Electron Transport Stiffness and Heat Pulse Propagation on DIII-D

by

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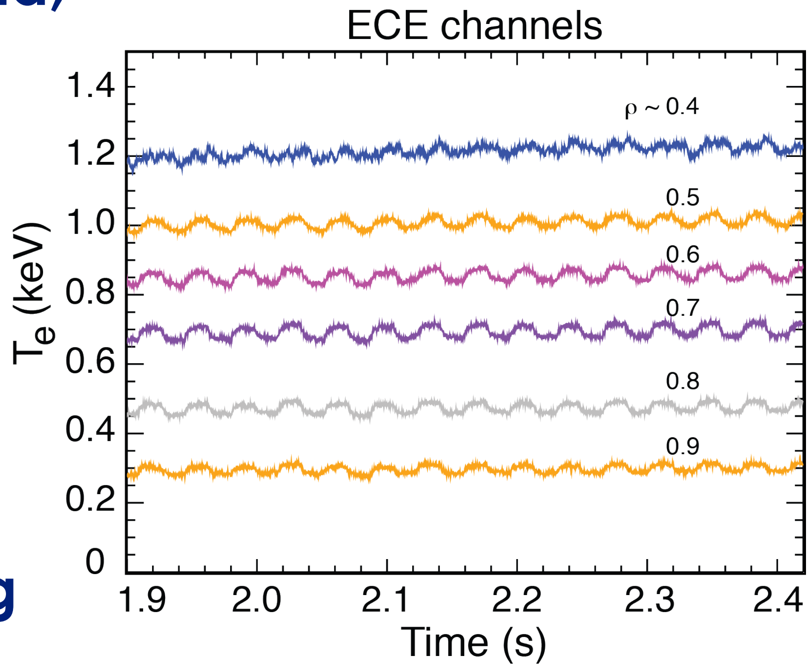

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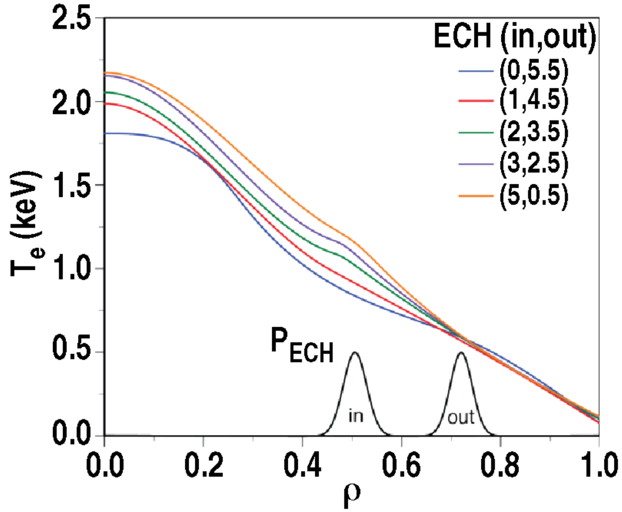
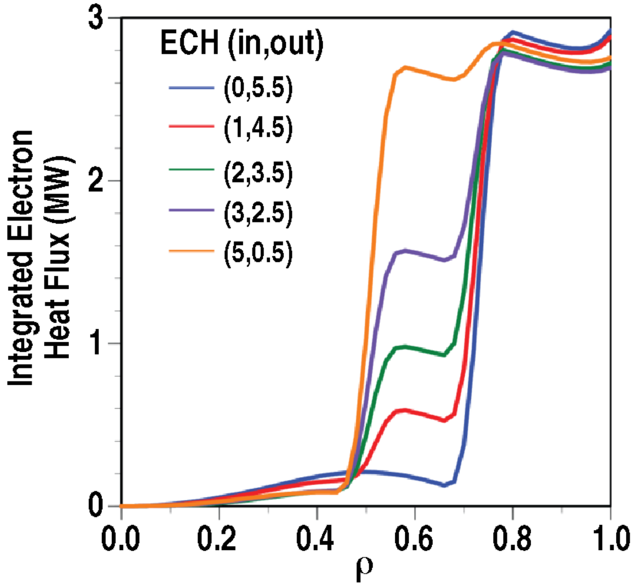
Fundamental Behavior of Drift Wave Turbulent Transport is Tested Using Heat Pulse Propagation

- **Carefully constructed experiment directly probes diffusive transport to test key predicted behaviors:**
  - Instability threshold in ∇T_e
  - Electron transport stiffness
- **Off-axis ECH varies electron heat flux to scan ∇T_e over large range**
  - Moved one gyrotron from outside to inside on shot-to-shot basis
- **Modulated one gyrotron (outside) for measurement of heat pulse propagation**





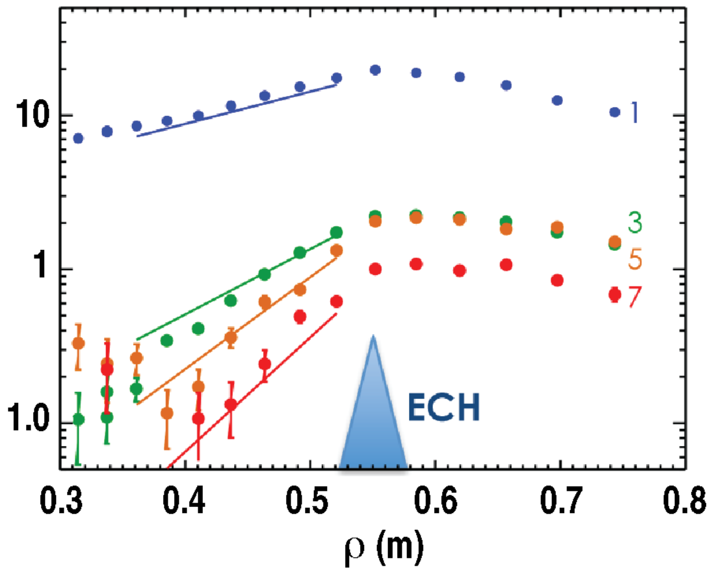
Modulation in Electron Temperature Profile is Fitted to Linearized Energy Conservation Equation

- **Fourier-transformed first-order equation:**

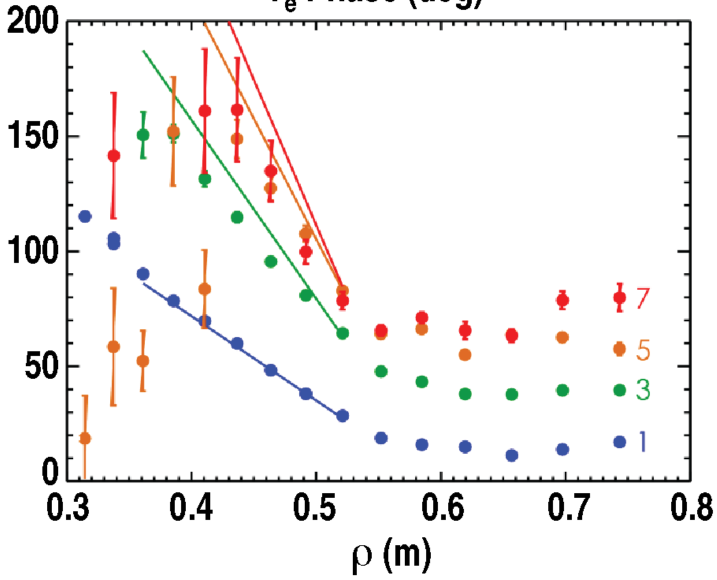
$$-D^{\mathrm{HP}}\nabla^{2}\tilde{T}_e + V^{\mathrm{HP}}\nabla\tilde{T}_e + \left(\frac{1}{\tau^{\mathrm{HP}}} + i\frac{3}{2}\omega\right)\tilde{T}_e = \tilde{S}_e$$

- **Multiple harmonics of T_e oscillations are simultaneously fit to determine D^{HP}, V^{HP}, τ^{HP}**

$\tilde{T}_e$ Amplitude (eV)



$\tilde{T}_e$ Phase (deg)



Heat Pulse Propagation is a Good Test of Transport Stiffness Models

- **This talk focuses on the relation between the "heat pulse" and "power balance" diffusivities:**

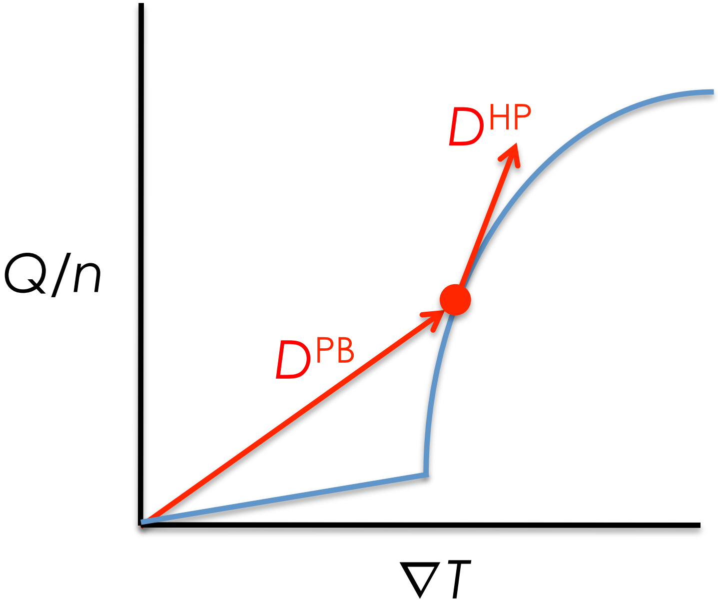
$$D^{\mathrm{HP}} = -\frac{1}{n_e}\frac{\partial Q^{\mathrm{PB}}}{\partial \nabla T_e} = \frac{\partial}{\partial \nabla T_e}\left(D^{\mathrm{PB}} \nabla T_e\right)$$

where

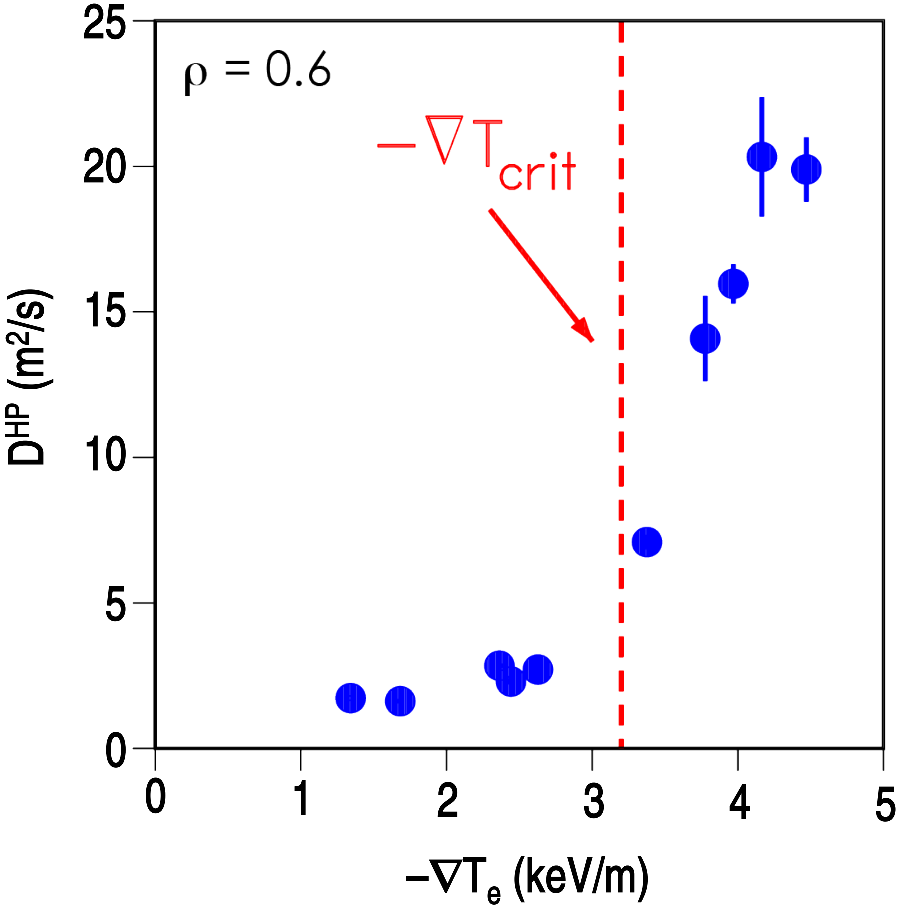
$$Q^{\mathrm{PB}} = -n_e D^{\mathrm{PB}} \nabla T_e + n_e V^{\mathrm{PB}} T_e$$

- **Comparing the incremental (D^{HP}) to equilibrium diffusivity (D^{PB}) relates stiffness to the shape of the heat flux curve:**

$$S = \frac{D^{\mathrm{HP}}}{D^{\mathrm{PB}}} = \frac{\partial \ln(Q/n)}{\partial \ln(\nabla T)}$$



The "Heat Pulse" Diffusivity at $\rho = 0.6$ Rapidly Increases for $-\nabla T_e > 3.2$ keV/m — Critical Gradient Threshold?

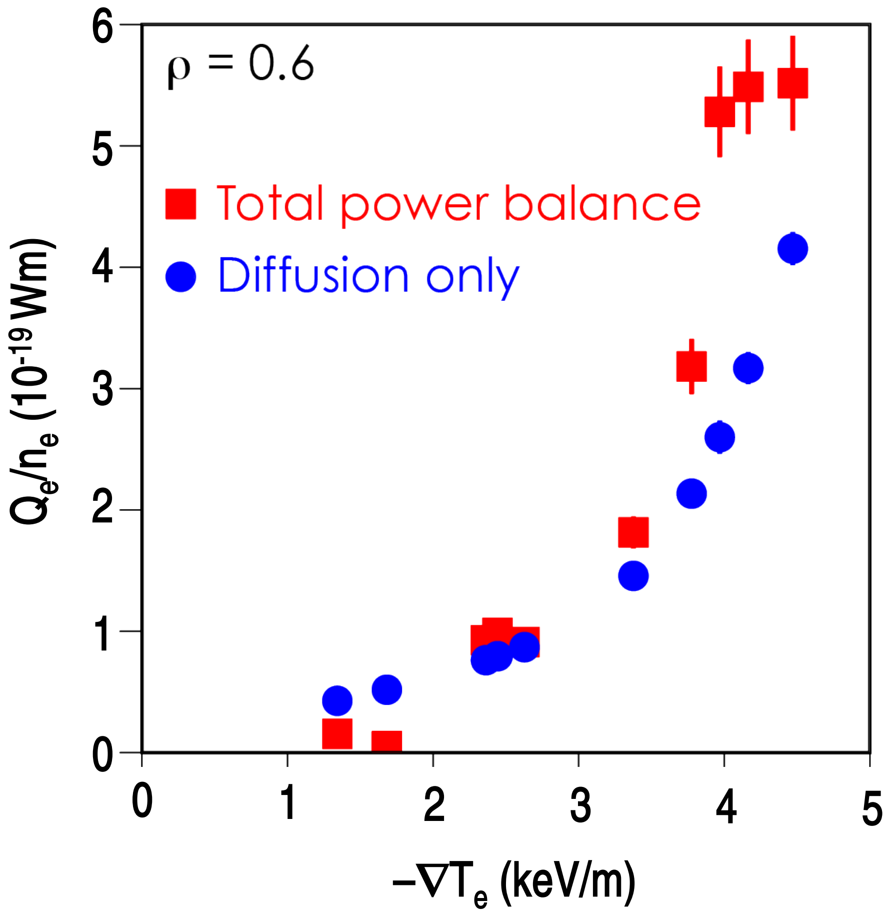


- **Key analysis step is to determine the "power balance" diffusivity by numerical integration of the measured "heat pulse" diffusivity:**

$$D^{\mathrm{PB}} = \frac{1}{\nabla T_e} \int_0^{\nabla T_e} D^{\mathrm{HP}} d(\nabla T_e)$$

- **This yields the purely diffusive portion of the equilibrium heat flux**

Diffusive Heat Flux Falls Short of Total Heat Flux from Power Balance – Indicating Something is Missing



- **Diffusive heat flux is**

$$Q^{\text{diff}} = -n_e D^{\text{PB}} \nabla T_e$$

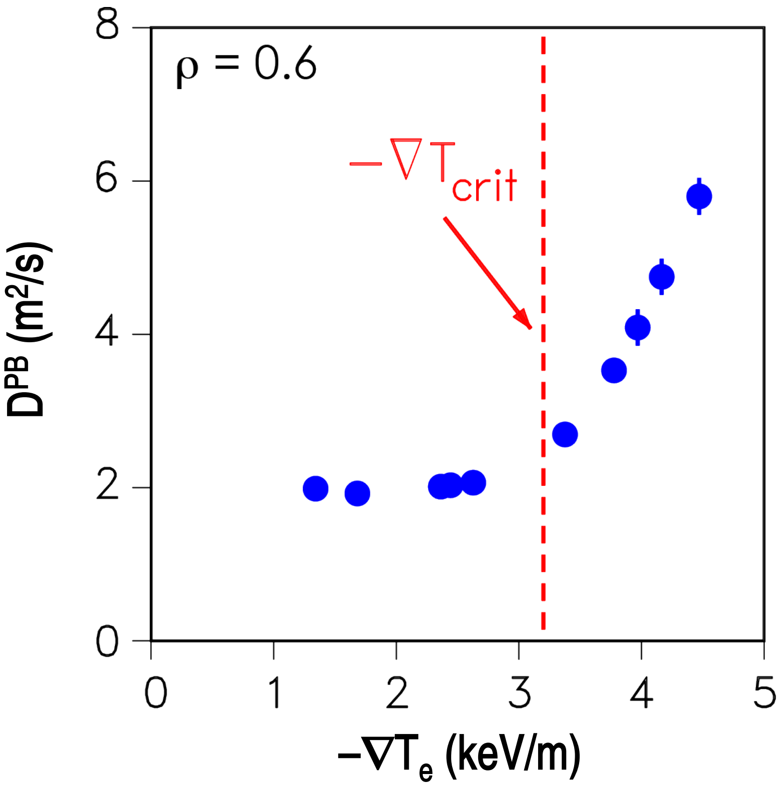
$$= n_e \int_0^{\nabla T_e} D^{\text{HP}} d(-\nabla T_e)$$

- **The difference between the heat fluxes can be reconciled by a non-zero "power balance" convective velocity**

$$V^{\text{PB}} = \frac{Q^{\text{PB}}}{n_e T_e} - \frac{1}{T_e} \int_0^{\nabla T_e} D^{\text{HP}} d(-\nabla T_e)$$

The "Power Balance" Diffusivity Increases Rapidly Above $-\nabla T_{crit}$ While Convection is Mainly Outwards

$$D^{\mathrm{PB}} = \frac{1}{\nabla T_e} \int_0^{\nabla T_e} D^{\mathrm{HP}} d(\nabla T_e)$$



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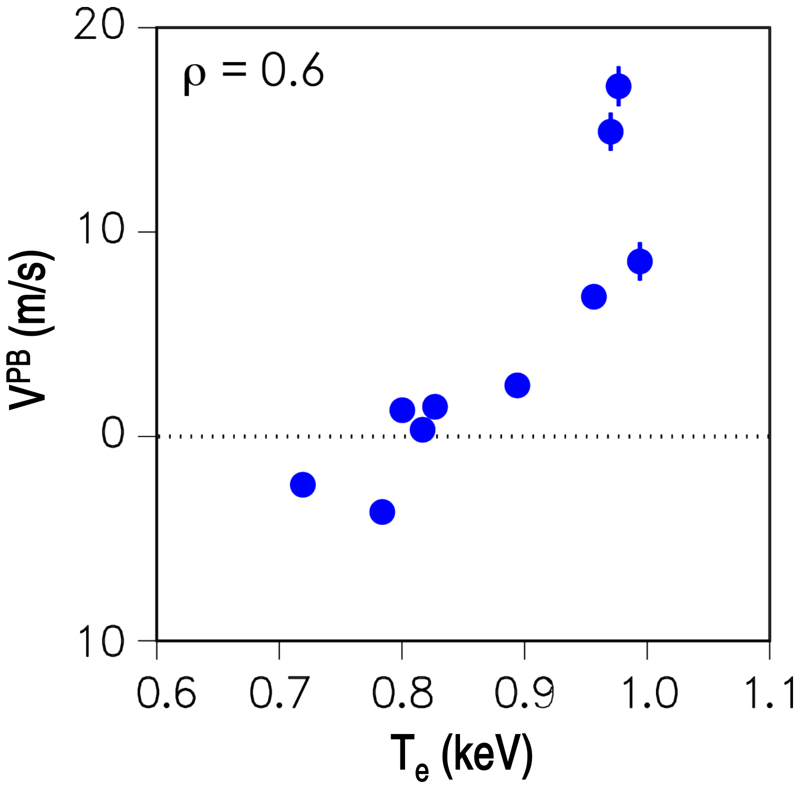

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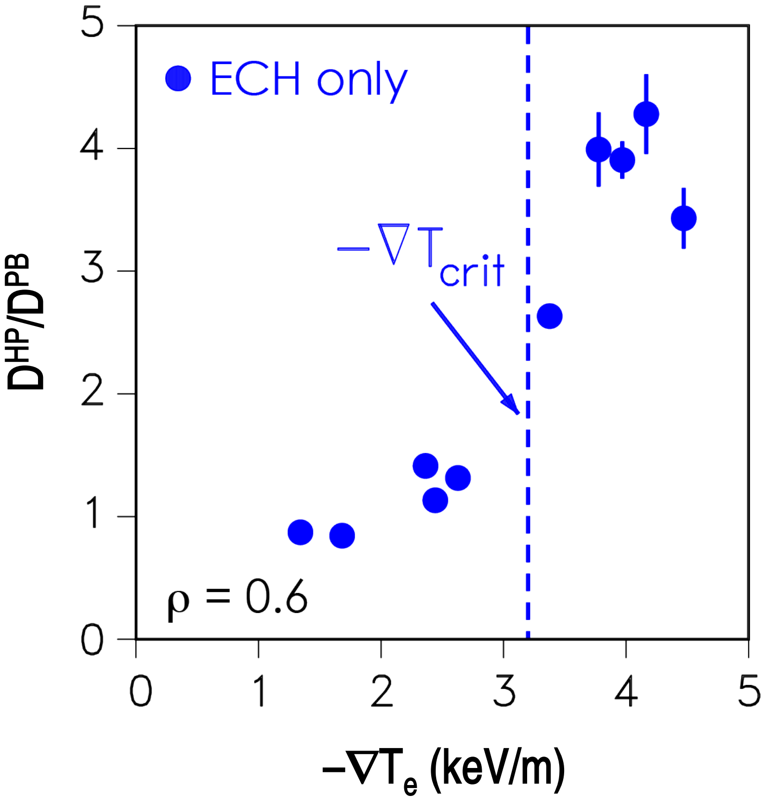
Measured Stiffness Factor Jumps Up ~4 Times When $-\nabla T_e/T_e$ Exceeds Critical Value

$$S = \frac{D^{\mathrm{HP}}}{D^{\mathrm{PB}}} = \frac{\partial \ln(Q^{\mathrm{PB}}/n_e - V^{\mathrm{PB}} T_e)}{\partial \ln(\nabla T_e)}$$



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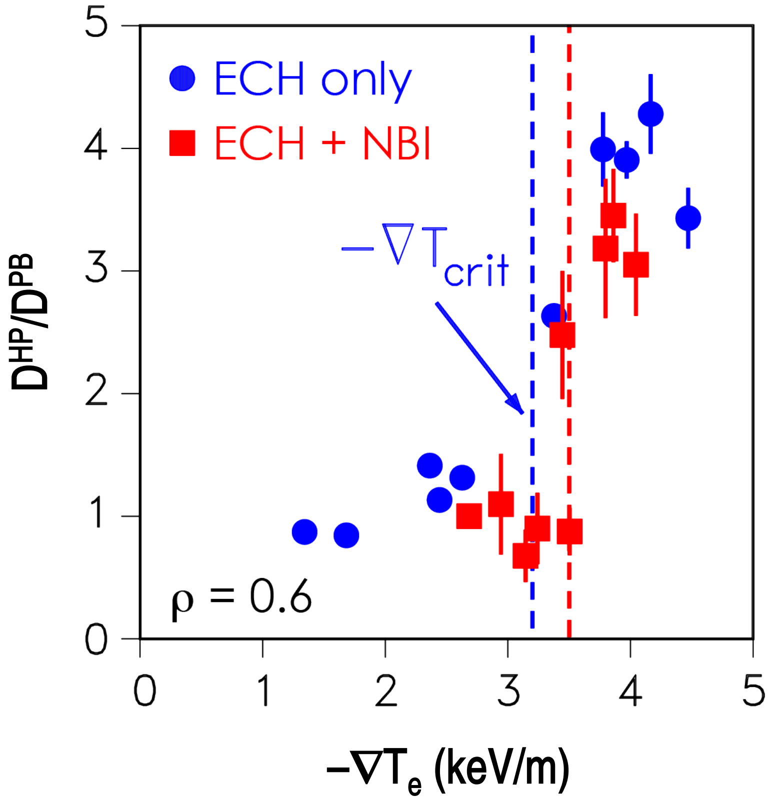

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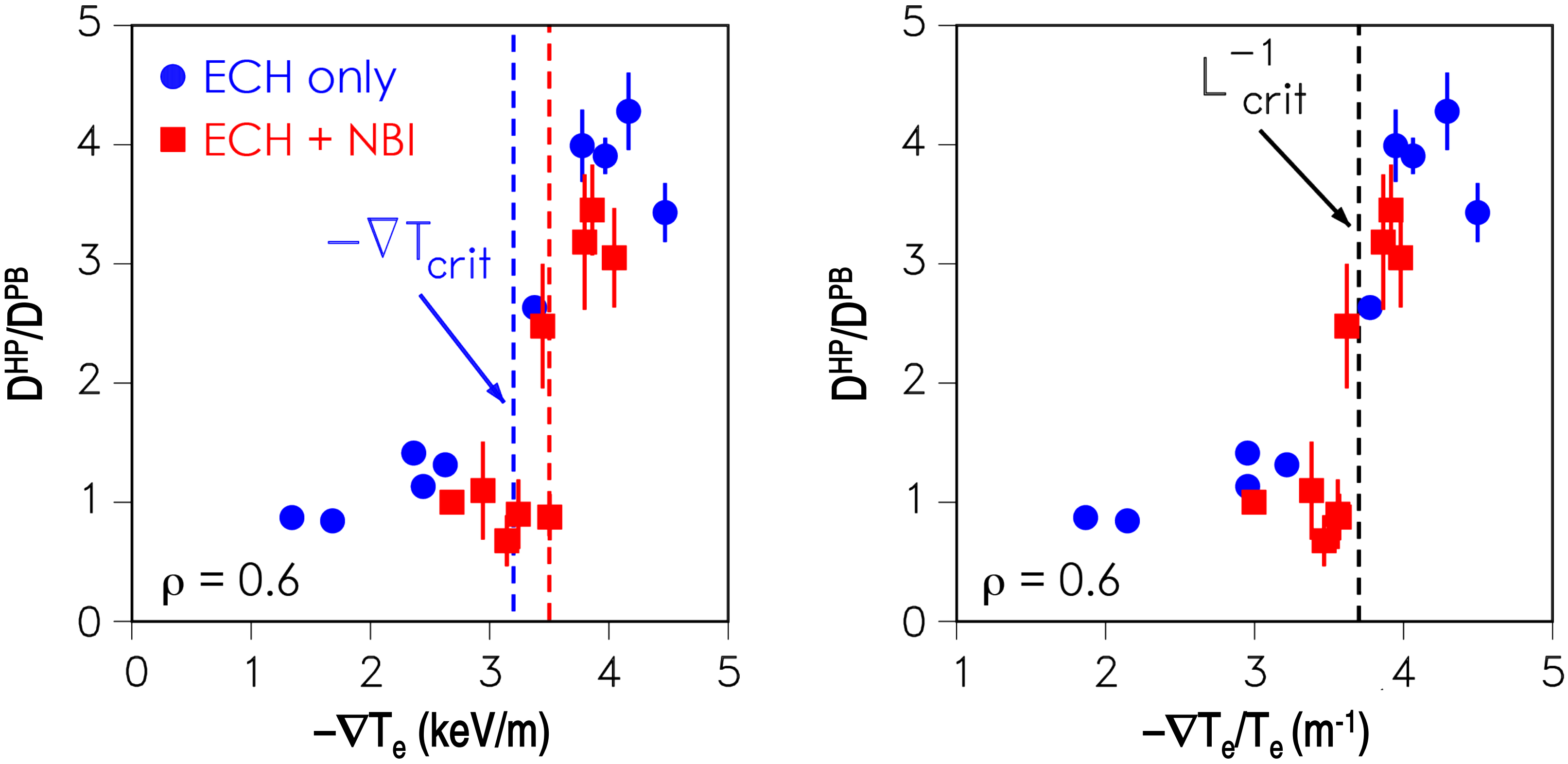
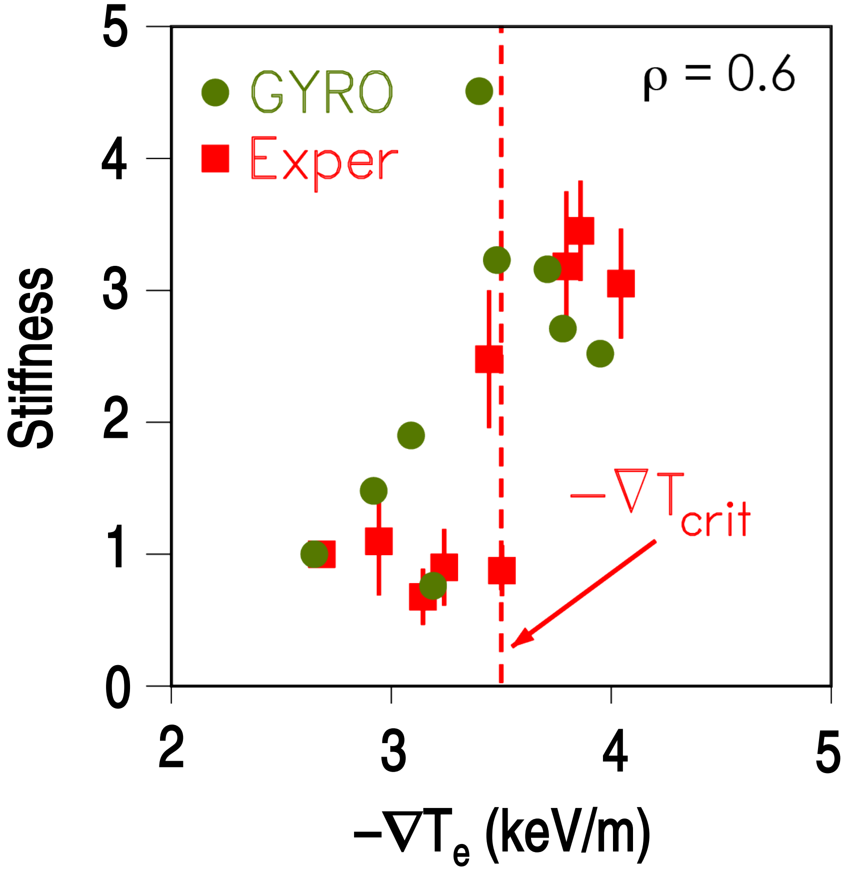


Critical Gradient and Stiffness Factor from Nonlinear GYRO Simulations Agree With Experiment

- **Comparison of ECH + co-NBI case**
- **GYRO stiffness factor determined using total heat flux**

$$S = \frac{\partial \ln Q_e}{\partial \ln \nabla T_e}$$



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The “Minimal” Critical Gradient Transport Model by Garbet Can Be Tested Against DIII-D Data

- **Simple transport model that preserves some basic properties of turbulent transport**
- **Main hypothesis is gyroBohm-like turbulent transport that is switched on above a threshold $\kappa_{\mathrm{crit}} = -R\nabla T_{\mathrm{crit}}/T$**

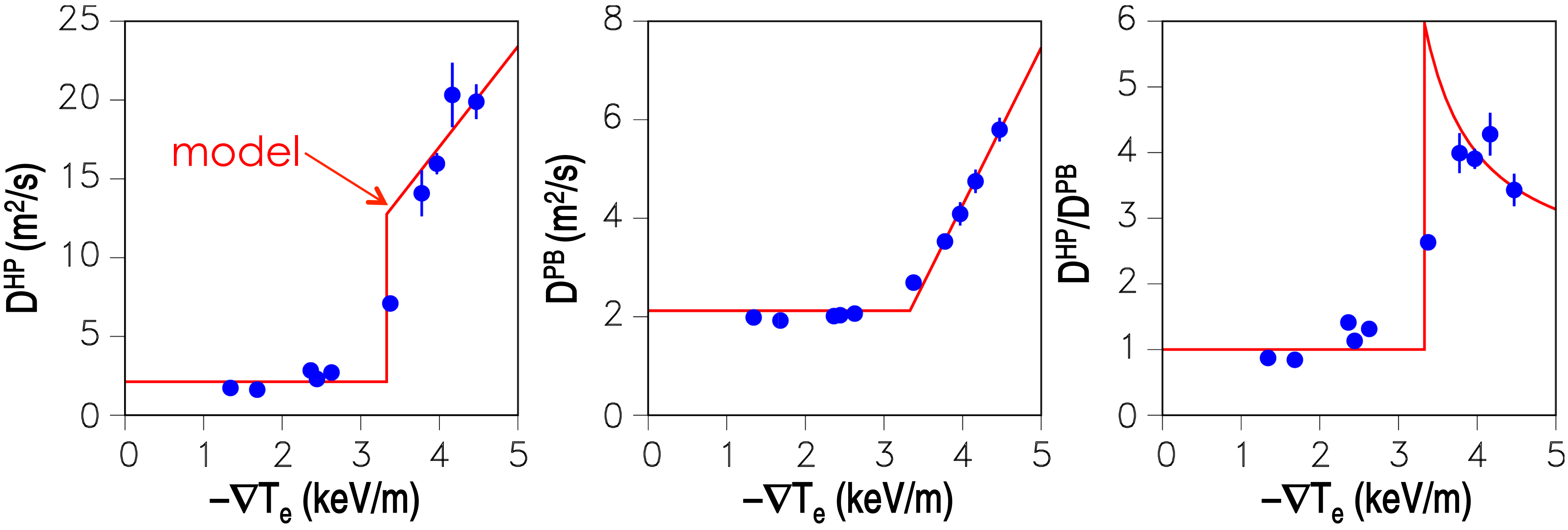
$$\frac{D}{D_{\mathrm{gB}}} = \chi_s q^{1.5}\left(-\frac{R\nabla T}{T} - \kappa_{\mathrm{crit}}\right) H\left(-\frac{R\nabla T}{T} - \kappa_{\mathrm{crit}}\right) + \chi_0 q^{1.5}$$

➔ **Note that there is no convective term**

- **χ_s and χ_0 are dimensionless coefficients to be fitted to data**
  - χ_s is the “effective stiffness factor”

X. Garbet *et al.* 2004 *Plasma Phys. Control. Fusion* **46** 1351

Diffusion Coefficients Exhibit Expected Behavior for Transport Switched On Above a Critical Gradient



ECH only: $L_{crit}^{-1} = 3.7\ \text{m}^{-1}$

$\chi_s = 0.80$

$\chi_0 = 1.04$

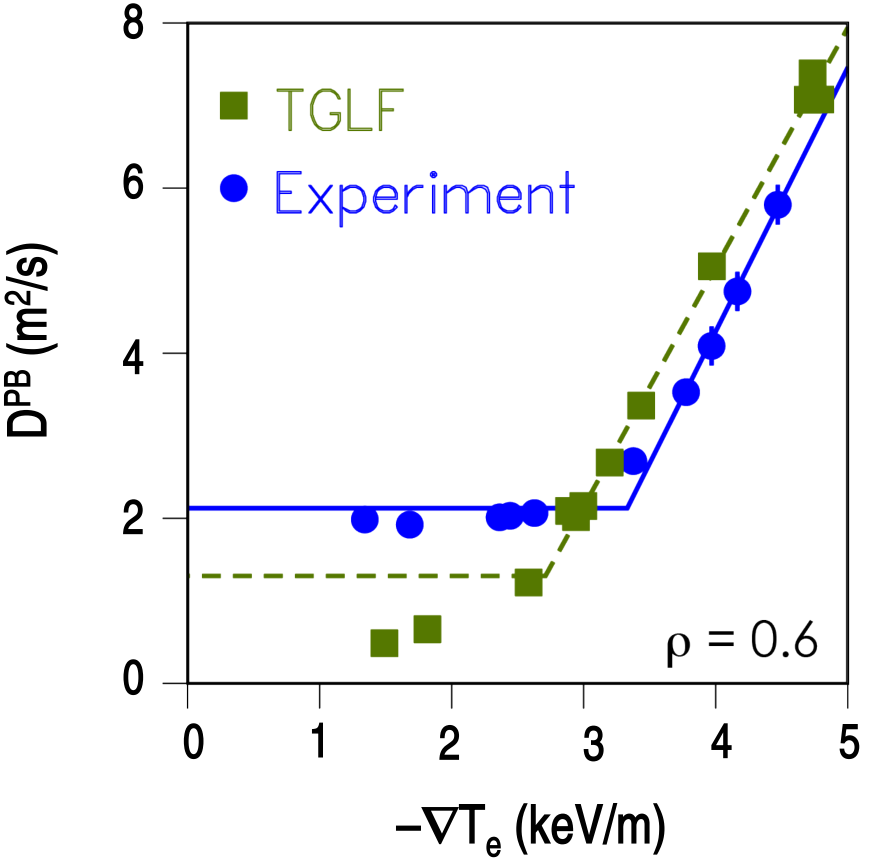
TGLF Transport Model has Similar Effective Stiffness Factor as Experiment But Predicts a Lower Critical Gradient

- **Comparison of ECH-only case**
- **TGLF diffusion coefficient determined using total heat flux**

$$D^{\mathrm{TGLF}} = -\frac{Q_e}{n_e \nabla T_e}$$

Experiment: L_{crit}^{-1} = 3.7 m^{-1}
χ_s = 0.80

TGLF: L_{crit}^{-1} = 3.1–3.4 m^{-1}
χ_s = 0.73



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Conclusions

- **We have developed a new method to look directly at diffusive behavior by combining heat pulse propagation and power balance analysis**
- **In L-mode plasmas with off-axis ECH, a critical value of ∇T_e is observed, above which there is a sudden increase (~4×) in the electron transport stiffness**
- **Predicted electron transport stiffness and critical ∇T_e from GYRO and TGLF are in good agreement (≈10%) with experiment**
  - Will extend this study to H-mode plasmas