Edge Turbulence Measurements

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Outline

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Apologies for many results not mentioned due to lack of space/time !

<u>**Motivation**</u>

- Edge turbulence in magnetic fusion devices strongly influences plasma-wall interaction and probably affects global confinement

=> *probably necessary to understand and control edge turbulence in order to make a fusion reactor*

Overview - Early History

- Bohm (1949): studied plasma ‘hash’ with Langmuir probes to explain cross-field diffusion in magnetized arc plasma
- Chen (1965): pointed out the ‘universal’ spectrum of low-β turbulence and tried to explain it with drift wave theory
- Young (1967): measured edge fluctuations in C-Stellarator and tried to identify transport mechanism from $\langle nv_r \rangle$
- Robinson and Rusbridge (1969, 1971): measured structure of “convective rolls aligned along magnetic field” in Zeta
- Nedospasov (1992) says that edge turbulence has been studied since the earliest tokamaks in Russia (1956)

Overview - Present Status

- Over 400 experimental papers on edge turbulence from over 40 devices (tokamak, RFP,stellarator, laboratory toroidal and linear devices)
- Many common features seen with different diagnostics on different machines, so there seems to be some 'universal' behavior underlying the apparent complexity
- Just beginning to make solid connections between theory and measurements, but so far there is no 'predictive' understanding, e.g. for SOL of ITER

Edge Turbulence Diagnostics

- Electric and magnetic probes
- Electromagnetic scattering
- Microwave reflectometry
- Optical line emission
- Heavy ion beam probe

Previous Reviews:

Gentle, K, Rev. Modern Phys. **67**, 809 (1995)

Bretz N, Rev. Sci. Inst. **68** (1997) 2927

Demidov, V.I., Rev. Sci. Inst. **73**, 3409 (2002)

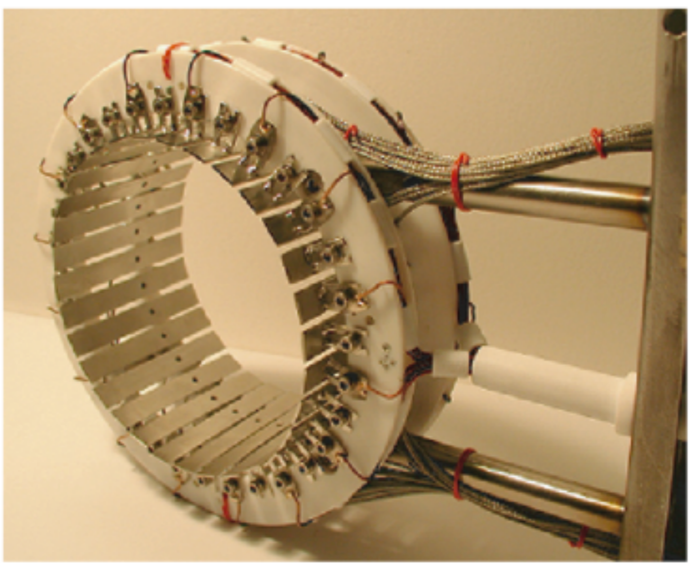
Donne AJH, Fus. Sci. and Tech. **45** (2004) 399

Hartfuss HJ, Plasma Phys. Cont. Fusion 39 (1997) 1693

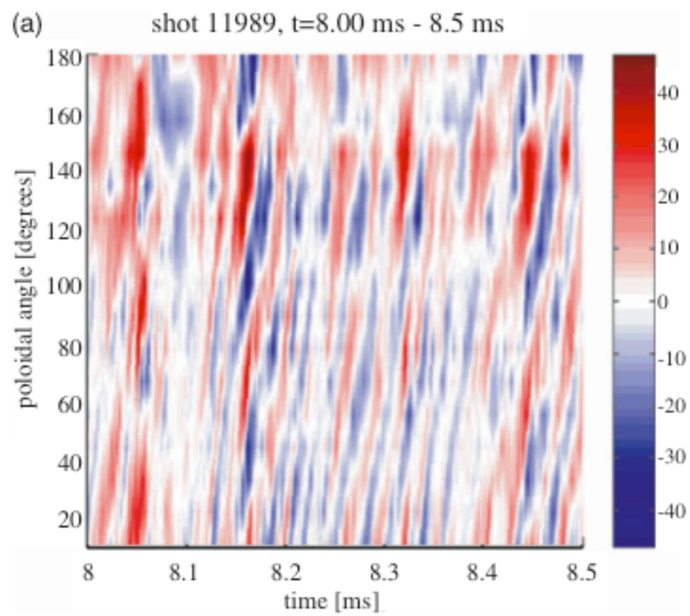
Electric and Magnetic Probes

- Relatively simple to implement and interpret
- Always some concern about probe perturbations

probe array in CASTOR



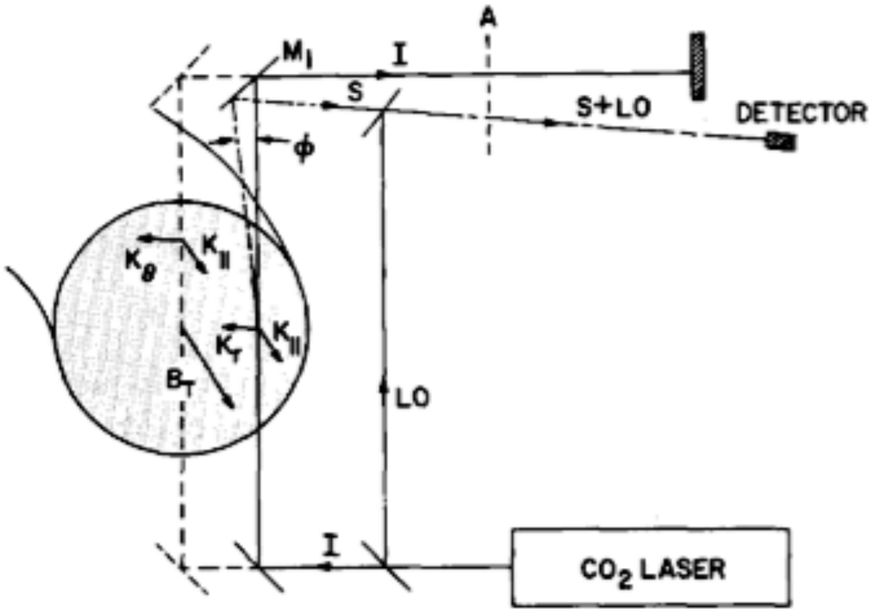
potential flucuations

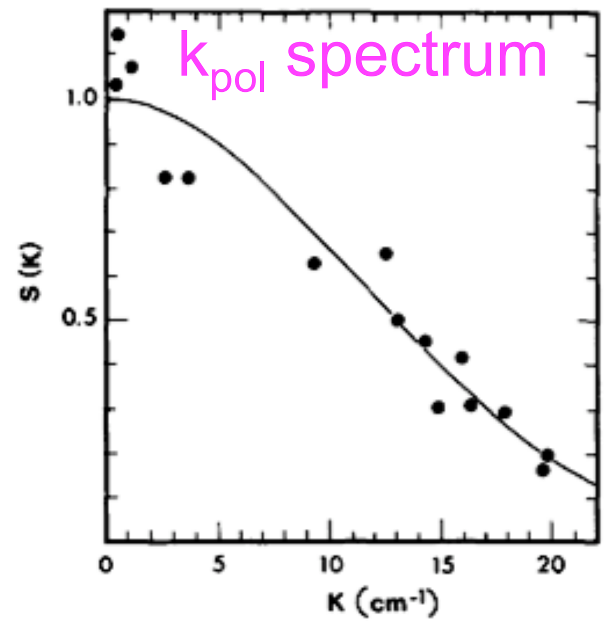


CASTOR tokamak, P.Devynck et al, PPCF 47 (2005) 269

Electomagnetic Wave Scattering

- Scattering volumes generally >> turbulence size scales
- Varying scattering angle provides k-spectrum resolution
- Cross-beam correlation can improve spatial resolution

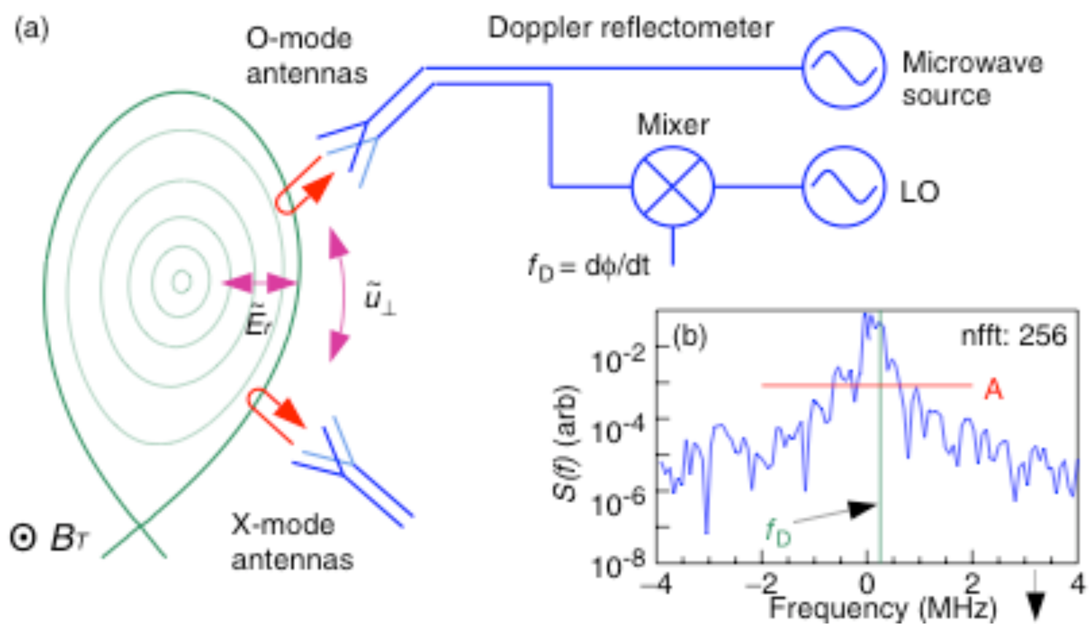




CO_2 scattering Alcator C tokamak, Watterson et al Phys. Fluids 28, 2859 (1985)

Microwave Reflectometry

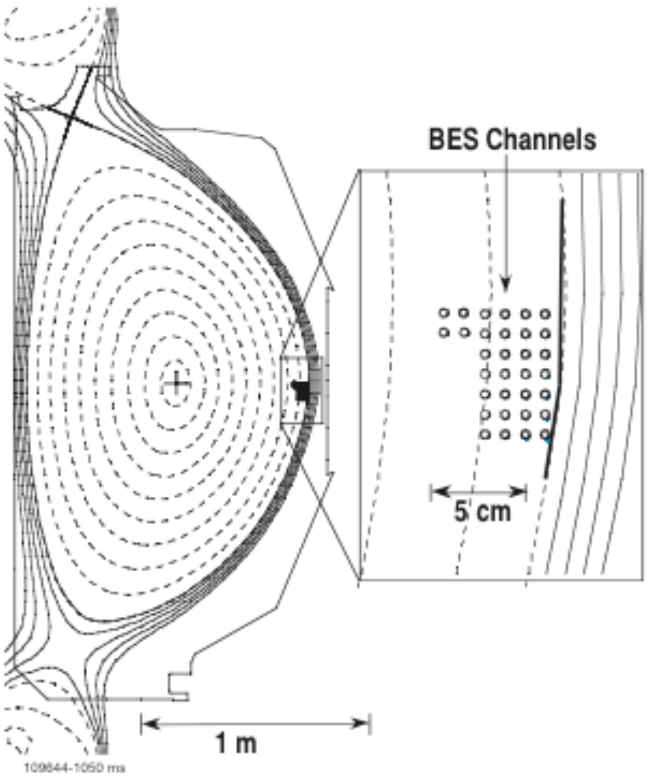
- Measures reflected power from moving cutoff layer
- Detailed interpretation in terms of ñ is complicated
- Tilting receiver allows measurement of poloidal flow

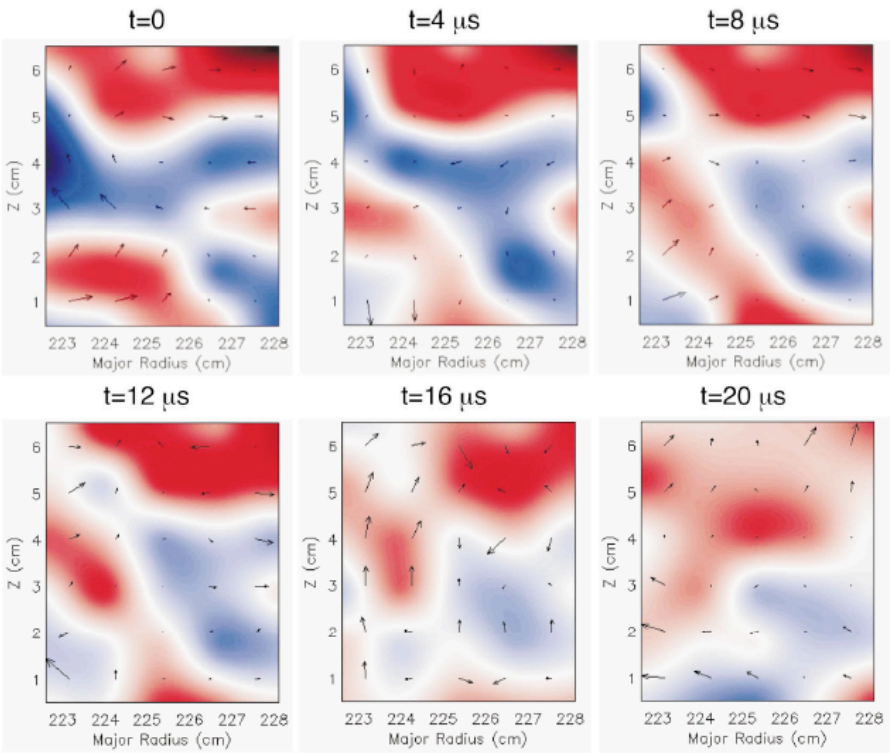


Doppler reflectometry in ASDEX Upgrade, Conway et al, PPCF 47, 1165 (2005)

Optical Line Emission

- View light from beam emission (D, Li, He), or a gas puff
- Emission $\propto n_o f(n,T_e)$, where f is a nonlinear function

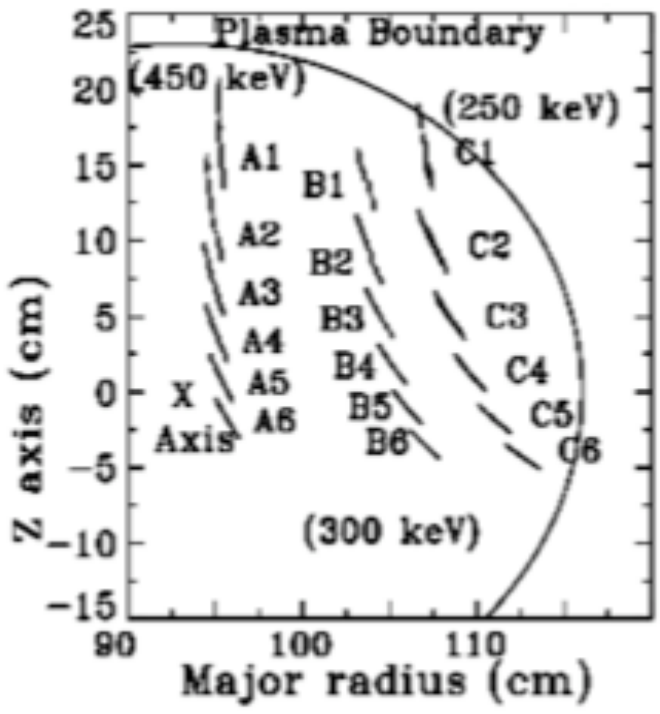


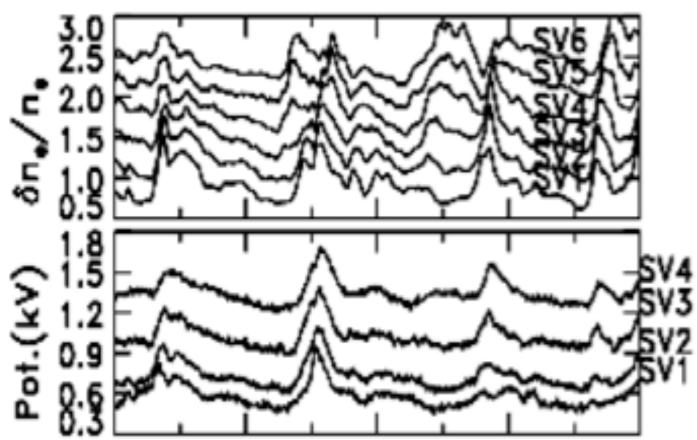


BES in DIII-D tokamak, McKee et al, PPCF, 45, A477 (2003)

Heavy Ion Beam Probe

- Ion beam (e.g. 50-500 keV Th^+) ionized again in plasma
- Secondary beam measures local n and φ at intersection





edge n

edge φ

HIPP-TIIU tokamak, Hamada et al, PRL 96, 115003 (2006)

Data Analysis Methods

- Single-point measurements:
  spectrum, correlation function, probability distribution function, skewness, intermittency, fractal dimension, waiting time distribution, symbolic dynamics, etc.

- Multiple-point measurements:
  phase speed, wavenumber, statistical $S(k,\omega)$, motion of coherent structures by ‘conditional sampling’, etc.

- Image analysis:
  full 2-D structure and motion analysis is possible

$\Rightarrow$ so far no there is no precise definition of a “coherent structure” (blob, intermittent object) in edge turbulence

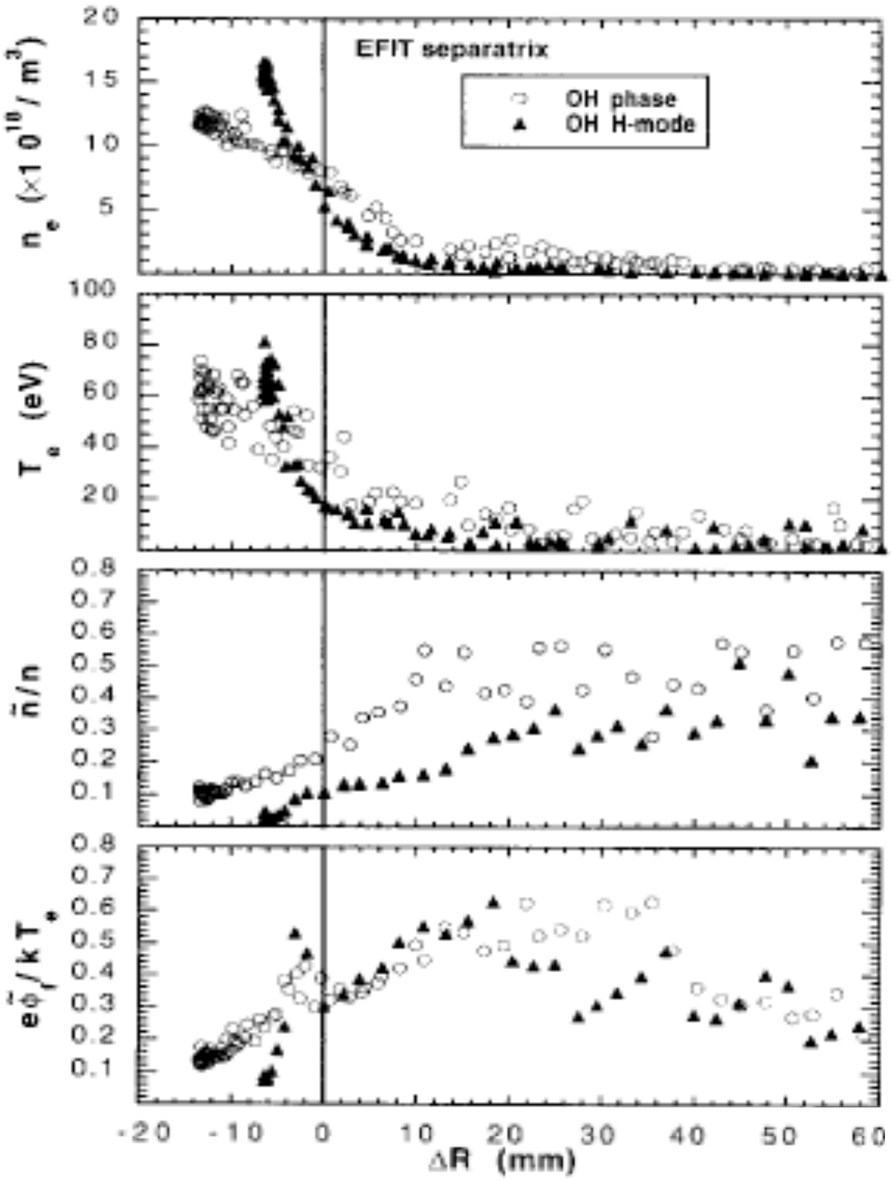
Experimental Results

- Turbulence levels
- Frequency spectra
- Spatial structure
- Poloidal variations
- Parameter Scalings
- Intermittency
- L-mode vs. H-mode
- Edge Flows
- Edge Transport
- Control

Previous Reviews:

Liewer, PC, Nucl. Fusion **25** (1985) 1281
Wootton, AJ et al, Phys. Fluids **B2** (1990) 2879
Nedospasov, AV, J. Nucl. Mat.**196** (1992) 90
Carreras, BA, IEEE Trans. Plasma Sci. **25** (1997) 1281
Endler, M, J. Nucl. Mater. **266-269** (1999) 84
Stangeby P, The Plasma Boundary…, IOP, Bristol (2000)
Hugill J, Plasma Phys. Cont. Fusion **42** (2000) R75
Carreras, BA, J. Nucl. Mater. **337-339** (2005) 315

Turbulence Levels



- Typical edge profiles:

  T_e = 5-50 eV
  $n_e = 10^{12} - 10^{13}$ cm^{-3}

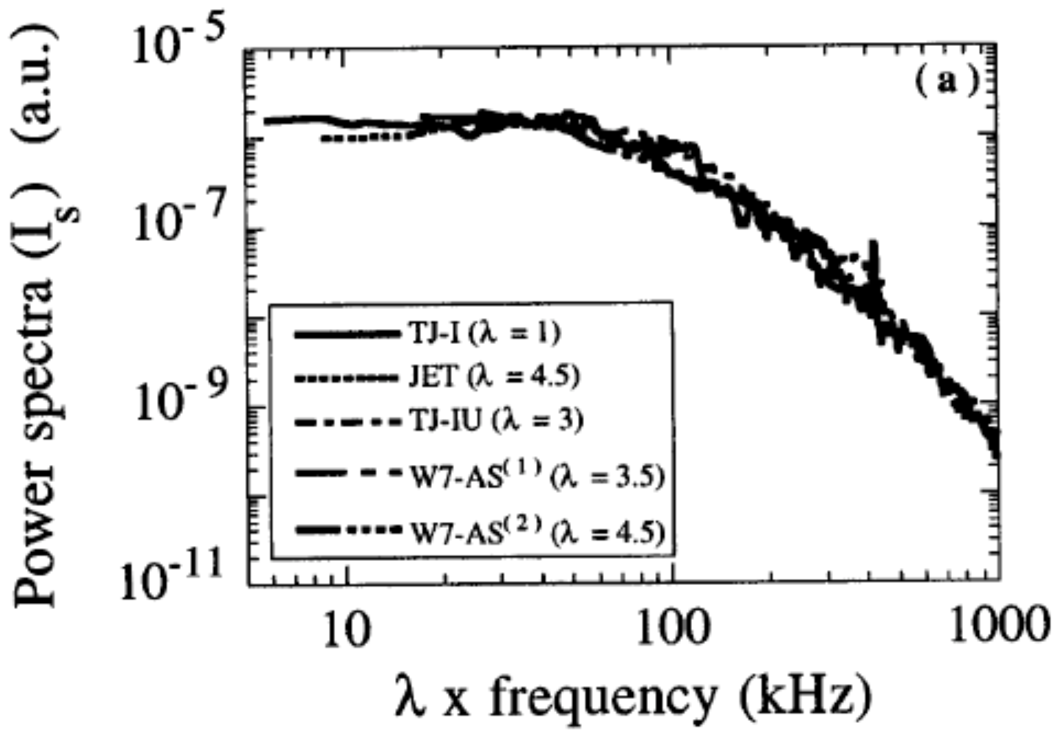
  $\tilde{n}/n \sim 5 - 50\%$
  $e\tilde{\varphi}/T_e \not\sim \tilde{n}/n$
  $\tilde{T}_e/T_e \sim (0.3 - 0.4)\ \tilde{n}/n$
  $\tilde{B}_r/B_T \sim 10^{-5}\ \tilde{n}/n$

DIII-D

Moyer RA et al, J. Nucl. Mat. 266 (1997) 1145

Frequency Spectra

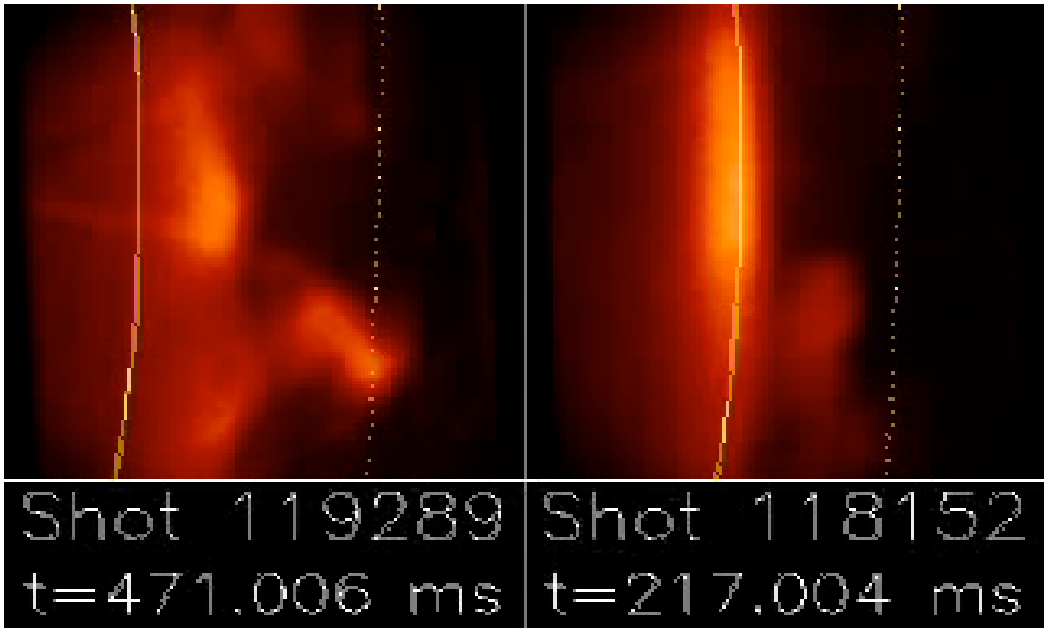
- Spectrum varies with V_{pol}, but usually V_{pol} ~ 0 near LCFS
- "Rescaled" frequency spectra at V_{pol} ~ 0 seem universal



Pedrosa et al, Phys. Rev. Lett. 82, 3621 (1999)

Spatial Structure

- Typically L_{pol} ~ few cm, $L_{rad} \leq L_{pol}$, $L_{II} >> L_{\perp}$
- Broad k-spectrum with $k_{pol}\,\rho_s$ ~ 0.02 - 0.1

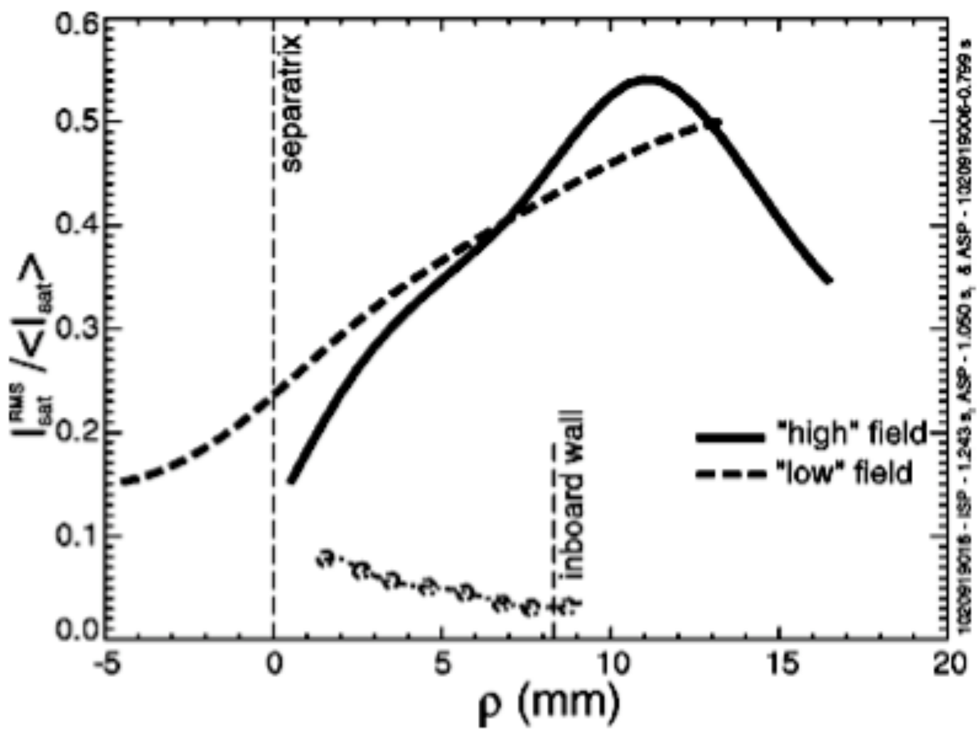


NSTX

R. Maqueda, 2006

Poloidal Variations

- Up/down asymmetry seen with limiters in tokamaks
- Large in-out ballooning seen in a diverted tokamak

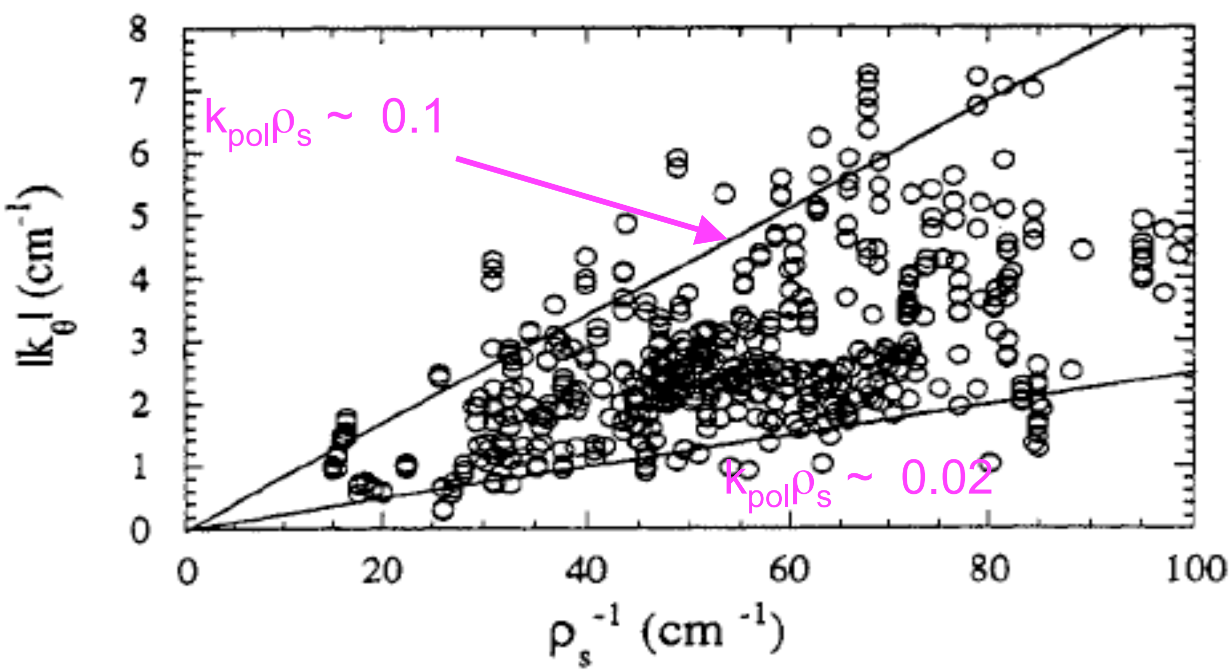


Langmuir probes
Alcator C-Mod

Terry et al, PoP 10, 1739 (2003)

Plasma Parameter Scalings

- Drift wave-like scaling $k_{pol}\rho_s \sim 0.02 - 0.1$ seems usual
- No universal scalings with local plasma parameters

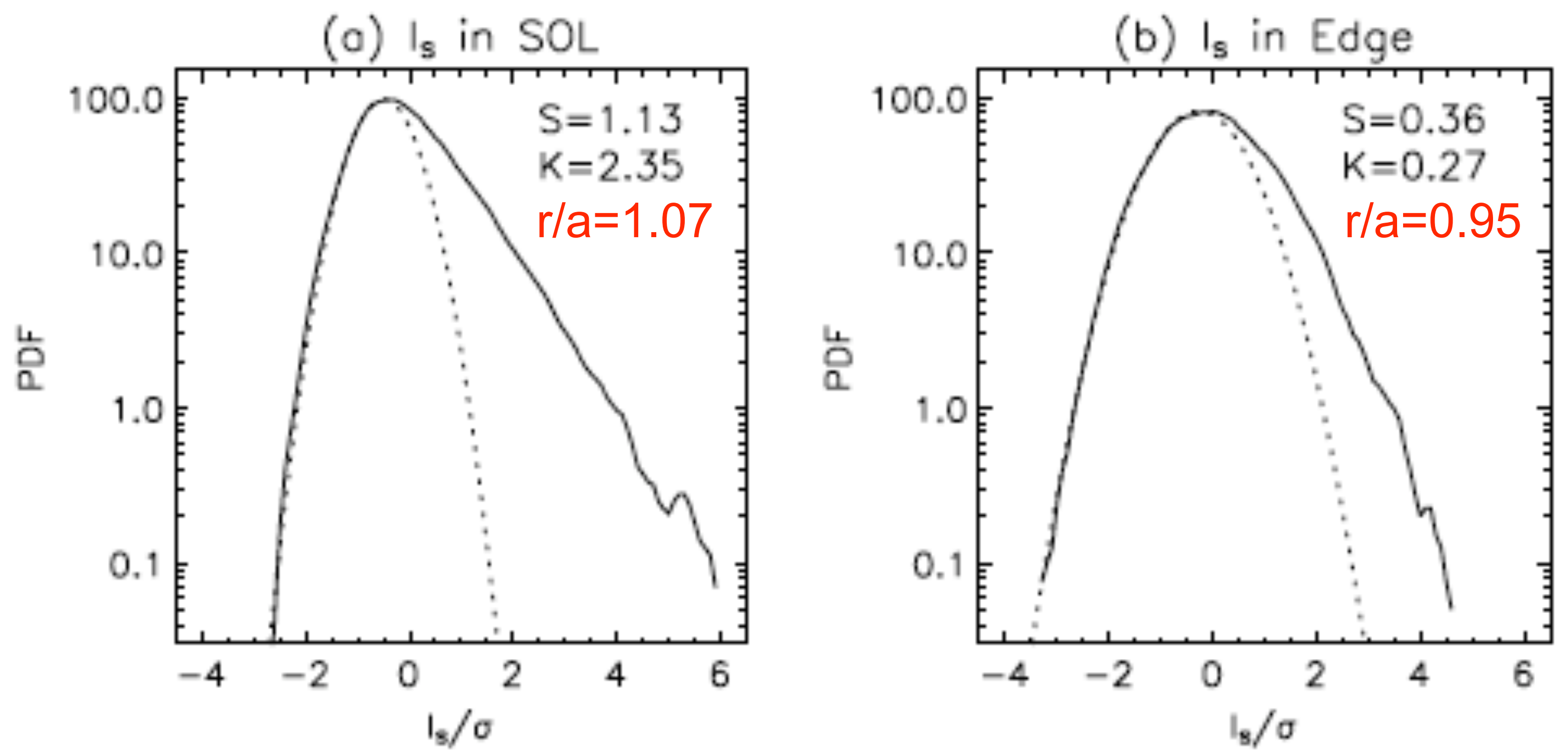


TEXT

Rhodes et al, Nucl. Fusion 33 (1993) 1147

Intermittency

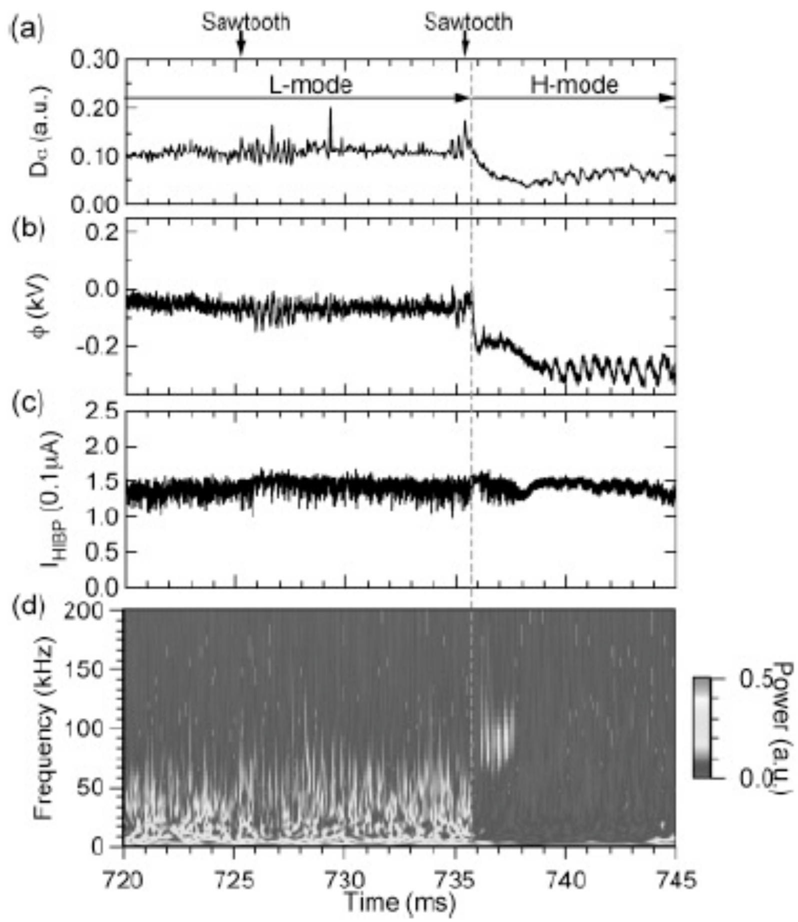
- Non-Gaussian tails in pdf, more pronounced in SOL
- Probably associated with coherent structures (blobs)



TEXTOR, Xu et al, Plasma Phys. Cont. Fusion 47 (2005) 1841

L-mode vs. H-mode

- Decrease in ñ/n usually seen at L-H transition
- Changes in transport are also affected by C(n,φ)

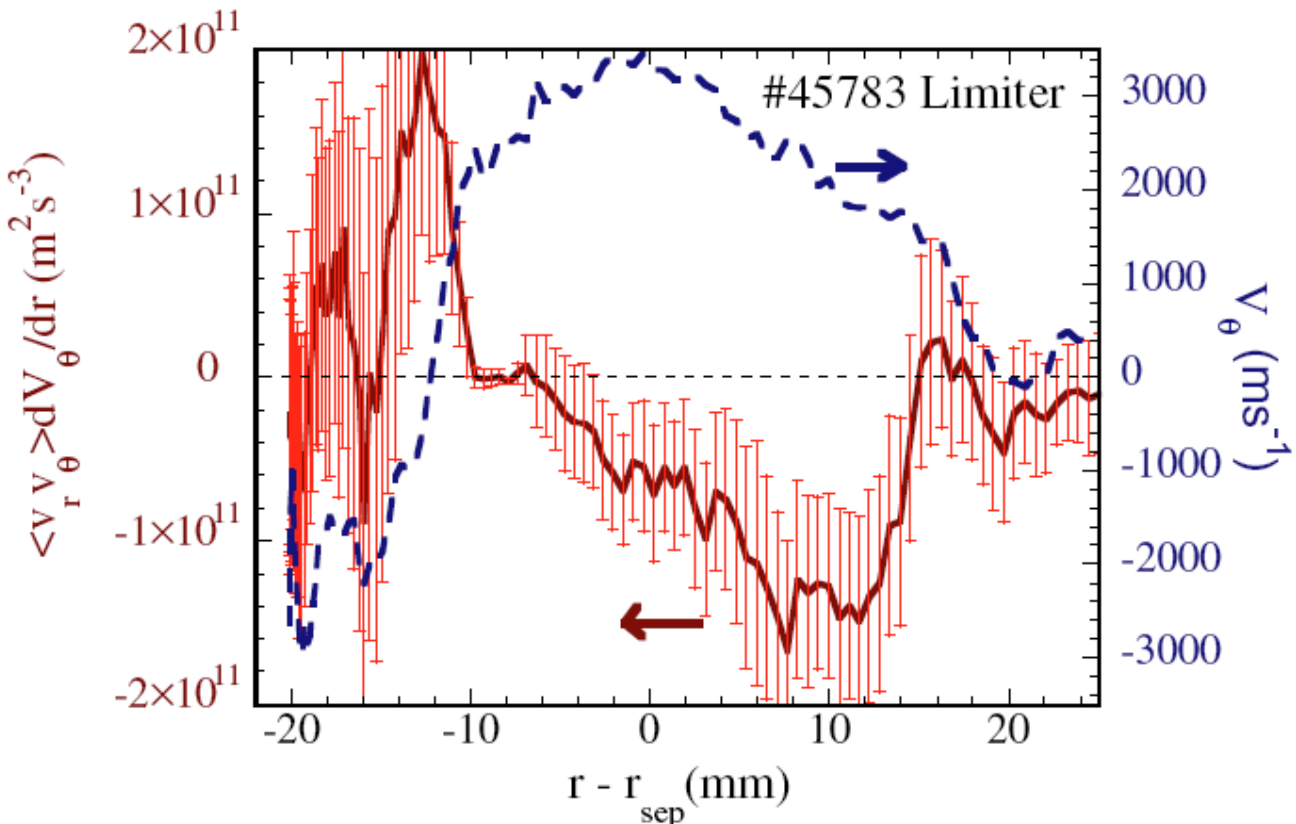


HIBP in JFT-2M

Ida et al, Fusion Sci. Tech. '06

Edge Flows

- Turbulence can generate flows through Reynold's stress
- Here flow transfers energy into turbulence in shear layer
- Apparently opposite result in Extrap (Vianello PPCF '06)

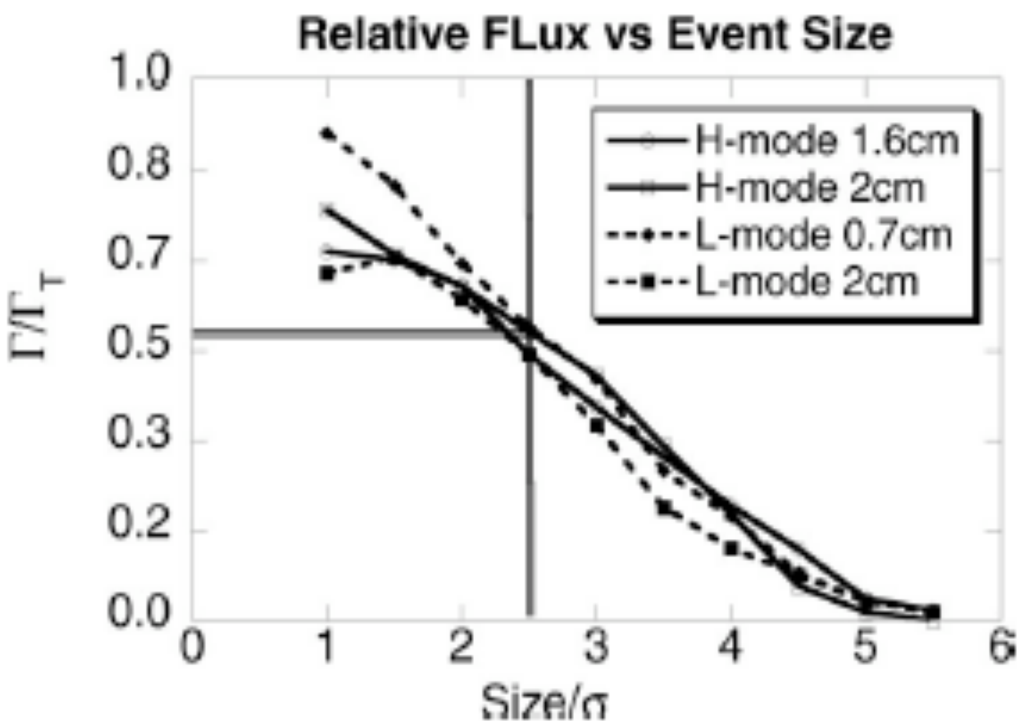


JET

Sanchez E et al, J. Nucl. Mat. 337 (2005) 296

Turbulent Transport

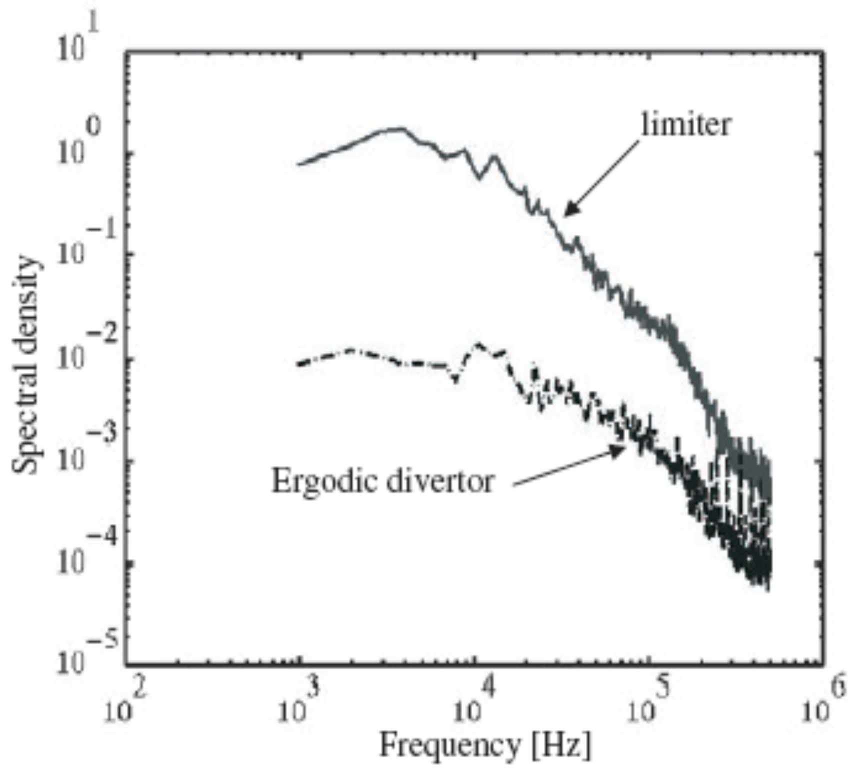
- ~ 50% of turbulent transport due to intermittent events



Boedo JA et al, Phys. Plasmas 8 (2001) 4826

Control of Edge Turbulence

- Changes can be made using edge biasing, ergodic divertor, RF waves, etc.

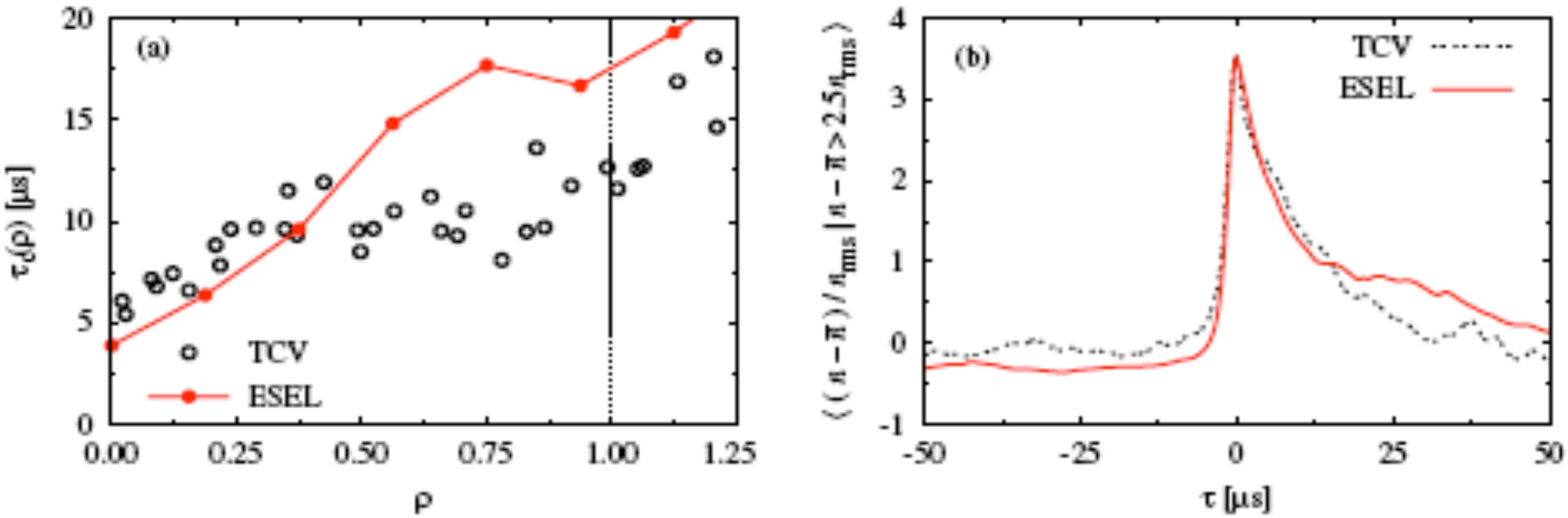


Effect of ergodic divertor in Tore-Supra

Devynck P et al, Nucl. Fusion 42 (2002) 697

Comparisons with Theory

- Relatively few direct comparisons of codes and data
- Recent comparison of TCV and ESEL (2D ES model)



Garcia OE et al, Plasmas Phys. Cont. Fusion 48 (2006) L1

Some Future Directions

- Improved measurements
  - full poloidal distribution
  - turbulence-induced flows
  - scaling near density limit

- Improved modeling
  - understand cause of intermittency
  - understand cause of L-H transition
  - predict edge/SOL in future devices (e.g. ITER)

- Improved control
  - learn how to increase SOL width