NSTX-U

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Response of Electron-scale Turbulence and Thermal Transport to Continuous ExB Shear Ramping-up in NSTX

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1. PPPL 2. U.C. Davis

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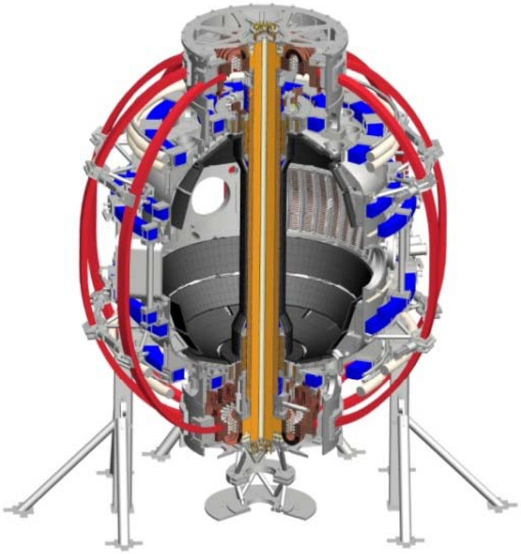

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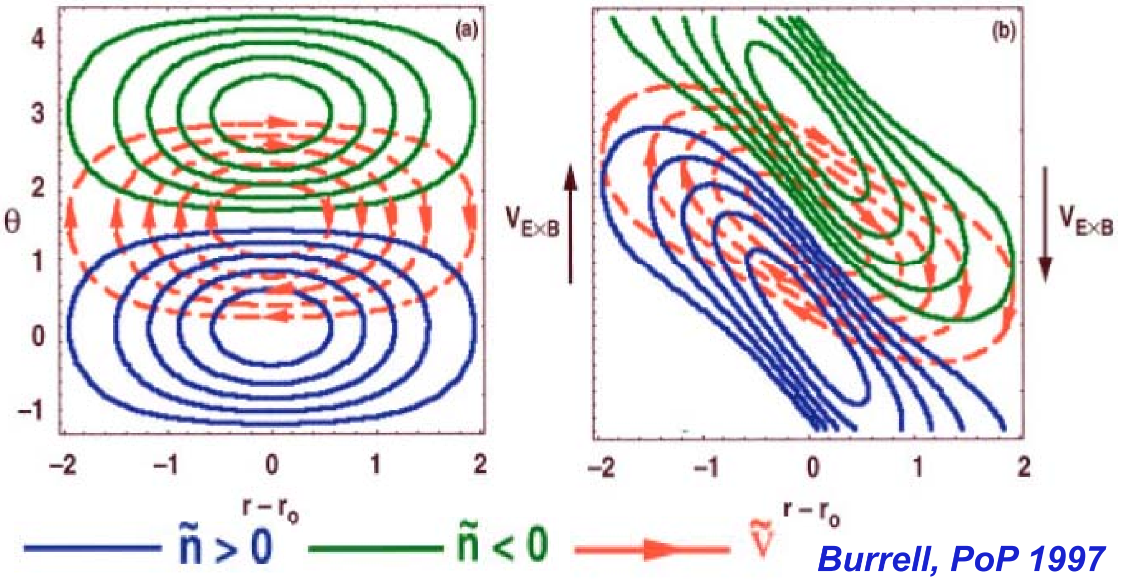
Highlights

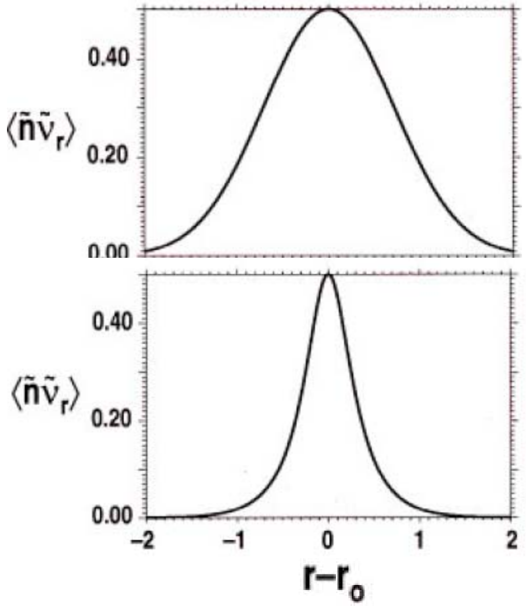
- Continuous ExB shear ramping-up driven by Neutral Beam Injection observed in a set of NSTX L-mode plasmas
  - H-mode-like confinement observed without forming a transport barrier
- Observed reduction in measured electron-scale turbulence and thermal transport in the core-edge transition region(r/a~0.66-0.78)
  - Correlated with the increase in ExB shear
  - Consistent with ExB shear stabilization of ITG turbulence
- Found both over- and under-prediction in thermal transport by nonlinear local ITG GK simulations around this transition region
  - Strong under-prediction at r/a=0.6
  - Strong over-prediction at r/a=0.71
  - Agreement within a factor of 2 with experiment at r/a=0.81
  - The energy transport shortfall at r/a>0.8 shows both similarity and difference with DIII-D results

ExB Shear can be a Powerful tool for Controlling Microturbulence in Future ST/ATs

- ExB shear affecting microturbulence and associated transport both linearly and nonlinearly (local theories)
  - Chang mode stability, e.g. enhance damping by coupling to stable modes
  - Change the relative phase between fluctuation quantities
  - Reduce fluctuation amplitude
- Example shown density and velocity perturbation with density as passive scalar convected by eddy velocity field



Burrell, PoP 1997



Without ExB shear

With ExB shear

How do We Define ExB Shearing Rate?

- Hahm-Burrell definition

$$\omega_{E\times B,HB} = \frac{(RB_\theta)^2}{B}\frac{\partial}{\partial\psi}\frac{E_r}{B_\theta R}$$

Hahm and Burrell, PoP 1995

  - Not a flux surface quantity
  - Clear physics meaning, i.e. directly related to the turbulence decorrelation rate at outer midplane
    - Turbulence decorrelation rate usually unknown
    - A rule of thumb: $\omega_{E\times B,HB} > \gamma_{max}$

- Waltz-Miller definition

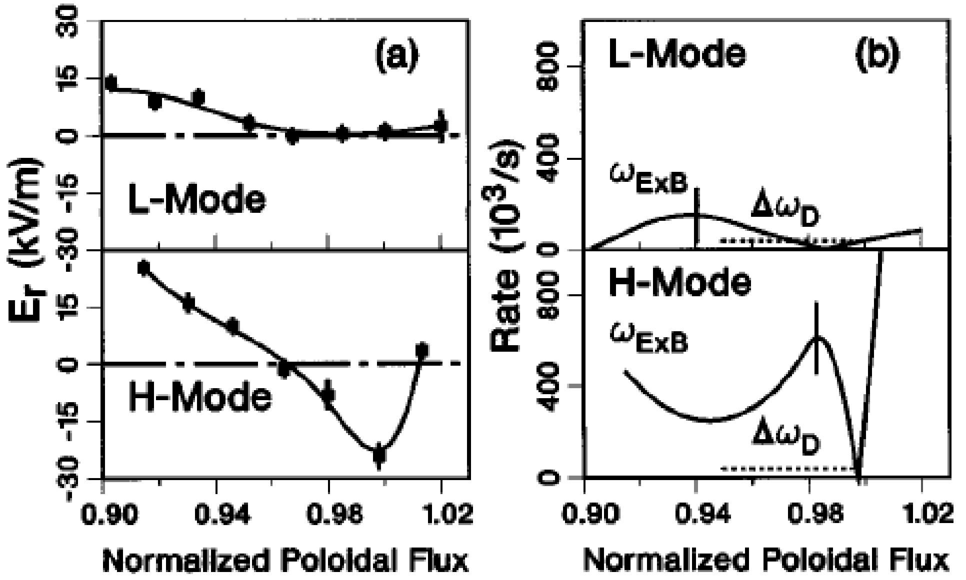
$$\omega_{E\times B,WM} = \frac{r}{q}\frac{d(E_r/B_\theta R)}{dr}$$

Waltz and Miller, PoP 1999

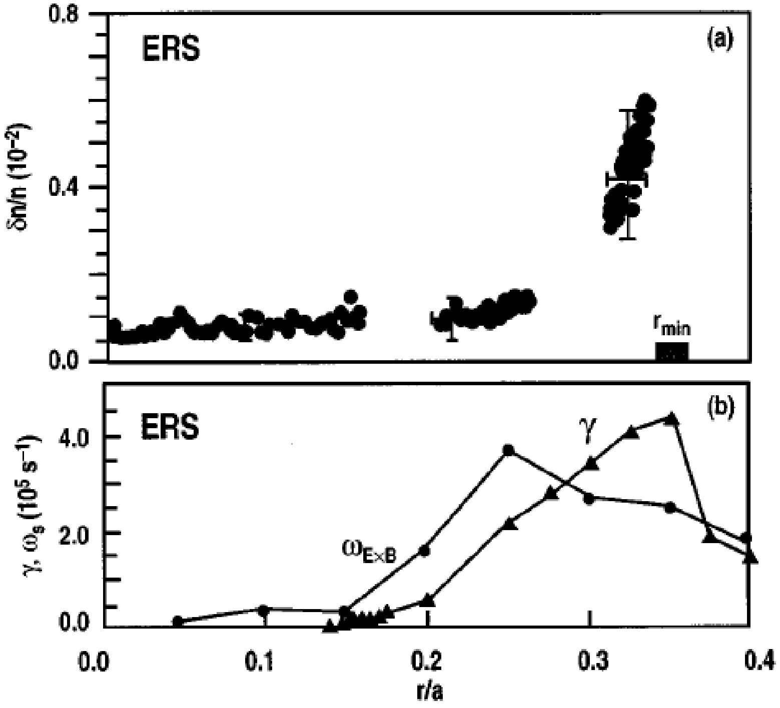
  - Flux surface quantity
  - Extensive quantitative comparisons with nonlinear gyrokinetic simulations
    - Quantitative quenching rule related to maximum linear growth rate studied
    - Critical $\omega_{E\times B}/\gamma_{max}$ found as a function of aspect ratio and elongation: $1.41(A/3)^{0.6}/(\kappa/1.5)$ *Kinsey et al., PoP 2007*

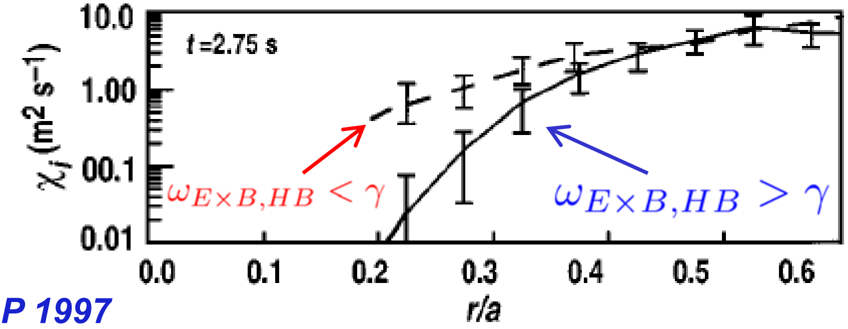
ExB Shear was Found to Correlate with Reduction in Transport and Turbulence

- H-mode edge transport barrier formation related to ExB shear
  - Deep E_r well formed in H-mode
  - ExB shearing rate much larger than turbulence decorrelation rate in H-mode
- Internal transport barrier formation consistent with ExB shear stabilization
  - Internal transport barrier and turbulence reduction location coincident with $\omega_{E\times B,HB} > \gamma$



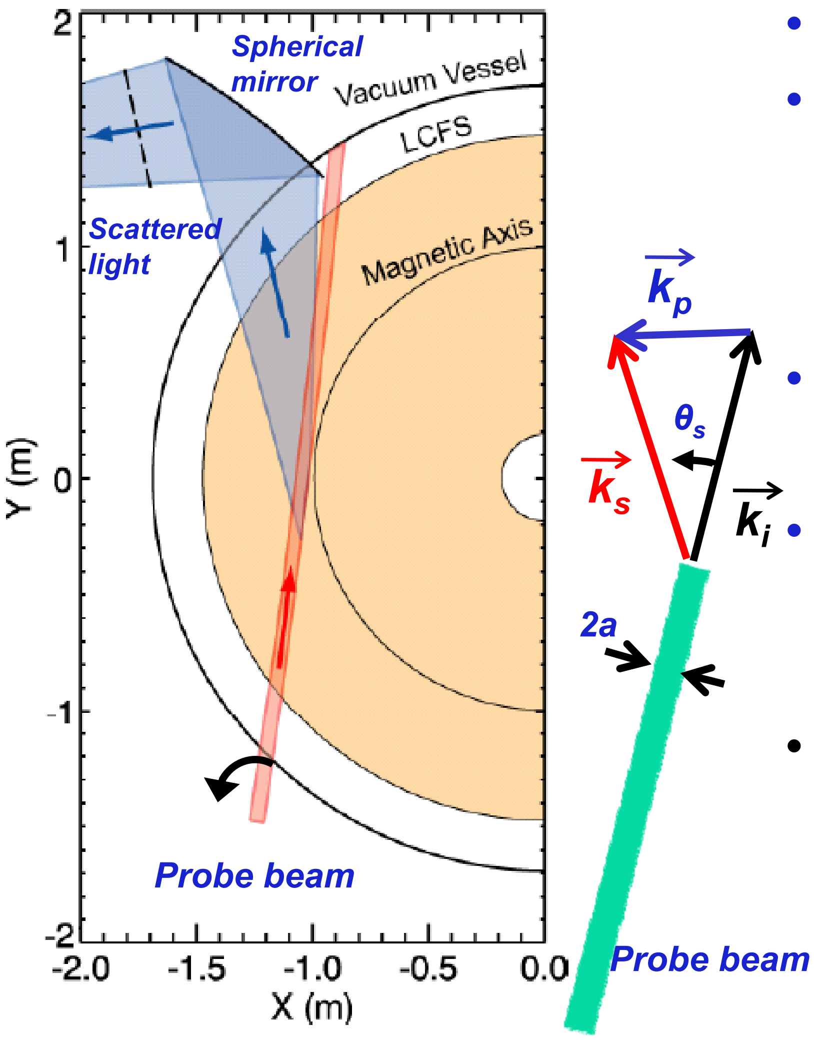
Ritz et al., PRL 1990





Burrell, PoP 1997

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



D.R. Smith, PhD thesis, 2009

- 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:

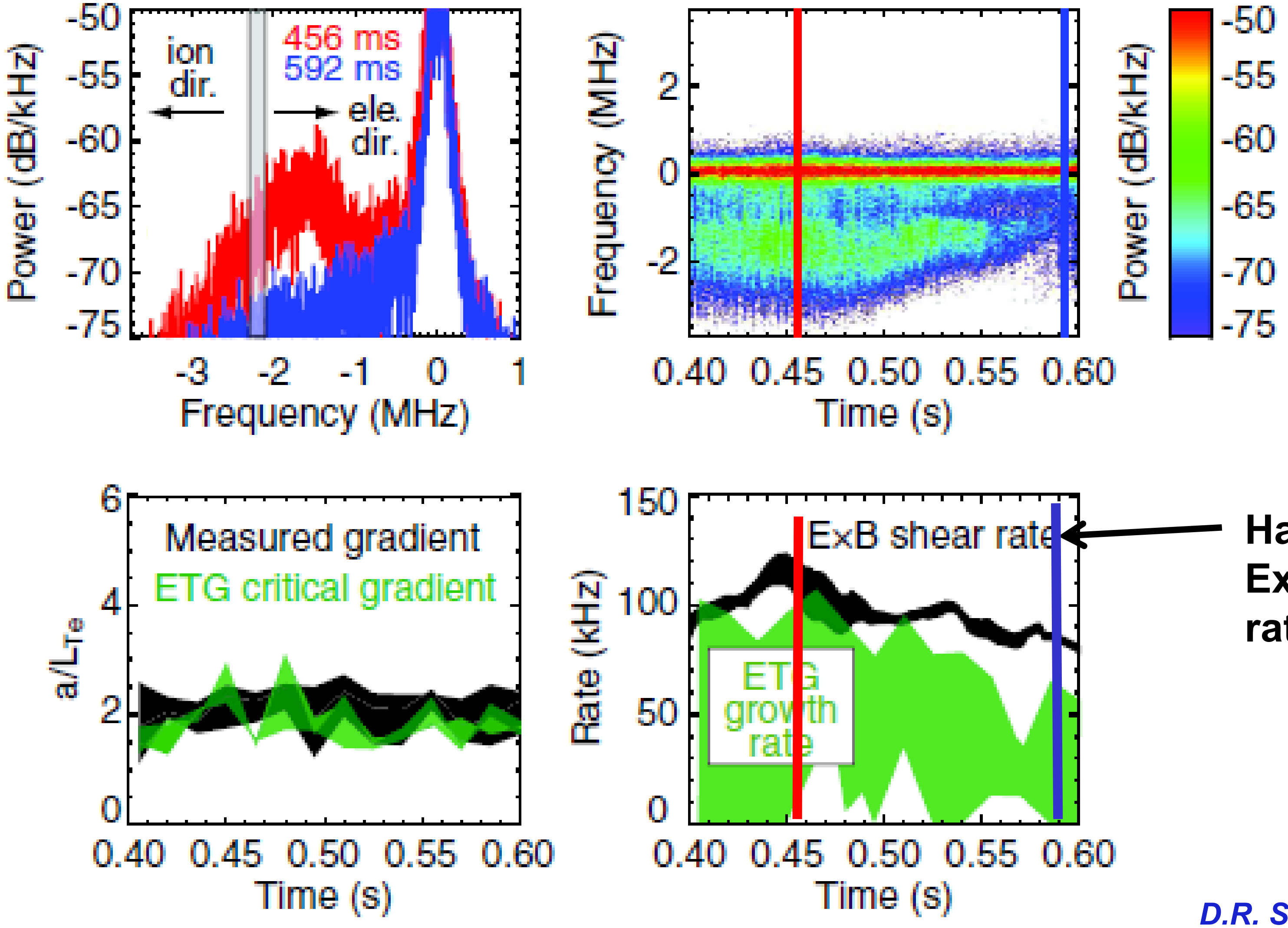
$$\omega_s=\omega_p+\omega_i$$

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:** $|\delta n_e(k)/n_e|^2 \approx 2\times10^{-11}$

Previous High-k Measurement is Consistent with ExB Stabilization of ETG Turbulence

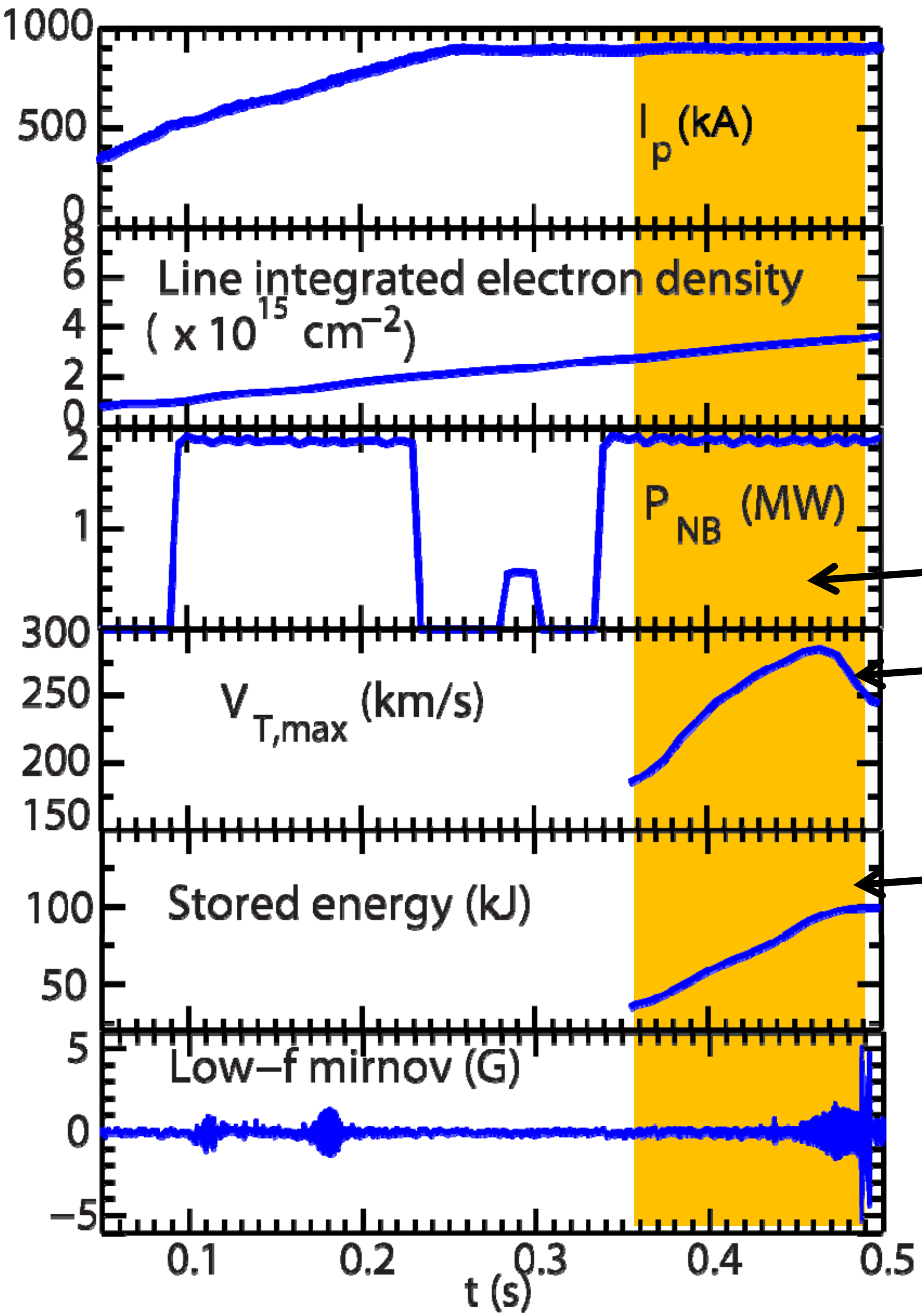
- The measured high-k turbulence power is shown to be reduced by ExB flow shear in NSTX H-mode plasmas



Hamh-Burrell ExB shearing rate

D.R. Smith et al., PRL 2008

Plasma Stored Energy Increases as Plasma Spins up in a Set of NSTX NBI-heated L-mode Plasmas



Shot=141716

Center-stack limited L-mode plasma with B_T =5.5 kG

Time range of interest

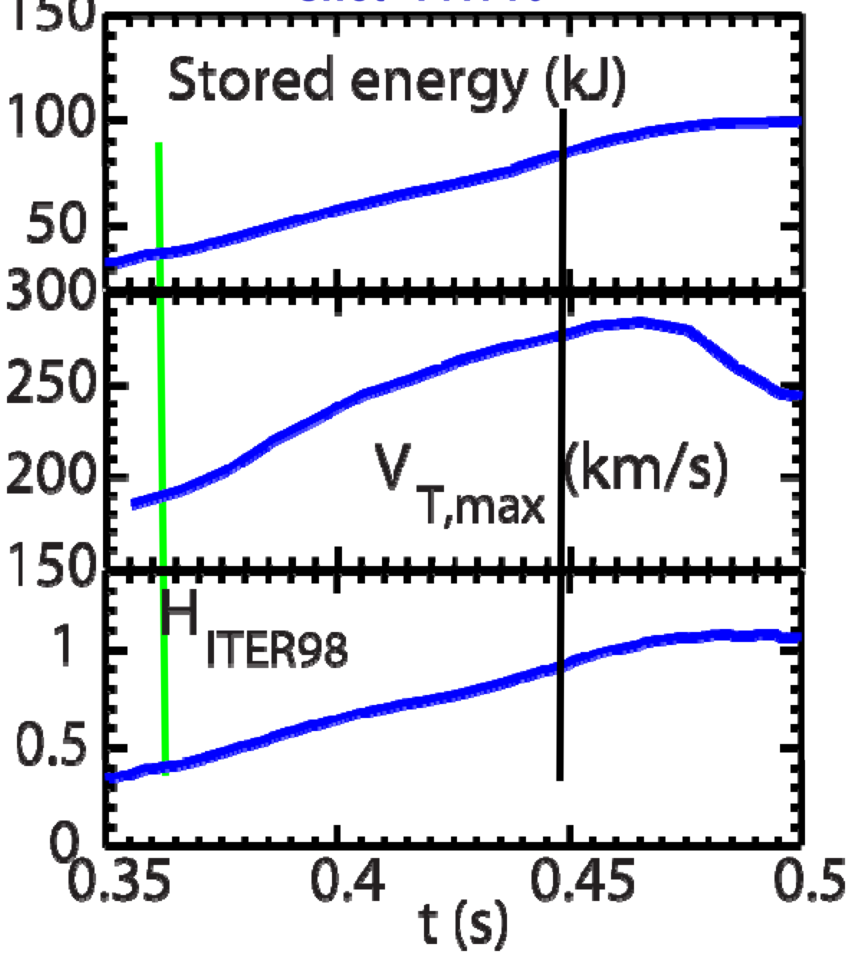
Measured by CHERS

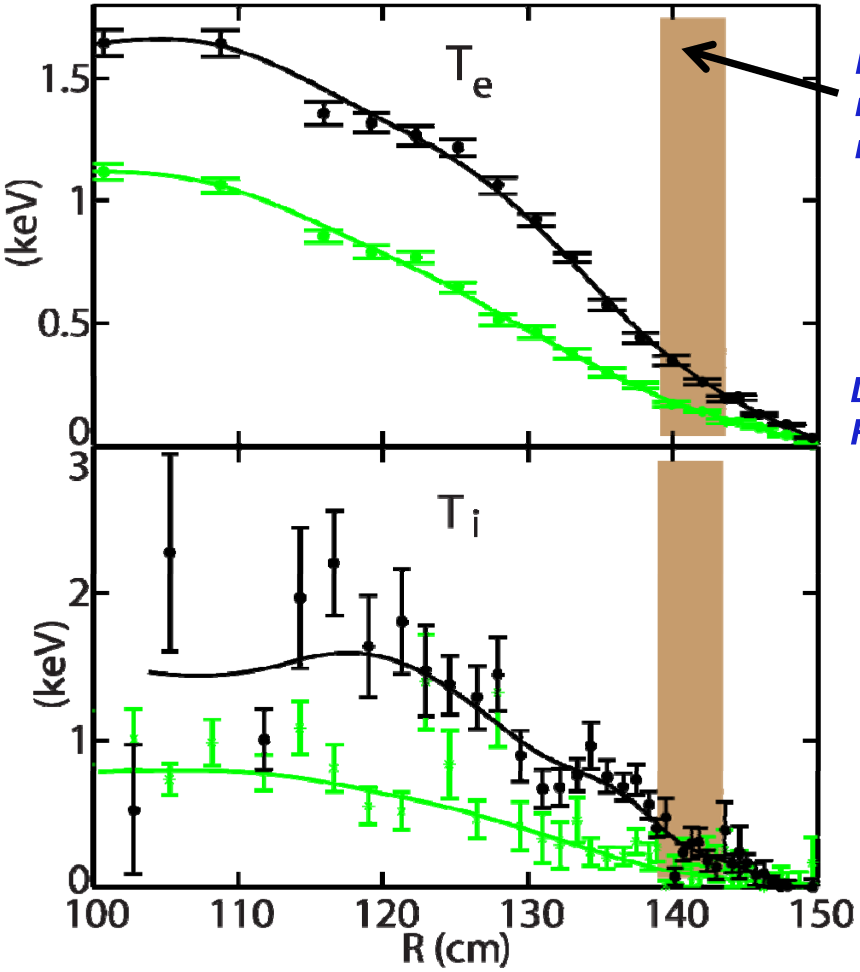
From TRANSP

L-mode Plasma Confinement Reaches that of the H-mode of Conventional Tokamaks

- Both T_i and T_e increase as plasma toroidal velocity increases
- No formation of a transport barrier is observed

Shot=141716

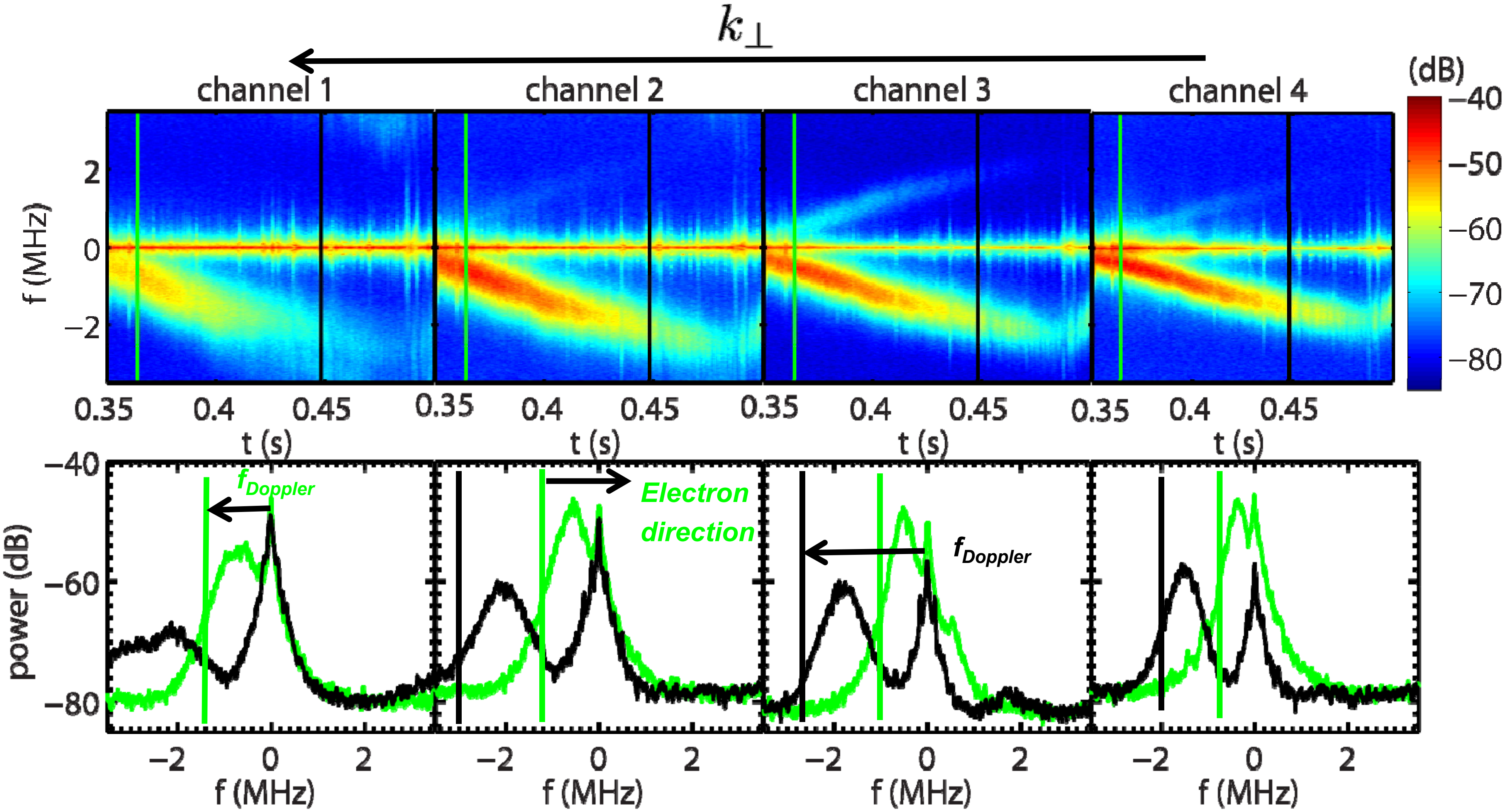




High-k measurement region

LCFS at R=151 cm

All Channels Saw Decreased Scattering Power as Plasma Spins up



- Plasma rotation leads to large Doppler frequency

Mode Frequency is Obtained by Removing Toroidal-Rotation-induced Doppler Frequency

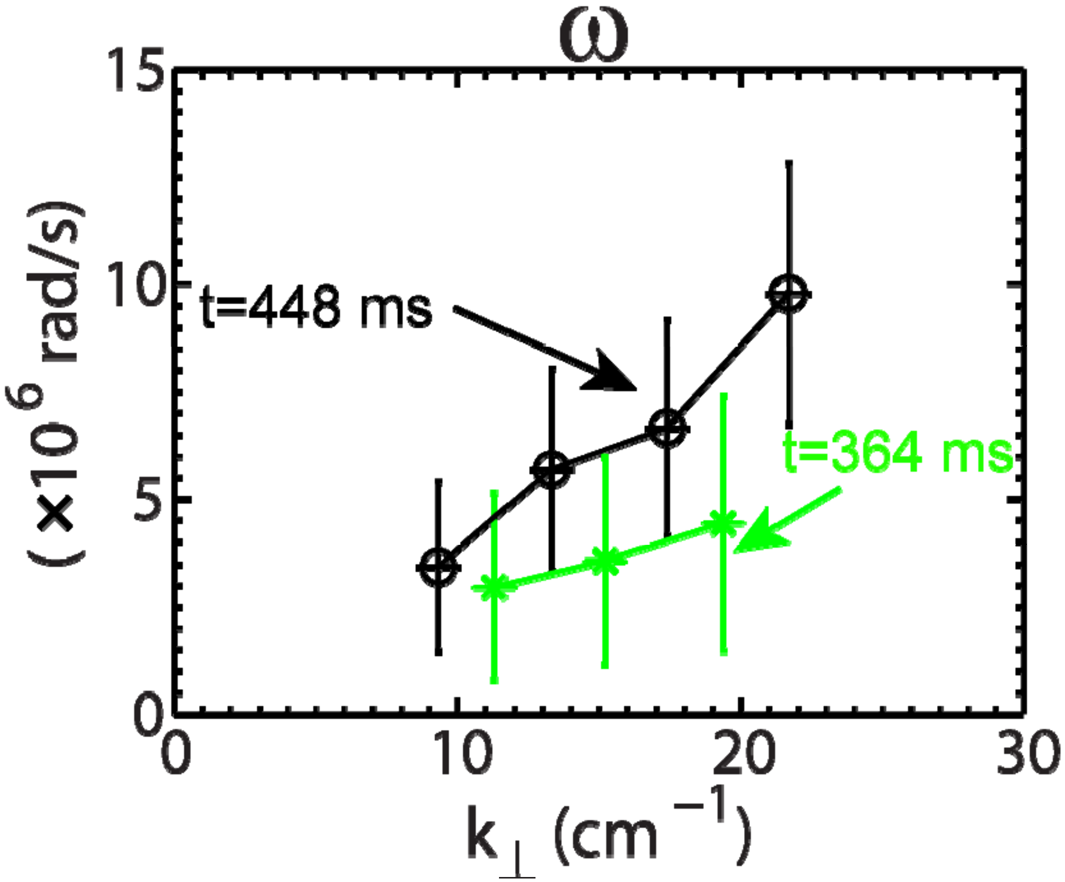
$$\omega = \left|\omega_{Lab} - k_T V_T\right|$$

Mode frequency in plasma rest frame

Spectral peak frequency measured in the lab frame

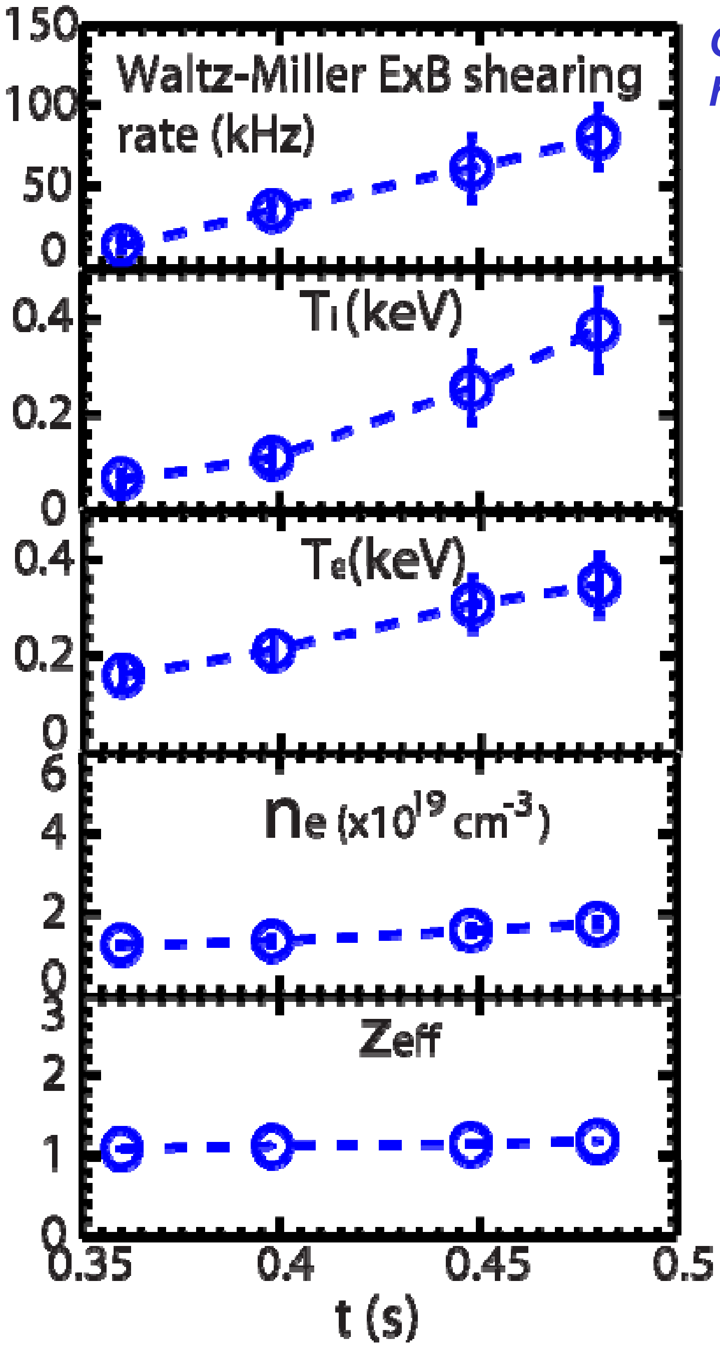
From Ray tracing

From CHERS measurement



- Mode frequency larger at t=448 ms, particularly at larger wavenumbers

Some Dimensional Quantities have Large Increase in the High-k Measurement Region



Quantities averaged in the high-k measurement region

- A factor of 6 for the ExB shearing rate
- A factor of 5 for T_i
- A factor of 2 for T_e
- Small change in Z_{eff} and n_e

Normalized Mode Dispersion Relations Show Little Change with Increased ExB Shearing Rate

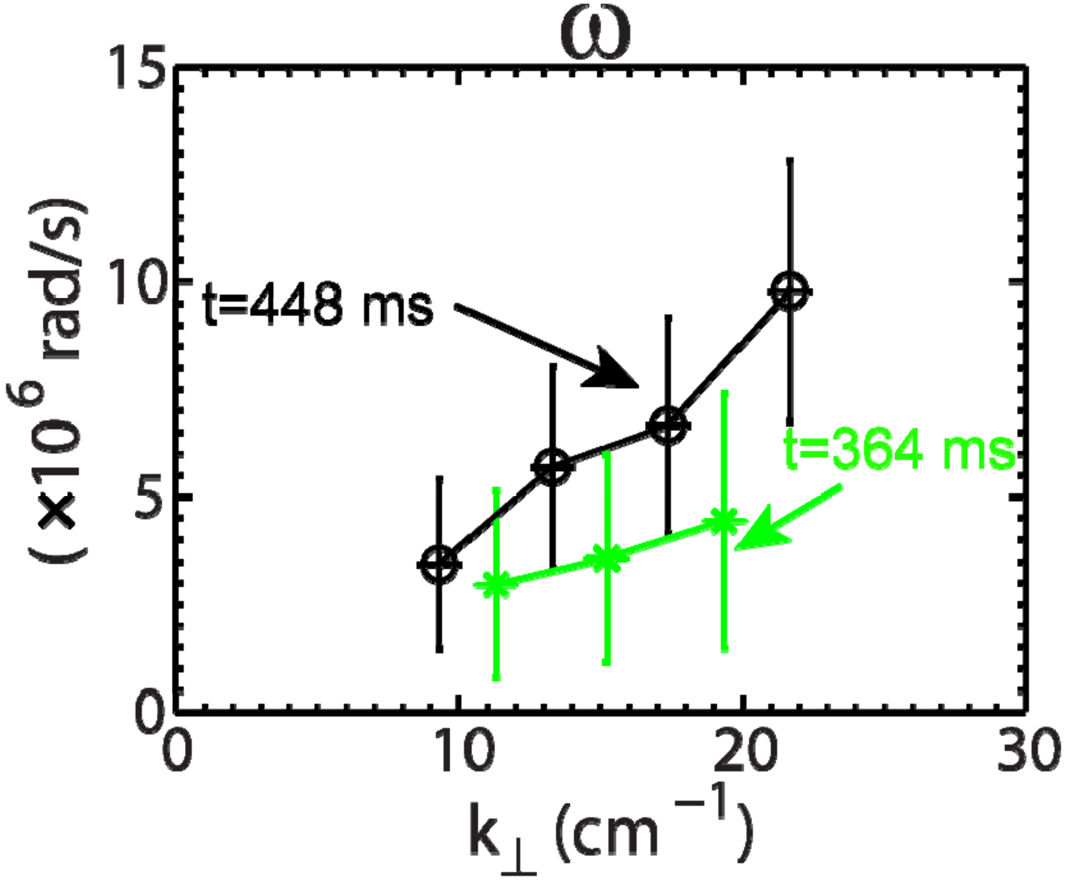
$$\omega = |\omega_{Lab} - k_T V_T|$$

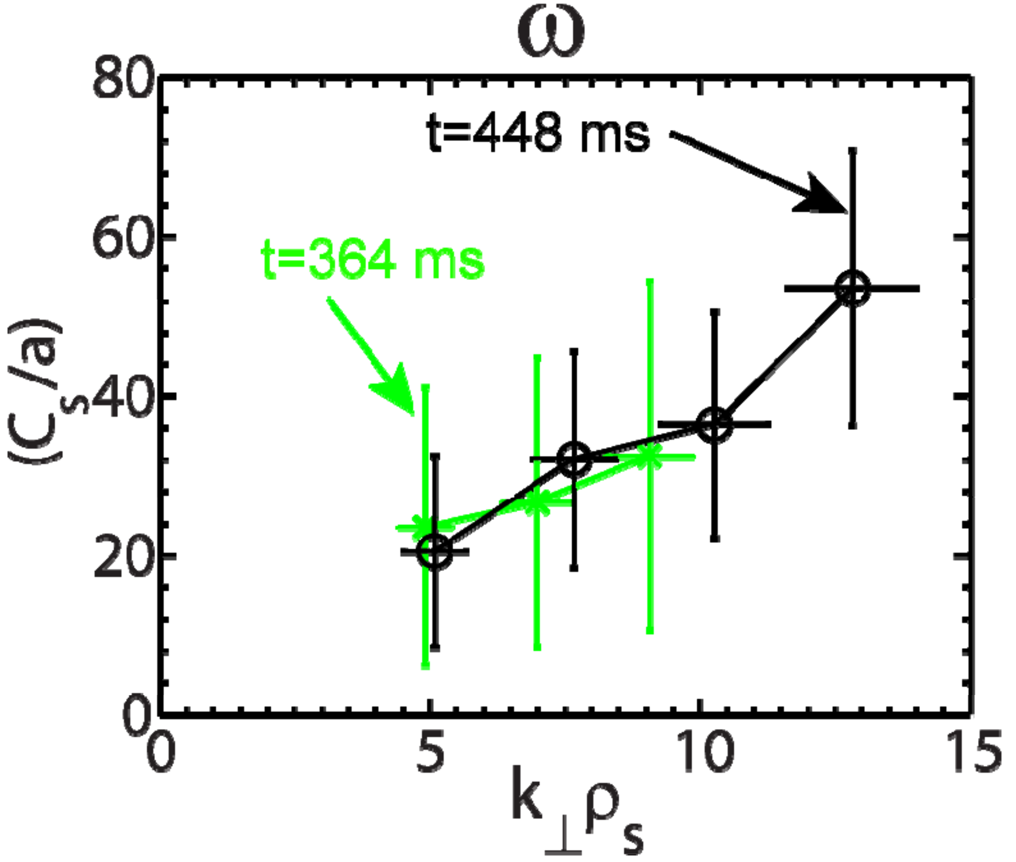
Mode frequency in plasma rest frame

Spectral peak frequency measured in the lab frame

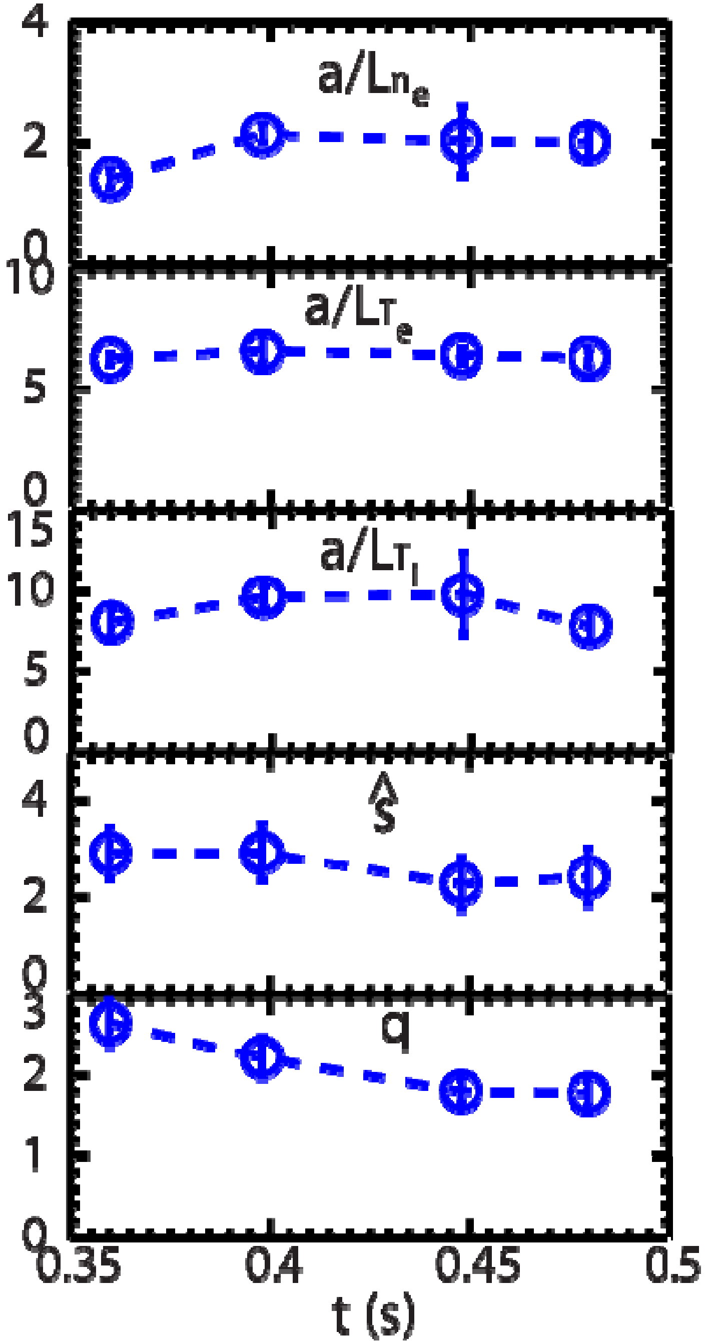
From Ray tracing

From CHERS measurement





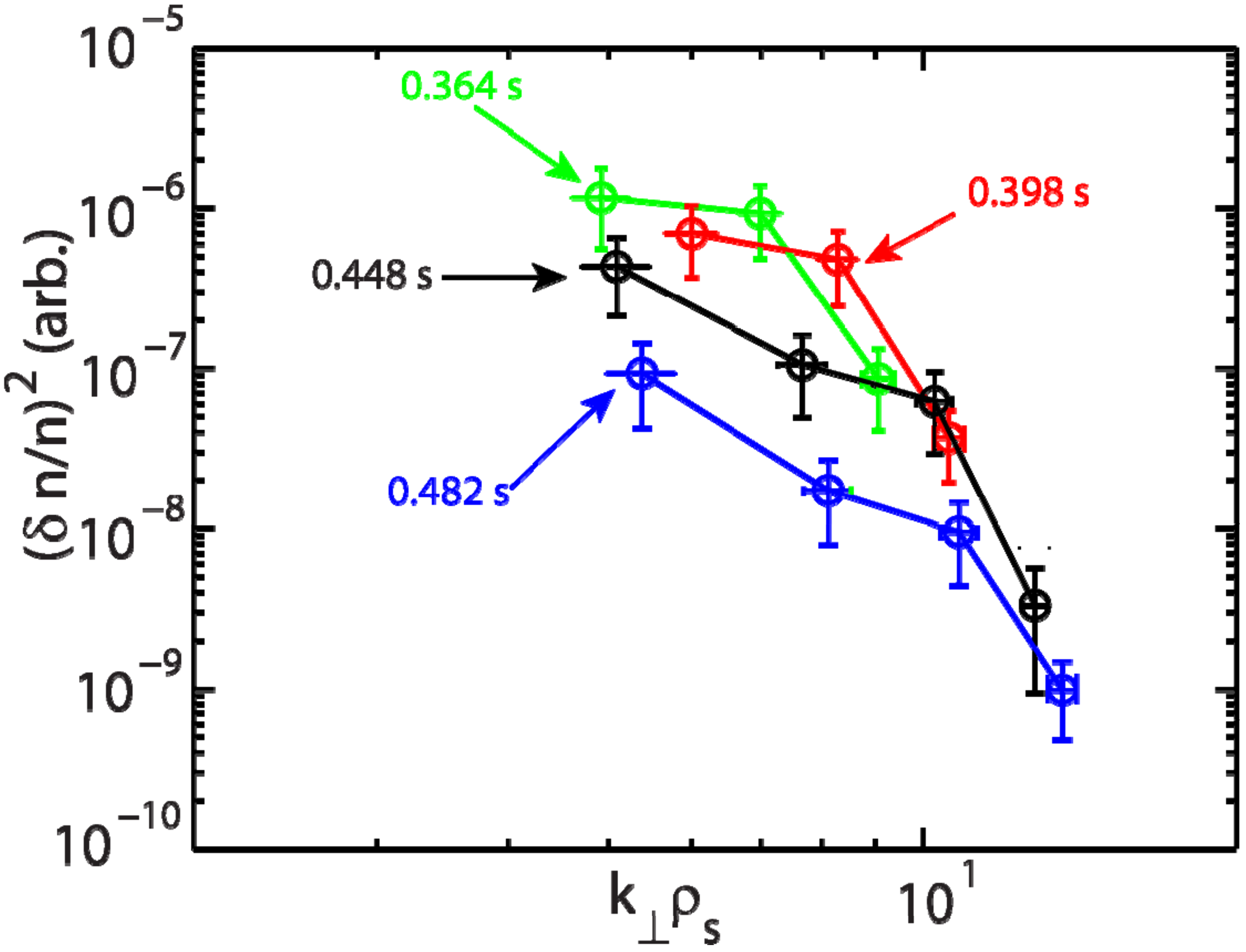
Dimensionless Quantities Show Small Change, Consistent with Small Change in Normalized Dispersion Relation



- All dimensionless quantities vary no more than 40%
- a/L_{n_e} has the largest variation
- In particular, a/L_{Te} is kept approximately constant

Peak Spectral Power is Reduced in the High-k Measurement Region as ExB Shearing Rate Increases

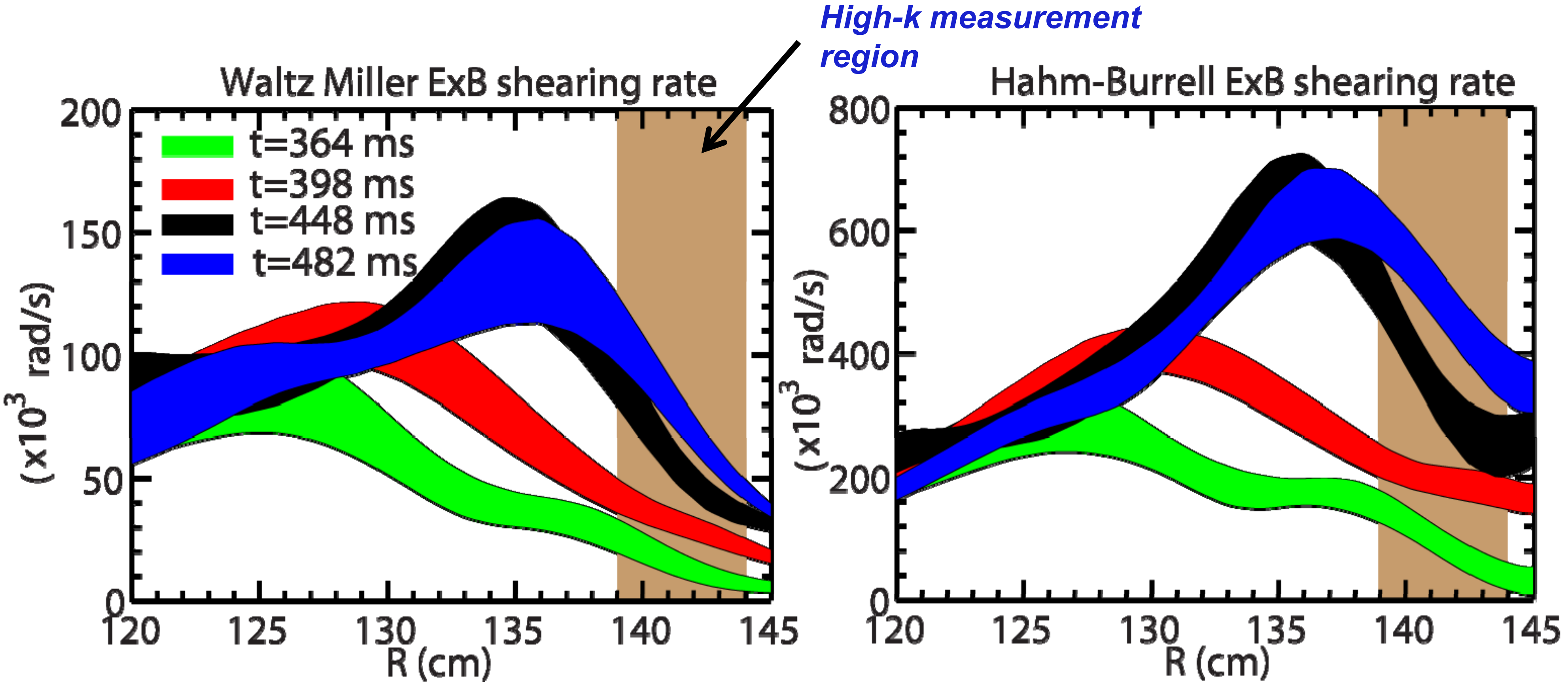
- One order of magnitude decrease in peak spectral power observed from t=0.364 s to t=0.482 s



$$\frac{S}{n_e^2} \propto \left(\frac{\delta n_e}{n_e}\right)^2$$

ExB Shearing Rate Increase is at the Outer Half of the Plasma (r/a>0.5)

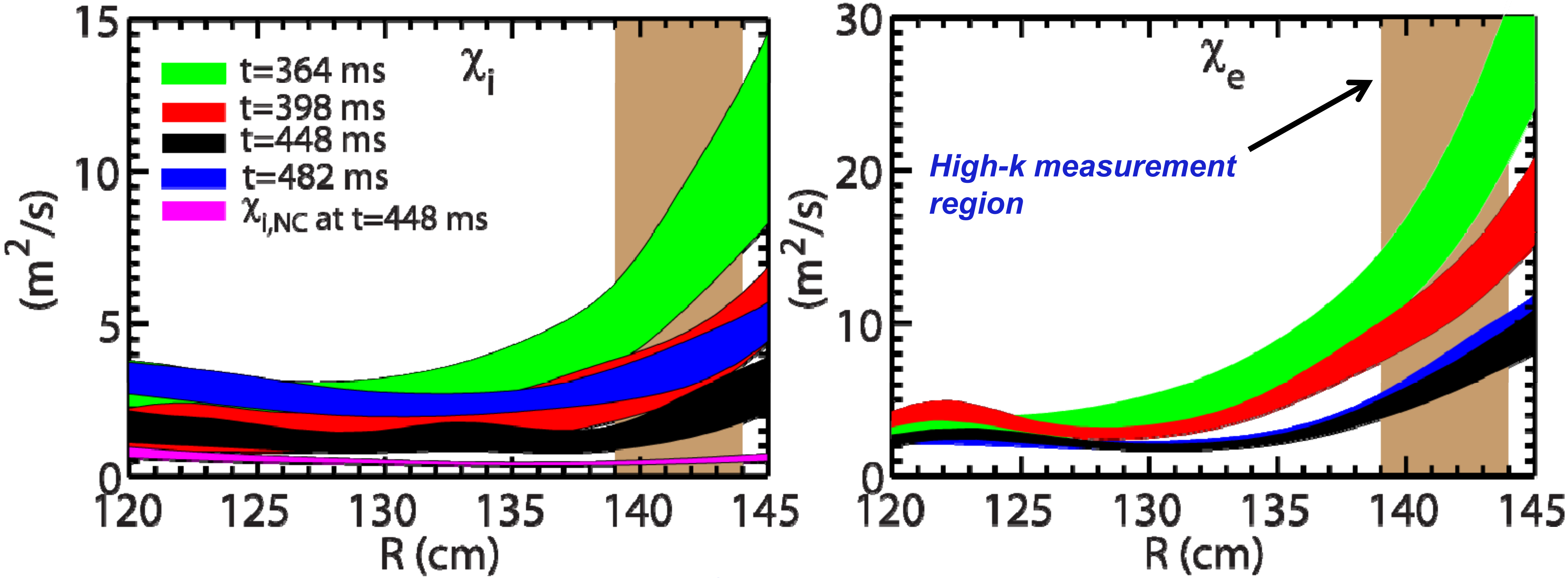
- Both Waltz-Miller and Hahm-Burrell ExB shearing rates show large increase
  - Hahm-Burrell ExB shearing rate 5 times larger than Waltz-Miller ExB shearing rate



High-k measurement region

Decrease in Thermal Diffusivities is Correlated with Increase in ExB Shearing Rate

- Large decrease in electron and ion thermal diffusivity also in the outer half of the plasma
- Decrease in χ_i and χ_e correlates with the decrease in peak spectral power in the high-k measurement region
  - Except when MHD activities become important at t=482 ms

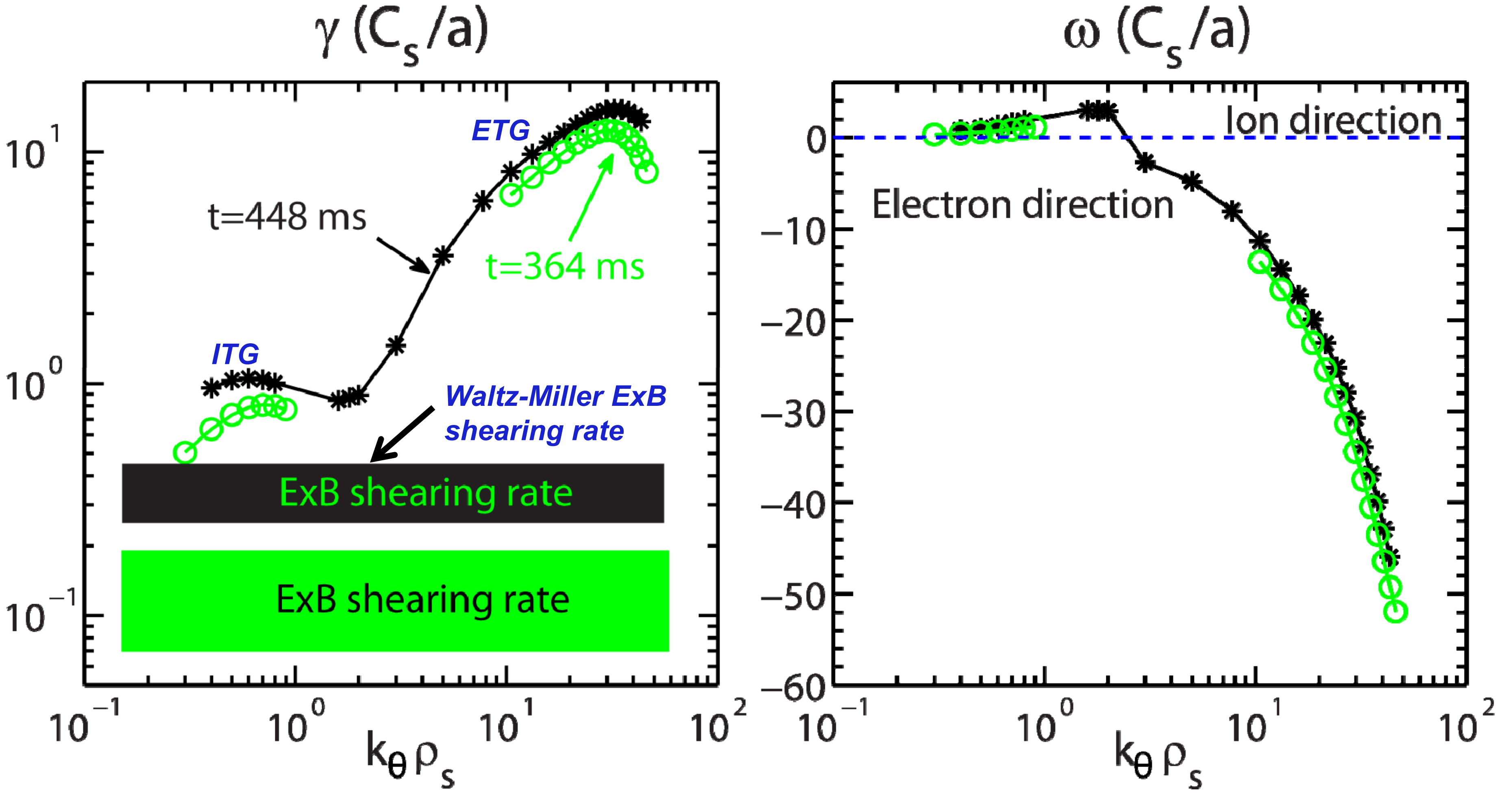


High-k measurement region

- *From TRANSP analysis*
- *The range in χ_i and χ_e due to uncertainties in ohmic heating and plasma equilibrium profiles*

Linear Stability Analysis Shows that ITG and ETG are both Unstable

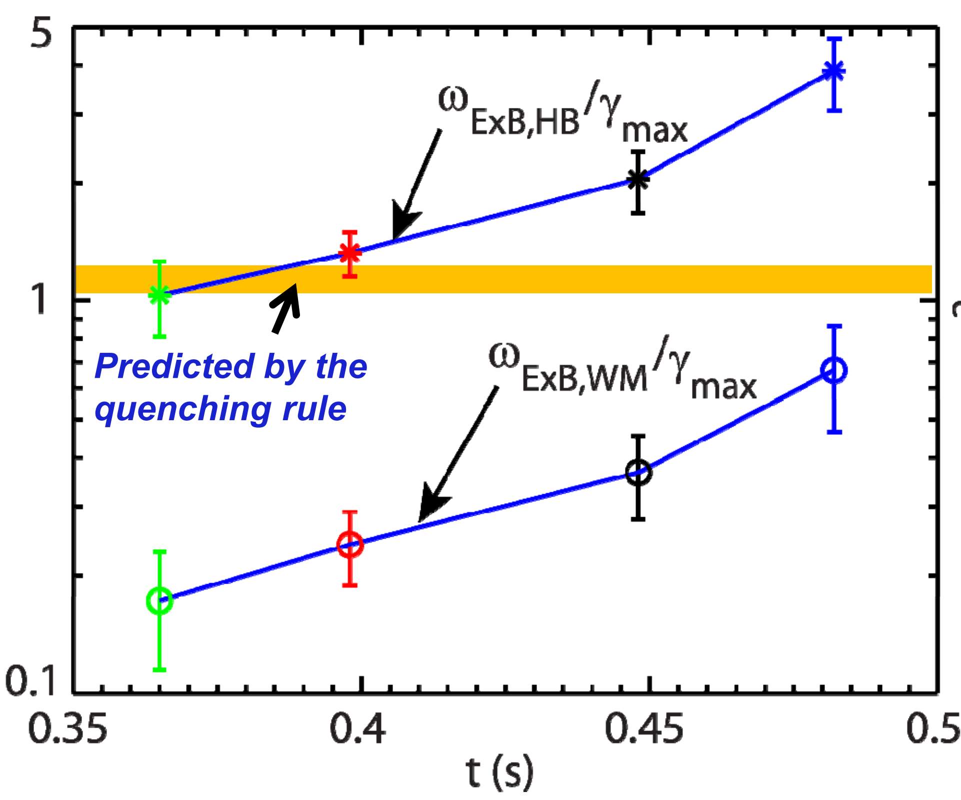
- Maximum ITG growth rate is comparable to ExB shearing rate
- Maximum ETG growth rate is more than 10 times larger ExB shearing rate



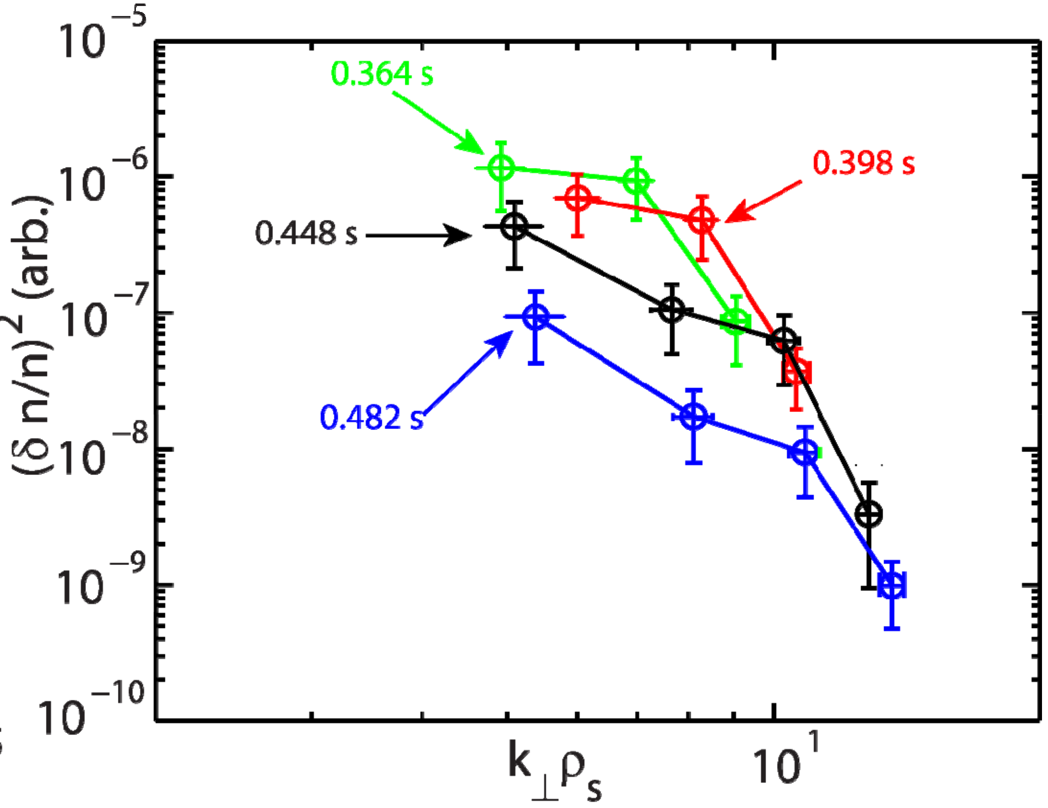
- Stability Analysis was performed with the GS2 code (Kotschenreuther et al., 1995)

Reduction in Peak Spectral Power in the High-k Measurement Region is Correlated with Increase in $\omega_{E\times \mathcal{B}}/\gamma_{max}$

- Quenching rule for ion-scale turbulence for shaped plasma is shown as $\omega_{E\times B}/\gamma_{max} \approx 1.41(A/3)^{0.6}/(\kappa/1.5)$ *Kinsey et al., PoP 2007*
- $\omega_{E\times \mathcal{B},\mathcal{WM}}/\gamma_{max}$ continuously increase to approach 1.1-1.2 predicted by the quenching rule with local A≈ 1.9-2.1 and κ≈ 1.5
  - Correlated with the continuous decrease in the high-k spectral power
  - Consistent with the nonlinear coupling between low-k and high-k turbulence

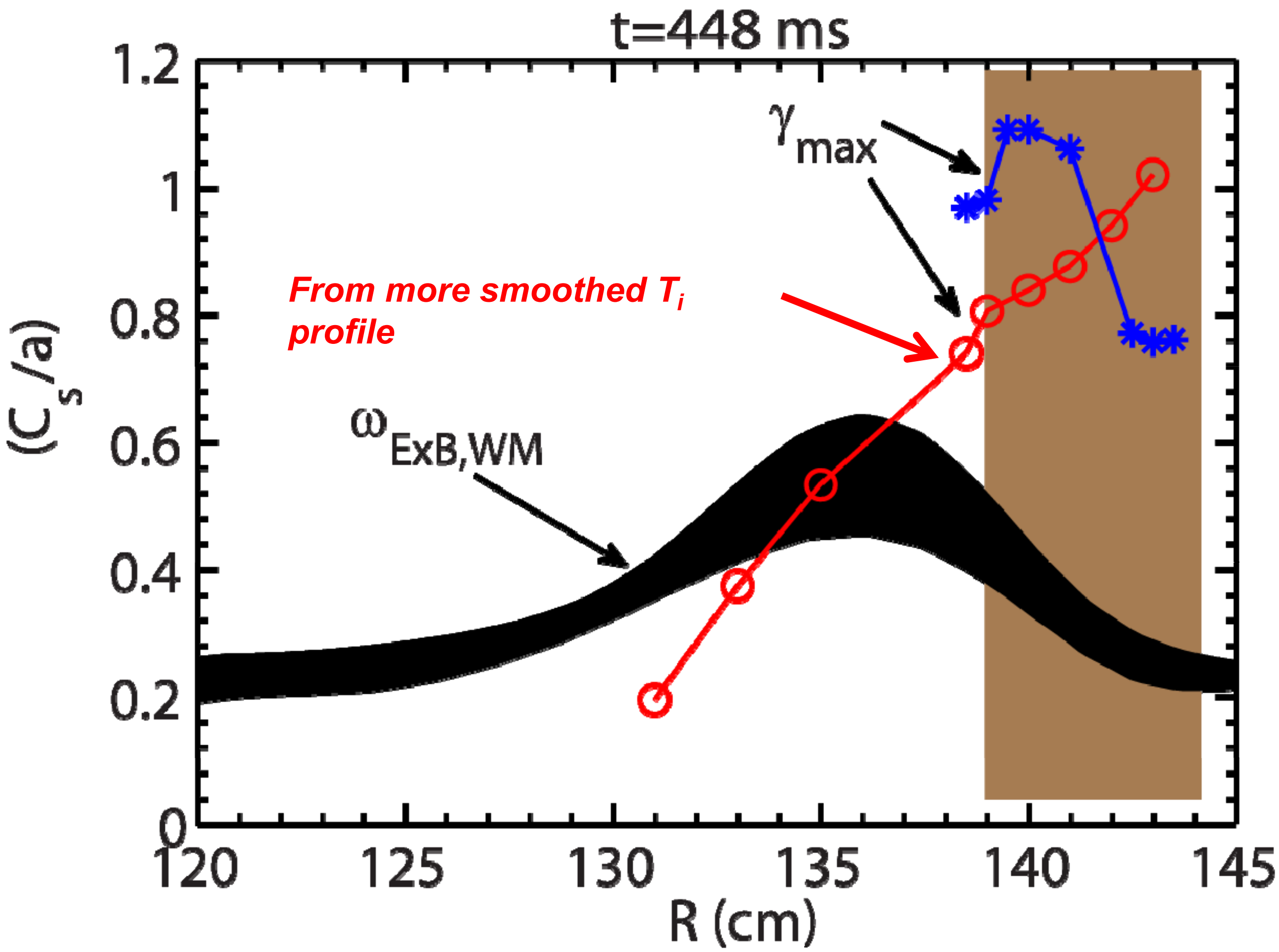


Predicted by the quenching rule



ExB Shearing Rate and Maximum ITG Growth Rate Profiles are Consistent with Peaked χ_i at Edge

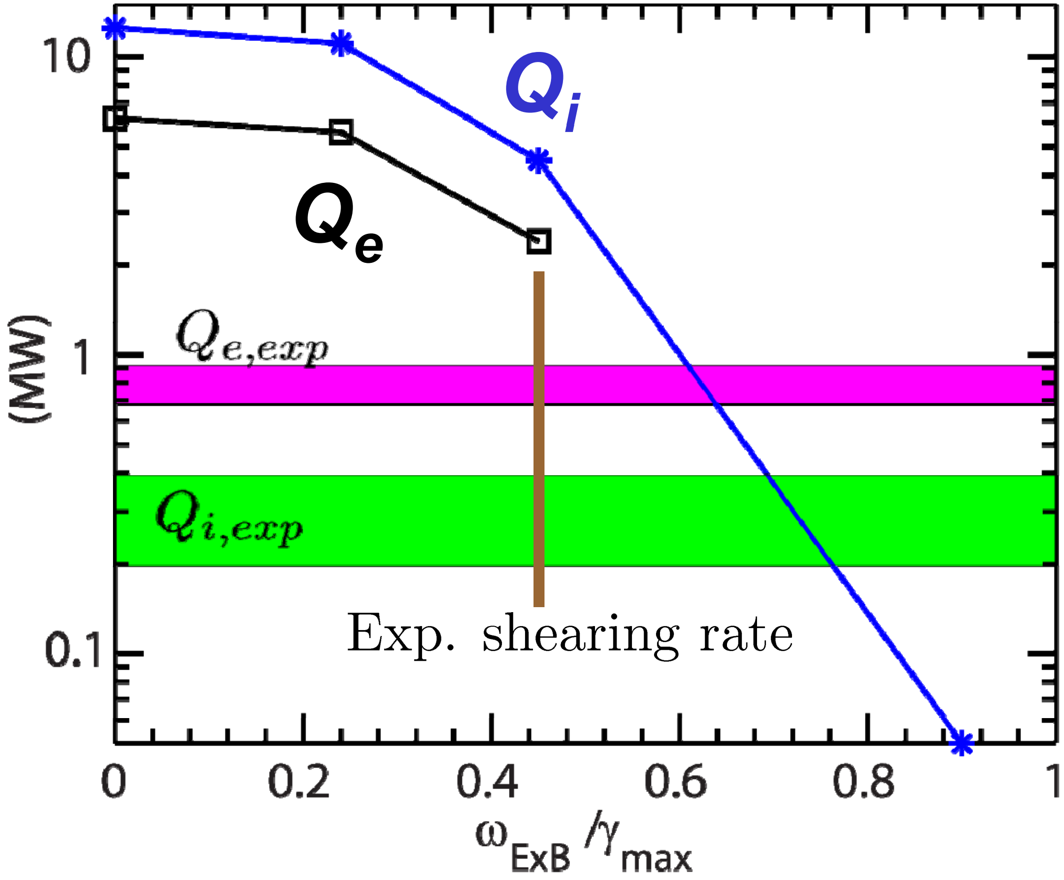
- Maximum ITG growth rate decreases rapidly toward plasma core while ExB shearing rate peaks at about R=135 cm
- More smoothed fitting to T_i profile can change a/L_{Ti} locally by about 40%, but γ_{max} is only changed by about 20%



- The ITG Growth rate is not quite stiff to ion temperature gradient
  - Reduction in ion temperature gradient leads to smooth transition to TEM

Local Nonlinear GK Simulations Demonstrate ExB Shear Stabilization of ITG Turbulence

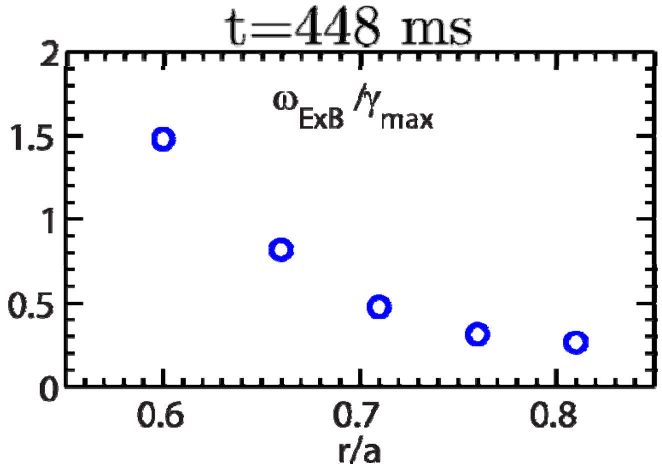
- Huge fluxes with not ExB shear ($\omega_{E\times B}$ =0) at r/a=0.71 and t=448 ms
- Completely suppressed between 1-2x$\omega_{E\times B}$
  - Q_e with 2x$\omega_{E\times B}$ is not physical

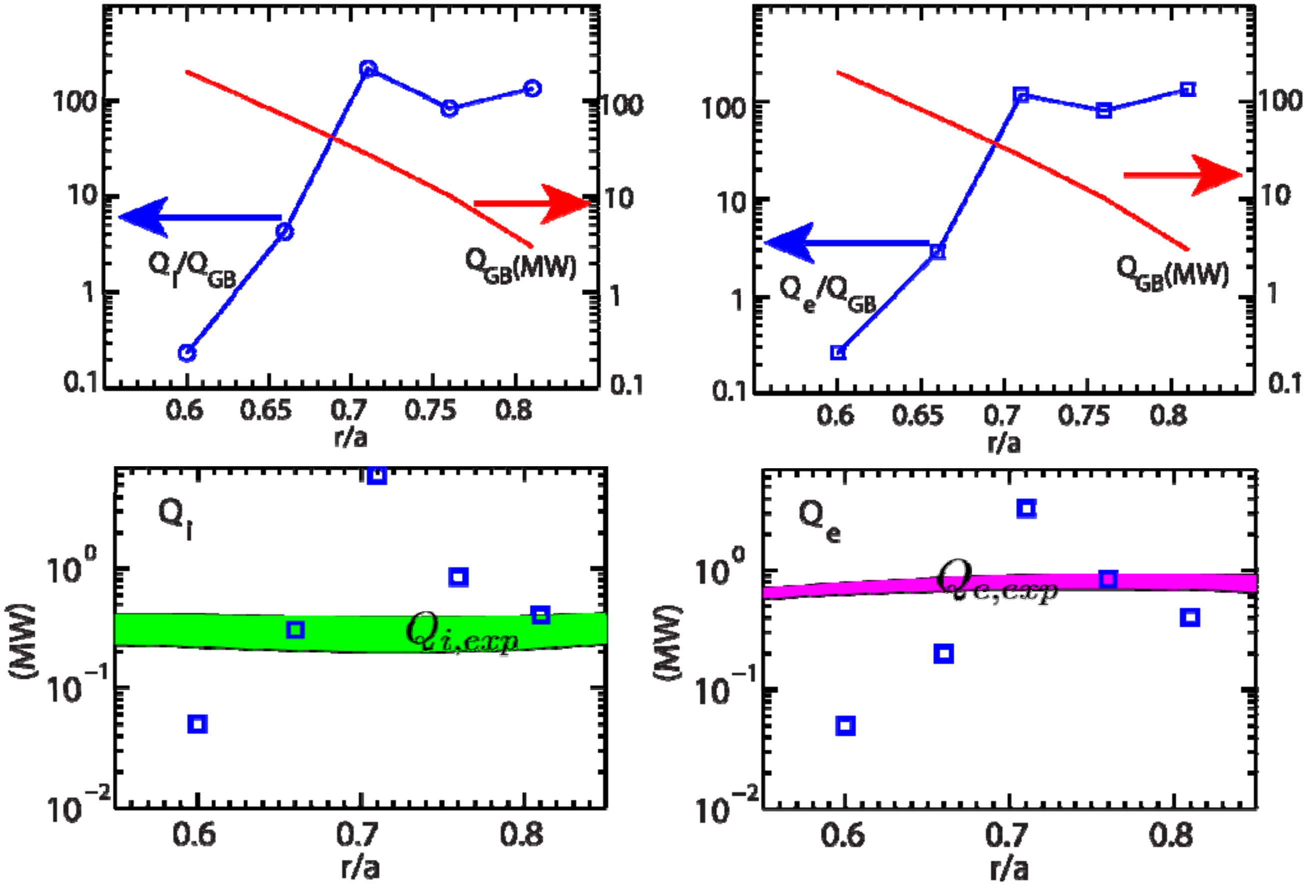


- ***Local ITG simulation using GYRO code with equilibrium from reconstruction***
- ***The range in Q_i and Q_e due to uncertainties in ohmic heating and plasma equilibrium profiles***

Radial Variation of $\omega_{E\times\mathcal{B}}$ has Strong Effects on Thermal Transport

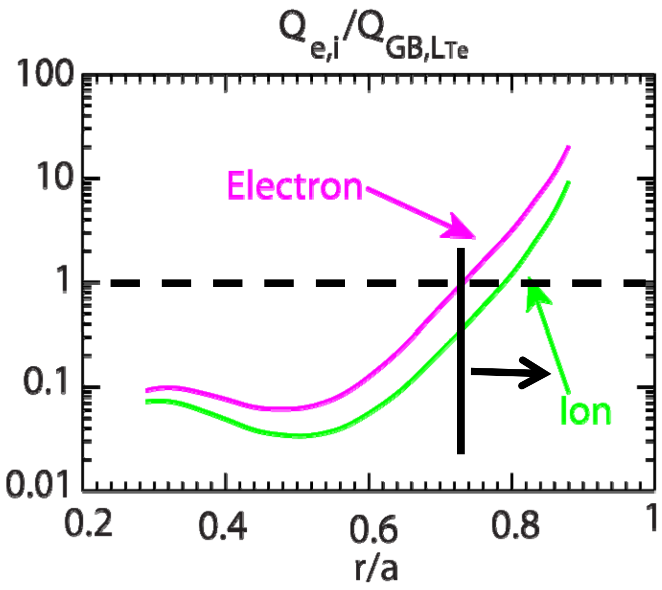
- Strong ExB shear significantly reduces Q/Q_{GB} at r/a<0.7
- Reduction in Q at r/a>0.7 is due to the strong Te dependence on Q_{GB} $[= n_e C_s T_e (\rho_{ref}/a)^2 S_{area}]$
- Global effects may be important (e.g. a/ρ_s ~200 at r/a=0.66); also need to test sensitivity on a/L_T and multi-scale

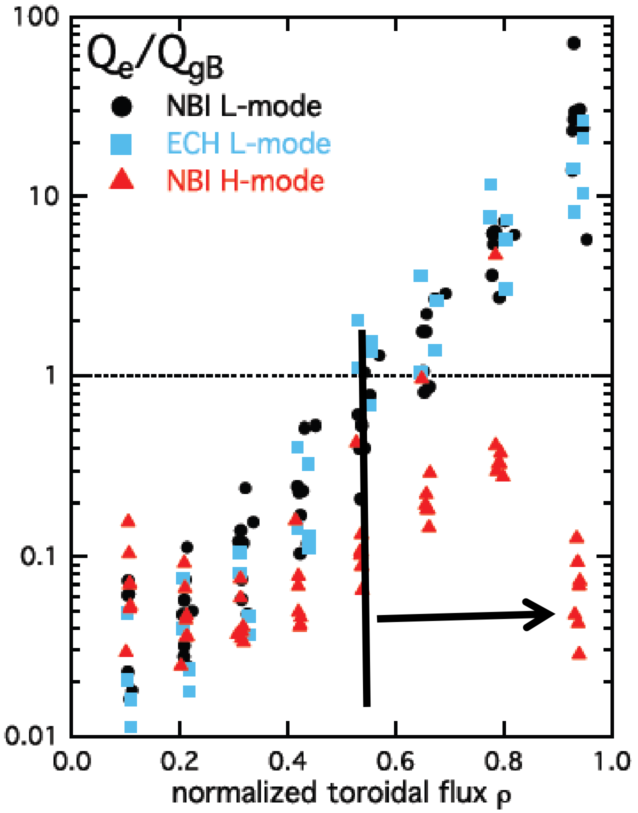


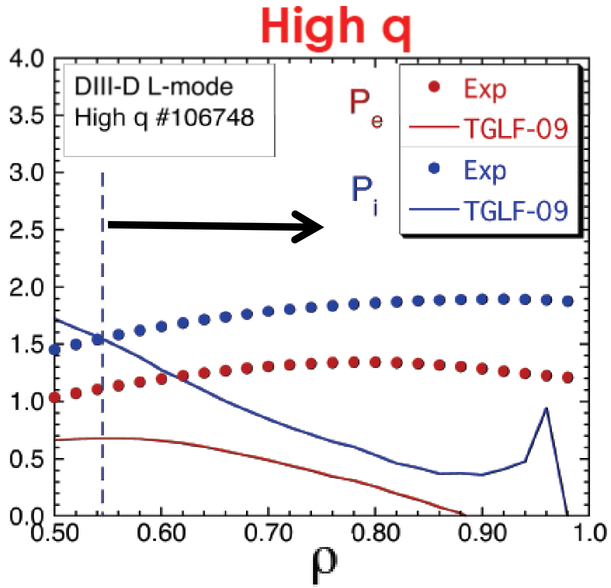


The Energy Transport Shortfall in these NSTX L-mode Plasmas Shows Similarity and Difference Compared with DIII-D Results

- Shortfall happens for NSTX and DIII-D cases at where $Q/Q_{GB,LT}$~O(1) is broken (see electron channel shown here)
- High-q DIII-D results show the shortfall region at about $\rho >\sim 0.54$
- Shortfall region for NSTX L-mode plasmas with similar q is significantly more outside: $\rho >\sim 0.7$ (r/a>~0.8)







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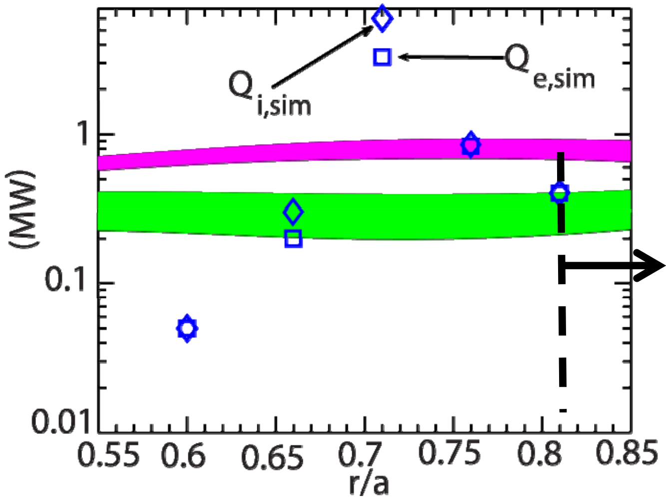

Summary

- The L-mode plasmas show comparable confinement as that of the H-mode of conventional tokamaks, i.e. H_{ITER98}≈1
  - Reduction in thermal transport and electron-scale turbulence without forming a transport barrier
- Observed reduction in the high-k spectral power and thermal transport is correlated with increase in $\omega_{E\times\ \mathcal{B},\mathcal{WM}}\ /\gamma_{max}$ for ITG modes
  - ETG maximum growth rate much larger than ExB shearing rate
  - Low-k and high-k coupling maybe important
- Nonlinear local gyrokinetic simulations demonstrate the ExB shear stabilization of ITG turbulence
  - Strong over (r/a=0.71) and under-predicting (r/a=0.6) Q_e and Q_i around the core-edge transition region (r/a~0.66-0.78)
  - Investigating a/L_T sensitivity, global effects and multi-scale transport
  - Shortfall at r/a>0.8 shows both similarity and difference with DIII-D results

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