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International Atomic Energy Agency

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Summer College on Plasma Physics

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Drift Wave Turbulence and Zonal Flows
Part II

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Drift Turbulence-Zonal Flow Studies in a Laboratory Plasma

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ICTP Summer College on Plasma Physics
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Outline

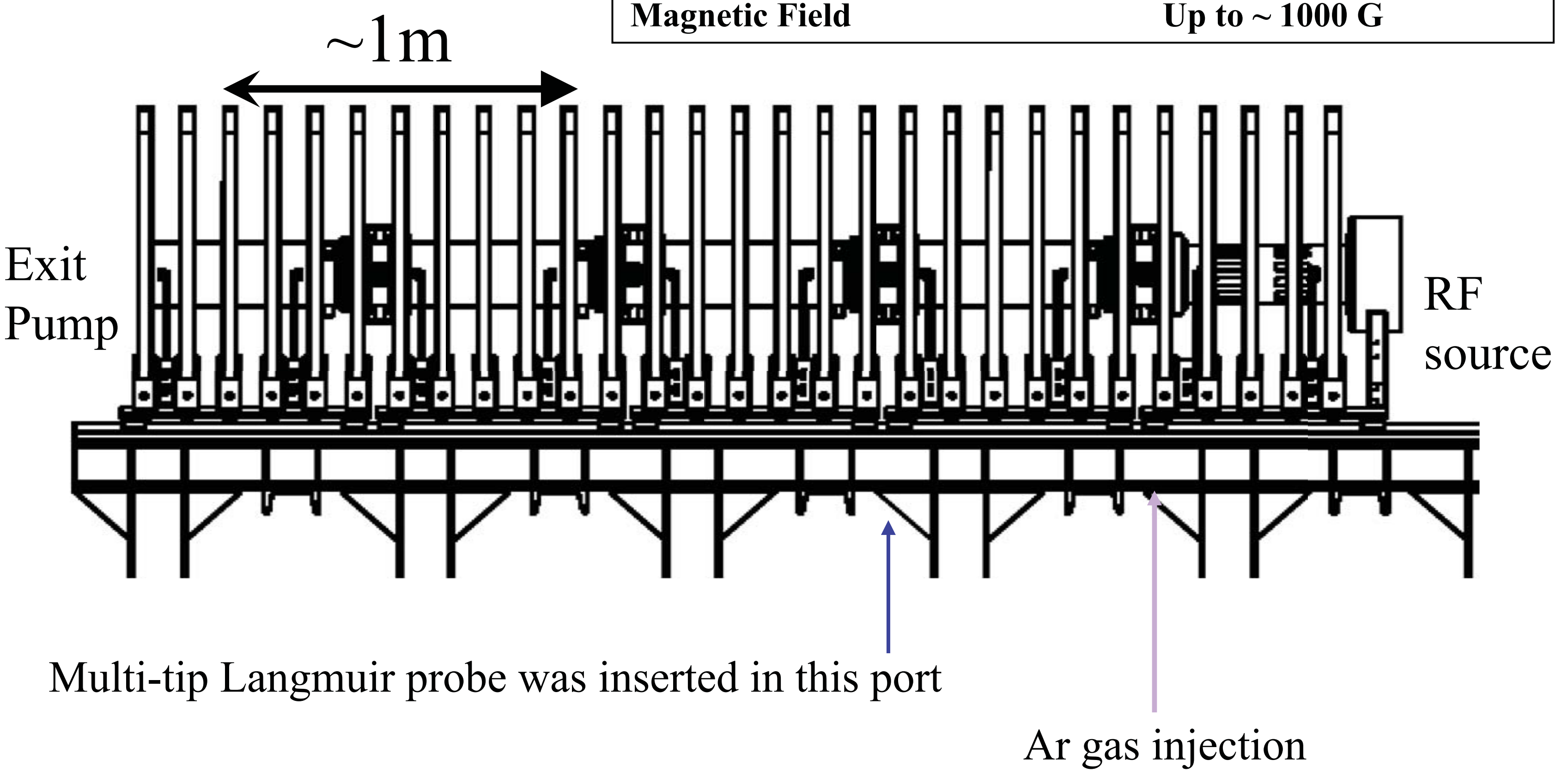
- **Demonstrate Development of "Weak" Turbulence from Drift Waves & Onset of Zonal Flows**
- Study Nonlinear dynamics of coupled DWT/ZF system in simple system
- Show evidence for a non-diffusive turbulent stress at plasma boundary acting to drive rotation
- Demonstrate Critical Gradient dynamics of the system

➔ SIMPLE PLASMA SYSTEM EXHIBITS THREE KEY NONLINEAR DYNAMICAL PROCESSES THOUGHT TO OCCUR IN FUSION SYSTEMS

Controlled Shear De-Correlation Experiment

CSDX parameter	Typical value
Gas pressure	0.5 - few mTorr
T_e	~ 3 eV
T_i	~ 0.7 eV
n_e	1-10 x 10^{12} cm^{-3}
Source (Helicon 13.56 MHz)	1500W (typically)
Magnetic Field	Up to ~ 1000 G

m=0 Helicon Plasma Source



Dimensionless Scales

Length Scales

$$\rho_i / L_n \sim 0.1$$

$$\rho_S / L_n \sim 0.5$$

$$\lambda_e^{mfp} / L_{\parallel} \sim 0.05 - 0.1$$

Collision Rates

$$\nu_e / \Omega_{C_e} \sim 0.005$$

$$\nu_{ii} / \Omega_{Ci} \sim 1$$

$$\nu_{i0} / \Omega_{Ci} \sim 0.01$$

Parallel Dissipation Rate

$$\frac{k_{\parallel}^2 C_s^2}{\nu_e \Omega_{Ci}} \sim 1$$

Non-ambipolar G.C. Drifts

Polarization Drift

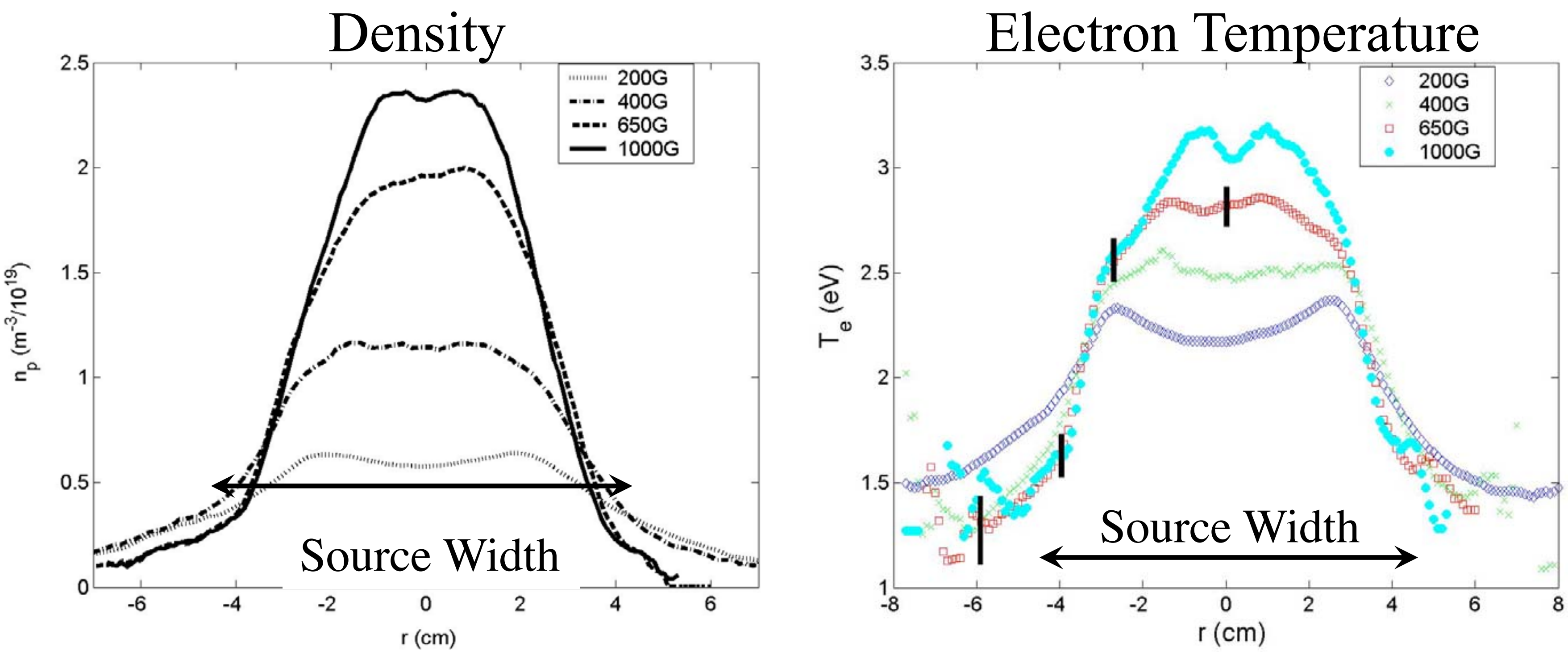
$$\omega / \Omega_{C_i} \sim 0.1 - 0.3$$

Ion-Ion Collisional Drift

$$\frac{\mu_{ii}}{L_{\perp}^2 \Omega_{ci}} \approx 0.01 - 0.1$$

DEVELOPMENT OF DRIFT WAVES

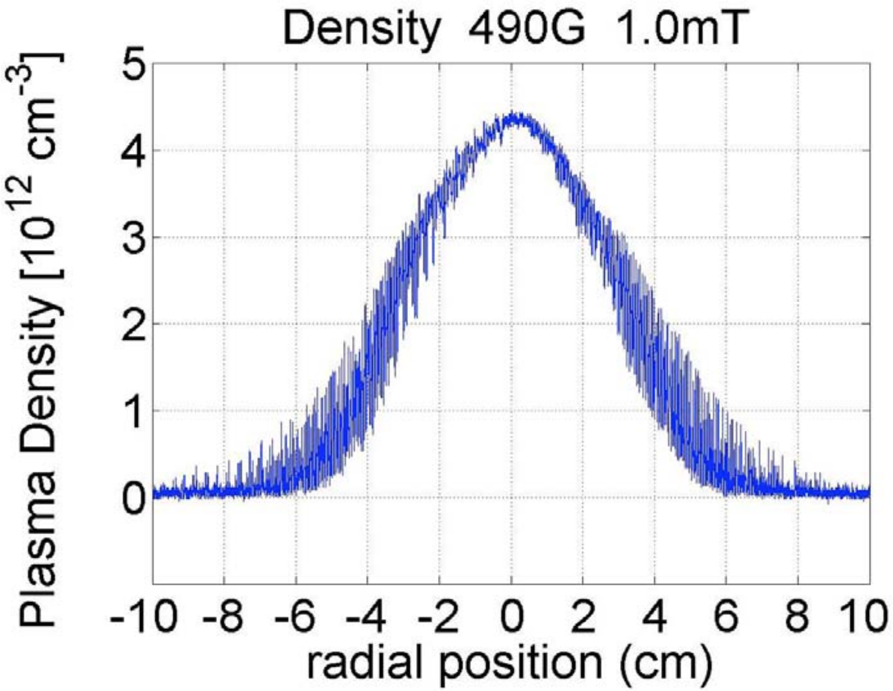
Equilibrium Profiles Evolve as B Field Increases in CSDX Helicon Plasma



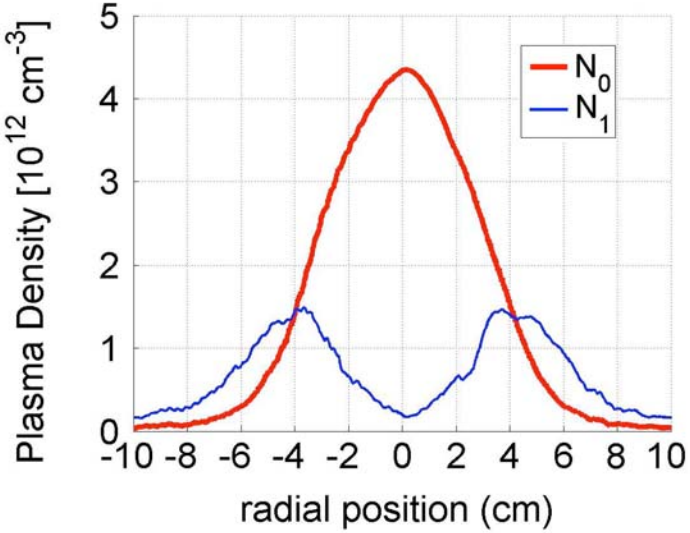
Burin et al, May 2005 PoP

Typical Result for B>Bcrit

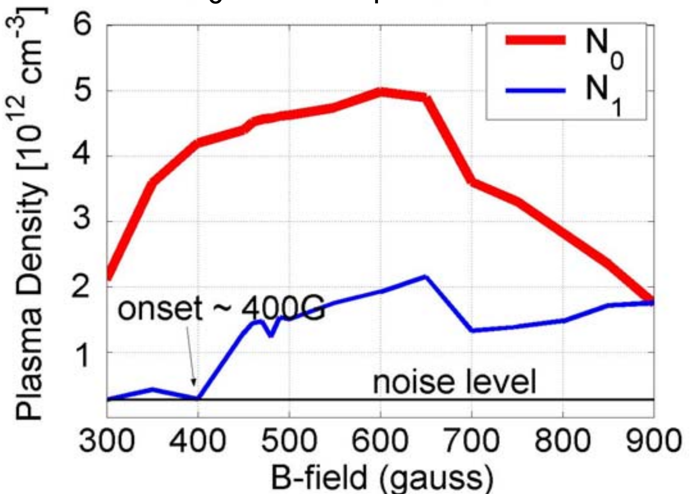
CSDX



N_0 and N_1 vs. radius



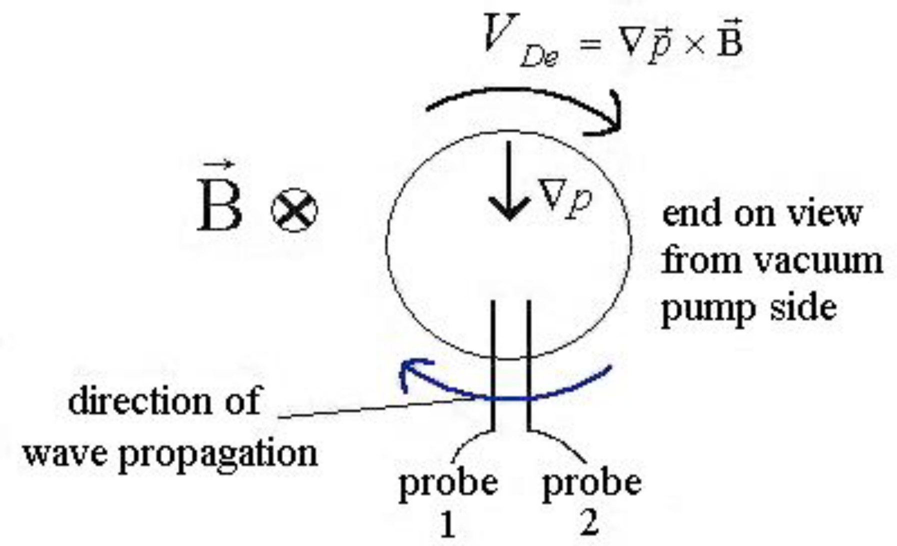
N_0 and N_1 vs. B

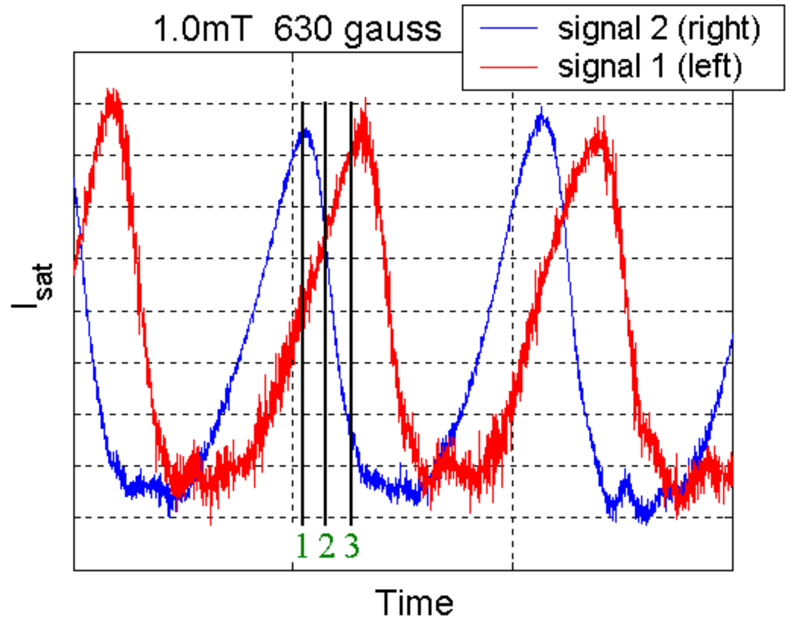


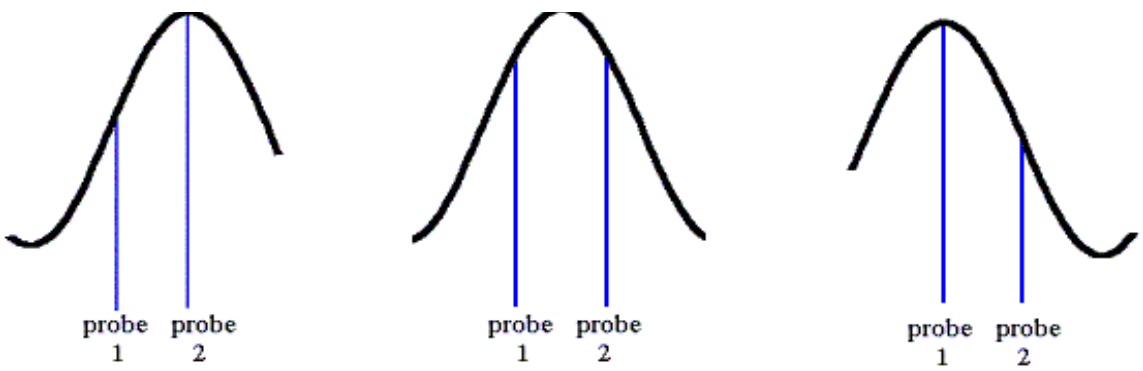
CER Center for Energy Research

UCSD Jacobs

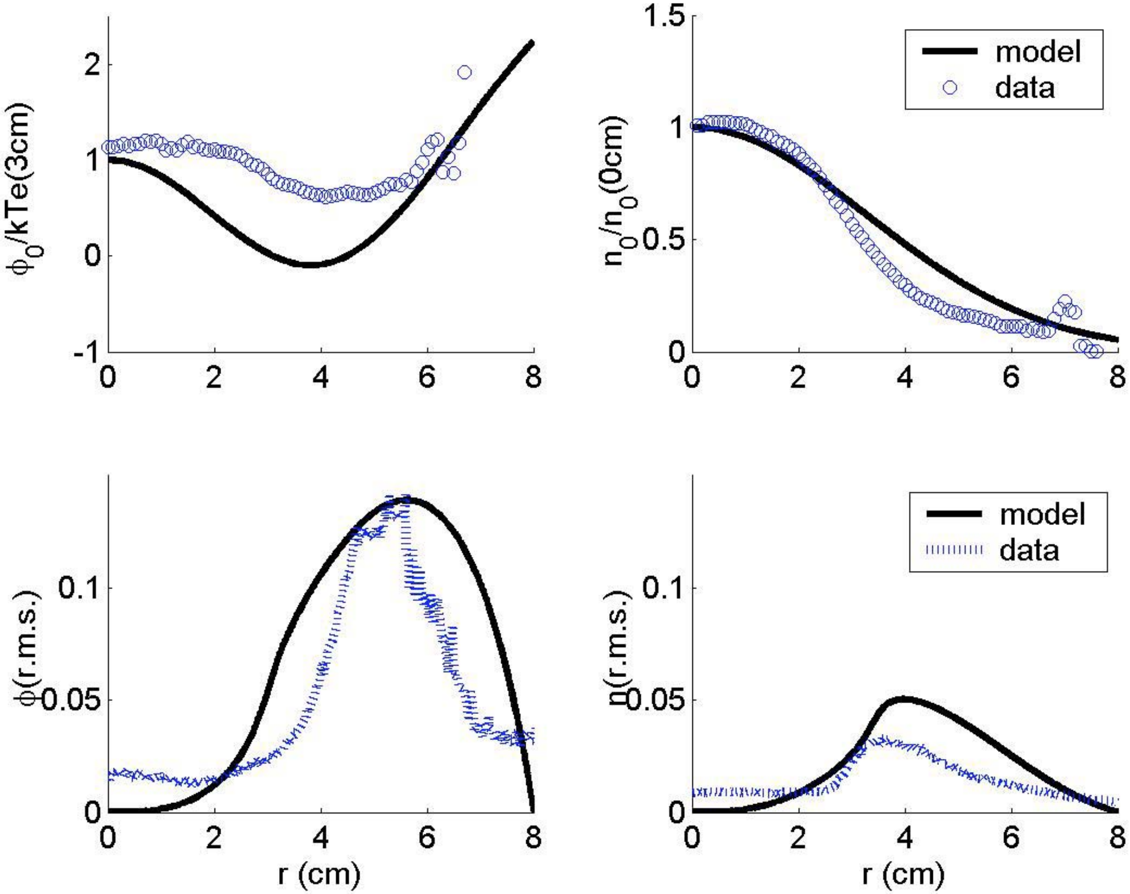
Wave at Onset Consistent w/ Collisional Drift Wave







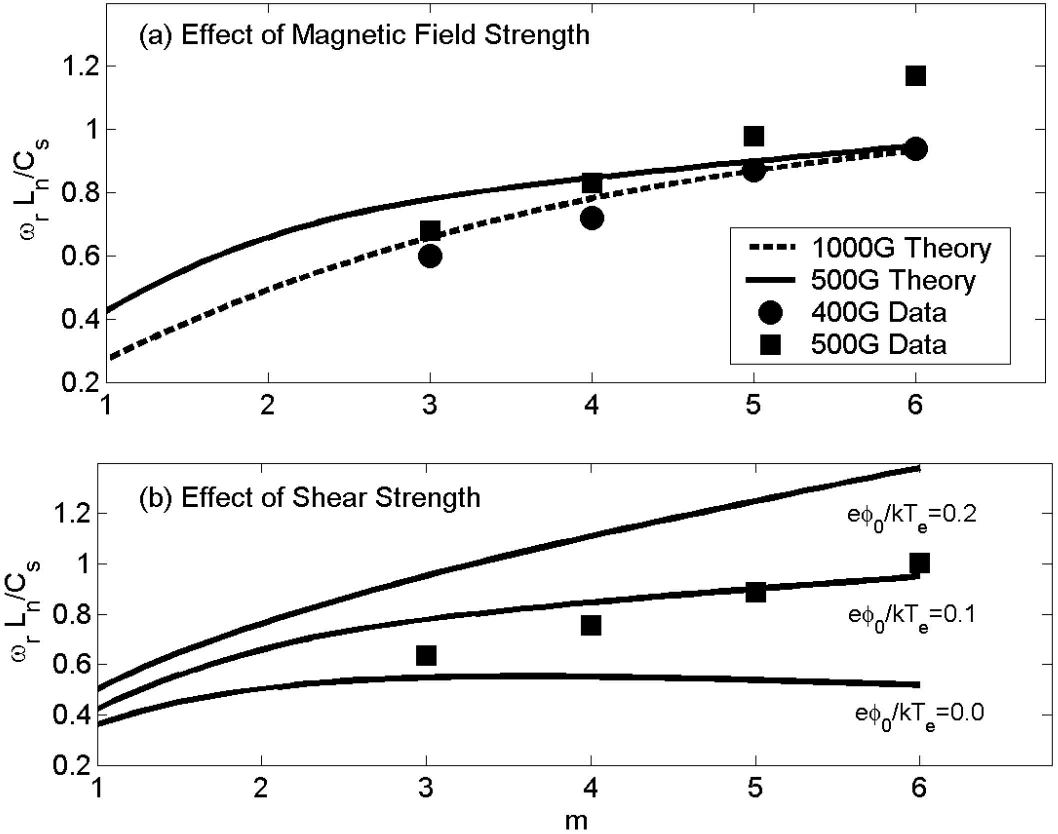
Linear Eigenmodes of DW w/ Flow Shear Match Observations Near Onset



Burin et al, May 2005 PoP

Close to Onset Measured Dispersion Agrees with Linear Theory

CSDX



Burin Phys. Plasmas 2005

A Few Useful Tools from Digital Signal Processing

Linear Signal Processing Gives **Average Spatio-temporal Scales** of TIME STATIONARY Turbulence

Fourier Transform:

$$f(t) = \sum_{\omega} f(\omega)\exp(i\omega t)\Delta\omega \qquad f(\omega) = \frac{1}{2\omega}\sum_{t} f(t)\exp(-i\omega t)\Delta t$$

Correlation Functions & Power Spectra:

$$C_{auto}(\tau) = \frac{1}{N_{ens}}\sum_{n=1}^{N_{ens}}\frac{1}{T}\int_{-T/2}^{T/2}\tilde{f}_i(t)\tilde{f}_i(t+\tau) \qquad P_{auto}(\omega) = \frac{1}{N_{ens}}\sum_{n=1}^{N_{ens}}\left|\tilde{f}_i(\omega)\right|^2$$

$$C_{crs}(\tau) = \frac{1}{N_{ens}}\sum_{n=1}^{N_{ens}}\frac{1}{T}\int_{-T/2}^{T/2}\tilde{f}_i(t)\tilde{g}_i(t+\tau) \qquad P_{crs}(\omega) = \frac{1}{N_{ens}}\sum_{n=1}^{N_{ens}}\tilde{f}_i(\omega)\tilde{g}_i^{\,*}(\omega)$$

Inter-relation Between Two Signals: coherence and crossphase

$$\gamma_{12}(\omega) = \frac{\left|P_{crs}(\omega)\right|}{\sqrt{P_1 P_2}}, \; \tan\phi(\omega) = \frac{\mathrm{Im}(P_{crs}(\omega))}{\mathrm{Re}(P_{crs}(\omega))}$$

Nonlinear Energy Transfer Comes from 3rd Order Spectrum:

Example: Collisional Drift Turbulence Model (Hasegawa-Wakatani 1983)

$$\frac{\partial W^n}{\partial t} = \frac{\Gamma_r}{L_n} + T^n + C_1\left(W^n - \left\langle n^* \phi \right\rangle\right)$$

$$\frac{\partial W^\phi}{\partial t} = T^\phi - C_2\left\langle \left|\nabla_\perp^2 \phi\right|^2 \right\rangle - C_3 W^\phi$$

Internal and Kinetic Energies Defined As

$$W^n = \sum_m \left|n_m(r,t)\right|^2$$

$$W^\phi = \sum_m \left|\nabla_\perp \phi_m(r,t)\right|^2$$

Nonlinear Energy Transfer From Cross-Bispectrum:

$$T_\theta^n(r,f,f') = -\mathrm{Re}\left\langle \tilde{n}^*(r,f)\,\tilde{v}_\theta(r,f-f')\frac{1}{r}\frac{\partial \tilde{n}}{\partial \theta}(r,f') \right\rangle$$

$$T_{ZF}^\phi(r,f,f') = -\mathrm{Re}\left\langle V_{ZF}{}^*(r,f)\,\tilde{v}_\theta(r,f-f')\frac{1}{r}\frac{\partial \tilde{v}_r}{\partial \theta}(r,f') \right\rangle$$

Rate and Direction of Energy Transfer Determined by BiSpectrum

Bi-spectrum Defined As

$$B(\omega_1,\omega_2)=\left\langle X(\omega_1)X(\omega_2)X^*(\omega_1+\omega_2)\right\rangle$$

Degree of Phase Coherence Determined by BiCoherence

$$\hat{b}^2(\omega_1,\omega_2)=\frac{B(\omega_1+\omega_2)}{\left\langle\left|X(\omega_1)X(\omega_2)\right|^2\right\rangle\left\langle\left|X^*(\omega_1+\omega_2)\right|^2\right\rangle}\quad ;\quad 0<\hat{b}<1$$

BiPhase Determines Phase Delay Between Interacting Waves:

$$\Theta(\omega_1,\omega_2)\equiv Tan^{-1}\left\{\frac{\mathrm{Im}\left[B(\omega_1,\omega_2)\right]}{\mathrm{Re}\left[B(\omega_1,\omega_2)\right]}\right\}\quad ;\quad -\pi<\Theta<\pi$$

Energy Transfer Direction and Rate:

$$\boxed{\mathrm{Re}\left[B(\omega_1,\omega_2)\right]=\left|B(\omega_1,\omega_2)\right|\cos\left[\Theta(\omega_1,\omega_2)\right]}$$

DEVELOPMENT OF DRIFT TURBULENCE FROM LINEAR DRIFT WAVES

Origins of Nonlinear DW Dynamics

Keep Convective Derivative in Eqn's

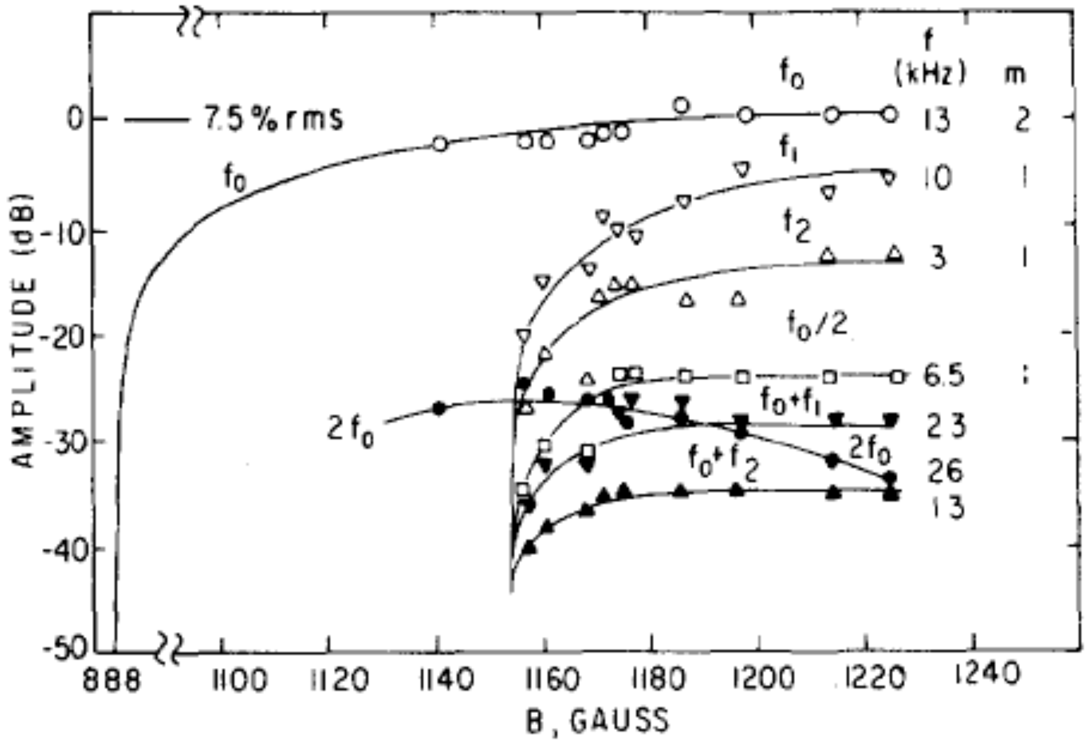
$$\frac{\partial n}{\partial t} + \mathbf{u}\bullet\nabla n = 0$$

$$\frac{\partial n\mathbf{u}}{\partial t} + \mathbf{u}\bullet\nabla n\mathbf{u} = RHS$$

In Fourier Domain (I.e. waves) Introduces Convolution in ([illegible],**k**), e.g.

$$\frac{1}{2}\frac{\partial\left\langle u^{2}(\mathbf{k})\right\rangle}{\partial t} + \sum_{\substack{\mathbf{k}_1\mathbf{k}_2 \\ \mathbf{k}=\mathbf{k}_1\pm\mathbf{k}_2}} \mathrm{Re}\left\langle u^{*}(\mathbf{k})\left(\tilde{\mathbf{u}}(\mathbf{k}_1)\bullet\nabla\right)\tilde{u}_{\theta}(\mathbf{k}_2)\right\rangle = RHS$$

Wave-Wave Coupling in Drift Wave Experiments



Chu et al Phys. Fluids 1973

3-Wave Resonance Criteria Was Satisfied:

$$\omega = \omega_1 \pm \omega_2$$

$$\mathbf{k} = \mathbf{k}_1 \pm \mathbf{k}_2$$

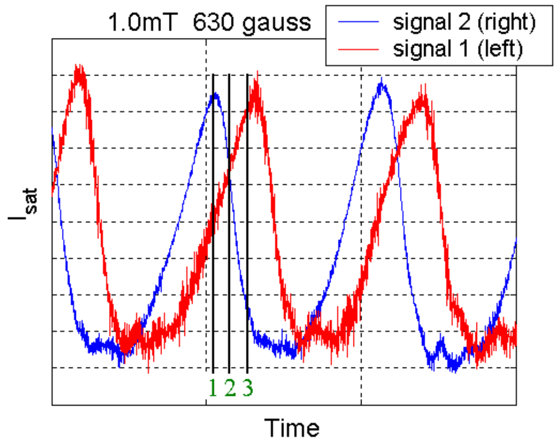
- Increase Free Energy Source and/or
- Decrease Linear Damping

- Two Experiments:
  - Klinger, 1997: Increase Free Energy ($J_{||}$)
  - Burin, 2005: Increase L_n / ρ_S, Decrease μ_{ii} viscous damping

Local k-spectra Are Constructed from 2-Point Measurements

Ref: J.M. Beall et al, J. App. Phys. 1982

Measure Fluctuations at 2 Points:

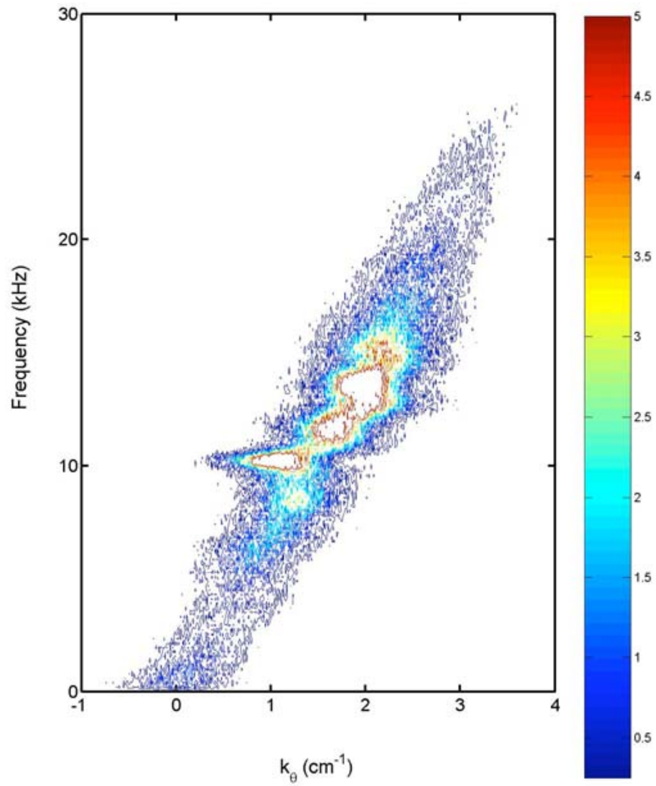


Find Phase Delay due to Propagation

$$\delta\vartheta = Tan^{-1}\frac{\mathrm{Im}(\langle X_1(f)X_2^*(f)\rangle)}{\mathrm{Re}(\langle X_1(f)X_2^*(f)\rangle)}$$

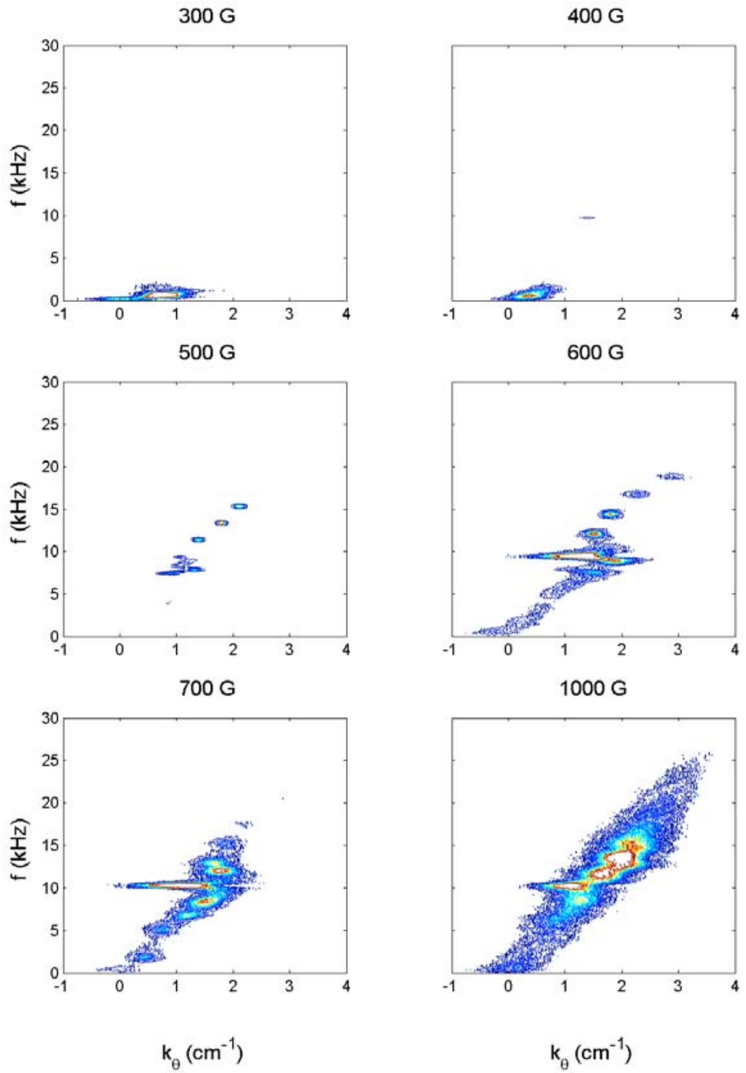
Local Wavenumber $k_{\theta_{local}} = \frac{\delta\vartheta}{\delta x}$

Build-up Local k-spectra from Multiple Realizations:



Burin et al, May 2005 PoP

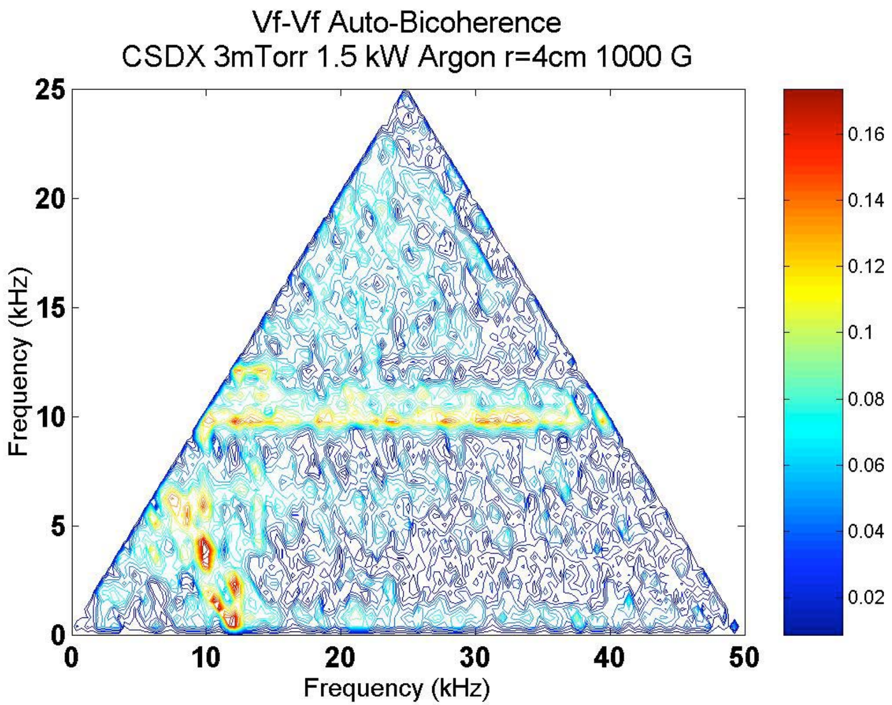
Evolution of $(\phi_f / kT_e)^2$ Power Spectrum with Increasing Magnetic Field



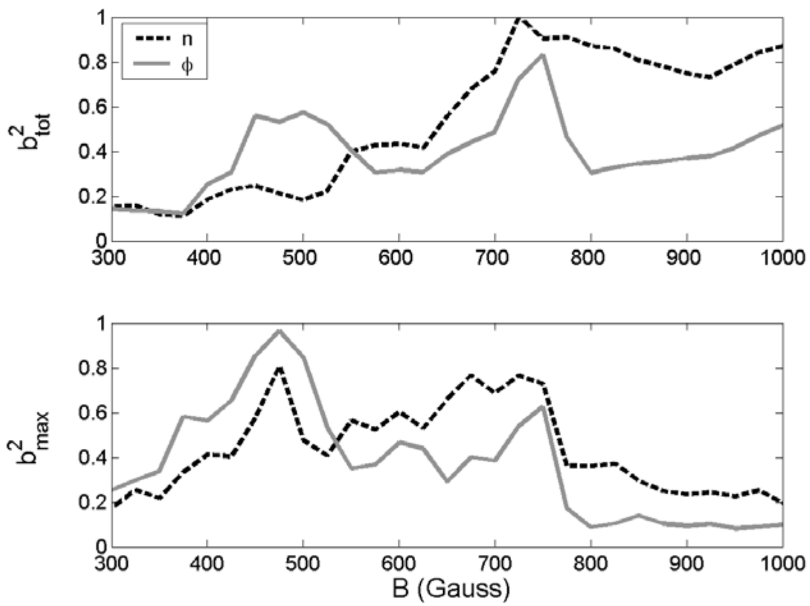
- Coherent Drift Waves Appear at ~400G
- Harmonics Develop As B Increases
- Coherent Modes at Intermediate B
- Broadband Spectra at 1kG

Burin et al, May 2005 PoP

3-wave Interaction Increases as Turbulence Develops



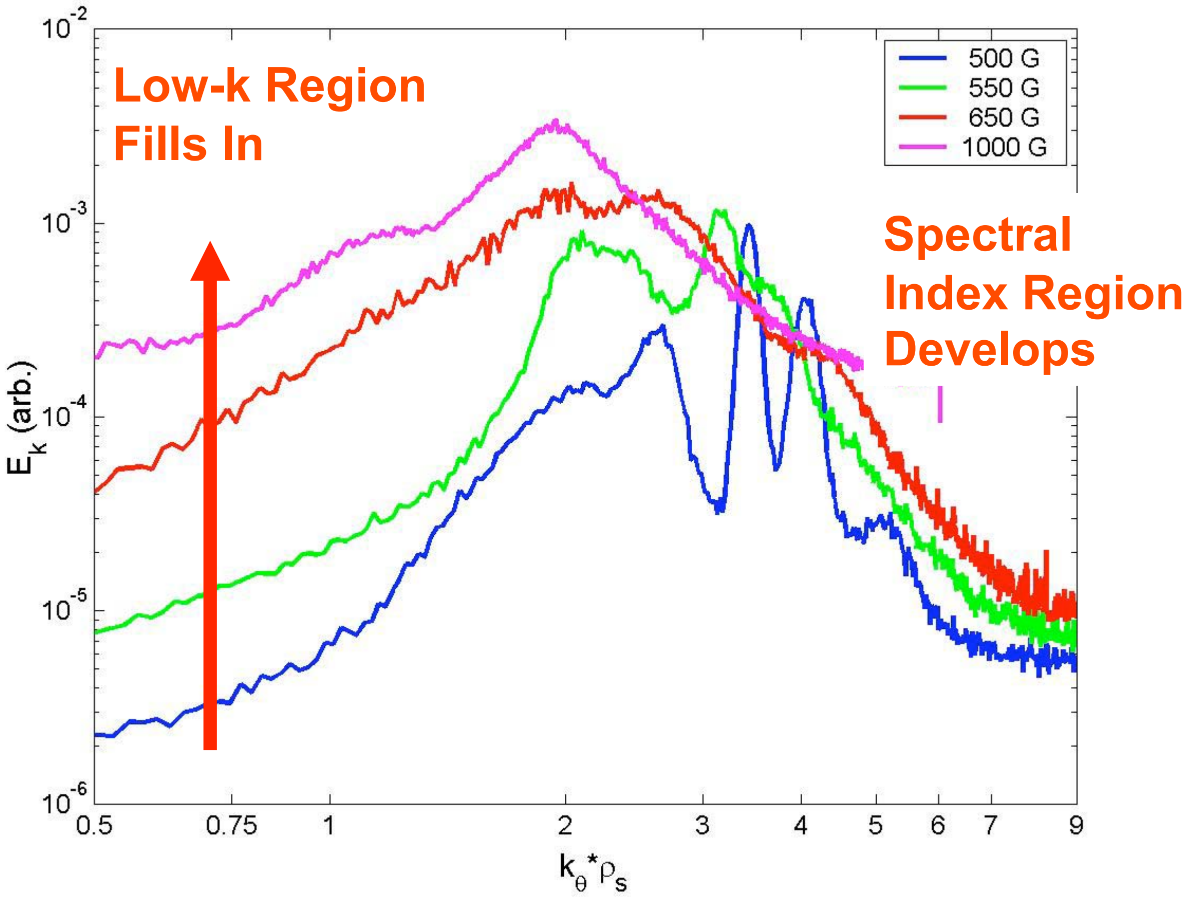
Tynan, PoP 2004



Burin, PoP 2005

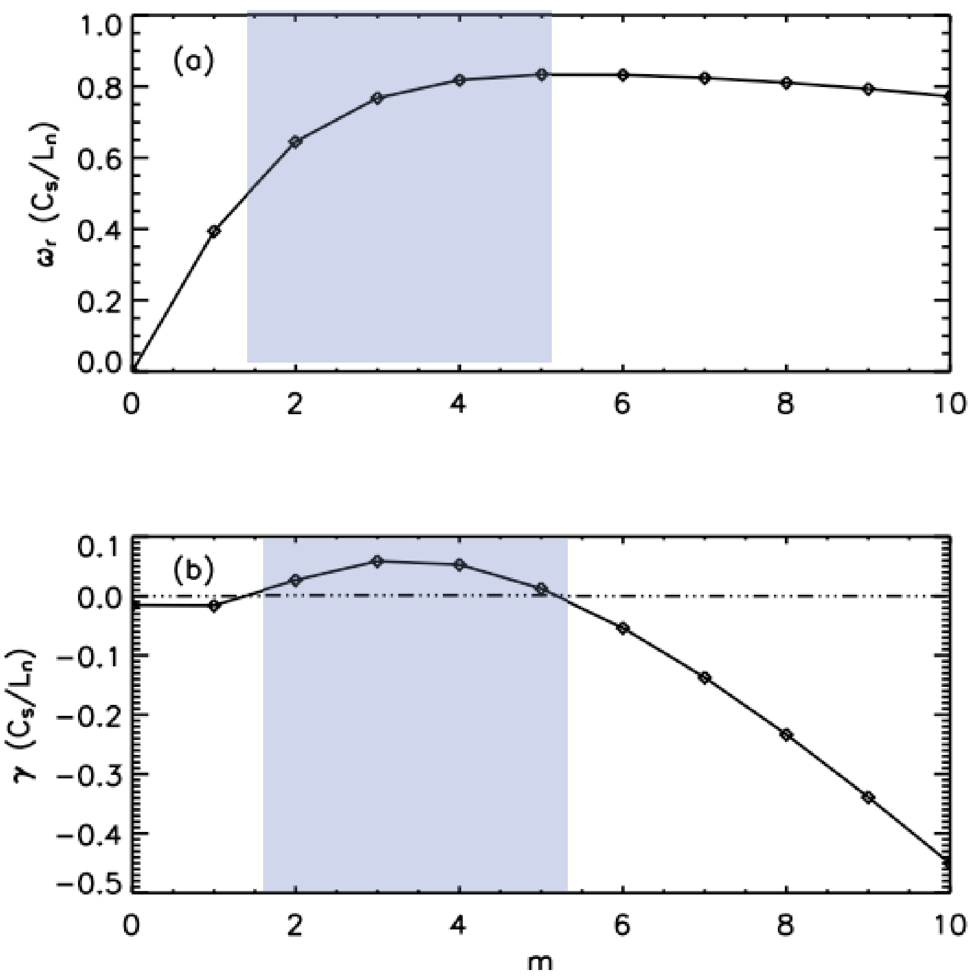
Evolution of Energy Spectrum w/ Magnetic Field

$$E_{k_\theta} = \left(\frac{n_{k_\theta}}{n}\right)^2 + k_\theta^2 \left(\frac{e\phi_{k_\theta}}{k_B T_e}\right)^2$$



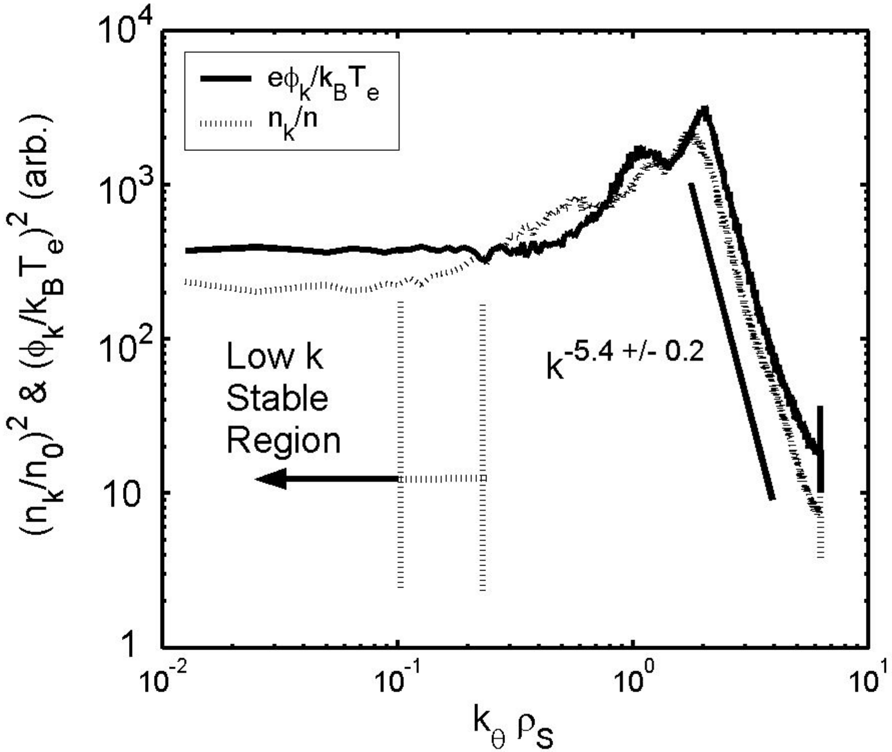
Burin et al, May 2005 PoP

Real and Imaginary Frequencies of Linear Eigenmodes



Free Energy Sources Are Known → Can Find Linearly Unstable Region

- Include grad-P, Vshear Free Energy Sources
- Include Neutral Flow Drag (Effective at high k), FLR Damping
- Find Stable & Unstable Regions

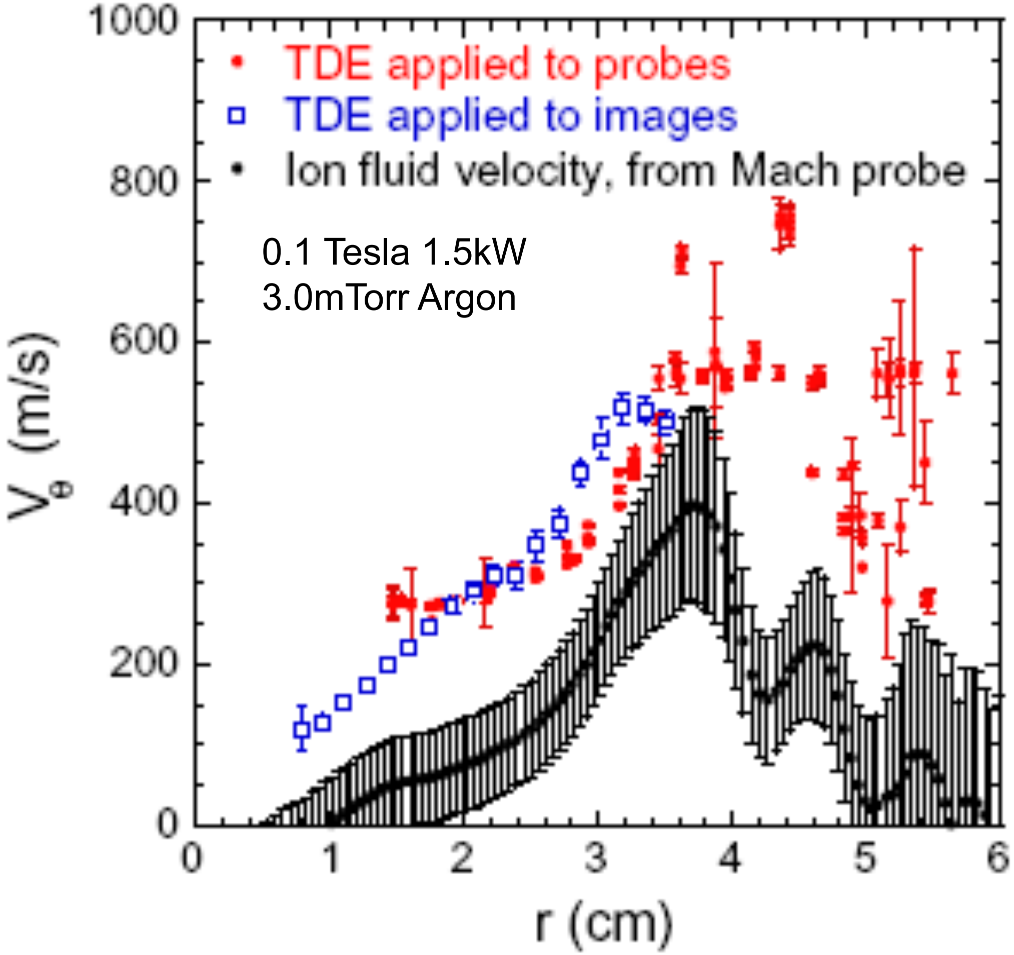


Local Wavenumber

Implies Energy MUST Be Transferred Into Low-k Region Via Nonlinear Processes

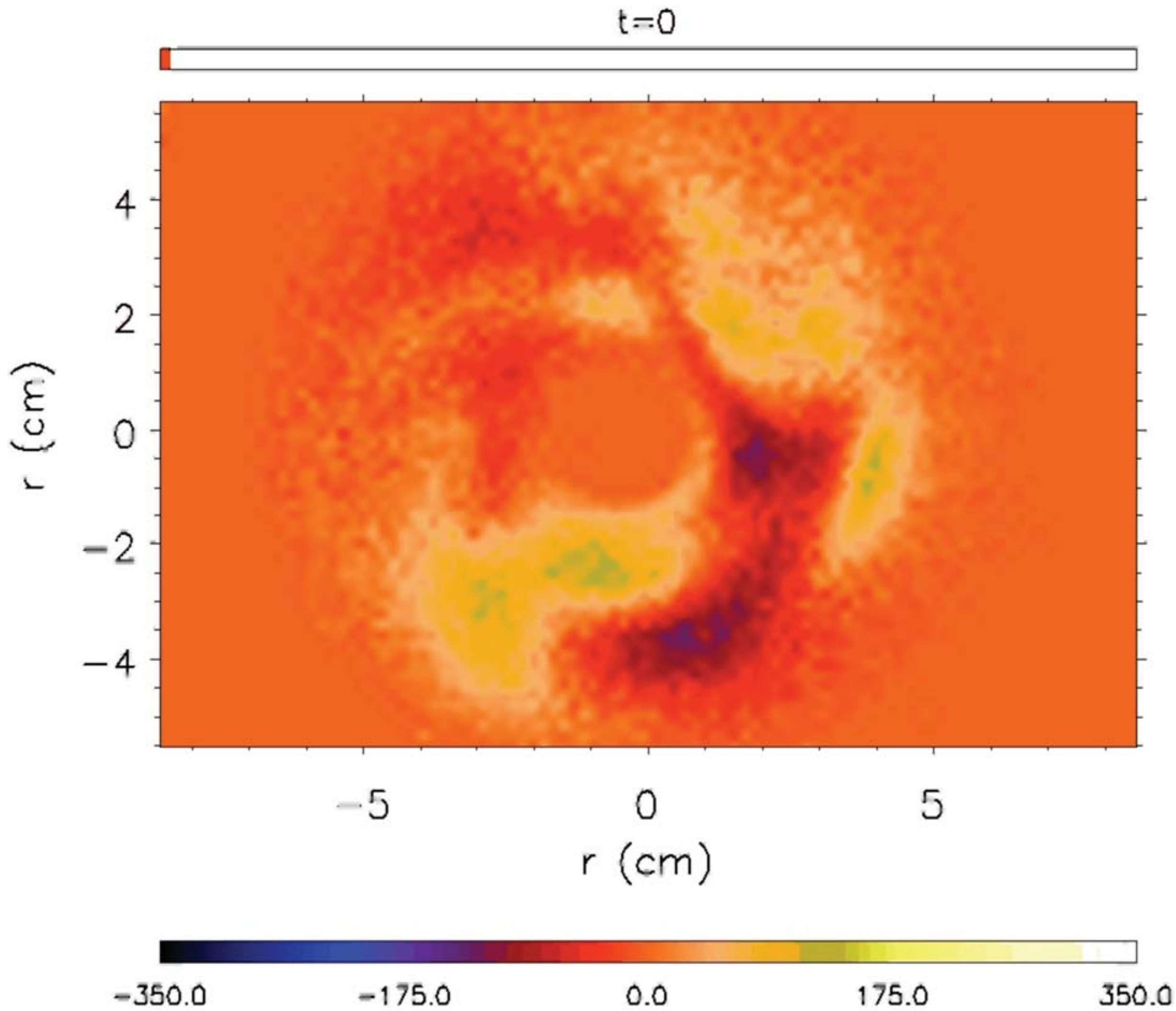
Tynan et al Nov 2004 PoP

Radially Sheared Azimuthal Fluid & Fluctuation Propagation Occurs at High B-field



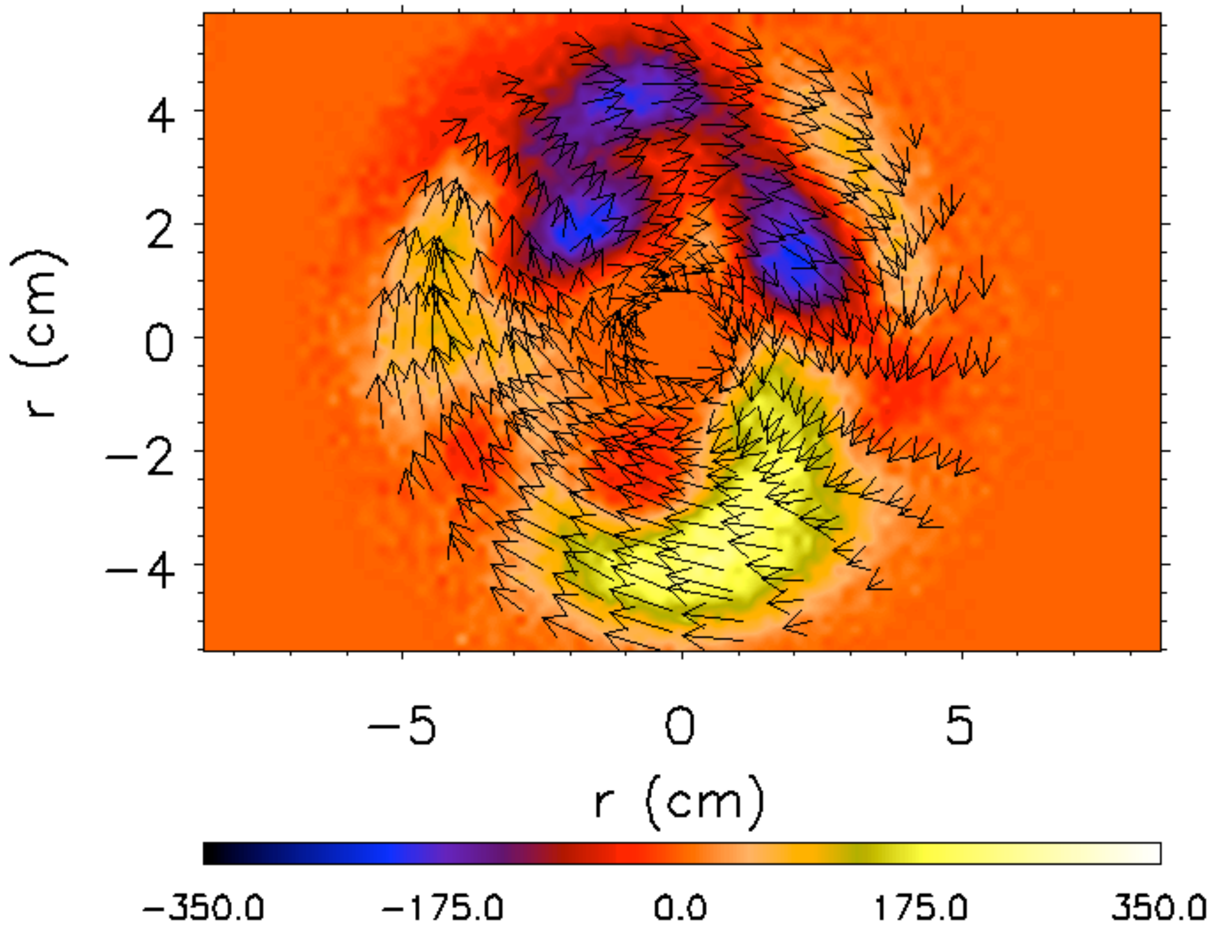
J.H.Yu, et al., Journal of Nuclear Materials, V363-365, 728, 2007

Fast Imaging of DWT Fluctuation Propagation



Radially Sheared Azimuthal Flow & Finite m DWT Fluctuations

CSDX

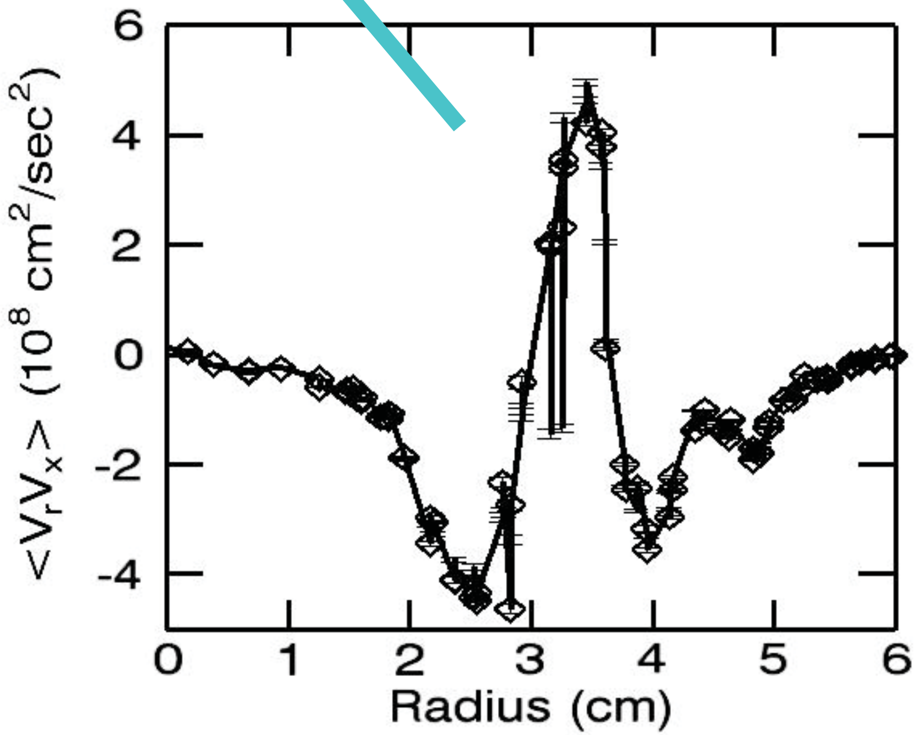


Evidence that Flow is Driven by the Turbulence

Turbulent Azimuthal Momentum Balance

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle\right) = -\nu_{io}\overline{V}_{i\theta} + \mu_{ii}\nabla^2\overline{V}_{i\theta}$$

Measured Reynolds stress



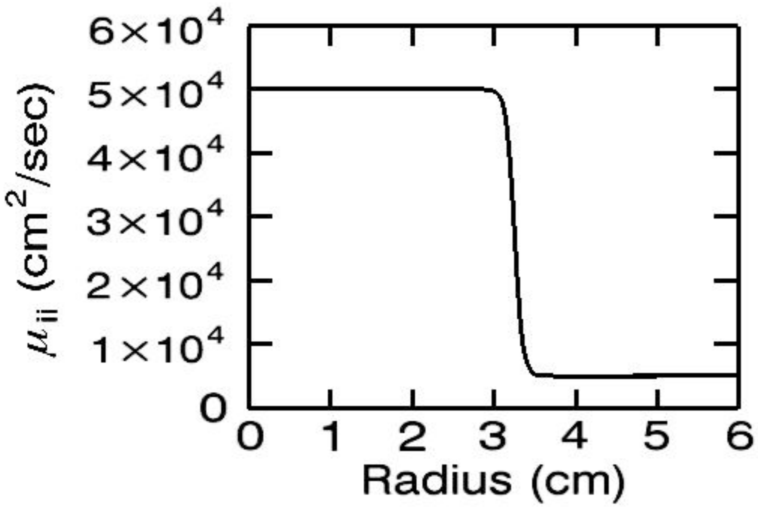
Tynan et al April 2006 PPCF Holland et al, in press, PRL

Estimate Dissipation from Measurements

Measure:

$$\int_{-a}^{a} T_i dl = 0.7 eV$$

$$\int_{-a}^{a} T_{gas} dl = 0.4 eV$$



Assume:

$$T_i(0) > T_i(a)$$

$$T_{gas}(a) = T_{wall}$$

$$\mu_{ii} = \frac{3}{10}\rho_i^2 \nu_{ii}$$

$$P_{gas} = n_{gas} T_{gas} = const$$

$$\Rightarrow \quad \mu_{ii} \propto n_i T_i^{1/2} \quad \Rightarrow$$

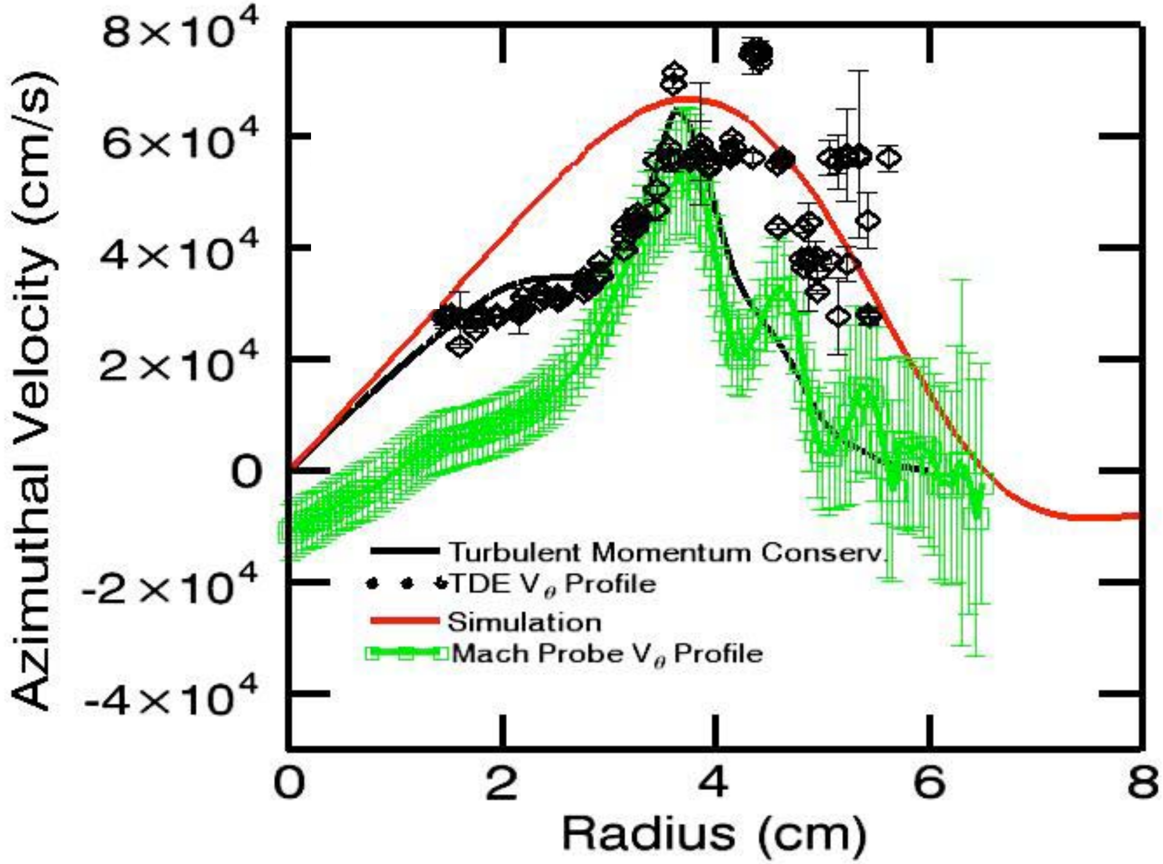
$$\bar{\mu}_{ii} \approx 4\times 10^4 \, cm^2/\sec$$

$$\mu_{ii}(0) > \mu_{ii}(a)$$

$$\nu_{i0} \sim 6\times 10^3 \sec^{-1}$$

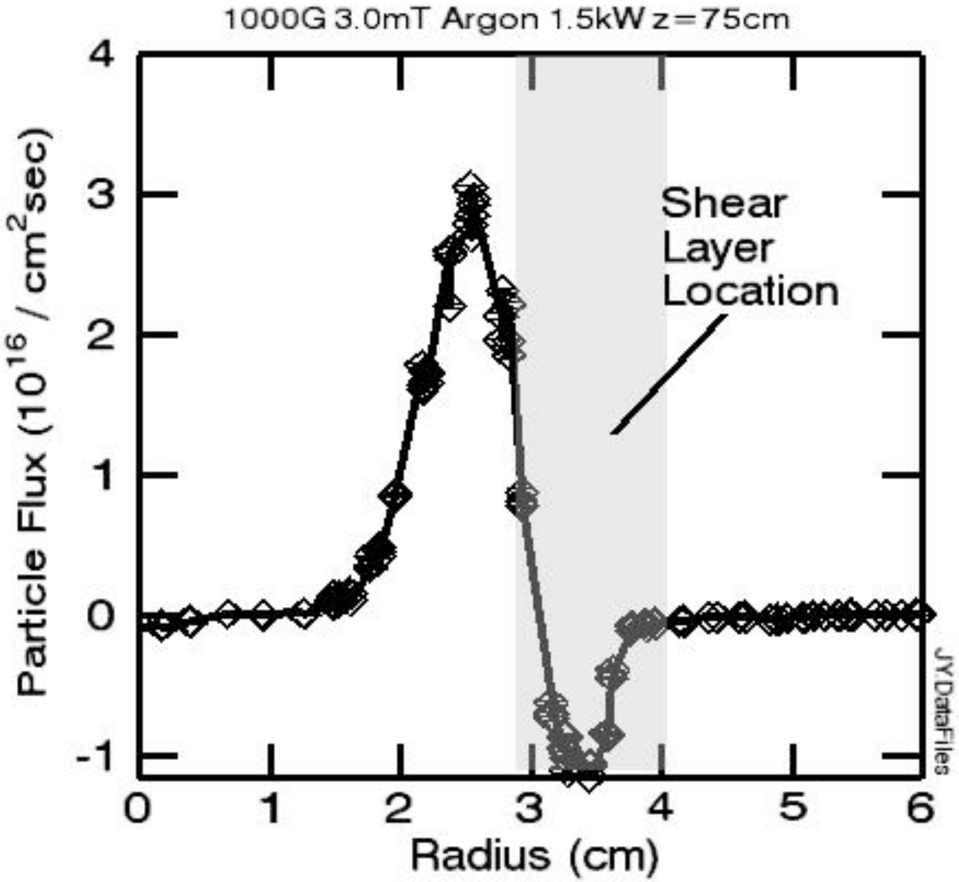
Tynan et al, April 2006 PPCF,
Holland et al, in press, PRL

Measured Profile Consistent with Turbulent Momentum Balance



Tynan et al, April 2006 PPCF, , Holland et al, PRL 2006

No Turbulent Particle Transport Across Zonal Flow



Tynan et al, April 2006 PPCF, Holland et al, In press, PRL

Shear Layer Formation in Collisional Drift Turbulence Simulations

Nonlinear Drift Turbulence Simulation

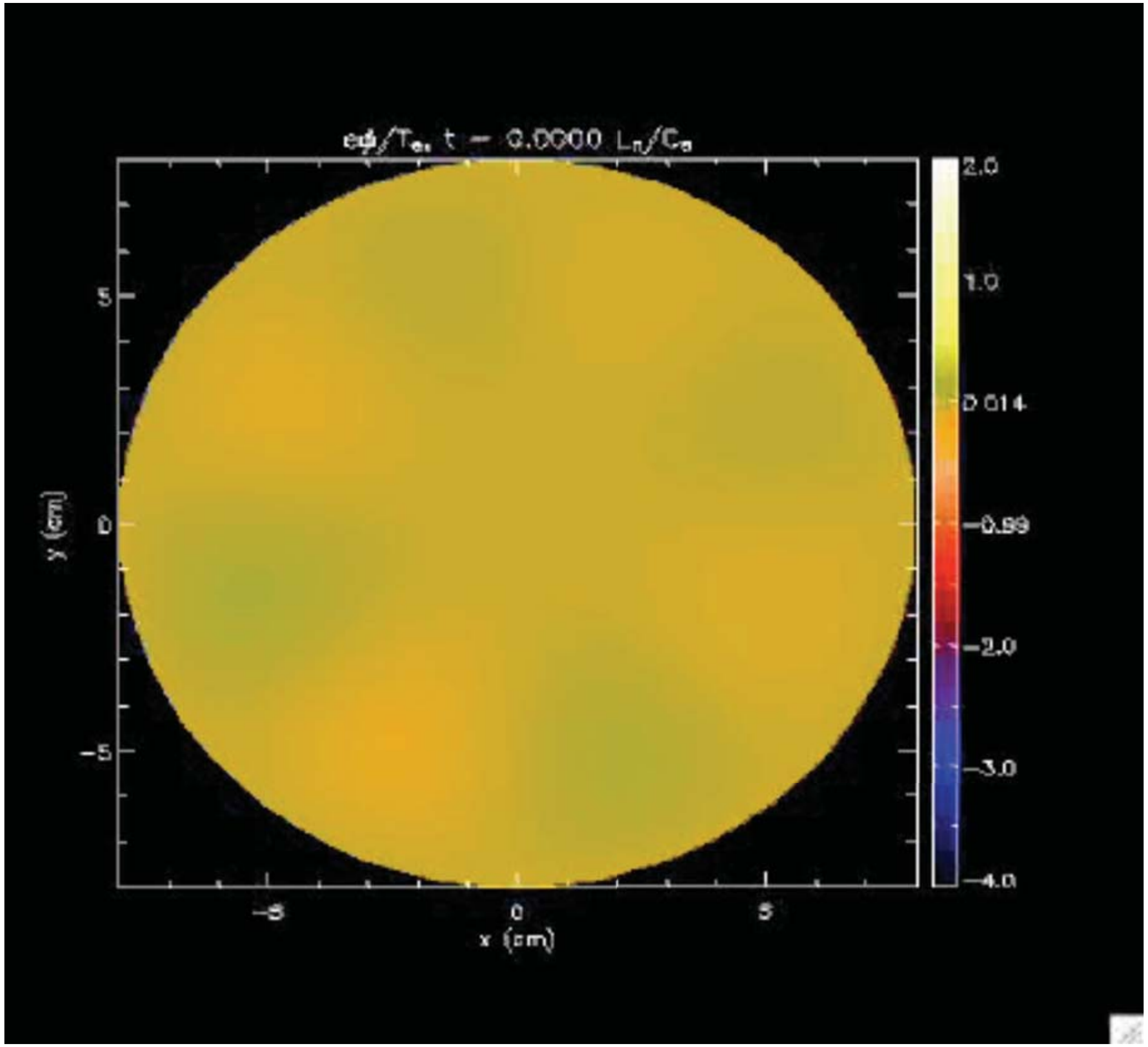
- (2D) Hasegawa-Wakatani model in cylindrical geometry.
  - Includes ion-neutral flow damping effect n, **neglects** nonlocal (finite r_s / L_n) terms, **fixed parallel wavenumber.**

$$\left(\frac{\partial}{\partial t}+\vec{V}_{E\times B}\cdot\vec{\nabla}\right)n+\frac{V^*}{r}\frac{\partial n}{\partial\theta}+\frac{k_{\|}^2 v_{th_e}^2}{\omega^* v_e}(n-\phi)=D_n\nabla_{\perp}^2 n$$

$$\left(\frac{\partial}{\partial t}+\vec{V}_{E\times B}\cdot\vec{\nabla}\right)\nabla_{\perp}^2\phi+\frac{k_{\|}^2 v_{th_e}^2}{\omega^* v_e}(n-\phi)=\nu\nabla_{\perp}^2\phi+\mu\nabla_{\perp}^4\phi$$

  - Parameters used reflect best estimates for average CSDX values:
    - r_s = 1 cm, L_n = 2 cm, $w_{||}$ = 1, n = 0.03C_s/L_n,
    - D_n = 0.01 r_s^2 C_s/L_n, m = 0.4 r_s^2 C_s/L_n
  - Advances eqns by combination of 2nd order RK and implicit treatment of diffusive terms (conserves energy to within 1%).

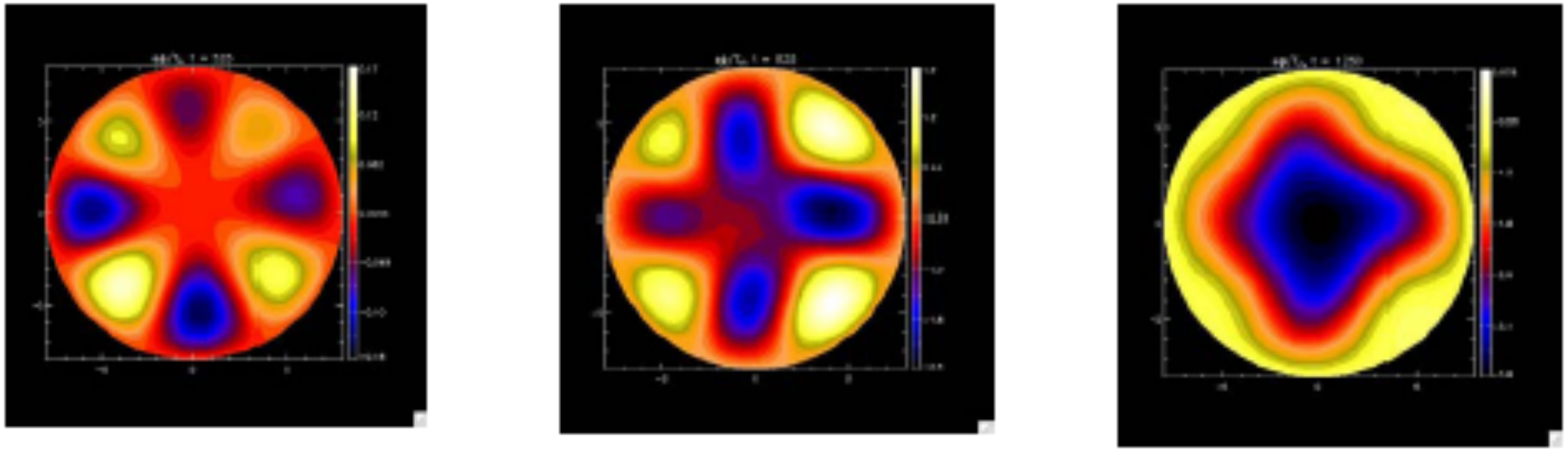
Iso-Potential Shows Zonal Flow Formation from Drift Vortices



Simulations Show Zonal Flow Formation
Vortex Merging

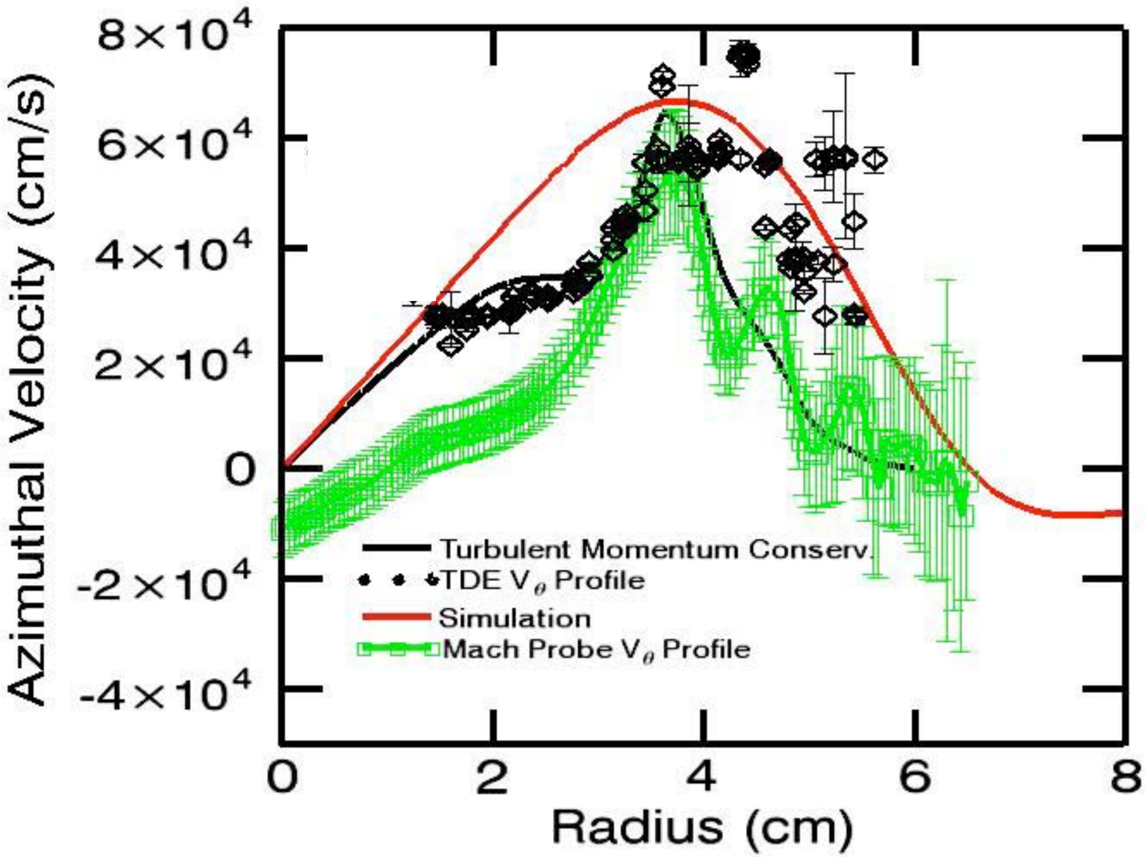
Iso-Potential Contours:

Time



- Simulation uses 64 x 64 pts, results insensitive to changes in D_n, n, m
- Changing L_n to 10 cm does not qualitatively affect results

Numerical Model Reproduces Key Features of Experiment and Analysis



Tynan et al April 2006 PPCF

Flow Generation from Turbulence: Fourier Space

Usual Reynolds Stress Term in Simplified Momentum Eqn
(ala Diamond et al. PRL 1994 and others)

$$\frac{\partial \bar{u}_\theta}{\partial t} + \frac{\partial \langle \tilde{u}_r \tilde{u}_\theta \rangle}{\partial r} = -\nu_{damp} \bar{u}_\theta$$

"Radial Transport of Angular Momentum"

Consider a Zonal Flow to Have:

$$\mathbf{u} = u_\theta^Z \hat{\theta} \qquad \mathbf{k}_r^Z = k_r^Z \hat{\mathbf{r}}$$

$$\left|\mathbf{k}_r^Z\right| << \left|\mathbf{k}_1\right|, \left|\mathbf{k}_2\right|$$

$$\tau_Z \sim 1/k_r^Z u_\theta^Z >> t_{corr}$$

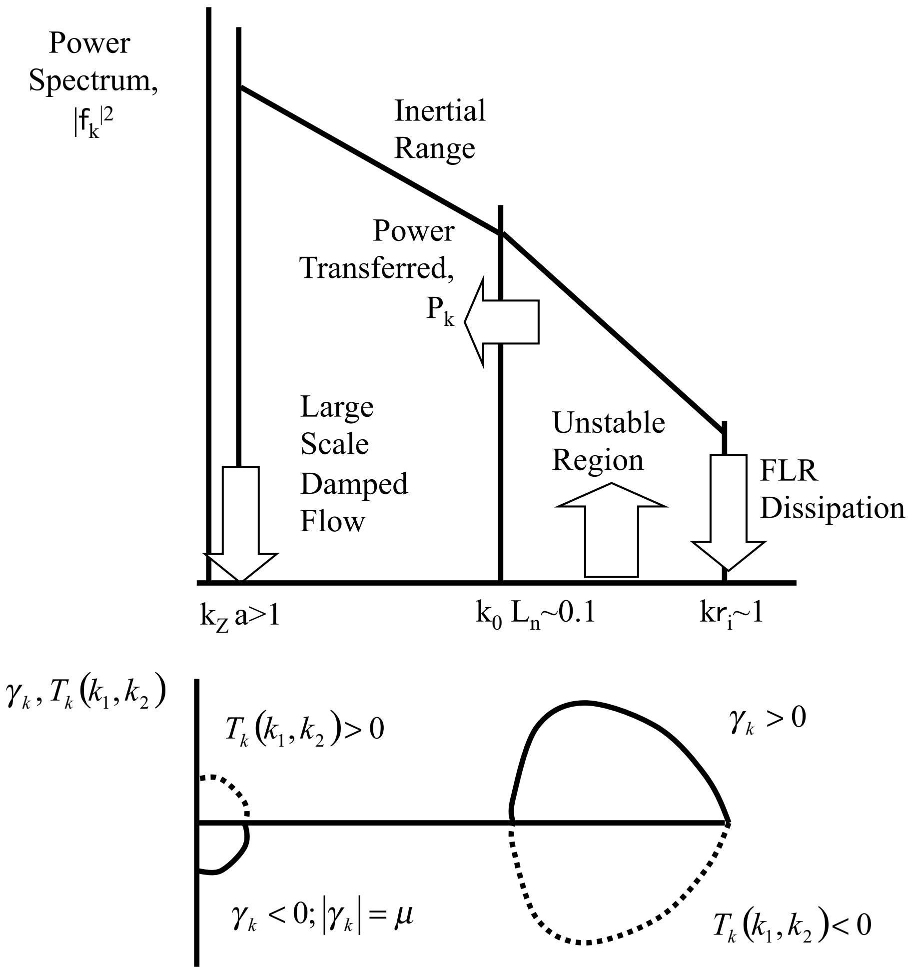
F.T., Write as KE, and Average Energy Eqn over Z-flow scales:

NL Energy Transfer

$$\frac{1}{2}\frac{\partial \left\langle u_{\theta_Z}{}^2(\mathbf{k}_Z)\right\rangle}{\partial t} - P_{k_Z}^{turb} = -\mu \left\langle u_{\theta_Z}{}^2(\mathbf{k}_Z)\right\rangle$$

where $$P_{k_Z}^{turb} = \sum_{\substack{\mathbf{k}_1 \mathbf{k}_2 \\ \mathbf{k}_Z = \mathbf{k}_1 + \mathbf{k}_2}} \boxed{\mathrm{Re}\left\langle u_{\theta_Z}{}^*(\mathbf{k}_Z)\left(\tilde{\mathbf{u}}(\mathbf{k}_1)\cdot\nabla\right)\tilde{u}_\theta(\mathbf{k}_2)\right\rangle}$$

Flow Generation from Turbulence: Fourier Space



- Free Energy Source Releases Energy On One Scale
- Nonlinear Energy Transfer Moves Energy to Dissipation Region
- Shear Flows Develop Via Transfer of Energy to LARGE SCALES (small k)

Nonlinear Energy Transfer

Internal energy

$$T_{\text{internal}} = -\mathrm{Re} \sum_{\substack{\omega_1,\omega_2 \\ \omega=\omega_1+\omega_2}} n_\omega^* (\hat{z} \times \nabla_\perp \phi_{\omega_1} \bullet \nabla_\perp) n_{\omega_2}$$

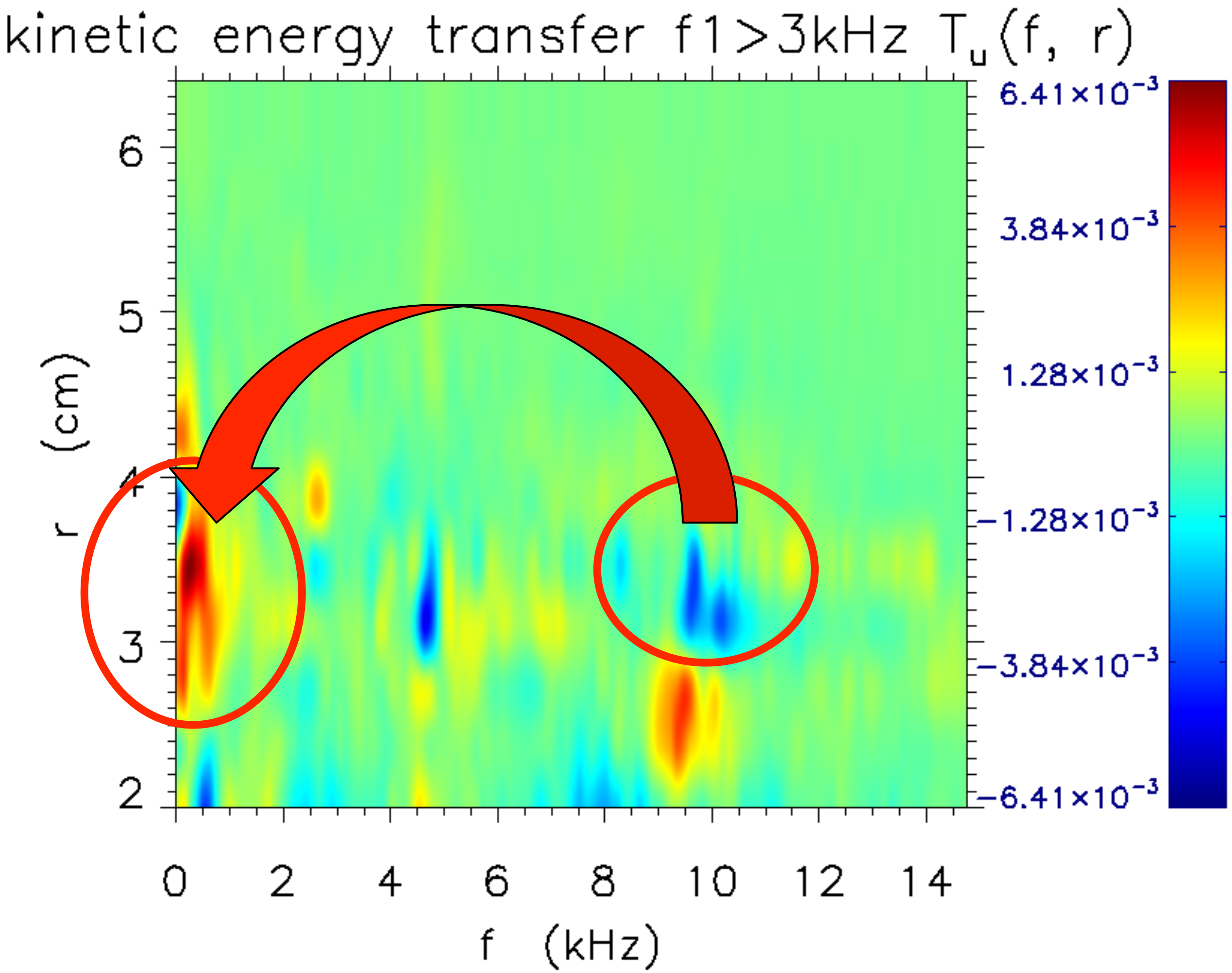
Kinetic energy

$$T_{Kinetic} = -\mathrm{Re} \sum_{\substack{\omega_1,\omega_2 \\ \omega=\omega_1+\omega_2}} u_\omega^* (u_{\omega_1} \bullet \nabla_\perp) u_{\omega 2}$$

$$where\ u_\omega = \frac{1}{B} \hat{z} \times \nabla_\perp \phi_\omega$$

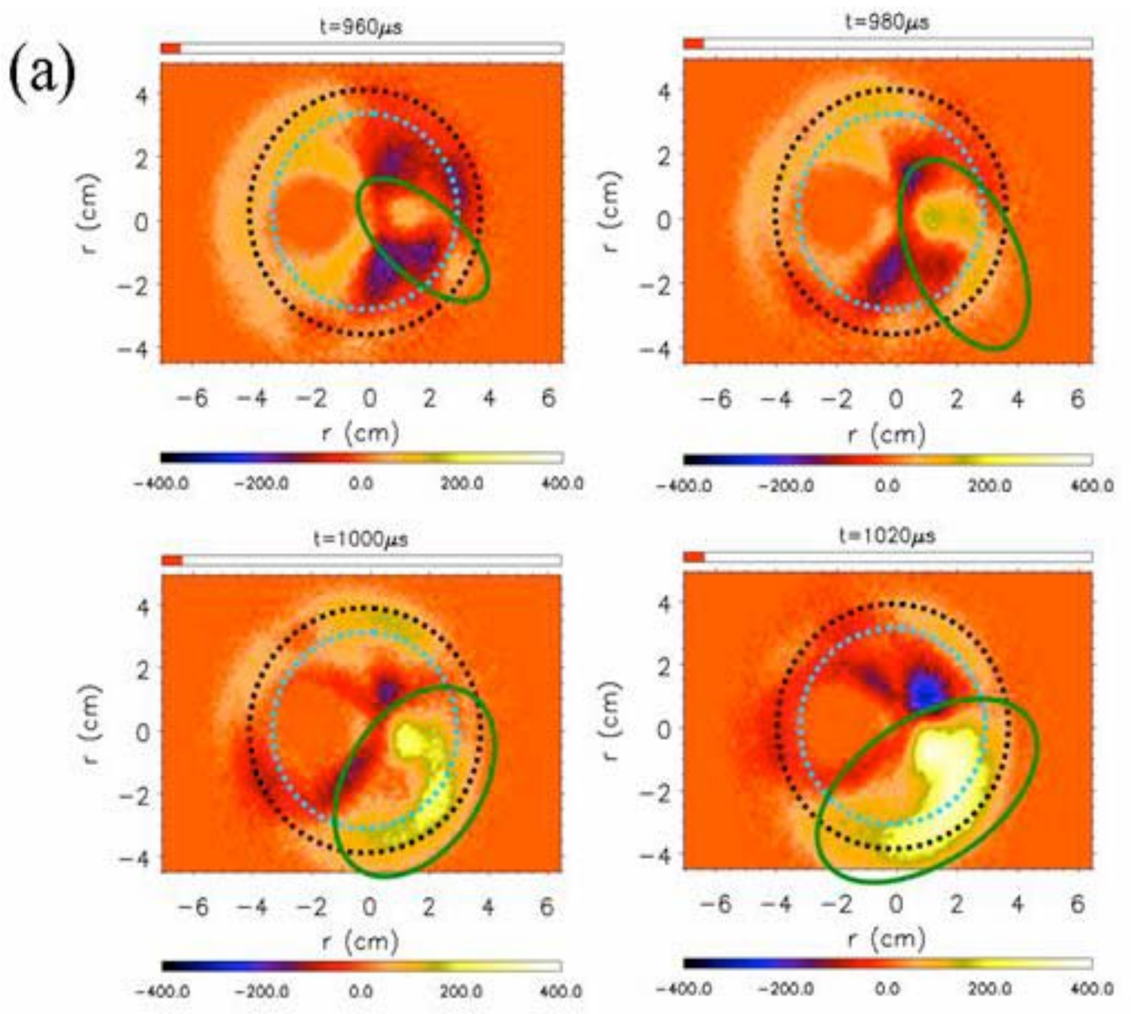
Nonlinear Kinetic Energy Transfer Confirms Turbulence Drive

CSDX



Direct Visualization of Drift Vortex-ZF Interaction

CSDX



- Vortex Born at Grad-n Max
- Moves in r,θ plane
- Stretched Out by ZF
- Merges w ZF

Outline

- Demonstrate Development of "Weak" Turbulence from Drift Waves & Onset of Zonal Flows
- **Study Nonlinear dynamics of coupled DWT/ZF system in simple system**
- Show evidence for a non-diffusive turbulent stress at plasma boundary acting to drive rotation
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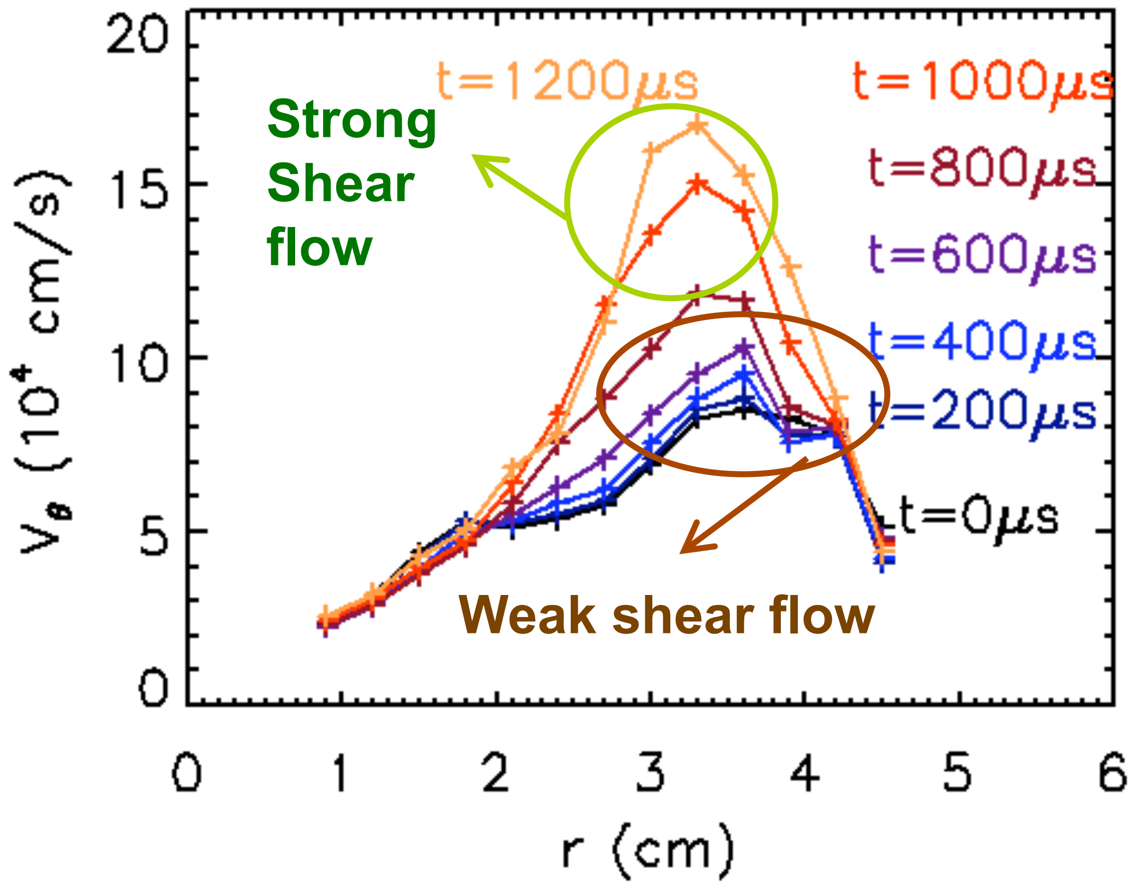
Flow Evolves at Slow Time Scale (250-300Hz)



Z. Yan, PhD Dissertation, UCSD, 2009

Reynolds Stress Modulated In Phase Coherent Manner with ZF

Azimuthal component of the ion momentum equation:

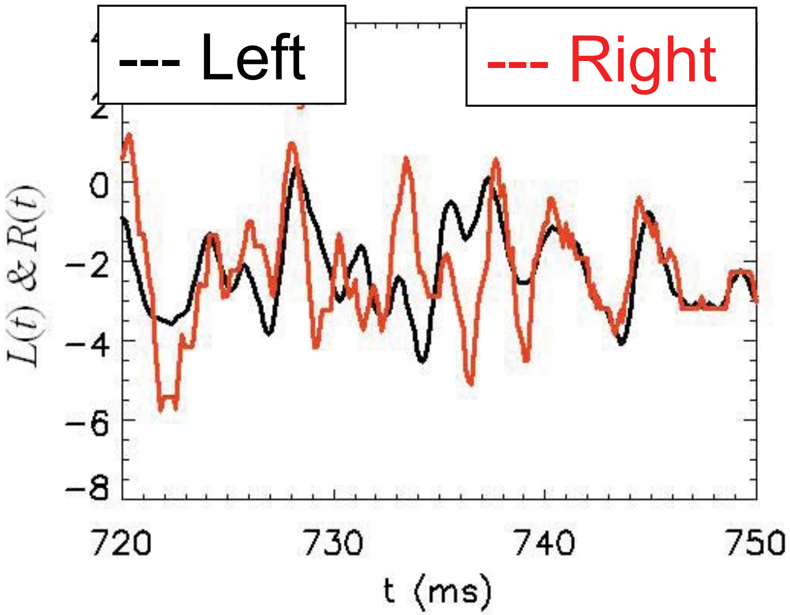
TDE

$$\boxed{\frac{\partial \langle V_\theta \rangle_t}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \langle \tilde{V}_r \tilde{V}_\theta \rangle_t\right)} = \boxed{-\upsilon_{i-n}\langle V_\theta \rangle_t + \mu_{ii}\left(\frac{\partial^2 \langle V_\theta \rangle_t}{\partial r^2} + \frac{1}{r}\frac{\partial \langle V_\theta \rangle_t}{\partial r} - \frac{\langle V_\theta \rangle_t}{r^2}\right)}$$

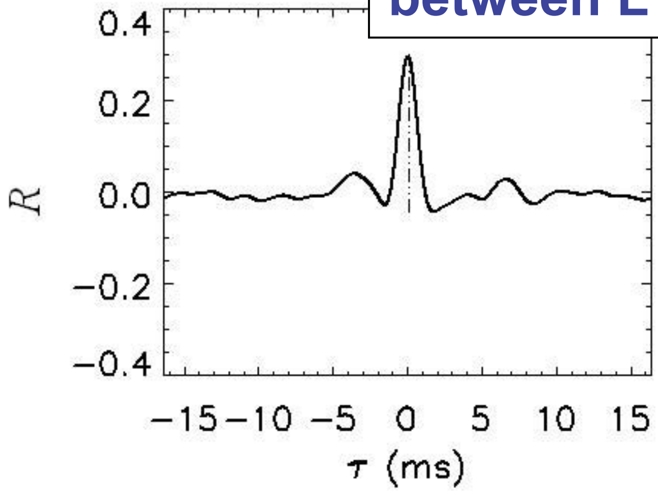
L

Probe

R

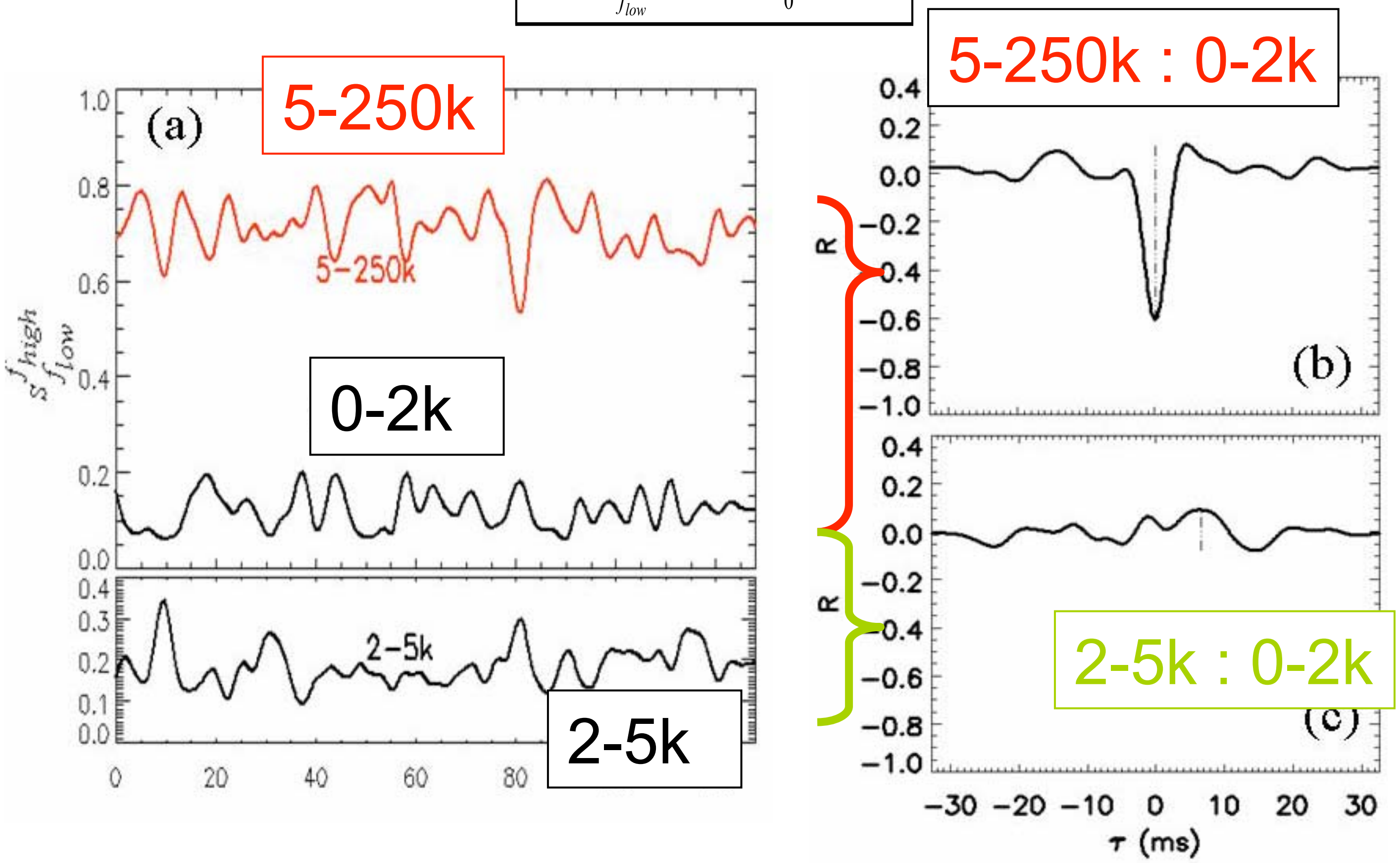


Cross-correlation between L and R



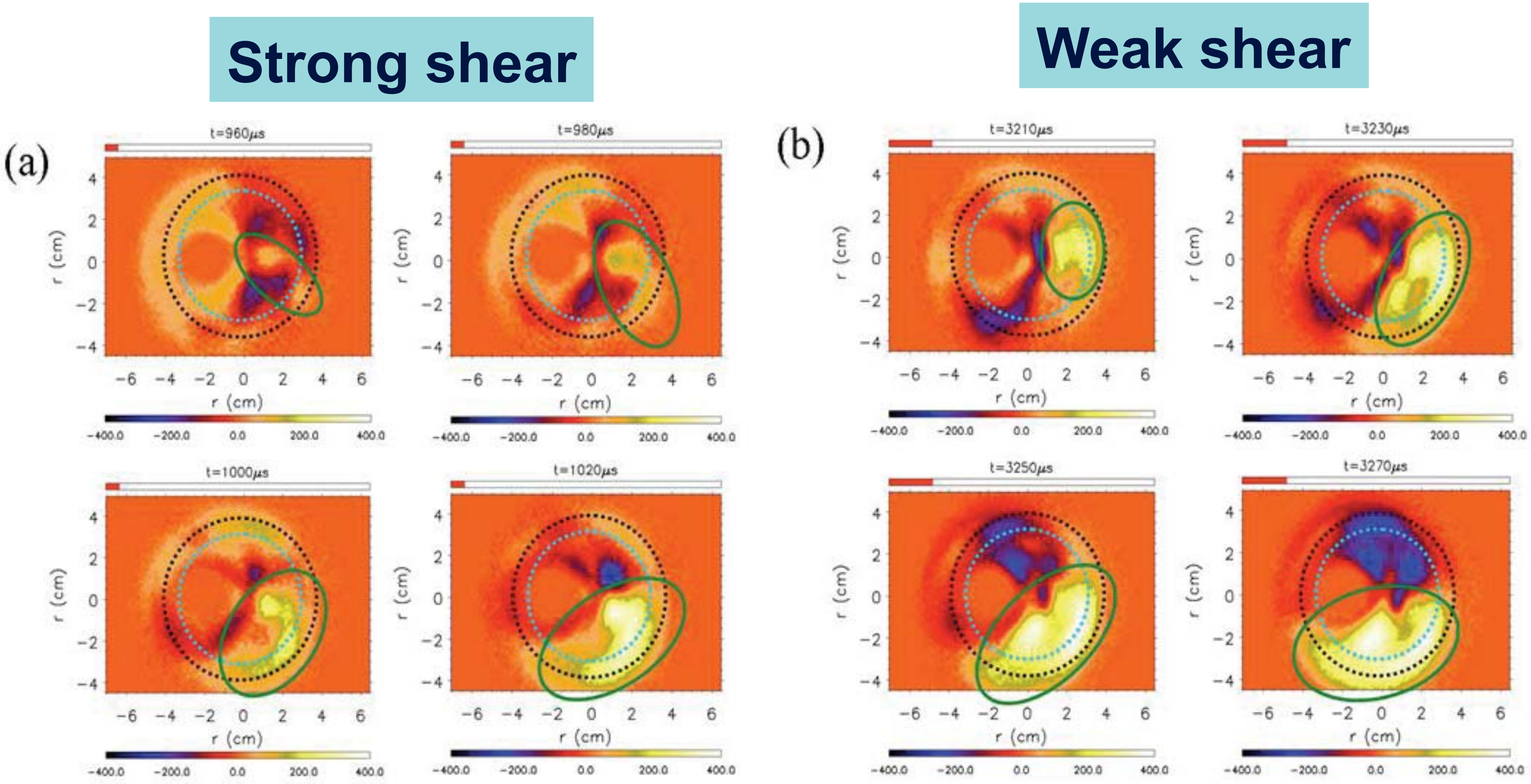
Turbulence Kinetic Energy and ZF Energy Anti-correlated

$$s_{f_{low}}^{f_{high}} = \int_{f_{low}}^{f_{high}} P(f)df \,/\, \int_{0}^{\infty} P(f)df$$



•Kinetic energy transferred between higher frequency turbulence and low frequency flow.

Direct Visualization of Turbulent Decorrelation w/ High ZF Shearing Rate



- Shear flow decorrelating turbulence structure is observed at strong shear case, but not at weak shear case.

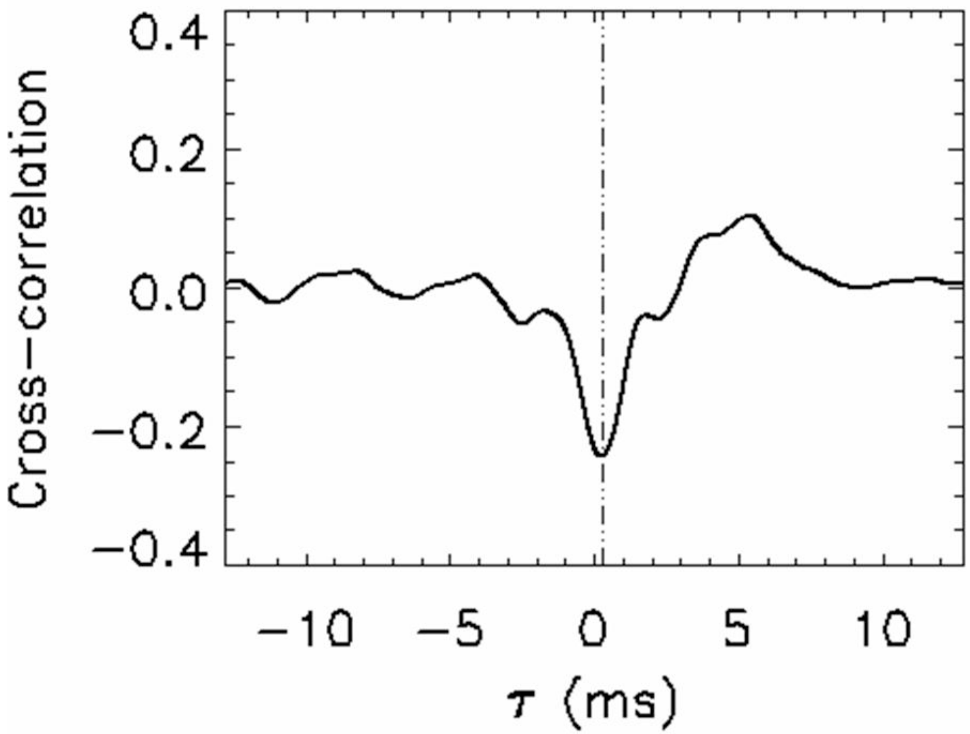
Anti-correlation between Flow Shear and Turbulence Radial Correlation Length

— Shear flow de-correlates turbulent structures

Correlation between

$$\omega_s = r\frac{d}{dr}\left(\frac{v_\theta}{r}\right)$$ and

radial correlation length



Outline

- Demonstrate Development of "Weak" Turbulence from Drift Waves & Onset of Zonal Flows
- Study Nonlinear dynamics of coupled DWT/ZF system in simple system
- **Show evidence for a non-diffusive turbulent stress at plasma boundary acting to drive "intrinsic" rotation**
- Demonstrate Critical Gradient dynamics of the system

➔ SIMPLE PLASMA SYSTEM EXHIBITS KEY NONLINEAR DYNAMICAL PROCESSES THOUGHT TO OCCUR IN FUSION SYSTEMS

Finite Nondiffusive Stress at Boundary is Required to Drive NET Instrinsic Plasma Rotation:

Azimuthal momentum balance w/o dissipation:

$$\frac{\partial\langle p_\theta\rangle}{\partial t} = -\frac{\partial}{\partial r}\left(\langle n\rangle S_{r\theta}\right)$$

$$S_{r\theta}^{tot} = -\chi_\theta \frac{\partial\langle V_\theta\rangle}{\partial r} + V_r^{eff}\langle V_\theta\rangle + S_{r\theta}^{res}$$

$$\chi_\theta = \tilde{v}_r^2\tau_c$$

zero

Diffusive part **Convective pinch** **Residual stress**

@ t=0 when

$$\frac{\partial\langle V_\theta\rangle}{\partial r} = 0 \; and \; \langle V_\theta\rangle = 0$$

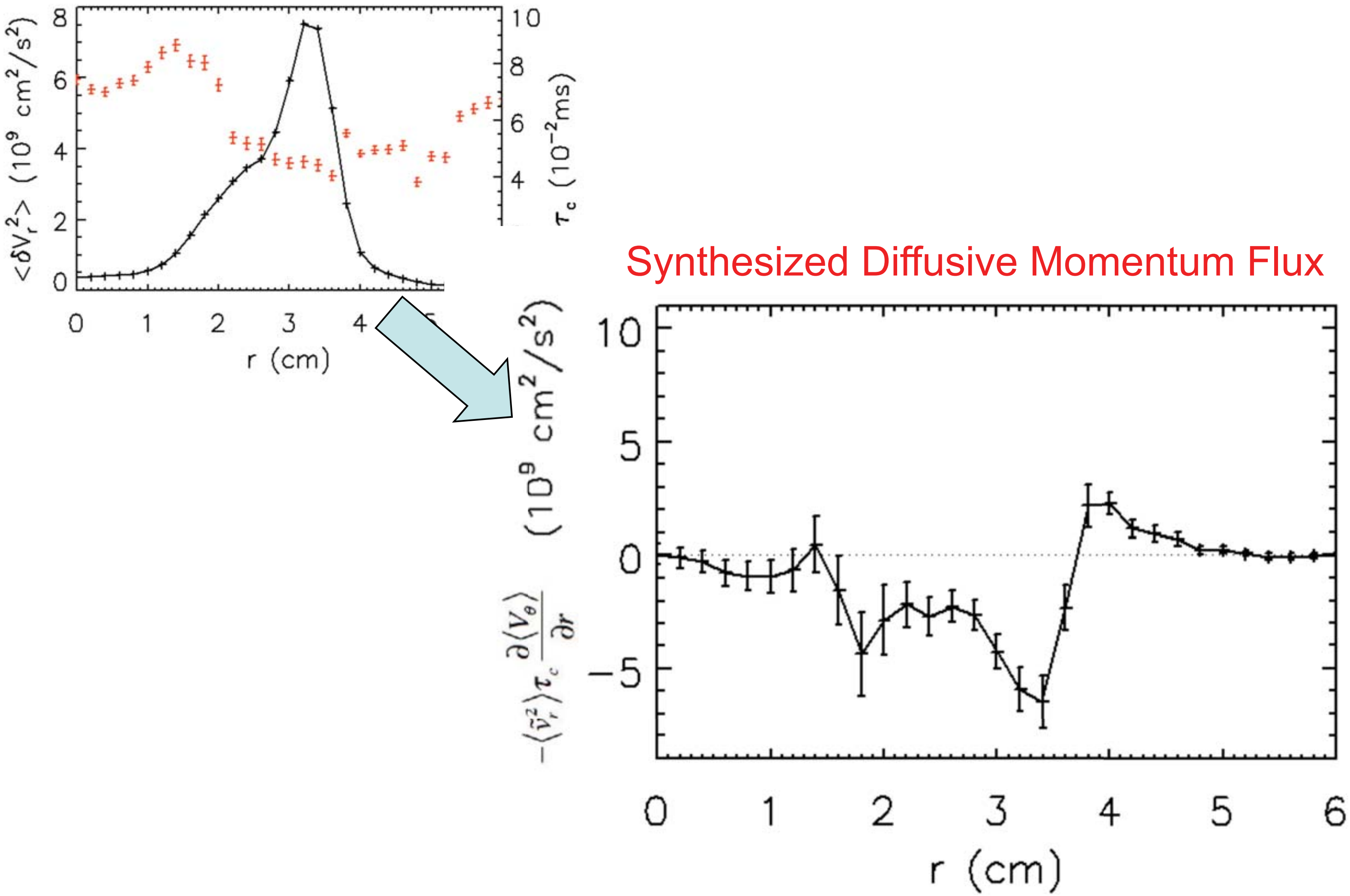
$$\boxed{\frac{\partial\langle p_\theta^{tot}\rangle}{\partial t} \neq 0 \quad \Rightarrow \quad S_{r\theta}^{res}\Big|_a \neq 0}$$

where $p_\theta^{tot} = \int_0^a p_\theta(r)dr$

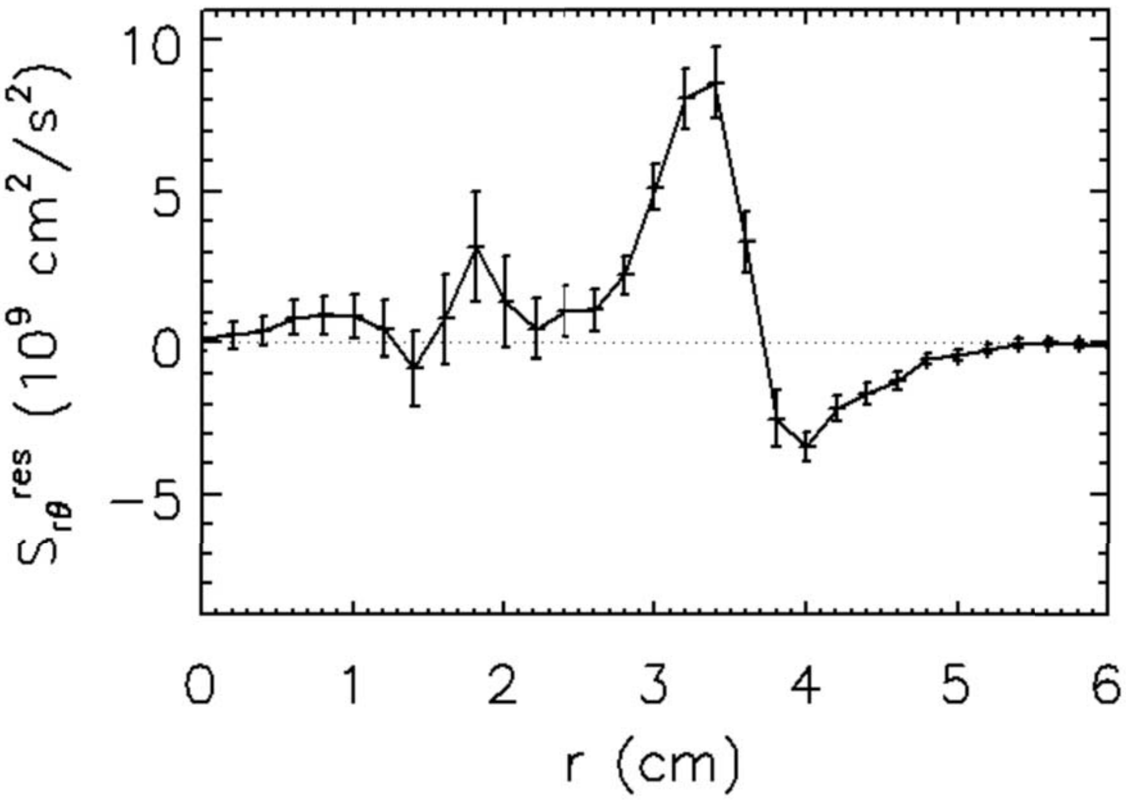
Diamond et al,'09

Synthesize Diffusive Flux from Measurements:

Measured Turbulence Properties



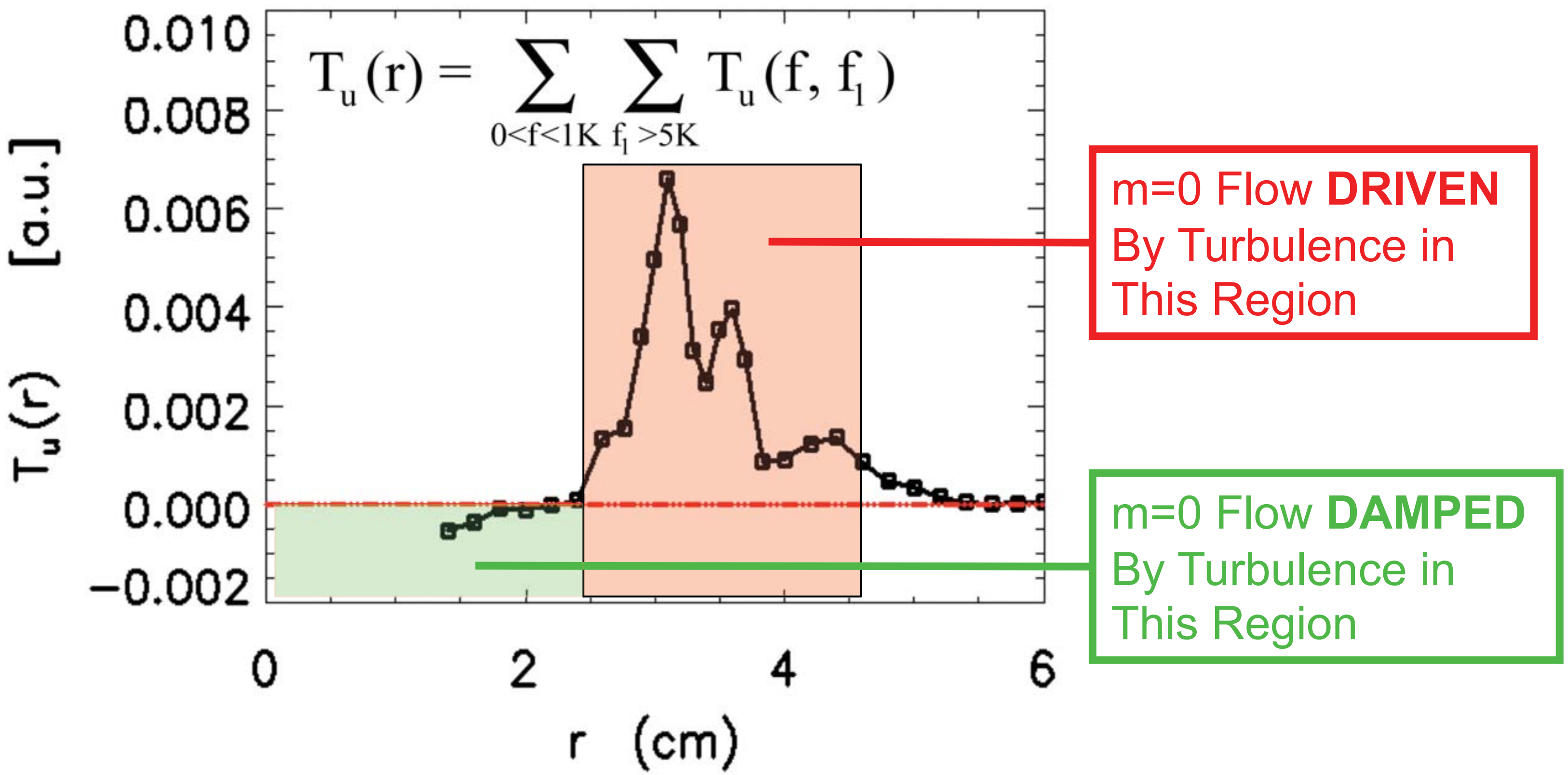
Non-diffusive Stress Localized to Boundary Region



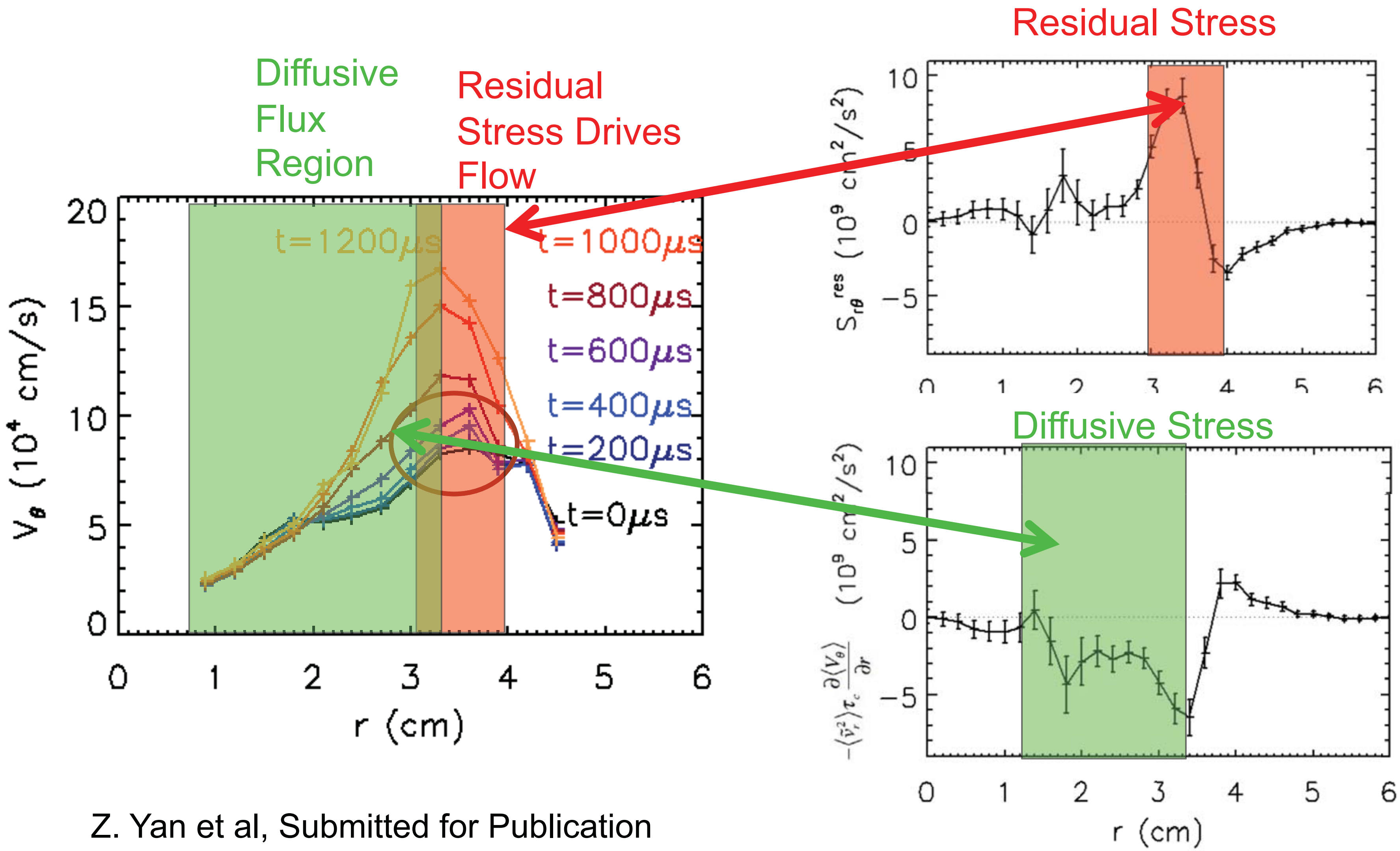
Nonlinear Kinetic Energy Transfer into m=0 Flow
LOCALIZED TO EDGE

Nonlinear K.E. Transfer into m=0 Flow

$$T_{V_\theta} = \sum_{\substack{f<1kHz \\ f_1>5kHz}} \left\langle V_\theta^*(f)\tilde{\mathbf{v}}(f-f_1)\cdot\nabla\tilde{\mathbf{v}}_\theta(f_1)\right\rangle$$



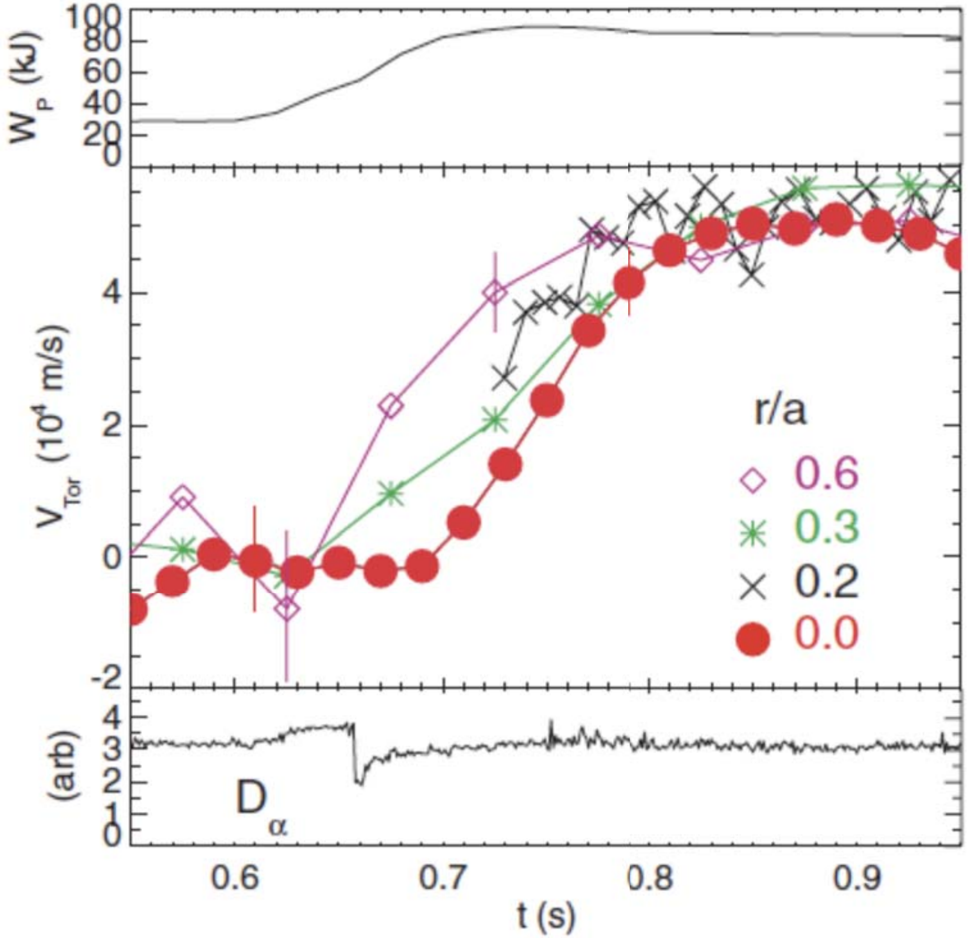
Schematic of Sheared Flow Dynamics



Z. Yan et al, Submitted for Publication

Results Similar to Momentum Transport in Tokamaks

ALCATOR C-MOD
EDA L-H Transition



Rice et al, Nuc Fusion 2004,
Lee et al, PRL 2003

Toroidal Momentum Transport Source Appears Localized to Edge & Diffused/ Convected Inwards

Outline

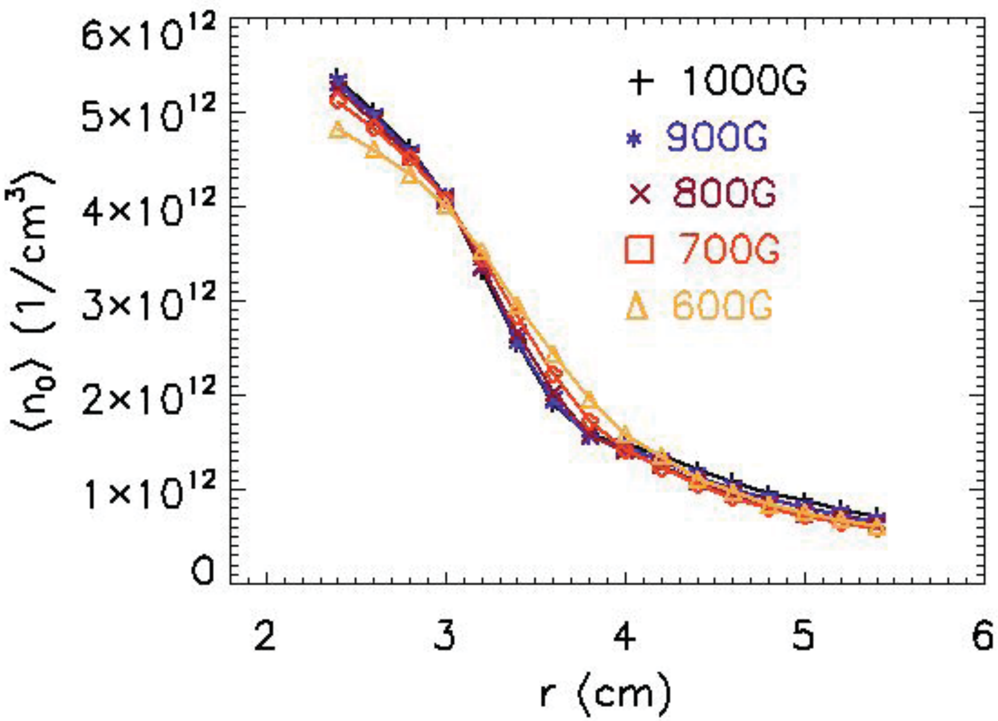
- Nonlinear dynamics of coupled DWT/ZF system in simple system
- Evidence for a non-diffusive turbulent stress at plasma boundary acting to drive rotation
- Demonstrate Critical Gradient dynamics of the system

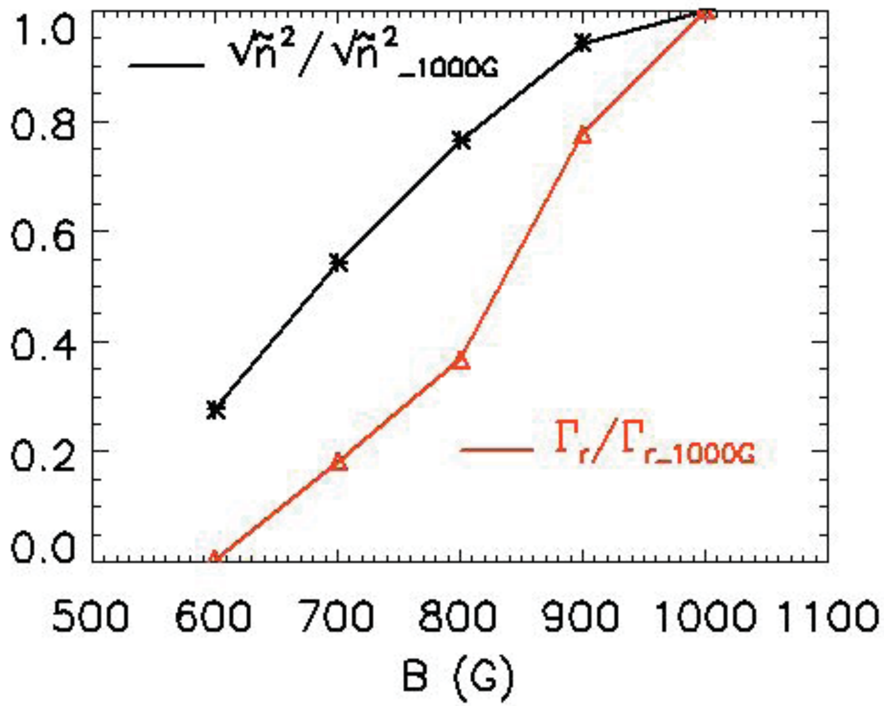
Magnetic field scaling of shear flow

- Equilibrium density

- Density fluctuation amplitude and radial particle flux

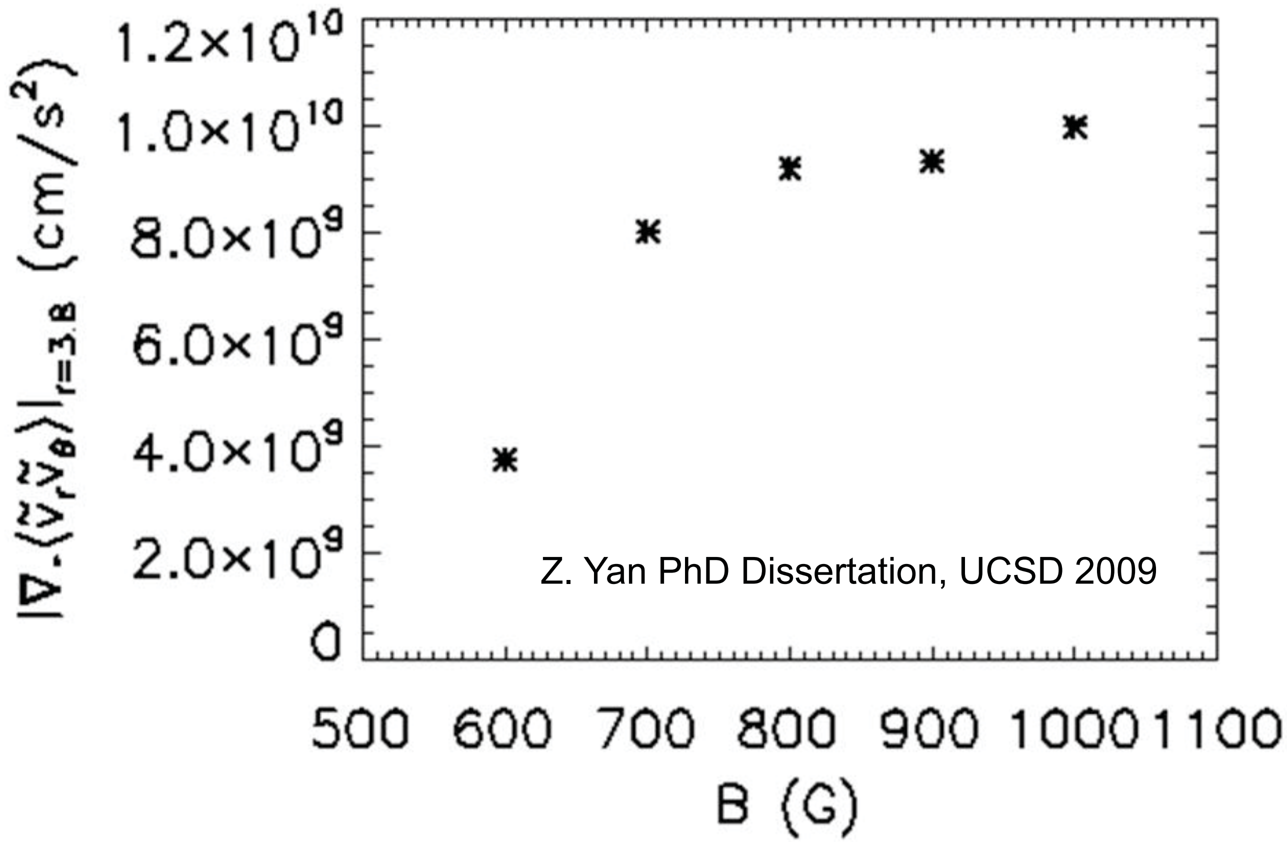
Z. Yan PhD Dissertation, UCSD 2009





Magnetic field scaling of shear flow (2)

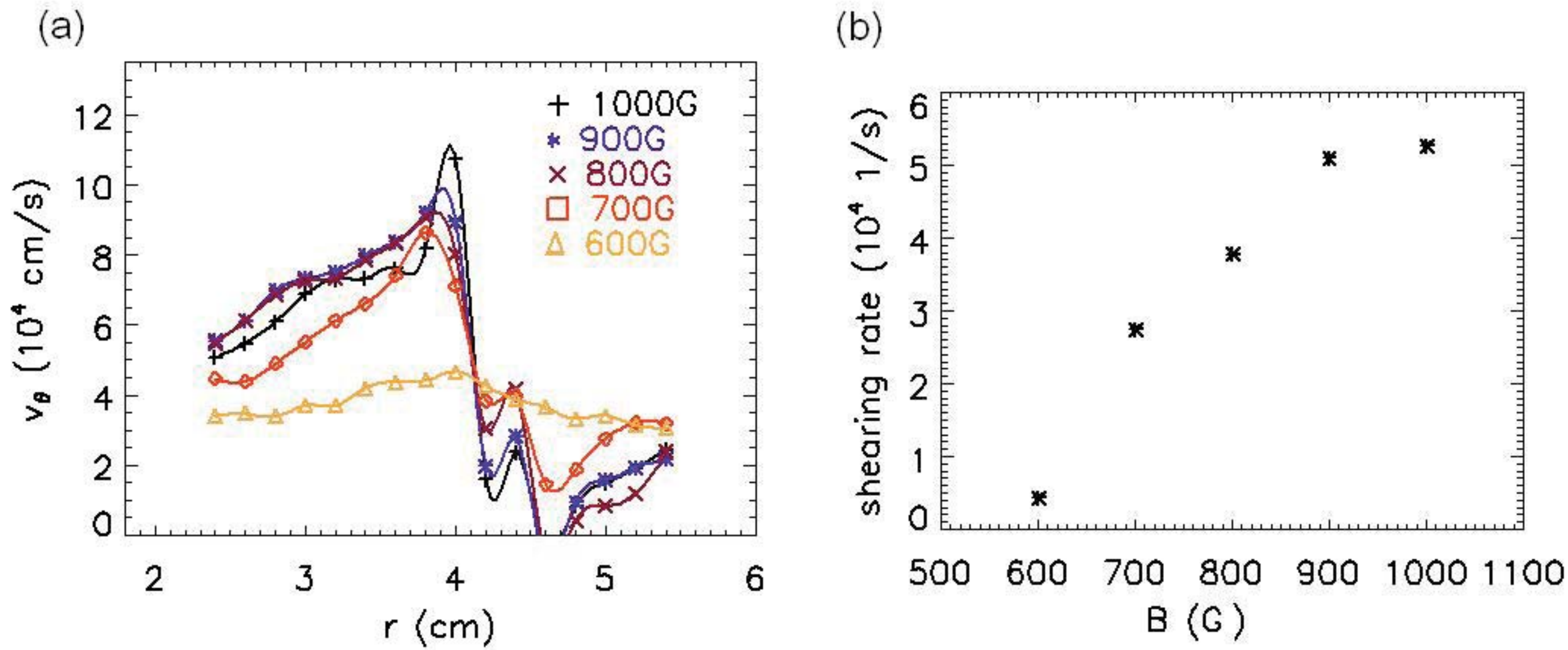
- **Divergence of turbulent Reynolds stress at shear layer increase with magnetic fields**



Development of Shear Flow w/ B-Field

CSDX

- **Shear flow increases with magnetic fields (~ 700G or above)**



Z. Yan PhD Dissertation, UCSD 2009

Re-casting in terms of Critical Gradient

Linear Dispersion Relation, including Cylindrical Geometry, Ion Viscosity, Ion-Neutral Damping:

$$-ik_{mn}^2\omega_{mn}^2 + \left\{\omega_{\parallel}\left(1 + k_{mn}^2\right) + \nu_k\right\}\omega_{mn} - \omega_{\parallel}\left(m\frac{\rho_s}{L_n} - i\nu_k\right) = 0$$

Where damping and wavenumbers are given by:

$$\nu_k = \left(\nu_{i-n} + \mu_{ii}k_{mn}^2\right)k_{mn}^2$$

$k_{mn} = X_{mn}/a$, where X_{mn} is the n^{th} zero of $J_m(x)$.

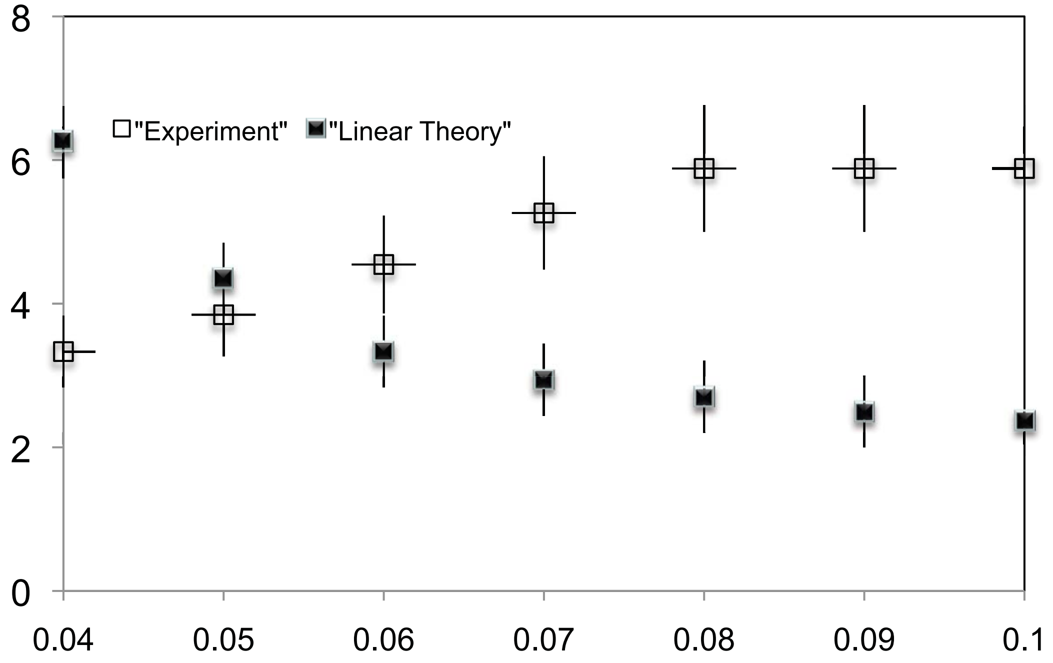
And Eigenmodes have the form:

$$\tilde{\phi}(r,\theta,t) = \mathrm{Re}\sum_{m,n}\tilde{\phi}_{mn}J_m\left(k_{mn}r\right)\exp\left\{i\left(m\theta - \omega_{mn}t\right)\right\}$$

Critical Gradient Development vs. |B|

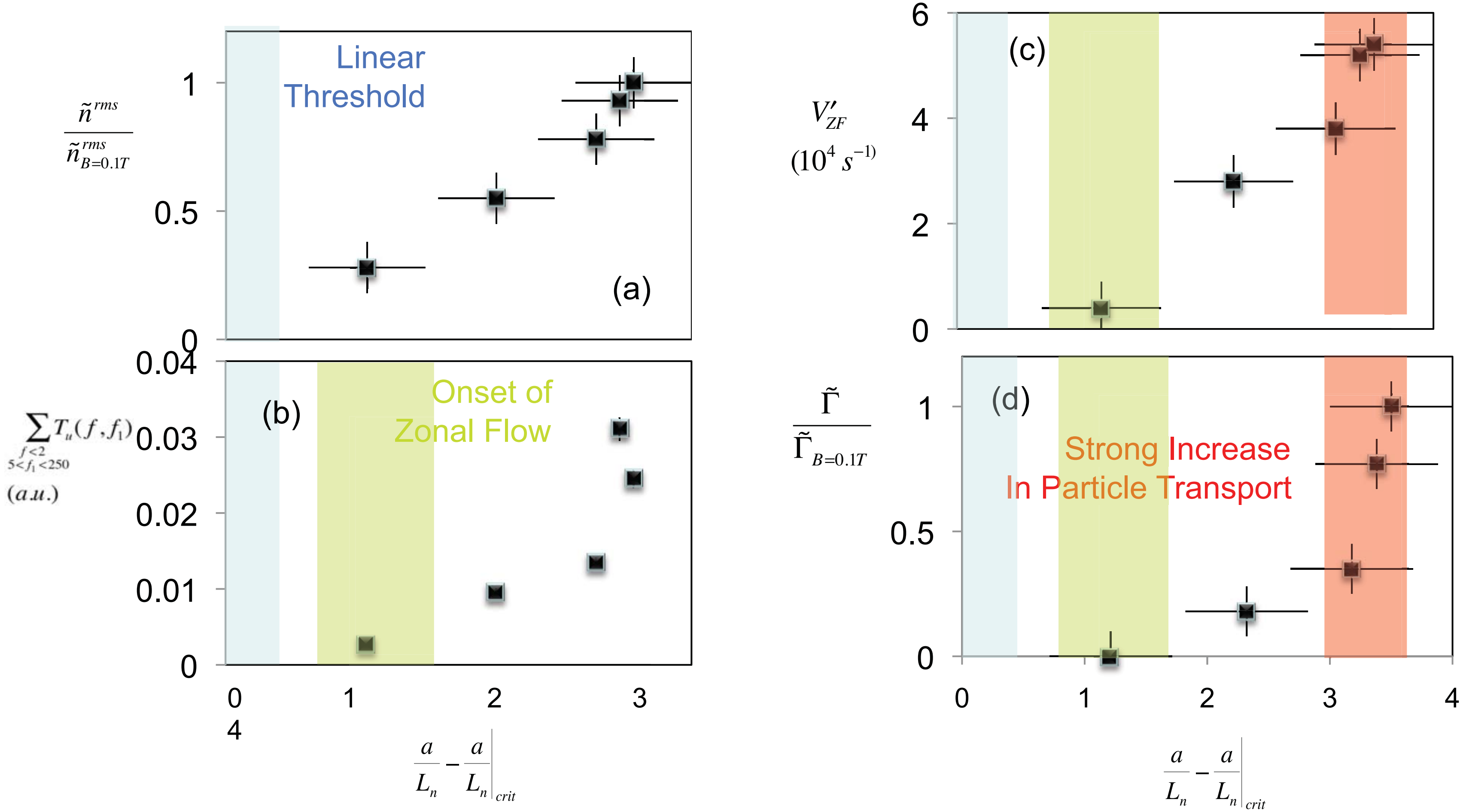
CSDX

$$\left.\frac{a}{L_n}\right|_{\exp}^{\max} \quad or \quad \left.\frac{a}{L_n}\right|_{crit}$$



$$B\ (Tesla)$$

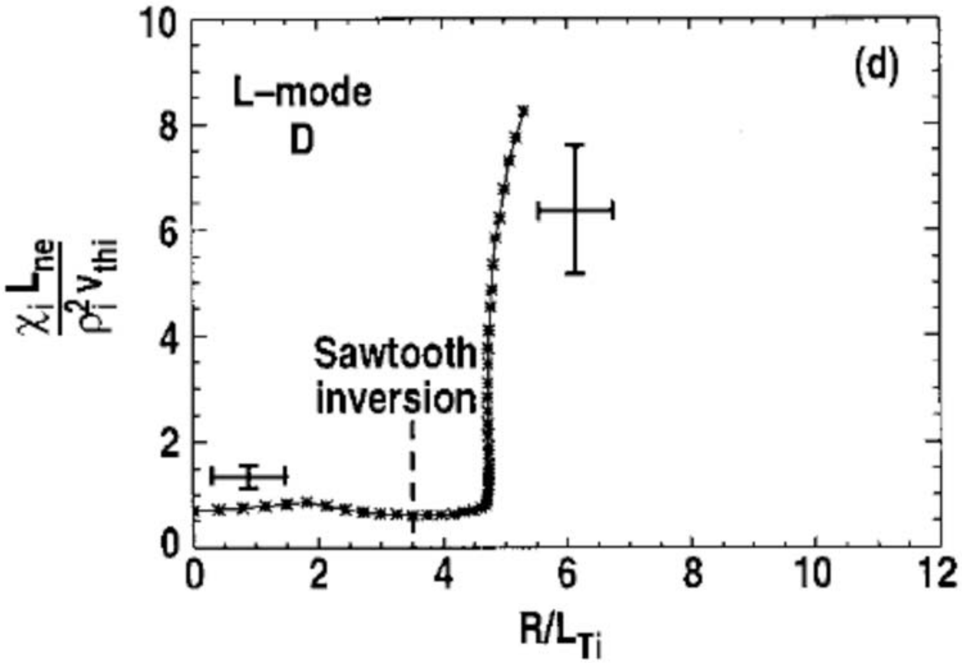
Evolution of DWT-ZF System vs. Critical Gradient



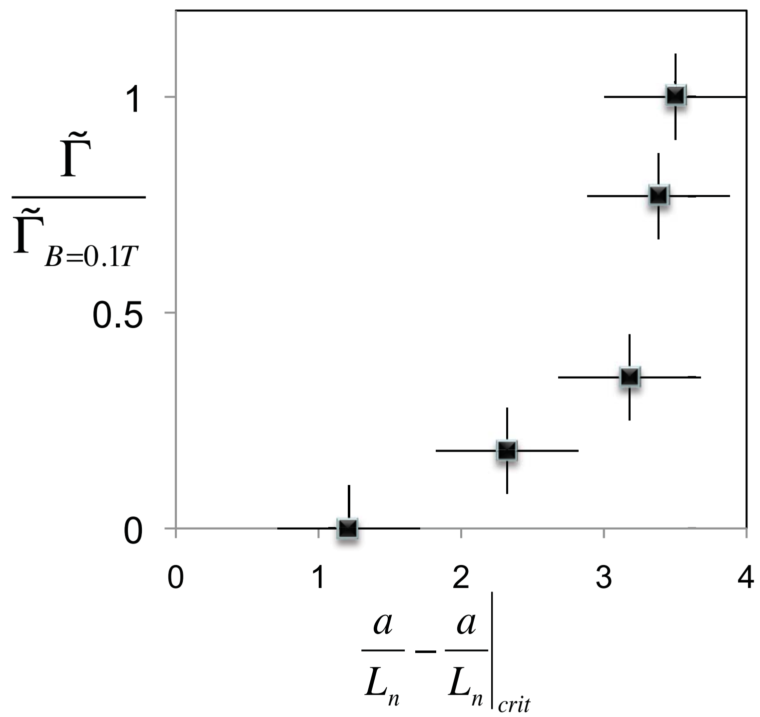
Implies "STIFF" Profiles vs Flux

Result is Similar to Tokamak Thermal Transport

DIII-D, Baker PoP'01



CSDX Linear Device



Implies "**STIFF**" Profiles At/Near Critical Gradient

Conclusions

- Nonlinear dynamics of coupled DWT/ZF system in simple system qualitatively consistent with theory
- Show evidence for a non-diffusive turbulent stress at plasma boundary & diffusive transport in center acting to drive rotation
- Demonstrate Critical Gradient dynamics of the system

→ SIMPLE PLASMA SYSTEM EXHIBITS THREE KEY NONLINEAR DYNAMICAL PROCESSES THOUGHT TO OCCUR IN FUSION SYSTEMS