Turbulent transport optimization in stellarators

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Motivation for this work is to improve the stellarator concept

- Techniques have been developed to reduce neoclassical transport in stellarators
  - Traditional weakness of conventional stellarator ~ poor transport at small collisionality (large temperature)
  - Various solutions have been discovered, Quasi-symmetry (QS), QI, QO, …

- Helically Symmetric Experiment (HSX) is demonstrating
  Quasi-Helical Symmetry (QHS) is a route to improved neoclassical transport
  - 3D shaping employed to optimally provide quasi-symmetry

\[
B \cong B_0(\psi)[1 + \epsilon_{41} \cos(4\zeta - \theta)]
\]
Turbulent transport determines confinement of optimized stellarators

- HSX experiments indicate electron heat transport is anomalously large

\[ \nabla \cdot \vec{q}_e = S_{\text{heat}} \]
\[ \vec{q}_e = -n \chi_e^{\text{eff}} \nabla T_e \]
\[ \chi_e^{\text{eff}} = - \frac{\int d^3 \vec{x} S_{\text{heat}}}{\oint d\vec{a} \cdot n \nabla T_e} \]

- Neoclassical transport predictions
  - Collisional transport accounting for magnetic field geometry
  - QHS predicted to improve neoclassical transport

- Cross-field transport is anomalously large over most of the confinement volume
  - Turbulent transport is the likely culprit

→ How do we use 3D shaping to control turbulent transport?
• Turbulent transport is a new frontier in stellarator optimization
  – Turbulence is the dominant transport channel in optimized stellarators

• Development of reduced models for use in optimization
  – Focus on turbulent saturation processes

• “Metrics” for turbulence optimization are emerging
  – Triplet correlation lifetime
  – Metrics assessed for a class of optimized stellarators
Micro-instabilities produce turbulent transport in magnetic confinement devices

- Inevitably, cross-field temperature and density gradients exist in all magnetic confinement devices
  - These produce drift wave instabilities $\sim e^{i k \cdot x - i \omega t}$
  - $\omega = \omega_R + i \gamma$ \quad $\omega_R \approx k \cdot v_s [1 + \ldots ]$

$$v_s = \frac{n_s B \times v_n}{q_s B^2} \quad v_s^T = \frac{B \times v_n}{q_s B^2}$$

- Typical scales --- $\frac{\Delta x_{\perp}}{\Delta x_{\parallel}} \ll 1$
  - $k_{\perp} \rho_s \sim 0.1 - 1$ \quad $\Delta x_{\perp} \sim \text{mms-cms}$
  - $k_{\parallel} R \sim 1$ \quad $\Delta x_{\parallel} \sim \text{meters}$
    - $\gamma \sim 10^{-3} - 10^{-4} \, \text{s}^{-1}$

- Various mechanisms produce instabilities $[\gamma > 0]$ over a broad range of wavelengths
  - Many instabilities grow in amplitude, interact nonlinearly, saturate at finite amplitude
  - Cross-field turbulent transport
    - $\chi \sim \frac{\Delta x_{\perp}^2}{\Delta t} \sim 1 \, \frac{m^2}{s}$

Contours of $\gamma$ as function of $k_{\perp}$ for HSX

Turbulent simulation using GENE

Faber, PhD '18
Sophisticated numerical tools are specialized to describe turbulent transport in magnetic confinement devices

- Gyro-kinetic computational tools are primarily used to simulate turbulent transport
  - Gyro-kinetic = kinetic theory of strongly magnetized plasmas on times long compared to cyclotron frequencies
  - Averaging over fast cyclotron timescales $\rightarrow$ reduce to 5D phase space
  - Scale separation: $\frac{\Delta x_\perp}{\Delta x_\parallel} \ll 1$

$\rightarrow$ "Flux tube" geometry – Fourier decomposition perpendicular to $B$, eigenmode extends along the field line

- Magnetic field line geometry impacts micro-instability induced turbulence
  - Curvature
    $$\kappa = (\hat{b} \cdot \nabla)\hat{b}$$
  - Torsion
    $$\tau_n = -\hat{n} \cdot (\hat{b} \cdot \nabla)(\hat{b} \times \hat{n})$$
  - Local magnetic shear
    $$s_{local} = (\hat{b} \times \hat{n}) \cdot \nabla \times (\hat{b} \times \hat{n})$$
Current focus is on reduced models

- Gyrokinetic simulations tools are available to stellarator applications --- GENE (Jenko et al ‘00; Xanthopolous et al ’07), GKV, GS2, EUTERPE …
  - Gyrokinetics commonly employed in tokamak applications

- For stellarator optimization:
  - Employing nonlinear gyrokinetic simulations as part of an optimization procedure is impractical

- Motivates the need to develop reduced models
  - Identify “metrics” that can be easily evaluated in optimization procedures
  - Focuses our thinking on physical understanding
  - Concentrate efforts towards discerning the role of 3D magnetic geometry
    --- for a given plasma density, temperature, magnetic field strength and size, what is the “best” way to arrange the magnetic field geometry?
Initial turbulence optimization efforts used simple estimate for transport coefficients

- How do we use 3D shaping to control micro-turbulence?
  - Initial studies targeted reducing linear growth rates (Mynick et al PRL ‘10)
  - Simple model for turbulent transport coefficients using quasi-linear/mixing length estimate
    \[ \chi^{\text{turb}}_\perp \approx \sum_k \gamma \frac{\Delta x^2}{k^2} \sim \frac{\Delta x^2}{\Delta t} \]
    \[ Q = -n\chi^{\text{turb}}_\perp \nabla T_i \]
  - Simple model for \( \gamma \) --- identify dependence of 3D geometry
  - Stellarator configurations generated that optimized 3D shaping for lowest \( \gamma \)
  - Nonlinear gyrokinetic simulations using GENE

Mynick et al PRL ’10 (ITG in NCSX)

Factor of \( \sim 3 \) reduction in turbulent transport
Linear instability properties are often employed as a predictor of turbulent transport.

Microinstability growth rates have been predicted for a number of stellarators—Quasi-helically Symmetric (QHS) have relatively poor linear properties.

- Geometric difference for QHS
- Short "connection length" → fast growth rates

\[ \Delta t \sim \frac{\Delta x_{||}}{C_s} \]

**Rewoldt et al., '05**

IBI contours for HSX show quasi-helical symmetry

IBI contours for NCSX show quasi-axisymmetry

**HOWEVER**, Linear theory is not the whole story → turbulent saturation needs to be quantified.
Linear growth rates properties are not clear indicators of turbulence transport rates in stellarators

- Despite large differences in linear growth rates, HSX has lower predicted ITG-induced turbulent transport than NCSX (I. J. McKinney et al, ‘19)

\[
\frac{a}{L_{T_i}} = 3 \quad \frac{a}{L_n} = 0
\]

\[
\frac{\langle \sum \frac{\gamma}{k_1^2} \rangle_{HSX}}{\langle \sum \frac{\gamma}{k_1^2} \rangle_{NCSX}} \sim 5
\]

\[
\chi_{HSX} \sim \frac{1}{3} \quad \chi_{NCSX} \sim \frac{1}{3}
\]

→ QHS has advantages with regard to turbulent saturation physics
Linear growth rates properties are not clear indicators of turbulence transport rates in stellarators

- Linear instability properties are not good indicators of TEM turbulent transport in HSX configurations (Smoniewski ‘18)

Mixing length/quasilinear estimates for transport coefficients $[\chi \sim \gamma/k_{\perp}^2]$ do not predict correct trends for turbulent transport
Micro-instability induced plasma turbulence has a different character than Kolmogorov-style fluid turbulence

- In classic fluid turbulence, we envision injecting energy at large scale, dissipation at small scale
- In plasma turbulence, we have instabilities and damped modes at “all” scales
  - Large number of stable eigenmodes excited in turbulent state

**Linear mode spectrum at \((k_x,k_y) = (0,0.9)\) for HSX**

![Linear mode spectrum plot](image)

\(\omega (c_s/a)\)

\(\gamma (c_s/a)\)

Faber et al, JPP ‘18
Focus on understanding turbulent saturation physics

- Paradigm of nonlinear energy transfer from **unstable** to **damped** modes at comparable wavenumber as the dominant saturation mechanism. (Terry et al ‘15)

\[
\frac{dE_k}{dt}
\]

- Damped modes play a role in turbulent saturation (Hatch et al ’11)
- Dominant energy transfer involves three-wave interaction (Terry et al ‘18)
  - 3\textsuperscript{rd} mode primarily regulates nonlinear energy transfer
    - In tokamaks: 3\textsuperscript{rd} mode = Zonal Flow
    - In stellarators: 3-wave interaction depends on geometry \(\rightarrow\) Identifies mechanisms to reduce turbulent transport
A reduced fluid model is developed to describe turbulent saturation processes in stellarators.

- Three field model for ion temperature gradient (ITG) turbulence
  - Flux tube formulation
  - Fluid advection is the dominant nonlinearity

\[
\frac{\partial}{\partial t} \left[ \Phi_k + \mathbf{B}_k (\Phi_k + T_k) \right] - i \mathbf{D}_k (\Phi_k + T_k) + \mathbf{v}_|| \frac{U_k B_0}{B} = \sum_{k'} (k'_x k'_y - k_y k'_x) \mathbf{B}_{k'k} \Phi_{k-k',} (\Phi_{k'}, + T_{k'})
\]

\[
\frac{\partial U_k}{\partial t} + \frac{B_0}{B} \mathbf{v}_|| (\Phi_k + T_k) = \sum_{k'} (k'_x k'_y - k_y k'_x) \Phi_{k-k',} U_{k'}
\]

\[
\frac{\partial T_k}{\partial t} + i k_y \frac{a}{L_{Ti}} \Phi_k = \sum_{k'} (k'_x k'_y - k_y k'_x) \Phi_{k-k',} T_{k'}
\]

- Key geometric quantities enter through \( \mathbf{D}_k, \mathbf{B}_k \mathbf{v}_|| \)
  - Curvature, local magnetic shear
  - Integrated local magnetic shear

\[
D_k \sim \frac{\kappa_n + \Lambda \kappa_g}{|\nabla \rho|} \quad B_k \sim \frac{1 + (\Lambda - \Lambda_0)^2}{|\nabla \rho|^2}
\]

\[
\Lambda = \frac{|\nabla \rho|^2}{B} \int \frac{dl}{B} s_{\text{local}} \frac{B^2}{|\nabla \rho|^2}
\]
Three linear eigenmodes for each $k$
--- instability, damped mode, marginally stable mode

- Linear analysis leads to identification of three eigenmodes at each $k$
  - Algebraic expressions involving $<D_k>$, $<B_k>$, $<k|^2>$

$$
\omega^3(1 + <B_k>) + \omega^2 \left( <D_k> + <B_k> \frac{k_y a}{L T_i} \right) + \omega \left( <D_k> \frac{k_y a}{L T_i} - <k|^2> \right) - <k|^2> \frac{k_y a}{L T_i} = 0
$$

- 2 nearly complex conjugate pairs (instability, damped mode) and one near marginally stable mode

$$
\omega_1(k_x, k_y) \approx \omega_R + i\gamma \\
\omega_2(k_x, k_y) \approx \omega_R - i\gamma \\
\omega_3(k_x, k_y) \approx Re(\omega_3)
$$

- With eigenvalue there is an associated eigenvector ($\omega_i \leftrightarrow \beta_i$)
Three linear eigenmodes for each $k$
--- instability, damped mode, marginally stable mode

- Linear analysis leads to identification of three eigenmodes at each $k$
  - Algebraic expressions involving $<D_k>$, $<B_k>$, $<k|^2>$
    \[ \omega^3 (1 + <B_k>) + \omega^2 \left( <D_k> + <B_k> \frac{k_y a}{L_{Ti}} \right) + \omega \left( <D_k> \frac{k_y a}{L_{Ti}} - <k|^2> \right) - <k|^2> \frac{k_y a}{L_{Ti}} = 0 \]
  - 2 nearly complex conjugate pairs (instability, damped mode) and one near marginally stable mode
    \[
    \begin{align*}
    \omega_1(k_x, k_y) &\approx \omega_R + i\gamma \\
    \omega_2(k_x, k_y) &\approx \omega_R - i\gamma \\
    \omega_3(k_x, k_y) &\approx \text{Re}(\omega_3)
    \end{align*}
    \]

- With eigenvalue there is an associated eigenvector ($\omega_i \leftrightarrow \beta_i$)
- Turbulent heat flux has contributions from unstable and damped eigenmodes

\[
Q = \int_{-\infty}^{\infty} \frac{d\eta}{\hat{B} \cdot \nabla \eta} \sum_k k_y^2 \epsilon_T \left\{ \frac{\gamma}{|\omega_1|^2} \left[ |\beta_1|^2 - |\beta_2|^2 + \text{Re}(\beta_3 \beta_1^*) - \text{Re}(\beta_3 \beta_3^*) \right] + \left( \frac{1}{\omega_3} - \frac{\omega_R}{|\omega_1|^2} \right)[\text{Im}(\beta_1 \beta_3^*) + \text{Im}(\beta_2 \beta_3^*)] \right\}
\]

Quasilinear contribution

Damped eigenmodes contributions
Nonlinear evolution expressed in terms
of evolution of each eigenmode

- Evolution equation for each eigenmode $\beta_p(k)$ ($p = 1, 2, 3$) can be derived
  \[ \frac{\partial \beta_p}{\partial t} + i \omega_p \beta_p = \sum_{k'} C_{pq,k} \Phi^Z_{k-k'} \beta_q(k') + \sum_{k''} C_{pqr} \beta_q(k') \beta_r(k-k') + \cdots \]

- Nonlinearly, eigenmode at $k$ coupled to modes at $k'$ and $k'' = k - k'$
- Nonlinearities segregated by couplings
  - involving Zonal flows ($\Phi^Z$)
  - Involving non-zonal eigenmodes

$C_{ijk} =$ coupling coefficients (depended on components of $k$ and eigenmode elements)

Nonlinear GENE simulations of HSX show zonal flow feature

Zonal quantities are "$y$"-independent
Nonlinear evolution expressed in terms of evolution of each eigenmode

- Evolution equation for each eigenmode $\beta_p(k)$ ($p = 1,2,3$) can be derived:
  \[
  \frac{\partial \beta_p}{\partial t} + i \omega_p \beta_p = \sum_{k'} C_{pqF} \Phi^Z_{k-k'} \beta_q(k') + \sum_{k'} C_{pqr} \beta_q(k') \beta_r(k - k') + \cdots
  \]

  - Nonlinearly, eigenmode at $k$ coupled to modes at $k'$ and $k'' = k' - k''$
  - Nonlinearities segregated by couplings
    - Involving Zonal flows ($\Phi^Z$)
    - Involving non-zonal eigenmodes
  
- Eigenmode evolution determined by triplet correlation functions:
  \[
  \frac{d}{dt} < |\beta_1|^2 > = 2\gamma < |\beta_1|^2 > + 2 \text{Re} \left[ \sum_{k'} C_{1qF} < \beta_1^* \Phi^Z_{k-k'} \beta_q' > \right] + 2 \text{Re} \left[ \sum_{k'} C_{1qr} < \beta_1^* \beta_q' \beta_r'' > \right] + \cdots
  \]
  - Expressions for triplet correlation functions can be derived (Makwana et al. '12)

  \[
  \left[ \frac{d}{dt} + i(\bar{\omega}_F' + \bar{\omega}_q' - \bar{\omega}_1^*) \right] < \beta_1^* \Phi^Z_{k-k'} \beta_q' > = S_0 \left[ \frac{d}{dt} + i(\bar{\omega}_r' + \bar{\omega}_q' - \bar{\omega}_1^*) \right] < \beta_1^* \beta_r' \beta_q' > = S_1
  \]
Effectiveness of nonlinear transfer rates is governed by a triplet correlation time

- Large nonlinear energy transfer with large three-wave correlation time
  \[ < \beta_1^* \Phi_{k-k'} \beta_q' > \sim \tau_{1qF} \quad < \beta_1^* \beta_q' \beta''_r > \sim \tau_{1qr} \]

- Large nonlinear transfer occurs with large triplet correlation lifetime
  \[ \tau_{1qF} = \frac{1}{i(\hat{\omega}_F'' + \hat{\omega}_q' - \hat{\omega}_1^*)} \quad \tau_{1qr} = \frac{1}{i(\hat{\omega}_r'' + \hat{\omega}_q' - \hat{\omega}_1^*)} \]
  - Two classes of 3-wave interactions yield largest correlation times:
    - Instability, damped mode, Zonal flow ($\tau_{12F}$)
    - Instability, damped mode, marginally stable mode ($\tau_{123}$)
Effectiveness of nonlinear transfer rates is governed by a triplet correlation time

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  - Two classes of 3-wave interactions yield largest correlation times:
    - Instability, damped mode, Zonal flow (\( \tau_{12F} \))
    - Instability, damped mode, marginally stable mode (\( \tau_{123} \))

- Large nonlinear energy transfer (and hence small levels of turbulent transport) are encouraged by large values of \( \tau_{12F} C_{12F} \) & \( \tau_{1pq} C_{1pq} \)

  - Turbulence optimization metrics

  - Theory for turbulent heat flux can be computed (Terry et al,’18, CCH et al ‘18)

\[ \chi^{turb}_\perp \equiv \alpha \frac{\gamma}{<k^2_\perp>} \quad \alpha \sim \frac{1}{C_{1qs} \tau_{1qs}} \]
Evaluation of metrics for QAS and QHS highlight how geometric differences could affect turbulent saturation

- Comparisons between QAS (NCSX) and QHS (HSX) have been made
  - QAS similar to tokamak
    - zonal triplet coupling dominant
  - QHS – similar zonal triplet coupling strengths
    - However --- not the only nonlinear transfer channel

\[
\frac{(C_{12F} \tau_{12F})^{QHS}}{(C_{12F} \tau_{12F})^{QAS}} \sim 1
\]

**Strength of saturation metric **\(C_\tau\) **for zonal triplet interaction vs.**\((k_x, k_y)\)
Evaluation of metrics for QAS and QHS highlight how geometric differences could affect turbulent saturation

- Comparisons between QAS (NCSX) and QHS (HSX) have been made
  - For QHS,
    - Large non-zonal triplet couplings are present
    - Consequence of QHS geometry --- short connection length

\[
\frac{(C_{1pq} \tau_{1pq})^{QHS}}{(C_{1pq} \tau_{1pq})^{QAS}} \sim 10^2 \gg 1
\]

Strength of saturation metric \( C_t \) for non-zonal triplet interaction vs. \((k_x, k_y)\)

- Gyrokinetic simulations also show indications of large non-zonal nonlinear energy transfer in QHS
Nonlinear saturation physics model can provide an explanation for observed advantages of QHS with regard to saturation

- Estimating turbulent transport coefficients

\[ \chi \sim \alpha \frac{\gamma}{k_L^2} \quad \alpha \sim \frac{\hat{s}}{\tau} \]

- Assuming zonal-triplets dominate for QAS
- Assuming non-zonal triplets dominate for QHS

\[
\frac{\chi_{QHS}}{\chi_{QAS}} \approx \frac{\left(\frac{\gamma}{k_L^2}\right)_{QHS}}{\left(\frac{\gamma}{k_L^2}\right)_{QAS}} \frac{\left(\hat{s}\right)_{NZ}^Z}{\left(\hat{s}\right)^Z} \frac{(C\tau)^Z}{(C\tau)^{NZ}}
\]

~ 5 \quad \sim 10^{-10^2} \quad \sim 10^{-2}
Non-zonal coupling much more prominent in QHS than in QAS

- Crucial quantity for non-zonal flow catalyzed energy transfer is $<\tau_{1pq}C_{1pq}>$

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$&lt;C_{12F_12F}&gt;$</th>
<th>$&lt;C_{1pq_1pq}&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QAS</td>
<td>0.159</td>
<td>0.261</td>
</tr>
<tr>
<td>QHS</td>
<td>0.027</td>
<td>23.89</td>
</tr>
</tbody>
</table>

$< C_{1pq_1pq} > = \frac{\int_{0}^{k_{max}} \int_{0}^{k_{max}} dk_x dk_y C_{1pq} \tau_{1pq} }{k_{x_{max}} k_{y_{max}}}$

→ QHS has intrinsic advantages relative to QAS with regard to turbulent saturation processes.
  → Much larger nonlinear energy transfer rate
  → Smaller turbulence levels

- Vigorous nonlinear energy transfer is a property of QHS → Can be accentuated in stellarator designs!
Theory correctly predicts trends seen in GENE simulations of ITG transport in HSX configurations

- Theory identifies metric for quantifying turbulent transport
  \[ Q_i \sim \alpha \frac{\nu}{k^2} \quad \alpha \sim \frac{1}{\langle C_{1qs} \tau_{1qs} \rangle} \quad Q_i \sim \frac{1}{\langle C_{1qs} \tau_{1qs} \rangle} \]

- Nonlinear saturation metric is quantified against configurations available to HSX
Theory correctly predicts trends seen in GENE simulations of ITG transport in HSX configurations

- Theory identifies metric for quantifying turbulent transport
  \[ Q_i \sim \alpha \frac{\gamma}{k^2} \quad \alpha \sim \frac{1}{< C_{1qs} \tau_{1qs} >} \quad Q_i \sim \frac{1}{< C_{1qs} \tau_{1qs} >} \]

- Nonlinear saturation metric is quantified against configurations available to HSX

Analytic theory predicts trends for nonlinear Saturation amplitude as a function of 3D shape

- Strong dependence of \(<C_{\tau}>\) on 3D shaping
Theory correctly predicts trends seen in GENE simulations of ITG transport in HSX configurations

- Theory identifies metric for quantifying turbulent transport
  \[ Q_i \sim \alpha \frac{v}{k_\perp^2} \quad \alpha \sim \frac{1}{< C_{1qs} \tau_{1qs} >} \quad Q_i \sim \frac{1}{< C_{1qs} \tau_{1qs} >} \]

- Nonlinear saturation metric is quantified against configurations available to HSX

Analytic theory predicts trends for nonlinear Saturation amplitude as a function of 3D shape

- Strong dependence of \(<C_\tau>\) on 3D shaping

Nonlinear GENE simulation of ITG in HSX configurations

- Nonlinear simulations consistent with analytic expectations
Strong nonlinear energy transfer physics is associated with the landscape of the local magnetic shear

- Crucial difference between optimized and unoptimized configurations is local magnetic shear

Local magnetic shear (includes variation of shear within flux surface) --- small change to curvature vector

\[ s_{local} = \hat{b} \times \hat{n} \cdot \nabla \times (\hat{b} \times \hat{n}) \]

\[ \Lambda = \frac{\|\rho\|^2}{B} \int \frac{dl}{B} s_{local} \frac{B^2}{\|\rho\|^2} \]

- Local magnetic shear in stellarators typically have "spikey" behavior
- Speculation: In optimized configuration, eigenmodes more cleanly fit into localized valleys of local magnetic shear --- more conducive to effective nonlinear energy transfer between eigenmodes --- Faber et al APS-DPP '18
Next steps in turbulent optimization

• Assess viability of the nonlinear energy transport model
  – Diagnostic in GENE capable of tracking nonlinear transfer between zonal and non-zonal channels

• Develop models for multiple transport channels
  – Mostly ion heat conduction so far
    → Expand to electron heat, particle, impurity transport, etc.

• Seek optimization principles for broad class of turbulent channels
  – Identify means to use 3D shaping to reduce turbulent transport
  – Employ in optimization codes
  – Test “optimized” configurations against nonlinear GENE simulations
Improving turbulent transport is a major element of the next generation of optimized stellarators

- Ongoing effort to improve the stellarator concept through improvements in plasma physics understanding, coil design and optimization algorithms.
  - Recent advances have uncovered improved configurations ---- A. Bader et al, this meeting
    - Excellent energetic ion confinement
    - Good quasi-helical symmetry
    - Vacuum well → ideal MHD stability
    - Improved turbulent transport
Summary

- Efforts are emerging to understand how to optimize stellarators for turbulent transport

- Proxies emanating from turbulent saturation theory are emerging
  - Triplet correlation lifetimes

- Metrics are being assessed for various stellarator configurations
  - Plausible explanation for why QHS has good turbulent saturation properties

- Favorable comparison of metrics against nonlinear gyrokinetic simulations

- New saturation physics optimization metrics have yet to be fully integrated into optimization procedures