Gyrokinetic Turbulence in Tokamaks and Stellarators

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Outline

A very brief review of some recent (tokamak) gyrokinetic results – for more details, see, e.g., E.J. Doyle et al., “Progress in the ITER physics basis”, Ch. 2, Nuclear Fusion 47, S18 (2007)

Some recent gyrokinetic turbulence simulations for:

- LHD
- NCSX
- W7-X

Long-term goal: Explore potential for systematic optimization of turbulent transport in stellarators
State of the art in nonlinear gyrokinetics

- Gyrokinetics has emerged as the standard approach to tokamak core turbulence.
- Experimental comparisons are rather promising.
- Extensions to tokamak edge and stellarator are underway.
- Variety of gyrokinetic codes is being used and (further) developed, differing both in physics and in numerics.
Gyrokinetic stellarator codes in production

GS2 (Mikkelsen, Dorland et al.); GOBLIN (Yamagishi et al.)
- Comprehensive physics (multispecies, finite beta, collisions etc.)
- Flux tube geometry

GKV (Watanabe, Sugama et al.)
- Adiabatic electrons, model geometry
- Flux tube geometry
- Under further development

GENE (Jenko, Xanthopoulos, Merz et al.)
- Comprehensive physics (multispecies, finite beta, collisions etc.)
- Flux tube or global (tokamak) geometry; includes eigenvalue solver
- Under further development
- Freely available via www.ipp.mpg.de/~fsj/gene
Code benchmarking efforts

- Are we solving the equations right?
- Such efforts tend to be a bit painful but are necessary
- Examples below: Nevins et al., PoP 2006 & 2007; Belli et al.
- Another recent example: Falchetto et al., PPCF 2008

### Nonlinear tokamak ETG case

![Graph showing nonlinear tokamak ETG case](image)

### Linear stellarator (NCSX) case

![Graph showing linear stellarator case](image)

See poster P1-18 by D. Mikkelsen; P. Xanthopoulos et al., PoP 12/2008
Massive parallelism

- Many codes scale well up to thousands of cores
- Both particle and grid-based codes can deal with massive parallelism
- Assistance by computer experts can be helpful

The community is prepared for computers with more than 10k cores. Further efforts are needed on the way towards PFlop/s computing.
Tokamak simulations
Gyrokinetic simulations for tokamaks

www.ipp.mpg.de/~fsj/gene
Physics issues

- Our physical understanding of microturbulence is still fragmentary at present

- Open questions (selection):
  1. Nonlinear saturation and mode interference
  2. Validity of quasilinear theory
  3. Impact of finite $\beta$ effects in (improved) H-modes
  4. Role of sub-ion-gyroradius scales
  5. Interactions between turbulence, neoclassics, MHD
  6. Predictive *ab initio* modeling of core plasmas and transport barriers

- Close interactions between theory, simulation, and experiment are called for
Nonlinear saturation of TEM turbulence

Statistical analysis of NL GENE runs:
- No significant shift of cross phases and frequencies w.r.t. linear ones
- Low $k_y$: nonlinearity $\sim$ eddy diffusion

[Merz & Jenko, PRL 2008]

$$\mathcal{N}l[g] \approx D(-k_\perp^2)g = D\nabla_\perp^2 g$$

This is in line with various theories, including Resonance Broadening Theory (Dupree), MSR formalism (Krommes), Dressed Test Mode Approach (Itoh).
Destructive ITG/TEM interference

[F. Merz, PhD Thesis 2008]

- Linear growth rates \((k_y=0.25)\), using GENE as an EV solver
- TEM regime: Electron heat flux is suppressed, not increased
- ITG regime: Nonlinear upshift of critical \(R/L_{Ti}\)
- Nonlinear ITG/TEM coexistence
Gyrokinetic turbulence at high beta

Finite-beta Cyclone Base Case simulations with the GENE code [Pueschel et al., PoP 2008]

Nonlinear drop clearly exceeds (quasi-)linear expectations; this is likely to be due to destructive ITG/TEM interference.
Role of sub-ion-gyroradius scales

GENE simulations of ITG/TEM/ETG turbulence: Large fraction of the electron heat transport is carried by the electron scales.

Mazzucato et al., PRL 2008
Smith / Yuh, APS invited 2008
Schmitz, APS invited 2008

[Görler & Jenko, PRL 2008]

> 100,000 CPUh
Electron heat diffusivity from edge ETG

ETG turbulence is able to explain the residual electron heat transport in H-mode edge plasmas.

GENE simulations Jenko, APS invited 2008
Stellarator simulations
Gyrokinetic simulations for stellarators

Linear simulations
- Rewoldt et al. 1999
- Kuroda et al. 2000
- Kendl 2001 & 2004
- Jenko & Kendl 2002
- Rewoldt et al. 2002 & 2005
- Lewandowski 2003
- Kornilov et al. 2004 & 2005
- Yamagishi et al. 2007
- Xanthopoulos & Jenko 2007

Nonlinear simulations
- Jenko & Kendl 2002 & 2002
- Xanthopoulos et al. 2007
- Watanabe et al. 2007 & 2008

Wendelstein 7-AS poloidal cuts

triangular plane

elliptical plane

Jenko & Kendl, NJP & PoP 2002
Stellarator-specific issues

- Fairly (physically) comprehensive flux tube simulations in real 3D MHD equilibria are becoming feasible
- Nonlocal codes to be developed; computational cost will be very substantial, however
- Open questions (selection):
  1. Similarities and differences w.r.t. tokamak turbulence?
  2. Impact of 3D shaping on linear properties of various microinstabilities and their nonlinear saturation mechanisms?
  3. Potential for systematic optimization of turbulent transport in stellarators (long-term goal)?
Some recent GKV results on LHD core turbulence (using non-axisymmetric model equilibria)

Studies by H. Sugama and T. Watanabe
Results from LHD experiments

For low collisionality, better confinement is observed in the inward-shifted magnetic configurations, where lower neoclassical ripple transport but more unfavorable magnetic curvature driving pressure-gradient instabilities are anticipated.

Anomalous transport is also improved in the inward shifted configuration.

Scenario:
Neoclassical optimization contributes to reduction of anomalous transport by enhancing the zonal-flow level.
Standard and inward-shifted configurations

$|B|$ along the fieldline on the magnetic surface at $r = 0.6a$

Inward
$\Rightarrow$ smaller neoclassical transport

Time evolution of zonal-flow potential

$L_{\text{residual zonal flow}}$ is found for the inward-shifted case.
Adiabatic ITG turbulence simulations

Smaller $\chi_i$ and larger zonal flows are found in the saturated turbulent state for the inward-shifted configuration than for the standard one!

$\overline{(\phi)^2} = \int_0^{\infty} S(k_r) dk_r$

Turbulent thermal diffusivity and squared zonal-flow potential

$k_r$ spectrum of zonal-flow potential (averaged over $60 < t < 250$)

Watanabe, Sugama & Ferrando, PRL(2008), Sugama, Watanabe & Ferrando, PFR(2008)
Zonal flow dynamics in ITG-ae simulations

Contours of potential fluctuations (Inward-Shifted Case)

Sugama, APS invited 2008
Some recent GENE results on NCSX and W7-X core turbulence (using real non-axisymmetric equilibria)
Geometry Interface for Stellarators/Tokamaks

Author: P. Xanthopoulos (thanks to W. A. Cooper)
Goal: Local simulations for non-axisymmetric devices
First example:
NCSX
Geometric coefficients for NCSX

[Xanthopoulos & Jenko, PoP 2006]
Adiabatic ITG turbulence in NSCX

Two different flux tubes on the same magnetic surface:
The turbulent transport differs by a few 10%;
moreover, the parallel mode structures differ.

Critical gradients also differ; softening of turbulence onset!
Flux-gradient relationship (adiabatic ITG modes)

- Offset-linear scaling for $\chi$ – not $Q$
- Moderate profile stiffness

Banana plane

$\chi_i/\rho_s c_s / R_i$

respective tokamak curve (schematically)
Parallel mode structure and linear threshold

NCSX exhibits strong ballooning controlled by localized bad curvature and local shear.

Example (nonlinear GENE simulation):

Linear thresholds of NCSX, W7-X, AUG, DIII-D are similar, but they can be increased by increasing the effective $k_{||}$
Second example:
Wendelstein 7-X
Geometric coefficients for W7-X

Wendelstein 7-X stellarator: optimized with respect to neoclassical transport

[Xanthopoulos & Jenko, PoP 2006]
ITG-ae turbulence: Subtle geometric effects

Two configurations which are geometrically virtually identical yield clearly differing results – although the linear physics is almost the same; there must be geometric control of the NL saturation mechanism.
Nonlinear ITG/TIM coexistence

GENE simulations for W7-X (close to the magnetic axis; adiabatic electrons): Trapped ion modes and ITG modes coexist linearly and nonlinearly.

Linear growth rate spectrum

Nonlinear transport spectrum

[Xanthopoulos, Merz, Görler & Jenko, PRL 2007]

Destructive interference phenomena?
Many modes are unstable, with similar growth rates.

Nonlinear runs exhibit strong ZF activity, 35% Dimits shift.
Many modes are unstable, with similar growth rates.

Nonlinear runs exhibit weak ZF activity, no Dimits shift.
Like in tokamaks, kinetic electrons reduce the impact of zonal flows.
Properties of TEM turbulence in W7-X

- Parallel structure: Transport reflects the structure of the magnetic wells
- Regions where bad curvature and magnetic wells overlap dominate transport

Side remark: Nonlinear and linear mode structure are quite similar; zonal flows are weak

Potential for turbulence control
Conclusions

Gyrokinetic simulations for stellarators:

- Comprehensive (local) gyrokinetic turbulence simulations are becoming feasible; nonlocal codes to be developed

- In principle, 3D shaping allows for fine-tuning:
  - linear drive of microinstabilities
  - nonlinear saturation (e.g., zonal flow physics)
  - destructive interference

  These changes affect critical gradients and turbulence onset

- Potential for systematic optimization of turbulent transport needs to be explored in more detail in the future