GENE simulations using realistic edge geometry

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Many thanks to:
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GENE Development Team

Gyrokinetics for ITER Workshop

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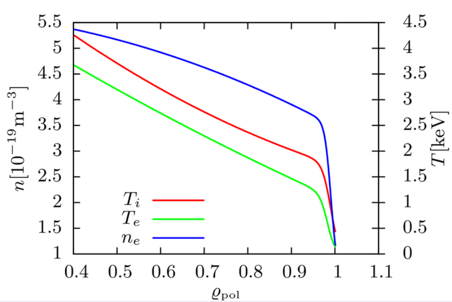
Outline

1. Introduction
2. Realistic edge geometry in GENE
3. Applying GENE to edge plasmas
4. Summary

Motivation for edge simulations

Edge physics vital for ITER success: Baseline scenario is H-mode, predict height/width of transport barrier?



Edge transport modeling:

- Ion heat transport close to neoclassical levels
- Electron heat transport anomalous
- Particle transport anomalous

Ion heat transport reduced by strong $E \times B$ shear flows

Aims

- Identify mechanisms of residual heat and particle transport
- Verify $E \times B$ transport reduction under edge conditions

Investigations by means of gyrokinetic turbulence code GENE

The GENE code

Gyrokinetic Electromagnetic Numerical Experiment

Solves δf gyrokinetic equations on a fixed 5D grid

Comprehensive physics

- Arbitrary number of species (here: Deuterium and electrons)
- Trapped and passing particles
- Electromagnetic effects (finite β)
- Collisions between like and unlike particle species
- Realistic (numerical) geometry
- Equations valid for arbitrary $k_\perp$

Modes of operation

- nonlinear/linear, nonlocal/local, initial value/eigenvalue solver

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

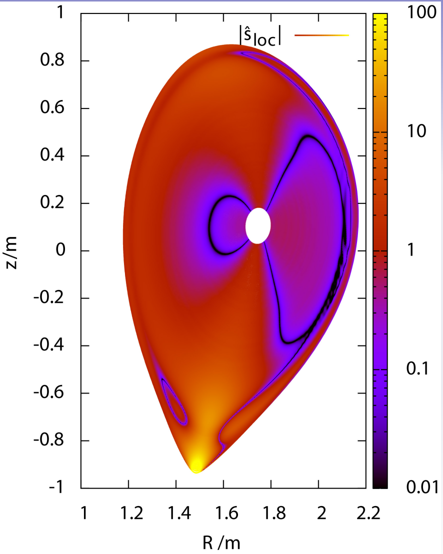
Geometry of an H-mode discharge

Similarity to $\hat{s} - \alpha$?

- Plot shows absolute value of local shear
- Negative shear even in the core, though global values positive
- Effect of elongation and triangularity

Shape near separatrix

- Metric coefficients have complex parallel structure (e.g. distance between flux surfaces varies strongly)
- Up-down asymmetry
- Strong local shear near X-point(s)
- Safety factor + magnetic shear diverge



Metric generated via field-line tracing

Field-line tracing method

- Implemented in TRACER/GIST[a]
- Magnetic field components allow tracing of field line

[a] P. Xanthopoulos et al. (2006, 2009)

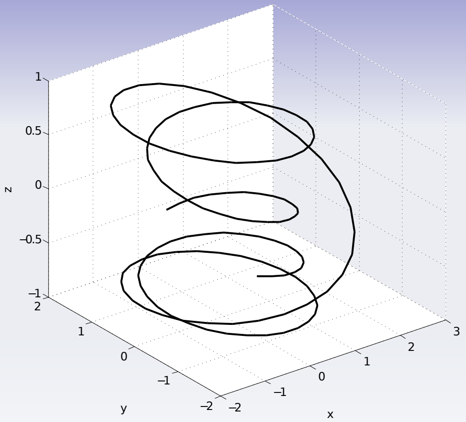
Field-aligned coordinate system

$$\boldsymbol{B} = B\,\nabla x \times \nabla y, \qquad (\nabla x, \nabla y \perp \boldsymbol{B})$$

$$x = \varrho = \sqrt{\Phi/\pi B_0}$$

$$y = \frac{\varrho_0}{q_0}(q\theta - \phi)$$

$$z = \phi/q_0$$



Field-line tracing method (2)

Resulting coordinate system is non-orthogonal

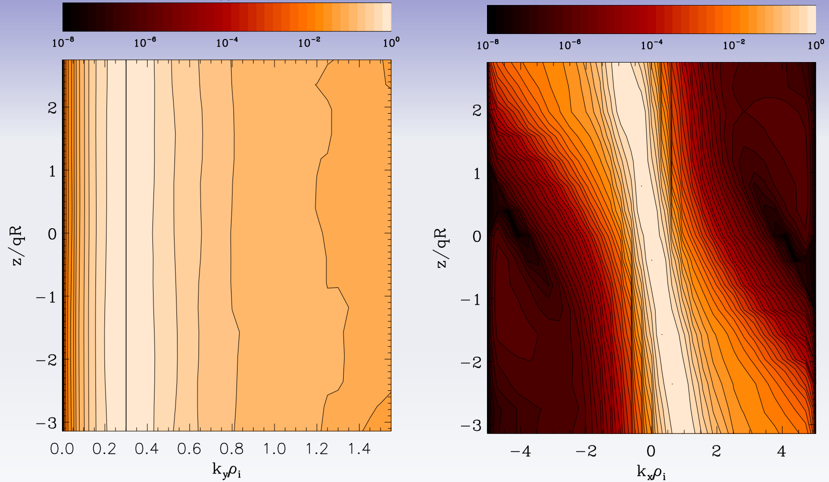
$$
\begin{aligned}
x &= \varrho \\
y &= \frac{\varrho_0}{q_0}(q(\varrho)\theta - \phi) \\
\nabla x &= \nabla \varrho, \\
\text{but } \nabla y &= \hat{s}\theta\nabla\varrho + \frac{\varrho_0}{q_0}(q\nabla\theta - \nabla\phi)
\end{aligned}
$$

$\Rightarrow g^{xy} \equiv \nabla x \cdot \nabla y = \hat{s}\theta g^{xx}$

Definition of local shear: $\hat{s}_{loc} = \frac{\partial}{\partial\theta}\left(\frac{g^{xy}}{g^{xx}}\right)$

Effect of shear in field-aligned simulations

Here: Run with sheared slab geometry, $\hat{s} = 1$
Plot: Spectra of Q_{es}^{i} with parallel dependence

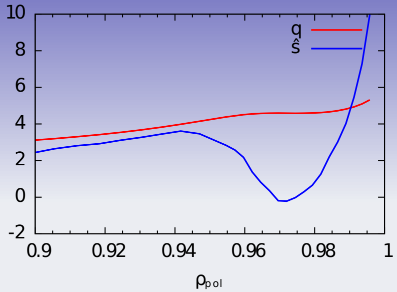


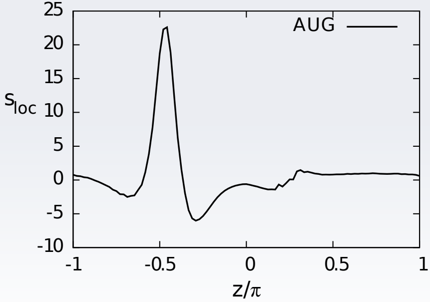
Large global shear ⇒ increased radial resolution requirements

Edge: Safety factor and shear diverge

Bootstrap current helps

- Steep profiles generate edge bootstrap current
- $\Rightarrow$ Locally flattened q profile
- But: strong parallel dependence remains (bottom right: #20431, $\varrho_{\mathrm{pol}} = 0.98$)

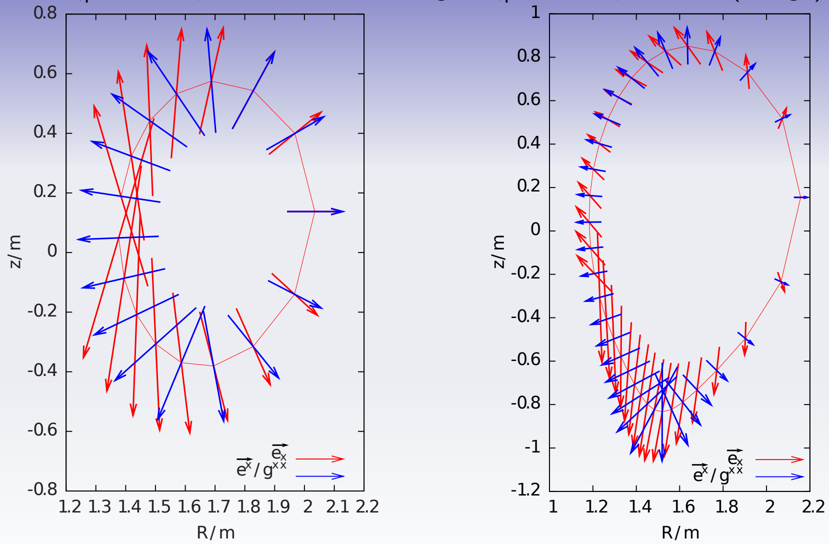




GENE simulations using realistic edge geometry

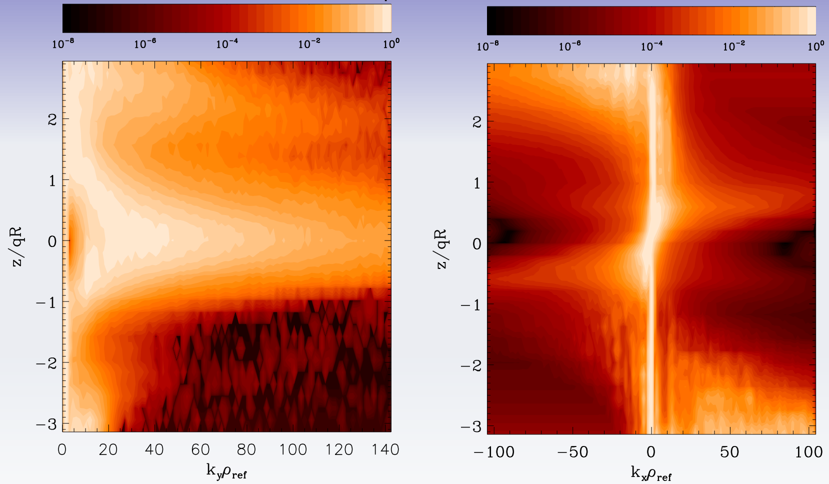
Flux tube shearing in core and edge

Left: $\varrho_{pol} = 0.73, \hat{s} = 0.87$ Right: $\varrho_{pol} = 0.98, \hat{s} = 0.84$ (benign)



Parallel dependence of edge heat flux spectra

Flux surface $\varrho_{pol} = 0.96$, $\hat{s} = 1.55$



Orthogonalizing procedure: shifted metric

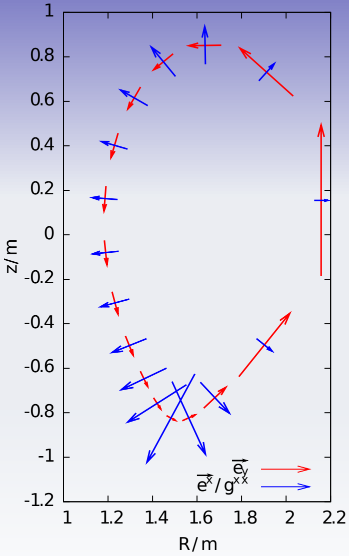
Method[a]:

- Force $g^{xy} = 0$ at every position z_k along the flux tube
- $\Rightarrow$ need transformation $y_k = y - \alpha_k x = y - \frac{g^{xy}}{g^{xx}}\Big|_k x$
- $\Rightarrow$ orthogonal coordinate system

[a] B. Scott (2001), E. Schmidt (1907)

Drawbacks:

- General geometry: shifts α_k arbitrary
- $\Rightarrow$ violate radial periodic boundaries
- $\Rightarrow$ not easily applicable to Fourier codes
- Implemented in nonlocal GENE, being tested



Linear edge simulations for AUG #20431

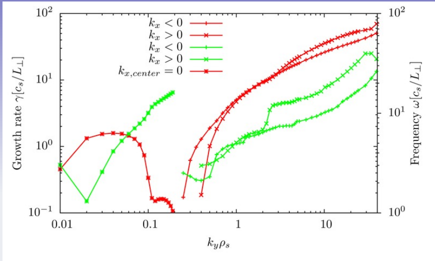
Microinstabilities at $\varrho_{\text{pol}} = 0.98$:

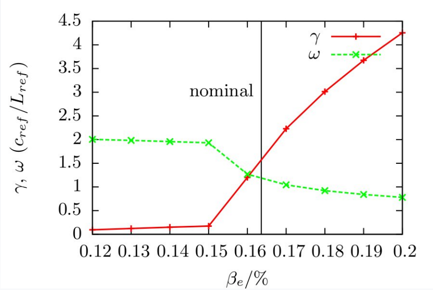
- $k_y \varrho_s \leq 0.1$: ITG/KBM mode
- $k_y \varrho_s \in [0.1, 0.2]$: Microtearing mode
- $k_y \varrho_s \geq 0.2$: ETG mode

Scan over β_e for low k:

- β_e close to ballooning boundary
- Matches expectation for ELMy H-mode edge (profiles are pre-ELM)

Nonlinear studies only for $\beta < \beta_{\text{crit}}$

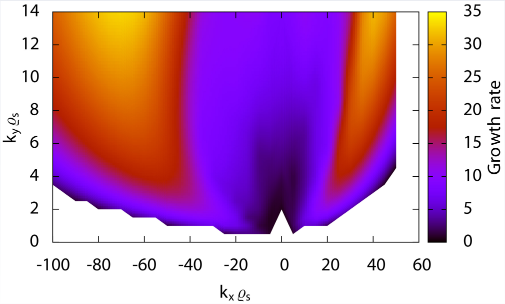


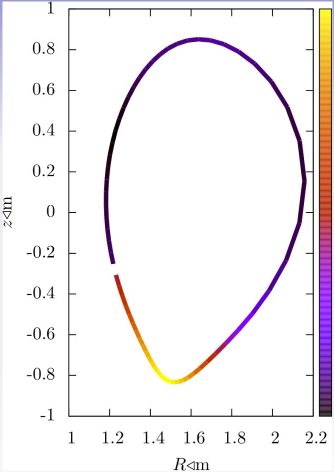


Linear properties of high-k modes

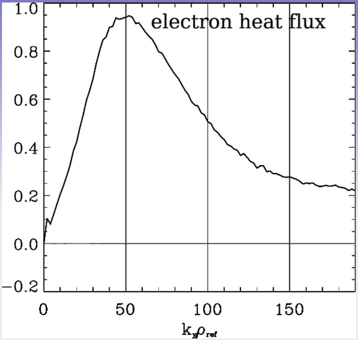
ETG characteristics:

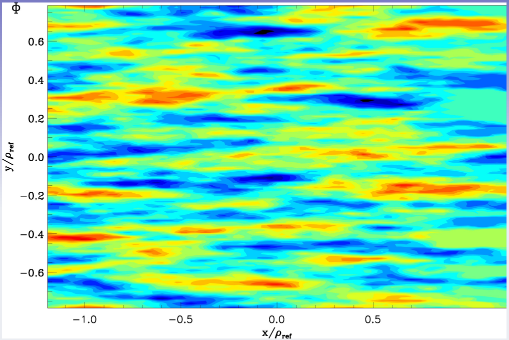
- Modes peak at finite k_x values $\leftrightarrow$ off outboard midplane
- Mode unstable above critical $\eta_e = (\nabla T_e/T_e)/(\nabla n/n) \approx 1.2$ (AUG H-modes: $\eta_e \gtrsim 1.5$)
- Collisions and ion dynamics can be safely neglected





ETGs can explain edge electron heat transport





Nonlinear runs for high k:

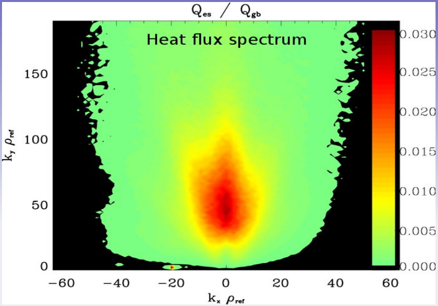
Runs with adiabatic ions:

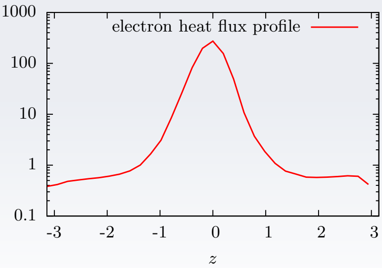
- ETG transport peaks at very small scales ($k_\perp \varrho_s \approx 15$)
- Electron heat diffusivity: $\chi_e = 0.66 \frac{m^2}{s}$
  (total $Q_e \approx 8\text{MW}$ @ $P_{\text{NBI}} + P_{\text{ICRH}} = 8.4\text{MW}$)

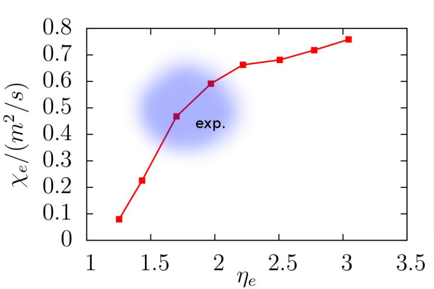
Further properties of edge ETG transport

Edge ETG turbulence

- Nonlinear spectrum peaks around $k_x \approx 0$ (contrast to linear simulations)
- Transport strongly localized on low field side
- η_e scan confirms linear result $\eta_{e,\mathrm{crit}} \approx 1.2$







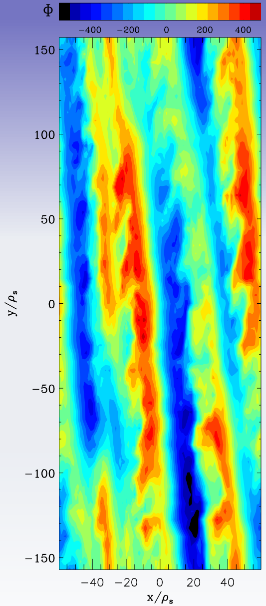
GENE simulations using realistic edge geometry

GENE simulations for low wavenumbers

Properties of low-k runs:

- Decreased β_e to 0.1% (exp. $\beta_e = 0.16\%$)
- Large radial extent of simulation domain $\boldsymbol{L} \cdot \boldsymbol{e}^x \approx 3.5\Delta_{\text{ETB}} \Rightarrow$ significant nonlocal effects must be expected for low-k runs
- Heat flux peak off outboard midplane ($k_x \varrho_s = 0.2$)
- Strong electromagnetic fluctuations despite low β: $\tilde{B}_y/B \lesssim 10^{-3}$ $\tilde{B}_y \approx 5\tilde{B}_x$ $\Rightarrow$ large shear fluctuations $\tilde{s} \approx 0.25$

Steady saturation difficult to achieve (Comparison with shifted metric runs under-way)



Summary

Simulations show complex behavior in edge geometry

- Edge plasma shape deviates strongly from traditional circular models
- Challenge for linear simulations: Modes peak at finite k_x
- Box size (relative to ϱ_s) varies strongly along flux-tube $\Rightarrow$ large resolution required

Simulation results

- ETG instability with critical $\eta_e \approx 1.2$
  $\Rightarrow$ unstable in most ASDEX Upgrade pedestals
- Small-scale ETG turbulence ($k_\perp \varrho_s \approx 15$) can generate heat transport comparable to transport modeling results

Plans

- Comparison against shifted metric runs
- Extend nonlinear runs to other radial positions
- Edge investigations with nonlocal GENE (especially for low wavenumbers)

Thank you for your attention!

- **[Jenko, 2009] F. Jenko, D. Told, P. Xanthopoulos, F. Merz, and L. D. Horton,**
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- **[Told, 2008] D. Told, F. Jenko, P. Xanthopoulos, L.D. Horton, E. Wolfrum, ASDEX Upgrade Team,**
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- **[Scott, 2001] B. Scott,**
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- **[Xanthopoulos, 2006] P. Xanthopoulos, F. Jenko,**
  Phys. Plasmas 13, 092301 (2006)
- **[Gene web page]** `www.ipp.mpg.de/~fsj/gene`