EUROfusion

The composition of ETG turbulence in JET-ILW pedestals

B. Chapman-Oplopoiou[1], J. Walker[2,3], D.R. Hatch[3], and T. Görler[4]

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JET

CCFE CULHAM CENTRE FOR FUSION ENERGY

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Outline

1. Problem description / Previous work

2. POD analysis of the turbulence simulations

3. The role of magnetic drifts

4. Summary

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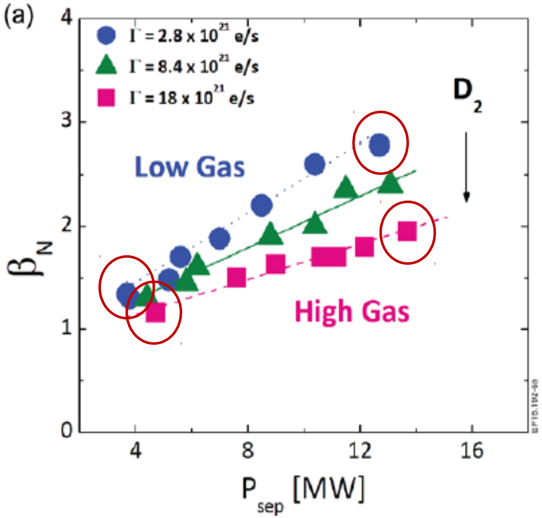
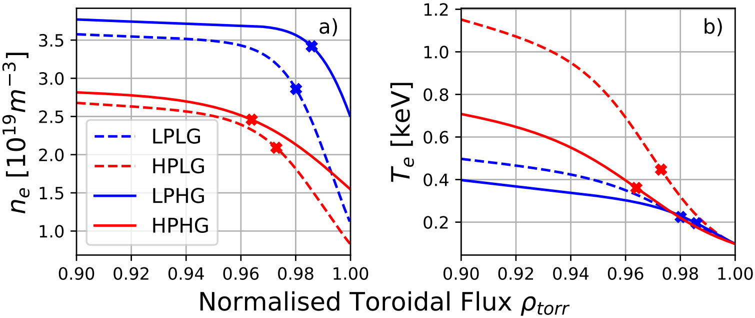
GENE simulations to understand the effect of gas puffing on ETG turbulence

Dataset



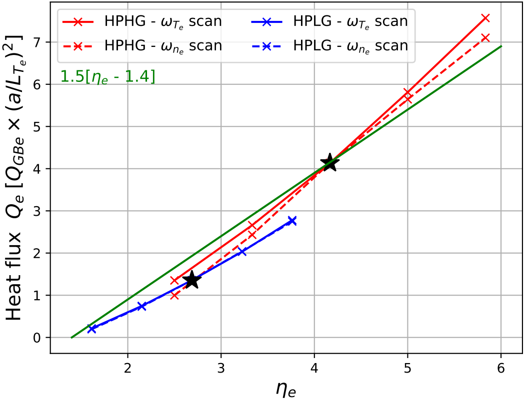
- JET-ILW dataset varying P_{NBI} for three levels of gas [C. F. Maggi *et. al.* Nucl. Fusion 2015]
- $I_p = 1.4$MA, $B_T = 1.7$T, $\delta \approx 0.25$

Density and Temperature profiles



- Pre-ELM $(80\% - 99\%)$ profiles
- HG has flatter density profiles $\rightarrow$ larger $\eta_e = \frac{n_e \nabla T_e}{T_e \nabla n_e} = \frac{\omega_{T_e}}{\omega_{n_e}}$
- HG has higher $n_{e,sep}$ - correlated with $n_e^{pos} - T_e^{pos} > 0$ [L. Frassinetti *et. al.* Nucl. Fusion 2019]
- **This talk** will focus only on the two HP pulses

High power ETG heat flux variation in the pedestal



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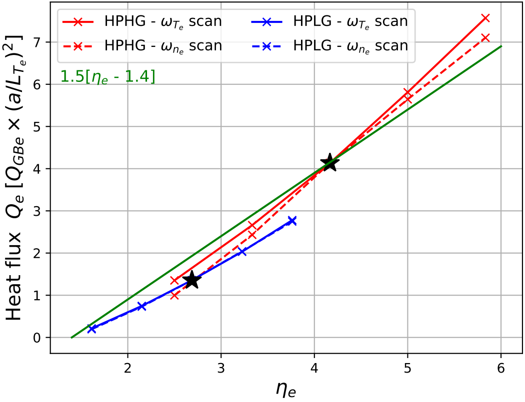

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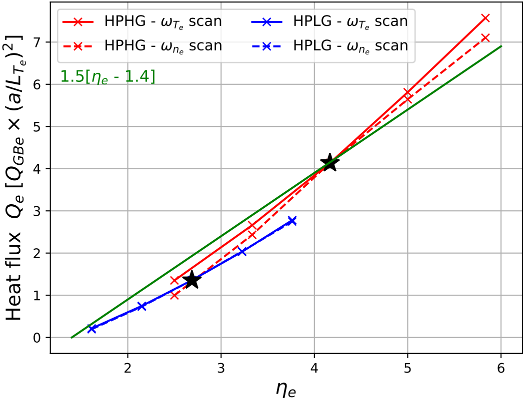

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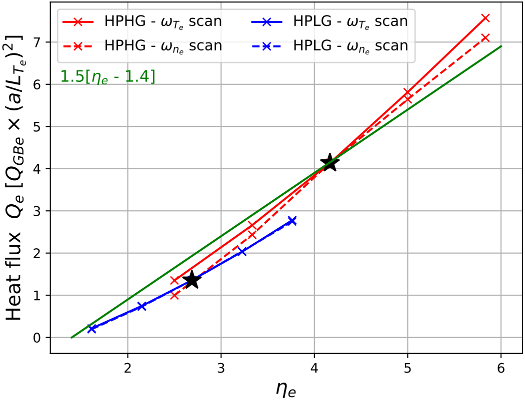

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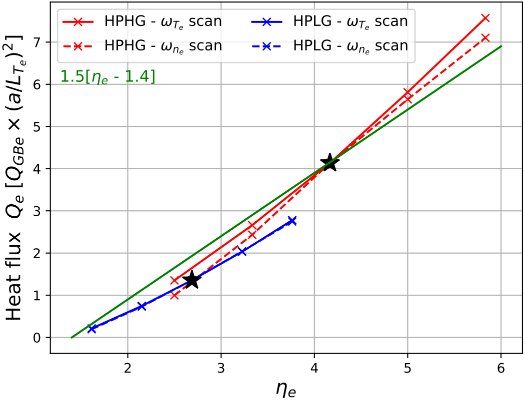

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- HPHG and HPLG pulses display "similar" trends

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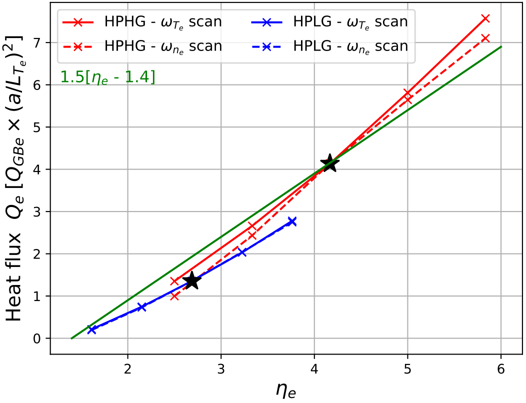
"Gas puffing flattens the density profile



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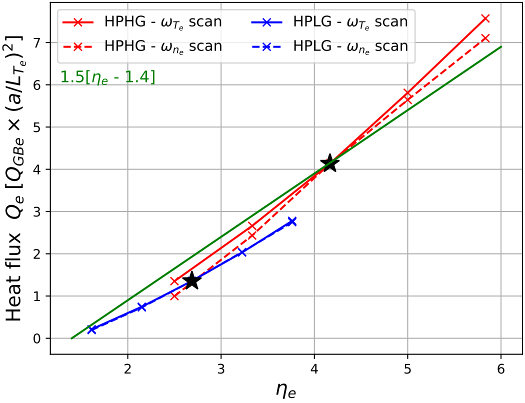

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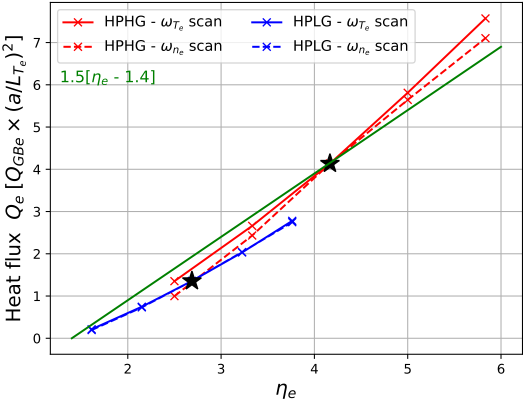

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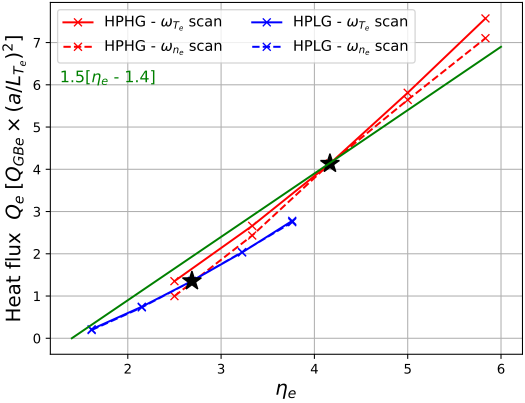

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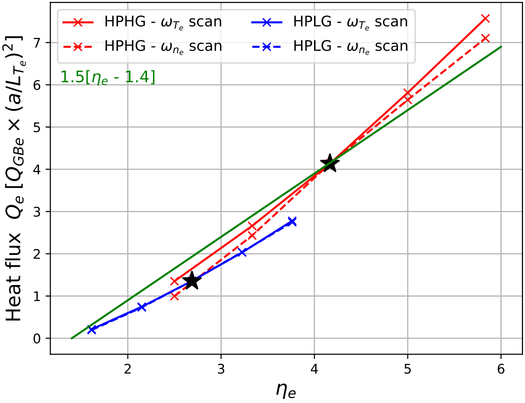

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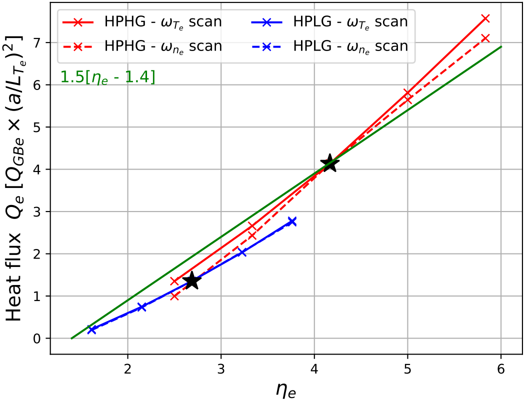

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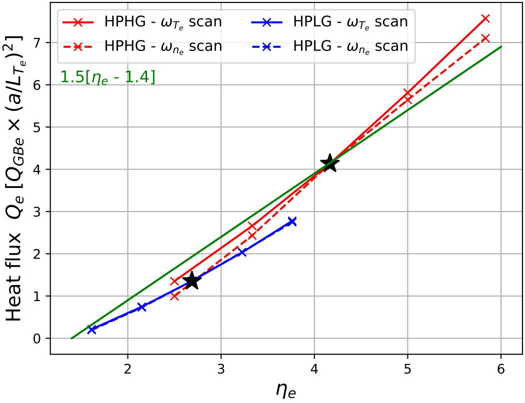

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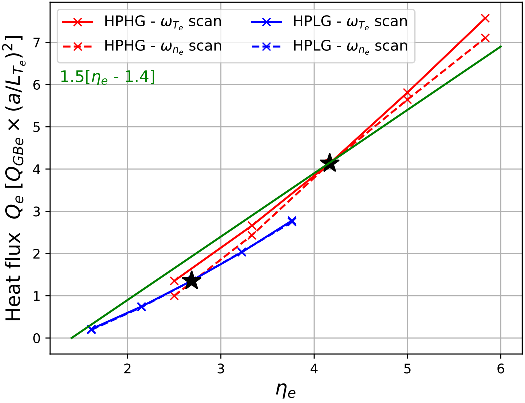

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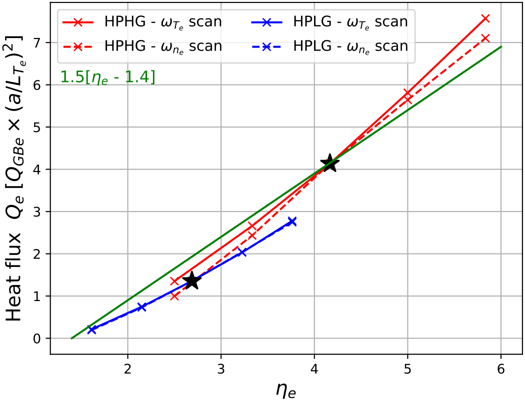

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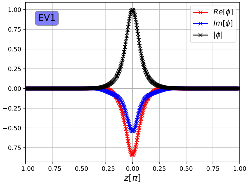
Is the turbulence of a different nature?

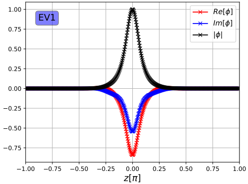
Outline

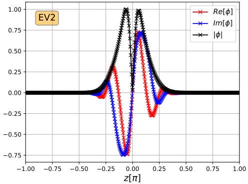
Linear eigenfunctions



- Modes with larger k_z become more important as ω_{T_e} is increased [M. J. Pueschel *et. al.* Plasma Phys. Control. Fusion 2019]

Linear eigenfunctions





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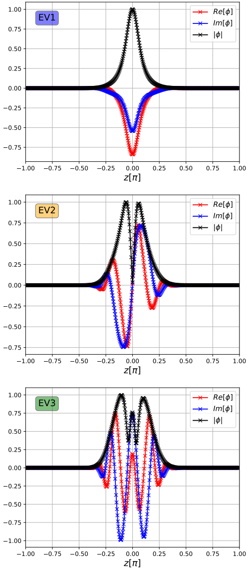

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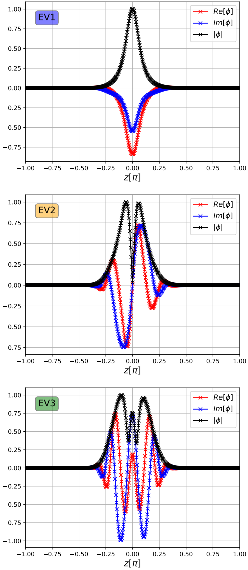

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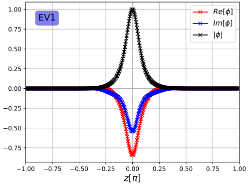

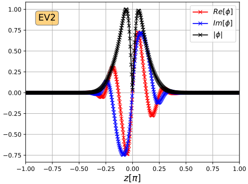

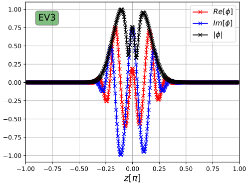

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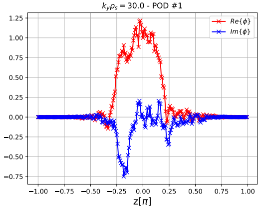

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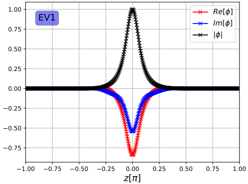

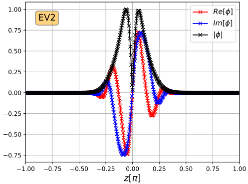

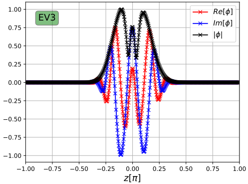

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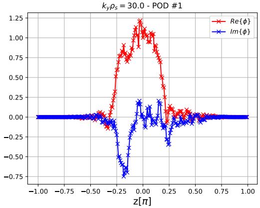
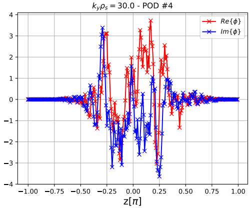
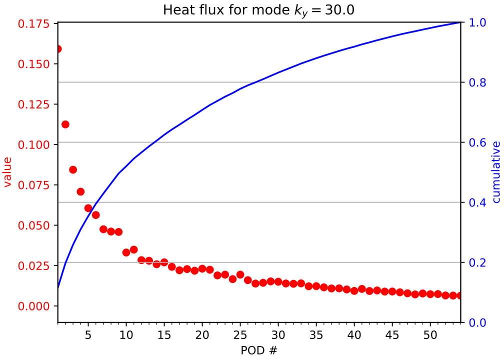




POD analysis



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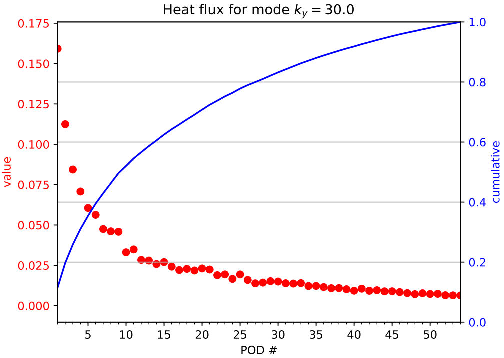

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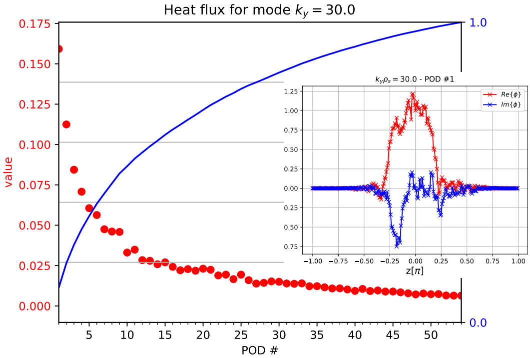

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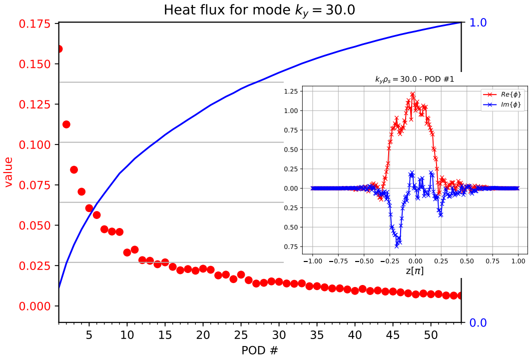

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See [J. Walker *et. al.* in preparation] for a detailed discussion

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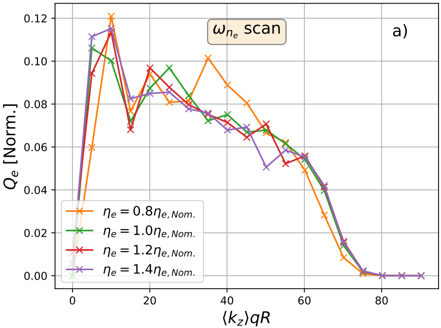

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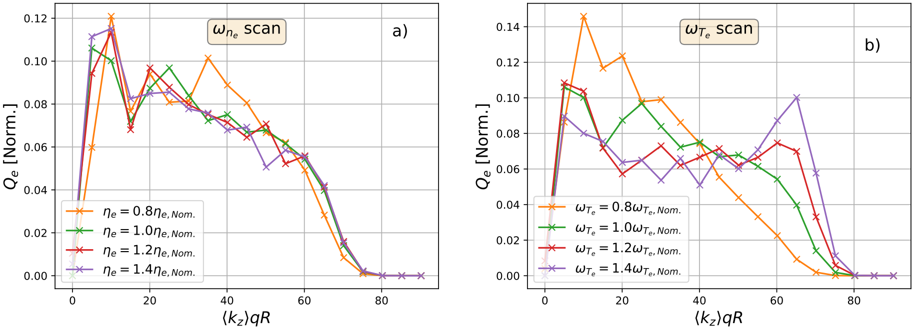
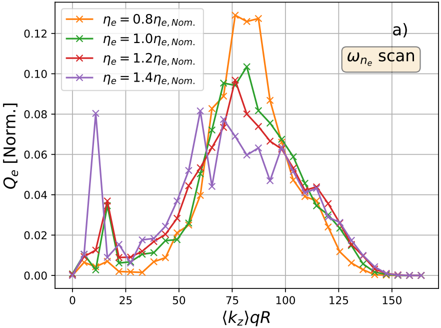


- No significant change in the spectrum as η_e is increased via decreases in ω_{n_e}
- Spectral pile-up at largest $\langle k_z \rangle$ as ω_{T_e} is increased above the nominal, evidence of critical balance [M. Barnes *et. al.* PRL 2011]

HPLG POD analysis



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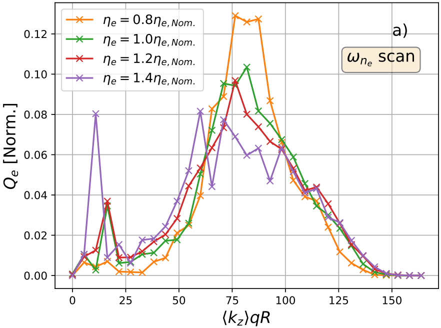

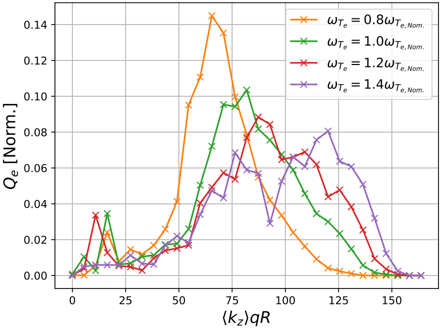

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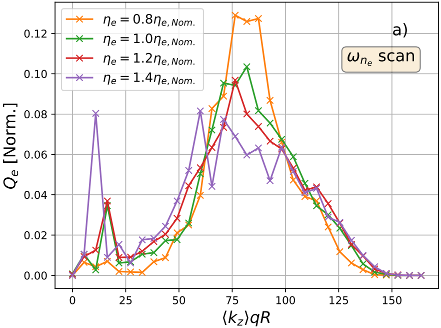
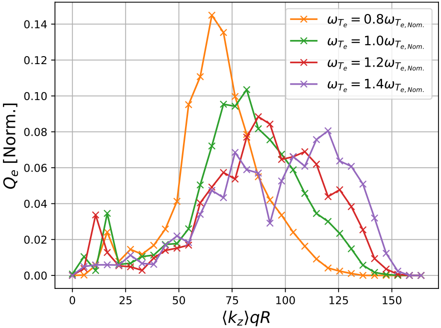
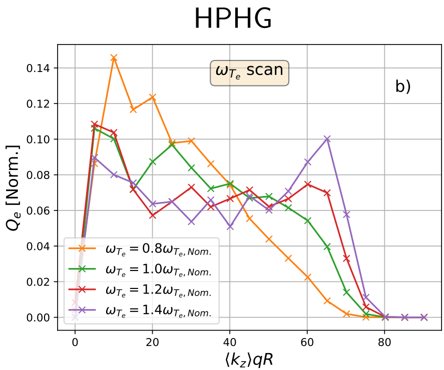
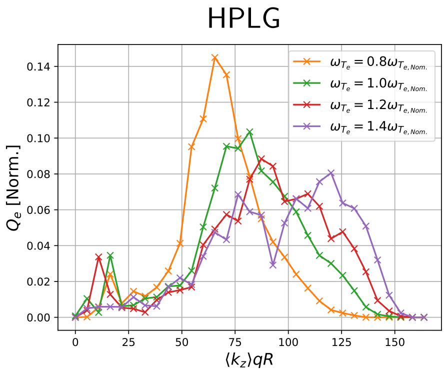




- As ω_{n_e} is decreased, $\langle k_z \rangle$ spectrum broadens and low $\langle k_z \rangle$ peak appears
- Spectra not the same for the same η_e
- Total Q_e remains approximately the same

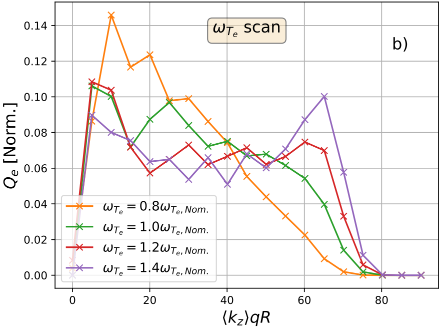
HPHG vs HPLG POD analysis



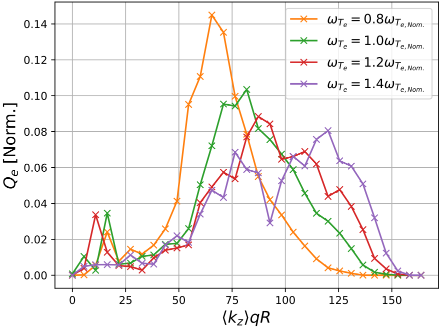


HPHG vs HPLG POD analysis

HPHG



HPLG



- HPLG peaks at higher k_y and $\langle k_z \rangle$ $\rightarrow$ turbulence more slab-like

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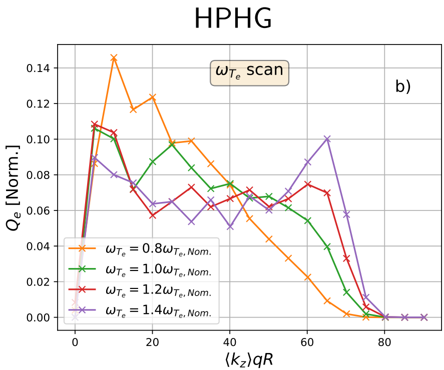

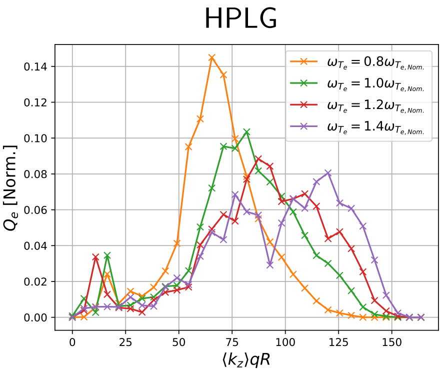

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- **Hypothesis:** HPHG is a mixture of slab and toroidal ETG turbulence

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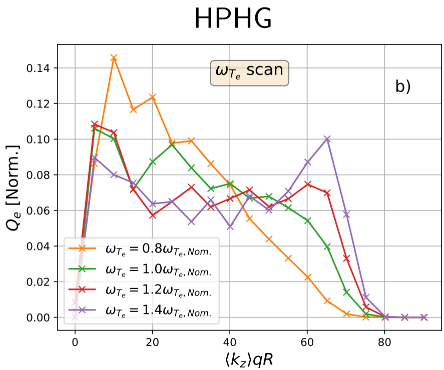

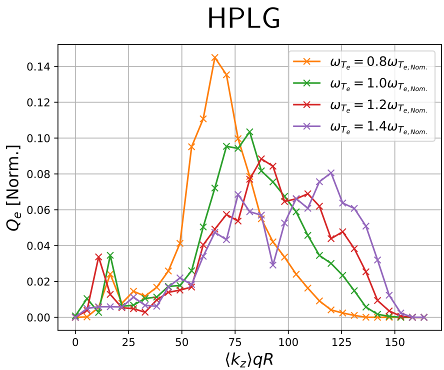

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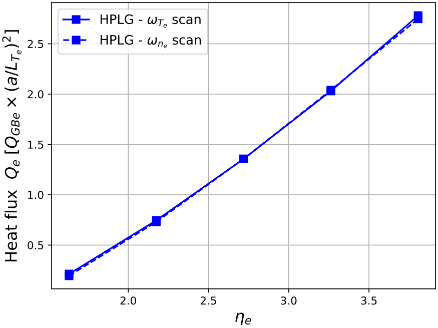
- **Hypothesis:** HPHG is a mixture of slab and toroidal ETG turbulence (at this flux-surface)

Outline

1. Problem description / Previous work
2. POD analysis of the turbulence simulations
3. The role of magnetic drifts
4. Summary

HPLG - the role of magnetic drifts



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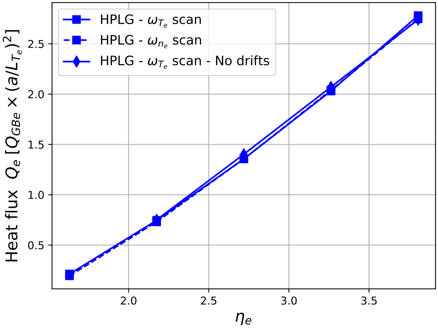

- Repeat some HPLG scan-points without the magnetic drift terms in the GK equation

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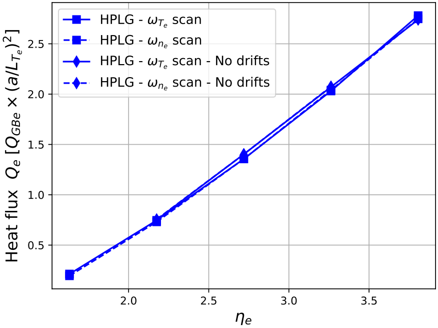

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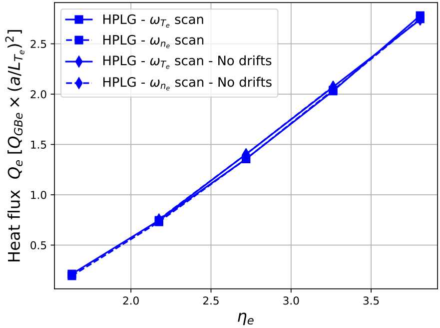

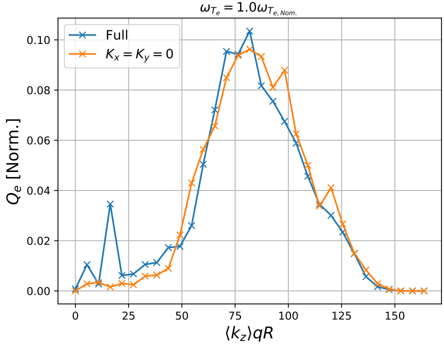

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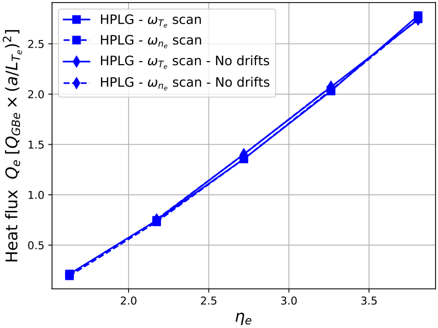

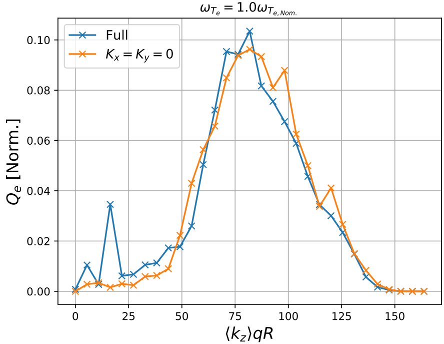

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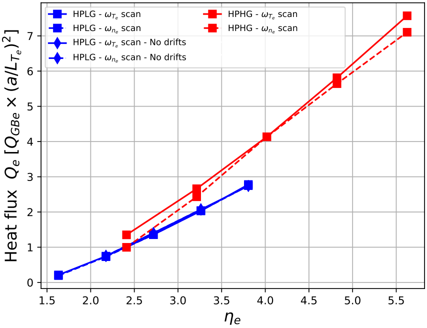

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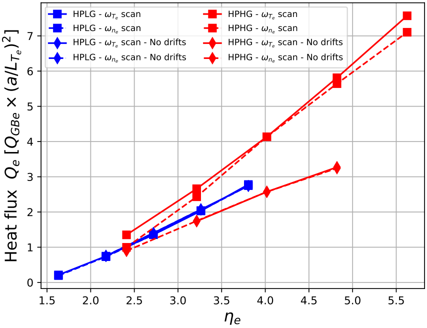

- Without drifts, Q_e trend is the same regardless of how η_e is varied, and extremely similar to the HPLG case → pure sETG turbulence

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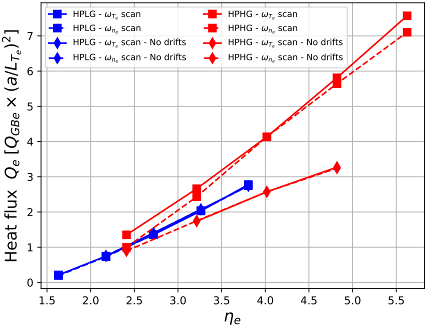

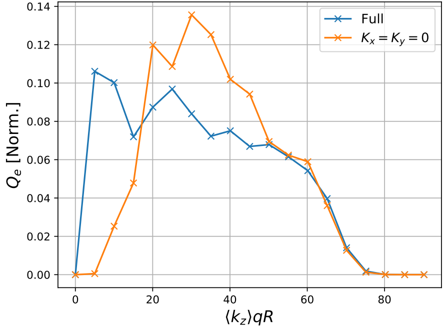

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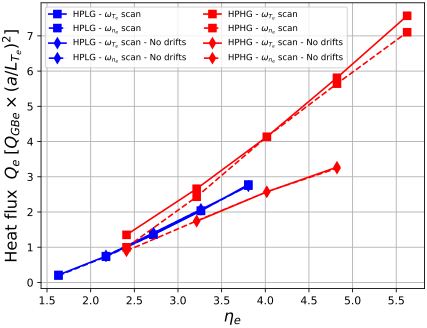

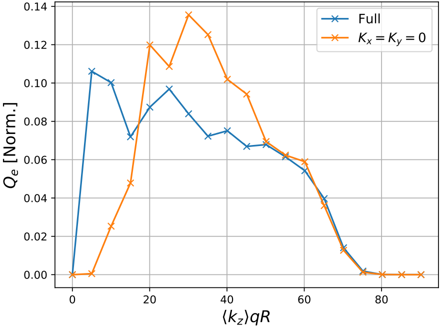

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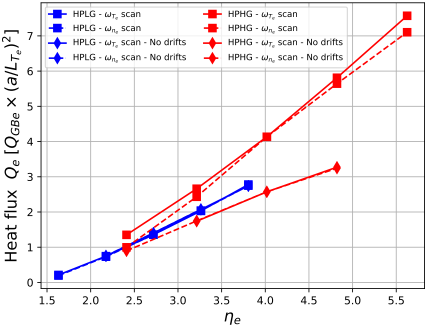

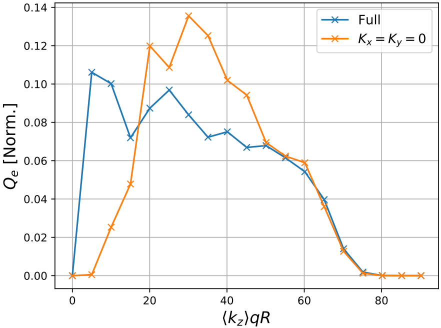

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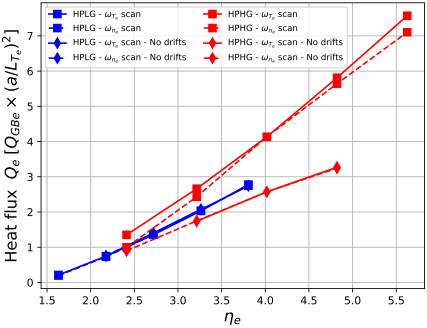

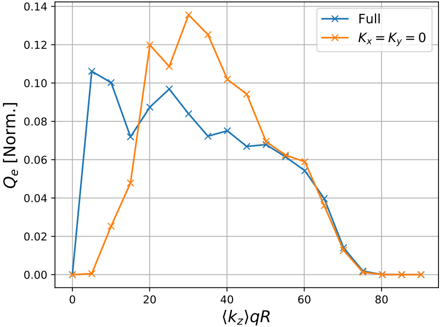

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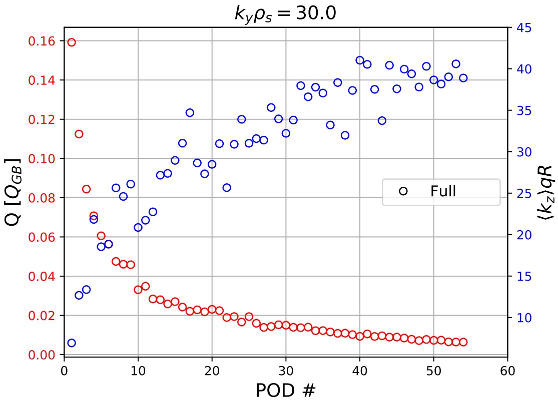
- HPHG heat flux reduces significantly when drifts removed $\rightarrow$ **Toroidal AND slab resonance important**
- Note: This is not the low k_y Toroidal ETG turbulence discussed in J.F. Parisi et al 2022 Nucl. Fusion 62 086045 - we are not resolving it here

HPHG POD structures revisited



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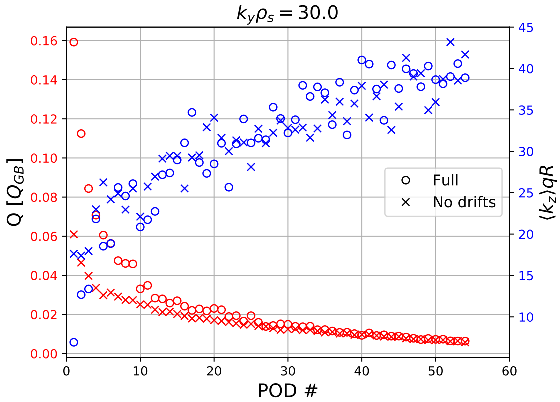

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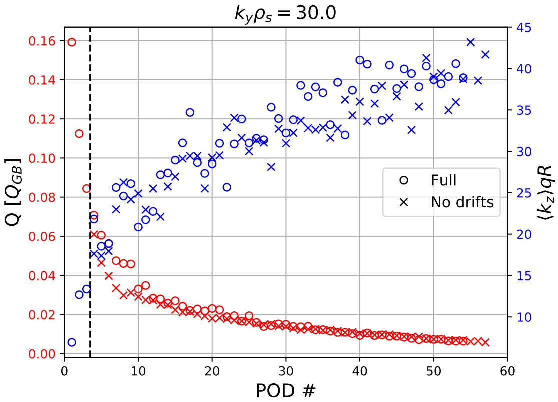

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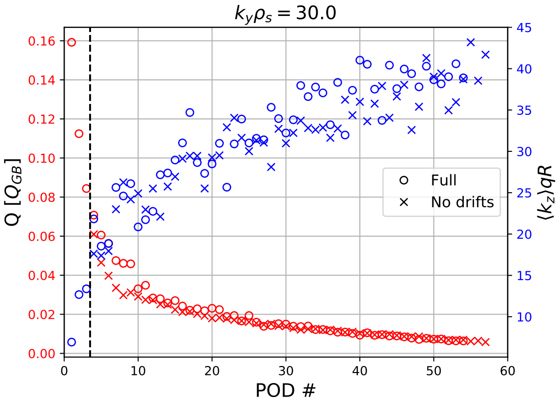

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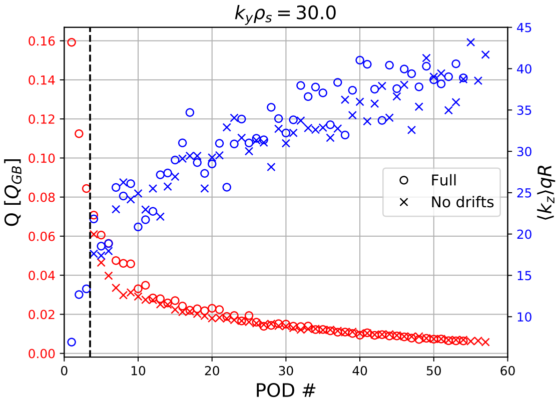
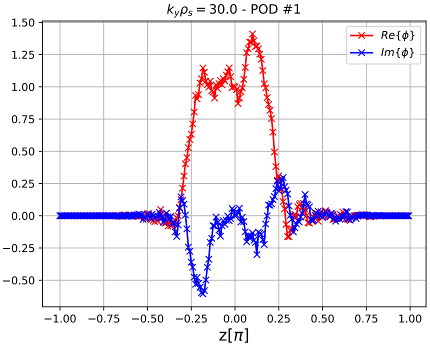


- At $k_y\rho_s = 30.0$, removing the magnetic drifts kills the first three POD modes which have low $\langle k_z \rangle$
- Full-drift and No-drift POD spectra in close correspondence when the first three POD modes are removed from the former (at $k_y\rho_s = 30.0$)

HPHG POD structures $k_y \rho_s = 30.0$ - Full-drift



- 1st POD structure looks ballooning - expected for Toroidal mode

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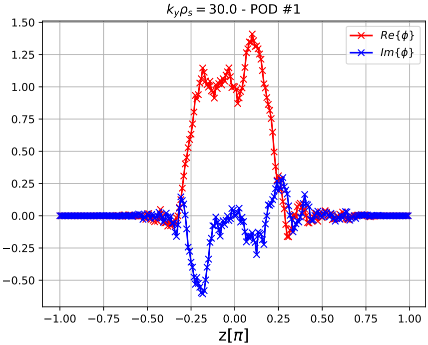

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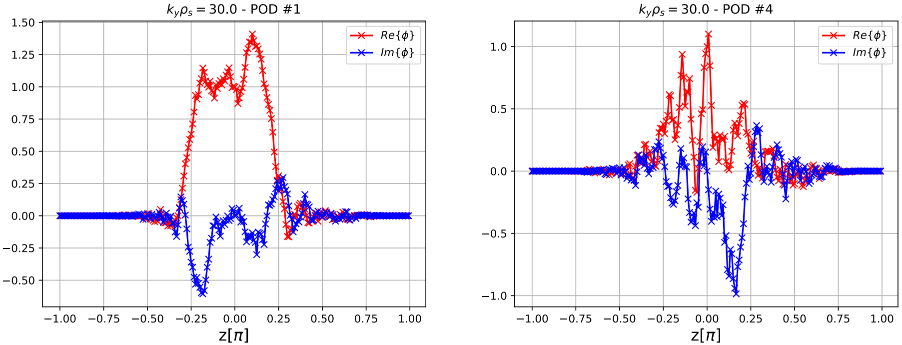

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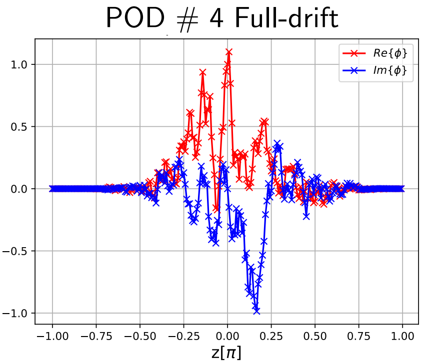
- 4th POD structure looks more slab like

POD structures $k_y \rho_s = 30.0$



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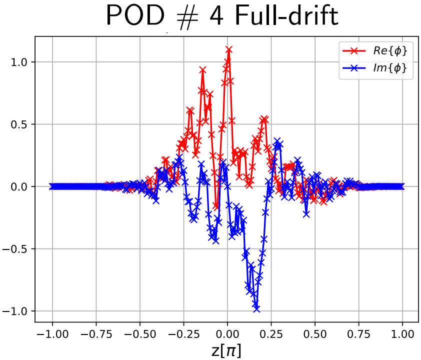

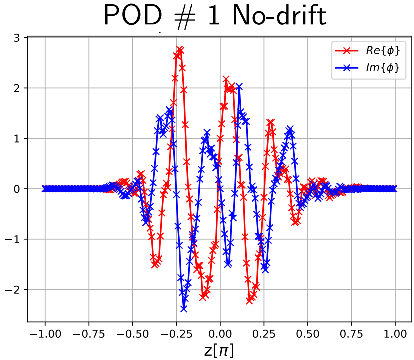

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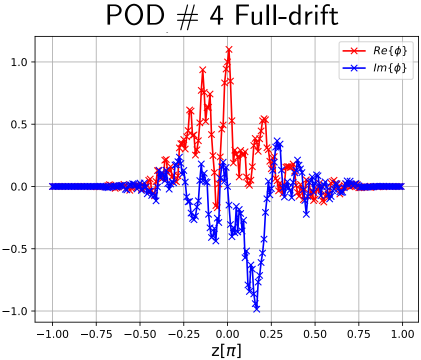

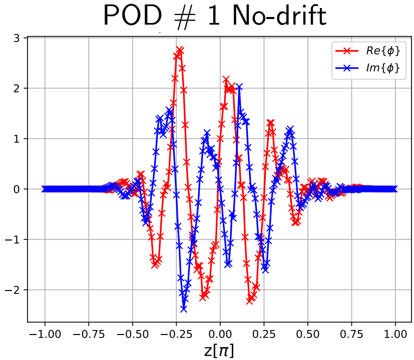

- The 1st No-drift (slab) POD structure looks similar to 4th Full-drift POD structure
- The other No-drift POD structures also look slab like

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- Multiple ETG eigenmodes with varying k_z are present linearly, and similar structures are found in nonlinear simulations
- Many POD modes contribute to total Q_e
- Nominal HPLG is "pure slab", whereas HPHG is a mixture of slab and toroidal turbulence

Revised understanding

OLD

OLD

“Gas puffing flattens the density profile

OLD

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Revised understanding

<u>OLD</u>

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"Gas puffing flattens the density profile $\rightarrow$ reduces $\omega_{n_e} = a/L_{n_e} \rightarrow$ increases $\eta_e = L_{n_e}/L_{T_e} \rightarrow$ more (slab-)ETG turbulence

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"Gas puffing flattens the density profile $\rightarrow$ reduces $\omega_{n_e} = a/L_{n_e}$ $\rightarrow$ **Addition of toroidal ETG turbulence in the steep gradient region**

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"Gas puffing flattens the density profile $\rightarrow$ reduces $\omega_{n_e} = a/L_{n_e}$ $\rightarrow$ **<u>Addition</u> of toroidal ETG turbulence in the steep gradient region** $\rightarrow$ higher power needed to sustain temperature pedestal"

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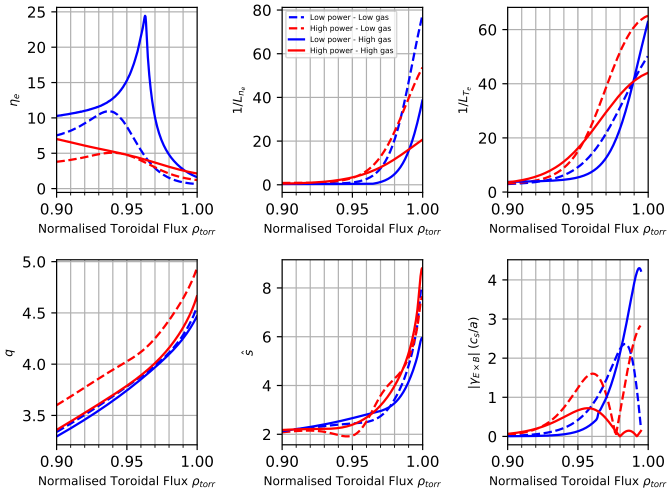
At least for these pulses at these flux-surfaces...

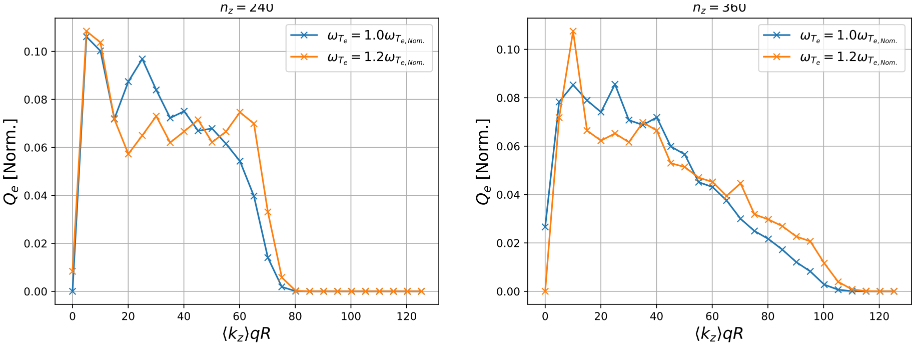
Important plasma profiles



Simulation details

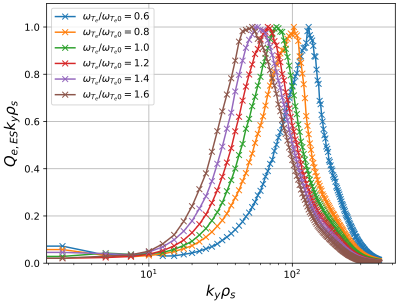
- Kinetic ions and electrons, impurities included via Z_{eff} in collision operator
- Realistic geometry taken from EFIT and improved using HELENA
- Equilibrium flow shear estimated using neoclassical formula
- $k_{y,min}\rho_s = 2.5,\ k_{y,max}\rho_s = 317.5$
- $k_{x,min}\rho_s \approx 1.29,\ 70 \lesssim k_{x,max}\rho_s \lesssim 82$
- Adaptive hyper-diffusion - GyroLES
- $n_z = 240,\ n_{v_{||}} = 36,\ n_{\mu} = 8$

HPHG POD analysis resolution testing

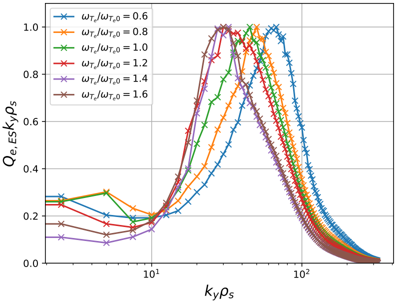


Spectral pile-up for $n_z = 240$ doesn't change our conclusions

HPLG - $\eta_{e0} \approx 2.7$

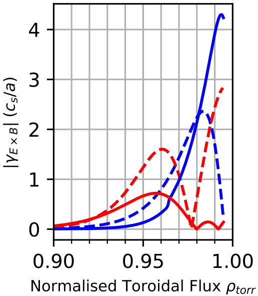


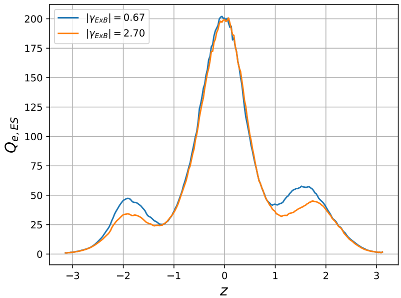
HPHG - $\eta_{e0} \approx 4.0$



- $k_{y,min}\rho_s = 2.5$, $k_{y,max}\rho_s = 317.5$, $k_{x,min}\rho_s \approx 1.3$, $k_{y,max}\rho_s \approx 83$, GyroLES
- HPLG is well resolved, hardly any under-resolved modes at low $k_y\rho_s$ and evidence of scale-separation
- HPHG shows some under-resolved modes at low $k_y\rho_s$ - primary ETG peak still prominent and well resolved
- NB - γ_E is small, and the time windows are different in all cases (see work of J.F. Parisi for a discussion of the importance of the simulation duration)

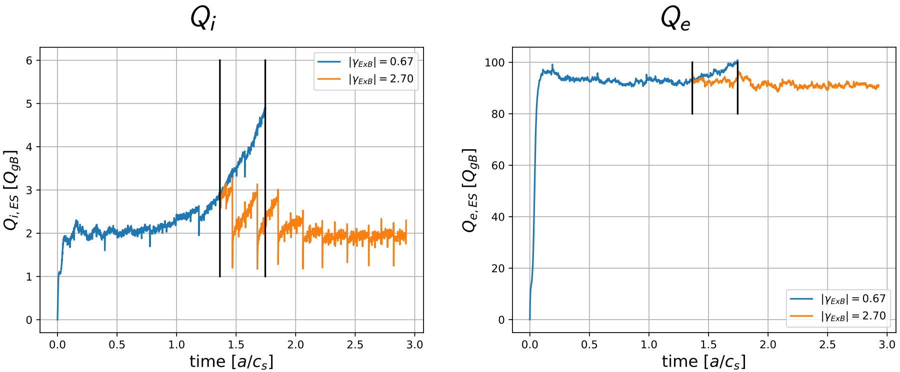
The effect of flow shear - HPLG - $\omega_{T_e} = 1.2\omega_{T_e0}$ - $Q_e(z)$





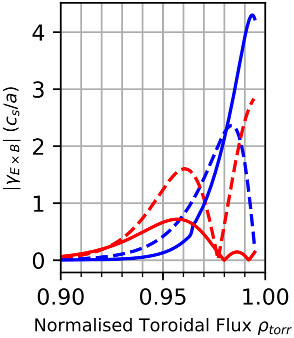
- $\gamma_{ExB} \approx 0.67$ at the nominal flux surface $\rho_t = 0.973$ (dashed-red)
- Close to unphysical "well" in γ_{ExB} (a consequence of the neoclassical E_r calculation) $\rightarrow$ actual γ_{ExB} could be much larger
- Quadruple γ_{ExB} and compare $Q(z)$ over same time window
- Primary ETG - peak at $z \approx 0$ unchanged
- Peaks at $z \approx \pm\pi/2$ decrease with γ_{ExB} (negligible change in total Q_e)
- Decrease in Q_e at $z \approx \pm\pi/2$ corresponds to a decrease in Q_e at low $k_y \rho_s$

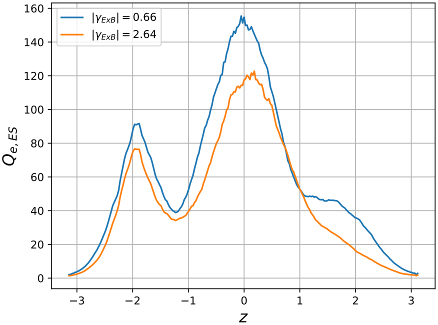
The effect of flow shear - HPLG - $\omega_{T_e} = 1.2\omega_{T_e0}$ - $Q_e(z)$



- Peaks at $z \approx \pm\pi/2$ are correlated with a gradual run-away in Q_i, commensurate with an up-tick in Q_e, which is remedied with increased γ_{ExB}
- Note - Q_z averaged over only a small time-window

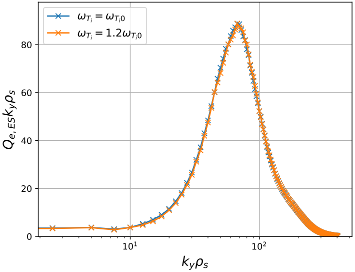
The effect of flow shear - HPHG - $\omega_{T_e} = 1.2\omega_{T_e0}$ - $Q_e(z)$

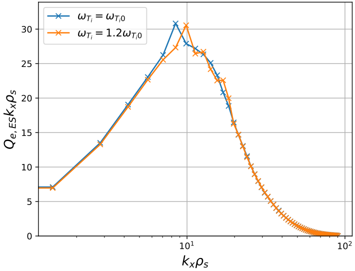


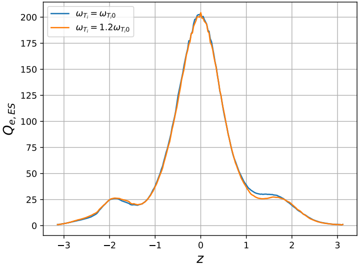


- $\gamma_{ExB} \approx 0.66$ at the nominal flux surface $\rho_t = 0.964$ (solid-red)
- Quadruple γ_{ExB} and compare $Q(z)$ over same time window - γ_{ExB} unphysically large in this case (but feasible for other pulses)
- All three peaks decrease with γ_{ExB}
- $\sim 22\%$ decrease in Q_e

HPLG - $\omega_{T_e} = 1.2\omega_{T_e 0}$ - $\omega_{T_e} = \omega_{T_i}$





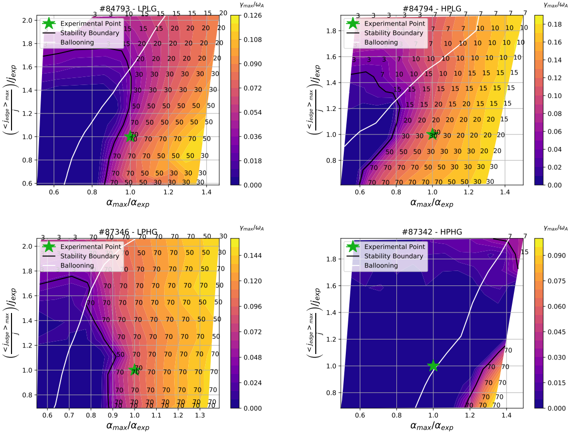


- Increase ω_{T_i} along with ω_{T_e} (previously held ω_{T_i} constant)
- No appreciable change with increasing ω_{T_i} $\rightarrow$ holding ω_{T_i} doesn't affect the ETG results shown here
- Note: the simulations are not self-consistent

A note on the experiment

- LG (on HT) and HG (on CT) have approximately the same $n_{e,ped}$
- This is due to CT having more efficient pumping, hence, a lower edge particle source term
- f_{ELM} also increases with gas, which may increase ELM particle losses
- Comparing LG and HG can be thought of as a gas scan at approximately constant $n_{e,ped}$ - considering how shape of the profiles effects transport
- MG (on CT) has lower $n_{e,ped}$ than HG, can be thought of as a "pure" gas scan with both profile shape and differing $n_{e,ped}$ effects

Peeling-ballooning stability diagrams



- Axes are normalised! PB boundary isn't actually moving much
- HPLG to the right of the PB boundary
- HPHG to the left of the PB boundary

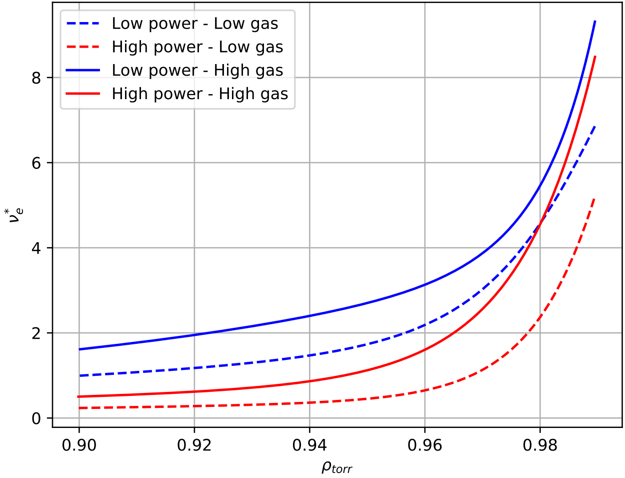
Calculation of γ_E

$$\gamma_E = \frac{\rho_t}{q}\frac{d}{d\rho_t}\Omega \tag{1}$$

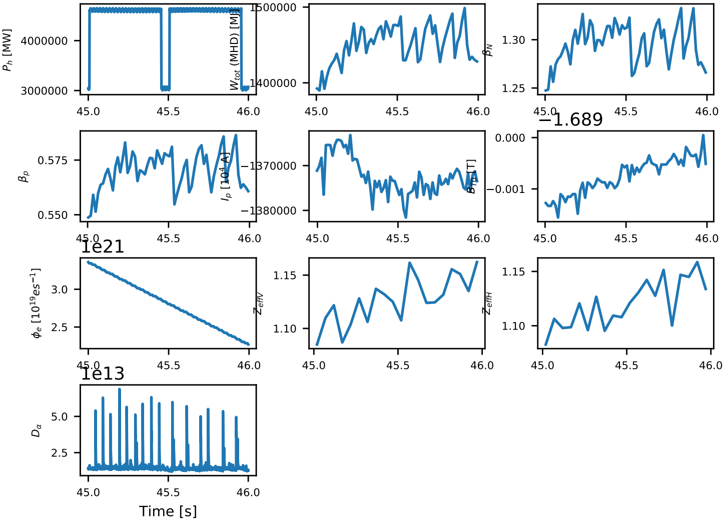
$$\Omega = \frac{E_r}{B_\theta R} \propto \frac{1}{n_i}\frac{dP_i}{d\psi} - k_\parallel \frac{dT_i}{d\psi} \tag{2}$$

$$V_\parallel = 0 \tag{3}$$

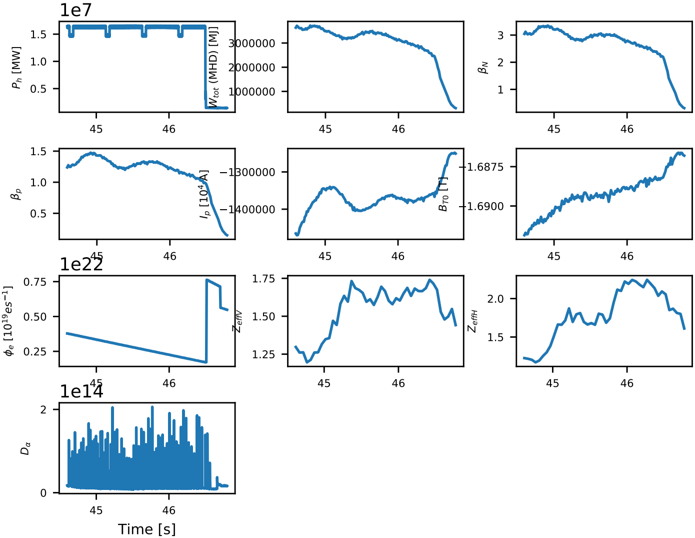
ν_e^* profiles



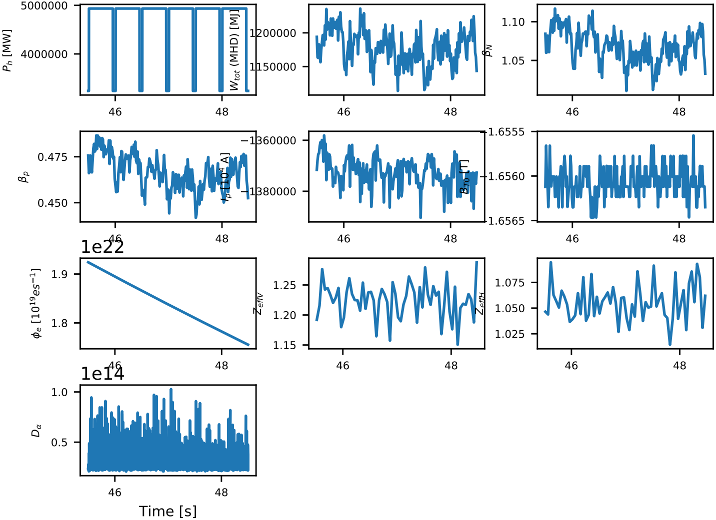
Experimental quantities LPLG - #84793



Experimental quantities HPLG - #84794



Experimental quantities LPHG - #87346



Experimental quantities HPHG - #87342