NSTX-U Alcator C-Mod Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Studying High-k Turbulence With Microwave Scattering on NSTX

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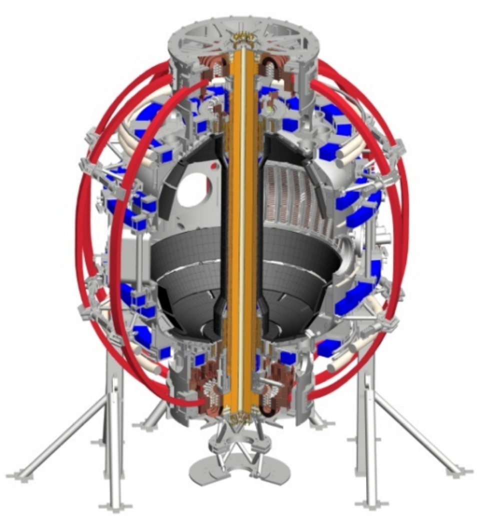

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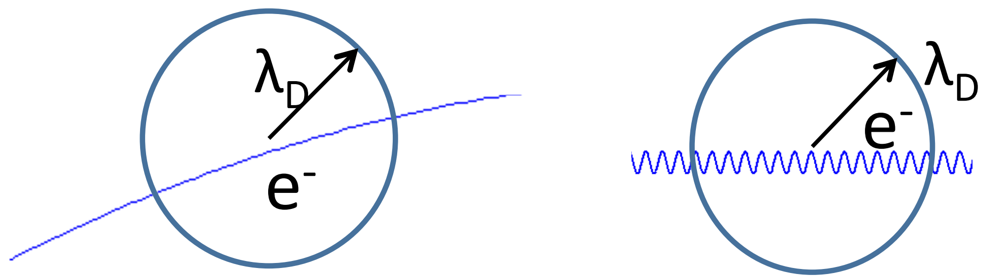
Anomalous electron thermal transport is observed in all NSTX confinement regimes

- Theory and experiments suggest that toroidal **ETG** turbulence is a candidate for anomalous electron thermal transport.
- A ***microwave collective scattering diagnostic*** at NSTX measures electron density fluctuations indicative of high-k turbulence on the electron gyro-scale $k_{\perp}\rho_e \leq 1$.
- A correlation between **electron density gradient** and electron scale high-k fluctuations measured by the high-k scattering diagnostic is established on a set of ***current ramp-down***, NBI heated H-mode plasmas.
- Linear stability analysis using GS2 code confirms the stabilizing effect of electron density gradient.
- GS2 linear runs show that wavenumbers at maximum linear growth rates shift to even higher k values ($k_{\perp}\rho_s > 40$) as electron density gradient is increased.
- Linear growth rates at high wavenumbers are less sensitive to electron density gradient than linear growth rates at lower wavenumbers.

Collective Thomson Scattering Theory is used to measure ETG-scale turbulence

- Collective/coherent and incoherent scattering



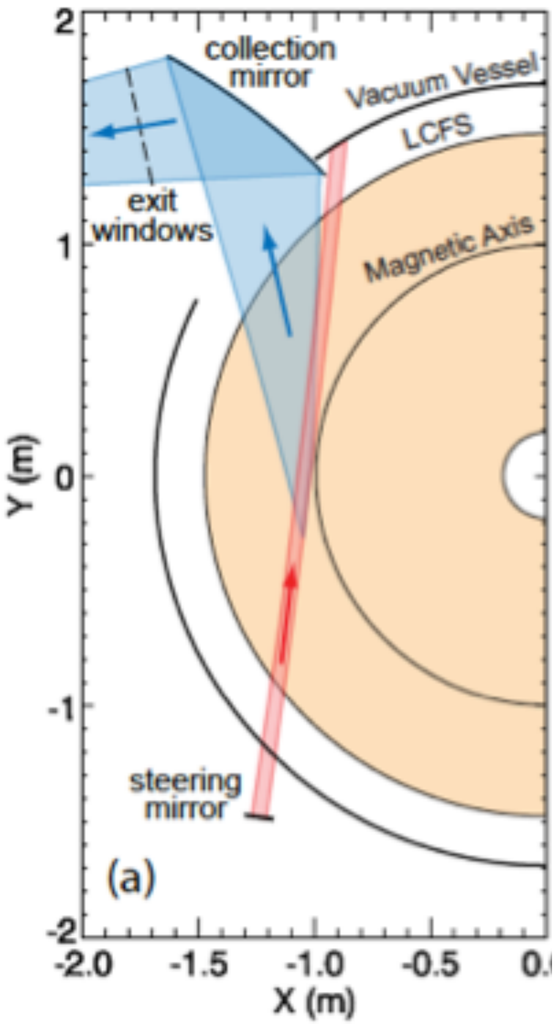
- Typical values at NSTX $\lambda_D \sim 10^{-5}$ m, $k \sim k_\perp < 10^4$ m^{-1} ⇒ $k\lambda_D < 1$ ***(collective scattering)***

- ***ETG/High-k*** fluctuations: $k_\perp \rho_e \leq 1$

- Scattered power density $$\frac{d^2P}{d\Omega d\nu} = P_i r_e^2 L_z \left|\Pi \cdot \hat{e}\right|^2 \frac{\left|\tilde{n}_e(k,\omega)\right|^2}{VT}$$

r_e	classical electron radius
V, L_z	volume and length of scattering volume
Π	polarization tensor
$\hat{e}$	direction of incident electric field
T	observation time

High-k Microwave Scattering Diagnostic at NSTX



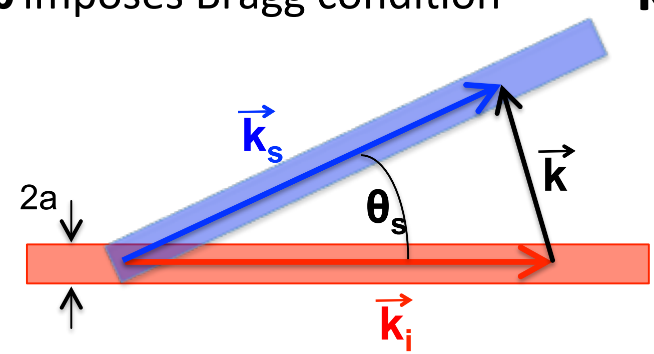
View from top of NSTX
(D.R. Smith PhD thesis 2009)

- Gaussian Probe beam: 200 mW, 280 GHz, $\lambda \sim 1.07$ mm, a = 3cm ($1/e^2$ radius).
- Propagation close to midplane => k_r spectrum.
- 5 detection channels => Wavenumber range $k_r \sim 5\text{-}30\ \text{cm}^{-1}$.
- Wavenumber resolution $\Delta k = \pm 0.7\ \text{cm}^{-1}$.
- Radial coverage: R = 106-144 cm.
- Radial resolution: $\Delta R = \pm 2$ cm.
- ***Three wave-coupling*** between incident probe beam $(\mathbf{k_i}, \boldsymbol{\omega_i})$ and plasma $(\mathbf{k}, \boldsymbol{\omega})$.

$$\vec{k}_s = \vec{k} + \vec{k}_i \qquad \omega_s = \omega + \omega_i$$

- $\omega_i, \omega_s \gg \omega$ imposes Bragg condition

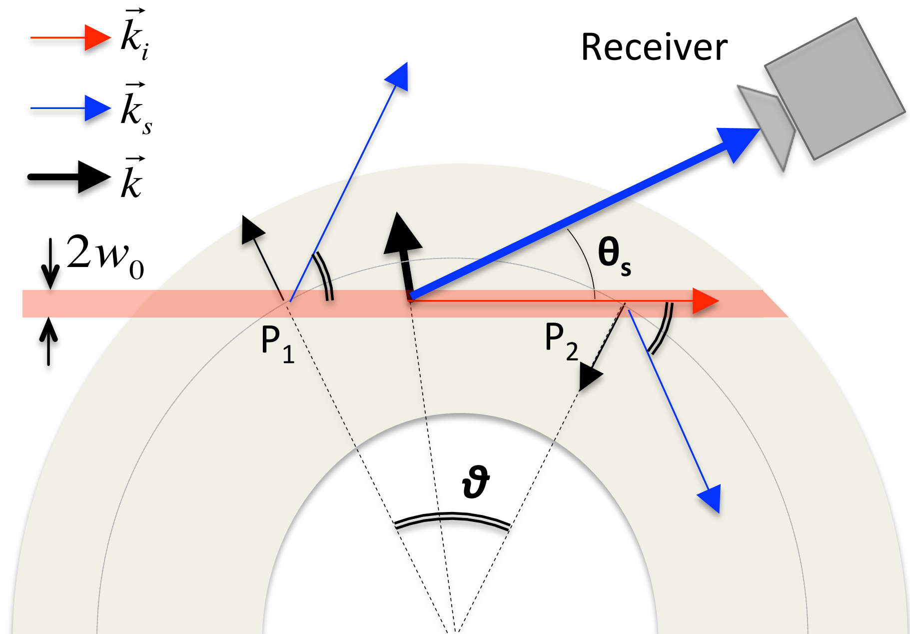
$$k = 2k_i \sin(\theta_s/2)$$



Spatial Localization and Wavenumber Resolution

- Volume overlap of incident and scattered beams leads to poor spatial localization.
- Theory [*cf. Horton Rev. Mod. Phys. 1999*] predicts $k_{//}$*~1/qR << $k_\perp$* => $\vec{k}\cdot\vec{B}\approx 0$
- Plasma fluctuations must satisfy: $\begin{cases} k\cdot B\approx 0 & (1) \\ k = 2k_i\sin(\theta_s/2) & (2) \end{cases}$ (1) Perpendicular fluctuations. (2) Bragg Condition
- When incident beam forms a small angle with ***B,*** (1) and (2) become highly dependent on ***toroidal curvature*** of magnetic field (*cf.* scattered beams at P_1 and P_2 in the figure). ***Oblique propagation*** (outside the midplane) of incident beam exploits this phenomenon and enhances *longitudinal localization* of fluctuations [*cf. Mazucatto Phys. Plasmas 2003*].
- For <u>midplane propagation</u>, (1) and (2) are only satisfied at P_1 and P_2 and fluctuation wavenumber is purely in the **radial direction**.
- In practice, beam propagation is out of midplane, but oblique angle is small (~ 5°). ***k*** is *mostly* radial.
- Gaussian beam width dictates k and R-resolution

$$A(r_\perp) = \exp(-r_\perp^2/w_0^2)$$
$$G(k_\perp) = \exp(-k_\perp^2/\Delta k^2)$$
$$\Delta k = 2/w_0$$



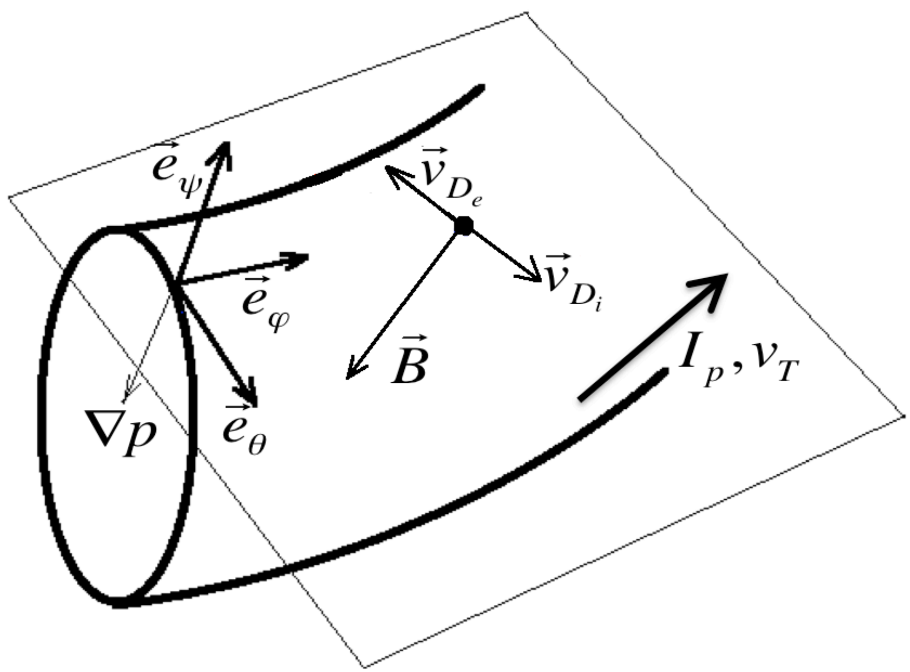
View from top (not to scale)

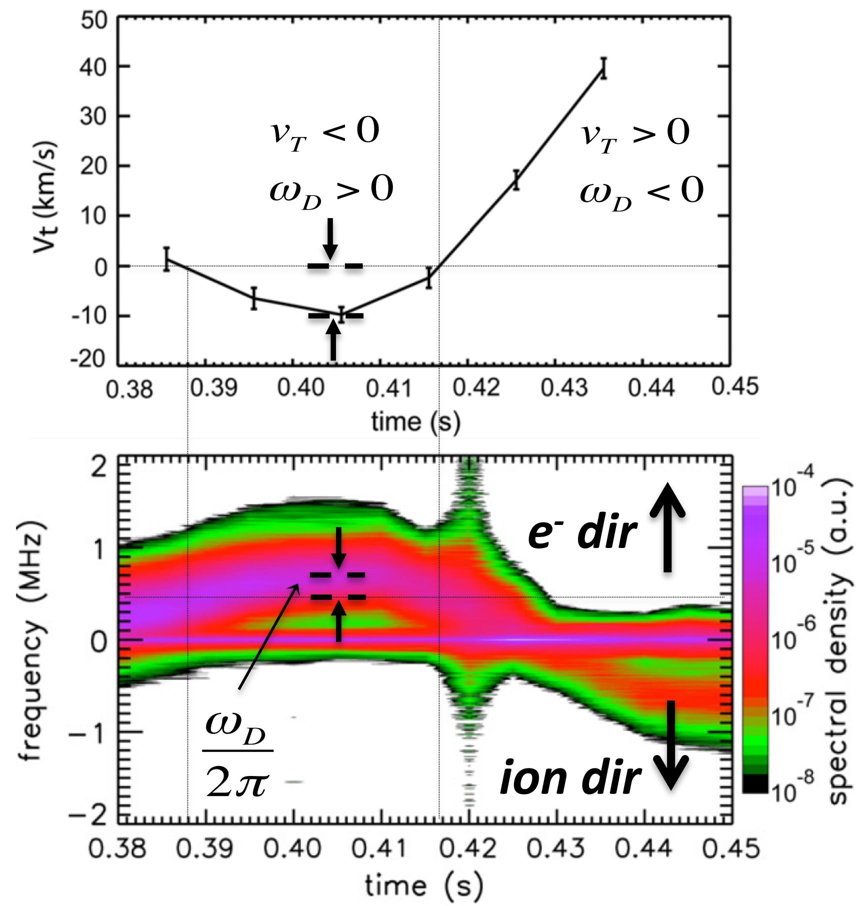
Toroidal Rotation has an Effect on Measured Fluctuations: Doppler Shift

Outboard measurements ($k_r < 0$)

$$if \quad \vec{v}_{D_e} \cdot \vec{e}_\varphi < 0 \quad (k_T < 0)$$

$$\Rightarrow \omega_D \approx k_T v_T < 0 \quad (for\ v_T > 0)$$





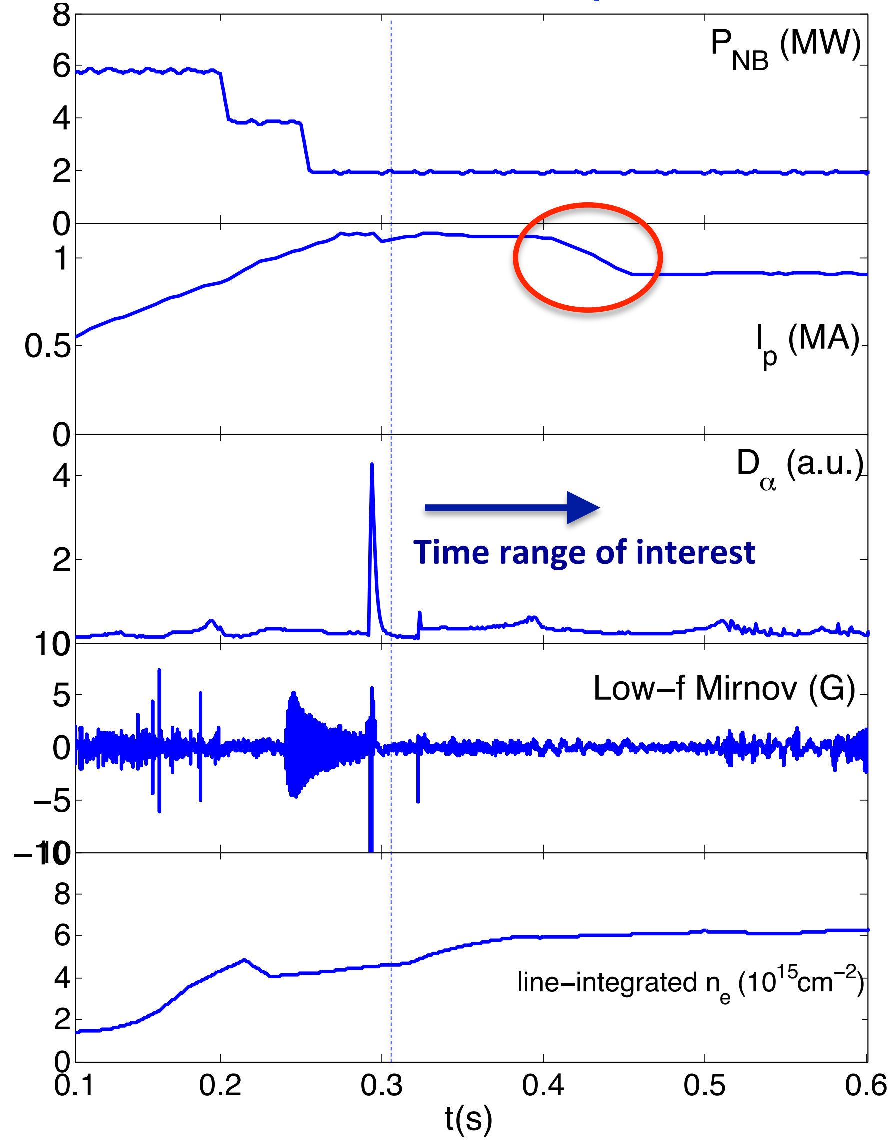
Adapted from Mazzucato Nuc. Fusion 2009.
Here *f>0* => e- direction.

Doppler shift is mainly affected by *toroidal* rotation component ($\omega_D \sim k_T v_T$). ***Doppler shift*** can make fluctuations *appear* to propagate in the **ion diamagnetic drift direction** (fig. t>0.42 s).

A Set of NBI-heated H-mode Plasmas is Used to Study High-k Turbulence during Current Ramp-down

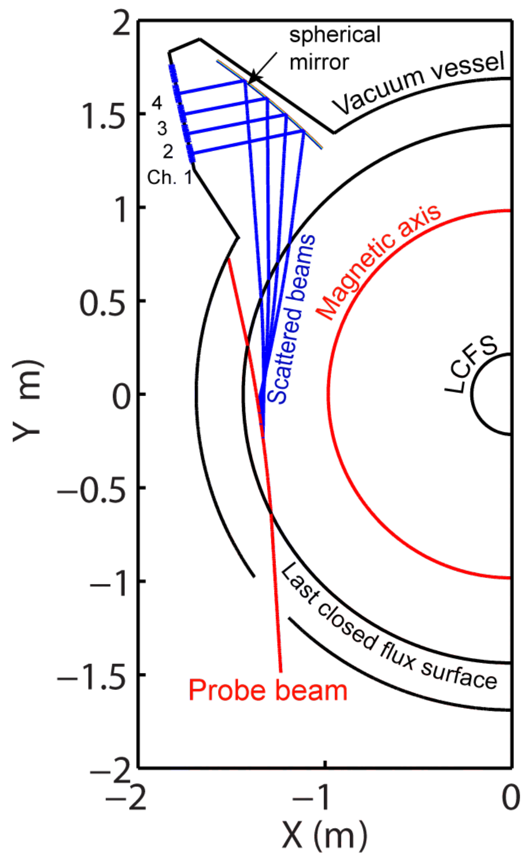
- **NBI heated**, HHFW heating is absent during the run.
- ***Current ramp down*** between
  t = 400 ms and t = 450 ms (from LRDFIT).
- Time range of interest is t >~ 300 ms, covering current ramp-down phase, and after ELM event at t ~ 290 ms.
- **MHD activity is quiet during that time.** Before t ~ 290 ms MHD activity is high (*cf.* low-f Mirnov signal).
- Line integrated density is fairly constant during the time range of interest.

Shot 141767. B_T ~ 5kG



Each Channel of the NSTX High-k Scattering System Detects a Fluctuation Wavenumber *k*

- Channel 1 detects highest $k_\perp$ and k_T, Doppler shift is greatest.
- High peak at *f ~0* corresponds to stray radiation.



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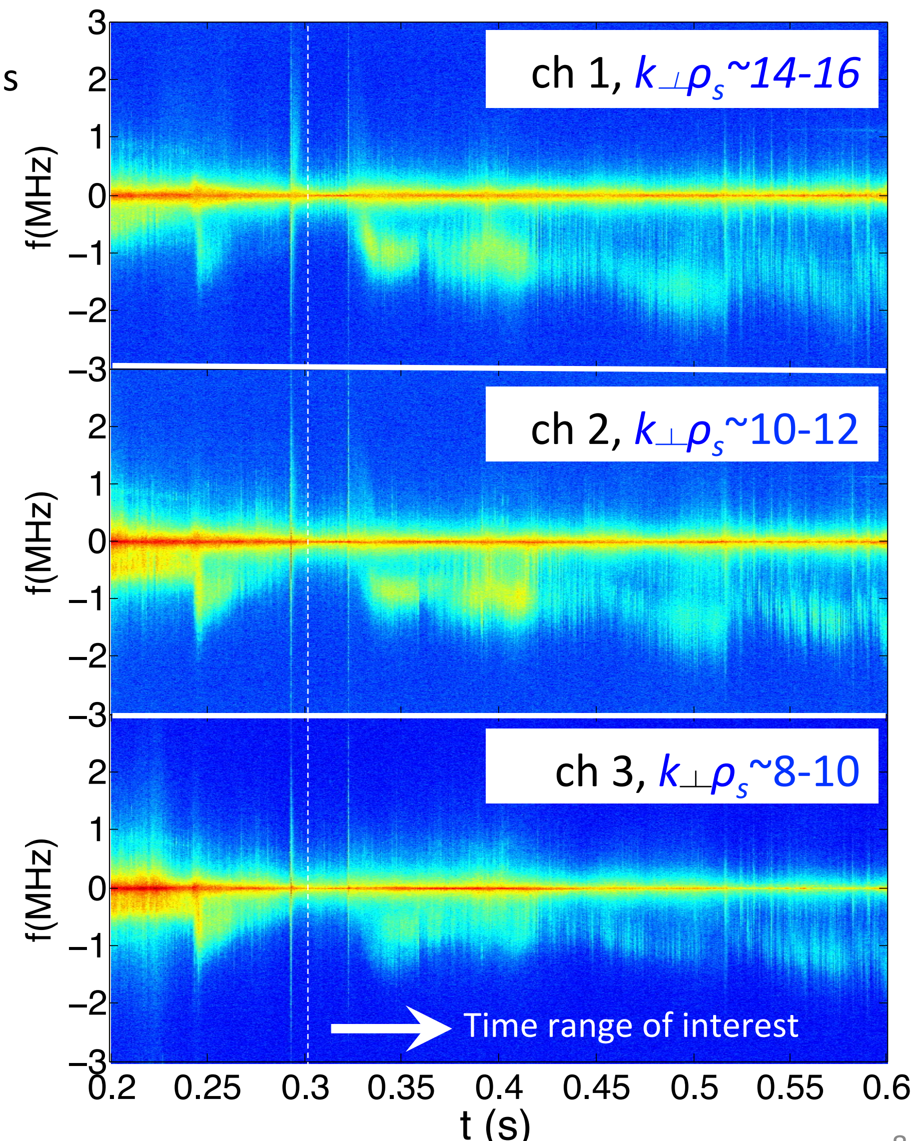
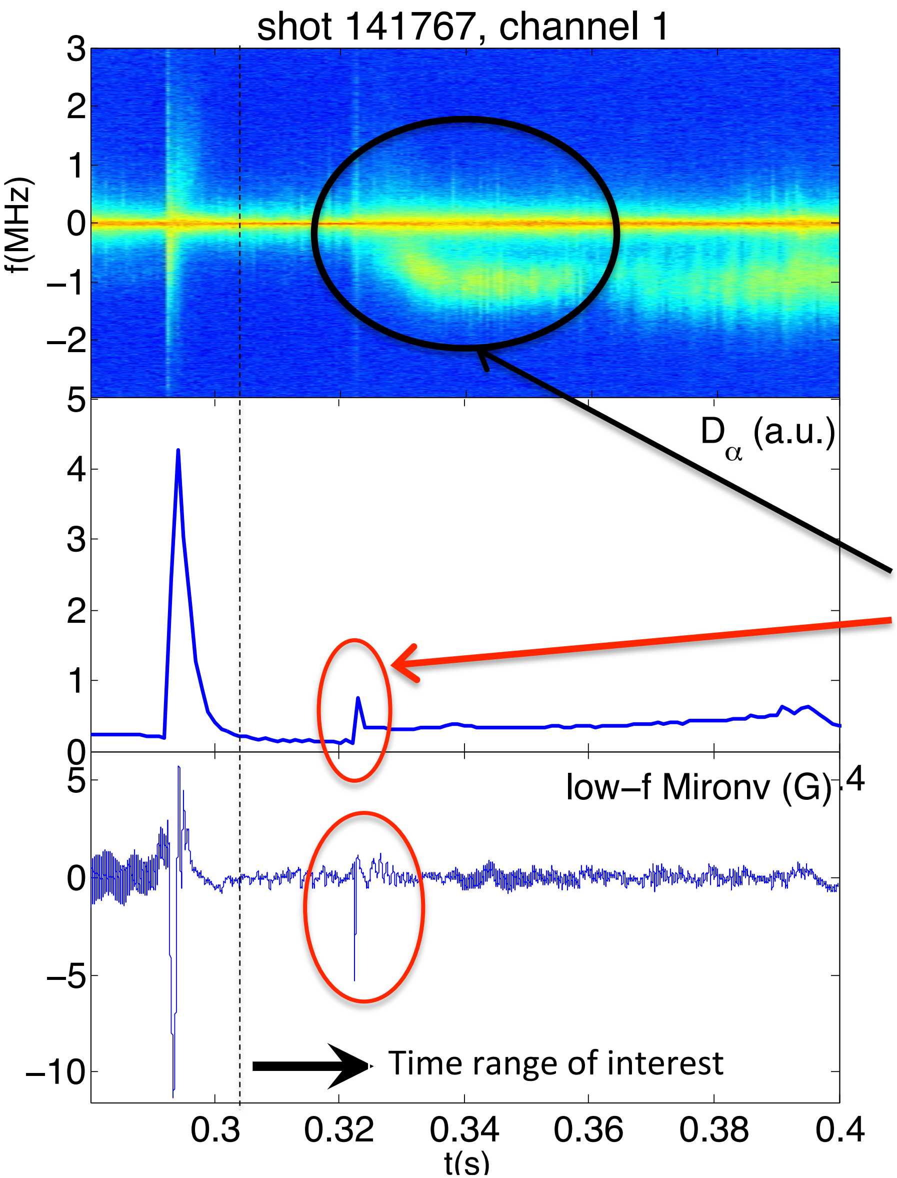


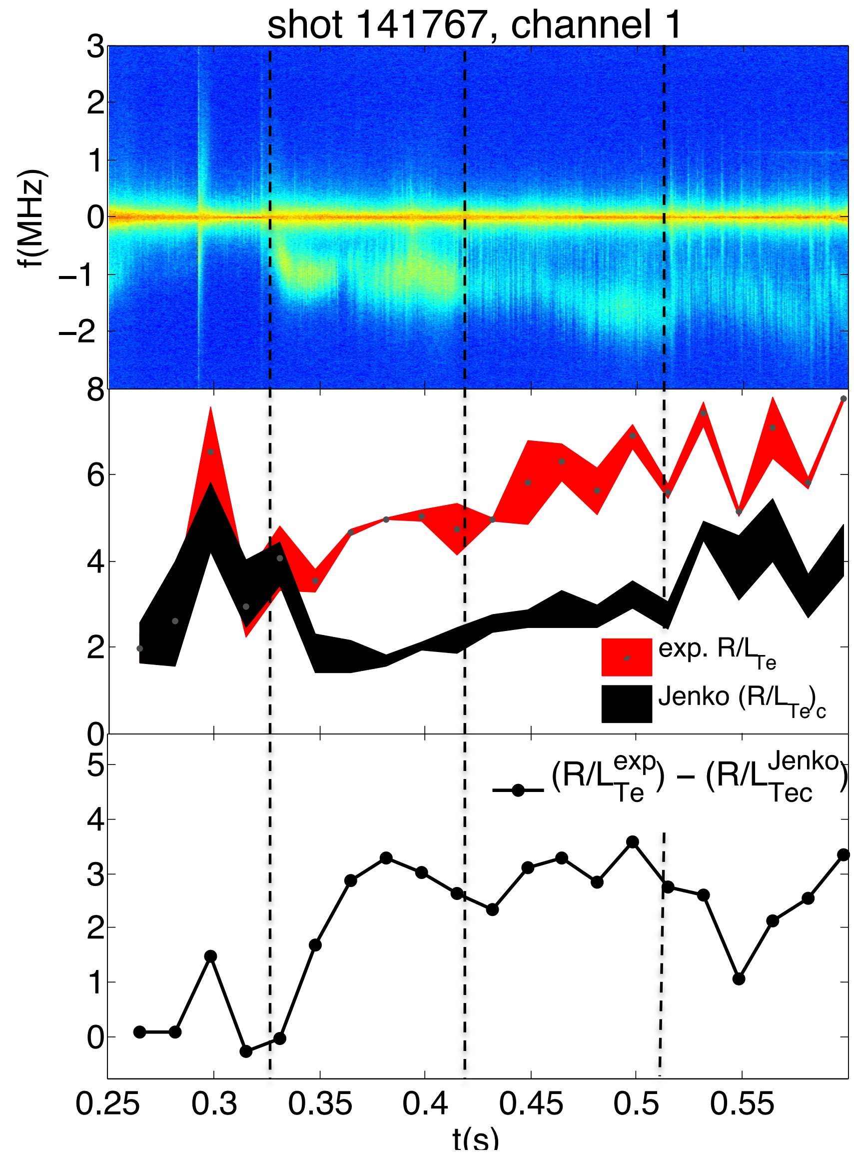
High-k Fluctuations Start after Small Spike in D_α and Mirnov Signal



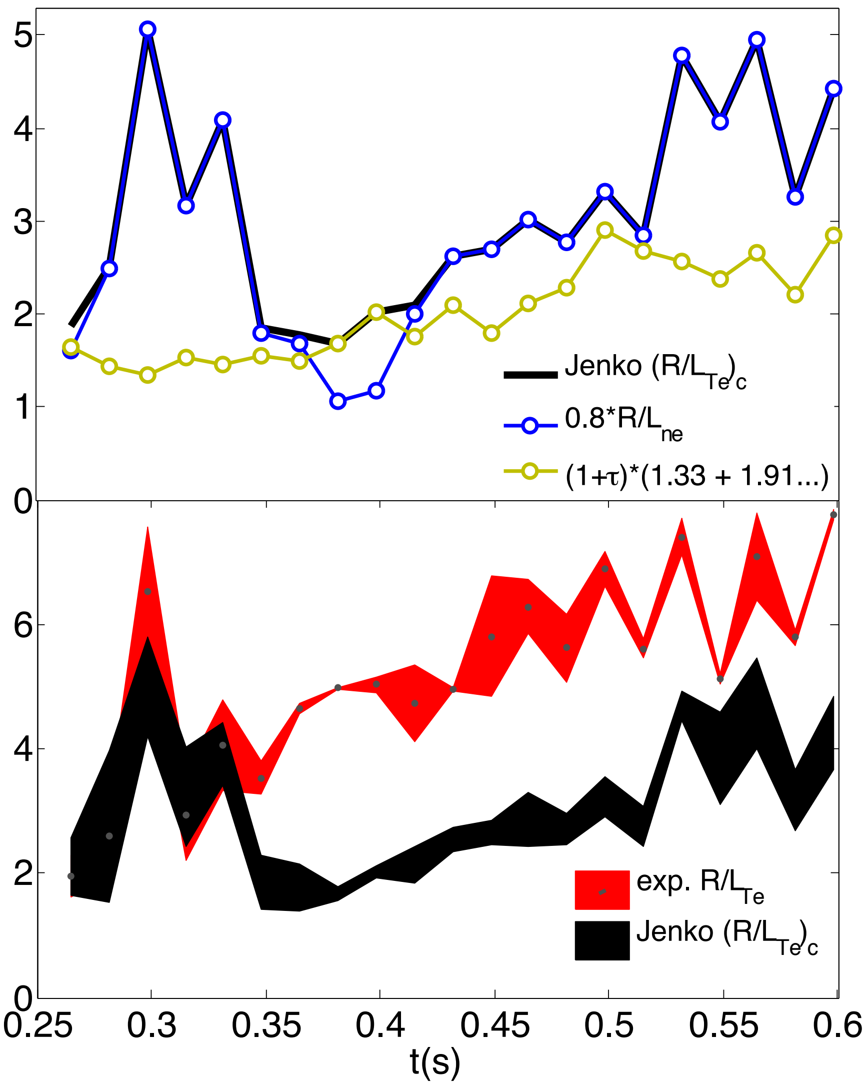
- Before t ~ 290 ms, MHD activity is high. At ~290 ms, an ELM event takes place and MHD activity quiets.
- Between t ~ 290 ms and t ~ 320 ms, high-k fluctuations are absent and MHD activity is quiet.
- **High-k fluctuations** start at t ~ 320 ms, after small ELM event, detected in ***D_α* *and Mirnov signal***.

Observed Fluctuations Correlate to Difference Between Critical and Experimental ETG

- **Normalized electron temperature gradient** (R/L_{Te}) is calculated at the scattering location (R~135 cm), and plot along with the ***Jenko critical gradient*** [*cf. Jenko Phys. Plasmas 2001].*
- Prior to **t ~ 320 ms**, R/L_{Te} ~ $(R/L_{Tec})^{Jenko}$ and ETG turbulence is marginally stable. No observed fluctuations. After t ~ 320 ms, $R/L_{Te} > (R/L_{Te})_{crit}$ and fluctuations develop.
- As $(R/L_{Te})_{crit}$ increases and gets closer to R/L_{Te} detected fluctuations decrease (**t ~ 410 ms** and **t ~ 510 ms**).
- During period ~ 350 ms < t < ~ 500 ms, a similar difference in R/L_{te} - $(R/L_{Te})_{crit}$ produces very different fluctuation levels. This will be later explained by the *density gradient stabilization of lower numbers*.
- The applicability of Jenko's critical ETG is discussed in slides 14 and 15.



Theory Predicts Electron Density Gradient Can Drive the Difference $(R/L_{Te})_c$ – R/L_{Te} and Stabilize Turbulence



- Jenko critical gradient is a maximum of a ***R/L*$_{ne}$** term and an ***s/q*** term [*cf. Jenko Phys. Plasmas 2001]*.

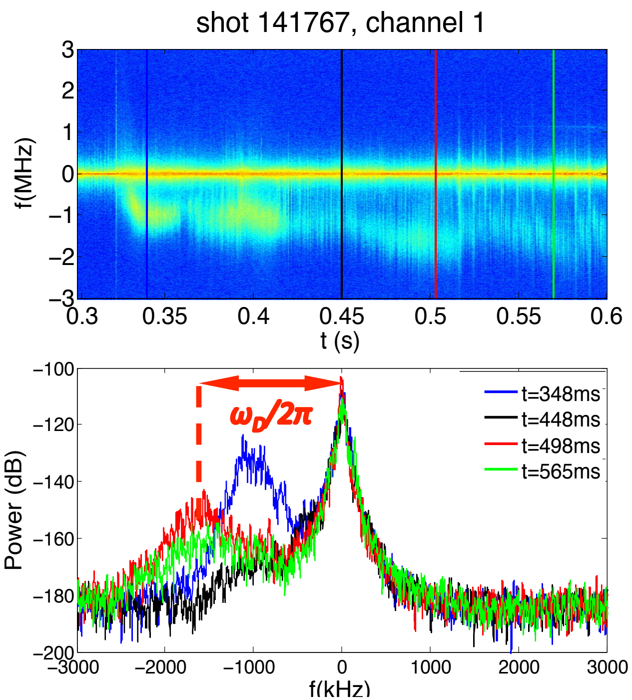
$$(R/L_{Te})_{crit} = \max \begin{cases} 0.8R/L_{ne} \\ (1+\tau)(1.33+1.91\hat{s}/q)(1-1.5\varepsilon) \end{cases}$$

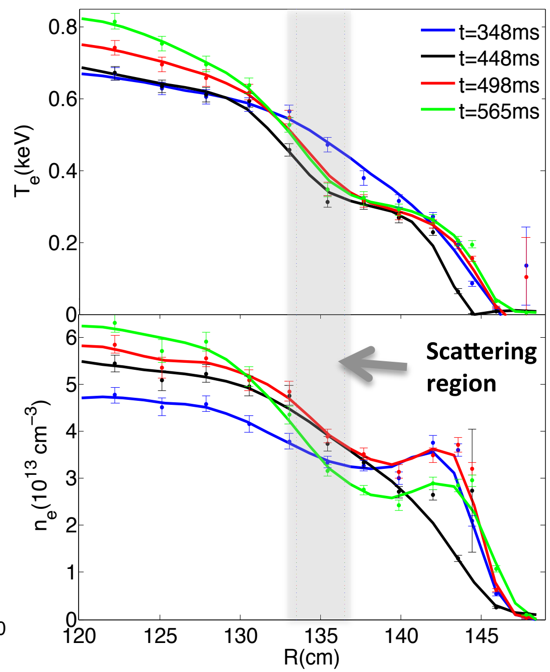
with $\tau = Z_{eff}T_e/T_i$

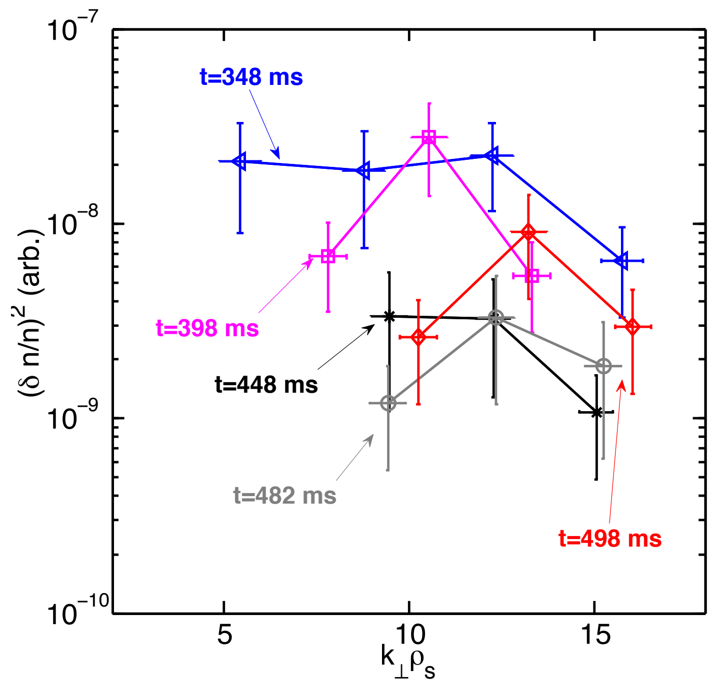
- High values of ***R/L*$_{ne}$** can make it the dominant term in Jenko's *$(R/L_{Te})_{crit}$* formula. According to this formula, ***R/L*$_{ne}$** can drive the difference between critical and experimental ETG.

- High enough values of ***R/L*$_{ne}$** *could* bring critical ETG to experimental ETG levels or even higher. This *should* have a ***stabilizing*** effect on turbulence.

Observed High-k Fluctuations Correlate to Local Electron Density Gradient

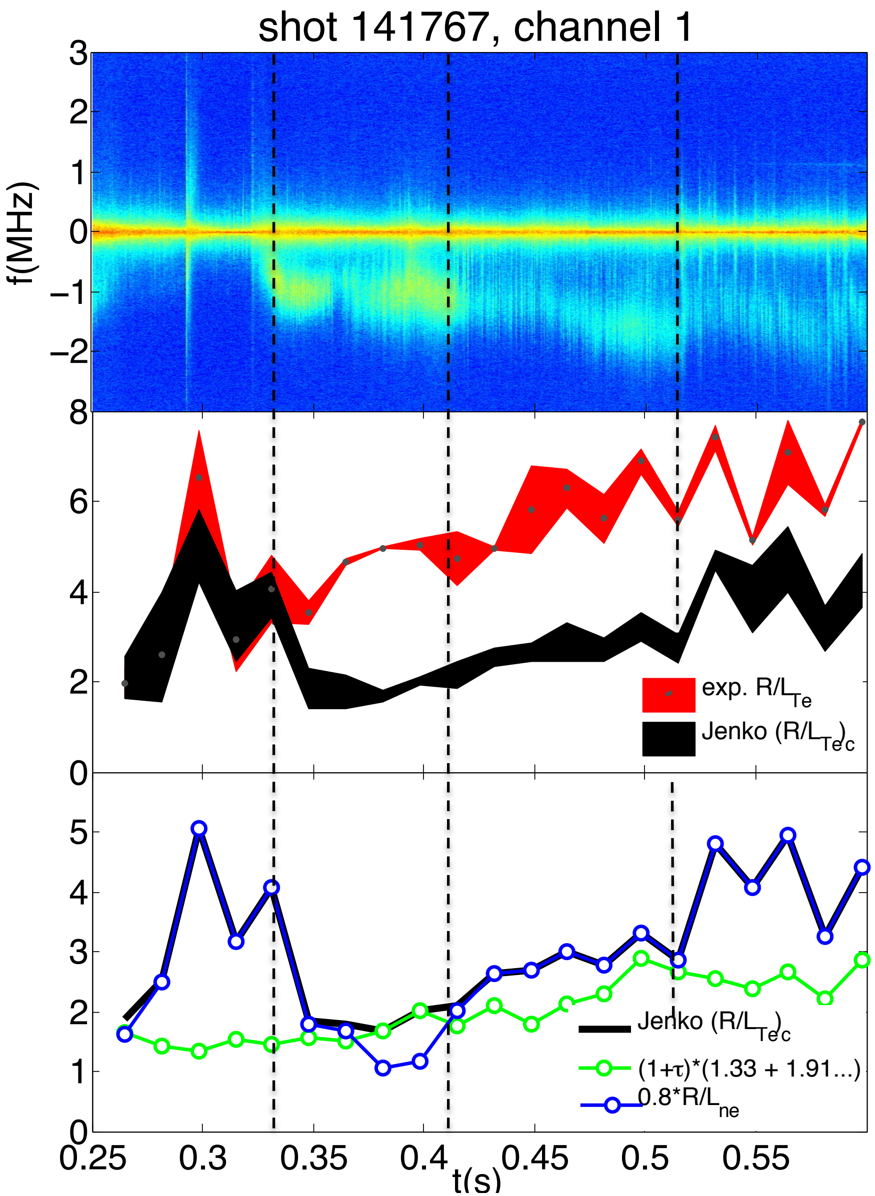






- Electron Density Gradient suffers the biggest change in the **scattering region**.
- Doppler shift is measured as distance from 0 to observed fluctuation frequency.
- A big change in the electron density fluctuation level (right figure) is observed between t = 348 ms and t = 448 ms. A notable change in R/L_{ne} takes place during that time.
- In general, fluctuation levels $(\delta n_e/n_e)^2$ at low wavenumbers ($k_\perp\rho_s$<10) decrease in time.
- After t = 448 ms, $(\delta n_e/n_e)^2$ at high wavenumbers ($k_\perp\rho_s$ ~ 15) increases.

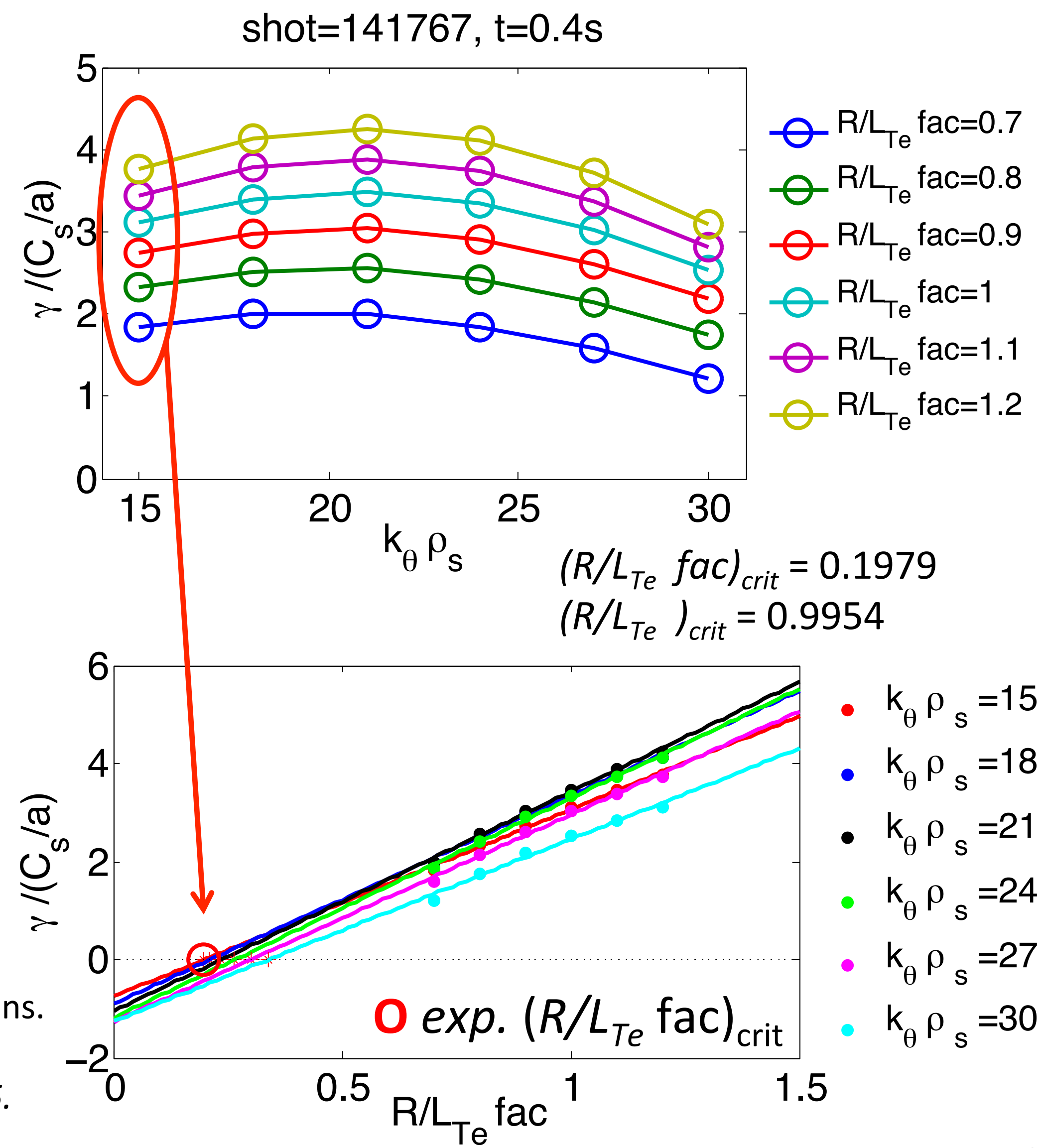
Time Traces of Local Electron Density Gradient Confirm its Influence on Observed Fluctuations



- As $\boldsymbol{R/L_{ne}}$ increases, it dominates in Jenko's formula $(R/L_{Te})_{crit}$ **(t < 340 ms, t > 410 ms & t > 515 ms)**. Fluctuations decrease during that time.
- Previous to t ~ 320 ms ETG is marginally stable with respect to Jenko critical gradient. No fluctuations are observed.
- $\boldsymbol{R/L_{ne}}$ has a ***stabilizing*** effect when it dominates Jenko critical gradient.
- Electron density gradient stabilization of ETG turbulence was already observed by Y. Ren *et al*, Phys. Rev. Letters 2011.

A Scan on R/L_{Te} is Performed to Compute a Critical Gradient with GS2 Linear Runs

- Electron temperature gradient (ETG or R/L_{Te}) is varied keeping all other quantities constant. The factor is called (R/L_{Te} fac)
- High-k linear growth rates saturate with increasing (R/L_{Te}), for different wavenumbers.
- $(R/L_{Te})_{crit}$ is found to be the minimum R/L_{Te} to satisfy $\Upsilon = 0$.

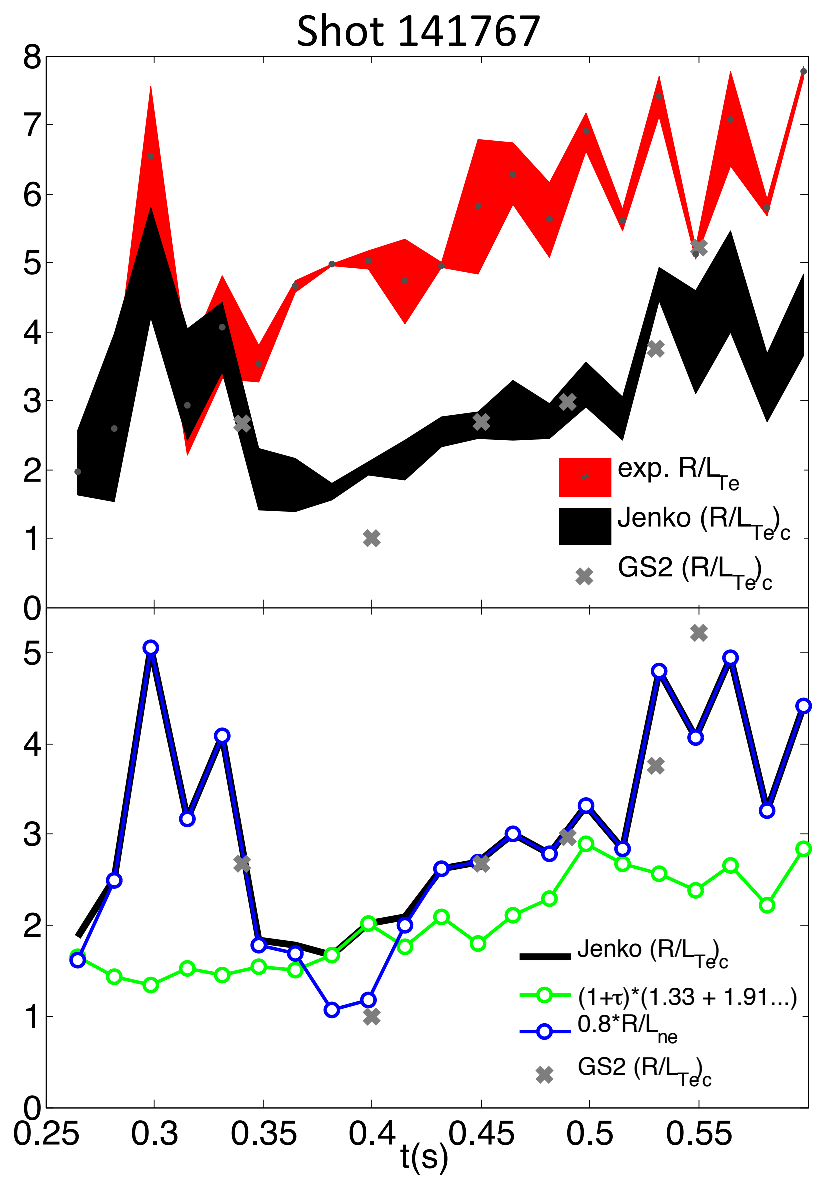


Features of GS2

- GS2 is an initial value gyrokinetic code.
- Uses flux tube geometry.
- Includes electromagnetic effects in these linear runs.
- Tracks fastest growing modes.
- *Cf. Kotschenreuther et al,Comp. Phys. Comm 1995.*

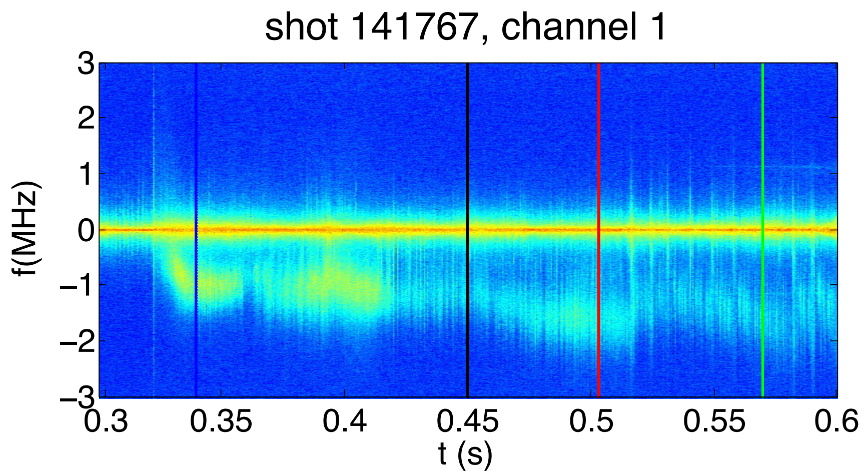
Critical Gradient Computed with GS2 Linear Runs Agrees with Jenko's Critical ETG

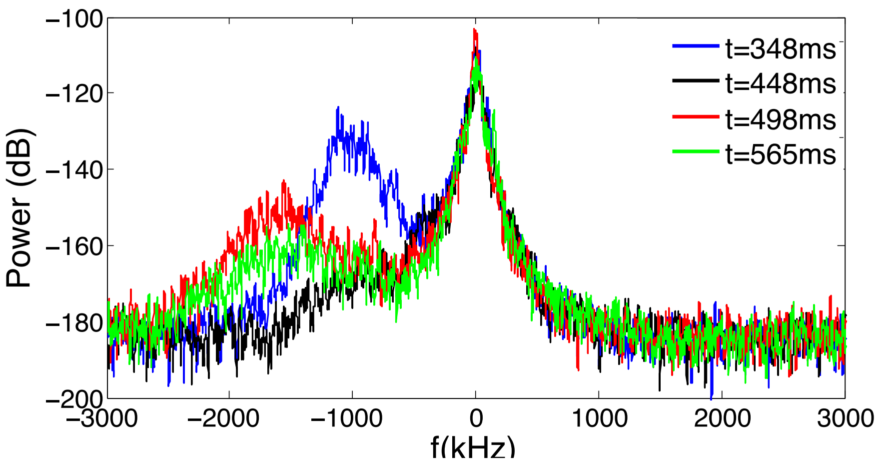
- A critical gradient computed with GS2 linear runs is plotted along with Jenko's critical gradient formula.
- Fairly good agreement is observed between GS2 calculations and Jenko's formula.
- This ***validates*** Jenko's critical ETG formula and previous comparisons with experimental ETG.

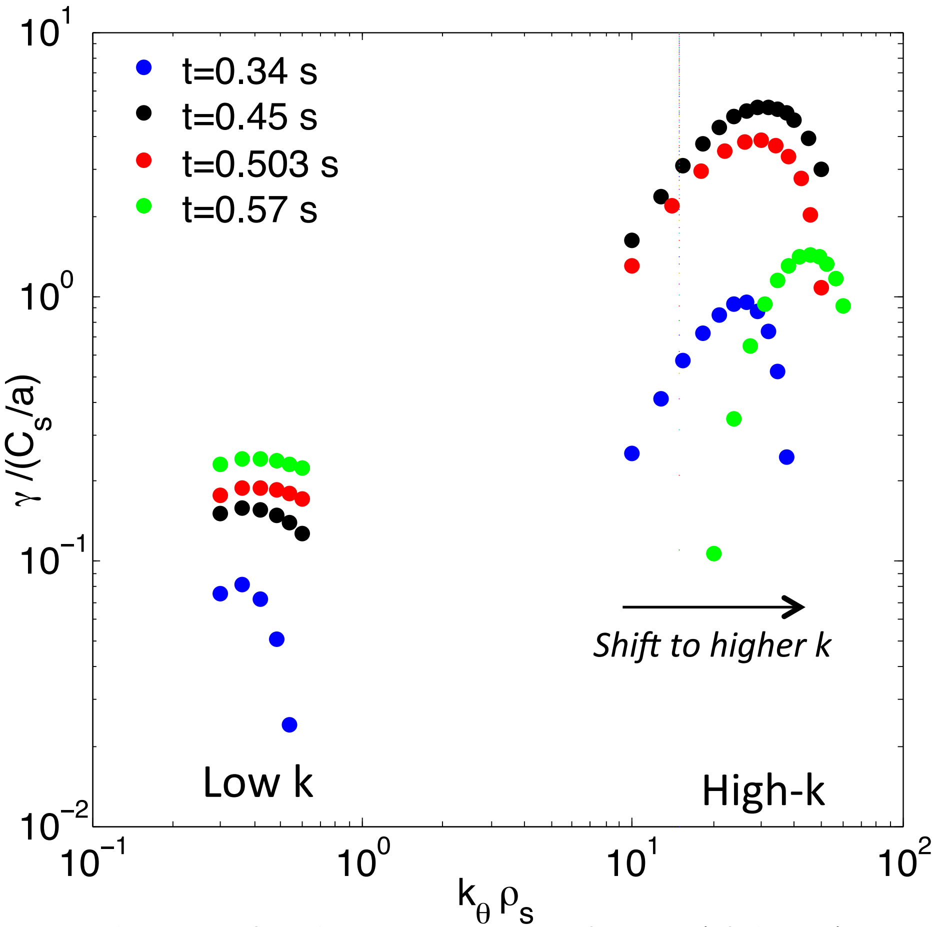


GS2 Linear Simulations Show the Wavenumbers at Maximum Growth Rate Shift to Higher *k* in Time

- Low-k linear growth rates ($k_\perp \rho_s \leq 1$) appear to increase with time, and are lower than high-k.
- Wavenumbers corresponding to maximum linear growth rate shift towards higher-k.
- As wavenumbers corresponding to maximum growth rate move to higher wavenumbers in time (e.g. t = 570 ms), observed fluctuations decrease (*cf.* bottom left figure).





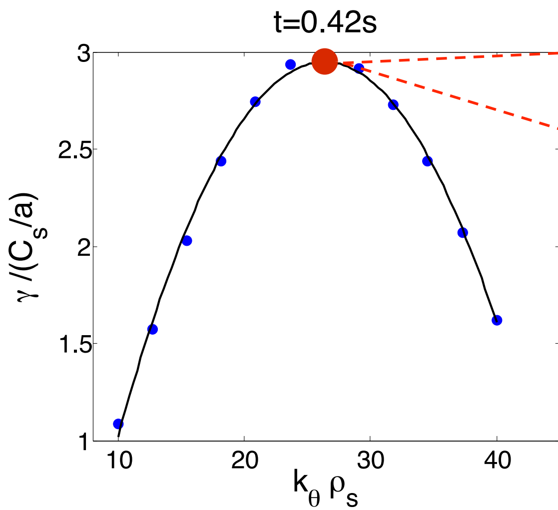


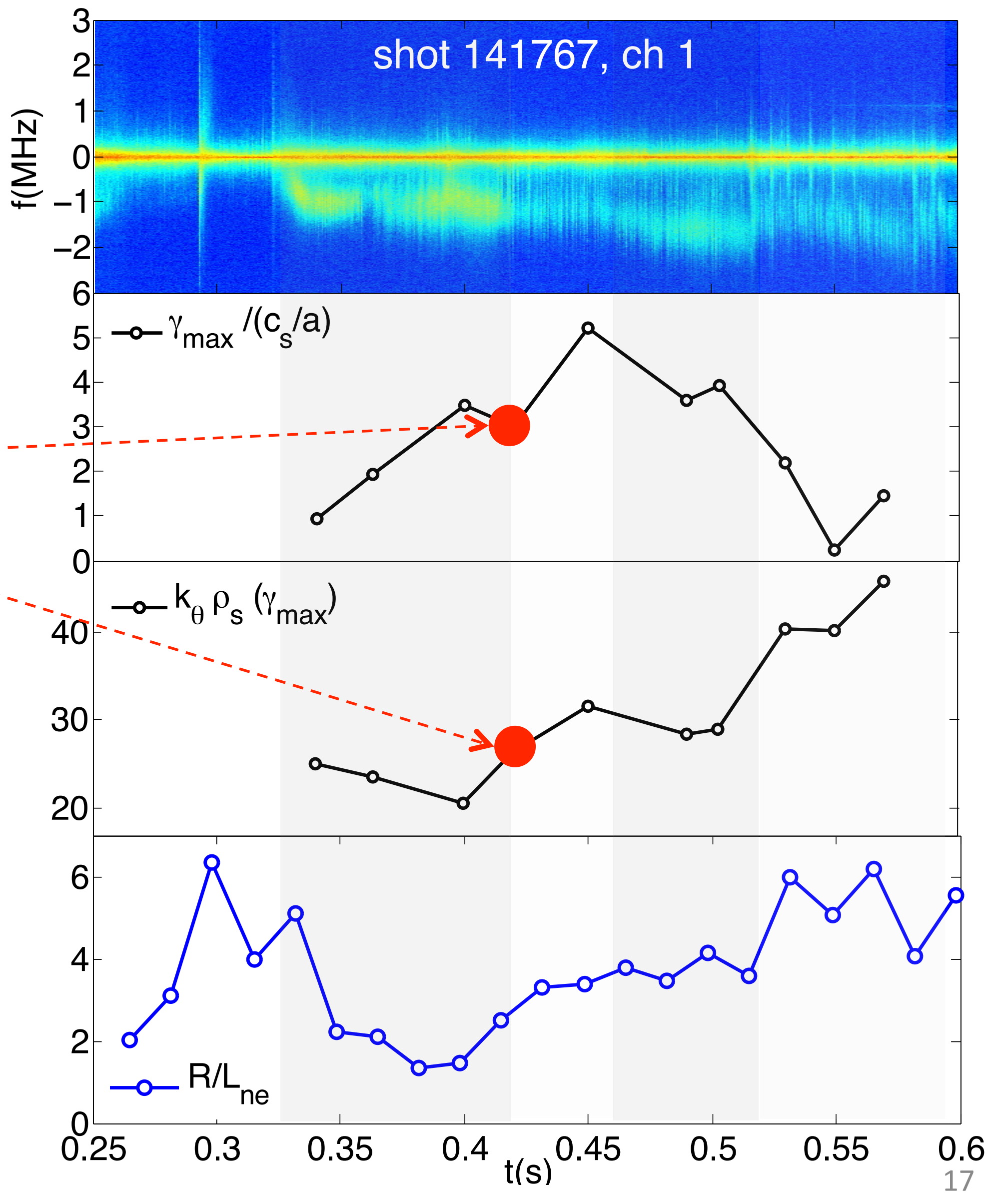
Linear growth rate $\gamma/(c_s/a)$ is a weak function of T_e through normalization. T_e does not change significantly during time range of interest (*cf.* slide 12).

Wavenumber at Maximum Linear Growth Rate Correlates to Electron Density Gradient and Observed Fluctuations

- Linear growth rates are plotted against k (at each time, *cf.* left figure) to determine the maximum growth rate $\gamma_{max}/(c_s/a)$ and the corresponding wavenumber $k_\vartheta\rho_s(\gamma_{max})$ (red dot).

- Note the evolution of $\mathbf{k_\perp\rho_s(\gamma_{max})}$ in time is very similar to R/L_{ne} at the scattering location.





- R/L_{ne} and $\mathbf{k_\perp\rho_s(\gamma_{max})}$ correlate well with observed fluctuations (*cf.* evolution within time panels).

- No correlation between maximum growth rate $\gamma_{max}/(c_s/a)$ and fluctuations is observed.

Correlation Between Wavenumber Values at Maximum Growth Rates and Electron Density Gradient

- ***Maximum linear growth rates*** ***(*** γ_{max}***)*** and the corresponding wavenumber values are plotted against local experimental ***R/L***$_{Te}$ (black) and ***R/L***$_{ne}$ (blue) along with linear fits.

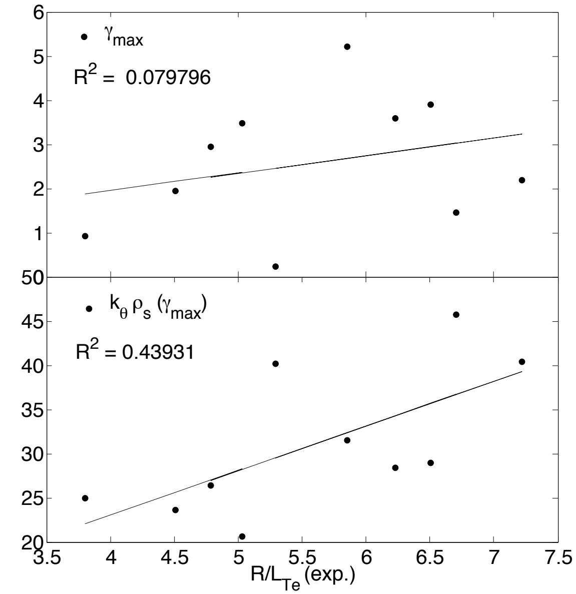
- Low correlation is observed between γ_{max} and experimental R/L_{Te} and R/L_{ne}.

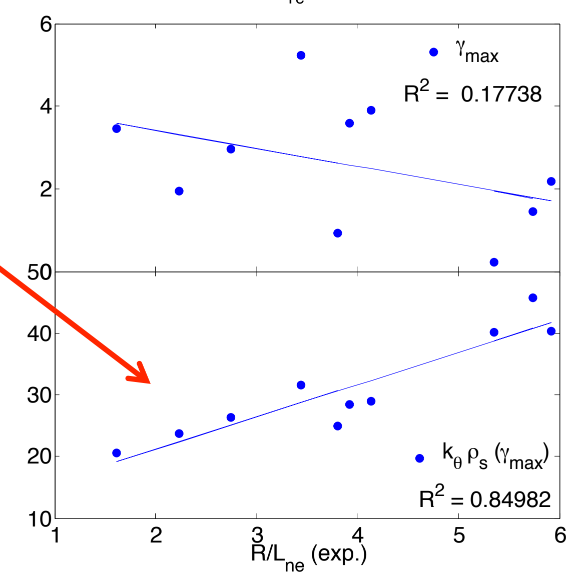
- ***Wavenumber values at maximum linear growth rates*** ($k_\vartheta \rho_s(\gamma_{max})$ *cf.* slide 17) correlate better to R/L_{Te} and R/L_{ne} than linear growth rates.

- Best correlation is observed between $k_\vartheta \rho_s(\gamma_{max})$ and R/L_{ne}. This could also be observed in the plots of slide 17.

- The conjecture is that R/L_{ne} is driving high-k turbulence to higher wavenumbers.

- Correlation is quantified by ***R^2*** coefficient of linear fit.





Correlation Between Wavenumber Values at Maximum Growth Rate and Wavenumber Spectrum of Fluctuations

Fig. a

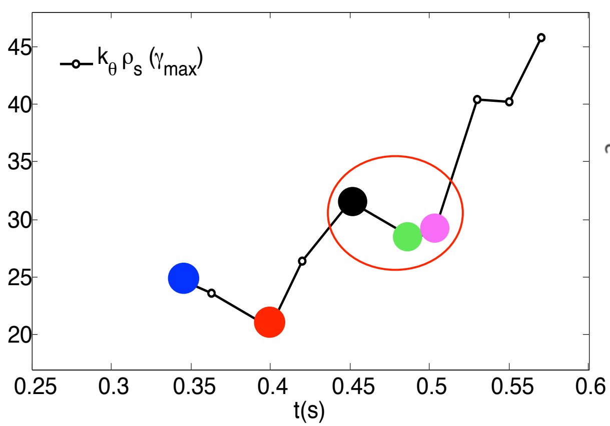


Fig. b

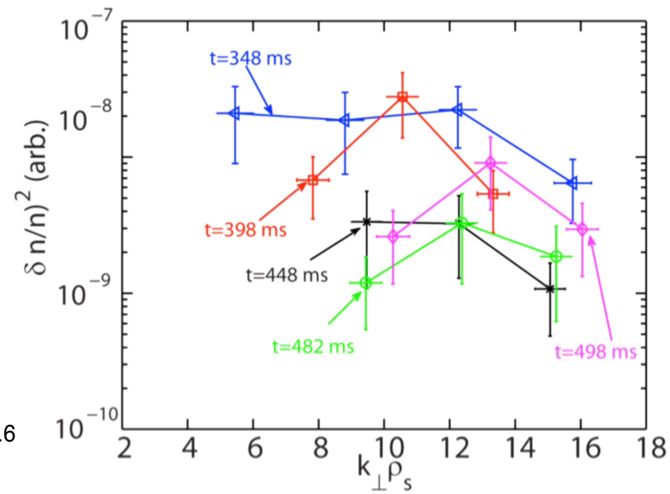
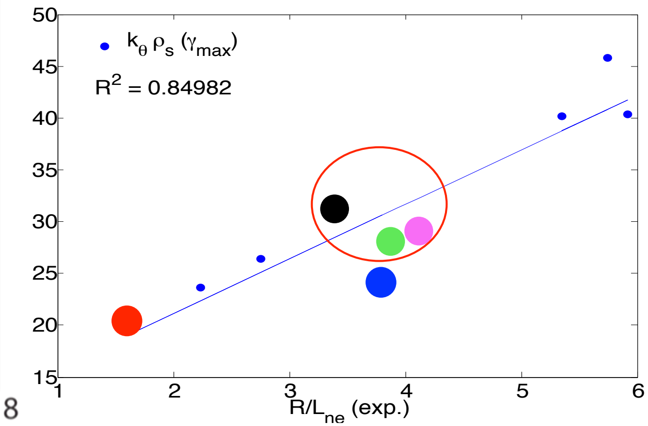


Fig. c



- A general increase of $k_\vartheta\rho_s(\gamma_{max})$ in time (linear GS2 simulations, Fig. a) is in agreement with a global decrease of lower-k ($k_\vartheta\rho_s < 10$) fluctuation level ($(\delta n_e/n_e)^2$ Fig. b).
- Big increase of $k_\vartheta\rho_s(\gamma_{max})$ for 398 ms <t< 448 ms agrees with decrease in observed fluctuation level for all *k*.
- After t ~ 448 ms, higher k ($k_\vartheta\rho_s$ ~ 12-15) fluctuation levels increase. During that time, R/L_{ne} increases (*cf.* red circle in Fig. c corresponding to same time period).
- Nonlinear gyrokinetic simulations have previously shown the effect of electron density gradient stabilization of low-k turbulence and the consequences on electron thermal transport [*cf. Y. Ren Phys. Plasmas 2012*].

A Scan in Electron Density Gradient is Performed to Confirm its Effect on High-k Turbulence

- Linear growth rates with GS2 are most sensitive when ***$0.8*R/L_{ne}$*** **term dominates Jenko's critical ETG** (t = 450 ms, t = 570 ms).

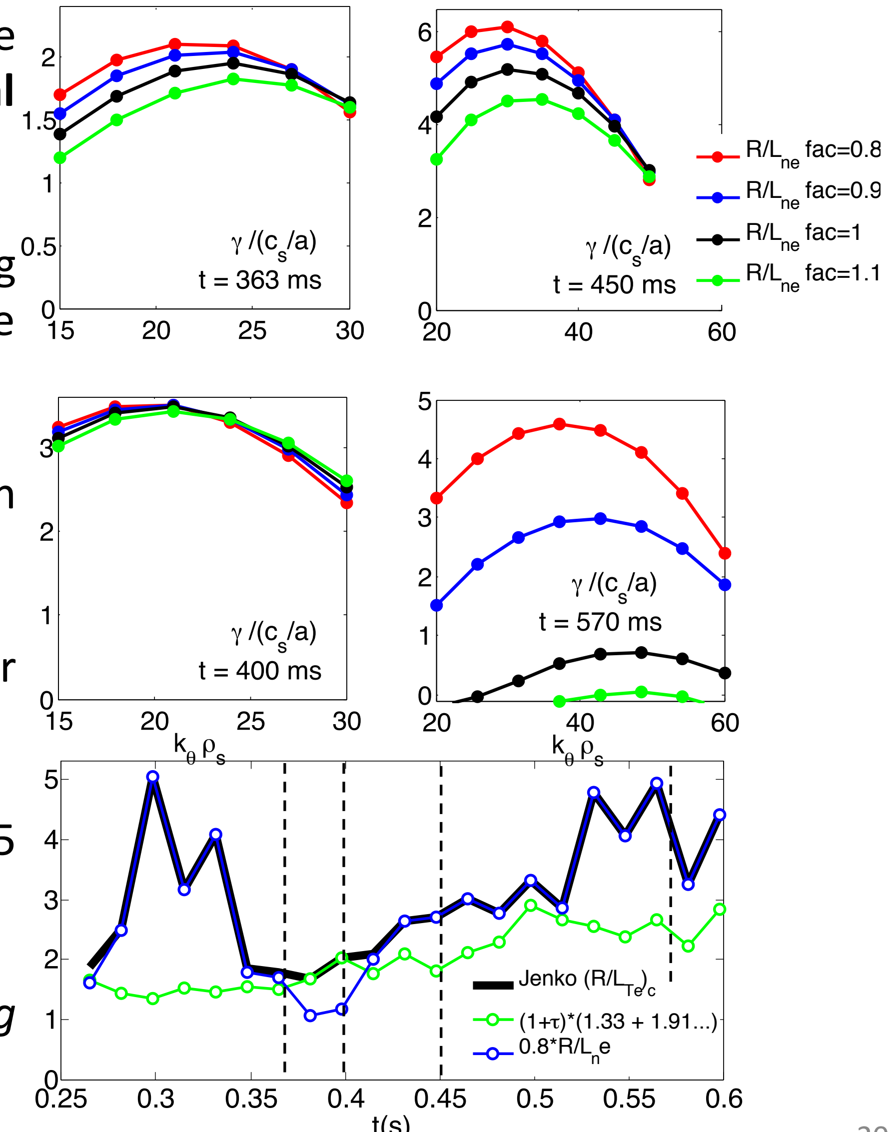
- At t = 400 ms, *$0.8*R/L_{ne}$* term is not dominating Jenko's critical ETG, and linear growth rates are not sensitive to *R/L_{ne}*.

- Lower-k values are more sensitive to *R/L_{ne}* than higher-k values.

- Except at t = 400 ms, *R/L_{ne}* decreases linear growth rates => **stabilizing effect**.

- At t = 400 ms, linear growth rates at $k_\theta \rho_s > 25$ increase with *R/L_{ne}*.

- *R/L_{ne}* could be a responsible factor for *driving* turbulence to higher k values (*cf.* slide 18).



Summary and Future Work

Summary

- High-k **electron scale density fluctuations** are detected with the coherent microwave scattering diagnostic at NSTX.
- Difference between local ETG values and Jenko's critical ETG correlates to observed fluctuations.
- As local **electron density gradient** (R/L_{ne}) increases, it dominates Jenko's critical ETG and is observed to have a stabilizing influence on observed fluctuations.
- Increasing R/L_{ne} produces a shift of high-k fluctuations to even higher k values.
- A scan on local R/L_{ne} with GS2 linear runs shows linear growth rates can be very sensitive to local R/L_{ne} when it is the dominant term in Jenko's **critical ETG**. In the opposite case, linear growth rates appear to be practically insensitive to local R/L_{ne}.
- Lower k-values in the high-k range appear more sensitive to R/L_{ne}, than higher k-values.

Future Work

- Carry out further studies for other NSTX shots with similar characteristics and compare the influence of local electron density gradient.
- Perform transport analysis to study influence of local electron density gradient in electron thermal transport.
- Carry out nonlinear gyrokinetic simulations to evaluate the effects of electron density gradient on turbulence and electron thermal transport.