Enhanced Pedestal (EP) H-mode on NSTX

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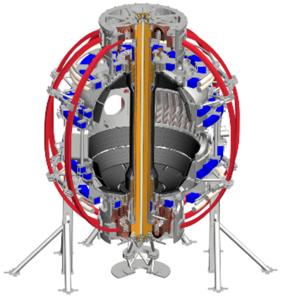
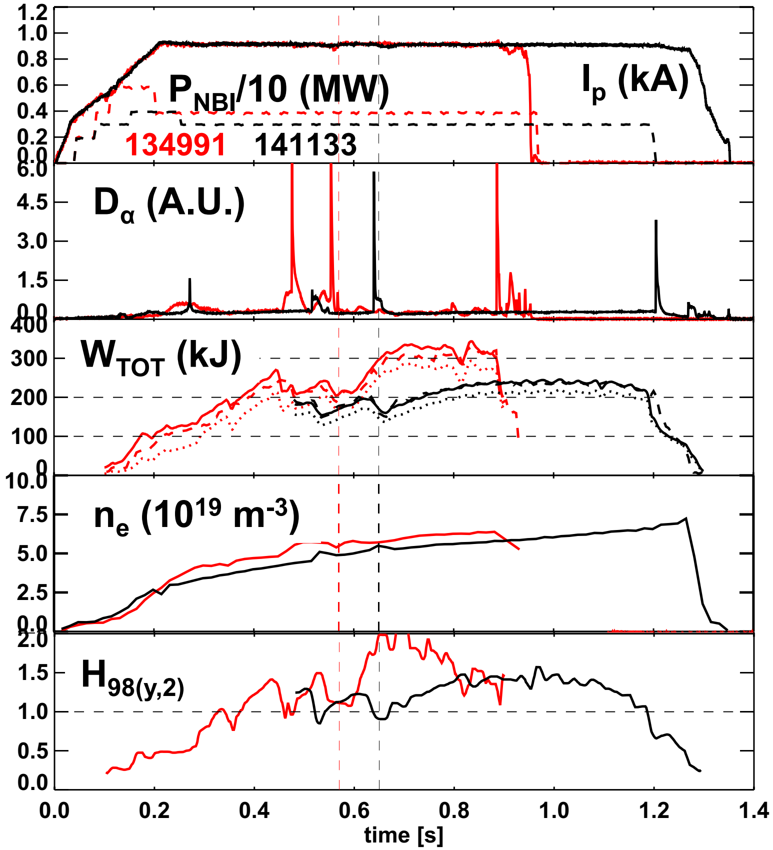


Enhanced Pedestal (EP) H-mode: improved τ_E without a large change in particle confinement

- EP H-mode usually triggered by type-I ELM
  - EP H-mode phase is ELM-free and MHD-free
- Density increase slower than ELM-free H-mode
- Two examples shown
  - NSTX Record $H_{98(y,2)}$: 134991
  - Longest EP H-mode: 141133



R. Maingi et al., J. Nucl. Mat. 390-1, 440-3 (2009)
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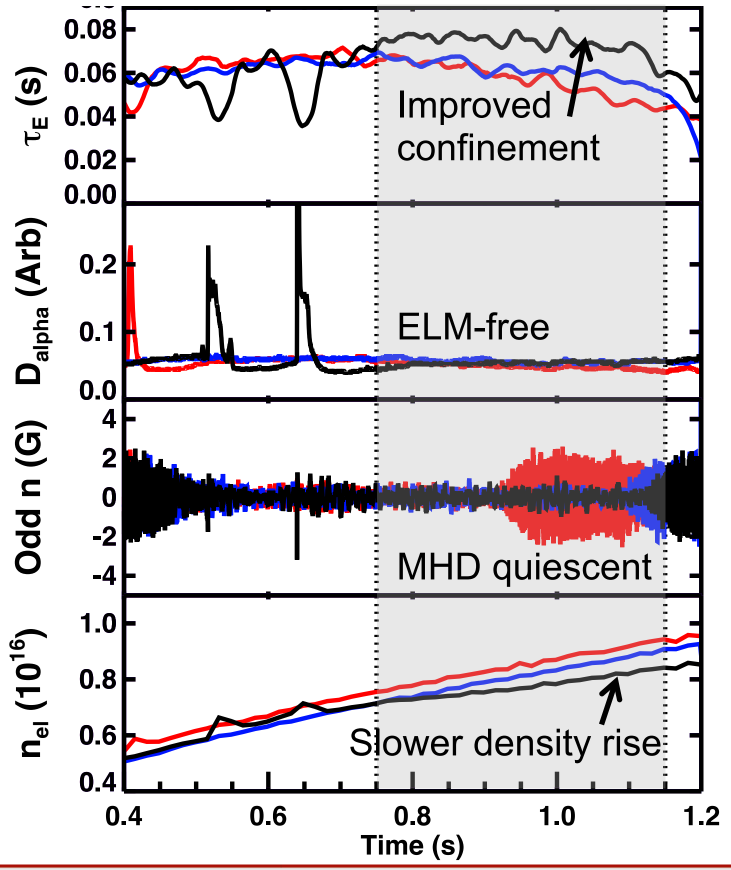
  - EP H-mode phase is ELM-free and MHD-free
- Density increase slower than ELM-free H-mode
- Longest EP H-mode discharge compared to ELM-free discharges



Type	n=3 fields	Shot
H-mode	EFC	141131
H-mode,	EFC + 400A	141125
EP H-mode	EFC + 500A	141133

Significant improvement in temperature profiles with subtle differences in E_r, density and flow

- Improved thermal barrier without a large change to the particle barrier
  - No q-shear reversal
- $\delta W_i/\delta W$ ~ 75% for EP H-modes
  - $T_i > T_e$ over most of the profile

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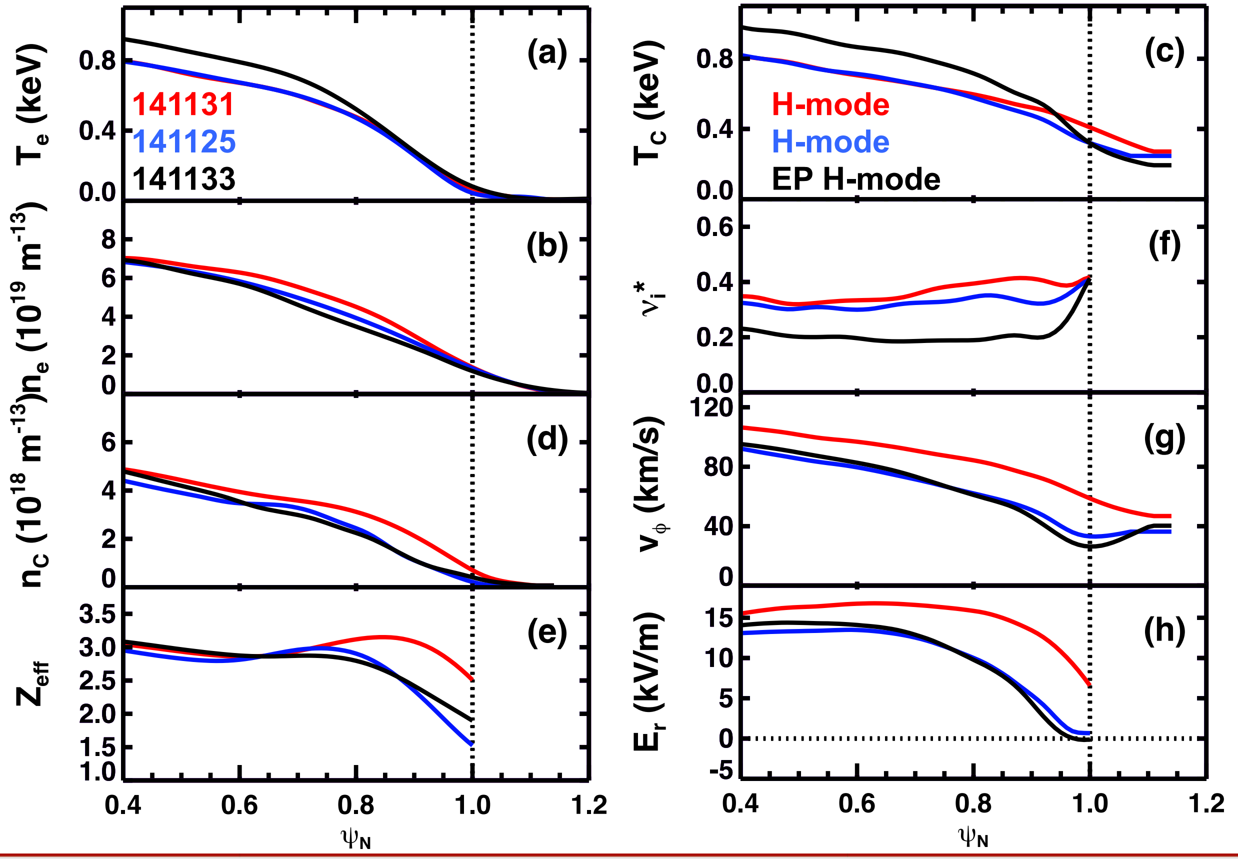
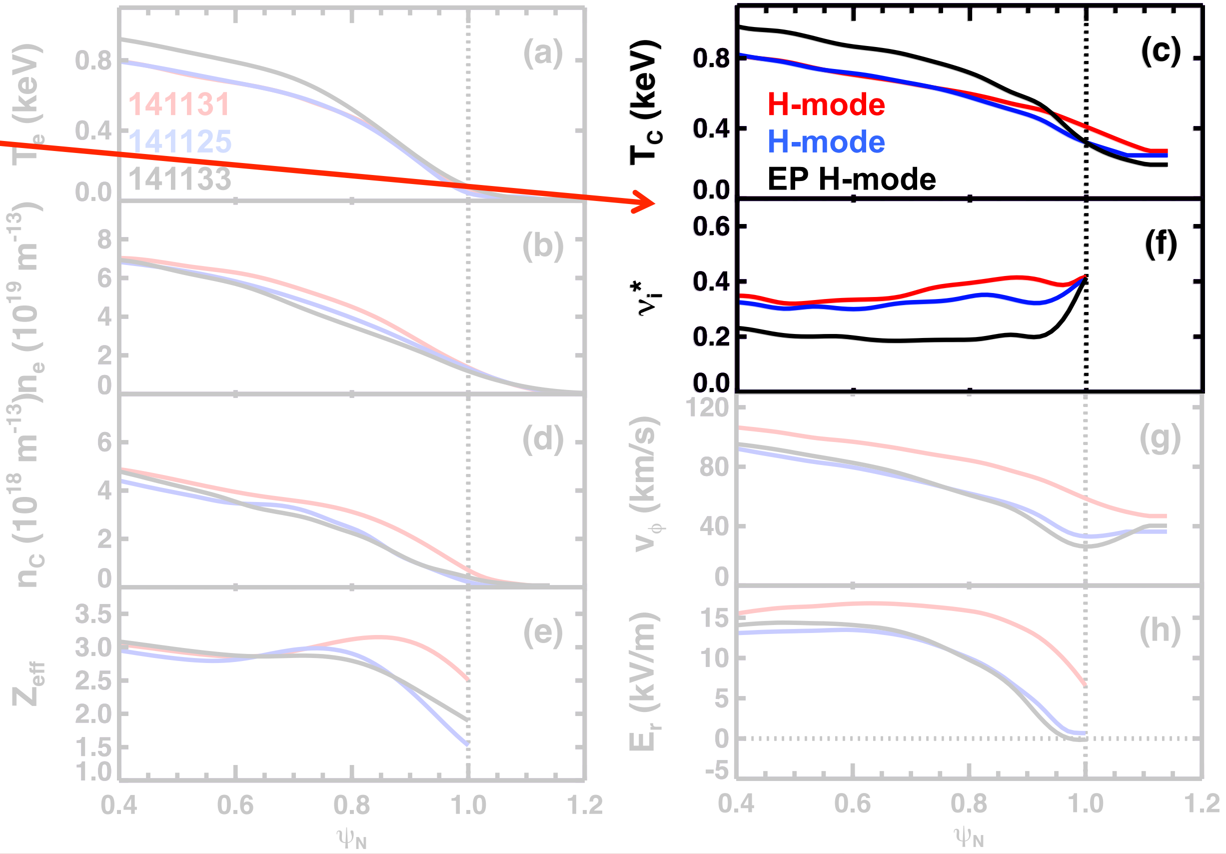


This talk aims to demonstrate …

Increased ∇T_i due to reduced neoclassical thermal transport with lower collisionality



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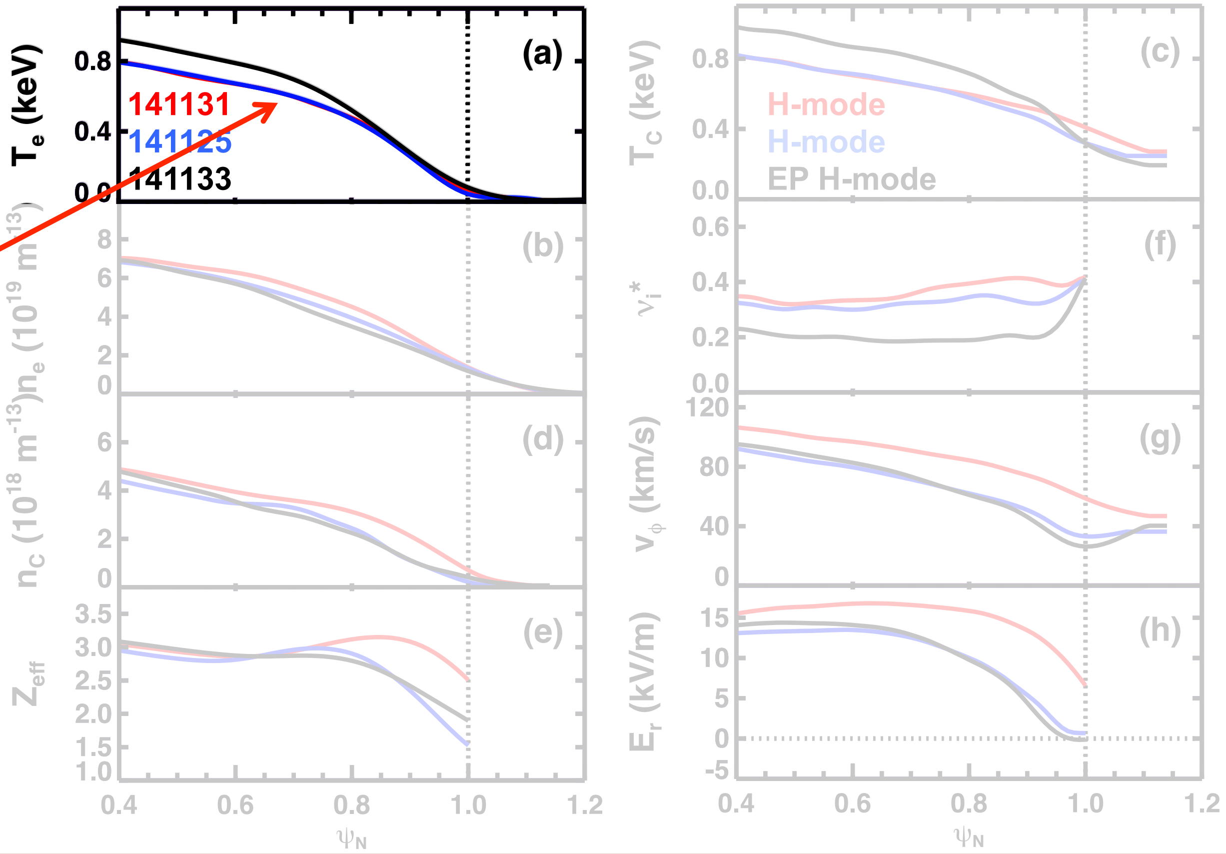
This talk aims to demonstrate …

Wider T_e pedestal can develop with larger electron heating (via ion-e coupling) and changes to turbulent transport



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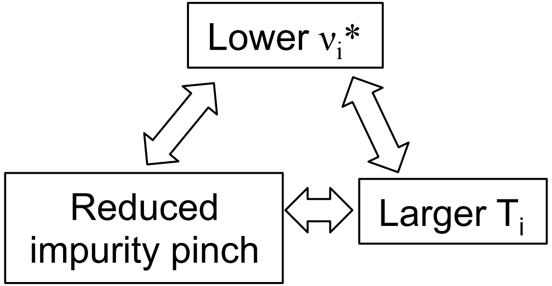
This talk aims to demonstrate …

An ELM can trigger a positive feedback neocl. mechanism:



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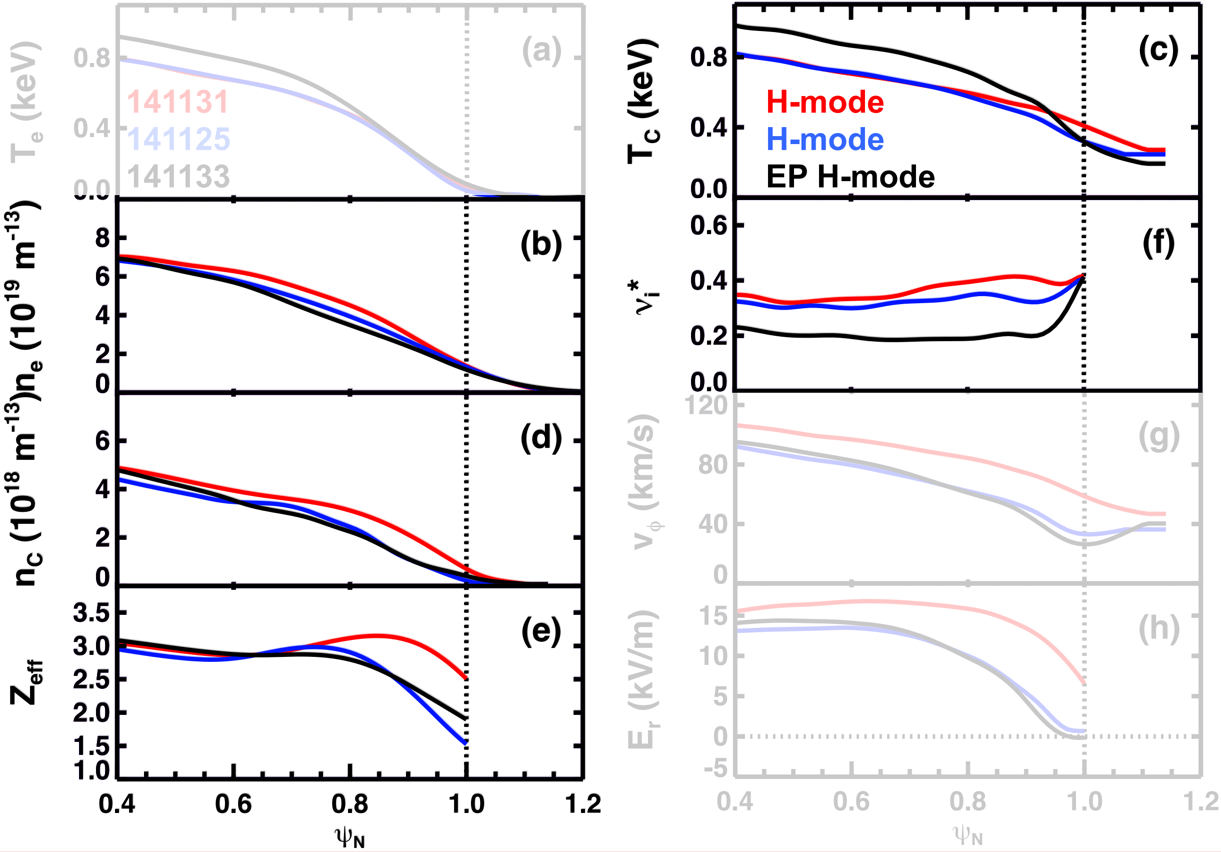

Outline of talk

- Characteristics of EP H-mode
- Neoclassical main ion transport at low collisionality
- Positive feedback mechanisms that reinforce improved ion thermal confinement

Characteristics of EP H-mode

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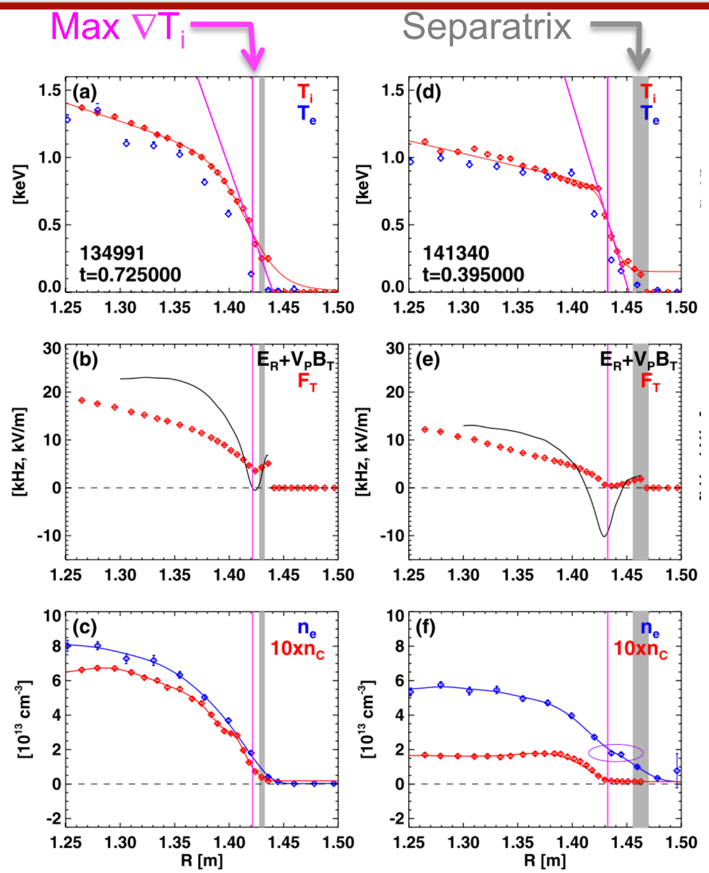
- Max $-\nabla T_i$ can occur anywhere within wide pedestal on NSTX
  - Location of max $-\nabla T_i$ is outboard of other max gradients (v_ϕ, E_r, T_e …)
  - Tends to align near minimum of E_r and v_ϕ well
- Transition most often triggered by an ELM
  - Increased $-\nabla T_i$ develops over transport timescales (order 10 - 100 ms)
  - Carbon rotation gradient grows concurrently
- Observed over a wide range of shapes, I_p, B_T, q_{95}, β_{p}, P_{NBI}, applied n=3 field
  - More common at low-q_{95}, but best performance at higher q_{95}
  - Reduced neutral fueling and large wall pumping is a common characteristic



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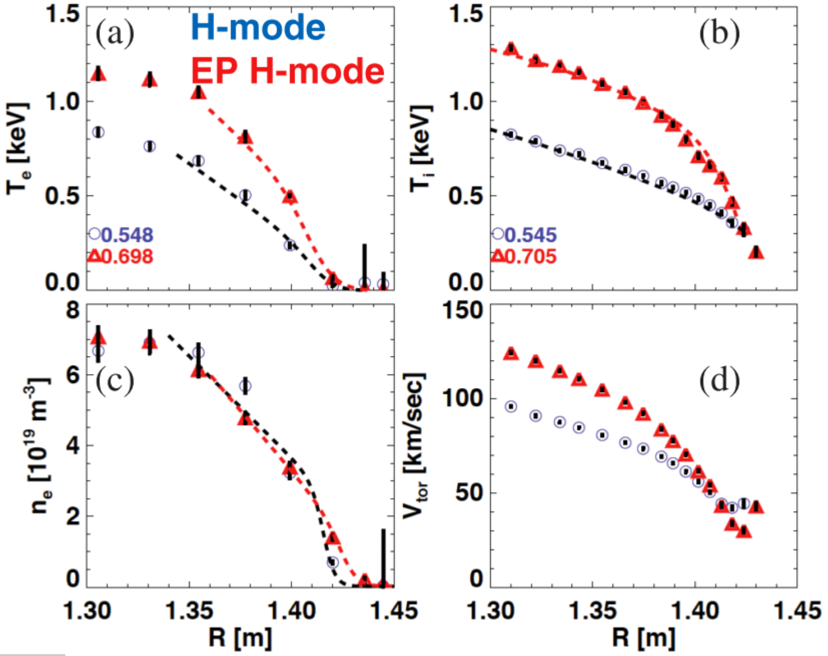
30 ms before ELM
120 ms after ELM



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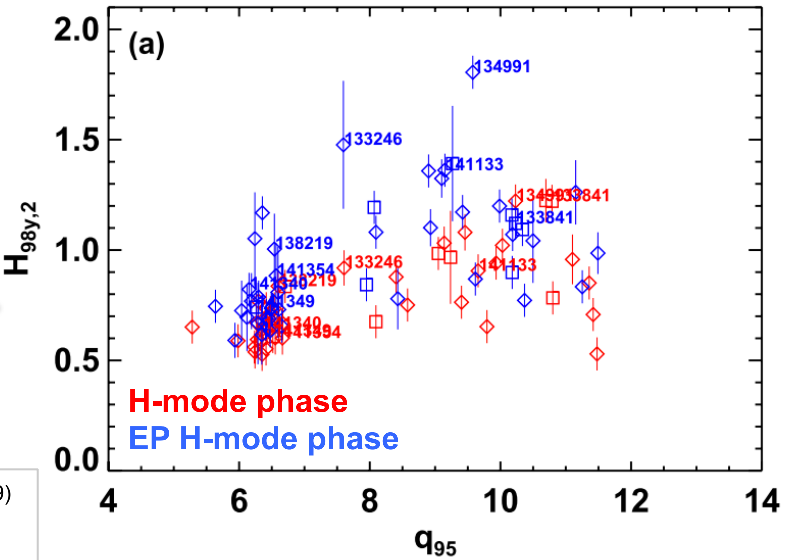

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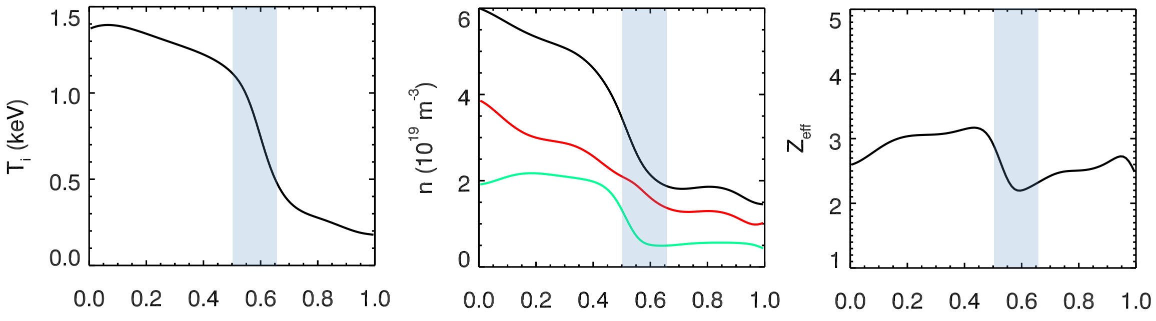
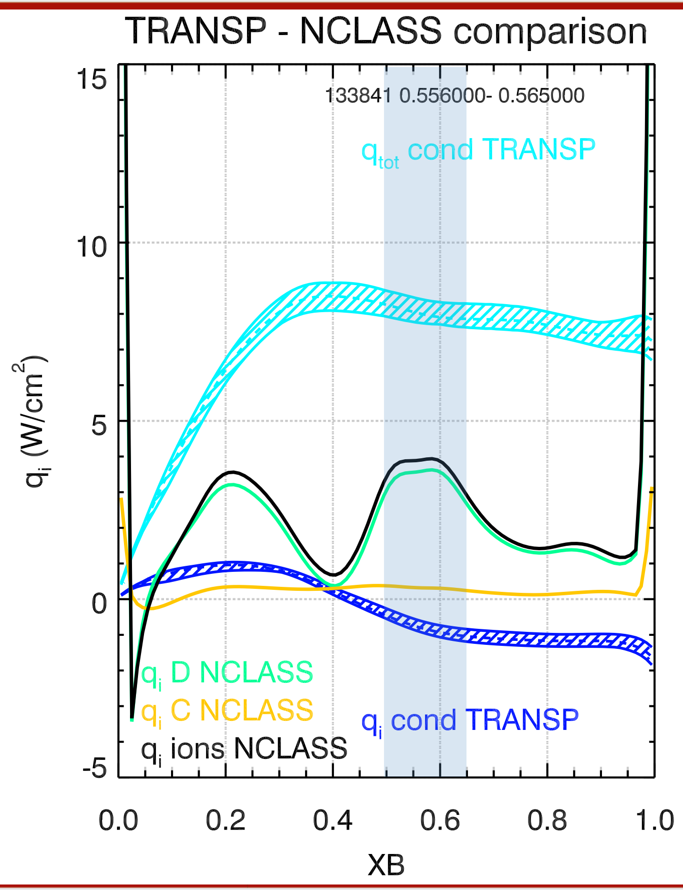
Large T_i gradient exceeds neoclassical predictions

- Examine transport for discharge with large ∇T_i well inside separatrix
  - Minimize edge ion-orbit loss effects
- TRANSP: conductive ion flux is negative outside of gradient
  - Large $T_i - T_e$ leads to significant thermal transfer to electrons in core





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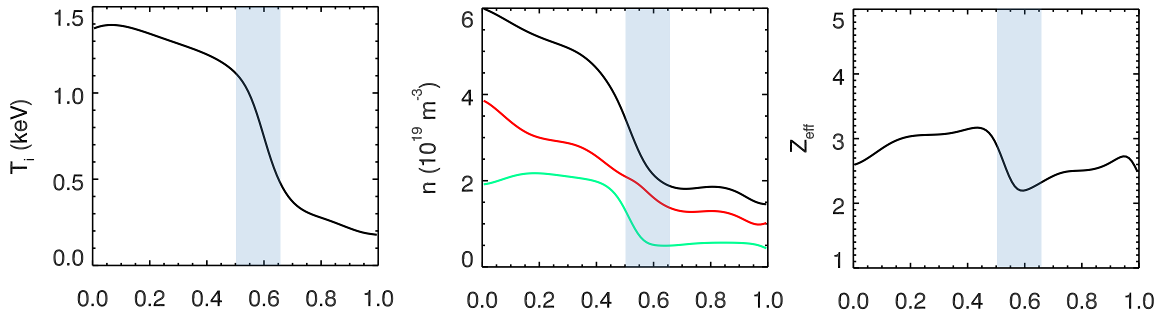
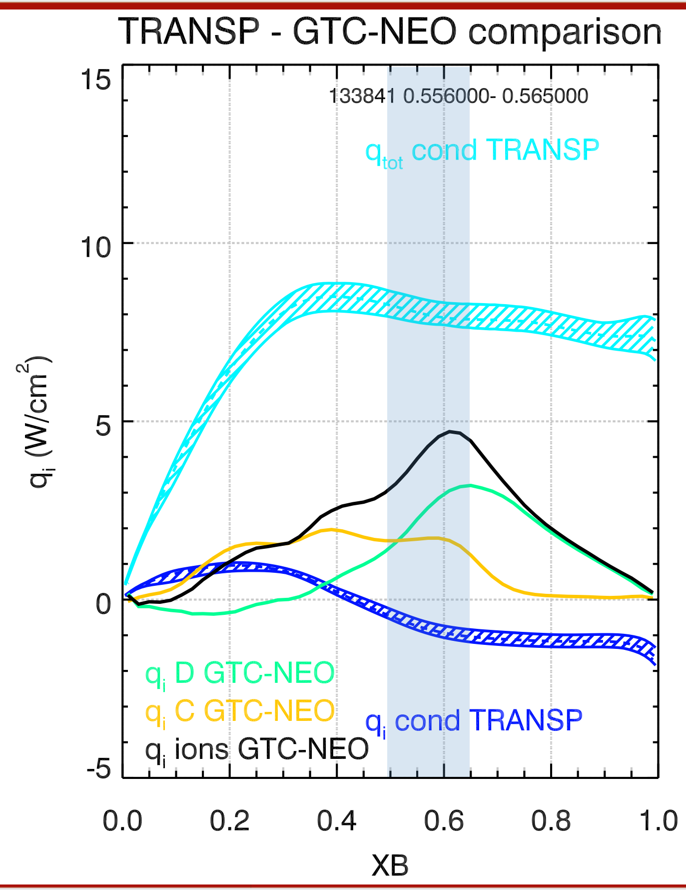
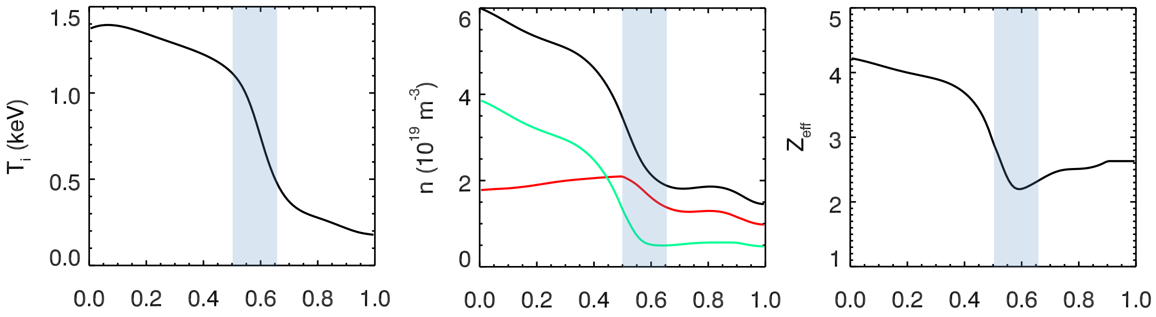


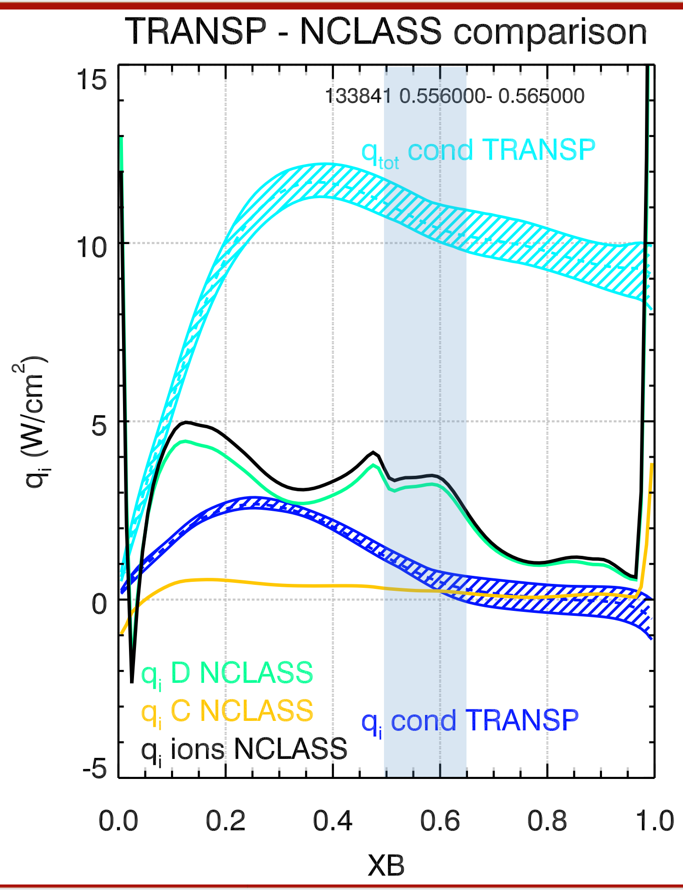


Large T_i gradient exceeds neoclassical predictions

- Increase Z_{eff} in core by modifying n_C profile
  - Increases $q_{i,cond}$ and improves agreement with neo calculations

- Work is ongoing to make quantitative agreement with neoclassical calculations
  - Sensitivity to equilibrium, profiles (T_C=T_D?)…
  - TRANSP, XGC0, GTC-NEO, NEO …
  - Take away: $\chi_i \sim \chi_{i,neo}$





Neoclassical transport at low collisionality

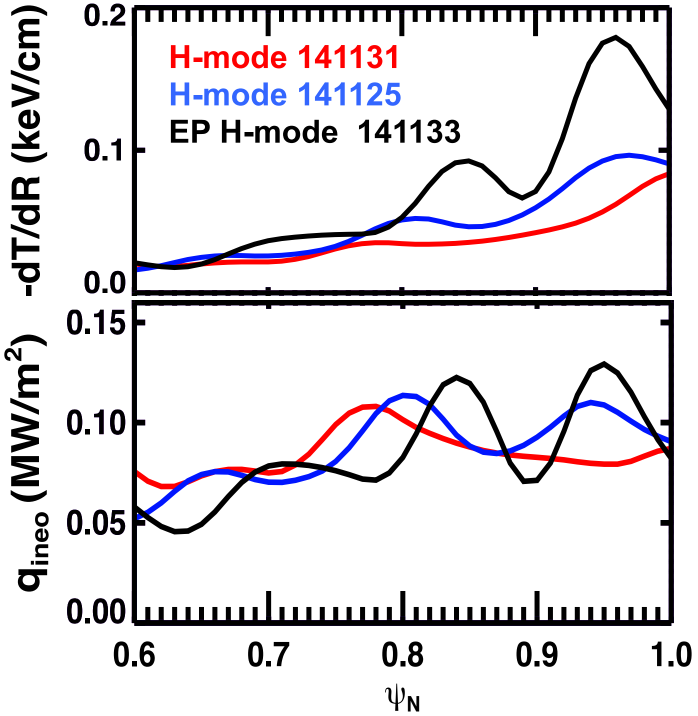
Sensitivity of ∇T_i to edge density consistent with neoclassical transport

Approximate banana regime main ion heat flux (Tokamaks, Wesson)

$$q_i = -0.68\frac{\varepsilon^{-3/2}q^2\rho_i^2}{\tau_i}\left(1+0.48\varepsilon^{1/2}\right)n\frac{dT_i}{dr}$$

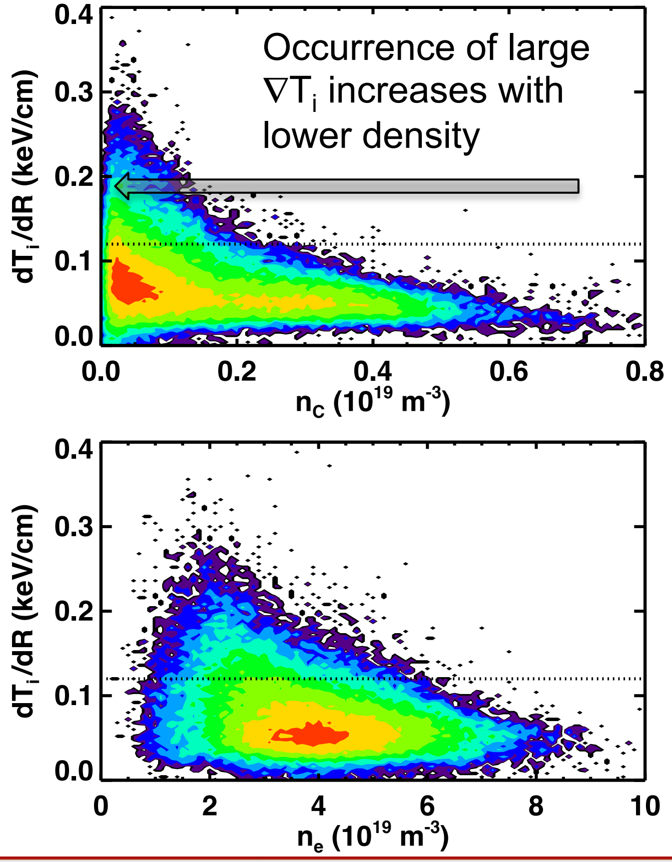
$$q_i \sim \frac{-\sqrt{T_i}}{Z_{eff}n_e n_i}\frac{dT_i}{dr}$$

Heat flux from neoclassical approximation similar for three discharges despite larger dT_i/dR in EP H-mode due to differences in density and T_i profiles

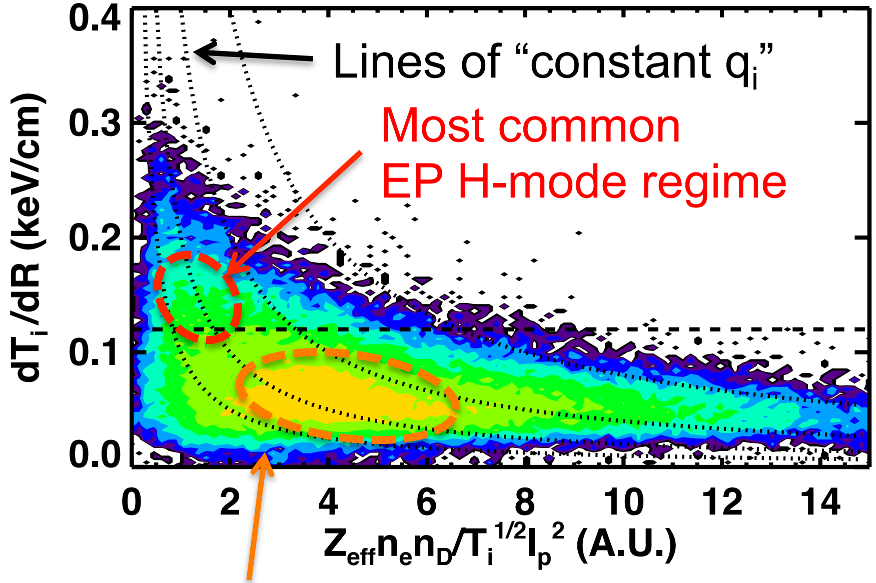


Maximum achievable $-\nabla T_i$ improves with lower density

- Database of all NSTX CHERS profiles with P_{NBI} > 2 MW
  - Identify largest $-\nabla T_i$ within a few cm of maximum $-\nabla v_\phi$
    - Most success identifying gradients $\psi_N < 1$
- Maximum $-\nabla T_i$ increases as local density decreases
  - Each color represents factor 2 increase in number of database entries
    - Black = 1, Red > 128
  - Strong scaling with $n_C < 0.2 \times 10^{19}$ m^{-3}
  - 10% of database entries satisfy typical EP H-mode designation
    - $dT_i/dR > 0.12$ keV/cm

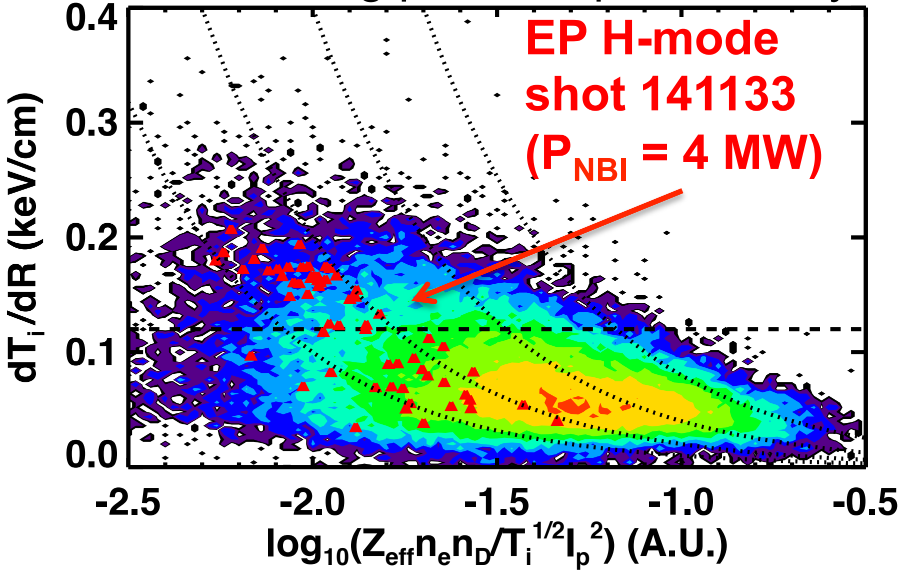


Max $-\nabla T_i$ increases at decreasing density and increasing I_p, consistent with neo model



Most common H-mode regime

X-axis log plot to improve clarity



Rearrange Wesson equation:

$$-\frac{dT_i}{dr} \sim q_i \frac{\varepsilon^{3/2}B^2}{Z_{eff}n_en_i}\frac{\sqrt{T_i}}{q^2\left(1+0.48\varepsilon^{1/2}\right)} \sim q_i\left(\frac{Z_{eff}n_en_i}{I_p^2\sqrt{T_i}}\right)^{-1}$$ (Constant shape)

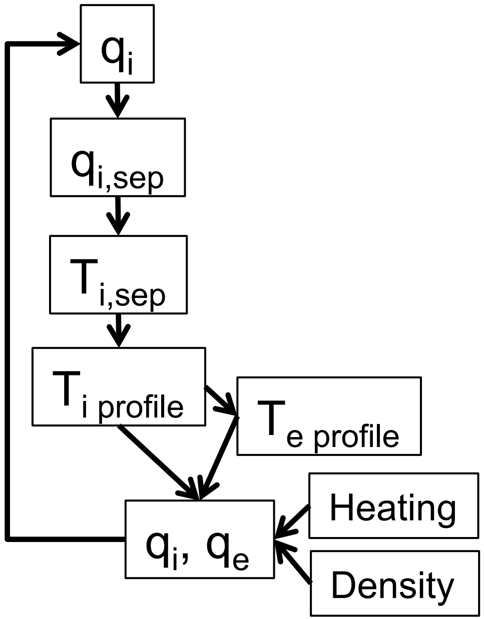
Main point: Increased ∇T_i in EP H-mode is consistent with reduction of $\chi_{i,neo}$ with lower ν_i^*

- Supported using analytic neoclassical expression and …
  - Comparison of matched H- and EP H-mode shots
  - Database of NSTX discharges

- Current work focuses on …
  - Completing more rigorous neoclassical calculations
    - GTC-NEO, NEO, XGC0…
  - Time-dependent transport modeling including sources and sinks
    - TRANSP, XGC0 …
    - Next slides describe simple 1D model to provide insight into transport

Simple 1D model used to examine impact of edge density on neo ion thermal transport

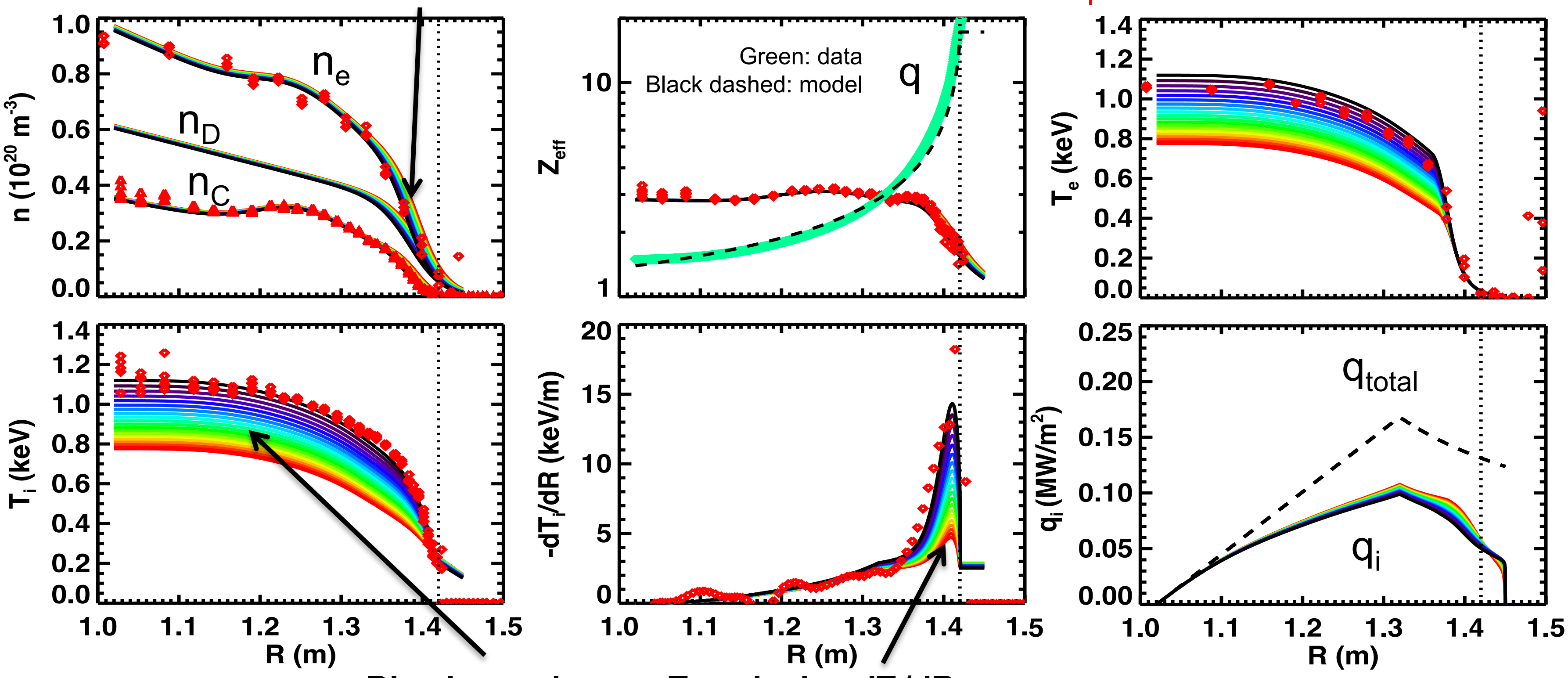
- Fixed geometry parameters and q-profile
- Density profiles (n_e, n_C) are modified tanh profiles
- Start with a guess for q_i
- $T_{i,sep}$ proportional to q_{isep}
- T_i profile determined from Wesson $q_{i,neo}$
  - Start at $T_{i,sep}$ and calculate inward to core
- Fixed T_e scale length from separatrix until $T_e = T_i$
  - Fixed T_e separatrix
  - Fixed χ_e where $T_e = T_i$ ($\chi_e \sim 3$ m^2/s)
- Compute heat flux
  - Fixed volumetric heating inside top of pedestal
    - No neutral sources/sinks included
  - q_i reduced by e→i coupling where ($T_i > T_e$)



Model illustrates large impact edge density has on T_i profile with neo transport

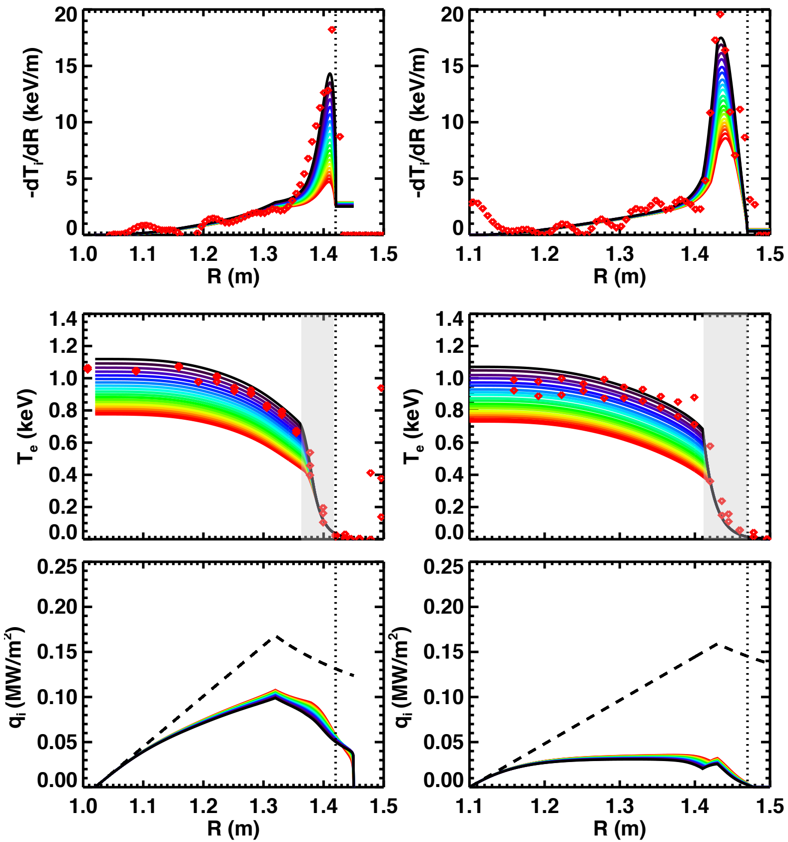
Shift n pedestal inward by 1.5 cm

Data points: EP H-mode shot 141133



Big change in core T_i and edge dT_i/dR

Position of max $-\nabla T_i$ in model sensitive to the T_e profile



Two EP H-mode discharges

141133 (left):

max $-\nabla T_i$ is near separatrix

141340 (right):

max $-\nabla T_i$ is 4 cm inside separatrix

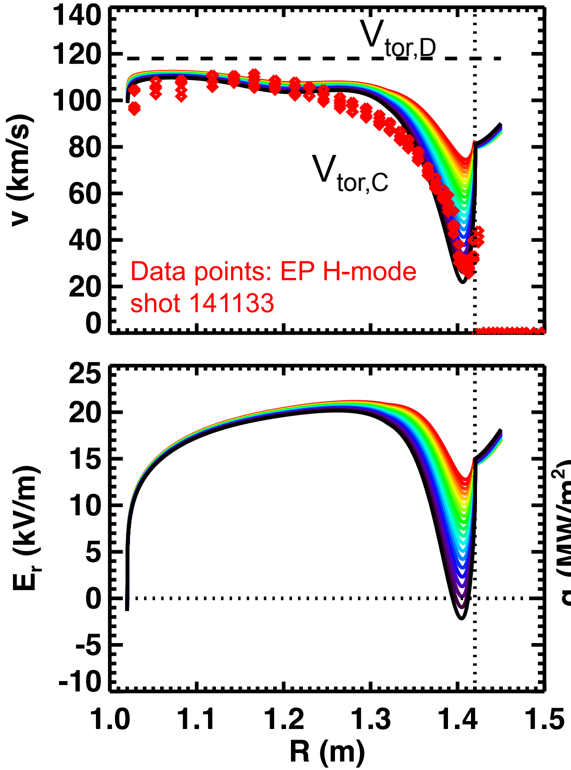
Top of T_e pedestal shifted inward compared to 141133

e → i coupling reduces q_i, and thus, dT_i/dR near separatrix

Provides explanation for why position of large T_i gradient can vary between examples

Differences in ion species v_{dia} may describe concurrent increase in ∇v_ϕ with ∇T_i

- C^{6+} and D^+ density pedestals are not aligned
  - Difference in v_{dia} increases with ∇T_i
- Concurrent increase in ∇v_ϕ and ∇E_r with ∇T_i is often observed during ELM recovery
  - Simple model reproduces this when using many assumptions
    - $V_{pol} = 0$ everywhere for all species
    - $V_D = V_{dia} + V_{ExB}$ does not change with density, T_i
    - $T_D = T_C$
- Change ∇T_i drives change in ∇v_ϕ



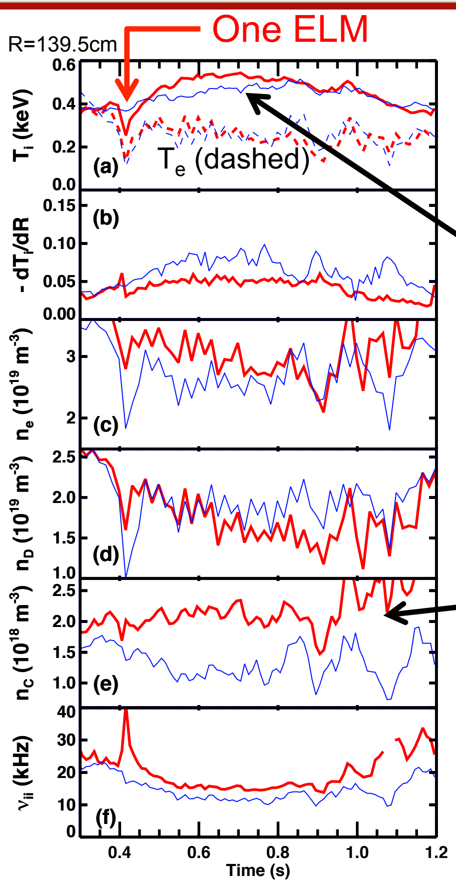
Edge gradients increase and location of maximum gradient shifts inward

Positive feedback mechanisms

- What roll does an ELM play in triggering EP H-mode?

- Why doesn’t every large ELM trigger EP H-mode?

ELMs can produce transient periods of elevated edge ion temperature



Local values at $\psi_N \sim 0.9$

141130 H-mode with one ELM

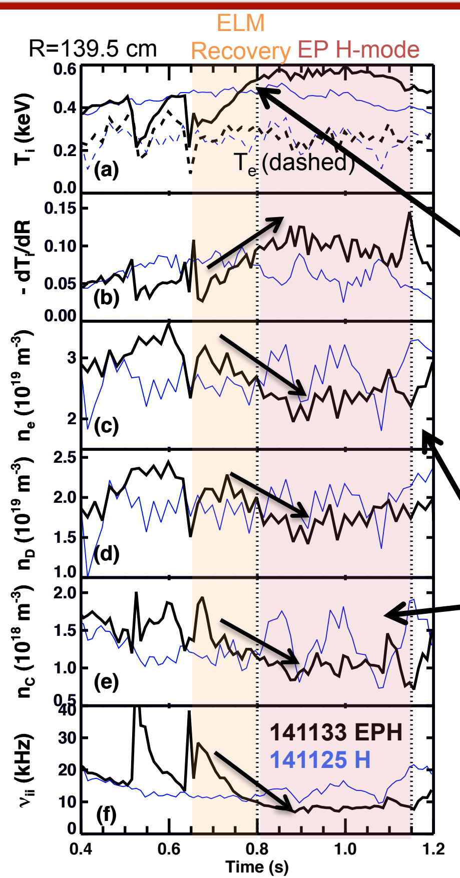
141125 H-mode ELM-free with 3D field applied

T_i "overshoots" during ELM recovery

Carbon density is larger for the discharge without 3D fields (Fields applied at 0.4s)

Ion-ion collision frequency is larger despite larger T_i

ELMs can produce transient periods of elevated edge ion temperature



Local values at $\psi_N \sim 0.9$

141131 EP H-mode following an ELM

141125 H-mode ELM-free with 3D field applied

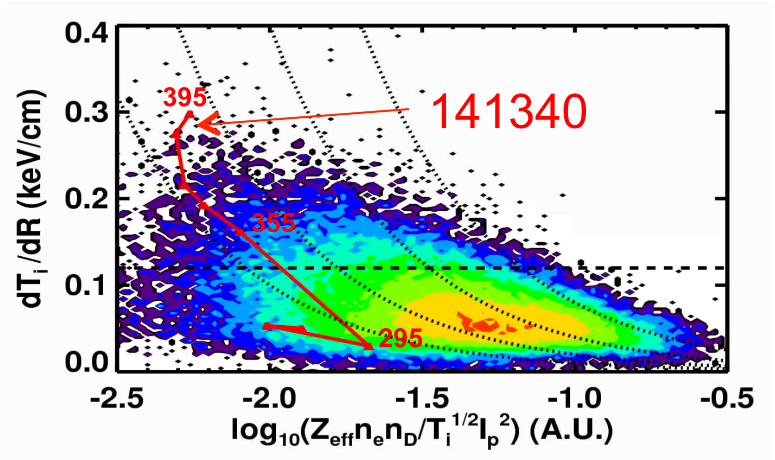
T_i "overshoots" during ELM recovery

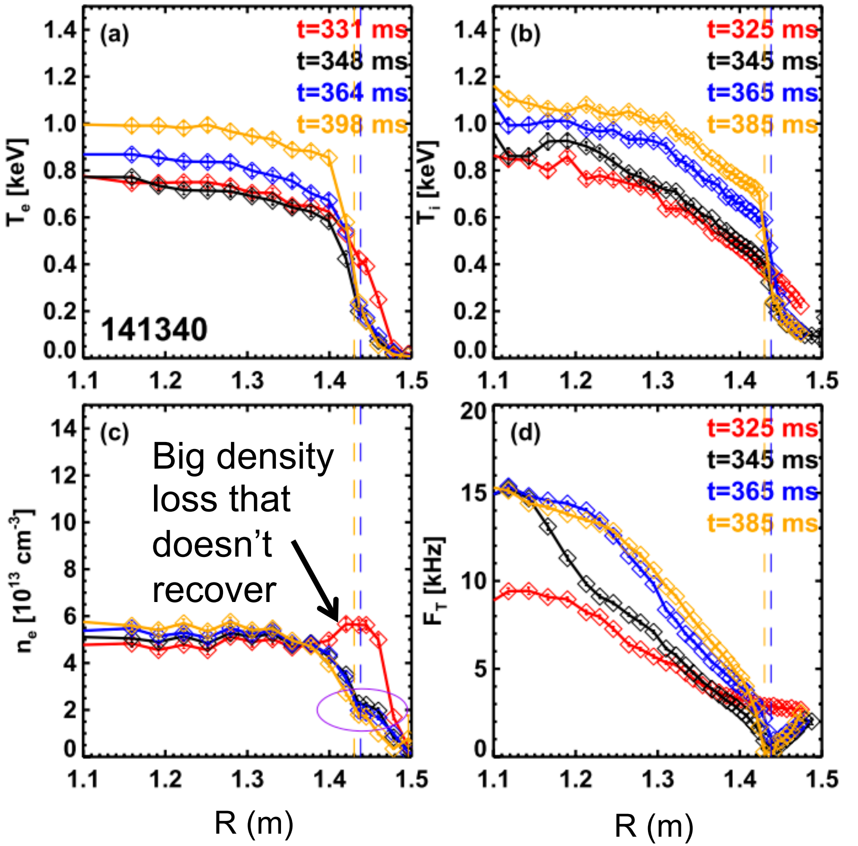
Density is, on average, lower in EP H-mode phase

Ion-ion collision frequency is lower due to changes in local T_i and density

ELM can provide transient period of low-collisionality

- Transient period of low-ν_i^* during ELM recovery can be driven by T_i overshoot, density loss or combination of both
  - Plots show example of ELM rapidly changing the edge density





Impurity pinch is a possible feedback mechanism for the EP H-mode bifurcation

- Positive feedback …
  - ELM transiently lowers edge collisionality
    - Slows impurity density pinch
    - Increases -∇T_i from neoclassical transport
  - Lower density, higher T_i reinforces low edge collisionality

Neoclassical carbon pinch

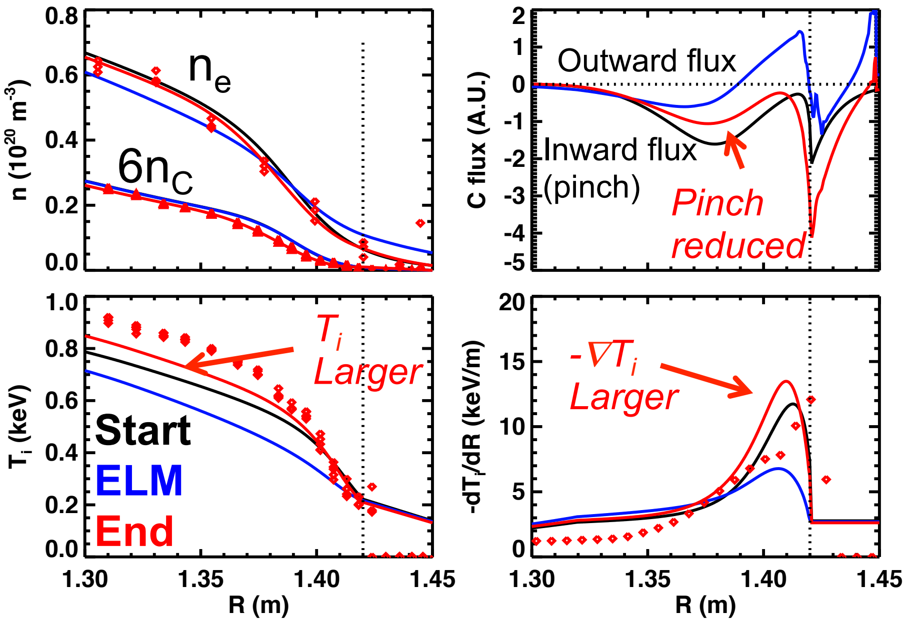
$$\Gamma^{PS}{}_C = \frac{q^2 n_D \rho_D \nu_{DC}}{Z_C} \times \left[K \left(\frac{\partial \ln(n_D)}{\partial r} - \frac{Z_D}{Z_C} \frac{\partial \ln(n_C)}{\partial r} \right) + H \frac{\partial \ln(T_D)}{\partial r} \right]$$

Collision frequency

Pinch

Screening

Simple 1D model extended to a pseudo time-dependent model for the ELM recovery

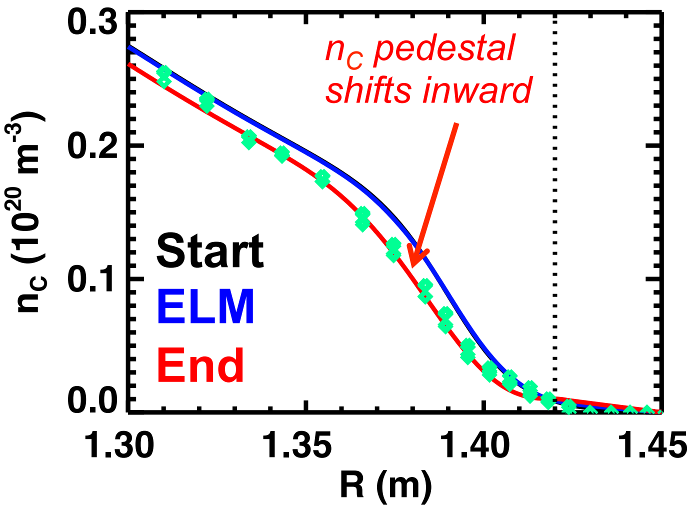


Find T_i for prescribed density profiles

Perturb n_D (wider tanh) to simulate an ELM

Slowly restore n_D to original profile

At each step, adjust n_C consistent with difference between neoclassical flux for present profiles and the original profile

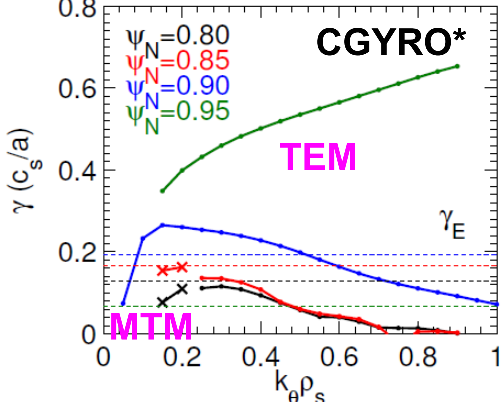


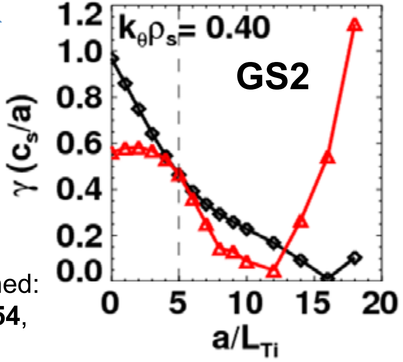
Profiles in ELM recovery reduce the carbon pinch

A second possible feedback mechanism: Increased $-\nabla T_i$ can improve electron thermal confinement

- Predominantly TEM driven by ∇T_e in pedestal ($a/L_{Te} > a/L_{ne} > a/L_{Ti}$)
  - Weak low-k_θ microtearing at some radii
- Growth rates larger than E×B shearing rates (γ_E) for $\psi_N > 0.9$
- Modes stabilized by increasing $\nabla T_i/T_i$
  - Similar to previous EP H-mode calculation using GS2 and H-mode calculations using GEM [Smith NF, 2013]
- Stabilization of TEM drives improvements in T_e pedestal
  - T_e pedestal impacts T_i through e→i coupling

Linear growth rates
141133 EP H-mode



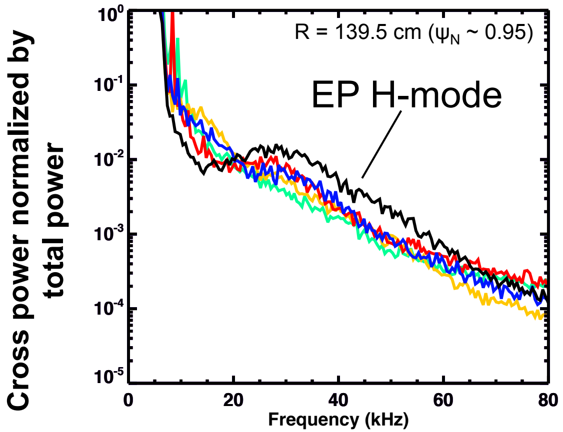


From J. Canik, published: S. Gerhardt et al, NF **54**, 083021 (2014)

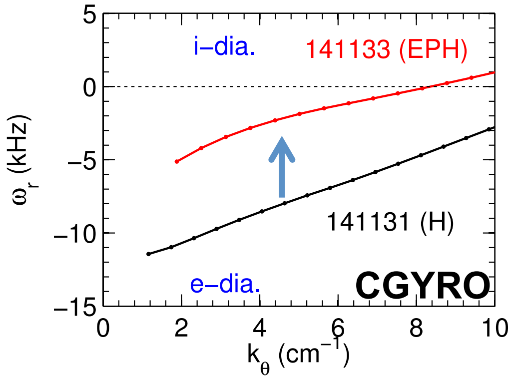
*J. Candy, E.A. Belli, JCP (2016)

BES spectrum shifts to higher frequency in the region with the largest T_i gradient

- BES cross power is suppressed below 30 kHz in EP H-mode
  - Largest change observed in region with large T_C gradient
  - Poloidal correlation length decreases in EP H-mode, consistent with shift to higher frequency

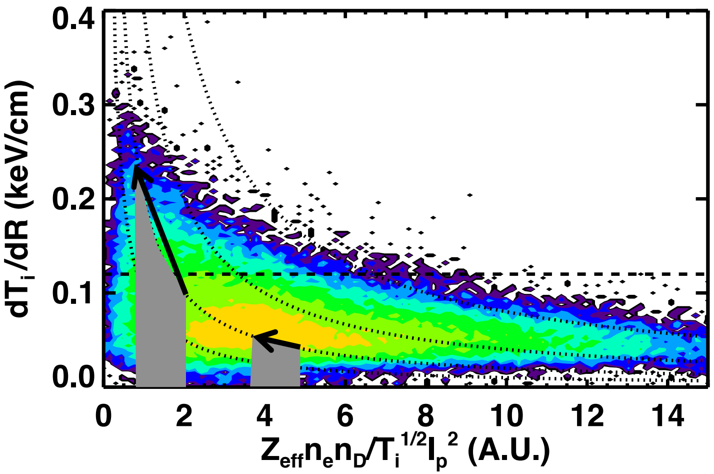


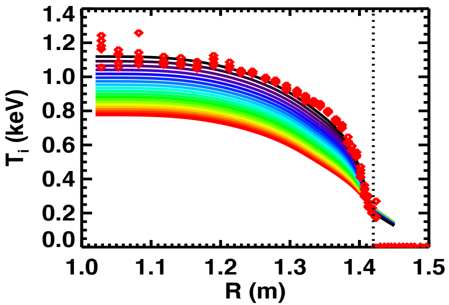
- Qualitatively consistent with predicted $\Delta\omega_r$ due to higher ∇T_i (opposite to change in $V_{doppler}$)
  - May provide opportunity to compare calculations to direct turbulence measurements

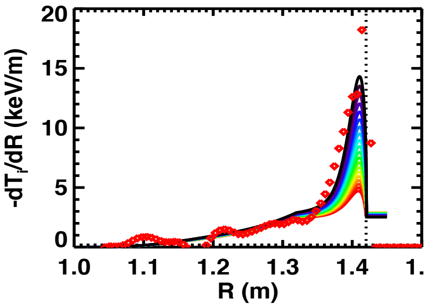


Summary: Recent analysis advances the understanding of EP H-mode on NSTX

- Neoclassical transport: small changes in density can result in large changes in ∇T_i at low density
  - Core T_i sensitive to edge ∇T_i
- A transient period during an ELM recovery can trigger a positive feedback mechanism at low edge density
  - Reduction in impurity pinch with lower collisionality, larger $\nabla T_i/T_i$
  - Reduction in electron transport with larger $\nabla T_i/T_i$







Ongoing and future work

- What neoclassical physics must be included to quantitatively describe observed ∇T_i?
  - Investigating with different codes, datasets and assumptions

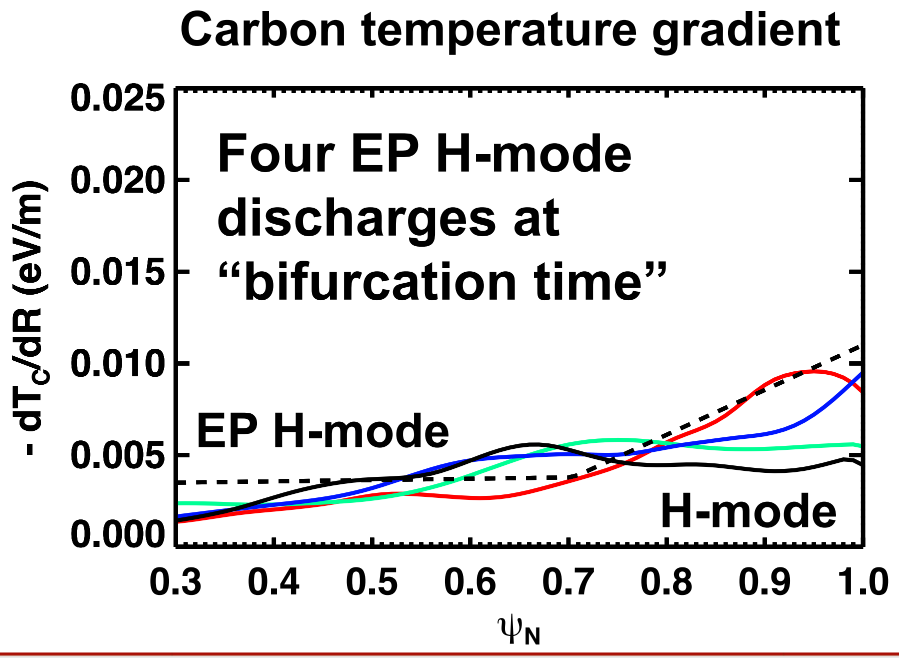
- Develop a time-dependent model that demonstrates positive feedback during ELM recovery
  - TRANSP and XGC0 are proposed tools
  - Are there requirements on the nature of the ELMs and/or the ELM recovery?

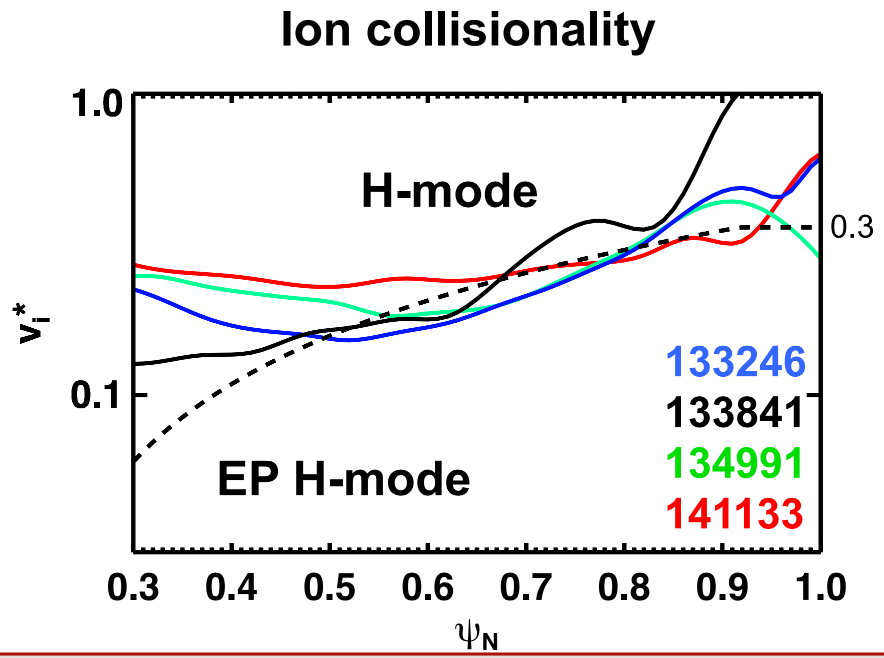
- Why NSTX? How does EP H-mode scale to other regimes?
  - NSTX had edge density control and ELM-free H-modes (unique for STs)
  - ST has wide pedestal that is ITG stable (neo thermal transport valid well inside separatrix)
  - DIII-D, JET observed VH-mode which is very similar to EP H-mode
  - Simple 1D model for NSTX-U: T_i gradients don't really scale larger if electron transport is unchanged

Backup

Ion collisionality may be the critical parameter

- Selective analysis of H-mode and EP H-mode discharges suggests a critical ion collisionality

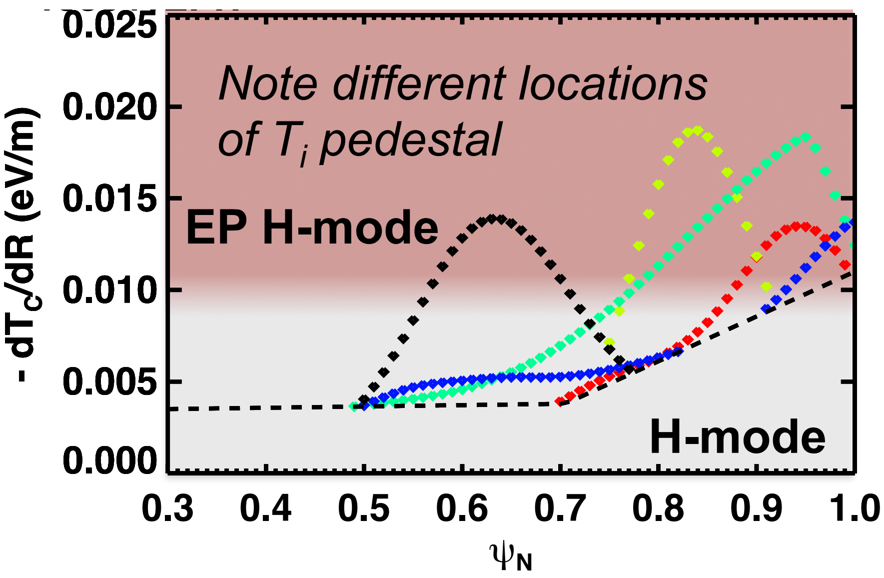




Ion collisionality may be the critical parameter

- Selective analysis of H-mode and EP H-mode discharges suggests a critical ion collisionality

Carbon temperature gradient



Ion collisionality