NSTX-U

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Studies of Electron-scale Turbulence and Thermal Transport in NSTX L-mode Plasmas

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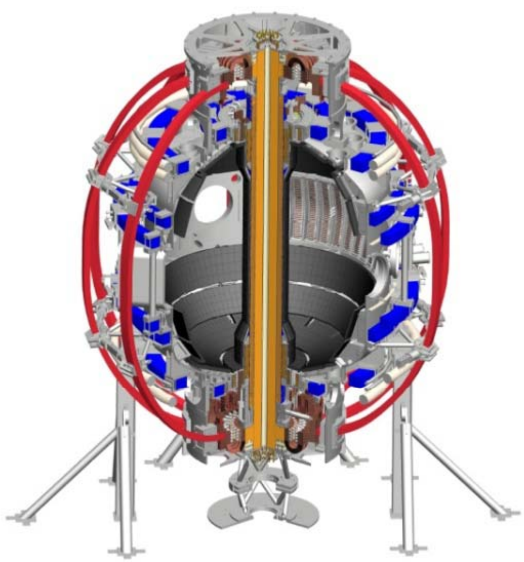
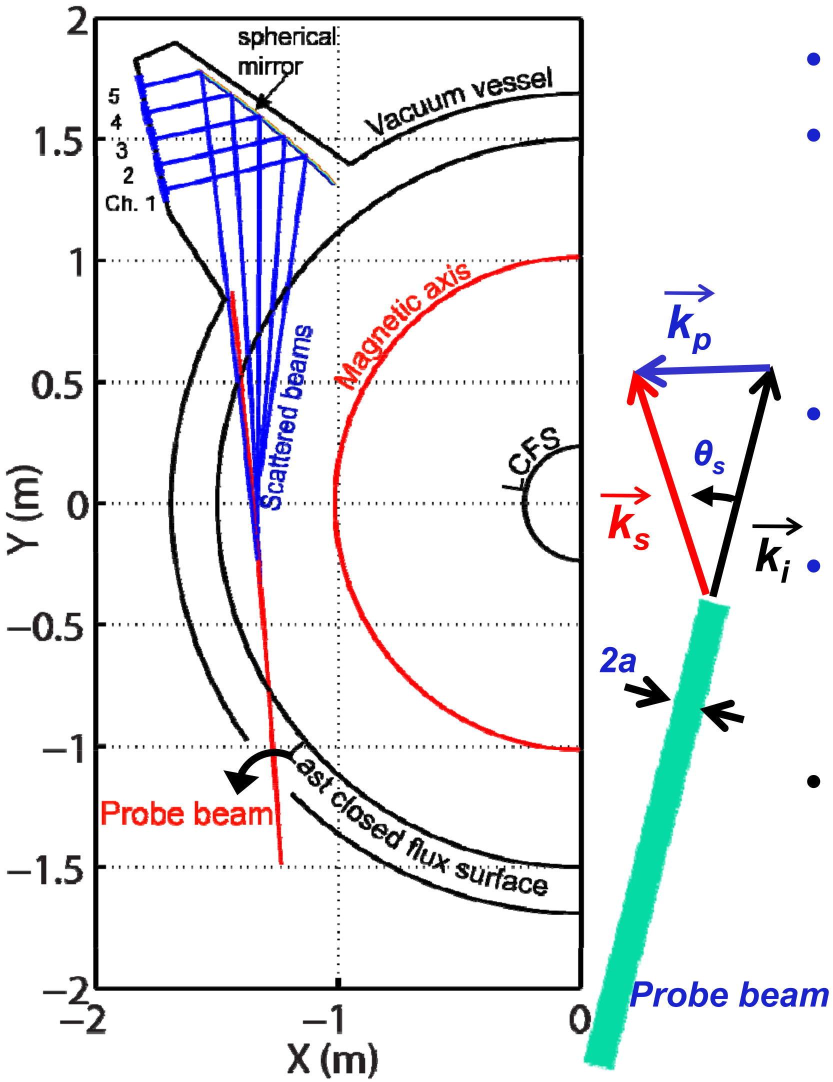


Introduction

- L-mode plasmas offer some favorable properties to facilitate the study of the relation between microturbulence and thermal transport
  - Easier to obtain stationary profiles
  - Easier to maintain MHD quiescence
  - No complications from edge transport barrier
- Studies to be presented for both NSTX RF/NBI-heated L-mode plasmas
  - A clear correlation between RF termination and a drop in high-k spectral power in 300 kA NSTX RF-heated L-mode plasmas
  - A correlation between electron thermal diffusivity and high-k spectral power observed
  - Unstable ITG/TEM and ETG modes found before and after RF termination
  - The fast drop in high-k spectral power after RF termination not consistent with linear stability analysis
  - Results from a global GTS simulation of NSTX NBI-heated L-mode plasmas show strong ExB shear stabilization of turbulence and transport

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:

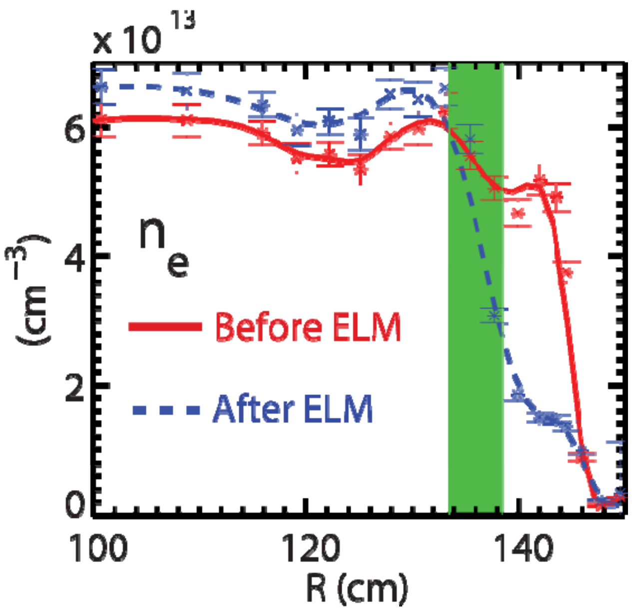
$$\omega_s = \omega_p + \omega_i$$

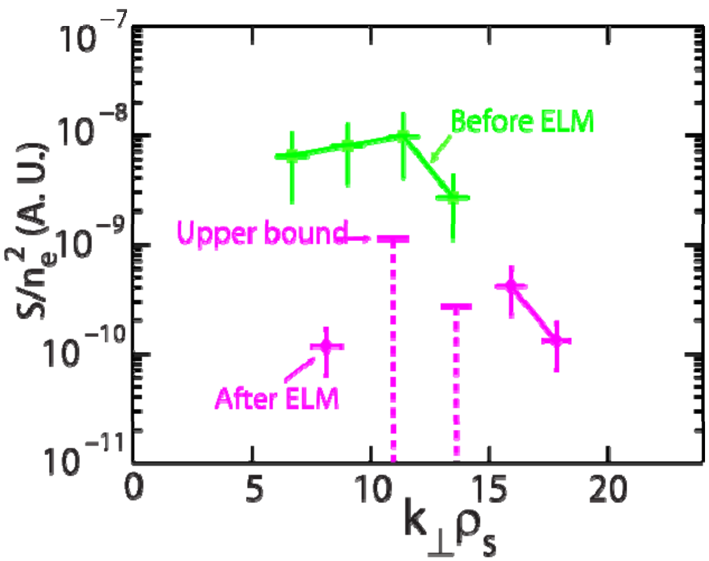
with ω_s and $\omega_i >> \omega_p$

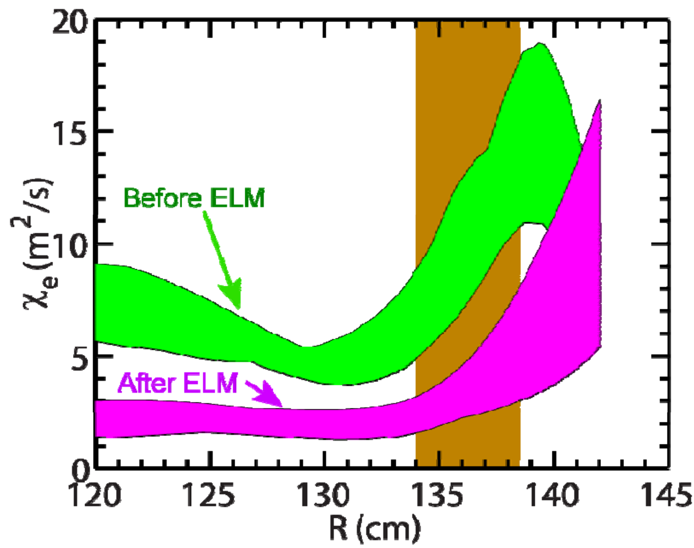
- The scattering system characteristics are:
  - **Frequency bandwidth: 5 MHz**
  - **Heterodyne receiver: Wave propagation direction resolved**
  - **Measurement: k_r spectrum**
  - **Wavenumber resolution: 0.7 cm^{-1} (2/a with a ≈ 3 cm)**
  - **Wavenumber *range (k_r): 5-30 cm^{-1} (~5-30 ρ_s^{-1})***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

Correlation between High-k Turbulence and Electron Thermal Transport Observed in NSTX H-mode Plasmas

- Density gradient stabilization of high-k turbulence observed
- Correlated with a factor of about two decrease in electron thermal diffusivity
- Consistent with theoretically predicted increase in critical electron temperature gradient for ETG modes due to density gradient





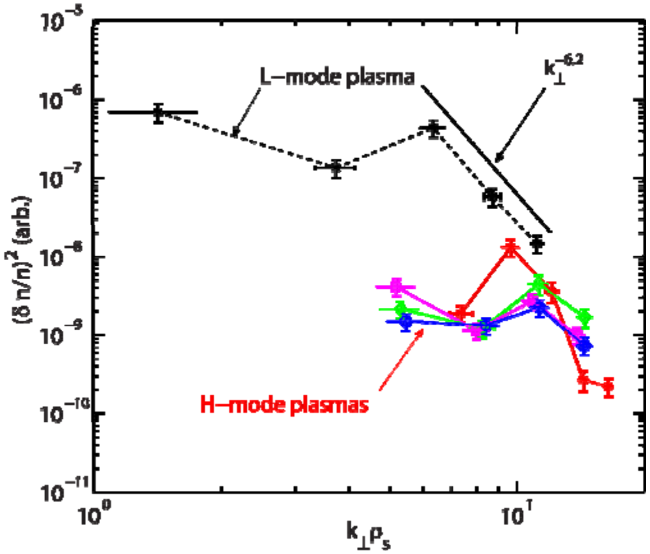


Ren et al., PRL, 2011 and PoP, 2012

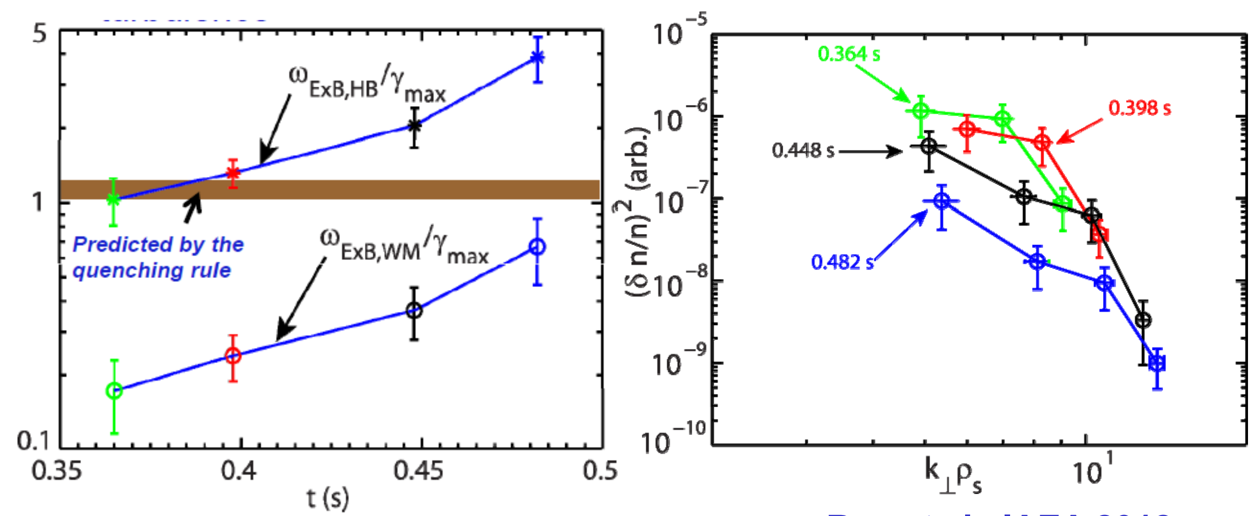
Previous Turbulence and Transport Studies in NSTX NBI-heated L-mode Plasmas

- Large differences, up to about 2 orders of magnitude, in spectral power found at $k_\perp \rho_s$ <10 between L and H-mode plasmas.
- Consistent with long wavelength turbulence being more important for driving anomalous transport.

- Reduction in peak spectral power of high-k turbulence correlated with the increase in $\omega_{E\times B}/\gamma_{max}$
  - Consistent with a quenching rule for ion-scale turbulence
- Observed decrease in χ_i and χ_e correlated with the stabilization of ITG turbulence
- Preliminary results from a Global GTS simulation to be shown



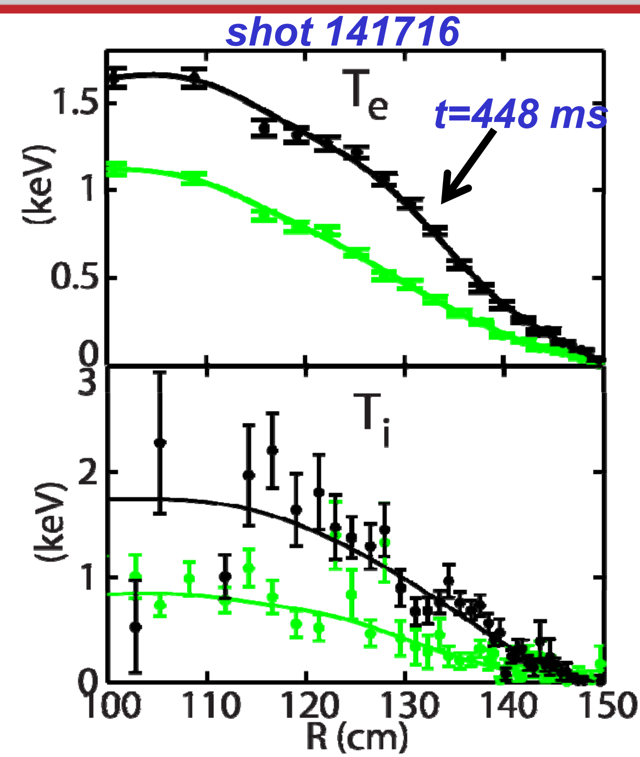
Raman et al., Nucl. Fusion 2011



Ren et al., IAEA 2012

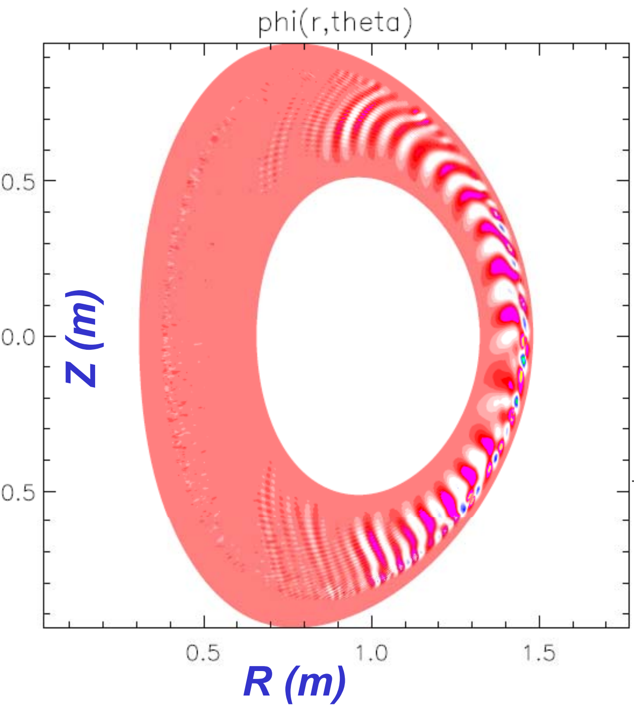
First Attempt of Global GTS Simulation of NSTX NBI-heated L-mode Shot 141716

- GTS addresses global effects
  - Large ion gyroradius and profile variation in NSTX
- Shot 141716 has strong ExB shear at t=448 ms
  - Strong ExB linear stabilization of ion-scale modes

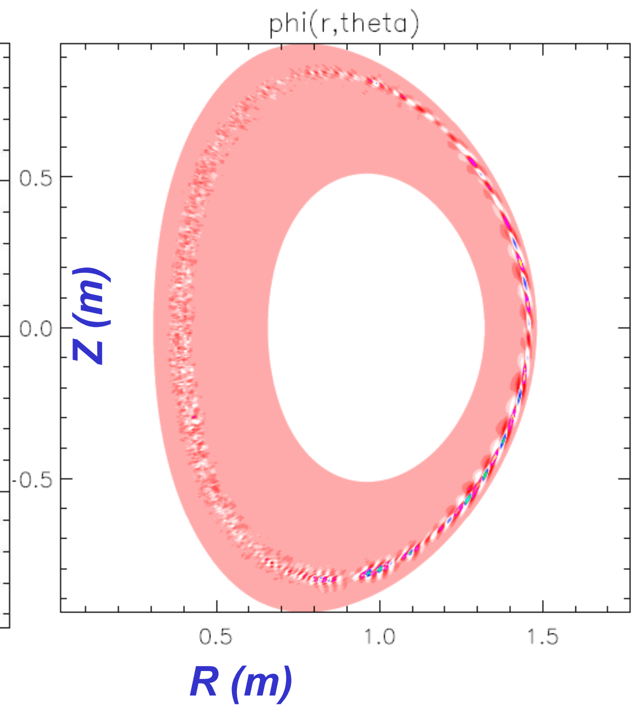


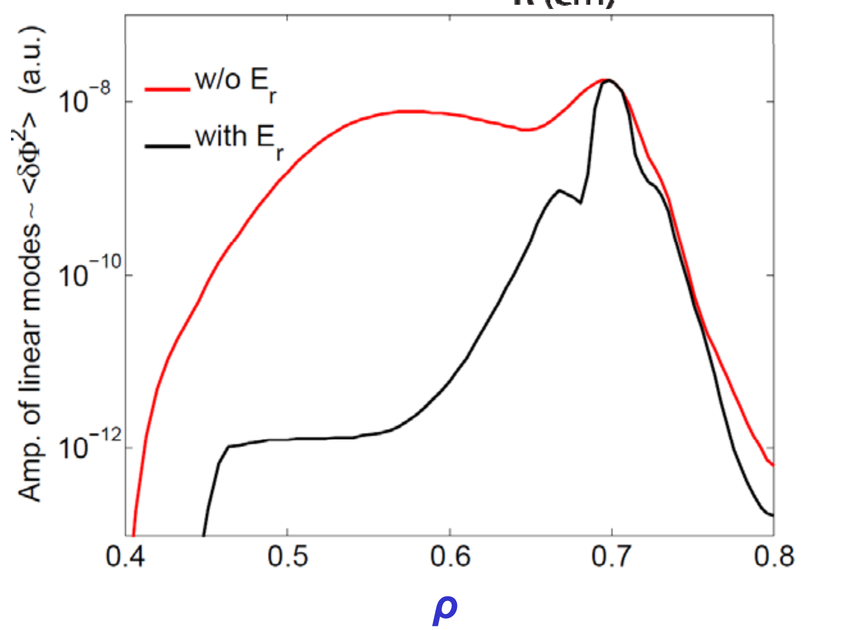
Ion scale simulation with kinetic electrons; domain ρ~ 0.3-0.8; 80 particles per cell; total particles ~ 4.5 x10^8

Without ExB shear



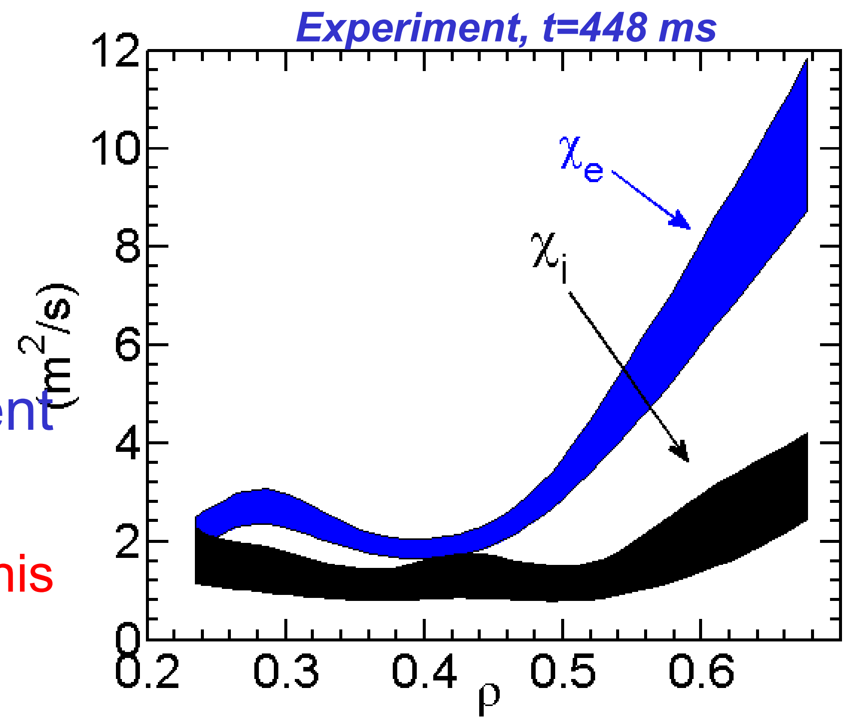
With ExB shear

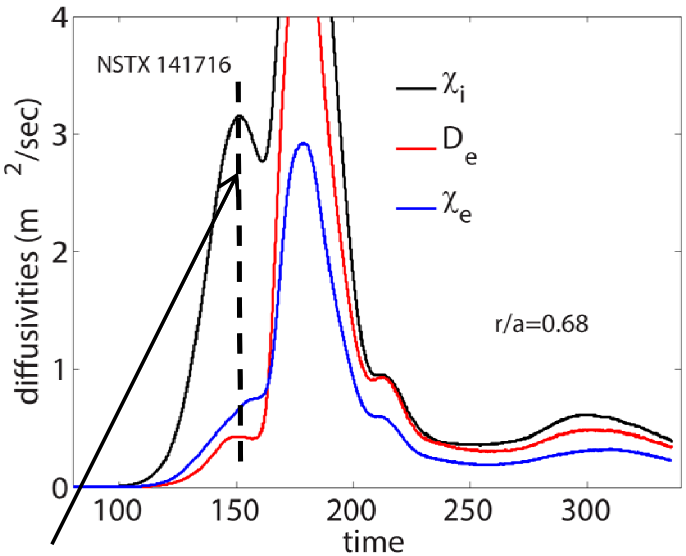




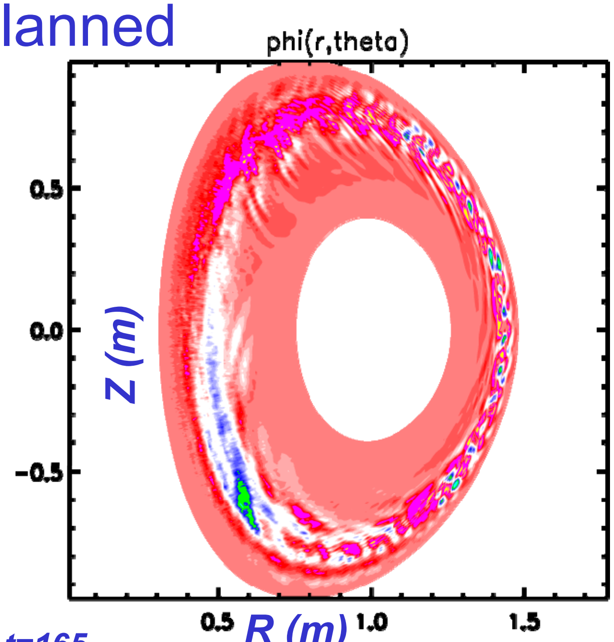
Nonlinear GTS Simulation Shows Strong Suppression of Ion-scale Turbulence and Reduction of Thermal Transport

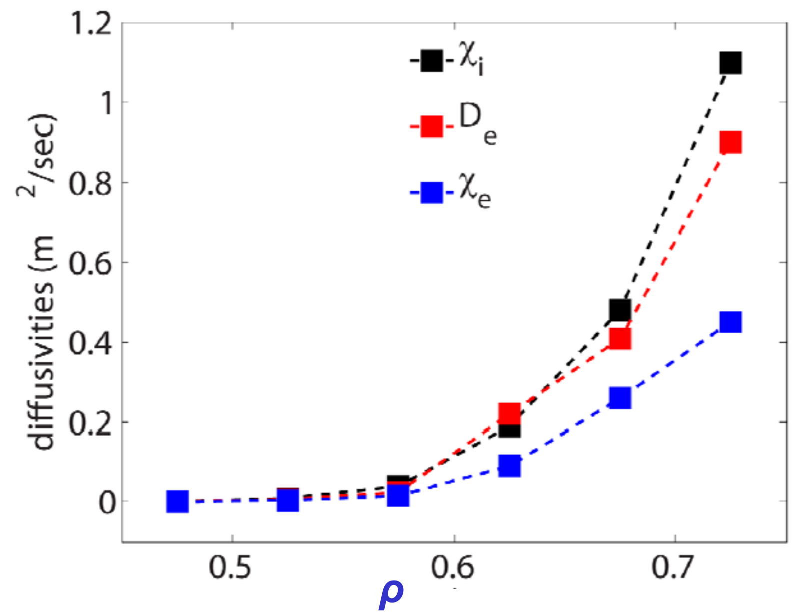
- ExB shear is gradually turned on after initial strong linear growth
- Qualitatively reproduces radial profiles of thermal diffusivities
  - Much larger diffusivities in the experiment
  - $\chi_e > \chi_i$ in the experiment
    - ETG may be important (not resolved in this GTS simulation)
  - Sensitivity studies planned





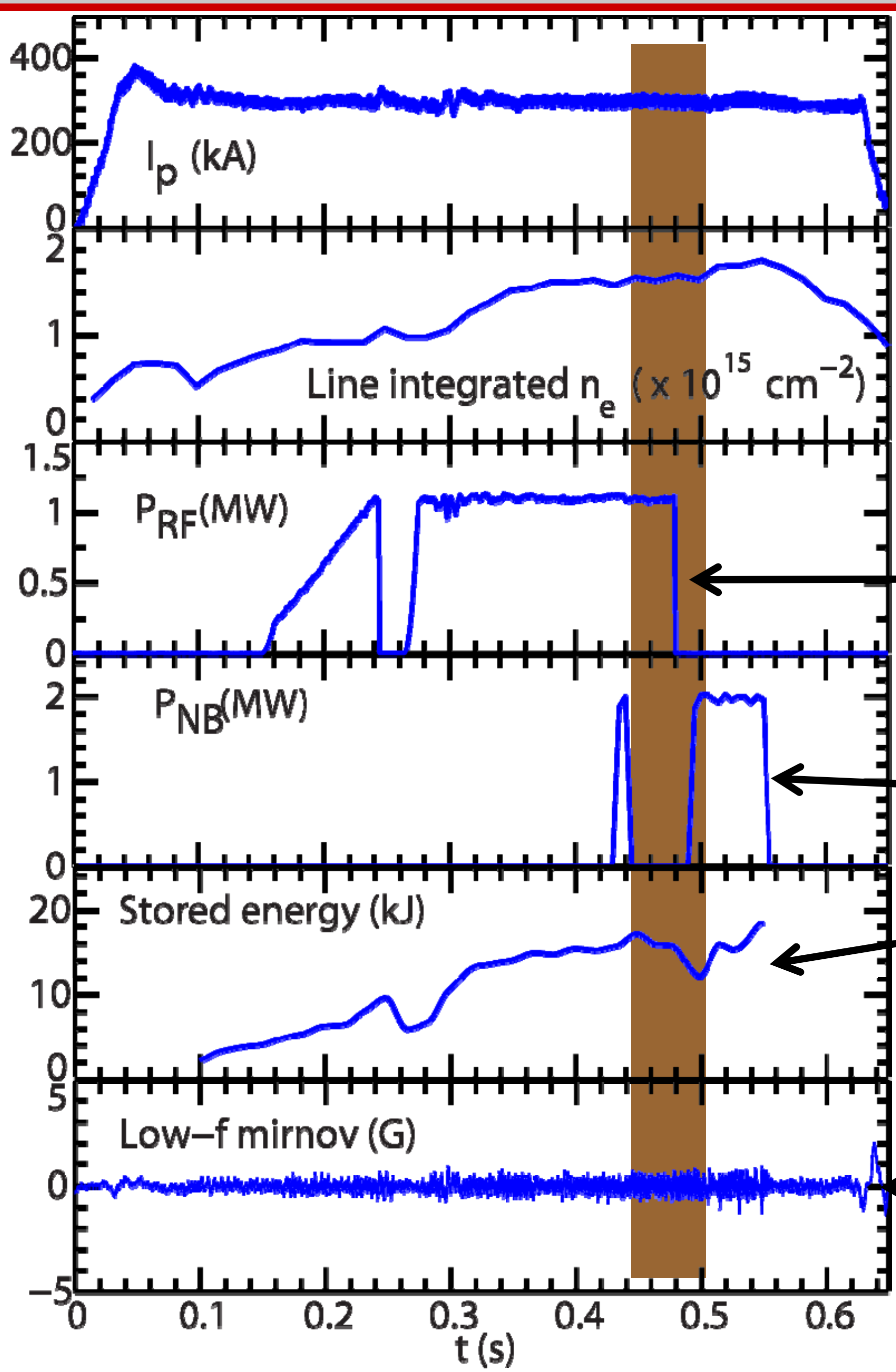
ExB shear turn-on at t=156, becoming full at t=165





A Set of NSTX RF-heated L-mode Plasmas is Used to Study Turbulence and Electron Transport

I_p=300 kA



Shot=140301

RF-heated L-mode plasma with B_T =5.5 kG

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

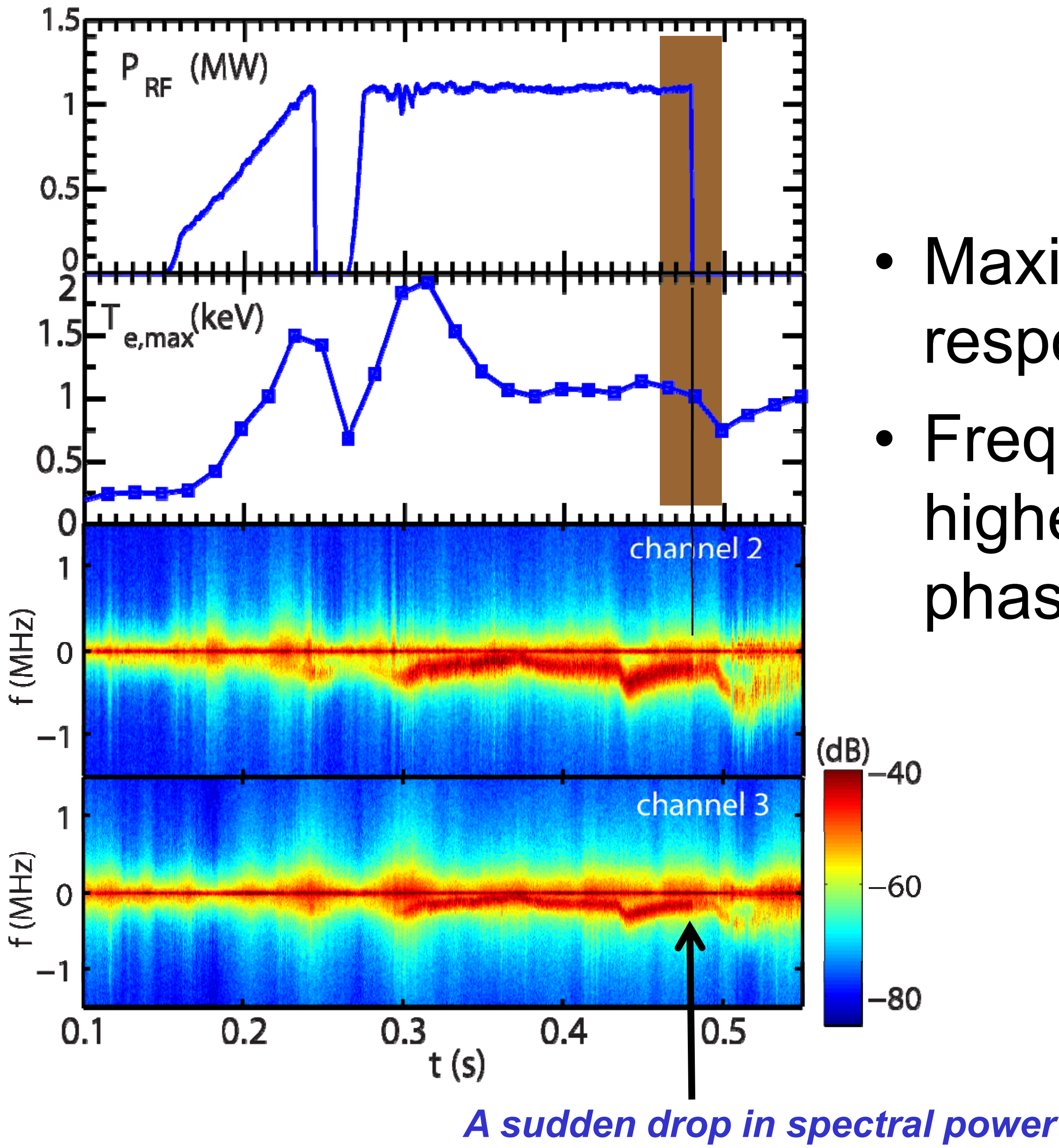
NBI blips for diagnostic purposes

From TRANSP

Decrease in stored energy following the RF termination

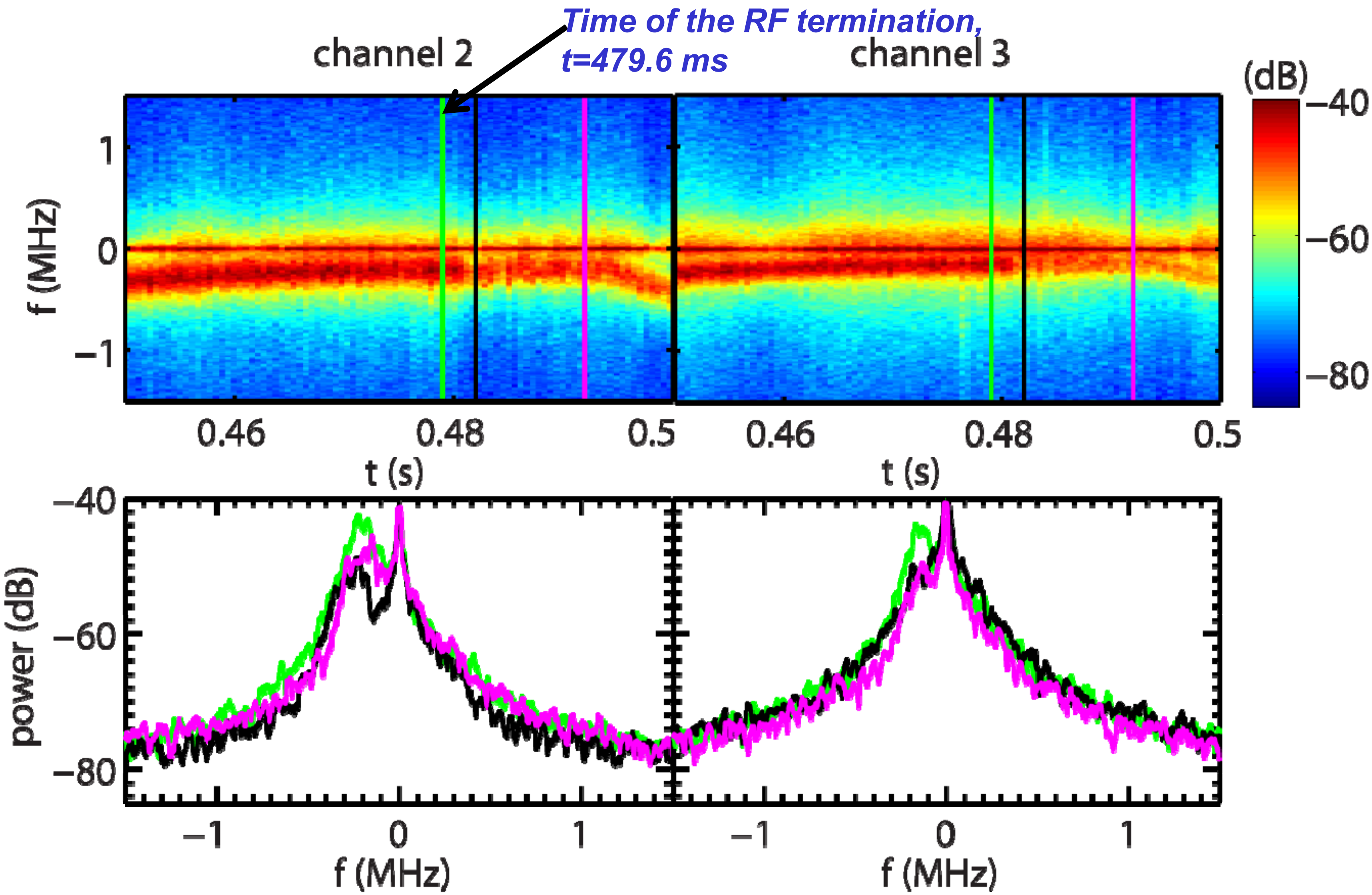
Small MHD activities

Frequency Spectral Power from the High-k Scattering System Shows a Sudden Drop Following the RF Termination



- Maximum T_e clearly responding to RF heating
- Frequency spectral power higher during RF heating phase

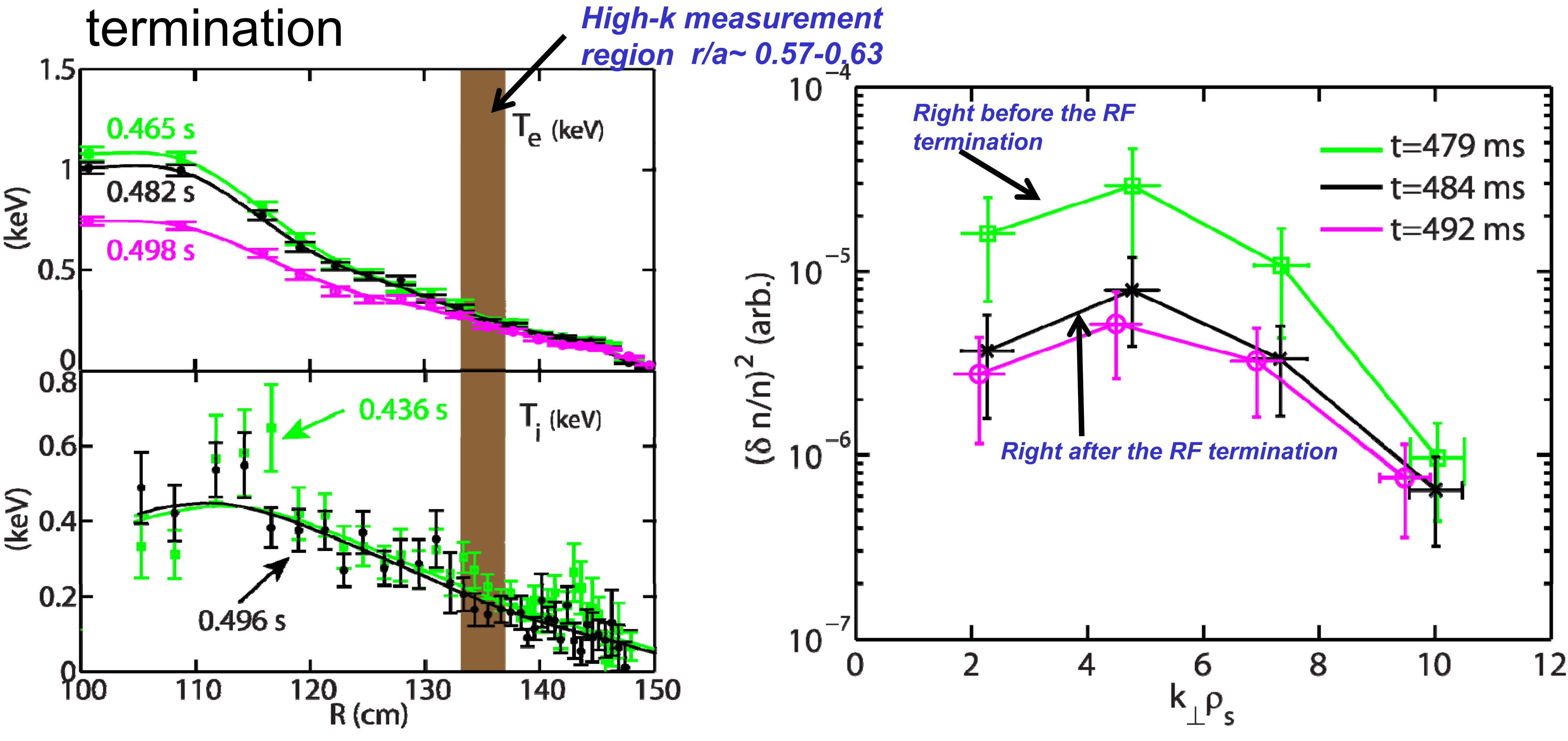
A Time Delay Exists between the Drop in Spectral Power and the RF Termination



- Spectral power decreases within 500 μs - 1ms and the delay time is about 1-2 ms
- What causes this drop in spectral power and time delay?

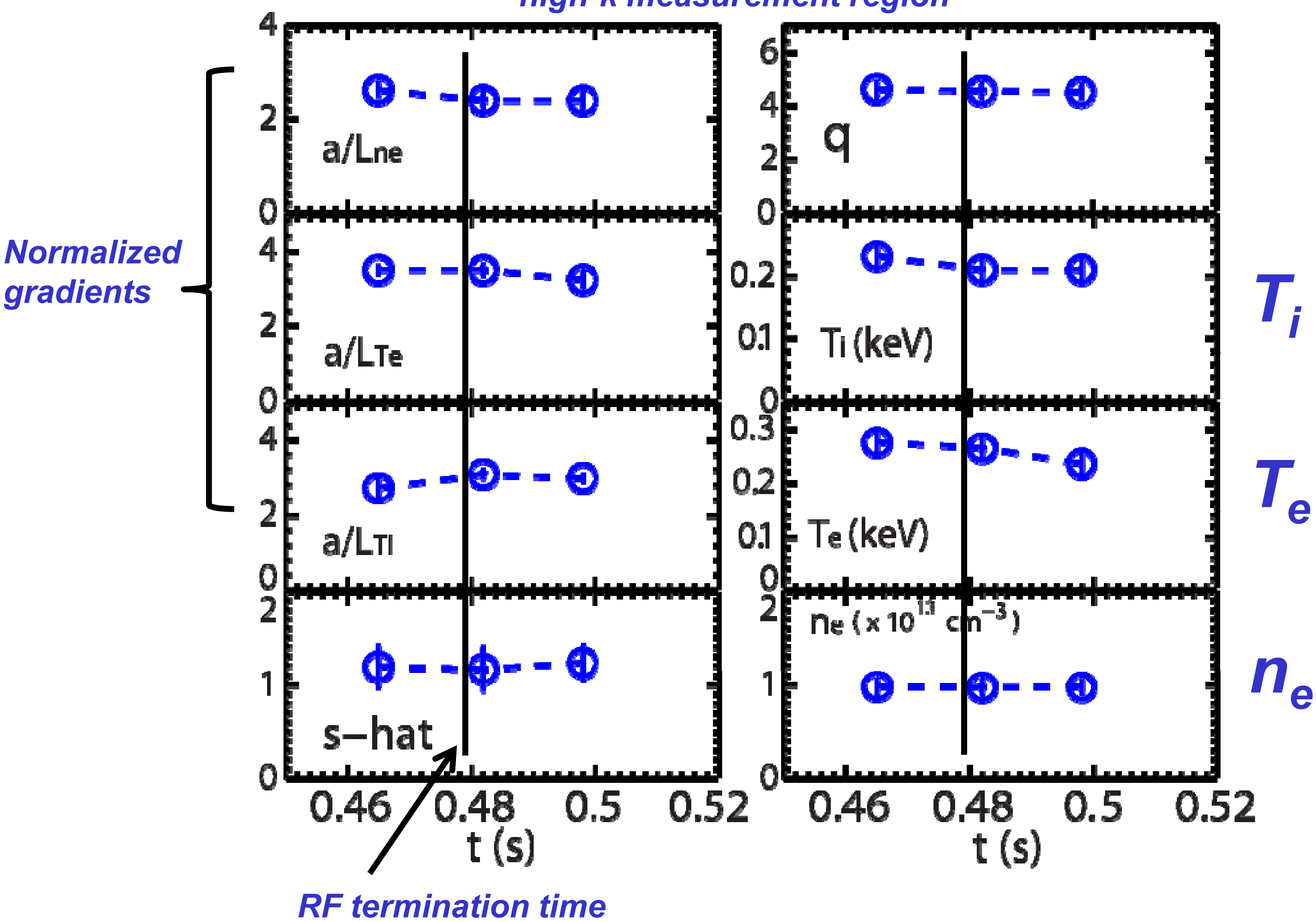
The Drop in High-k Spectral Power may not be Due to T_e and Ti Profile Changes

- T_e profile with small changes before and right after the RF termination
- T_i profile almost invariant from 436 ms to 496 ms
- Up to 7 times drop in High-k spectral power right after the RF termination

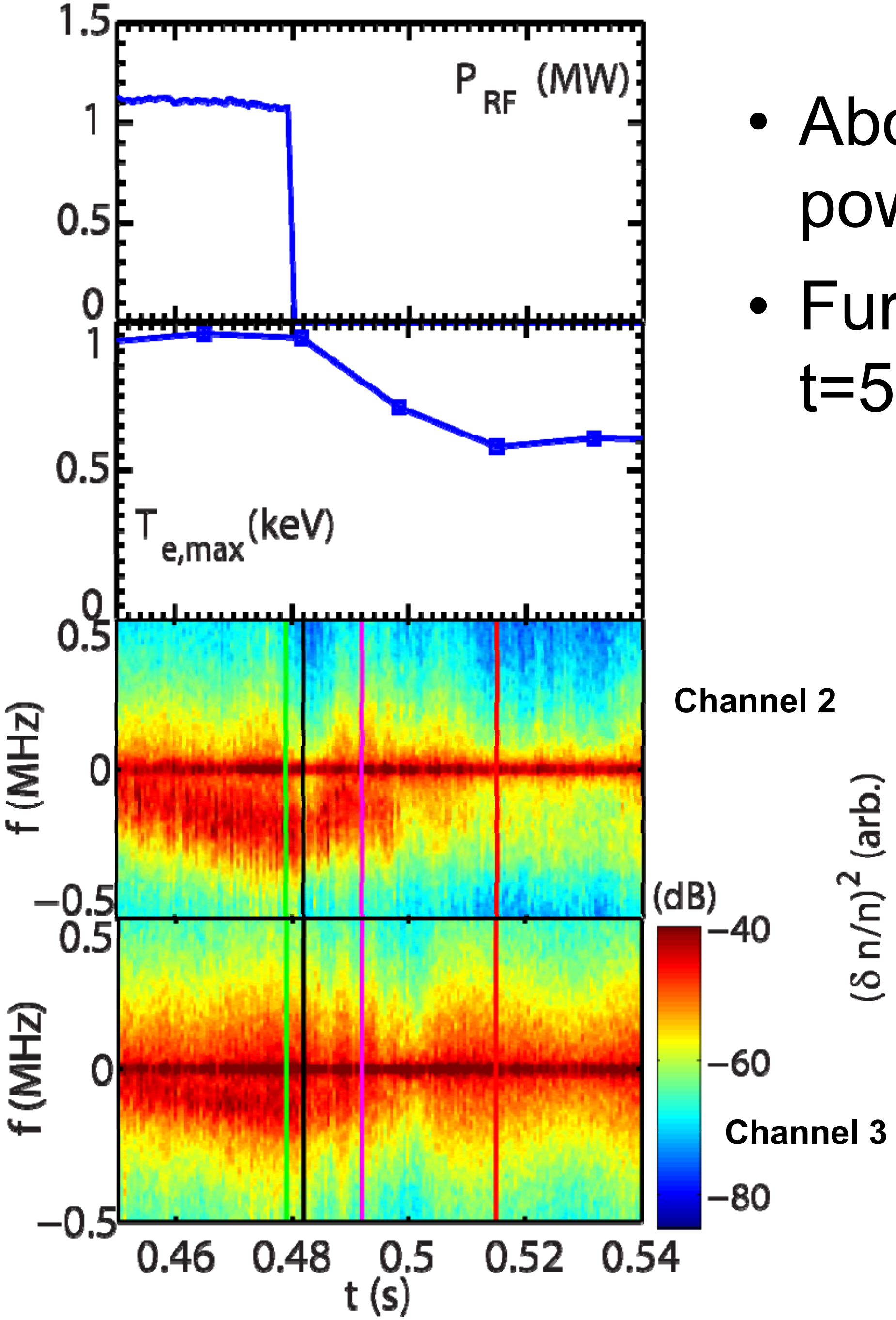


Local Equilibrium Quantities Show Small Changes around the RF Termination Time

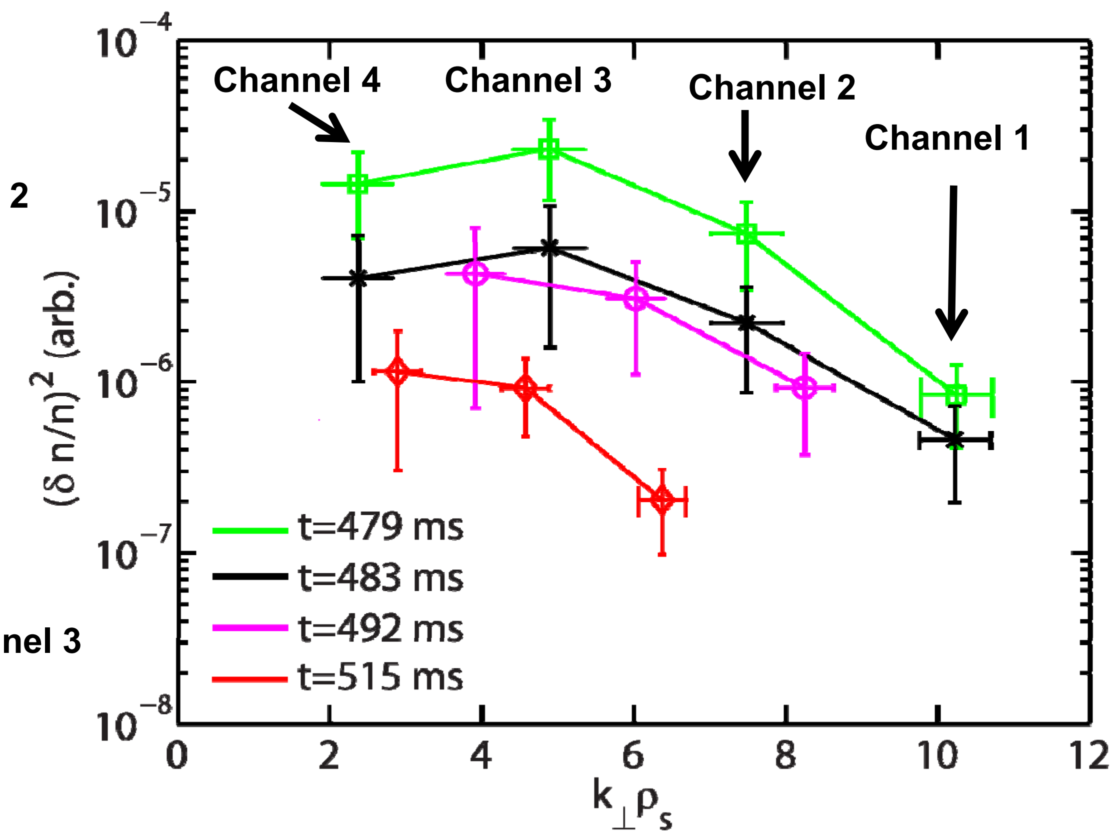
Quantities averaged in the high-k measurement region



Another Similar Observation with RF Termination

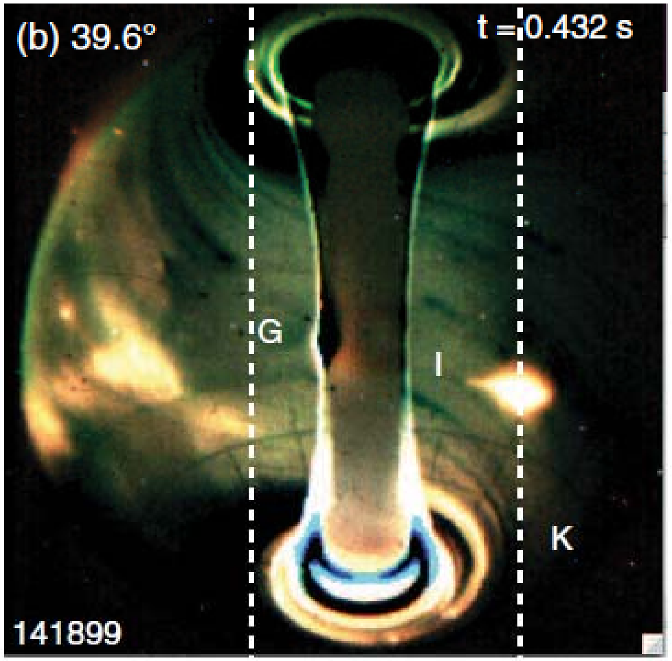


- About 3 times drop in high-k spectral power right after the RF termination
- Further drop in high-k spectral power at t=515 ms



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

Methods to Determine the Coupled RF Heating Power

- Using the change in stored energy during the RF turn-on and turn-off phases
  - No way to determine coupled RF heating power during steady-state phase
  - Need to assume transport does not change
- The global power balance equation for the RF turn-on phase:

$$\frac{dW_{stored}}{dt} = P_{RF} + P_{Ohmic} - P_{loss} \quad \Longrightarrow \quad \frac{dW_{stored}}{dt} \leq P_{RF} \text{ with } P_{loss} \geq P_{Ohmic}$$

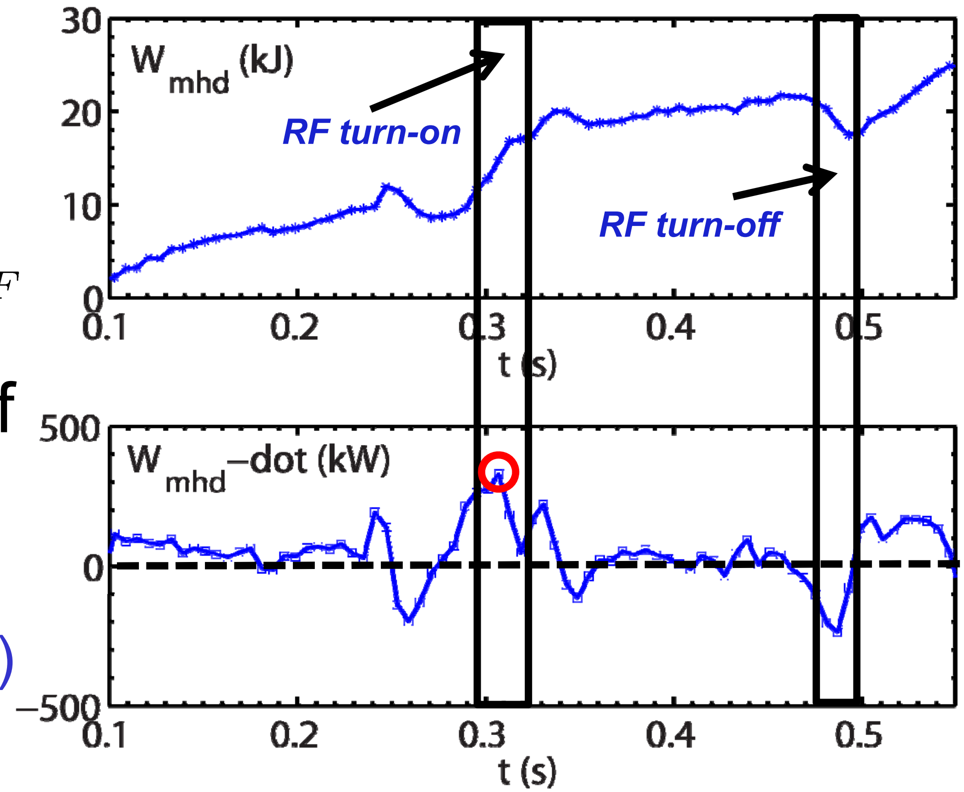
- For the turn-of phase:

$$\frac{dW_{stored}}{dt} = P_{Ohmic} - P_{loss}$$

$$\Longrightarrow$$

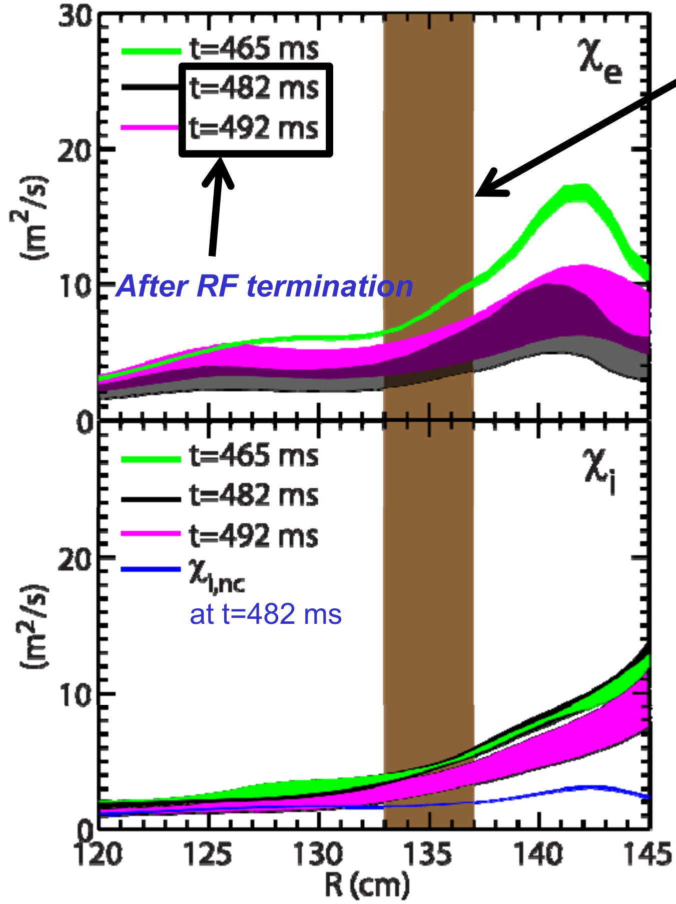
$$\left|\frac{dW_{stored}}{dt}\right| \leq P_{RF} \text{ with } P_{loss} - P_{Ohmic} \leq P_{RF}$$

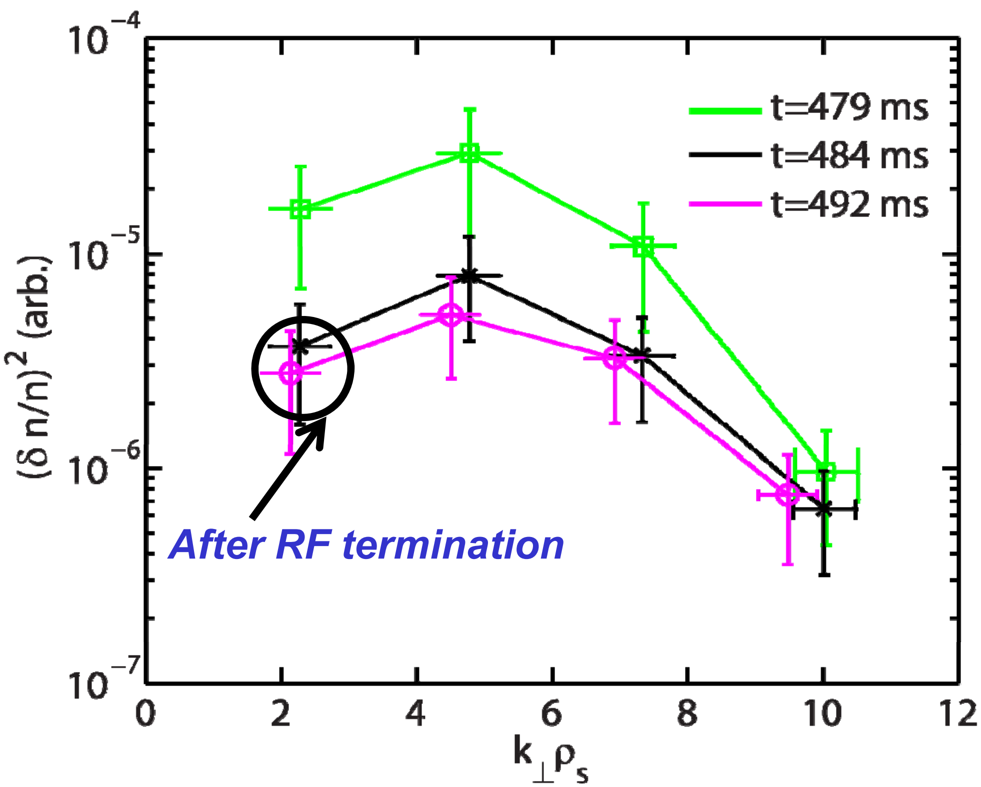
- Thus dw/dt can give an estimate of lower bound of the P_{RF}
  - P_{RF} is set to the largest dw/dt in the turn-on and turn-off phases (~ 300 kW)



High-k Spectral Power is Correlated with Electron Thermal Diffusivity

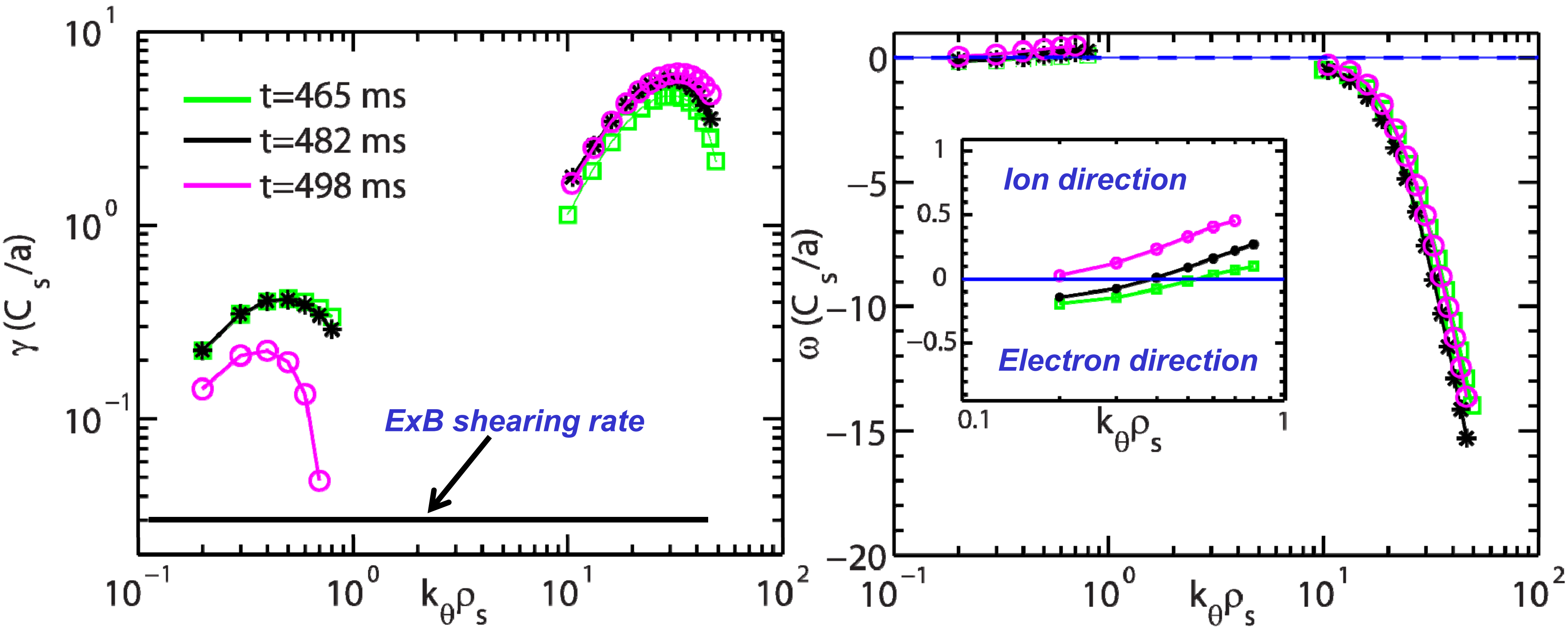
- About a factor of 2 decrease in electron thermal diffusivity after the RF termination.
  - Correlated with the decrease in high-k spectral power
- Ion diffusivity showing smaller changes
  - Anomalous at R>130 cm





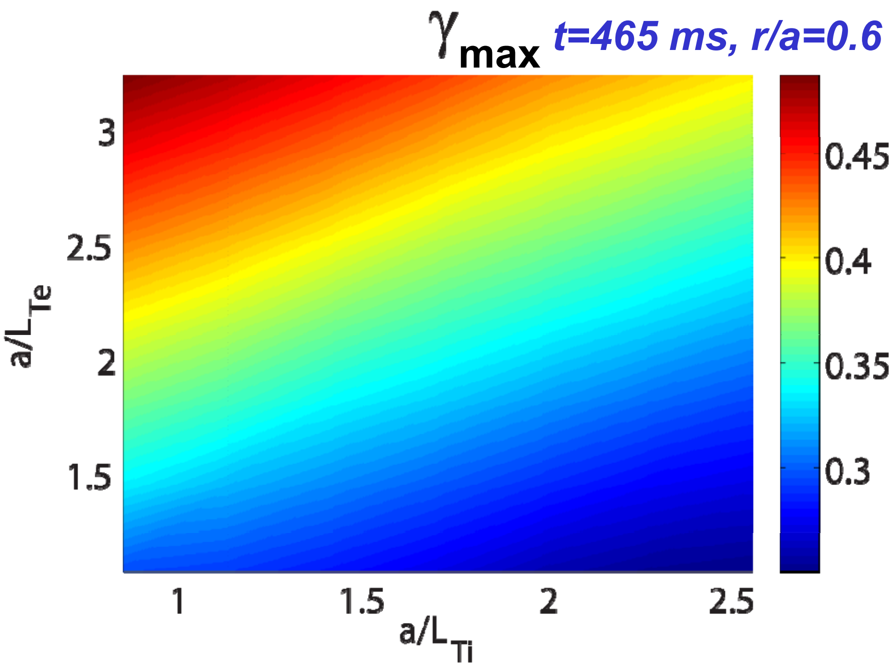
Linear Stability Analysis Shows that ITG/TEM and ETG modes are Unstable

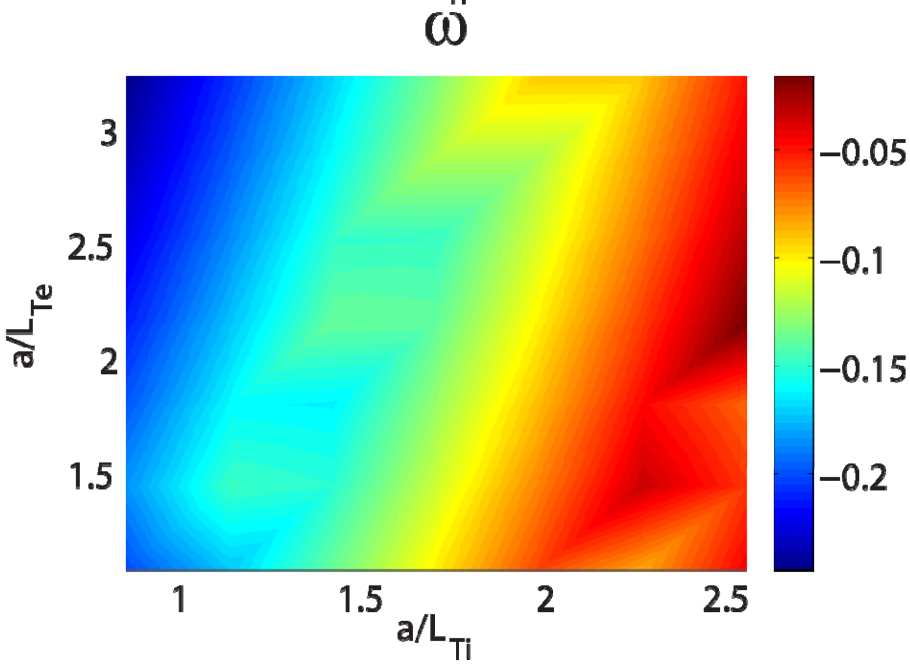
- Ion scale modes are ITG/TEM hybrid
  - Growth rate similar between t=465 and 482 ms; more like ITG at 498 ms
- ETG mode maximum growth rates increase from t=465 to 498 ms
  - Inconsistent with the drop in the measure high-k spectral power
  - Ideally need to compare growth rates between t=479 and 482 ms



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

ITG/TEM and ETG Modes are Robustly Unstable





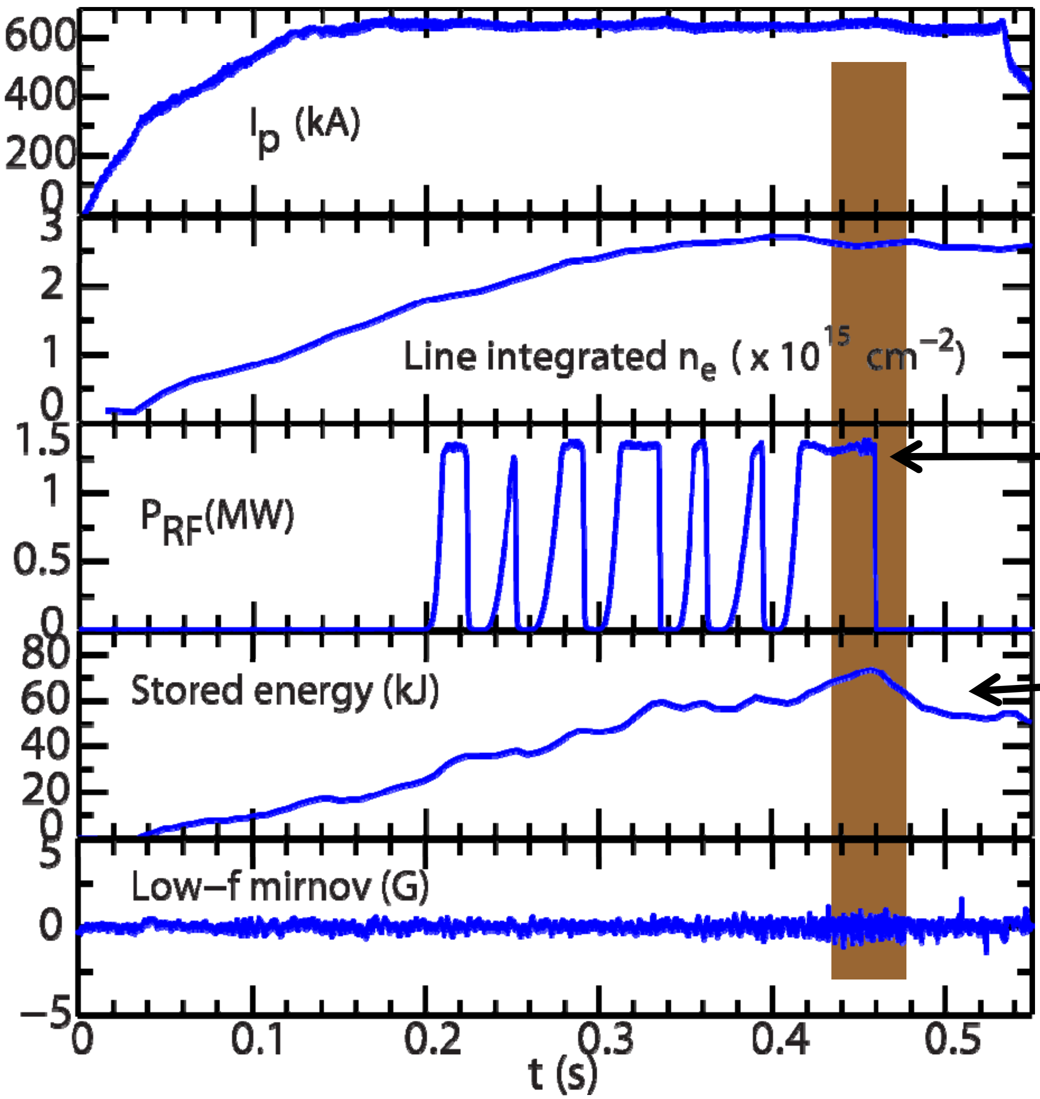
- T_e/T_i gradients are scanned
  - Gradient scans carried out with β' kept fixed for ITG/TEM modes but not for ETG modes
- The ion-scale modes are driven by both electron and ion temperature gradients
  - $a/L_{Te,exp}=3.6$
  - $a/L_{Ti,exp}= 2.83$
- ETG modes critical a/L_{Te} is determined to be 2.1 ($a/L_{Te,exp}=3.6$) from T_e gradient scan
- Investigation of s, q, T_e/T_i and Z_{eff} effects is in progress

RF Termination in RF-heated L-mode Plasmas with Higher Current is also Studied

I_p=600 kA

Shot=141805

RF-heated L-mode plasma (He) with B_T =5.5 kG



Time range of interest: around the RF heating termination at t=459.2 ms

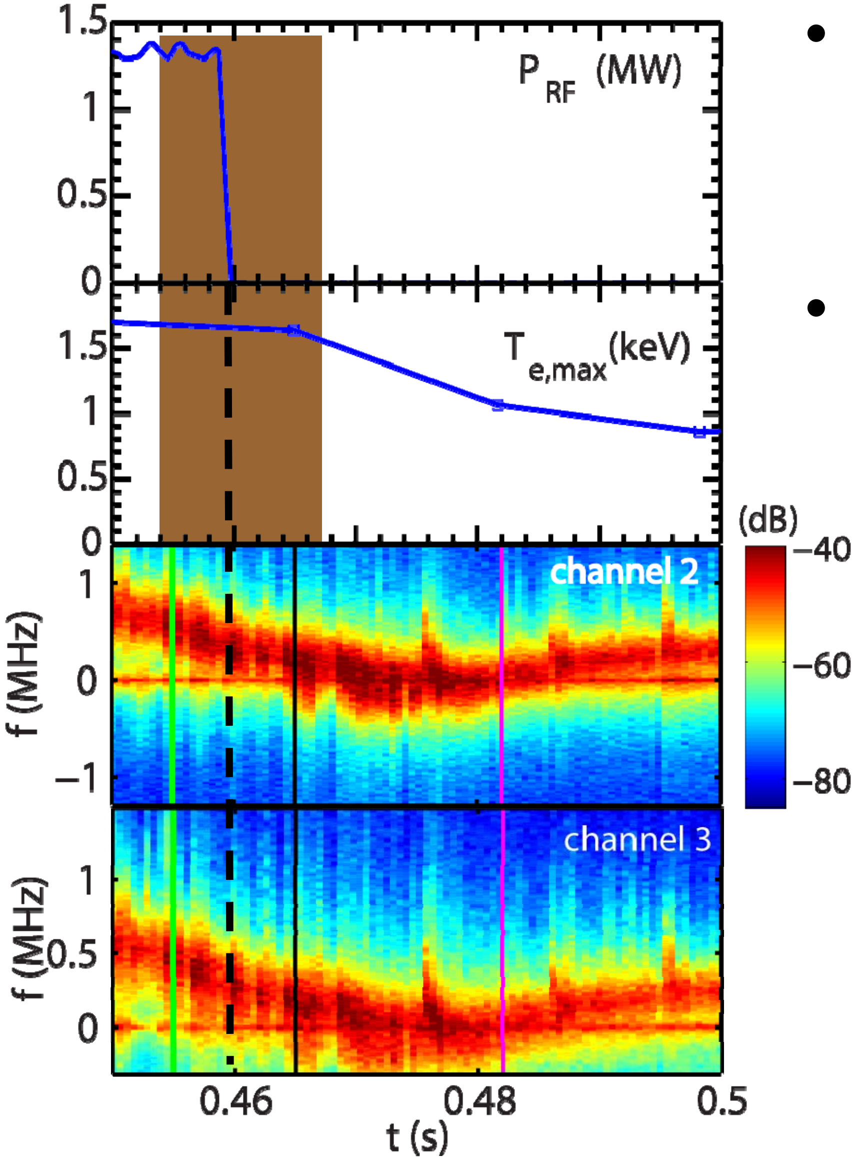
From EFIT02

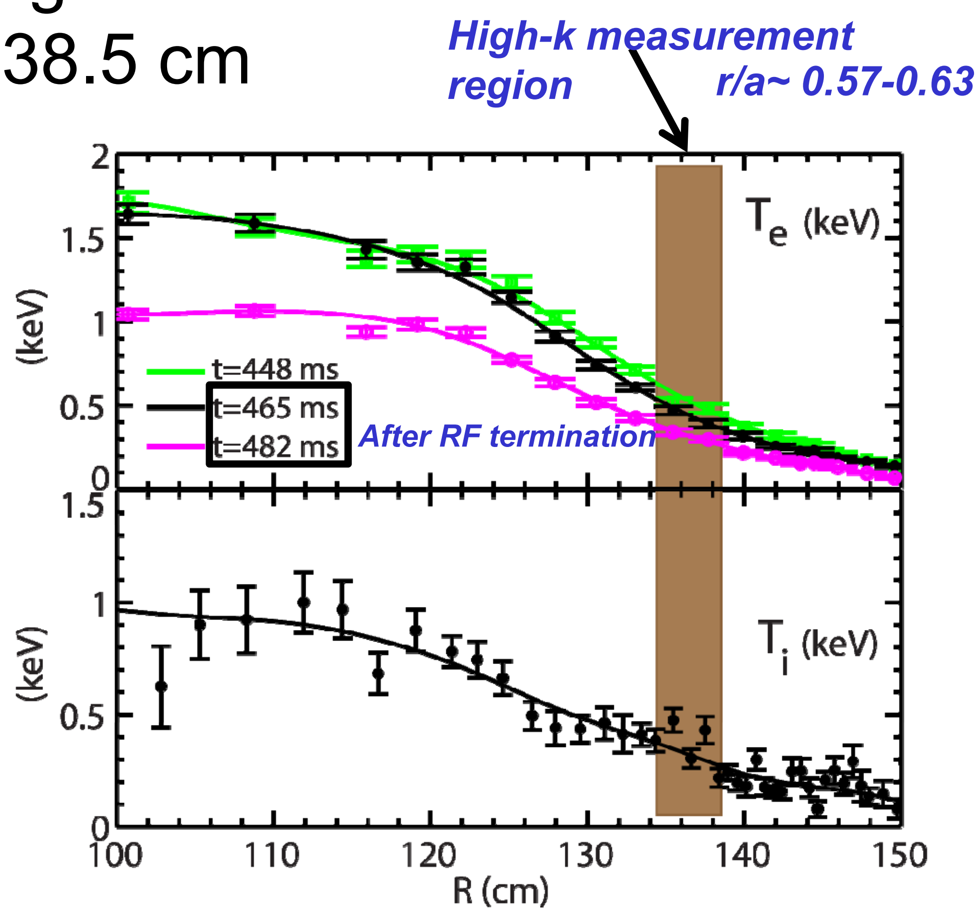
Decrease in stored energy following the RF termination

Small MHD activities

Frequency Spectral Power from the High-k Scattering System Shows no Obvious Drop Following the RF Termination

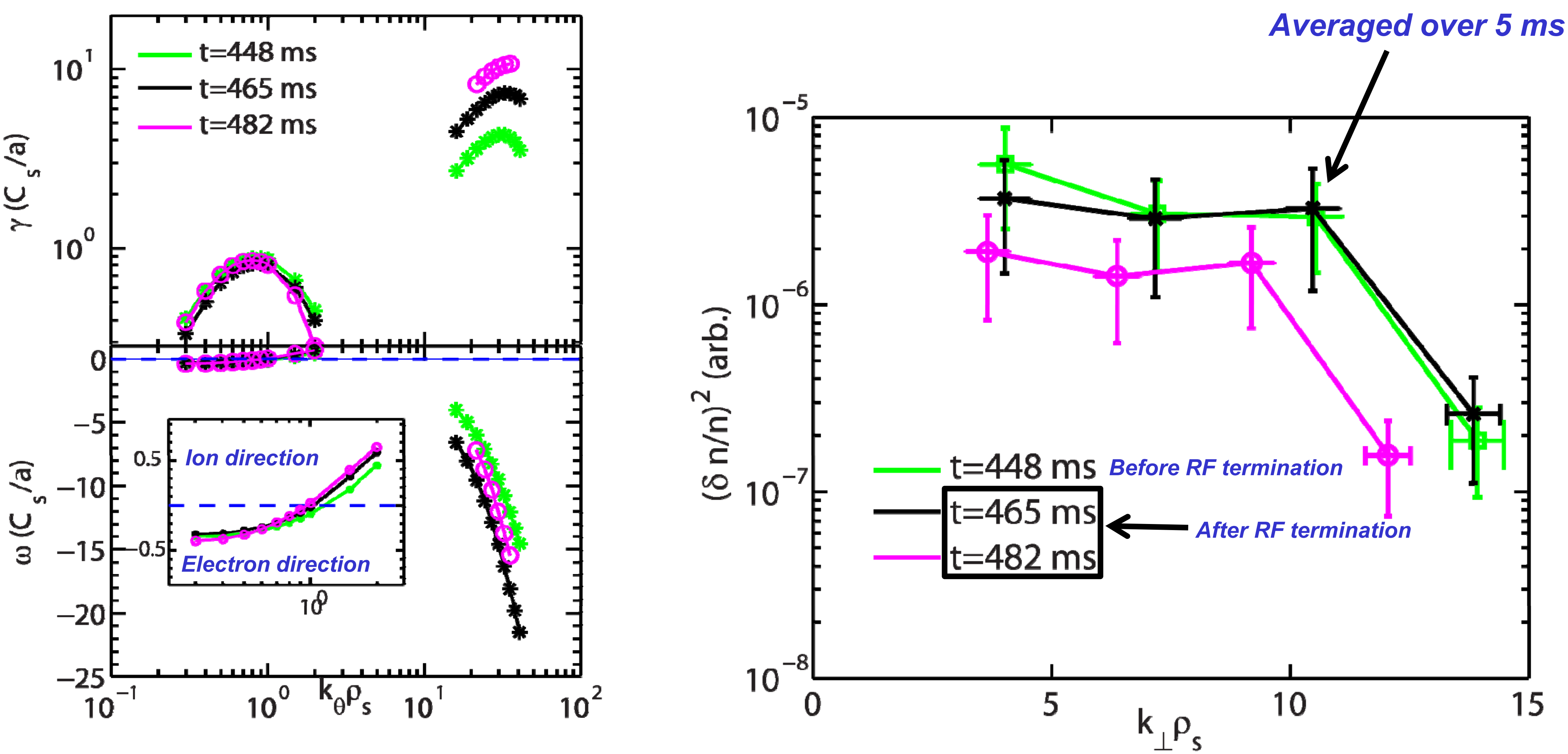
- T_e Drops after the RF termination
- Frequency spectral power remains large after the RF termination
- High-k measurement R=134.5-138.5 cm





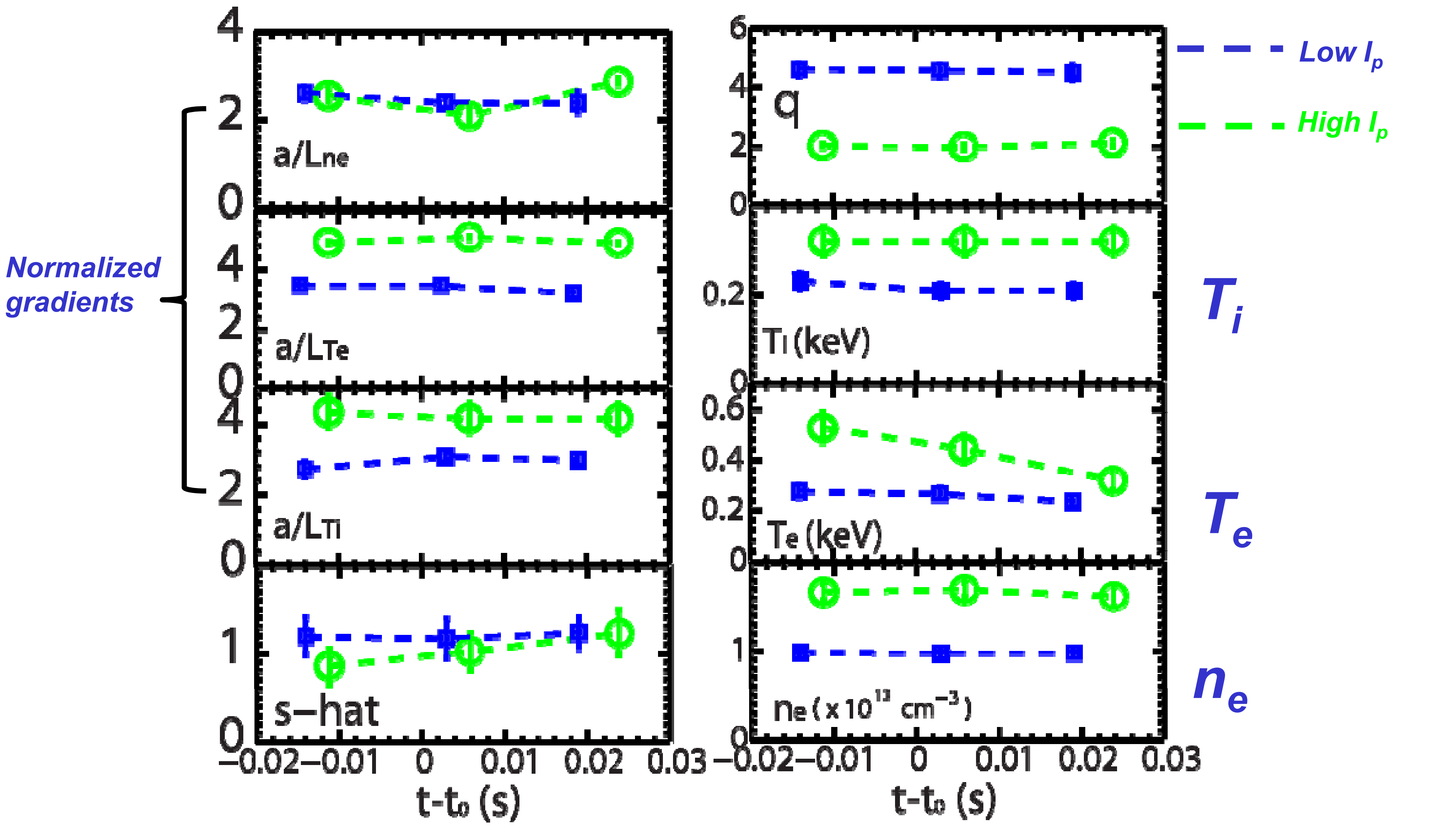
Linear Growth Rate Trend is not Consistent with the Observed High-k Spectra Variation

- A factor of 3 increase in ETG linear growth rate from t=448 to 482 ms
  - Much smaller change in ITG/TEM growth rate
- No change in measured high-k spectral power right after the RF termination and then a factor 3 drop at t=482 ms



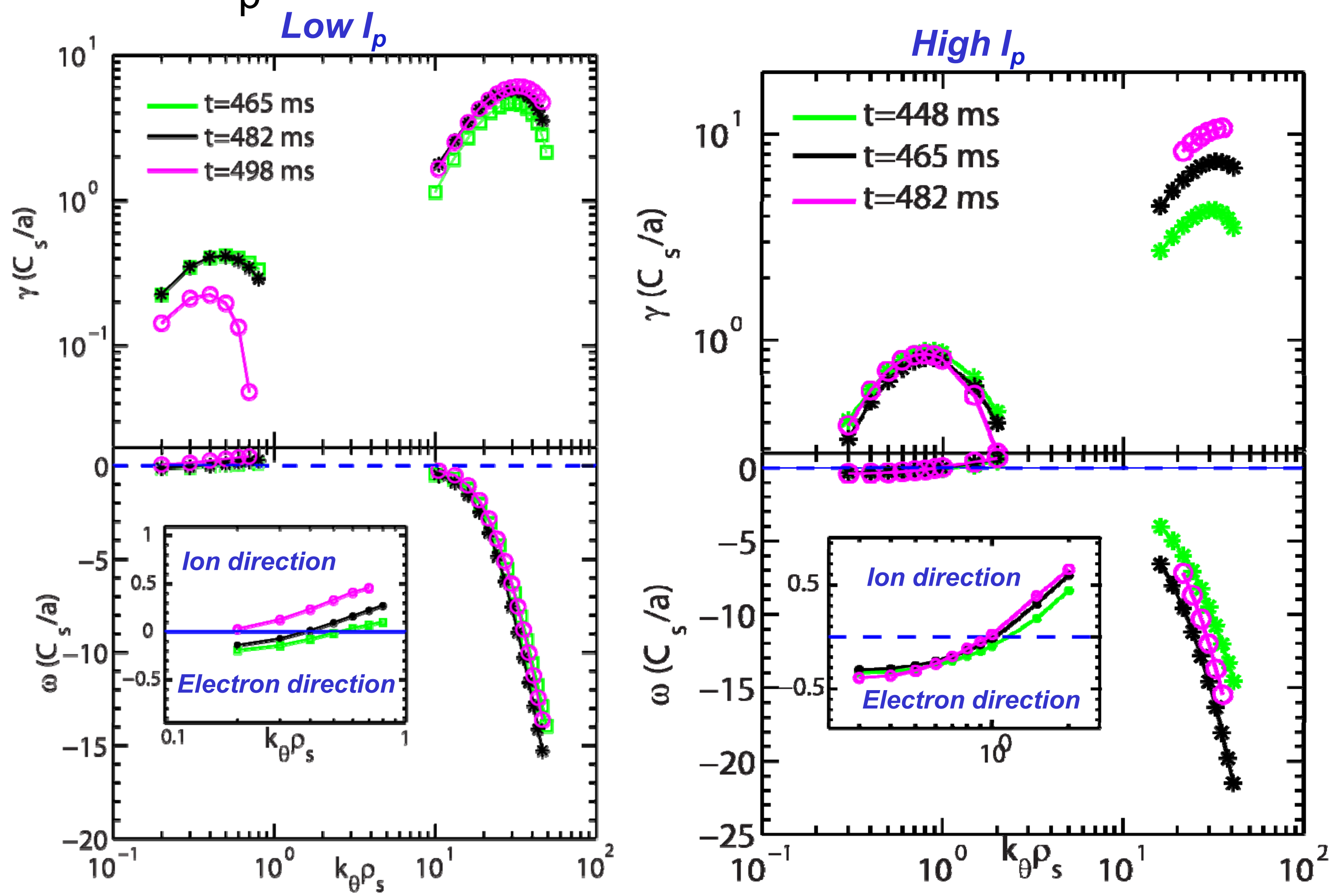
Compare Local Equilibrium Quantities of the Low Current (140301) and High Current (141805) L-mode

- The high current L-mode plasma has larger T_e and T_i gradients and lower q in r/a~ 0.57-0.63 than the low current shot



Compare Linear Growth Rates of the Low Current (140301) and High Current (141805) L-modes

- ITG/TEM and ETG growth rates are higher in the high I_p shot than in the low I_p shot
- TEM is more dominant in the low-k modes in the high I_p shot than in the low I_p shot



Summary

- Observed a correlation between RF termination and a fast drop in high-k spectral power in 300 kA NSTX RF-heated L-mode plasmas
  - A correlation between electron thermal diffusivity and high-k spectral power found with transport analysis from TRANSP coupled with TORIC
  - Unstable ITG/TEM and ETG mode found using GS2 code
  - The fast drop in high-k spectral power after RF termination is not correlated with the change in linear growth rates
- No obvious correlation in the 600 kA NSTX RF-heated L-mode plasma
  - Larger local T_e and T_i gradients than the low current shot
  - Larger ITG/TEM and ETG growth rate and TEM more dominant
- Nonlinear GK simulations planned to explain the observation
  - Flux driven simulations may be needed
- Results from a Global GTS simulation of NSTX NBI-heated L-mode plasmas show strong ExB shear stabilization

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