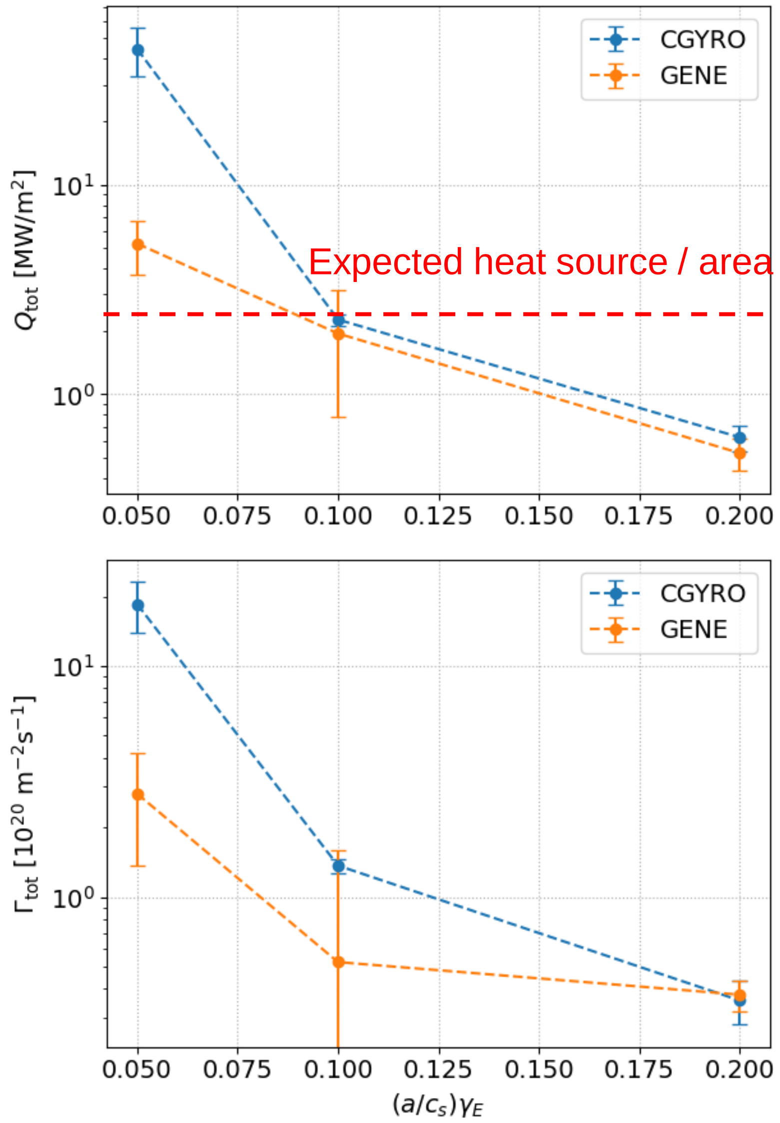


- Heat fluxes several orders of magnitude larger than target value from available sources!
- Modes at $k_y\rho_s < 0.1$ grow slowly but saturate at very large values.
- Strong dependence of linear growth rate on θ_0 suggests importance of flow shear.

Equilibrium flow shear plays a key role in saturation

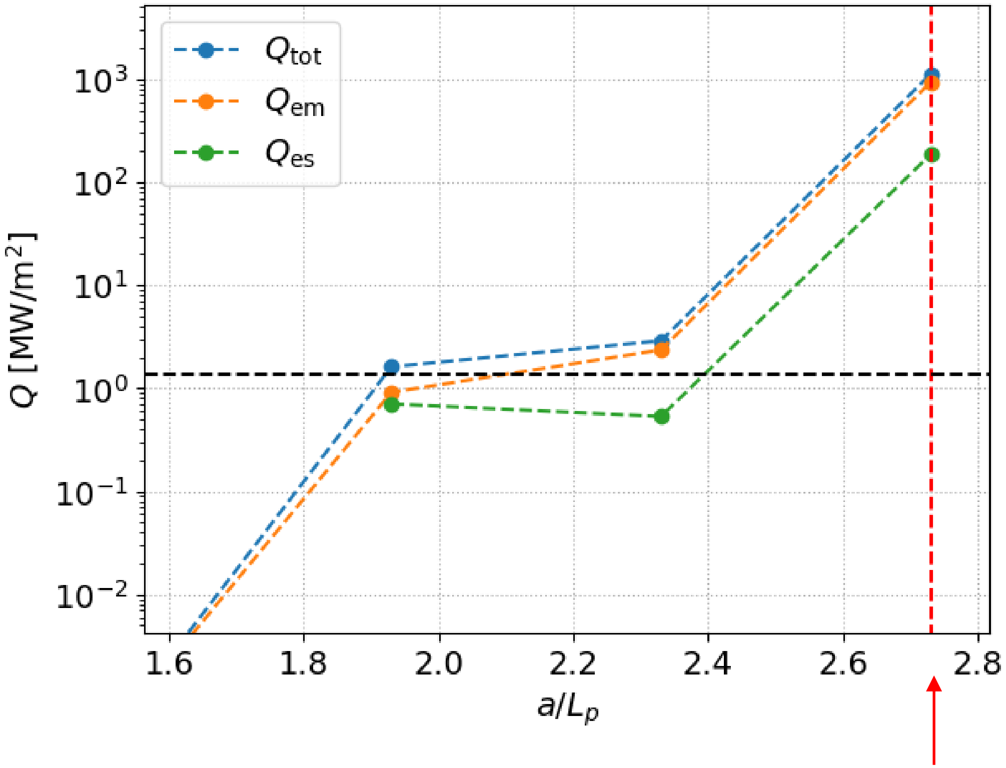
- Equilibrium flow shear reduces the heat flux substantially.
- Particle and heat fluxes values compatible with heating power at $\gamma_E > 0.1\ c_s/a$.
- The flow shear values considered here are comparable with the diamagnetic level.
- Relying entirely on flow shear is risky. No external rotation in STEP and large uncertainty on flux predictions.

Can we mitigate this instability without relying entirely on flow shear?



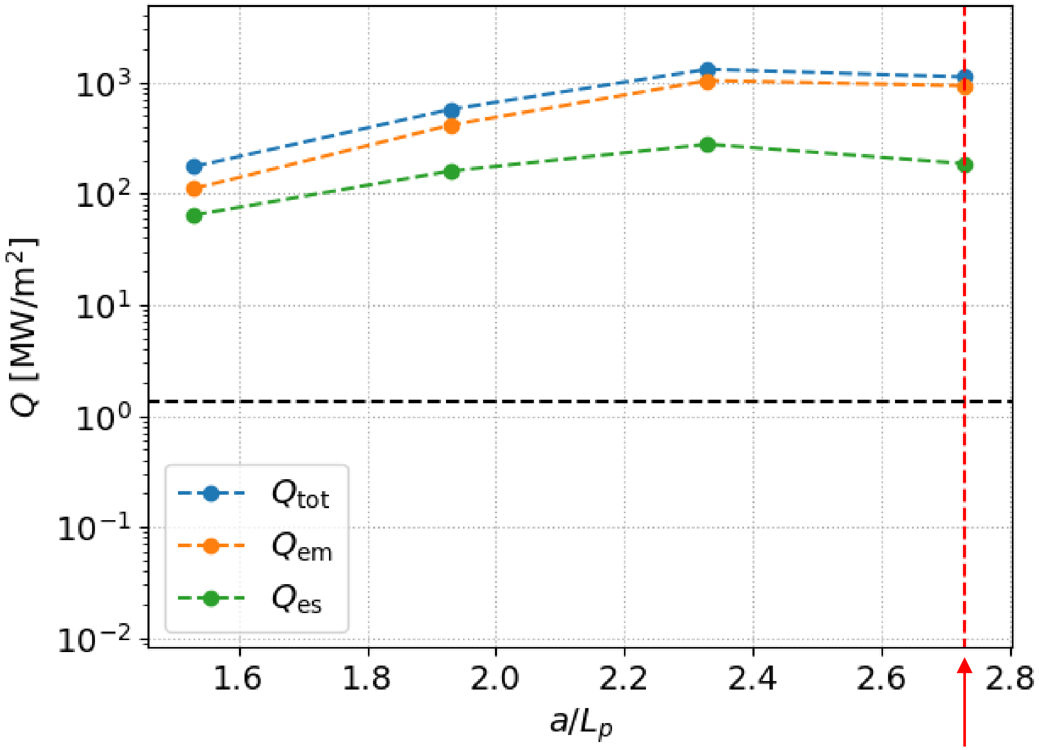
Sensitivity to pressure gradient

Heat flux can be easily reduced by decreasing a/L_{T_e} (and a/L_{T_i}) keeping everything else fixed.



Reference value

But if $\beta' \propto dp/dr$ is varied consistently, the dependence on a/L_p is much weaker …

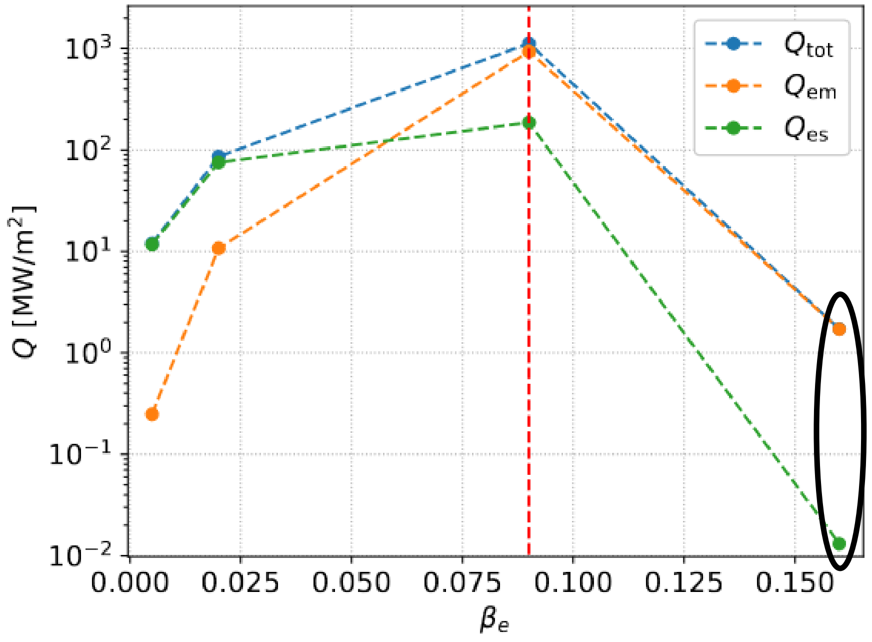


Reference value

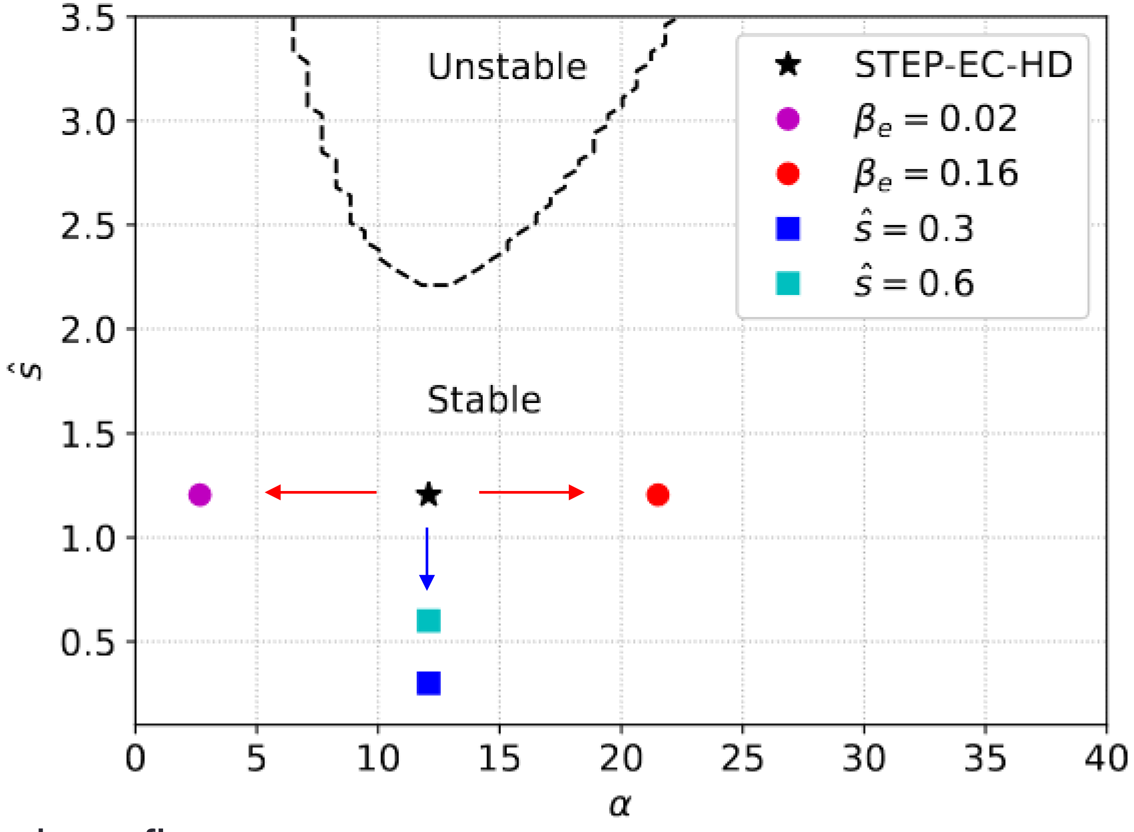
Sensitivity to β and β' (ideal ballooning boundary proximity)

KBM-driven heat flux decreases if

- β (and β') is reduced
- β (and β') is increased

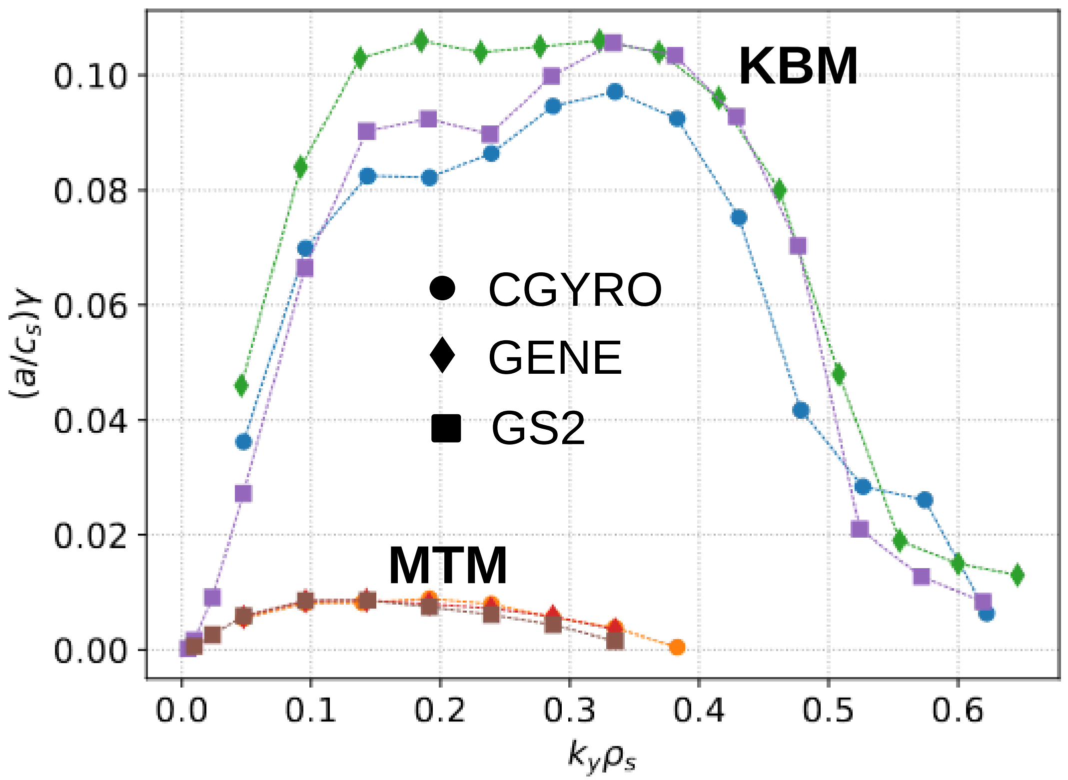


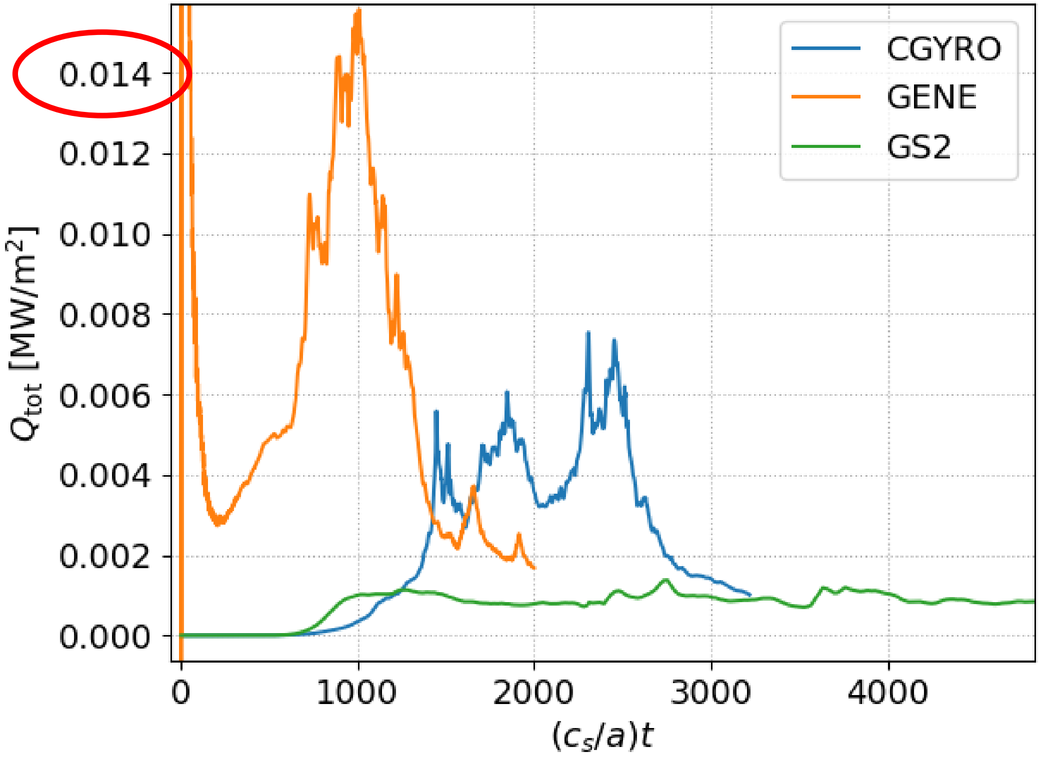
MTM-driven heat flux



The role of subdominant MTMs

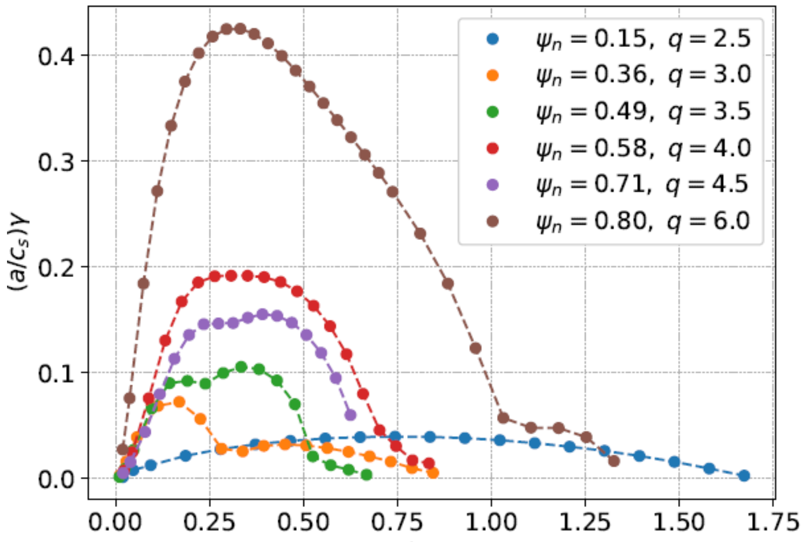
- Subdominant MTMs at $k_y\rho_s < 0.4$
- Subdominant mode are isolated from KBMs by artificially removing $\delta B_\parallel$.
- MTM turbulence may potentially drives large electron heat flux because of magnetic stochasticity [1, 2].
- MTM turbulence is negligible at the radial surface with $\Psi_n = 0.5$.

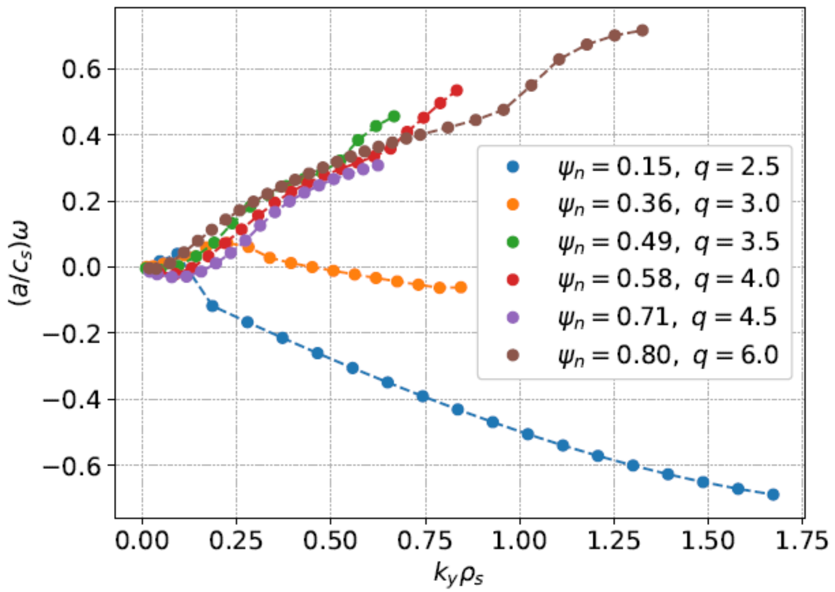




[1] NSTX: Guttenfelder *et al,* PRL 106 (2011)
[2] MAST: Giacomin *et al,* PPCF 65 (2023)

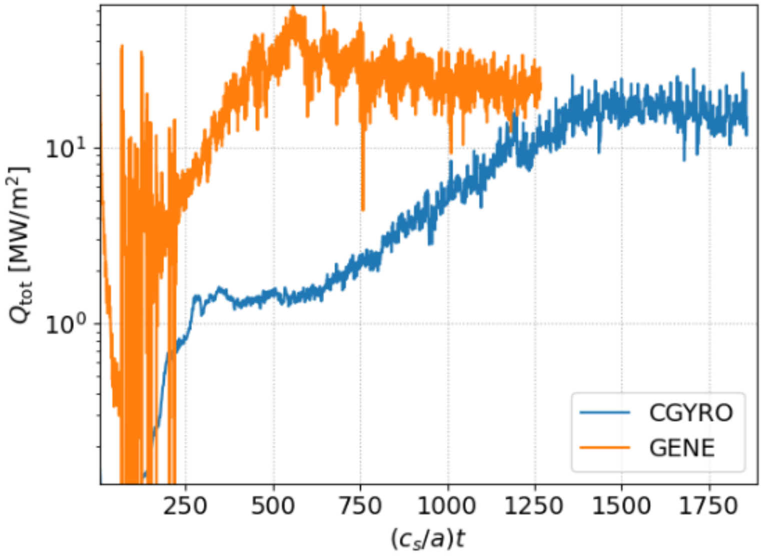
Outlook: Hybrid KBMs unstable across a wide radial range

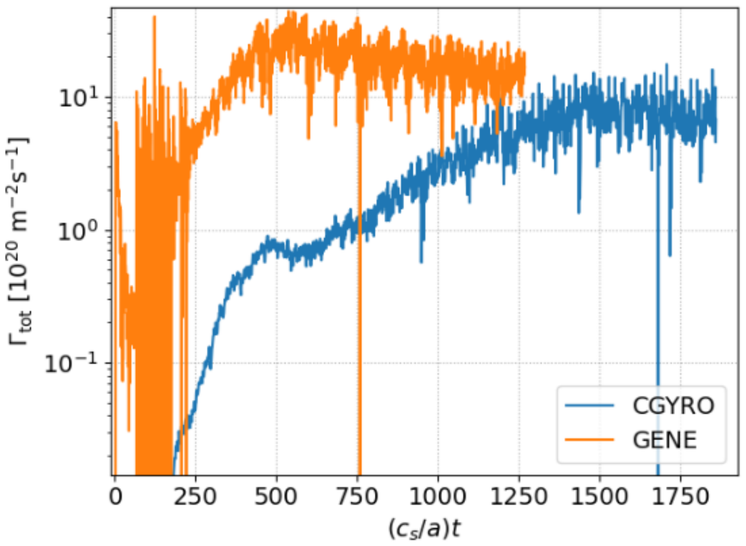




- KBMs dominate in the intermediate and outer core region.
- MTMs dominate in the inner core region.
- Heat flux from KBMs can be reduced to target values with equilibrium flow shear near the diamagnetic level at $\Psi_n \simeq 0.36$.
- Flux-driven simulations are currently being performed with a reduced model built from STEP nonlinear simulations.

Simulations at $\Psi_n \simeq 0.36$ with $\gamma_E \simeq \gamma_{dia}$





Summary and future direction

- Linear analysis:
  - KBM-like instability at low toroidal mode numbers.
  - Strong sensitivity on θ_0 and β'.

- Nonlinear analysis:
  - Heat flux well above target values in absence of equilibrium flow shear.
  - Equilibrium flow shear provides the main saturation mechanism, but with uncertainty.
  - MTMs drive no heat flux at the considered surface.

- Ongoing work:
  - Effect of fast α on turbulence: possible mitigation of hybrid KBMs.
  - Development of reduced transport models (see talk from H. G. Dudding tomorrow morning)
  - Flux-driven STEP simulations to evolve profiles.
  - Investigating global effects: are local simulations reliable in STEP regime?
  - Analysis of the ramp-up: can this flat-top point be reached?
  - Validation in present-day high-β spherical tokamaks such as MAST-U (see talk from B. S. Patel later)

Parameter STEP flat-top operating point

	STEP-EC-HD	STEP-EB-HD
R_{geo}	3.60	3.60
A	1.8	1.8
$B_T\,(R_{\text{geo}})$ [T]	3.2	3.2
I_p [MA]	20.9	22.0
n_{e0} [10^{20} m^{-3}]	2.05	1.98
T_{e0} [keV]	18.0	18.0
κ	2.93	2.93
δ	0.59	0.50
P_{fus} [GW]	1.76	1.77
P_{heat} [MW]	150	154
P_{ECCD} [MW]	150	55.40
P_{EBW} [MW]	0	98.60
P_{rad} [MW]	338	341
Q	11.8	11.5
β_N	4.4	4.1
H98	1.60	1.48
H98*	1.10	1.02
f_{BS}	0.88	0.78
HCD technique	ECCD	ECCD / EBW

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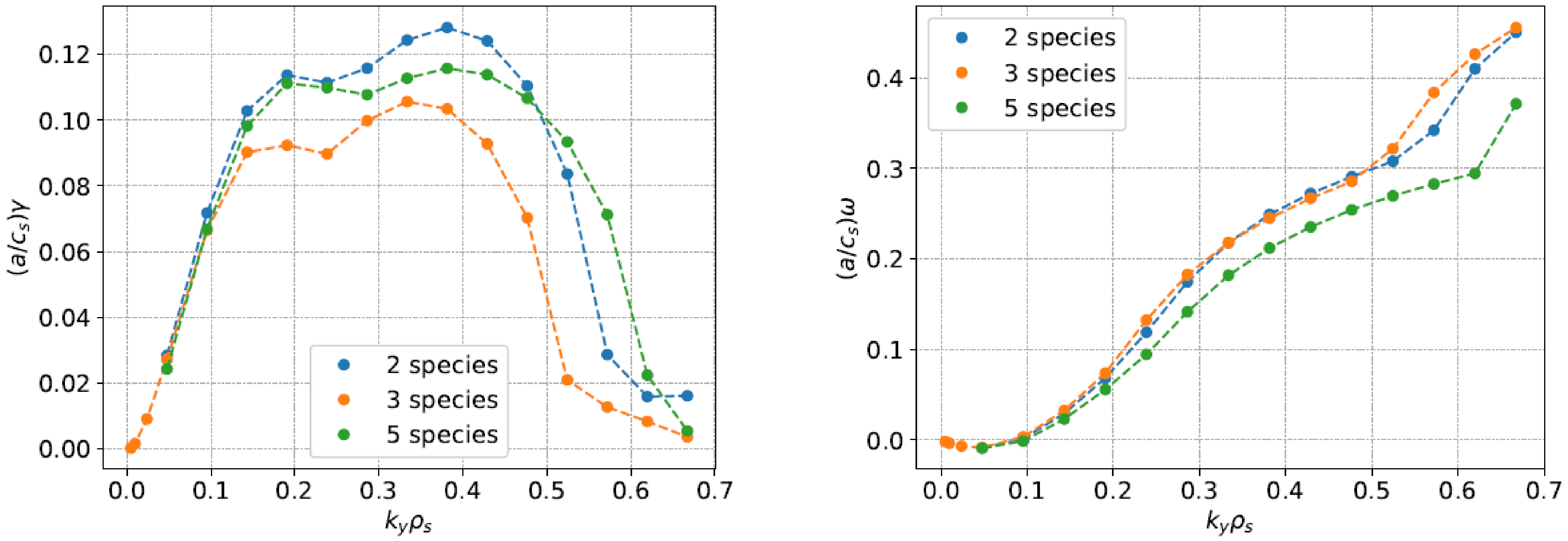
Effect of impurities

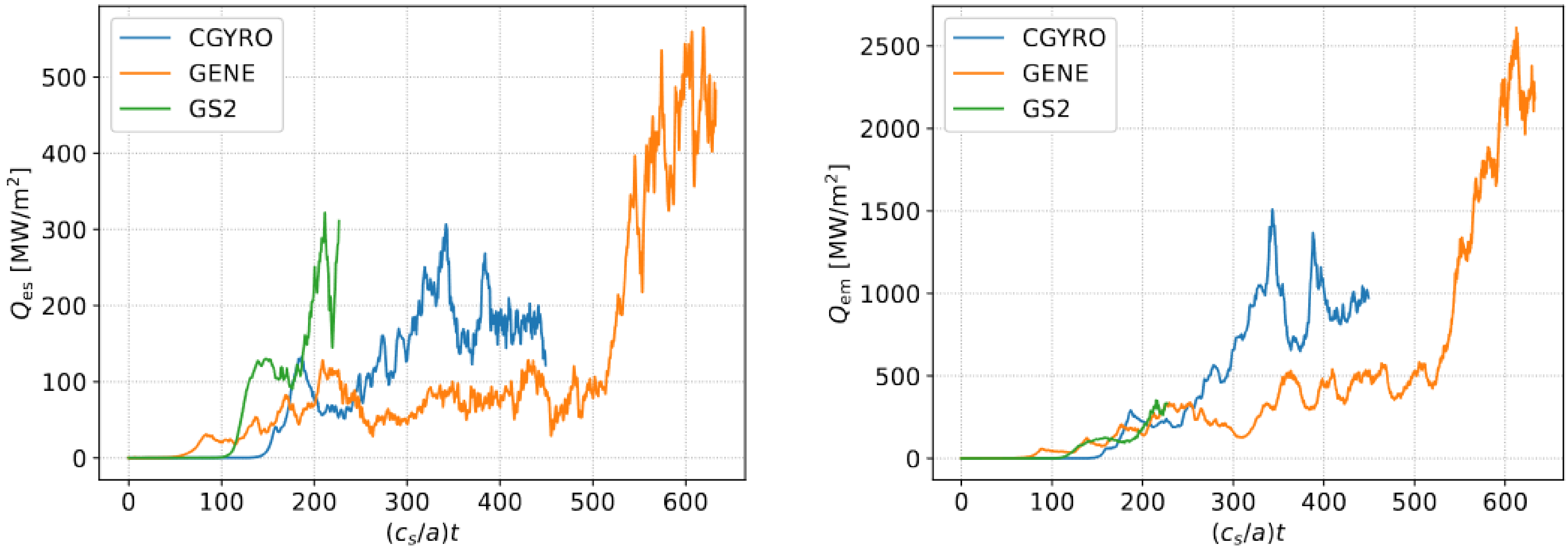
5 species: e, D, T, He (ash), Xe



Heat flux "saturates" at similar large value

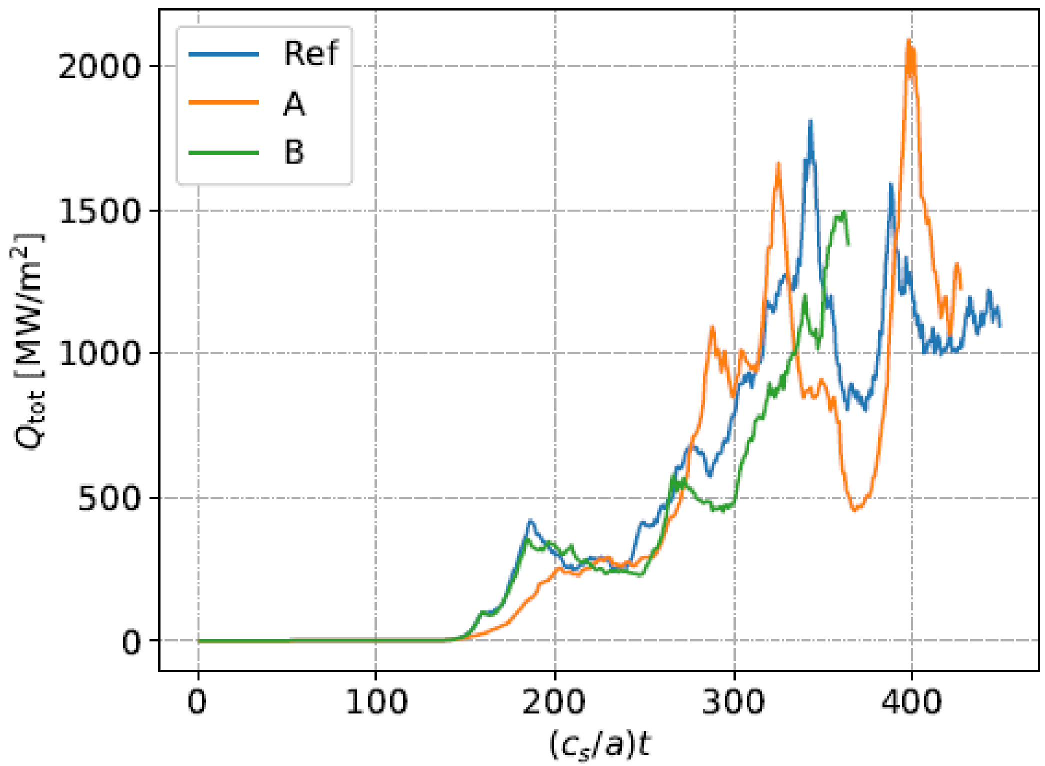
Saturation at large heat flux values robustly predicted by CGYRO, GENE and GS2

Simulations without equilibrium flow shear



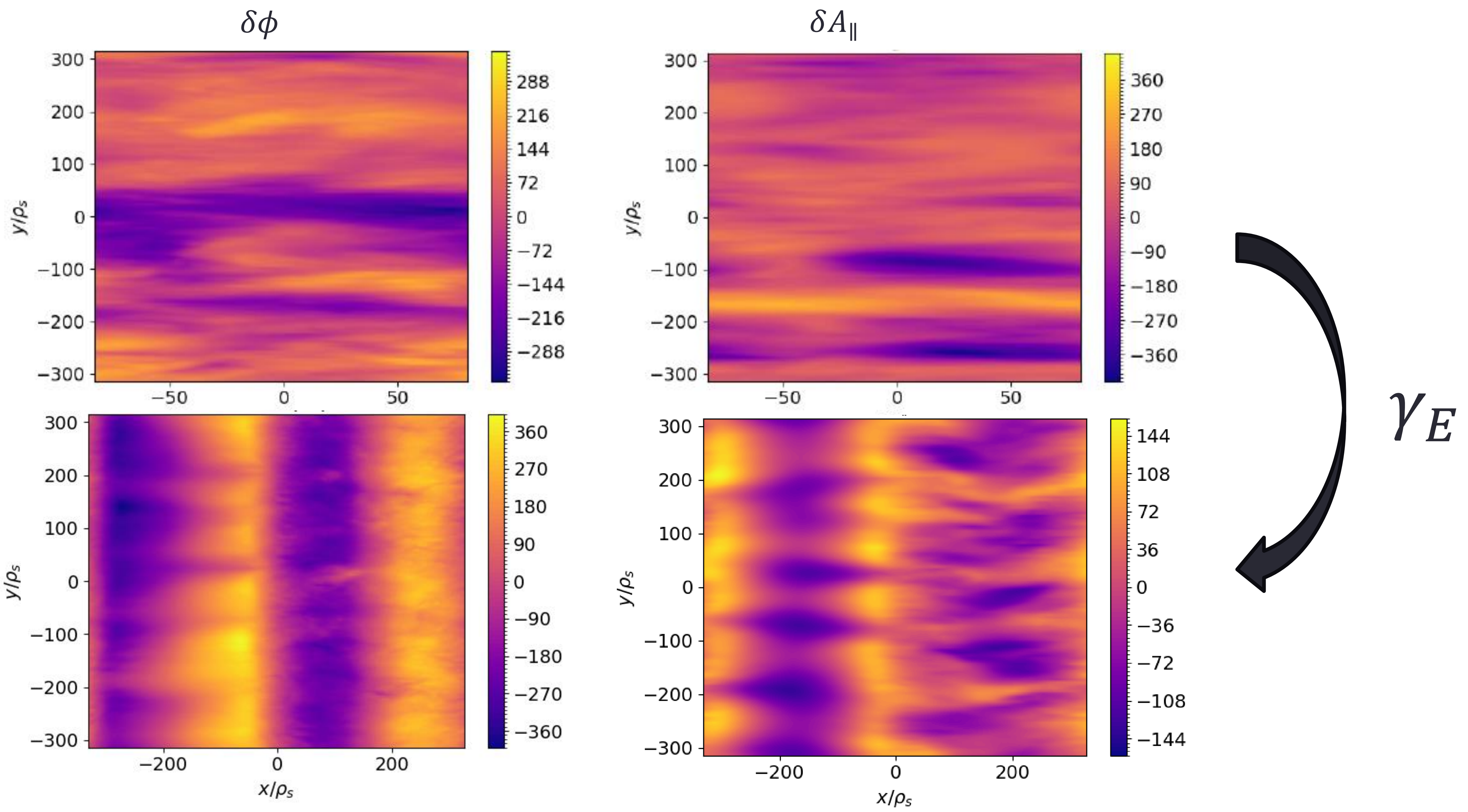
- Heat fluxes several orders of magnitude larger than available sources!
- Electrostatic and electromagnetic fluxes are comparable.
- Numerical convergence studies show that simulations are well converged.

Numerical convergence of nonlinear simulations

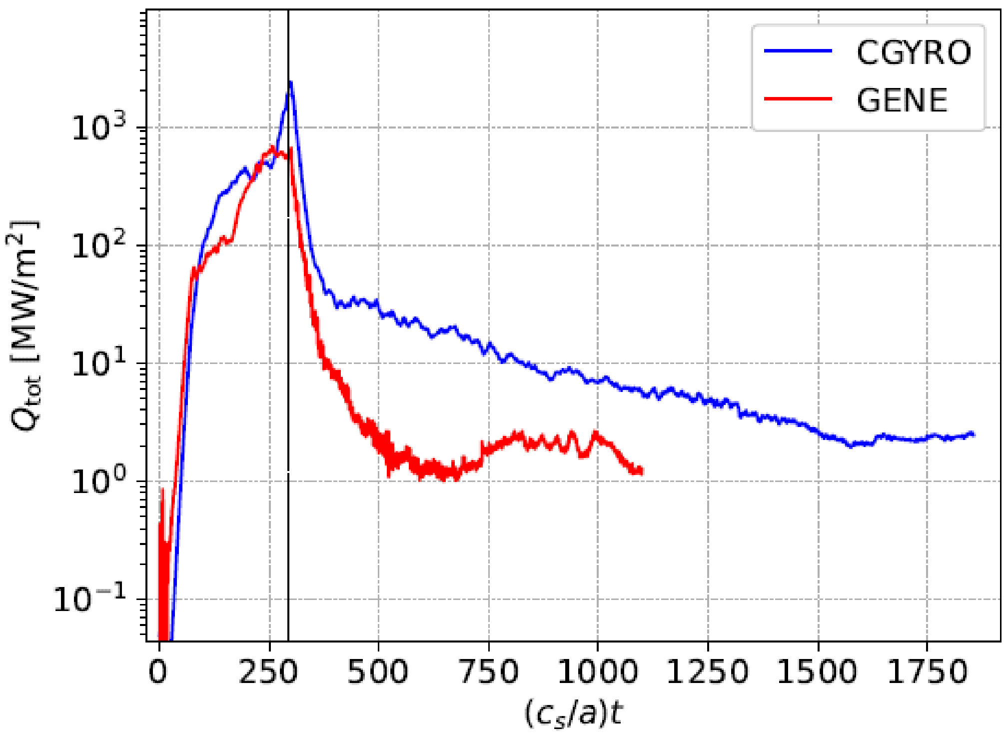


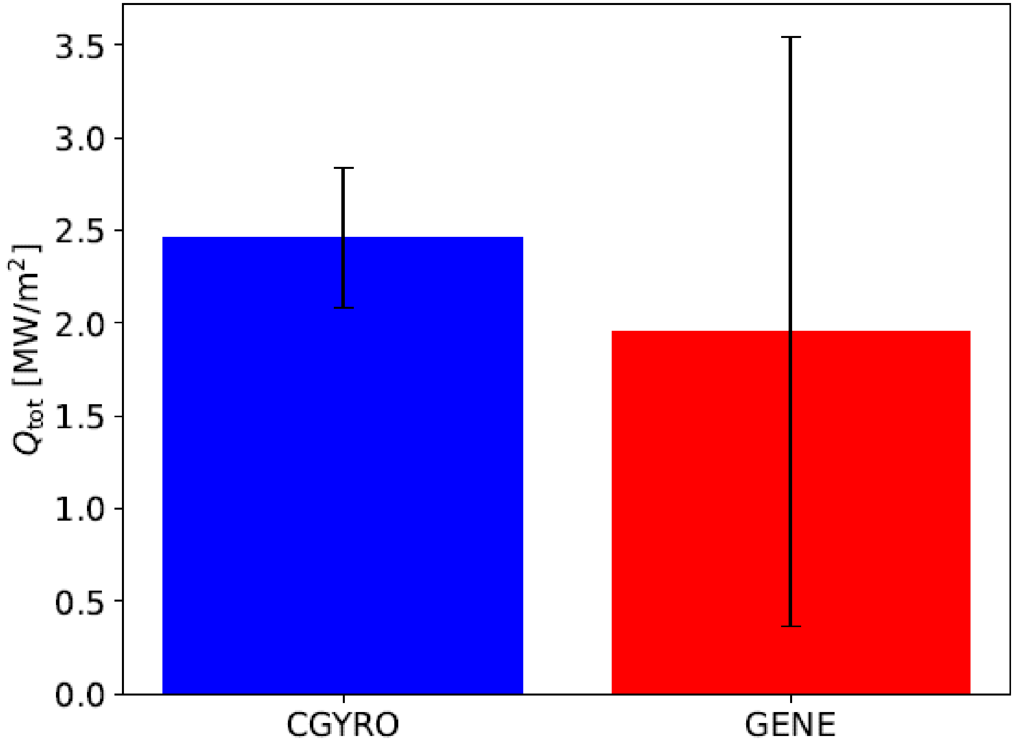
	CGYRO		
	Ref	A	B
n_θ	32	32	32
n_r	64	64	64
n_ξ, n_v	32	32	64
n_ϵ, n_μ	8	8	8
n_{k_y}	64	64	64
$k_{y,\mathrm{min}}\rho_s$	0.01	0.01	0.01
L_x/ρ_s	166	332	166

Turbulence structures

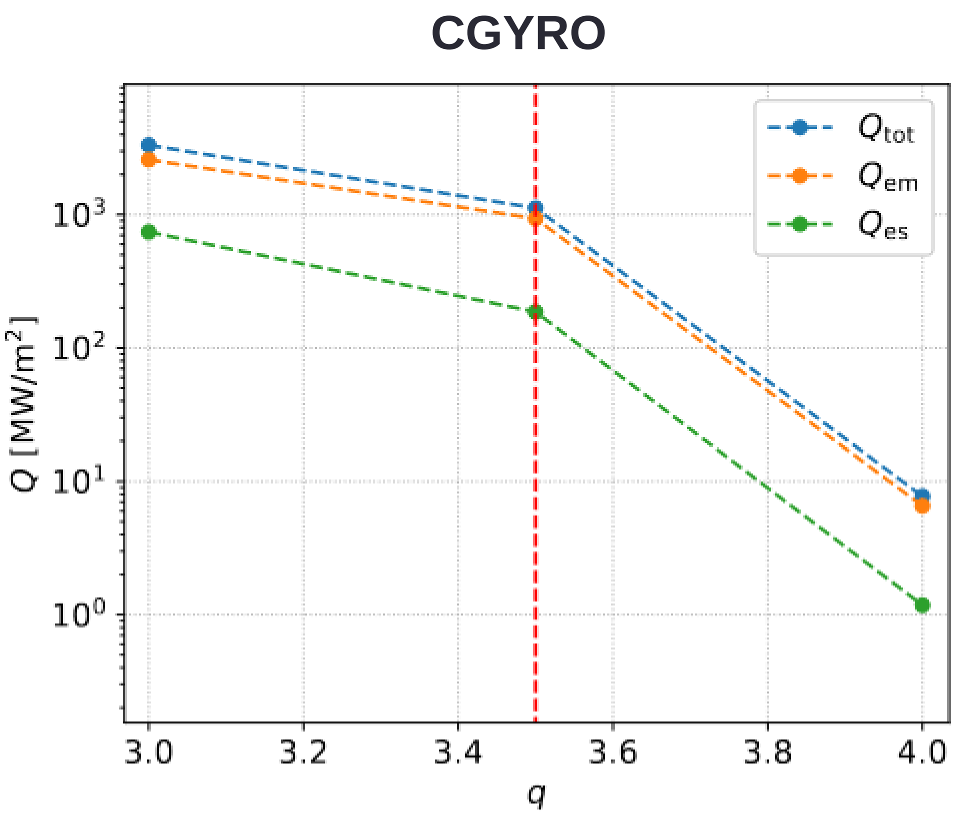


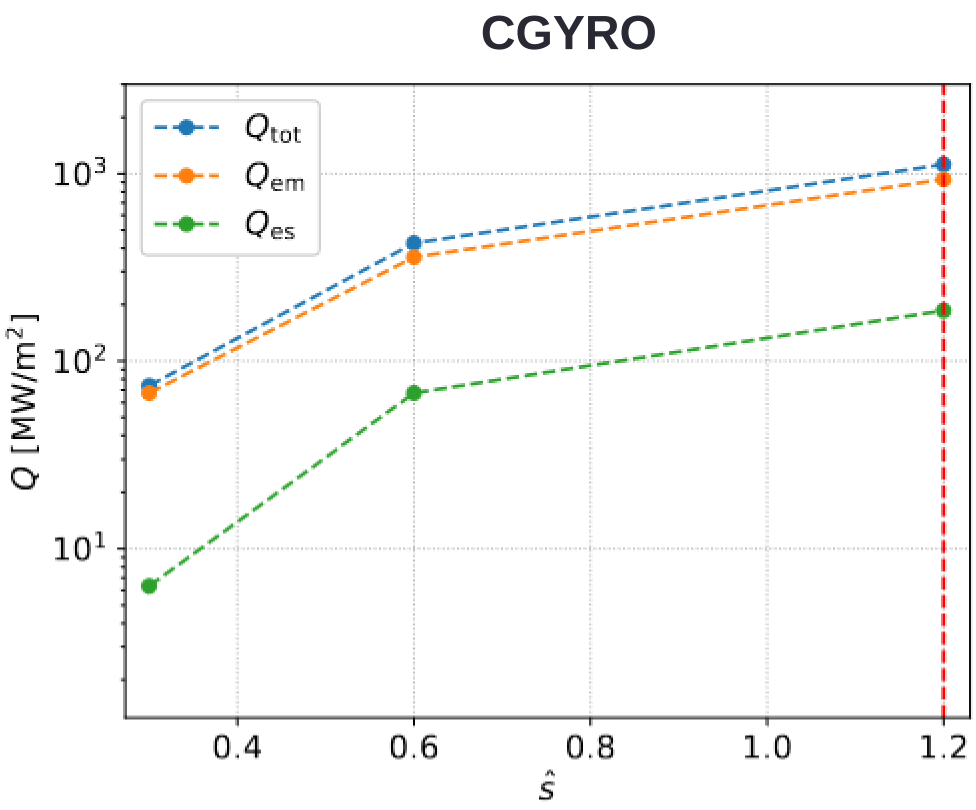
Simulations with flow shear





Sensitivity to q and $\hat{s}$ shows promising results





- Heat flux decreases as q increases or $\hat{s}$ decreases.
- There is some flexibility on safety factor radial profile.
- Fluxes decrease when the equilibrium moves away from the ideal ballooning instability boundary.