Experimental Observation of Nonlocal Electron Thermal Transport in NSTX RF-heated L-mode Plasmas (EX/P6-43)

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(presented by K. C. Lee)
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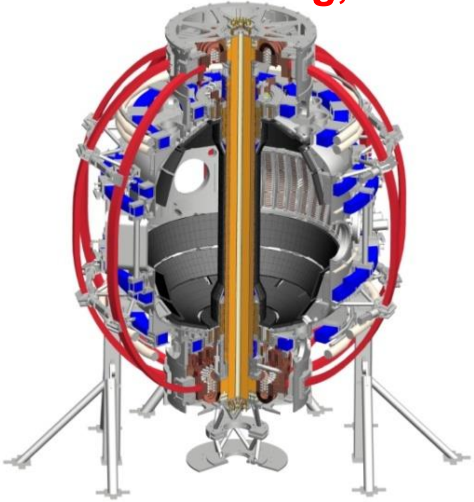

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Highlights

- First experimental observation of nonlocality in high-k turbulence and electron thermal transport in NSTX
  - Observations made around RF cessation in 300 kA RF-heated L-mode plasmas
- Decoupling of turbulence and thermal transport from local equilibrium quantities
  - Fast reduction in turbulence on a 0.5-1 ms time scale, much smaller than energy confinement time, and correlated with RF heating cessation
  - No significant change in equilibrium profiles before and right after the RF cessation
- Linear ion-scale and electron-scale modes are robustly unstable, far from marginal stability
- Local nonlinear gyrokinetic simulations does not show stiff enough transport to explain the observations

Understanding Nonlocal Transport is Crucial for Achieving Predictive Capability for Future Devices

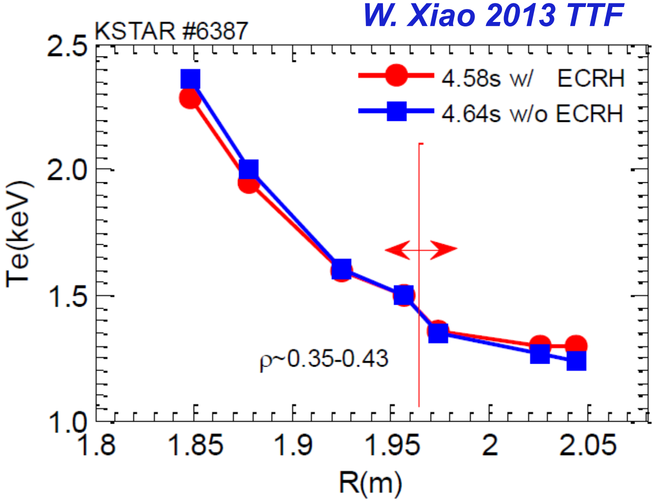
- The observations of nonlocal transport and turbulence in fusion devices challenge the standard local model of transport
  - Nonlocality means that transport and turbulence can be independent of local equilibrium thermodynamic quantities and their gradients
  - Present predictive codes all assume local model of transport, e.g. TGYRO+GYRO/TGLF, XPTOR+TGLF
- Experimental studies of nonlocality in electron thermal transport and turbulence usually involve measuring dynamic responses of plasma due to sudden cooling or heating
  - Earliest observation from injecting carbon into tokamak edge plasmas to induce a sudden edge cooling (Gentle et al, PRL, 1995)
    - Simultaneous rise in core electron temperature with respect to edge cooling was observed
  - Recent edge cooling experiment on C-Mod tokamak showing nonlocal electron thermal transport in low collisionality linear Ohmic confinement regime but not in the high collisionality saturated Ohmic confinement regime (Chao et al., NF, 2014)

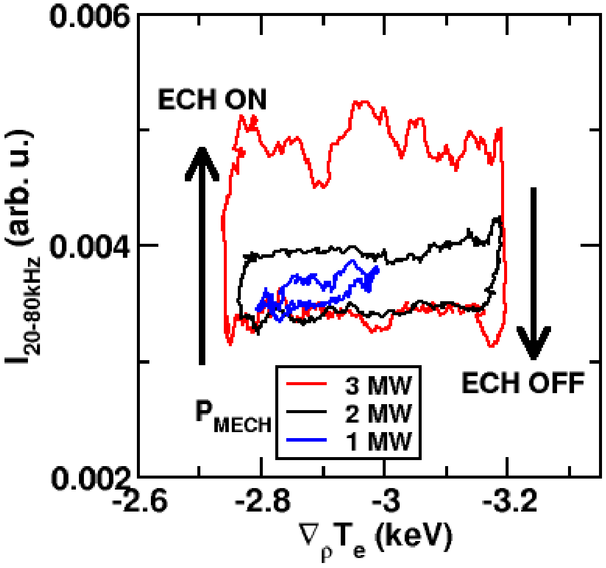
Recent Observations of in KSTAR and LHD Provide more Evidence of Nonlocal Transport and Turbulence

- Core T_e responses similarly in KSTAR H-mode with edge cooling and heating
  - Cold pulse from SMBI at edge leads to fast reduction in core T_e
  - ECRH at edge also leads to fast reduction in core T_e
  - Different from the early observations (Gentle et al.)
- Fast response of low-k turbulence in LHD may explain observed nonlocal behavior
  - Fast inward radial propagation (V ~ 100m/s) of microturbulence observed at the ELM events, which can explain the fast drop of density deep inside the LCFS (-10cm) in LHD
  - Fast response of turbulence to ECH modulation in LHD indicates that the transport and amplitude of micro turbulence are not determined by the local temperature gradient (r = 0.6- 0.7a)

No study of the response of electron-scale turbulence to sudden change in heating power has been reported

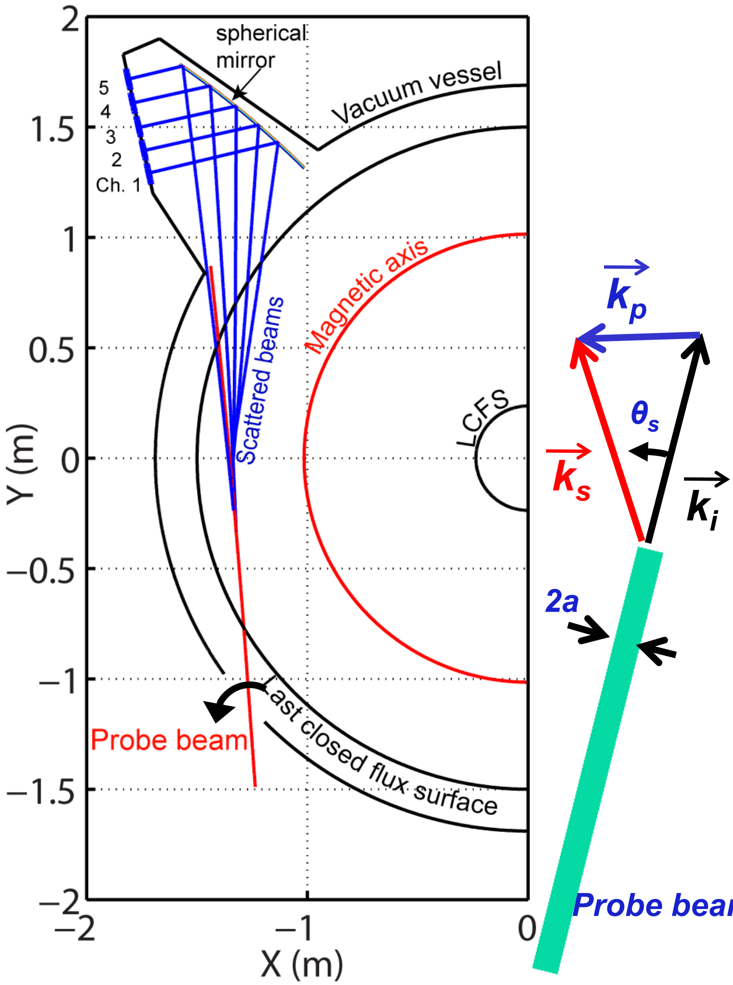
W. Xiao 2013 TTF





K. Ida, 2013 TTF

High-k Microwave Scattering System was Used to Measure Electron-Scale Turbulence



- 280 GHz microwave is launched as the probe beam.
- Coherent scattering by plasma density fluctuations occurs when the three-wave coupling condition is satisfied:

$$\vec{k}_s = \vec{k}_p + \vec{k}_i$$

- Bragg condition determines k_p:

$$k_p = 2k_i \sin(\theta_s/2)$$

- The scattered light has a frequency of:

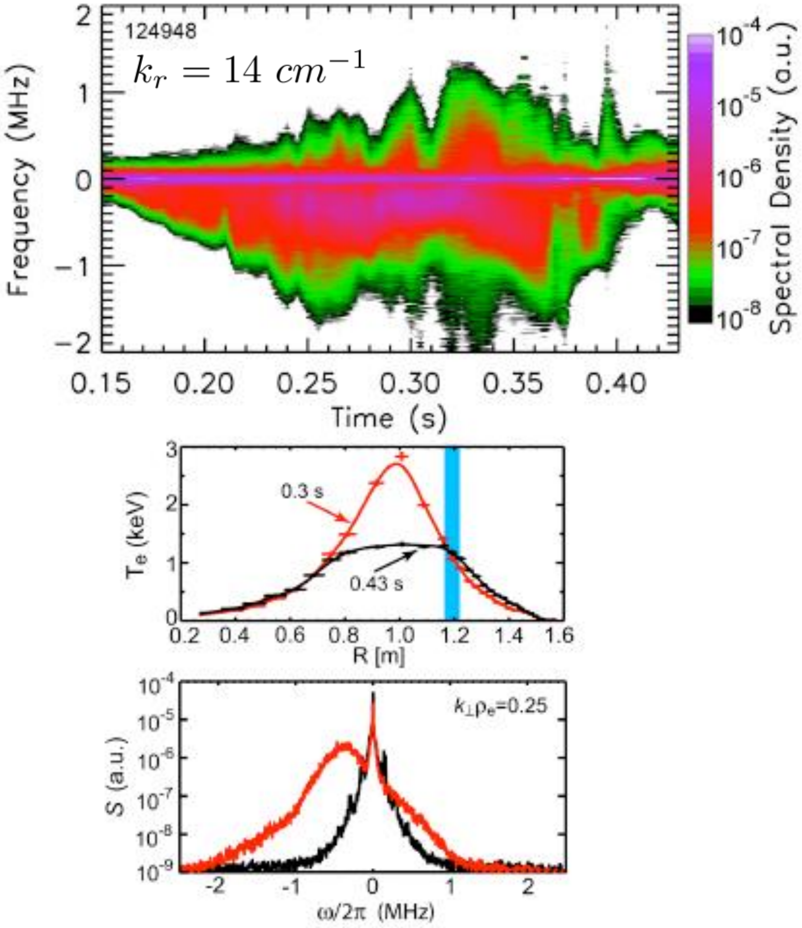
$$\omega_s = \omega_p + \omega_i$$

with ω_s and $\omega_i >> \omega_p$

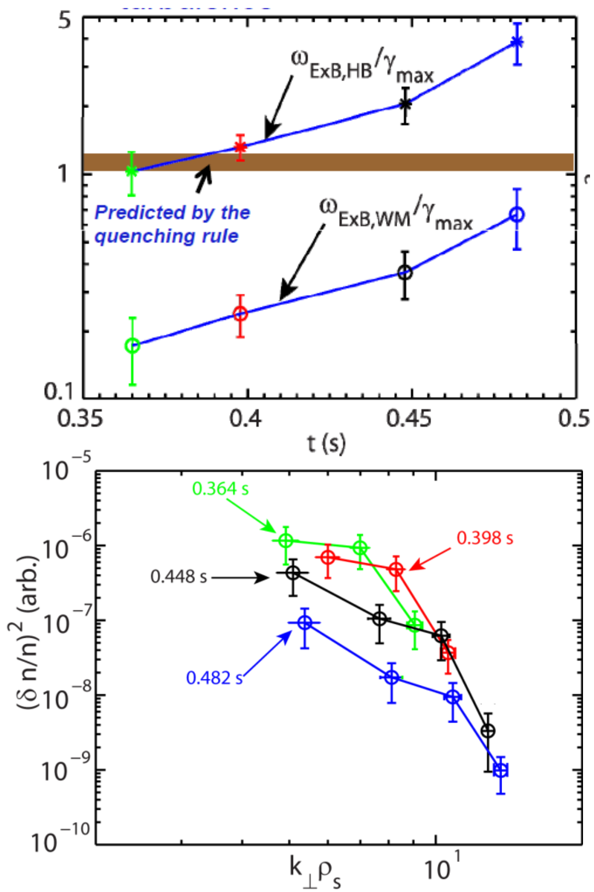
- The scattering system characteristics are:
  - **Frequency bandwidth: 5 MHz**
  - **Heterodyne receiver: Wave propagation direction resolved**
  - **Measurement: k_r spectrum**
  - **Wavenumber resolution: 0.7 cm^{-1} (2/a with a ≈ 3 cm)**
  - **Wavenumber *range (k_r): 5-30 cm^{-1} (~5-30 ρ_s^{-1})***
  - **Radial resolution: $\pm$2 cm**
  - **Tangential resolution: 5-15 cm**
  - **Radial range: R=106 – 144 cm**
  - **Minimal detectable density fluctuation: $|\delta n_e(k)/n_e|^2 \approx 2\times10^{-11}$**

Previously Measured High-k Turbulence Consistent with ETG and Coupling between Low-k and High-k Turbulence

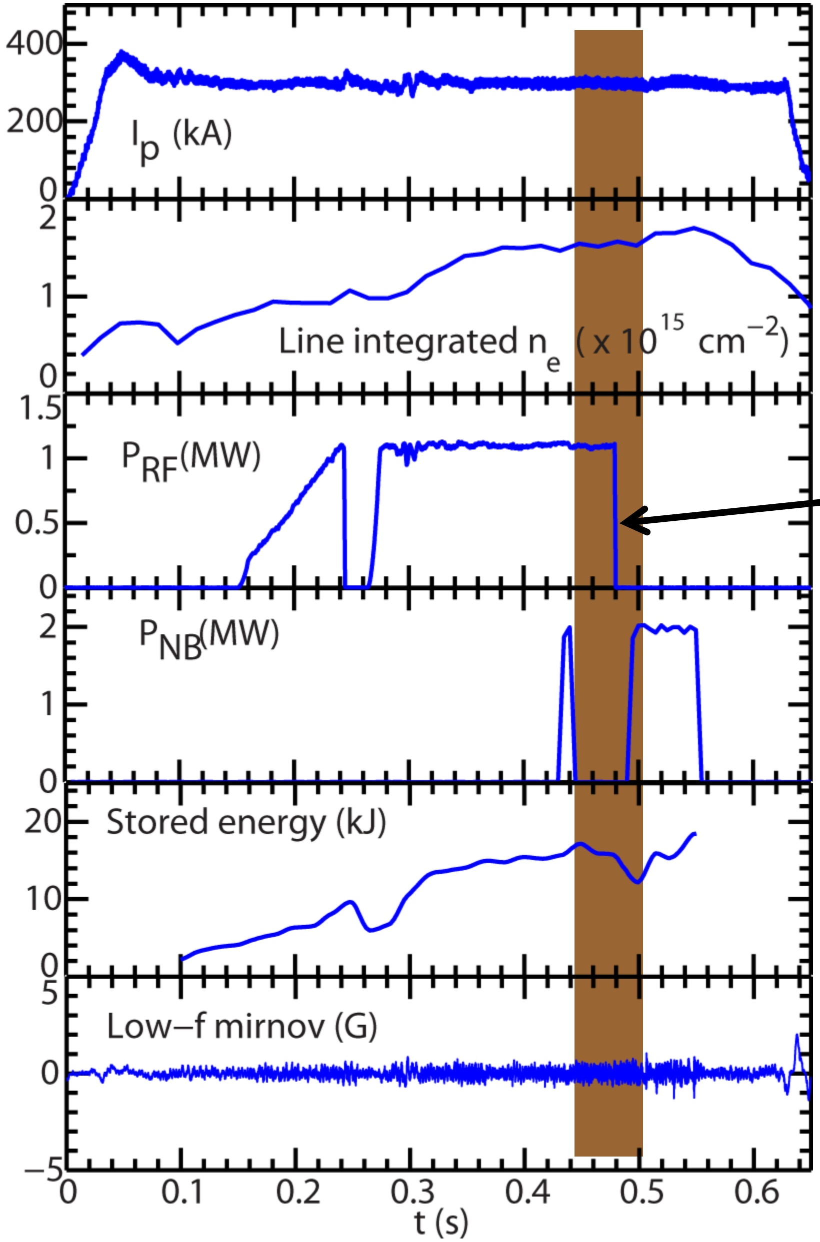
- The measured high-k turbulence is shown to be driven by electron temperature gradient (Mazzucato et al., PRL, 2008).



- Reduction in peak spectral power of high-k turbulence is correlated with the increase in $\omega_{E\times B}/\gamma_{max}$ (Y. Ren et al., NF, 2013)
  - Consistent with ExB stabilization of ion-scale turbulence and a nonlinear coupling between ion and electron-scale turbulence



Experimental Observation of Nonlocality was Made in a Set of NSTX RF-heated L-mode Plasmas



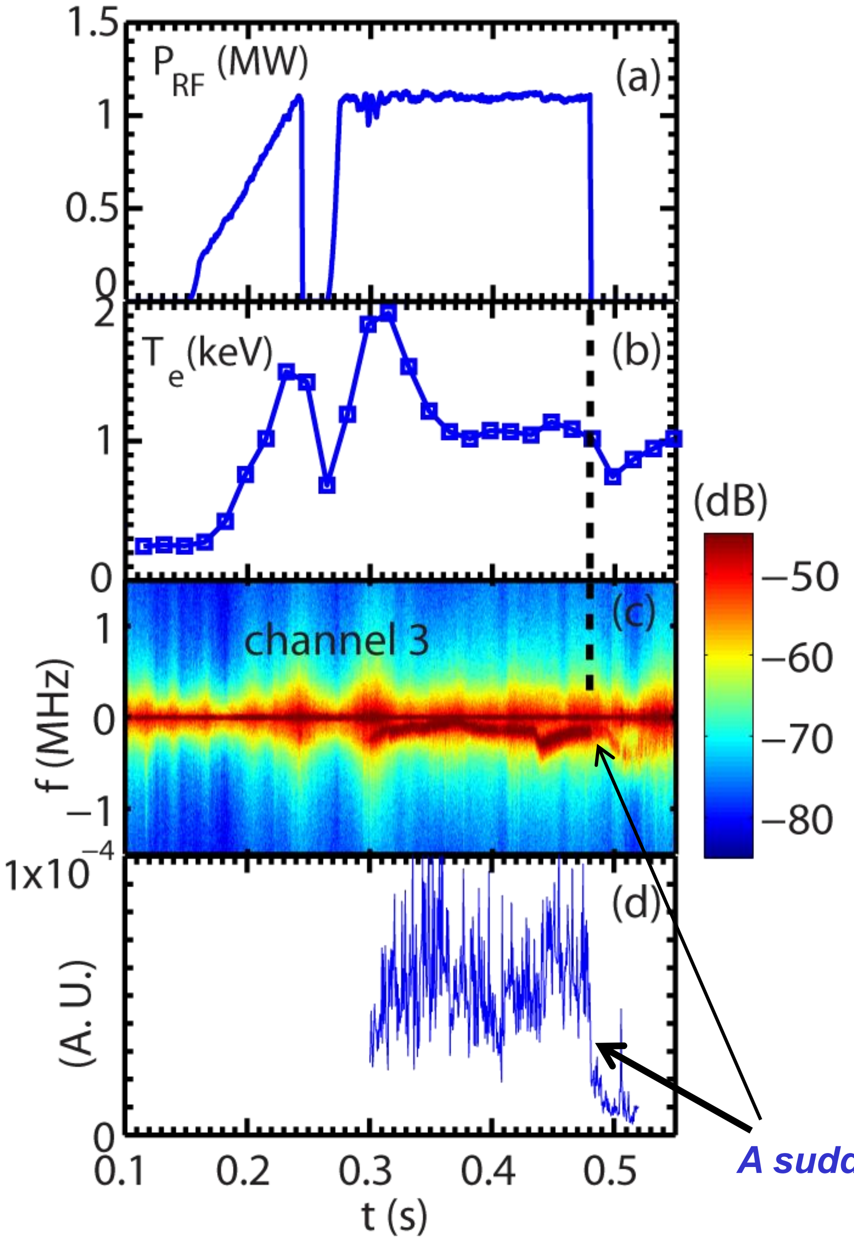
Shot=140301

RF-heated L-mode plasma with

B_T =5.5 kG

Time range of interest: around the RF cessation at t=479.6 ms

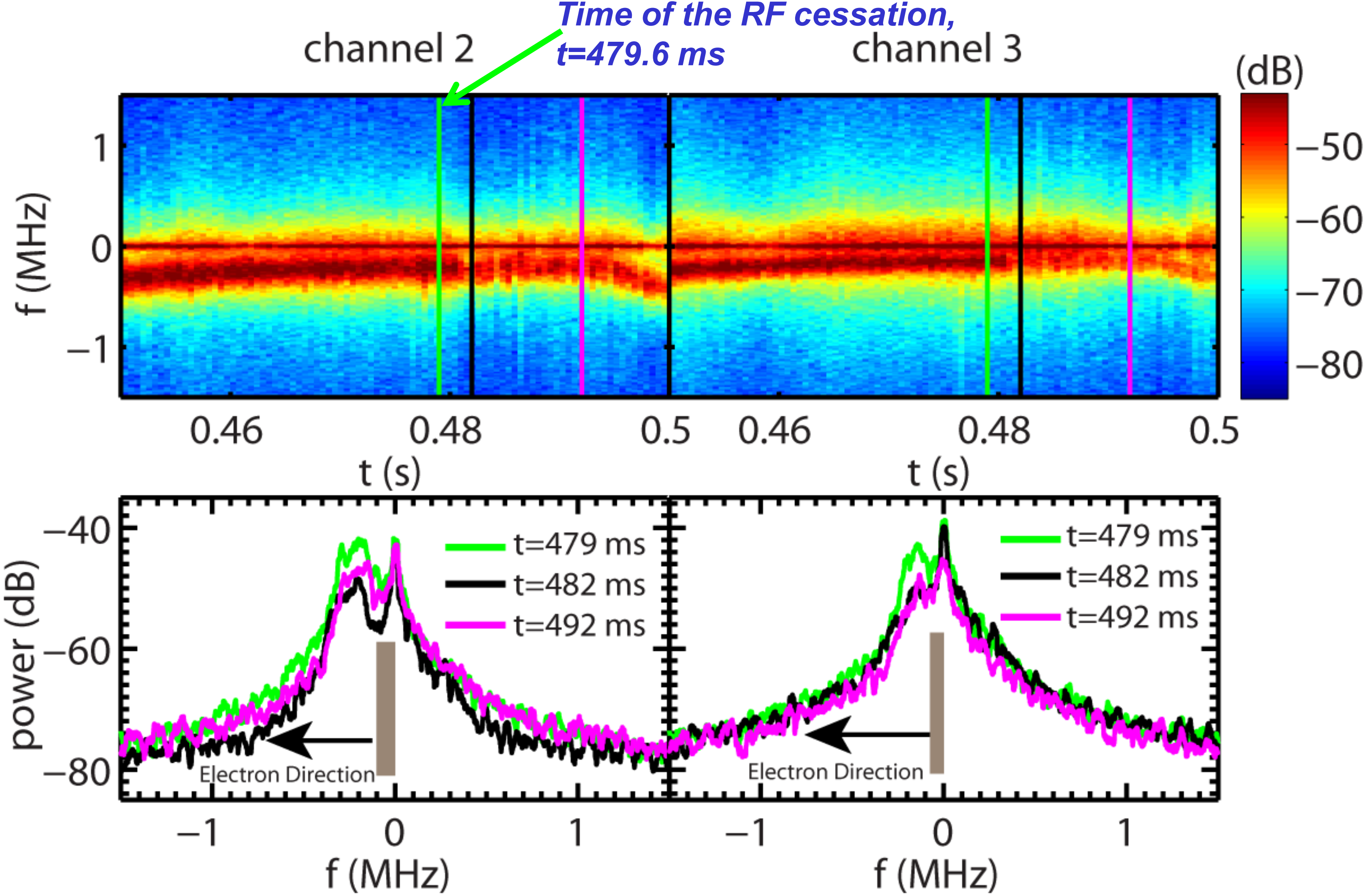
Measured Turbulence Frequency Spectral Power Shows a Significant Drop Following the RF Cessation



A sudden drop in spectral power

- Drop in turbulence frequency spectral power at the time of RF cessation
- High-k measurement region r/a~ 0.57-0.63

A Time Delay between the Drop in Spectral Power and RF Cessation Indicates a Causal Relationship

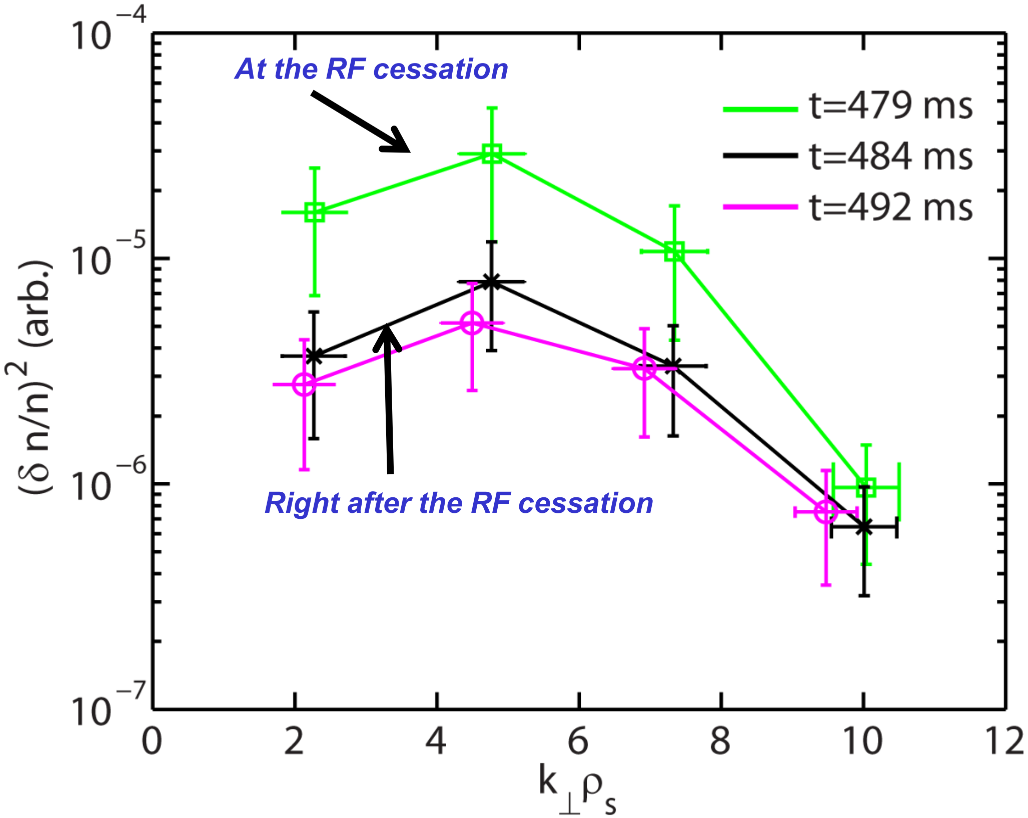


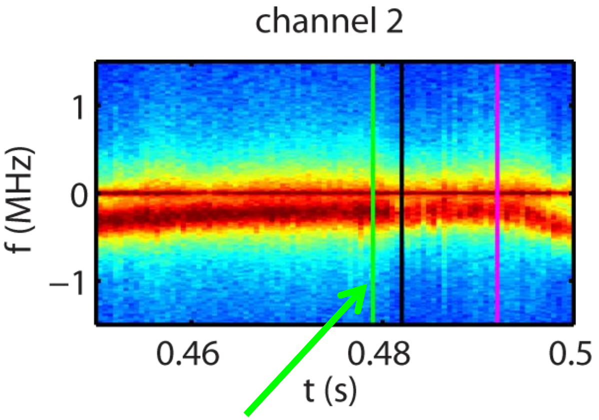
Time of the RF cessation, t=479.6 ms

- Spectral power decreases within 0.5 - 1 ms and the delay time is about 1-2 ms
- Turbulence propagates in electron diamagnetic direction

Turbulence Wavenumber Spectra Show Significant Reduction in Smaller Wavenumbers, $k_\perp \rho_s$ <9-10

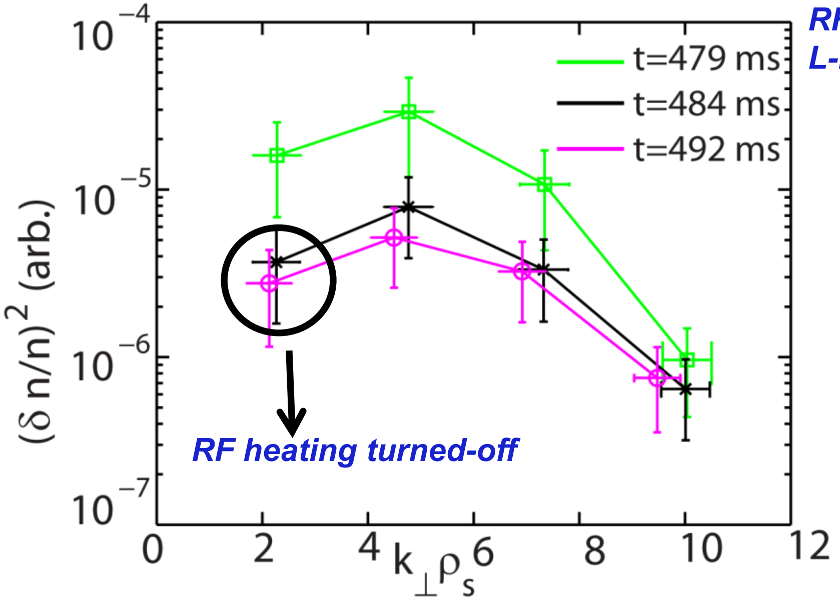
- Up to a factor of 7 drop in wavenumber spectral power right after the RF cessation
- The drop in spectral power only occurs at $k_\perp \rho_s$ <9-10



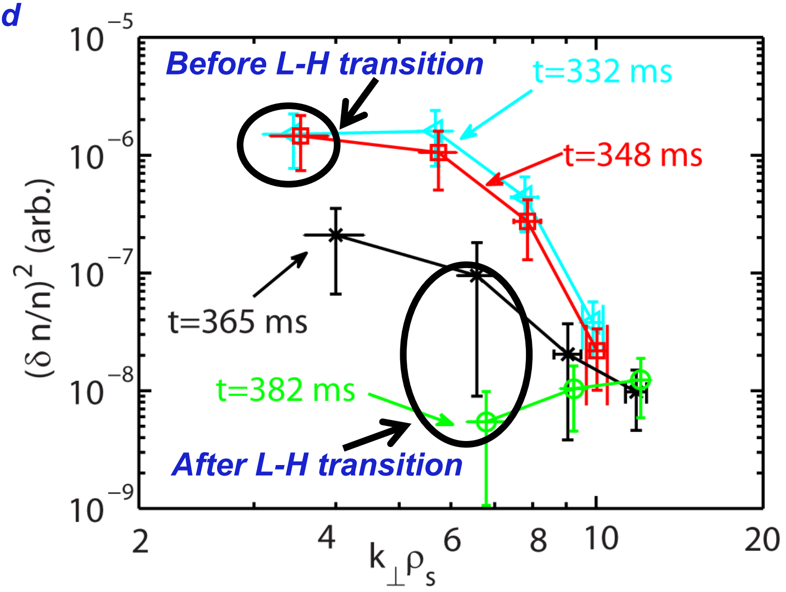


Time of the RF cessation, t=479.6 ms

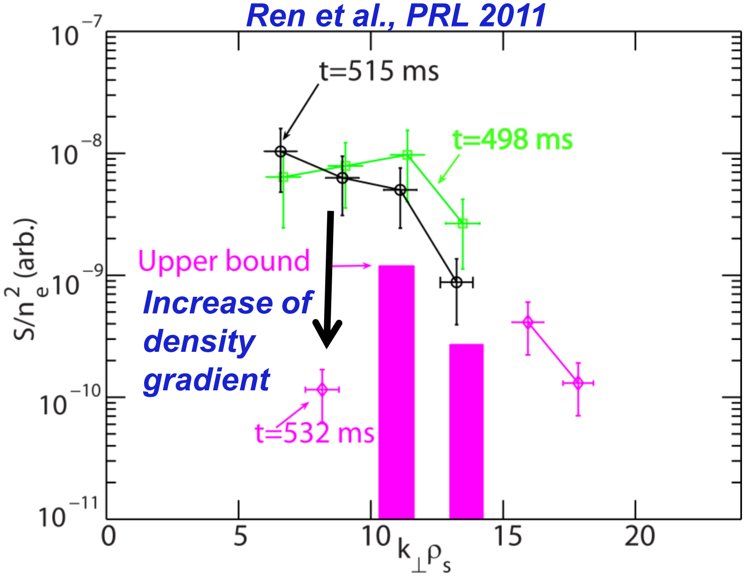
Similar Observations of Spectral Power Drop in Lower Wavenumbers in Different NSTX Scenarios



RF-heated L-mode

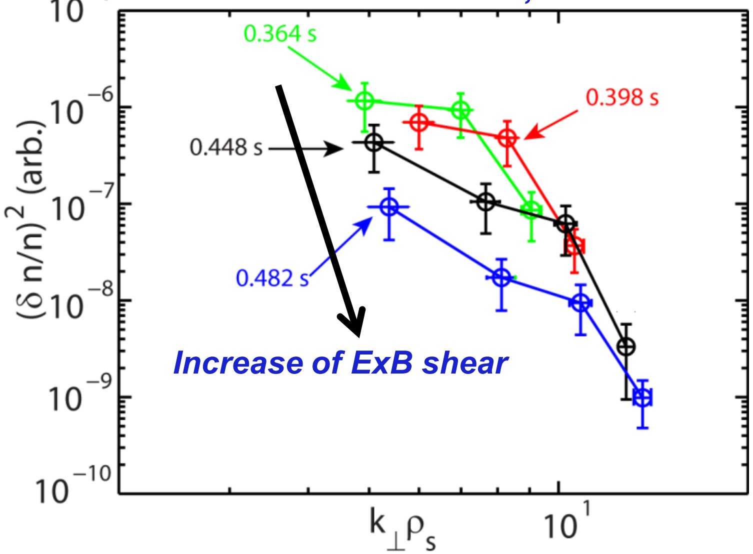


Ren et al., PRL 2011



NBI-heated H-mode

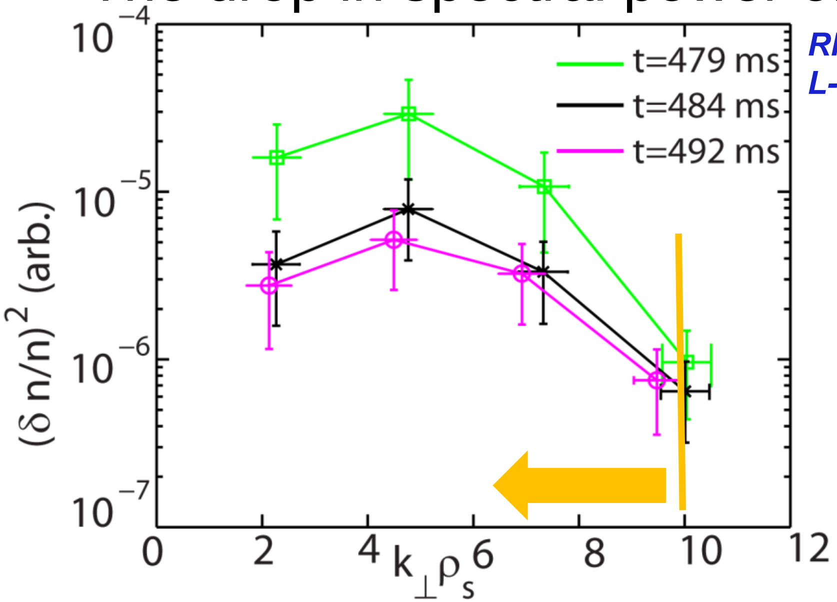
Ren et al., NF 2013



NBI-heated L-mode

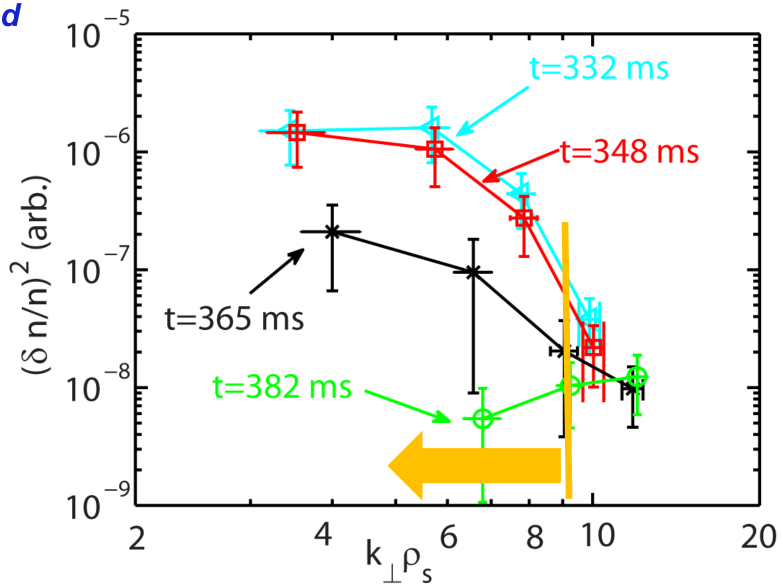
Spectral Power Drop in Lower k is Consistent with Lower k being more Important for Driving Thermal Transport

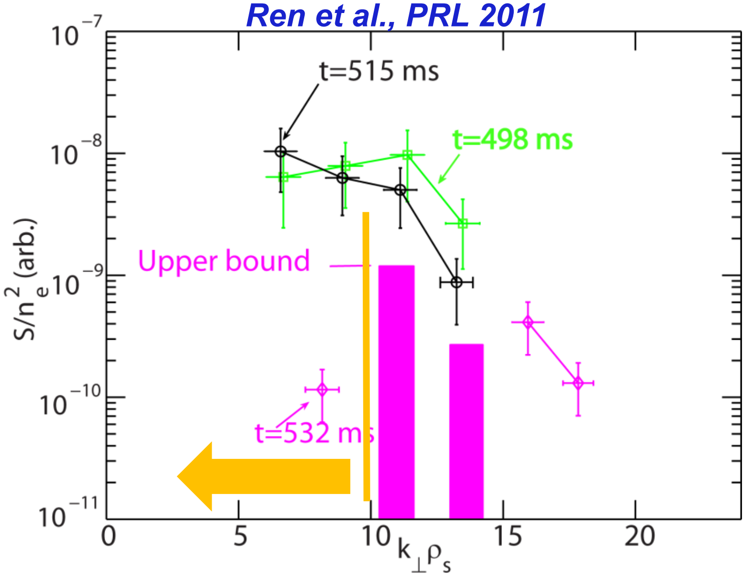
- The drop in spectral power only occurs at $k_{\perp}\rho_s$ <9-10



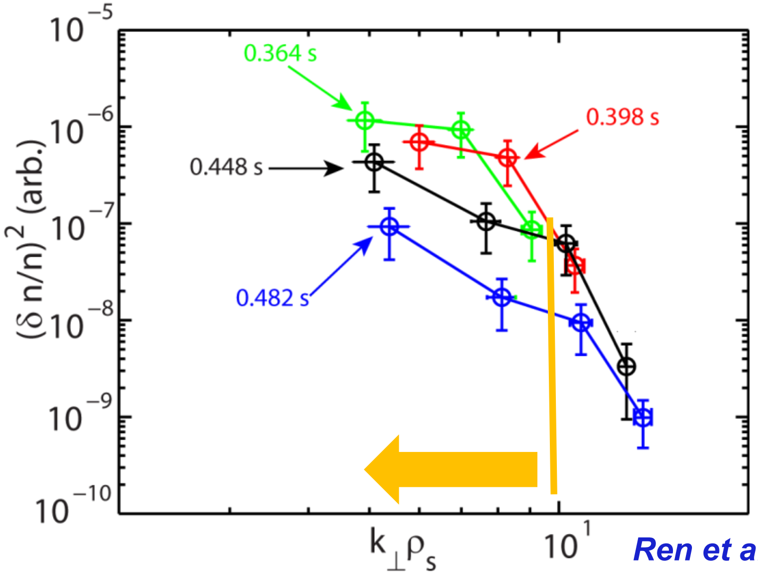
RF-heated L-mode

Ren et al., PRL 2011





NBI-heated H-mode



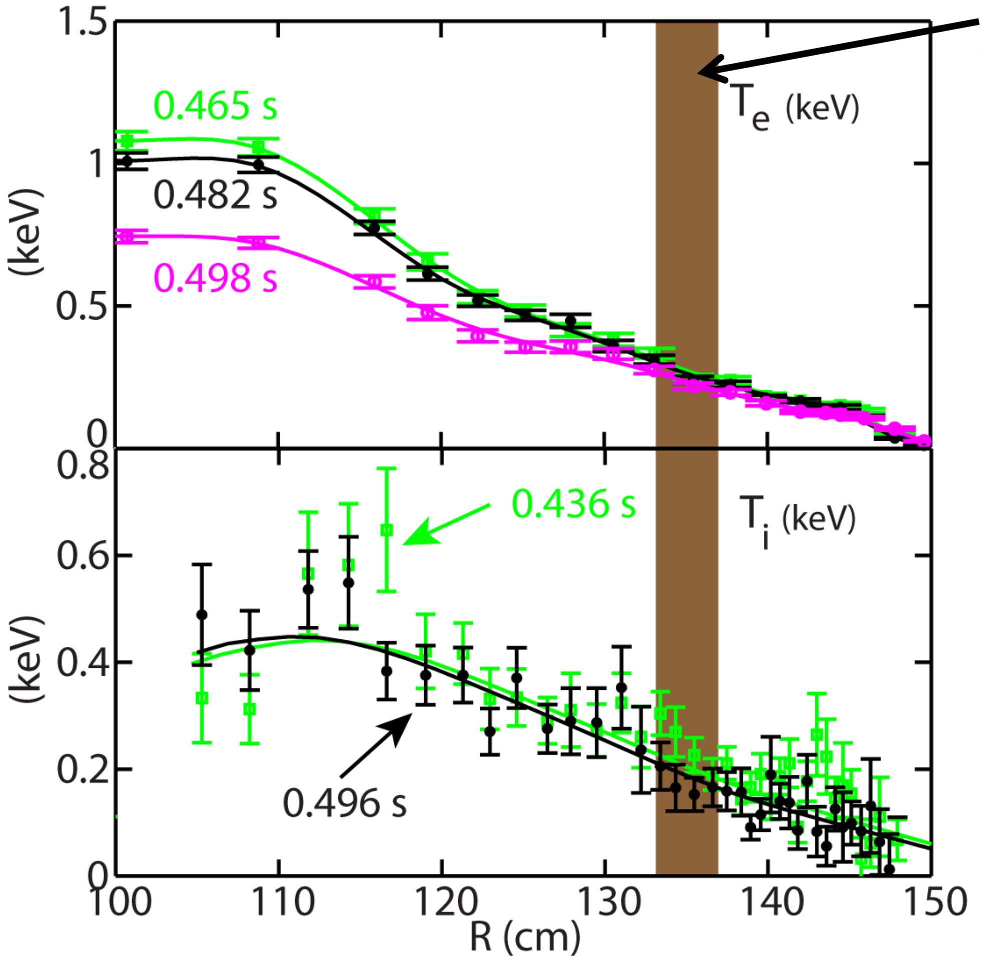
NBI-heated L-mode

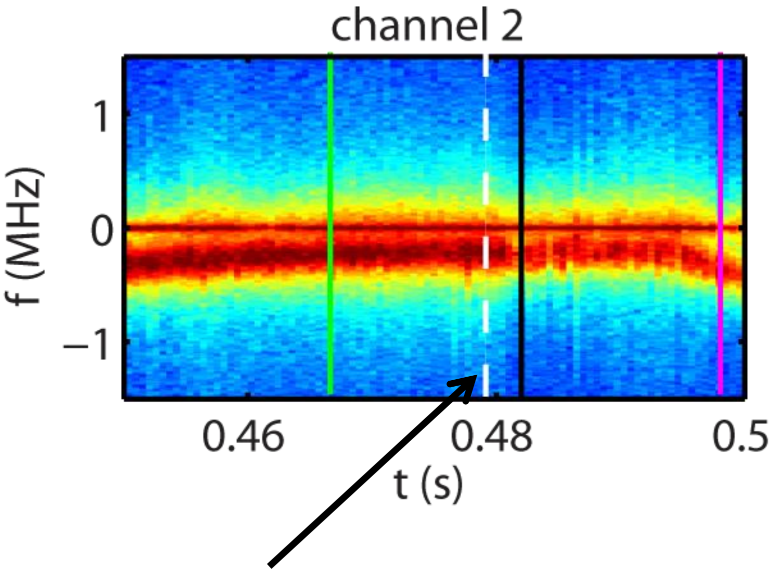
Ren et al., NF 2013

T_e and Ti Profile Changes are Small across the RF Cessation

- One Thomson measurement point is at t=482 ms, right after the drop of high-k turbulence
- T_i profile is measured by CHERS

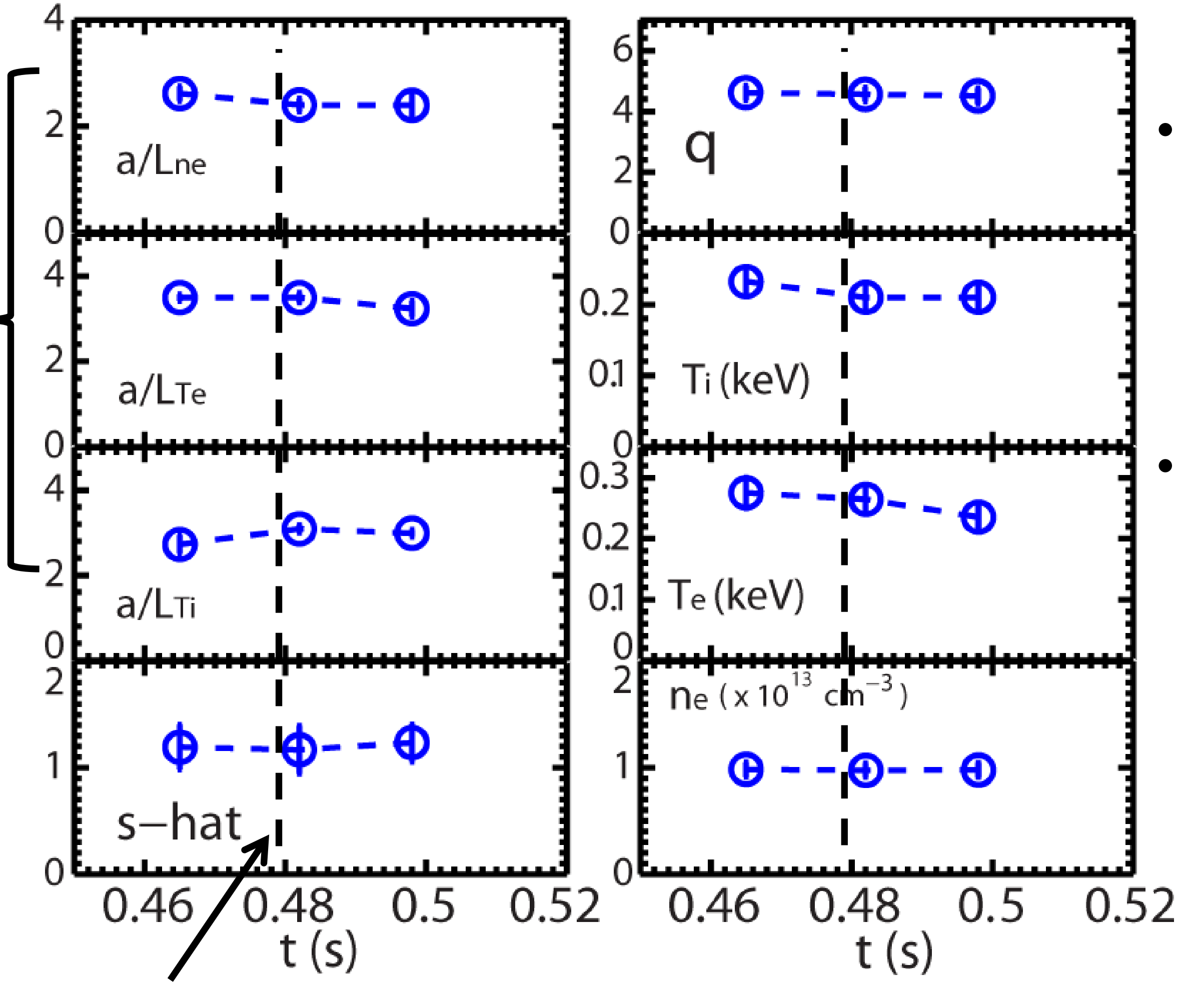
High-k measurement region r/a~ 0.57-0.63





Time of the RF cessation

Local Equilibrium Quantities Show Small Changes around the RF Cessation



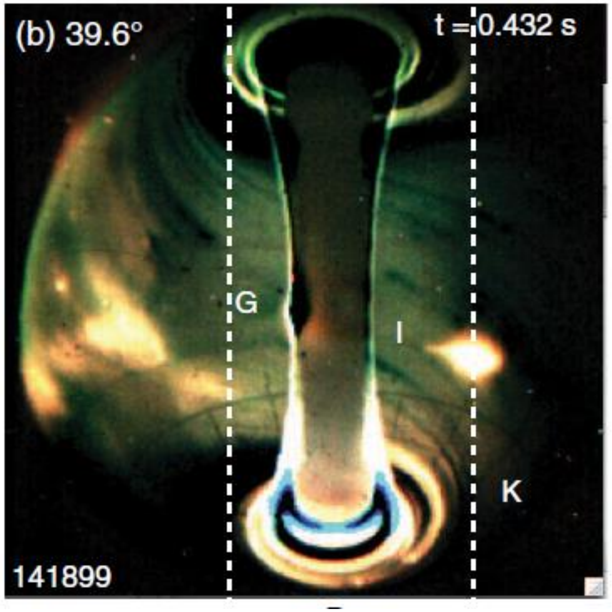
Normalized inverse gradient scale lengths

Time of the RF cessation

- <15% variation in equilibrium quantities before and right after the RF cessation (over 17 ms)
- Equilibrium quantities not expected to change significantly on the time scale on which the turbulence changes (0.5-1 ms), i.e. <<15%

RF Coupling is the issue of Transport Analysis of NSTX RF-heated Plasmas

- Use TRANSP code coupled with TORIC full wave solver to calculate RF heating profile
  - HHFW on NSTX mainly heats electrons
- The biggest uncertainty of this calculations is to estimate how much RF power is coupled into plasma core
  - A significant amount of RF power can be lost in the scrape-off layer
  - Lowering plasma density in front of RF antenna improving core coupling
  - However, there is no code or direct measurement to determine the core coupling efficiency



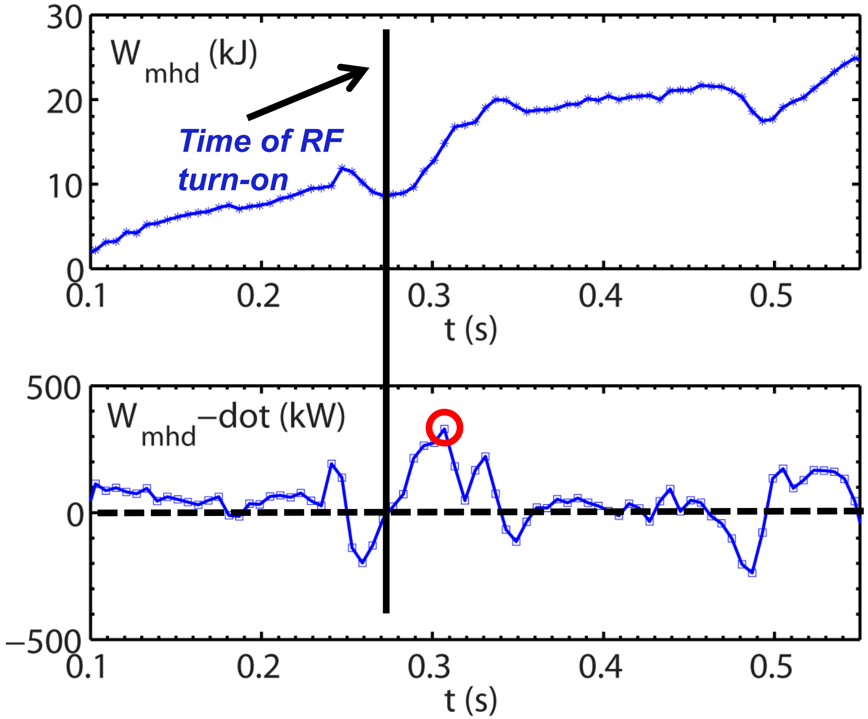
Perkins et al., PRL, 2012

The RF turn-on Phase is used to Estimated the Coupling of RF Heating Power

- Using the change rate in stored energy after RF turn-on
  - No way to determine coupled RF heating power during steady-state phase
  - Assume constant RF coupling, constant Ohmic heating and same thermal transport as before RF turn-on
- Global power balance equation:

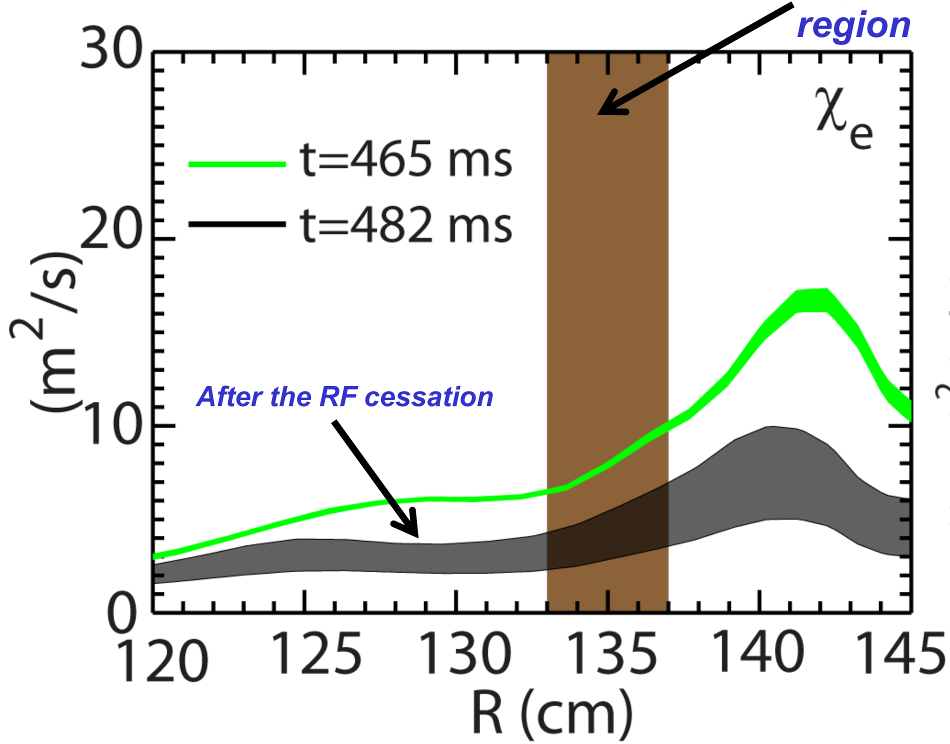
$$\frac{dW_{MHD}}{dt} = P_{RF} + P_{Ohmic} - P_{loss} \Longrightarrow \frac{dW_{MHD}}{dt} \approx P_{RF} \text{ with } P_{loss} \approx P_{Ohmic}$$

- Thus dw_{MHD}/dt gives an estimate of coupled P_{RF}
  - P_{RF} is set to the peak dw_{MHD}/dt after RF turn-on
- Coupled RF power is estimated to be about 330 kW vs 1.1 MW of input RF power



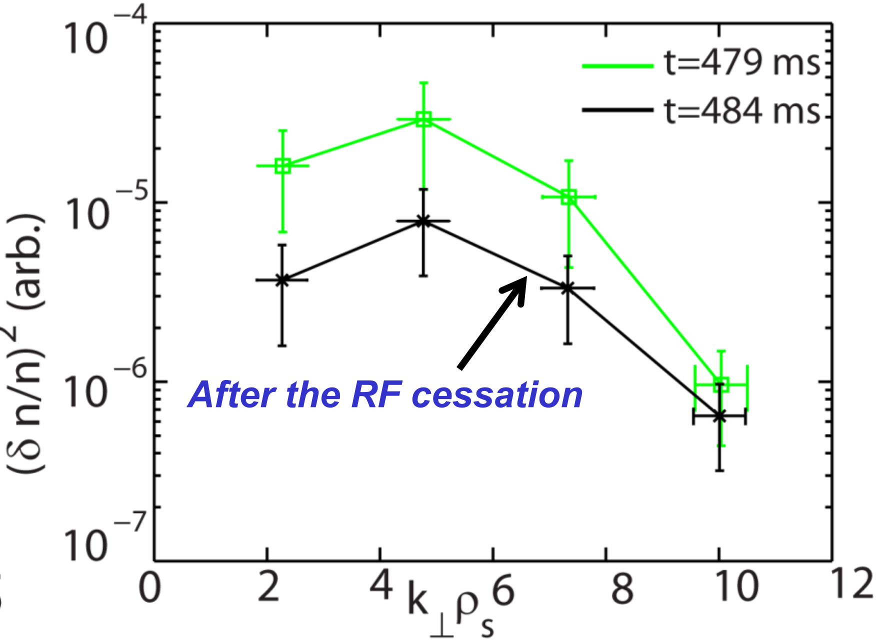
Turbulence Wavenumber Spectral Power is Correlated with Electron Thermal Diffusivity

- About a factor of 2 decrease in electron thermal diffusivity after the RF cessation
  - Correlated with the decrease in turbulence wavenumber spectral power



High-k measurement region

After the RF cessation

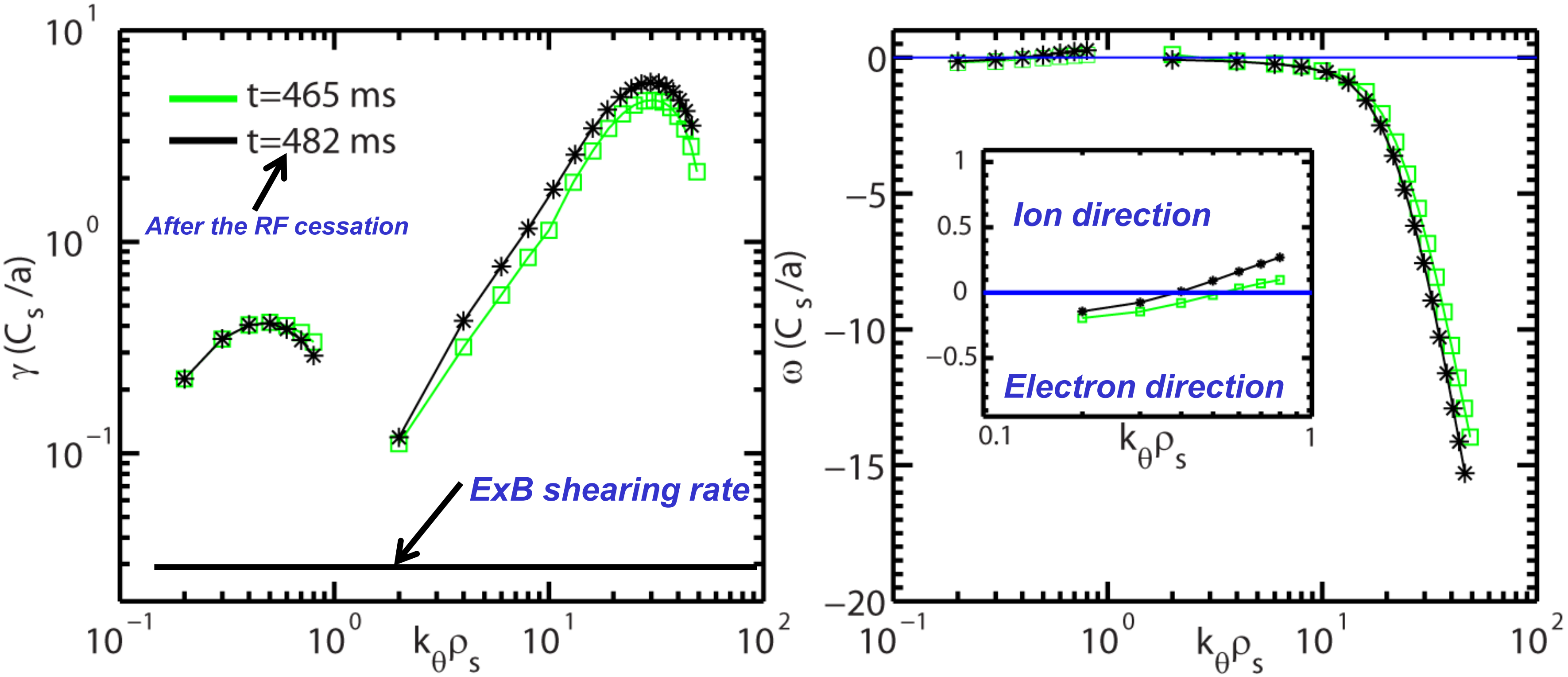


After the RF cessation

From TRANSP analysis with TORIC

Changes in Linear Growth Rate Cannot Explain the Observed Significant Drop in High-k Turbulence

- Ion scale modes are ITG/TEM hybrid
  - Growth rate similar between t=465 and 482 ms
- ETG mode maximum growth rates show small increase from t=465 to 482 ms
  - Inconsistent with the drop in the measure high-k spectral power



After the RF cessation

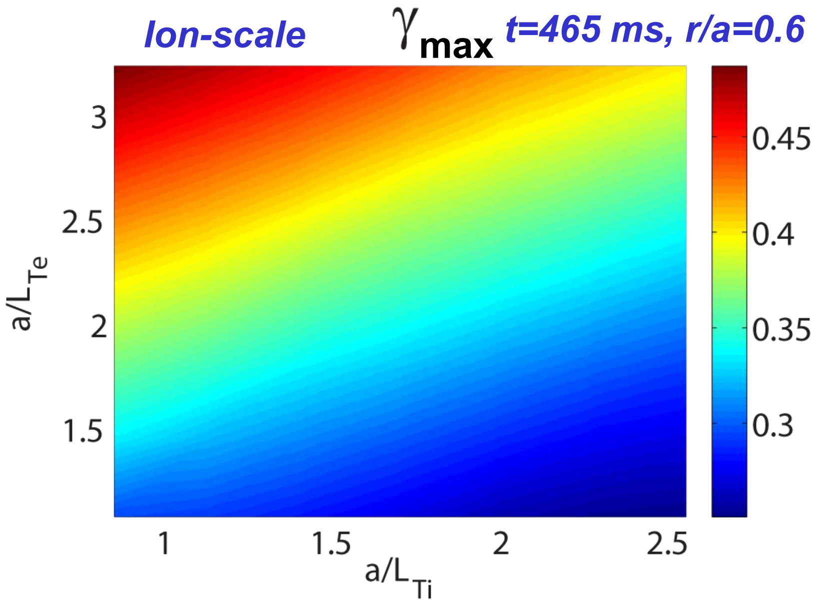
ExB shearing rate

Ion direction

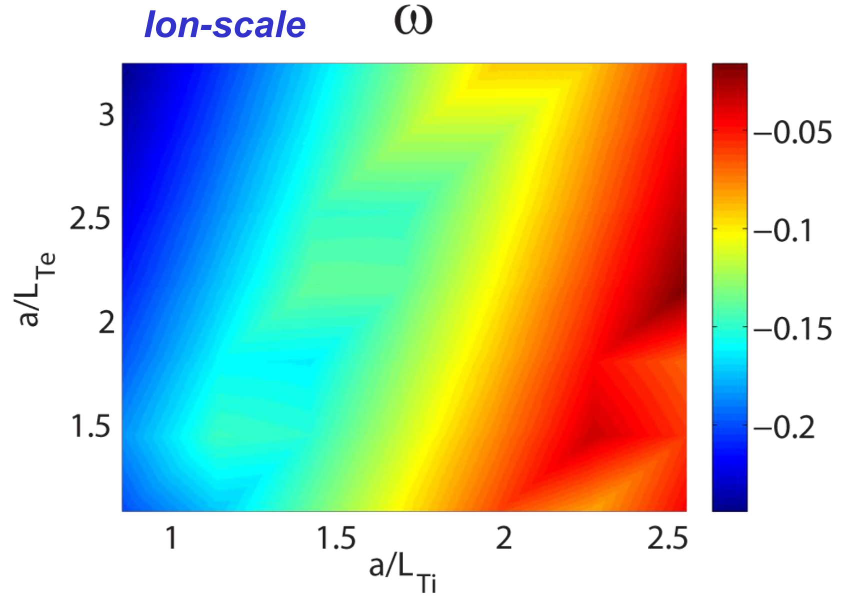
Electron direction

- Stability Analysis was performed with the GS2 code (Kotschenreuther et al., 1995)

Linear ITG/TEM and ETG Modes are Robustly Unstable



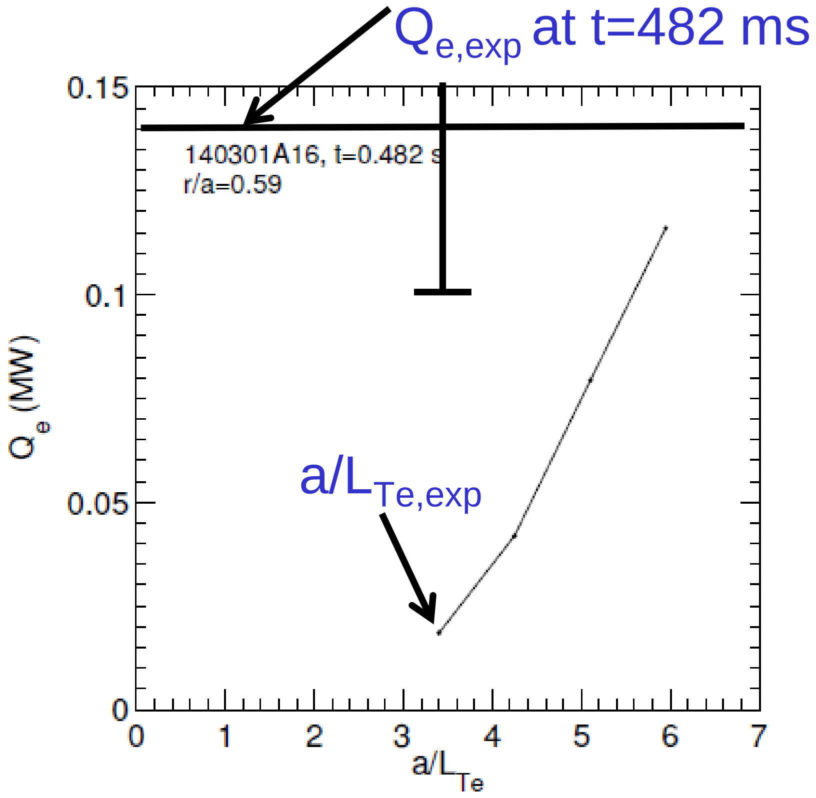
Ion-scale $\gamma_{\mathbf{max}}$ ***t=465 ms, r/a=0.6***



Ion-scale ω

- T_e and T_i gradients are scanned
  - Gradient scans carried out with β’ kept fixed for ITG/TEM modes but not for ETG modes
- The ion-scale modes are driven by both electron and ion temperature gradients
  - $a/L_{Te,exp}=3.6$
  - $a/L_{Ti,exp}= 2.83$
- Critical a/L_{Te} of ETG modes is determined to be 2.1 ($a/L_{Te,exp}=3.6$) from T_e gradient scan
- Z_{eff} is found to have little effects on linear growth rate

Local Nonlinear Gradient-driven ETG Gyrokinetic Simulations do not Show Enough Stiffness to Explain the Observations



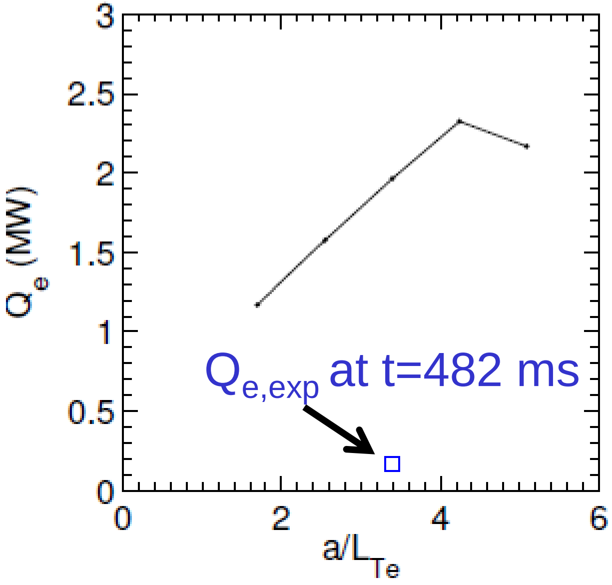
$Q_{e,exp}$ at t=482 ms

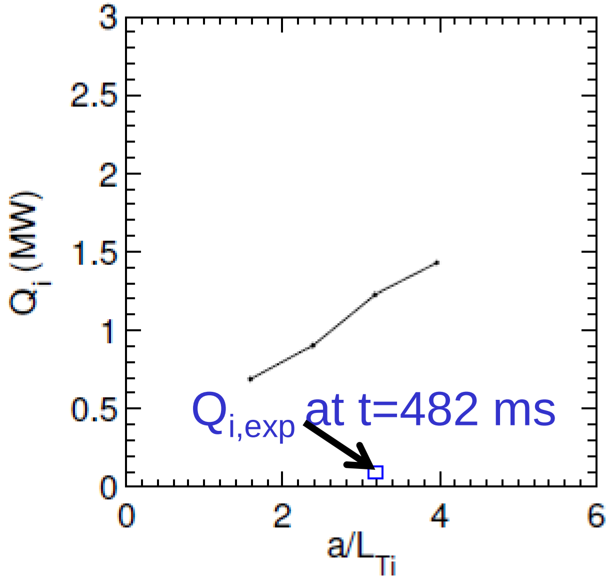
$a/L_{Te,exp}$

3 kinetic species: D,C,e, (Zeff~1.6)
Electromagnetic: ($A_{||}+B_{||}$, β_e~0.1%)
With collisions
Resolution parameters
Lx x Ly = 6x4 ρ_s (360x240 ρ_e), nx x ny = 192x48
$k_\theta\rho_s$ [min, max] = [1.6, 73], $k_r\rho_s$[min, max] = [1.0, 50]
[$n_{||}$,nλ,ne]=[14,12,12]x2

- Nonlinear ETG simulations were carried out using GYRO
- A scan in a/L_{Te} shows:
  - A 75% increase in a/L_{Te} is needed for ETG to explain observed electron heat flux at t=482 ms (after the RF cessation)
  - At least a 20% change in a/L_{Te} is needed to double Q_e
- The stiffness inconsistent with experimental observations
  - Equilibrium quantities changes much less than 15% right after the RF cessation with a factor of two decrease in Q_e

Local Nonlinear Gradient-driven Ion-scale Gyrokinetic Simulations do not Show Enough Stiffness to Explain the Observations





- Nonlinear ion-scale simulations were carried out using GYRO
- Scans in a/L_{Te} and a/L_{Ti} show:
  - Gradient-driven ion-scale gyrokinetic simulations significantly over-predict thermal transport for both electron and ion channels
  - A 25% increase in a/L_{Te} only leads to 18% increase in Q_e
  - Less stiffness is observed in the ion channel than the electron channel
  - The stiffness cannot explain observed reduction in transport and turbulence
- Future investigation of global effects using GTS planned

Resolution parameters

Lx x Ly = $107 \times 42\rho_s$, nx x ny = 128x24 ($\Delta n=2$)

$k_\theta\rho_s$ [min, max] = [0.059, 1.37], $k_r\rho_s$[min, max] = [0.059,1.89]

$[n_{||}, n\lambda, ne]=[14,12,8]\times 2$

Summary

- We have made further progress in understanding the role of the high-k turbulence in NSTX plasmas
- First experimental observation of nonlocality in high-k turbulence and electron thermal transport is observed in NSTX
  - Showing that turbulence and thermal transport can be decoupled from local equilibrium quantities
    - After the RF cessation: ~7 times drop in the high-k spectral power and about a factor of 2 decrease in χ_e
    - Turbulence reduction on 0.5-1 ms time scale much smaller than confinement time
  - High-k turbulence and the RF-heating has a causal relationship
    - A 1-2 ms time delay between the RF cessation and turbulence reduction
  - Linear ion-scale and electron-scale modes are robustly unstable
  - Nonlinear gyrokinetic simulations do not show enough stiffness to explain experimental observations
- Suppression of high-k turbulence at lower wavenumbers, i.e. $k_\perp \rho_s \leq 9$, observed in different NSTX scenarios

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