Global Gyrokinetic Electron Temperature Gradient Turbulence and Transport in NSTX Plasmas*

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NSTX

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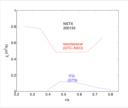
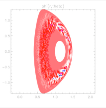
NSTX offers a unique platform to study electron transport

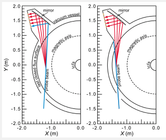
- Transport in NSTX is dominated by electron transport
- Strong E x B flow shear largely suppress low-k fluctuations
- ITG is a minor player
- Ion transport is close to neoclassical level
- Plasma transport has strong geometry dependence

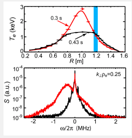




Measurements of high-k fluctuations in NSTX

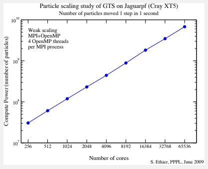
- Coherent tangential scattering of EM waves
- *Mazzucato et al., Nuclear Fusion* **49** No 5, 055001 (May 2009)





Gyrokinetic Tokamak Simulation code (GTS)

- Generalized gyrokinetic simulation model
- Particle-in-cell approach; global simulation (Wang et al., PoP'06)
- Turbulence fluctuations are perturbations on top of neoclassical equilibrium
- Full kinetic electrons: drift kinetic for ITG, TEM etc.; gyrokinetic for ETG
- Linear Coulomb collisions conserving particles, momentum and energy
- $\{\langle n(r,t)\rangle, T(r), \Phi_0(r), \text{and } \omega_t(r)\}$ ➔ turbulence & transport (energy, particles, momentum flux
- Interfaced with MHD equilibrium codes and experimental data base (via TRANSP)
- Refine MHD equilibrium using JSOLVER with TRANSP profiles
- Interfaced with Neoclassical via GTC-NEO (Wang et al,. CPC'04)
  - GTC-NEO ➔ Neoclassical equilibrium f_0, Φ_0 and transport
  - Non-local physics associated with large ion orbits and steep gradients
- Use of PETSc parallel library to solve the field quantities
- High Performance parallel I/O with ADIOS (Adaptable I/O library, ORNL)



ETG simulation model and parameters

- Adiabatic ions (neglecting coupling with low-k fluctuations)
- Global simulation covers ~ 450ρ_e and full toroidal and poloidal regions
- Grid size in perpendicular directions ~ ρ_e
- Real electron mass
- Simulation of NSTX shot #124901 at 300 msec
- Plasma parameters read into GTS from TRANSP run of shot 124901
- Working gas is helium (Z_{eff} = 2)
- Simulations carried out at NCCS/ORNL on Jaguar and Jaguarpf
- 22.6 billion particles, 400 million grid points
- Simulations used 31,232 and 65,536 cores for 48 hours

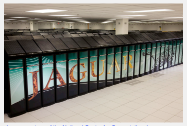
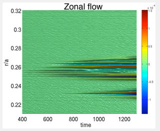
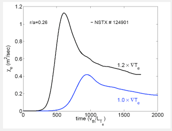


Image courtesy of the National Center for Computational Sciences, Oak Ridge National Laboratory

Characteristics of simulated ETG turbulence

- Slowly growing, nonlinearly generated zonal flows display fine radial structures
- Experimental identification of streamers to validate nonlinear ETG simulation models and to understand effects of multi-scale coupling
- Calculated χ_e ~ 0.2 – 0.3 m²/sec – too low for this case close to ETG marginality (estimated experimental χ_e = 1.2 ±50%)
- Tested for sensitivity to experimental errors in plasma profiles: gradient Te increased by 20% leads to about 2X increase in growth rate and saturated flux





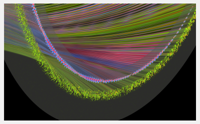
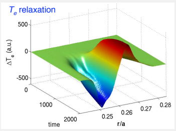


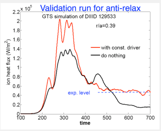
Image generated by Kwan-Liu Ma (P.I.), Chad Jones, and Chris Ho of UC Davis, as part of the SciDAC Ultrascale Visualization Institute

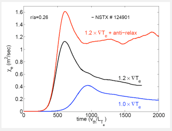
Anti-relaxation scheme implemented to maintain a constant gradient drive

- ETG-driven transport causes considerable relaxation in T_e profile during simulation
- Effective driver $(\nabla T_{e0} + \langle\delta T_e\rangle_{\delta f})$ decreases → q_e drops with time
- Anti-relaxation scheme was implemented to maintain a constant gradient drive during the simulation:

  → $D\delta f/Dt = -\{\mathbf{v}_E.\nabla f_0 - \mathbf{v}_E.\nabla\delta f_0 + \ldots\}$ where $\delta f_0 \approx (mv^2/(2T_0) - 3/2)(\langle\delta T\rangle/T_0)f_0$ with $\delta T = (1/3n)\int d\mathbf{v}mv^2\delta f$
- Validation of anti-relaxation scheme for ITG-driven ion transport against DIII-D discharge: matches experimental value of heat flux
- Eliminating the influence of profile relaxation seems essential to achieve steady-state in collisionless ETG simulations
- A value of χ_e ~ 1.2 is obtained with the constant drive and the uncertainties over local plasma profiles, indicating the ETG may be contributing to some of the electron heat transport.

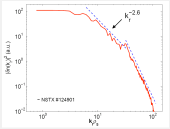


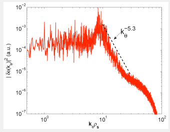


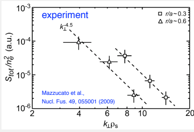


Comparable density fluctuation spectra between simulation and experiment

- Exponential power -2.6 (in k_r spectrum) and -5.3 (in k_θ) in simulation compared to -4.5 of $k_\perp$ spectrum in experiments
- Ray-tracing calculation (by F. Poli) suggests the need for a more comprehensive synthetic diagnostic that takes into account the beam trajectories and experimental uncertainties

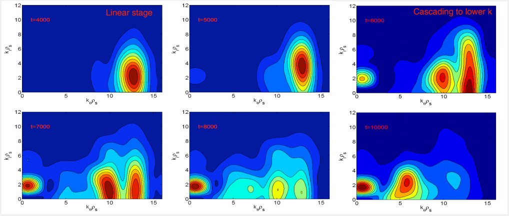






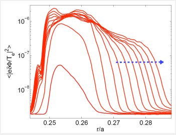
Nonlinear energy coupling and spectral dynamics

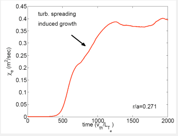
- Strong spectrum anisotropy: $k_\theta >> k_r$
- Nonlinear streamer generation
- Strong energy coupling to e-GAM
- e-GAM & zonal flow damping important

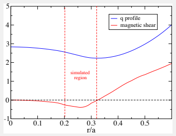


ETG turbulence spreads

- Ballistic outward spreading (to positive magnetic shear region)
- How fast: ~ (1 – 2) x 10^{-3} c_s ; How far: ~ a few tens of ρ_e
- Little inward spreading due to reversed magnetic shear
- Results are for the case with anti-relaxation and 20% increase in Te gradient







Summary and remarks

- First global, nonlinear ETG simulations for realistic discharges carried out for direct validation against experimental measurements in NSTX
- Qualitative agreement with experiment in density fluctuation spectrum
- ETG contribution to electron transport may be marginal within plasma profile uncertainties
- Eliminating influence of profile relaxation is crucial in simulations
- Highly remarkable nonlinear spectral dynamics: strong spectrum anisotropy with $k_r << k_\theta$; strong energy coupling to e-GAM; long term zonal flow effect ...
- ETG turbulence spreading and effect identified
- Ongoing work:
  - → effects of collisions on zonal flow and e-GAM damping and their influence on steady state spectrum and turbulence level
  - → Impact of E_r equilibrium electric field on ETG transport (NSTX has significant rotation which is believed to impact transport)
  - → More studies of the influence of experimental uncertainties for Z_{eff}, $T_e(r)$, q(r), etc.

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