Recent Advances in Understanding and Predicting Turbulence in Stellarators

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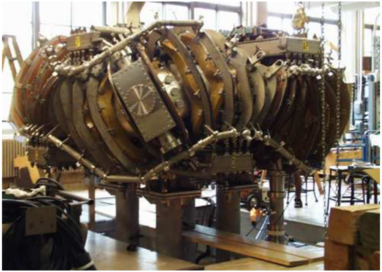
Stellarators and Gyrokinetics

Stellarator vs. tokamak:

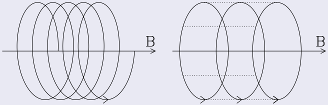
- steady-state
- 3D optimization
- *but*: more expensive

HSX: QH-symmetric
low-magnetic-shear stellarator



Gyrokinetic Approximation

kinetic theory (6D) →



→ gyrokinetics (5D)

The GENE Code

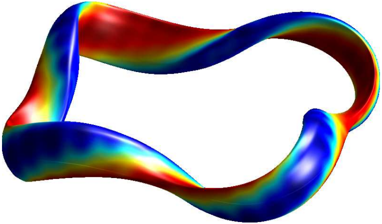
- massively parallel
- local/global
- initial-/eigenvalue
- general geometry

Flux Tubes/Surfaces

Modern devices: **MHD** equilibrium, **neoclassically** optimized, limited by **turbulence** ⇒ *next step* is **turbulent optimization**

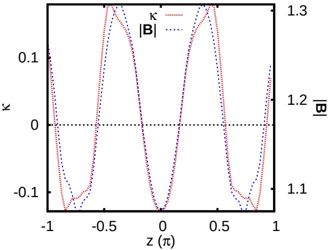
Towards fully optimized devices with **gyrokinetic simulations**

Flux surface contains multiple distinct flux tubes



Most unstable flux tube tends to capture turbulence physics fairly well

HSX: two primary **flux tubes**, **bean** (below) and **triangle**



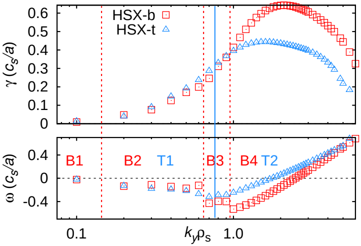
Here: magnetic wells line up with bad curvature

1. Turbulence in HSX
2. Zero-Shear Simulations
3. Quasilinear Transport Modeling

A Zoo of TEMs

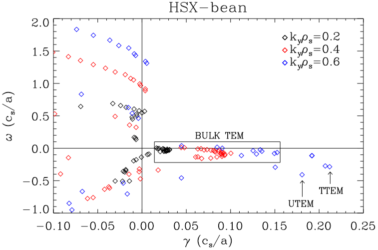
∇n-driven Trapped-Electron Modes dominate near $r/a \approx 0.7$ (fairly cold ions, $\eta_{\rm e} = \omega_{Te}/\omega_n = L_n/L_{Te} < 1$)

Initial value runs: moderate bean/triangle differences



Also: **many regimes** of different dominant modes

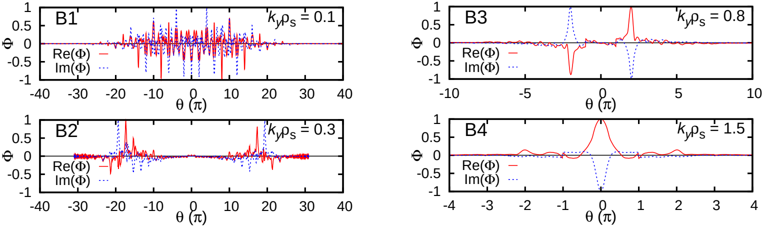
Eigenvalue spectrum:



$\Rightarrow$ complex picture, many **subdominantly** unstable modes

Mode Structures

To get intuition of these modes, look at $|\Phi|$ ballooning structure

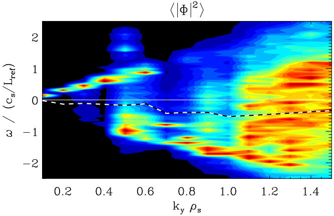


- TEMs **extremely extended** at low k_y, in part due to low $\hat{s}$
- computational requirements much-increased due to radial resolution, multi-eigenvalue runs particularly difficult
- **even-** and **odd-parity** (TTEM) modes, akin to tokamak pedestal (*ask me about it if interested. . .*)

TEM Turbulence

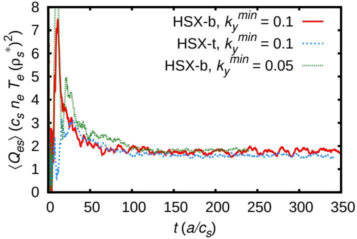
Nonlinearly, only some features of linear simulations apparent

Frequency spectra show very different behavior than linear (dashed)



Nonlinear physics at play?

However, bean/triangle flux tubes have similar transport



(similar zonal flow dynamics)

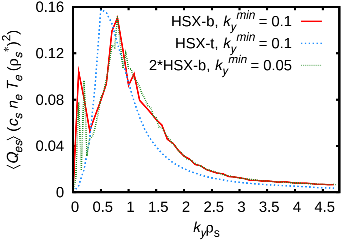
Note: **simulated** heat **flux agrees with experimental** data
Caveat: still need to study impact of ion temperature

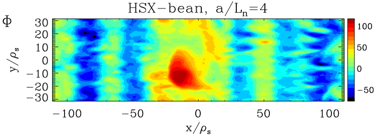
The Coherent Structure

To further complicate matters. . .

For higher ω_n, a **coherent structure** forms at rational surface

enhances flux levels at low k_y (but: resolved!),
can have **significant contribution** to total Q





However, eventually (high ω_n)
coalesces into zonal flow,
no further Q increase

Current effort to investigate ion-frequency **pseudo-eigenmode** from $\hat{s} = 0$ case (may play role for finite $\hat{s}$!)

1. Turbulence in HSX
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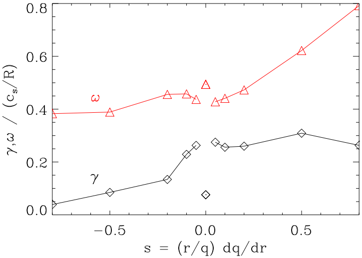
Complications at $\hat{s} = 0$

What if we had a simulation technique where we could do extremely cheap linear runs and capture most relevant physics?

Shearless ($\hat{s} = 0$) runs: no linear k_x coupling, can **easily** compute **all** linear **EVs**

But: not continuous in finite $\hat{s} \to 0$ *linearly*



(but: continuous **nonlinearly**)

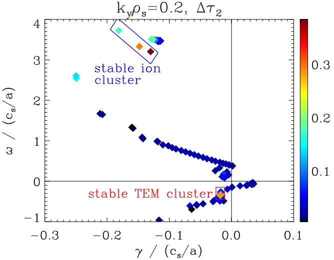
⇒ run **shearless HSX simulations** in order to compare linear and nonlinear behavior to sheared case

Eigenmode Projections

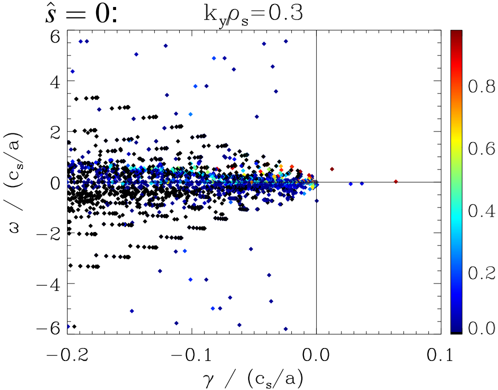
Both dominant mode scaling and transport **similar** between zero and finite-shear; however, **important details differ**

Below, projection of nonlinear state onto eigenmodes:

$\hat{s} = -0.044$:



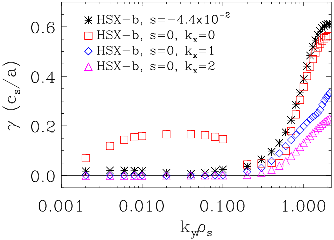
$\hat{s} = 0$:



Zero shear shows linear **ion mode** may be **responsible**

Ultra-Low-k_y Instability

Some issues require more study at $\hat{s} = 0$,
especially a **very-low-k_y streamer** mode:



- exact nature of mode not clear yet
- nonlinearly, seems to cause extreme amplitude overshoot
- no finite-$\hat{s}$ equivalent

- nonlinear run covering $k_y \geq 0.002$: no saturation

⇒ Is this mode **physical and relevant to HSX/W7-X?**
If not, can we disable it without affecting other modes?

Quasilinear Flux Estimating

Background

Use *mixing length* estimate, get heat flux from linear runs

Very cheap, useful for

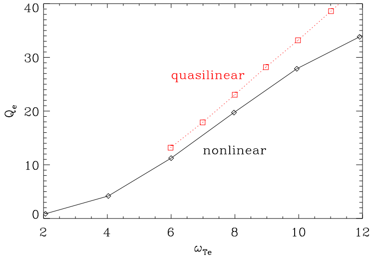
- n-D parameter scans
- real-time control (Iter?)
- distinguishing linear/ nonlinear physics

Common (too) simple model:

$$Q_{\text{QL}} = \mathcal{C}\omega_T \max_{ky} \frac{\gamma}{k_y^2}$$

with constant $\mathcal{C}$ and $\omega_T \equiv \frac{R}{L_T}$

Example: TEM turbulence (data from Jenko PoP 2005)



Above, improved model, $k_y^2 \rightarrow \langle k_\perp^2 \rangle = k_y^2(1 + \hat{s}^2\langle\theta^2\rangle)$

Good prediction for tokamak *if no mode regime changes*

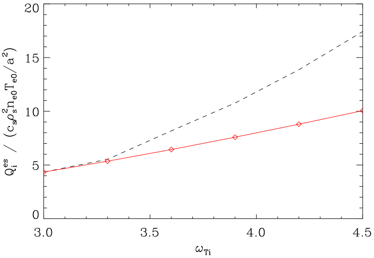
Most Unstable Mode

Now, **apply** this model **to the stellarator** – scan gradient ω_{Ti} (*note*: more accurate, computing $Q_{\rm QL}$ for every k_y) – **ITG** in HSX

Including only **most unstable mode**

⇒ model **fails**

(dashed: nonlinear Q, solid: QL, 1st mode)



⇒ *try including more modes*

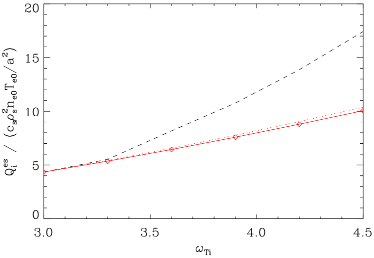
5 Most Unstable Modes

Now, **apply** this model **to the stellarator** – scan gradient ω_{Ti} (*note*: more accurate, computing Q_{QL} for every k_y) – **ITG** in HSX

Summing **five most unstable modes**

⇒ model **fails**

(dashed: nonlinear Q, solid: QL, 1st mode, dotted: QL, 5 modes)



⇒ *try including more modes*

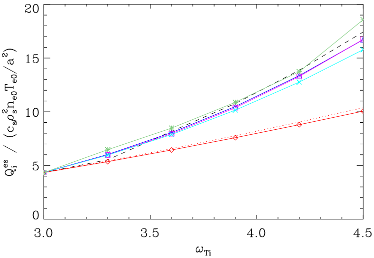
Full Quasilinear Model

Now, **apply** this model **to the stellarator** – scan gradient ω_{Ti} (*note*: more accurate, computing $Q_{\rm QL}$ for every k_y) – **ITG** in HSX

Summing over **all subdominant modes**

⇒ model **works**

(dashed: nonlinear Q,
blue−cyan: all subdominant,
green: QuaLiKiz-like)



Full models: include **geometry** $\langle k_\perp^2\rangle$, QL weights $\frac{Q}{n^2}$
cyan curve: every k_y separately; green: model spectral shape

⇒ **good QL** predictions are **possible for stellarator**

Summary

- Better understanding of stellarator turbulence necessary for **fully, turbulence-optimized stellarator** design
- **HSX**: zoo of **density-gradient-driven TEMs** dominates eigenvalue spectrum; complex extended mode structures
- nonlinear features include significant **zonal flows** (but at low $\omega_{\rm s} \sim \gamma$), **coherent structure** formation
- **zero-shear** simulation may shed light on nonlinear properties, allow **much cheaper** linear computation
- for accurate **quasilinear transport modeling** (here: ITG), need to take into account **all unstable eigenmodes**

B.J. Faber *et al.*, Phys. Plasmas **22**, 072305 (2015)
M.J. Pueschel *et al.*, Phys. Rev. Lett. **116**, 085001 (2016)