7^{th} Workshop on the Interrelationship between Plasma Experiments in Laboratory and Space, IPELS 2003

Anisotropic Turbulence in Laboratory Plasmas

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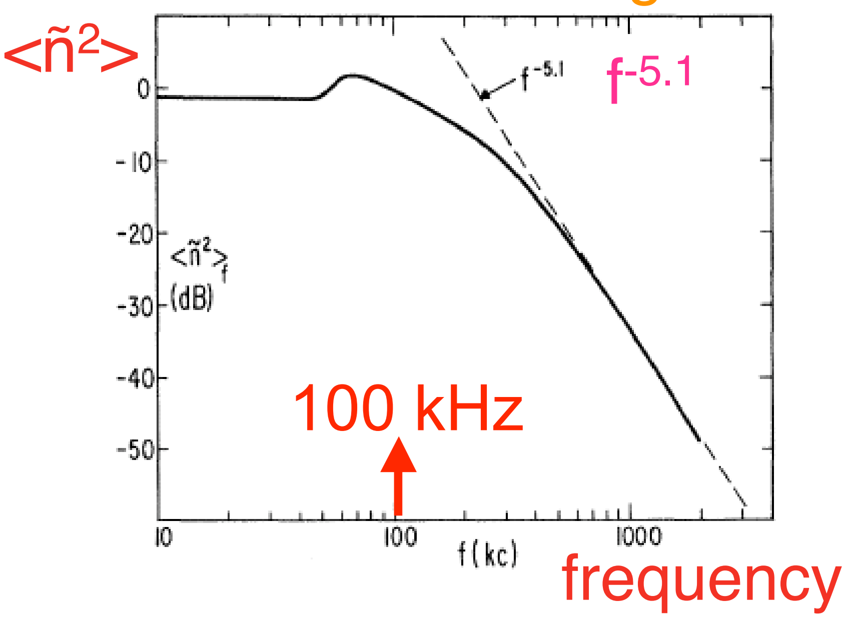
Outline

- Introduction: anisotropic turbulence in lab plasmas
  - summary of observations
  - drift wave model *vs.* experiments
- Drift wave turbulence in tokamak plasmas
  - motivation
  - 2-D imaging of edge turbulence
  - comparison of simulation *vs.* experiment
- Relationship to turbulence in space plasmas

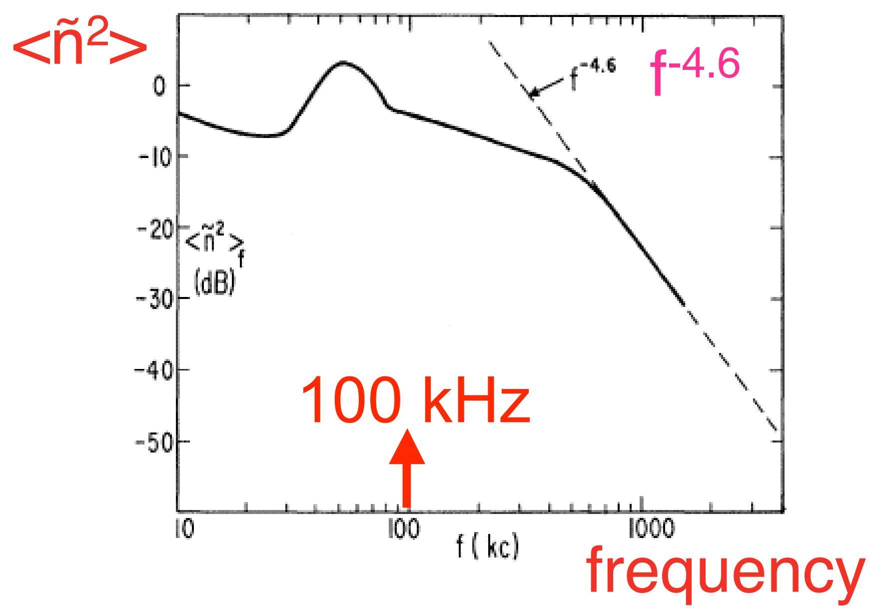
Turbulence in Laboratory Plasmas

- Most easily seen as low frequency (□ < □$_{ci}$) random fluctuations in Langmuir probe signals (i.e. in □n and □□), perhaps first reported by Bohm in 1940's
- Apparent universality of spectrum noted by Chen in '65

Linear discharge



Etude stellarator



Characteristics of Lab Turbulence

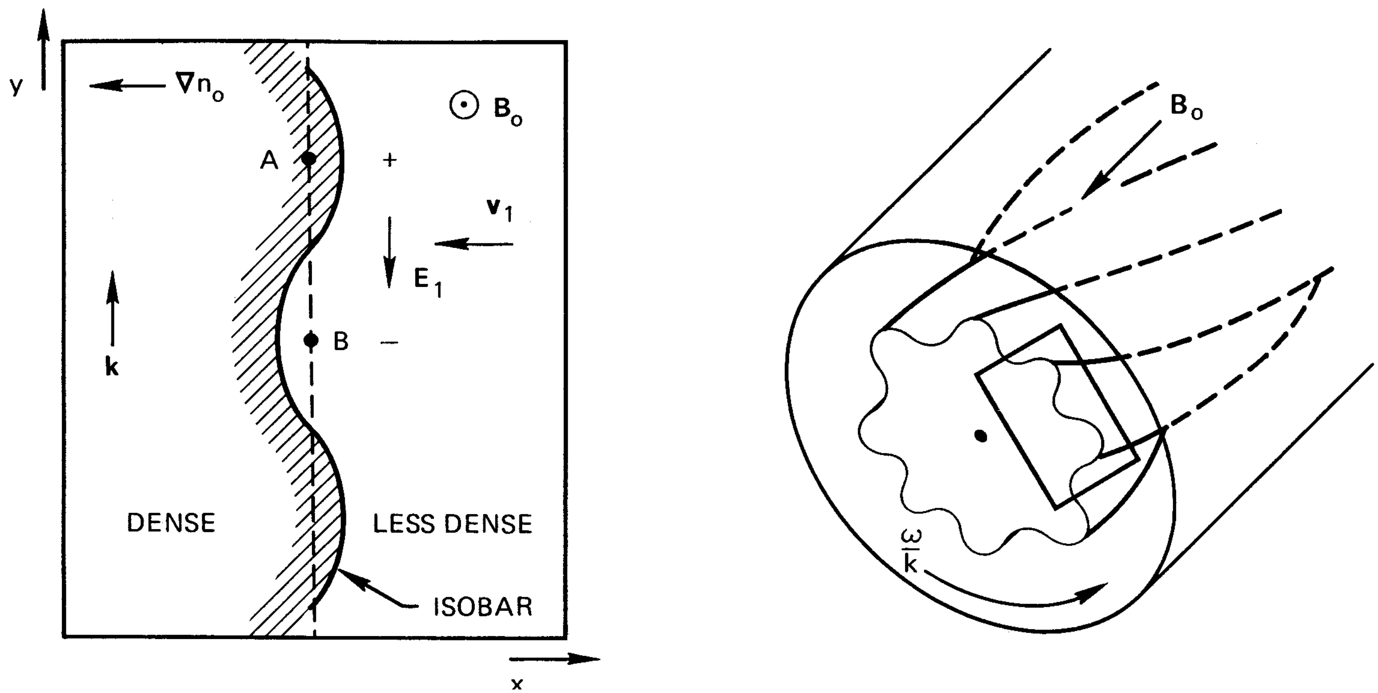
In low β magnetized plasmas with $\rho_i < a$:

- $\omega \approx \omega_{drift} \ll \Omega_{ci}$ => near diamagnetic drift frequency
- $k_\perp \rho_i \approx 0.3$ => transverse scale set by ion gyroradius
- $k_\parallel \ll k_\perp$ => highly anisotropic with respect to B
- $\delta n/n \approx 1/(k_\perp L_n)$ => level reaches "mixing length" limit
- $|e\delta\phi/kT_e| \approx |\delta n/n|$ => seems dominantly electrostatic
- $\delta B_\perp/B \ll \delta n/n$ => small magnetic fluctuations

=> all consistent with "*drift wave turbulence*"

Drift Wave Model

- Driven by pressure gradients in magnetized plasma
- Destabilized by resistivity, rotation, parallel current, etc.
- Linear theory very well developed since 60's



from Chen, Plasma Physics (1984)

Lab Experiments vs. Drift Waves Model

- Early experiments on Q-machines identified *coherent* oscillations as drift waves based on *linear theory* (e.g. Hendel and Chu, Phys. Fluids '68)

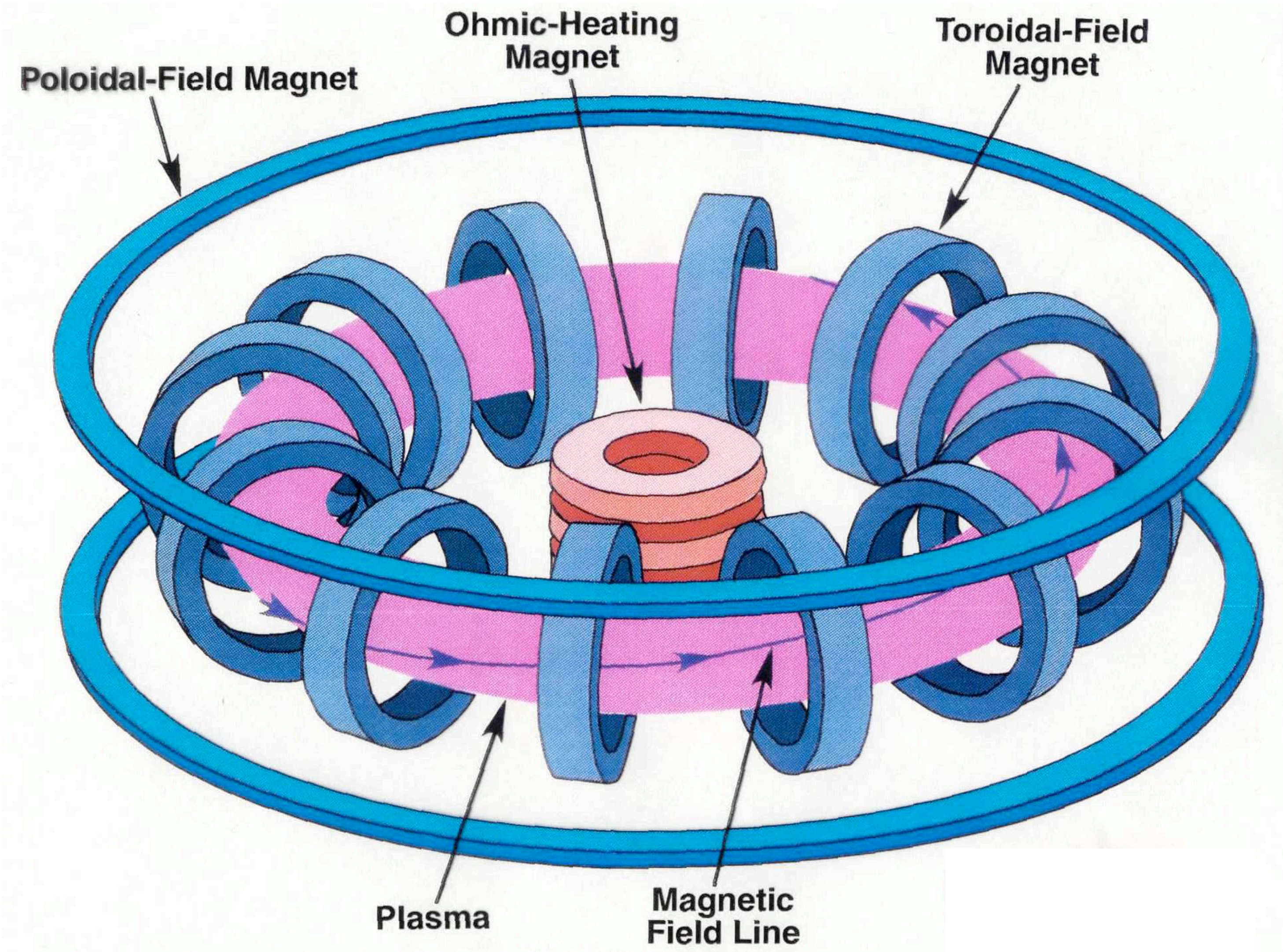
- But quantitative comparisons were difficult since waves were observed in their "saturated" steady-state
  => *need to compare with nonlinear theory*

- Comparisons of drift wave experiments with nonlinear theory are so far *marginally successful* at best (e.g. Sen, Klinger, Tynan)

=> good quantitative agreement not yet obtained

Tokamak

Tokamak = toroidal magnetic chamber (Russian acronym)



Turbulence in Tokamaks

Motivations for studying this:

- Drift wave turbulence probably causes the anomalous (i.e. non-collisional) plasma energy loss in tokamaks
- Understanding this process might lead to the design of a better MFE reactor

Tokamak parameters ($R \approx 1$ m, $R/a \approx 3$, $B \approx 1$ Tesla):

Core: $T \approx 1\text{-}10$ keV
$n \approx 10^{14}$ cm^{-3}
□ $\approx 1\text{-}100\%$

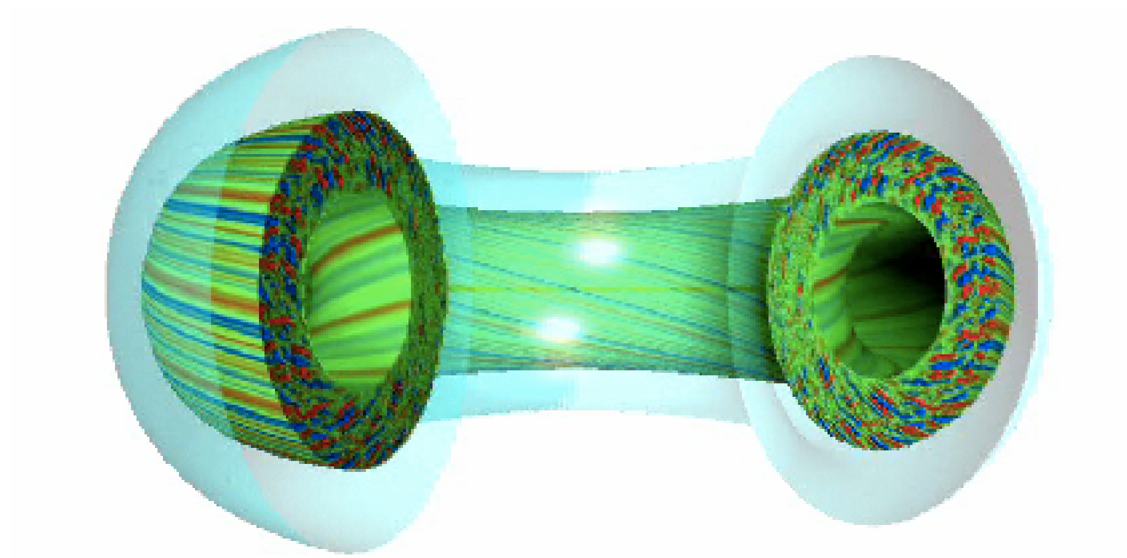
Edge: $T \approx 10\text{-}100$ eV
$n \approx 10^{12}\text{-}10^{13}$ cm^{-3}
□ $\approx 10^{-4}\text{-}10^{-5}$

Drift Wave Turbulence in Tokamaks

- Measured turbulence looks similar to laboratory turbulence
  - limited measurements in hot core (e.g. scattering)
  - extensive probe measurements in edge (≤ 50 eV)
- Nonlinear simulations show electrostatic turbulence with

  $k_{||} << k_{\perp}$ driven by temperature or density gradients

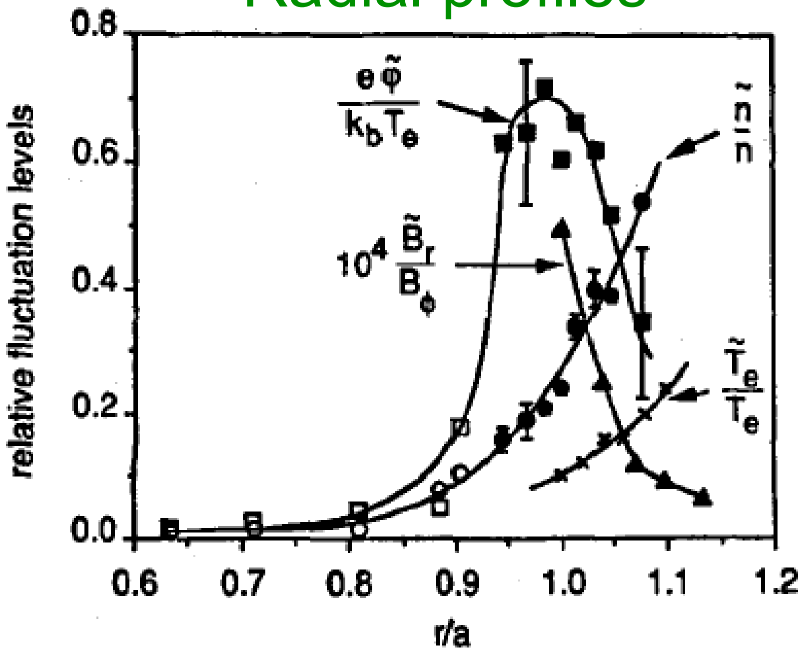
3-D simulation of tokamak drift wave core turbulence (Candy and Waltz, '03)



Edge Turbulence in Tokamaks

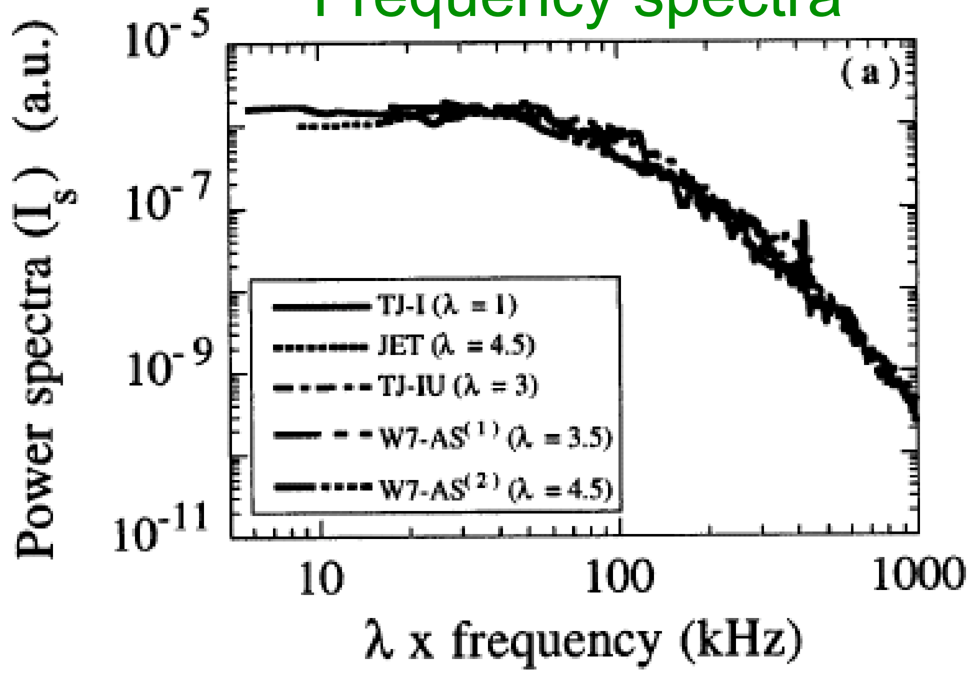
- Dominantly electrostatic with $\delta n/n \geq 0.1$ but $\delta B_{\theta}/B \approx 10^{-5}$
- Similar broadband frequency spectrum in many devices
- Responsible for particle and heat transport across edge

Radial profiles



Wootton et al, Phys. Fl. B ‘90

Frequency spectra



Pedrosa et al, PRL ‘99

Edge Density Turbulence Imaging

NSTX

R = 85 cm

a = 68 cm

A = 1.25

I ≤ 1.5 MA

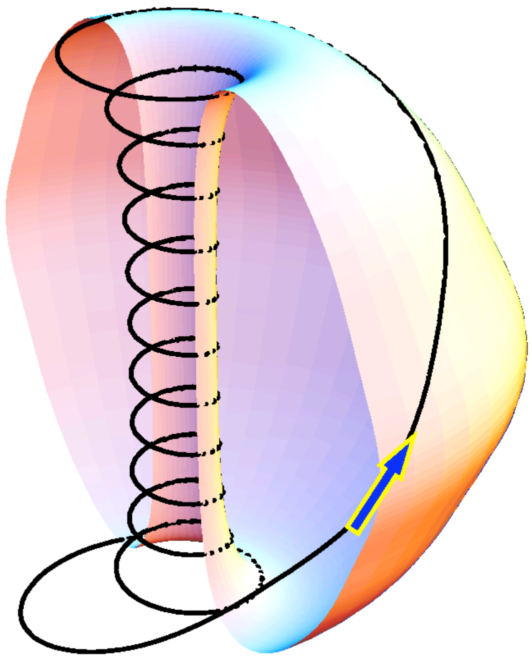
B ≤ 6 kG

5 MW NBI

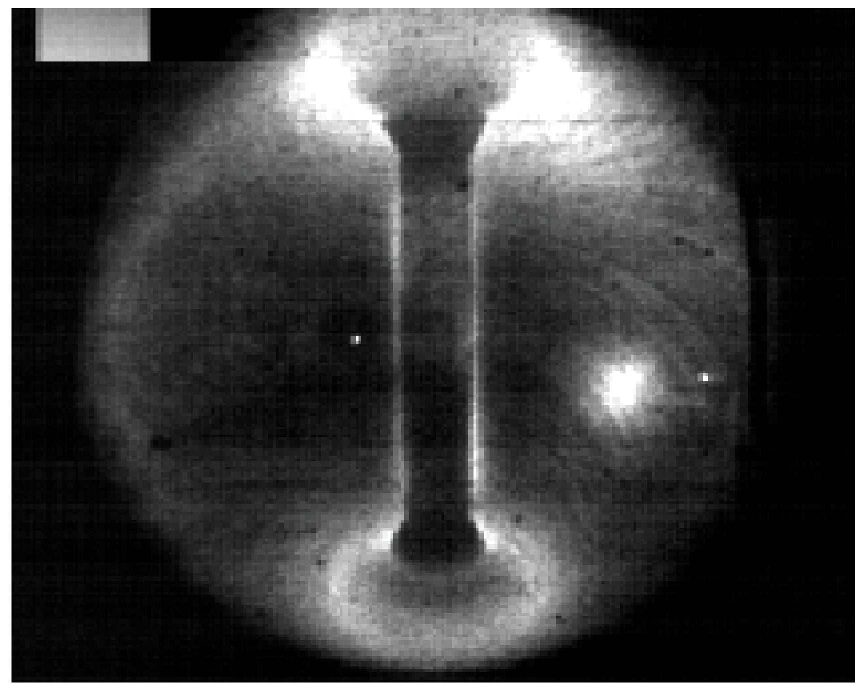
6 MW ICRH

$\beta_T \leq 35\%$

Magnetic structure of edge plasma

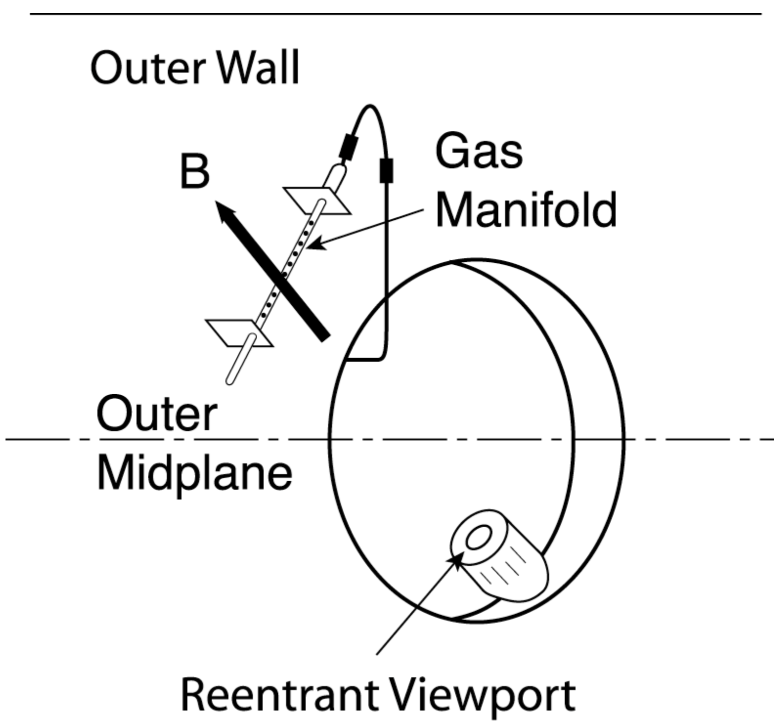


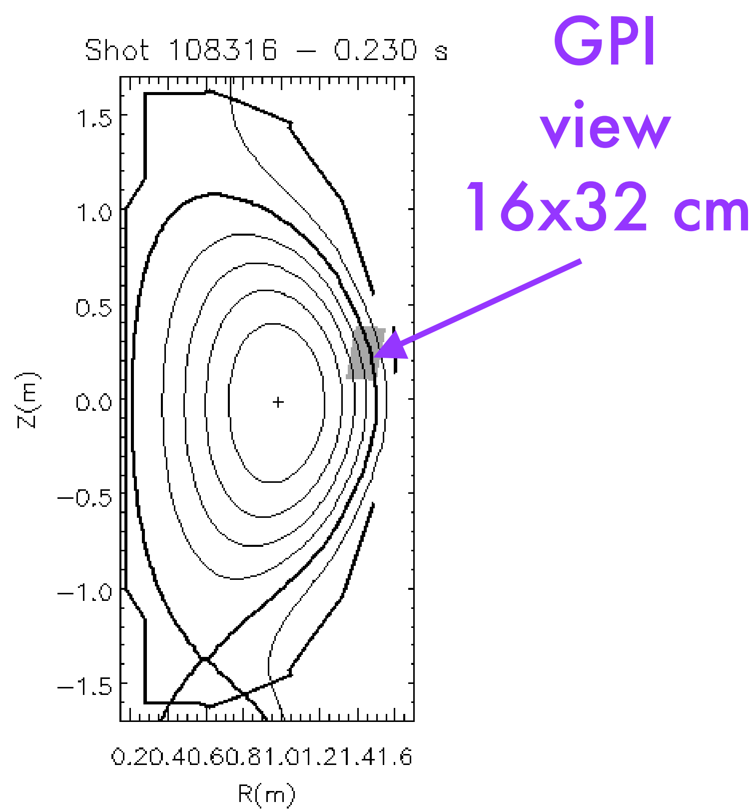
fast camera 10 µsec/frame at 1000 frames/sec



Gas Puff Imaging Diagnostic

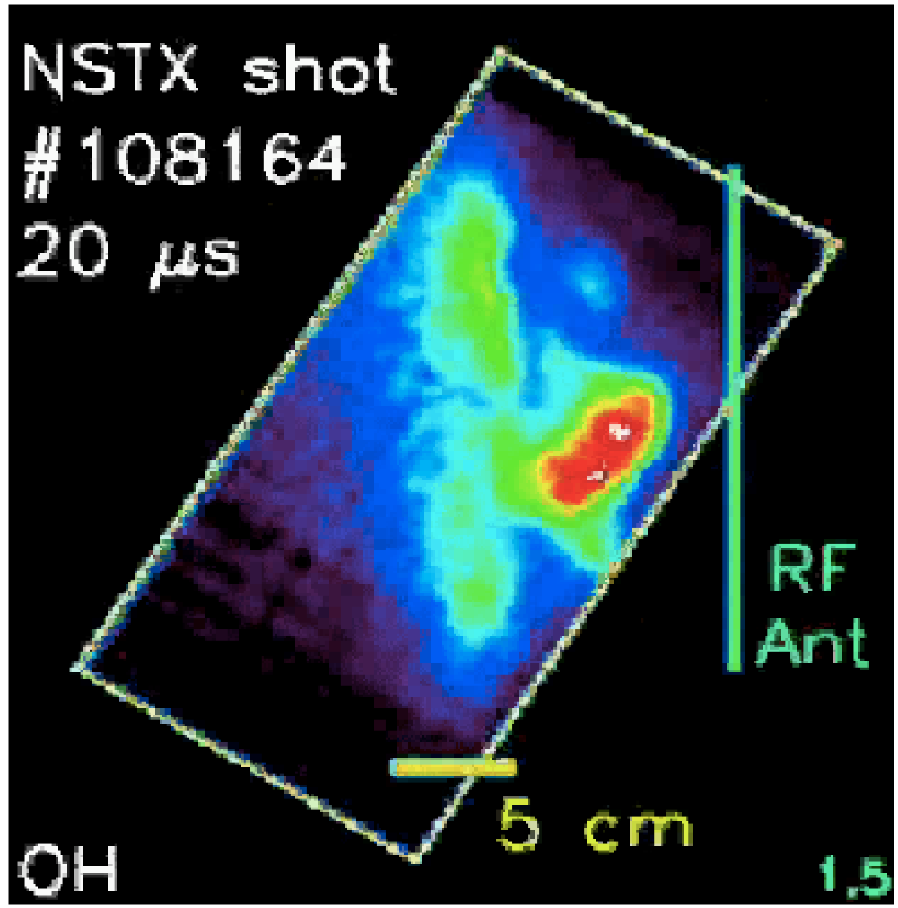
- Looks at He1(578.6 nm) from gas puff I $n_o n_e f(n_e,T_e)$
- View along B field line to see 2-D structure B





Imaging of NSTX Edge Turbulence

CCD camera with
100,000 frames/sec
at 10 μsec/frame
for 28 frames/shot



[Zweben, Maqueda et al, sub. to NF ‘03]

Imaging of Alcator C-Mod Turbulence

- This plasma has 15 times the toroidal field of NSTX

Alcator C-Mod

R = 67 cm

a = 23 cm

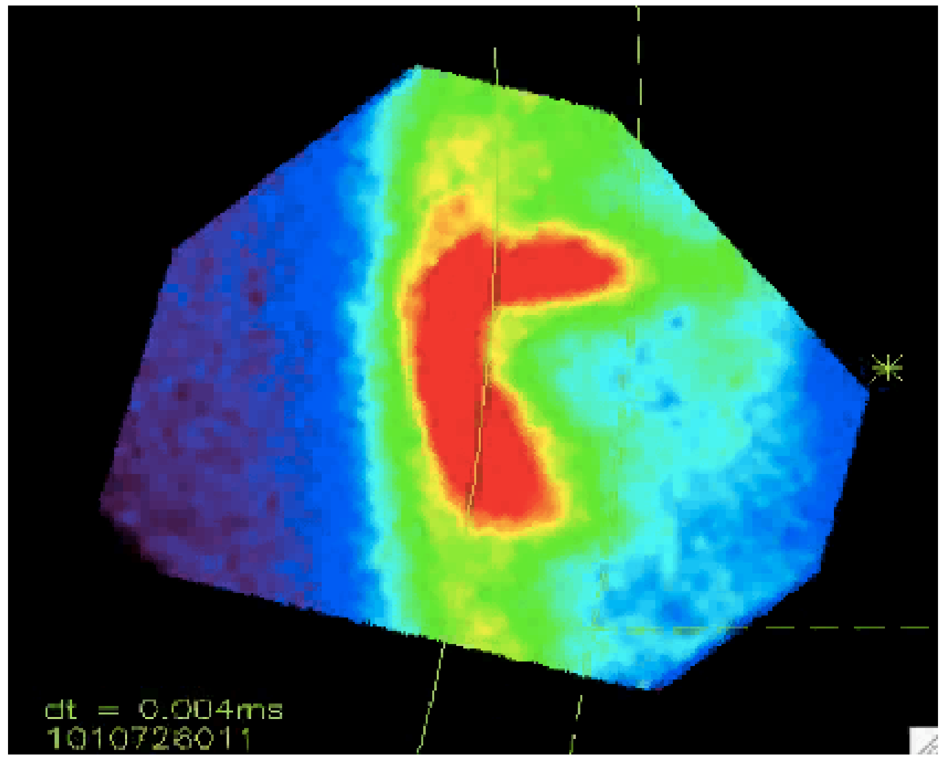
A = 3

I ≤ 1.5 MA

B ≤ 80 kG

5 MW ICRH

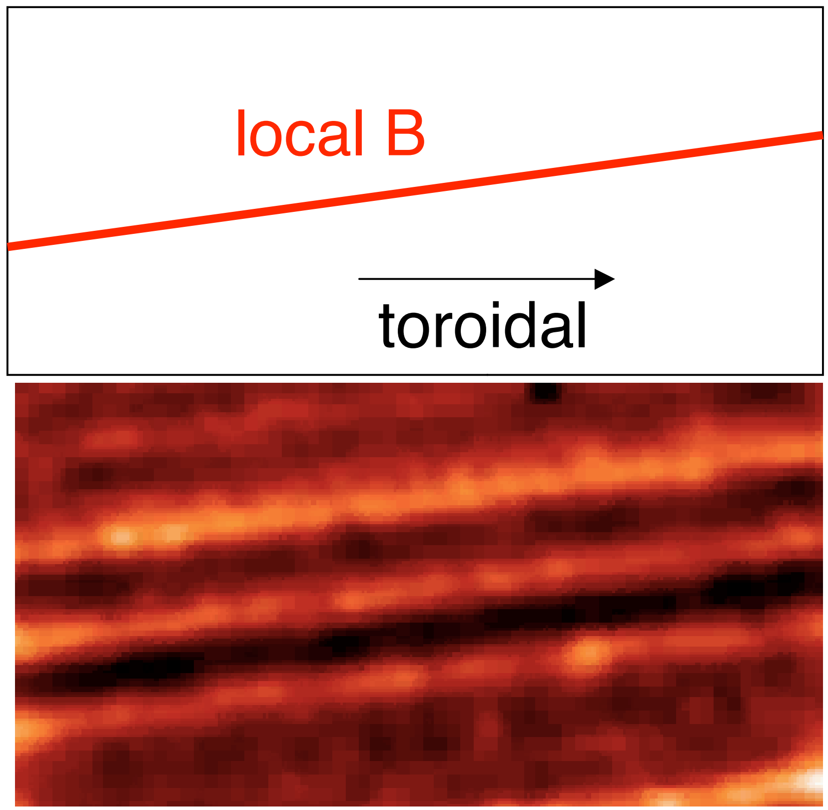
$\beta_T \approx 1\%$



[Zweben, Terry et al, Phys. Plasmas ‘02]

Anisotropy of C-Mod Edge Turbulence

- View D_{α} light emission horizontally from side of tokamak



Simulation of Edge Turbulence

- Use 2-fluid equations in 3-D geometry
- Assume initial conditions and evolve

$$\hat{\alpha}[\partial_t \tilde{\psi} + \alpha_d \partial_y \tilde{\psi}(1 + 1.71\eta_e)] - \nabla_\| [\tilde{\phi} - \alpha_d(\tilde{p}_e + 0.71\tilde{T}_e)] = \tilde{J}, \qquad (1)$$
□B

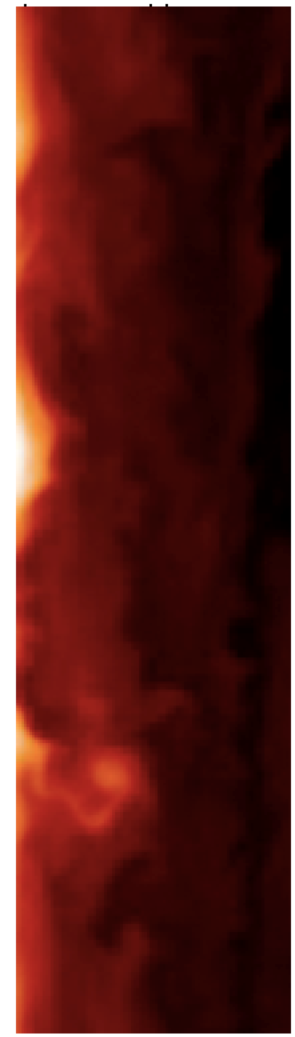
$$\nabla_\perp \cdot d_t \nabla_\perp (\tilde{\phi} + \tau \alpha_d \tilde{p}_i) + \hat{C}(\tilde{p} + \tilde{G}) - \nabla_\| \tilde{J} = 0, \qquad (2)$$
□E

$$d_t \tilde{n} + \partial_y \tilde{\phi} = \tilde{F}, \qquad \tilde{F} = \epsilon_n \hat{C}(\tilde{\phi} - \alpha_d \tilde{p}_e) - \epsilon_v \nabla_\| \tilde{v}_\| + \alpha_d \epsilon_n (1 + \tau) \nabla_\| \tilde{J}, \qquad (3)$$
□n

$$d_t \tilde{T}_i + \eta_i \partial_y \tilde{\phi} = \frac{2}{3}[\tilde{F} + \frac{5}{2}\epsilon_n \tau \alpha_d \hat{C} \tilde{T}_i + \kappa_i \nabla_\| (\nabla_\| \tilde{T}_i + \hat{\alpha} \eta_i \partial_y \tilde{\psi})], \qquad (4)$$
□T_i

$$d_t \tilde{T}_e + \eta_e \partial_y \tilde{\phi} = \frac{2}{3}[\tilde{F} - \frac{5}{2}\epsilon_n \alpha_d \hat{C} \tilde{T}_e + 0.71 \alpha_d \epsilon_n (1 + \tau) \nabla_\| J + \kappa_e \nabla_\| (\nabla_\| \tilde{T}_e + \hat{\alpha} \eta_e \partial_y \tilde{\psi})], \qquad (5)$$
□T_e

$$d_t \tilde{v}_\| = -\epsilon_v [\nabla_\| (\tilde{p} + 4\tilde{G}) + (2\pi)^2 \alpha \partial_y \tilde{\psi}], \qquad (6)$$
□$v_{||}$



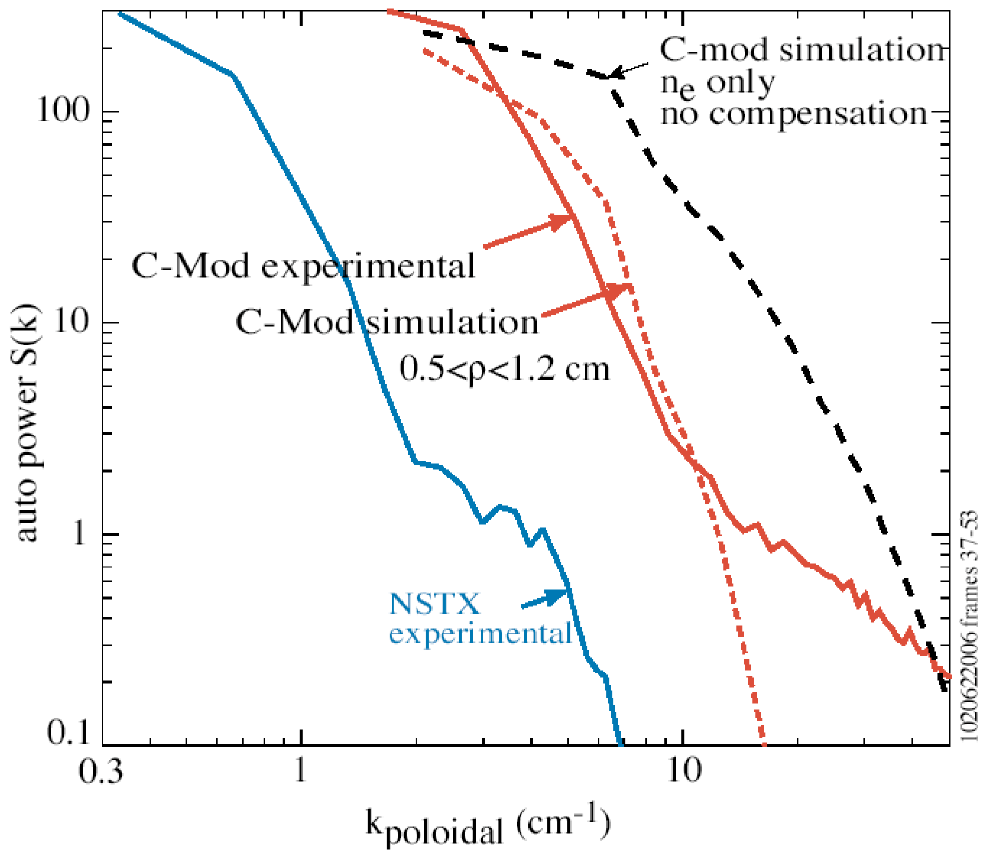
[Rogers, Drake, and Zeiler, PRL '98]

[Hallatschek '02]

radius

Simulation *vs.* Experiment

- Simulation reproduces k_{pol} spectrum fairly well, after taking into account the instrument resolution
- Also reproduces fluctuation level, frequency spectrum, and transport to within a factor of x 2 or so
- Similar level of agreement obtained in a comparison with core turbulence [Ross et al, PoP ‘02]



Terry et al, IAEA ‘02

Is there Similar Turbulence in Space ?

thanks for references: T. Carter, F. Cheng, O. Grulke, G. Hammett, H. Ji, J. Johnson, S. Kaye, R. Kulsrud, G. Morales, D. Newman, B. Rogers, M. Yamada

- Look for low-β plasma fluctuations with:
  - $k_{||} << k_{\perp}$
  - $k_{\perp}\rho_i \approx 1$
  - $e\delta\phi/kT_e \approx \delta n/n$
  - $\delta B_{\perp}/B \approx \beta\ \delta n/n$

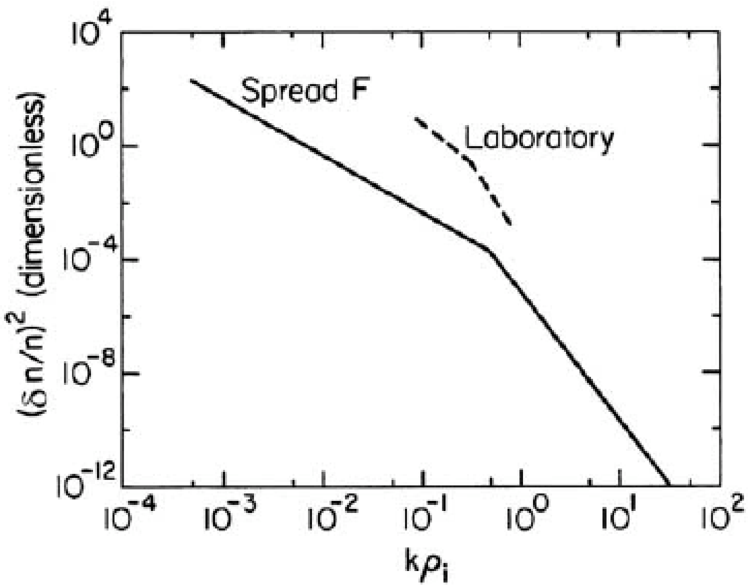
- In:
  - ionosphere
  - aurora
  - magnetosphere
  - solar coronal loops
  - interstellar space

Turbulence in "Equatorial Spread F"

[Kelley, Franz et al , JGR '02, Steigies, Block et al , JGR '01]

- See fluctuations in ionospheric n_e with radar and rockets at ≈ 300 km above equator

  $n_e \approx 10^{11}\ m^{-3}$; $T_e \approx 0.1$ eV ; B= 0.3 G



- Kelley invokes collisional R-T instability for large-scale structure (□n opposite g)

- Considers drift waves for small-scale structure based on analogy with lab spectra (Prasad et al , PoP '94), but concludes they are *not unstable in the ionosphere*

Turbulence in Aurora

- Broadband □E and □B in aurora
  seen by Cluster at 4-5 R_E
  with $k_□ □_s \approx k_□ □_e \approx 1$, □ <<1

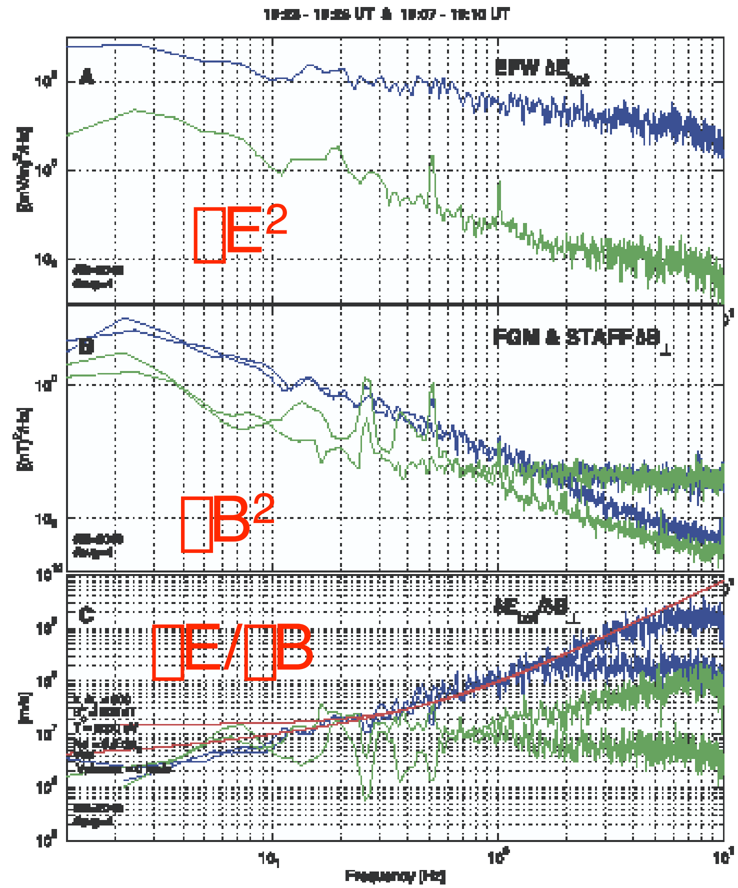
- Identified as Dispersive Alfven
  Wave with $k_{II} << k_□$ and:

  $□E/□B \approx V_A [(1+k_□ □_s) (1+k_□ □_e)]^{1/2}$

- Tokamak edge has (e.g. TEXT):

  $□E/□B \approx (3x10^3 \text{ V/m} / 10^{-4} \text{ T}) \approx V_A$!

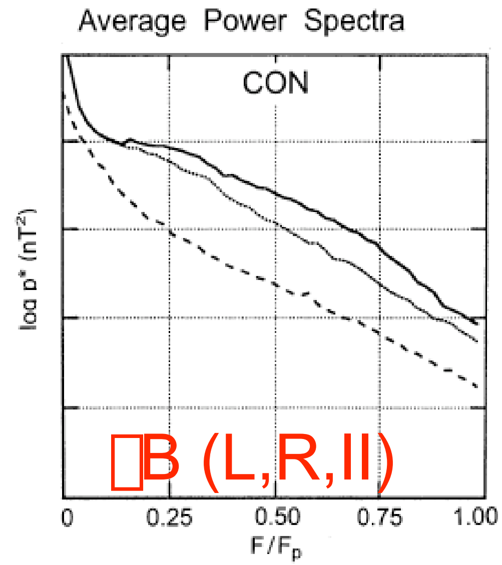
=> looks similar to tokamak ?



Cluster, Wahlund et al, GRL ‘03
Stasiewicz et al, Sp. Sci. Rev. ‘00

Magnetosheath and Magnetopause

- Low frequency turbulence in *magnetosheath* identified as Alfven/ion cyclotron or mirror modes (Schwartz et al, Ann. Geophy. '96);



$n=10^8\ m^{-3}$, $T_\perp \approx 0.2$ keV, $T_{II} \approx 0.1$ keV, $\beta \approx 0.67$

- Similar turbulence in *magnetopause* either local K-H, microtearing modes, or Alfven waves transferred from magnetosheath (Rezeau, Space Sci. Rev. '01)

- Suggestion of gradient-drift instability (Hasegawa '85) considered unlikely since turbulence seems to be independent of local ∇n

Plasma Sheet and Magnetotail

- Small-scale turbulence in *plasma sheet* has spikey electric fields attributed to kinetic Alfven waves (Wygant et al, JGR ‘00, ‘02)

$n \approx 0.3\ cm^{-3}$
$T \approx 2\text{-}4\ keV$
$B \approx 400\ nT$
$\beta \approx 10^{-3}$

$k_{\perp} >> k_{\parallel}$
$k_{\perp}\rho_i \approx 1$
$e\delta\phi/kT_e \approx \delta n/n \approx 0.1 - 1$
$\delta B_{\perp}/B \approx 10^{-3}$

=> *looks similar to tokamak turbulence*

- Substorm may be due to drift-ballooning or compressional-drift wave in *magnetotail* (Miura Sp. Sci. Rev. ‘01, Horton JGR ‘03), but plasma there has $\beta > 1$

Solar Coronal Loops

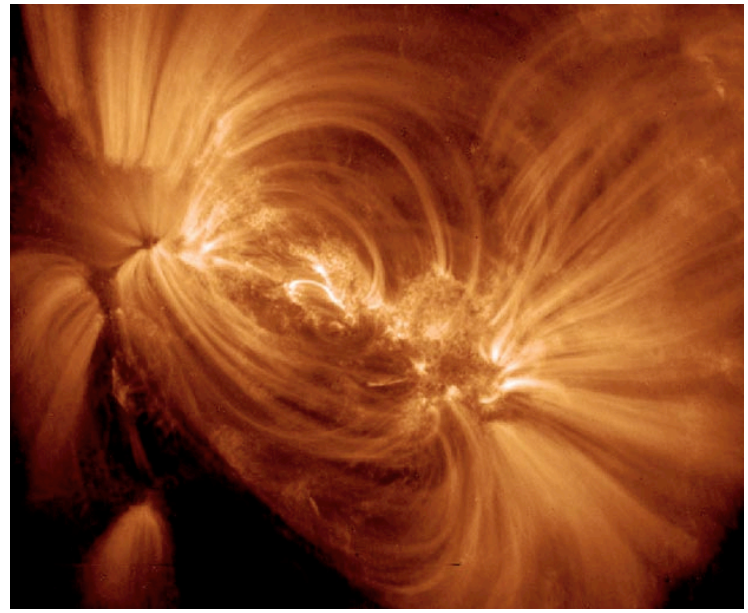
- Fine structure of loops seen by TRACE look like tokamak turbulence with $k_{\perp} >> k_{||} \approx 0$

- However, $k_{\perp} \rho_i \approx 10^{-6}$!

  $L_{\perp} \approx 10^{6}$ m (?)

  $\rho_i \approx 0.3$ m (100 eV, 10 G)

  => *not like tokamaks !*



http://vestige.lmsal.com/TRACE/Science/ScientificResults/trace_cdrom/html/trace_images.html

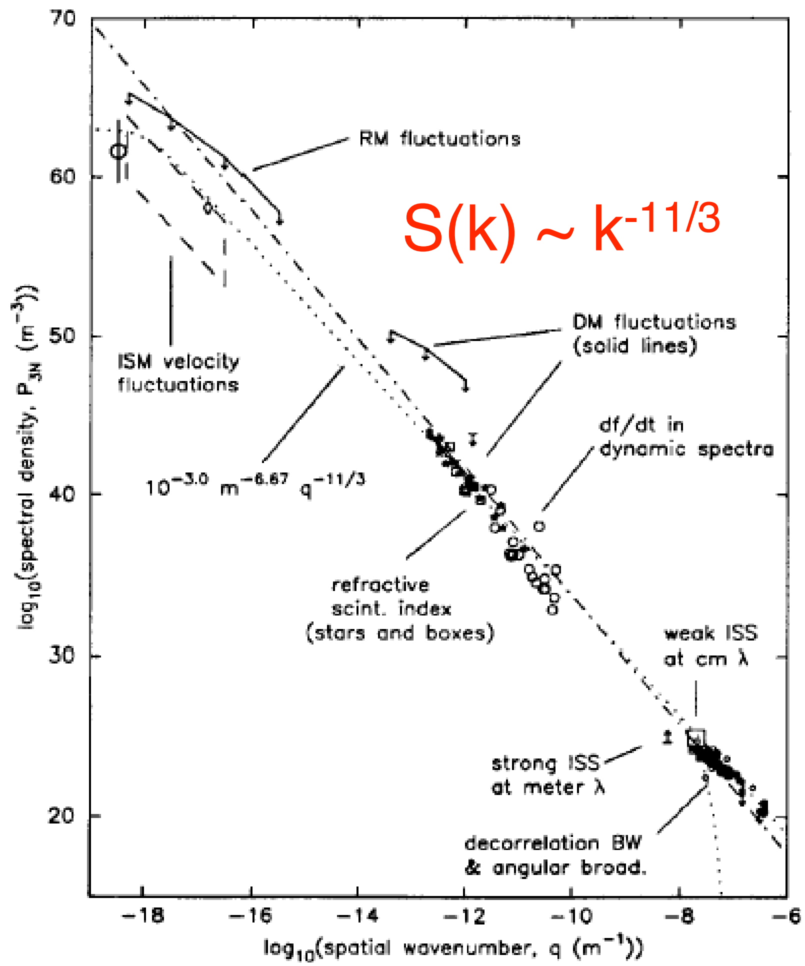
- But maybe this structure is the low-$k_{\perp}$ limit of an “inverse cascade” due to instability at much smaller scales ?

Interstellar Medium (ISM)

- Broad density fluctuation spectrum inferred by RF measurements, evidence for δB and anisotropy

- Turbulence seems generated by large-scale MHD instability not small-scale drift-waves, but near $k_{\perp}\rho_i \approx 1$ it can be modelled with “gyrokinetics”

[Hammett et al, LMS Durham 2002]



Spangler, Sp. Sci. Rev. ‘00

Summary of Lab vs. Space Turbulence

	$k_{\parallel}/k_{\perp}$	$k_{\perp}\rho_i$	$\delta n/n$	$e\delta\phi/kT_e$	$\delta B_{\perp}/B$
tokamak	≈ 0.01	0.1-1	0.01-1	0.01-1	≈ 10^{-5}
ionosph.		10^{-3}-10^{1}	10^{-6}-10^{1}		
aurora	≈10^{-3}	≈ 0.1-10			
pl..sheet	≈ 10^{-3}	≈ 1	0.1-1	0.1-1	≈ 10^{-3}
corona	≈ 0.01 ?	≈ 10^{-6}	≈ 1 ?	≈ 1 ?	≈ 1 ?
ISM	1-10^{-3}	10^{-9} - 1	1-10^{-3}	1-10^{-3}	1-10^{-3}

=> some similarities between tokamak turbulence and space turbulence

Some Questions

- Is the relationship of δE and δB in tokamaks Alfvenic ?
- Does space turbulence depend on local gradients ∇B ?
- Is the perpendicular size scale set mainly by ρ_i or ρ_e ?
- How much can we understand with nonlinear simulations ?
- Can we make better lab simulations of space turbulence ?