Measurements of plasma turbulence in toroidal magnetic confinement devices

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AST559/APC539
Turbulence and nonlinear processes in fluids and plasmas
March, 2014

This talk is completely biased and in no way comprehensive

- I've used examples I'm familiar with and find useful for illustration
- See the following for broader reviews and thousands of useful references

- Transport & Turbulence reviews:
  - Liewer, Nuclear Fusion (1985)
  - Wootton, Phys. Fluids B (1990)
  - Carreras, IEEE Trans. Plasma Science (1997)
  - Wolf, PPCF (2003)
  - Tynan, PPCF (2009)
  - ITER Physics Basis (IPB), Nuclear Fusion (1999)
  - Progress in ITER Physics Basis (PIPB), Nuclear Fusion (2007)

- Drift wave reviews:
  - Horton, Rev. Modern Physics (1999)
  - Tang, Nuclear Fusion (1978)

- Gyrokinetic simulation review:
  - Garbet, Nuclear Fusion (2010)

- Zonal flow/GAM reviews:
  - Diamond et al., PPCF (2005)
  - Fujisawa, Nuclear Fusion (2009)

- Measurement techniques:
  - Bretz, RSI (1997)

Outline

- Tokamaks and confinement
- General turbulence characteristics

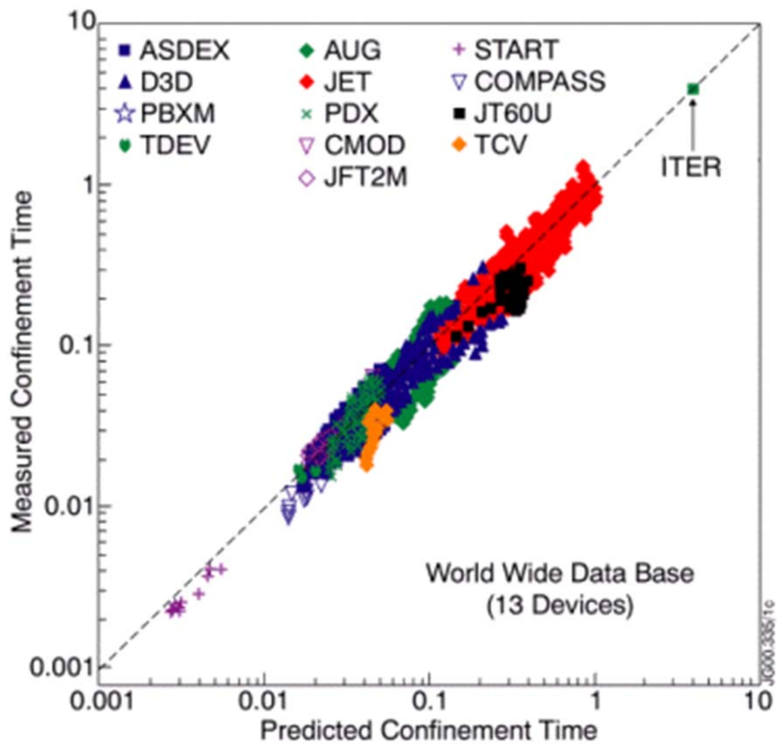
- Core ion scale turbulence
- Core electron scale turbulence
- Magnetic turbulence
- Zonal flows, GAMs

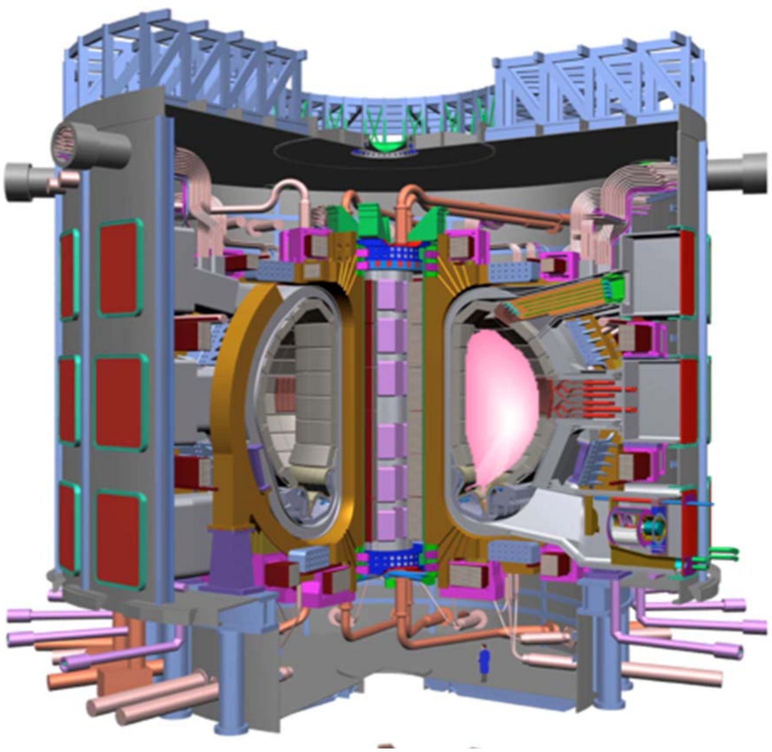
- Edge turbulence: L-H transition
- Edge turbulence: H-mode pedestal
- Scrape off layer turbulence

TOKAMAKS AND CONFINEMENT

Magnetic fusion plasmas are a possible solution for large-scale clean energy production

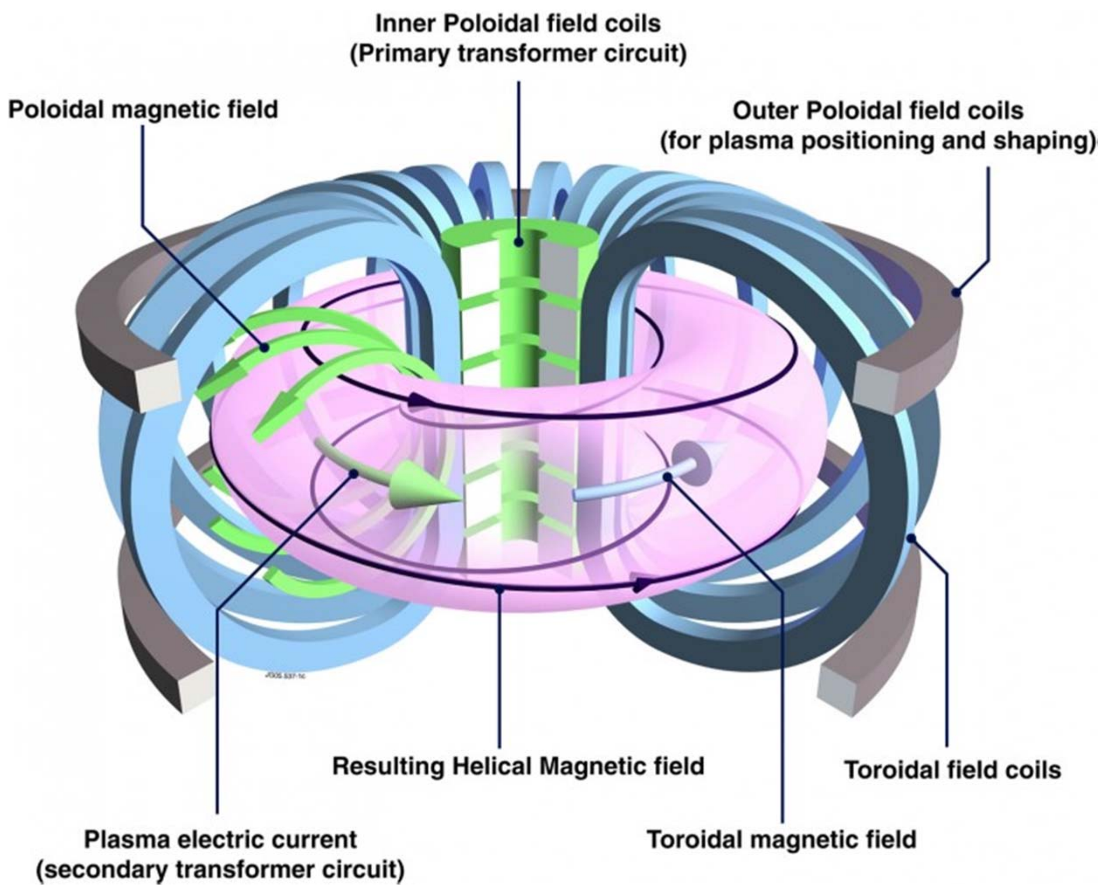
- Need sufficient pressure (p~2-4 atmospheres, at >100 Million °C) confined for sufficiently long (τ_E~2-4 s) for high gain ($P_{fusion} >> P_{heat}$) burning plasmas
- Confinement time set by turbulence, forces us to pursue huge ($$$) machines, $\tau_E \sim$ pressure × <u>volume</u> / power
- Can we understand turbulence, and therefore reduce/optimize it for better/cheaper solutions? ⇒ **Requires measurement and theory**



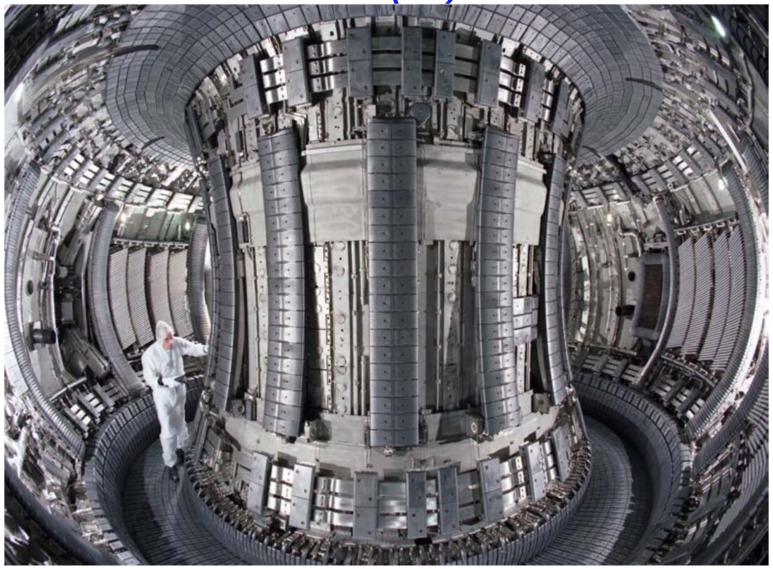


Tokamaks

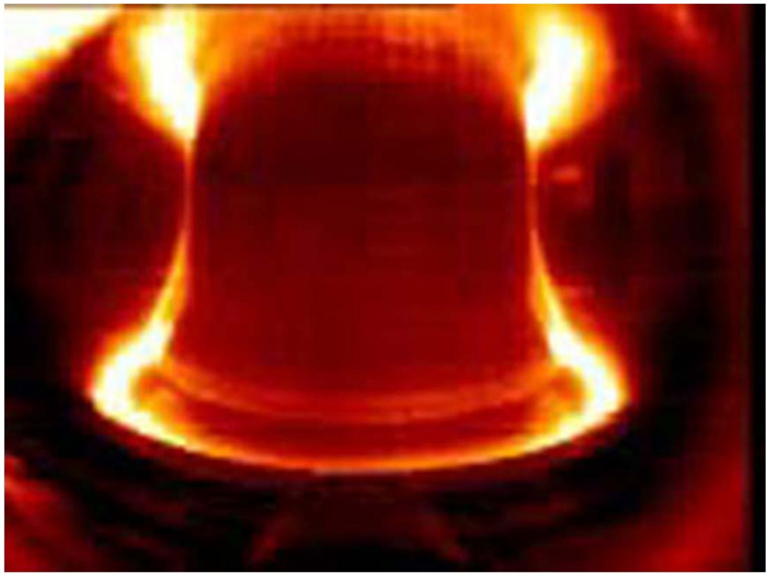
- Axisymmetric
- Helical field lines confine plasma



JET (UK)

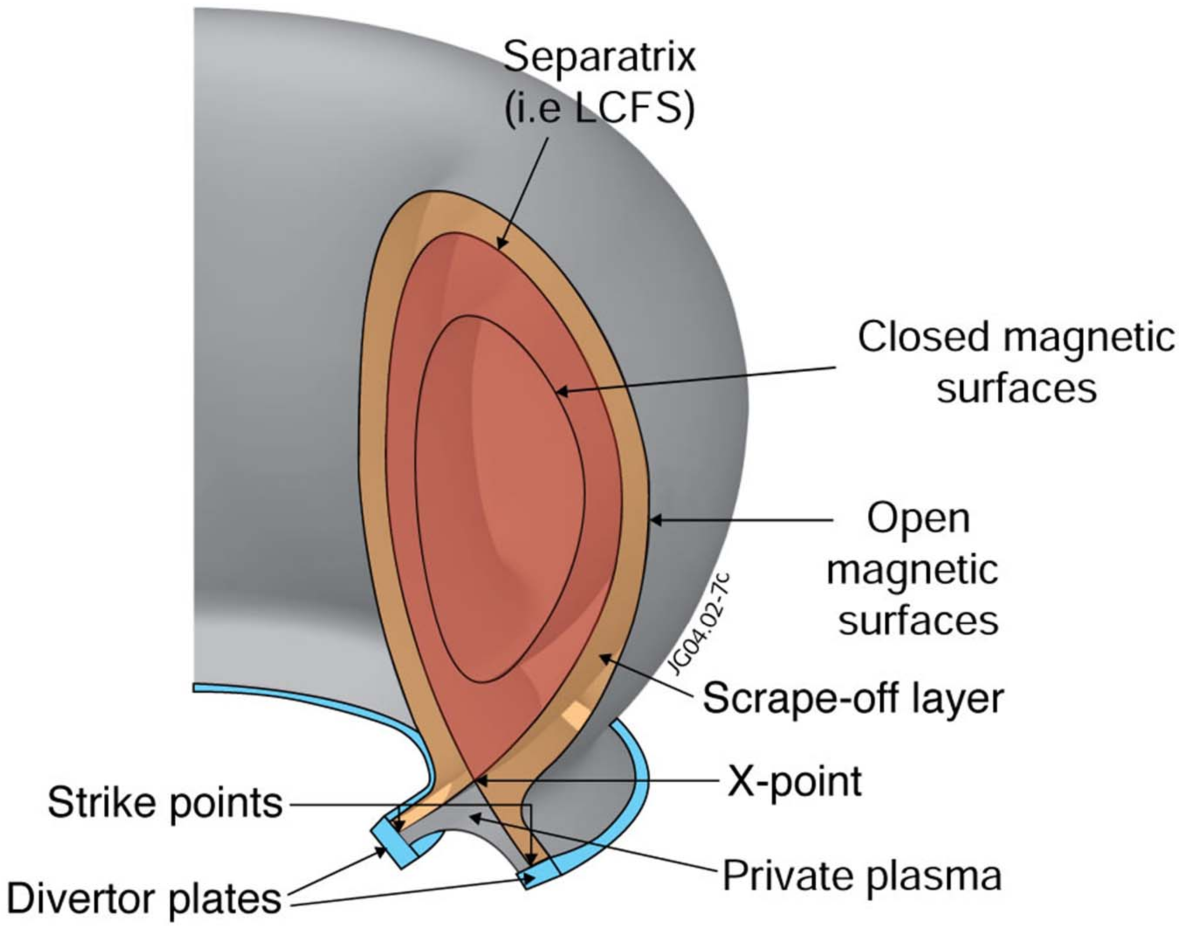


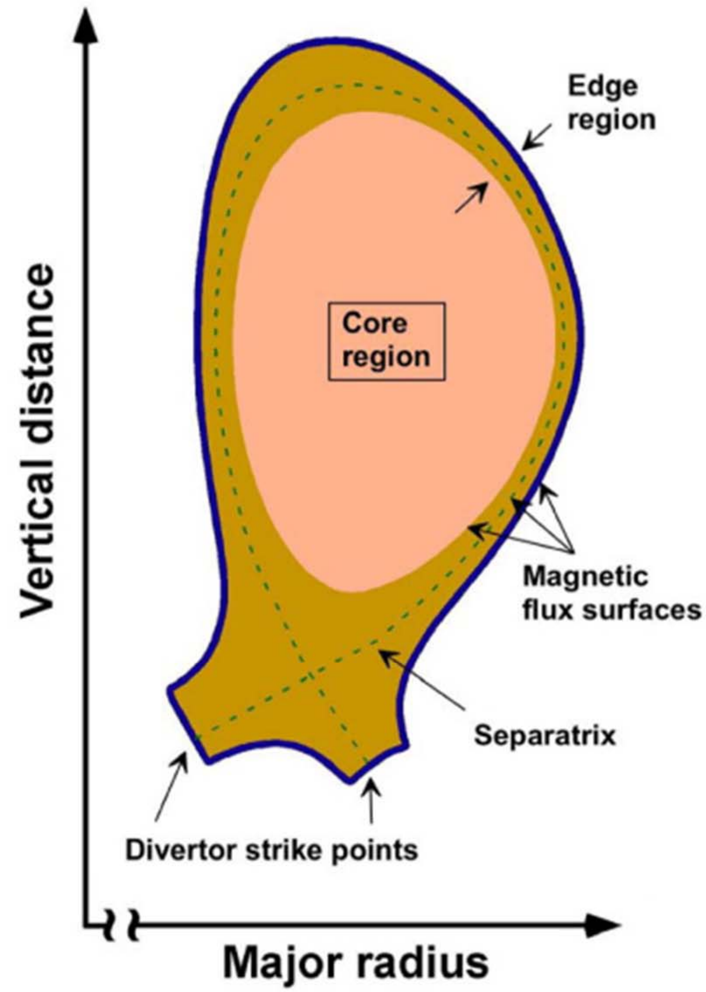
Alcator C-Mod (MIT)



Going to refer to different spatial regions in the tokamaks

- Especially **core**, **edge** (just inside separatrix), and **scrape-off layer** (SOL, just outside separatrix)





Inferred experimental transport larger than collisional (neoclassical) theory – extra "anomalous" contribution

Hawryluk, Phys. Plasmas (1998)

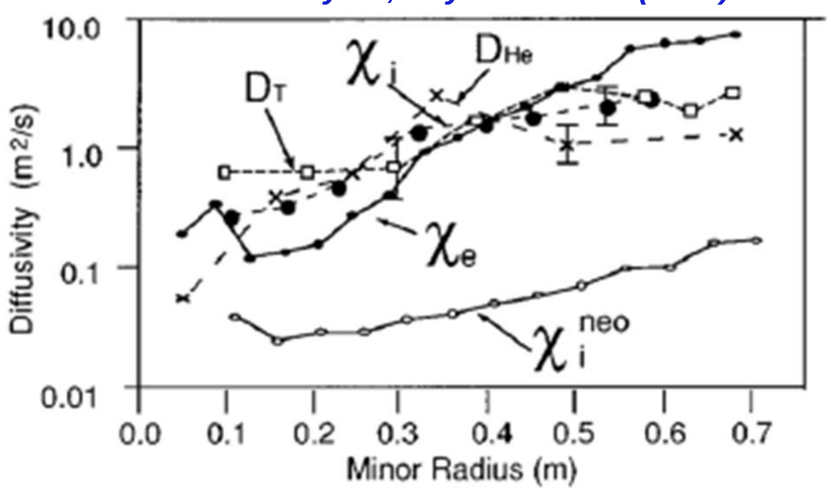
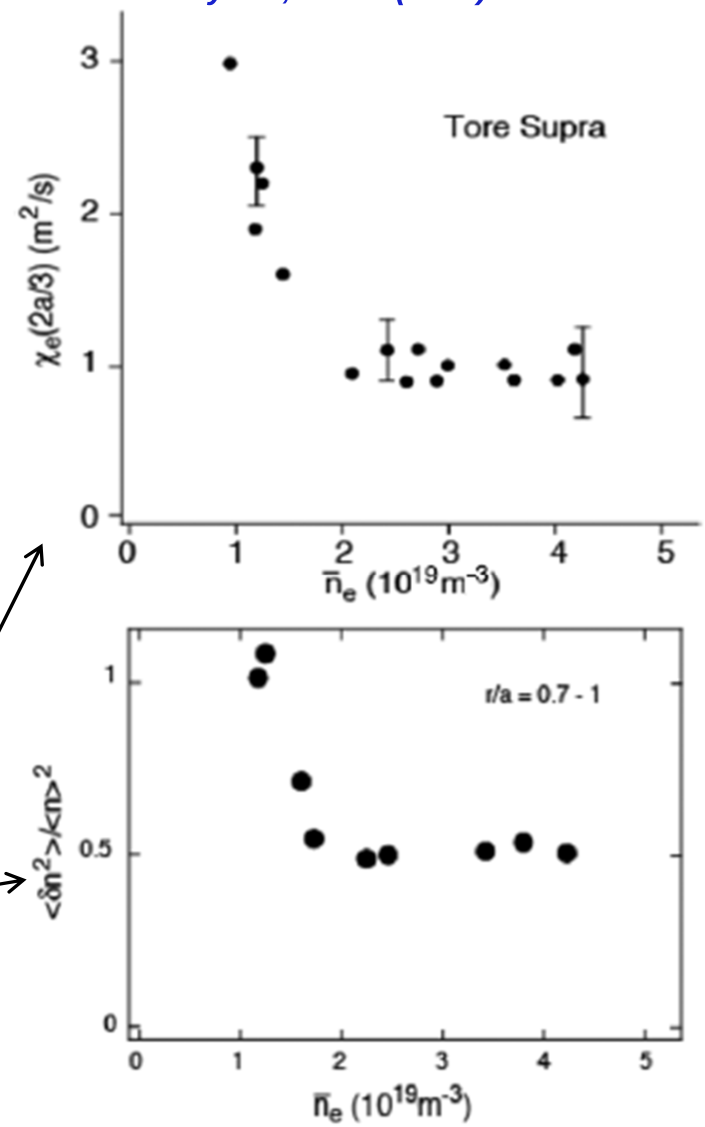


Figure 1. Results from TFTR showing ion thermal, momentum, diffusivities in an L-mode discharge; reprinted with permission fr American Institute of Physics.

Garbet, Nuclear Fusion (1992)
Tynan, PPCF (2009)



- Correlation between local transport and density fluctuations hints at turbulence

GENERAL TURBULENCE CHARACTERISTICS

40+ years of theory predicts turbulence in magnetized plasma should often be drift wave in nature

General predicted drift wave characteristics

- Fluctuations in EM fields (φ, B) and fluid quantities (n,v,T) (although really kinetic at high temperature/low collisionality)
- Finite-frequency drifting waves, $\omega(k_\theta)\sim\omega_*$
  - Can propagate in ion or electron diamagnetic direction, depending on conditions
- Perpendicular sizes linked to local gyroradius, $L_\perp\sim\rho_{i,e}$ or $k_\perp\rho_{i,e}\sim1$
- Correlation times linked to acoustic velocity, $\tau_{cor}\sim c_s/R$
- Quasi-2D, elongated along the field lines ($L_{||}>>L_\perp$, $k_{||} << k_\perp$)
  - Particles can rapidly move along field lines to smooth out perturbations
- Expected to be “ballooning”, i.e. stronger on outboard side
  - Due to “bad curvature”/”effective gravity” pointing outwards from symmetry axis
  - Often only measure at one location, outboard side

Microwave, far-infrared (FIR) scattering used extensively for density fluctuation measurements

Park, RSI (1985)

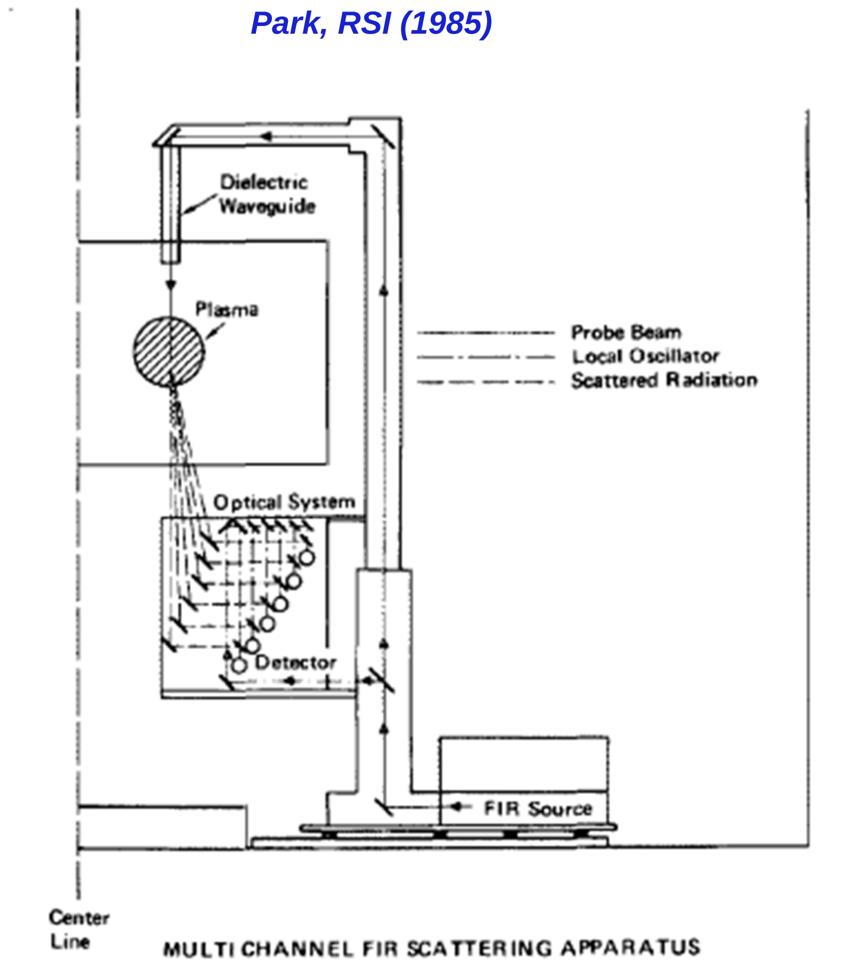


FIG. 1. Scannable mutichannel FIR scattering apparatus employed on the TEXT tokamak.

- Geometry and frequency determine measureable ω, k

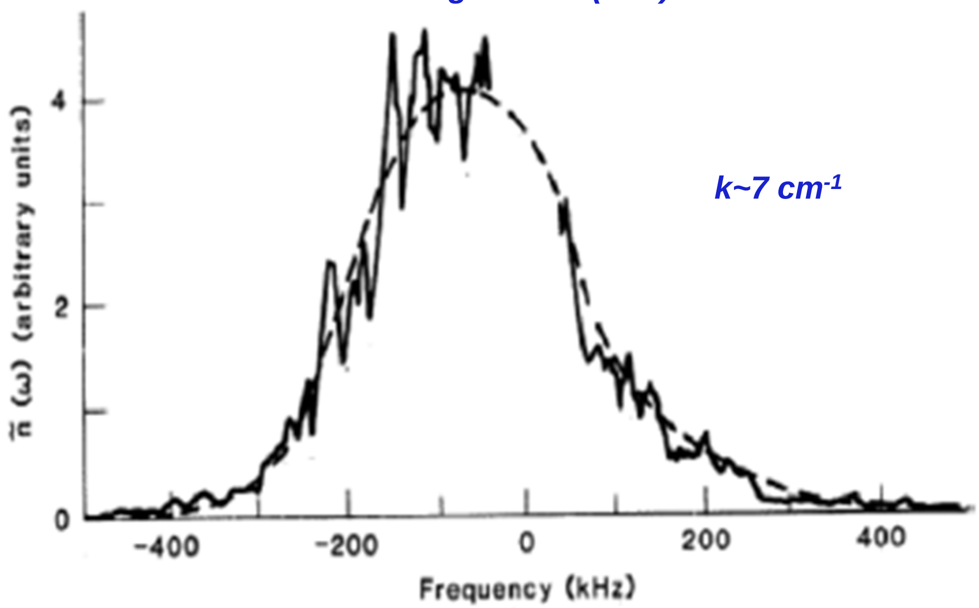
$$\omega_{meas} = \omega_{scat} - \omega_{incident}$$
$$k_{meas} = k_{scat} - k_{incident}$$

- Can be configured for forward scattering, backscattering, reflectometery, …

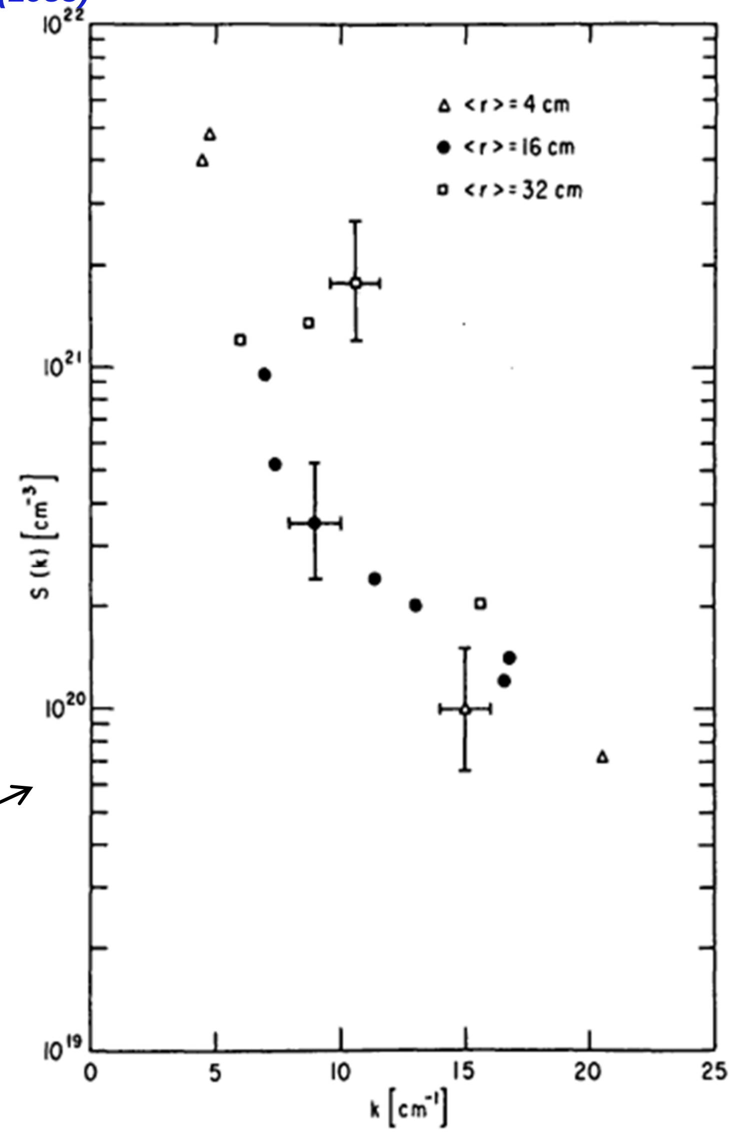
Broad frequency spectra measured for given scattering wavenumber

Mazzucato, PRL (1982)
Surko&Slusher, Science (1983)

Princeton Large Torus (PLT)



k~7 cm^{-1}



- Different scattering angles measure different k, observe spectral decay in wavenumber

Broad drift wave turbulent spectrum verified simultaneously with Langmuir probes and FIR scattering

TEXT, Ritz, Nuclear Fusion (1987)
Wooton, Phys. Fluids B (1990)

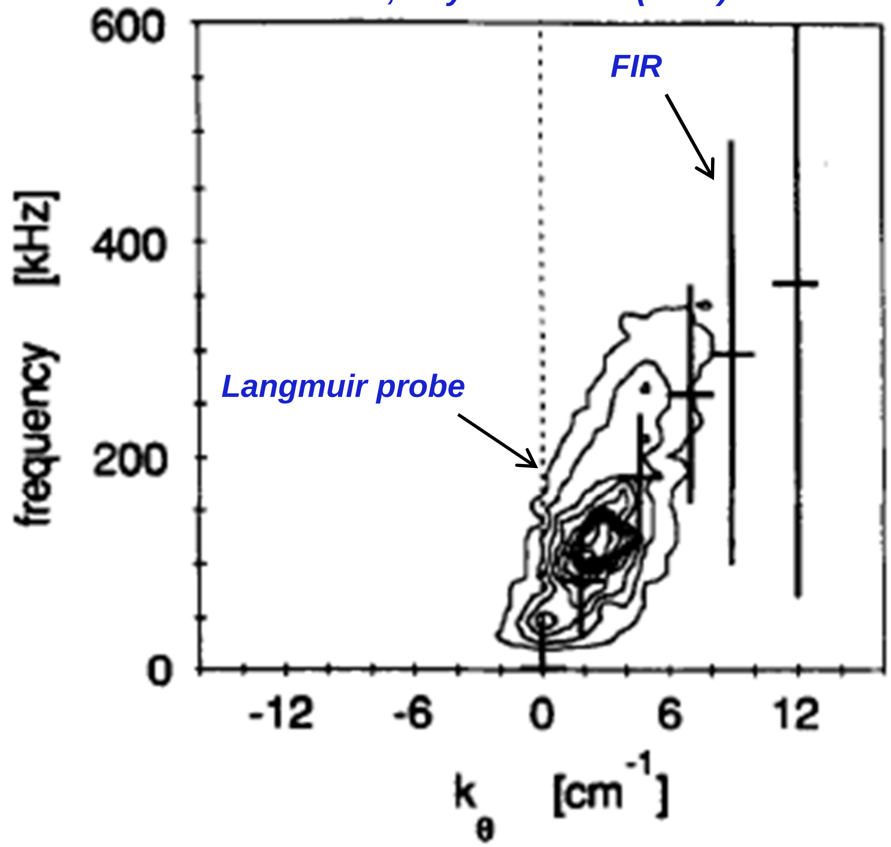


FIG. 1. The $S(k_\theta,\omega)$ spectrum at $r = 0.255$ m in TEXT, from Langmuir probes (contours) and FIR scattering (bars indicate FWHM).

- Illustrates drift wave dispersion
- However, real frequency almost always dominated by Doppler shift

$$\omega_{lab} = \omega_{mode}(k_\theta) + k_\theta v_{doppler}$$

- Often challenging to determine mode frequency (in plasma frame) within uncertainties

Small normalized fluctuations in core (≤1%) increasing to the edge

- Combination of diagnostics used to measure fluctuation amplitudes
- Measurements also often show $\delta n/n_0 \sim \delta\varphi/T_0$ (within factor ~2)

ATF stellarator, Hanson, Nuclear Fusion (1992)

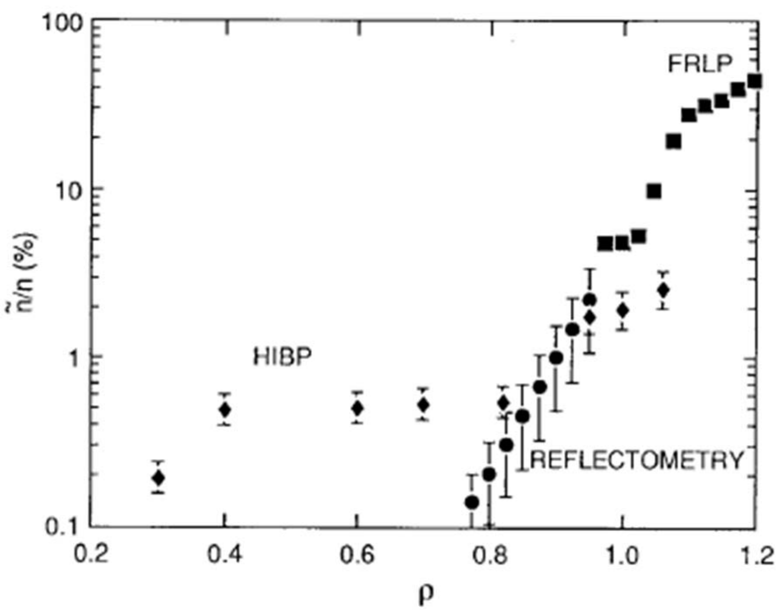


Fig. 4. Radial profile of density fluctuations (in %) in ATF stellarator obtained by combining results from different diagnostics [177].

TEXT tokamak, Wooton, PoFB (1990)

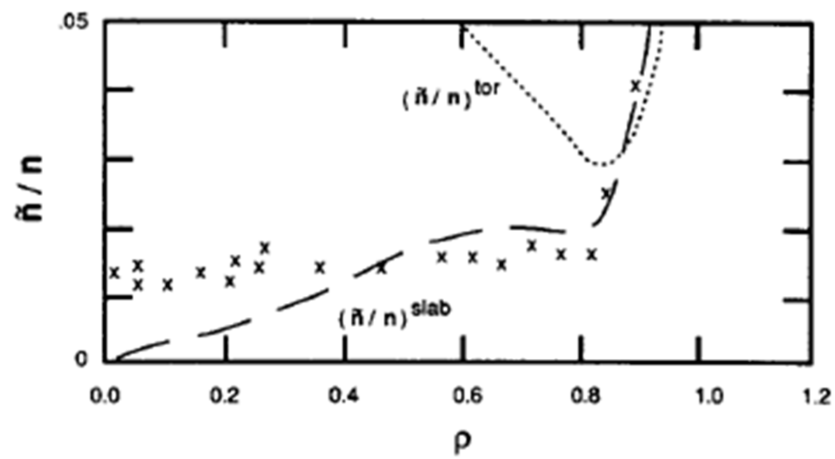


FIG. 6. The spatial variation of $\tilde{n}/n$ from TEXT ($B_\phi = 2$ T, $I_p = 200$ kA, $\bar{n}_e = 2$ to 3×10^{19} m^{-3}, H$^+$), shown as crosses (HIBP). Also shown are the predictions of two mixing length estimates, $(\tilde{n}/n)^{tor}$ and $(\tilde{n}/n)^{slab}$. Both electron feature $\tilde{n}/n$ and k_θ ($\bar{k}_\theta \rho_s = 0.1$) are interpreted assuming no ion feature is present.

Mixing length estimate for fluctuation amplitude

- In the presence of an equilibrium gradient, ∇n_0, turbulence with radial correlation L_r will mix regions of high and low density

$$\delta n \approx \nabla n_0 \cdot L_r$$

$$\frac{\delta n}{n_0} \approx \frac{\nabla n_0}{n_0} \cdot L_r \approx \frac{L_r}{L_n} \quad \left(1/L_n = \nabla n_0 / n_0\right)$$

$$\frac{\delta n}{n_0} \sim \frac{1}{k_\perp L_n} \sim \frac{\rho_s}{L_n} \quad \left(k_\perp^{-1} \sim L_r; k_\perp \rho_s \sim \text{constant}\right)$$

IF turbulence scale length linked to ρ_s, would loosely expect $\delta n/n_0 \sim \rho_s/L_n$

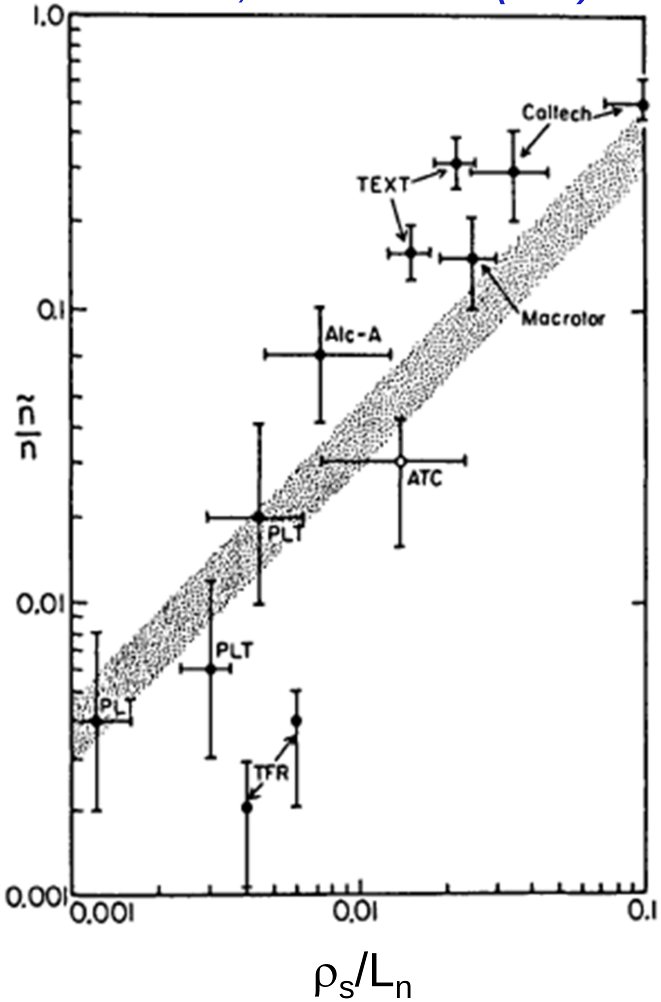
- Another interpretation: local, instantaneous gradient limited to equilibrium gradient

$$\nabla \tilde{n} \approx \nabla n_0$$

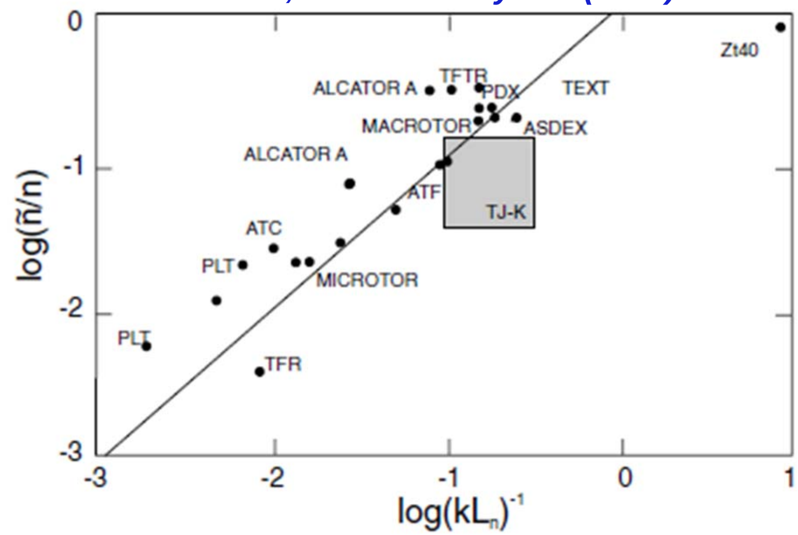
$$k_r \tilde{n} \approx \nabla n_0$$

Fluctuation intensity across machines loosely scales with mixing length estimate, reinforces local ρ_s drift nature

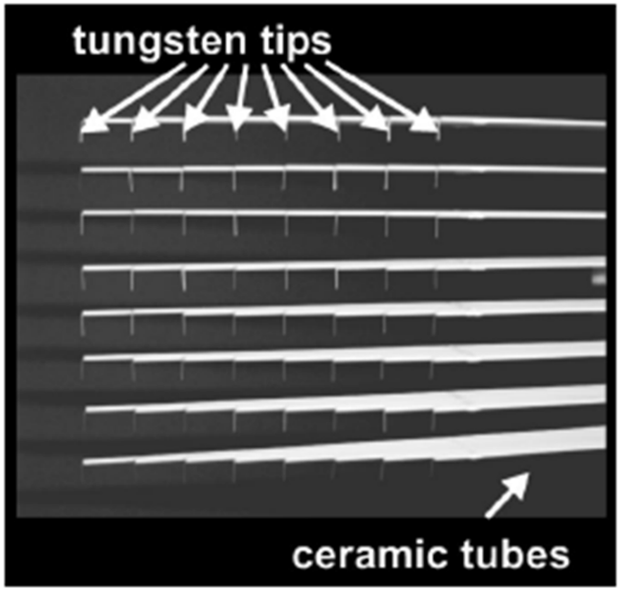
Liewer, Nuclear Fusion (1985)

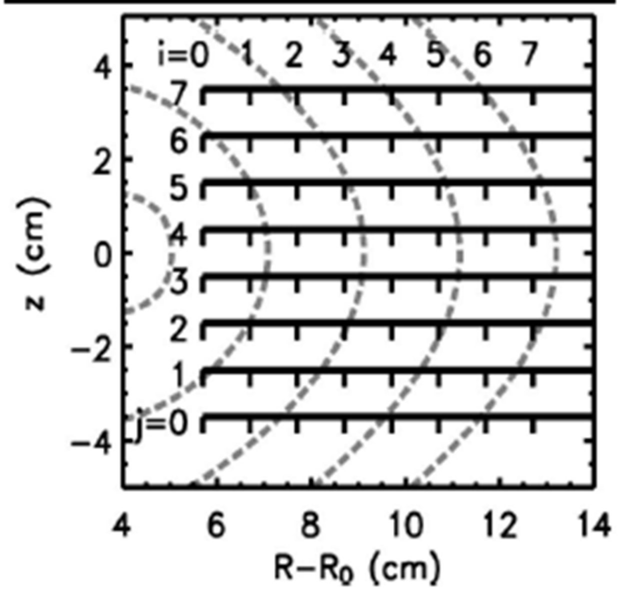


Lechte, New J. of Physics (2002)

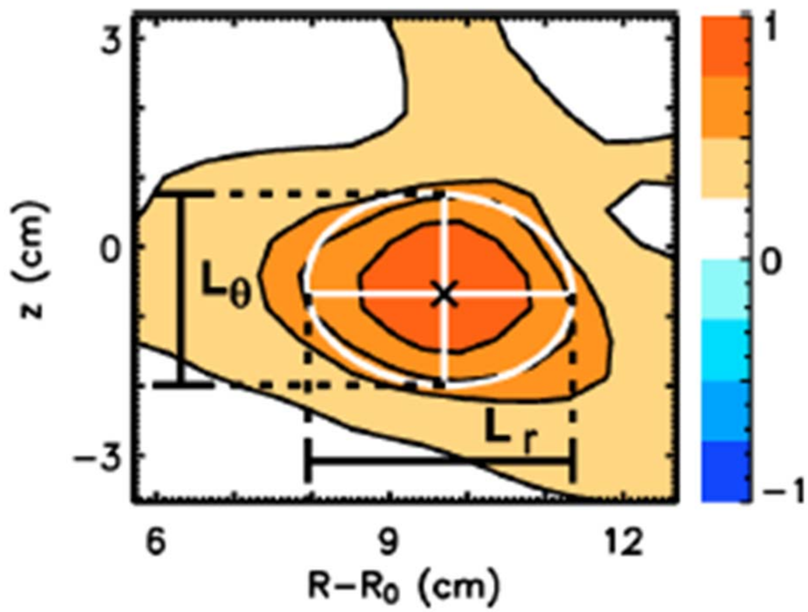


2D Langmuir probe array in TJ-K stellarator used to directly measure spatial and temporal structures





- Simultaneously acquiring 64 time signals – can directly calculate 2D correlation, with time
- Caveat – relatively cool (T~10 eV) compared to fusion performance plasmas (T~10 keV)



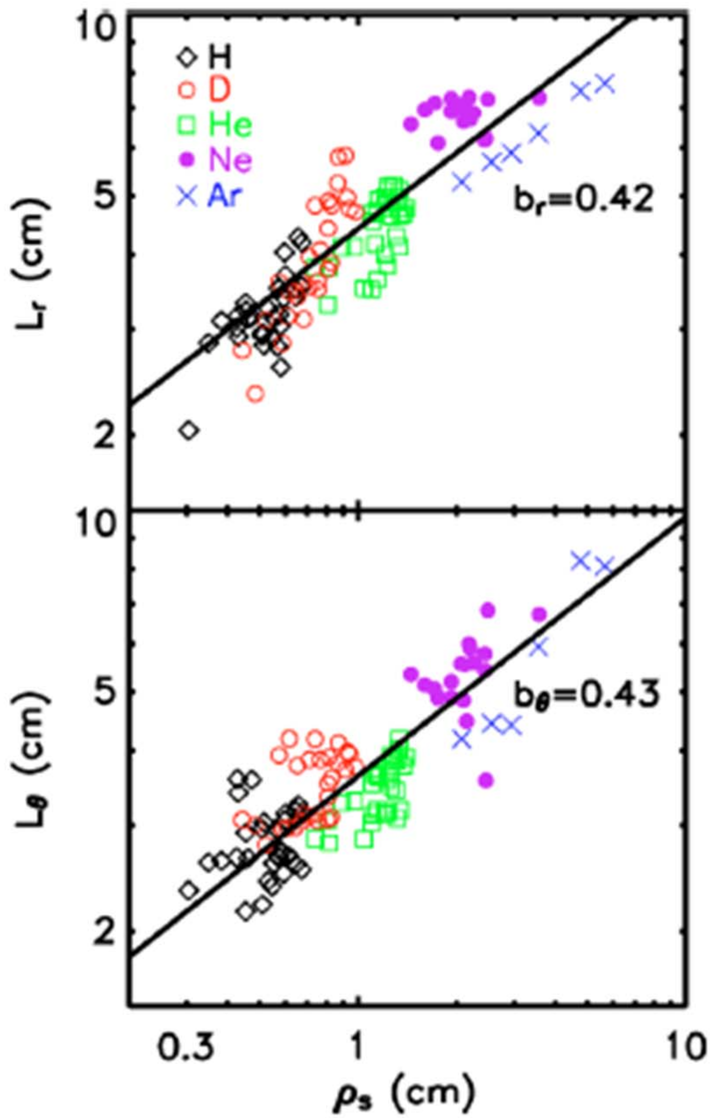
TJ-K [Ramisch, PoP (2005)]

Radial and poloidal correlation lengths scale with ρ_s reinforcing drift wave nature

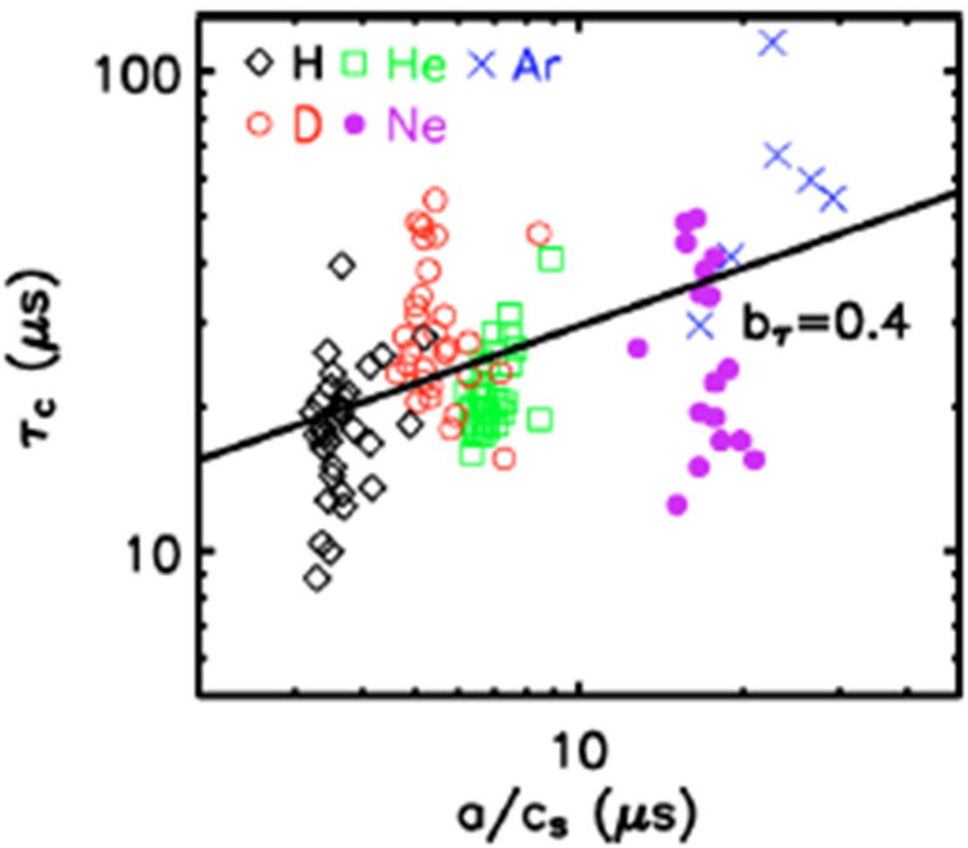
TJ-K [Ramisch, PoP (2005)]

- Turbulence close to isotropic

$$L_r \sim L_\theta$$



Temporal scales loosely correlated with acoustic times c_s/a

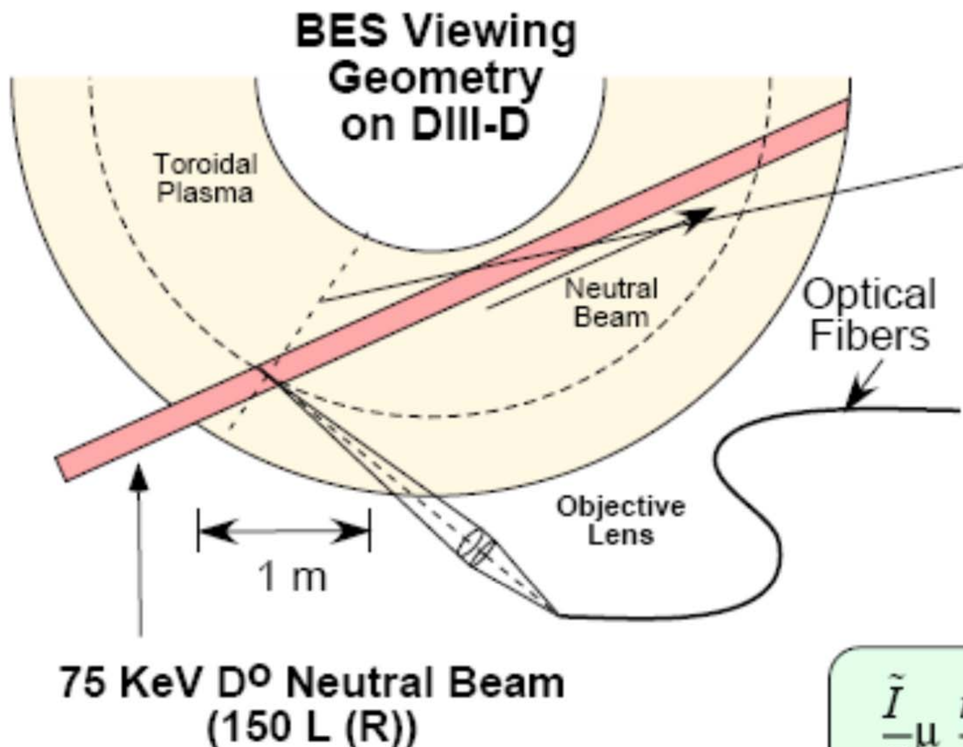


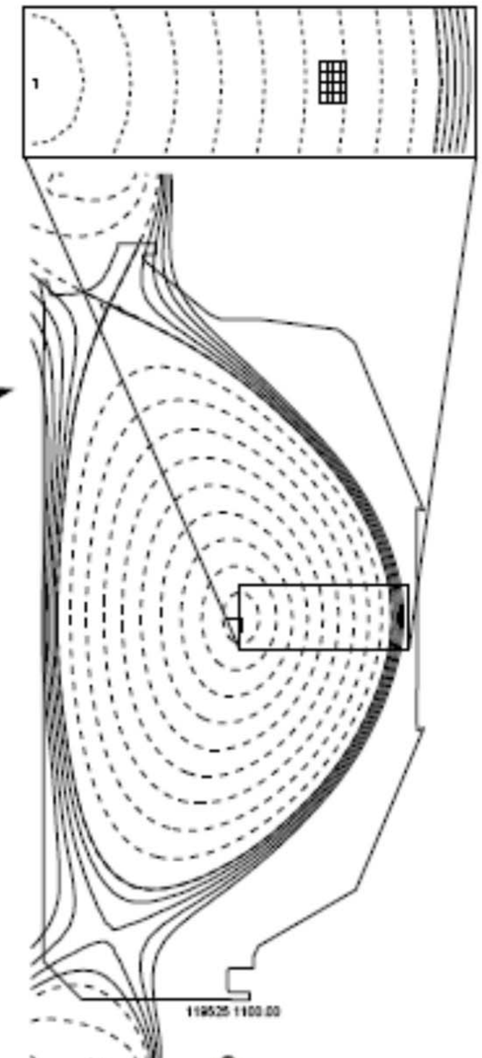
TJ-K [Ramisch, PoP (2005)]

Beam Emission Spectroscopy Measurement of Localized, Long-Wavelength ($k_{\perp}\rho_I < 1$) Density Fluctuations

Collisionally-excited, Doppler-shifted neutral beam fluorescence

$$D^o + e,i \rightarrow \left(D^o\right)^* \rightarrow D^o + \gamma(n=3 \rightarrow 2, \lambda_o = 656.1\ \mathrm{nm})$$



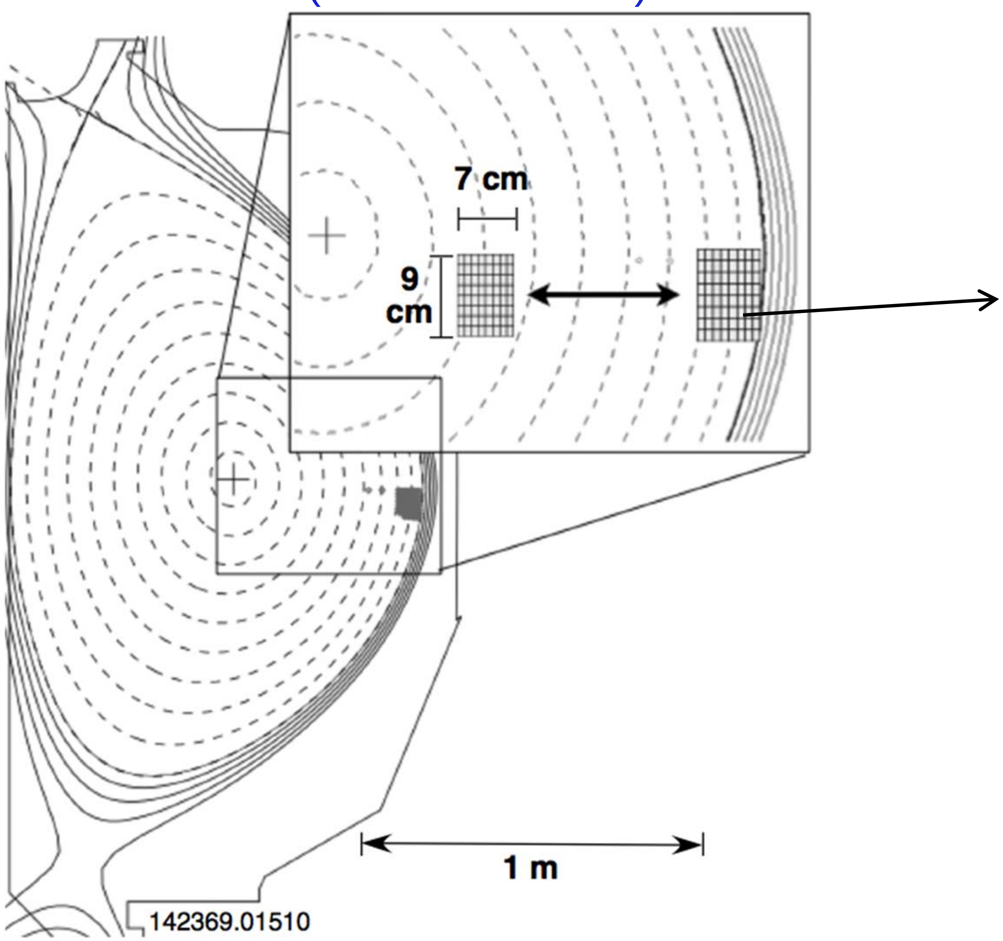


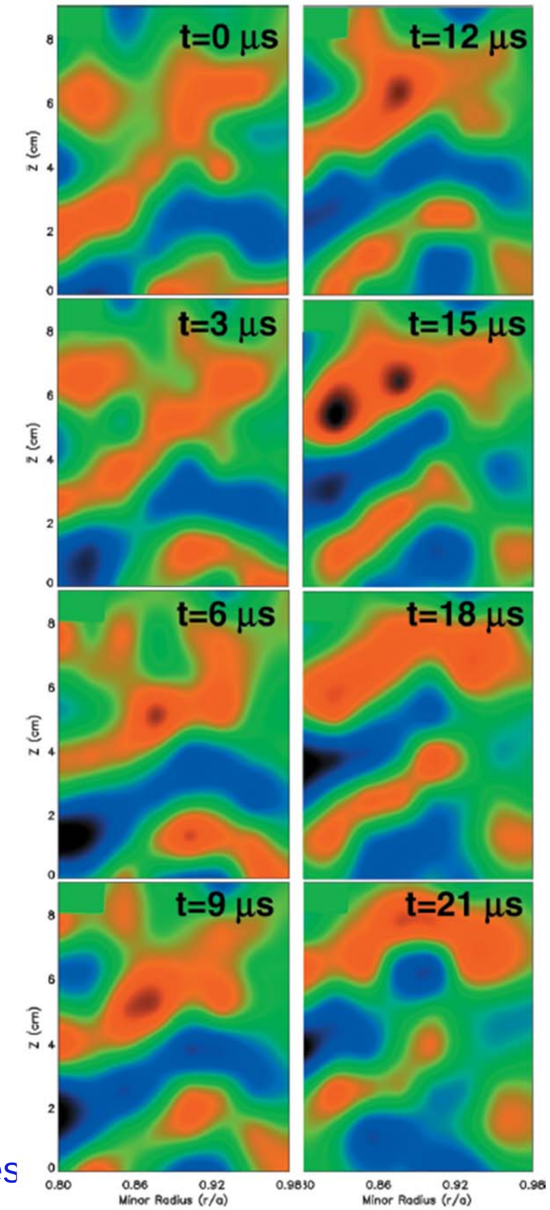
$$\frac{\tilde{I}}{I} \mu \ \frac{\tilde{n}}{n}$$

Spectroscopic imaging provides a 2D picture of turbulence in hot tokamak core: cm spatial scales, μs time scales

- Utilize interaction of neutral atoms with charged particles to measure density

DIII-D tokamak (General Atomics)





Movies at: https://fusion.gat.com/global/BESMovies

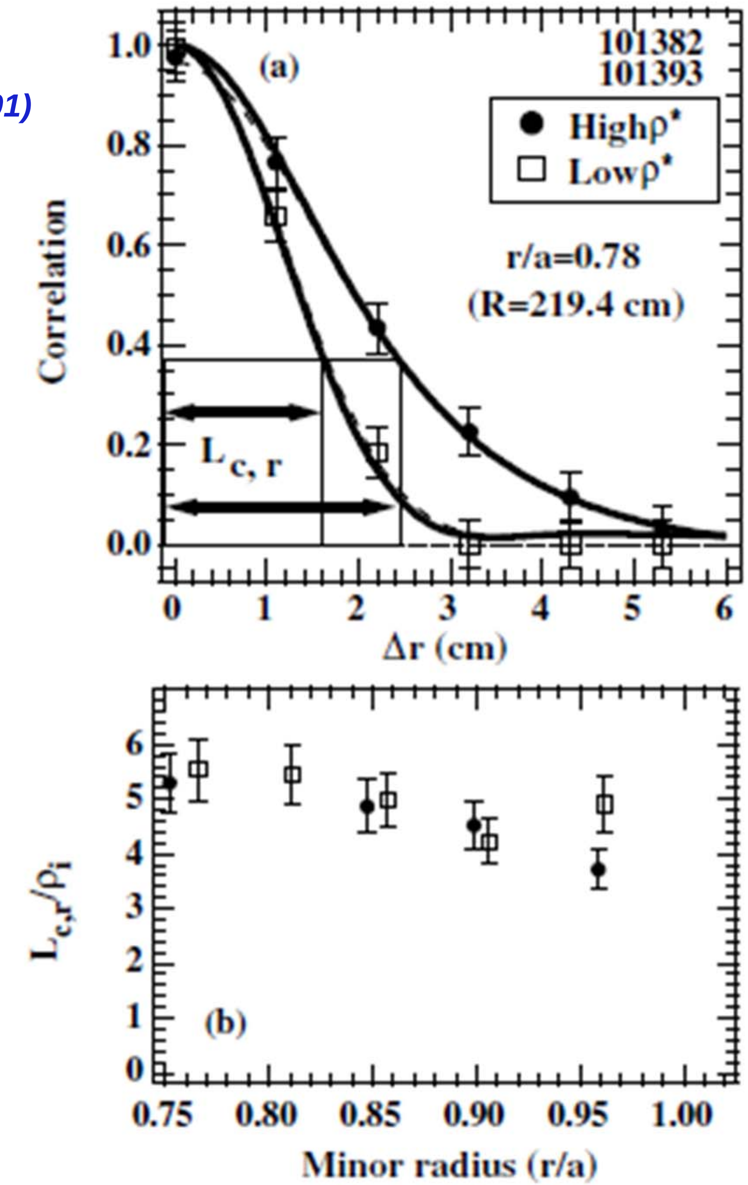
BES videos

https://fusion.gat.com/global/BESMovies

(University of Wisconsin; General Atomics)

Radial and poloidal correlation lengths scale with ρ_s in core imaging, reinforcing local drift wave nature

DIII-D
Mckee, Nucl. Fusion (2001)



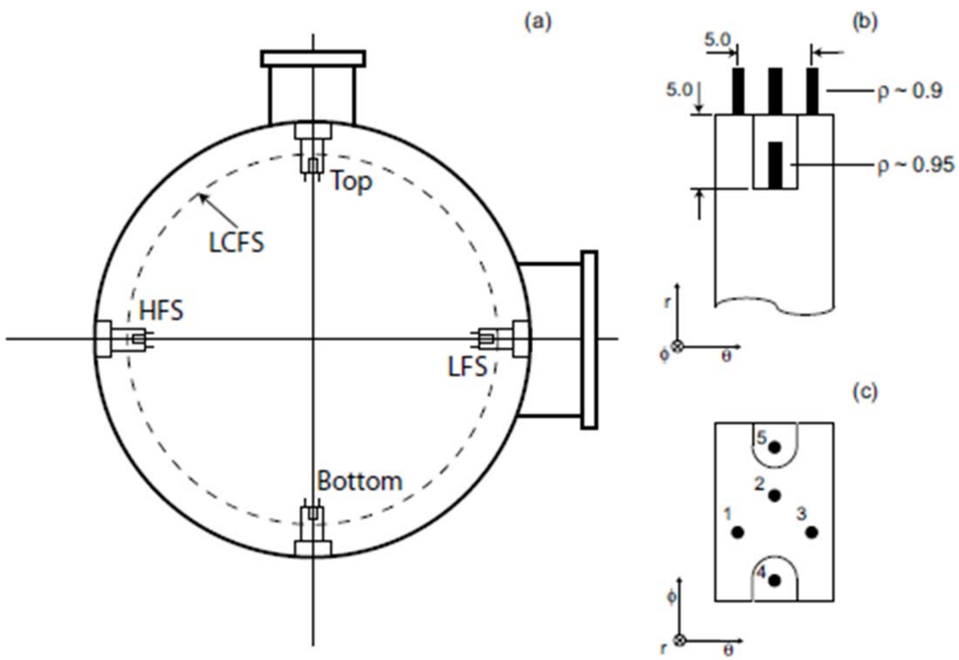
- Correlation length increases with local gyroradius ρ ($\rho_*=\rho/a$)

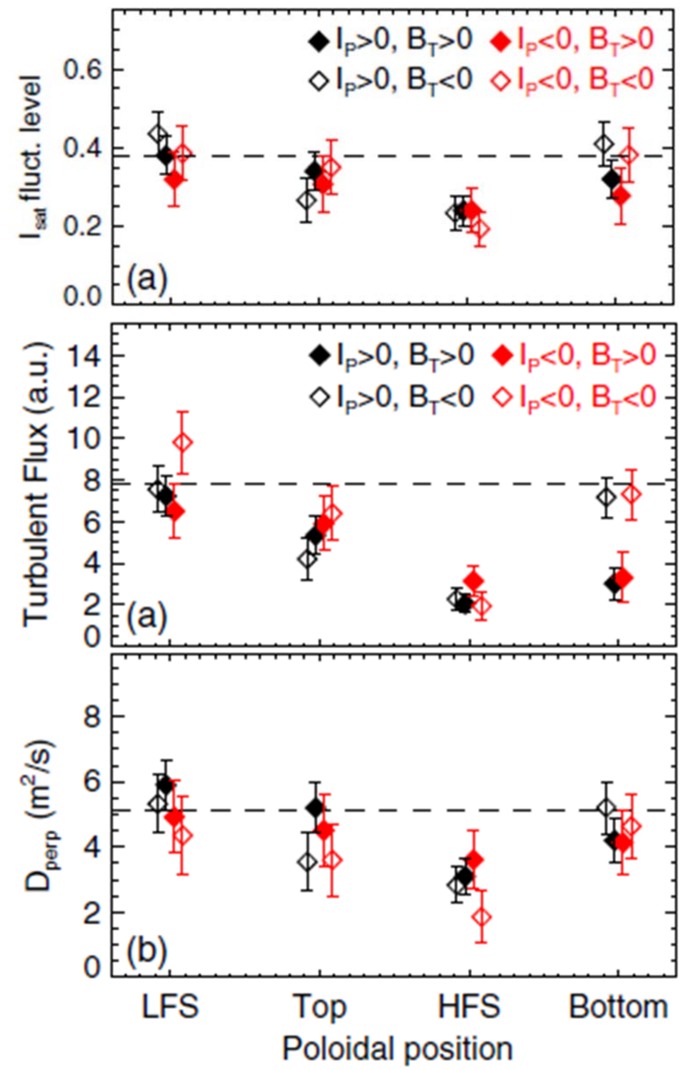
- Ratio of L_r/ρ relatively constant in radius, for the two different ρ_* discharges

Example of stronger turbulence measured on outboard side, "ballooning" in nature

- Consistent with bad curvature drive

ISSTOK [Silva, PPCF (2011)]





R

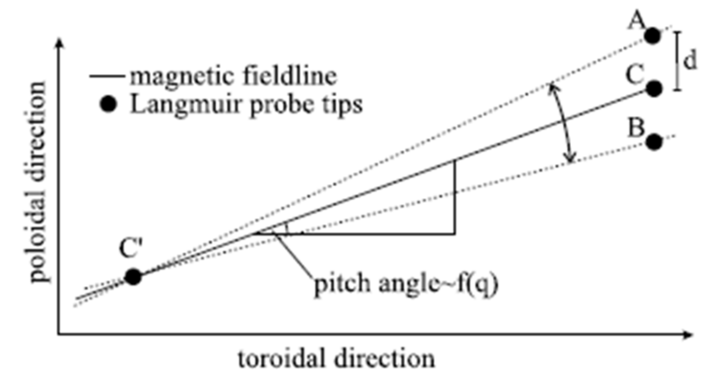
Curvature, "effective gravity"

Evidence for quasi-2D ($L_{||} >> L_{\perp}$)

- Assume an exponential or Gaussian correlation function

$$C(\Delta_{\perp}, \Delta_{||}) \approx \exp(-\Delta_{\perp} / L_{\perp}) \exp(-\Delta_{||} / L_{||})$$

JET edge [Thomsen, Contrib. Plasma Phys. (2001)]

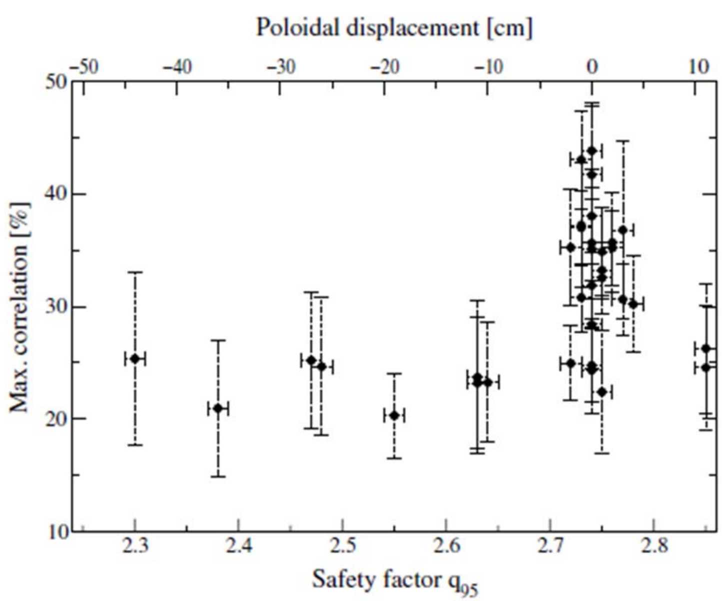


- Measure correlation between two probes "on the same field line" ($\Delta_{\perp} \approx 0$) separated a large distance $\Delta_{||} >> 0$

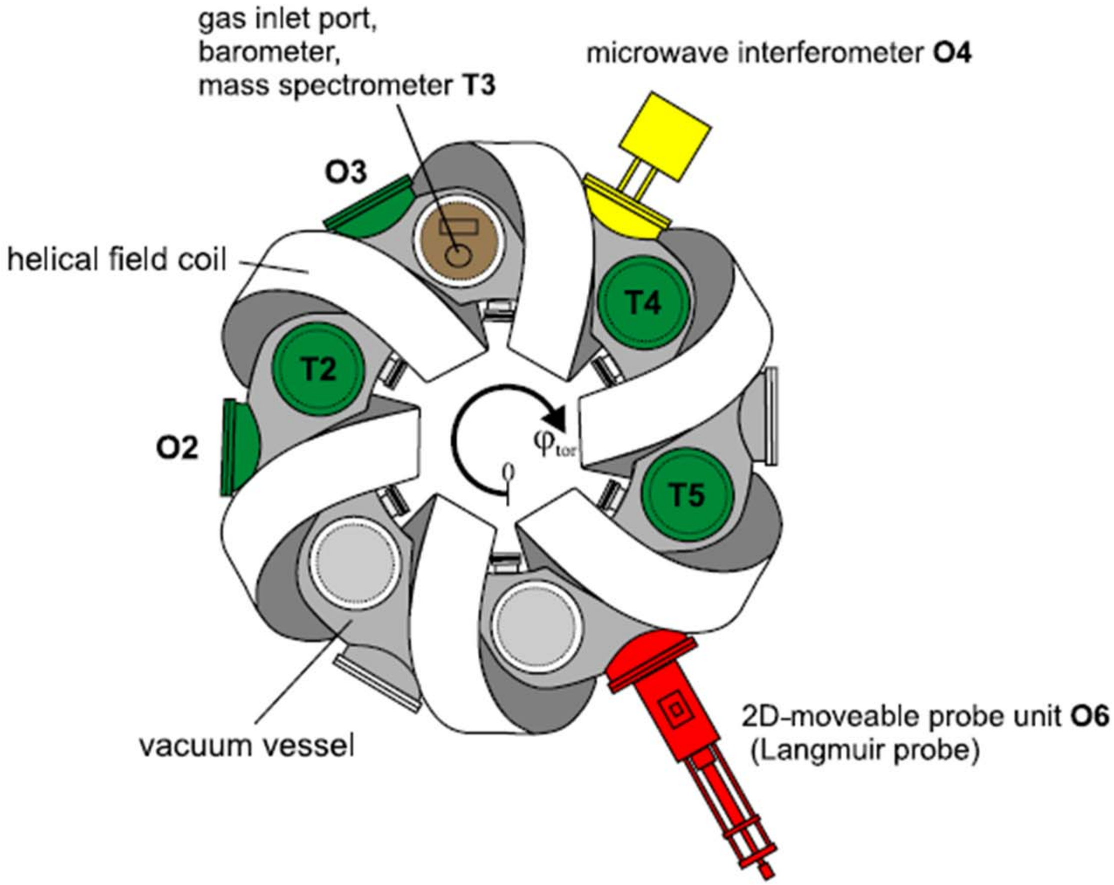
<u>JET edge plasma</u>

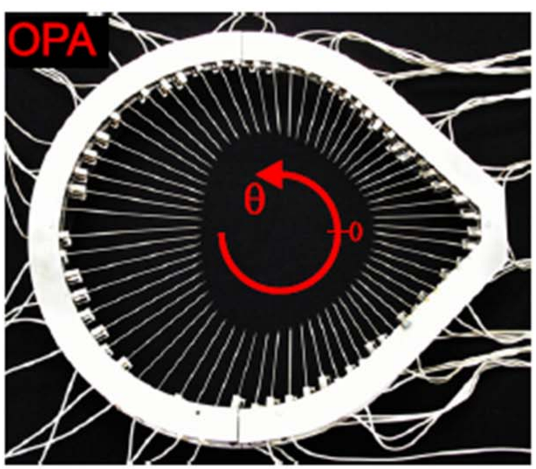
$L_{||}$ ~ many meters

$L_{\perp}$ ~ mm-cm

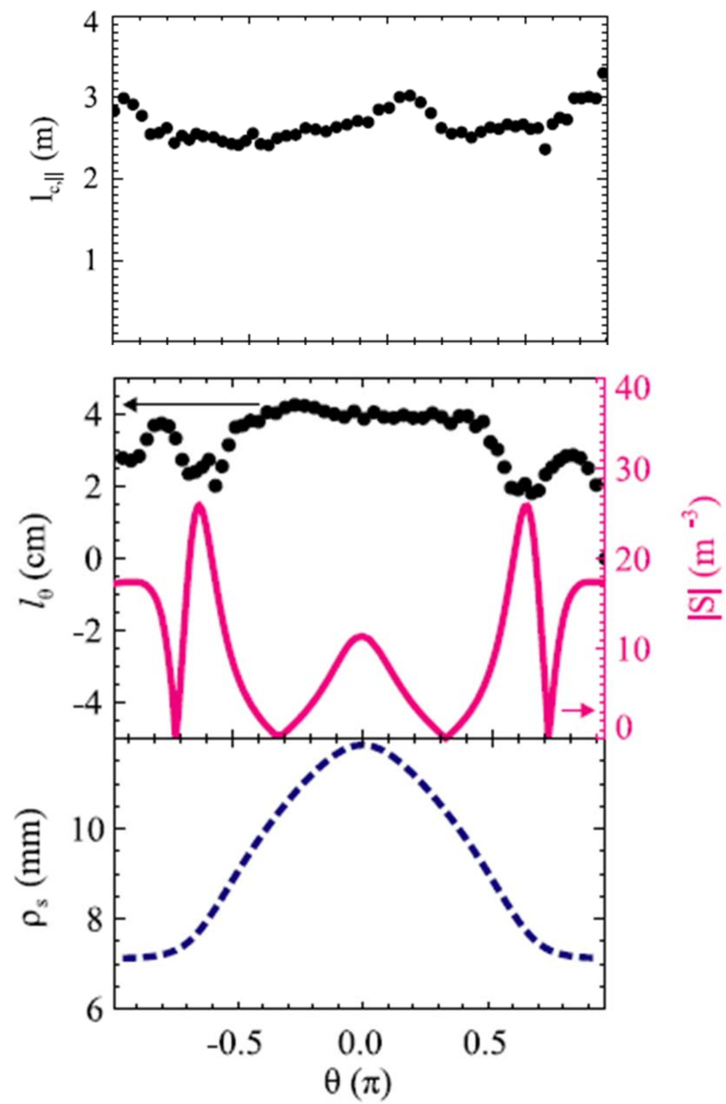


More direct measurement in TJ-K plasmas





TJ-K [Birkenmeier, PPCF (2012)]



General turbulence characteristics are useful for testing theory predictions, but we mostly care about transport

- Transport a result of finite average correlation between perturbed drift velocity (δv) and perturbed fluid moments (δn, δT, δv)
  - Particle flux, $\Gamma = \langle \delta v \delta n \rangle$
  - Heat flux, $Q = 3/2 n_0 \langle \delta v \delta T \rangle + 3/2 T_0 \langle \delta v \delta n \rangle$
  - Momentum flux, $\Pi \sim \langle \delta v \delta v \rangle$ (Reynolds stress, just like Navier Stokes)

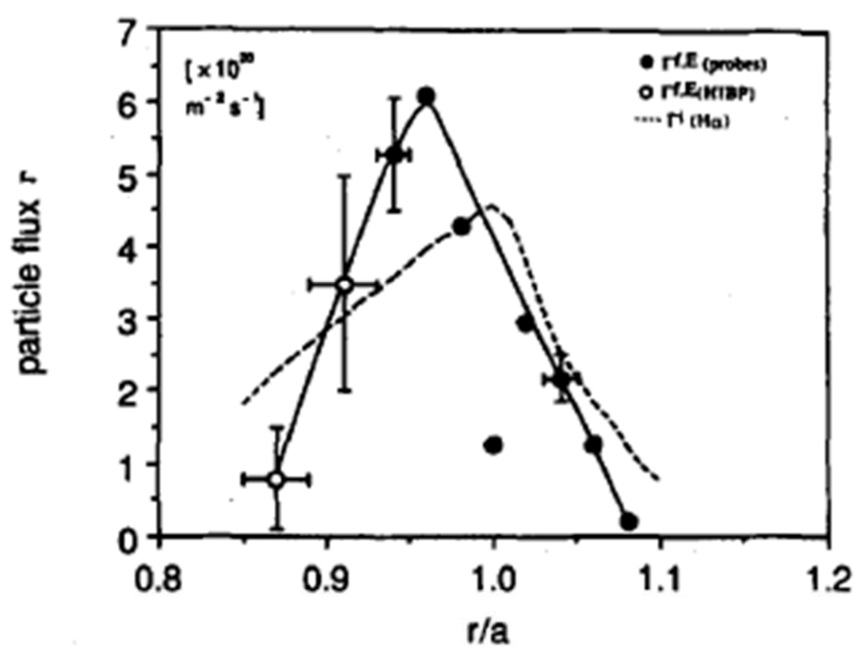
- Electrostatic turbulence often most relevant $\rightarrow$ $E \times B$ drift from potential perturbations: $\delta v_E = B \times \nabla(\delta\varphi)/B^2 \sim k_\theta(\delta\varphi)/B$

- Can also have magnetic contributions at high beta, $\delta v_B \sim v_{||}(\delta B_r/B)$ (magnetic "flutter" transport)

Measuring turbulent particle and heat fluxes using Langmuir probes

- Illustrates that turbulent transport can account for inferred anomalous transport (only possible in edge region)

TEXT, Wooton, PoFB (1990)



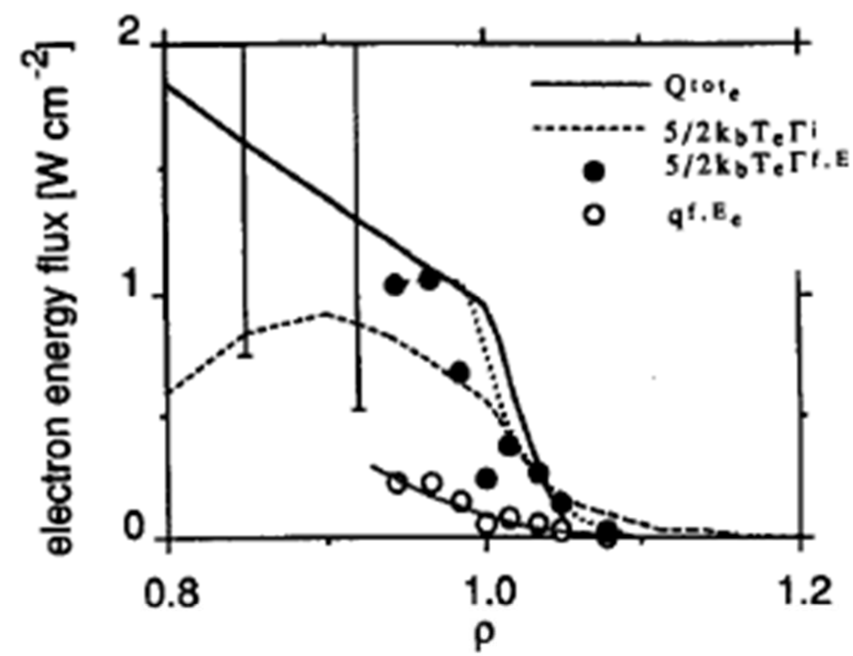


FIG. 3. A comparison of working particle fluxes in TEXT ($B_\phi = 2$ T, $I_p = 200$ kA, $\bar{n}_e = 3\times 10^{19}$ m^{-3}, H$^+$), the total Γ^i (from H_α), and $\Gamma^{f,E}$ driven by electrostatic turbulence. $\Gamma^{f,E}$ is measured with Langmuir probes (solid line, solid points) and the HIBP (open points).

Useful to Fourier decompose transport contributions, especially for theory comparisons

- E.g. particle flux from electrostatic perturbations:

$$\Gamma(k_\theta) = \frac{nT}{B} \sum_{k_\theta} k_\theta \left| \frac{\delta n(k_\theta)}{n_e} \right| \left| \frac{\delta \varphi(k_\theta)}{T_e} \right| \gamma_{n\varphi}(k_\theta) \sin \alpha_{n\varphi}(k_\theta)$$

Amplitude spectra

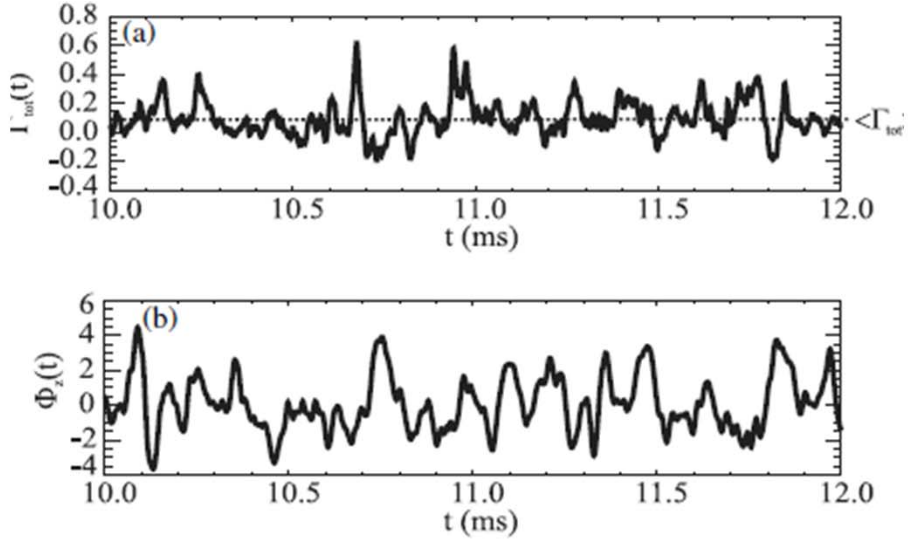
coherence

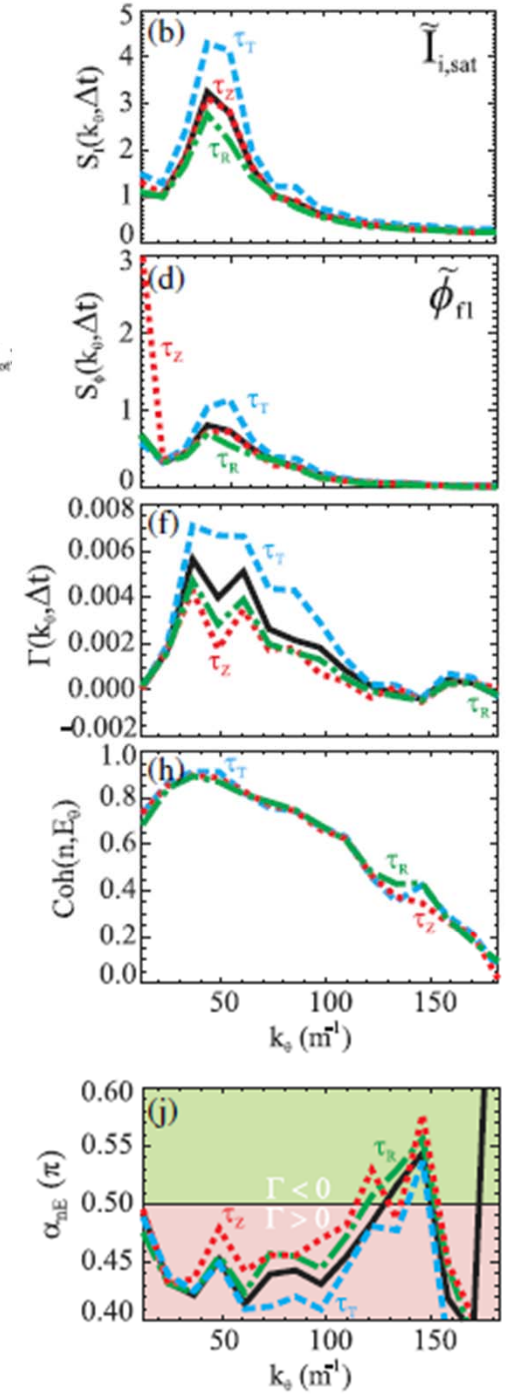
Cross phase

- Everything is a function of wavenumber

Edge Langmuir probe arrays used to decompose turbulent fluxes in k_θ

TJ-K [Birkenmeier, PPCF (2012)]





- Very rare to measure this comprehensively!
- Useful for challenging theory calculations
- Yet to be done this thoroughly for hot tokamak core, where comprehensive gyrokinetic simulations available for comparison

Beyond general characteristics, there are many theoretical "flavors" of drift waves possible in tokamak core & edge

- Usually think of drift waves as gradient driven (∇T_i, ∇T_e, ∇n)
  - Often exhibit threshold in one or more of these parameters
- Different theoretical "flavors" exhibit different parametric dependencies, predicted in various limits, depending on gradients, T_e/T_i, ν, β, geometry, location in plasma…
  - Electrostatic, ion scale ($k_\theta \rho_i \leq 1$)
    - Ion temperature gradient (ITG) – driven by ∇T_i, weakened by ∇n
    - Trapped electron mode (TEM) – driven by ∇T_e & ∇n_e, weakened by ν_e
  - Electrostatic, electron scale ($k_\theta \rho_e \leq 1$)
    - Electron temperature gradient (ETG) - driven by ∇T_e, weakened by ∇n
  - Electromagnetic, ion scale ($k_\theta \rho_i \leq 1$)
    - Kinetic ballooning mode (KBM) - driven by $\nabla \beta_{pol}$
    - Microtearing mode (MT) – driven by ∇T_e, at sufficient β_e

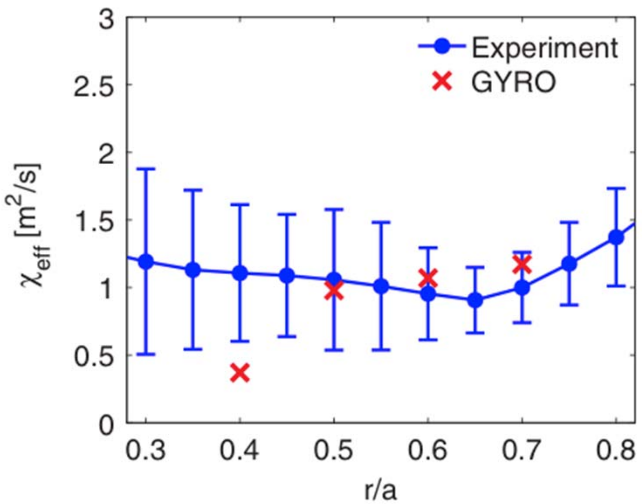
Challenging to definitively identify a particular theoretical turbulent transport mechanism

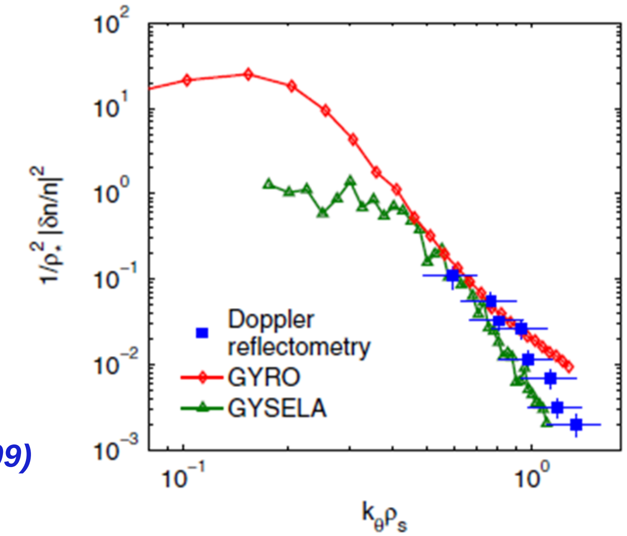
- Best we can do:
  - Measure as many turbulence quantities as possible (amplitude spectra, cross-phases, transport
  - Compare with theory (simulation) predictions
  - Scaling equilibrium parameters to investigate trends/sensitivities

CORE ION SCALE TURBULENCE

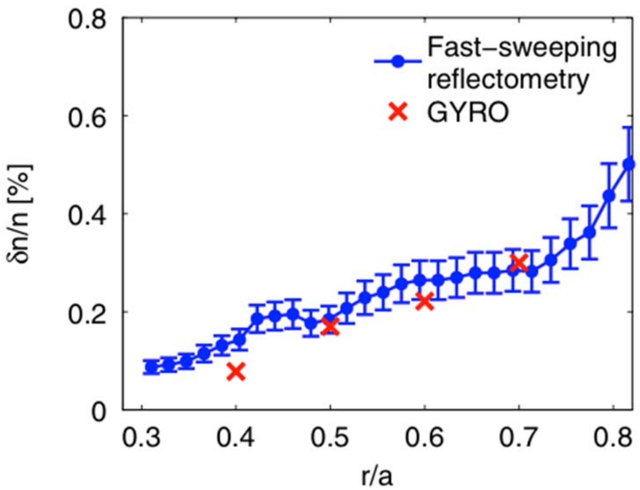
Transport, density fluctuation amplitude (from reflectometry) and spectral characteristics all consistent with nonlinear ITG simulations in Tore Supra

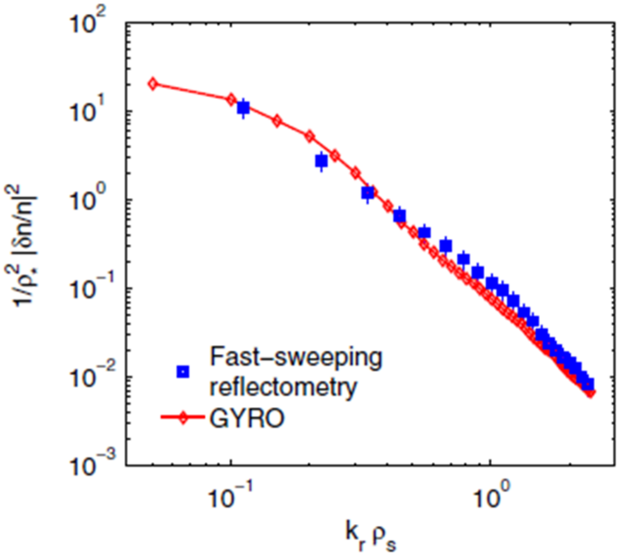
- Provides confidence in interpretation of transport in conditions when ITG instability/turbulence predicted to be most important





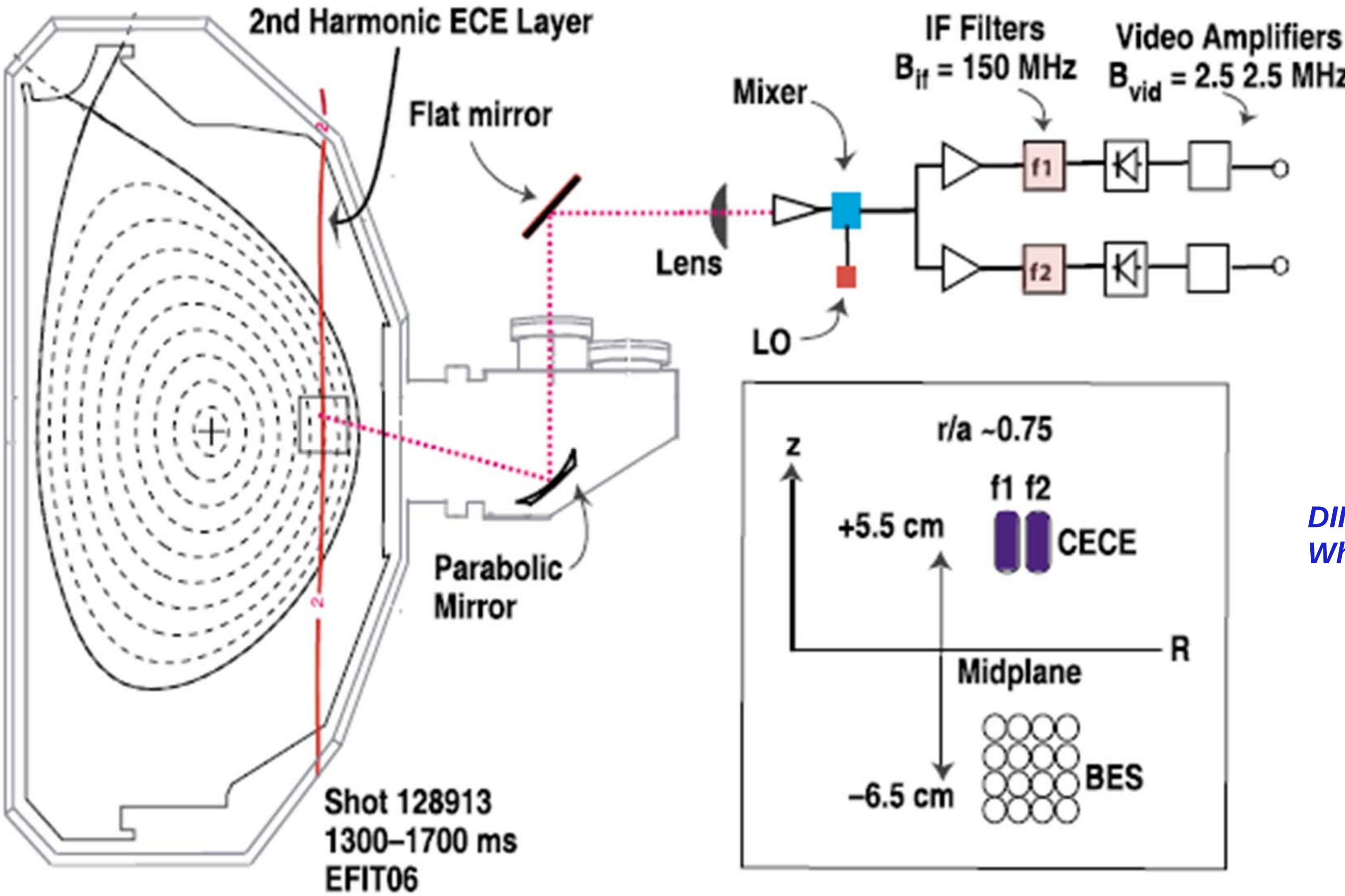
Casati, PRL (2009)





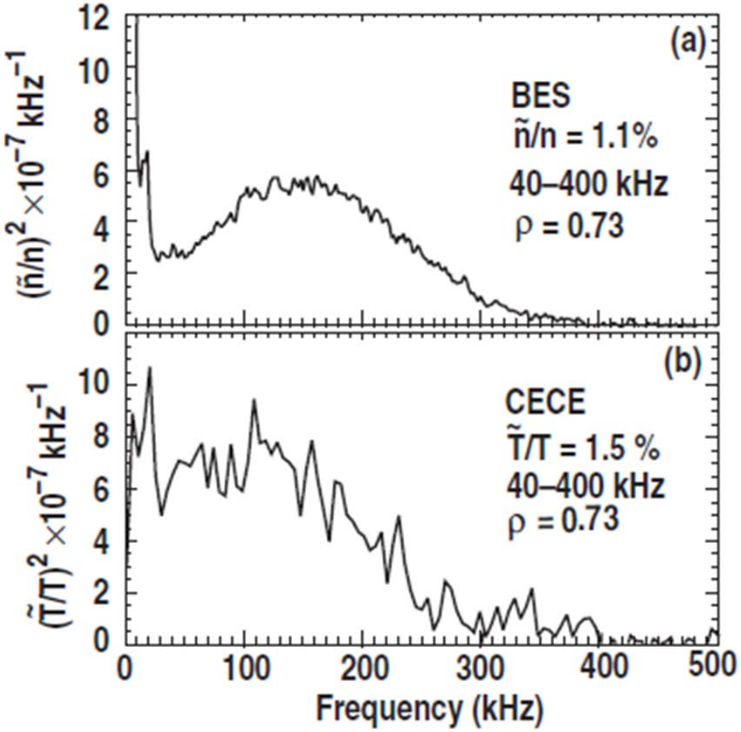
Measurement of both electron density and temperature fluctuations at overlapping locations (DIII-D)

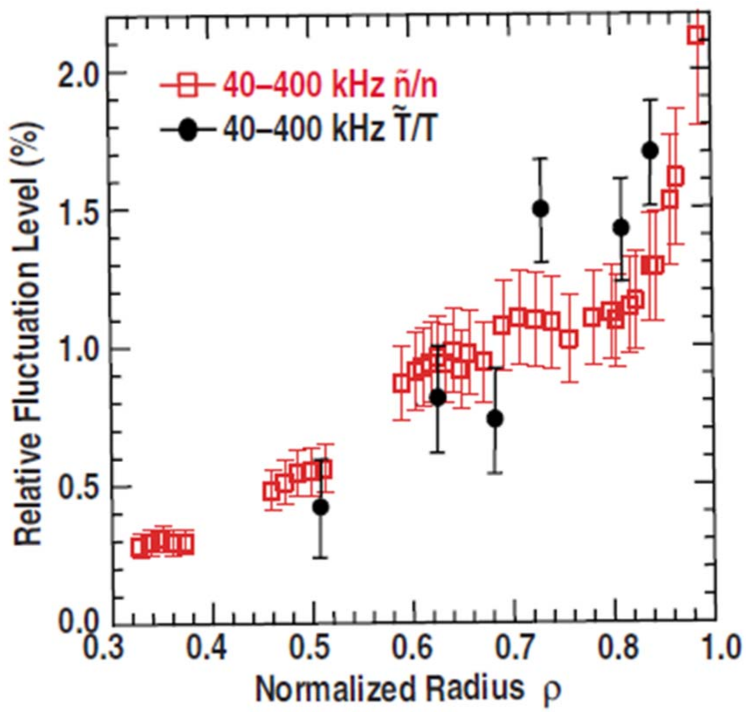
- Using electron cyclotron emission (ECE) to measure δT_e



DIII-D
White, PoP (2008)

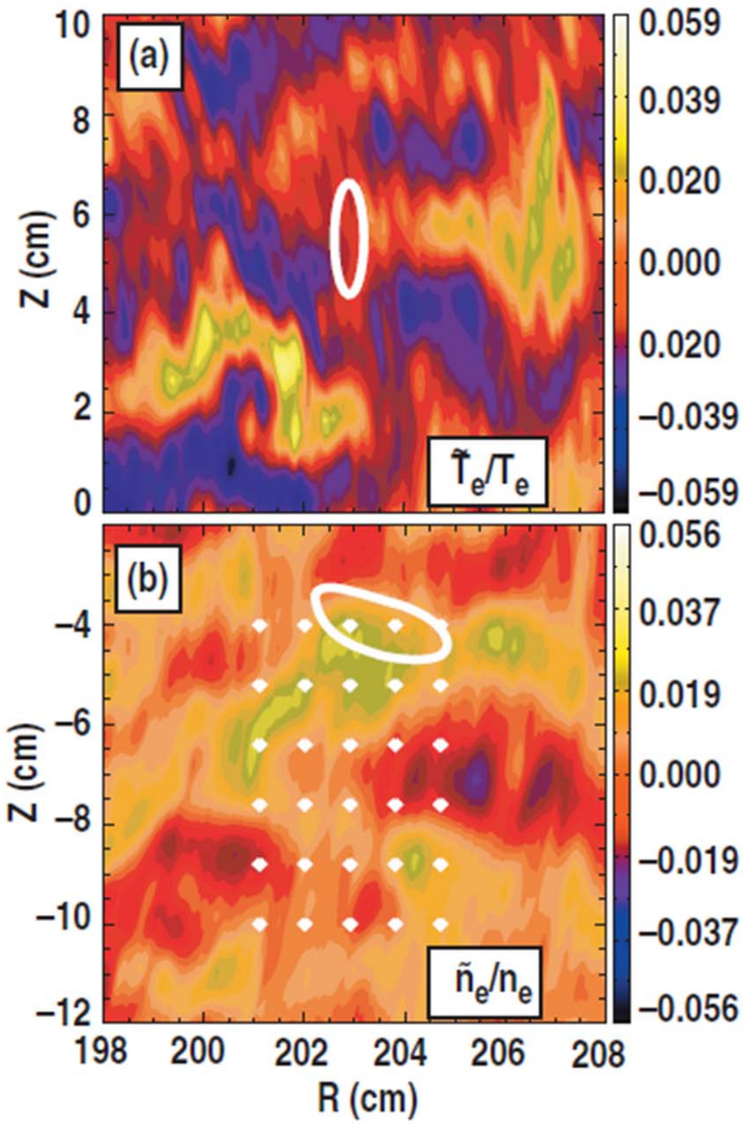
Normalized density and temperature fluctuations are very similar in amplitude





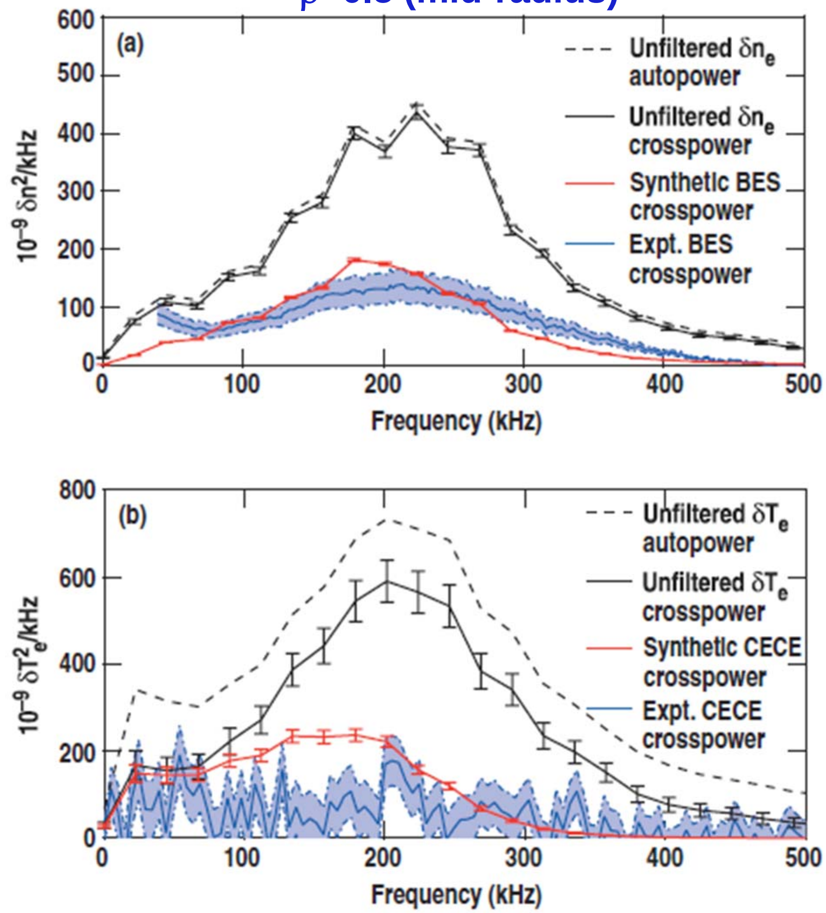
DIII-D
White, PoP (2008)

Comparing δn_e, δT_e fluctuation spectra with simulations using synthetic diagnostic



- Level of agreement sensitive to accounting for realistic instrument function

ρ=0.5 (mid-radius)

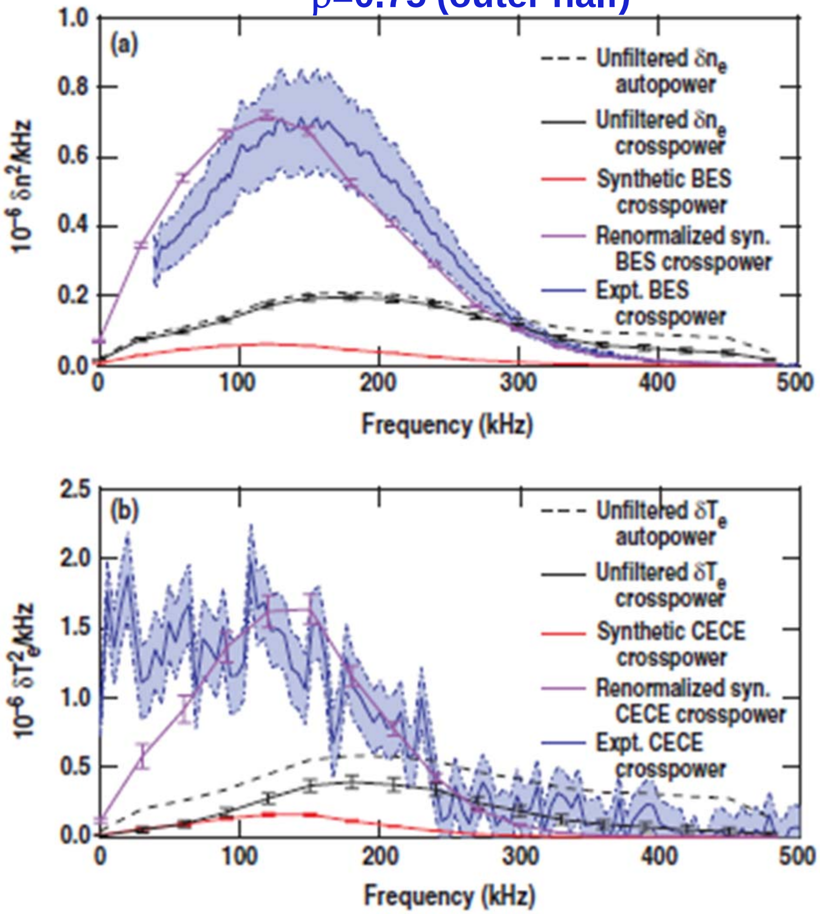


Holland, PoP (2009)

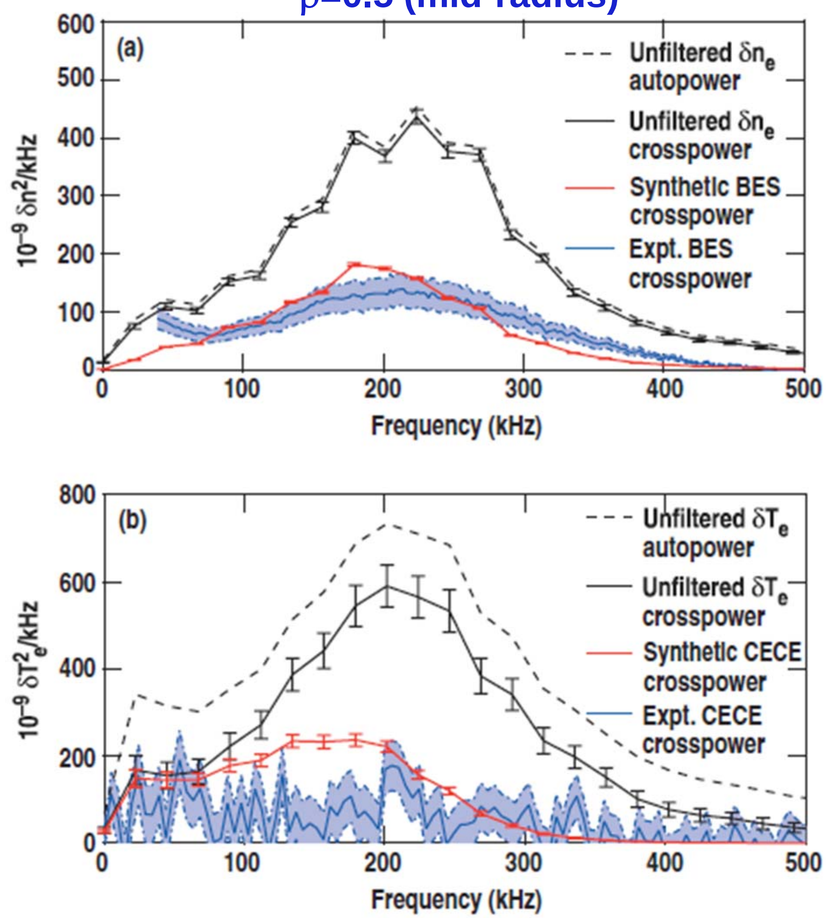
Agreement worse further out

- Measured intensity larger than simulations, so called “shortfall” problem challenging gyrokinetic simulations

ρ=0.75 (outer half)

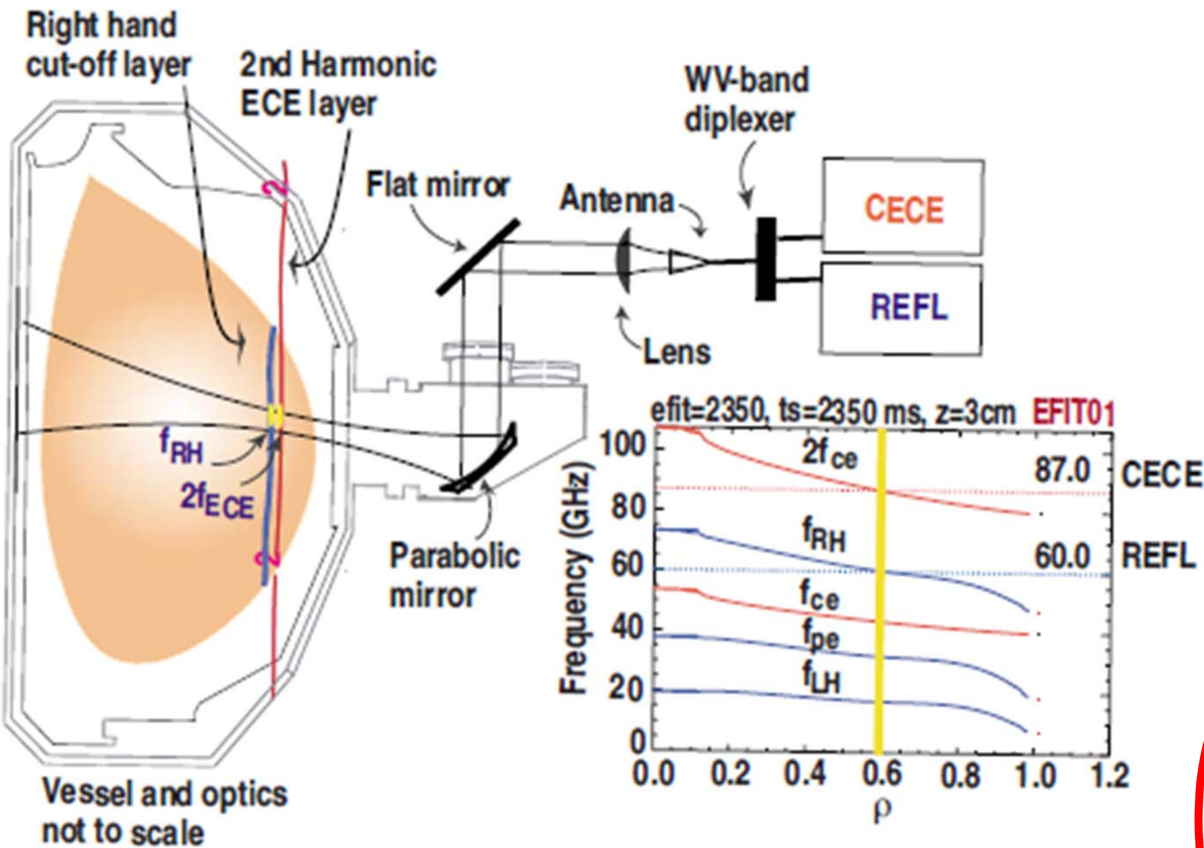


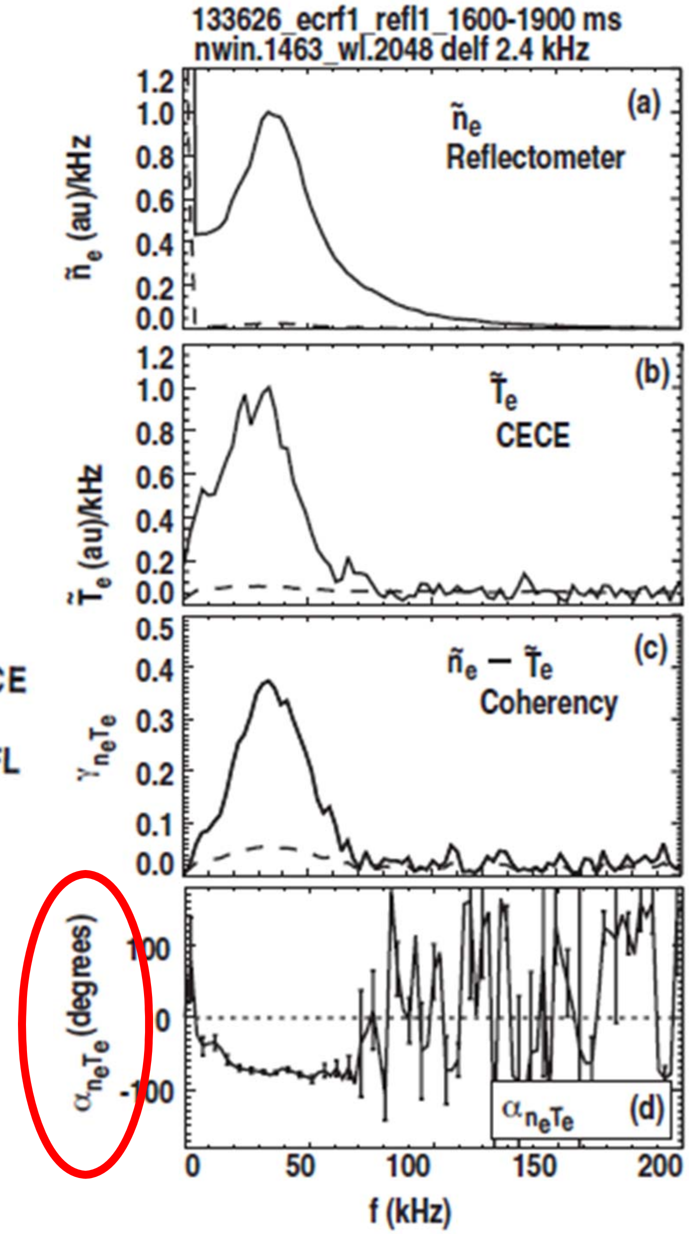
ρ=0.5 (mid-radius)



Holland, PoP (2009)

Simultaneous measurement of n_e and T_e using same beam path allows for cross-phase measurement





$$\gamma_{n_eT_e}(f) = \frac{|\langle S^*_{\tilde{n}_e} S_{\tilde{T}_e}\rangle|}{|\langle S_{\tilde{n}_e}\rangle|^2 |\langle S_{\tilde{T}_e}\rangle|^2}.$$

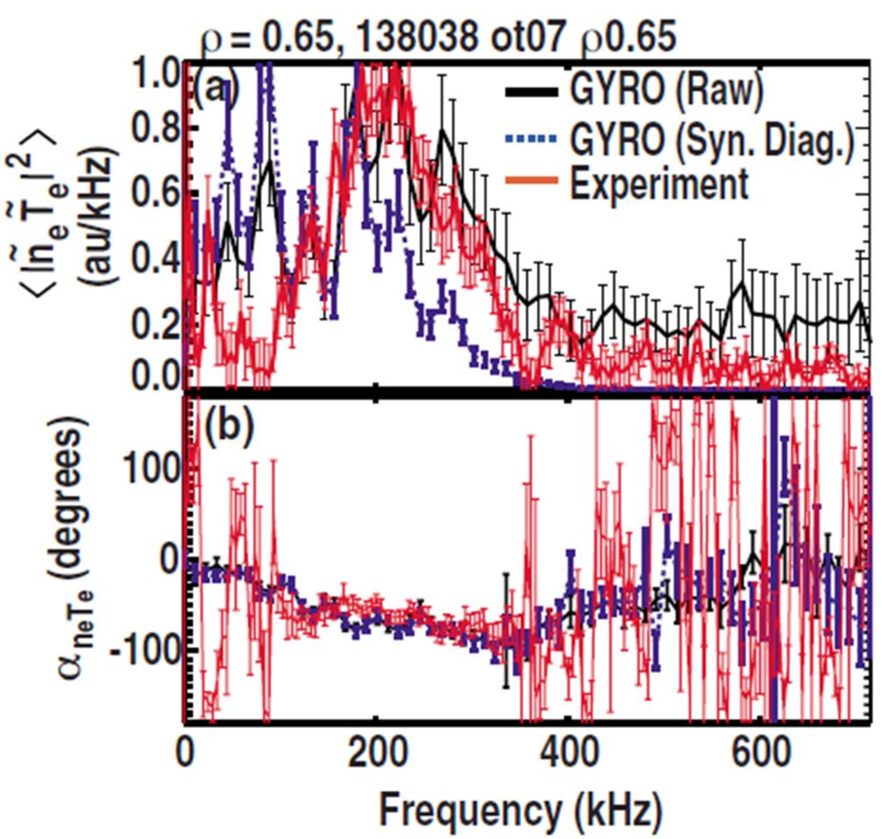
DIII-D
White, PoP (2010)

ne-Te cross phases agree well with simulations

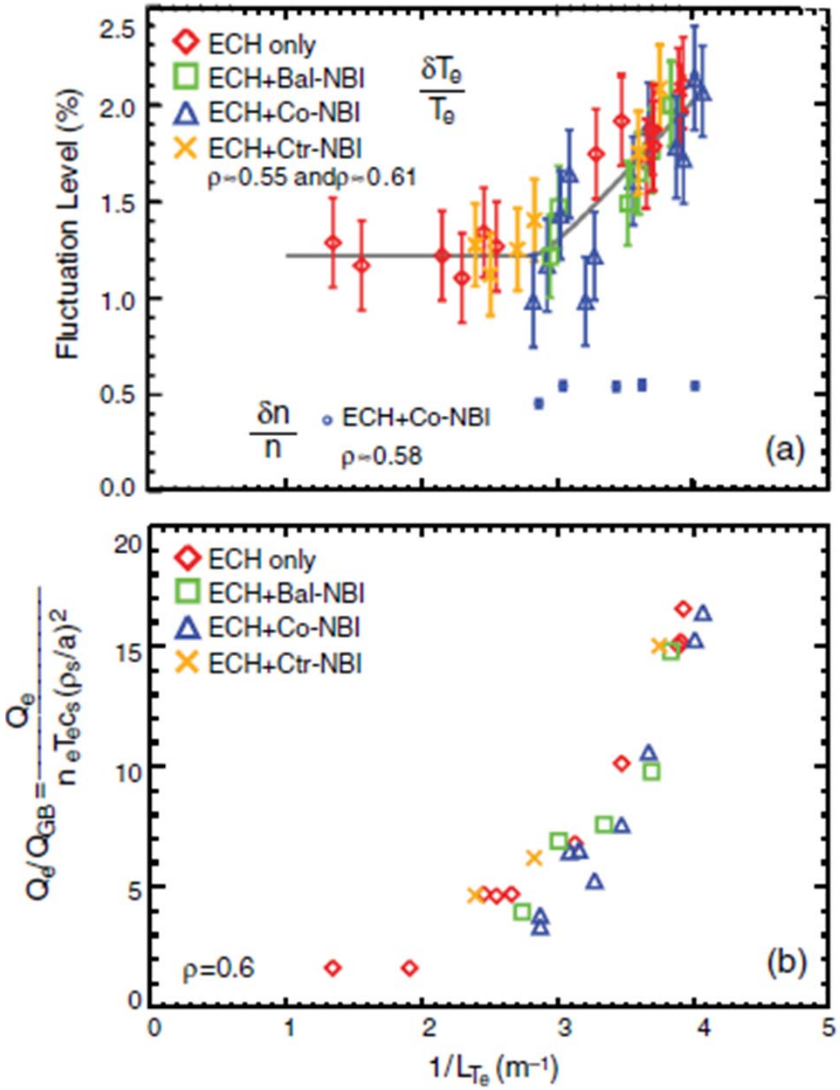
- Amplitude spectra and transport fluxes still off by 2-3

TABLE IV. Postexperiment GYRO simulations from 138 038, ρ=0.65, t=1525 ms. Turbulence amplitudes and cross phase are compared with synthetic diagnostic results.

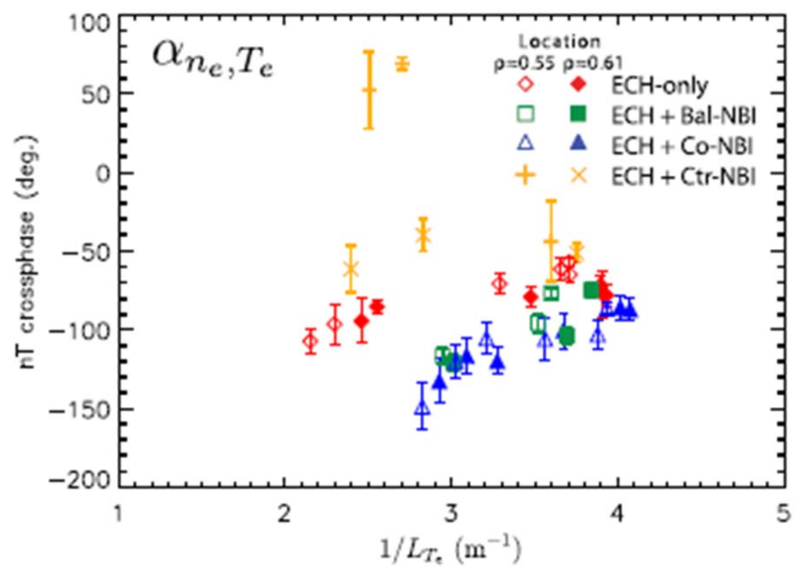
Parameter	GYRO	Experiment
Q_e (MW)	3.77 ± 0.06	2.43 ± 0.02
Q_i (MW)	0.34 ± 0.01	1.32 ± 0.02
$\tilde{T}_e/T_e$ (%)	1.07 ± 0.10	0.95 ± 0.05
$\tilde{n}/n$ (%)	0.25 ± 0.01	0.57 ± 0.06
$\alpha_{n_eT_e}$ (degrees)	71 ± 1	61 ± 12



Measured changes of δT_e, n_e-T_e crossphase and transport with increasing ∇T_e provides constraint for simulations

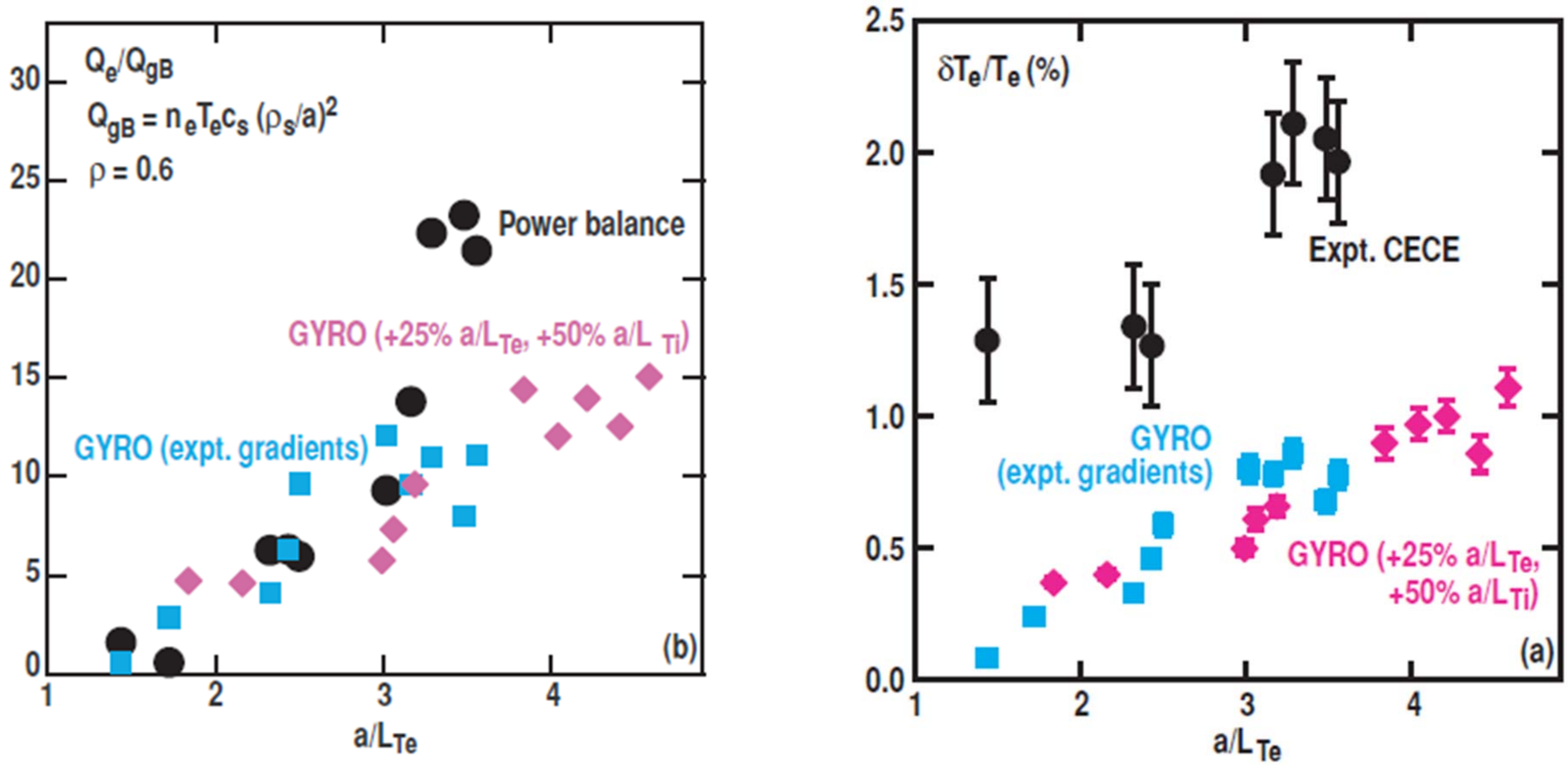


DIII-D
Hillesheim, PRL,PoP (2013)



Simulations can reproduce transport for some observations

- Predicted turbulence levels always too small, even when accounting for sensitivity to ∇Te
- Discrepancies point to missing physics in theory/simulation



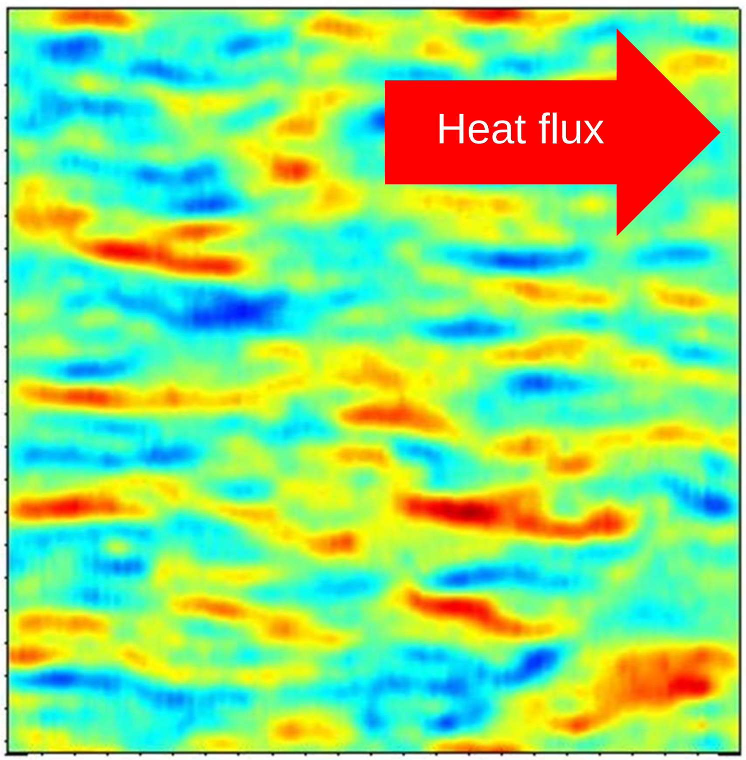
Holland, PoP (2013)

ELECTRON SCALE TURBULENCE

Large scale sheared flows can tear apart turbulent eddies, reduce turbulence → improve confinement

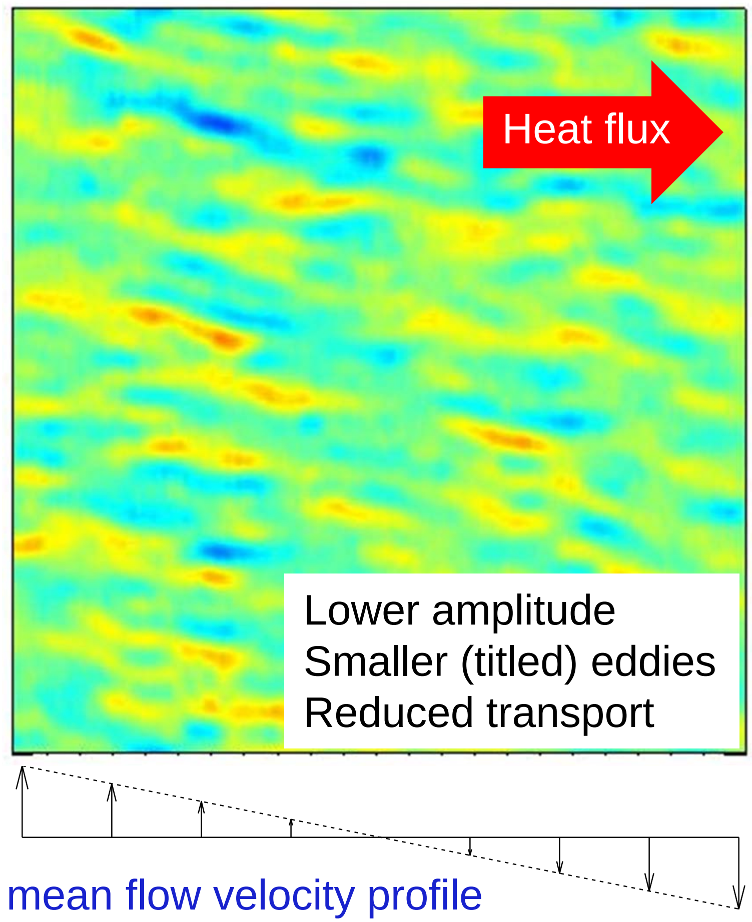
Simulations for NSTX – a low aspect ratio tokamak

Snapshot of density without flow shear



100 ion radii
6,000 electron radii
~50 cm

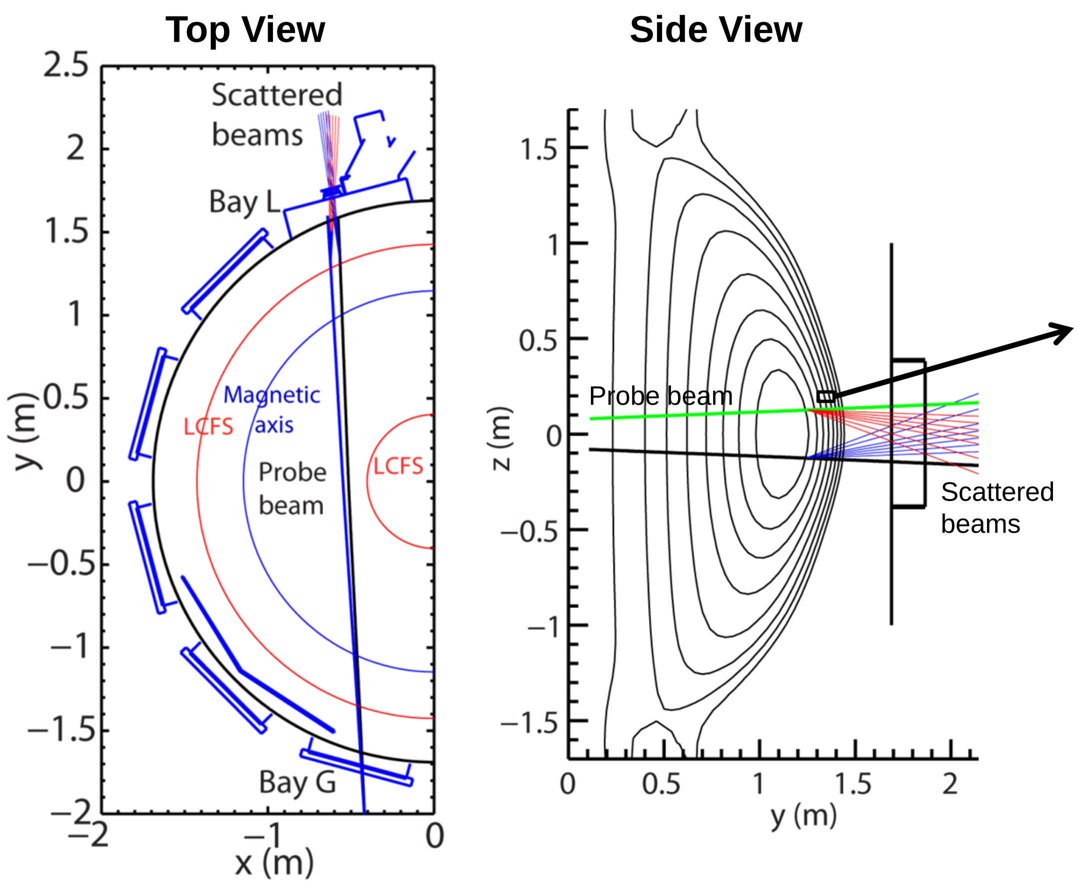
Snapshot of density with flow shear



mean flow velocity profile

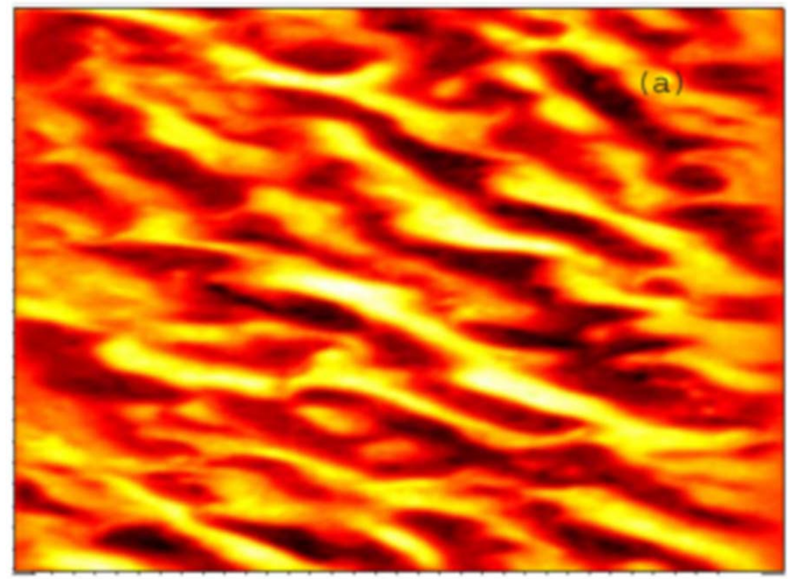
Challenge to diagnose ρ_e scale fluctuations – high-k microwave scattering

NSTX tokamak (PPPL)



UC-Davis

density fluctuations

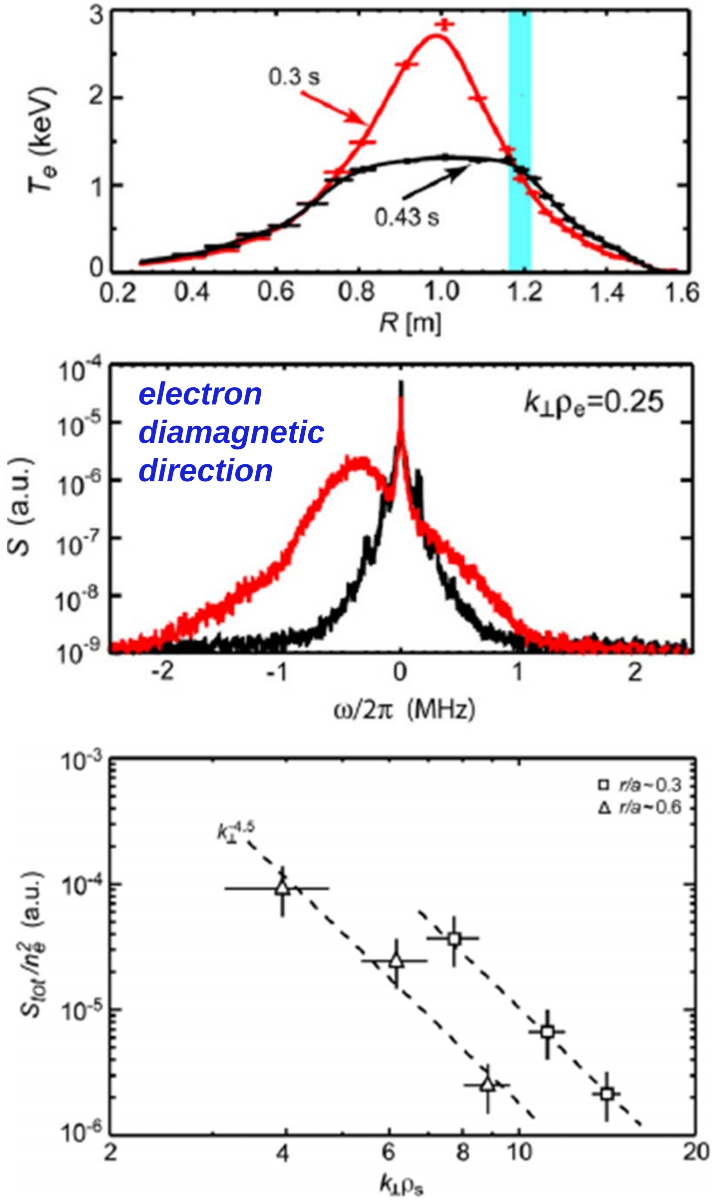


6 ion radii

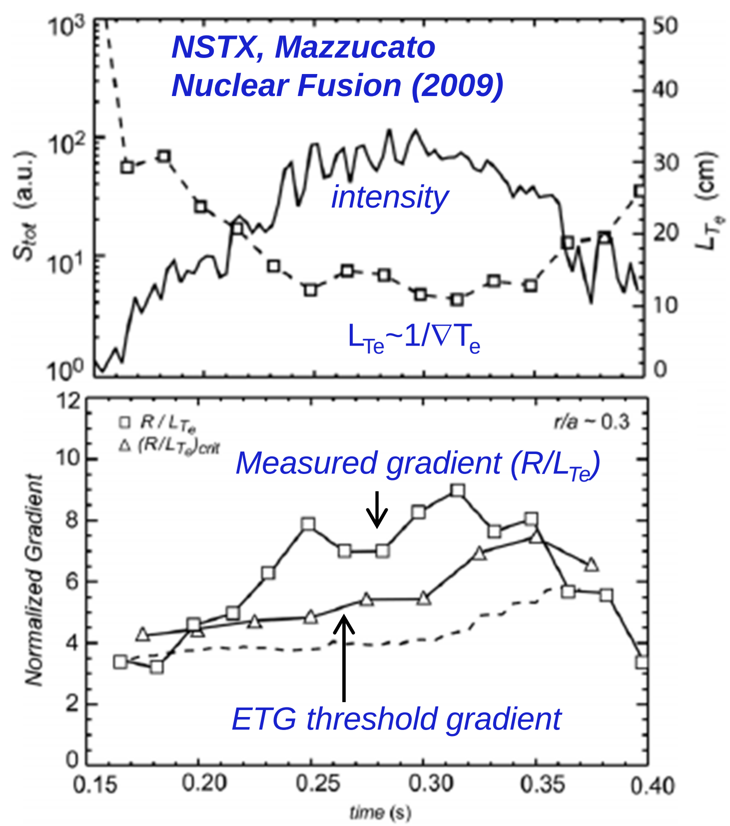
360 electron radii

~2 cm

Evidence for ETG turbulence at electron gyroradius scales ($k\rho_e \lesssim 1$)



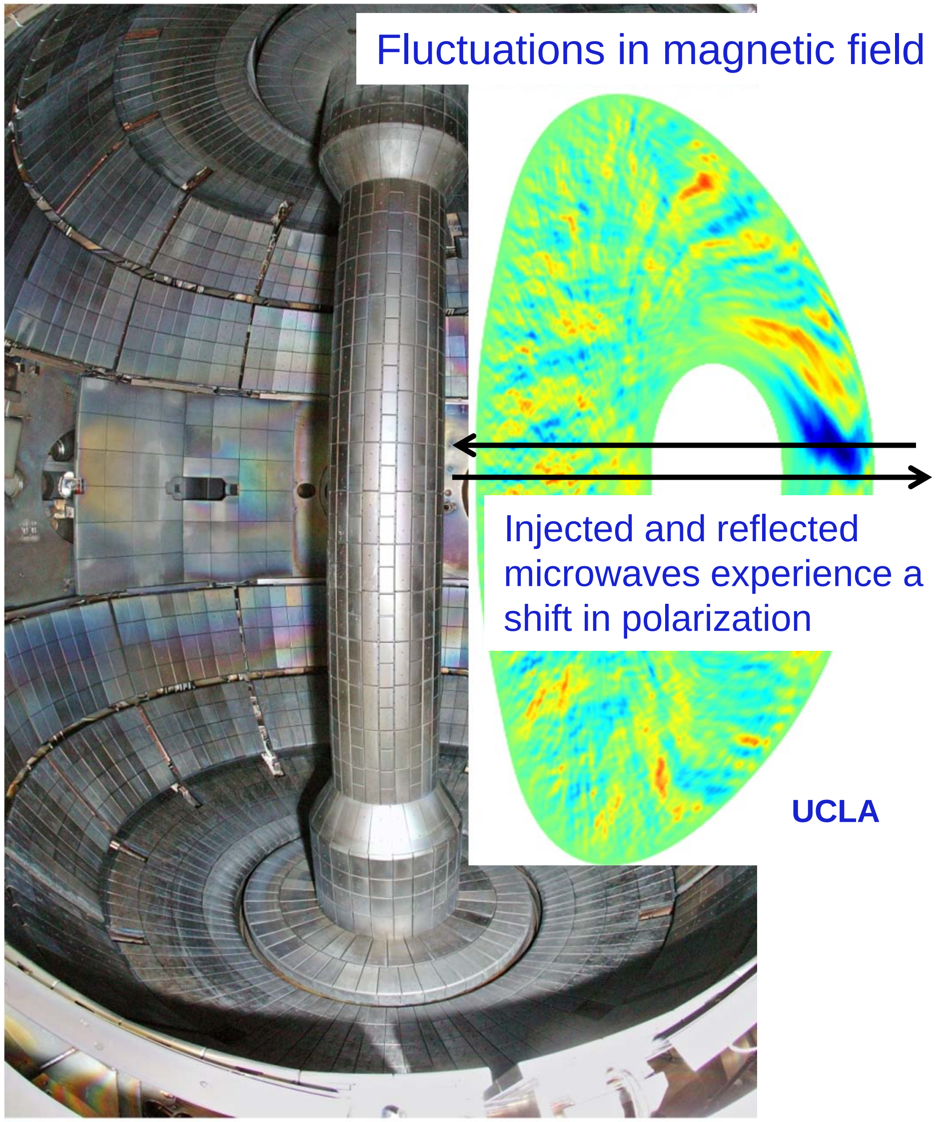
- High k ($k\rho_e$=0.25) fluctuation intensity increases with ∇T_e
- Correlated with surpassing ETG threshold, $R/L_{Te} > R/L_{Te,crit,etg}$



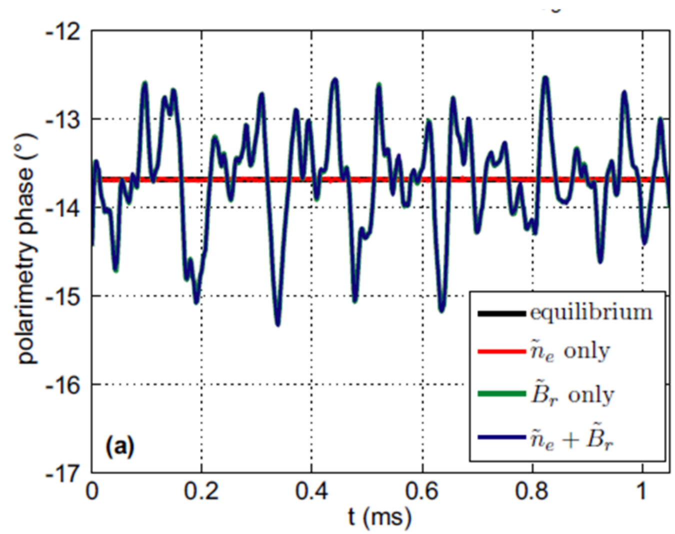
MAGNETIC TURBULENCE

NSTX also operates at very high beta – simulations suggest magnetic (microtearing) turbulence can be important

NSTX (PPPL)



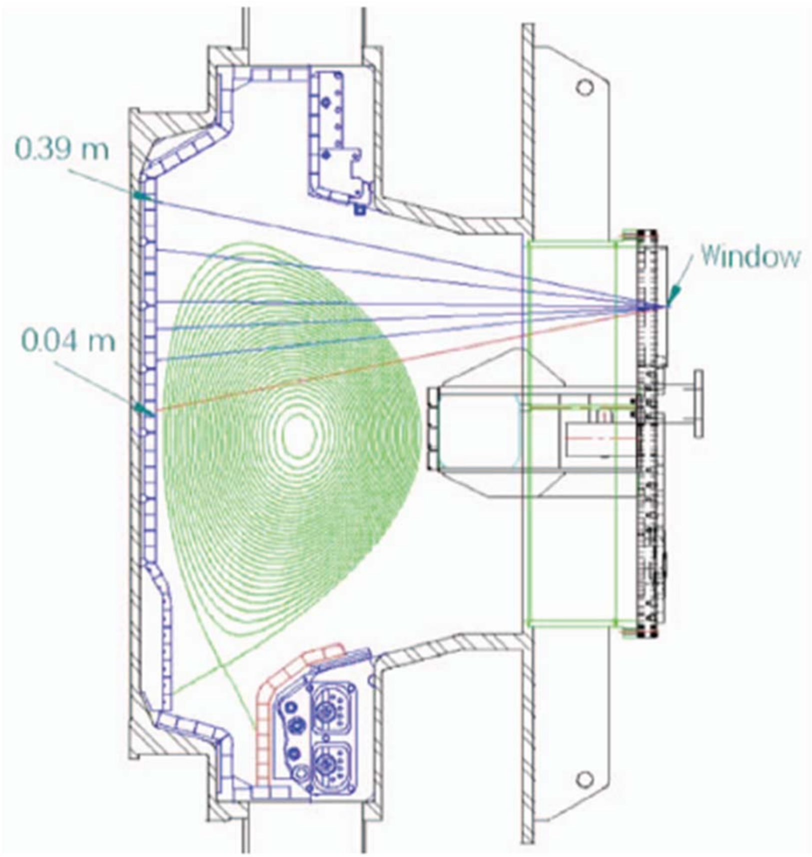
- Very challenging to measure internal magnetic fluctuations
- Synthetic diagnostic calculations predict polarimetery could be sensitive – will be tested on NSTX-Upgrade (2015+)

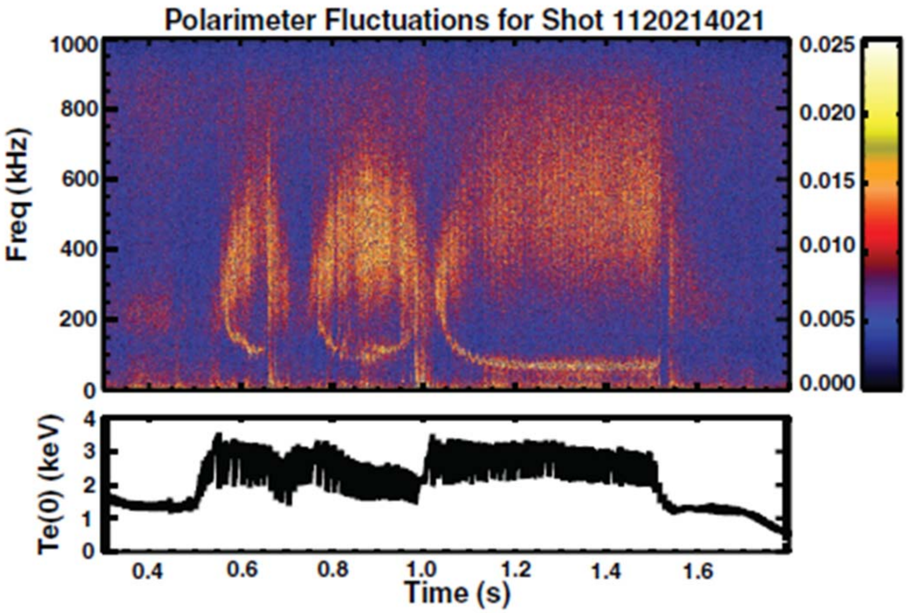


Zhang, PPCF (2013)
Guttenfelder, PRL (2011)

Polarimetry on C-Mod has observed broadband high frequency polarization fluctuations

- Requires careful interpretation to separate δn_e and δB influence

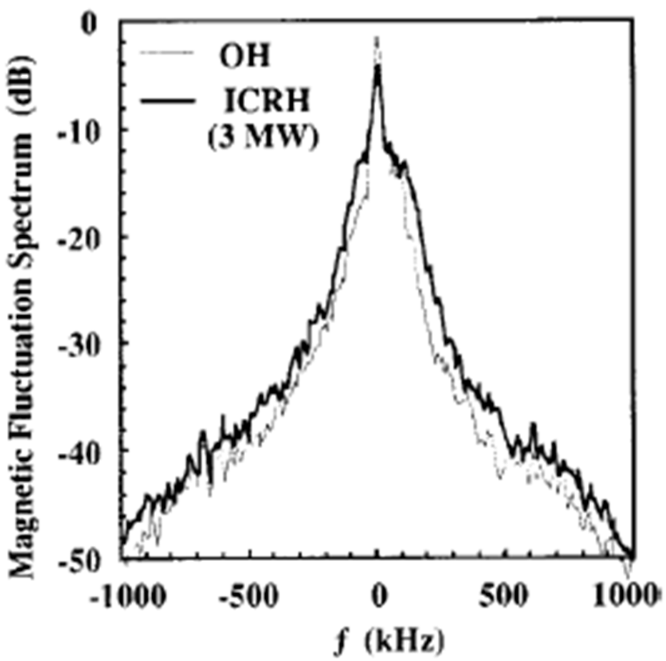


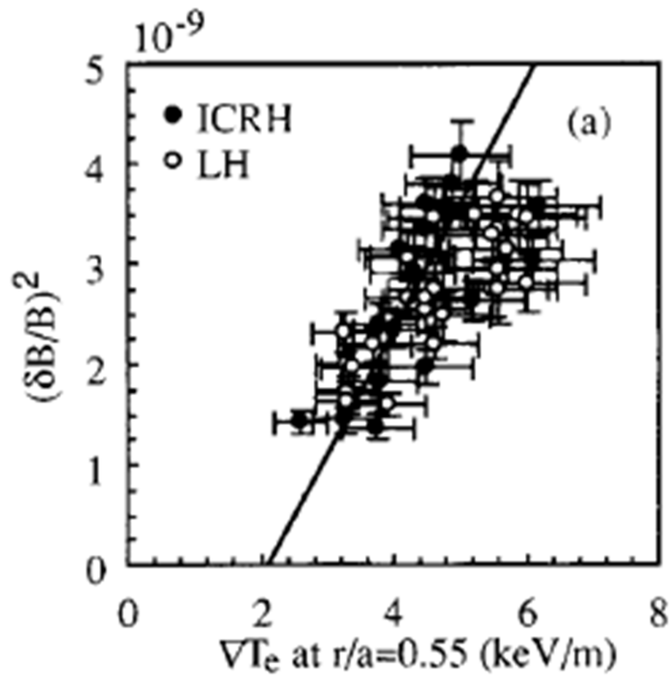


Bergerson, RSI (2012)

Cross polarization scattering used on Tore Supra to measure internal magnetic fluctuations

- Broad δB frequency spectra
- Correlation between δB/B increasing with local ∇Te
- However, require additional measurements/simulations to determine weather δB due to
  - $j_{||}$ from predominantly electrostatic turbulence (Callen PRL 1977)
  - fundamentally different turbulence (e.g. microtearing)





Colas, Nuclear Fusion (1998)

ZONAL FLOWS, GAMs

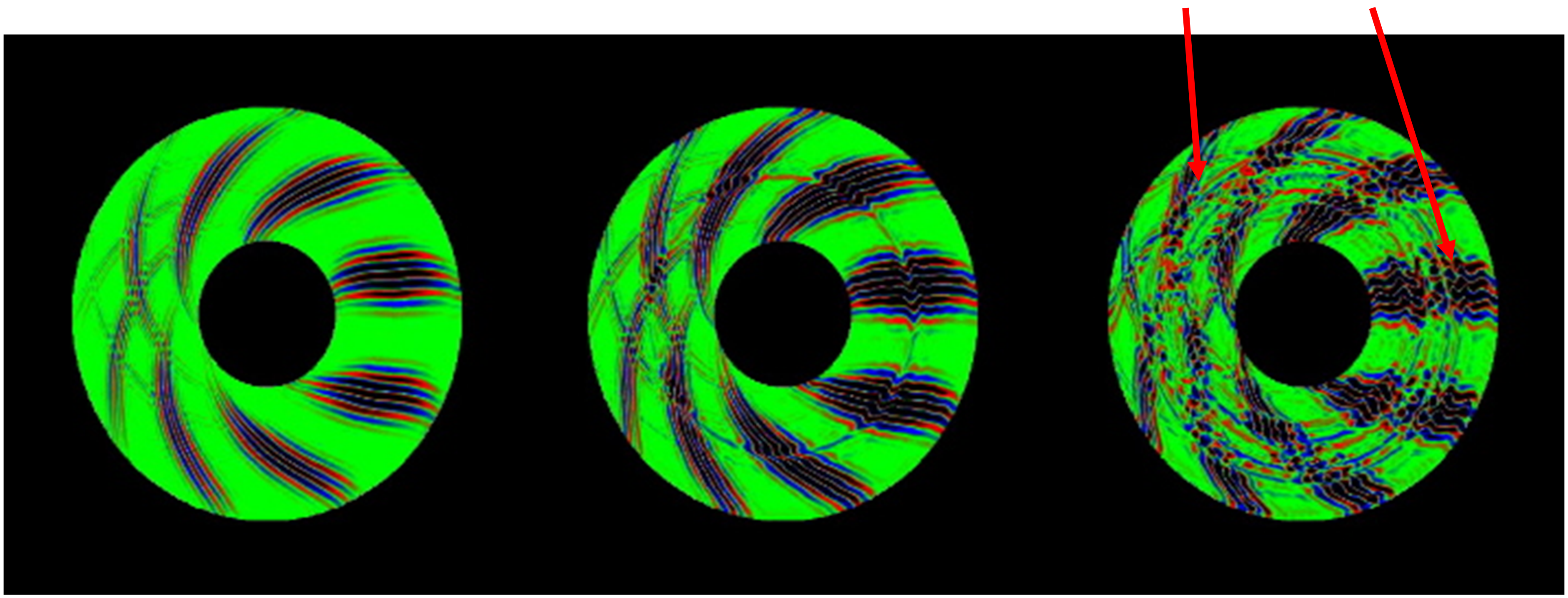
Self-generated “zonal flows” impact saturation of turbulence and overall transport (roughly analogous to jet stream)

- Potential perturbations uniform on flux surfaces, near zero frequency (f~0)
- Predator-prey like behavior: turbulence drives ZF, which regulates/clamps turbulence; if turbulence drops enough, ZF drive drops, allows turbulence to grow again…

Linear instability stage demonstrates structure of fastest growing modes

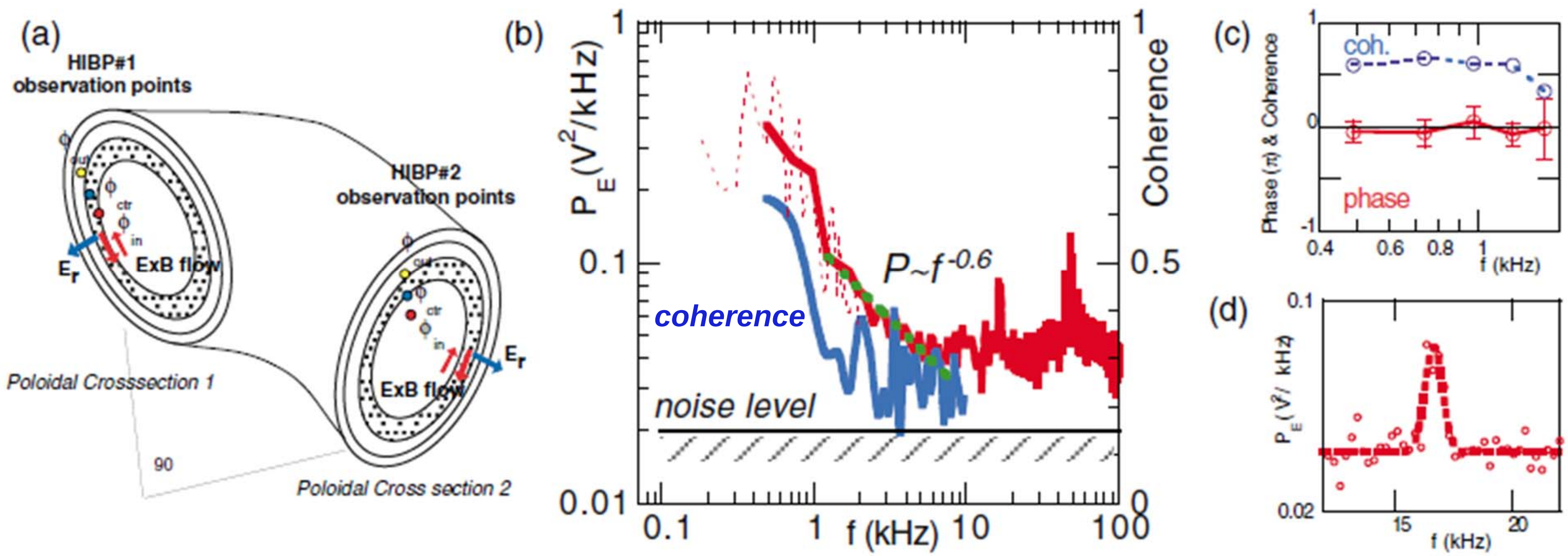
Large flow shear from instability cause perpendicular “zonal flows”

Zonal flows help moderate the turbulence!!!



Evidence of zonal flows from measuring potential on same flux surface at two different toroidal locations

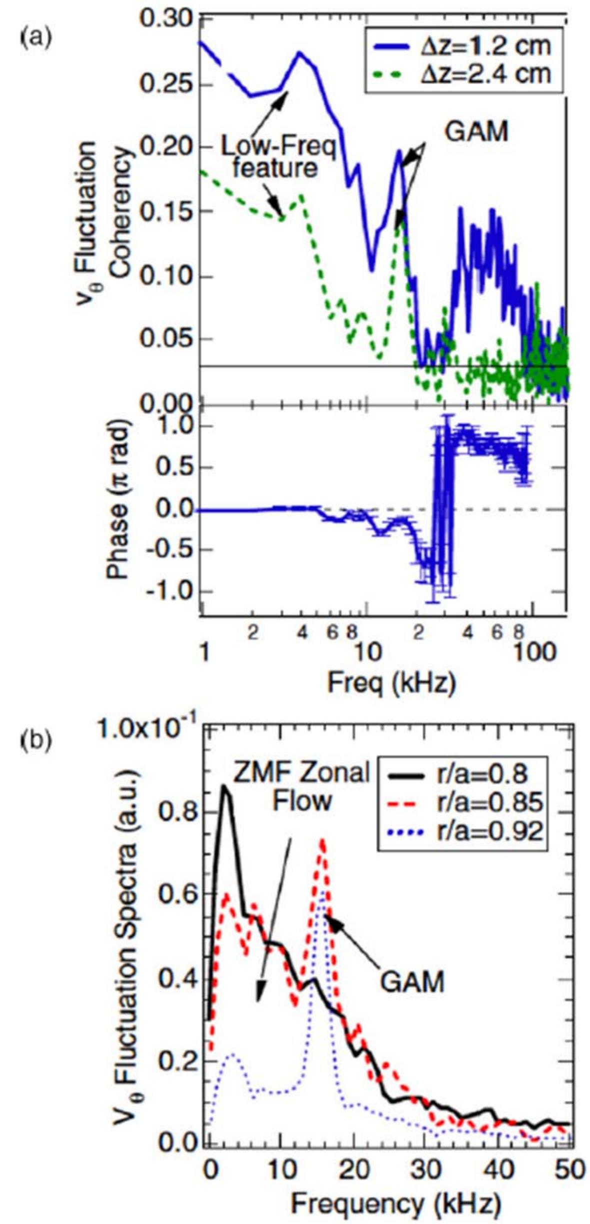
- High coherency at very low frequency with zero phase shift suggests uniform zonal perturbation
- Also evidence of a coherent mode around 17 kHZ - geodesic acoustic mode ($\omega_{GAM} \approx c_s/R$) from associated n=0, m=1 pressure perturbation



CHS, Fujisawa, PRL (2004)

Also found using poloidal flow measurements from BES on DIII-D

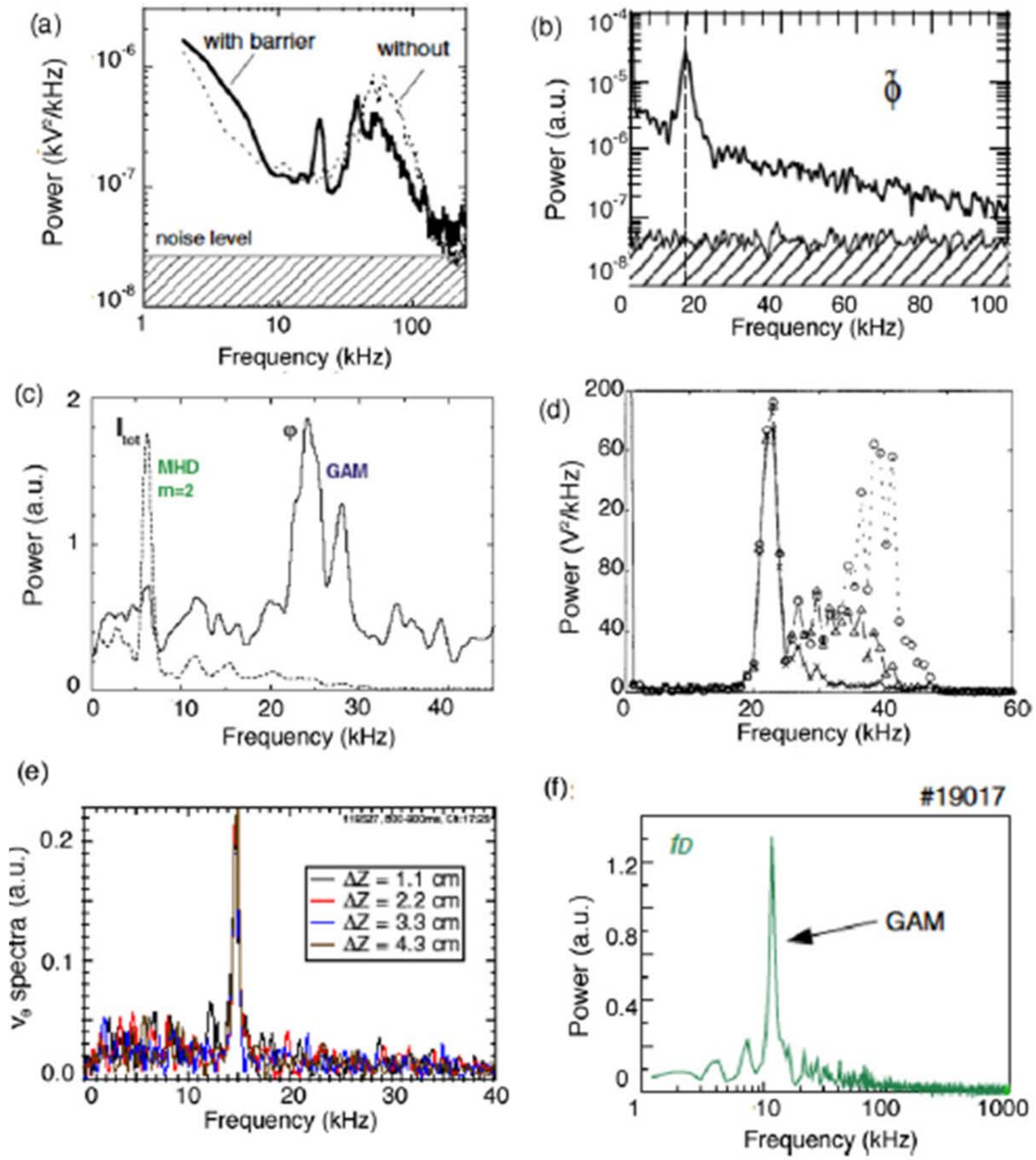
- Poloidal flow determined from time delay estimation of poloidally separated BES channels
- High coherency at low frequency, zero phase shift
- Evidence of GAM oscillation
- Relative strength of each varies with radius



DIII-D, Gupta PRL (2003)

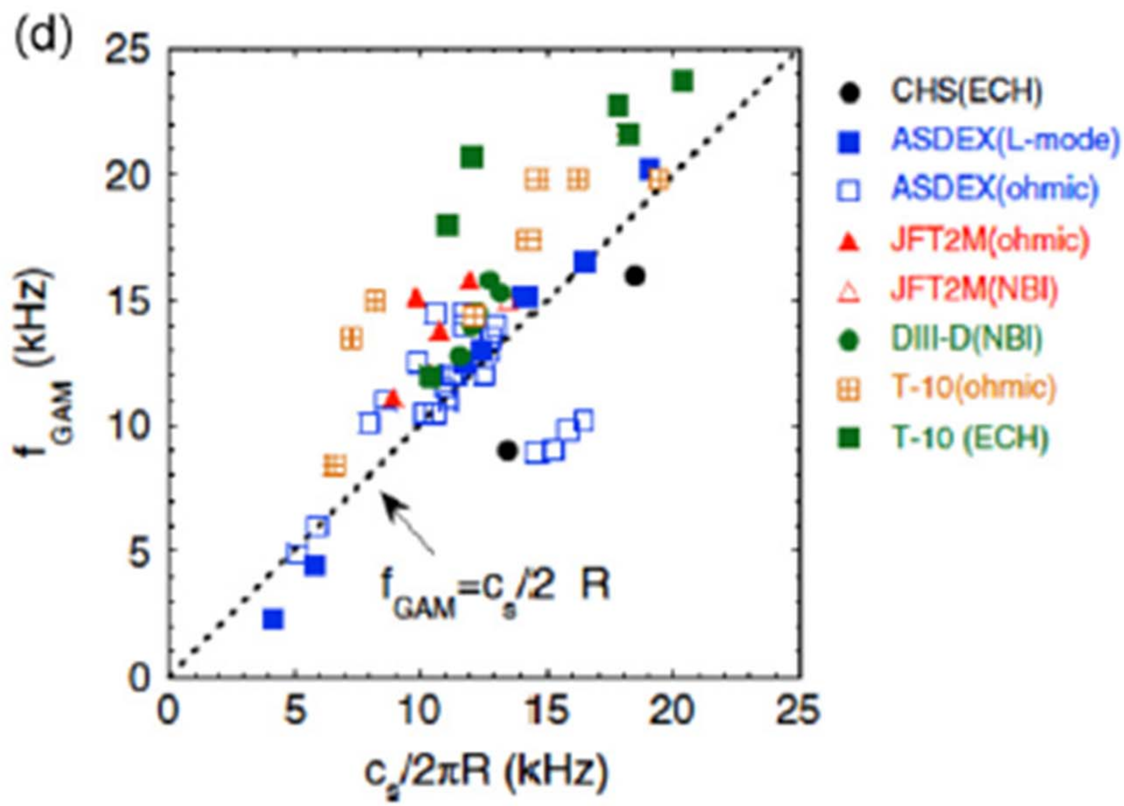
GAM seen on numerous devices using different measurement techniques

- Seems to be in nearly all machines, if looked for
- See Fig. 11 of Fujisawa, Nuclear Fusion (2009) for legend



Broad cross-machine agreement of GAM frequency with theory

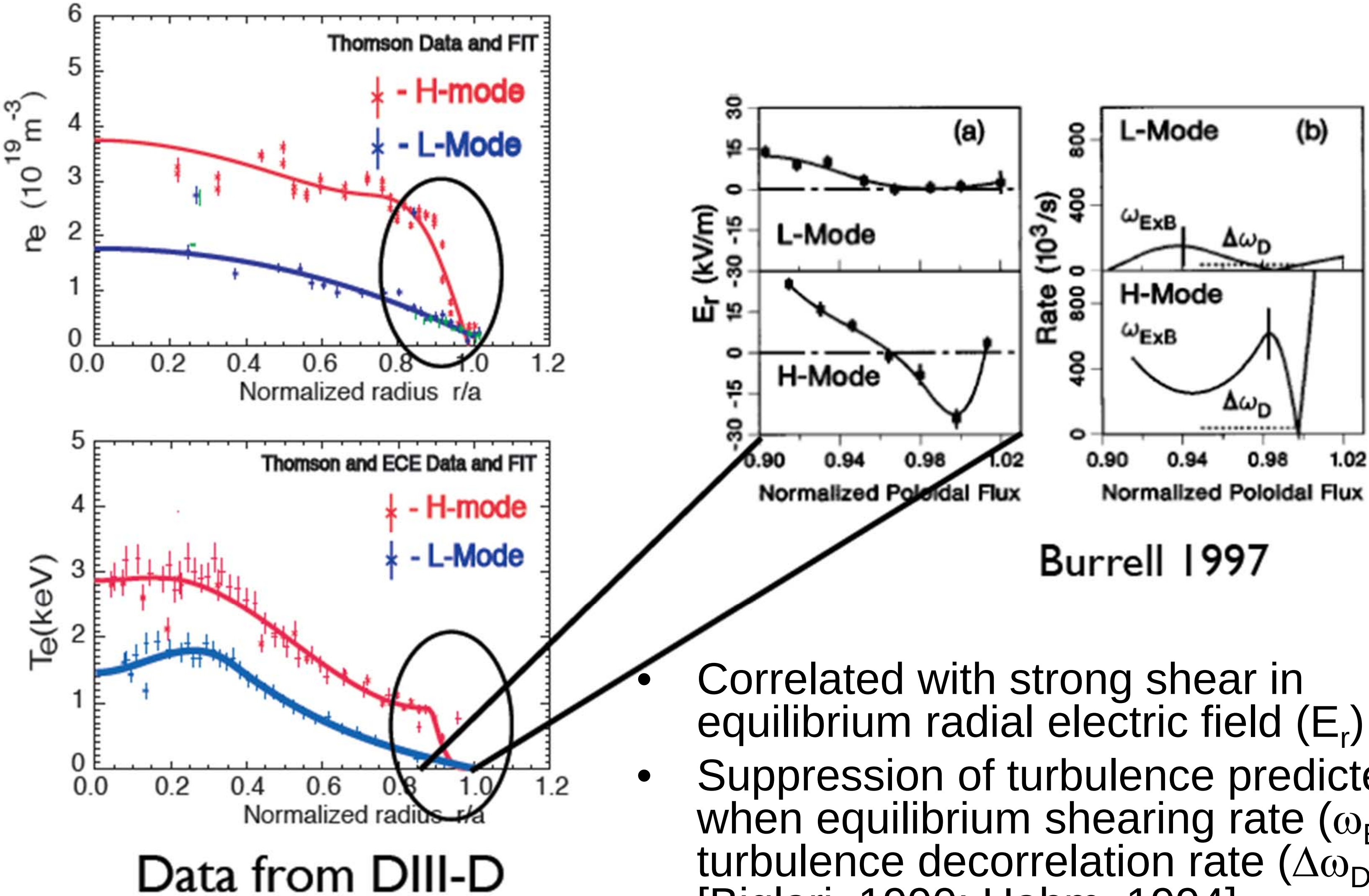
- Discrepancies have spurred additional theory developments to refine gam frequency and damping rates (due to geometry, nonlinear effects, …)



Fujisawa, NF (2009)

EDGE TURBULENCE
L-H TRANSITION

Spontaneous "H-mode" edge transport barrier can form with sufficient heating power

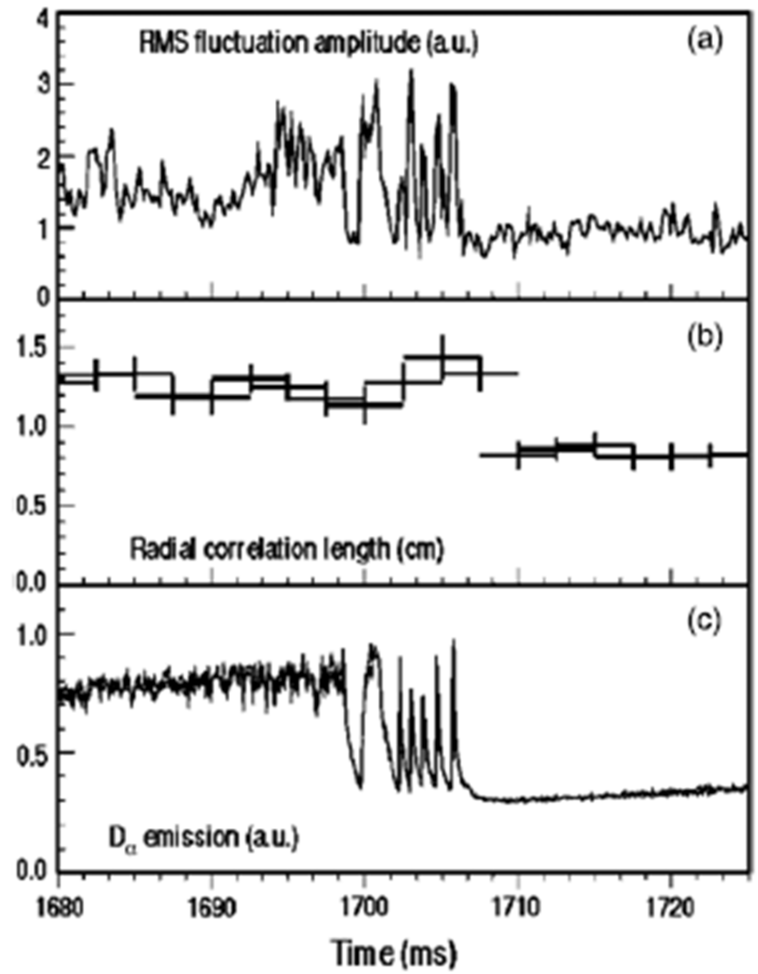


(from Carter, 2013)

- Correlated with strong shear in equilibrium radial electric field (E_r)
- Suppression of turbulence predicted when equilibrium shearing rate ($\omega_{E\times B}$) > turbulence decorrelation rate ($\Delta\omega_D$) [Biglari, 1990; Hahm, 1994]

Transition from L→H correlated with drop in turbulence amplitude, reduction in radial correlation length

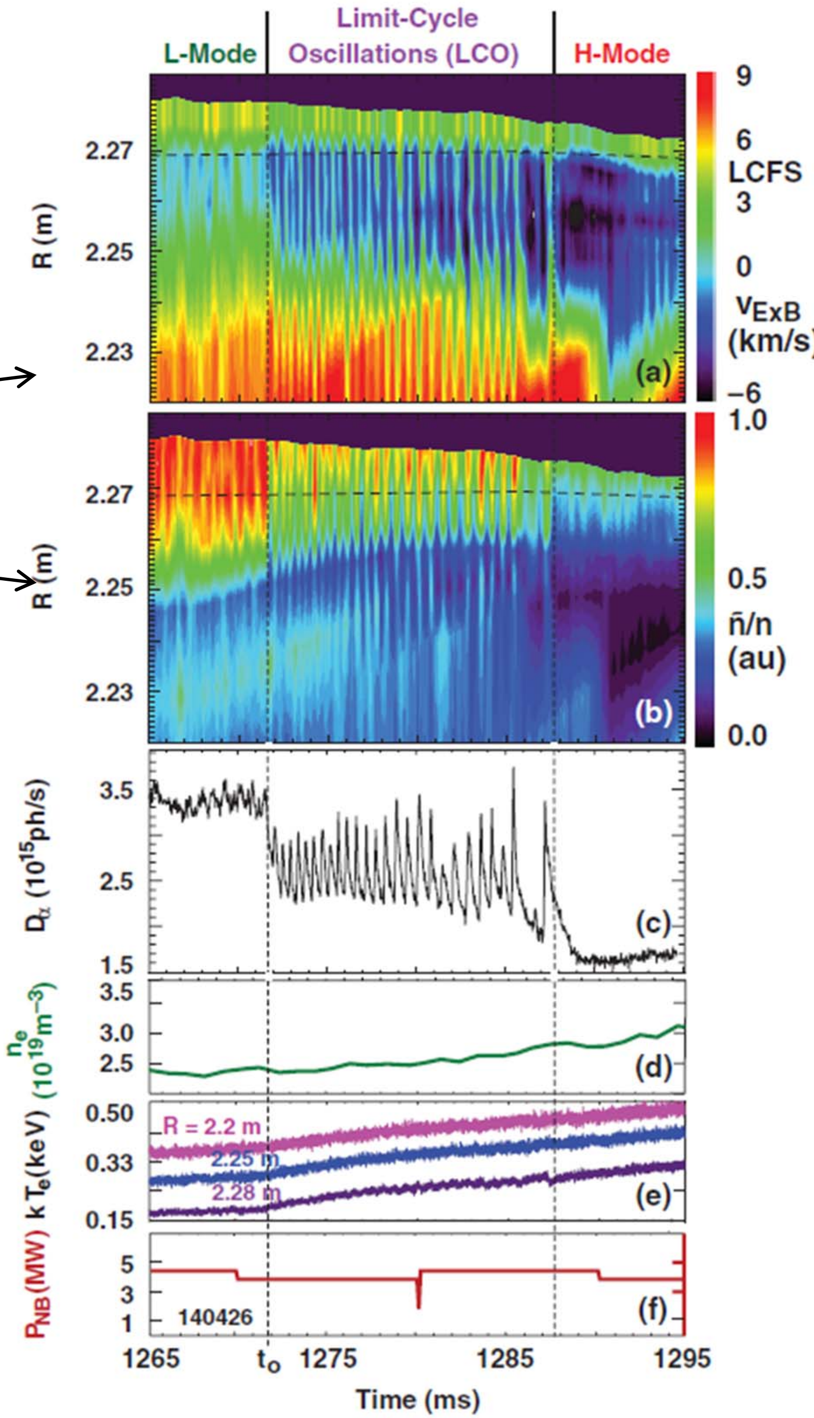
- Consistent with E×B shear suppression
- However, there is still no clear understanding regarding what *initiates* the transition and the dynamics involved
- Practically important for understanding how much power required to reach H-mode



Burrell, PoP (1997)
Coda, Phys. Lett. A (2000)

Multiple doppler backscattering diagnostics provide δn, $\delta v_{E\times B}$ at multiple radii simultaneously

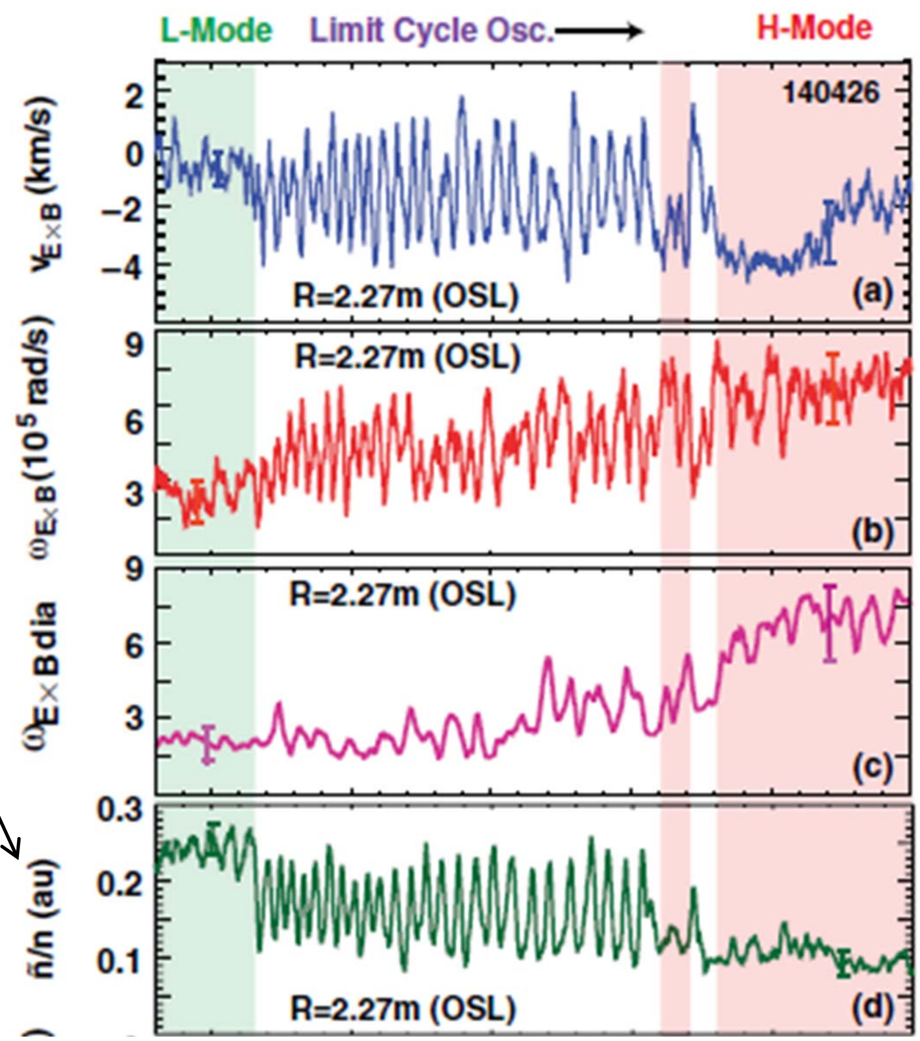
- During dithering L-H phase (identified by D_α signal), $\delta v_{E\times B}$ and δn start to oscillate
- Equilibrium n_e, T_e begin to increase
- Eventually strong equilibrium flow shear locks in, fluctuations drop permanently, and pedestal finishes forming



DIII-D, Schmitz, PRL (2012)

Dynamics consistent with two-predator – prey model (Kim, PRL 2003)

- In L-mode, increasing turbulence drives stronger ZF
- Eventually starts to suppress turbulence, leads to predator-prey limit cycle oscillation between ZF and turbulence
- As confinement (and gradients) increases, equilibrium Er driven by ∇Pi increases, until it is strong enough to maintain suppression

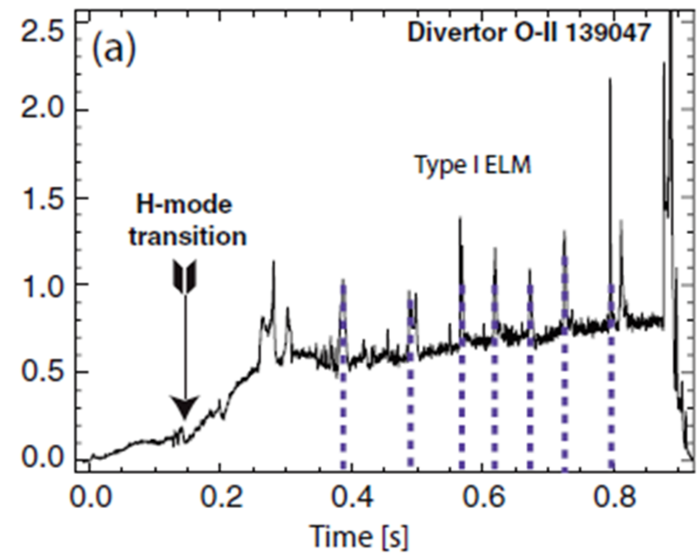


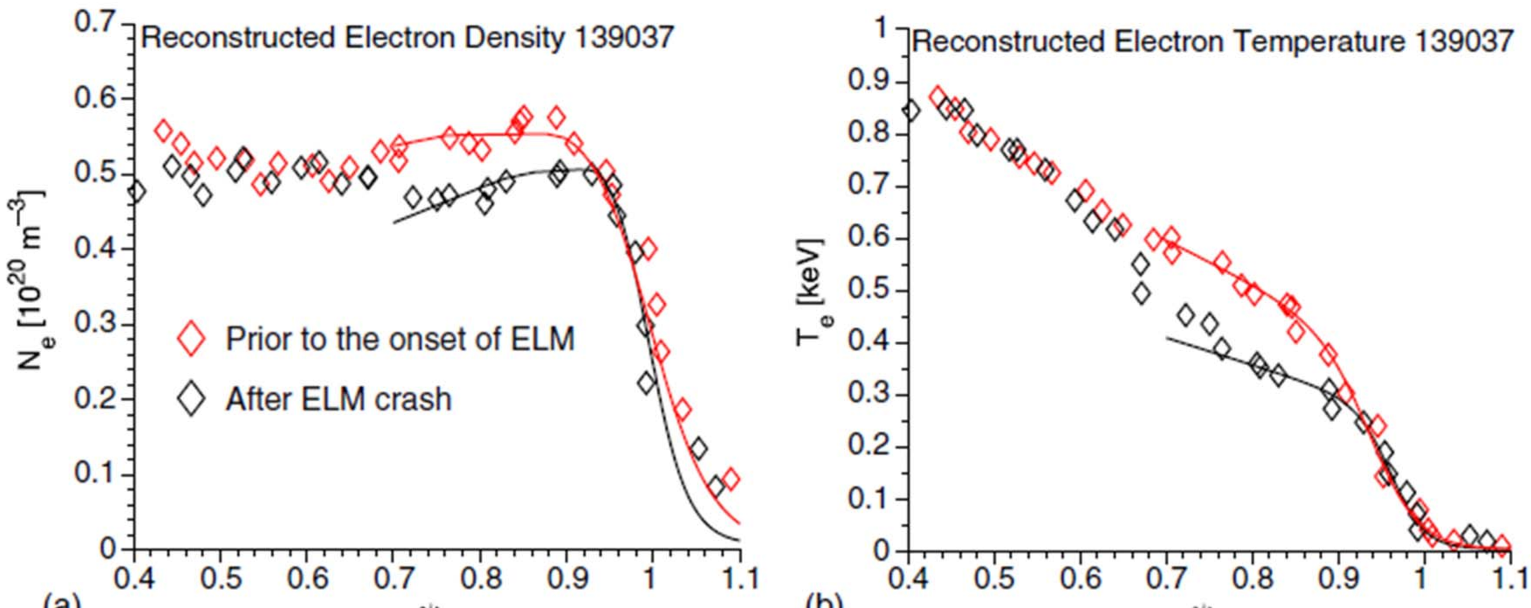
DIII-D, Schmitz, PRL (2012)

EDGE TURBULENCE
H-mode pedestal

In established H-modes, periodic MHD instabilities (Edge Localized Modes, ELMs) often occur

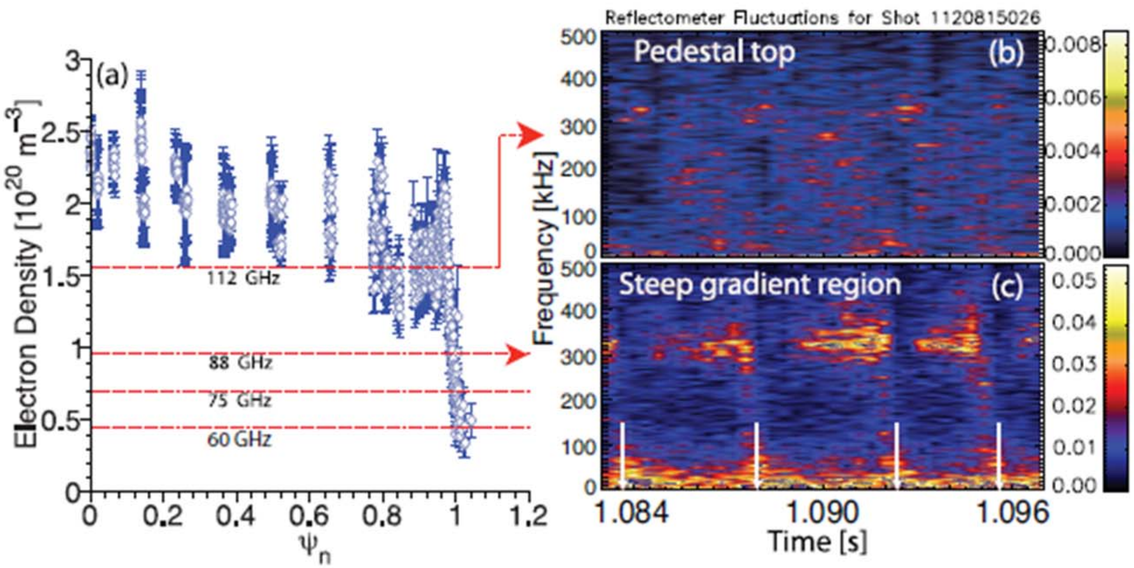
- Rapidly expels energy
- Profiles drop after ELM, recover between ELMs
- General question of what transport mechanism limits H-mode pedestal & post-ELM recovery

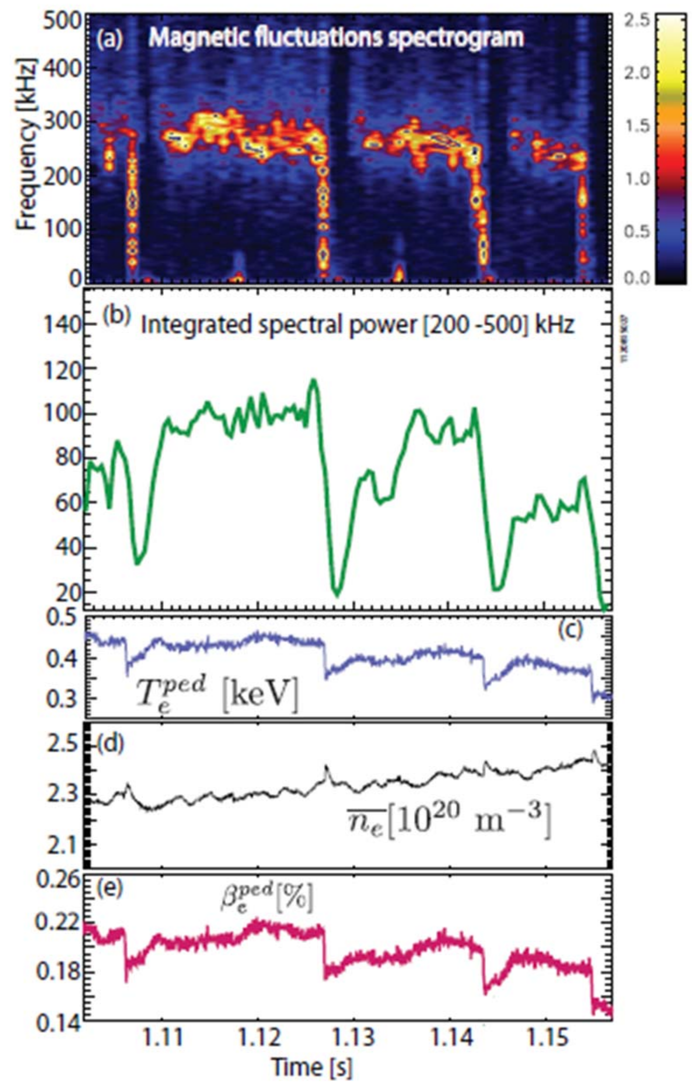




NSTX, Diallo, NF (2011)

Local density and magnetic fluctuations measured inter-ELM - possible importance of EM turbulence



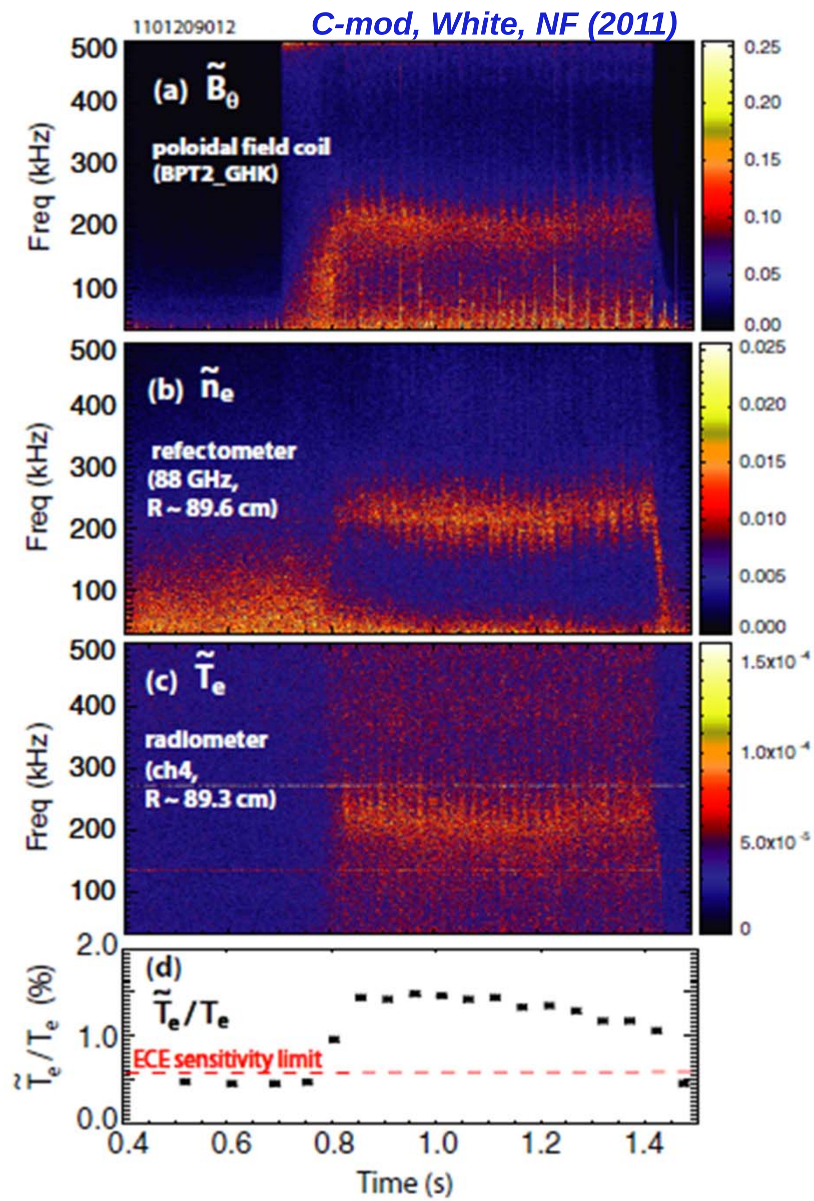


- Density from reflectometry (& Gas Puff Imaging)
- Magnetic probes inserted 2 cm from separatrix (measures same k_θ as density)
- Evidence for importance of EM turbulence?
- Leading theory posits KBM (EM drift wave) as a key contributor setting H-mode pedestal (Snyder, NF, 2011)

C-Mod, Diallo, PRL (2014)

Various fluctuations observed in ELM free pedestal regions – Weakly Coherent Mode in C-mod I-mode

- I-mode in C-mod similar to H-mode except temperature pedestal only
- Evidence for weakly coherent density, temperature & magnetic fluctuations associated with increased particle transport preventing density pedestal
- Other examples exist in ELM-free H-modes (EHO in DIII-D; QCM in C-Mod)

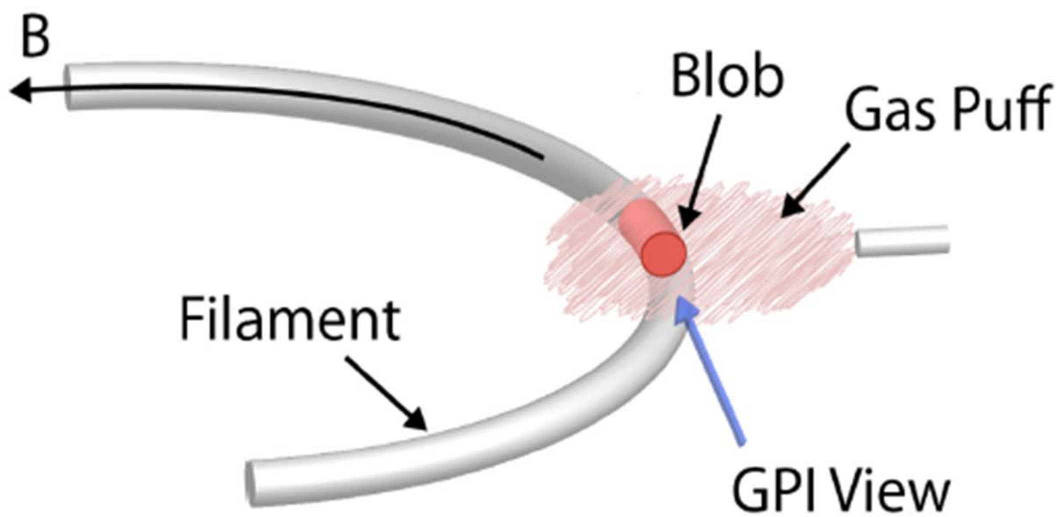


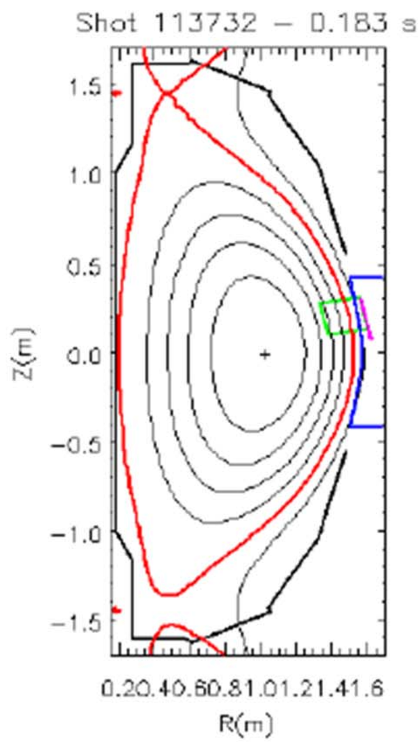
SCRAPE OFF LAYER TURBULENCE

Courtesy S. Zweben

Edge Turbulence Measurements in NSTX

- High speed cameras make images of edge turbulence
- 3-D 'filaments' localized to 2-D by gas puff imaging (GPI)



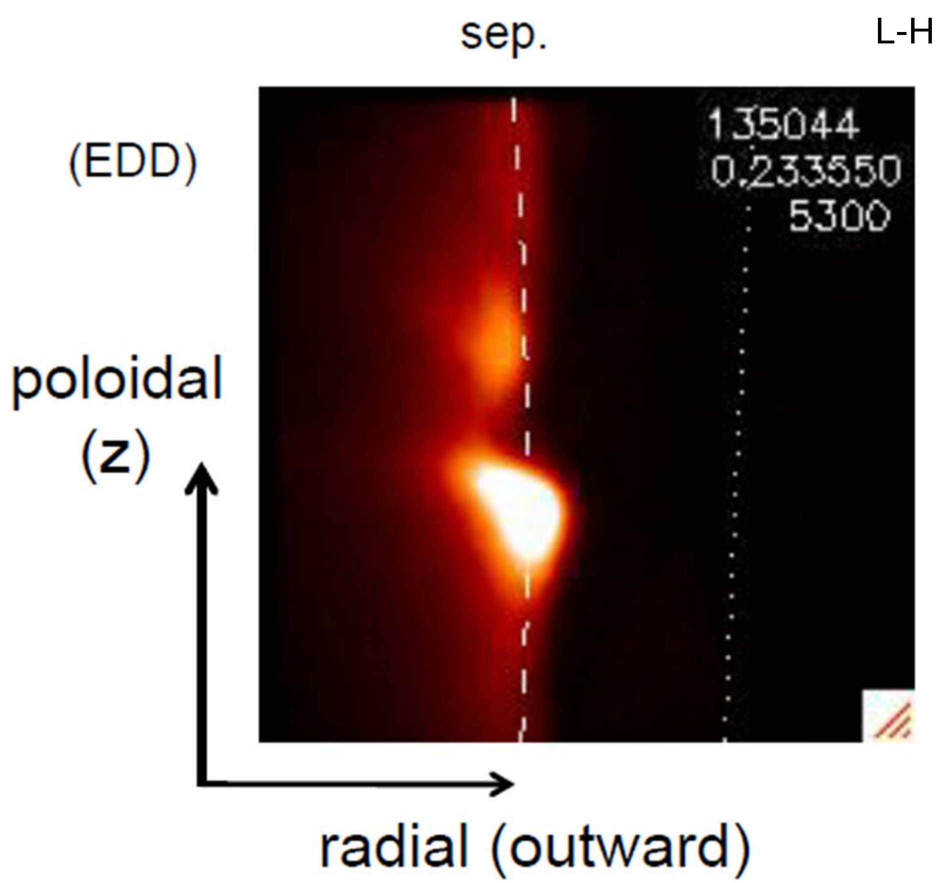


Zweben et al, Nuclear Fusion 44 (2004), R. Maqueda et al, Nucl. Fusion 50 (2010)

Lots of videos via Stewart Zweben: http://w3.pppl.gov/~szweben/

- This movie 285,000 frames/sec for ~ 1.4 msec
- Viewing area ~ 25 cm radially x 25 cm poloidally

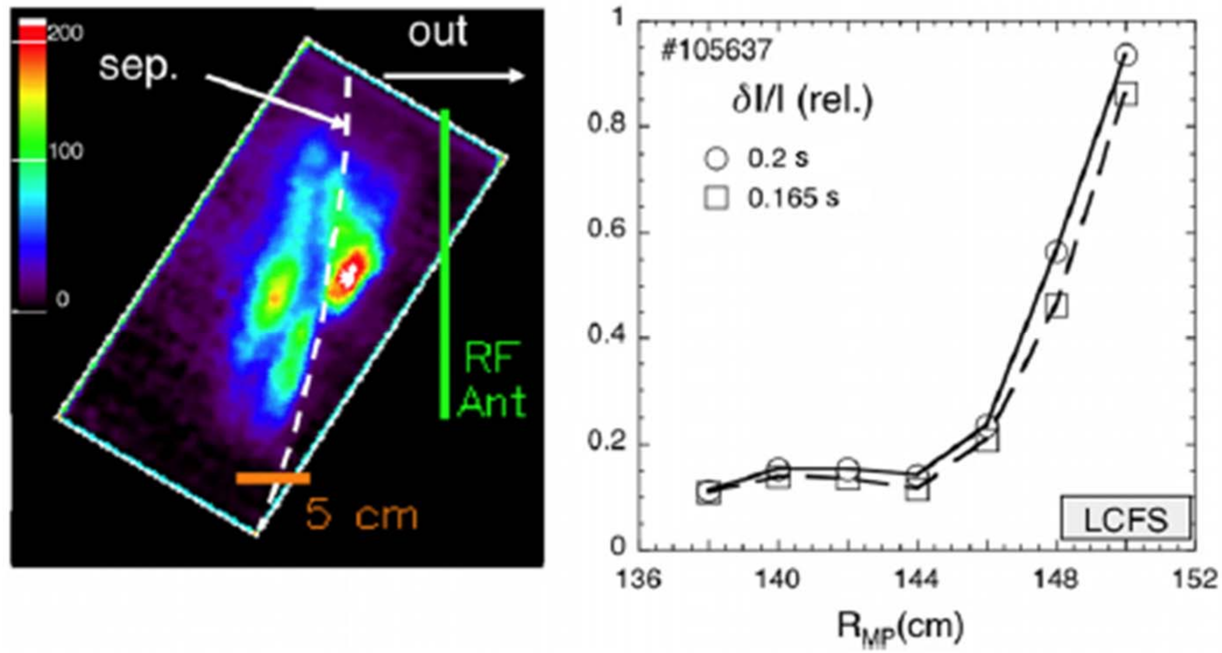
L-H mode transition t~0.245 s



playback @ 35 μsec/sec

Outside separatrix, blobs can be ejected and self-propagate to vessel wall

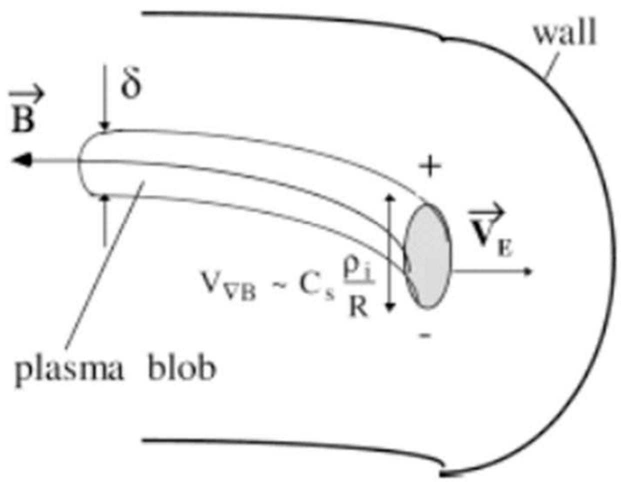
- Plasma is much less dense farther out in scrape-off layer
- Relative intensity of blob becomes large ($\delta I/I$)



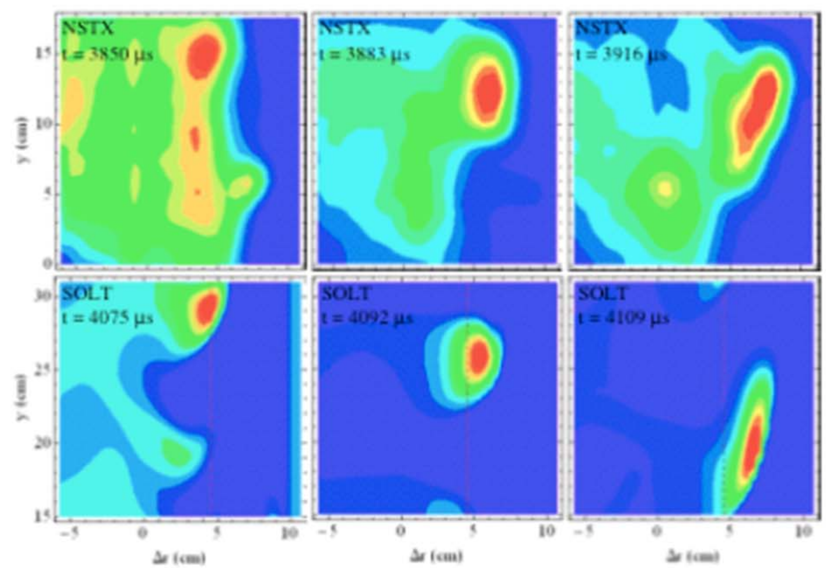
Theories and simulations exist that predict blob characteristics: size, density, velocity

- Simulations further out in edge become progressively more challenging, more effects to deal with (neutrals, open field lines to conducting walls, dust, …)

simple 'blob' model (Krash. 2001)



2D turbulence model (D'Ippolito 2008)



SUMMARY

- Many experiments and diagnostics developed to measure fluctuation amplitudes, spectra, cross-phases, transport, etc… in various regions of magnetically confined plasmas
- Have seen progress in comparing theory/simulation & measurements, with agreement approving from order-of-magnitude to factor of 2-3 or better in limited cases
- Improves confidence (in some regimes) in our physics understanding, which improves our predictive ability (not really addressed here)
- Plenty more to do