NSTX-U

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

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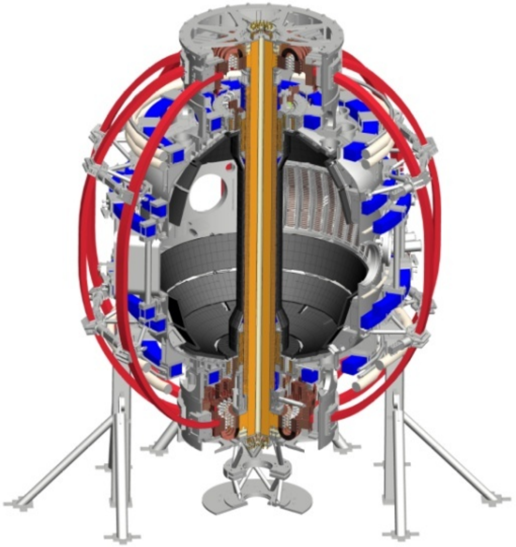

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Outline

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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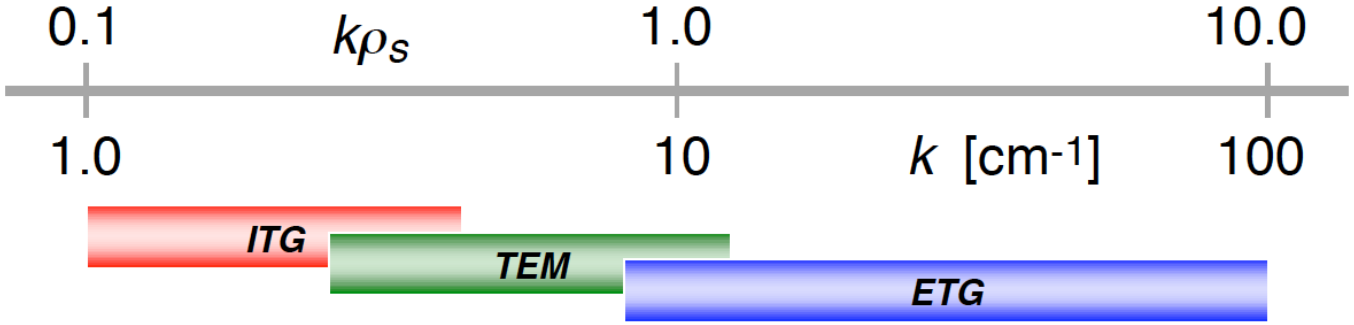
Anomalous Electron Thermal Transport is Observed in All NSTX Confinement Regimes

- **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.

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



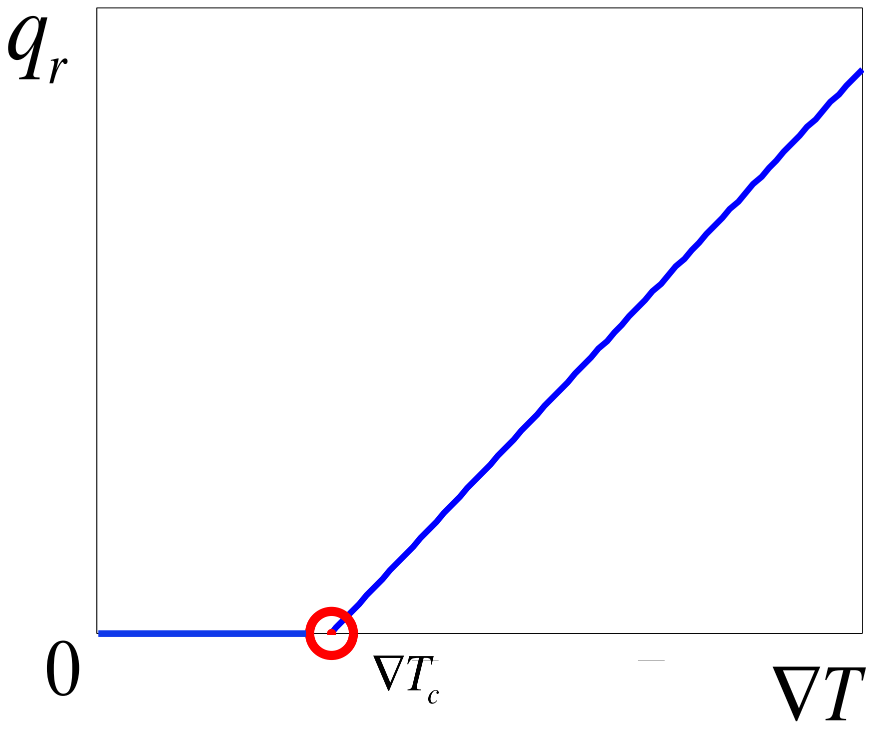
From Mazzucato PPPL presentation

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]*.

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

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

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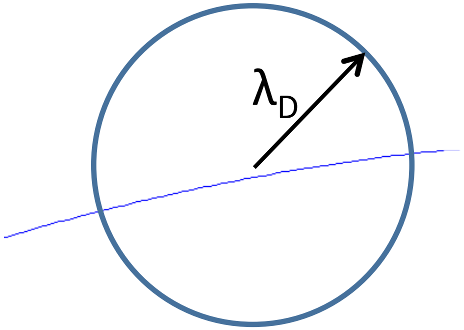
Collective Thomson Scattering is used to measure High-k Turbulence

- Collective/coherent Thomson scattering



$$k\lambda_D \le 1$$

- Scattered power density

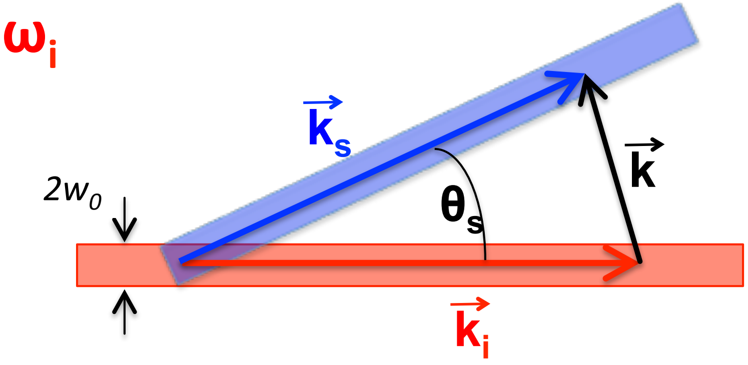
$$\frac{d^2P}{d\Omega d\nu} = P_i r_e^2 L_z \left|\Pi \cdot \hat{e}\right|^2 \frac{\left|\tilde{n}_e(k,\omega)\right|^2}{VT}$$

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

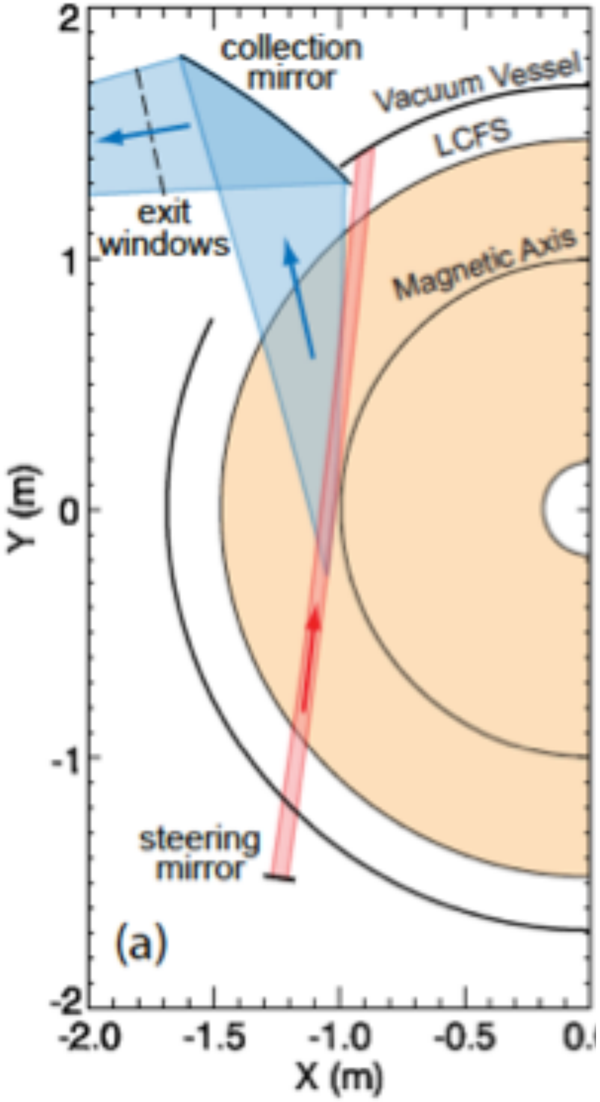
$$\vec{k}_s = \vec{k} + \vec{k}_i \qquad \omega_s = \omega + \omega_i$$

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

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



High-k Microwave Scattering Diagnostic at NSTX

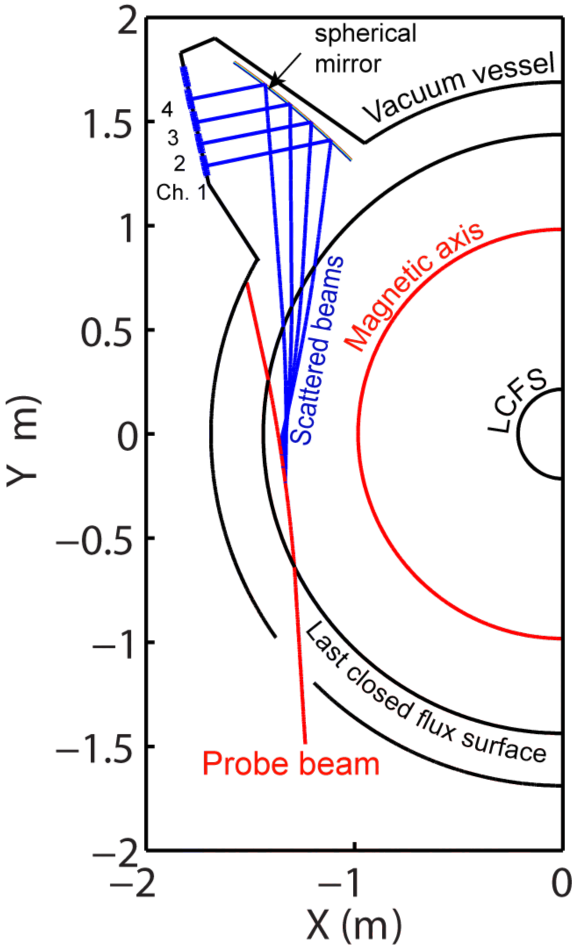


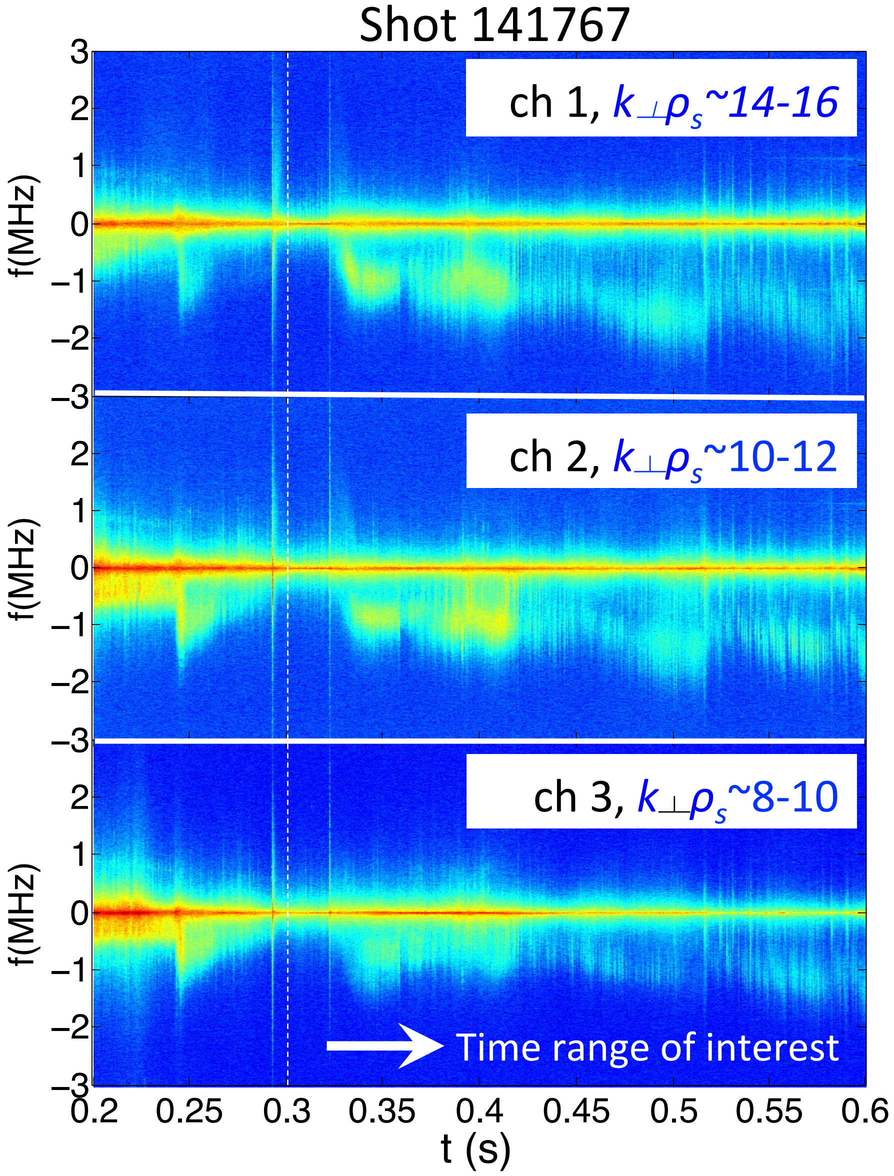
View from top of NSTX (D.R. Smith PhD thesis 2009)

- Gaussian Probe beam: 200 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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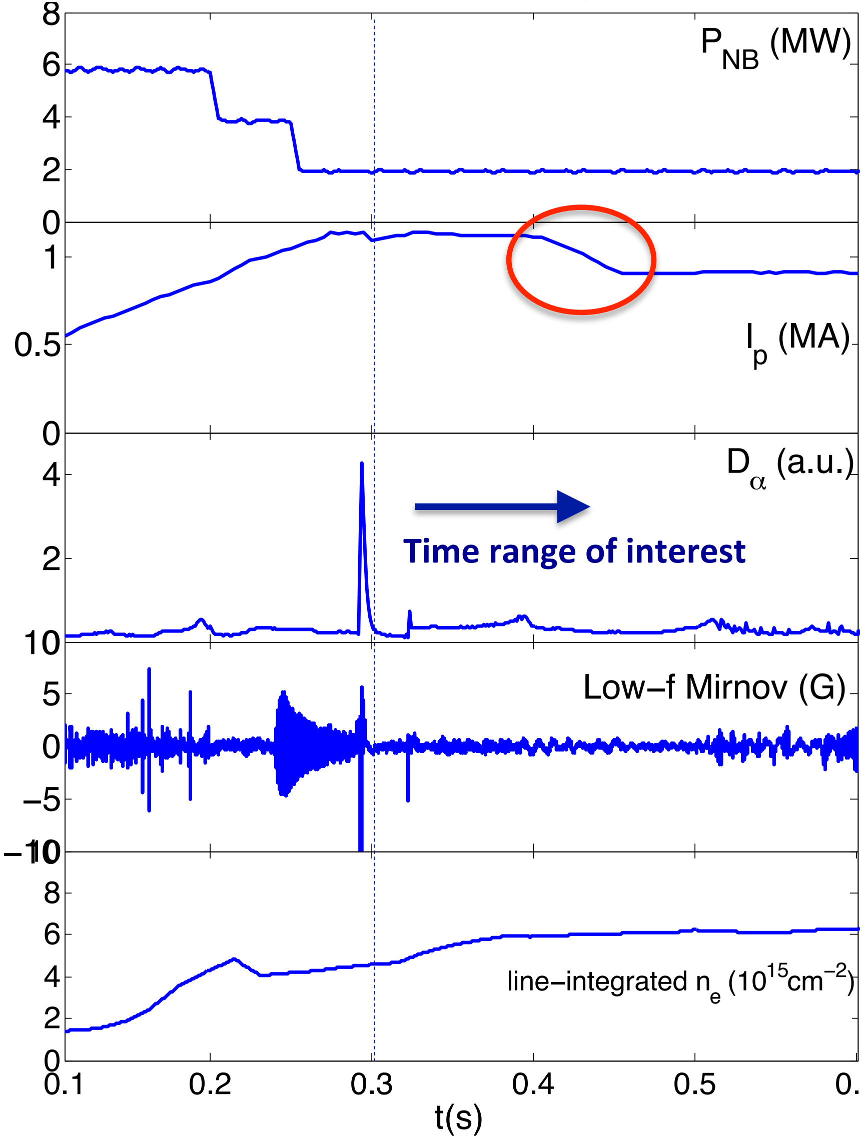
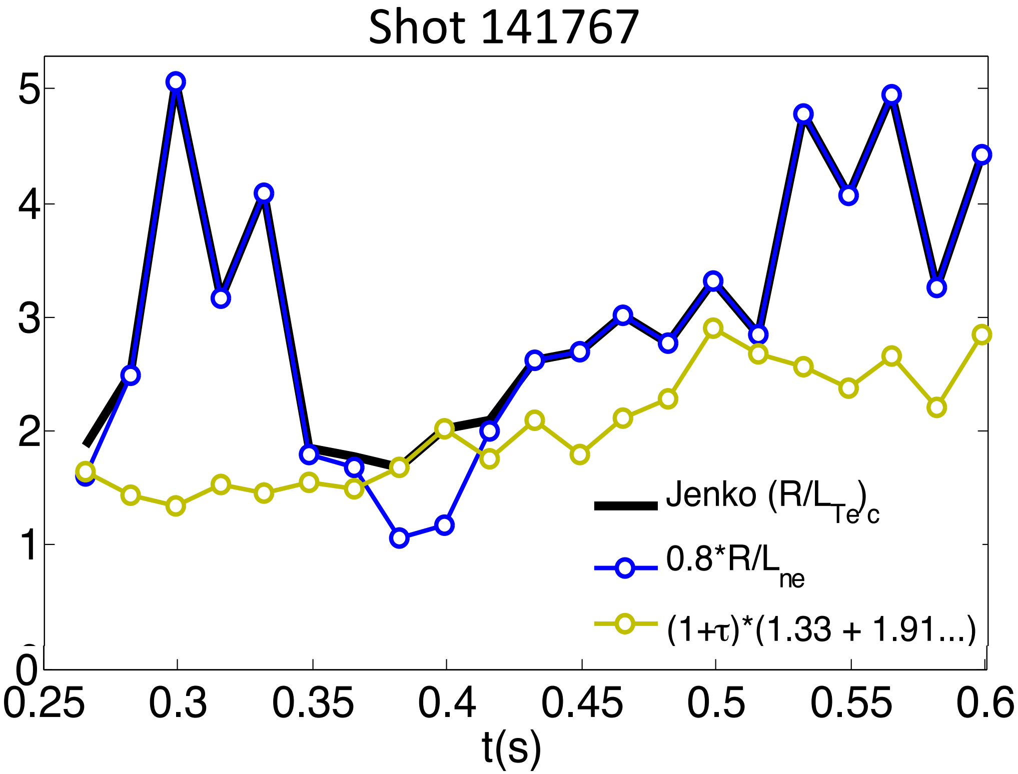
A Set of NBI-heated H-mode Plasmas is Used to Study High-k Turbulence during Current Ramp-down

- **NBI heated**, HHFW heating is absent during the run.
- *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



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



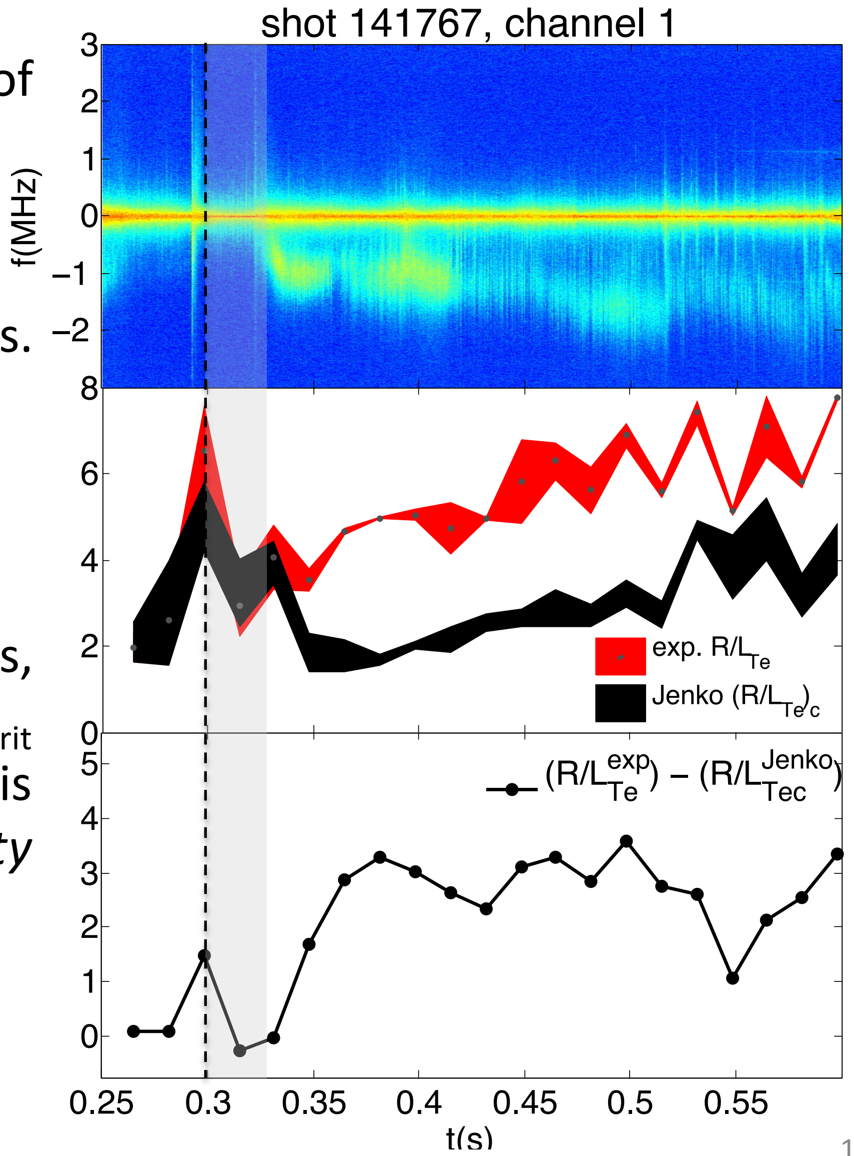
- Jenko critical gradient is a maximum of a ***R/L_{ne}*** term and an ***s/q*** term.

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

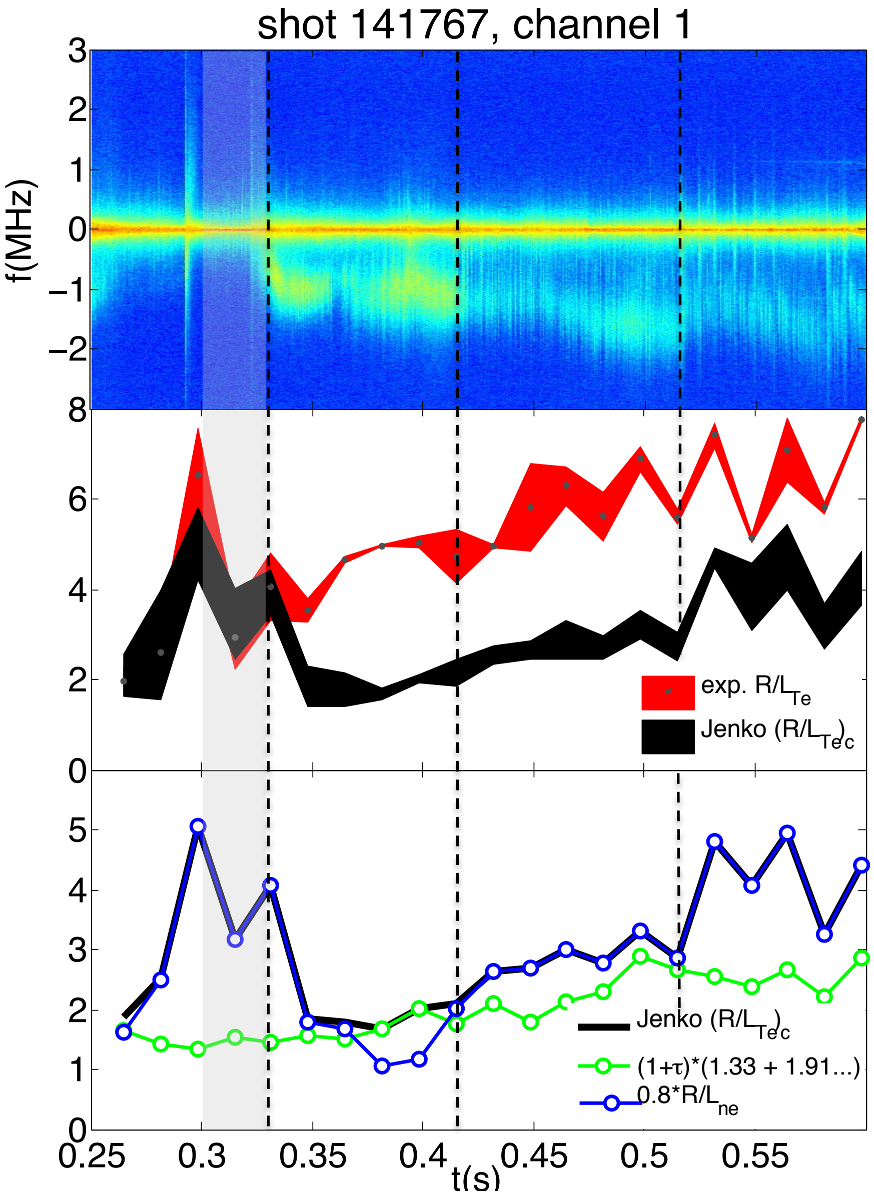
- High enough values of ***R/L_{ne}*** *could* bring critical ETG to experimental ETG levels or even higher. This *should* have a ***stabilizing*** effect on turbulence.

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*.



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**).

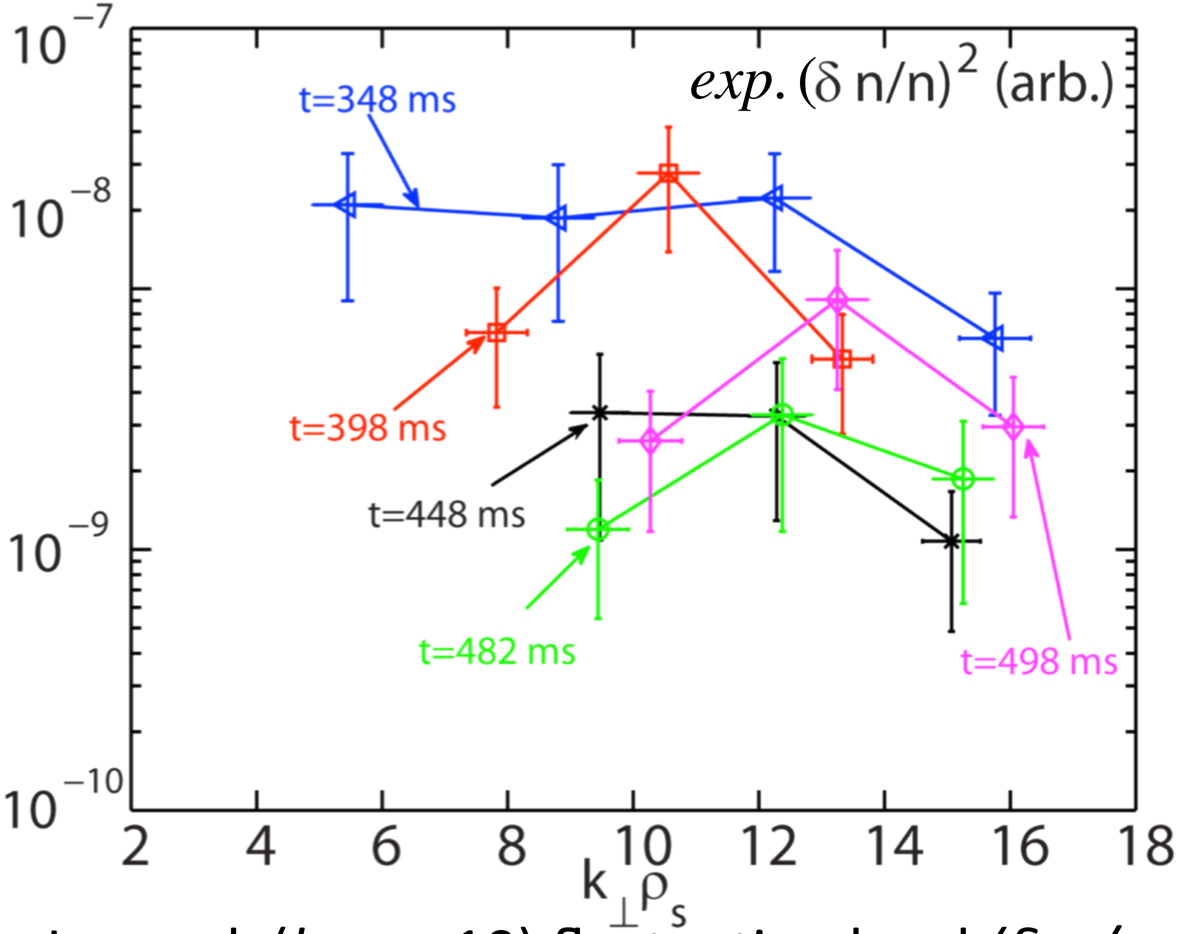
➔ Fluctuations decrease.

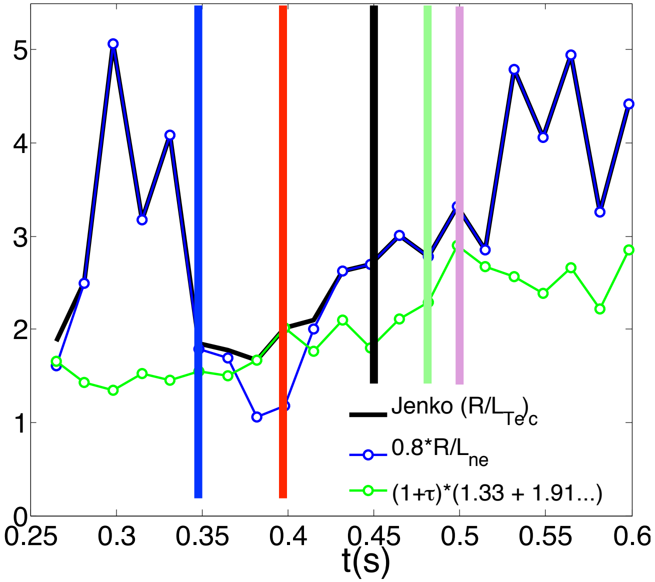
- Previous to t ~ 320 ms ETG is marginally stable. No fluctuations.

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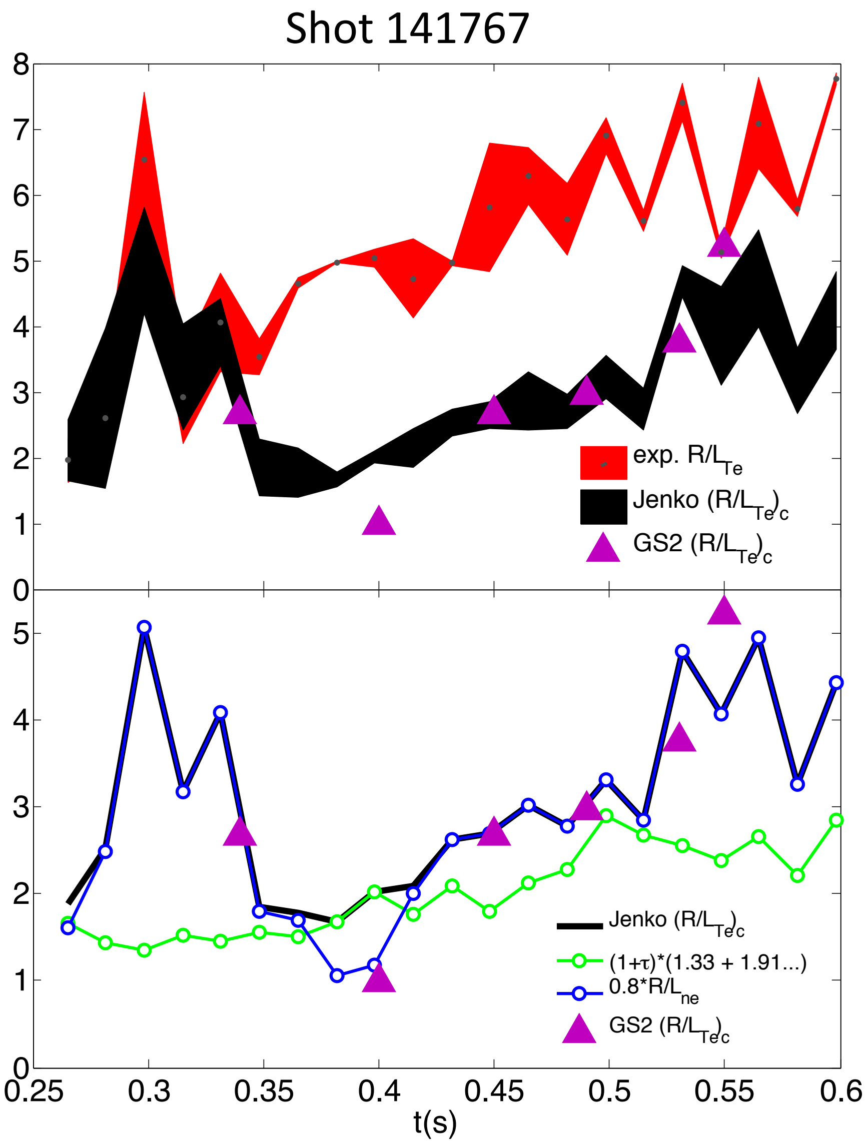
Critical Gradient Computed with GS2 Linear Runs Agrees with Jenko's Critical ETG

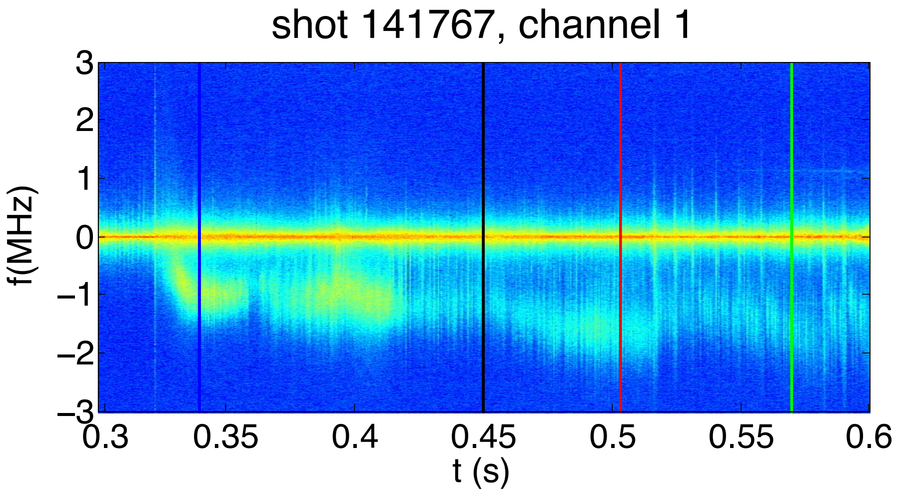
- *$(R/LTe)_{crit}$* is explicitly calculated using GS2.

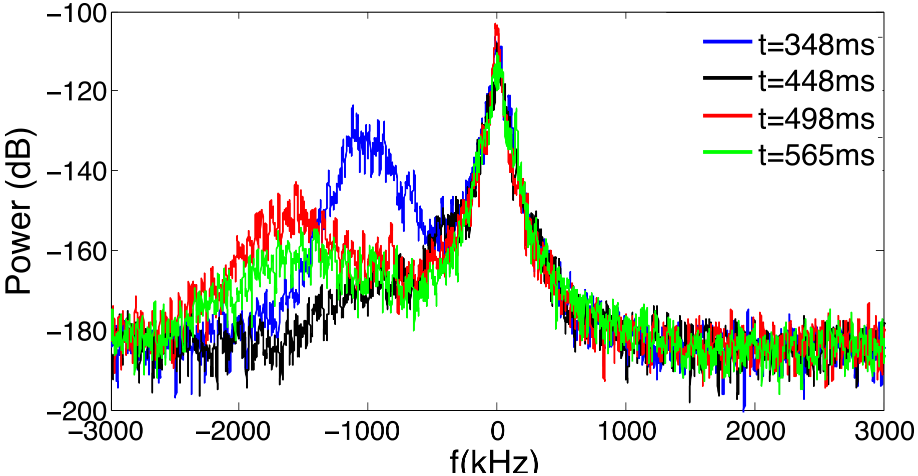
- Fairly good agreement is observed between GS2 *$(R/L_{Te})_{crit}$* calculations and Jenko's formula.

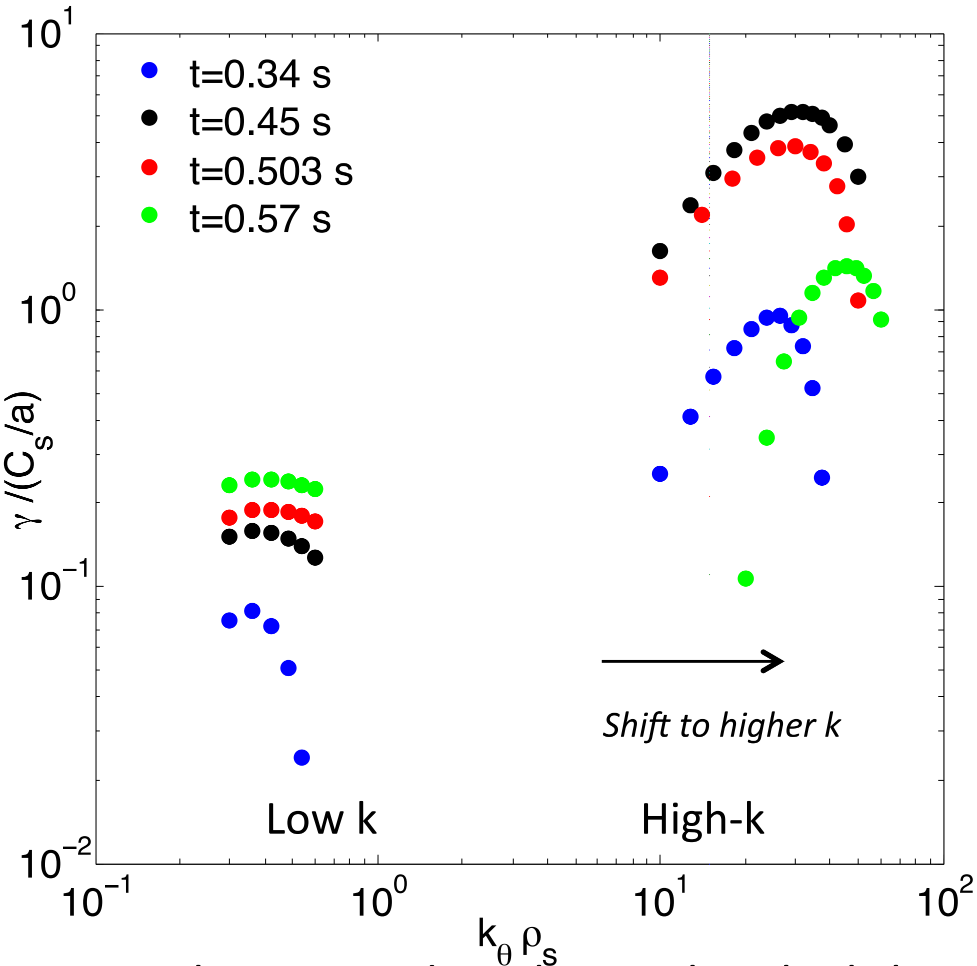
- This is consistent with Jenko's critical ETG formula and previous comparisons with experimental ETG.



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



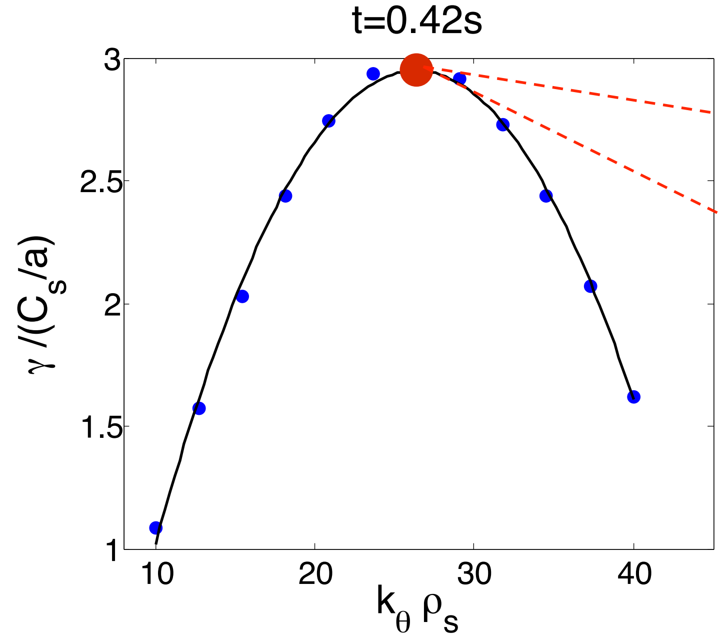


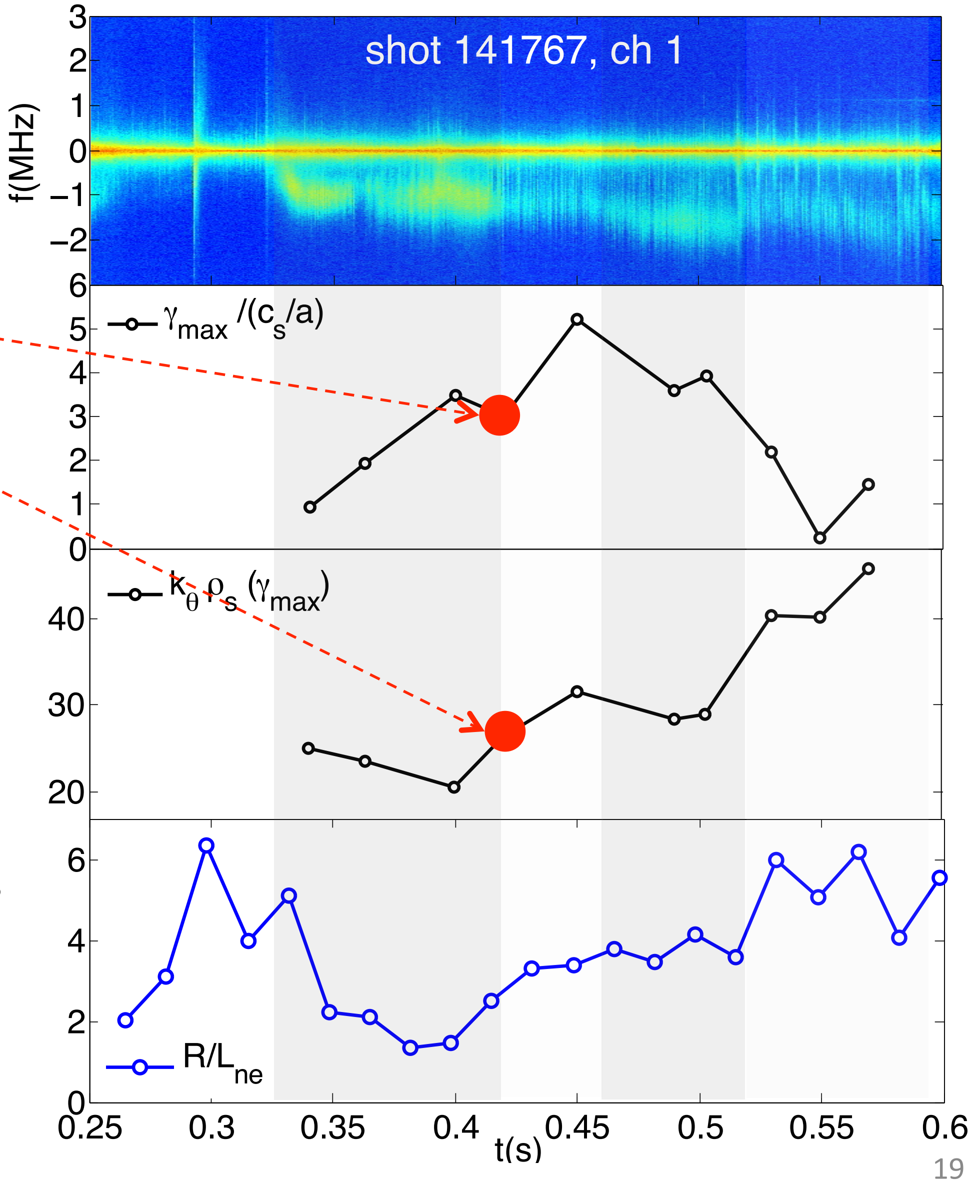


- Low-k linear growth rates ($k_\perp\rho_s \leq 1$) increase with time, and are lower than high-k.
- High-k wavenumbers at maximum linear growth rate shift to higher-k.
- As $\mathbf{k_\perp\rho_s(\gamma_{max})}$ moves to higher k (e.g. t = 570 ms), observed fluctuations decrease.

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

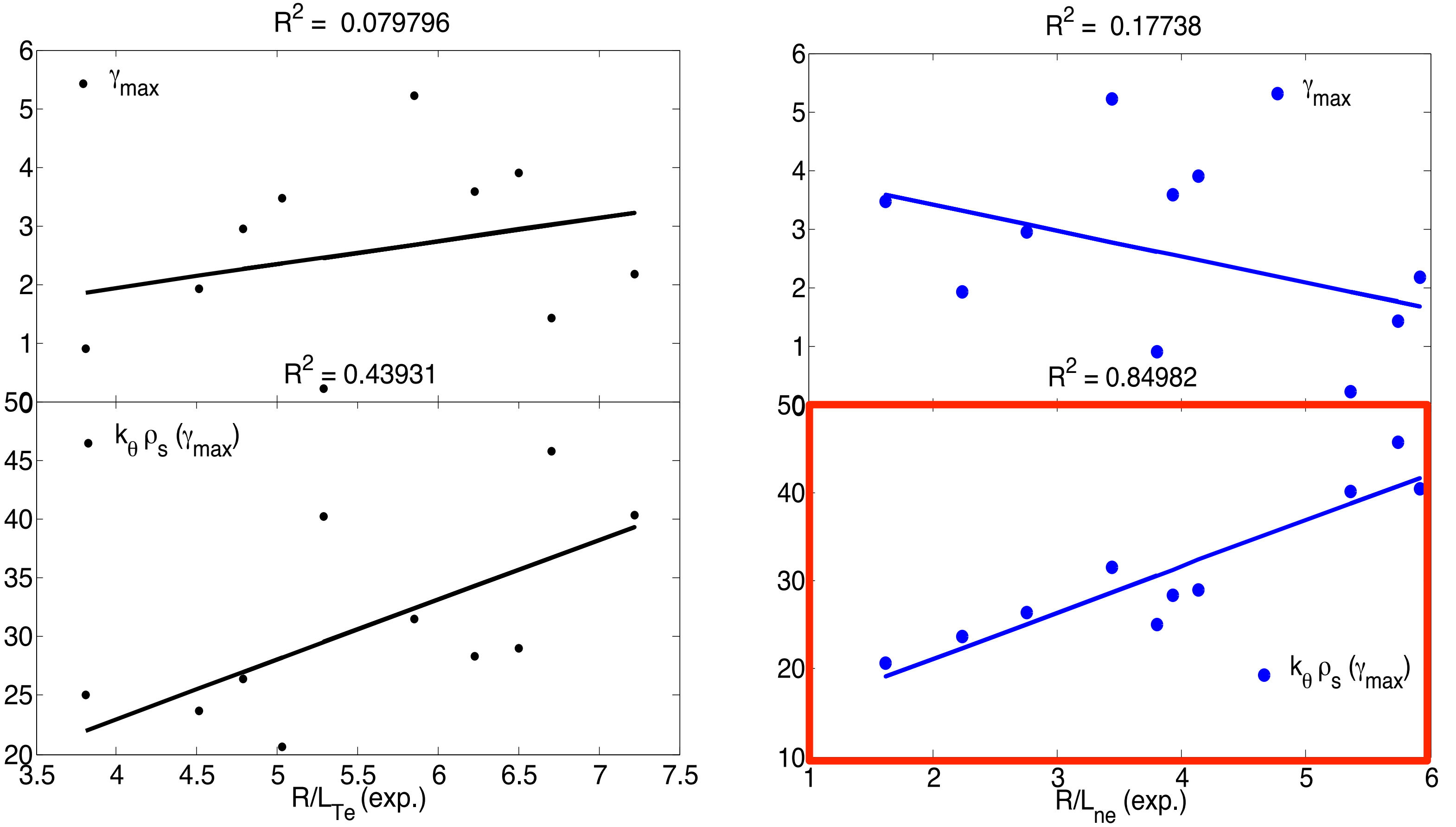
- At each time, determine
  - $\gamma_{max}/(c_s/a)$
  - $k_\vartheta \rho_s(\gamma_{max})$





- 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.

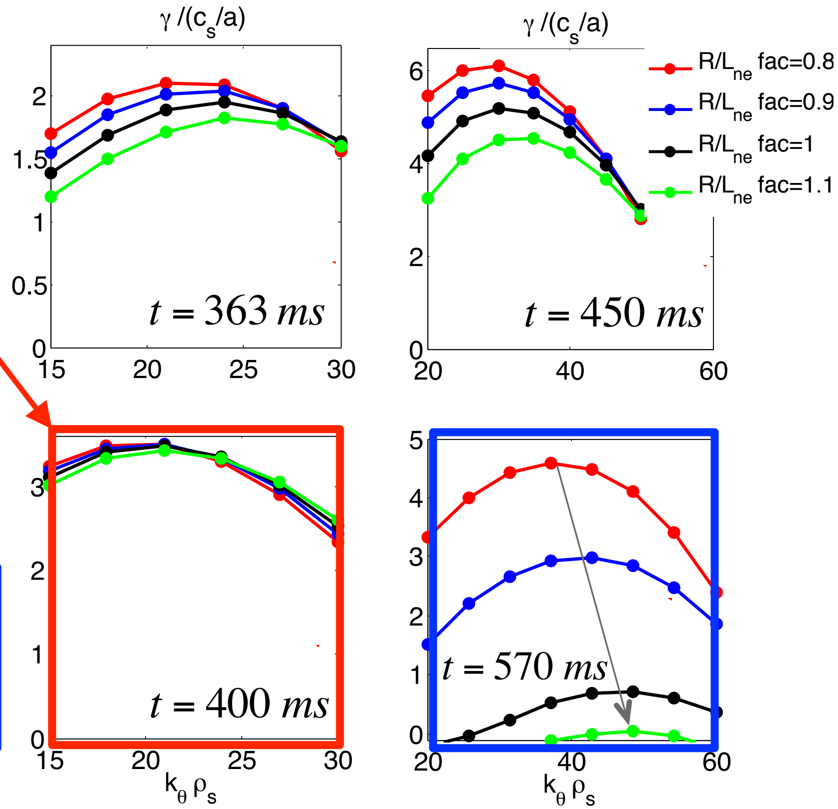
Correlation Between Wavenumber Values at Maximum Growth Rates and Electron Density Gradient

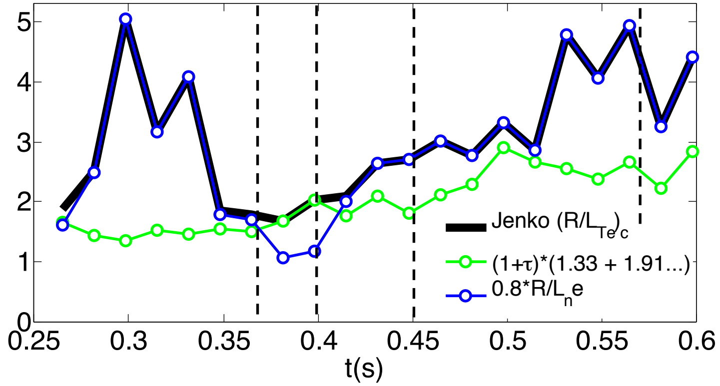


- Low correlation between γ_{max} and experimental R/L_{Te} and R/L_{ne}.
- $k_\vartheta\rho_s(\gamma_{max})$ correlates better to R/L_{Te} and R/L_{ne} than linear growth rates.
- Best correlation is observed between $k_\vartheta\rho_s(\gamma_{max})$ and R/L_{ne}.
- The conjecture is that R/L_{ne} is driving high-k turbulence to higher wavenumbers.

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} ➔ high-k fluctuations shift to even higher k values.

- 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.

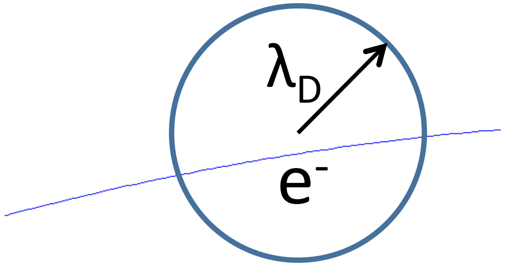
Future Work

- 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.

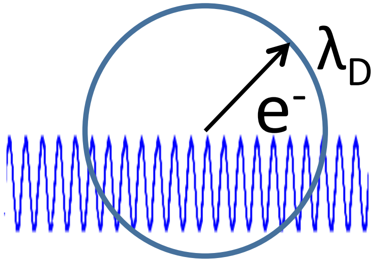
Back up slides

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

- Collective/coherent and incoherent scattering



$k\lambda_D \leq 1$



$k\lambda_D \geq 1$

- 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

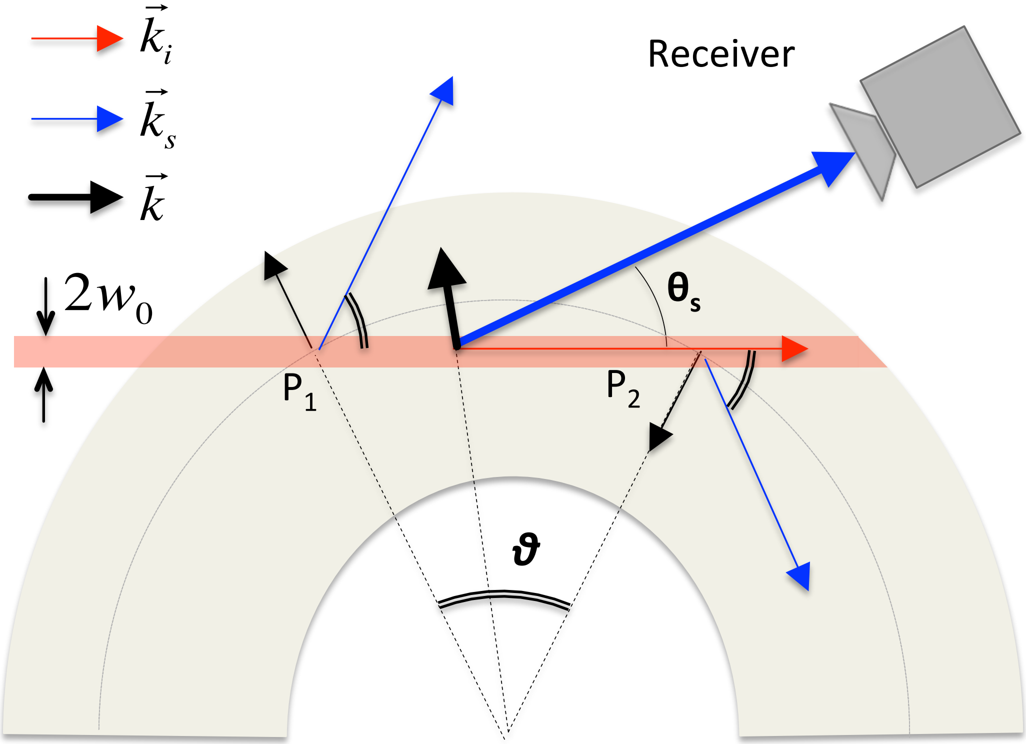
Spatial Localization and Wavenumber Resolution

- 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.
- Midplane propagation ➔ ***k*** is radial.
- Strong dependence on ***toroidal curvature*** => Oblique propagation enhances localization.
- At NSTX, beam propagation is out of midplane (~ 5°) ➔ ***k*** ~ *radial*.
- Gaussian beam ➔ *Δk* and *ΔR*

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

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

$$\Delta k = 2 / w_0$$

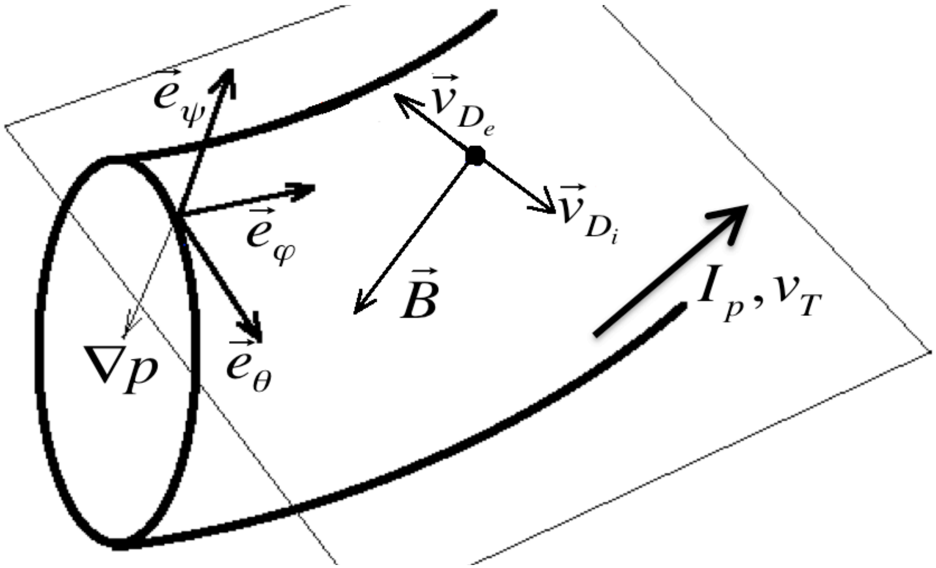


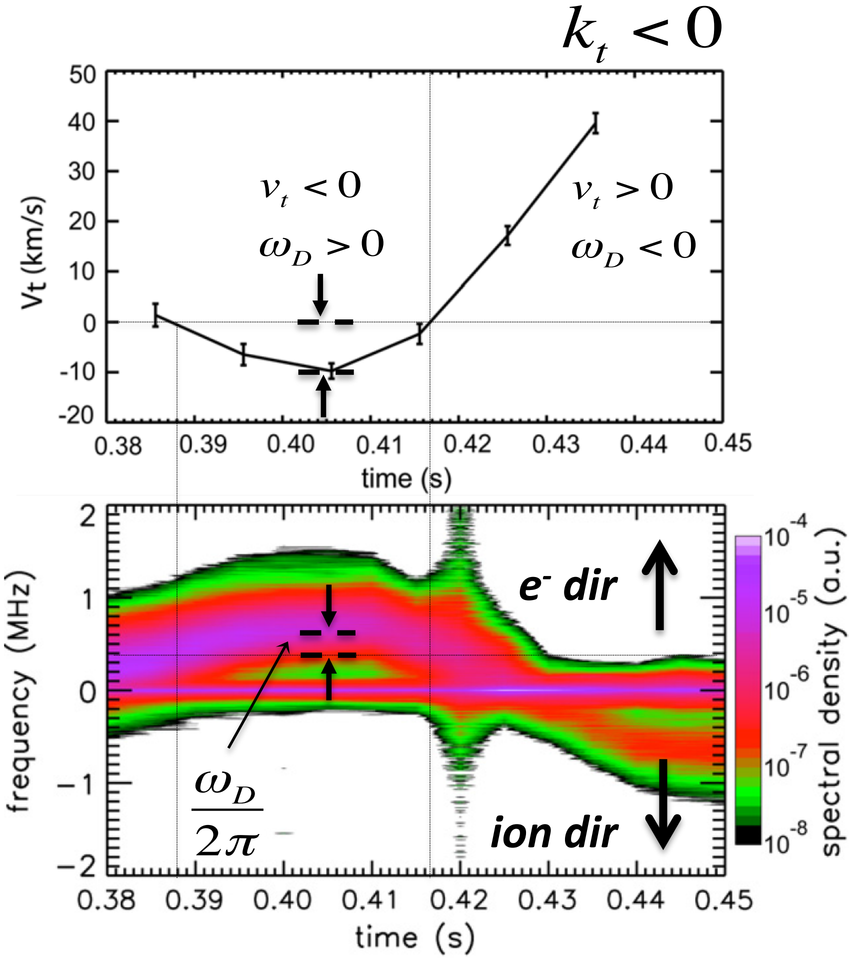
View from top (not to scale)

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

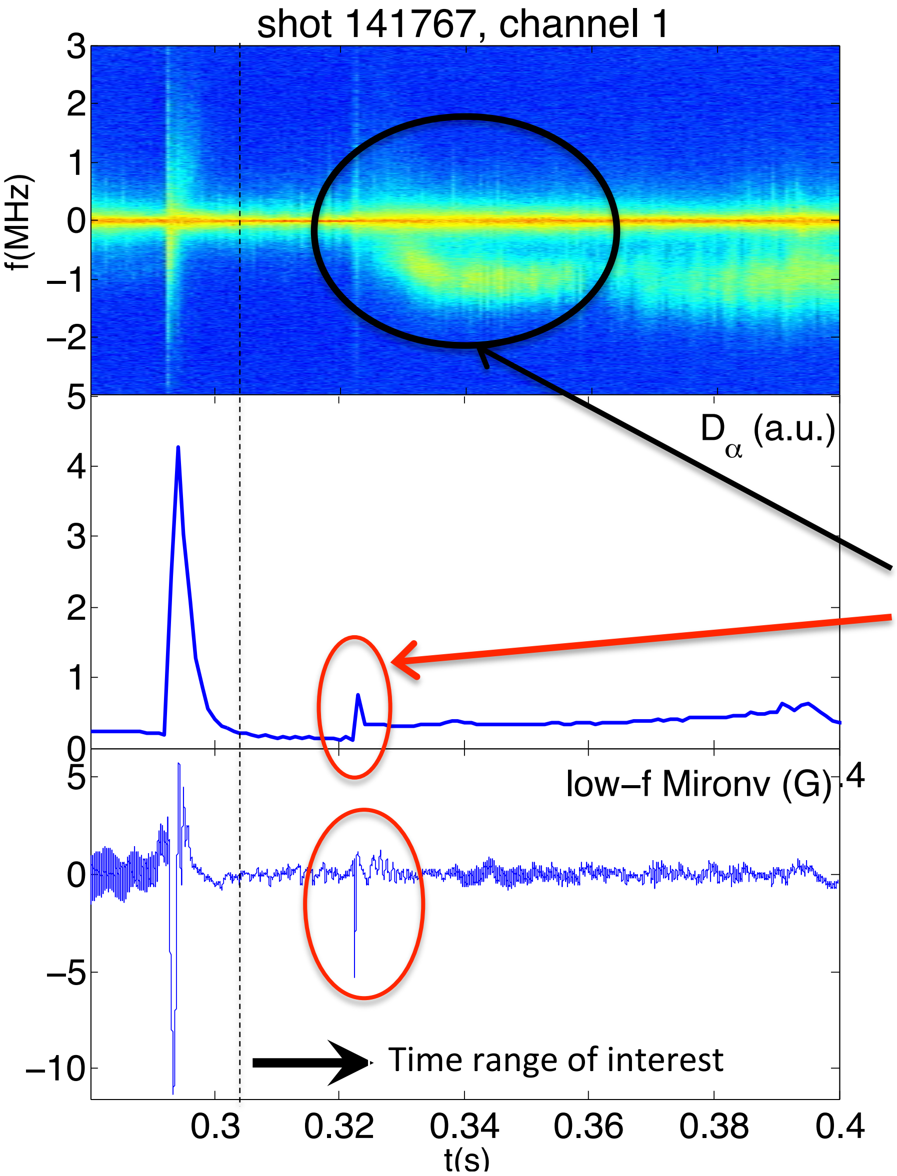
$$\begin{cases} \vec{v}_{De} \cdot \vec{e}_\varphi = -\dfrac{|\nabla p_e| B_\theta}{e n_e B^2} < 0 & e^- \ waves \\ \vec{v}_{Di} \cdot \vec{e}_\varphi = \dfrac{|\nabla p_i| B_\theta}{e n_i B^2} > 0 & ion \ waves \end{cases}$$





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

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

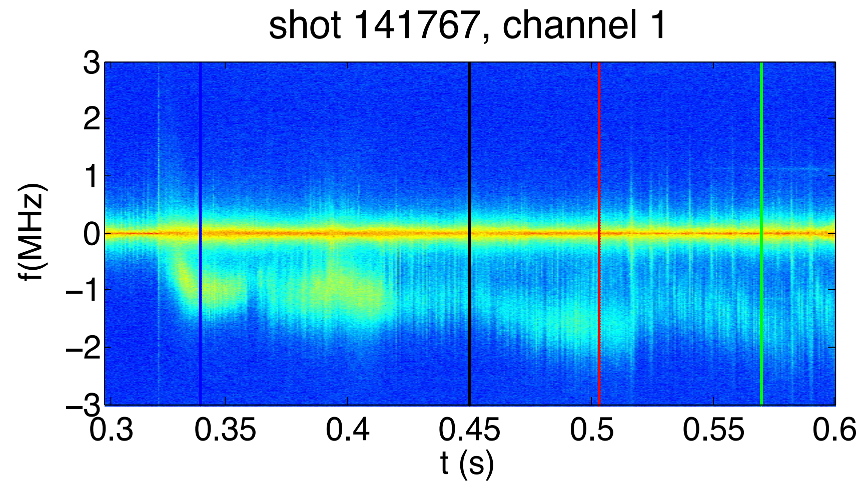


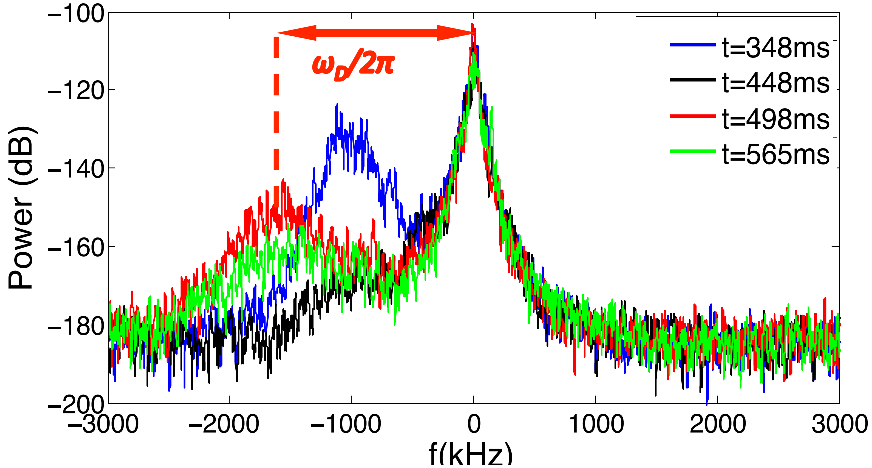
- Before t ~ 290 ms, MHD activity is high. At ~290 ms, an ELM event takes place and MHD activity quiets.

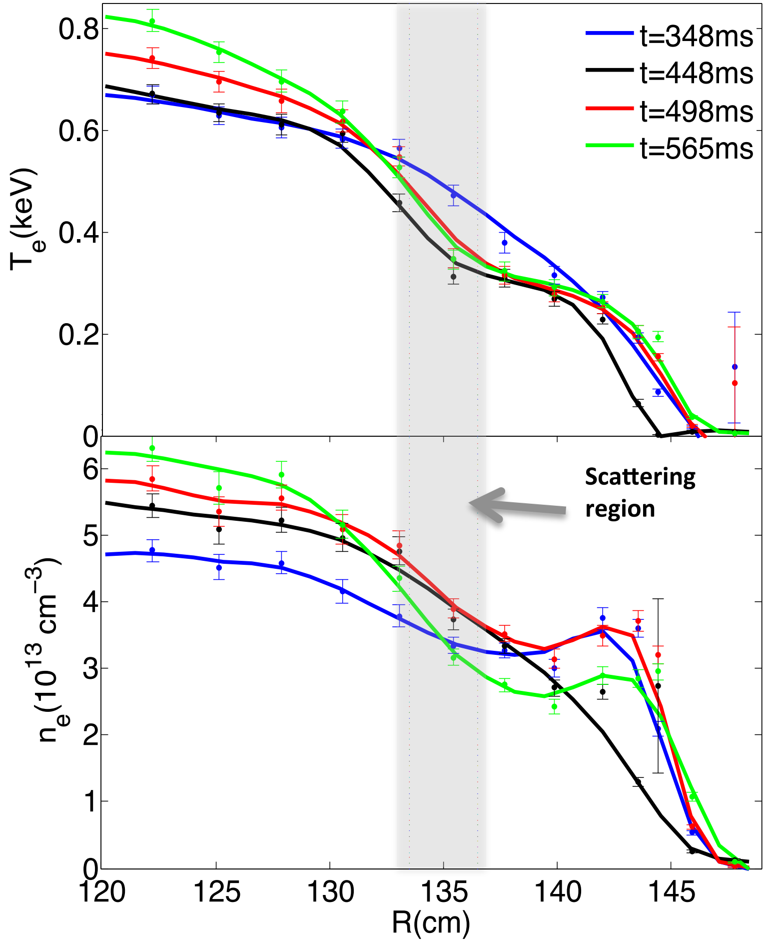
- Between t ~ 290 ms and t ~ 320 ms, high-k fluctuations are absent and MHD activity is quiet.

- **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







Scattering region

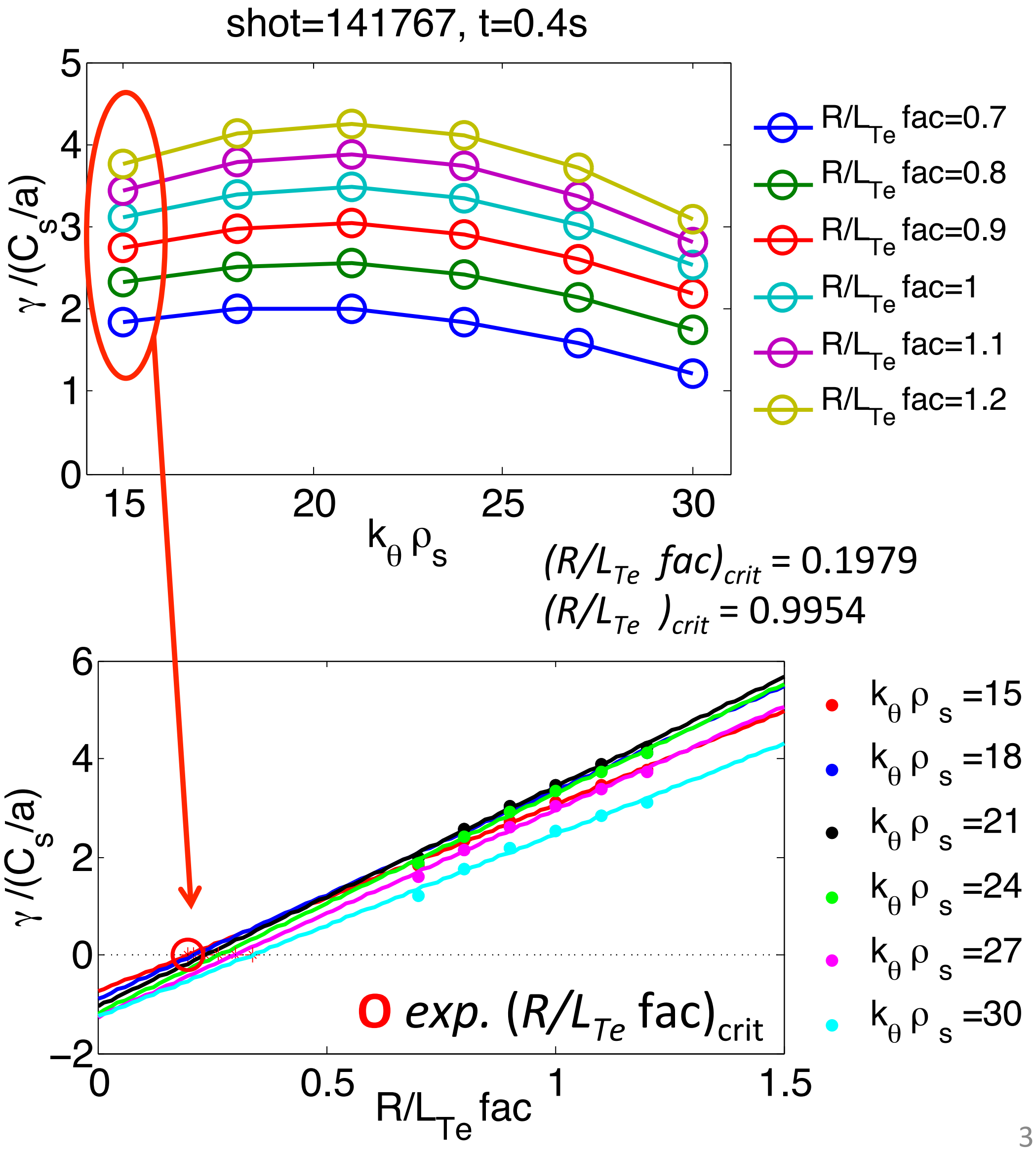
- Electron Density Gradient suffers the biggest change in the **scattering region**.
- Doppler shift is measured as distance from 0 to observed fluctuation frequency.

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).

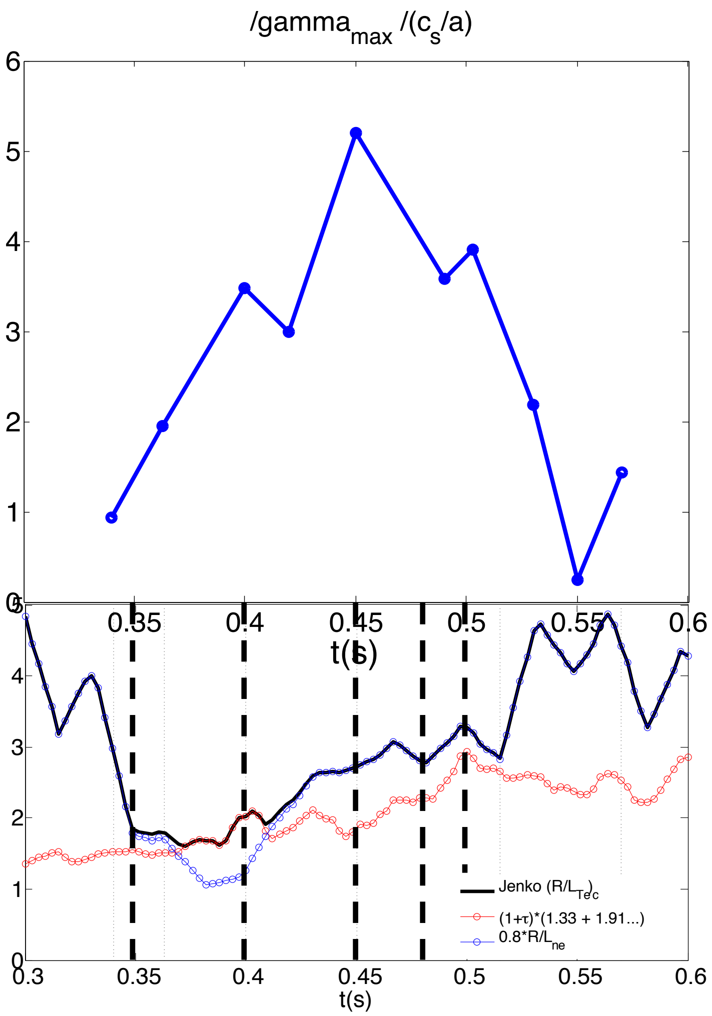
- $(R/L_{Te})_{crit}$ is found to be the minimum R/L_{Te} to satisfy $\Upsilon = 0$.

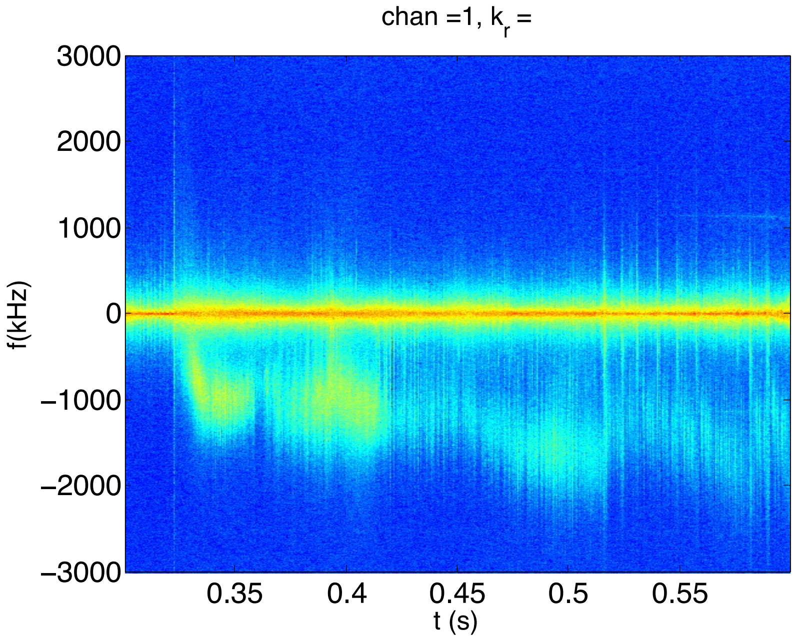


$(R/L_{Te}\ fac)_{crit} = 0.1979$
$(R/L_{Te})_{crit} = 0.9954$

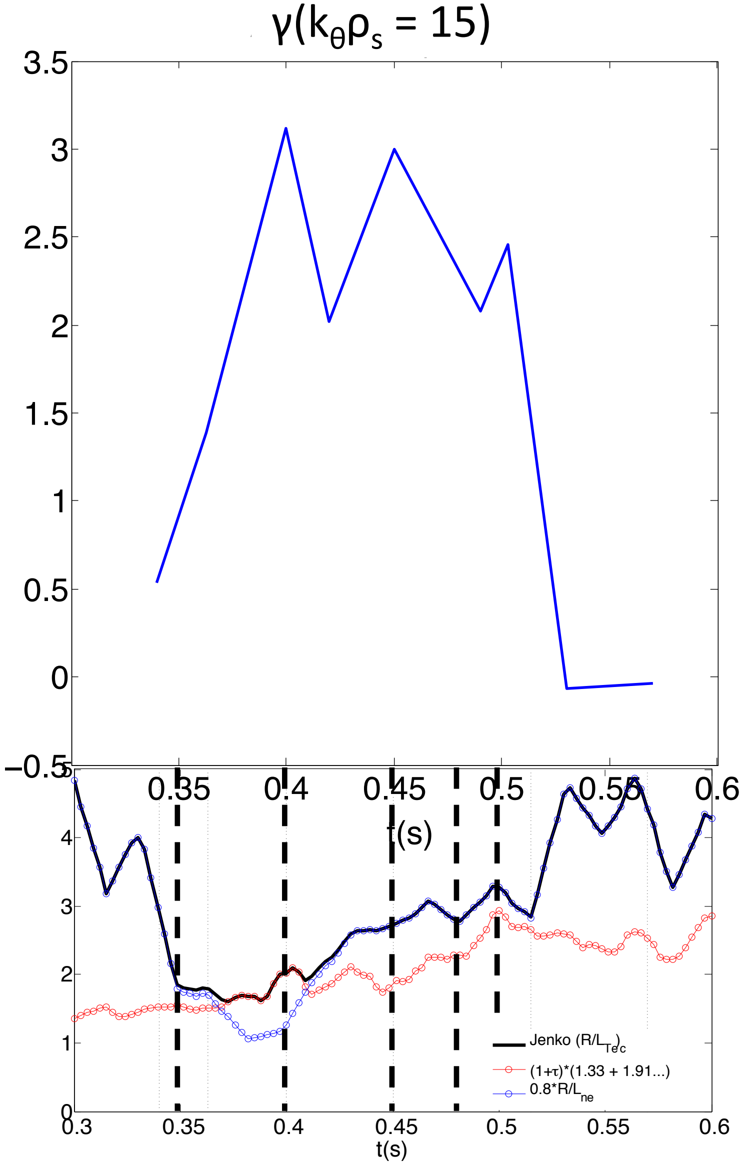
O *exp.* (R/L_{Te} fac)$_{crit}$

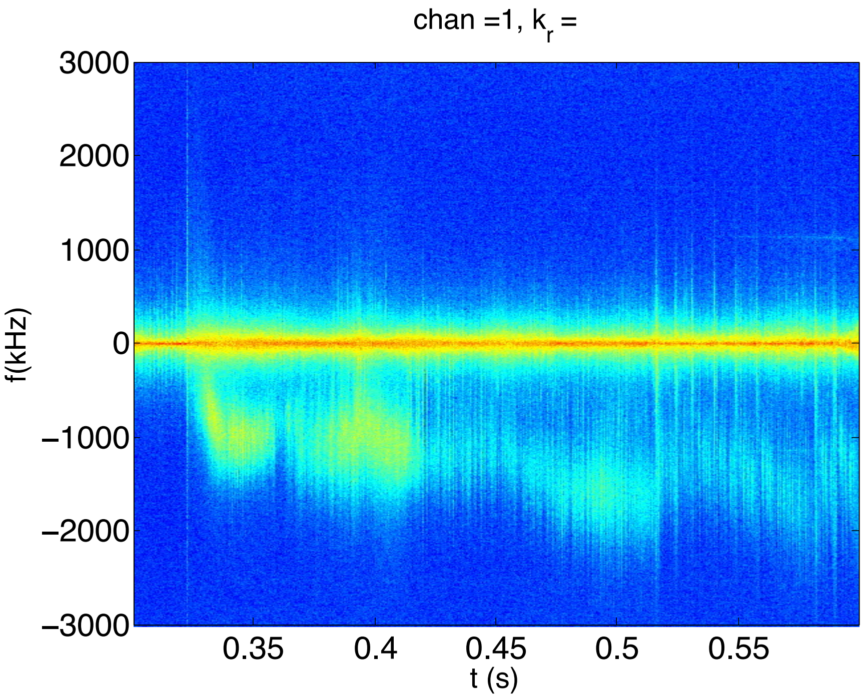
Issues


/gamma$_{max}$ /(c$_s$/a)
6
5
4
3
2
1
0
0.35
0.4
0.45
0.5
0.55
0.6
t(s)
5
4
3
2
1
0
0.3
0.35
0.4
0.45
0.5
0.55
0.6
t(s)
Jenko (R/L$_{Te}$)$_c$
(1+τ)*(1.33 + 1.91...)
0.8*R/L$_{ne}$

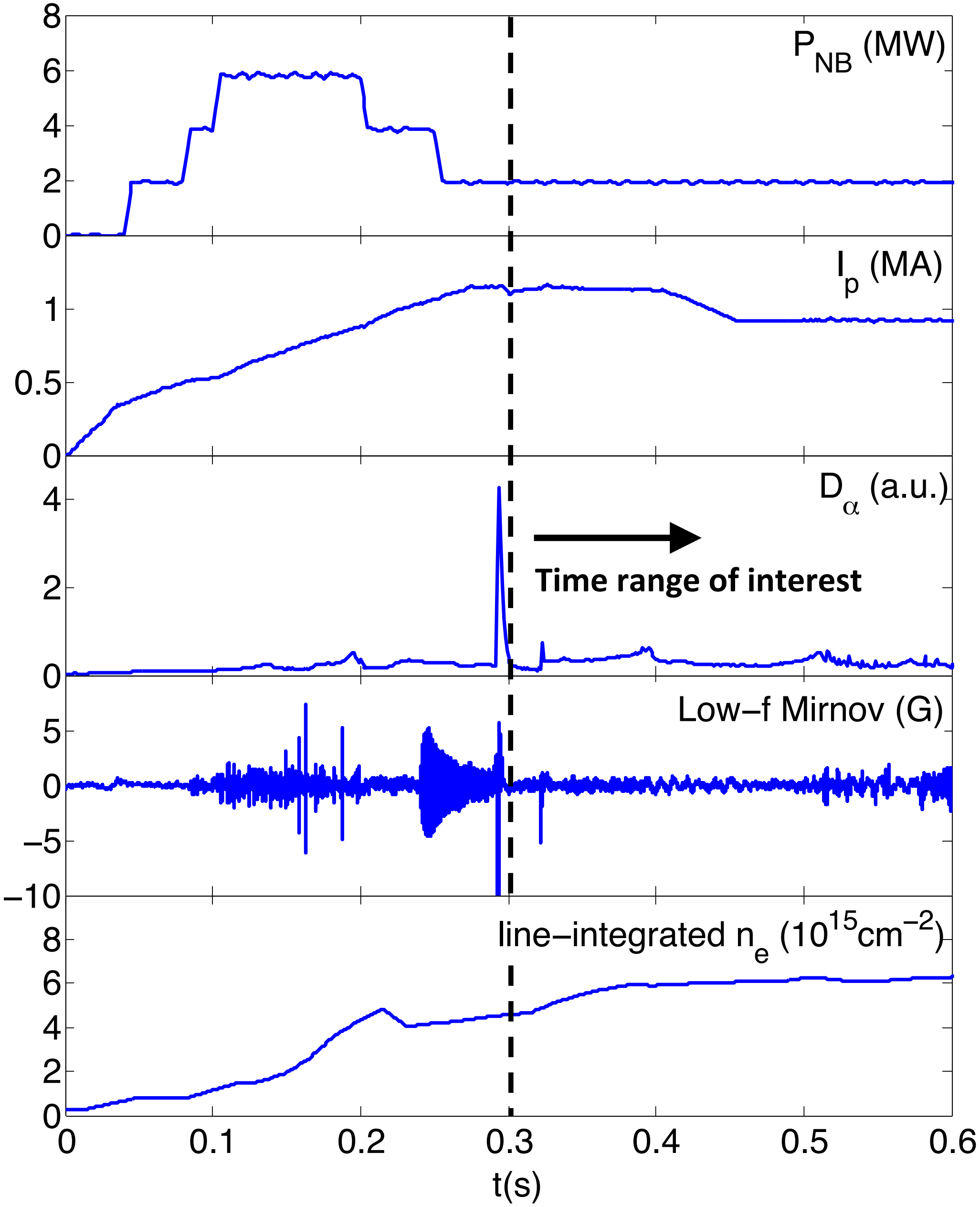

chan =1, k$_r$ =
f(kHz)
3000
2000
1000
0
−1000
−2000
−3000
0.35
0.4
0.45
0.5
0.55
t (s)

Issues

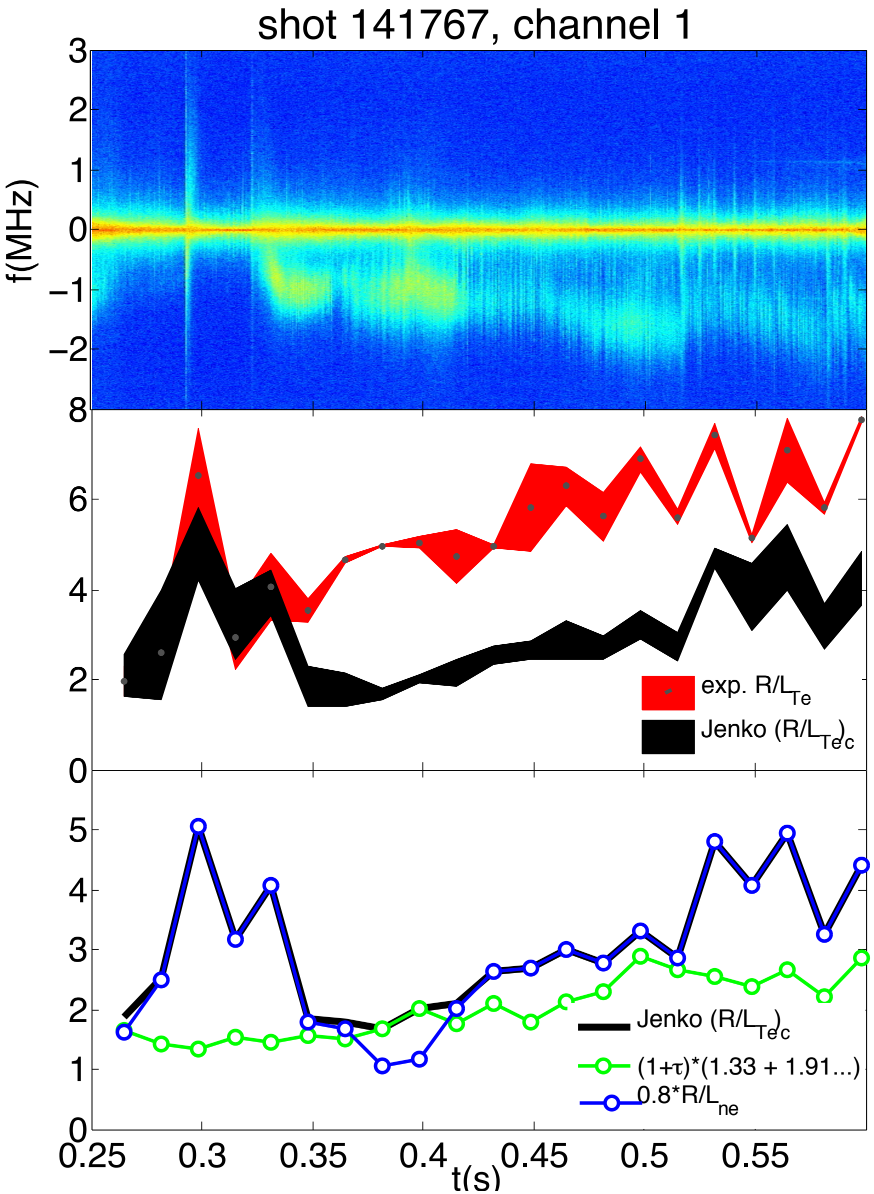

γ(kθρs = 15)
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
0.35
0.4
0.45
0.5
0.55
0.6
t(s)
4
3
2
1
0
0.3
0.35
0.4
0.45
0.5
0.55
0.6
t(s)
Jenko (R/LTe)c
(1+τ)*(1.33 + 1.91...)
0.8*R/Lne

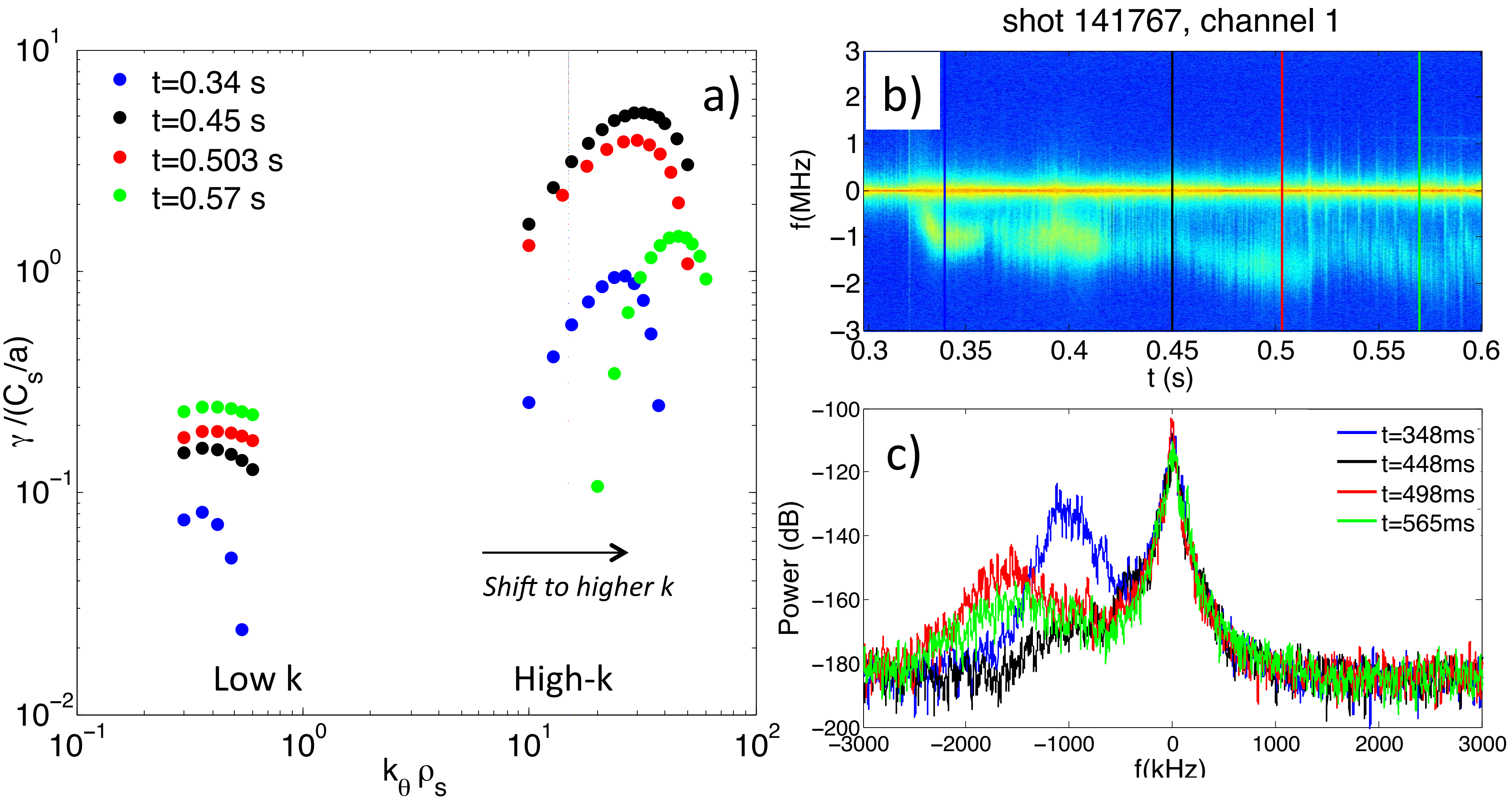

chan =1, kr =
3000
2000
1000
0
−1000
−2000
−3000
f(kHz)
0.35
0.4
0.45
0.5
0.55
t (s)

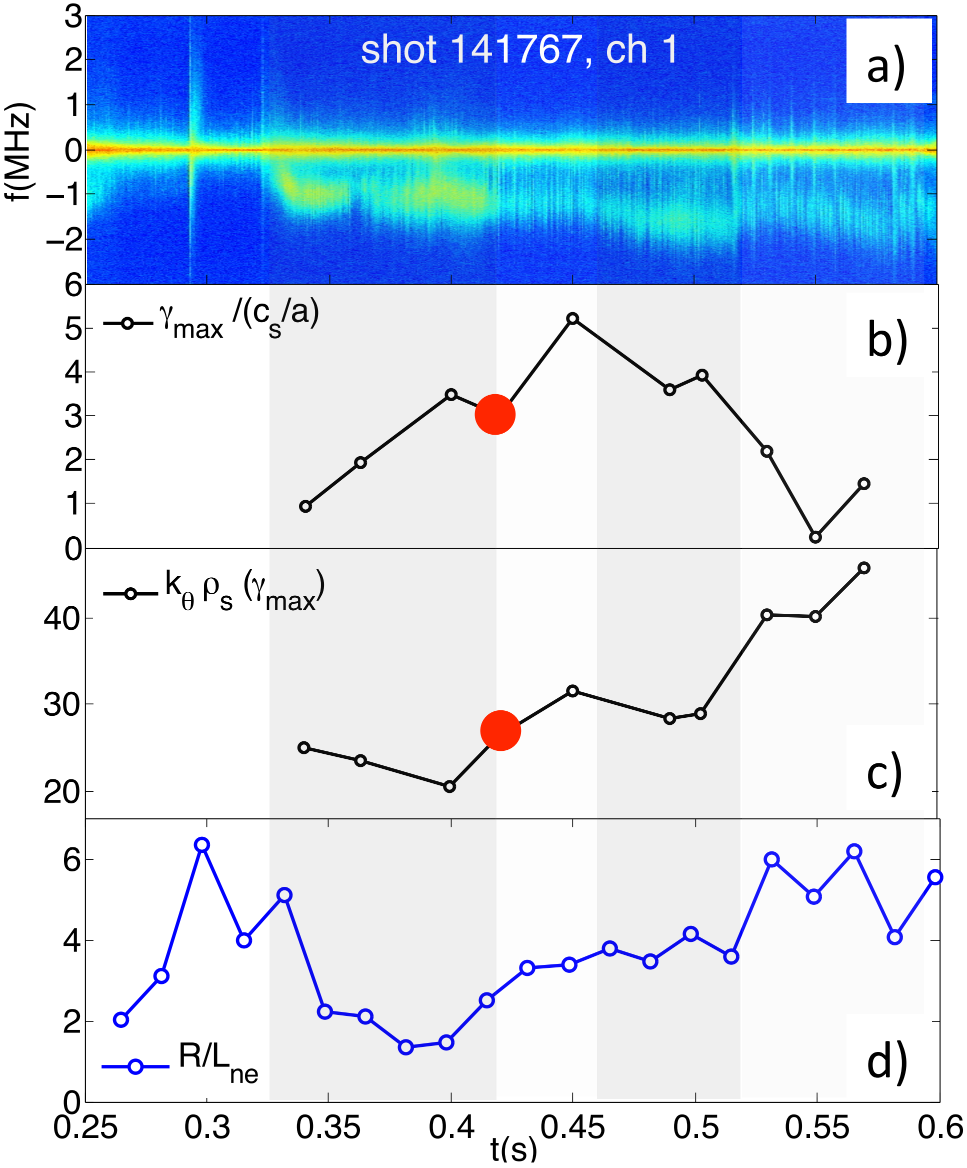
Shot 141767

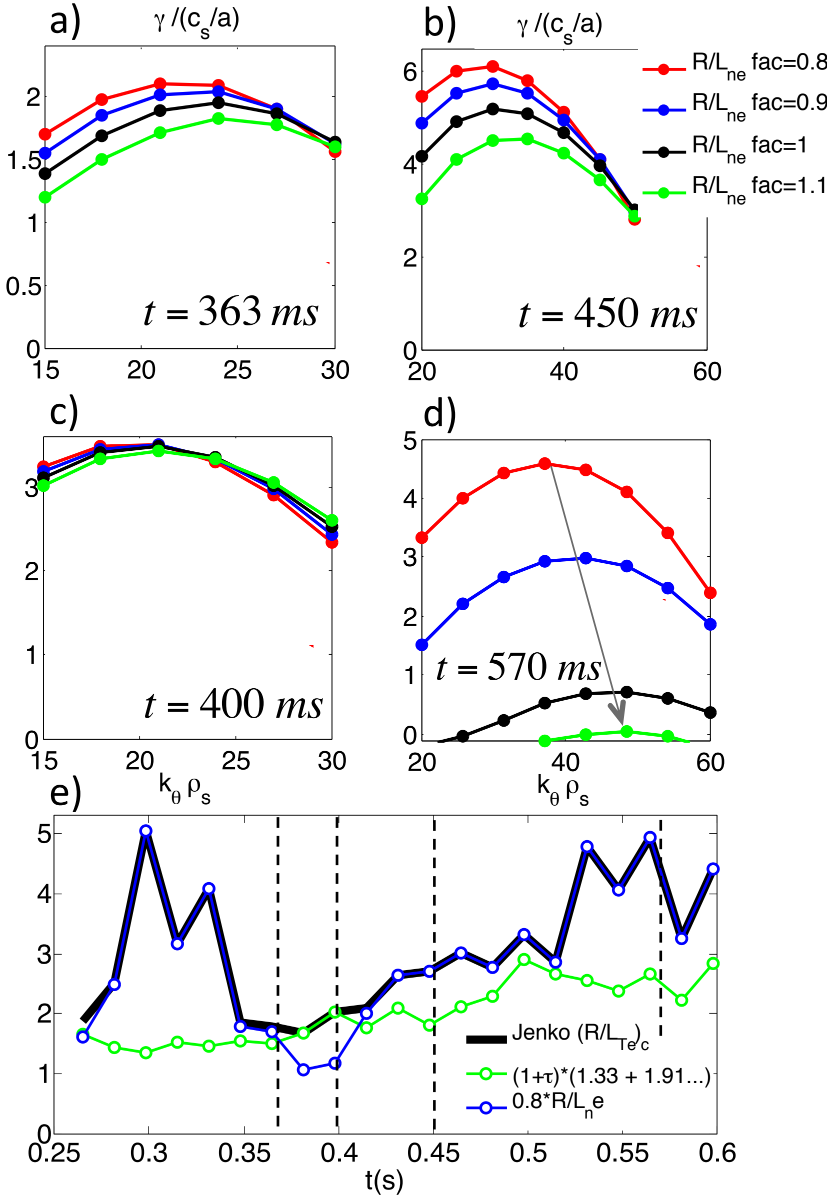


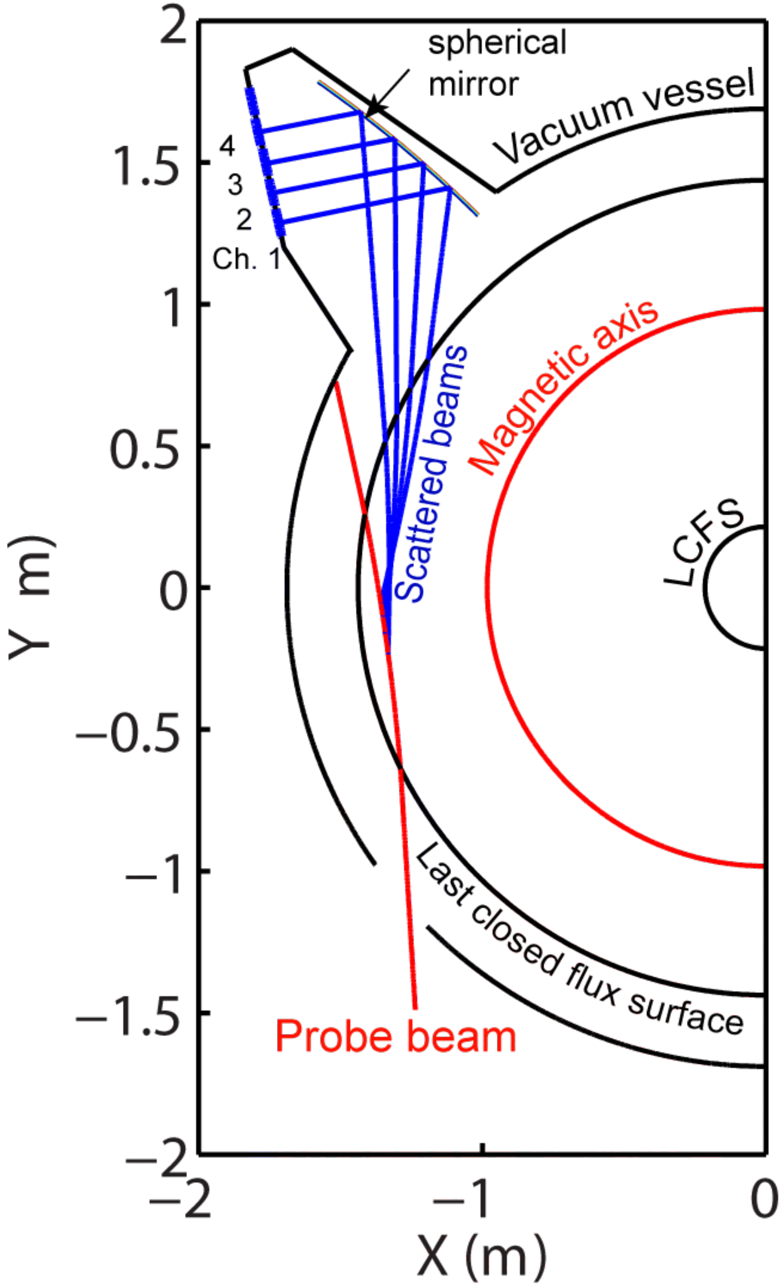
Time range of interest


shot 141767, channel 1
f(MHz)
3
2
1
0
−1
−2
8
6
4
2
0
exp. R/L$_{Te}$
Jenko (R/L$_{Te}$)$_c$
5
4
3
2
1
0
Jenko (R/L$_{Te}$)$_c$
(1+τ)*(1.33 + 1.91...)
0.8*R/L$_{ne}$
0.25
0.3
0.35
0.4
0.45
0.5
0.55
t(s)


a)
t=0.34 s
t=0.45 s
t=0.503 s
t=0.57 s
γ /(C$_s$/a)
$k_\theta\ \rho_s$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{2}
Shift to higher k
Low k
High-k
shot 141767, channel 1
b)
f(MHz)
3
2
1
0
−1
−2
−3
0.3
0.35
0.4
0.45
0.5
0.55
0.6
t (s)
c)
Power (dB)
−100
−120
−140
−160
−180
−200
−3000
−2000
−1000
0
1000
2000
3000
f(kHz)
t=348ms
t=448ms
t=498ms
t=565ms


shot 141767, ch 1
a)
f(MHz)
3
2
1
0
−1
−2
b)
γmax /(cs/a)
6
5
4
3
2
1
0
c)
kθ ρs (γmax)
40
30
20
d)
R/Lne
6
4
2
0
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)
0 0.5 1 1.5 2
15 20 25 30
0 2 4 6
20 40 60
0 1 2 3
0 1 2 3 4 5
0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6


spherical
mirror
Vacuum vessel
4
3
2
Ch. 1
Scattered beams
Magnetic axis
LCFS
Last closed flux surface
Probe beam
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2
−1
0
Y (m)
X (m)