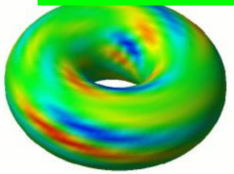
Institute
for
Fusion Studies

Electron Thermal Transport

W. Horton

Institute for Fusion Studies

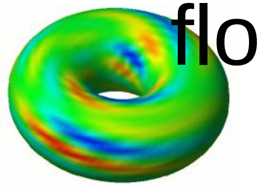
Collaborators: G. T. Hoang, John Kim, H. Park, T.-H. Watanabe and H. Sugama and E. Asp



First ITER School, Aix-en Provence
July 16-20, 2007

Outline and Topics

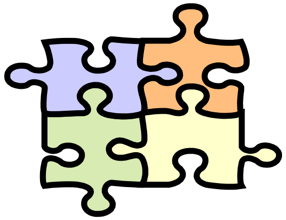
- Electron Thermal Transport- unique character.
- Power Balance and inferred diffusivity.
- Gyrofluid simulations showing strong inverse cascade from high k to ITG scale from Te driver.
- High k-scattering data.
- Electromagnetic streamers and zonal flows.

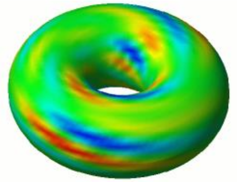


Electron Thermal Transport

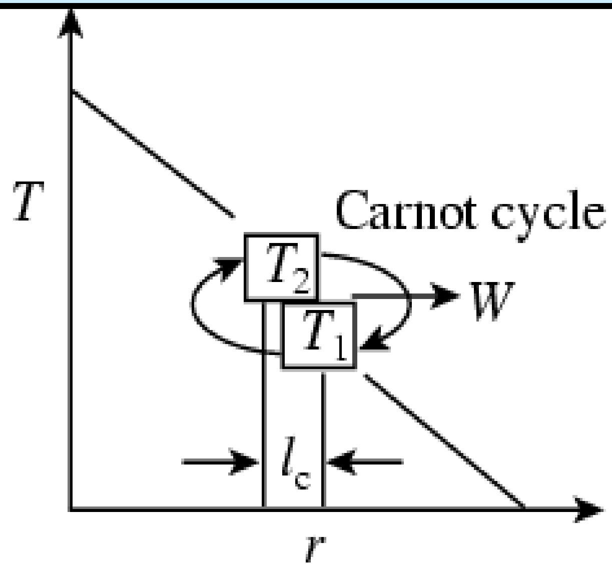
- **Electron transport** is a phenomenon with its own characteristics
  - Kadomtsev – “Tokamak Plasma: A Complex Physical System” (1992)
- **TTF declares electron transport** a top priority issue ~2004
- Electron transport has universal features across confinement geometries
- Electron transport space/time scales are small/fast

Electron transport is a “puzzle”



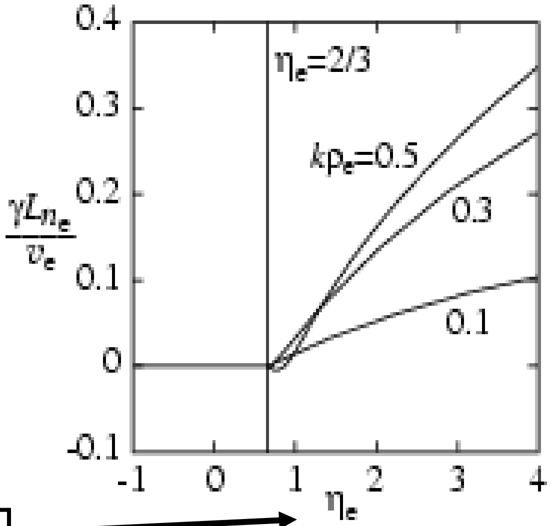


Threshold ∇T for Convection

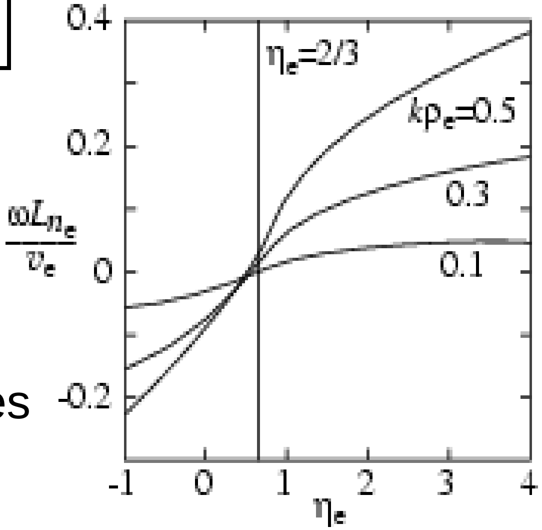


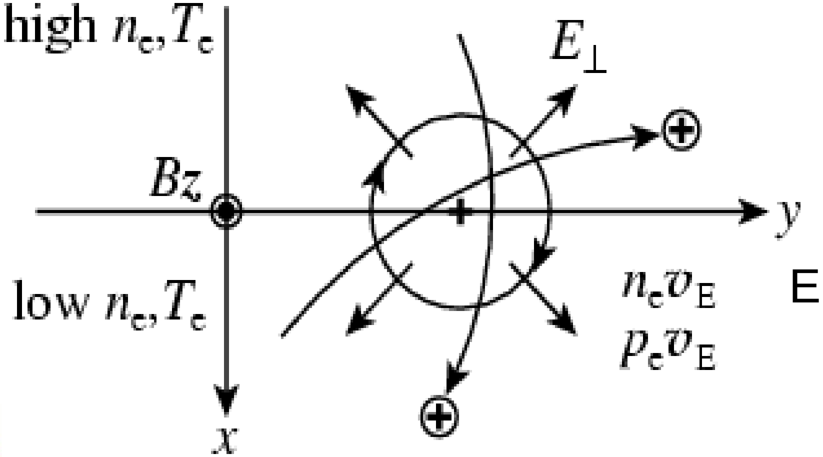
ETG Drift Waves

Vlasov (GKE) Equation Growth Rate

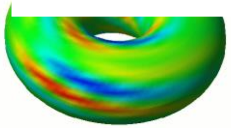


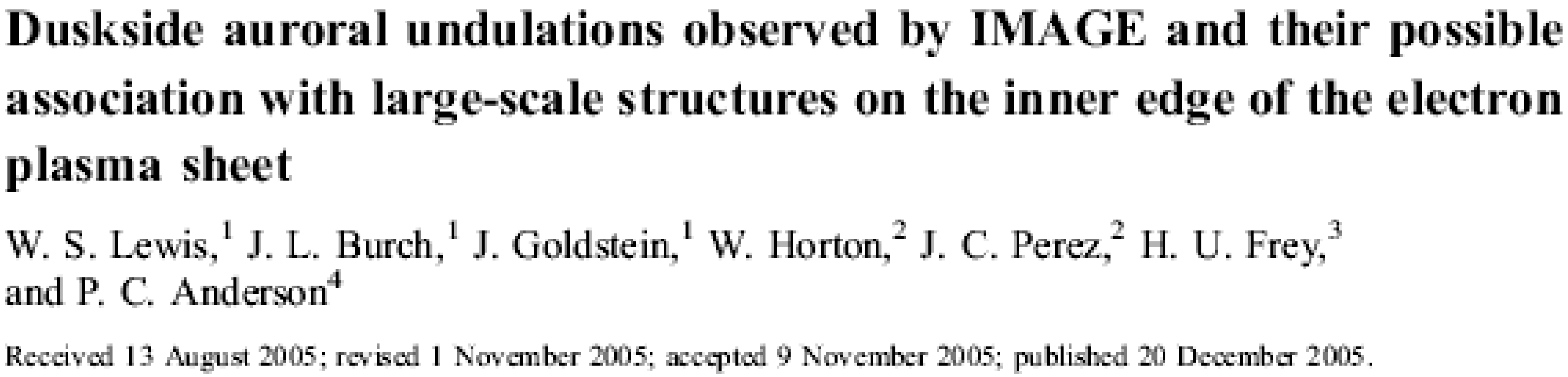
$$\eta_e = \frac{\partial\, \ln T_e}{\partial\, \ln n_e}$$





Entropy Profiles





Duskside auroral undulations observed by IMAGE and their possible association with large-scale structures on the inner edge of the electron plasma sheet

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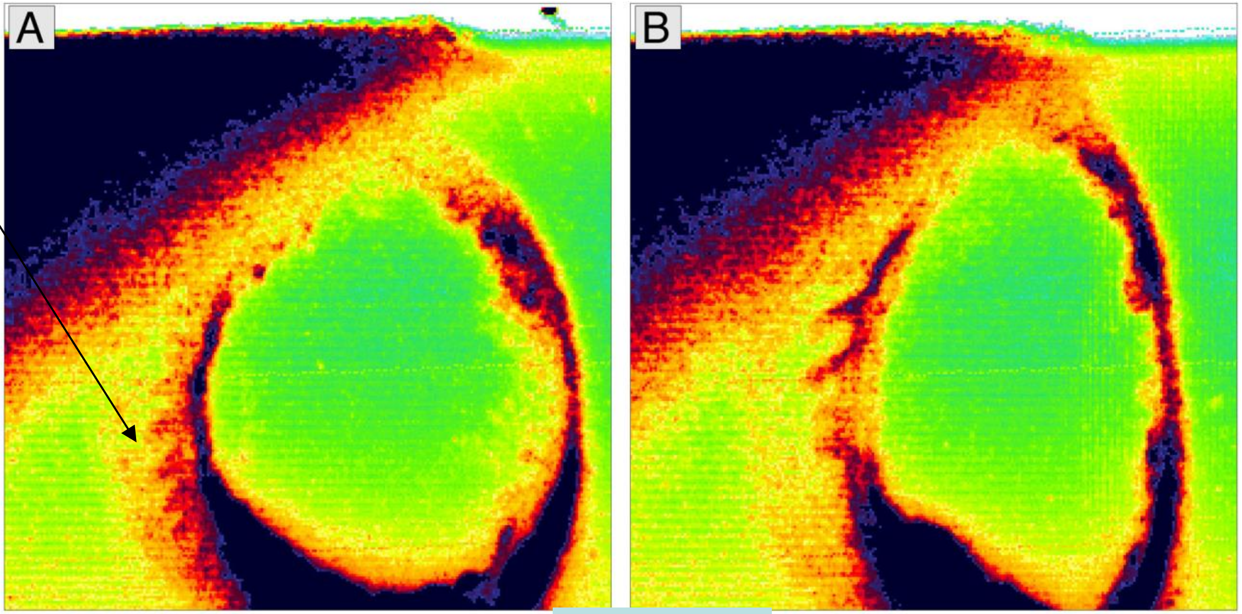
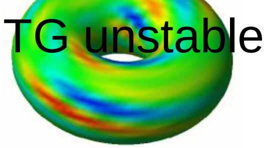
Received 13 August 2005; revised 1 November 2005; accepted 9 November 2005; published 20 December 2005.

Large-scale undulations in recovery phase of storms are observed in FUV from IMAGE in the diffuse aurora. ‘Fingers’ map to the equitorial plane from inner edge of plasma sheet T_i~2-3kev to the center of Ring Current where T_i~ 15kev. The flux tubes are MHD stable but ITG unstable.





Drift Wave Turbulence in Torus with Magnetic Shear --ETG

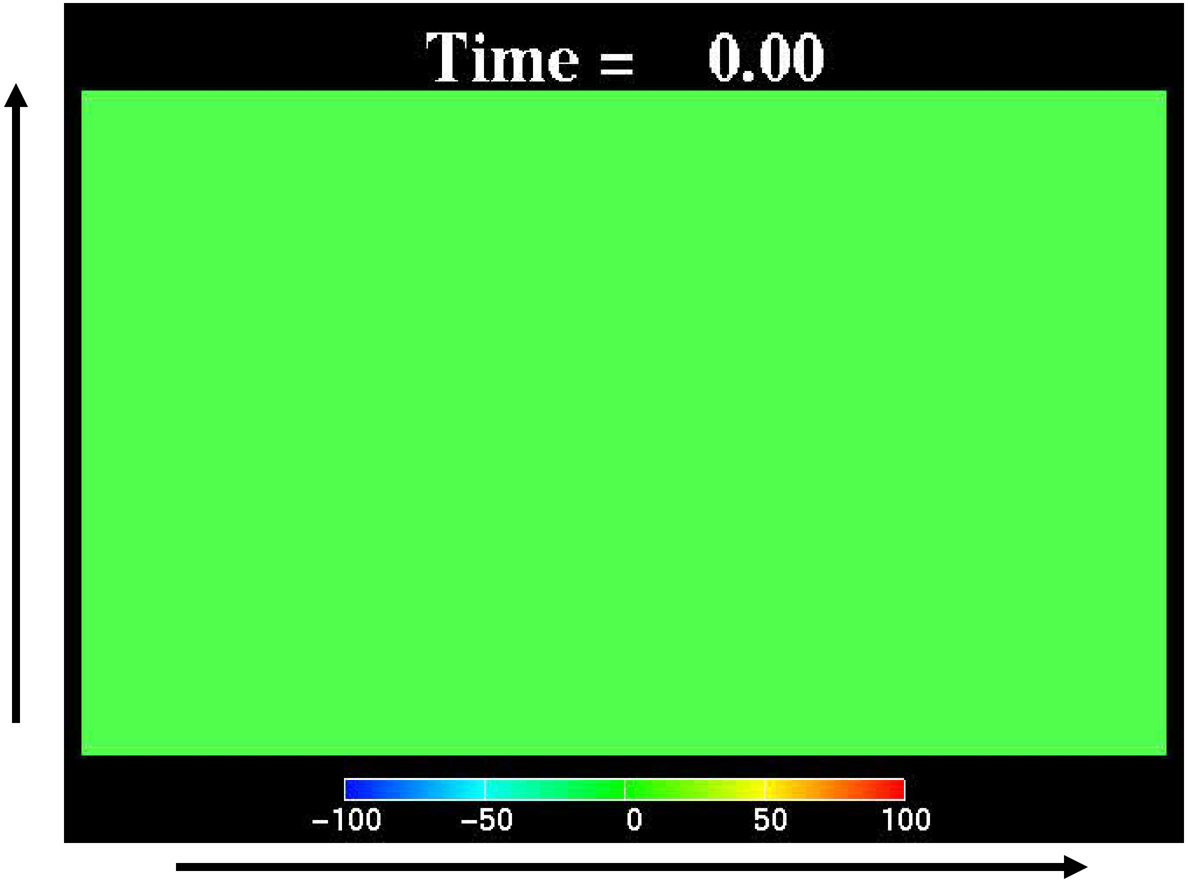
$[t]=L_n/v_e$

$\eta_e=3$

s/q=.8/1.4

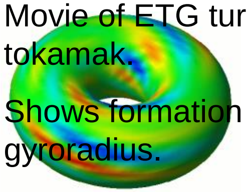
Chi-e ~80gBohme

T.-H. Watanabe GKV simulations (2006) 5D Shows how toroidal R/L_T curvature creates long “fingers”



y/ρ_e [0,190]

x/ρ_e [0,292]



Movie of ETG turbulence in flux tube coordinates for annulus in a tokamak.

Shows formation of long radial streamers of about size of ion gyroradius.

Supported by

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Confinement and Local Transport in the National Spherical Torus Experiment

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Chengdu, China

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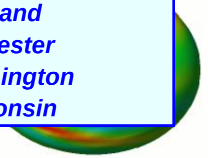
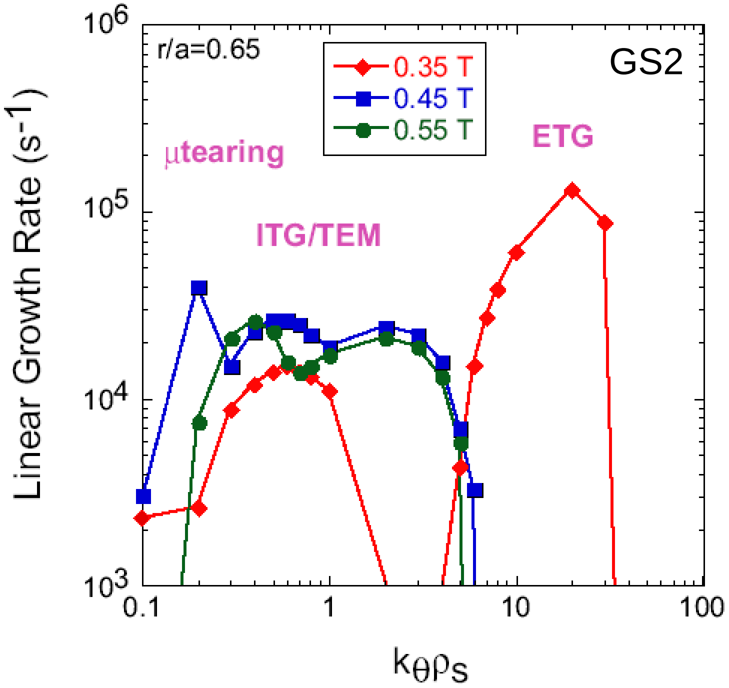


ETG Dominates Electron Transport at Low B_T in NSTX

ETG linearly unstable only at lowest B_T

- 0.35 T: R/L_{Te} 20% above critical gradient
- 0.45, 0.55 T: R/L_{Te} 20-30% below critical gradient



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- Experimental χ_e profile consistent with that predicted by e-m ETG theory [Horton et al., NF 2004] at 0.35 T
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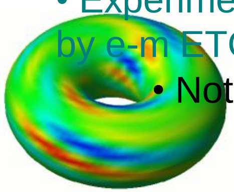
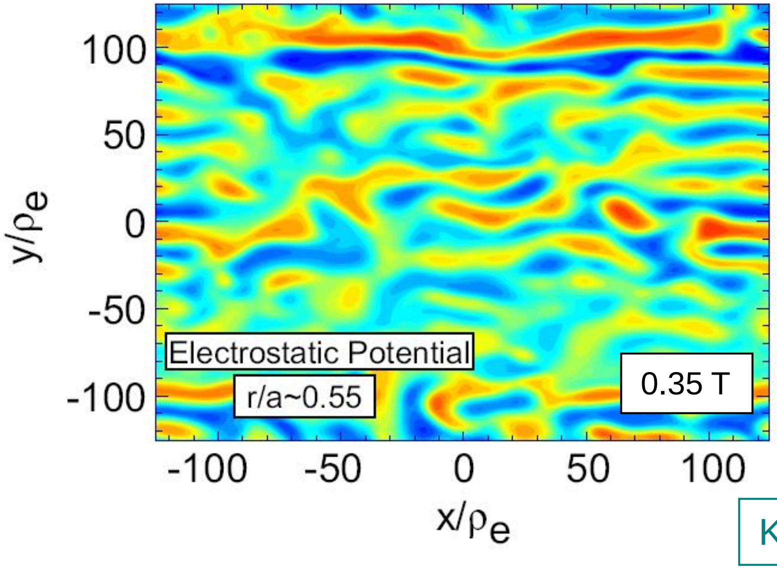
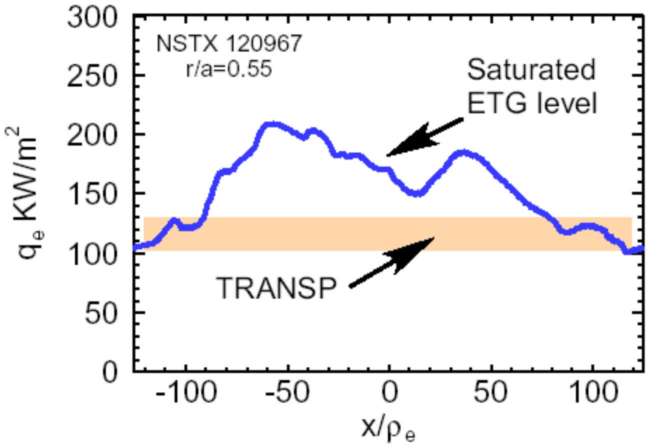


Non-linear simulations indicate formation of radial streamers (up to $200\rho_e$): FLR-modified fluid code [Horton et al., PoP 2005]



Kim, IFS



Three PDEs of ETG Dynamics

1. **Divergence of the electric current =0**
2. **Generalized Ohm's law =0**
3. **Thermal balance for the electron pressure=0**

Eq.1 = $d_t\Delta$ phi + Two Poisson Bracket (BP) nonlinearities + viscosity

Eq. 2 = $d_t \delta B_x$ +Three PB nonlinearities + resistivity

Eq. 3 =$d_t T_e$ + Two PB nonlinearities + perp & parallel thermal diffusivity

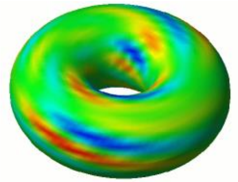
5 core parameters + 4 dissipation coefficients

5 energy densities and energy dissipation theorem

eg, Horton et al NF 2005,

Li & Kishimoto PoP 05

Holland and Diamond, PoP 2004



Electron dynamics

Ohm's Law and Frozen in Motion

$$\underset{1}{\frac{m_e}{e}\frac{\partial j_\|}{\partial t}} + \underset{2}{enE_\|^{(\mathrm{A})}} + \underset{3}{\frac{B_x}{B}\frac{dp_e}{dx}} + \underset{4}{enE_\|^{(\mathrm{ES})}} + \underset{5}{\nabla_\| p_e} = \underset{6}{en\eta j_\|}$$

Ampere's Law

$$j_\| = -\frac{1}{\mu_0}\nabla^2 A_\|$$

$$E_\|^{(\mathrm{A})} = -\frac{\partial A_\|}{\partial t} \quad \text{and} \quad E_\|^{(\mathrm{ES})} = -\nabla_\| \phi$$

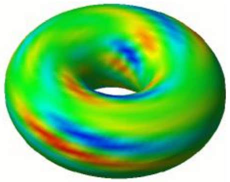
$$T_1/T_2 \qquad \frac{m_e}{en\mu_0}\frac{1}{L^2} \rightarrow \frac{k_\perp^2 c^2}{\omega_p^2} = \begin{cases} \equiv 0 \ \text{MHD}\ (m_e = 0) \\ \gg 1 \ \text{ES - DWs} \end{cases}$$

$$\text{at} \quad k_\perp \sim 1/\rho_s \qquad = \frac{m_e}{m_i \beta_e}$$

$A_\|$ - resonance $\quad T_1 + T_2 + T_3 = 0$

ϕ - DW $\quad T_4 + T_5 + T_6 = 0$

Frozen in Dynamics $\quad T_2 + T_4 = 0$



Magnetic Perturbations for Drift Waves

Electron Continuity Equation gives

$$e\delta(nu_{\|}) = \frac{\omega - \omega_{*e}}{k_{\|}} e\delta n$$

Ampere's Law gives

$$\delta B_x = \frac{1}{ik_y}\mu_0 \delta j_{\|} \simeq \frac{\mu_0 en(\omega - \omega_{*e})}{ik_y k_{\|}} \frac{\delta n}{n}.$$

So for TS we estimate

$$\delta j_{\|} \sim 5 \times 10^6 A/m^2 \left(\frac{\delta n}{n}\right)$$

$$\text{and} \qquad \delta B_x = 5 \times 10^{-2} T \left(\frac{\delta n}{n}\right)$$

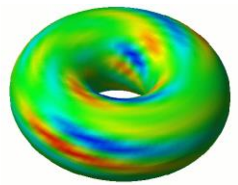
The fractional perturbation is

$$\frac{\delta B_x}{B} = \frac{\mu_0 en\omega_*}{2k_y k_{\|} B}\frac{\delta n}{n} = \frac{\mu_0 n T_e}{2B^2}\frac{1}{k_{\|} L_n}\frac{\delta n}{n} = \frac{1}{4}\frac{\beta_e}{k_{\|} L_n}\frac{\delta n}{n} \sim 5\times 10^{-4}.$$

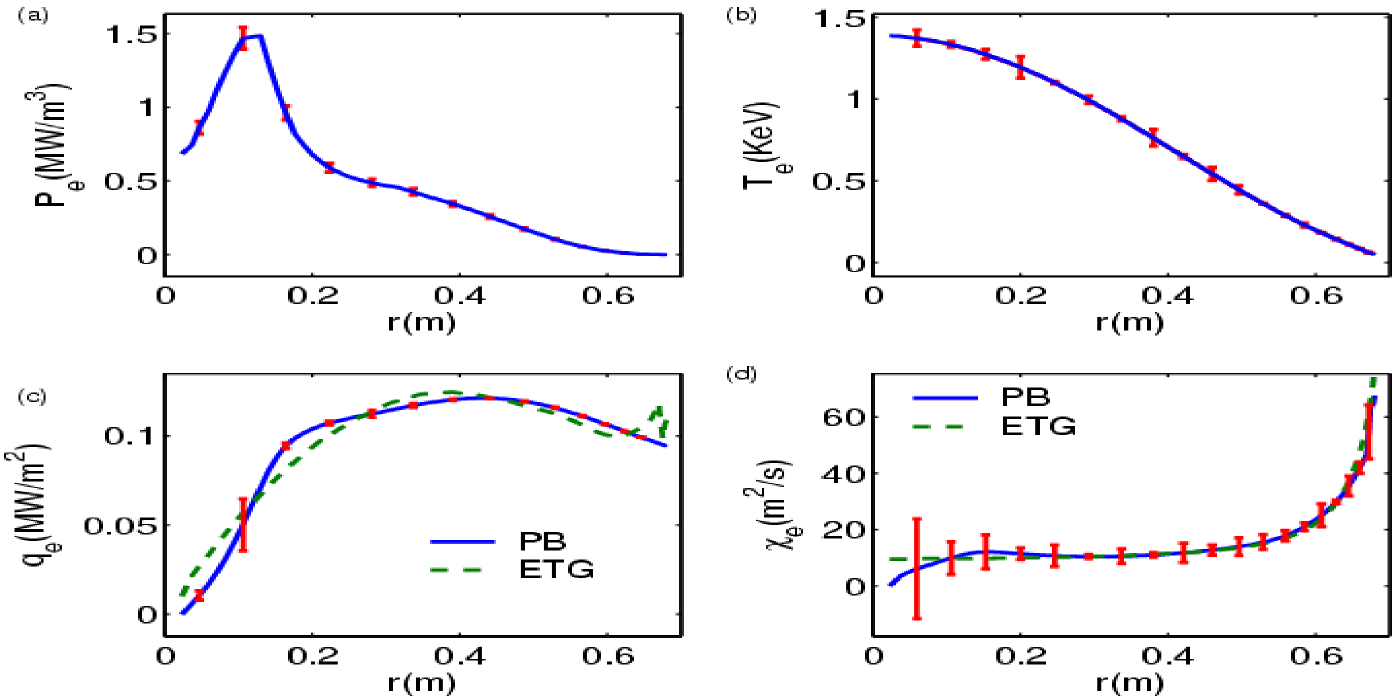
Magnetic Stochastic Transport

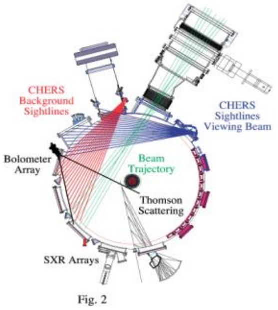
$$\chi_e^{\mathrm{RR}} = \frac{\pi v_e}{|k_{\|}|}\left|\frac{\delta B_x}{B}\right|^2 \sim \frac{\pi 10^7 m/s}{10^{-2} m^{-1}} 25 \times 10^{-8} \sim 10^2 m^2/s$$

An estimate, used for illustration only



ETG Modeling of NSTX with HHFW heating in high beta regime





106194 discharge from Le Blanc et al. (Nucl Fusion 2004) and Horton et al. (Nucl Fusion 2005)

Coherent Structures in T_e field. Movie of RF heating-limiter cooling simulation at low shear.

RF heating is up to an order of magnitude larger than the Ohmic heating. The plasma current is essential to the confinement properties.

ETG Plays an Important Role in Determining Electron Transport at Low B_T NSTX

ETG linearly unstable only at lowest B_T

- 0.35 T: R/L_{Te} 20% above critical gradient
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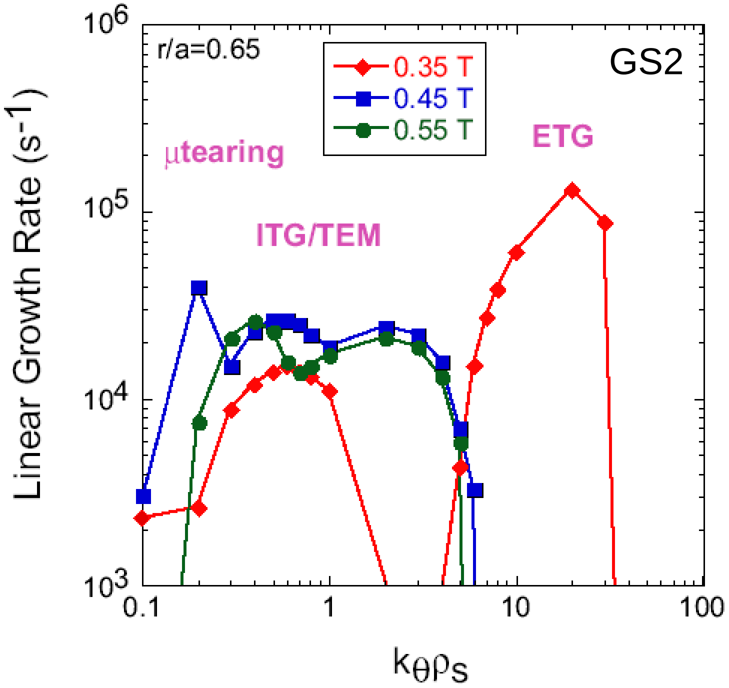

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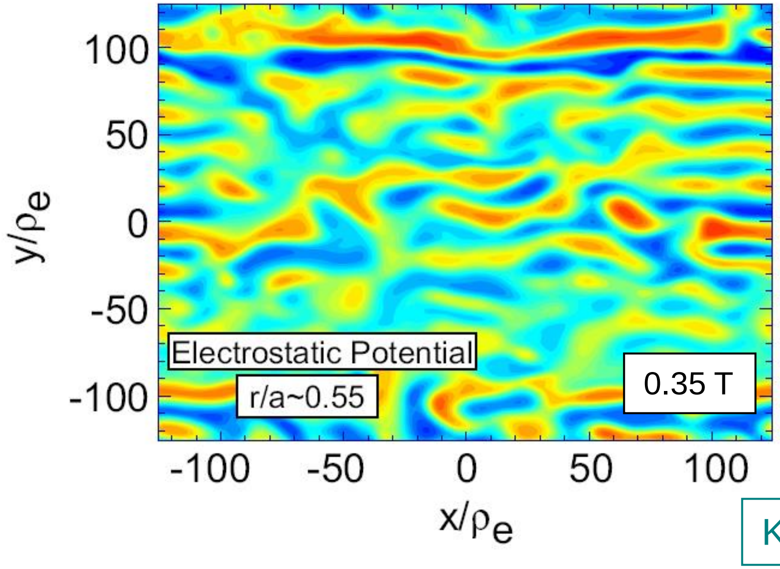

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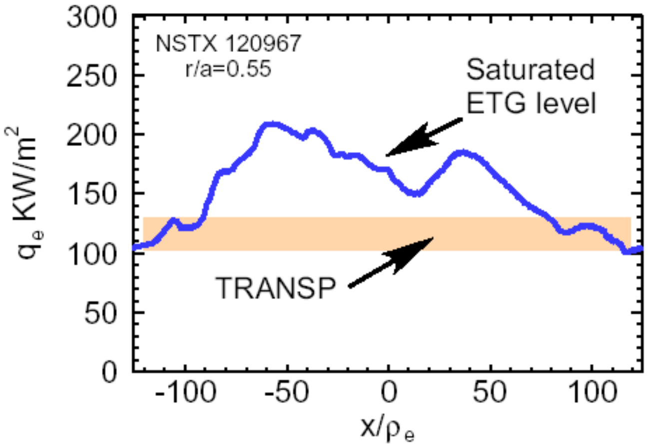

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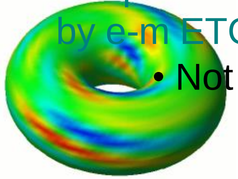

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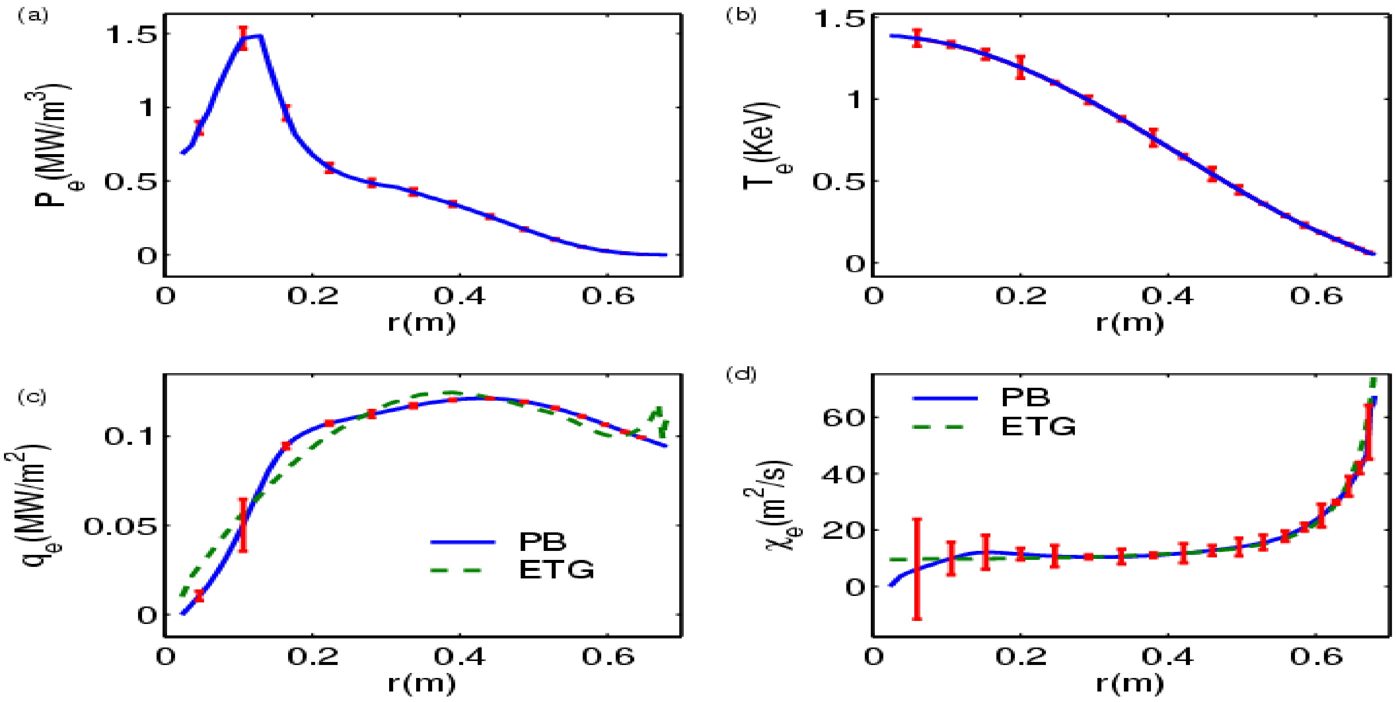

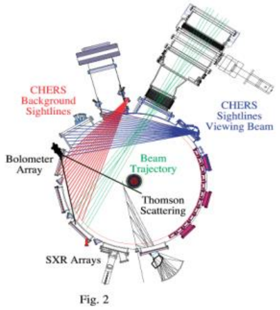

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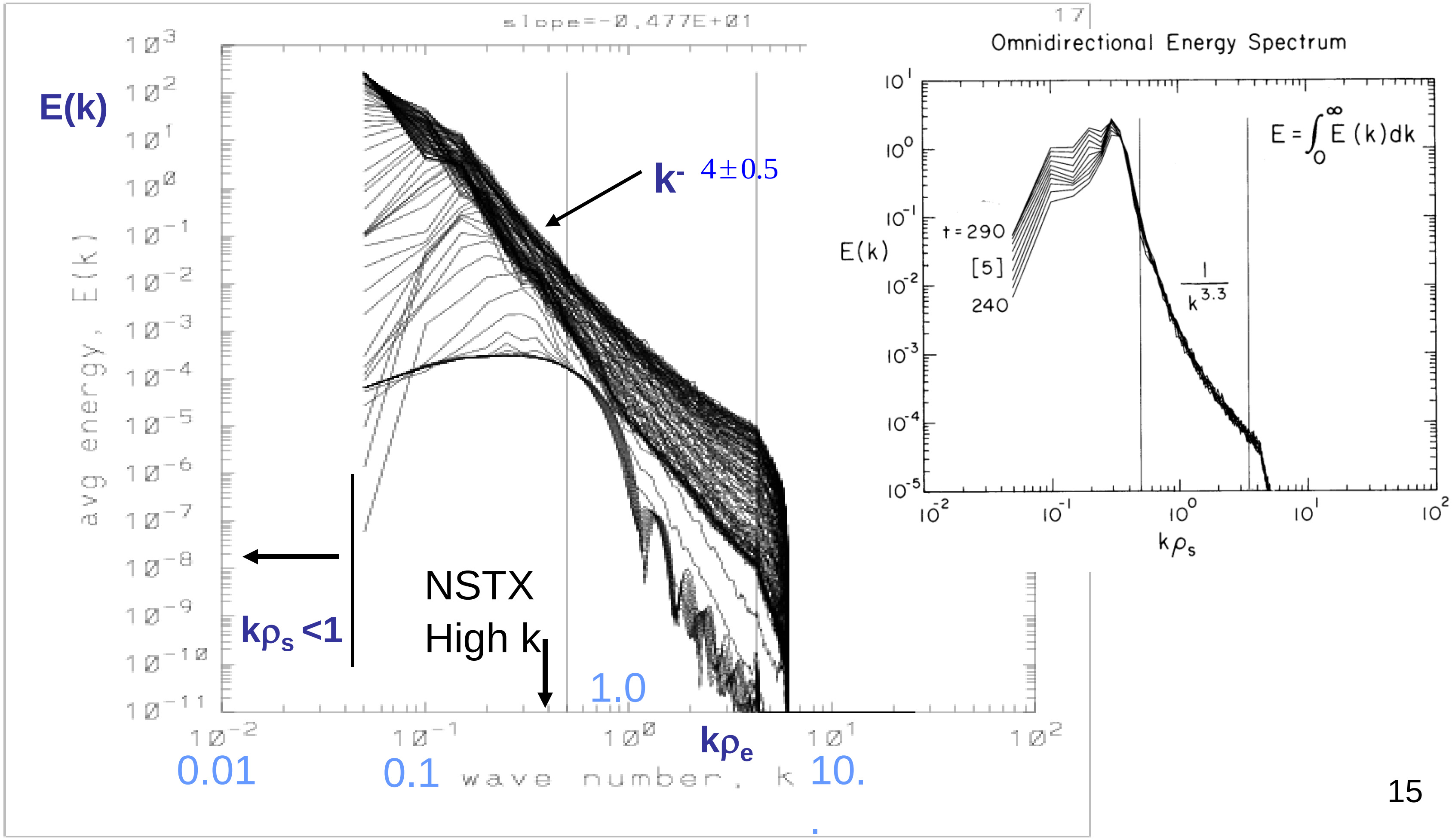
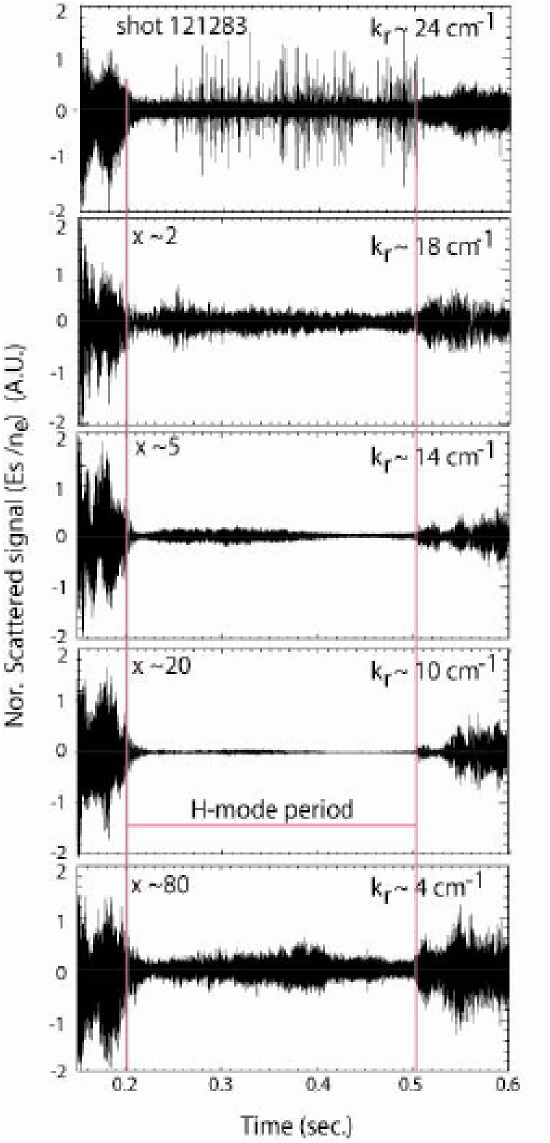
Inverse Cascade from ρ_e to ρ_s and c/ω_{pe}



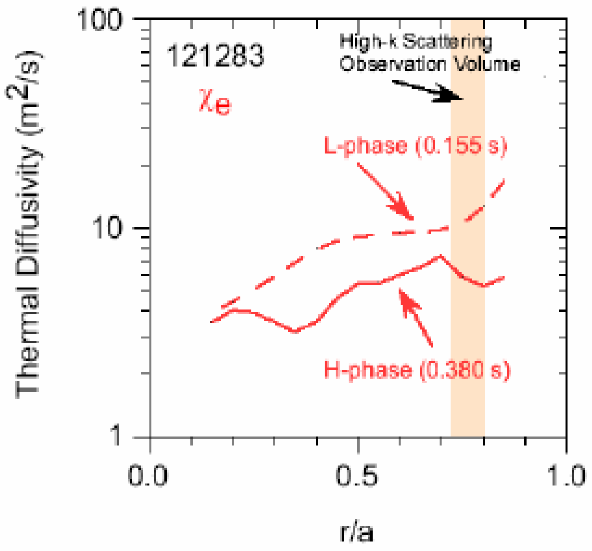
$k_x\rho_e$~0.3

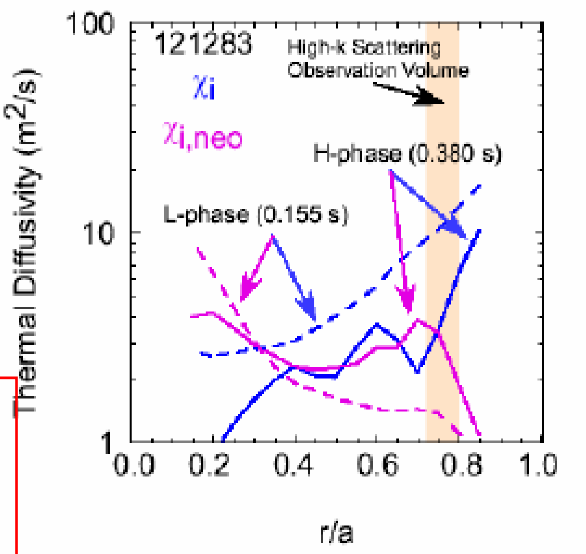
improved confinement



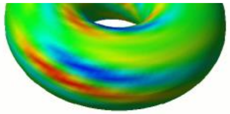
- ❑ Scattering system measures reduced fluctuations ($\frac{\tilde{n}_e}{n_e}$) both upper ITG/TEM and ETG ranges during H-mode
- ❑ Ion and electron transport change going from L- to H-modes
- ❑ Bursts of scattered signal at the highest k is noted.

High-k scattering shows significant level of turbulence that remains w/o ITG turbulence.

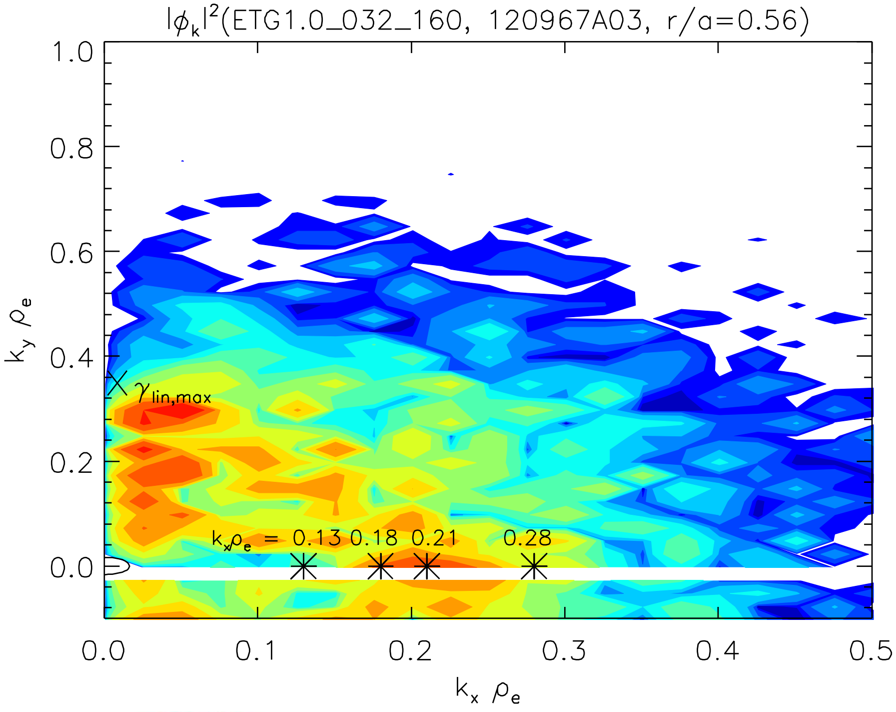


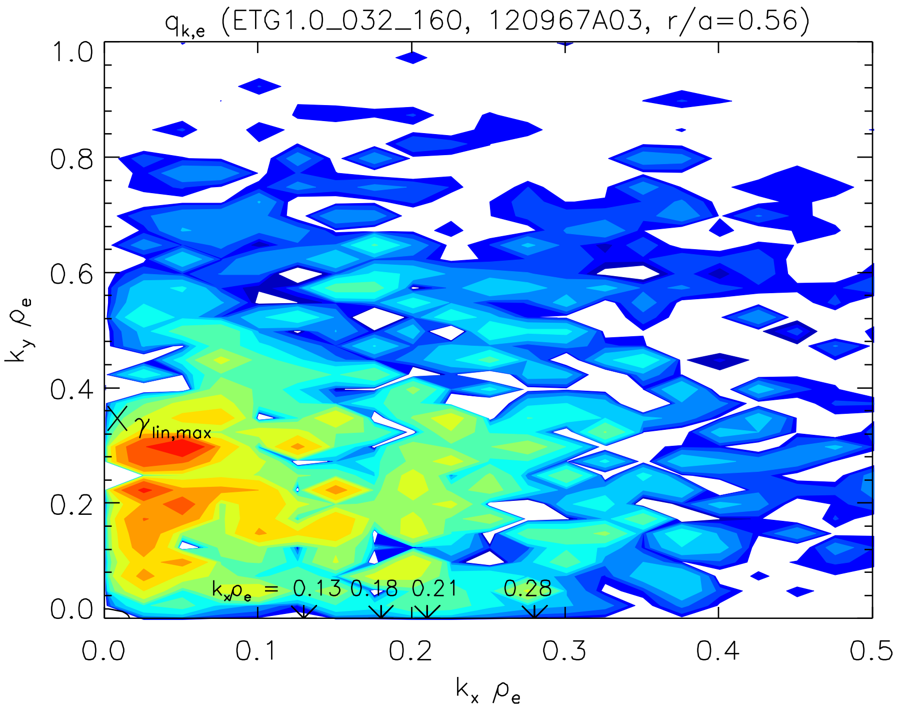


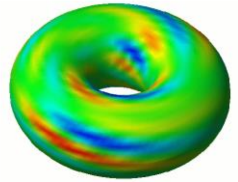
From Hyeong Park expts



Spectral Densities of $<\delta n_e \, \delta n_e>$ and the Radial Heat Flux from $<v_x \, \delta T_e> \sim \mathrm{Re}[ik_y\varphi(k)^* \, \delta T_e(k)]/B$







Tore Supra electron transport data base for plasmas heated by fast-wave ion cyclotron

✓**Quasi-steady-state plasmas**
(duration ≈ 20 - 120 τ_E)

✓ **No fast particles, no sawteeth**

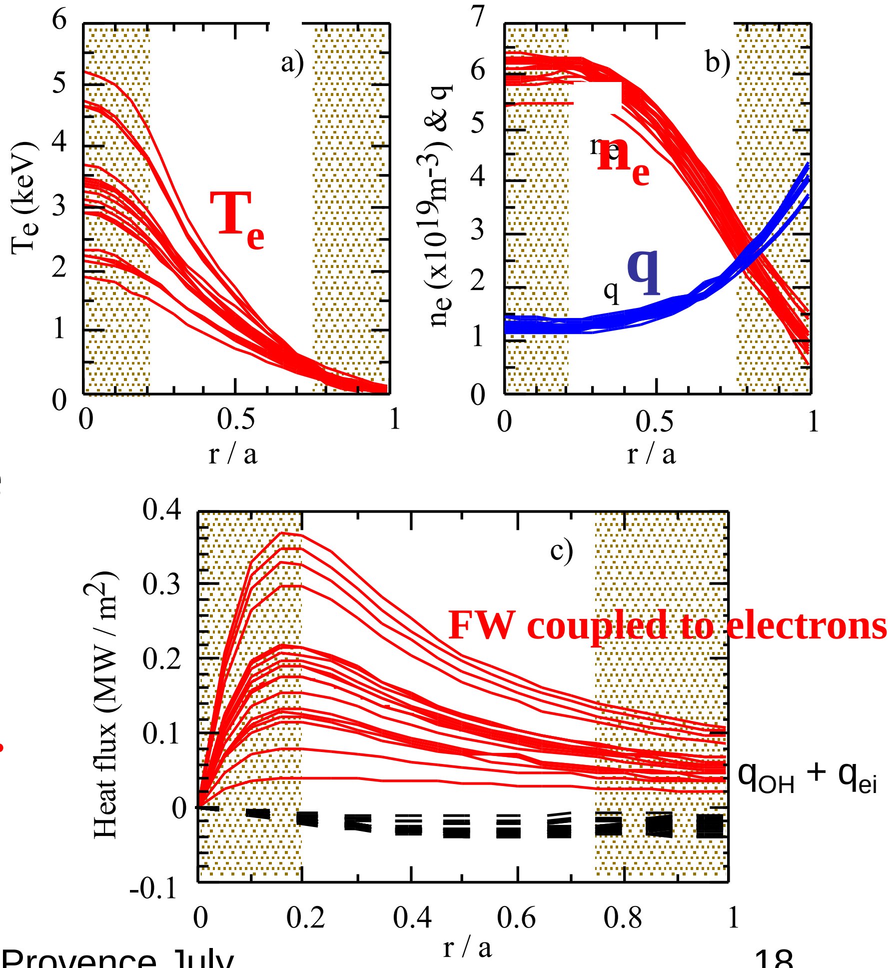
✓ **Electron & ion channels are decoupled**
($T_e >> T_i$)

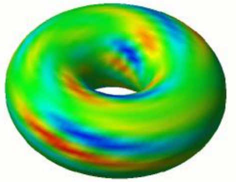
✓ **Core-localized FW power deposition**
(up to 90% coupled to electrons)

✓ **Up to 90% of FW power coupled to the electrons: ($q_{rf}^e >> q_{ei}, q_{ohm}$)**

➔Good confidence in transport analysis and controlled comparison with theory.

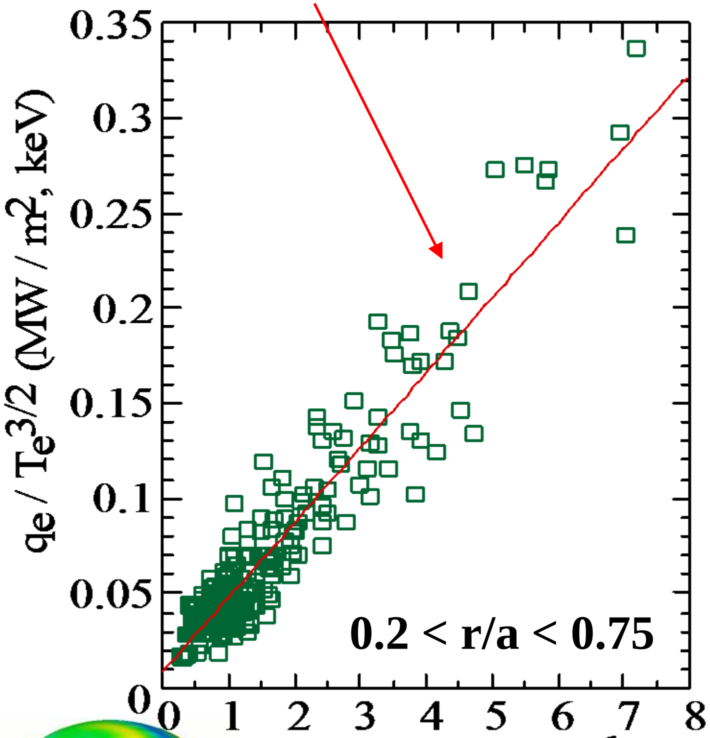
Ip = 0.6MA, B = 2.2T, P_{tot} = 1.5 -7.5 MW
(P_{OH} = 0.1 - 0.75 MW and P_{FW} = 0.75 -7.4 MW)

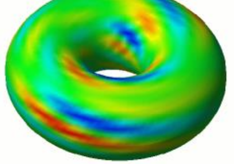




Simulation of Fast-Wave Heating with ETG Transport

$\chi_e^{\mathrm{ETG}} = 4.3 \times (1.00 \pm 0.15)\ \mathrm{m}^2/\mathrm{s}$

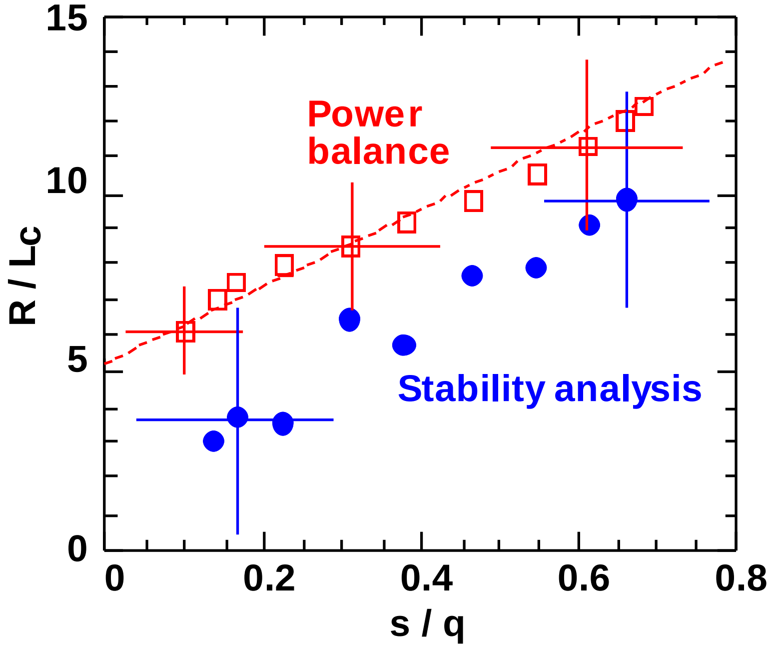




Movie of φ and Te fields:

Analog of Hadley Cells

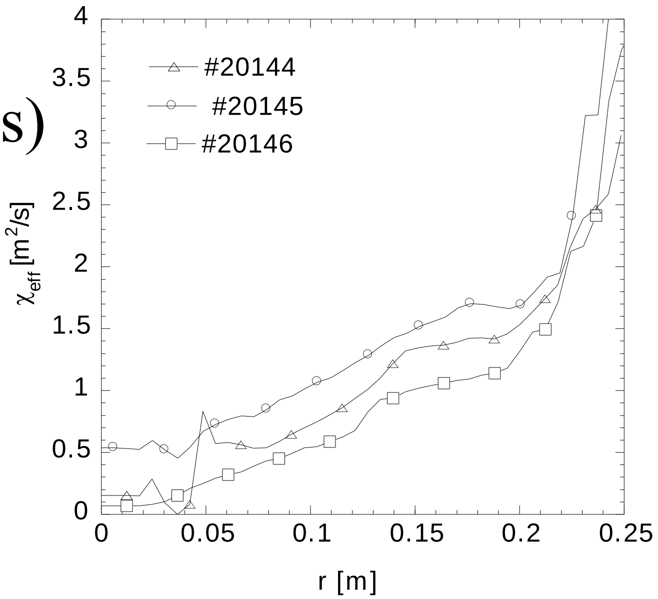
$R / L_c = 5\ (\pm 1) + 10(\pm 2)\ s / q$

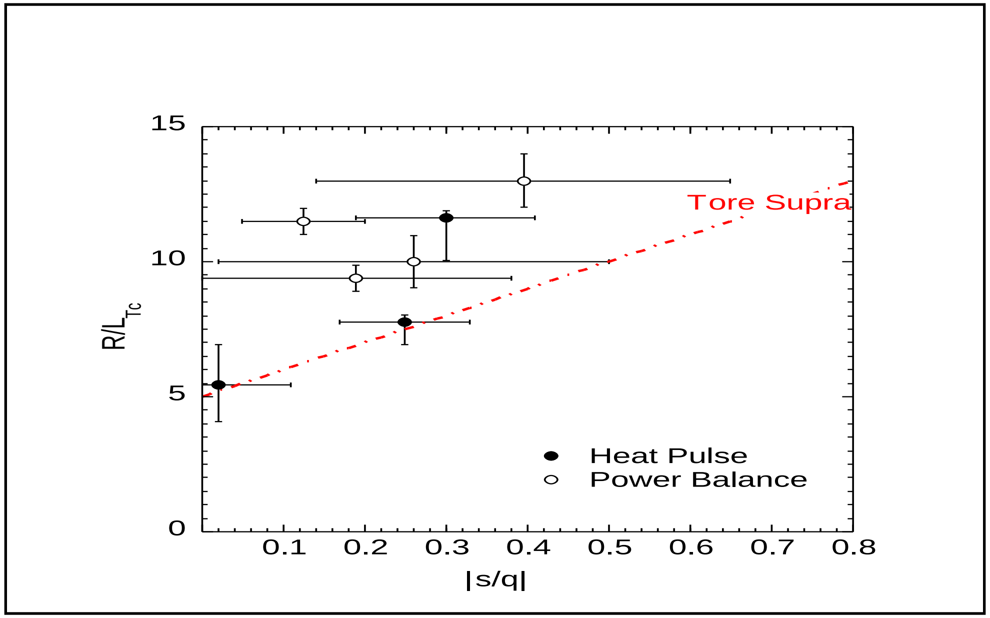


Hoang, Bourdelle, Horton, et al., PRL87(2001).

χ_e from Modulated ECH in Frascati Tokamak FTU Analysis Supports ETG Transport

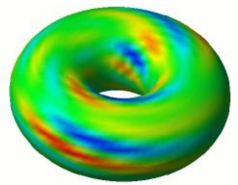
$\chi_e(m^2/s)$



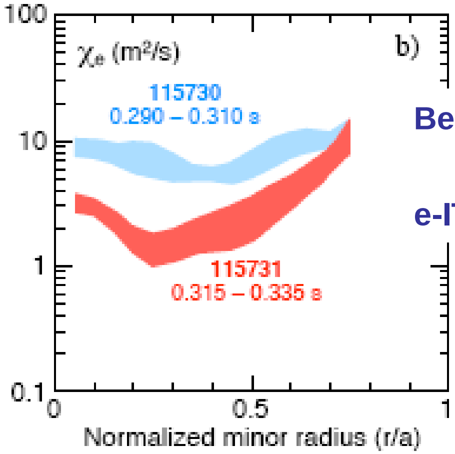


Jacchia, De Luca,Cirant et al.
Nuclear Fusion vol. 42, 1116 (2002)

Agreement between two machines and theory..



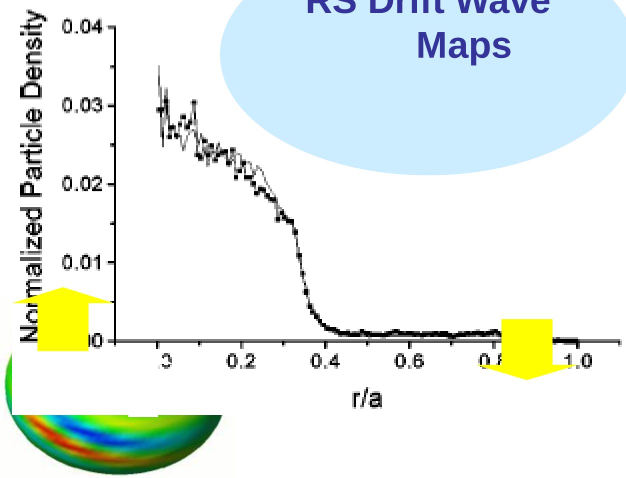
Electron Transport Barriers



Bell et al NSTX 2006 NF

e-ITBs

Approach I: N~100 radial cells with MPI radial transport code using theory flux formulas dE_r/dr and q(r). High resolution integrators and steep gradients as in ITBs.



RS Drift Wave Maps

Approach II: Analytic drift wave maps with action-angle variables. Leaky barriers with correlated particle steps through broken KAM theorem.

Reversed Shear: creates local mirror symmetry. Morrison and Horton show this leads to factor 3 for the level of fluctuations required for validity of the diffusion approximation across the barrier. Creates e-ITB.

3D FLR Fluid Simulation

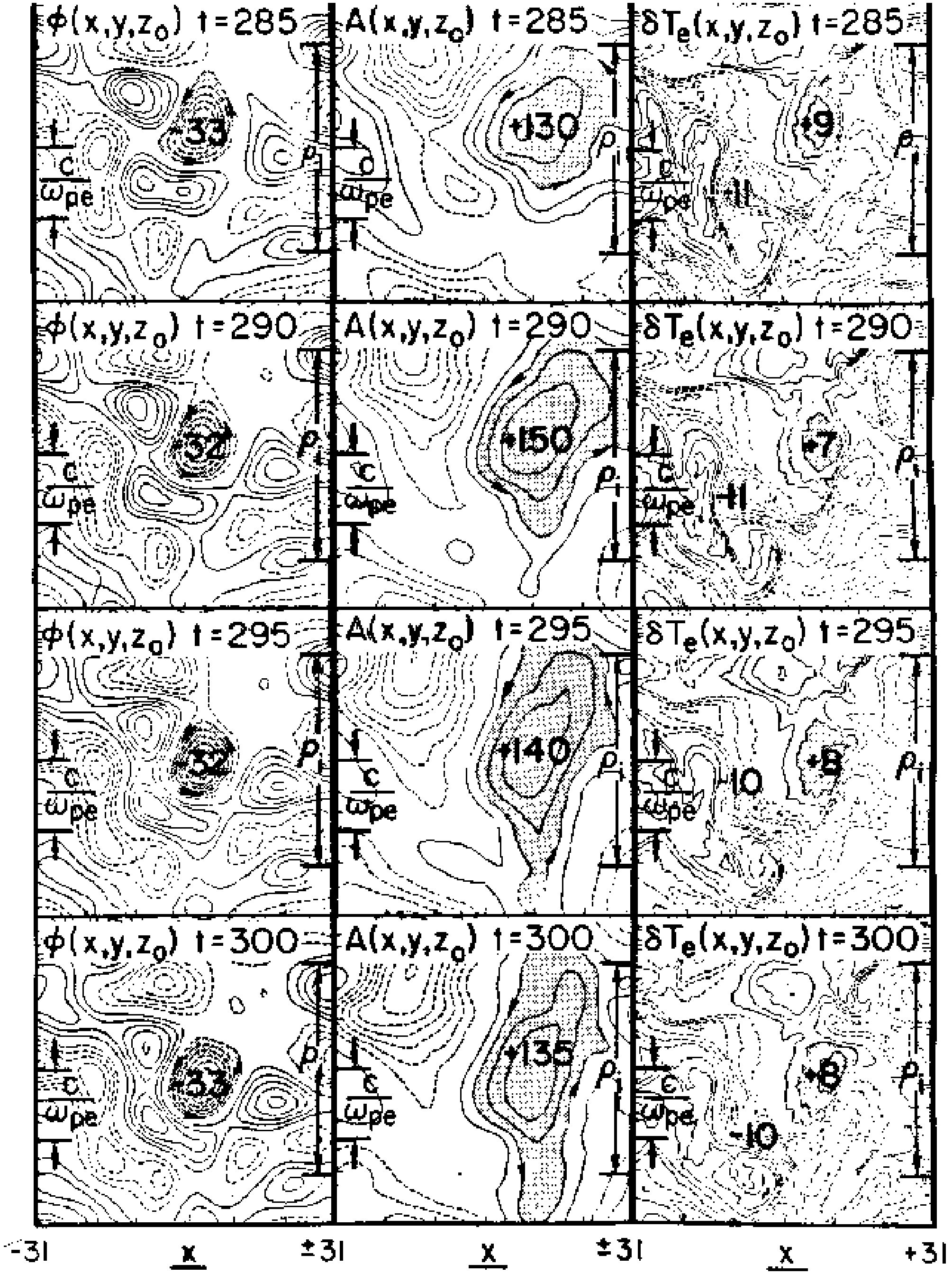
$\frac{Y}{\rho_e}$

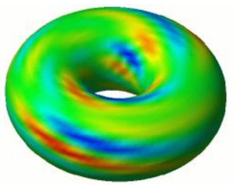
t_1

t_2

t_3

t_4





3D ETG turbulence from 3 FLR pde's

Local toroidicity and weak mag shear

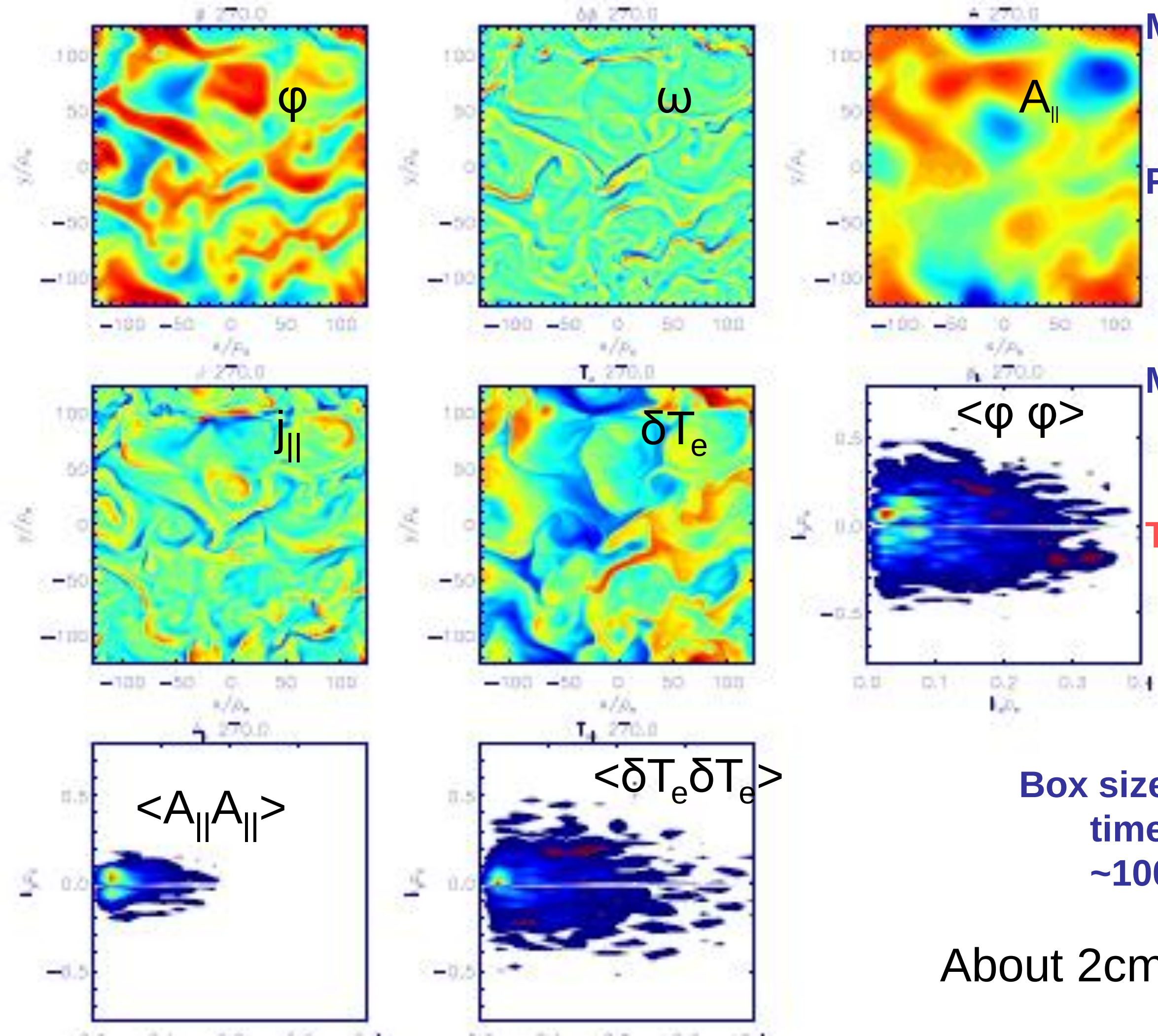
Same pde's

describe Micro-tearing modes.

IFS -1988- IAEA

October 2006 ETG gyrofluid simulations for modeling NSTX high-k scattering data at $k_x\rho_e$=0.3 and $k_y\rho_e\approx0$

Kaye et al IAEA Chengdu 2006



Modern version of original ETG gyrofluid simulations.

Formation of streamers both in the flow field and in the perpendicular magnetic field.

Multiscale turbulence with intermittency in the turbulent heat flux $q_e(t)$

Thermal diffusivity reaches 50 to 60 times the electron-gyroBohm level.

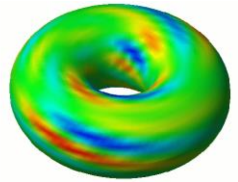
Box size is $2\rho_i$ X $2\rho_i$ (~126 ρ_e)
time scale 500 L_{Te}/v_e
~100μs

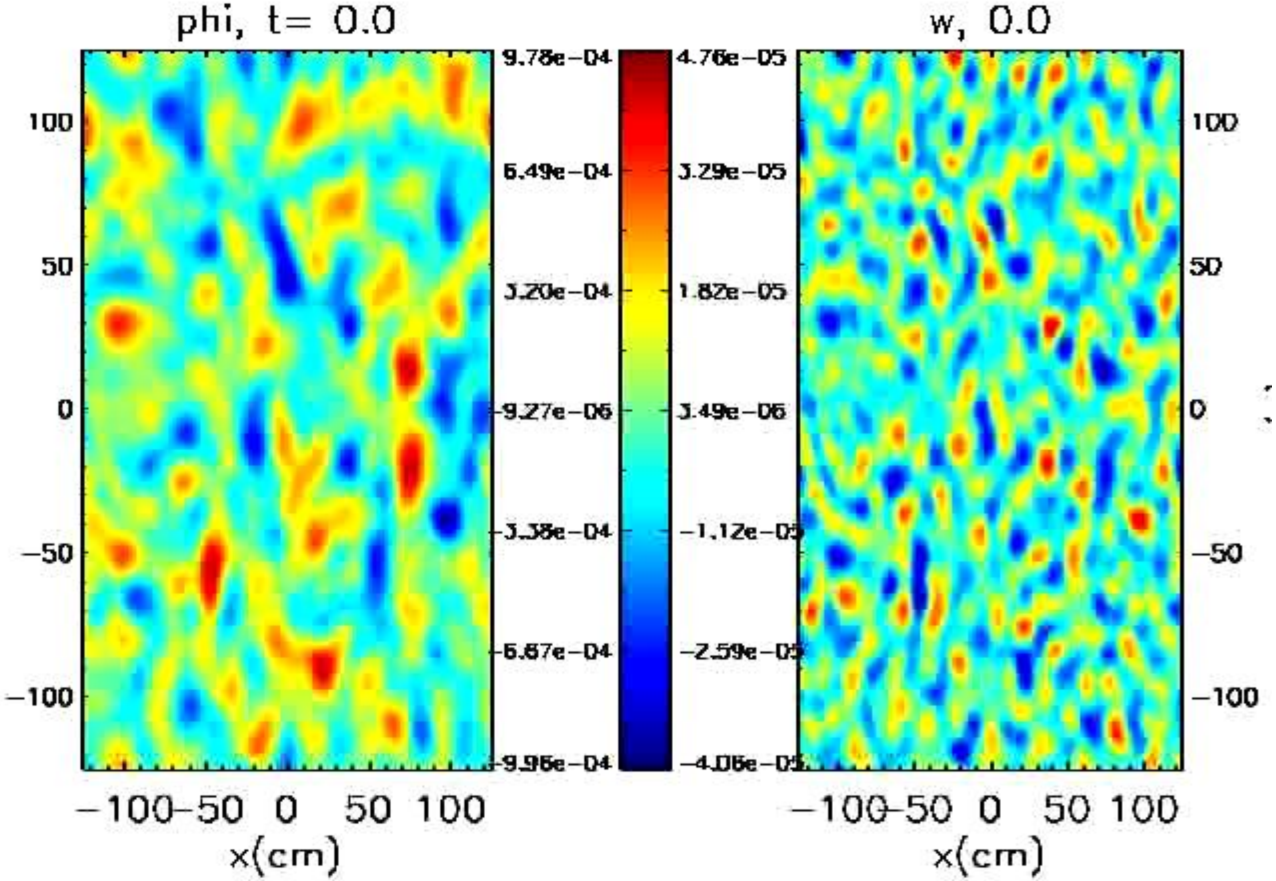
About 2cmX2cm in NSTX

Summary of Transport Results and Future Plans

- ETG has become the standard model: plays key roles in NSTX, FTU, C-Mod, DIII-D and Tore Supra
- Consistent with $\delta B^2_\perp \propto \nabla T_e - (\nabla T_e)_{crit}$ from Cross-Polarization Scattering
- Ion-scale turbulence (TEM and ITG) produces further turbulence. Controlled by E_r-shear: vortices, streamers, and zonal flows and by ICRF heating.
- New electromagnetic datasets from LAPD and Helimak (Lee & Gentle) for electron transport comparisons with ETG theory.
- New tool GKV (Watanabe) being ported to TACC – NSF TeraGrid
- Theory of Reversed Magnetic Shear induced electron transport barrier by Horton and Morrison [PoP, 3910, 1998] continuing.
- Broken B-symmetry at the q-min reversal layer.
- High-plasma pressure systems are being investigated in the Gamma-10 Tandem Mirror as attractive platforms for the study of ETG.

Horton and Pastukhov APS-DPP 2006.

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4.76e-05
3.29e-05
1.82e-05
3.49e-06
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-4.06e-05
100
50
0
-50
-100
-100 -50 0 50 100
x(cm)