Collisionless zonal flow damping in quasisymmetric stellarators

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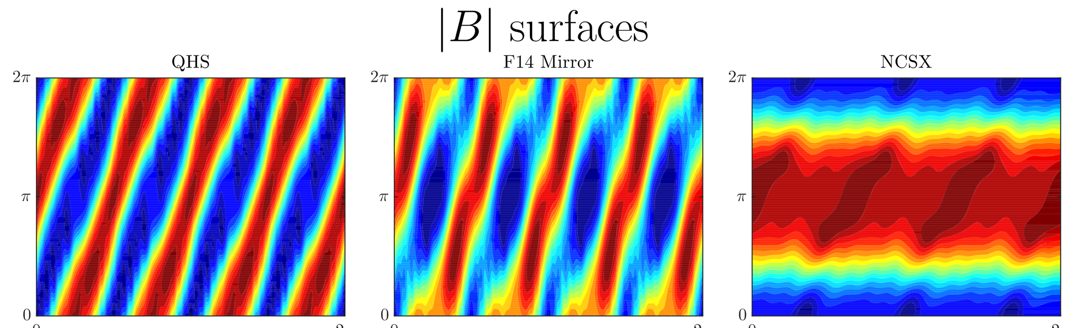
Motivation

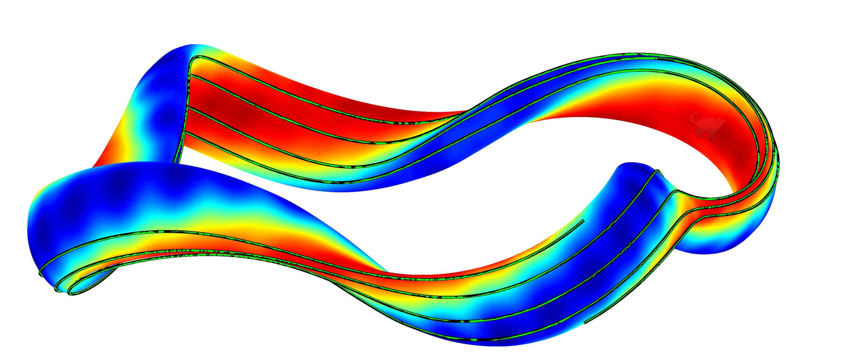
- Optimization for turbulent transport requires predictive capabilities.
- Zonal flows are often important to turbulence saturation, and thus transport.
- Collisionless zonal flow damping – simple linear calculation for an optimization loop.
- Can a linear zonal flow (ZF) damping calculation predict the turbulence heat flux ?
  - Not the residual alone, but perhaps damping/oscillation.
- ZF residual finite as $k_x\rho_s \to 0$ in tokamaks, vanishes in non-axisymmetry (Monreal 2016).
- Are real quasi-symmetric stellarators similar to tokamaks (finite R_{ZF} as $k_x\rho_s \to 0$) ?
  - No, $R_{ZF} \to 0$ as $k_x\rho_s \to 0$ if *any* radial particle drift.

I. HSX and NCSX configurations

- **HSX** auxiliary coils → allows variation of radial drift (neoclassical transport), important for ZF oscillation.
- 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 like a conventional stellarator.



- **NCSX** – Quasi-axisymmetry, three period device with a dominant [n,m] = 0,1 mode. Large bootstrap current similar to a tokamak.



- Gyrokinetics: Gene (`www.genecode.org`) & Euterpe
  - Gene local flux tube, with 1–8 poloidal turns.
  - Gene full flux surface, real space poloidal discretization.
  - Euterpe fully global domain.
- No unstable modes, no gradient drive, no collisions, adiabatic electrons.
- Initialize a $k_y = 0$, finite-k_x zonal mode and calculate time evolution.

II. Zonal flow damping in a stellarator

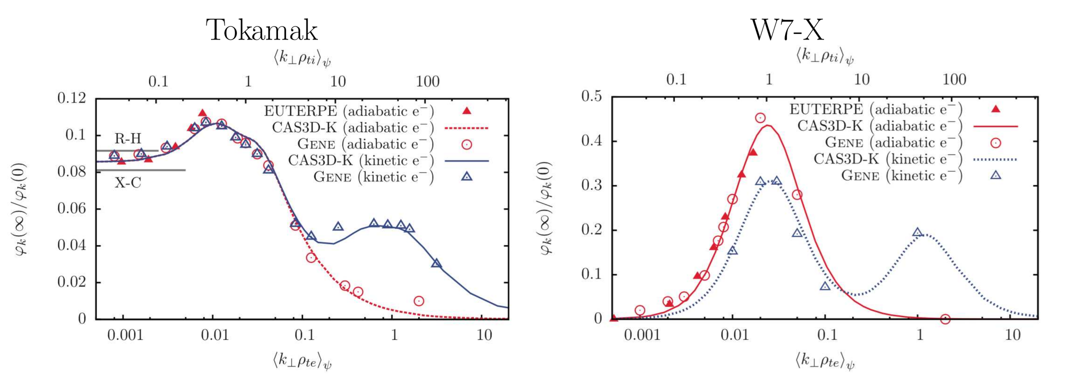
- Zonal Flow (ZF) – poloidally symmetric potential perturbation, drives flows by $E \times B$ drift.
- Flows shear turbulent eddies, reduce radial correlation length, and regulate transport.
- Given initial impulse, long time residual may relate to ability to support zonal flows.
- In a circular tokamak, Rosenbluth-Hinton zonal flow residual R_{ZF} finite as $k_x\rho_s \to 0$.:

$$\lim_{t\to\infty}\frac{\phi(t)}{\phi(0)} = \frac{1}{1+1.6q^2/\epsilon^{1/2}}$$

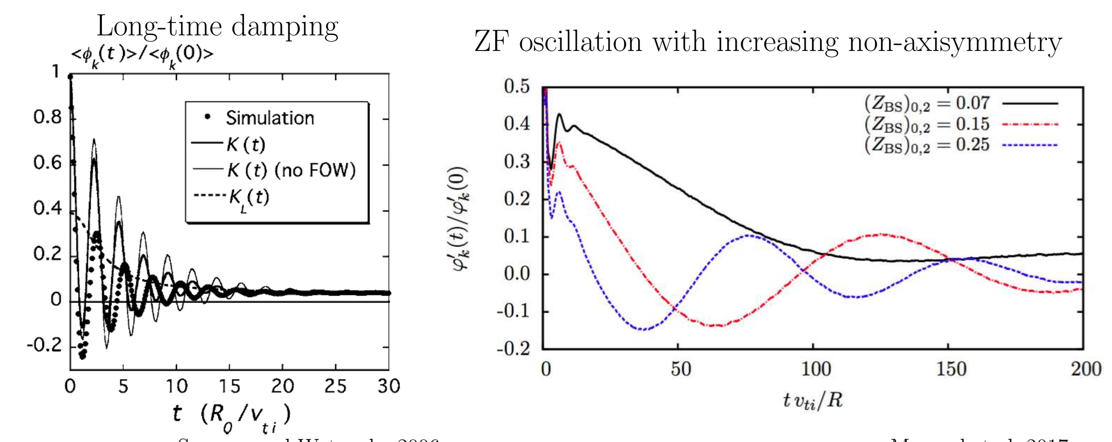
- Tokamak with $q = 1.5$ and $\epsilon \approx \frac{a}{R} \approx 0.13$,

$$\lim_{t\to\infty}\frac{\phi(t)}{\phi(0)} = 0.09$$

- In Wendelstein 7-X, $R_{ZF} \to 0$ at small $k_x\rho_s$.
- Differences for non-axisymmetry: long-time damping and zonal flow oscillations.
- GAMs quickly damped for low-shear stellarators, and not discussed here.



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



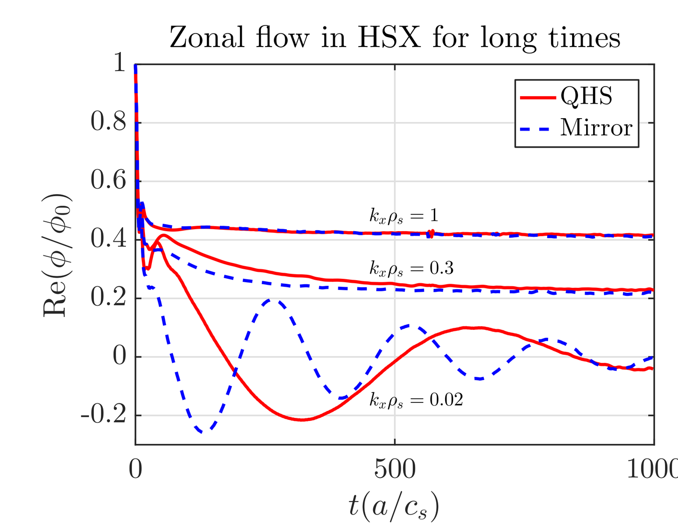
Sugama and Watanabe 2006 Monreal et al. 2017

- Long-time damping related to radial drift, $\tau_c \sim 1/|k_r\bar{v}_{dr}|$.
- ZF oscillation present if Landau damping small enough, and frequency Ω_{ZF} increases with radial drift.
- Optimized devices minimize neoclassical loss, reduce long-time damping, reduce frequency of zonal flow oscillations.

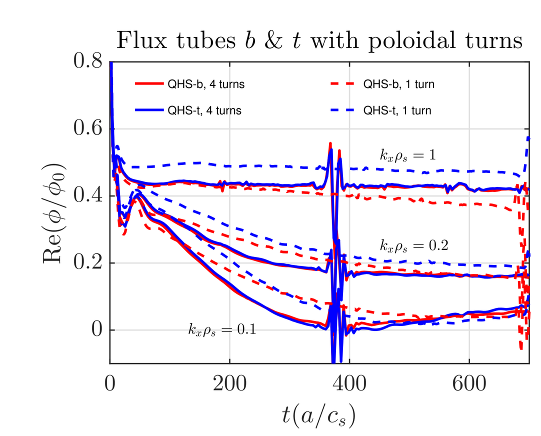
III. Realistic HSX configurations match other stellarators

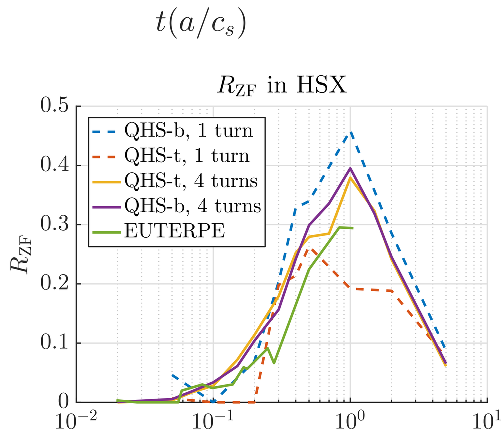
- Do non-ideal quasi-symmetric devices have finite R_{ZF} as $k_x\rho_s \to 0$?
- HSX-equivalent tokamak, $q \to q_{\text{eff}} = \frac{1}{|m\iota - n|} = 1/3$, $\epsilon \to \epsilon_h \approx 0.14(r/a) \approx 0.1$ $\lim_{t\to\infty}\frac{\phi(t)}{\phi(0)} = 0.64$
- Real HSX, $R_{ZF} \to 0$ as $k_x\rho_s \to 0$, R_{ZF} is smaller than Rosenbluth-Hinton estimate.
- ZF oscillation parameters found by nonlinear least squares fit.
- Fit – ZF oscillation amplitude A_{ZF}, frequency Ω_{ZF}, and damping γ_{ZF}, ZF residual R_{ZF}, and algebraic damping.

$$\varphi_k'(t)/\varphi_k'(0) = A_{ZF}\cos(\Omega_{ZF}t)\exp(-\gamma_{ZF}t) + R_{ZF} + \frac{c}{1+dt^e}$$

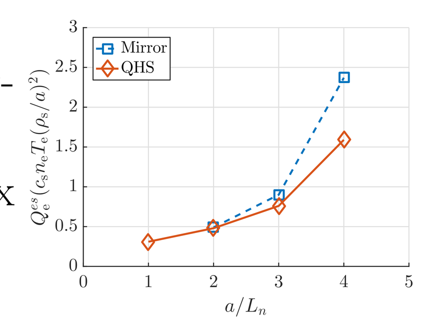


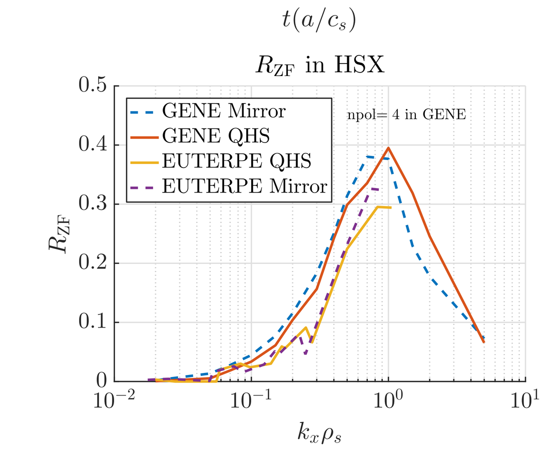
- Zonal flow oscillations present at low-$k_x\rho_s$. Frequency decreases with reduced radial drifts from neoclassical optimization.
- Two stellarator symmetric flux tubes for local Gene calculations. QHS-b(ean) and QHS-t(riangle) centered in good and bad curvature, respectively.
- Damping depends on flux surface averages → long flux tube (> 1 poloidal turn) required to match different flux tubes and global Euterpe.
- No significant difference in R_{ZF} between QHS/Mirror. Large difference in Ω_{ZF}.
- For short times comparable to turbulence correlation time – no difference in QHS/Mirror.

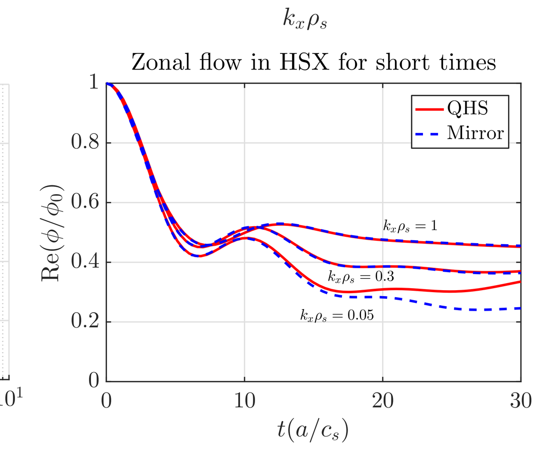




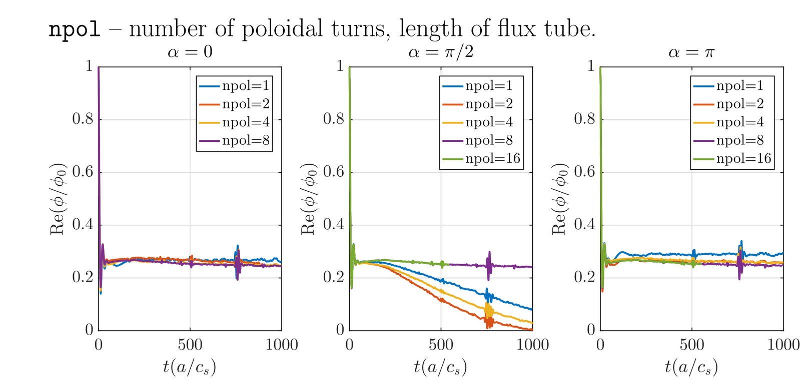
- Heat flux larger in F14 Mirror, despite matched R_{ZF}. (Nonlinear simulation in flux tube with 4 poloidal turns)



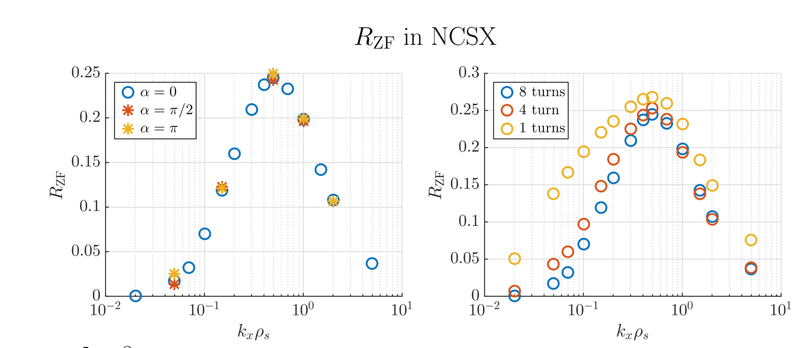


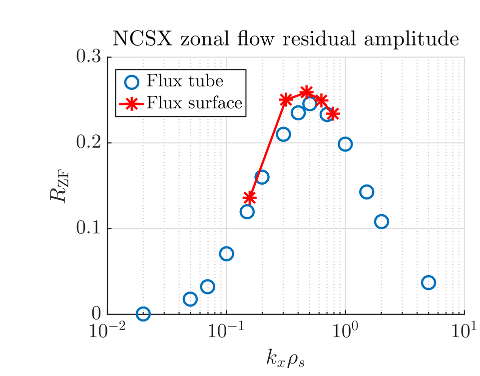


IV. Zonal flow residual in NCSX

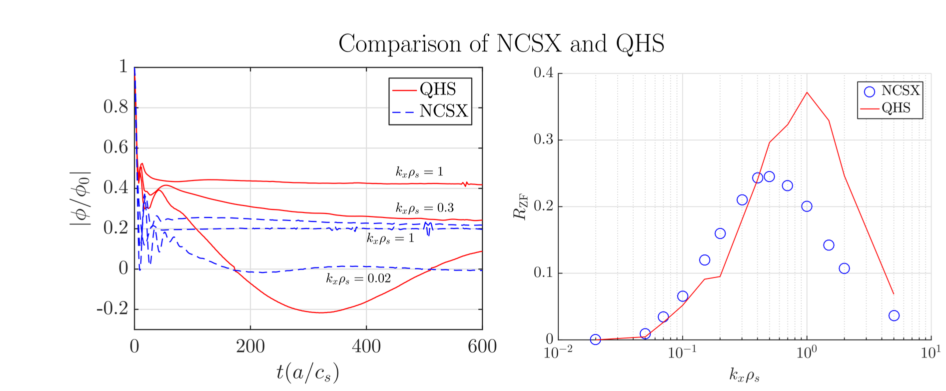


- Stellarator flux tubes unique, $\alpha = \pi/2$ flux tube does not support zonal flow for `npol` < 8.
- $\alpha = 0, \pi$ flux tubes capture ZF damping at `npol` $= 2$, for large k_x.
- For long enough domain, matched zonal flow damping for all flux tubes.
- Most sensitive to `npol` at small k_x, where may need global effects.
- NCSX similar to other stellarators, not ideal tokamak: $R_{ZF} \to 0$ as $k_x\rho_s \to 0$, and exhibit ZF oscillations.





- Full flux surface R_{ZF} in agreement with flux tube calculations for `npol` $= 8$. Global simulations in progress.
- Agreement of flux tube and full surface suggests communication between flux tubes not important for residual.
- Zonal flow oscillations only present for very small k_x, amplitude much smaller than QHS.



- Peak R_{ZF} and peak k_x smaller than QHS. Requires further consideration.

V. Summary

- Zonal flow damping requires flux surface averages – sensitive to geometry representation. R_{ZF} captured by local calculation only with extended flux tube.
- Poloidal turn requirements depend on geometry: some flux tubes do not support zonal flows unless sampling enough of the surface.
- Realistic, as opposed to ideal, quasi-symmetric devices differ from tokamaks with $R_{ZF} \to 0$ as $k_x\rho_s \to 0$ and finite ZF oscillation frequency.
- QHS, compared to Mirror, exhibits reduced oscillation frequency and decay consistent with reduced radial particle drifts in optimized stellarators.
- Trends between configurations that are not captured by linear instability dynamics cannot be explained by R_{ZF} behavior alone.

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