A look at turbulent impurity and energy transport in stellarators using linear gyrokinetic simulations

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Background I

- Neoclassically optimized stellarators: relatively large turbulent energy transport

$\Longrightarrow$ Want to minimize turbulent energy transport.

- Quasi-isodynamic stellarators: small neoclassical transport at high collisionality

$\Longrightarrow$ Turbulent impurity transport likely needed to avoid impurity accumulation.

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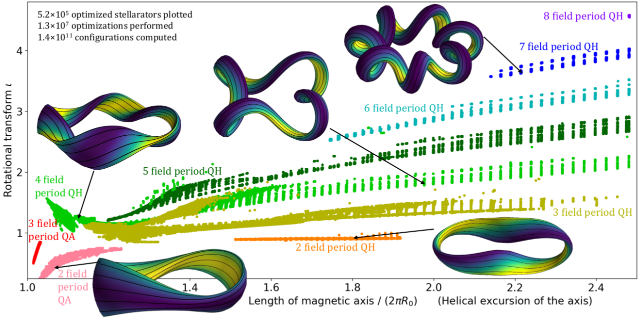
- **Compare the ITG turbulence and resulting energy & impurity fluxes between different quasi-symmetric stellarators**

Image from *Matt Landreman*



Recently published large database of quasi-symmetric stellarators

Theory and definitions

Electrostatic gyrokinetic equation solved with Stella code M. Barnes 2019, *JoCP* **391** p 365

$$\frac{\partial g_s}{\partial t} + v_\parallel \vec{b}\cdot\nabla z\left(\frac{\partial g_s}{\partial z} + \frac{Z_s e}{T_s}\frac{\partial \langle\phi\rangle_{\vec{R}}}{\partial z}F_s\right) - \frac{\mu_s}{m_s}\vec{b}\cdot\nabla B\frac{\partial g_s}{\partial v_\parallel}$$
$$+ \vec{v}_{Ms}\cdot\left(\nabla_\perp g_s + \frac{Z_s e}{T_s}\nabla_\perp \langle\phi\rangle_{\vec{R}} F_s\right) + \langle\vec{v}_E\rangle_{\vec{R}}\cdot\nabla_\perp g_s + \langle\vec{v}_E\rangle_{\vec{R}}\cdot\nabla_E F_s = 0, \quad (1)$$

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Expanded $g = g_{k_x,k_y}\exp\left(\mathrm{i}k_x x + \mathrm{i}k_y y\right)$ and linearize. ($k_x = 0$ here)

(Raw) fluxes

$$\Gamma_{s,k_y} = -\frac{1}{n_s}k_y\,\mathcal{I}\int \mathrm{d}^3 v g_s J_0\phi^*, \tag{2}$$

$$Q_{s,k_y} = -k_y\,\mathcal{I}\int \mathrm{d}^3 v\frac{mv^2}{2}g_s J_0\phi^*. \tag{3}$$

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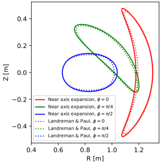
Mixing-length estimate of fluxes

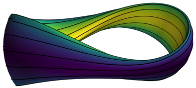
$$\Gamma^{\mathrm{QL}}_{k_y} = \frac{\Gamma_{k_y}\gamma_{k_y}}{\left\langle|\phi_{k_y}|^2\right\rangle k_y^2} \tag{4}$$

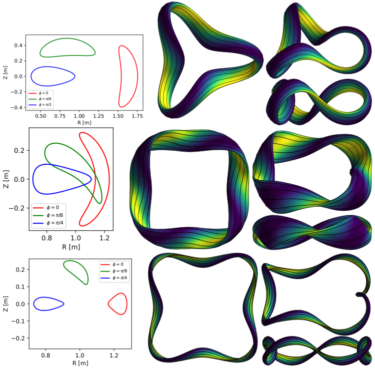
ITG turbulence in different quasi-symmetric stellarators

- Magnetic configurations specified by n_{fp} and boundary Fourier coefs.
- Gradients set to promote ITG
  $\frac{\mathrm{d}\ln T_i}{\mathrm{d}\psi_{\mathrm{t}}} = -5,$
  $\frac{\mathrm{d}\ln T_e}{\mathrm{d}\psi_{\mathrm{t}}} = \frac{\mathrm{d}\ln n}{\mathrm{d}\psi_{\mathrm{t}}} = -0.1$
- Trace Ar+16 ($Z = 16$, $A = 40$) with gradients:
  $\frac{\mathrm{d}\ln T_z}{\mathrm{d}\psi_{\mathrm{t}}} = -2.75,$
  $\frac{\mathrm{d}\ln n_z}{\mathrm{d}\psi_{\mathrm{t}}} = -0.42$

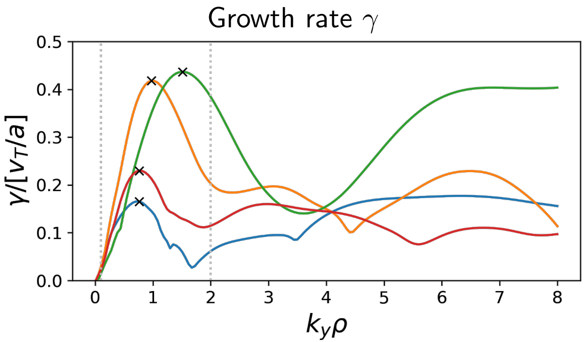


Images from [Landreman 2022]





ITG turbulence in different quasi-symmetric stellarators



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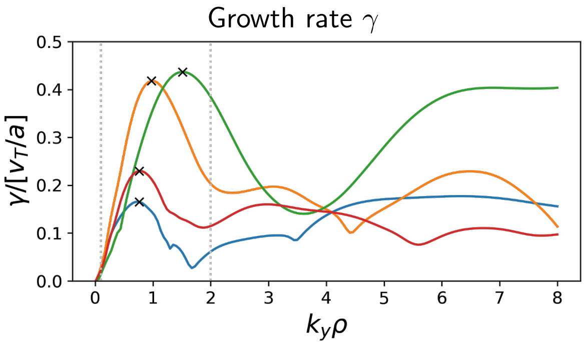

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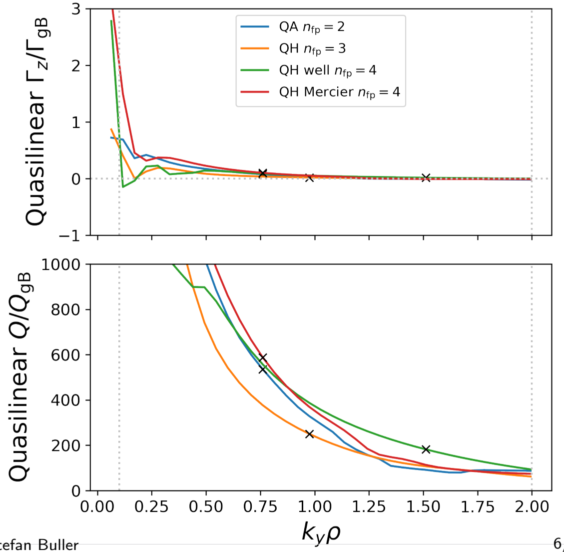
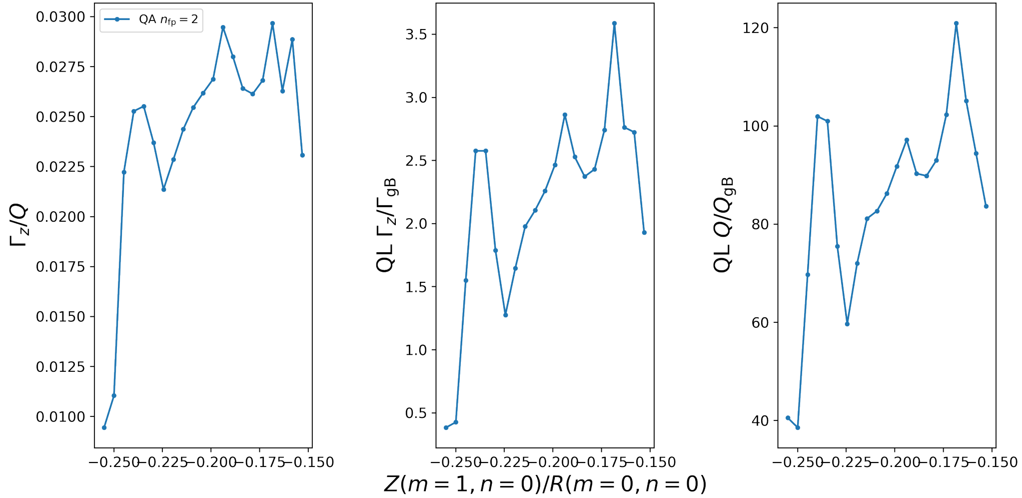


1D scan in a boundary Fourier mode

$$\Gamma^{\mathrm{QL}} = \frac{1}{N_y} \sum_{k_y} \Gamma^{\mathrm{QL}}_{k_y}$$



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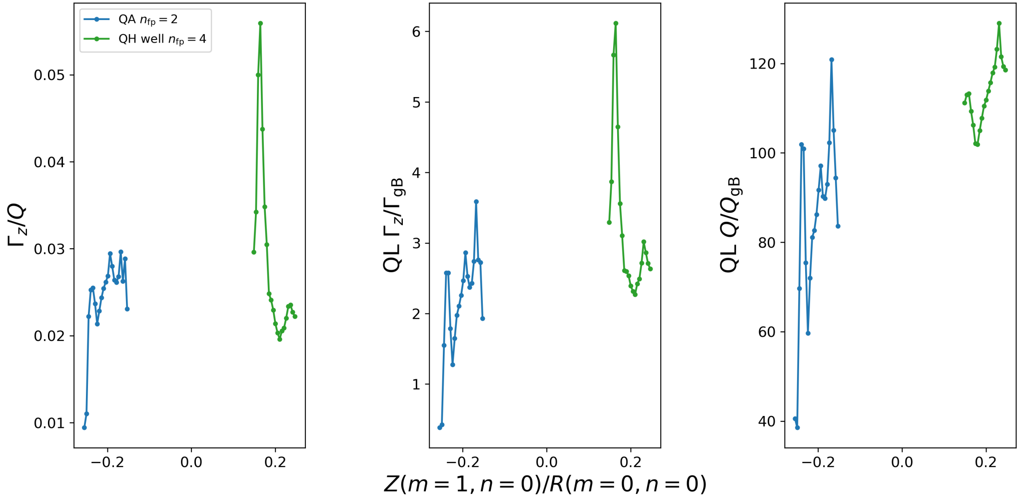

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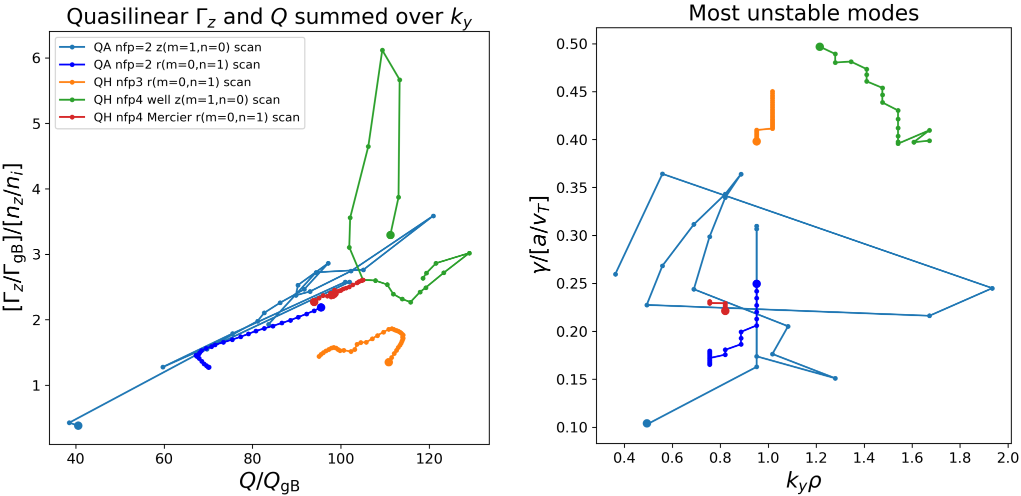
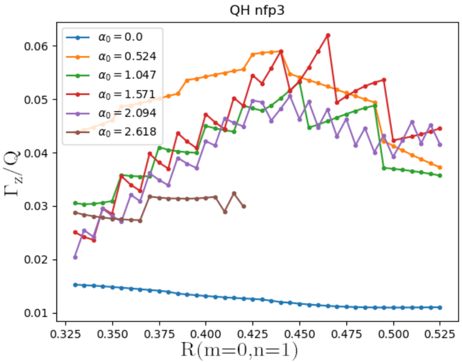
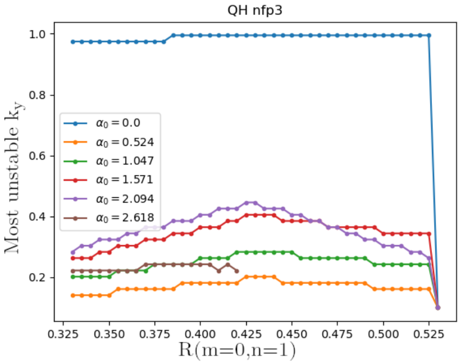


Conclusions & Outlook

- We have investigated a mixing-length estimate for impurity and energy fluxes from linear gyrokinetic simulations
- Impurity and energy flux are found to generally be correlated.
  However, we have found some configurations with twice the impurity flux per energy flux.
- Optimization on one field-line is probably not sufficient.
- Nonlinear verification of the optimization is ongoing.

Bonus slide


QH nfp3
$\alpha_0 = 0.0$
$\alpha_0 = 0.524$
$\alpha_0 = 1.047$
$\alpha_0 = 1.571$
$\alpha_0 = 2.094$
$\alpha_0 = 2.618$
Γ_z/Q
R(m=0,n=1)
0.01
0.02
0.03
0.04
0.05
0.06
0.325
0.350
0.375
0.400
0.425
0.450
0.475
0.500
0.525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$\alpha_0 = 1.047$
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$\alpha_0 = 2.618$
Most unstable k_y
R(m=0,n=1)
0.2
0.4
0.6
0.8
1.0
0.325
0.350
0.375
0.400
0.425
0.450
0.475
0.500
0.525