NSTX

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Study of turbulent fluctuations with the electron gyro-scale in the National Spherical Torus Experiment

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Evolution of ETG-mode scale turbulence spectra and anomalous electron transport in dynamic experiments at FT-2 tokamak

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VTT

Motivation

- *Anomalous transport of electron energy in tokamaks is still an outstanding issue*
- *For a long time, the ETG mode was not considered a possible explanation because of the low mixing-length estimate of electron thermal conductivity*

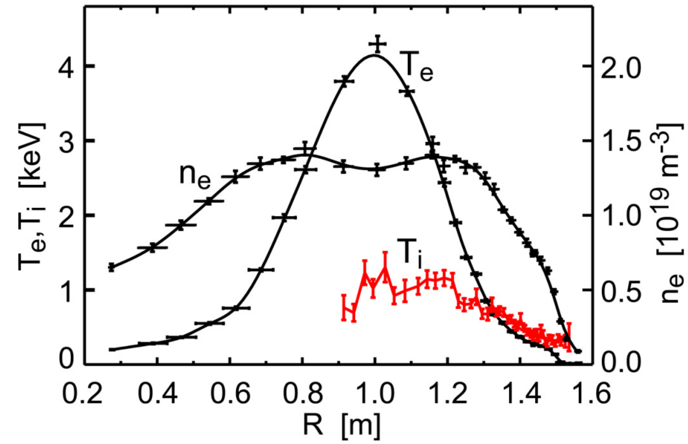
$$\chi_i \propto \frac{v_i}{L}\rho_i^2 \xrightarrow[\text{isomorphism}]{\text{ITG / ETG}} \chi_e \propto \frac{v_e}{L}\rho_e^2$$

- *However, recent non-linear numerical simulations of short-scale turbulence in tokamaks have indicated the the ETG mode could drive levels of transport significantly larger than the mixing-length estimate*
- *The primary goal of both experiments was to find a direct experimental proof of the existence of an electron gyro-scale turbulence driven by the electron temperature gradient in tokamak plasmas*

Experimental Setup

- *The PPPL experiment was performed on the National Spherical Torus Experiment*

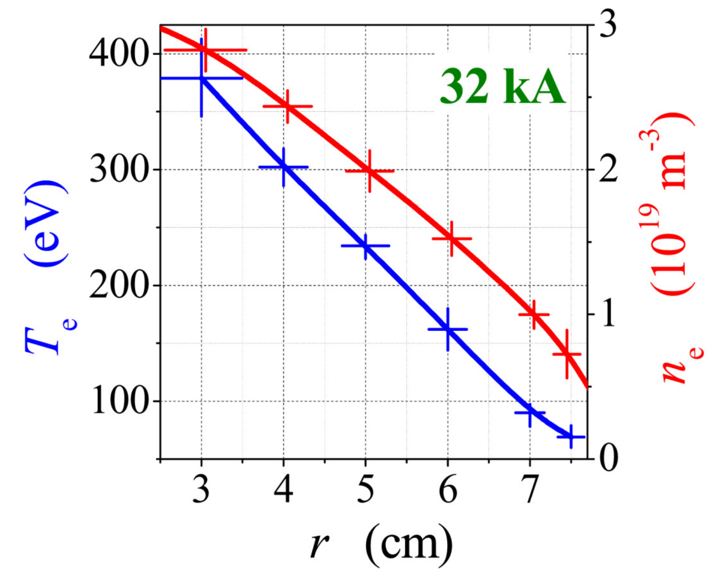
  R=0.85 m, *A*=*1.3*, κ=2.0,
  B=0.55 T, *I*=750 kA,
  $n_e < 2\times10^{19}$ m^{-3}, $T_e < 6.0$ keV, $T_i < 1.0$ keV



- *Use of High Harmonic Fast Wave heating (30 MHz, 3 MW) – best available tool on NSTX for producing high T_e with steep gradients*

- *The IOFFE experiment was performed on the FT-2 tokamak*

  R=0.55 m, *A*=7, κ=1.0
  B=2.7 T, *I*<50 kA,
  $n_e < 7\times10^{19}$ m^{-3}, $T_e < 0.6$ keV, $T_i < 0.3$ keV



- *Use of Lower Hybrid heating (920 MHz, 100 kW) for studying the evolution of turbulence*

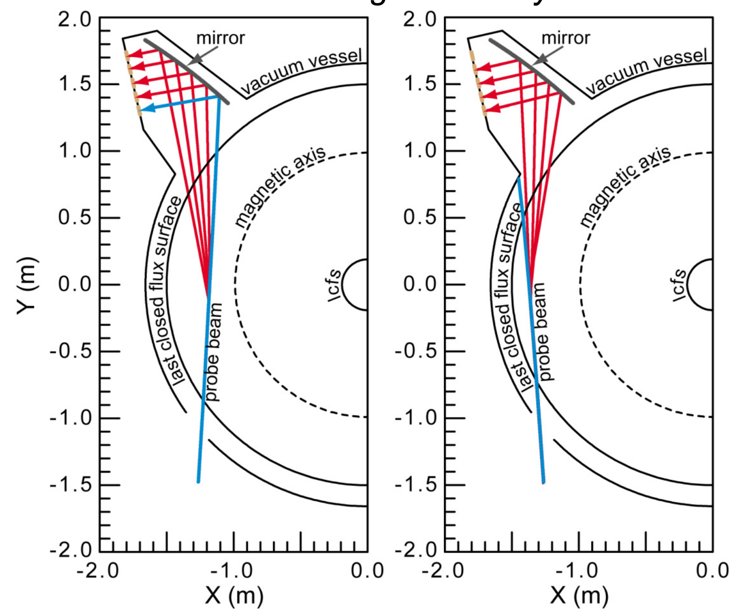
Diagnostic Tools

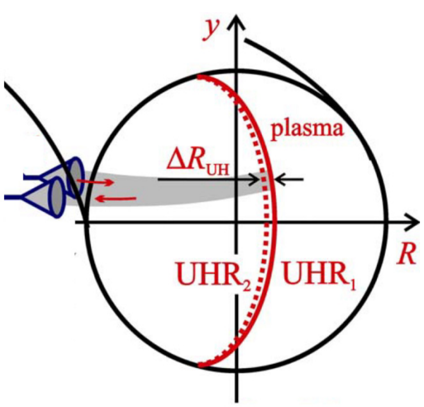
- On NSTX, turbulent fluctuations were measured with coherent scatering of 280 GHz waves
- The scattering geometry takes advantage of the anisotropy of plasma fluctuations ($k_{\perp} >> k_{||} \sim 1/qR$) and the curvature of magnetic field lines to obtain a resolution of

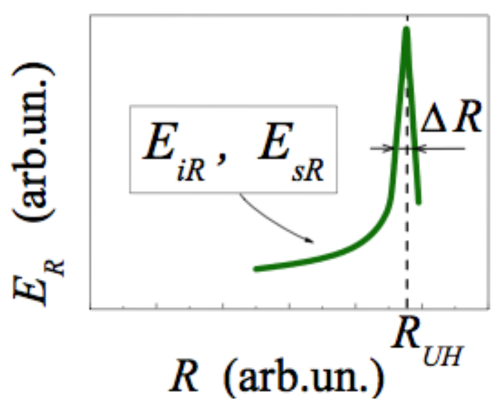
$$\Delta_r = \pm 2.5 \text{ cm} \quad \text{and} \quad \Delta_k = \pm 1 \text{ cm}^{-1}$$

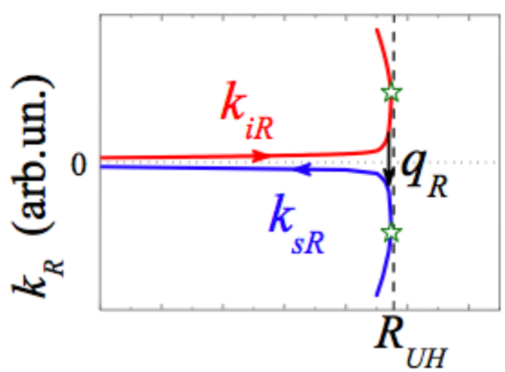
- On FT-2, turbulent fluctuations were measured with enhanced backscattering (ES) near the Upper Hybrid Resonance (53-69 GHz)
- Use of correlation techniques (CES) for improving the k_r-resolution of ES

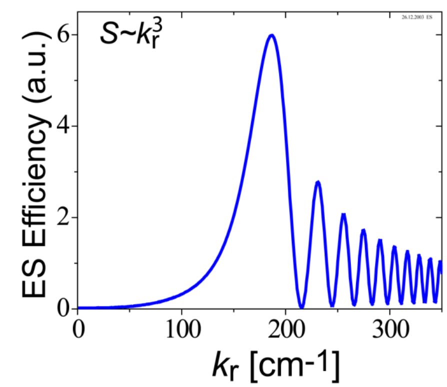
Scattering Geometry





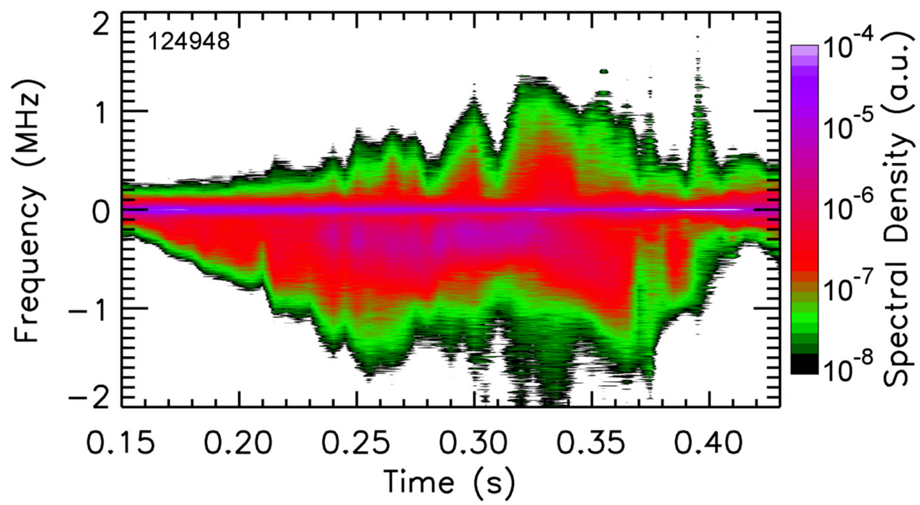


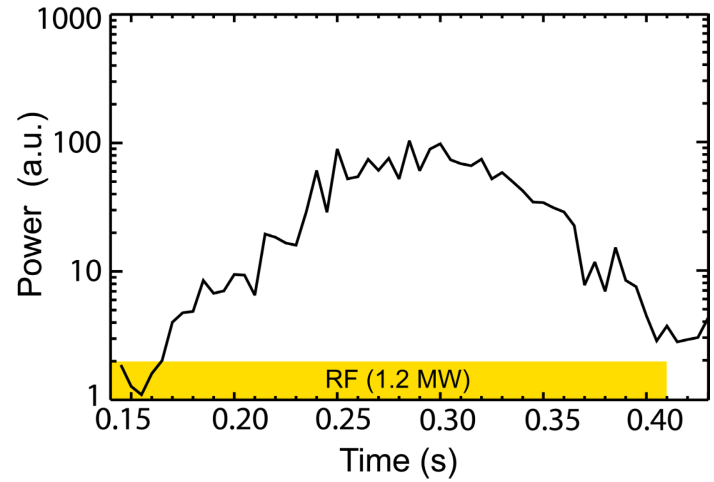


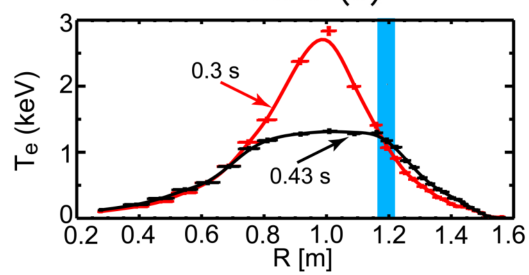


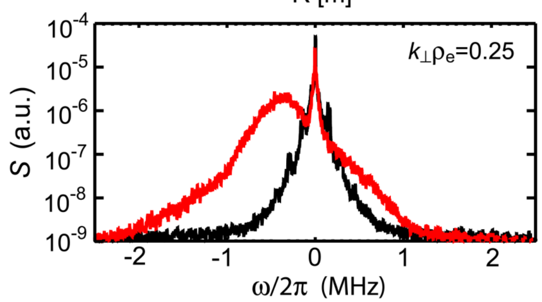
High-k Turbulent Fluctuations on NSTX

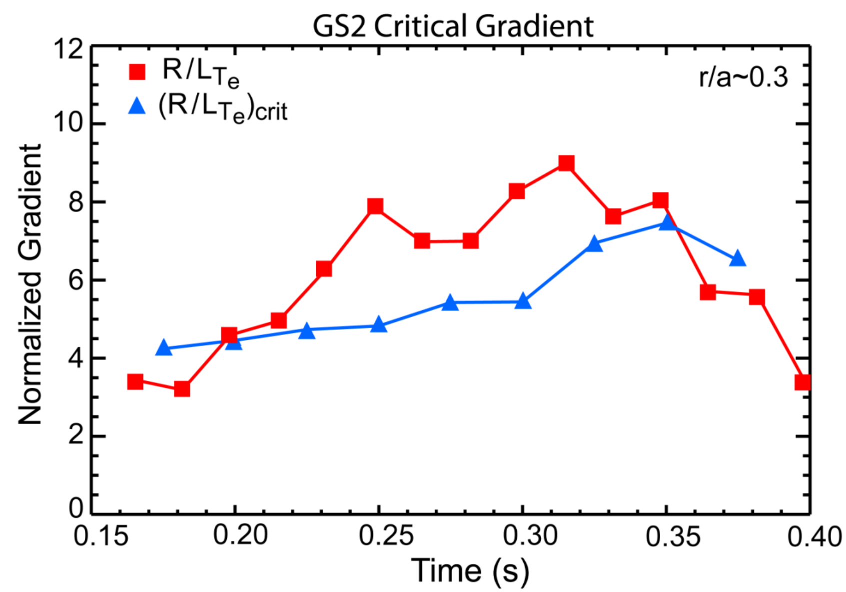
- *High-k fluctuations have been observed in the plasma core (r/a~0.3) with wave numbers in the range $k_\perp\rho_e$=0.2-0.4 ($k_\perp\rho_s$=8.5-17, $k_\perp\rho_i$=8-10)*







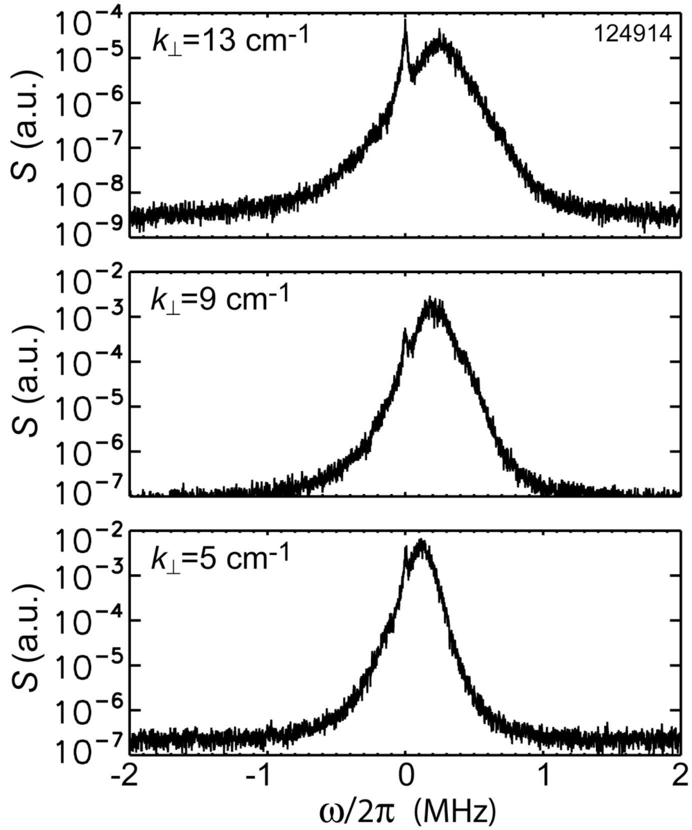


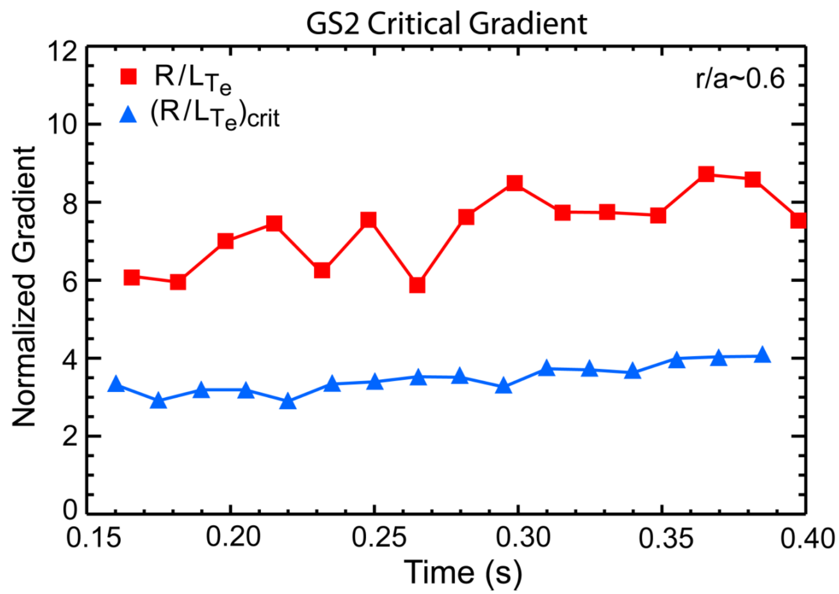


- *Dependence on scale of T_e*
- *Agreement with predictions of GS2 code*

High-k Turbulent Fluctuations on NSTX

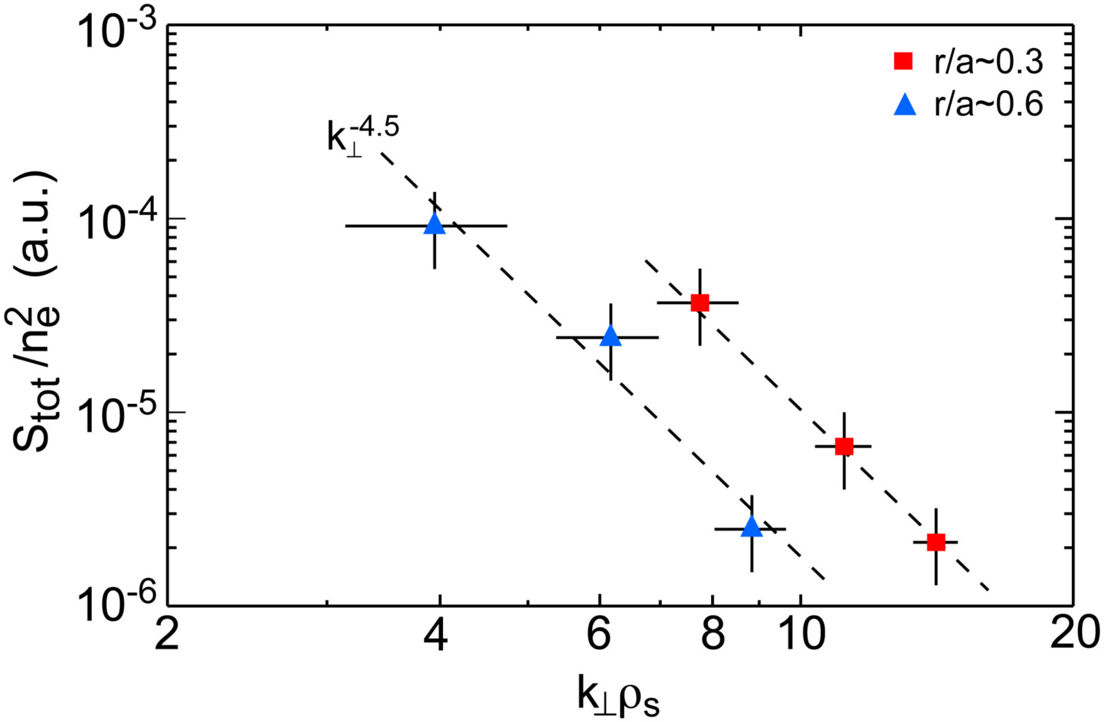
- Fluctuations were also detected on the plasma outer region (r/a~0.6), with wave numbers in the range $k_\perp\rho_e$=0.08-0.2 ($k_\perp\rho_s$=$k_\perp\rho_i$=3.5-8.5)





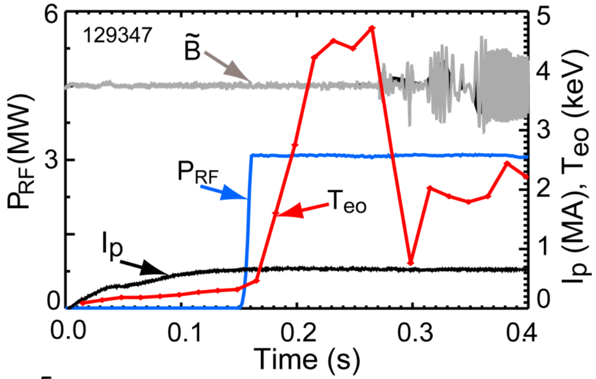
- Again, fluctuations coincide with the gradient of T_e being larger than the critical gradient

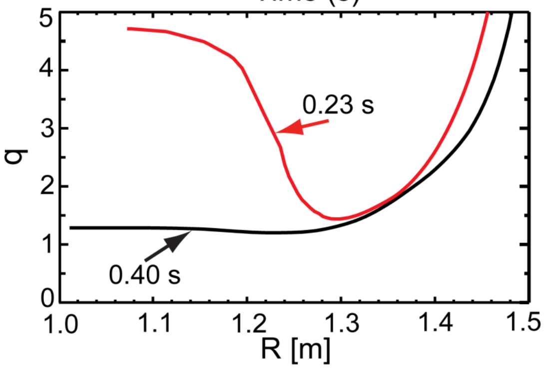
Power Spectrum on NSTX

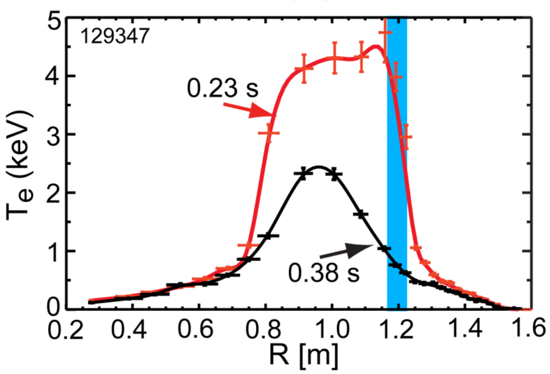


- *At both radial locations, the plasma density fluctuation seems to follow a power law*
- *Also, $k_\perp \delta_{sk}$=1-2, with $\delta_{sk}=c/\omega_{pe}=\rho_e/\beta_e^{1/2}$ the collisionless skin depth*
- *This would imply the mixing-length estimate of thermal conductivity varying like $1/n_e$*

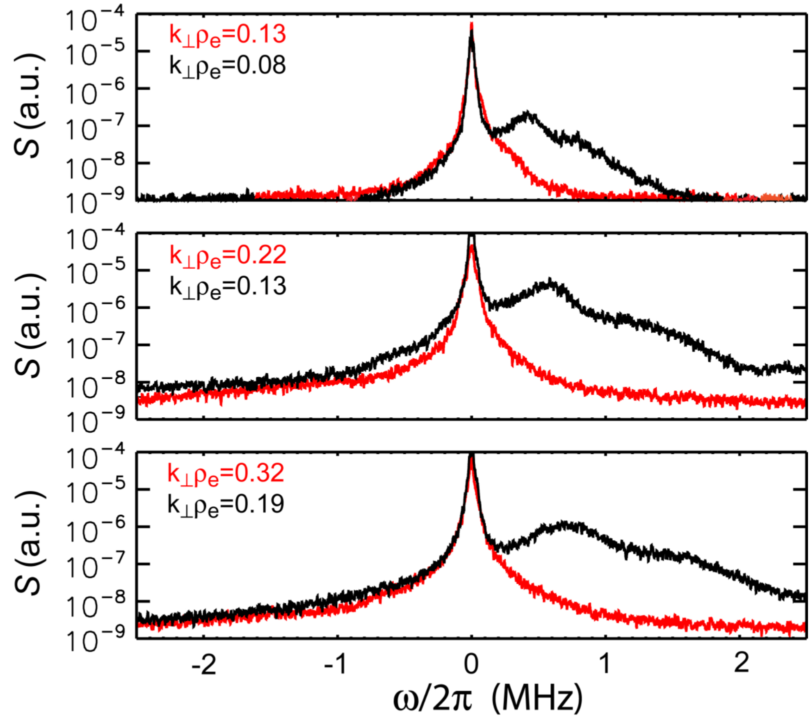
Effect of negative magnetic shear on turbulence







- A strong negative magnetic shear was obtained with the RF heating (3 MW) starting early in the plasma pulse when current penetration was not complete



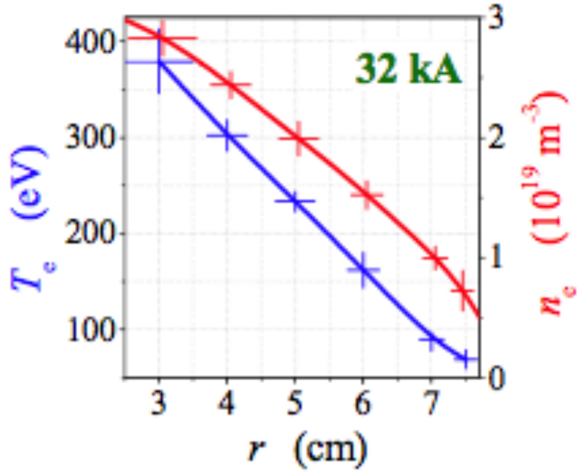
- The suppression of turbulent fluctuations coincides with the formation of a very large temperature gradient at the location of measurement – transport barrier?

- The suppression of turbulent fluctuations agrees with results of the GS2 code, predicting complete stabilization of the ETG mode

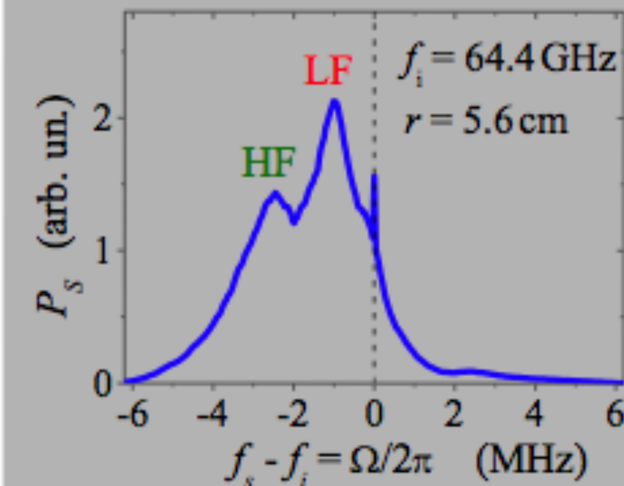
Conclusions

- *Results indicate the existence of turbulent fluctuations with an electron gyro-scale in NSTX*
- *Large values of $k_\perp \rho_i$, a phase propagation along the electron diamagnetic direction and a strong correlation with the gradient of T_e rule out the ITG mode as the source of turbulence*
- *Agreement with the predictions of the linear gyrokinetic GS2 code supports the conjecture that the observed turbulence is driven by the electron temperature gradient*
- *The suppression of fluctuations by negative magnetic shear coincides with the formation of an internal transport barrier*
- *This could be interpreted as evidence of the role played by the ETG turbulence on plasma transport. However, additional experiments together with nonlinear numerical simulations of turbulence (in progress) are needed before reaching any definite conclusion*

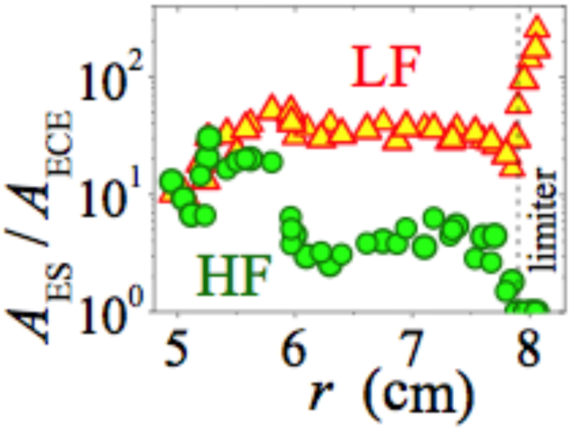
Two-component ES spectrum investigation in the ohmic discharge.

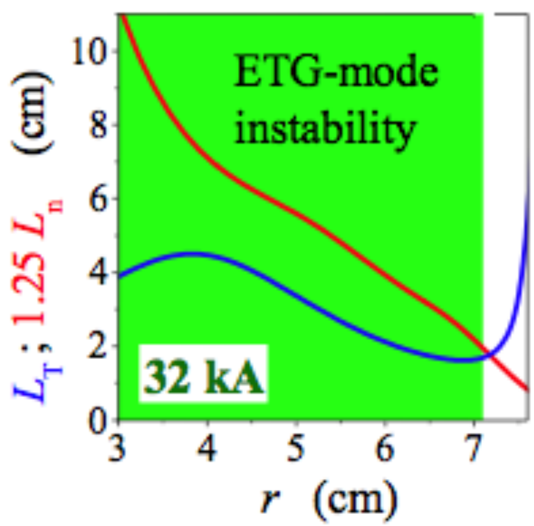


Experimental density and temperature profiles

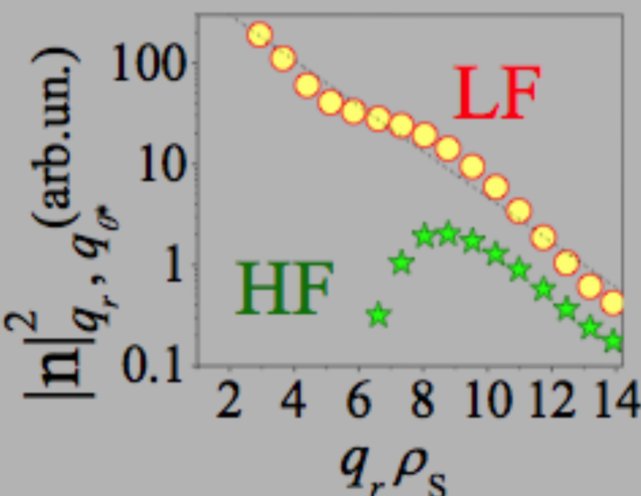


ES frequency spectrum

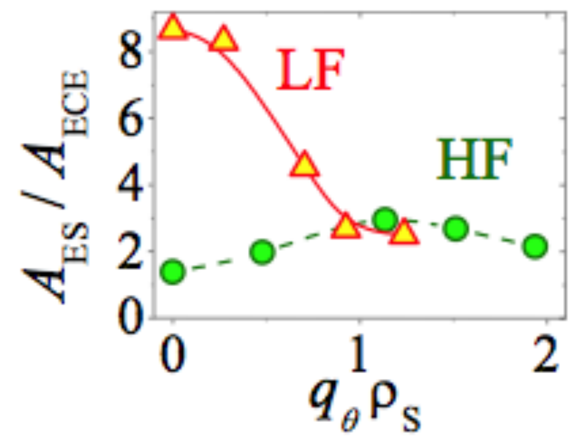




ETG instability threshold
L_T< 1.25L_n



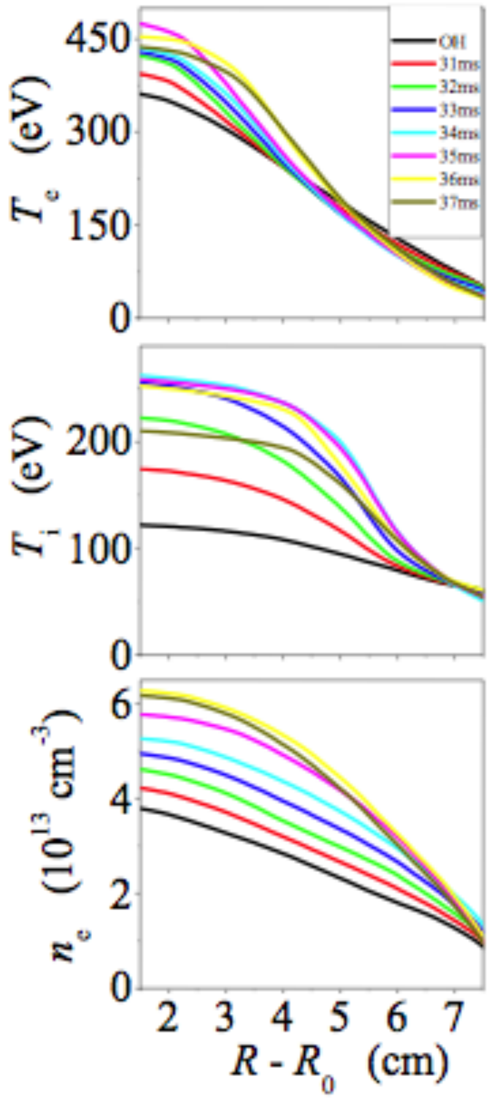
Different LF and HF q_r spectra
Exponential spectrum for LF and maximum at ETG scale for HF



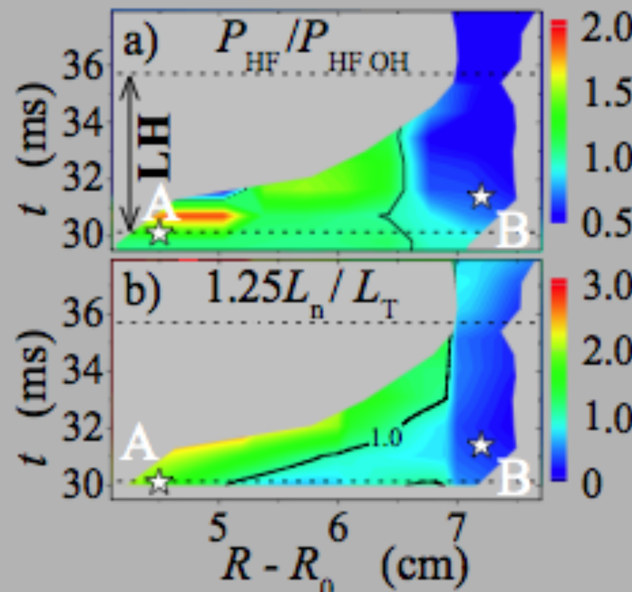
Different LF and HF dependence on radius and poloidal wavenumber

E Z Gusakov, A D Gurchenko, et al. PPCF 48 (2006) B443-B451

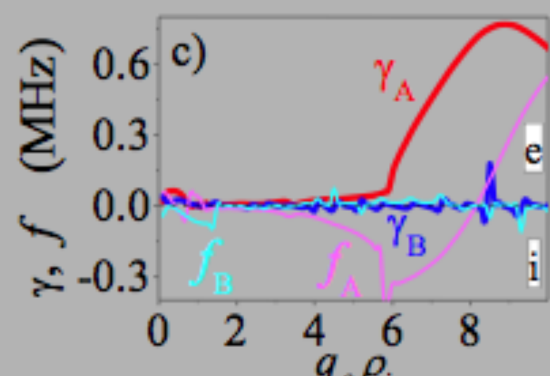
Evolution of HF and LF ES spectral components during LHH pulse (920MHz, 100kW)



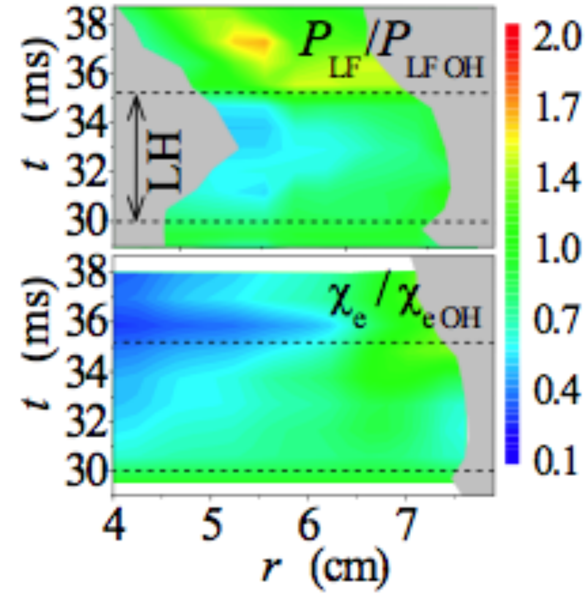
Evolution of temperature and density profiles during LHH



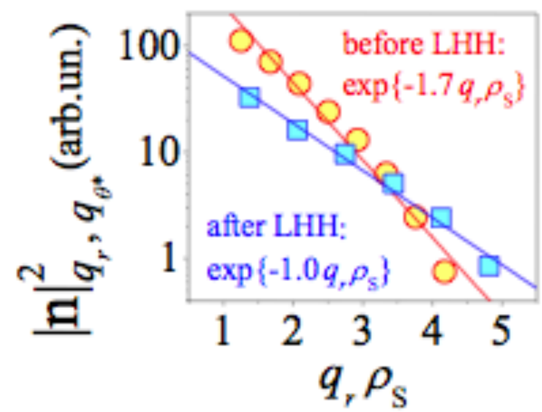
ES HF signal power (a) is strongly correlated to the ratio of L_n and L_{Te} (b) (the ETG mode criteria)



GS2 confirms $L_T < 1.25L_n$ criteria for FT-2 parameters



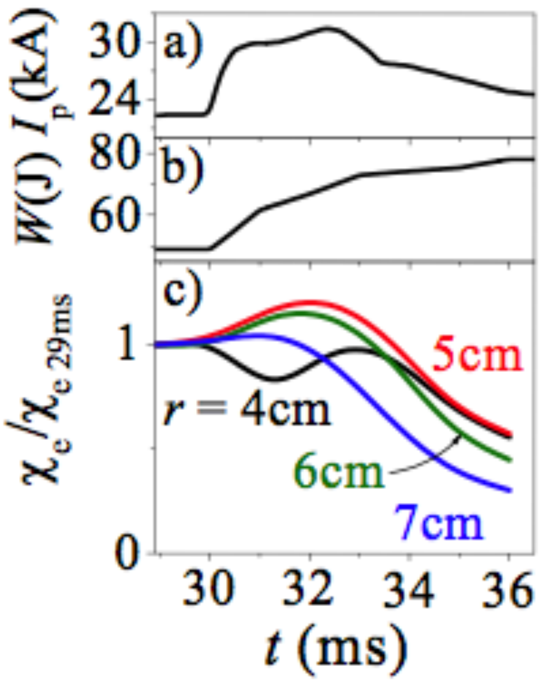
LF signal power (a) is correlated to electron thermal diffusivity (b)



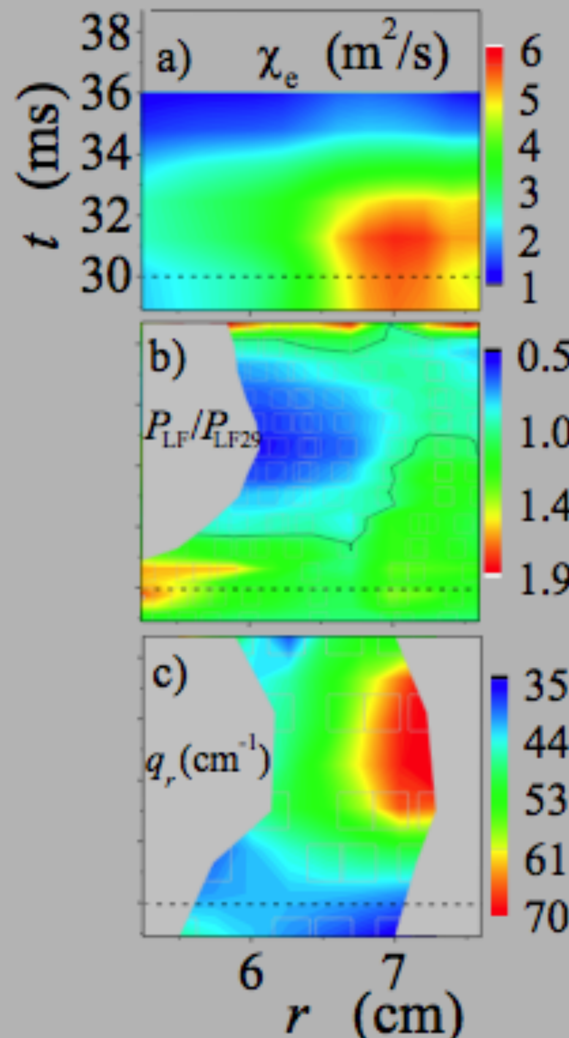
LF q_r-spectra are exponential both before and after LHH

*A.D. Gurchenko et al. Nucl. Fusion **47** (2007) 245–250*

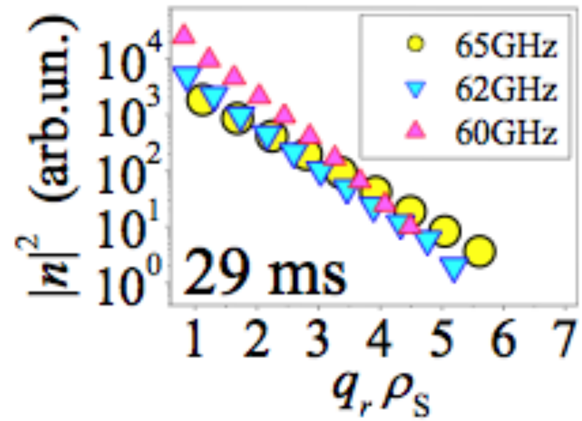
The LF spectra evolution in the Current Ramp Up scenario discharge

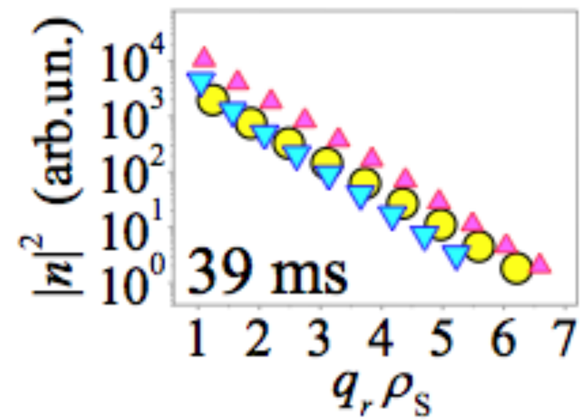


Evolution of plasma current (a), energy content (b) and electron thermal diffusivity (c)



LF signal power suppression (b) is well correlated to electron thermal diffusivity behaviour (a) and is opposite to ES q_r spectrum maximum shift c).

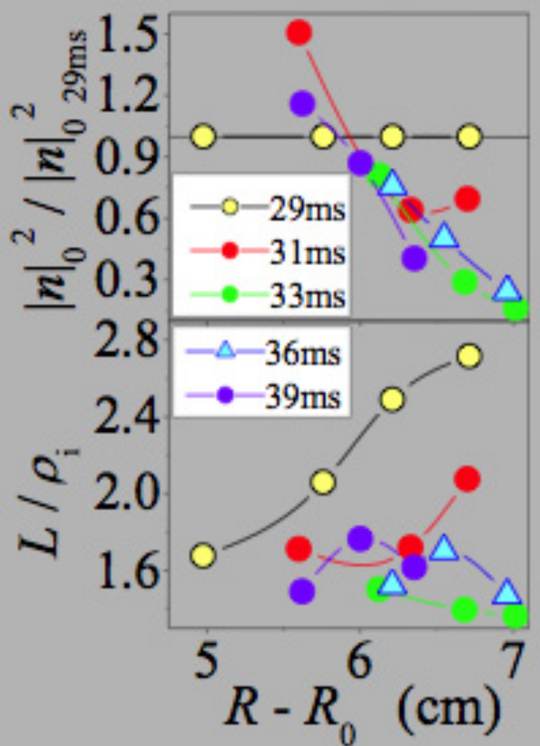


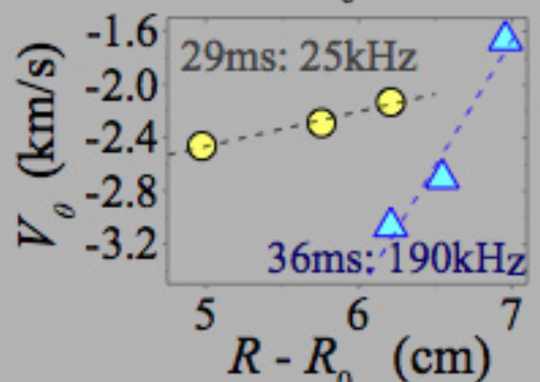


All during the CRU the spectra could be surprisingly well described by universal exponential dependence

$$|n|^2_{q_r} \sim |n|^2_0 \exp\{-q_r L\}$$

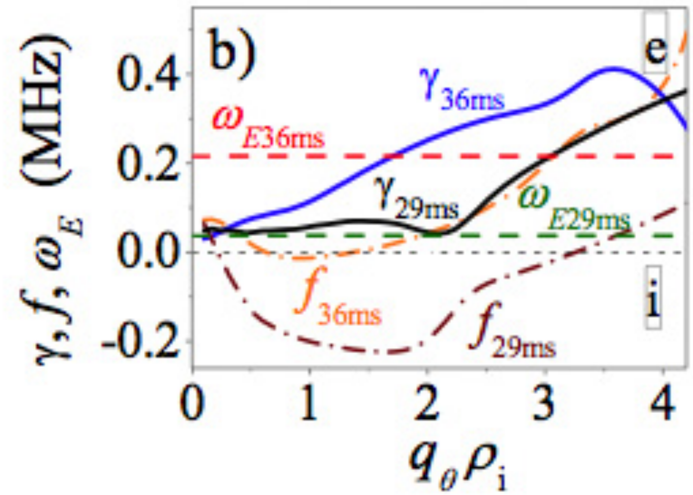
Evolution of the LF turbulence exponential spectrum parameters





Both parameters are found to decrease substantially after CRU simultaneously with strong increase of the gradV_θ (obtained from the Doppler frequency shift of the ES spectrum)

The linear analysis with GS2 code of the most unstable mode possessing frequency f and growth rate γ.



Before CRU (29ms): $\omega_E < \gamma$ is fulfilled for the whole q-range which makes the development of instabilities possible.
Current relaxation stage (36ms): $\omega_E > \gamma$ holds for turbulence with $q_\theta < 50$ cm^{-1} which, according to [H.Biglari, P.H.Diamond, P.W.Terry 1990 Phys. Fluids B 2 1], makes turbulence suppression at these scales possible, as observed in the experiment!

Conclusions

- The new highly localized correlative Enhanced Scattering diagnostics capable of determining the very small scale turbulence wave number spectra has been developed at the FT-2 tokamak in the Ioffe Institute

- Two modes are found in the ES spectra under conditions when the threshold for the ETG mode instability $L_T < 1.25L_n$ is overcome.

- The first, identified as the ETG mode, is possessing frequency higher than 2 MHz and radial wave number $q_r\rho_s$ =8 close to the position of the ETG mode growth rate maximum. Its phase velocity is twice as high as for the LF mode and amplitude is growing towards the centre increasing where and when the ETG instability threshold is overcome according to GS2 code, as it is shown in dynamic lower hybrid heating experiment.

- The second possessing frequency close to 1 MHz is correlated to the anomalous electron thermal diffusivity. It is maximal at the plasma periphery and presumably associated with the small-scale component of the dissipative TEM mode.

- It is found that this turbulence component at small scales possesses a wide *q*-spectrum which could be described by universal exponential dependence in the range of 3-4 orders of amplitude characterized by only two parameters related to the turbulence level and scale length. Both parameters are found to decrease substantially during the dynamic current ramp up discharge when the shear of the poloidal plasma rotation increases at plasma periphery exceeding the growth rate of drift instability determined with the GS2 code. Simultaneously transition to the improved confinement resulting in suppression of anomalous electron transport is observed in the experiment.

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