Search for a Critical Electron Temperature Gradient in DIII-D L-mode Discharges

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Introduction

- Previous experiments on DIII-D L-mode and H-mode discharges showed no evidence of nonlinear behavior in the T_e response to modulated ECH.

- Other tokamaks, notably ASDEX-U and FTU, have found that a transport model based on a critical temperature gradient scale length agrees well with both steady state power balance analysis and the response from modulated ECH.

- Two experiments on DIII-D have been performed with the purpose of searching for evidence of χ_e dependent on a critical value of $\nabla T_e/T_e$.
  - ECH “swing” experiment (based on FTU experiments)
  - systematic heat flux scan (based on AUG experiments)

ECH Swing Experiment

- **First carried out in FTU (Cirant, IAEA 2003).**

- **Critical temperature gradient model**

$$\chi_e = \chi_o + f(T_e)\left(\frac{\nabla T_e}{T_e} - k_{crit}\right)H_k \qquad \chi_e^{HP} \equiv \frac{\partial(q/n)}{\partial \nabla T_e} = \chi_o + f(T_e)\left(2\frac{\nabla T_e}{T_e} - k_{crit}\right)H_k$$

- **If the drive is strong enough to cause the local $\nabla T_e/T_e$ to go from below a critical value to above it then the nonlinear change in χ_e^{HP} will produce a nonlinear response in T_e.**

- **Utilize 180° out-of-phase, square wave modulation of pairs of gyrotrons absorbed at slightly different radii in order to localize the heat flux and ∇T_e modulation at constant total input power.**

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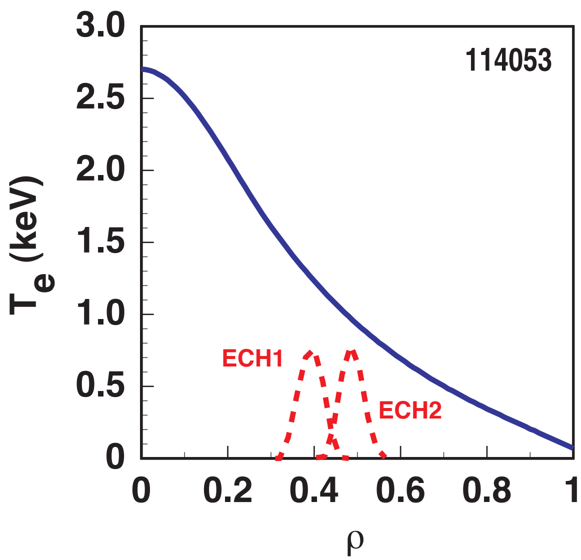
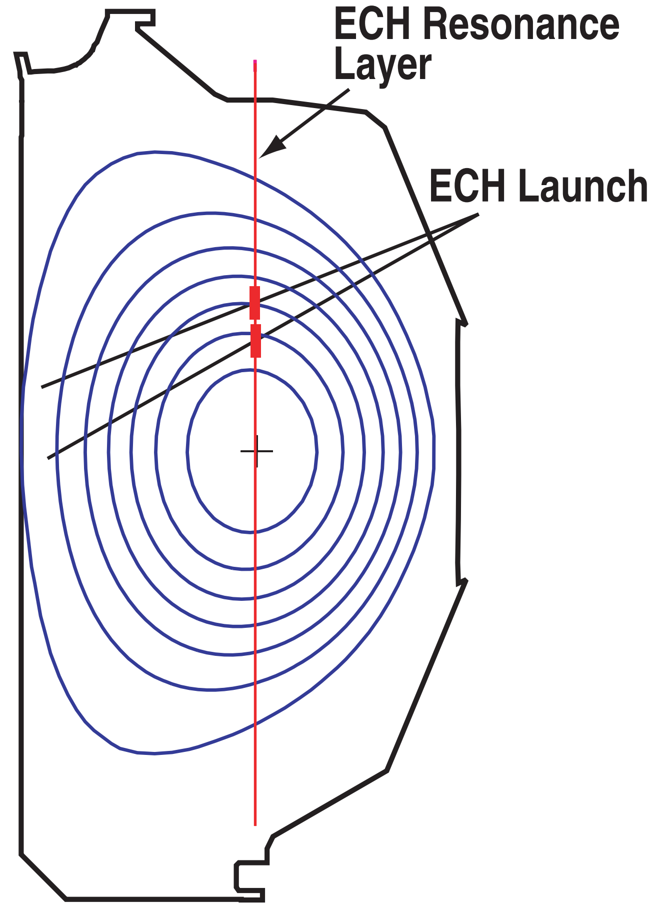
L–MODE TARGET PLASMA

- Inside wall limited L–mode
  - 0.8 MA, 2.0 T
  - $1.5\text{-}2.9 \times 10^{19}\ m^{-3}$
- Sawtooth free
- ECH resonance at ρ_{ECH} = 0.2-0.3 and 0.4-0.5
  f_{mod} = 25 Hz and $P_{ECH1} \sim P_{ECH2} \sim$ 1 MW
- Three heat flux conditions: 4.0, 2.8, 0 MW NBI



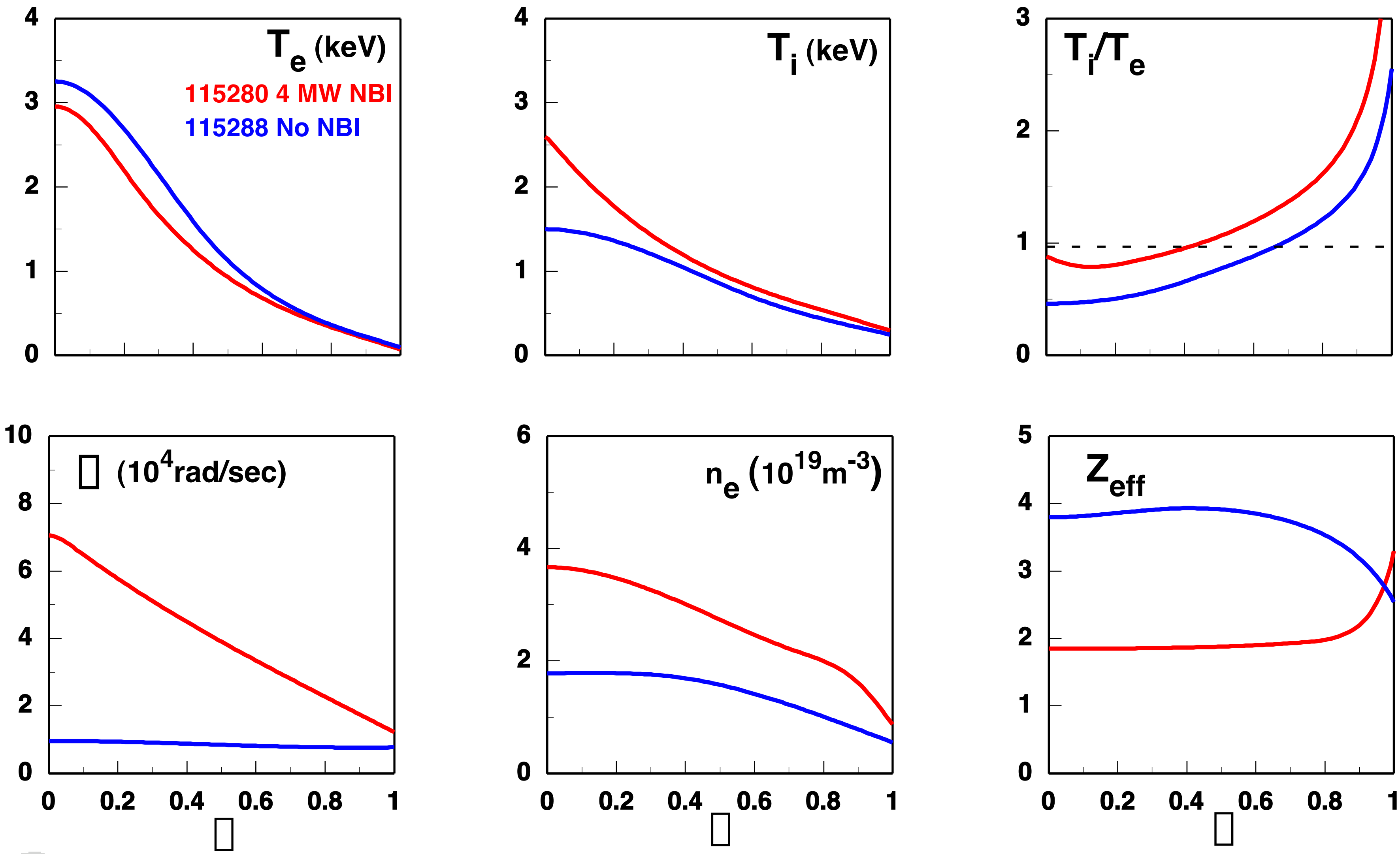
R (m) = 1.64-1.73   a (m) = 0.62

κ = 1.5-1.6



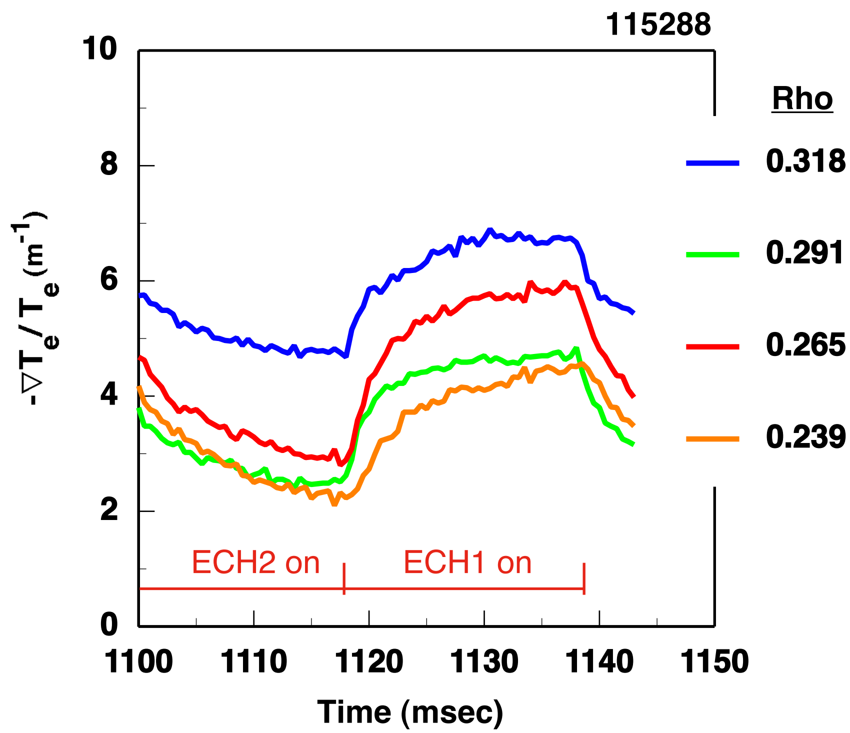
Comparison of Profiles with P_{NBI} = 4 MW and 0 MW

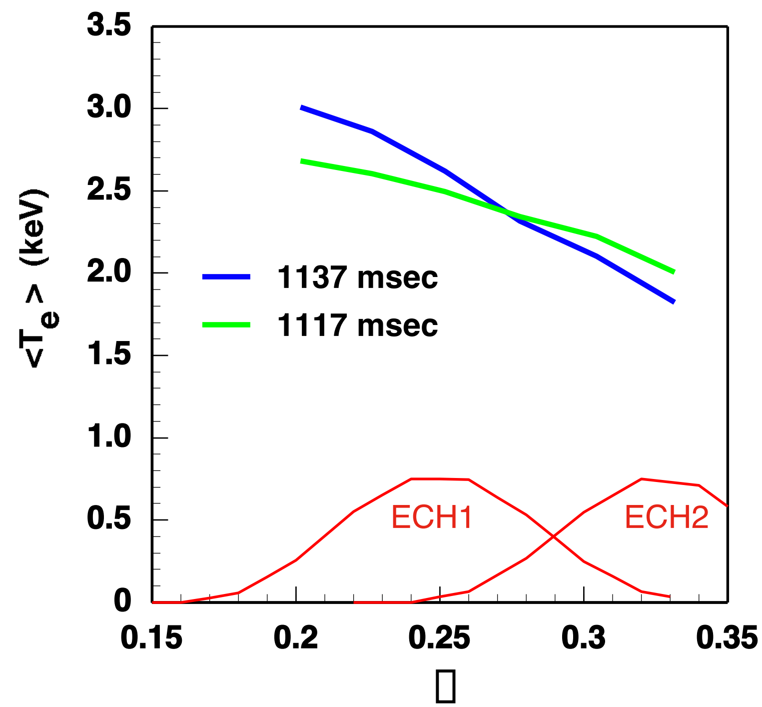
- ECH deposition at ρ_{ECH} = 0.2-0.3
- Central T_i is reduced without NBI
- Lower density causes an increase in Zeff



$-\nabla T_e/T_e$ in the ECH Absorption Region

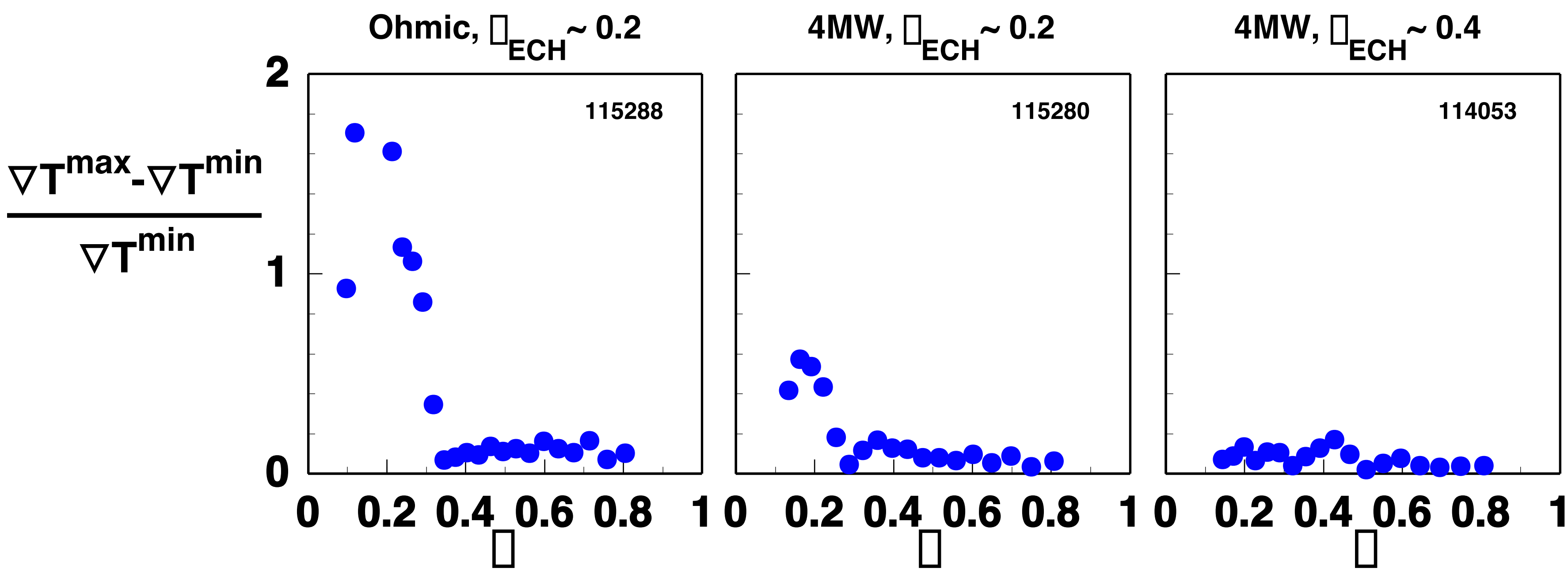
- $-\nabla T_e/T_e$ varies from 2.5 to 5 m^{-1} at ρ = 0.29 where T_e is nearly constant
- T_e response is clearly not very stiff as ∇T_e varied by factor 2
- T_e averaged over 9 modulation periods from 1100-1460 msec on shot 115288





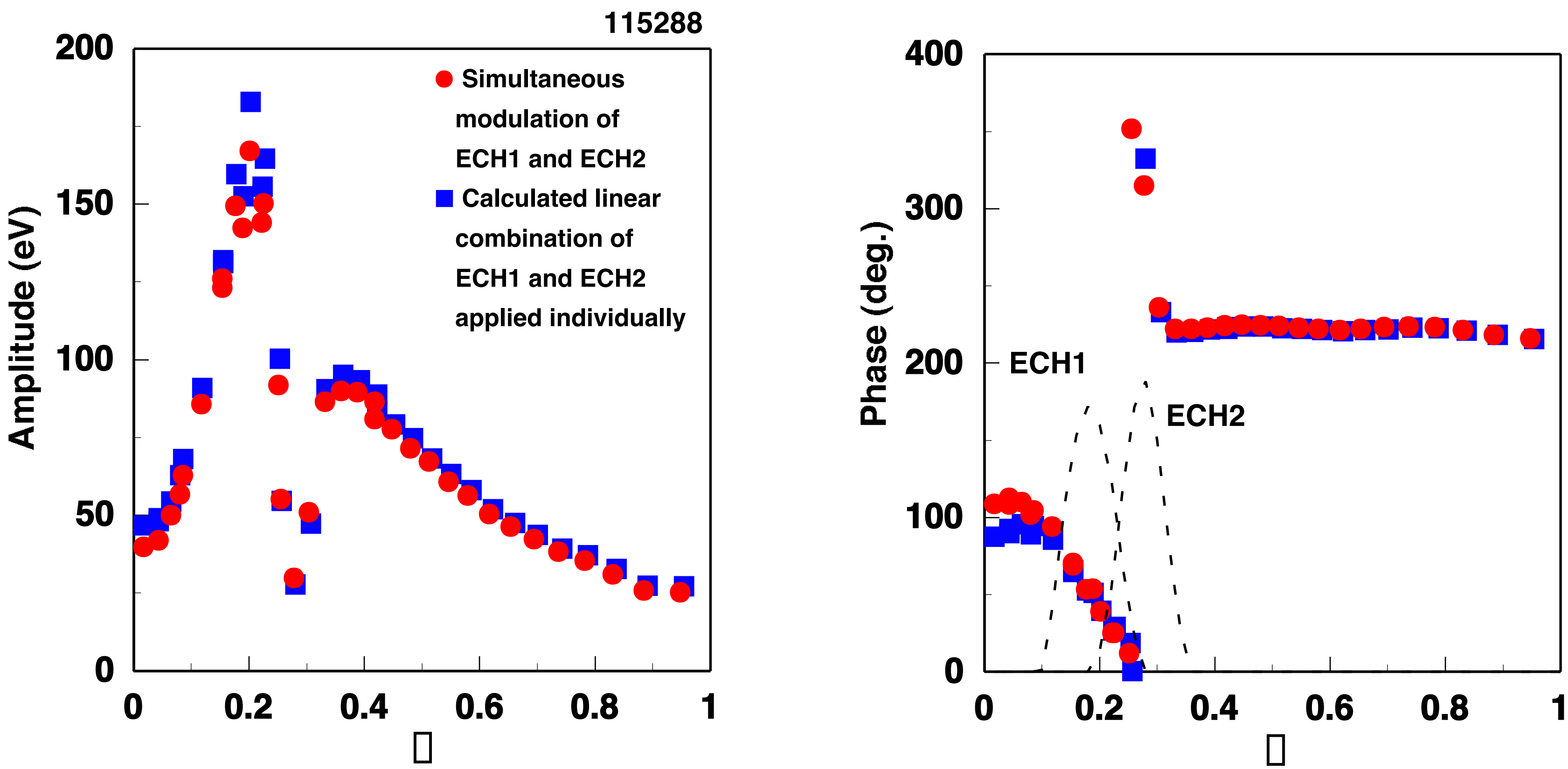
The Relative Change in ∇T_e Is Largest For The Ohmic Case

- The Ohmic case is most likely case to observe nonlinear behavior
- Changes in ∇T_e are small outside the ECH deposition since in this region the ECH heat flux is essentially constant



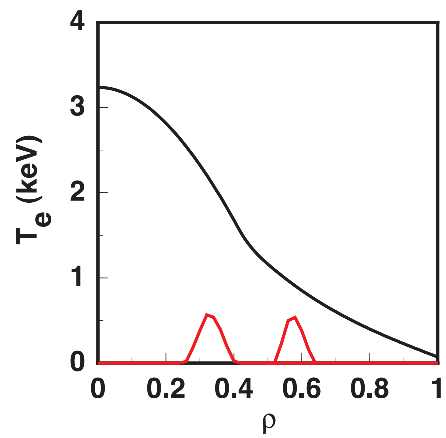
No Evidence of a Non-linearity in χ_e^{HP} is Observed For Case with no NBI and ρ_{ECH} = 0.2-0.3 or Any Other Case

- The linear combination of the Fourier amplitude and phase of the Te oscillations due to ECH1 and ECH2 applied individually is the same as the result with ECH1 and ECH2 modulated simultaneously and out of phase with respect to each other



Heat Flux Scan Experiments

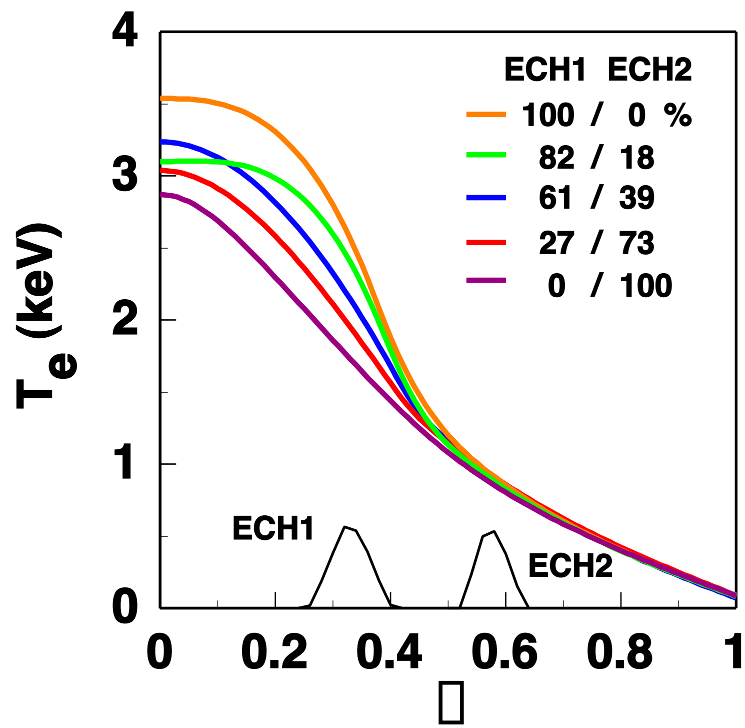
- Experimental approach (follow experiments on AUG, Ryter NF 43 2003)
  - scan $\nabla T_e/T_e$ locally by varying the electron heat flux while holding the flux at the edge (total power) constant
  - ECH at two locations, ρ_1 and ρ_2
  - vary P_{ECH1} and P_{ECH2} at constant $P_{ECH1} + P_{ECH2}$
  - modulate one gyrotron at ρ_2 to obtain χ^{HP}



- Target plasma (similar to low density ECH swing plasmas)
  - L-mode limited on inside wall of vessel
  - $I_p = 0.8$ MA, $B_T = 2.0$T, $n_e = 1.7 \times 10^{19}$ m^{-3}, $q_a = 7$
  - early NBI to delay onset of sawteeth, then ECH only

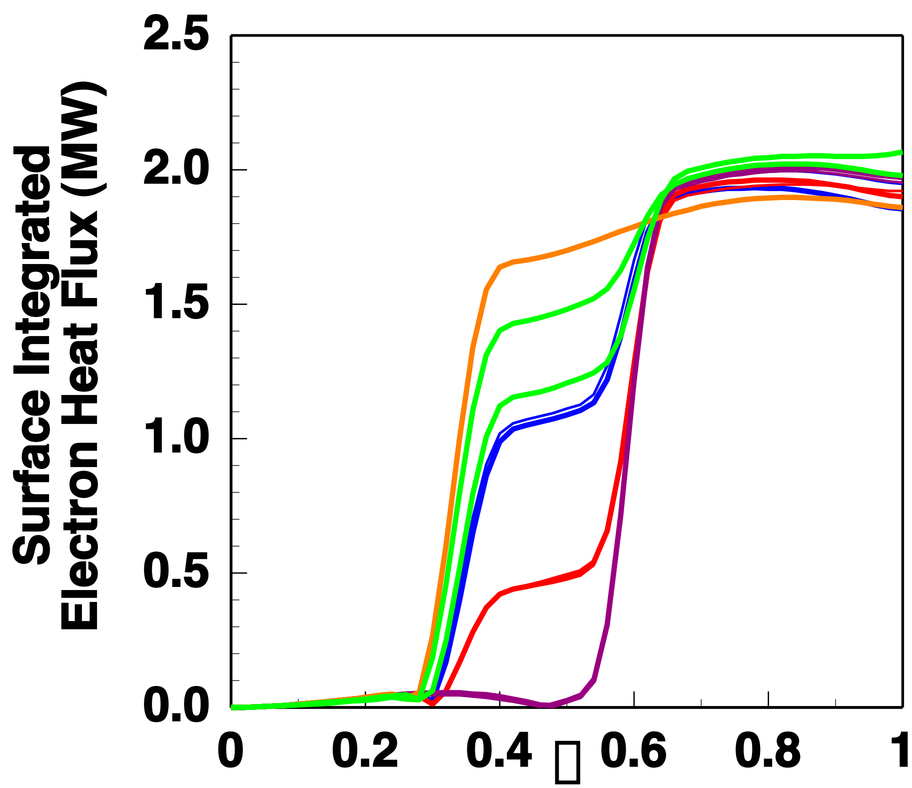
□T_e is Systematically Varied Between ECH1 and ECH2 Locations

- EC power is moved from ECH1 to ECH2 shot by shot
- T_e profile outside ECH2 is constant since PECH1+PECH2 is held fixed



The Electron Heat Flux is Systematically Varied at the Half Radius

- The total power in the electrons is comprised of P_{ECH} ~ 1.5 MW and P_{OH} ~ 0.5 MW.
- The dominant loss is by conduction, convection is negligible.
- At ρ = 0.45 radiation and collisional transfer to ions is small.



Modulate ECH Power on One Gyrotron at Outside Location to Obtain Heat Pulse Diffusivity

- **Modulate at 28 Hz with 50% duty cycle**
  - **frequency chosen to avoid matching sawtooth frequency**

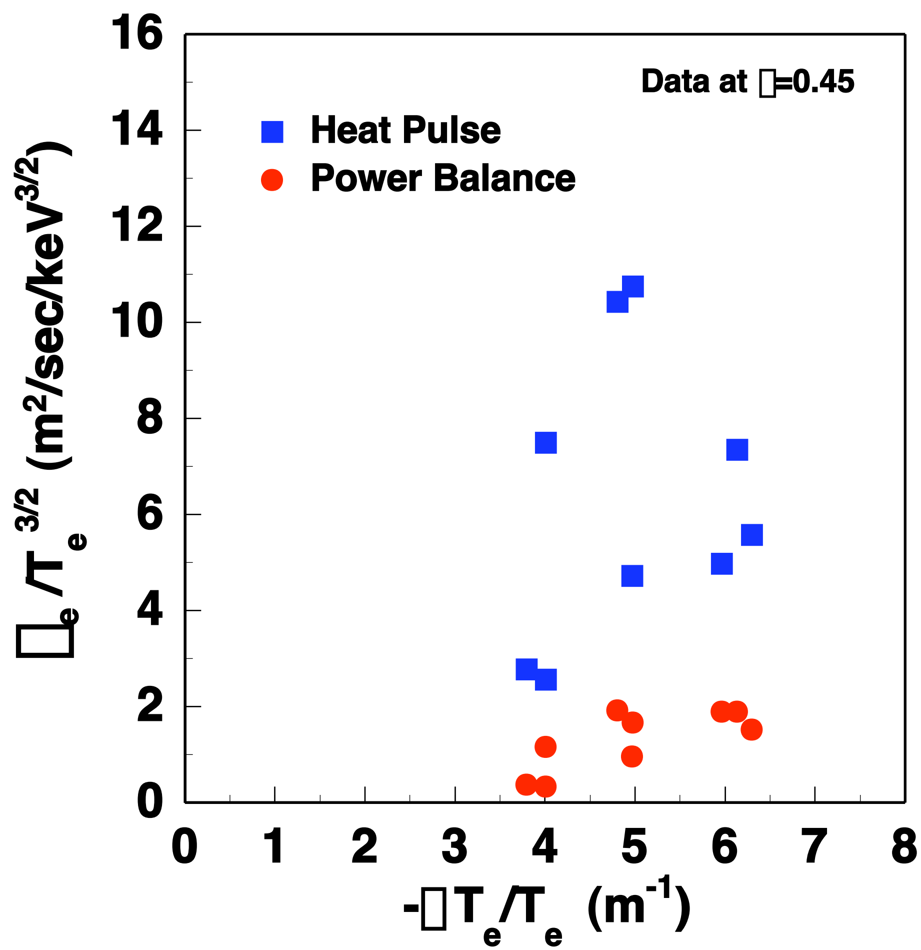
- **Fourier analyze ECE channels**

- **Spatial derivative of pulse amplitude and phase yields an estimate of the heat pulse diffusivity χ^{HP}**

- **Use 3rd harmonic pulse amplitude and phase to estimate χ^{HP}**

No Evidence of a Critical Gradient Scale Length Was Observed But the Existence of One Cannot Be Ruled Out

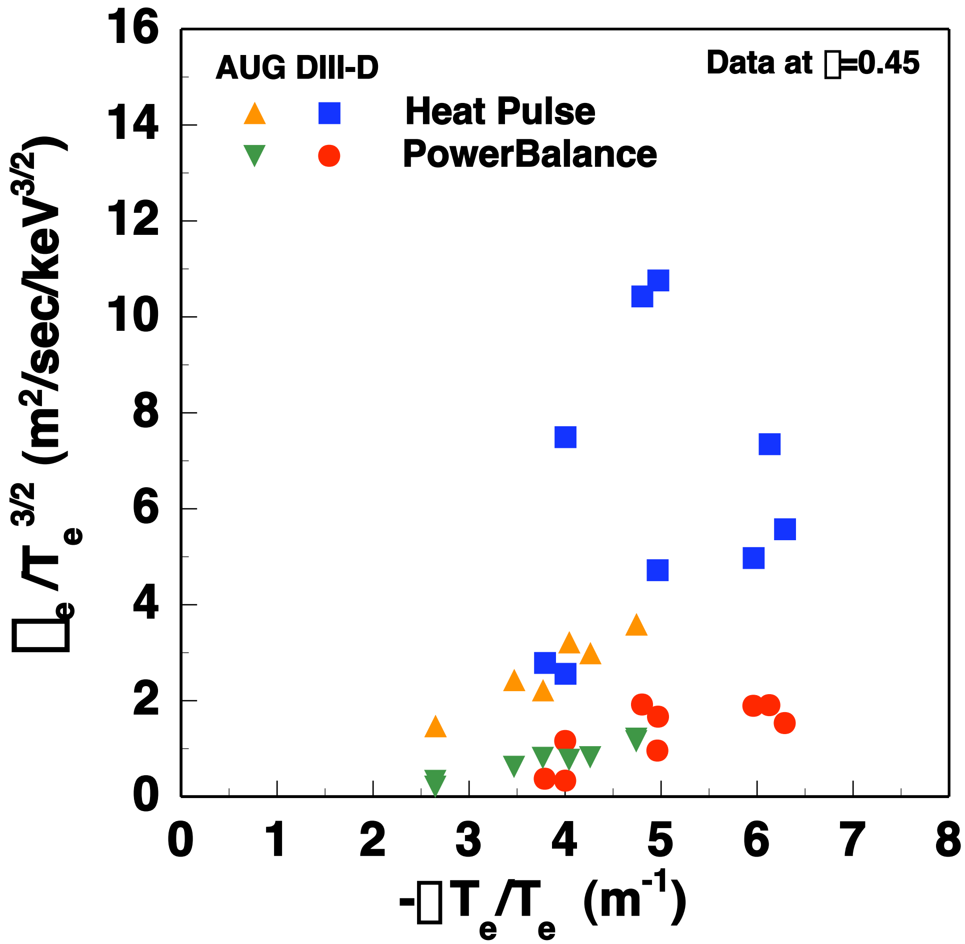
- A critical gradient scale length, k_{crit}, could exist below $\nabla T_e/T_e = 3.8\ m^{-1}$ at $\rho = 0.45$. This corresponds to $L_{T_e} \geq 0.26$ m or over 40% of the plasma radius.
- If k_{crit} exists it would be at values typically found near the plasma core, indicating most of the temperature profile would be above it.



χ_e normed to $T_e^{3/2}$ to take out gyro-Bohm dependence

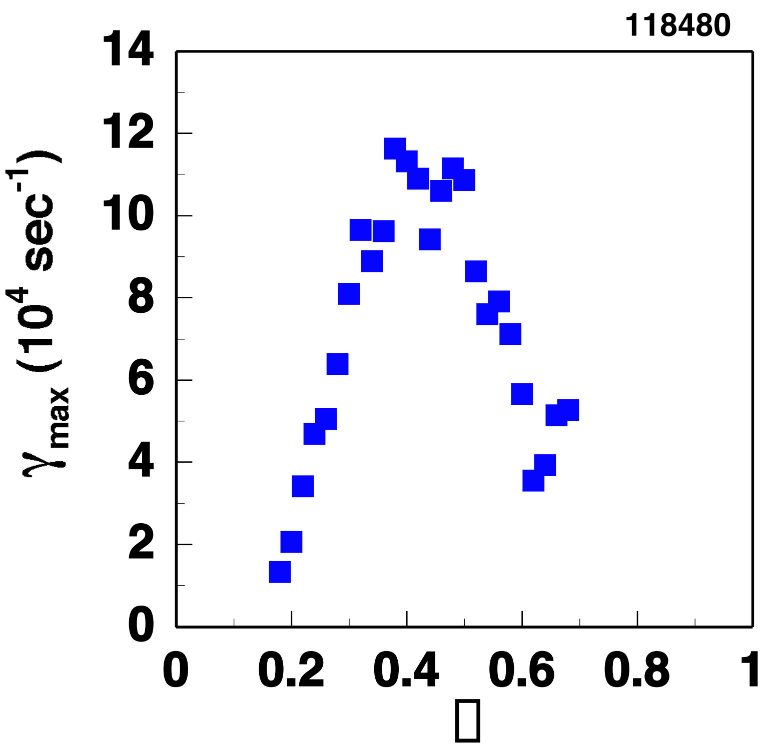
Results Of This Experiment Are Consistent With ASDEX Upgrade Experiments

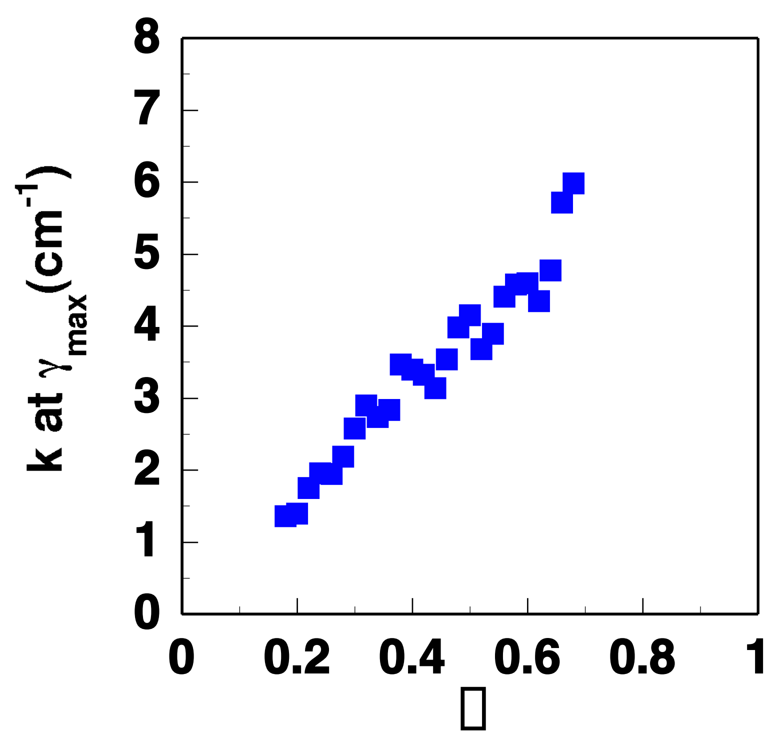
- The diffusivity levels and trends with $1/L_{Te}$ are similar
- ASDEX Upgrade found $k_{crit} = 2.3\ m^{-1}$ fit their data (Ryter, NF 43 2003)



TEMs Dominate Drift Wave Spectrum in Region of Interest

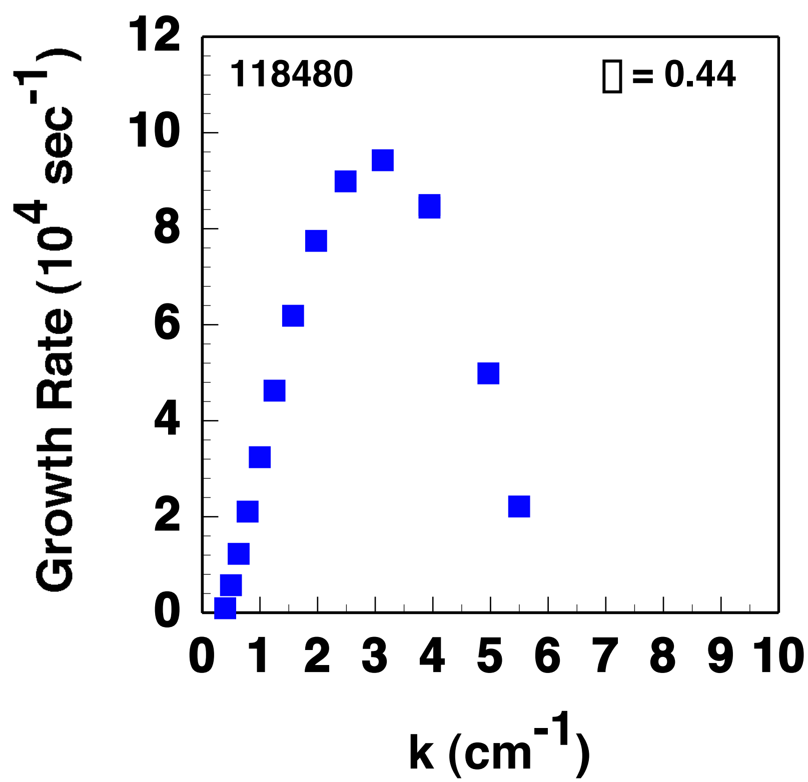
- Analysis performed with the linear gyrokinetic stability code GKS
- TEMs are unstable over most of plasma minor radius
- Largest growth rates for most unstable modes occur at $0.4 \le \rho \le 0.5$





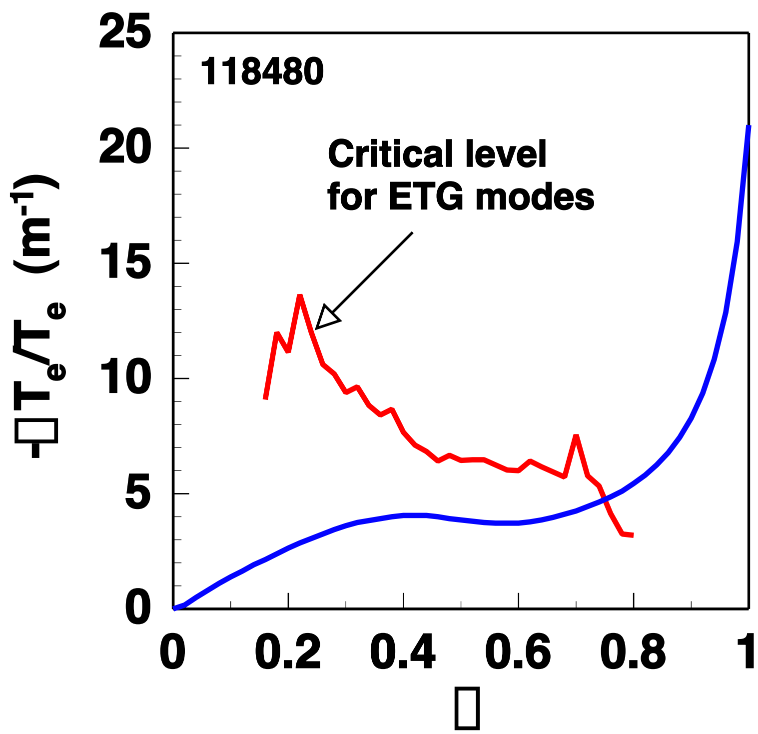
Spectrum of Wavenumbers Where Growth Rate Is Maximum

- Spectral width at □ = 0.44 is □k ~ 3 cm^{-1}
- Frequency at the largest growth rate is f ~ 120 kHz



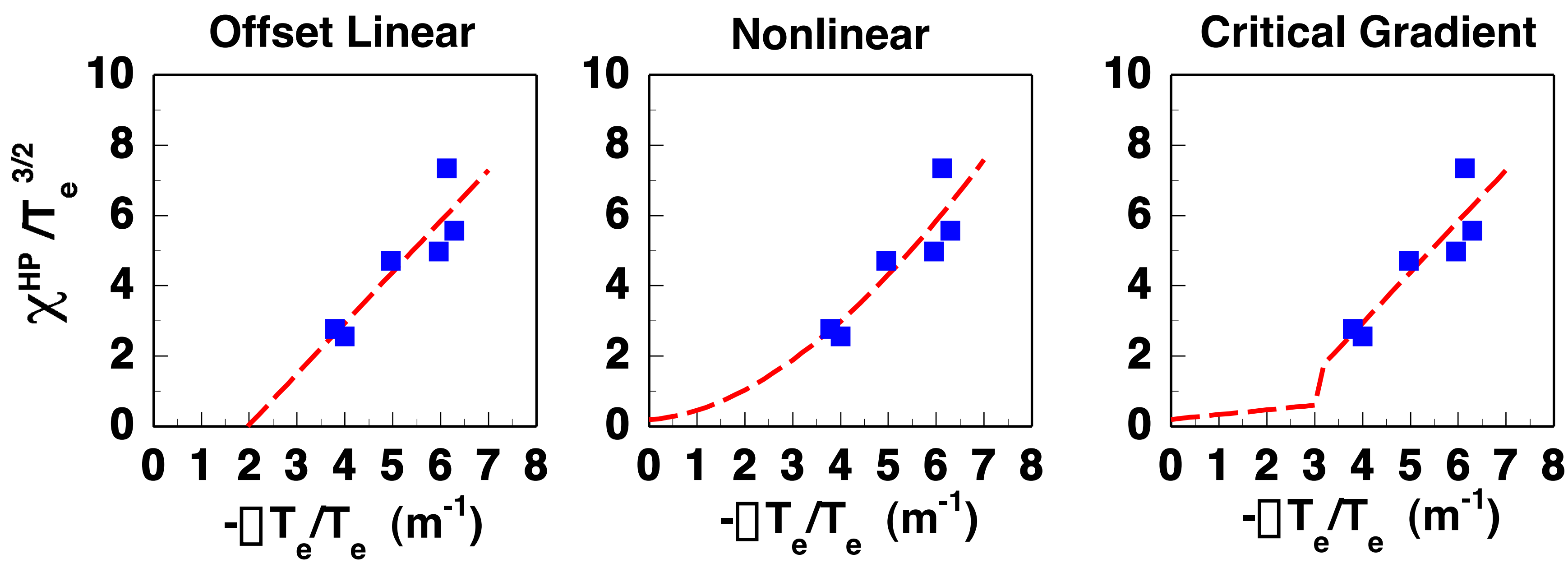
ETG Modes Are Stable In The Region Of Interest

- ETG modes unstable only near plasma edge, ρ > 0.8
- Critical gradient for ETG modes calculated from linear gyrokinetic stability code GKS



Three Possible Dependencies of χ^{HP} on $\nabla T_e/T_e$

- **Offset linear:** χ^{HP} becomes negative for $\nabla T_e/T_e < 2\ m^{-1}$, implying heat flux decreases as the gradient becomes steeper (perhaps due to a heat pinch)
- **Nonlinear:** $(\nabla T_e/T_e)^{\alpha}$, fit shows $\alpha \sim 5/3$. Exponent can not be too large in order to remain consistent with earlier experiments where no obvious nonlinear behavior was observed.
- **Critical gradient:** If a critical gradient exists it must be at $\nabla T_e/T_e < 3.8\ m^{-1}$ at $\rho = 0.45$ (arbitrarily chose $3.0\ m^{-1}$ for illustration). AUG has reported a critical value of $k_{crit} \sim 2.3\ m^{-1}$.



Summary

- No evidence of a critical gradient scale length dependence of χ^{HP} was observed but the existence of one cannot be ruled out by the experimental results.
- The T_e profile was not very stiff since the gradient was varied by a factor of 2 at locations in the profile that were above k_{crit} , if k_{crit} exists.
- If a critical gradient scale length exists, all experimental results to date are consistent with the observations being made at values above it.
- The results indicate that if k_{crit} exists then $k_{crit} < 3.8\ m^{-1}$ at $\rho=0.45$ and $k_{crit} < 2.5\ m^{-1}$ at $\rho=0.29$ corresponding to a critical gradient scale length larger than 43% and 65% of the plasma minor radius, respectively.
- Models other than one based on k_{crit} are also consistent with the experimental observations such as an offset linear or power law dependence of χ^{HP} on $1/L_{Te}$.