

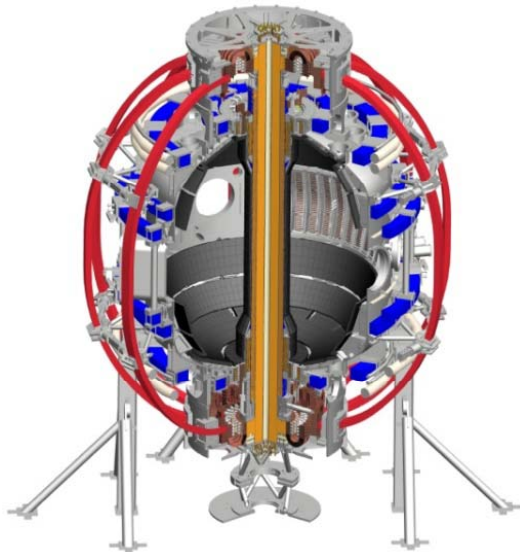
Response of Electron-scale Turbulence and Thermal Transport to Continuous ExB Shear Ramping-up (EX/P7-02)

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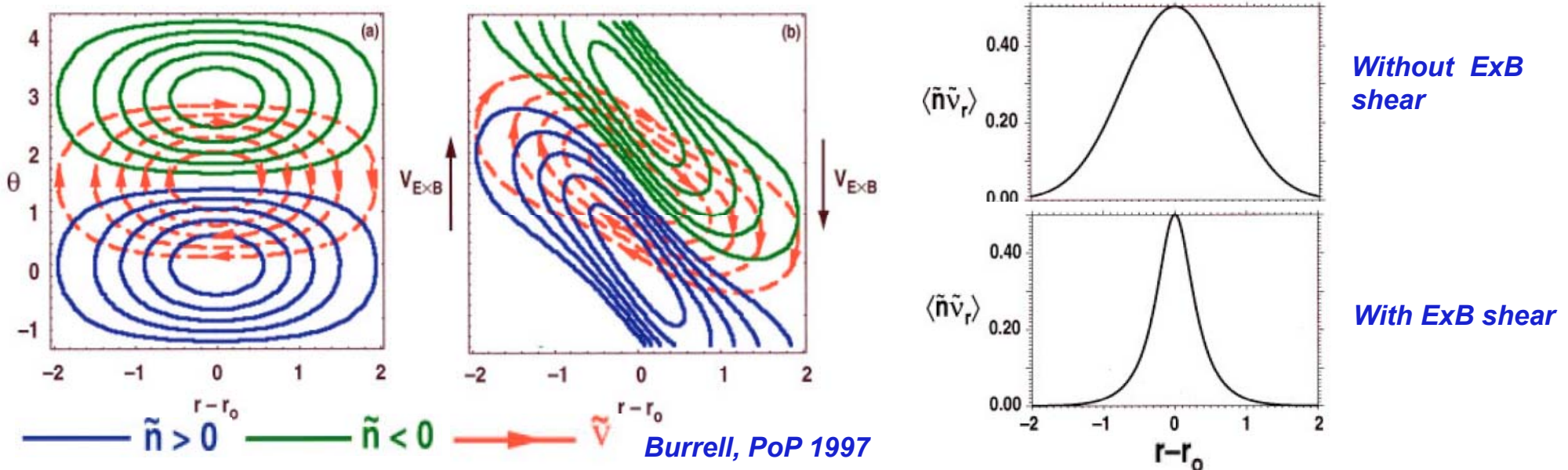
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Highlights

- 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($r/a \sim 0.66-0.78$)
 - 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 $r/a=0.81$

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)
 - Change 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



How do We Define ExB Shearing Rate?

- Hahm-Burrell definition

$$\omega_{E \times B, HB} = \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial \psi} \frac{E_r}{B_\theta R} \quad \text{Hahm and Burrell, PoP 1995}$$

- 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: $\omega_{E \times B, HB} > \gamma_{max}$

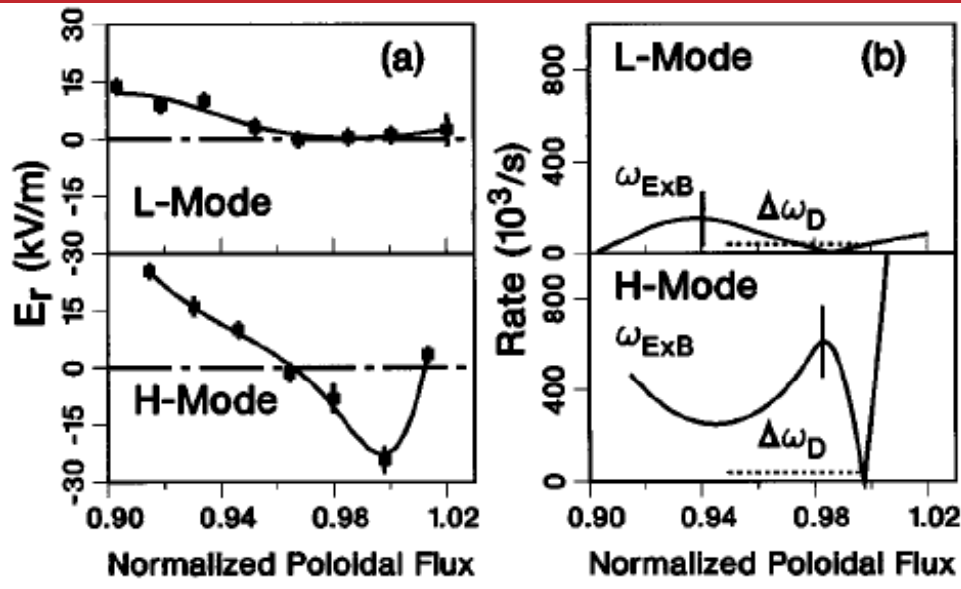
- Waltz-Miller definition

$$\omega_{E \times B, WM} = \frac{r}{q} \frac{d(E_r / B_\theta R)}{dr} \quad \text{Waltz and Miller, PoP 1999}$$

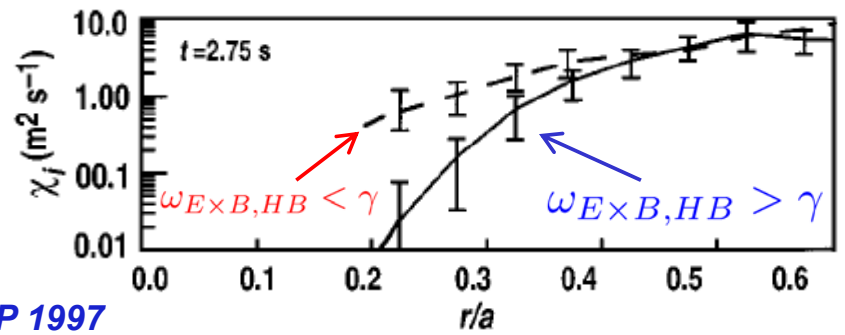
- Flux surface quantity
- Extensive quantitative comparisons with nonlinear gyrokinetic simulations
 - Quantitative quenching rule related to maximum linear growth rate studied
 - Critical $\omega_{E \times B} / \gamma_{max}$ found as a function of aspect ratio and elongation: $1.41(A/3)^{0.6} / (\kappa/1.5)$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

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

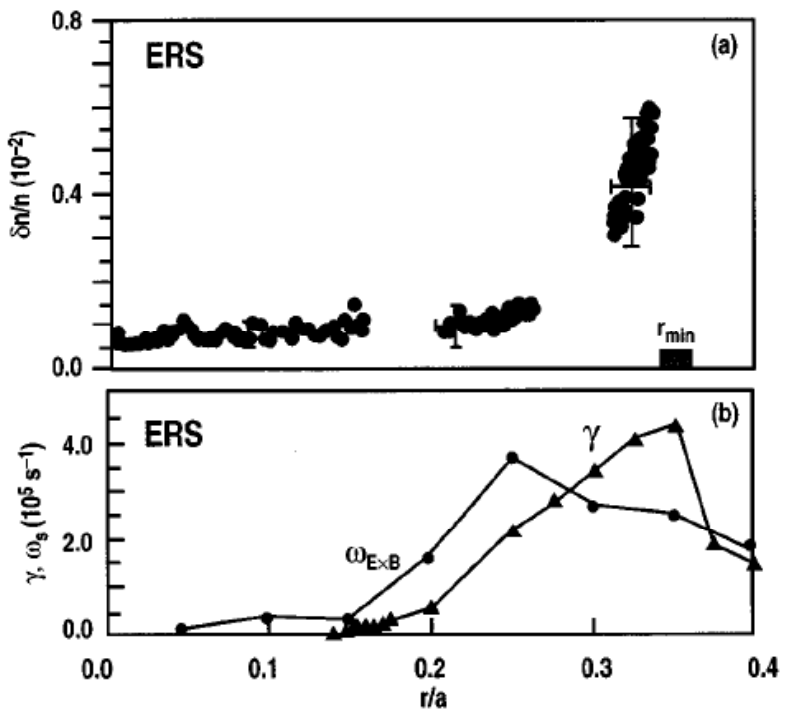
- H-mode edge transport barrier formation related to ExB shear
 - Deep E_r well formed in H-mode
 - ExB shearing rate much larger than turbulence decorrelation rate in H-mode
- Internal transport barrier formation consistent with ExB shear stabilization
 - Internal transport barrier and turbulence reduction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



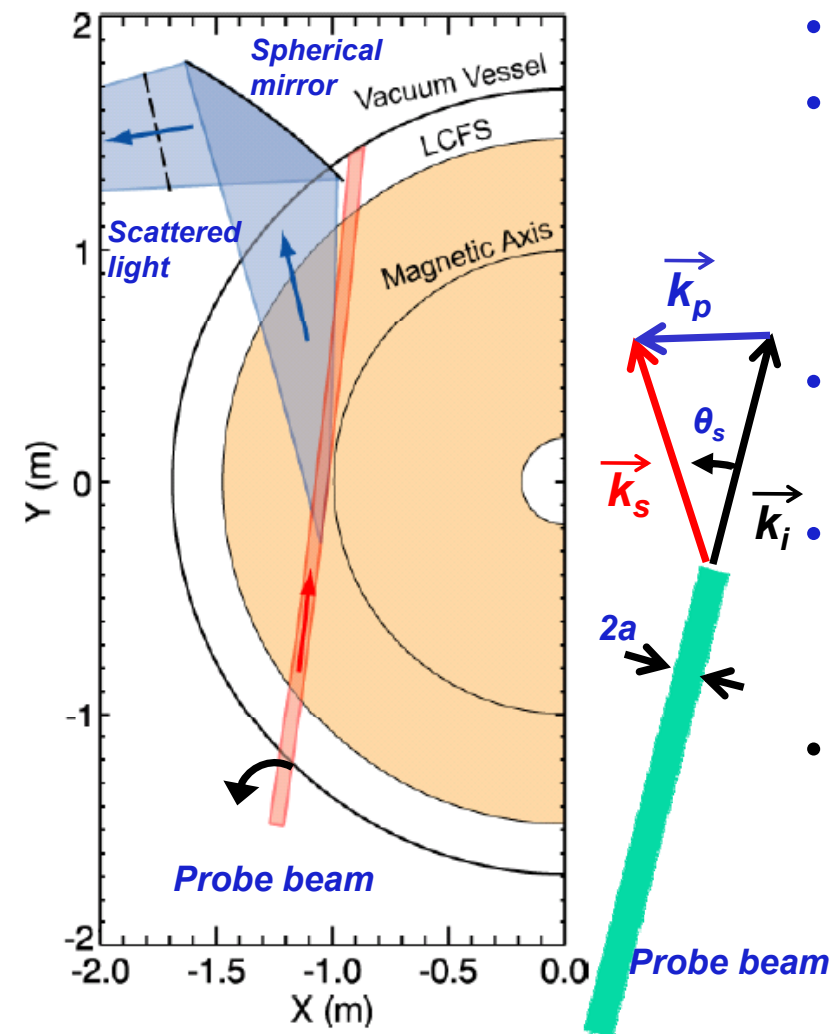
Ritz et al., PRL 1990



Burrell, PoP 1997



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



- 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 $\omega_i \gg \omega_p$

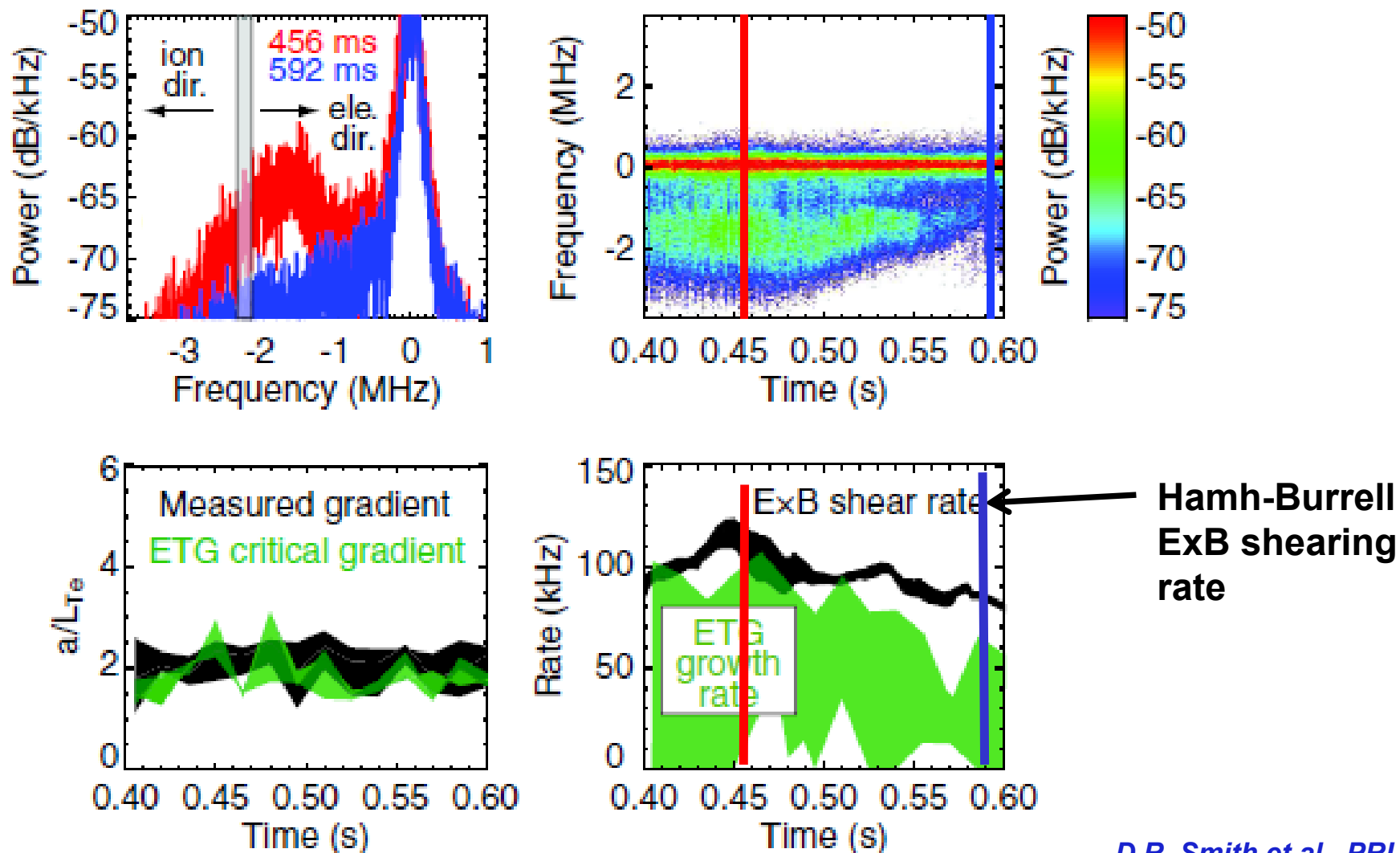
- The scattering system characteristics are:

- Frequency bandwidth: 5 MHz
- Heterodyne receiver: Wave propagation direction resolved
- Measurement: k_r spectrum
- Wavenumber resolution: 0.7 cm^{-1} ($2/a$ with $a \approx 3 \text{ cm}$)
- Wavenumber range (k_r): $5\text{-}30 \text{ cm}^{-1}$ ($\sim 5\text{-}30 \rho_s^{-1}$)
- Radial resolution: $\pm 2 \text{ cm}$
- Tangential resolution: 5-15 cm
- Radial range: R=106 – 144 cm
- Minimal detectable density fluctuation: $|\delta n_e(k) / n_e|^2 \approx 2 \times 10^{-11}$

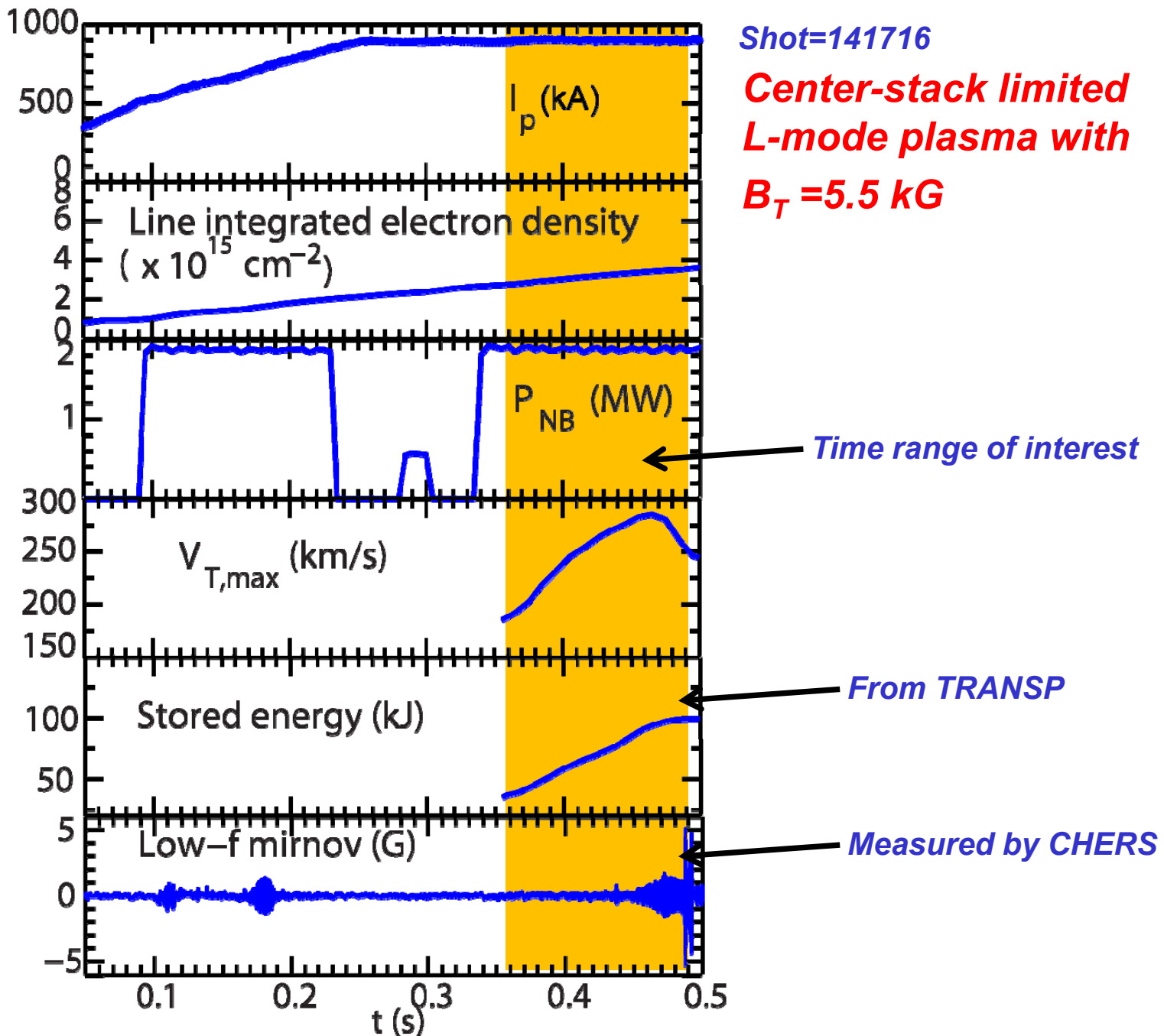
D.R. Smith, PhD thesis, 2009

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

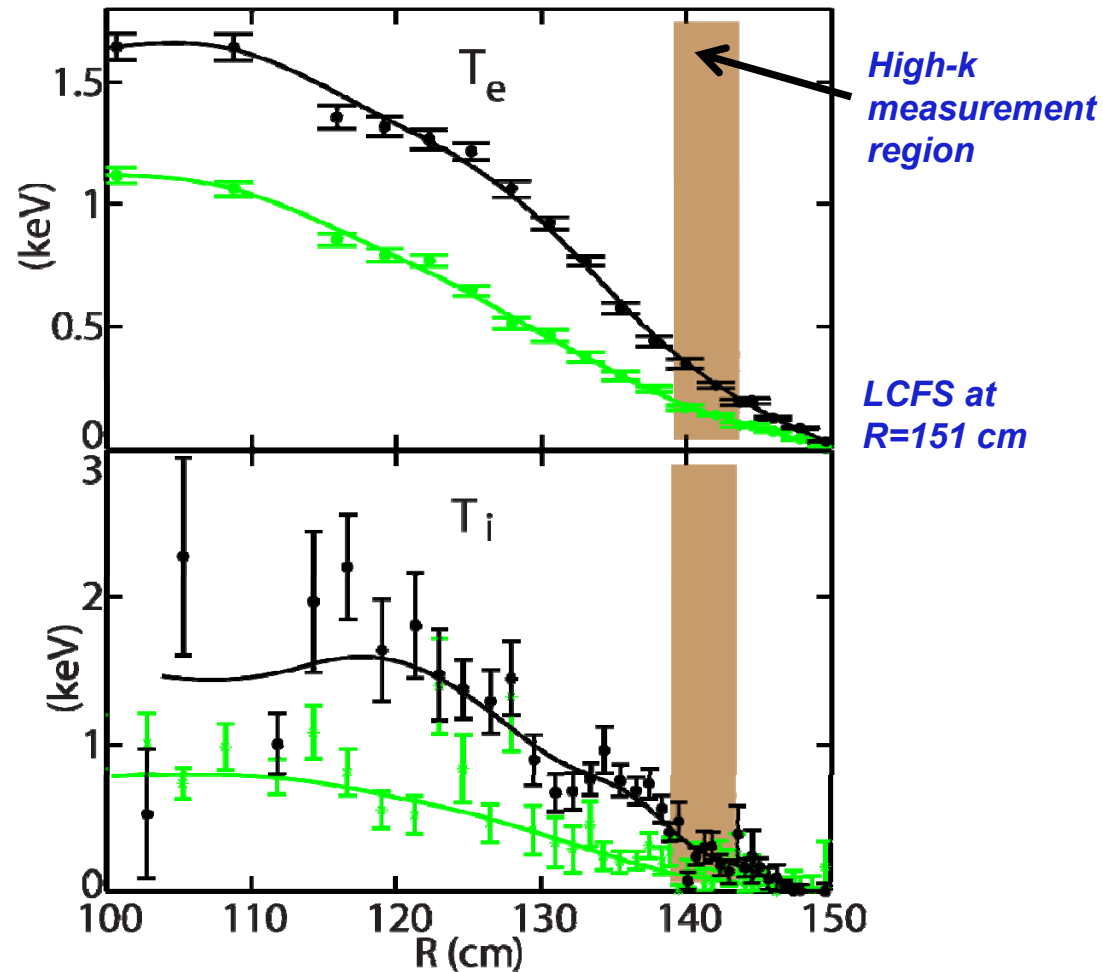
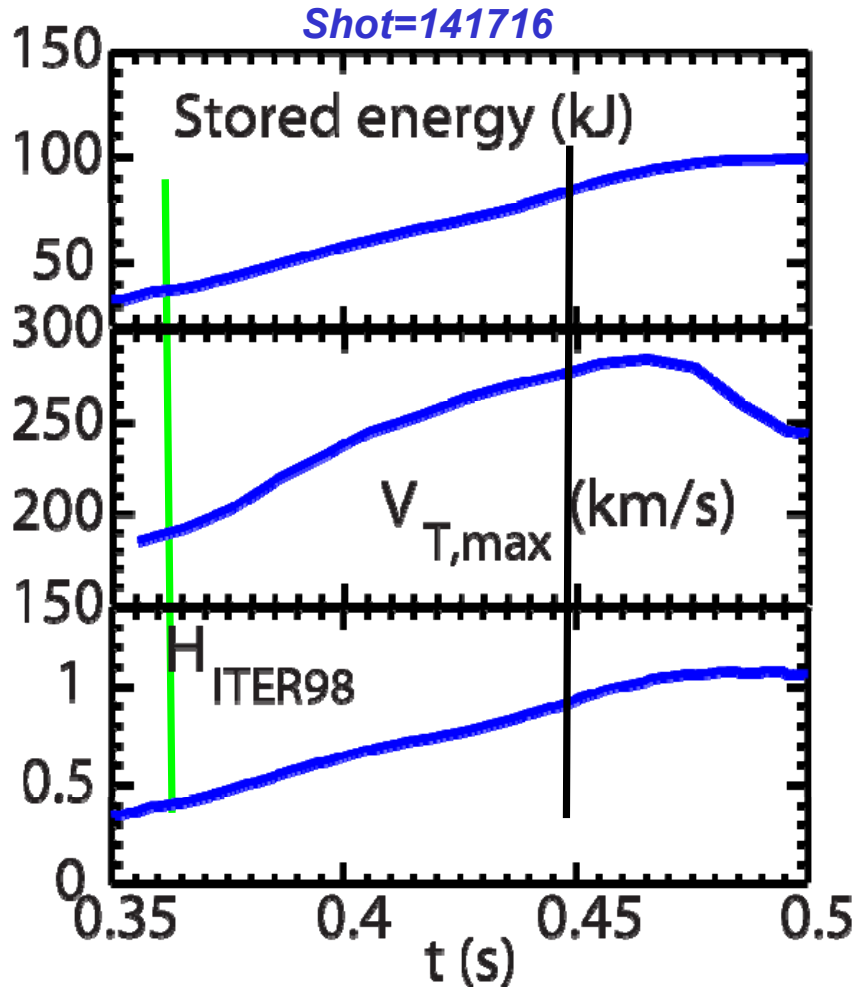


Plasma Stored Energy Increases as Plasma Spins up in a Set of NSTX NBI-heated L-mode Plasmas

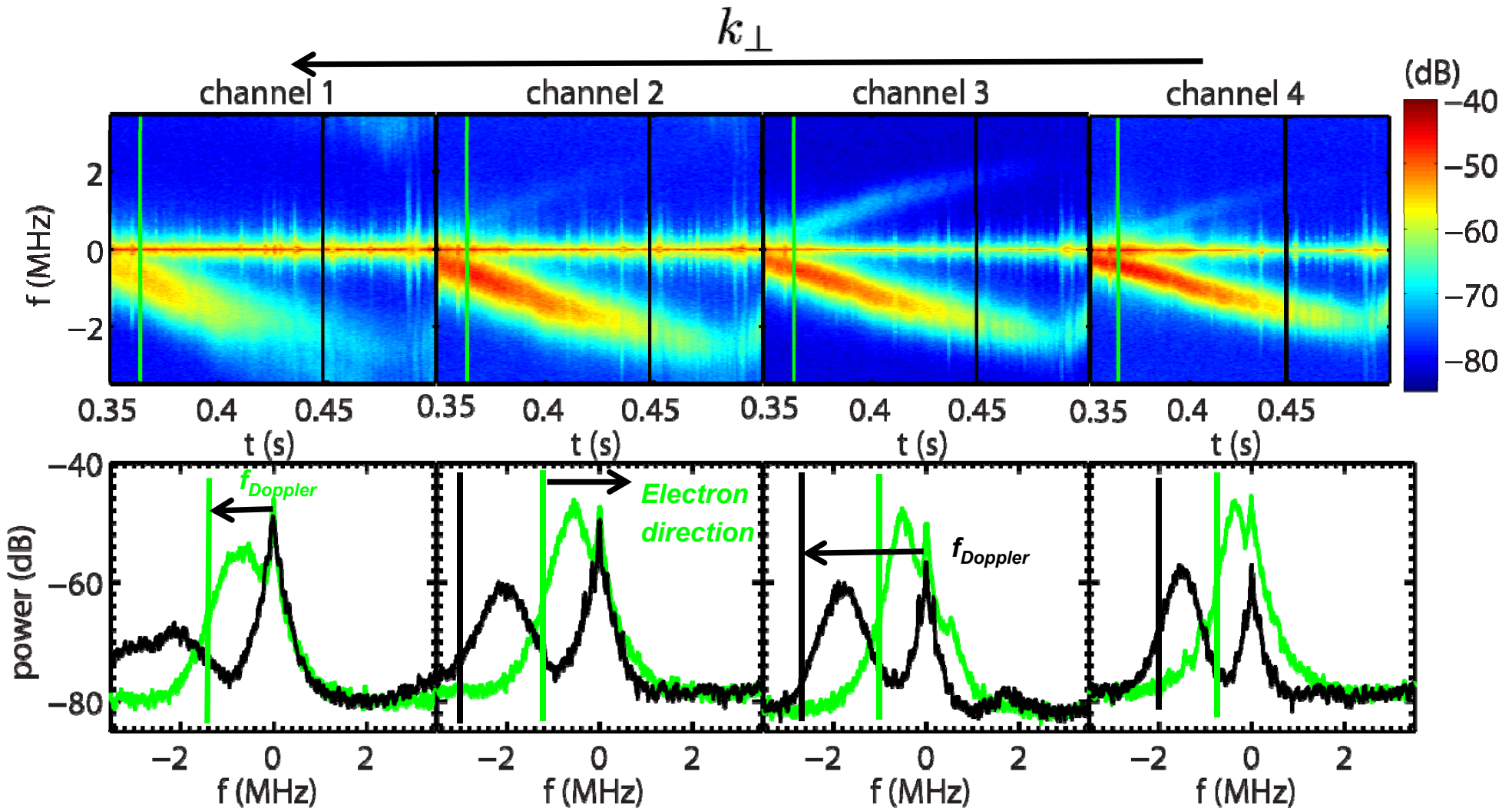


L-mode Plasma Confinement Reaches that of the H-mode of Conventional Tokamaks

- Both T_i and T_e increases as Plasma Toroidal Velocity Increases
- No formation of a transport barrier observed



All Channels Saw Decreased Scattering Power as Plasma Spins up

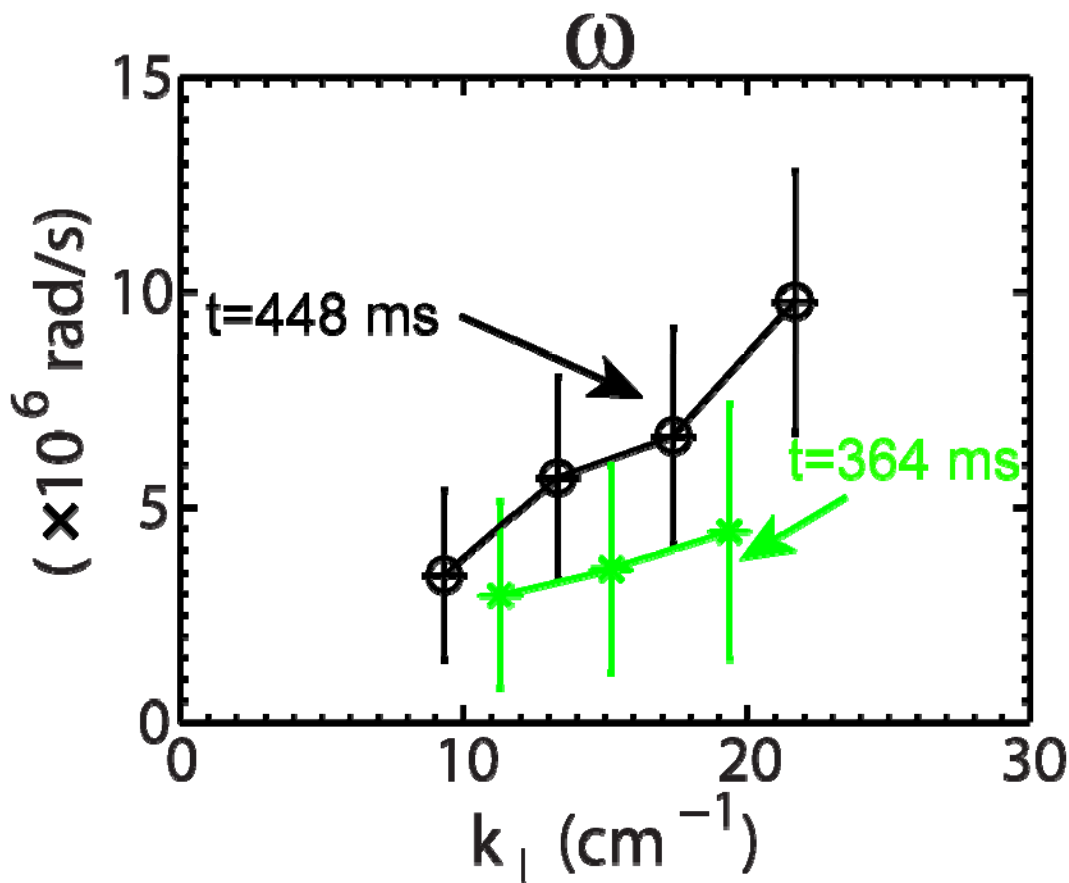


- Plasma rotation leads to large Doppler frequency

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

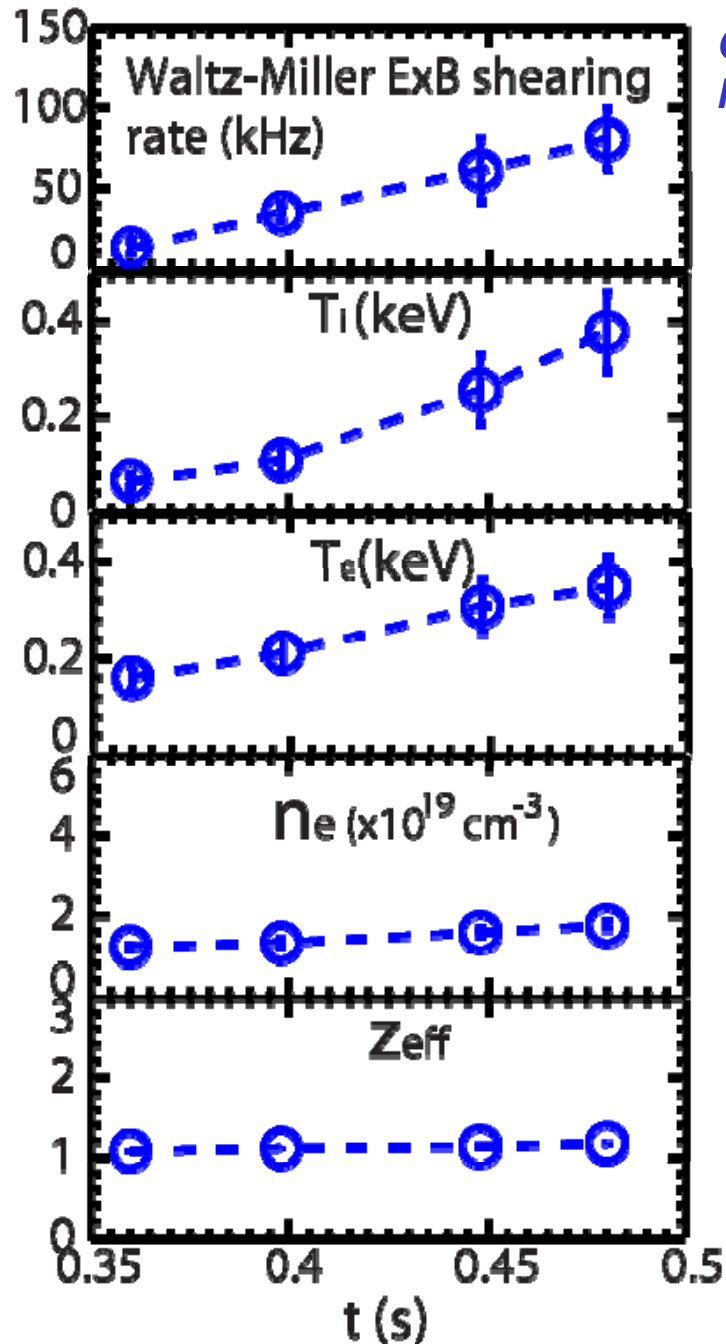
$$\omega = |\omega_{Lab} - k_T V_T|$$

Mode frequency in plasma rest frame *Spectral peak frequency measured in the lab frame* *From Ray tracing* *From CHERS measurement*



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

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



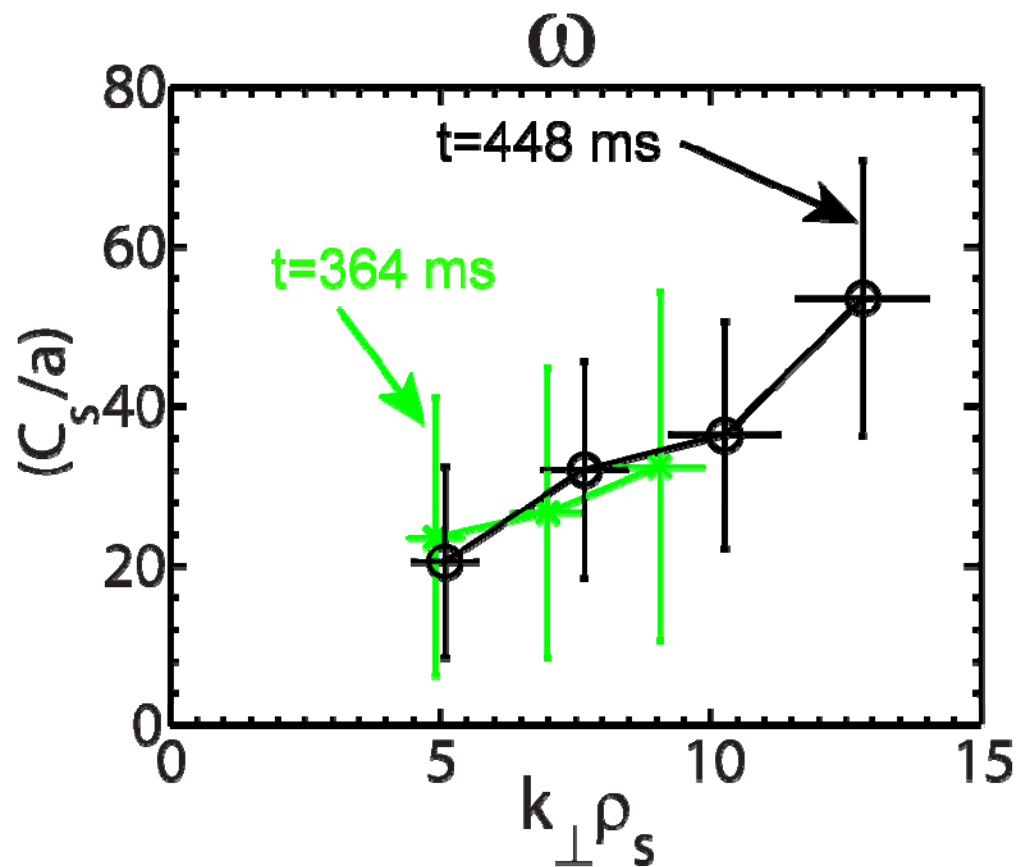
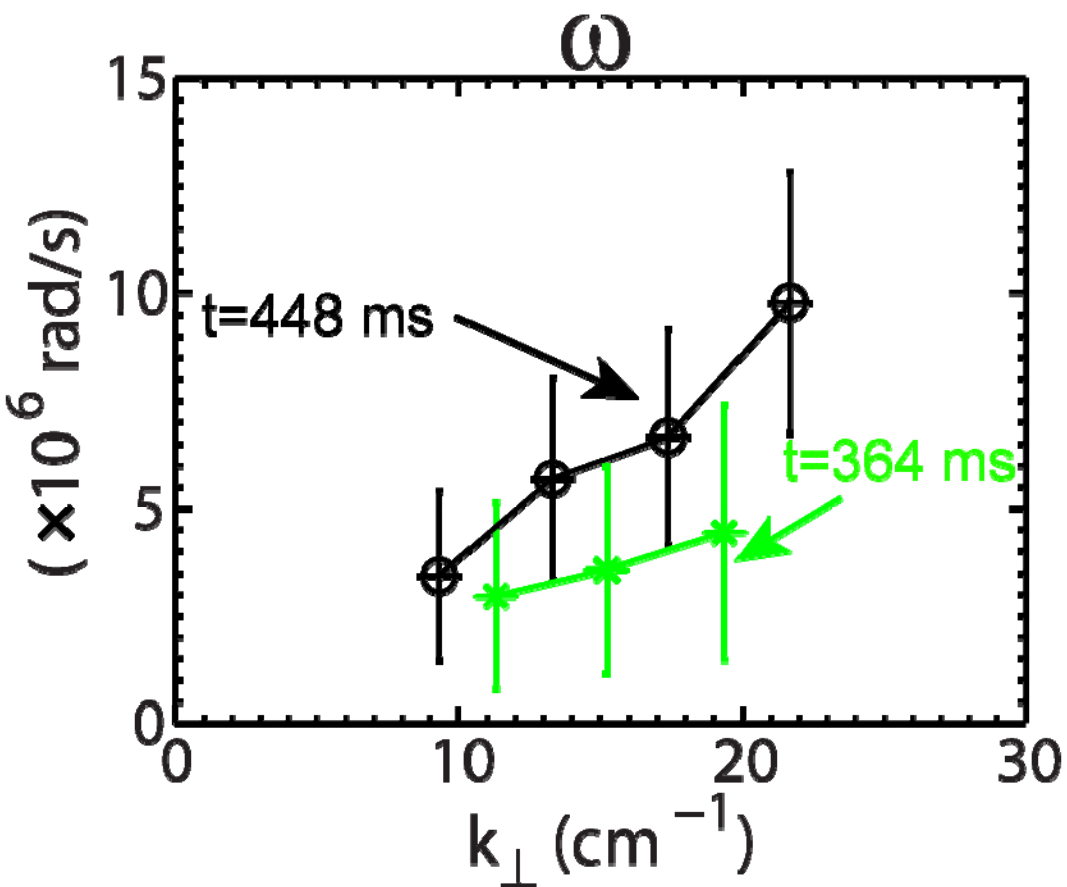
Quantities averaged in the high-k measurement region

- 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

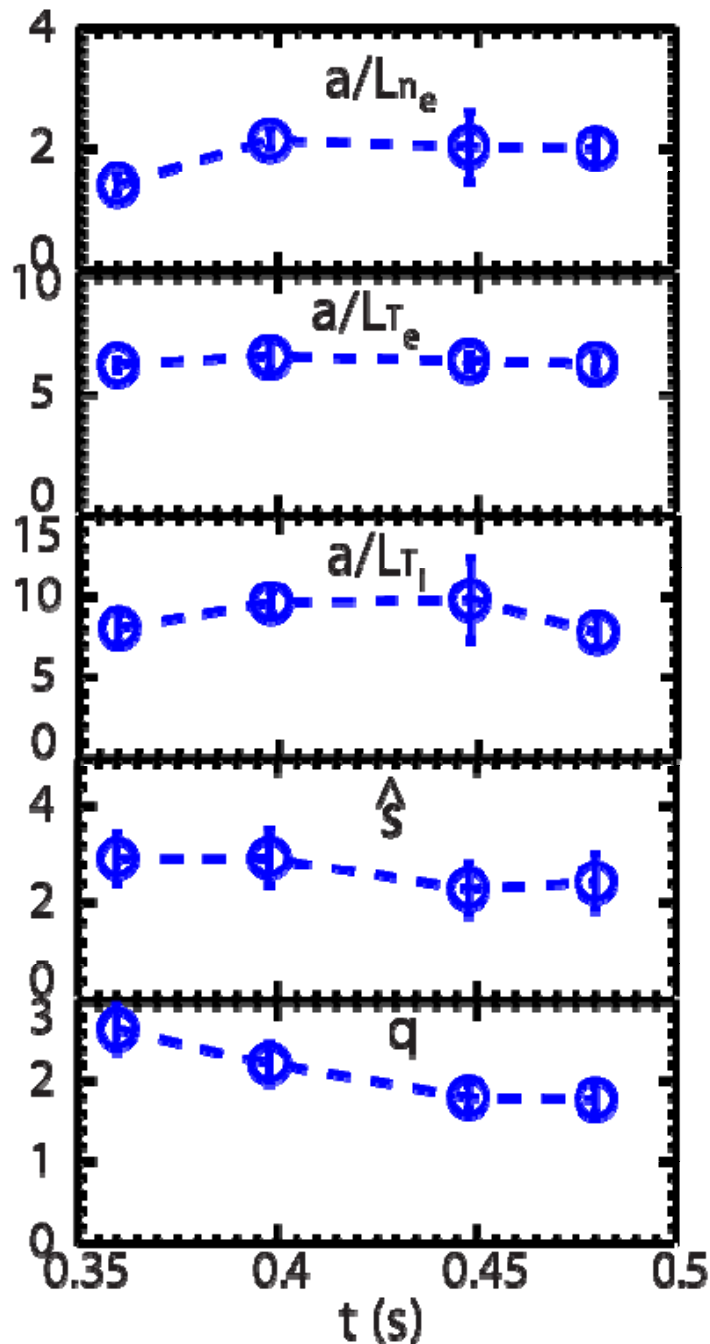
Normalized Mode Dispersion Relations Show Little Change with Increased ExB Shearing Rate

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

ω → Mode frequency in plasma rest frame
 ω_{Lab} → Spectral peak frequency measured in the lab frame
 k_T → From Ray tracing
 V_T → From CHERS measurement



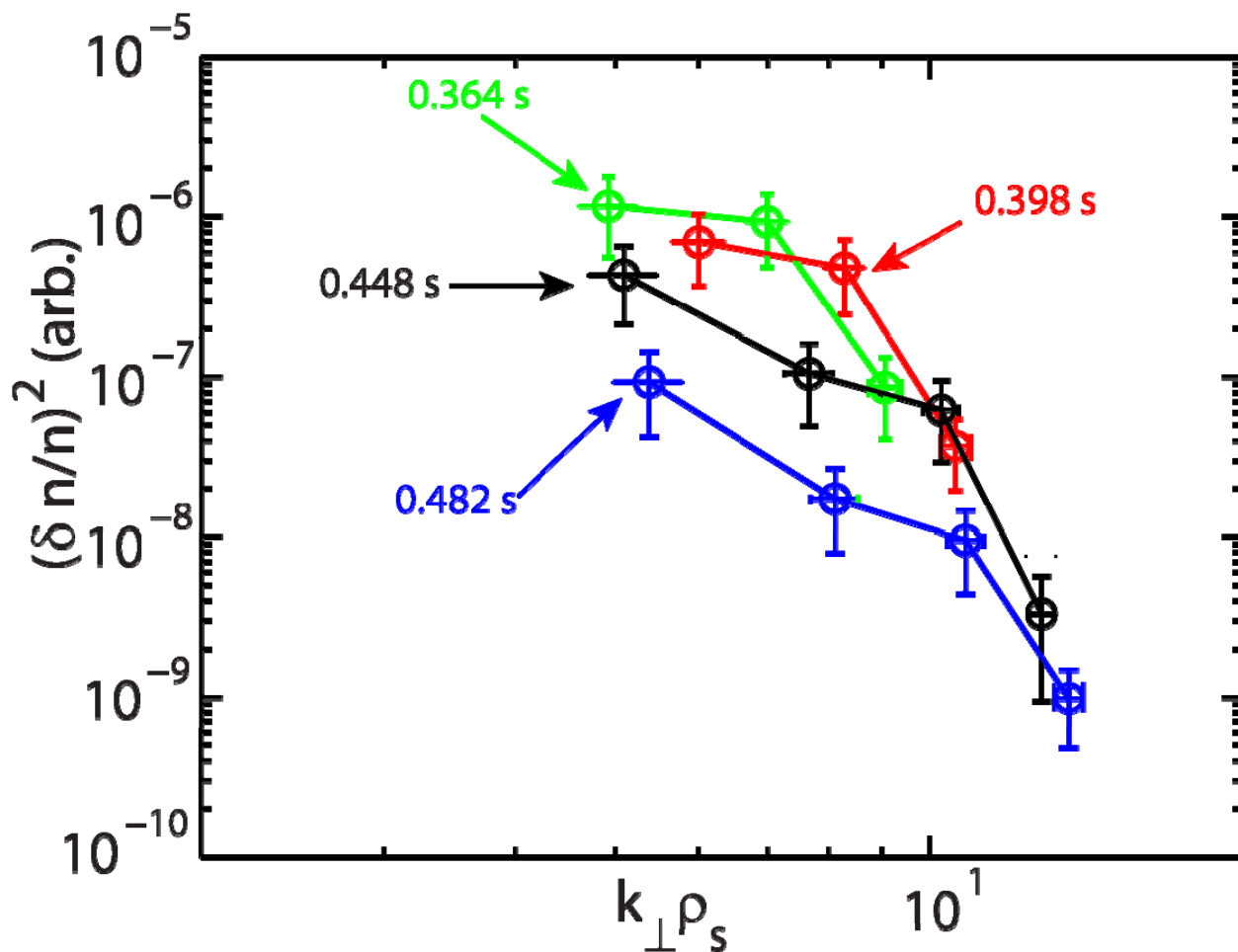
Dimensionless Quantities Show Small Change, Consistent with Small Change in Normalized Dispersion Relation



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

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

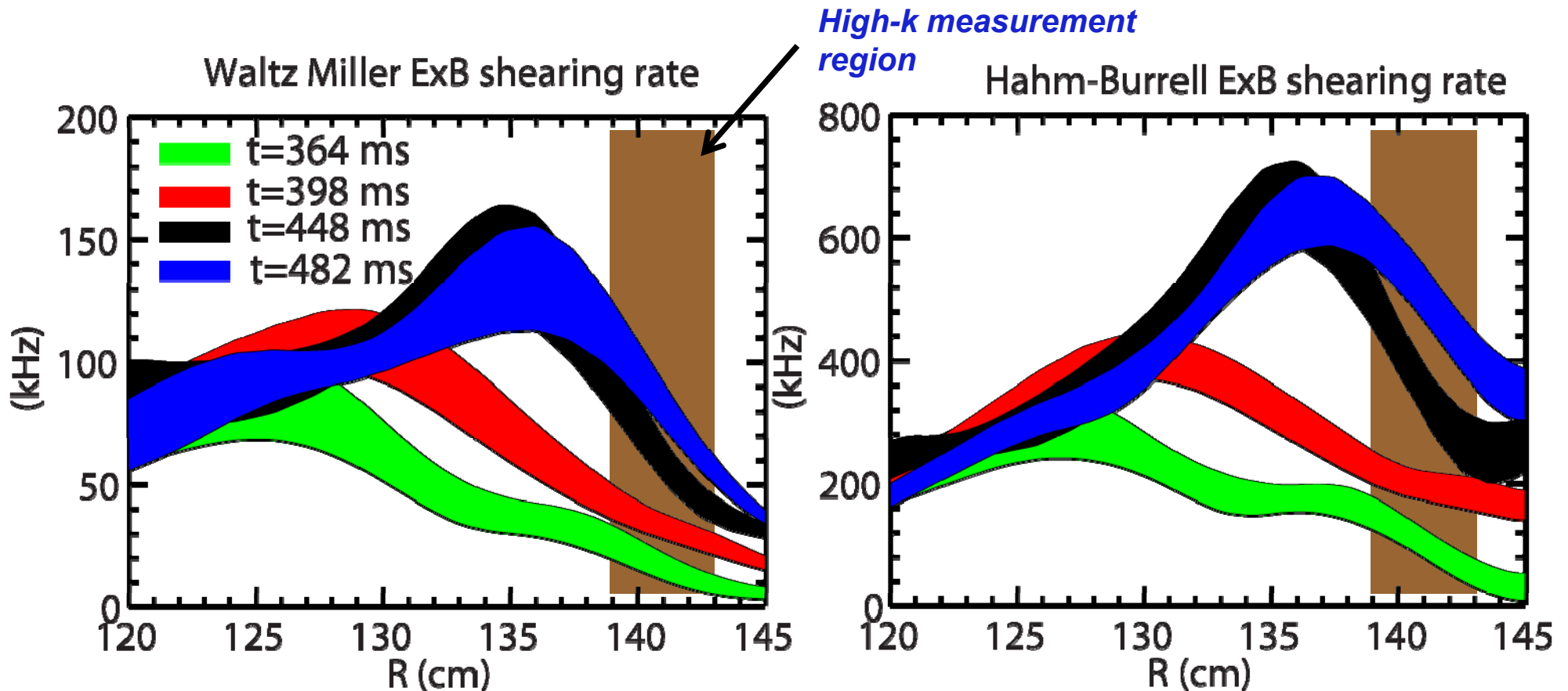
- One order of magnitude decrease in peak spectral power observed from t=0.364 s to t=0.482 s



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

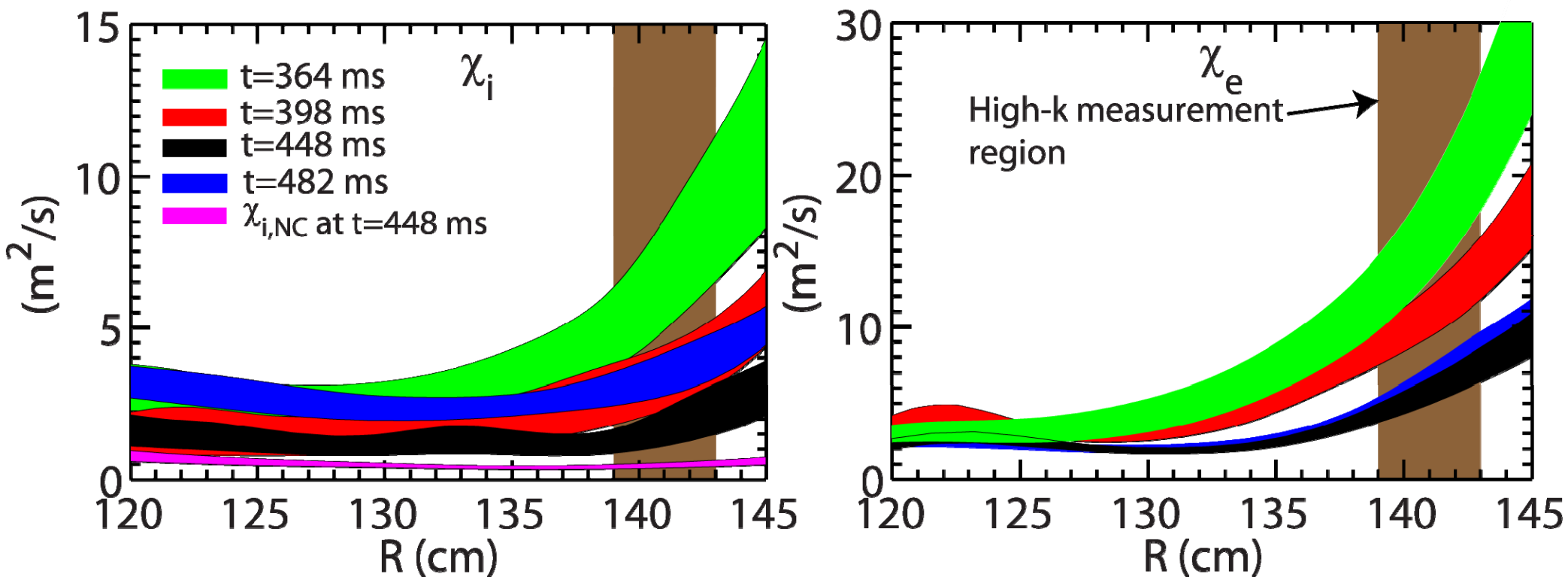
ExB Shearing Rate Increase is at the Outer Half of the Plasma ($r/a > 0.5$)

- 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



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

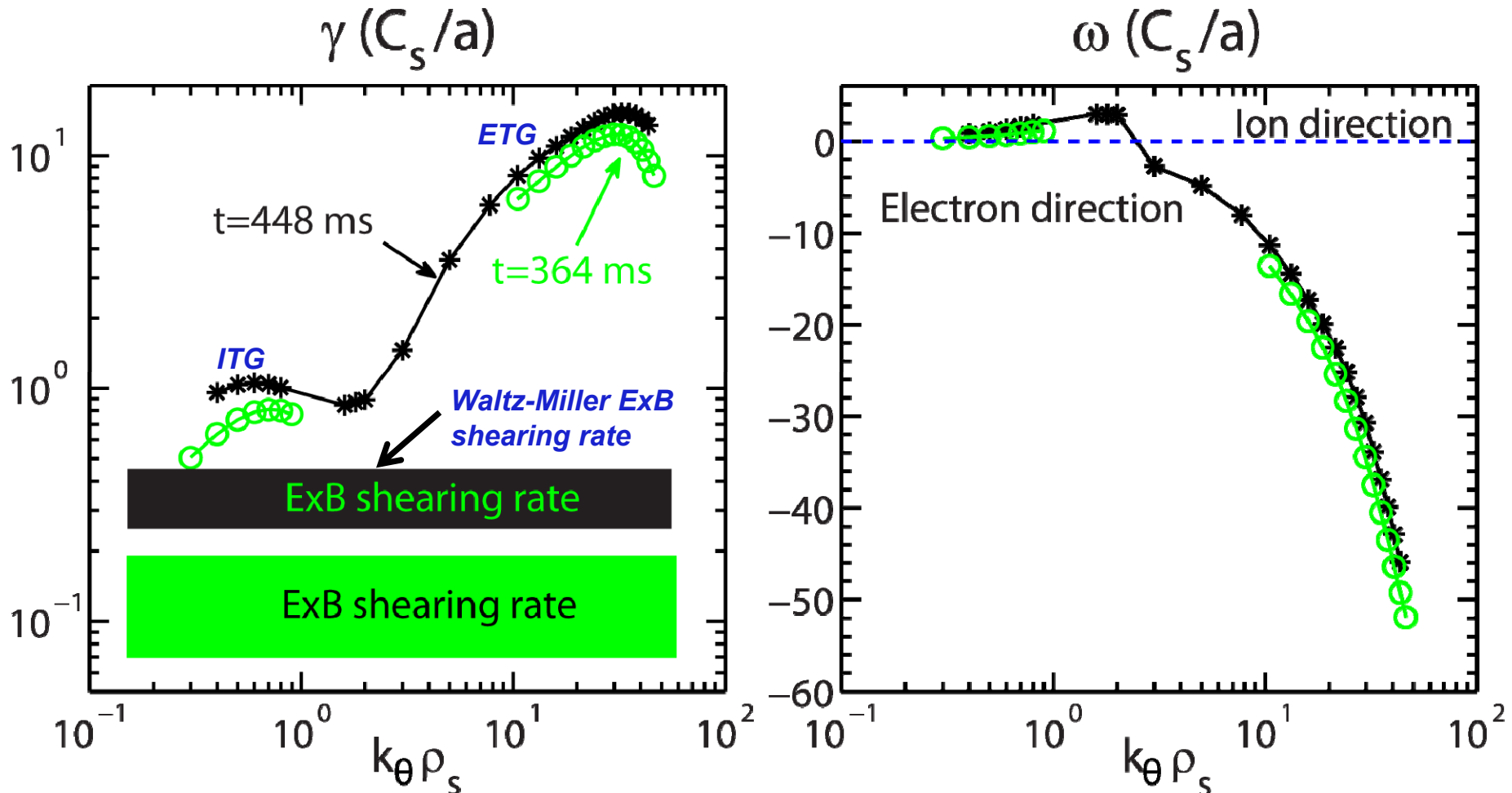
- Large decrease in electron and ion thermal diffusivity also in the outer half of the plasma
- Decrease in χ_i and χ_e correlates with the decrease in peak spectral power in the high-k measurement region
 - Except when MHD activities become important at t=482 ms



- 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

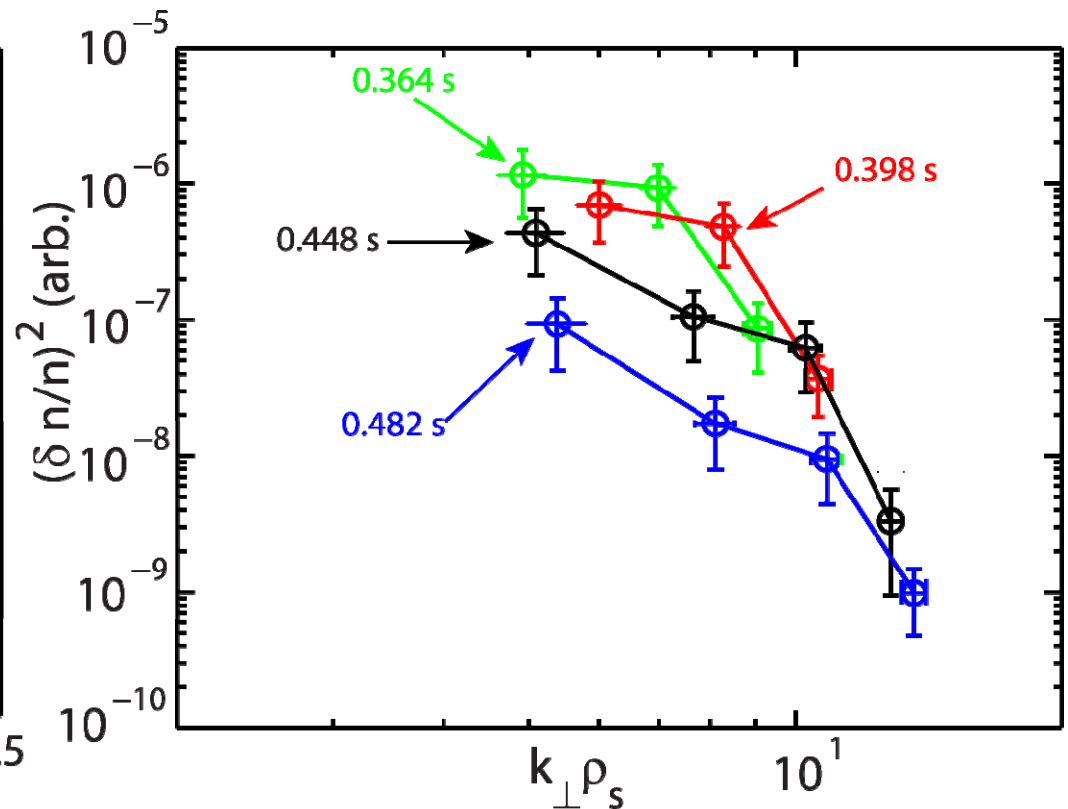
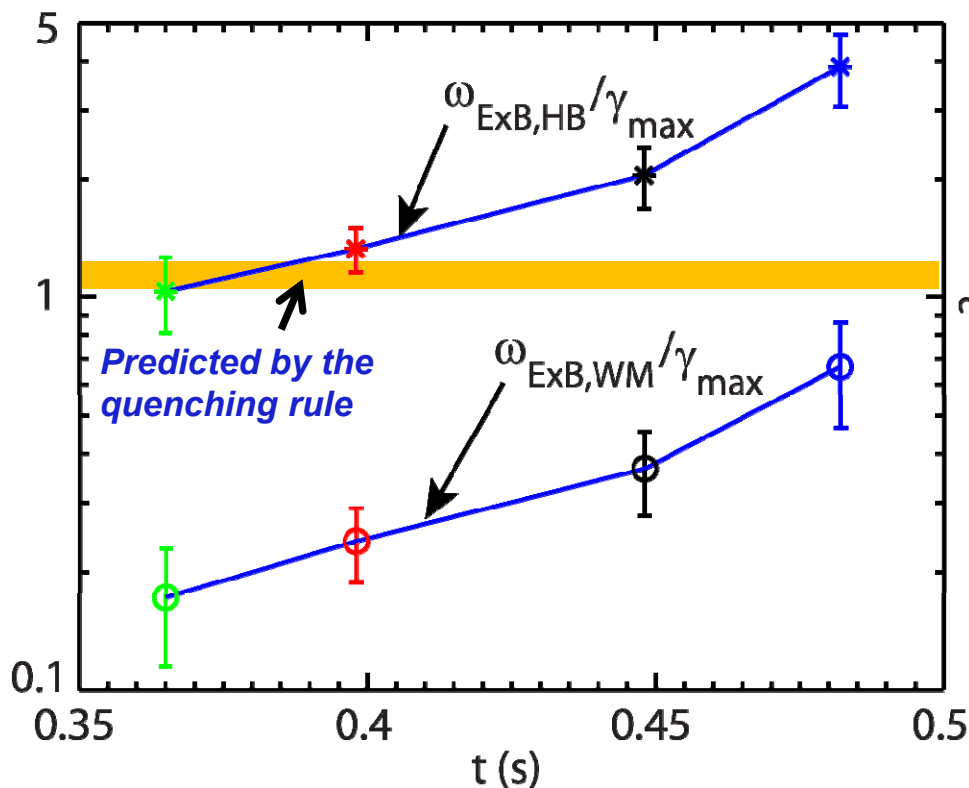
- Maximum ITG growth rate is comparable to ExB shearing rate
- Maximum ETG growth rate is more than 10 times larger ExB shearing rate



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

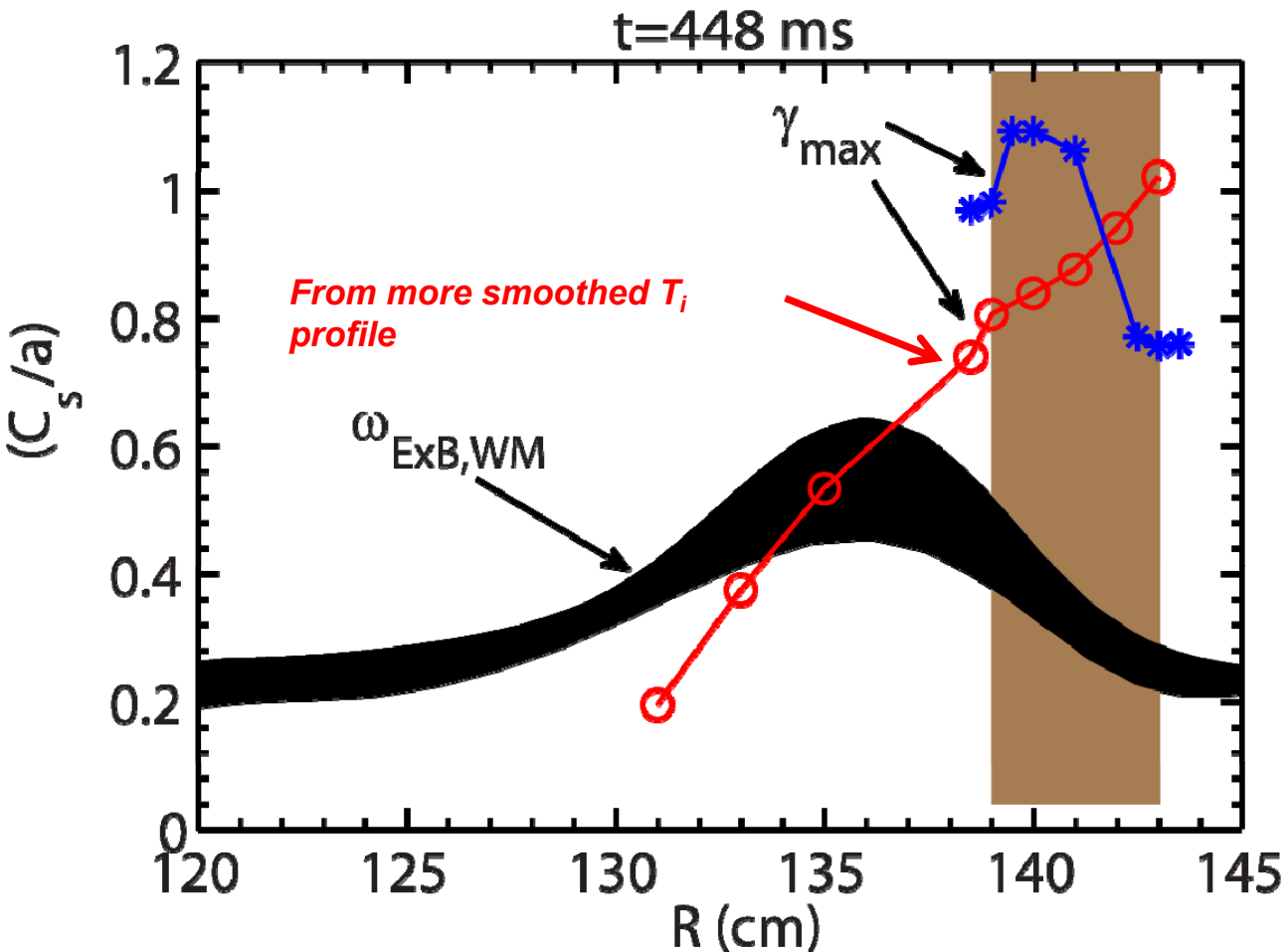
Reduction in Peak Spectral Power in the High-k Measurement Region is Correlated with Increase in $\omega_{E \times B} / \gamma_{max}$

- 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*
- $\omega_{E \times B, WM} / \gamma_{max}$ continuously increase to approach 1.1-1.2 predicted by the quenching rule with local $A \approx 1.9-2.1$ and $\kappa \approx 1.5$
 - Correlated with the continuous decrease in the high-k spectral power
 - Consistent with the nonlinear coupling between low-k and high-k turbulence



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_{T_i} locally by about 40%, but γ_{max} is only changed by about 20%

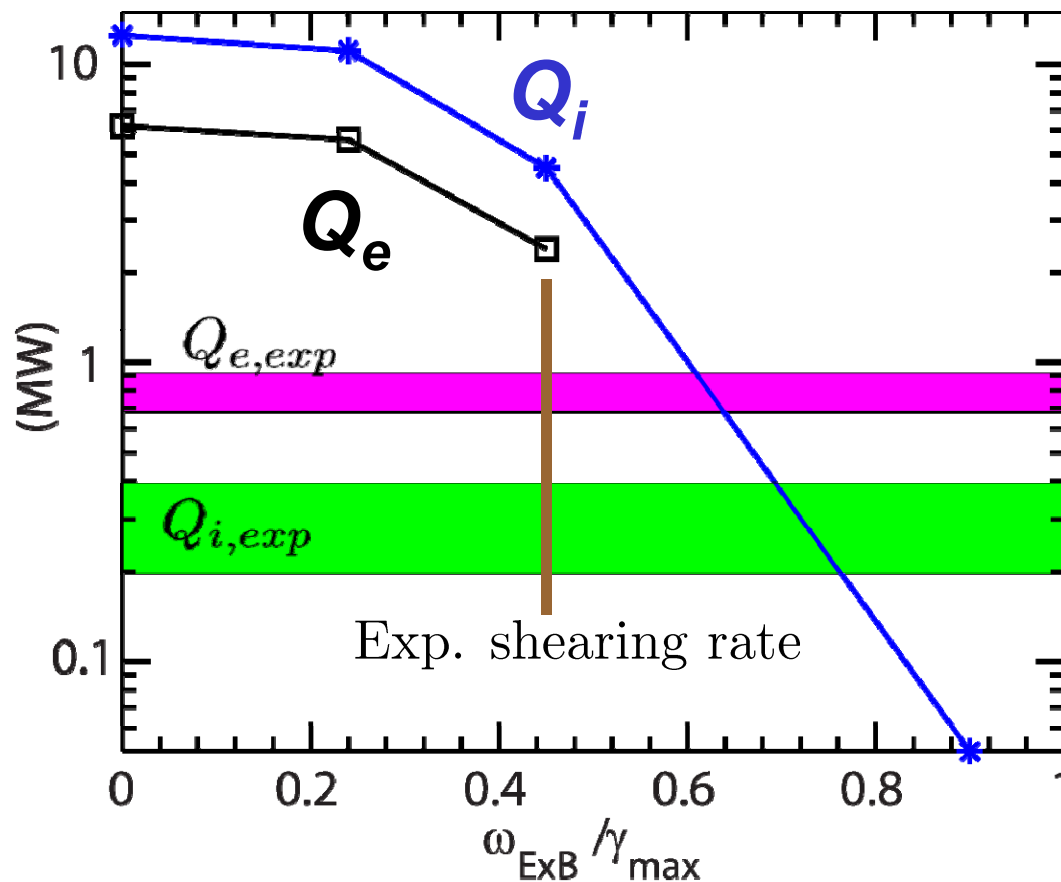


– The ITG Growth rate is not quite stiff to ion temperature gradient

- Reduction in ion temperature gradient leads to smooth transition to TEM

Local Nonlinear GK Simulations Demonstrate ExB Shear Stabilization of ITG Turbulence

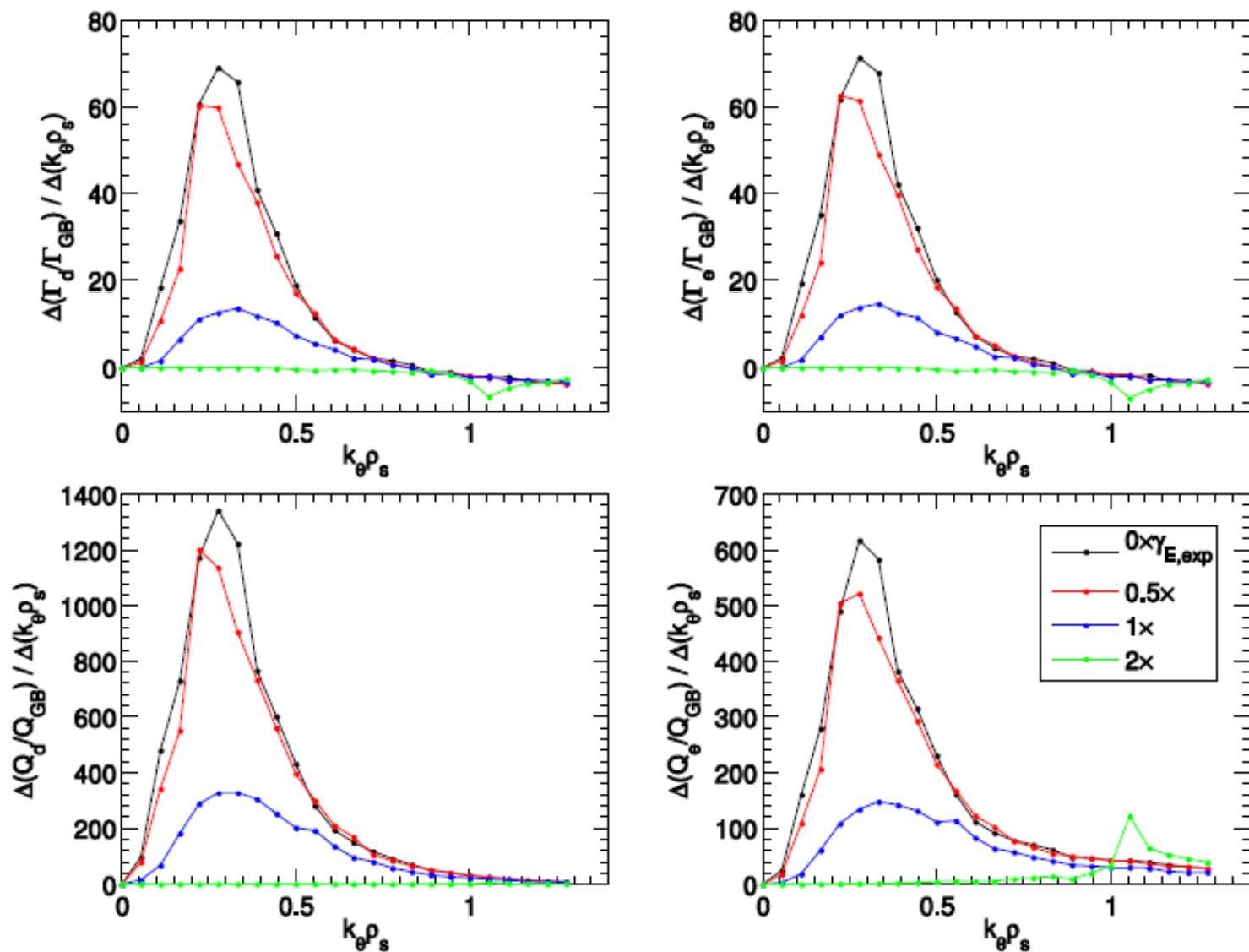
- Huge fluxes with not ExB shear ($\omega_{E \times B} = 0$) at $r/a=0.71$ and $t=448$ ms
- Completely suppressed between $1-2 \times \omega_{E \times B}$
 - Q_e with $2 \times \omega_{E \times B}$ is not physical (see next slide)



- 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

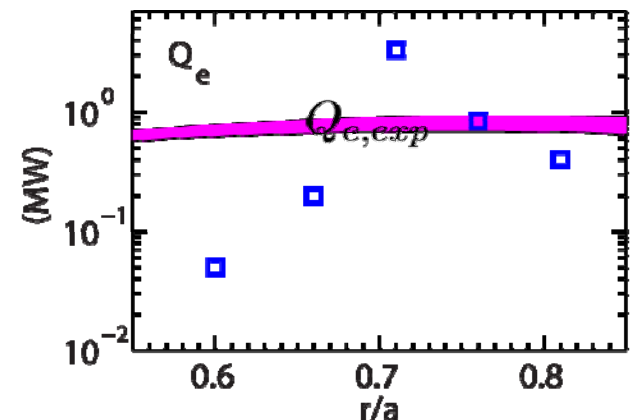
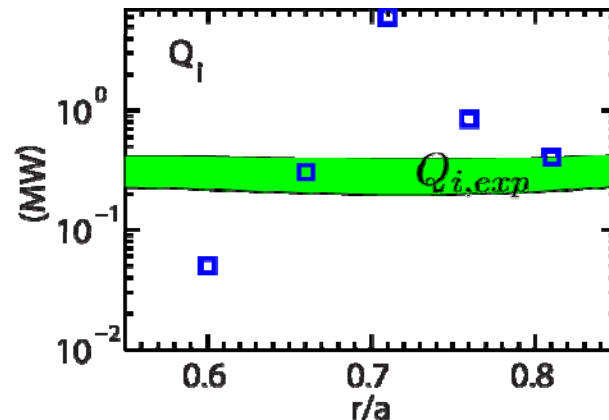
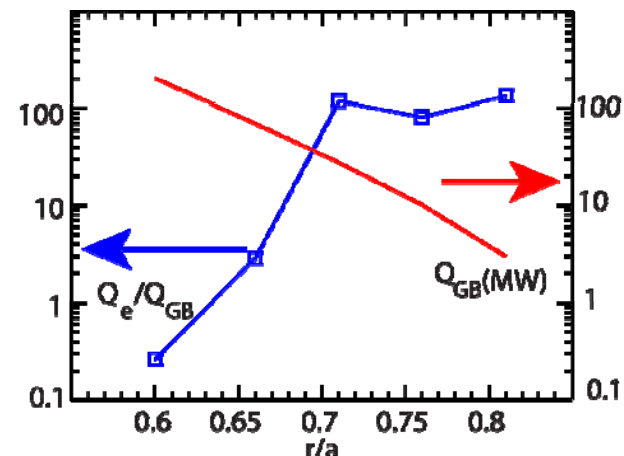
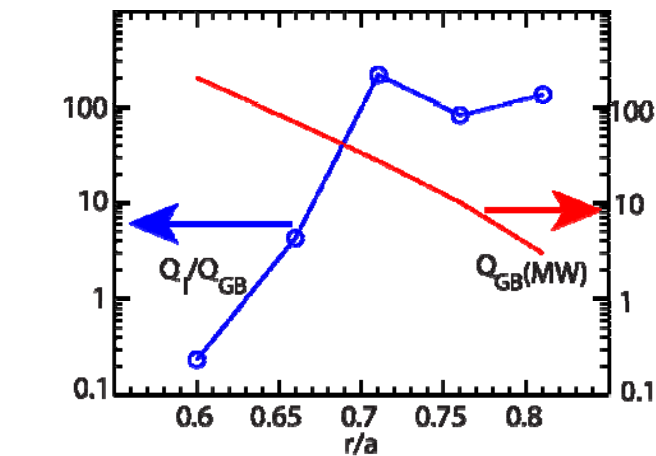
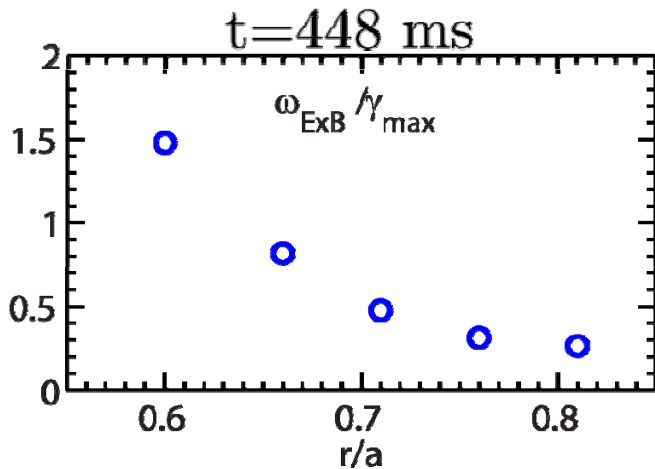
Fractional Transport Spectra Show Transport Dominated by Lower k modes

- Finite ExB shear suppresses lowest k_θ modes
- $2x\omega_{E \times B}$ leads to high- k_θ peaking of Q_e (non-physical) & reversal of Γ



Radial Variation of $\omega_{E \times B}$ 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 T_e dependence on Q_{GB} [$= n_e C_s T_e (\rho_{ref}/a)^2 S_{area}$]
- Global effects may be important (e.g. $a/\rho_s \sim 200$ at $r/a = 0.66$); also need to test sensitivity on a/L_T and multi-scale



Summary

- The L-mode plasmas show comparable confinement as that of the H-mode of conventional tokamaks, i.e. $H_{\text{ITER98}} \approx 1$
 - 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 $\omega_{E \times B, \text{WM}} / \gamma_{\text{max}}$ 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 ($r/a \sim 0.66-0.78$)
 - Investigating a/L_T sensitivity, global effects and multi-scale transport

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