Transport Predictions for Density-Gradient-Dominated Regimes

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2011 U.S. Transport Task Force Workshop

Abstract

Tokamak energy confinement is often limited by turbulent transport due to temperature-gradient-driven instabilities; however, a low-recycling plasma boundary may support high edge temperatures, resulting in a flattened temperature profile and eliminating the drive mechanism for ITG and ETG turbulence. In this regime, modes driven by the density gradient may dominate the overall transport. To characterize transport in this regime, the dependence of particle and thermal fluxes as a function of density gradient with zero temperature gradient were examined, using the GYRO[Candy and Waltz, 2003] code. The nonlinear scaling of flux with density gradient indicates a nonlinear upshift in the critical gradient as reported elsewhere[Ernst et al., 2004]. In addition, the outward heat flux is less than the convective heat flux, due to preferential transport of low-energy particles. Thus, the transport attempts to drive a temperature gradient.

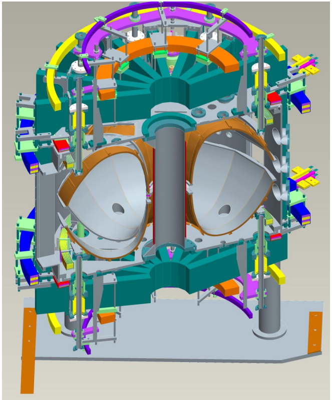
Abstract, contd.

The GYRO code has been used to assess the performance predictions for the Lithium Tokamak Experiment (LTX), a spherical torus designed to investigate the low-recycling lithium wall regime.[Majeski et al., 2009]
Linear simulations indicate that during active gas-puffing, both ITG and TEM modes are unstable. Charge-exchange losses with gas puff neutrals and weak electron-ion coupling suppress the edge T_i resulting in a steep ion temperature gradient and low T_i/T_e which drive the ITG mode.

Abstract, contd.

The relatively small size of LTX (a/ρ_s ~25–40) permits global nonlinear simulations of most of the plasma volume at reasonable computational cost, though it also complicates the simulations by making the role of the wall, sources, and sinks more important. Initial nonlinear simulations using predicted profiles during gas puffing failed to saturate indicating that the transport may be greater than expected. Saturation is achieved after relaxing the density and temperature profiles.

LTX Description



Cutaway view of internal shells and coils

Available Diagnostics:

- Comprehensive magnetics
- 2 mm scanning interferometer
- 1 mm fixed interferometer
- Multi-point Tomson Scattering
- Poloidal Lyman-α & Bolometer Arrays
- Edge Langmuir Probe
- Gas Puffer, Supersonic Gas Injector
- Molecular Cluster Injector
- Filterscopes & Visible survey spectrometers

Coming Soon:

- XUV spectrometer
- passive spectroscopy for n_i, T_i, u_i
- Digital Holography
- Neutral beam (late 2011 or early 2012)

LTX Achieved and Target Parameters

Parameter	Achieved (Ohmic)	Goal (beam-heated)
Major Radius (R_0)	40 cm	40 cm
Minor Radius (a)	26 cm	26 cm
Elongation (κ)	1.55	1.55
Toroidal Field (B_T)	1.8 kG	3.5 kG
Plasma Current (Ohmic) (I_p)	67 kA	$>$ 250 kA
Central Density ($n_e(0)$)	$\sim 8 \times 10^{18}\ \mathrm{m}^{-3}$	$5 \times 10^{19}\ \mathrm{m}^{-3}$
Central T_e	$\sim$100 eV	$>$ 500 eV
Central T_i	?	$>$ 150 eV
Current Flattop	$\sim$5 ms (20 ms duration)	$>$ 100 ms

Reference Transport Model

- $D_{e,i} = \chi_i = \chi_e = \chi_i^{neo}$
- implemented in ASTRA with the equilibrium and stability code ESC
- flux boundary condition for the temperature profile
- ideal situation is zero recycling: no cold neutrals at the wall to suppress the edge temperature
- zero recycling is not compatible with edge particle fueling

Outline

1. Transport Model Linear Evaluation
   - During Gas Puffing
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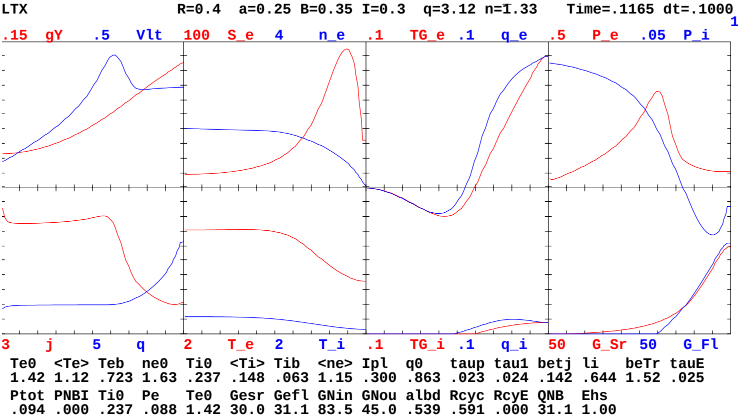
RTM Predictions during Gas Puffing

Sample low-βequilibrium ($\beta \sim 4\%$)[Majeski et al., 2009]



```
LTX                R=0.4  a=0.25 B=0.35 I=0.3  q=3.12 n=1.33   Time=.1165 dt=.1000
```

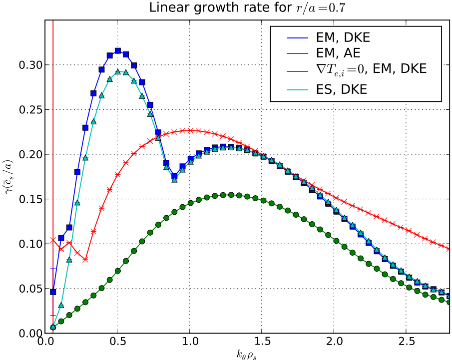
```
 Te0  <Te> Teb  ne0  Ti0  <Ti> Tib  <ne> Ipl  q0   taup tau1 betj li   beTr tauE
 1.42 1.12 .723 1.63 .237 .148 .063 1.15 .300 .863 .023 .024 .142 .644 1.52 .025
 Ptot PNBI Ti0  Pe   Te0  Gesr Gefl GNin GNou albd Rcyc RcyE QNB  Ehs
 .094 .000 .237 .088 1.42 30.0 31.1 83.5 45.0 .539 .591 .000 31.1 1.00
```

Objectives of gyro-kinetic simulations:

- develop interface between ASTRA/ESC and GYRO
- examine consistency of RTM with gyro-kinetic simulations
- gain insight into the expected density fluctuation levels in the experiment

$r/a = 0.7$, GYRO Linear γ during gas puffing

R_0/a	1.66
Δ	-0.11
κ	1.32
s_κ	0.018
δ	0.16
s_δ	0.20
q	1.12
s	1.38
ρ_*	0.035
ν_{ei}	0.022
ν_{ii}	0.008
a/L_n	1.56
a/L_{T_e}	1.78
a/L_{T_i}	2.57
T_i/T_e	0.126
β_e	1.9%



Weak electromangetic effects due to low β (2.1%). For $k_y\rho_s < 1.0$, TEM dominates; for $k_y\rho_s > 1.0$ ITG dominates.

$r/a = 0.7$, GYRO Linear ω_r during gas puffing

R_0/a	1.66
Δ	-0.11
κ	1.32
s_κ	0.018
δ	0.16
s_δ	0.20
q	1.12
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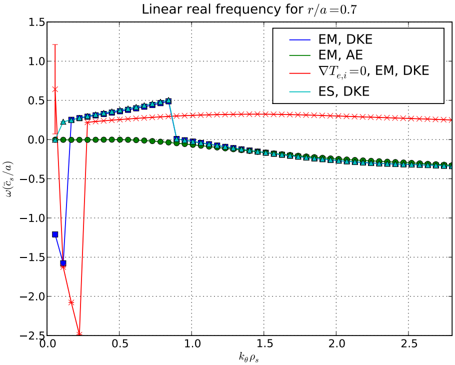
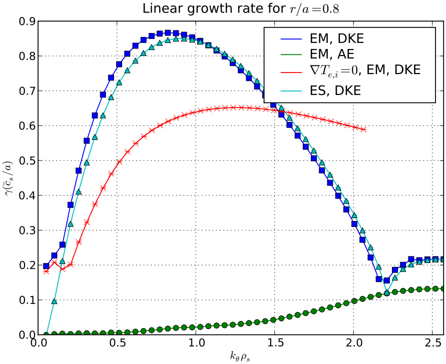


For $k_y \rho_s < 1.0$, drift is in the elec. diamag. direction; for $k_y \rho_s > 1.0$ in the ion direction.

$r/a = 0.8$, GYRO Linear γ during gas puffing

R_0/a	1.65
Δ	-0.17
κ	1.33
s_κ	0.11
δ	0.20
s_δ	0.38
q	1.44
s	2.48
ρ_*	0.029
ν_{ei}	0.026
ν_{ii}	0.011
a/L_n	2.80
a/L_{T_e}	1.98
a/L_{T_i}	3.24
T_i/T_e	0.111
β_e	1.0%



Strongly-driven TEM mode due to large density gradient.

$r/a = 0.8$, GYRO Linear ω_r during gas puffing

R_0/a	1.65
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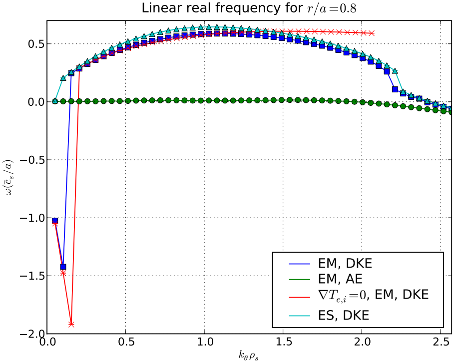

Shift to ion diamag. direction (ITG) for $k_y \rho_s > 2.2$.

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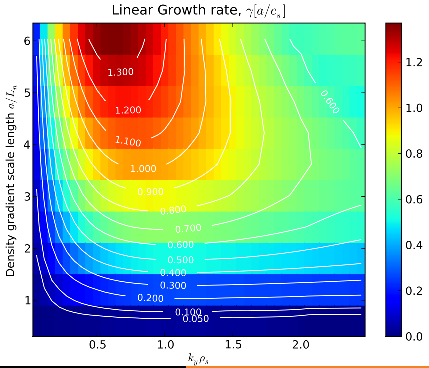
Linear, Local Parametric Scan

Values at $r/a = 0.75$ were taken, then $\nabla T \rightarrow 0$, $\rho_* \rightarrow 0.1\rho_*$ to get local limit of idealized flat $T_{e,i}$ regime. $T_i/T_e \rightarrow 1$ for reactor, low β (1.6%).

R_0/a	1.66
Δ	-0.14
κ	1.33
s_κ	0.06
δ	0.17
s_δ	0.28
q	1.25
s	1.95
ρ_*	0.0033
ν_{ei}	0.0
ν_{ii}	0.0



Linear, Local Parametric Scan

Real frequency can be in either electron or ion diamagnetic direction.

R_0/a	1.66
Δ	-0.14
κ	1.33
s_κ	0.06
δ	0.17
s_δ	0.28
q	1.25
s	1.95
ρ_*	0.0033
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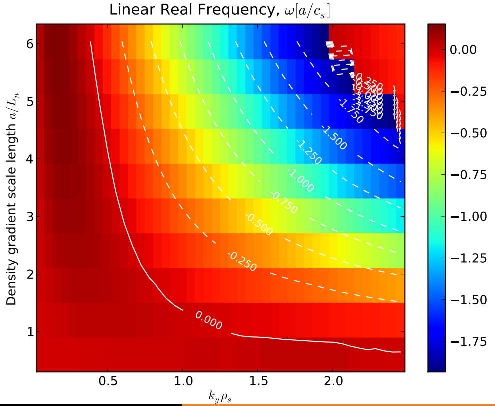
ν_{ii}	0.0



Linear, Local Parametric Scan

R_0/a	1.66
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ρ_*	0.0033
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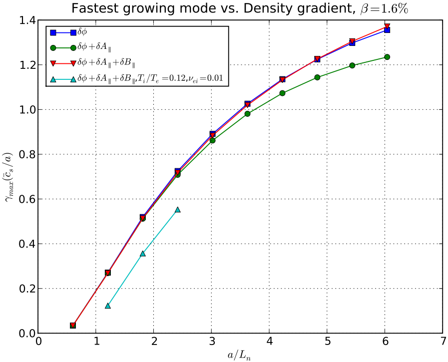
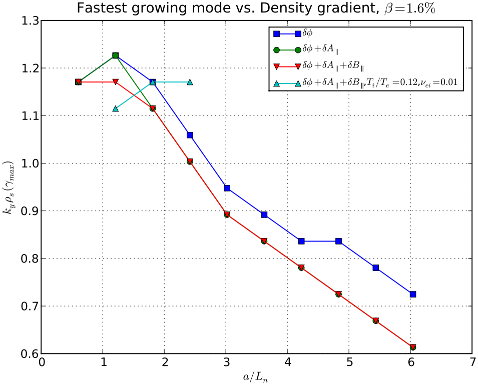


Small linear critical gradient: $a/L_n \approx 0.45$ ($R/L_n \approx 0.75$).

Linear, Local Parametric Scan

R_0/a	1.66
Δ	-0.14
κ	1.33
s_κ	0.06
δ	0.17
s_δ	0.28
q	1.25
s	1.95
ρ_*	0.0033
ν_{ei}	0.0
ν_{ii}	0.0



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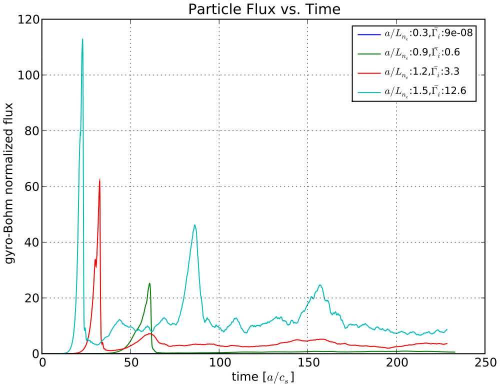
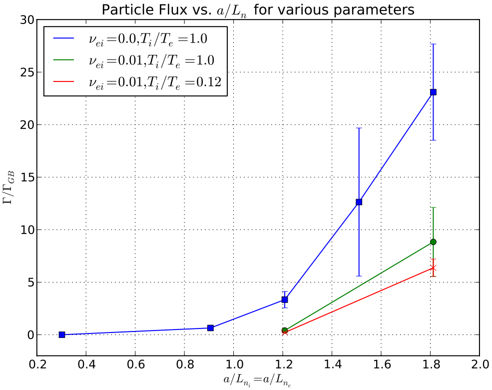
Nonlinear, Local Parametric Scan



directory: "/p/gyro/egranste/sim/tem_ltx/nl/nuei0"Sun Apr 11 22:00:36 2010

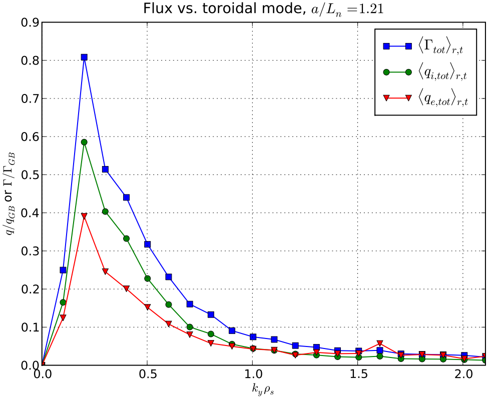
Strong zonal flows are driven nonlinearly which then damp the turbulence resulting in bursts of flux.

Nonlinear, Local Parametric Scan



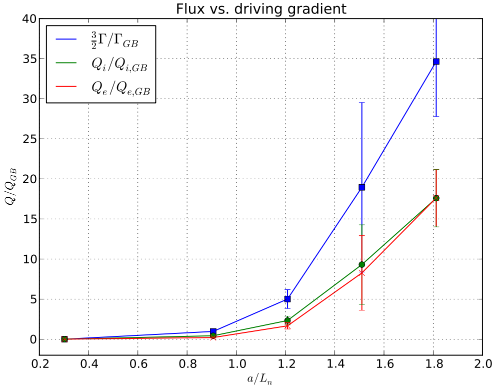
Significant nonlinear upshift due to zonal flows.

Nonlinear, Local Parametric Scan



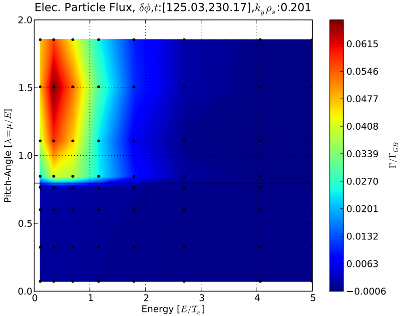
Flux is dominated by modes with $k_y \rho_s < 0.5$.

Nonlinear, Local Parametric Scan

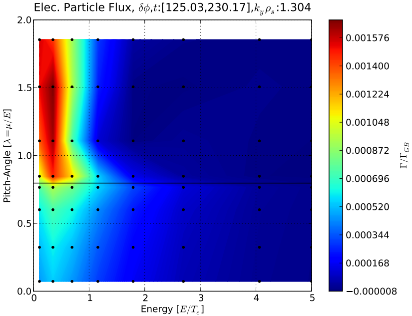


Q_e, $Q_i < 3/2\Gamma$: the transport is driving particles and heat outward but also redistributing free energy among ∇n, ∇T_e, and ∇T_i by driving a finite ∇T_e and ∇T_i.

Velocity-space fluxes



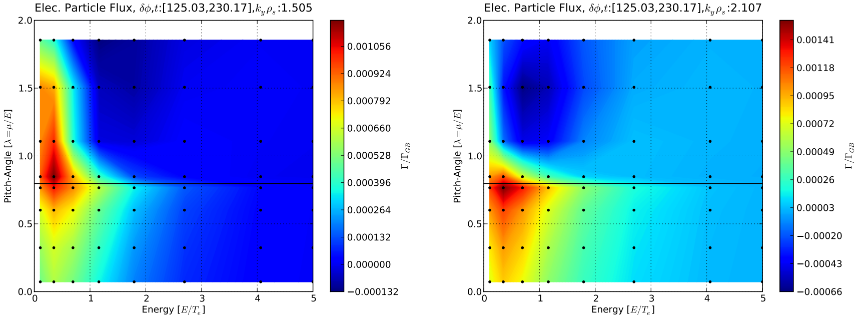
Elec. Particle Flux, $\delta\phi$,t:[125.03,230.17],$k_y\rho_s$:0.201



Elec. Particle Flux, $\delta\phi$,t:[125.03,230.17],$k_y\rho_s$:1.304

At low and moderate k_y/ρ_s which dominate the total flux ($k_y\rho_s \lesssim 0.6$), the flux is due to low-energy trapped particles.

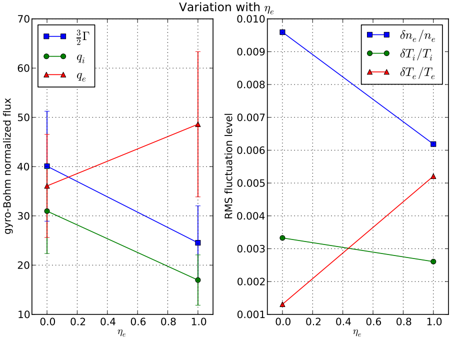
Velocity-space fluxes, contd.



At higher k_y/ρ_s, passing and higher-energy particles diffuse radially outward, but these modes contribute very little to the total flux.

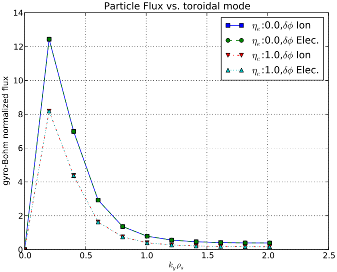
Variation with η_e

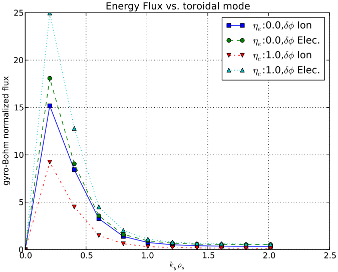
To test examine changes in the turbulence as ∇P is distributed between the ∇n and ∇T_e, nonlinear GYRO simulations were performed using "Cyclone Base Case" parameters with $\nabla T_i = 0$, $R_0/L_n + R_0/L_{T_e} = 20$ to test variation with η_e.



As η_e increases for fixed ∇P, and $\nabla T_i = 0$, $\delta T_e/T_e$ and Q_e increase, while $\delta n_e/n_e$, Γ, and Q_i decrease. Q_i remains $> 3/2\Gamma$. Relative RMS fluctuation levels behave similarly to the fluxes.

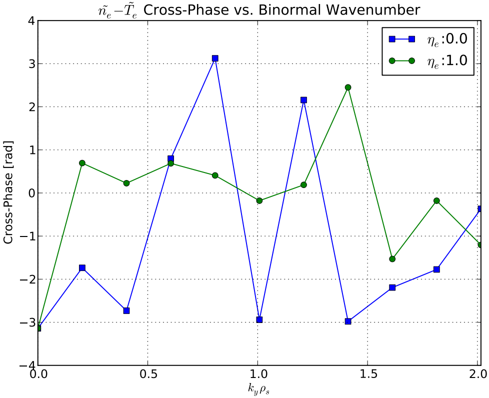
Variation with η_e, contd.





The relative contribution of various binormal wavenumbers remains relatively unchanged.

Variation with η_e, contd.



Cross-phase shows qualitative difference: for the dominant modes, δn_e and δT_e are nearly in-phase in the case of $\eta_e = 1$, while they are 90°–180° out-of-phase for $\eta_e = 0$.

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LTX Global Nonlinear Simulation Challenges

LTX is relatively “small”: $a/\rho_s \sim 30$**, therefore:**

- must simulate most of radial cross-section
- LTX has no “local” limit; must do global simulation
- damping regions at boundaries of simulation domain reduce usable simulation volume

LTX Global Nonlinear Simulation Challenges

Convergence issues: (simulations centered at $r/a = 0.53$)

- $n = 1$ mode tends to blow-up
- for convergence: need to soften density gradient, adjust q profile
- simulations blow-up unless electrostatic, or T_e, T_i reduced by half
- converged simulations are unphysical

Convergence issues: (simulations centered at $r/a = 0.7$)

- T_e, T_i flattened to examine limiting case and eliminate ITG
- need to flatten density gradients at edge
- simulations blow-up unless strength of electromagnetic effects reduced by half

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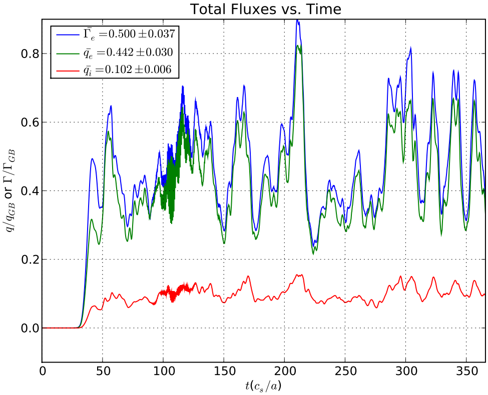
Preliminary Results

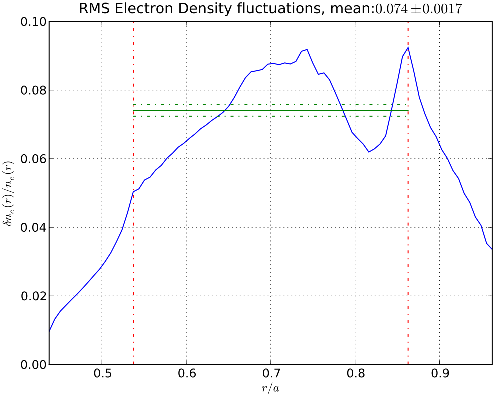
- Limiting case of $\nabla T_{i,e} = 0$, centered at $r/a = 0.7$, βreduced by half. $n(r)$ flattened in the outer damping region. Large fluxes and significant density fluctuations across the radial domain.
- diffusion typically 10-30 times the RTM prediction
- large-scale mode extends across radial domain
- would result in flattening of density profiles
- predicted fluctuation level $\delta n/\bar{n}_e \sim$5–10%, $\delta n_e \sim 0.5$–$1 \times 10^{12}\mathrm{cm}^{-3}$

Saturation of Fluxes



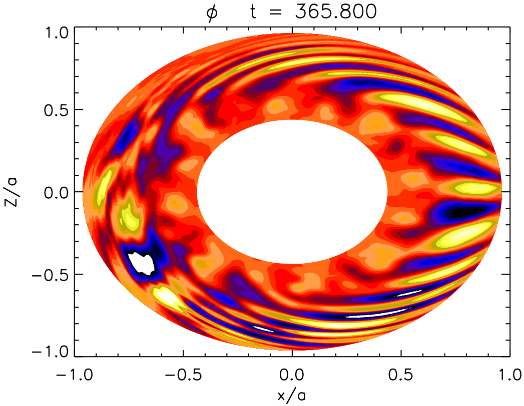
Large oscillations in the particle and heat fluxes. Small q_i/q_e primarily due to small T_i/T_e.

RMS Electron Density Fluctuations



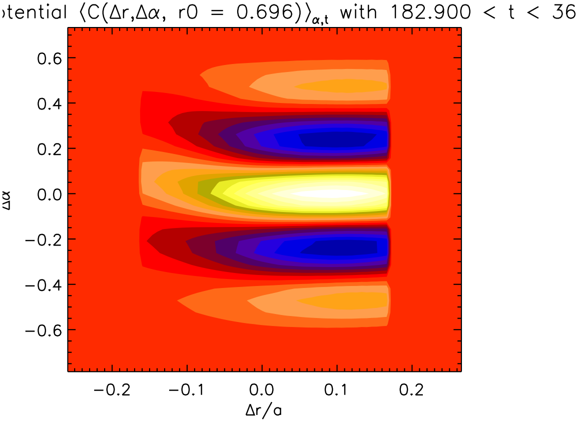
Zero radial boundary condition may be affecting result. May need additional damping at boundaries.

Poloidal cut of ϕ fluctuations



Long, radially-extended eddies.

Midplane ϕ correlation function



Likely not converged with box.

Conclusions

- Linear simulations indicate that during active gas-puffing, both ITG and TEM modes are unstable. Due to a low T_i/T_e, the ITG peak is counter-intuitively at higher binormal wavenumber.
- Obtaining converged, global nonlinear gyro-kinetic simulations of a small device $a/\rho_s \sim 30$ is a challenge because of the boundary treatment effects and possibly a subcritical βinstability.
- The RTM may be significantly under-predicting the particle and thermal transport.

Conclusions, contd.

- Nonlinear simulations with zero temperature gradients reveal a nonlinear upshift of the critical density gradient.
- The outward particle flux is primarily due to low-energy trapped particles interacting with modes with $k_y \rho_s \sim$ 0–0.6 and being preferrentially lost. Since q_i, $q_e < 3\Gamma/2$, the transport attempts to drive a finite temperature gradient.

Future Work

- Integrate a more complete transport model such as GLF23 or TGLF into ASTRA to better predict LTX performance.

Acknowledgments

The authors appreciate help from L. Zakharov with setting up ASTRA, and J. Candy and R. Waltz for use of the GYRO code. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-0646086. LTX is supported by US DOE contract DE-AC02-09CH11466.

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R. Majeski, L. Berzak, T. Gray, R. Kaita, T. Kozub, F. Levinton, D. Lundberg, J. Manickam, G. Pereverzev, K. Snieckus, et al., Nuclear Fusion **49**, 055014 (2009), ISSN 0029-5515.

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