TEM heat transport and fluctuations in the HSX stellarator: experiments and comparison with gyrokinetic simulation

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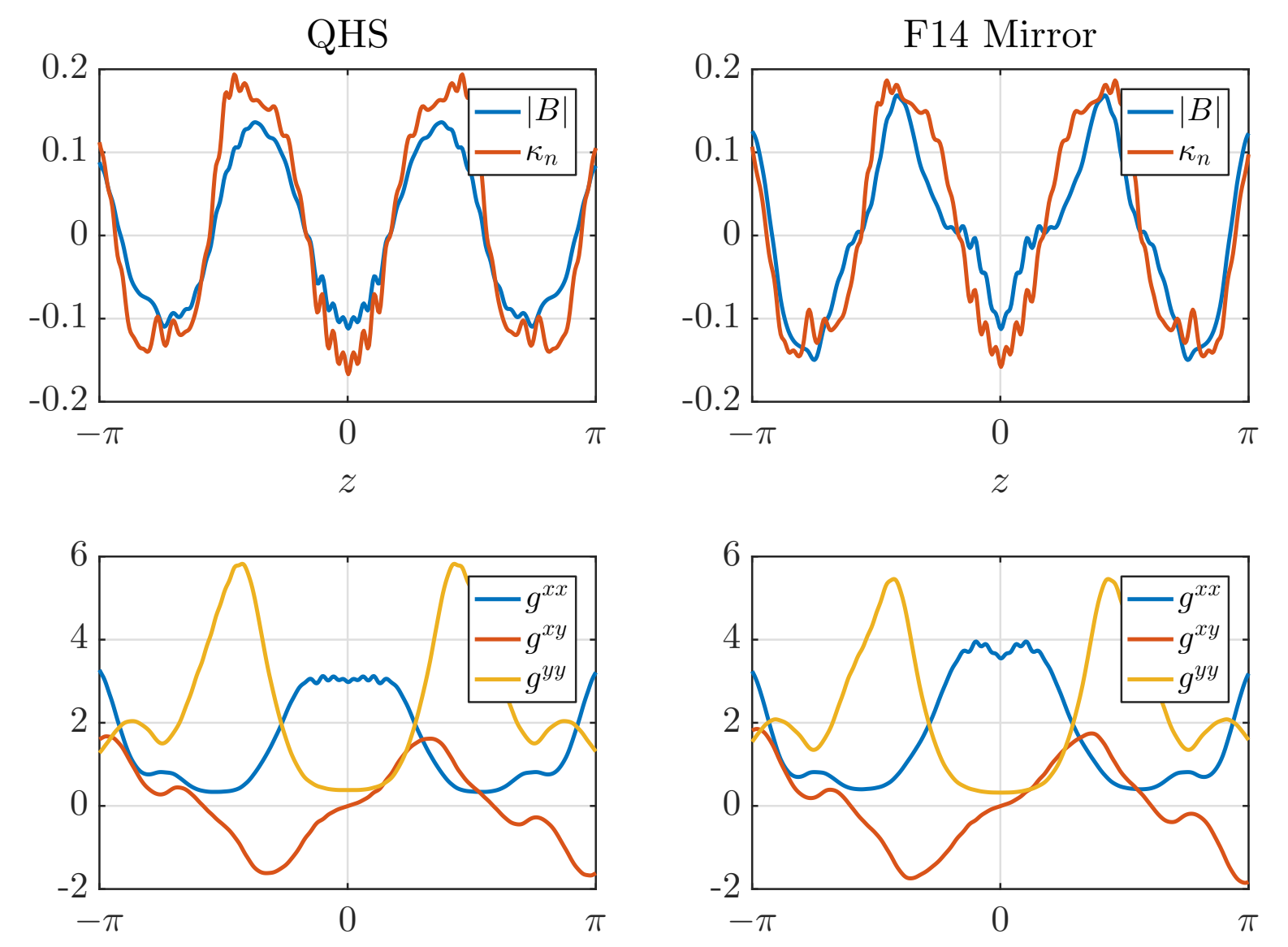
MOTIVATION

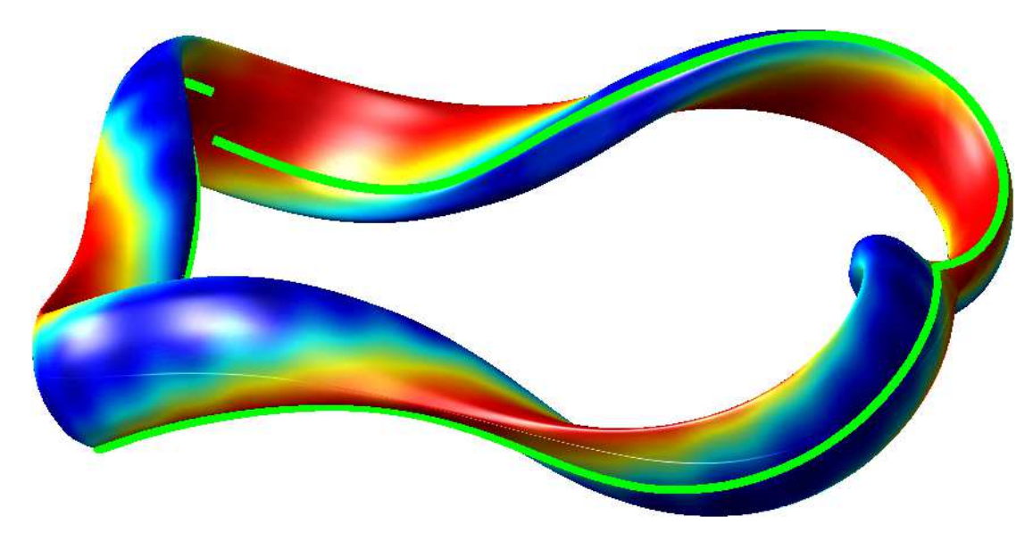
- Optimization for turbulent transport requires predictive capabilities.
- Thus, experimental validation of codes is needed for stellarators.
- Zonal flows regulate transport in many turbulence regimes, also present in quasi-symmetric stellarators.
- Zonal flow residual finite as $k_x\rho_s \to 0$ in tokamaks, but vanishes in W7-X (Monreal 2016). Similar for quasi-symmetric stellarators ?

I. Configurations on HSX

- HSX auxiliary coils → comparison of geometries as perturbations on one machine.
- QHS - Quasi-Helical Symmetry, configuration optimized for reduced neoclassical transport and flow damping.
- F14 Mirror - Broken symmetry with [n,m] = 4,0 and 8,0 mirror term, effective ripple similar to conventional stellarator.



- Mirror configuration has narrower $|B|$ well, no difference in curvature κ_n.
- In Mirror, larger flux compression g^{xx} at $z = 0$, smaller local shear g^{yy} at $z = \pm\pi/2$.
- Gyrokinetics: GENE (`www.genecode.org`) – local flux tube domain with 4 poloidal turns.



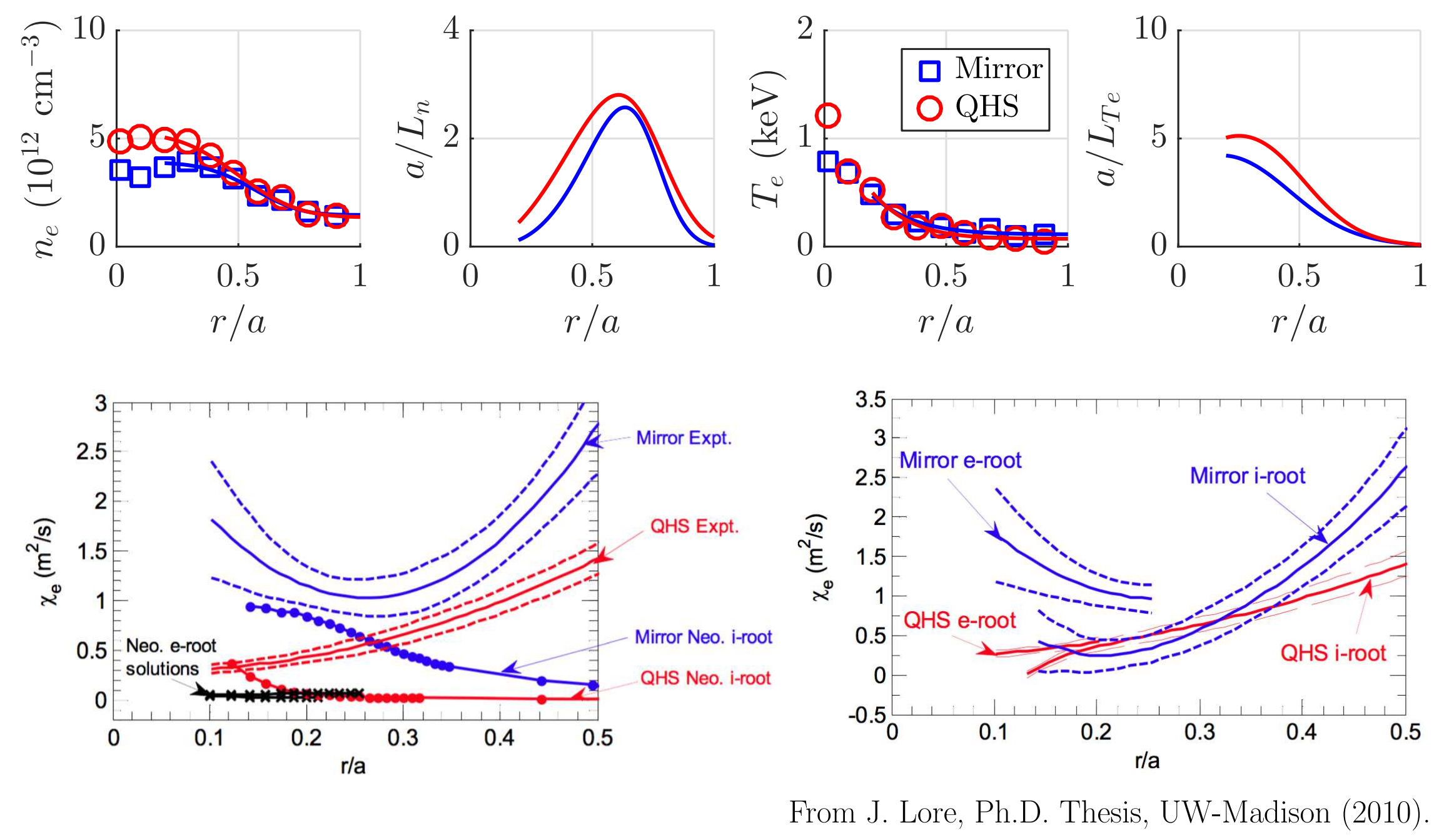
For more on poloidal turns in GENE at HSX, see talk by B.J. Faber GO4.00001 9:30 Tuesday.

II. Experimental profile analysis: differences in χ_e

- Plasma profiles are matched in QHS and Mirror with different ECRH power (QHS = 26 kW, Mirror = 44 kW).
- Peak ∇n outside $r/a \approx 0.5$, peak ∇T_e in core – separation of driving gradients.
- Assuming diffusive heat flux ($Q_e = -n_e\chi_e\nabla T_e$), χ_e is a normalized measure of energy transport.

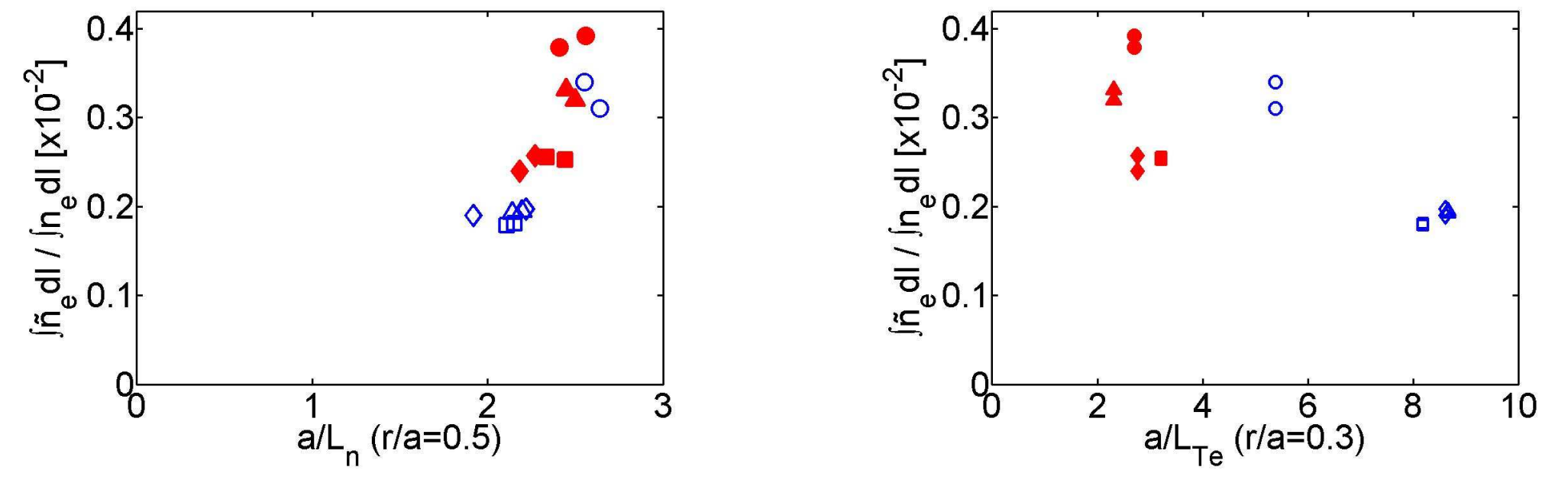
$$\chi_e = \frac{P_{abs}}{V'\left\langle|\rho|^2\right\rangle n_e \frac{\partial T_e}{\partial\rho}}$$

- Neoclassical transport approaches zero outside $r/a \approx 0.3$ → anomalous dominated.
- At $r/a = 0.5$, χ_e differs by factor of two between configurations, not accounted by neoclassical transport.
- Interferometry – density fluctuations scale with ∇n, but no discernible trend with ∇T_e.
- Density scaling consistent with ∇n-driven TEM.



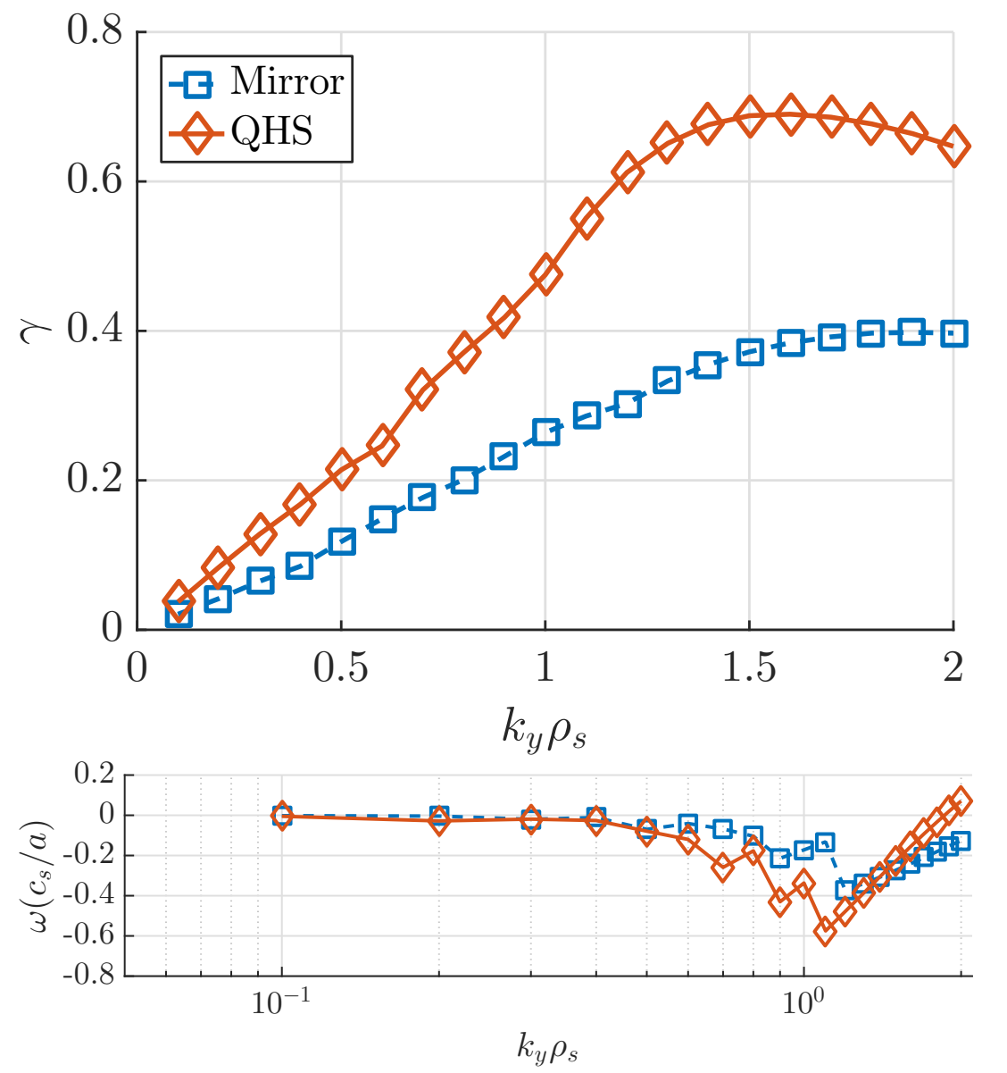
From J. Lore, Ph.D. Thesis, UW-Madison (2010).

Density fluctuations from interferometry:

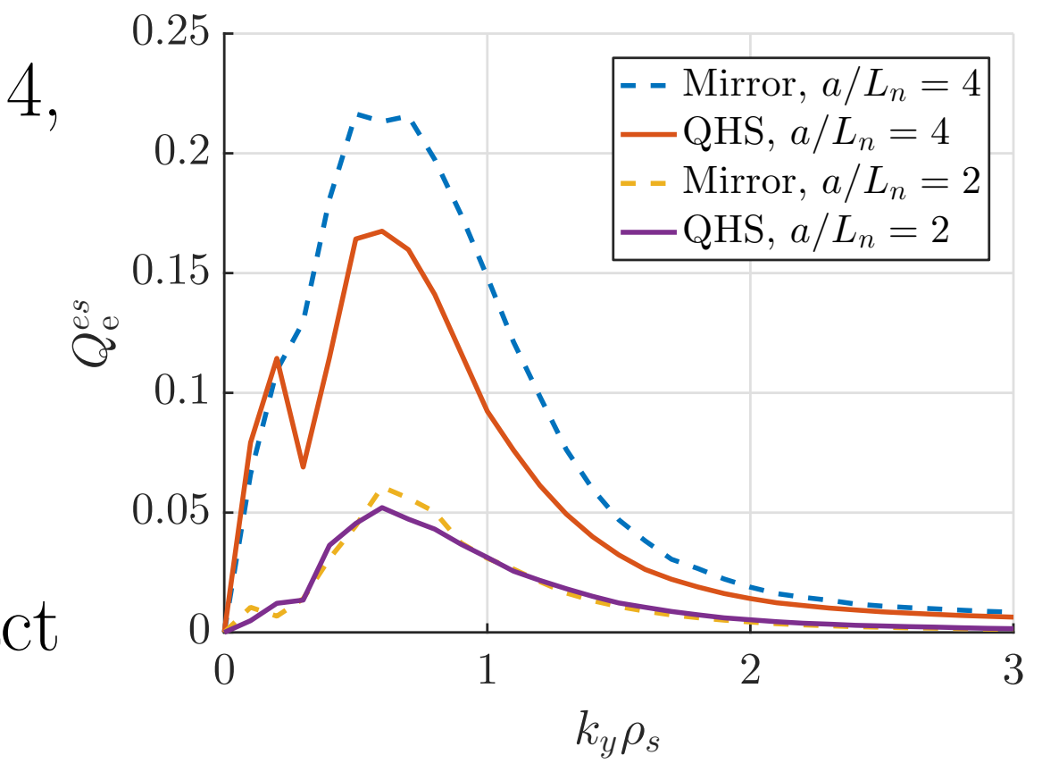


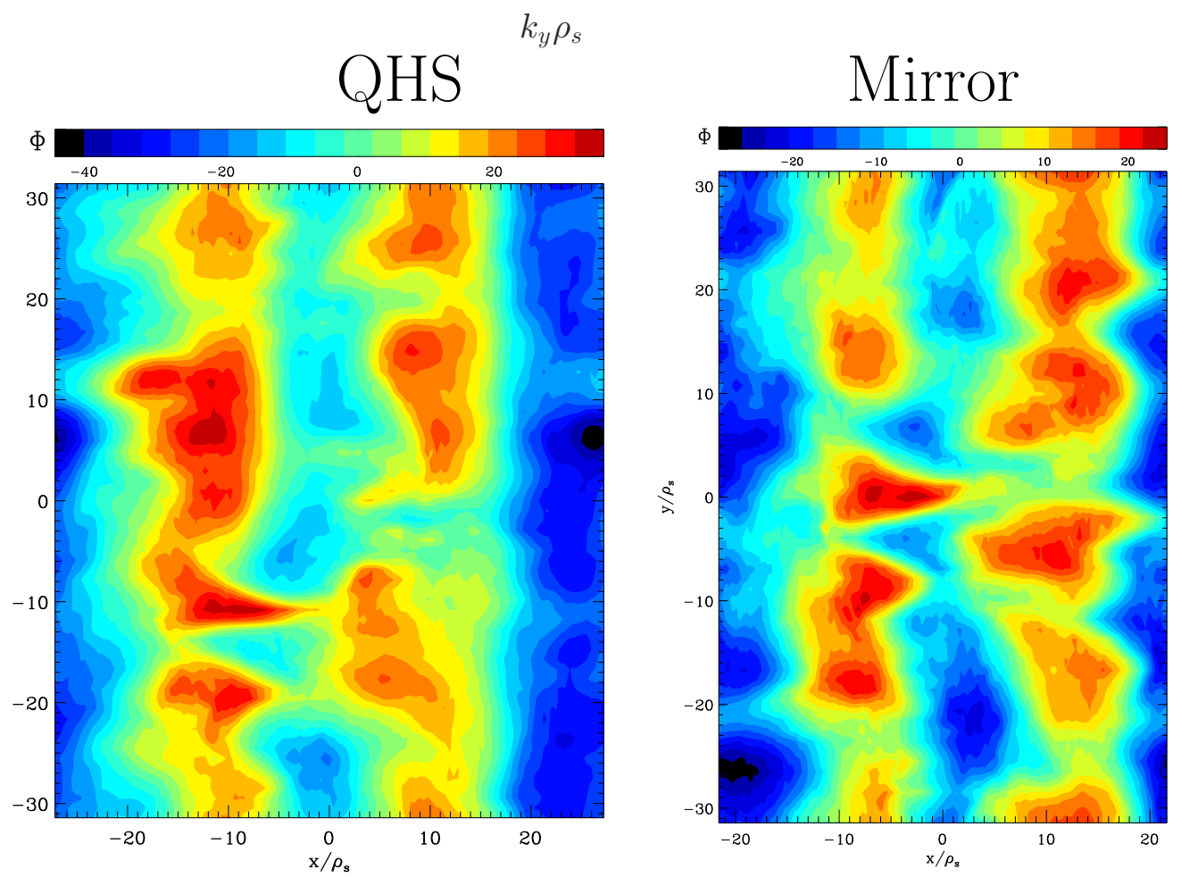
From C.B. Deng *et al.*, Nucl. Fusion. 55 (2015).

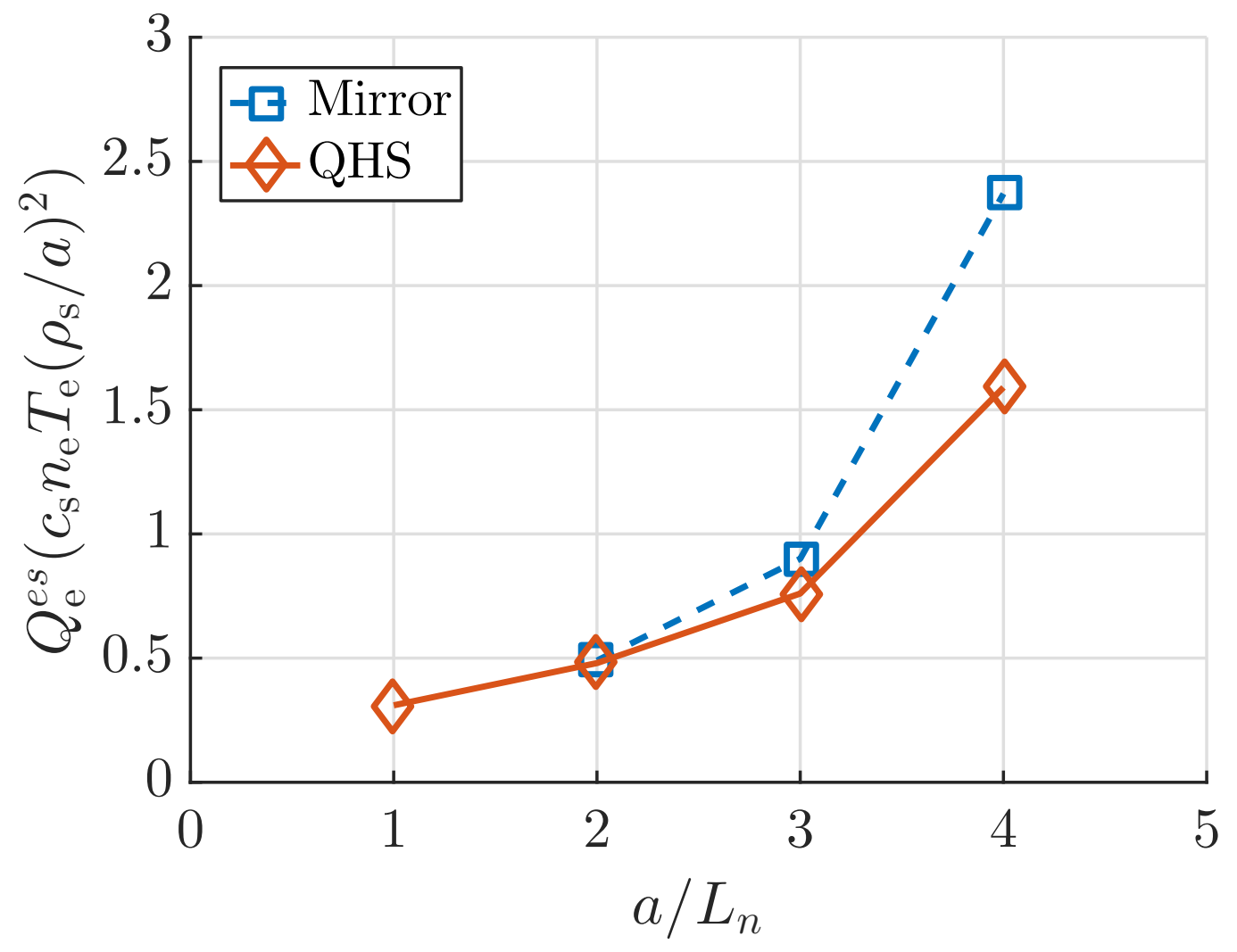
III. Simulation heat flux in qualitative agreement with experiment

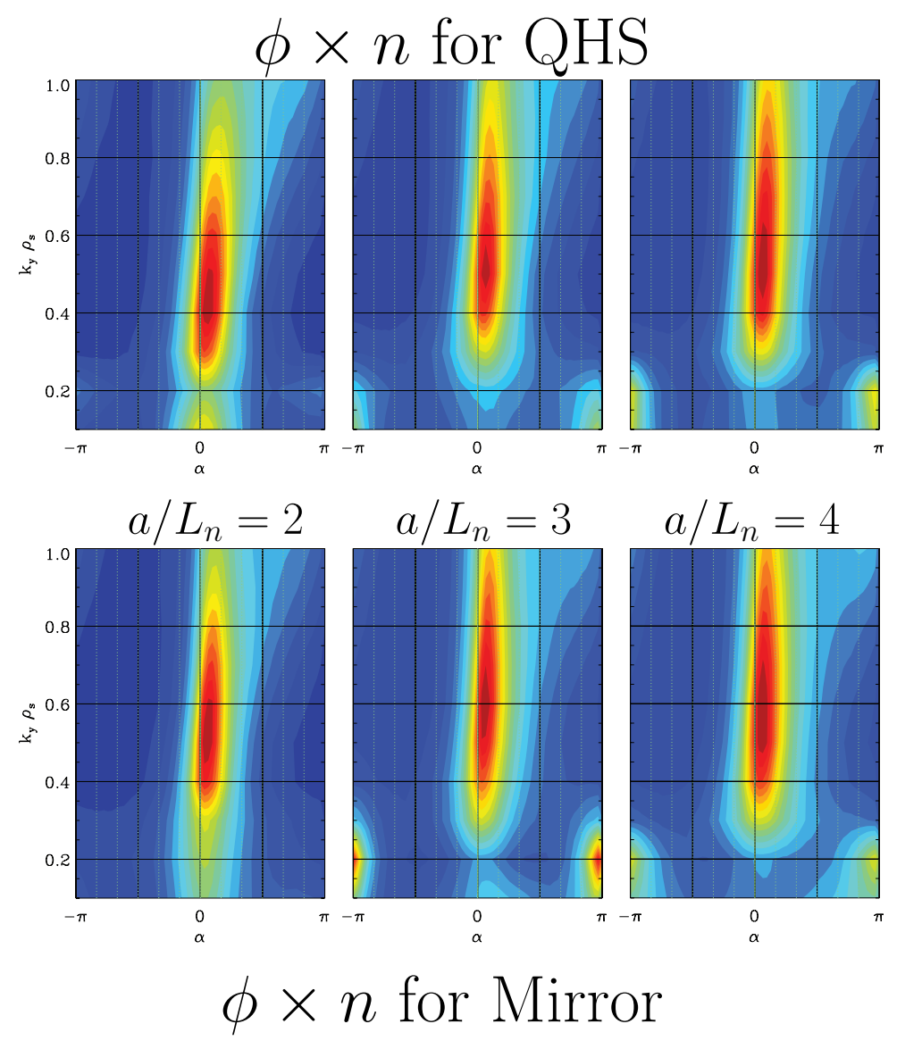


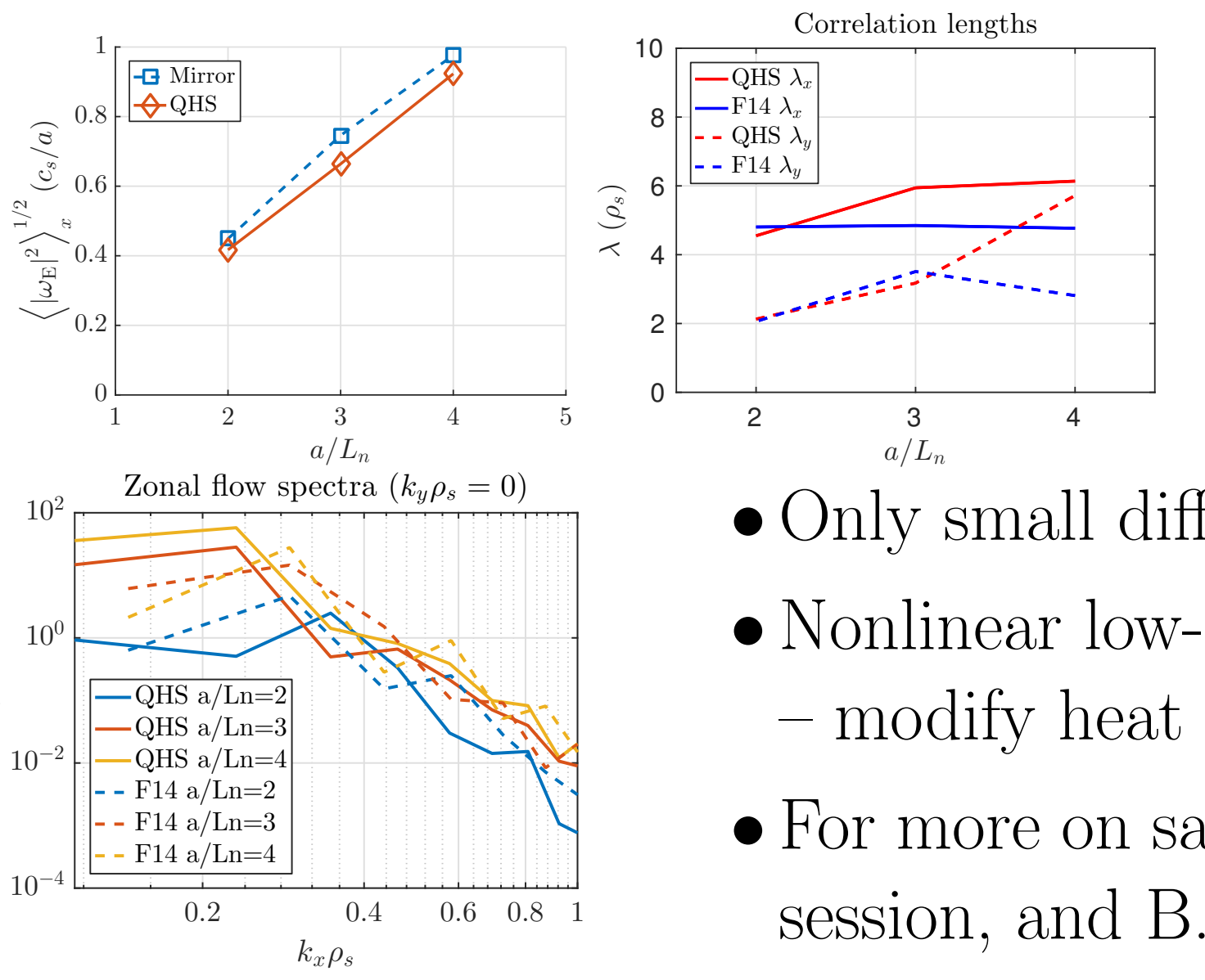
- Most unstable linear growth rates ($a/L_n = 4$, $a/L_{Te} = 0$) significantly smaller in Mirror.
- Nonlinear turbulence similar in configurations: – consistent spectra, prominent zonal flows, no change in crossphases.
- Nonlinear GENE simulations *not* modeling exact experimental parameters ($a/L_{Te} = 0$, $T_i = T_e$).
- At high a/L_n, heat flux is larger in Mirror than in QHS. Encouraging for future validation.



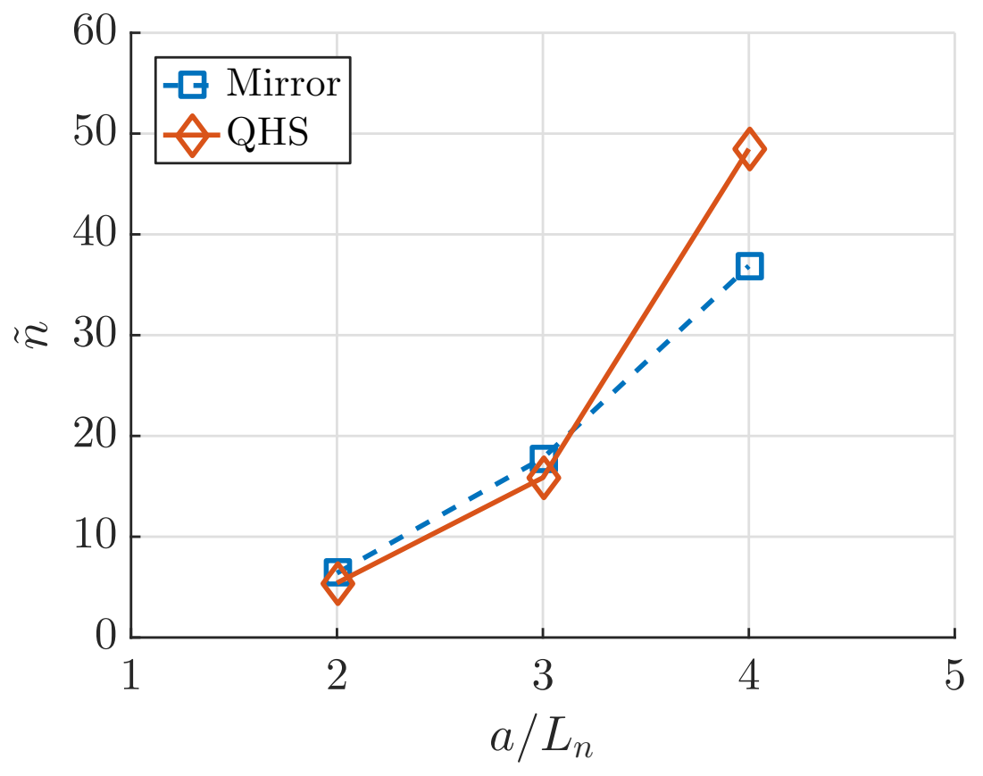






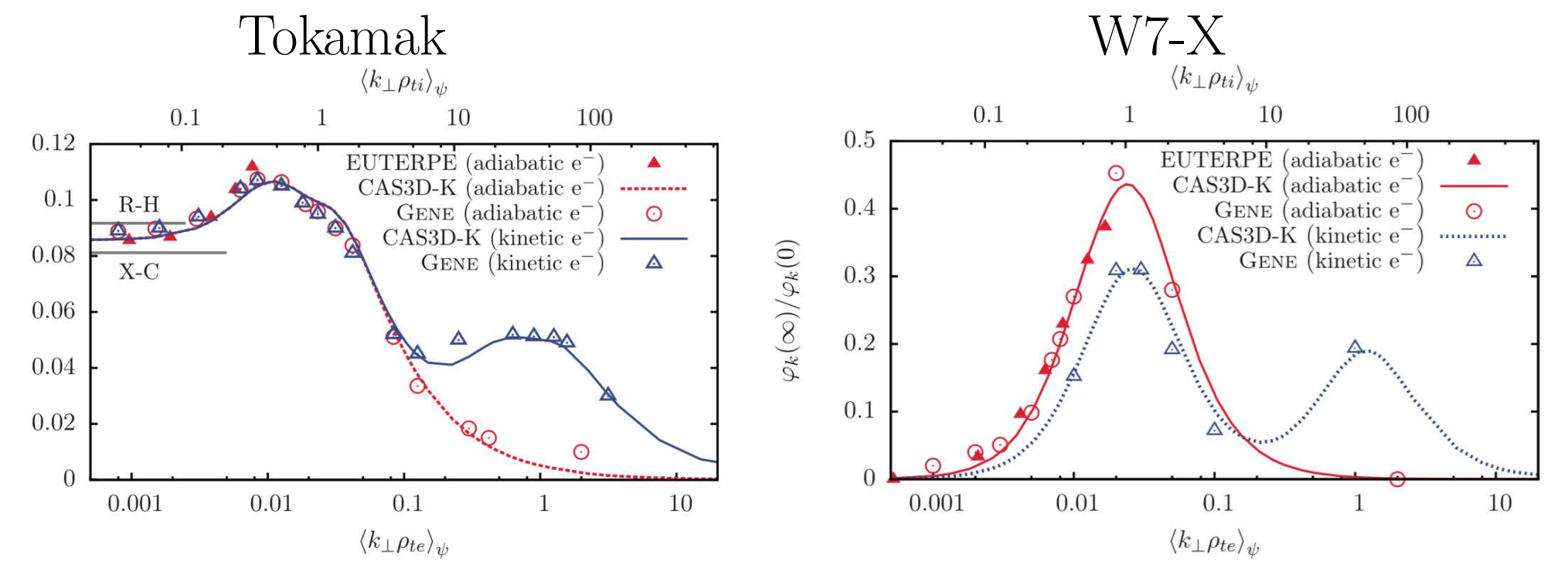


- Radial and poloidal correlation lengths reduced in Mirror at large gradient.
- Density fluctuations larger in QHS at large a/L_n – opposite heat flux.
- Only small difference in zonal flow shearing rate.
- Nonlinear low-$k_y\rho_s$ mode develops at large a/L_n – modify heat transport and saturation properties.
- For more on saturation, see C.C. Hegna CP11.0072 this session, and B.J. Faber GO4.00001 9:30 Tuesday.

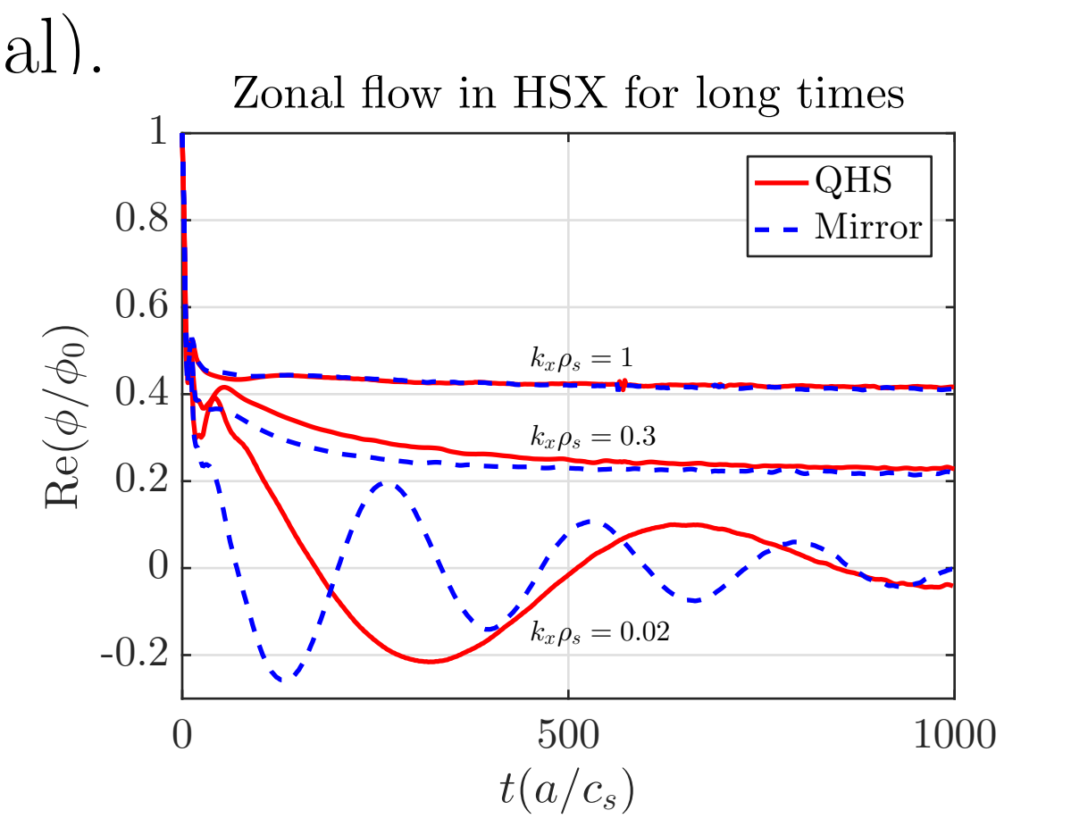


IV. Zonal flow residual in quasi-symmetry

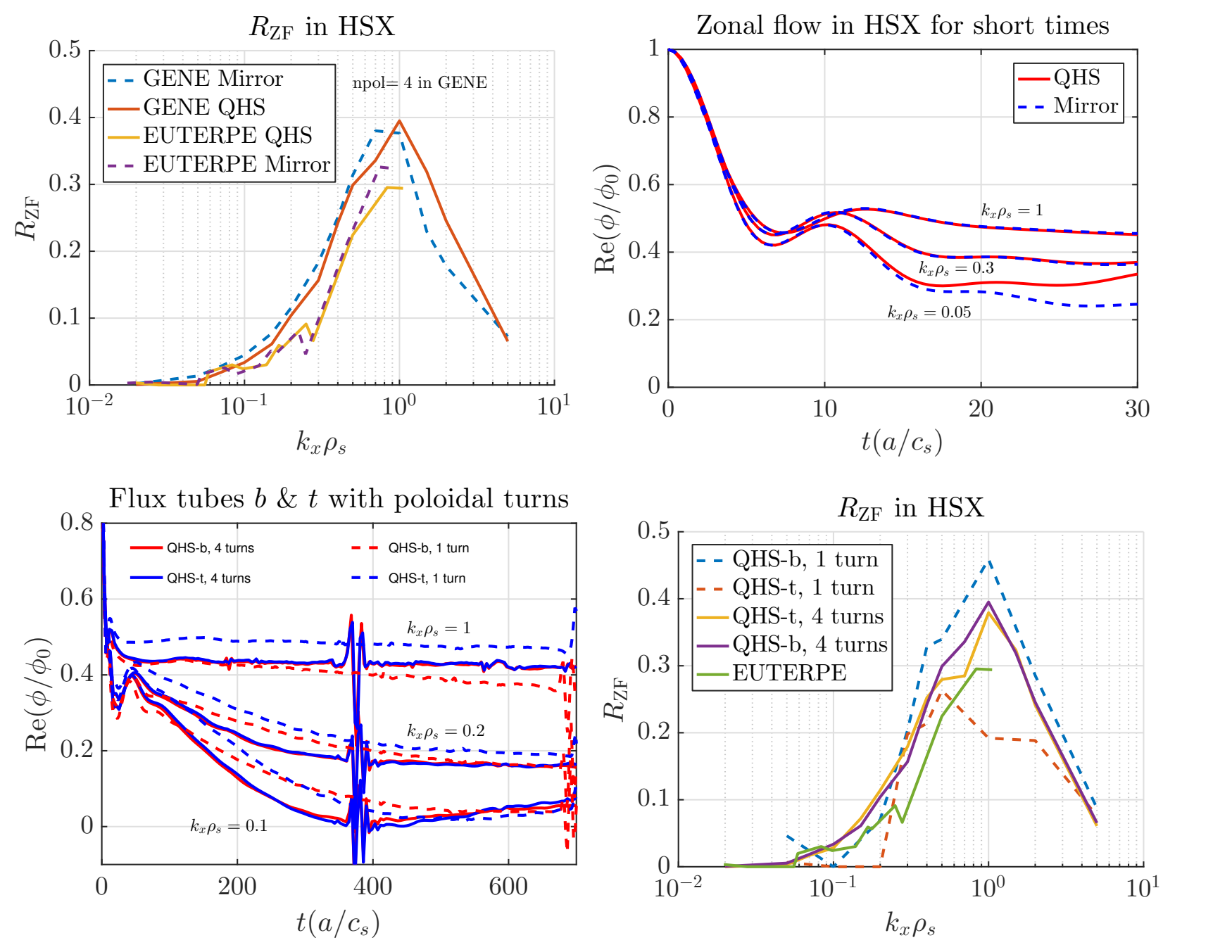
- In a tokamak, Rosenbluth-Hinton zonal flow residual R_{ZF} finite as $k_x\rho_s \to 0$.
- In Wendelstein 7-X, $R_{\mathrm{ZF}} \to 0$ at small $k_x\rho_s$ and exhibits zonal flow oscillations at Ω_{ZF}.
- Do non-ideal quasi-symmetric devices have finite R_{ZF} as $k_x\rho_s \to 0$? We compare zonal damping in HSX using GENE (local flux tube) and EUTERPE (global).

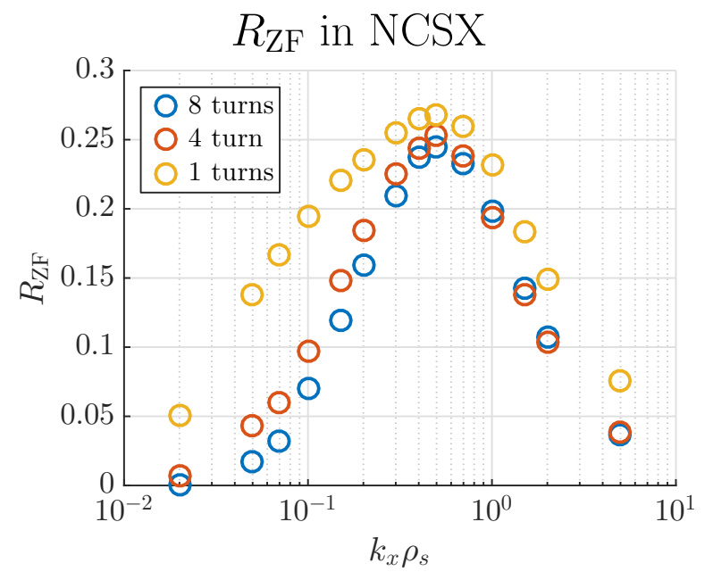


Figures from P. Monreal *et al.*, Plasma Phys. Control. Fusion 58 (2016).



- Zonal flow oscillations present at low-$k_x\rho_s$. Frequency decreases with reduced radial drifts from neoclassical optimization.
- No significant difference in R_{ZF} between QHS/Mirror. Large difference in Ω_{ZF}.
- For times comparable to turbulence correlation time – no difference in QHS/Mirror.
- Damping depends on flux surface averages – long flux tube (> 1 poloidal turn) required to match multiple flux tubes and global.





- Initial results for NCSX similar: $R_{\mathrm{ZF}} \to 0$ as $k_x\rho_s \to 0$.
- Poloidal turn requirements depend on geometry: in all cases studied here, 1 turn yields qualitatively incorrect results.

V. Summary

- Anomalous thermal diffusivity χ_e at peak density gradient is larger in a broken symmetry configuration than with quasi-helical symmetry.
- Gyrokinetic simulations reproduce a higher electron heat flux with broken symmetry, but not modeling exact experimental parameters. Not predicted by most unstable linear growth rate.
- Zonal flow damping requires flux surface averages – sensitive to computational domain.
- Real, as opposed to ideal, quasi-symmetric devices are more similar to non-symmetric stellarators than tokamaks – $R_{\mathrm{ZF}} \to 0$ as $k_x\rho_s \to 0$ and exhibit zonal flow oscillations.
- Zonal flow damping in QHS, compared to Mirror, exhibits reduced oscillation frequency and decay consistent with reduced radial particle drifts in optimized stellarators.
- Future work: validation of density fluctuations with reflectometer localized to large ∇n region with simulations at experimental a/L_{Te} and T_i. Collaboration at W7-X starting in November.

Acknowledgments

- This work is supported by US DOE Grant DE-FG02-93ER54222, and used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
- This work has been partially funded by the Ministerio de Economía y Competitividad of Spain under project ENE2015-70142-P. The authors thankfully acknowledge the computer resources, technical expertise and assistance provided by the Barcelona Supercomputing Center-Centro Nacional de Supercomputación and the CIEMAT computing center.
- This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

59th Annual Meeting of the APS Division of Plasma Physics, October 23-27, 2017, Milwaukee, WI