NSTX-U

Alcator C-Mod

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Stabilization of Electron-Scale Turbulence by Electron Density Gradient in NSTX

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1. MIT 2. PPPL

NSTX-U Physics Meeting
Princeton Plasma Physics Laboratory
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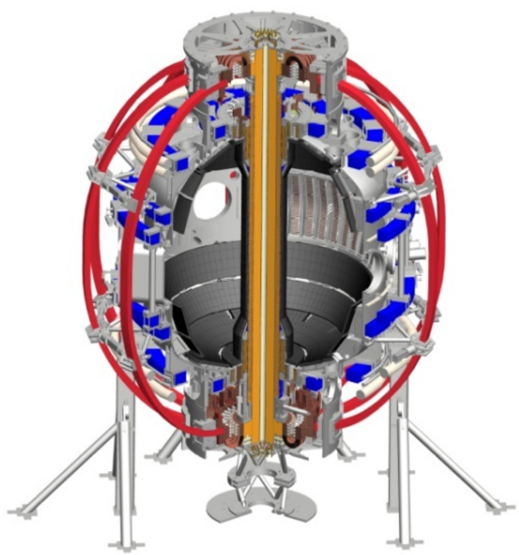

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Outline

1. Introduction.
2. High-k Scattering Measurement.
3. Experimental Results.
4. Comparison with Linear Simulations.
5. Summary.
6. Discussion and Future Work.

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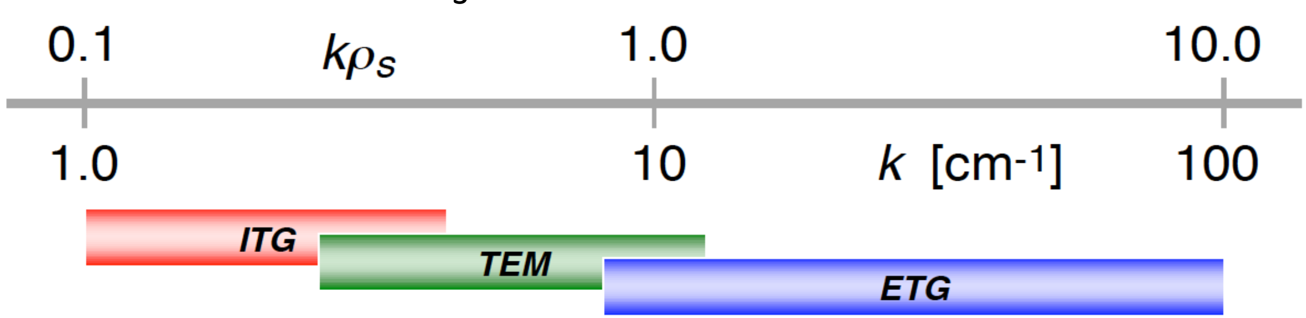
Anomalous Electron Thermal Transport is Observed in All NSTX Confinement Regimes

- **Transport of electron energy** in most tokamak experiments is observed to exceed predictions of neoclassical theory.

- Theory and experiments suggest that toroidal **ETG** turbulence is a candidate for anomalous electron thermal transport in some operating regimes.

- A ***microwave collective scattering diagnostic*** was implemented at NSTX to measure electron-scale density fluctuations indicative of ***high-k turbulence*** ($k_\perp \rho_s > 1$).



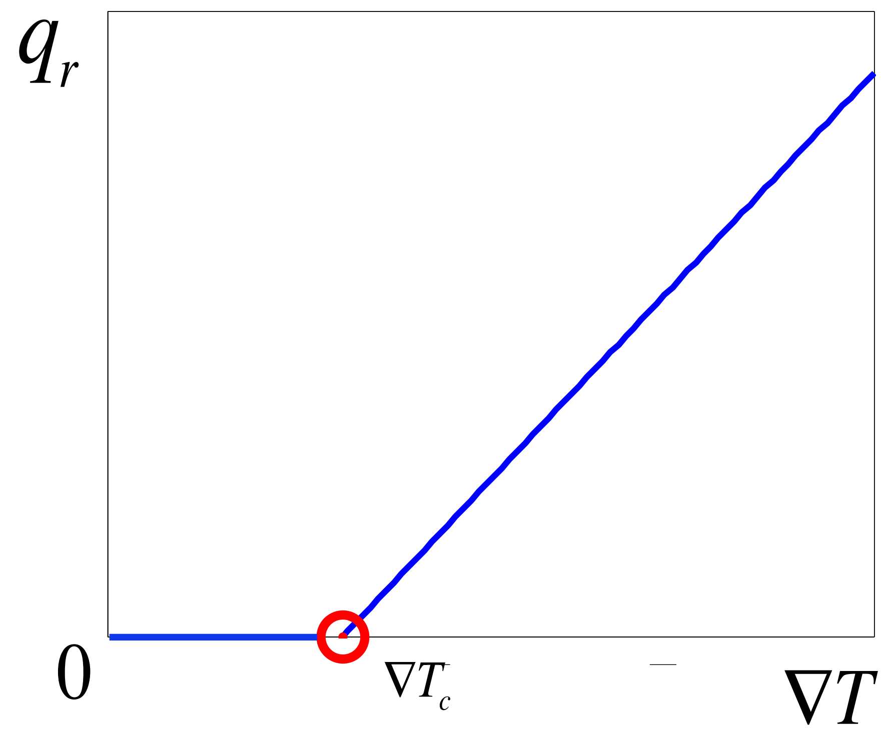
From Mazzucato PPPL presentation

Critical Gradient and Critical ETG Formula

- Critical gradient

$$q_r^{turb} \propto \left(\nabla T_e - (\nabla T_e)_c\right)$$

$\nabla T_e \leq (\nabla T_e)_c$ *~ threshold for instability*



- Normalized gradient of quantity X

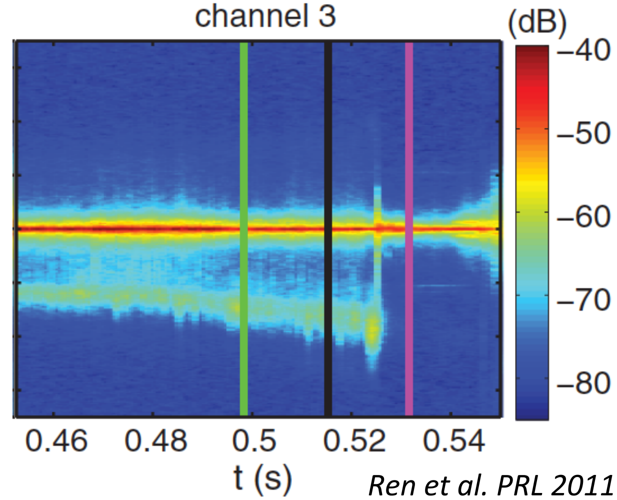
$$R / L_X = -R(\nabla X / X)$$

- Jenko critical ETG [*cf. Jenko Phys. Plasmas 2001]*.

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

Previous Work

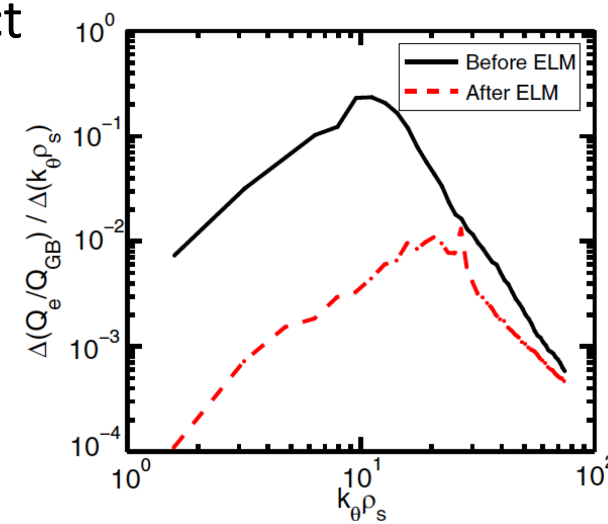
- First direct experimental demonstration of density gradient stabilization of e⁻-scale turbulence (*Ren et al. PRL 2011*). Shot 140620.
  - **ELM event** at t~525 ms ➔ change in density gradient.
  - Stabilization of lower-k e⁻-scale fluctuations ($k_{\perp}\rho_s < 10$).



Ren et al. PRL 2011

- Nonlinear gyrokinetic simulations show the effect of density gradient on transport (*Ren et al. PoP 2012*). Shot 140620.

- Here, I focus on the effect of density gradient on *e⁻-scale fluctuations* and on the *ETG unstable wavenumbers* on shot 141767.



Ren et al. PoP 2012

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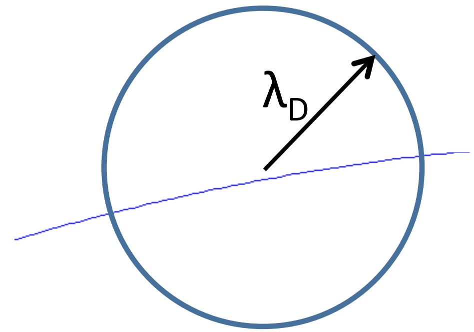
Collective Scattering is used to measure High-k Turbulence

- Collective/coherent scattering

$$k\lambda_D \leq 1$$



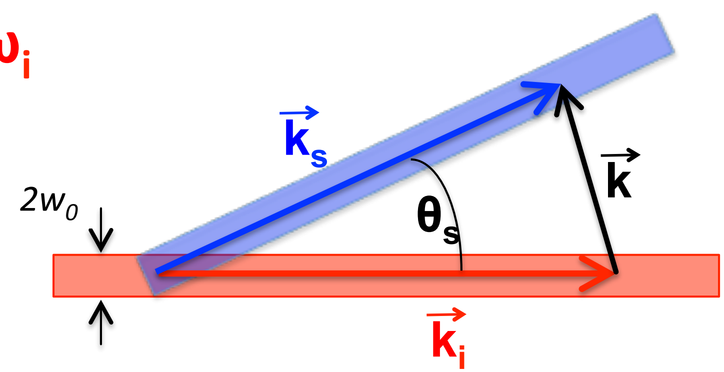
- Scattered power density $$\frac{d^2P}{d\Omega d\nu} = P_i r_e^2 L_z \left|\Pi \cdot \hat{e}\right|^2 \frac{\left|\tilde{n}_e(k,\omega)\right|^2}{VT}$$

- ***Three wave-coupling*** between incident beam **(k_i , ω_i)** and plasma **(k , ω)**

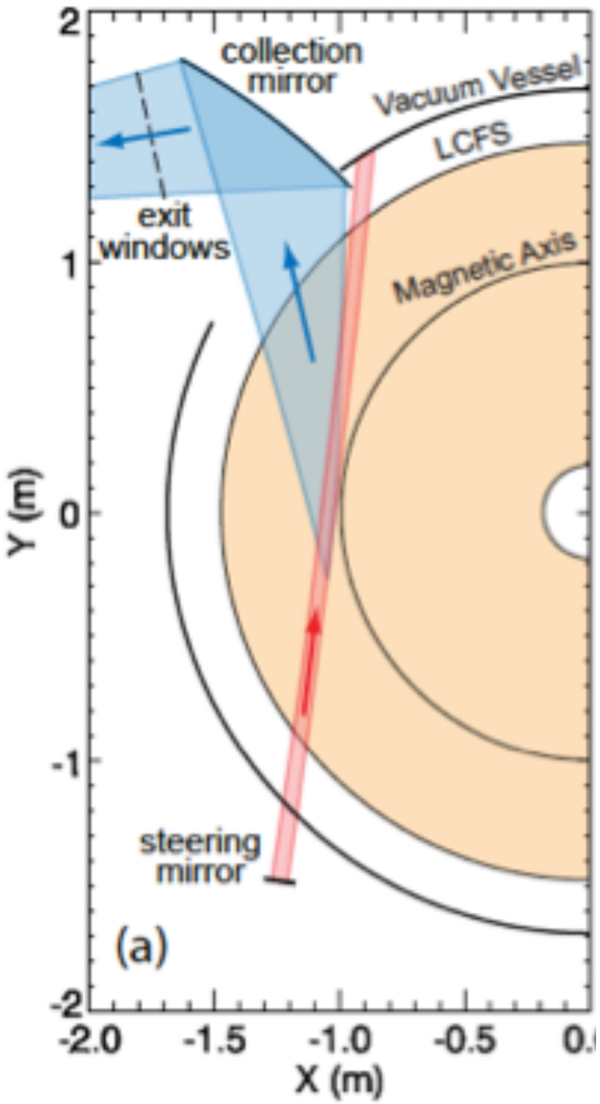
$$\vec{k}_s = \vec{k} + \vec{k}_i \qquad \omega_s = \omega + \omega_i$$

- ω_i , ω_s >> ω imposes Bragg condition

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



High-k Microwave Scattering Diagnostic at NSTX

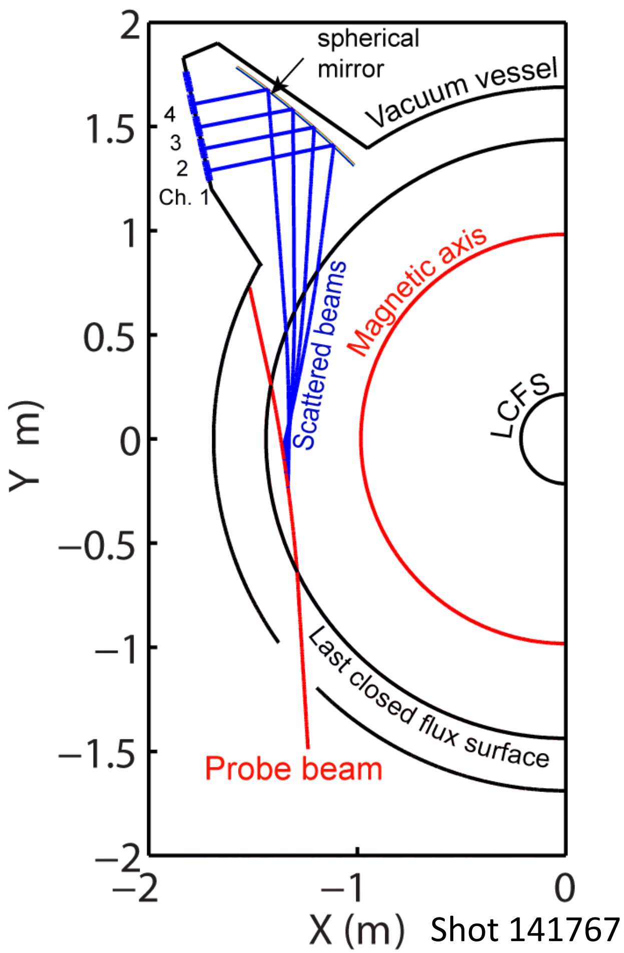


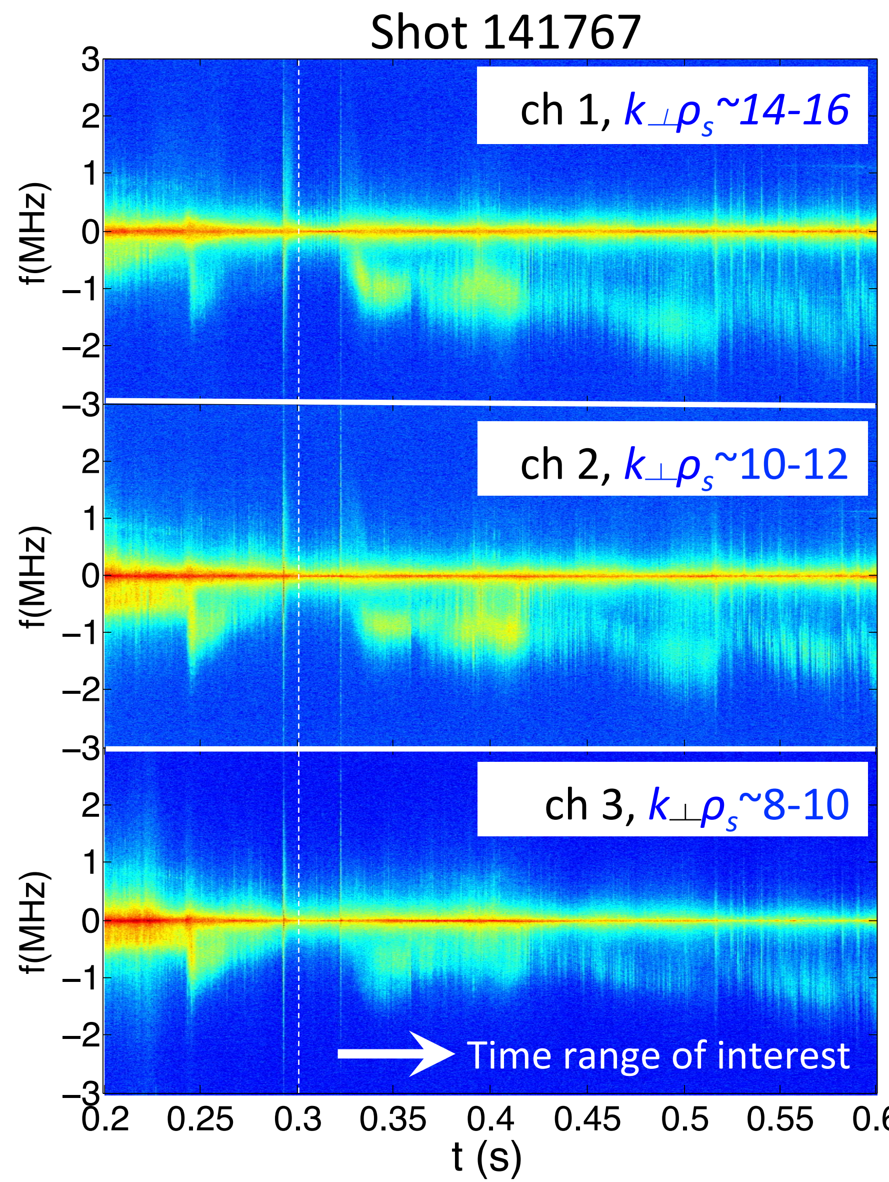
View from top of NSTX (D.R. Smith PhD thesis 2009)

- Gaussian Probe beam: 15 mW, 280 GHz, λ_i ~ 1.07 mm, a = 3cm ($1/e^2$ radius).
- Propagation close to midplane => k_r spectrum.
- 5 detection channels => range k_r ~ 5-30 cm^{-1} (*high-k*).
- Wavenumber resolution Δk = ± 0.7 cm^{-1}.
- Radial coverage: R = 106-144 cm.
- Radial resolution: ΔR = ± 2 cm (unique feature).

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

- Different channels measure different *k.*
- Each k has a different ***Doppler shift***.





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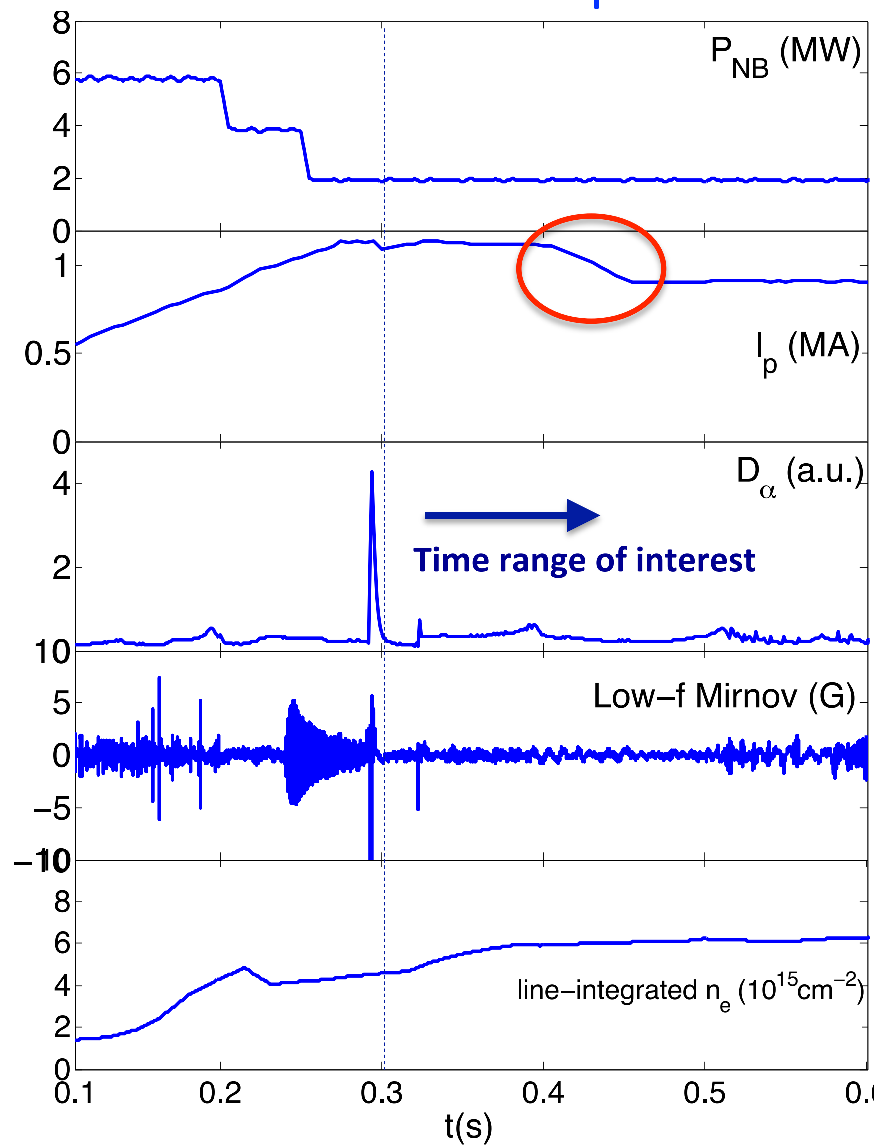
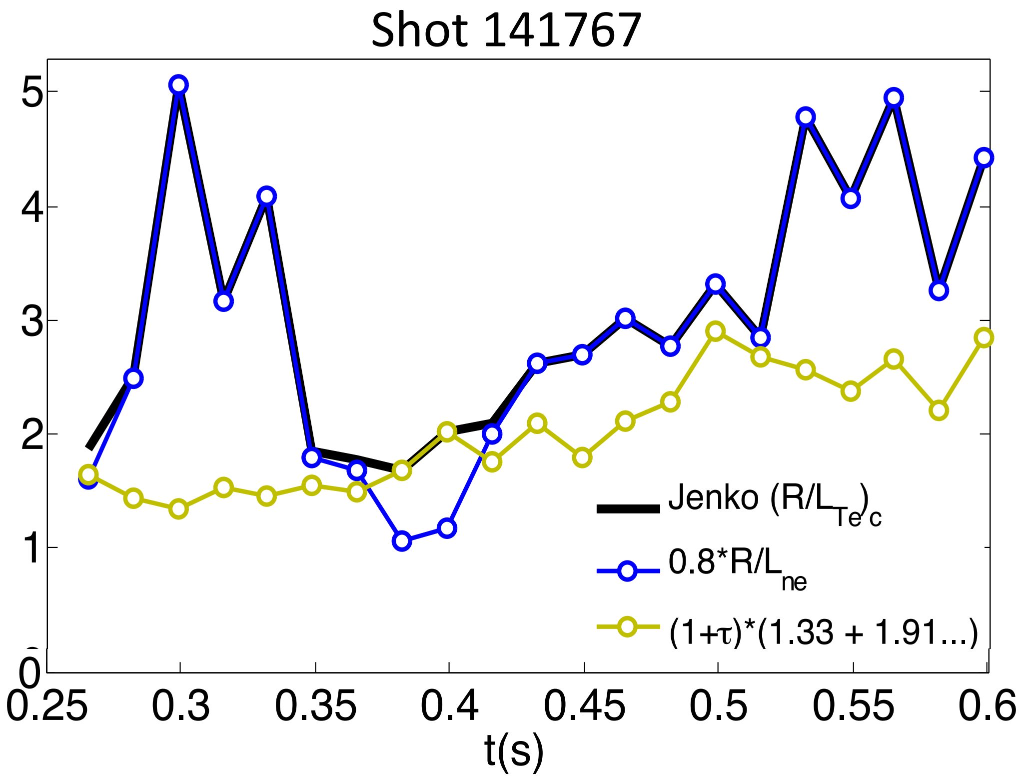
A Set of NBI-heated H-mode Plasmas is Used to Study High-k Turbulence during Current Ramp-down

- **NBI heated**, HHFW heating is absent during the run.
- *Controlled 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 time range of interest.** (*cf.* low-f Mirnov signal).
- Line integrated density is fairly constant during the time range of interest.

Shot 141767. B_T ~ 5kG



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



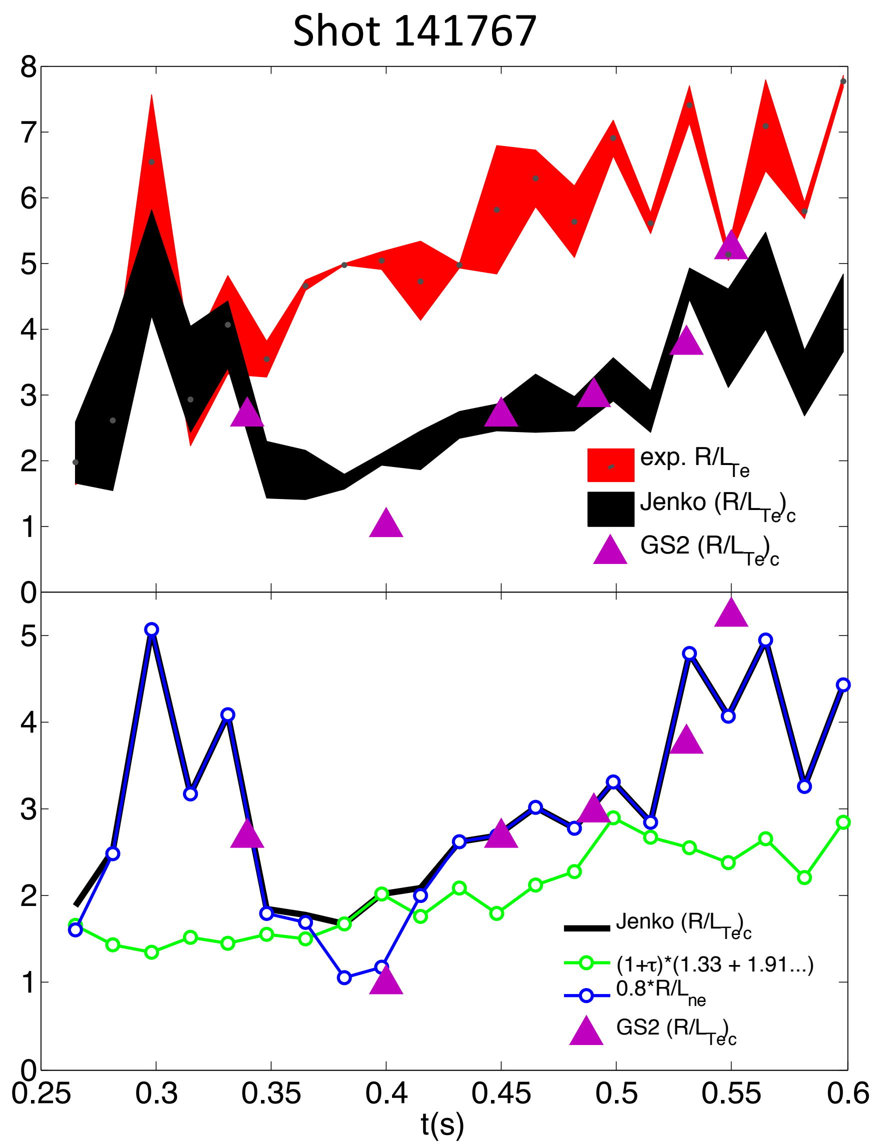
- Jenko critical gradient is a maximum of a ***R/L*$_{ne}$** term and an ***s/q*** term.

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

- 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.

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

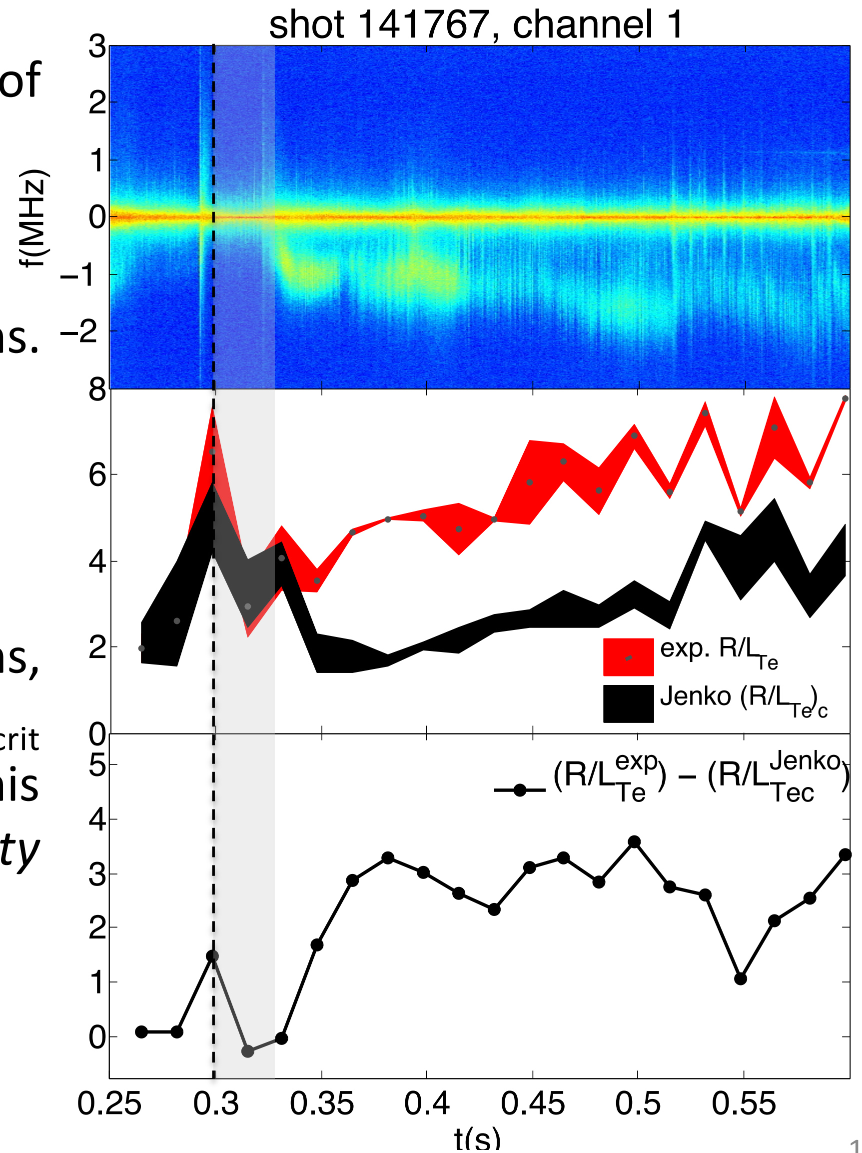
- $(R/LTe)_{crit}$ is explicitly calculated using GS2.
- Fairly good agreement is observed between GS2 $(R/L_{Te})_{crit}$ calculations and Jenko's formula.
- This is consistent with Jenko's critical ETG formula and previous comparisons with experimental ETG.
- GS2 $(R/L_{Te})_{crit}$ seems to follow R/L_{ne}.



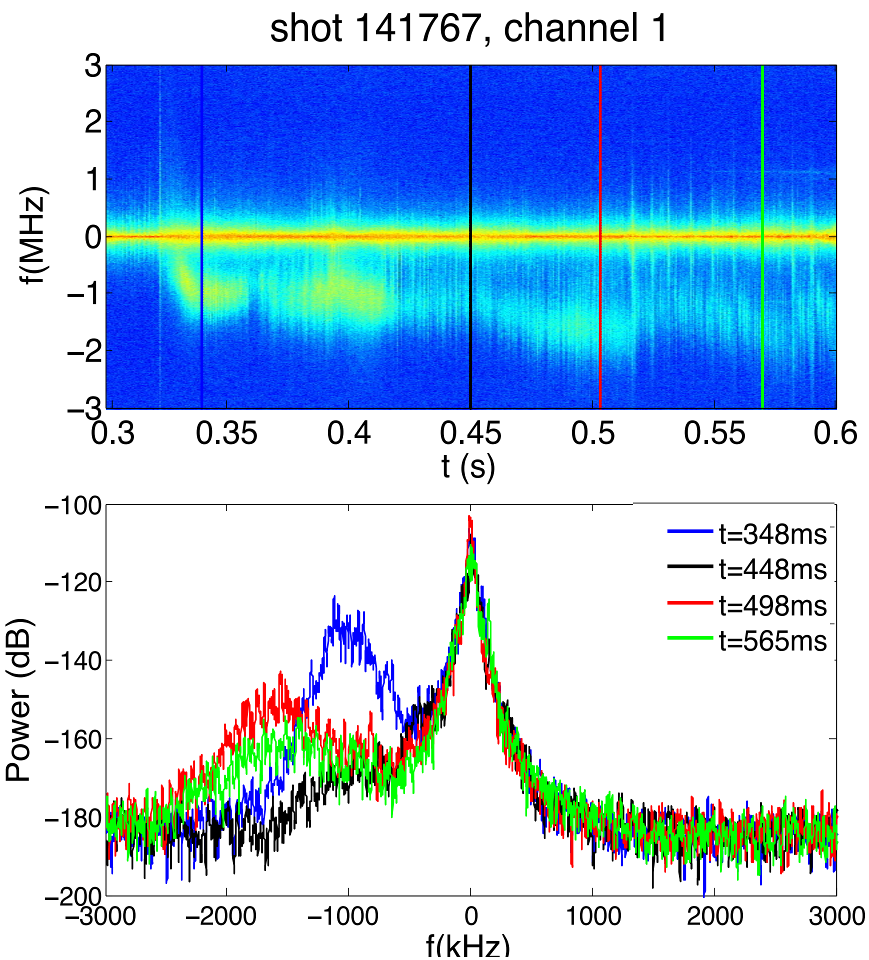
Observed Fluctuations Correlate to Difference Between Critical and Experimental ETG

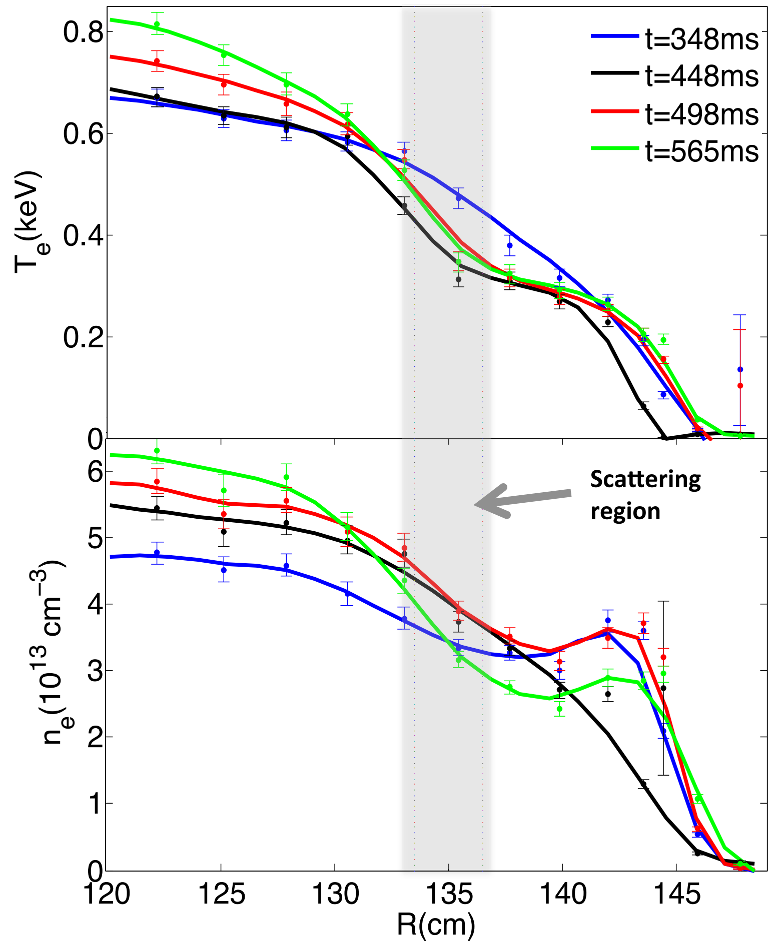
- $(R/L_{te}^{exp}) \sim (R/L_{Te})_{crit}$ dictates the *presence* of fluctuations.
- Prior to **t ~ 320 ms**, $(R/L_{te}^{exp}) \sim (R/L_{Te})_{crit}$
  ➔ ETG is marginally stable, no fluctuations.
- After t ~ 320 ms, $(R/L_{te}^{exp}) > (R/L_{Te})_{crit}$
  ➔ fluctuations develop.

★ During period ~ 350 ms < t < ~ 500 ms, similar difference (R/L_{te}^{exp}) - $(R/L_{Te})_{crit}$ produces ***VERY* different fluctuations**. This will be later explained by the *density gradient stabilization of lower numbers*.



Observed High-k Fluctuations Correlate to Local Electron Density Gradient



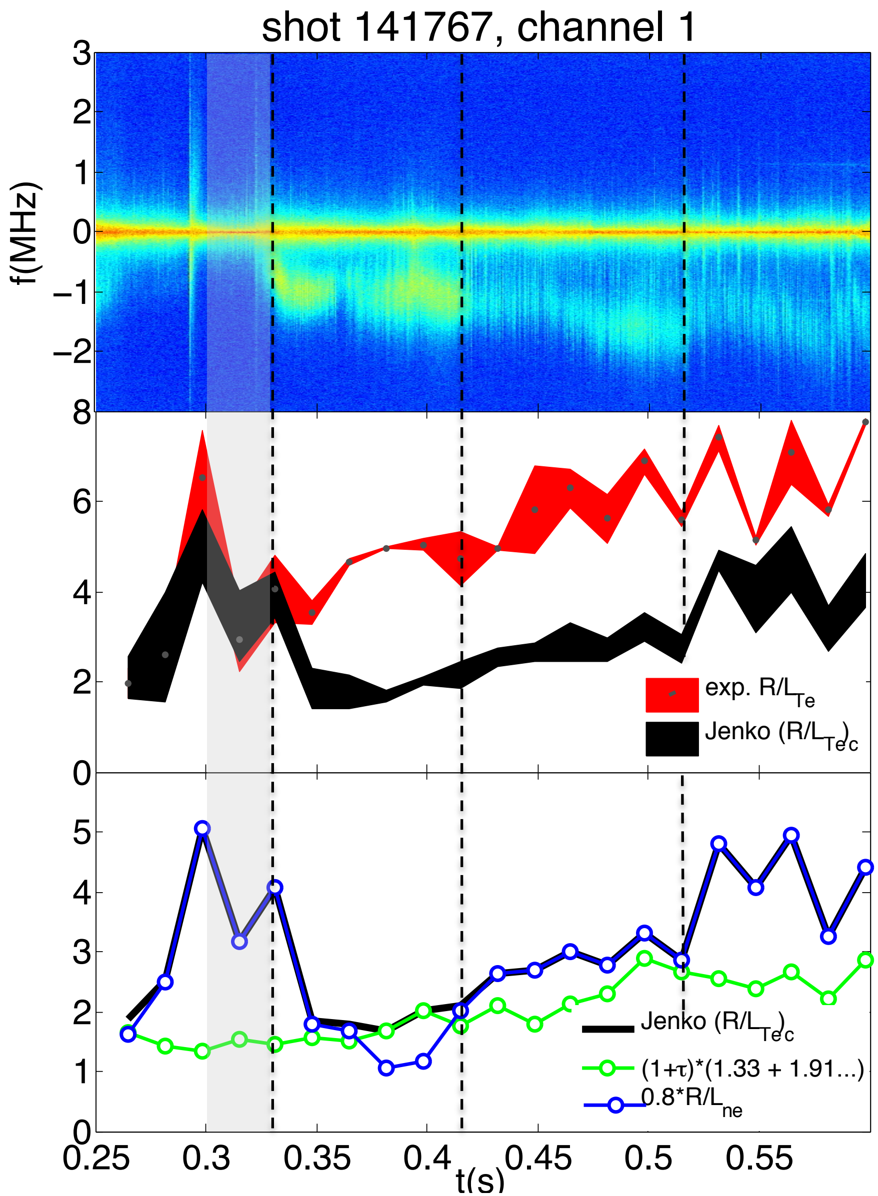


∇T_e → ***Drives*** ETG

∇n_e → ***Stabilizes*** ETG

Two competing effects: ∇n_e is dominant effect.

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



- As ***R/L_{ne}*** increases, it dominates in Jenko's formula *$(R/L_{Te})_{crit}$* **(t < 350 ms, t > 410 ms & t > 515 ms)**.

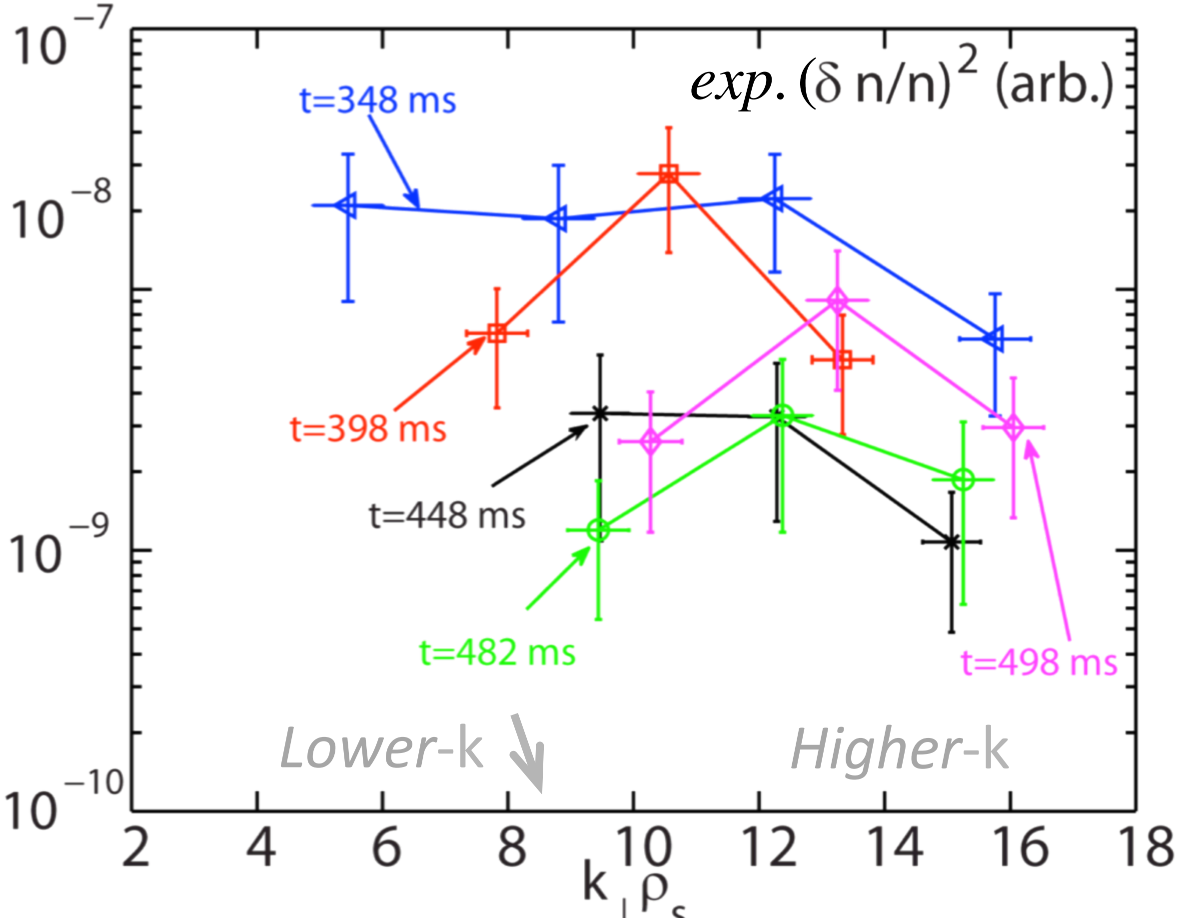
➔ Fluctuations decrease.

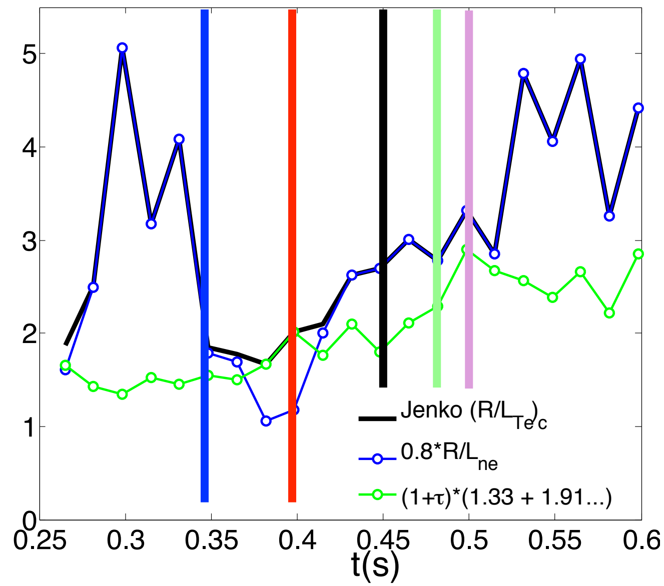
- Previous to t ~ 320 ms ETG is marginally stable. No fluctuations.

- ***R/L_{ne}*** has a ***stabilizing*** effect when it dominates Jenko critical gradient.

★ *R/L_{Te}* is the ***drive*** of ETG turbulence. Even though *R/L_{Te}* is increasing in time, *R/L_{ne}* is driving *$(R/L_{Te})_{crit}$* and able to stabilize ETG turbulence.

Wavenumber Spectrum of Fluctuations and Electron Density Gradient





- Lower-k ($k_\vartheta \rho_s < 10$) fluctuation level $(\delta n_e/n_e)^2$ decreases.
- After t ~ 448 ms, higher k ($k_\vartheta \rho_s$ ~ 12-16) fluctuation levels increase. During that time, R/L_{ne} increases.

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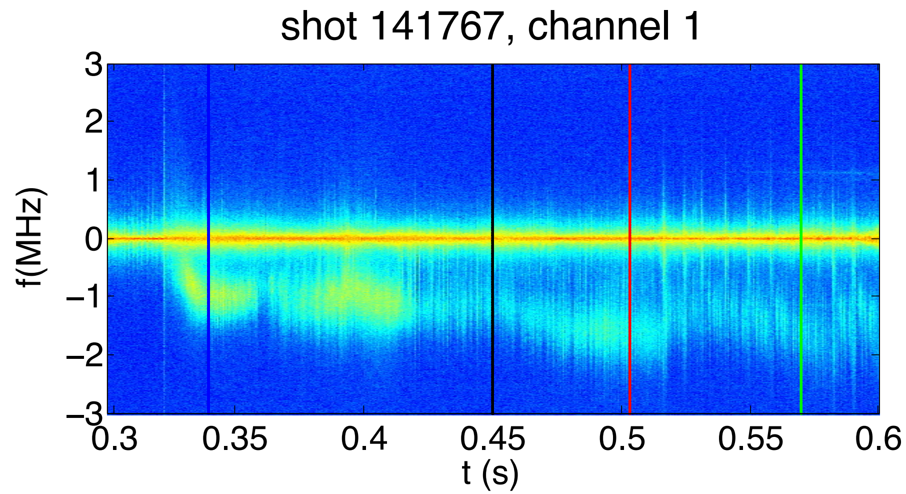
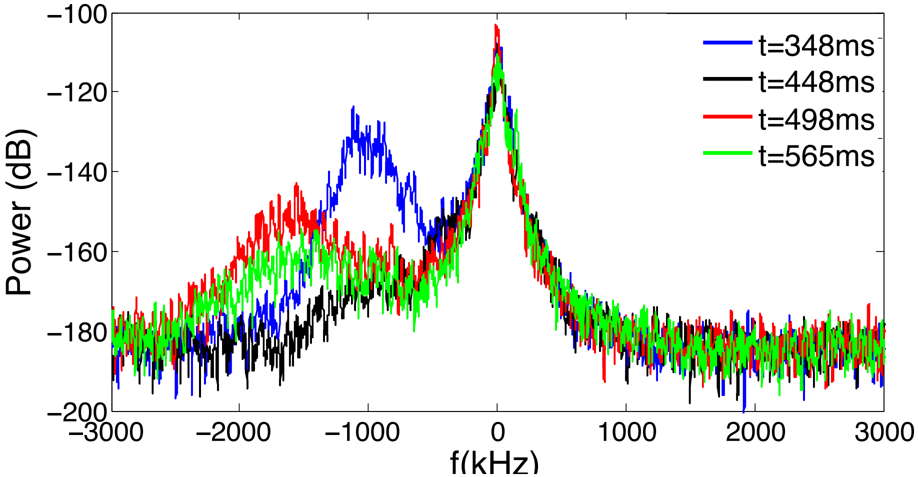
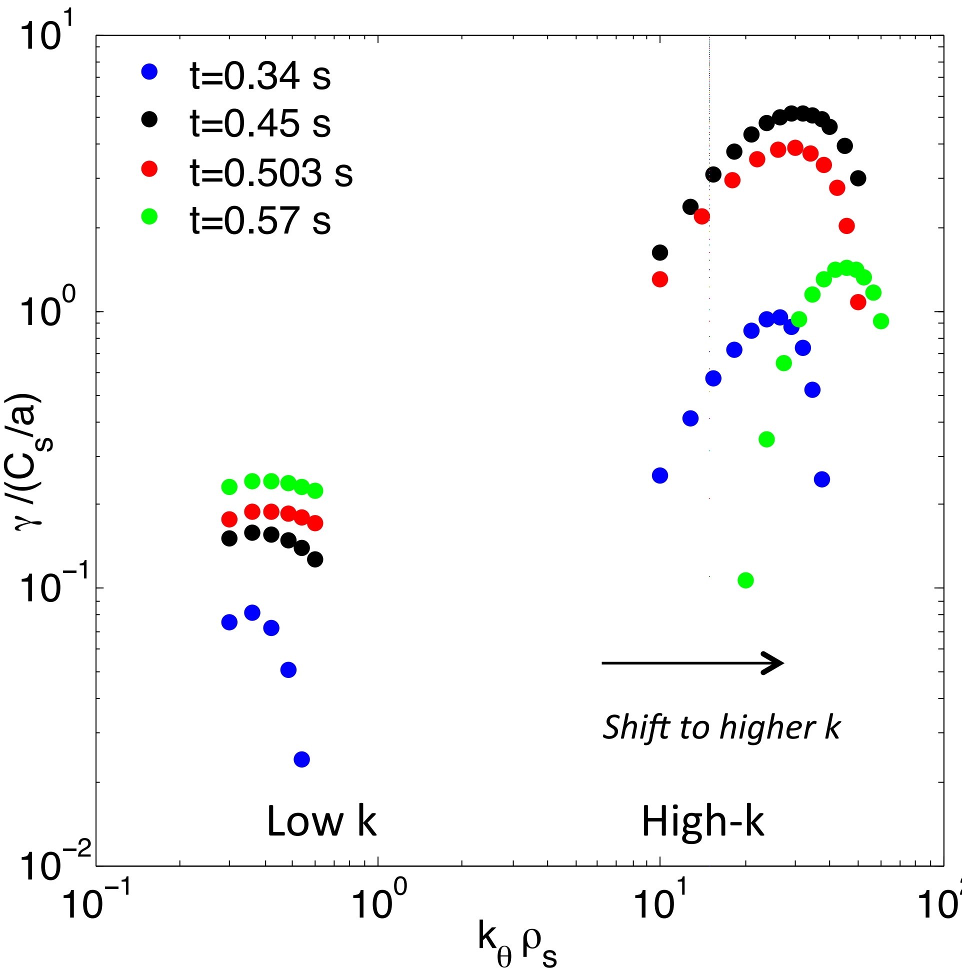
GS2 Linear Simulations Show the Wavenumbers at Maximum Growth Rate Shift to Higher *k* in Time



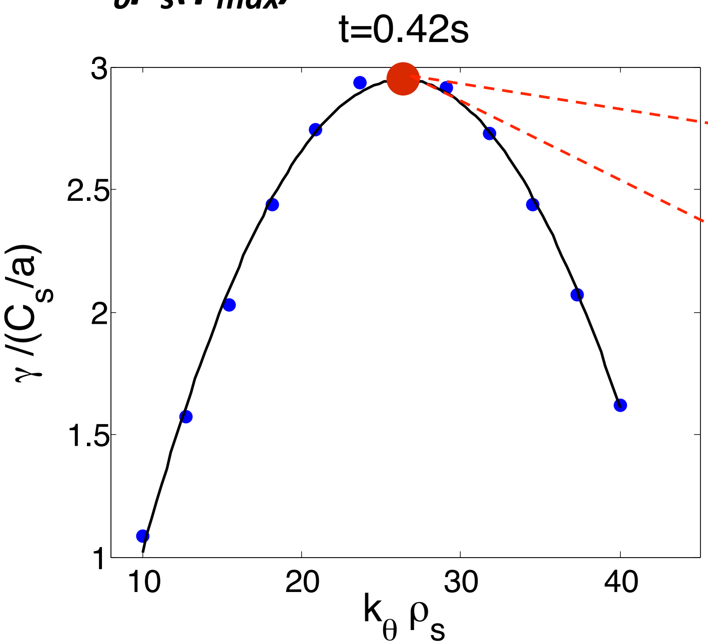


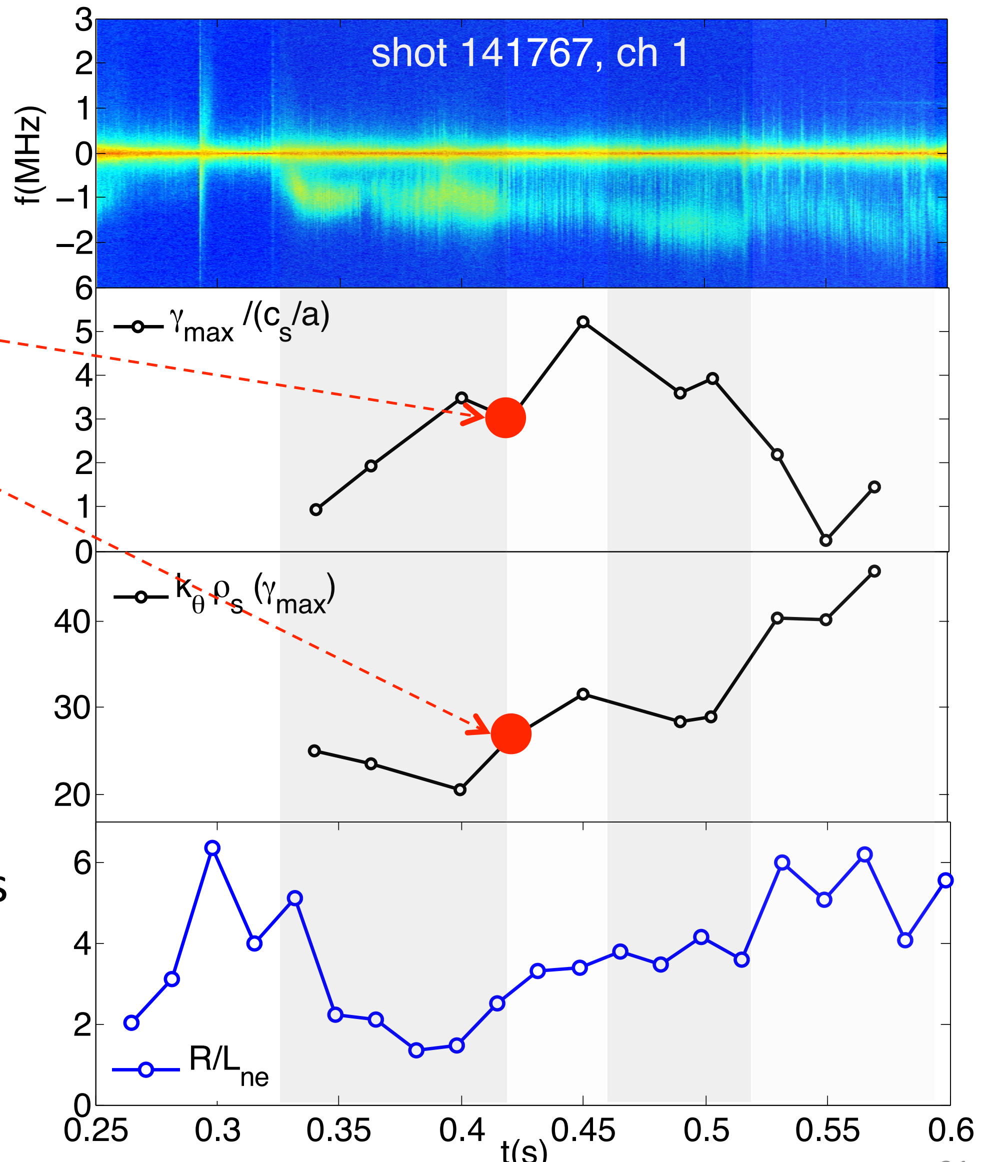


- **IMPORTANT:** GS2 wavenumbers do not correspond with exp. wavenumbers.
- High-k wavenumbers at maximum linear growth rate shift to higher-k.
- As $\mathbf{k_{\perp}\rho_s(\gamma_{max})}$ moves to higher k (e.g. t = 570 ms), observed fluctuations decrease.

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

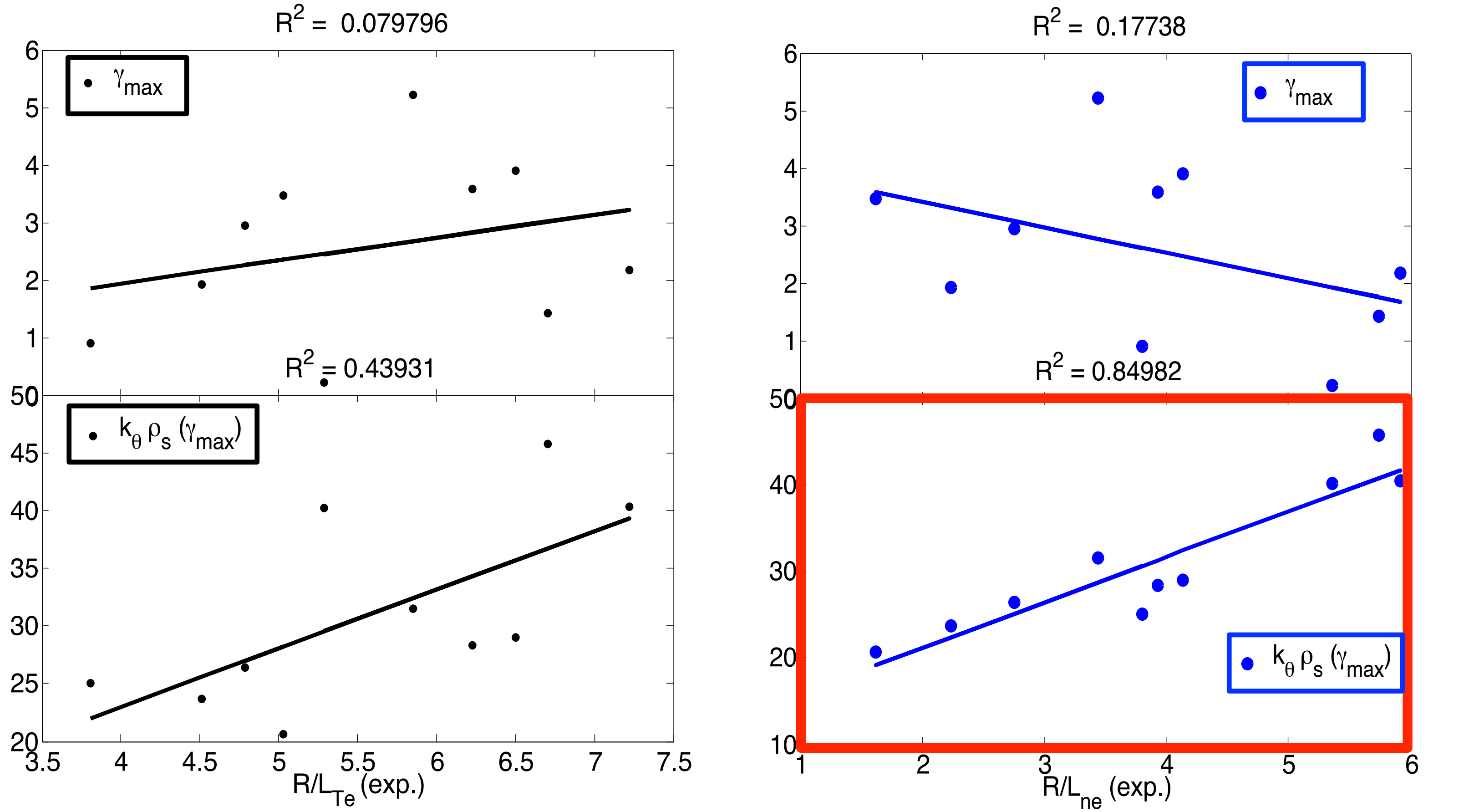
- At each time, determine
  - $\gamma_{max}/(c_s/a)$
  - $k_\vartheta \rho_s(\gamma_{max})$





- Evolution of $\mathbf{k_\perp \rho_s(\gamma_{max})}$ in time follows ***R/L$_{ne}$*** at the scattering location.
- ***R/L$_{ne}$*** and $\mathbf{k_\perp \rho_s(\gamma_{max})}$ correlate well with observed fluctuations.

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



- Low correlation between γ_{max} and experimental R/L_{Te} and R/L_{ne}.
- $k_\vartheta\rho_s(\gamma_{max})$ correlates 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}.

A Scan in R/L_{ne} is Performed with GS2 to Confirm its Effect on High-k Turbulence

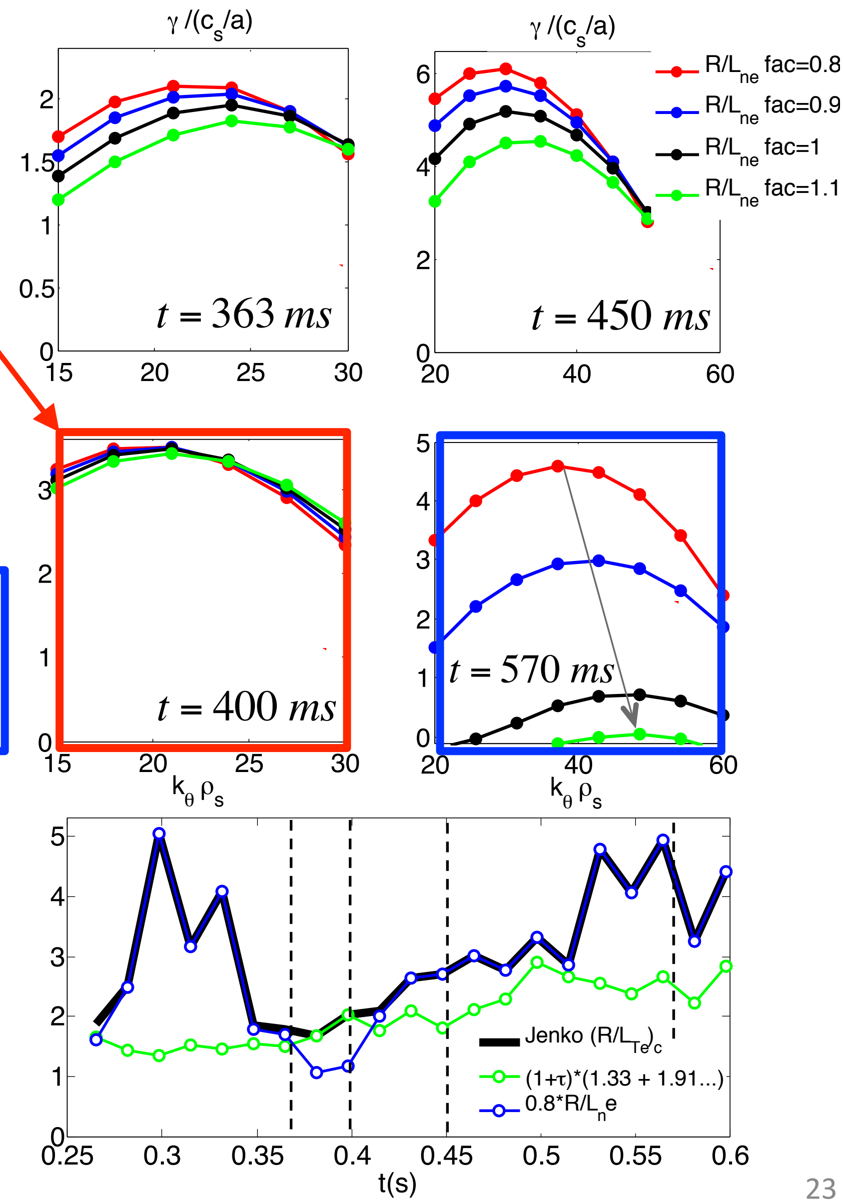
- γ most sensitive when ***$0.8{*}R/L_{ne}$*** **dominates Jenko's critical ETG** (t = 363, 450, 570 ms).

- t = 400 ms, *$0.8{*}R/L_{ne}$* term not dominant
  ➔ γ insensitive to R/L_{ne}.

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

- When R/L_{ne} dominates, R/L_{ne} decreases growth rate and shifts *γ* to higher-k (*cf. t = 570 ms*)
  ➔ **stabilizing effect**.

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



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Summary

- Difference R/L_{Te} – $(R/L_{Te})_{crit}$ dictates the *presence* of observed high-k fluctuations.

- High values of local **electron density gradient** (R/L_{ne}) make it the dominant term in $(R/L_{Te})_{crit}$ ➔ *stabilizing* effect on observed fluctuations.

- Increasing R/L_{ne} ➔ $\boldsymbol{k_\theta \rho_s(\gamma_{max})}$ from GS2 shifts to even higher k values. Similar trend can be observed experimentally.

- A scan on local R/L_{ne} with GS2 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 are practically insensitive to local R/L_{ne}.

Discussion and Future Work

Issues and Discussion

- Linearly unstable high-k modes (GS2) **do not correspond** with measured k from the scattering system.

  ➔Measured k is NOT the most unstable mode.

  ➔Dominant k_r with small k_θ => mismatch with GS2 unstable k.

  ➔Need to establish a *connection* between the experimental-k and the simulation-k to compare simulation and experiment.

Future Work

- Perform transport analysis to study the influence of the 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.

Back up slides

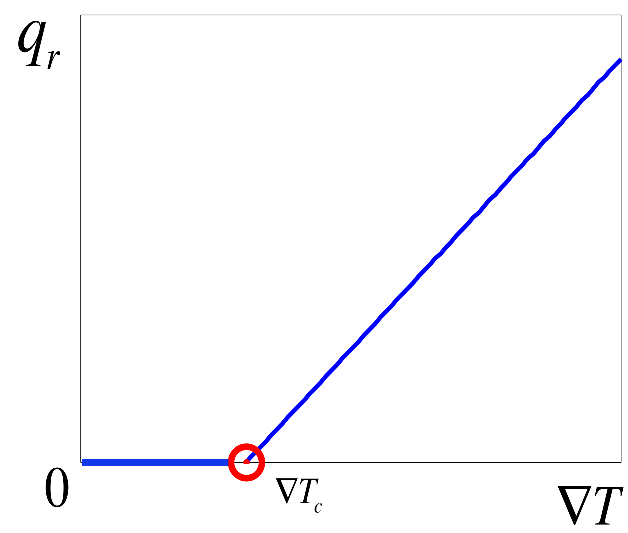
Critical Gradient and Critical ETG Formula

- Normalized gradient of quantity X

$$R / L_X = -R(\nabla X / X)$$

- Critical gradient

$$q_r^{turb} = \underbrace{\chi_{GB} f(\hat{s}, q, \nabla n_e, ..)}_{\text{Nonlinear}} \underbrace{\left(R / L_{T_e} - (R / L_{T_e})_c\right)}_{\text{Linear threshold}}$$

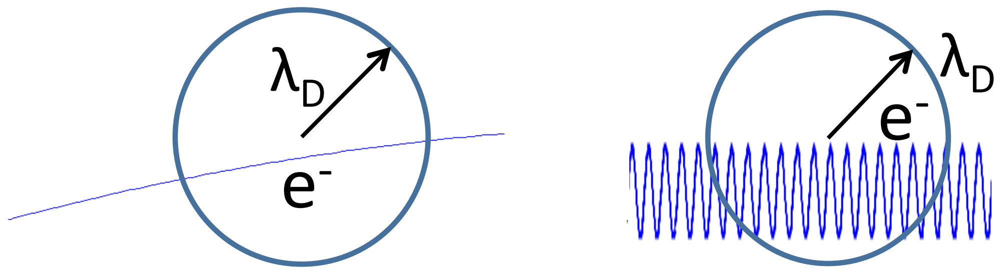


- Jenko critical ETG [*cf. Jenko Phys. Plasmas 2001]*.

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

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

- Collective/coherent and incoherent scattering



$k\lambda_D \leq 1$ $\qquad$ $k\lambda_D \geq 1$

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

  ⇒ $k\lambda_D < 1$ ***(collective scattering)***

- 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

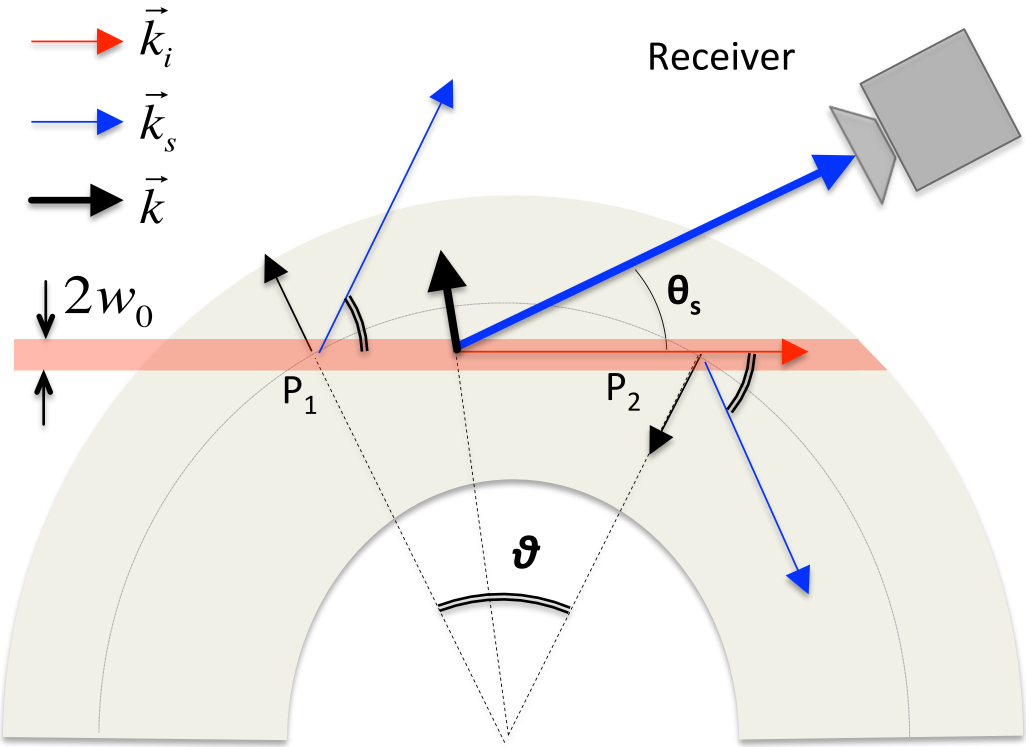
Spatial Localization and Wavenumber Resolution

- Plasma fluctuations satisfy $\begin{cases} k \cdot B \approx 0 \\ k = 2k_i \sin(\theta_s / 2) \end{cases}$ (1) Perpendicular fluctuations. (2) Bragg Condition.
- <u>Midplane propagation</u> ➔ ***k*** is radial.
- Strong dependence on ***toroidal curvature*** => <u>Oblique propagation</u> enhances localization.
- At NSTX, beam propagation is out of midplane (~ 5°) ➔ ***k*** *~ radial.*
- Gaussian beam ➔ *Δk* and *ΔR*

$$A(r_\perp) = \exp(-r_\perp^2 / w_0^2)$$

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

$$\Delta k = 2 / w_0$$

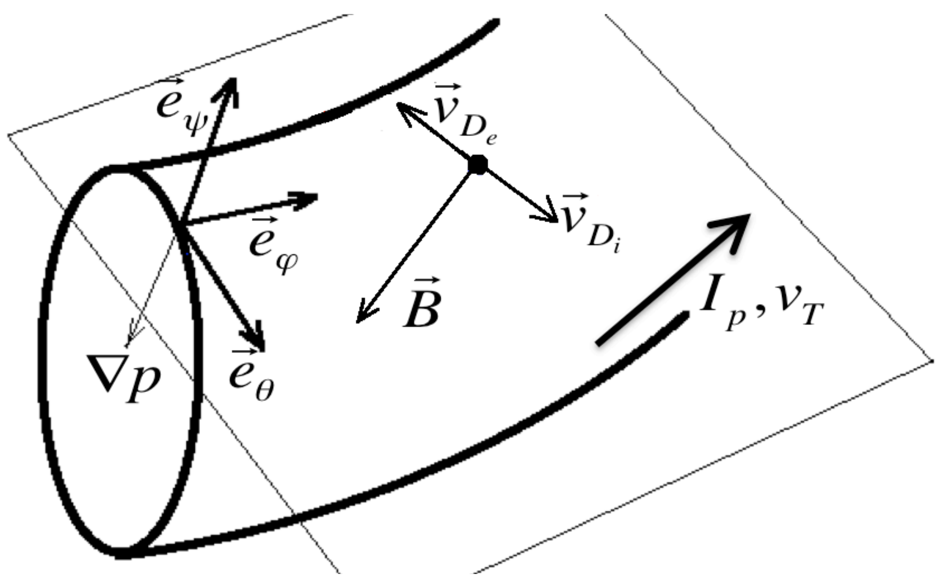


View from top (not to scale)

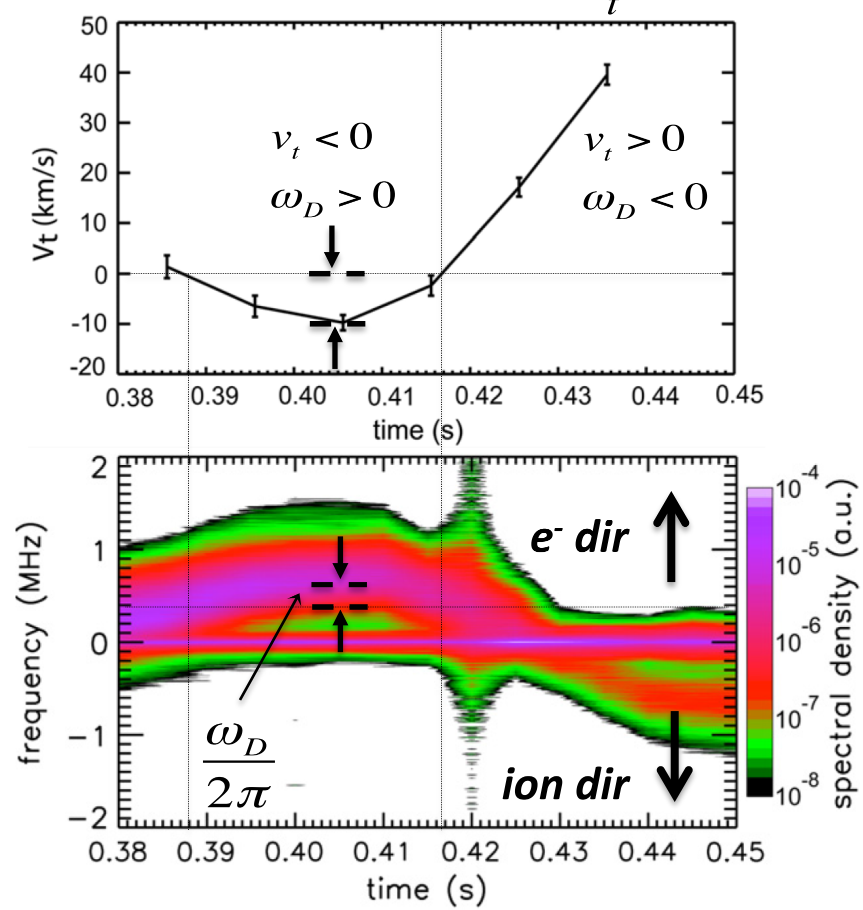
Toroidal Rotation has an Effect on Measured Fluctuations: Doppler Shift

- Doppler shift $\omega_D \approx k_t v_t$
- Diamagnetic velocity component in *toroidal* direction

$$\begin{cases} \vec{v}_{De} \cdot \vec{e}_\varphi = -\dfrac{|\nabla p_e| B_\theta}{e n_e B^2} < 0 & e^- \ waves \\ \vec{v}_{Di} \cdot \vec{e}_\varphi = \dfrac{|\nabla p_i| B_\theta}{e n_i B^2} > 0 & ion \ waves \end{cases}$$

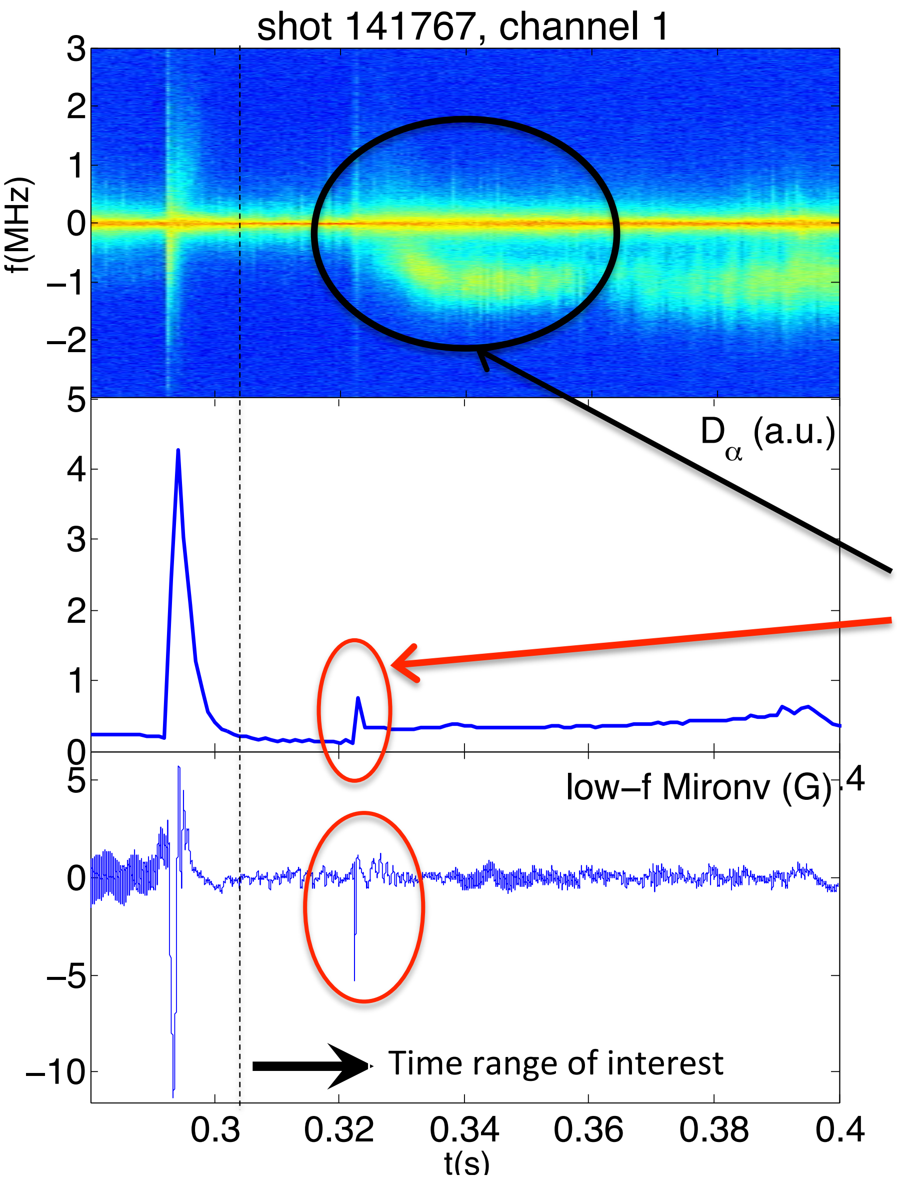


$k_t < 0$



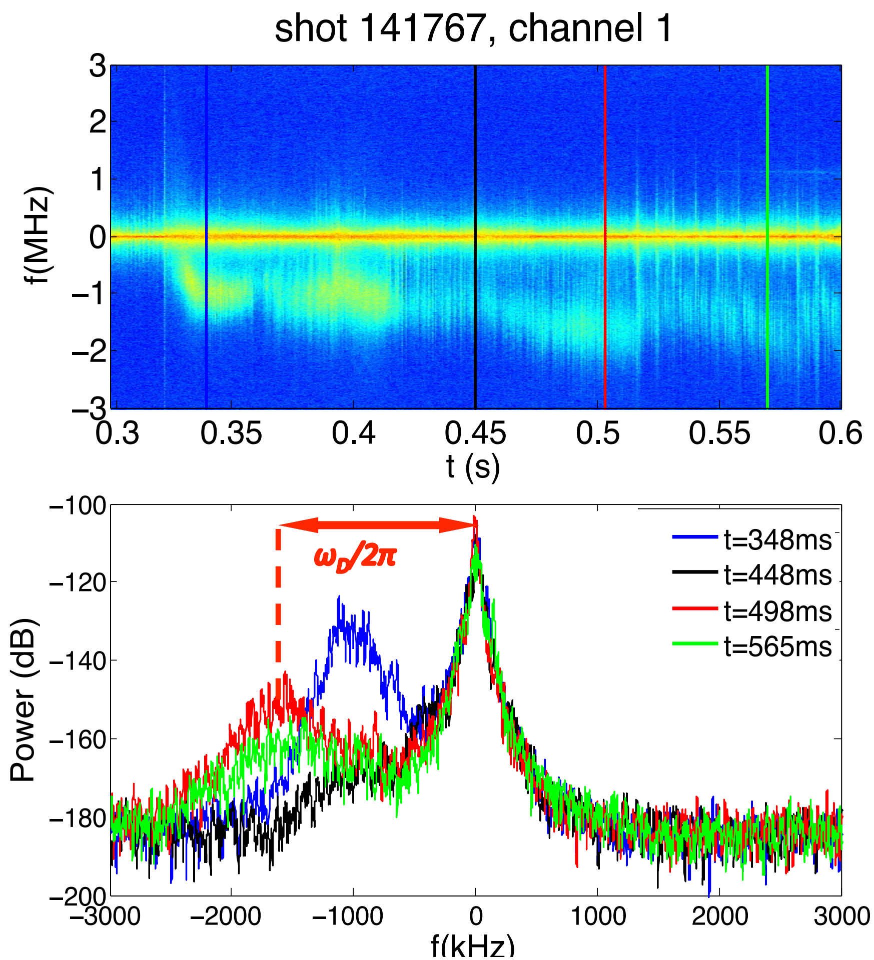
Adapted from Mazzucato Nuc. Fusion 2009.
Here *f>0* ➔ e- direction.

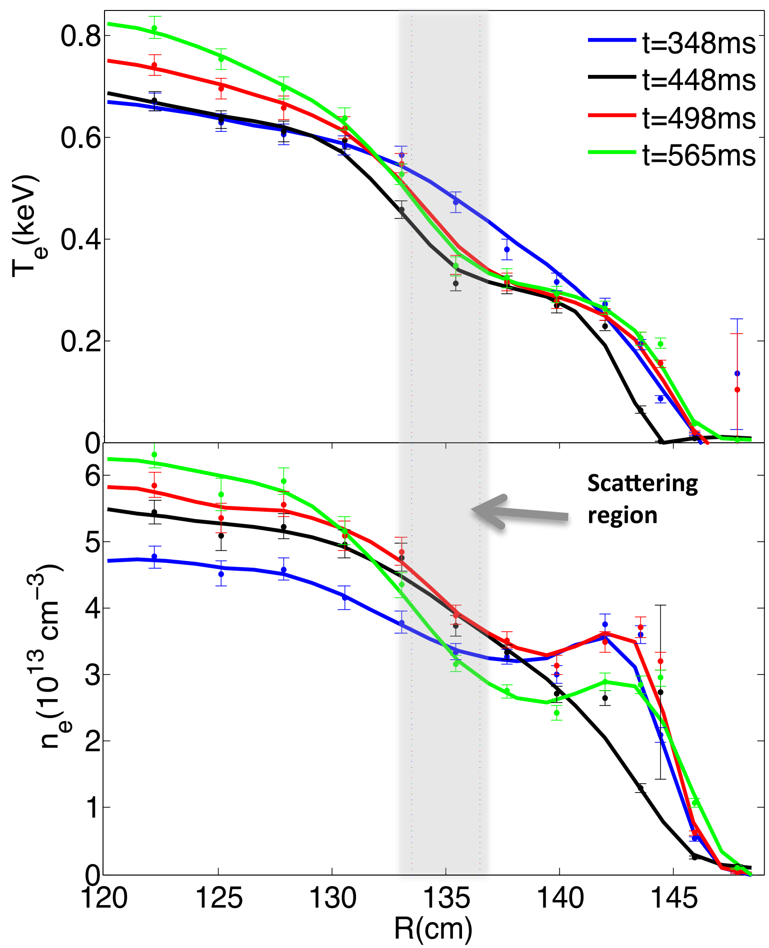
High-k Fluctuations Start after Small Spike in D_α and Mirnov Signal



- 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 High-k Fluctuations Correlate to Local Electron Density Gradient

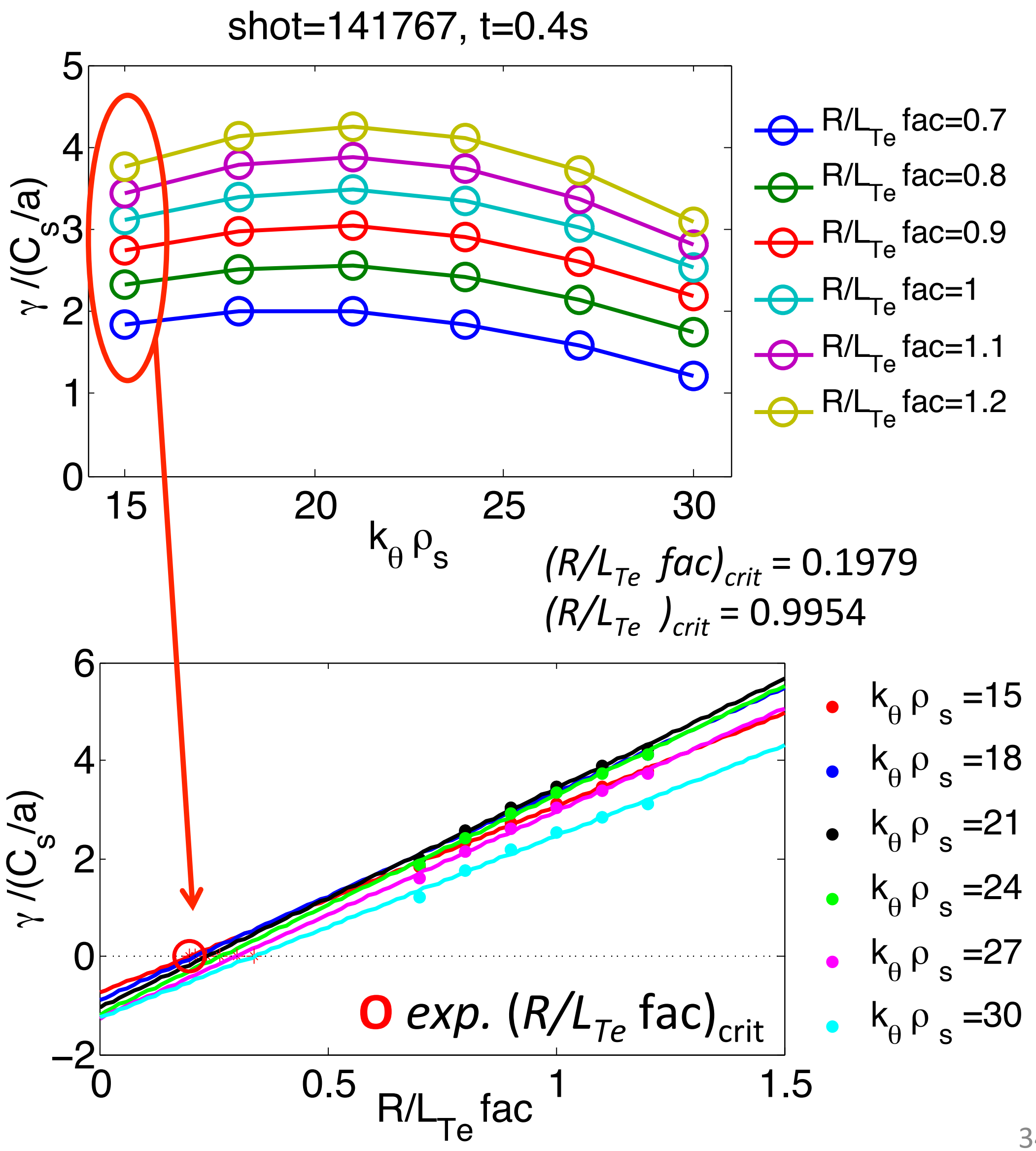




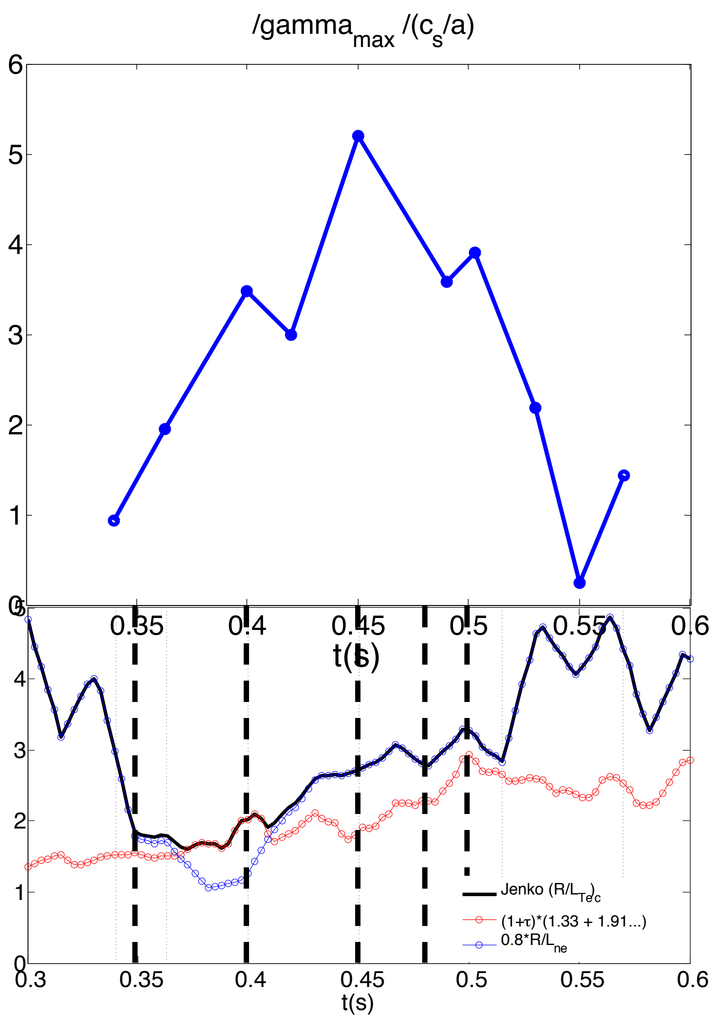
- Electron Density Gradient suffers the biggest change in the **scattering region**.
- Doppler shift is measured as distance from 0 to observed fluctuation frequency.

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

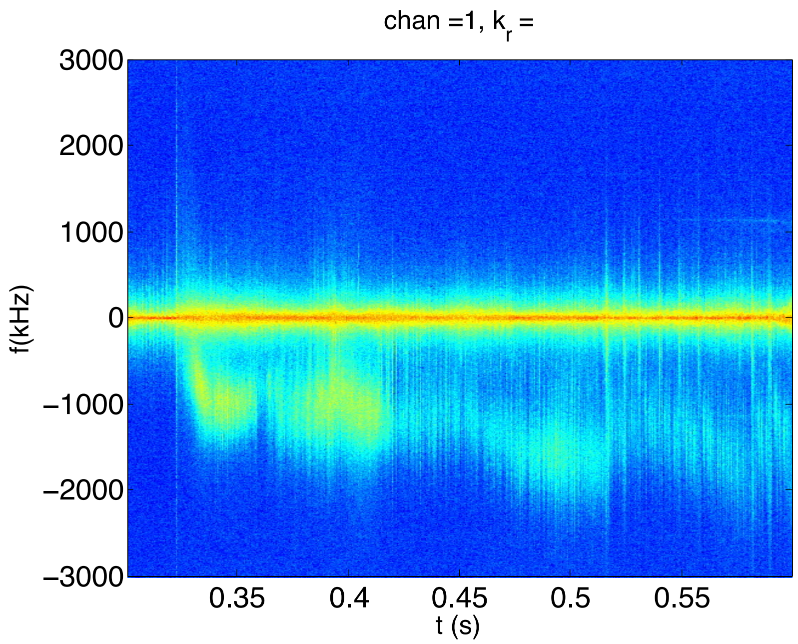
- R/L_{Te} is varied keeping all other quantities constant. The factor is called (R/L_{Te} fac).
- High-k linear growth rates saturate with decreasing (R/L_e).
- $(R/L_{Te})_{crit}$ is found to be the minimum R/L_{Te} to satisfy $\Upsilon = 0$.



Issues

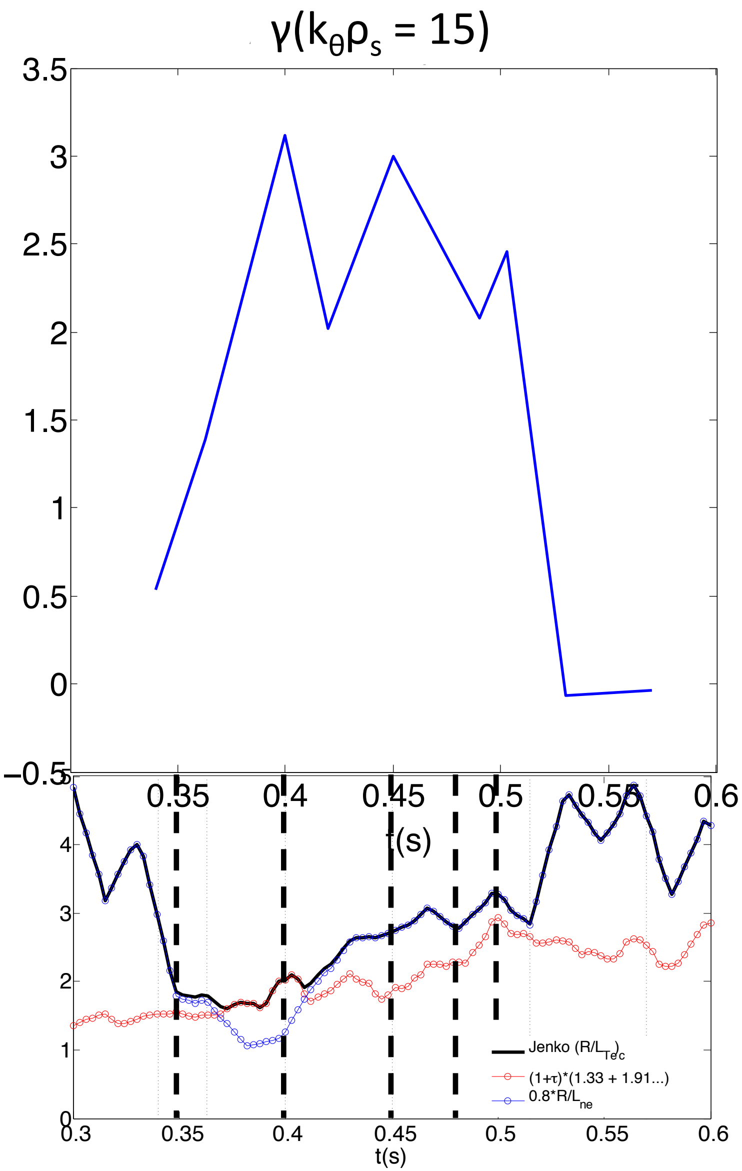


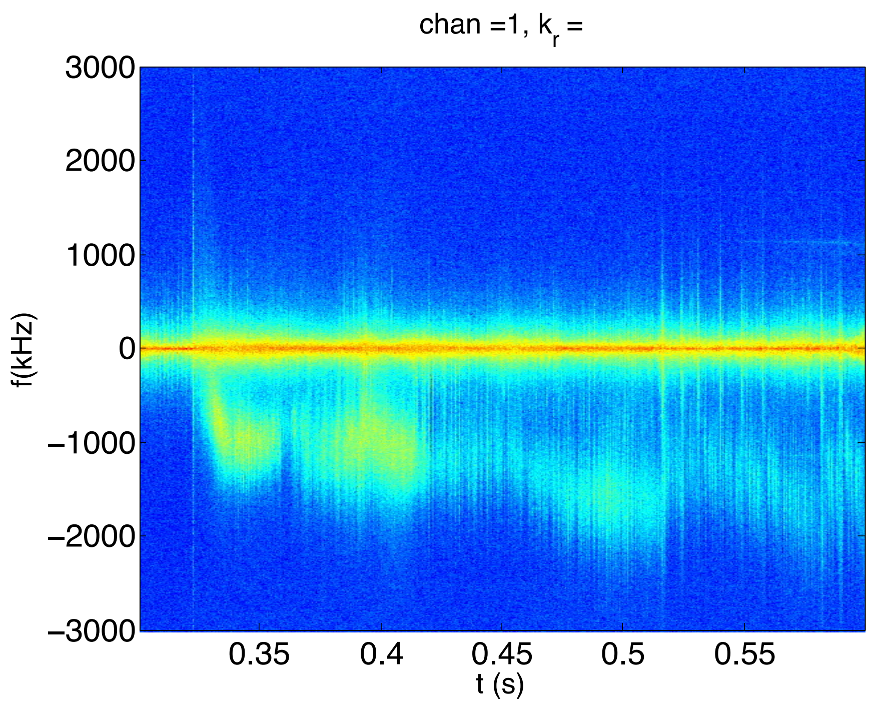
/gamma$_{max}$ /(c$_s$/a)
t(s)
Jenko (R/L$_{Te}$)$_c$
(1+τ)*(1.33 + 1.91...)
0.8*R/L$_{ne}$



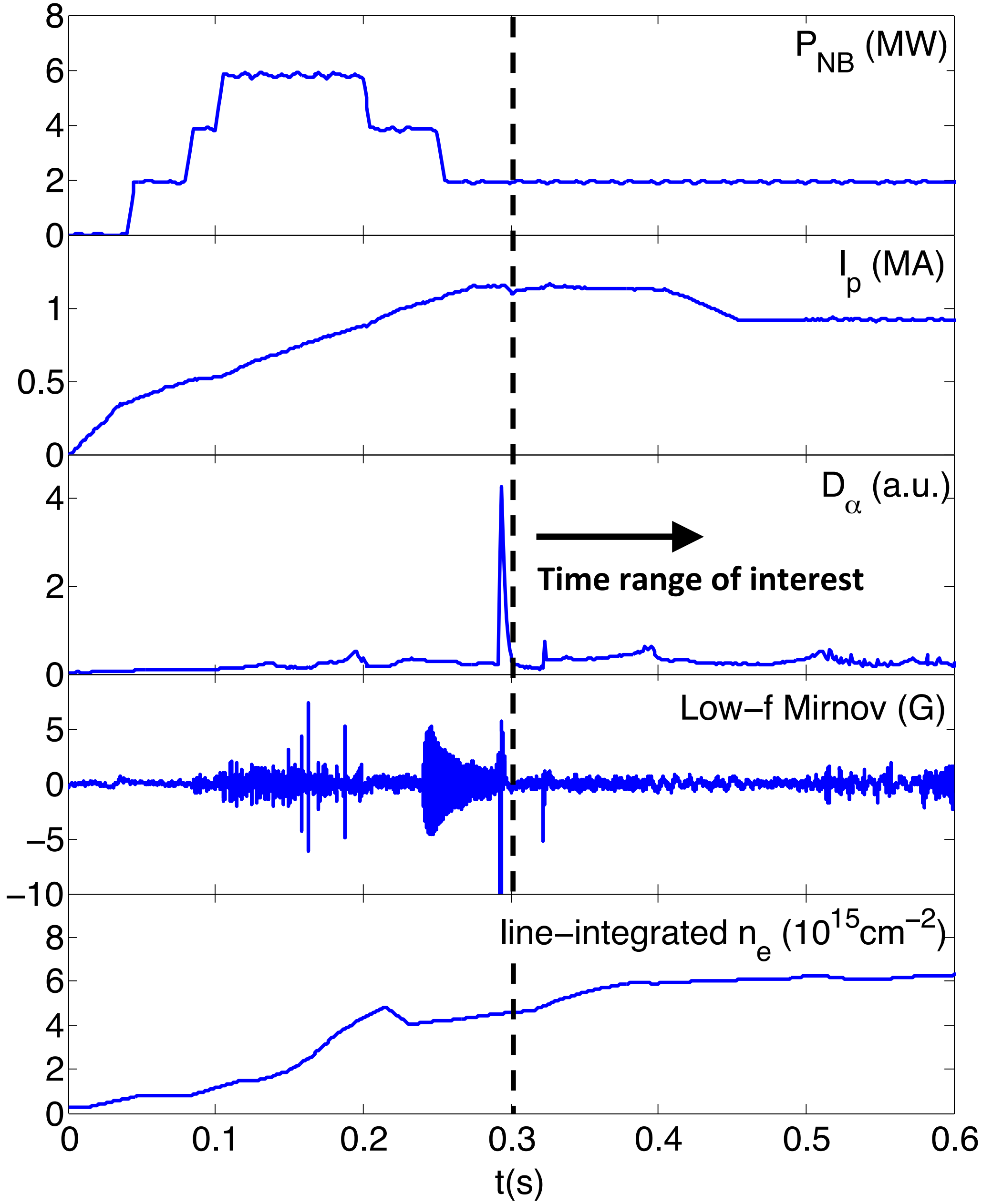
chan =1, k$_r$ =
f(kHz)
t (s)

Issues

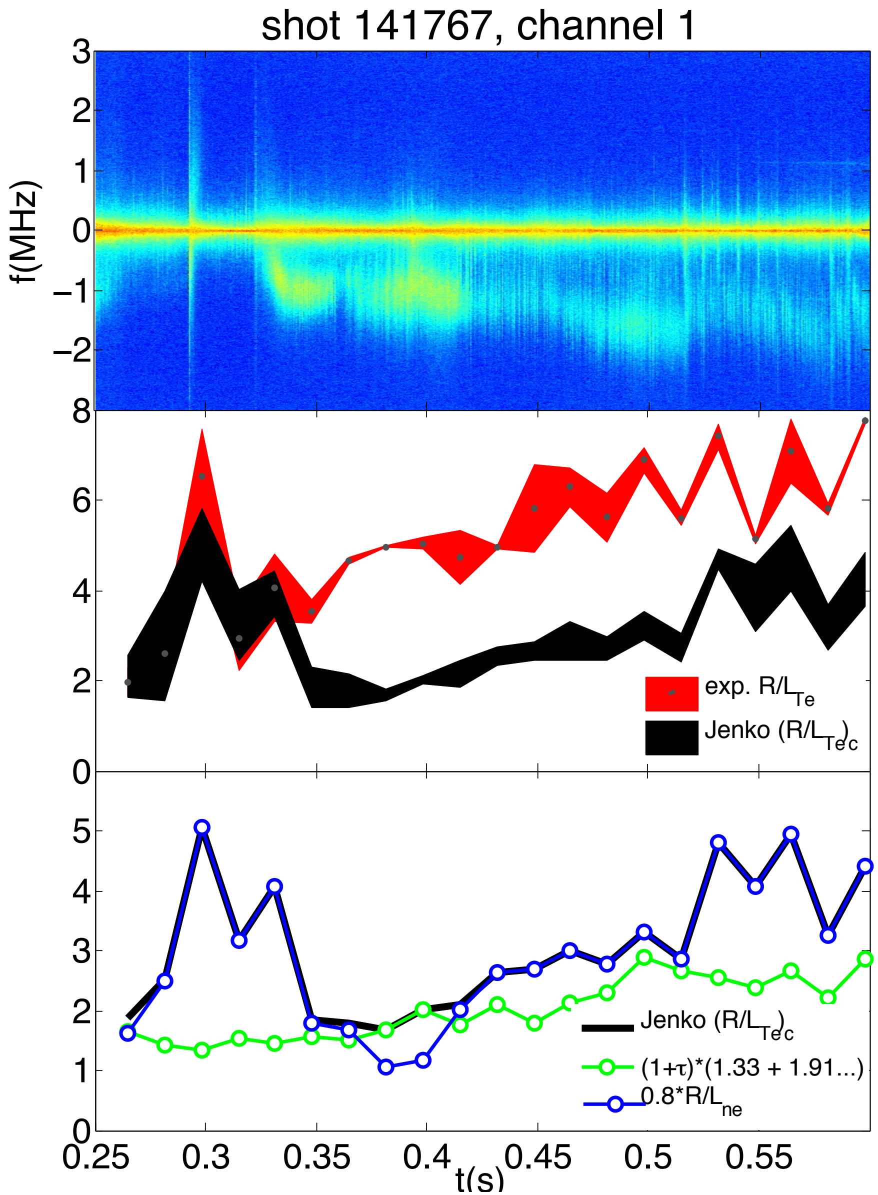

γ(kθρs = 15)
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
0.35
0.4
0.45
0.5
0.55
0.6
t(s)
4
3
2
1
0
0.3
0.35
0.4
0.45
0.5
0.55
0.6
t(s)
Jenko (R/LTe)c
(1+τ)*(1.33 + 1.91...)
0.8*R/Lne


chan =1, kr =
3000
2000
1000
0
−1000
−2000
−3000
f(kHz)
0.35
0.4
0.45
0.5
0.55
t (s)

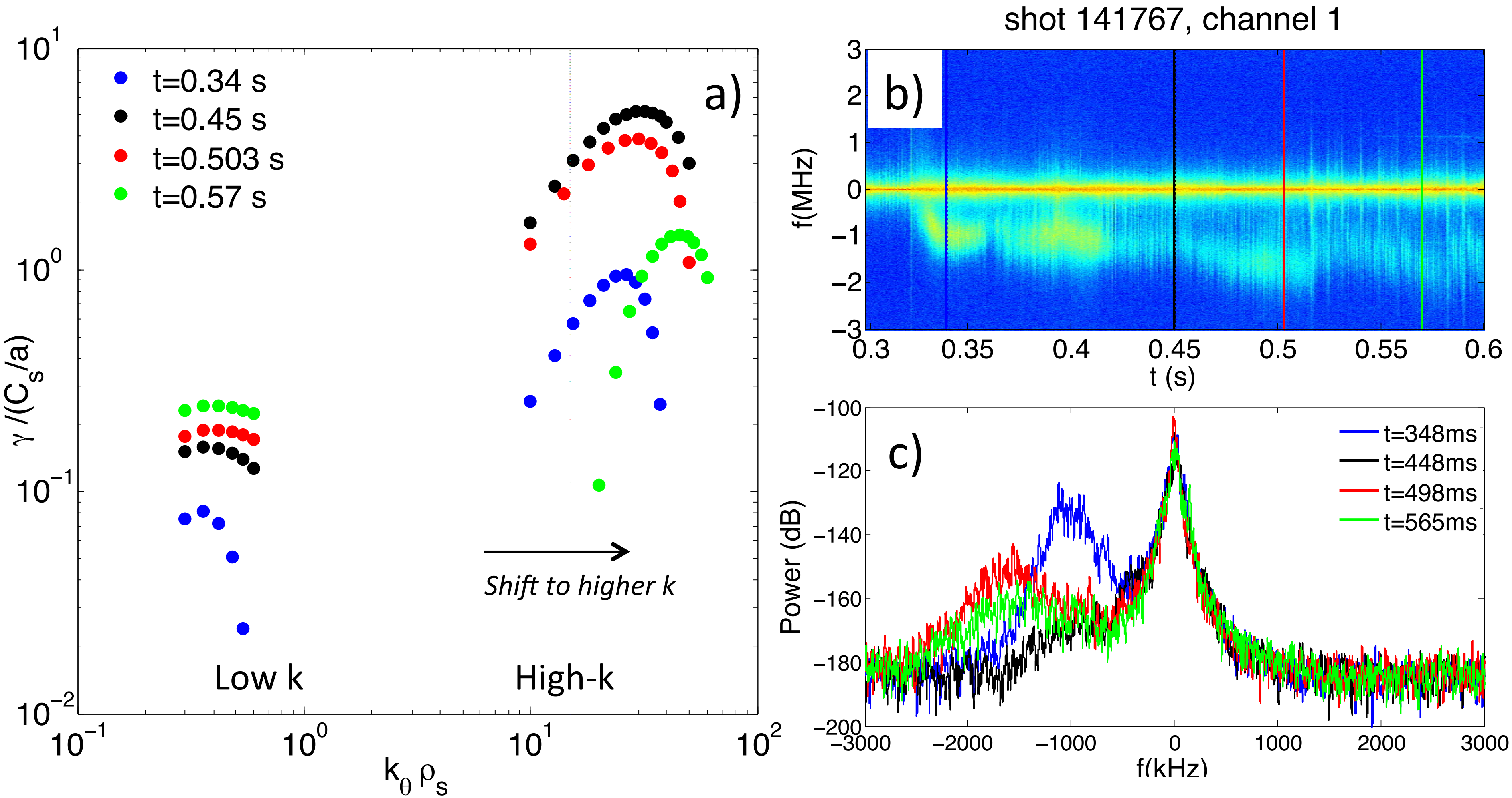
Shot 141767



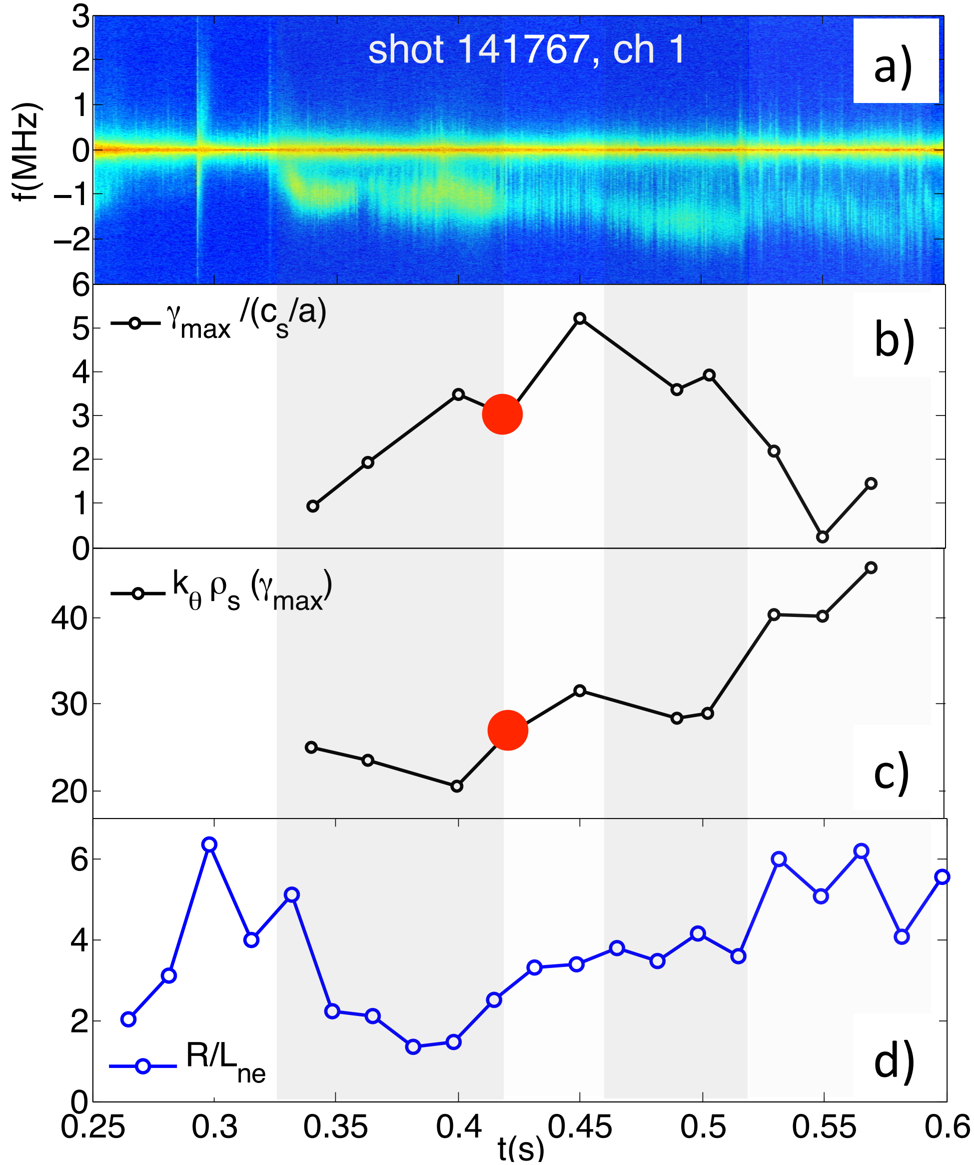
8
6
4
2
0
P_{NB} (MW)
I_p (MA)
1
0.5
0
D_α (a.u.)
4
2
0
Time range of interest
Low–f Mirnov (G)
5
0
–5
–10
line–integrated n_e ($10^{15}cm^{-2}$)
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
t(s)



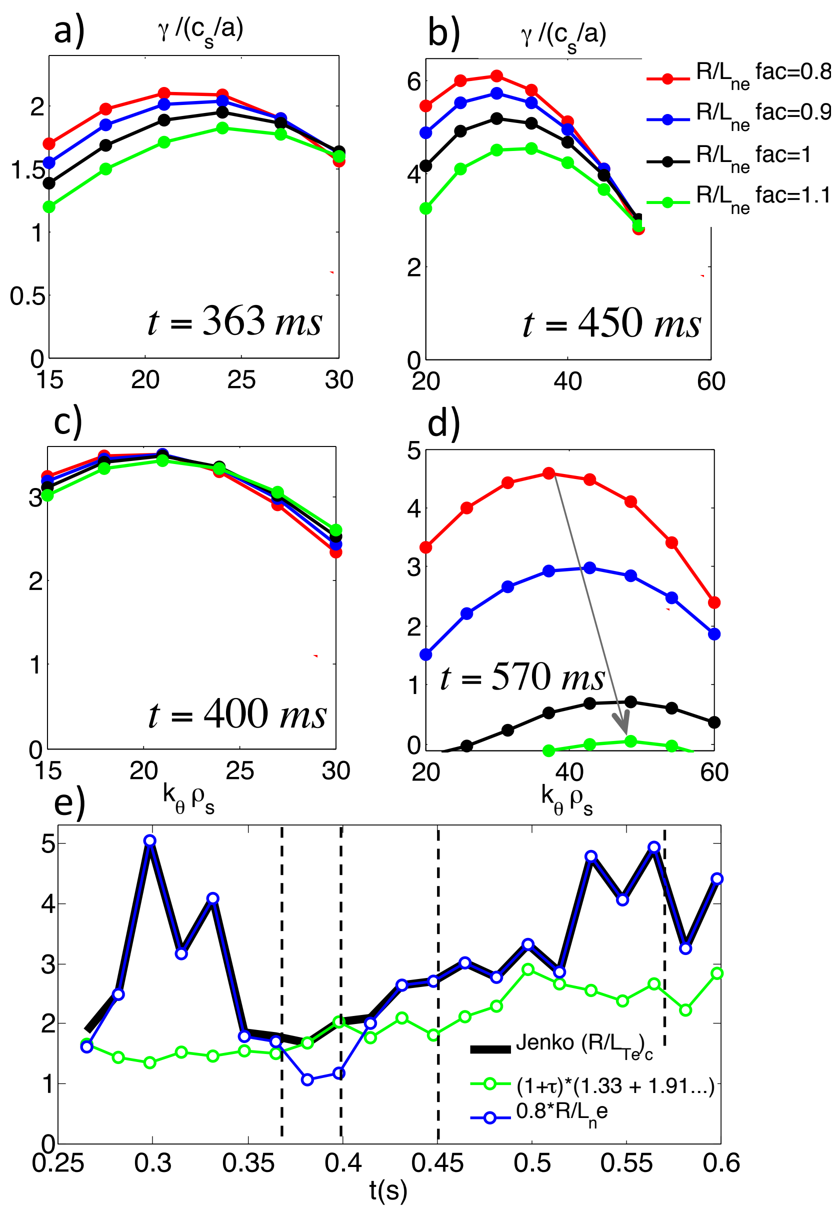
shot 141767, channel 1
f(MHz)
exp. R/L_Te
Jenko (R/L_Te)c
Jenko (R/L_Te)c
(1+τ)*(1.33 + 1.91...)
0.8*R/L_ne
t(s)

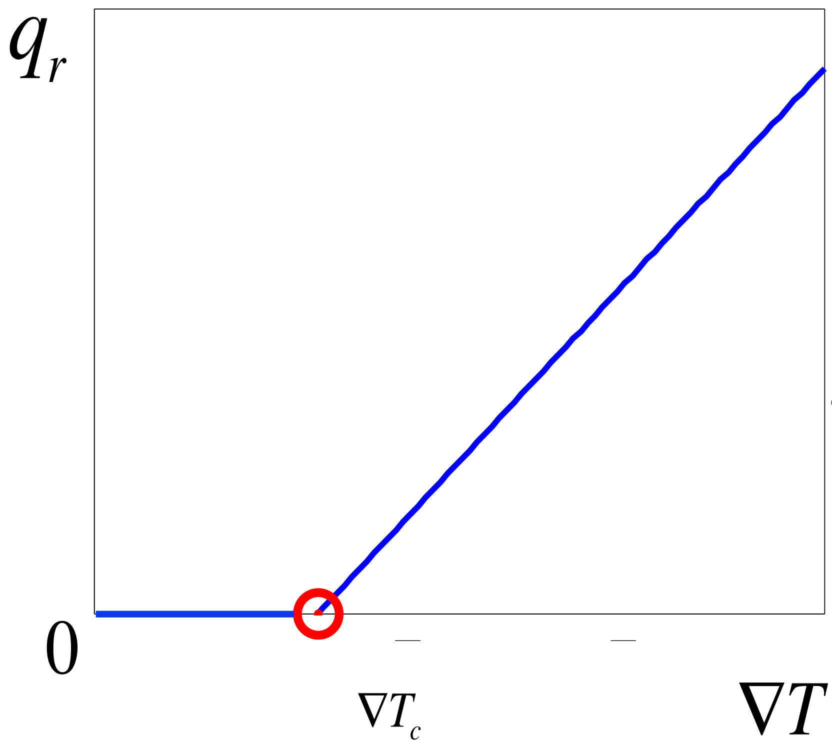


t=0.34 s
t=0.45 s
t=0.503 s
t=0.57 s
a)
Shift to higher k
Low k
High-k
$\gamma /(C_s/a)$
$k_\theta \rho_s$
shot 141767, channel 1
b)
f(MHz)
t (s)
c)
t=348ms
t=448ms
t=498ms
t=565ms
Power (dB)
f(kHz)

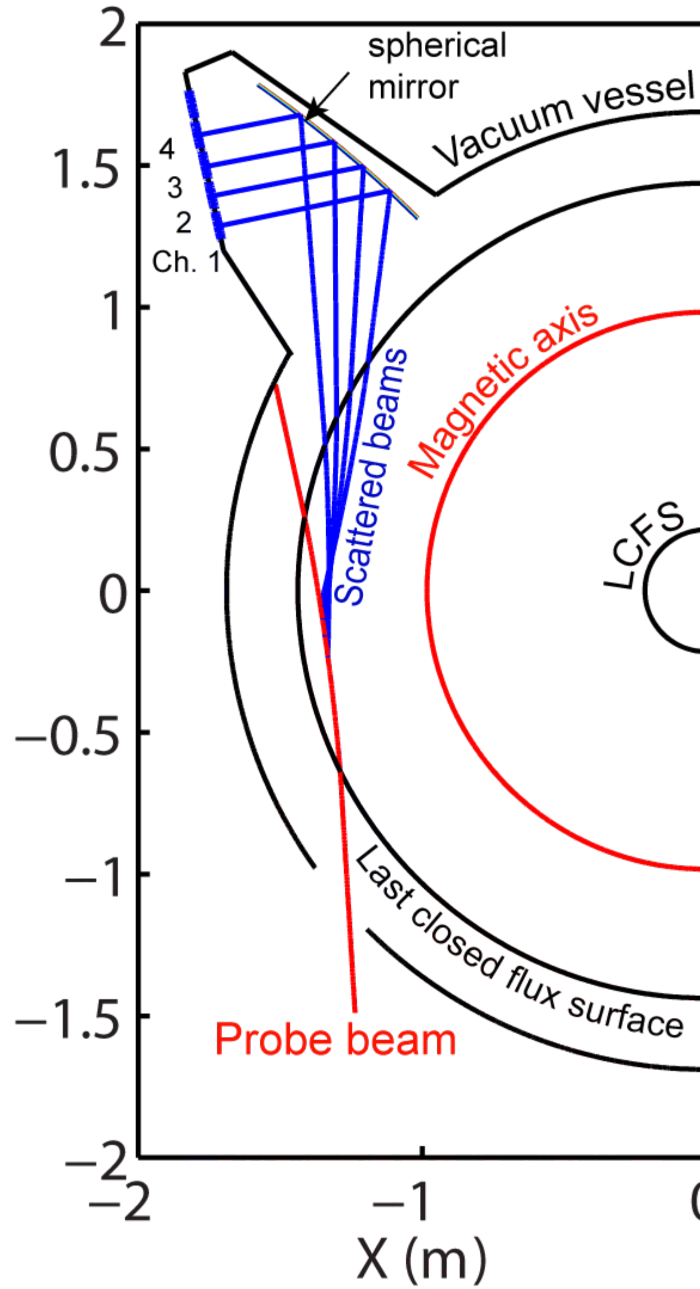


shot 141767, ch 1
a)
f(MHz)
3
2
1
0
−1
−2
6
5
4
3
2
1
0
γ_{max} /(c_s/a)
b)
k_θ ρ_s (γ_{max})
40
30
20
c)
6
4
2
0
R/L_{ne}
d)
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
t(s)


a)
γ /(c_s/a)
t = 363 ms
b)
γ /(c_s/a)
t = 450 ms
R/L_ne fac=0.8
R/L_ne fac=0.9
R/L_ne fac=1
R/L_ne fac=1.1
c)
t = 400 ms
d)
t = 570 ms
k_θ ρ_s
k_θ ρ_s
e)
Jenko (R/L_Te)_c
(1+τ)*(1.33 + 1.91...)
0.8*R/L_n e
t(s)



q_r
0
∇T_c
∇T



spherical
mirror
Vacuum vessel
4
3
2
Ch. 1
Scattered beams
Magnetic axis
LCFS
Last closed flux surface
Probe beam
Y (m)
X (m)