Progress and Plans on Physics and Validation

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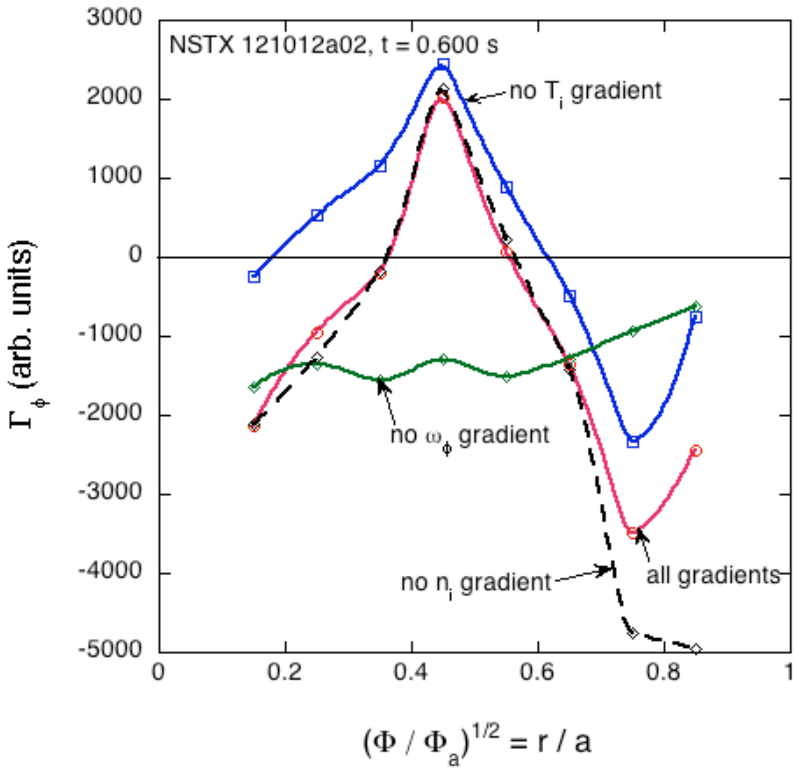
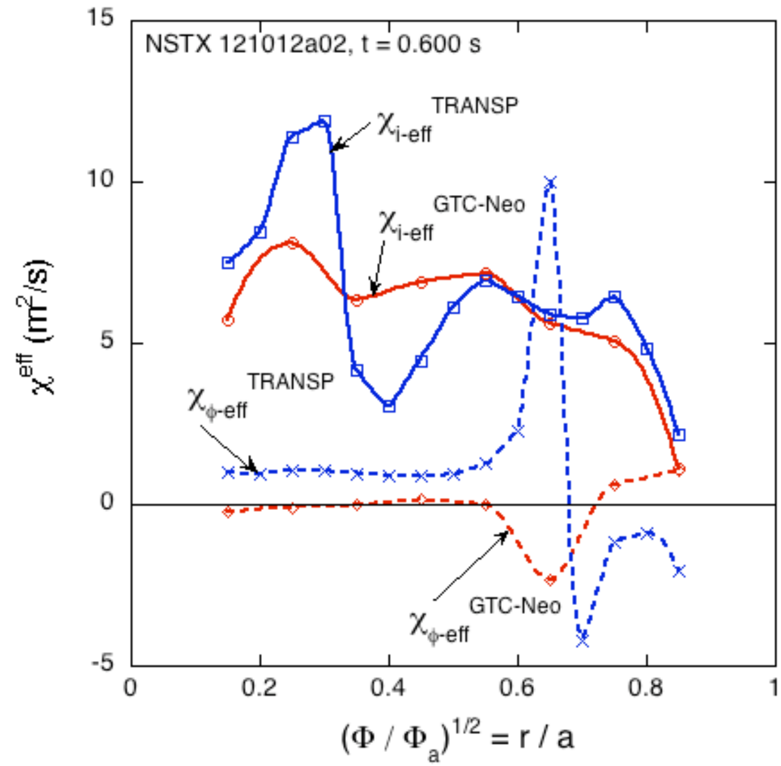
- Momentum Transport Studies: Turbulence and Neoclassical Physics
- Role of Trapped Electrons in Core Turbulence: Phase-space Dynamics
- Synthetic Diagnostics for Expt-Simulation Validations
- Short Term Plans

for GPS-TT-BP Team, Mar 28, Boulder, CO

Plans & Progress for GTC-Neo (W.X. Wang, G. Rewoldt, …)

• GTC-Neo is a global δf gyrokinetic particle-in-cell code, including finite-orbit-width (banana width) effects, which make the transport nonlocal. GTC-Neo can calculate neoclassical particle, momentum, and energy fluxes, along with E_r, E_θ, j_b, etc.

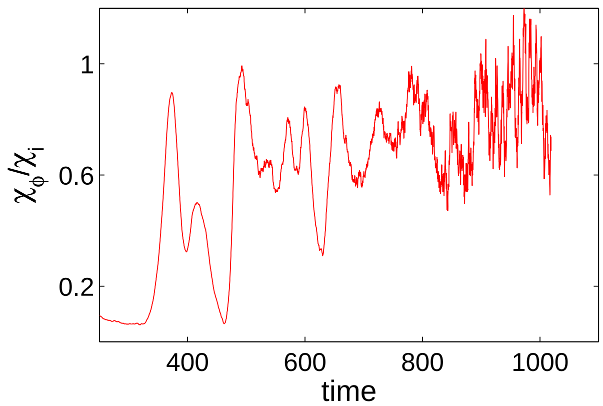


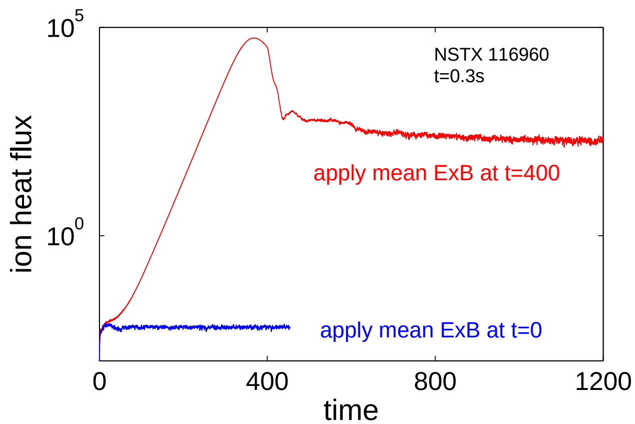


• Here Γ_ϕ, the radial flux of toroidal angular momentum, is shown for an NSTX case (in internal code units) versus r/a. The n_i gradient contribution is small, the T_i gradient contribution is moderate and is always inward (pinch!), and the ω_ϕ gradient contribution is largest, and has both signs.

• Here we show $\chi_\phi^{eff} = \Gamma_\phi / [R^2 n_i m_i (d\omega_\phi/dr)]$ (in m^2 / s) versus r/a for the same NSTX case. Ion energy transport is comparable to neoclassical (so anomalous ion energy transport is small), yet angular momentum transport is much larger than neoclassical (so anomalous angular momentum transport is dominant)!

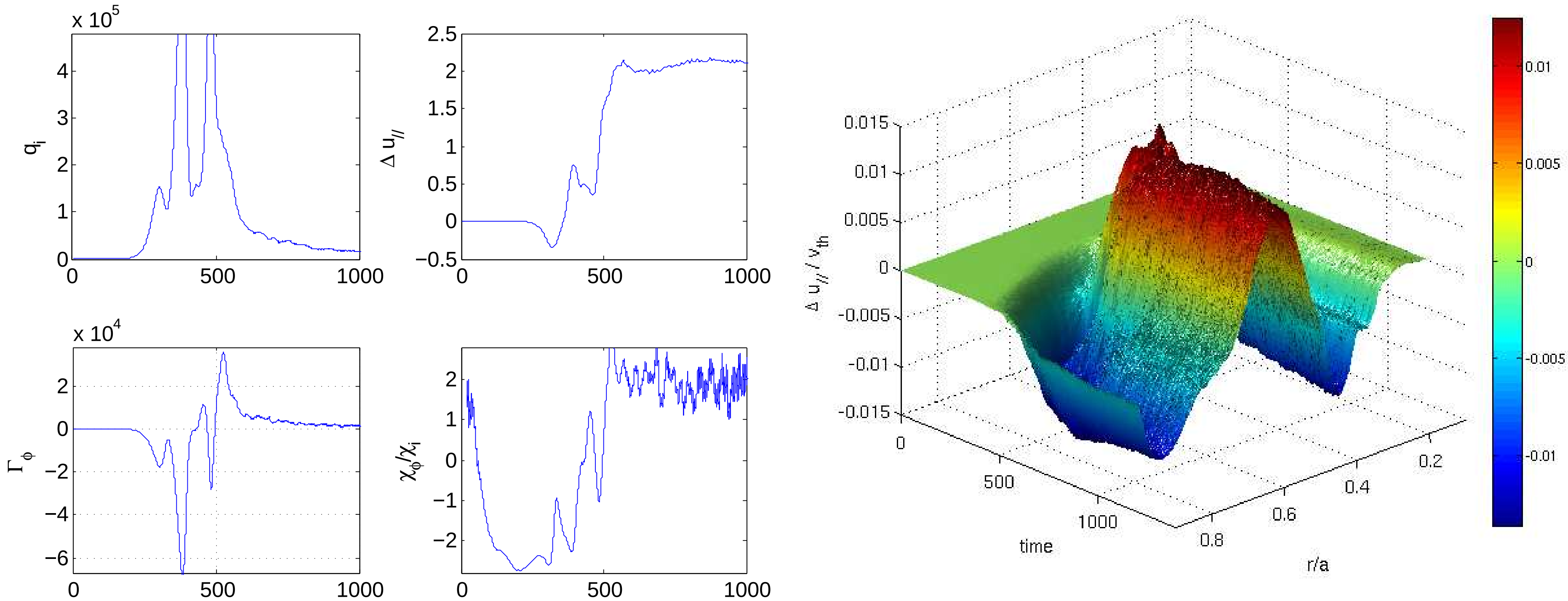
GTS/GTC-NEO V & V excise: co-existence of normal ion heat transport and anomalous momentum transport





- GTC-NEO simulations with finite orbit effects show that neoclassically $\chi_\phi/\chi_i \sim 0.01 - 0.1$, due to the absence of banana orbit enhancement, and the neoclassical contribution to the toroidal momentum transport is negligibly small.
- GTS simulations verify that the effective χ_ϕ/χ_i associated with low-k turbulence is on the order of unity, in broad agreement with experimental observations in conventional tokamaks.
- It is found that residual turbulence can survive the dissipation of a strong mean $\mathbf{E}\times\mathbf{B}$ flow shear and drive a significant momentum flux.
- These findings may offer an explanation for recent experimental observations that the toroidal momentum transport remains highly anomalous, even while the ion heat flux is reduced to a neoclassical level.

GTS simulation study: ITG turbulence driven toroidal momentum transport



- A significant inward toroidal angular momentum flux found during the transient phase of turbulence, which is is in the direction opposite to the diffusive momentum flux which is outward for this case.

- This inward momentum flux pumps the toroidal momentum from the outer region to the core, resulting in a change in toroidal rotation with a magnitude of a few percent of the local thermal velocity.

GTC Simulation of Momentum Transport

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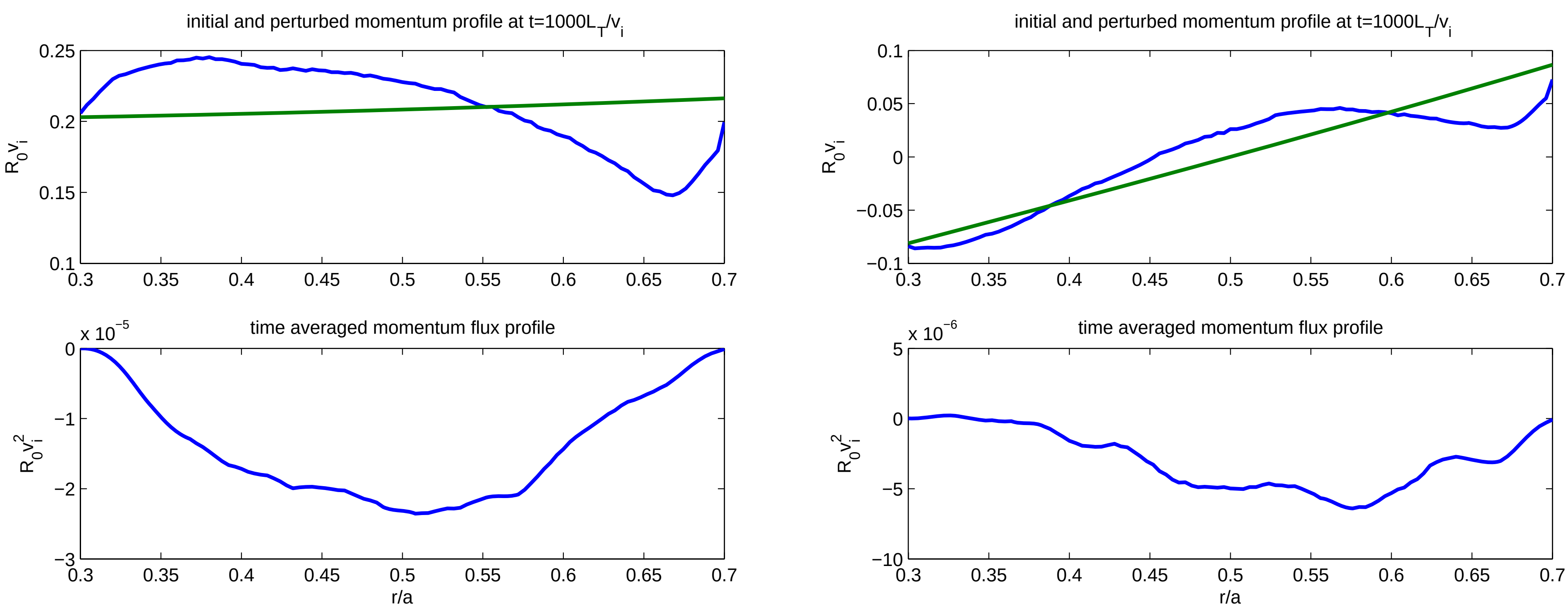
- Re-distribution of toroidal angular momentum is observed in GTC global simulation of ion temperature gradient (ITG) turbulence ***[Holod & Lin, APS07, TTF08]***
- For equilibrium with a rigid rotation, inward flux of toroidal momentum is observed, resembling a inward "pinch" of toroidal momentum
- For equilibrium with a sheared rotation, inward flux of toroidal momentum includes both gradient-driven and "pinch" components
  - Scan rotation rate and rotation shear to delineate gradient-driven vs pinch



GTC Simulation of Physics Basis for Transport Modeling

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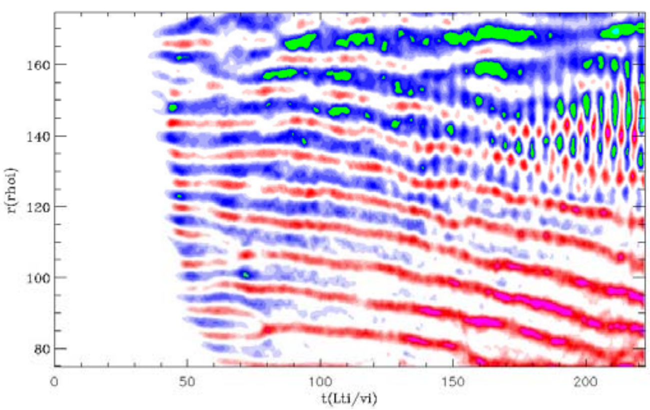
- Comprehensive statistical analysis of spatial and temporal scales in GTC simulation of microturbulence to test validity of quasilinear theory (QLT) underlying existing transport models *[Lin et al, PRL**99**, 265003(2007)]*

- QLT verified for electron transport in electron temperature gradient (ETG) turbulence and ion transport in ion temperature gradient (ITG) turbulence
  - Instability driven by resonant particles; nonlinear wave-particle decorrelation regulates transport; Overlap of phase space islands leads to diffusive radial scattering of resonant particles; ITG saturates via zonal flow shearing; ETG via spectral cascade by nonlinear toroidal coupling

- QLT not verified for electron transport in ITG and ion transport in CTEM

- Validity of QLT for collisionless trapped electron (CTEM) turbulence?
  - Zonal flow regulates saturation and electron transport in CTEM with Cyclone-like parameters; Detuning of toroidal precessional resonance weak; Ballistic propagation of fluctuations and electron transport observed in GTC simulation ***[Xiao and Lin, TTF08]***



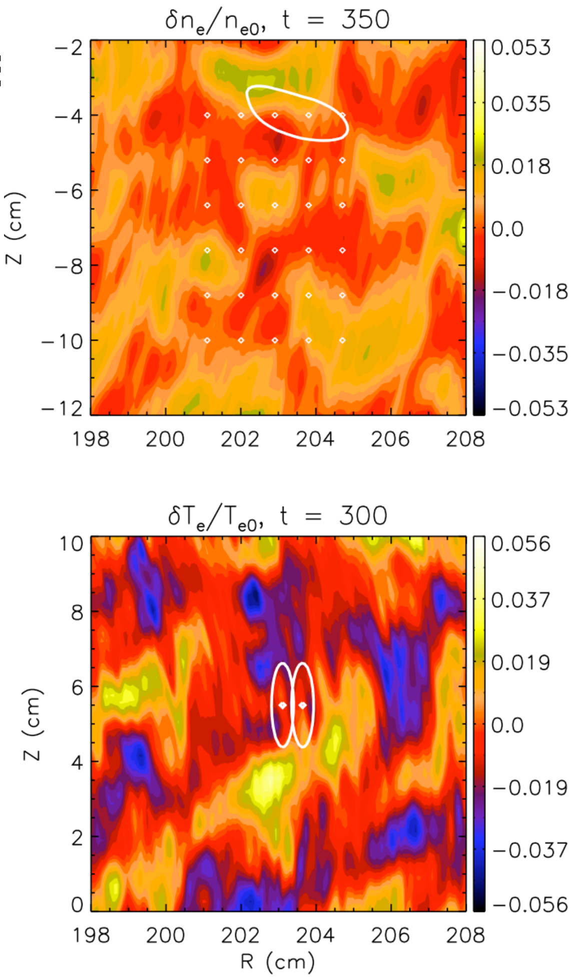
$[\frac{L_{ne}}{v_i}]$	$\tau_{wp} = \frac{4\chi}{3\delta v_r^2}$	$\tau_\parallel = \frac{1}{\Delta k_\parallel v_i}$	$\tau_\perp$	τ_{eddy}	τ_{rb}	τ_{au}	τ_s	$\frac{1}{\gamma}$
ETG	1.3	1.7	2.5	13.4	139	110		11
$ITG(A)$	1.6	1.7	2.2	4.9	23	15	1.4	9.1
$ITG(k)$	1.6	1.8	1.64	3.6	12.6	6.6	0.87	5.0
$ITG(k)$	0.7		8.8		67			
$CTEM(i)$	0.26	1.91	7.7	1.82	19.3	9.27	0.65	4.0
$CTEM(e)$	0.61		7.8		19.6			

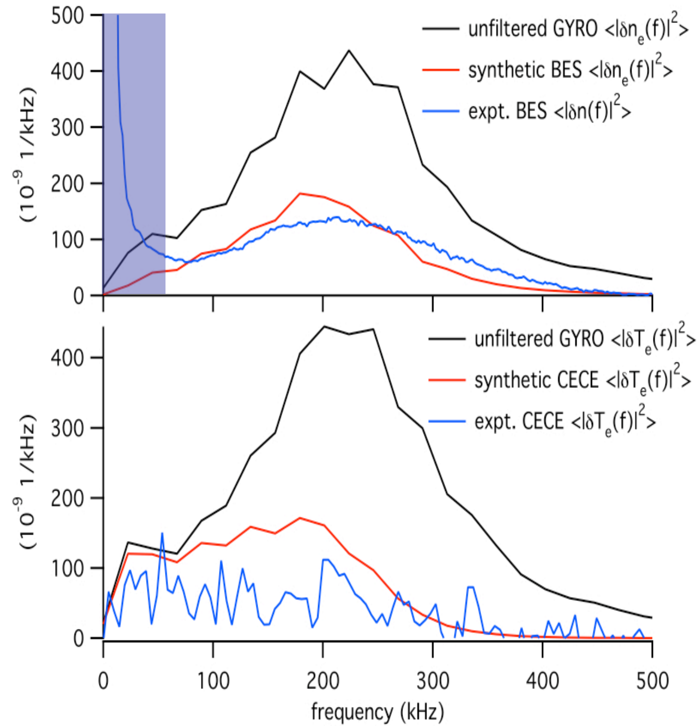
Table 1: Time scales in ITG, ETG and CTEM turbulences

New Synthetic Diagnostic Capability Allows Direct Comparisons of Simulated and Measured Turbulence Characteristics

- **Synthetic BES and CECE diagnostics have been developed as IDL post-processing tools for use with GYRO simulations**

- **Short term goal is to develop corresponding IDL interface for GTC which will use same tools**





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Short Term Plans on Physics and Validation

- Nonlinear Simulations of Turbulence Driven Momentum Transport:

  Identify non-diffusive flux (pinch and residual stress),

  Compare with theory predictions,

  Relevance of transients ? Is time-averaged flux more meaningful?

  Study turbulence modification of mean flows (plenty of examples exist where neoclassical predictions fail, when supposed to work)
- Role of Trapped Electrons in Core Turbulence

  Detailed characterization of ZF: (ω, q_r) spectra, shearing rate,…

  Phase-space info: Distortion of “f” due to precession resonance

  Plot δT_e as well as density fluctuations

  Look for evidence of T.E. Particle pinch from TEP theory
- Radial Dependence of Turbulence and Transport

  High fluctuation towards the edge ---> Revisit Turbulence Spreading
- Validation

  Develop Synthetic BES, CECE, High-k Scatt. Diagnostics

  Develop and use formula which quantifies the degree of agreement in flux, fluctuation amplitudes (density, temperature), correlation function,…

Energetic Particle Diffusion by Microturbulence

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- Recent tokamak experiments revive interest of fast ion transport induced by microturbulence *[Gunter et al, NF**47**, 920 (2007); Heidbrink and Sadler, NF**34**, 535 (1994)]*
- Radial excursion of test particles found to be diffusive in GTC global simulation of ion temperature gradient (ITG) turbulence ***[Zhang et al, TTF08]***
- Detailed studies of diffusivity in energy-pitch angle phase space
  - Diffusivity drops quickly at higher particle energy due to larger Larmor radius/orbit width, and faster transit/bounce frequency
- Beam ions: lower diffusivity for higher born energy