Enhanced Pedestal H-mode Regime on NSTX

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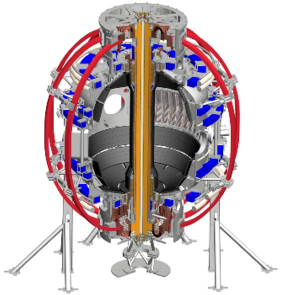
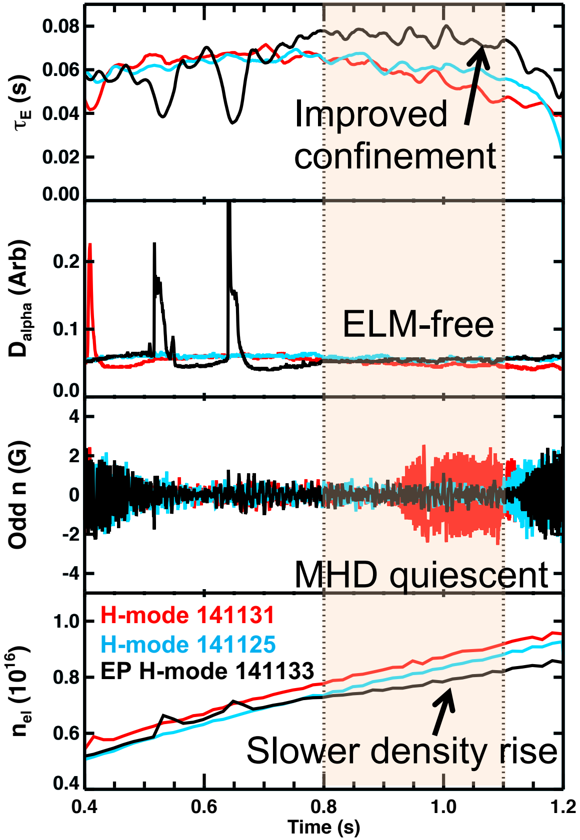


Enhanced Pedestal (EP) H-mode: ELM-free with improved τ_E and reduced particle confinement

- ELM-free H-modes are attractive scenarios provided suitable particle transport is achieved
- EP H-mode on NSTX achieves larger τ_E and particle transport compared to ELM-free H-mode
  - Often observed after a large ELM
  - Sustained without ELMs and large MHD activity
  - $H_{98y,2}$ ~ 1.2 – 2 with largest gains in ion stored energy
- Observed over a wide range of shapes, I_p, B_T, q_{95}, P_{NBI}
  - Requires reduced neutral fueling and large wall pumping
  - About 50 EP H-mode discharges identified

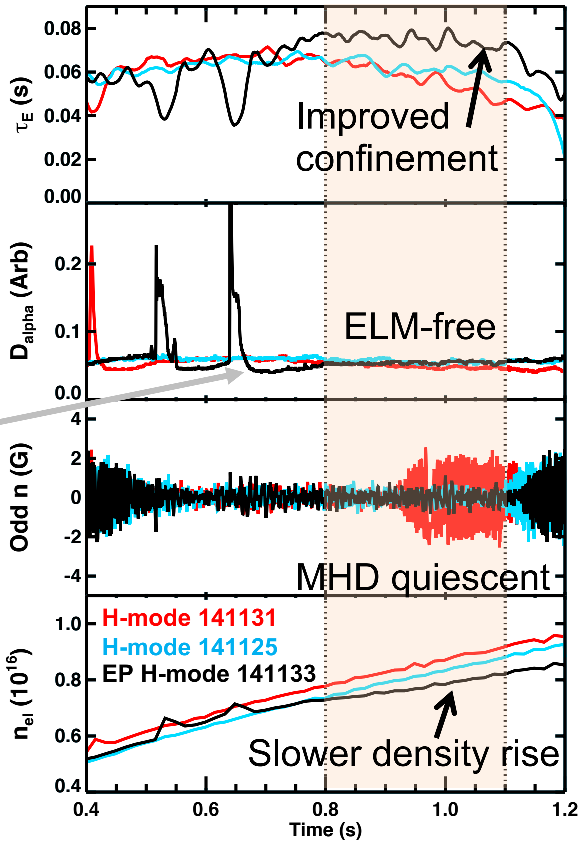


R. Maingi et al., J. Nucl. Mat. 390-1, 440-3 (2009)
R. Maingi et al., PRL 105, 135004 (2010)
S. Gerhardt et al., NF 54, 083021 (2014)

Enhanced Pedestal (EP) H-mode: ELM-free with improved τ_E and reduced particle confinement

This talk aims to show…

- Positive feedback in the pedestal transport and stability can occur at low ion collisionality
  - Sufficiently low pedestal collisionality is achieved on NSTX with reduced neutral fueling
- Reduced neutral recycling during the ELM recovery can trigger the positive feedback
- EP H-mode occurs when …
  - An increase in the edge turbulent transport…
  - Reduces the edge density that …
  - Drives a significant decrease in the neoclassical ion thermal transport



Improved confinement

ELM-free

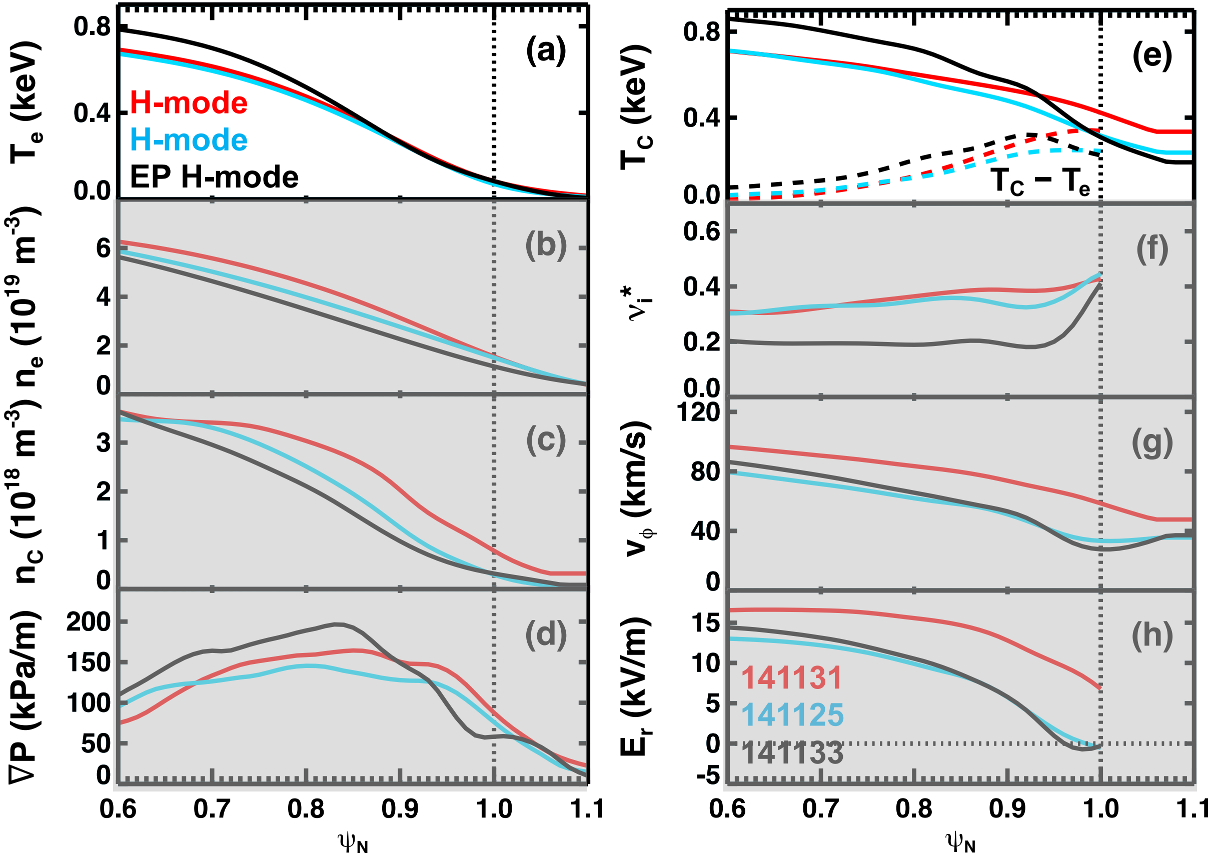
MHD quiescent

H-mode 141131
H-mode 141125
EP H-mode 141133

Slower density rise

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

- Larger ∇T_i
  - T_e pedestal can get wider and/or increase in gradient
  - $T_C - T_e$ increases
- Reduction in ∇n and density at edge
  - ∇P shifts inward, improving ELM stability
- Lower v_i^* due to lower n, larger T
- Larger ∇E_r and ∇v_ϕ and shifted inwards



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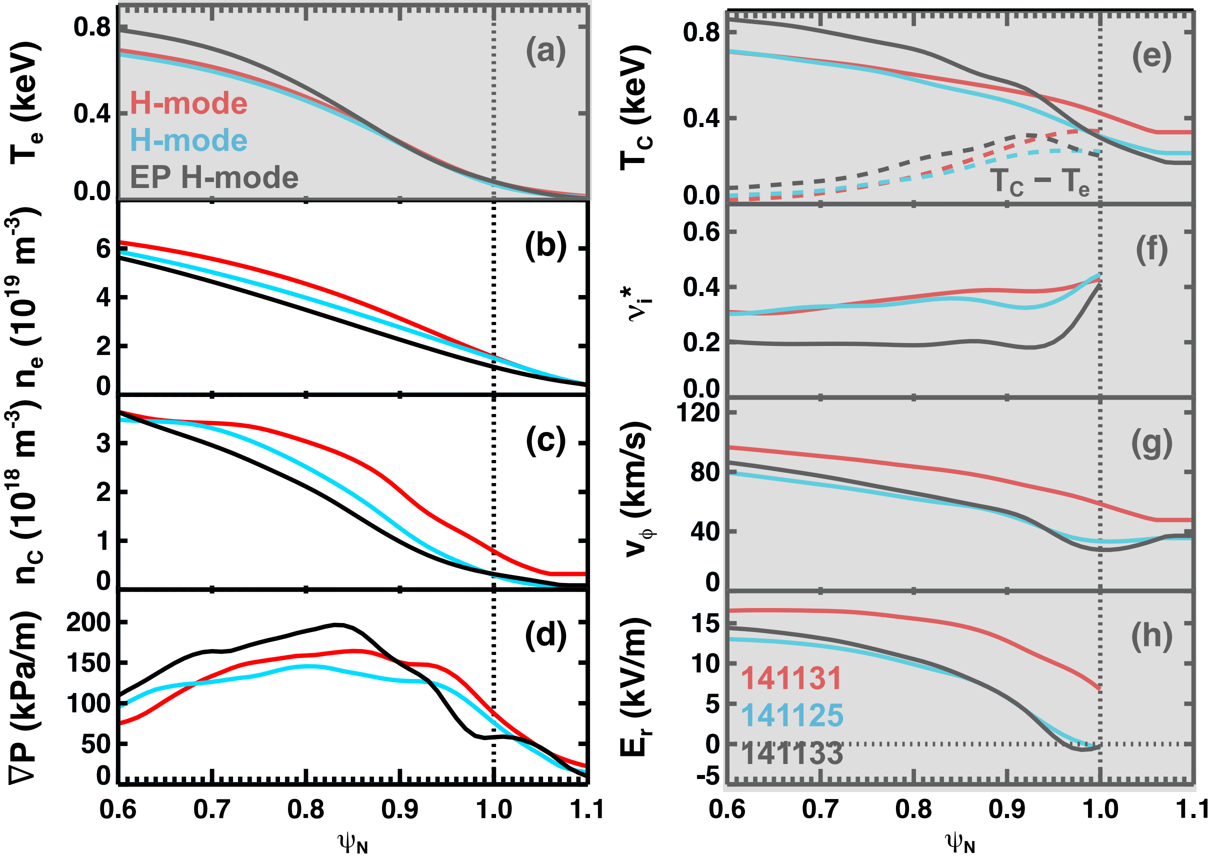

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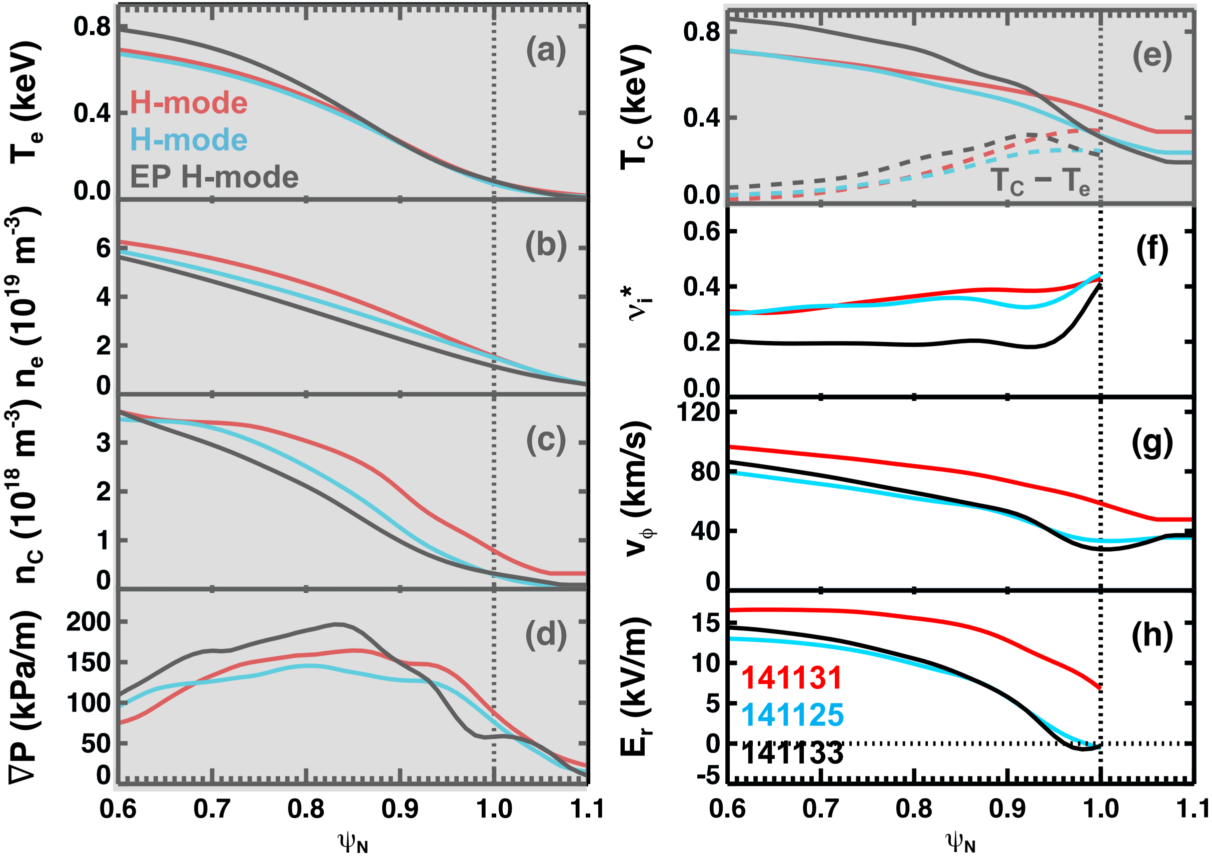


Larger ∇T_i in EP H-mode is consistent with neoclassical transport

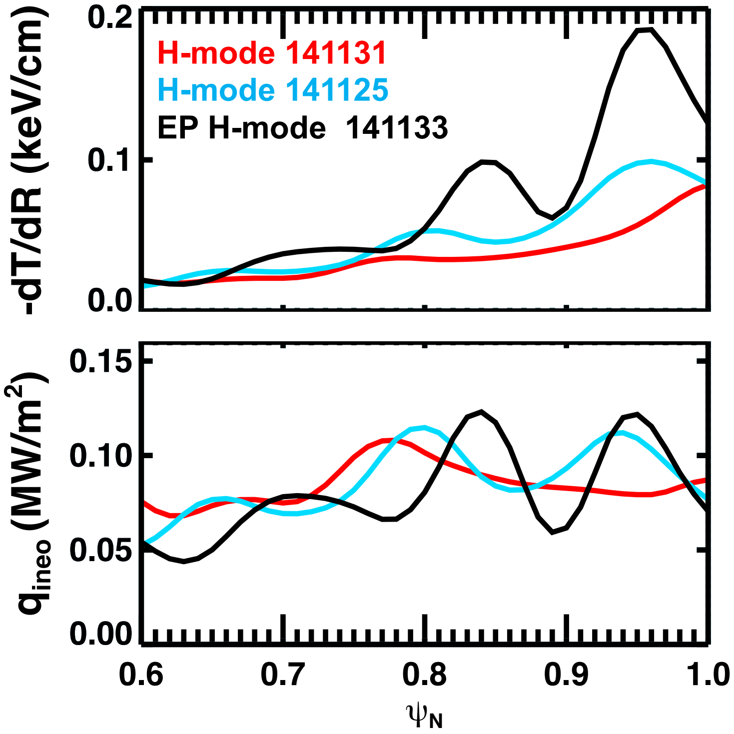
- Stabilization of ITG in high-rotation STs drives $\chi_i \rightarrow \chi_{i,neo}$
- Approximate banana regime main ion heat flux (Tokamaks, Wesson):

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

$$q_i \sim \frac{-Z_{eff} n_e n_i}{I_p^2 \sqrt{T_i}} \frac{dT_i}{dr}$$

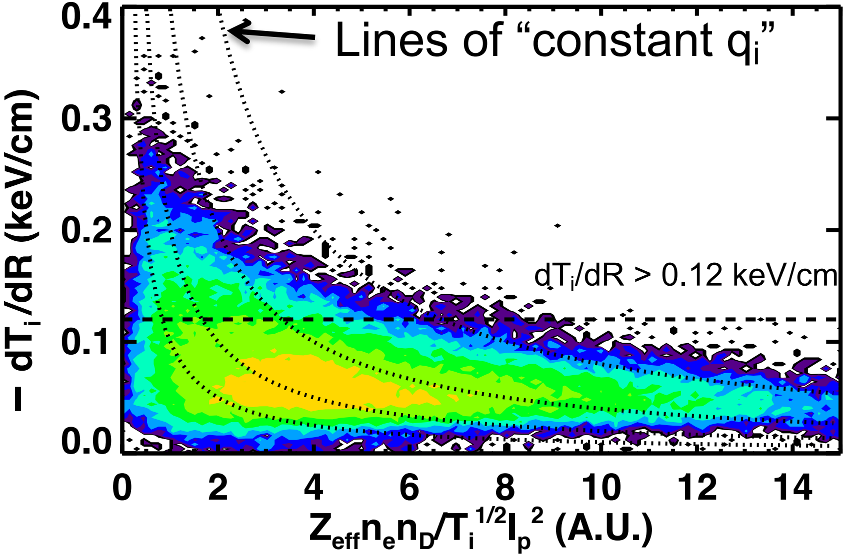
(Constant shape)

- ∇T_i increases as density decreases at constant $q_{i,neo}$



Database illustrates largest $-\nabla T_i$ achieved when neoclassical transport expected to be small

- Database of all NSTX CHERS profiles with $P_{NBI} > 2$ MW
  - Identify max $-\nabla T_{i,ped}$ for each profile
  - Each color represents factor 2 increase in database entries
- Rapid rise in ∇T_i at low density, high I_p at constant q_i
  - 10% of database entries satisfy typical EP H-mode designation



$$-\frac{dT_i}{dr}\sim q_i\left(\frac{Z_{eff}n_en_i}{I_p^2\sqrt{T_i}}\right)^{-1}$$

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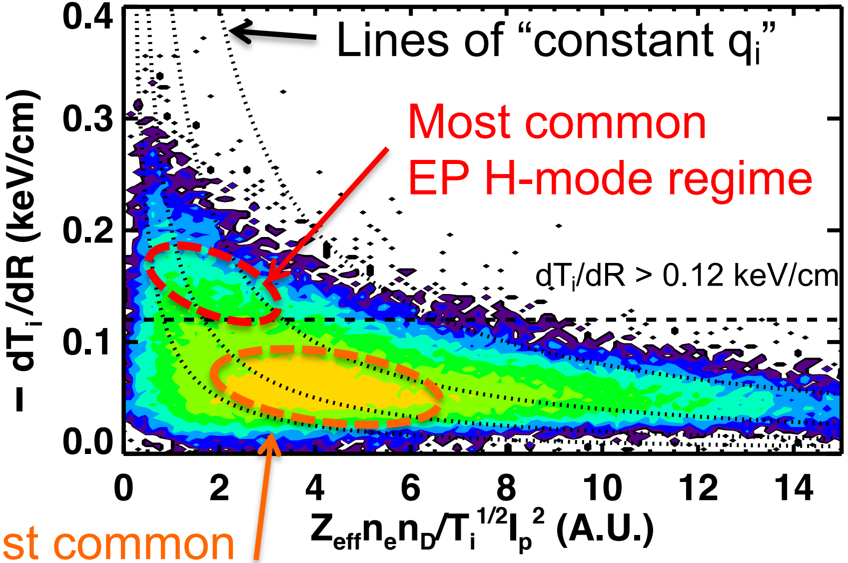


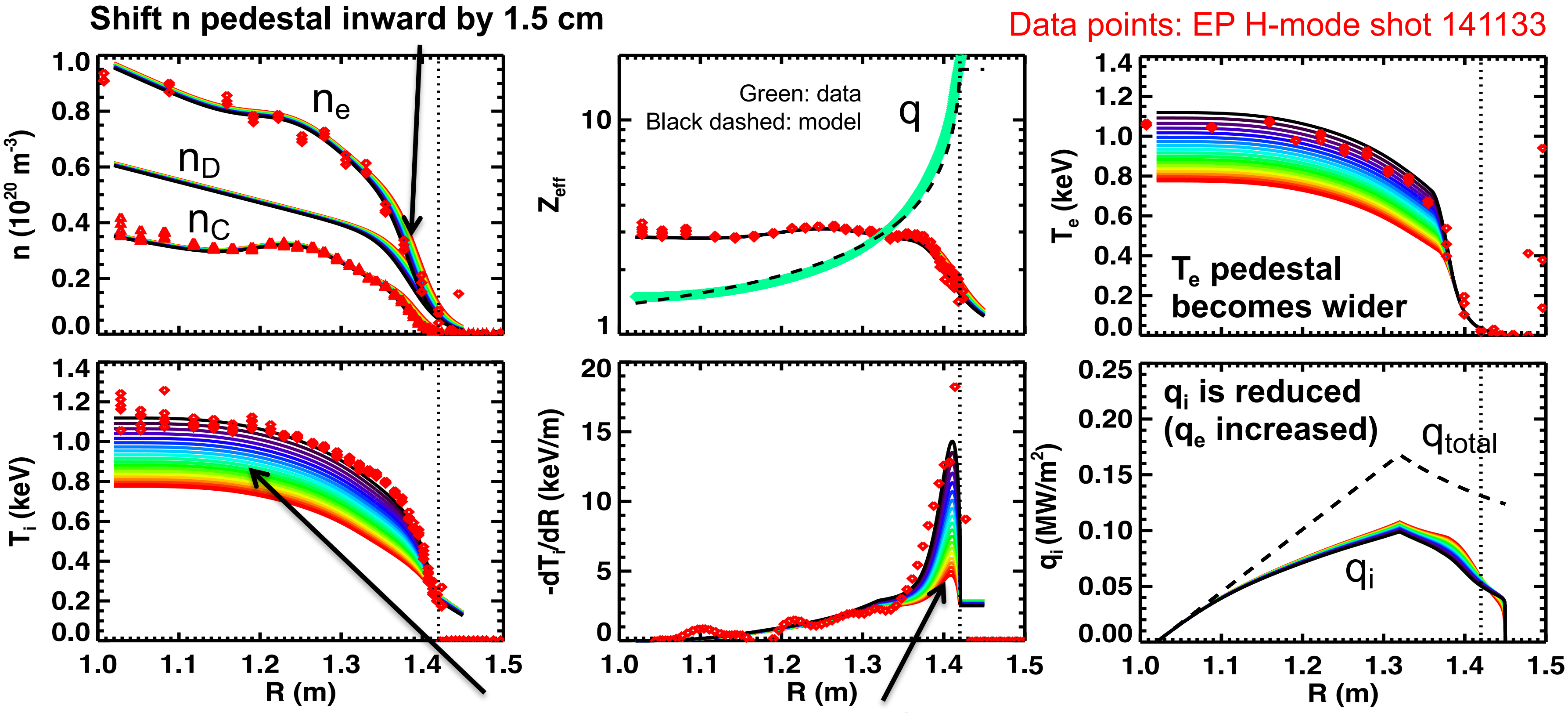
Most common H-mode regime

$$-\frac{dT_i}{dr} \sim q_i \left(\frac{Z_{eff} n_e n_i}{I_p^2 \sqrt{T_i}} \right)^{-1}$$

1-D transport model illustrates large impact edge density has on T_i profile when $\chi_{i,neo} >> \chi_{i,anom}$

Shift n pedestal inward by 1.5 cm

Data points: EP H-mode shot 141133



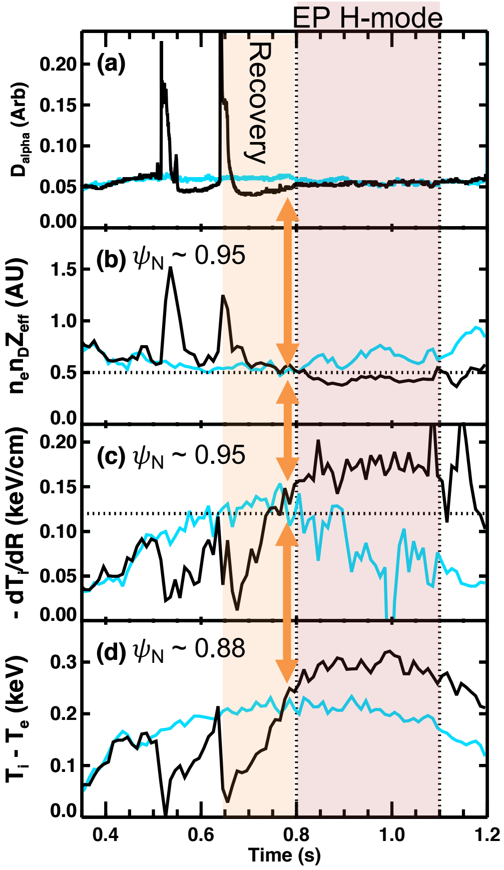
Big change in core T_i and edge dT_i/dR

Hypothesis: Lower neutral fueling during ELM recovery can trigger positive feedback at low collisionality

Increase in $\nabla T_{i,edge}$ ($\chi_{i,neo} > \chi_{i,anom}$)

Increase in $T_i > T_e$ in core

Reduction in recycling during ELM recovery can reduce edge density, slow impurity pinch and reduce CX losses



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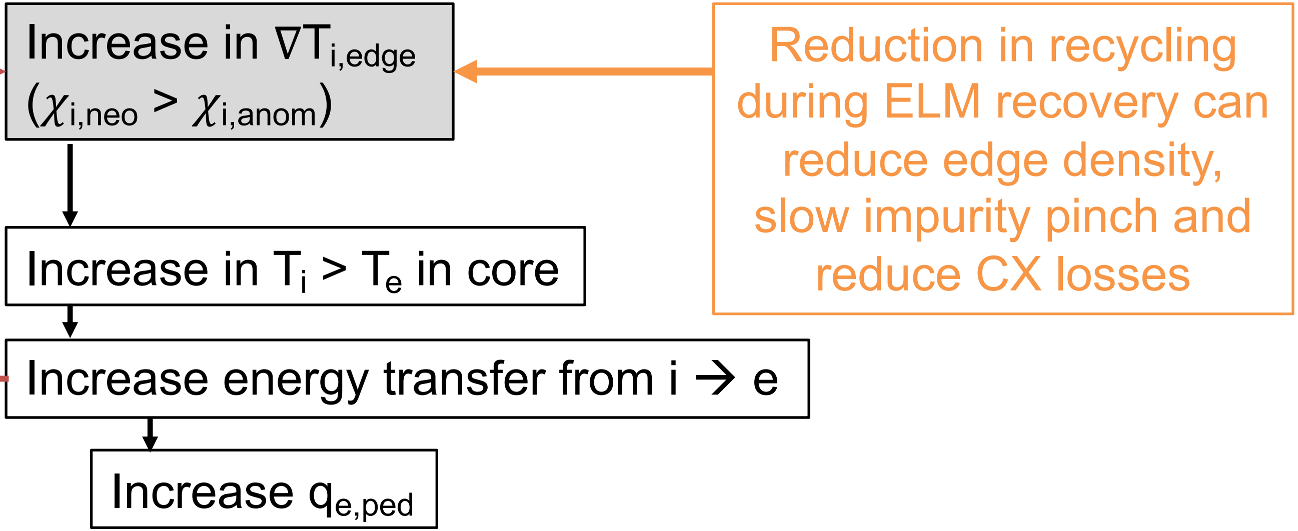

Increase in $\nabla T_{i,edge}$ ($\chi_{i,neo} > \chi_{i,anom}$)

Increase in $T_i > T_e$ in core

Increase energy transfer from i → e

Increase $q_{e,ped}$

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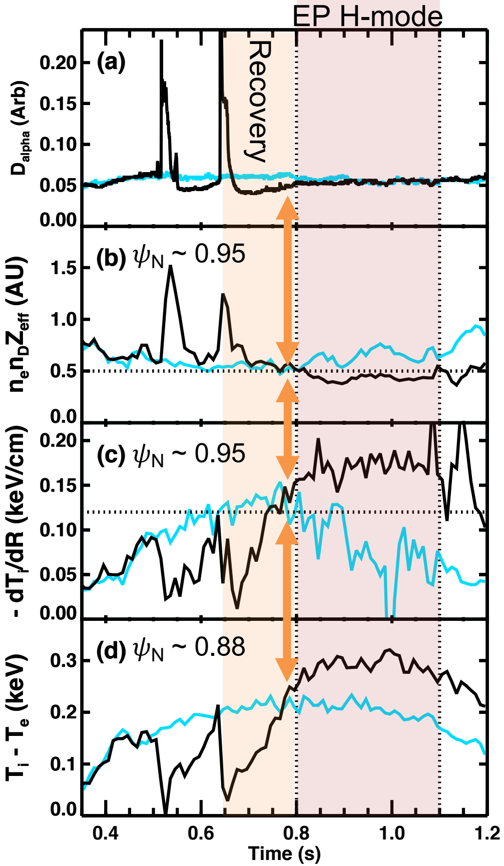

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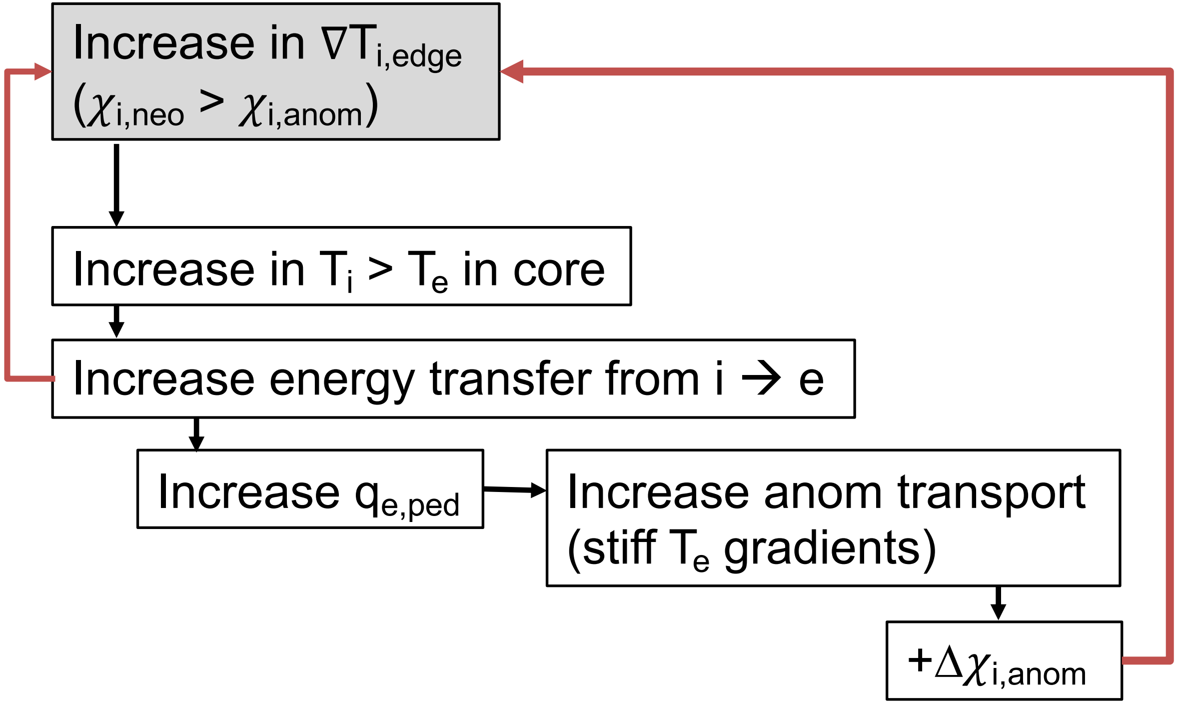


Increase in $\nabla T_{i,edge}$ ($\chi_{i,neo} > \chi_{i,anom}$)

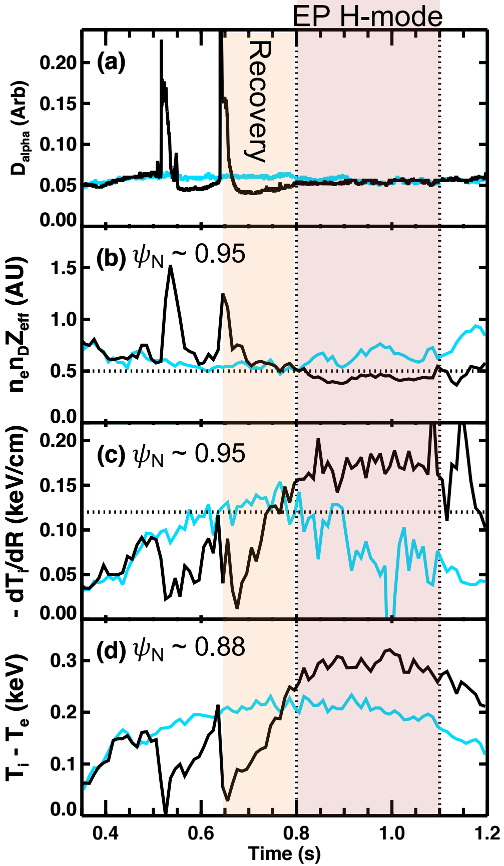
Increase in $T_i > T_e$ in core

Increase energy transfer from i → e

Increase $q_{e,ped}$

Increase anom transport (stiff T_e gradients)

$+\Delta\chi_{i,anom}$



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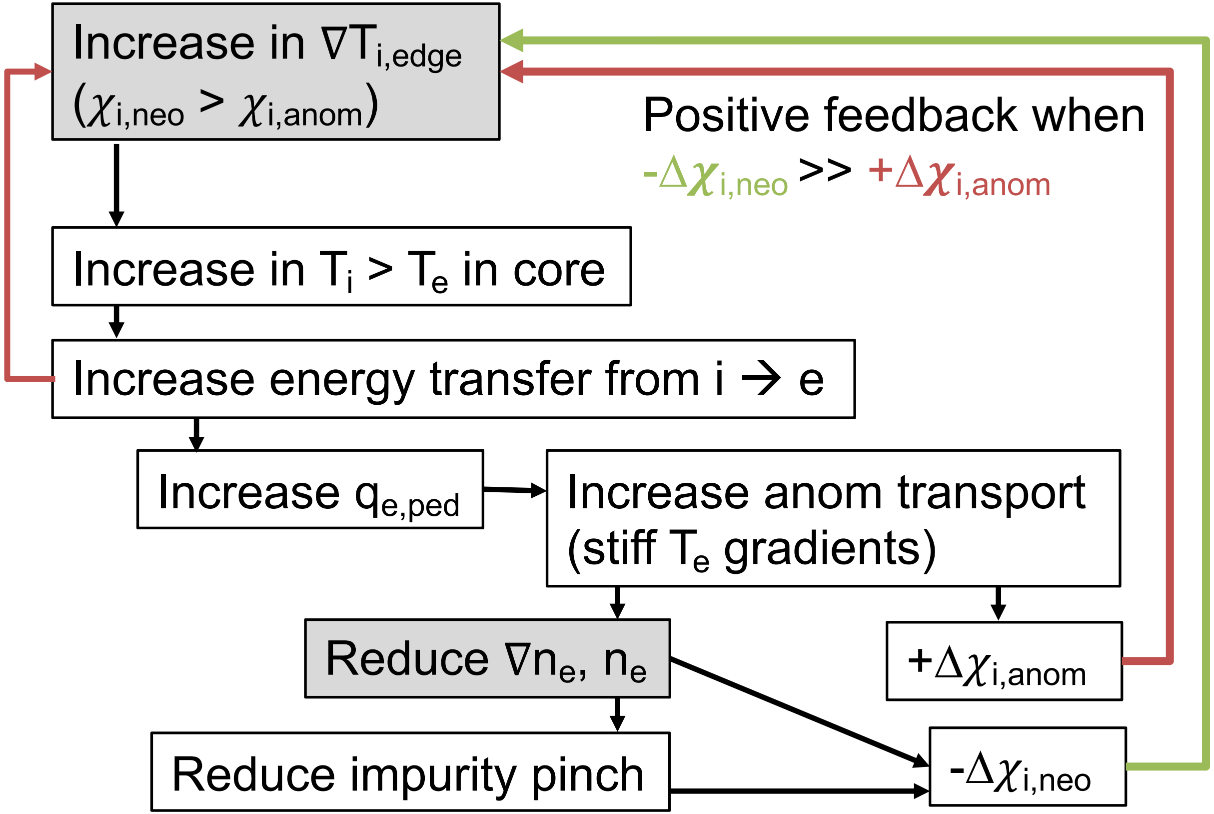


Increase in $\nabla T_{i,edge}$ ($\chi_{i,neo} > \chi_{i,anom}$)

Increase in $T_i > T_e$ in core

Increase energy transfer from i → e

Increase $q_{e,ped}$

Increase anom transport (stiff T_e gradients)

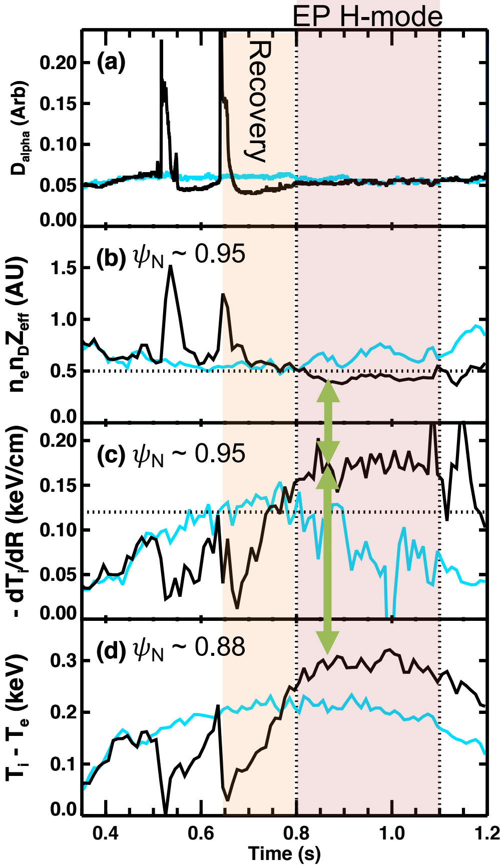
Reduce ∇n_e, n_e

$+\Delta\chi_{i,anom}$

Reduce impurity pinch

$-\Delta\chi_{i,neo}$

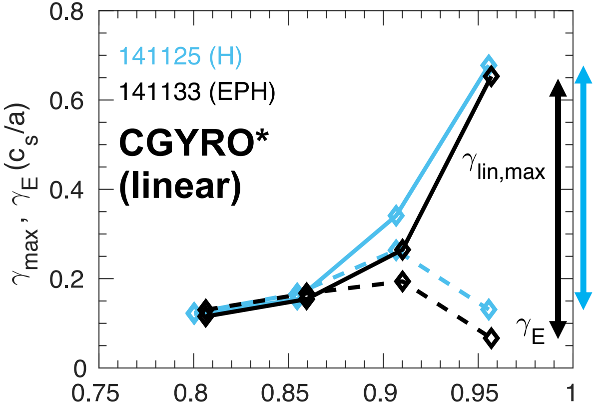
Positive feedback when $-\Delta\chi_{i,neo} >> +\Delta\chi_{i,anom}$



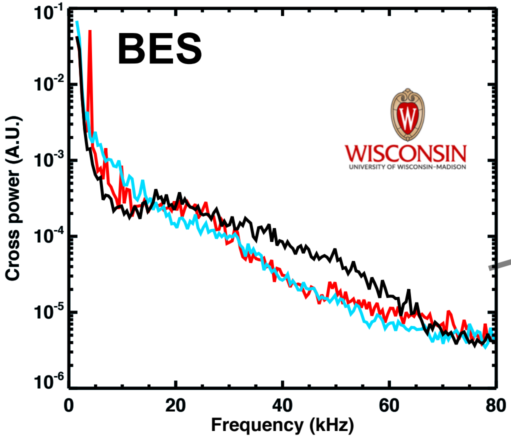
Ion-scale turbulence measurements and calculations indicate TEM drives transport at the pedestal foot

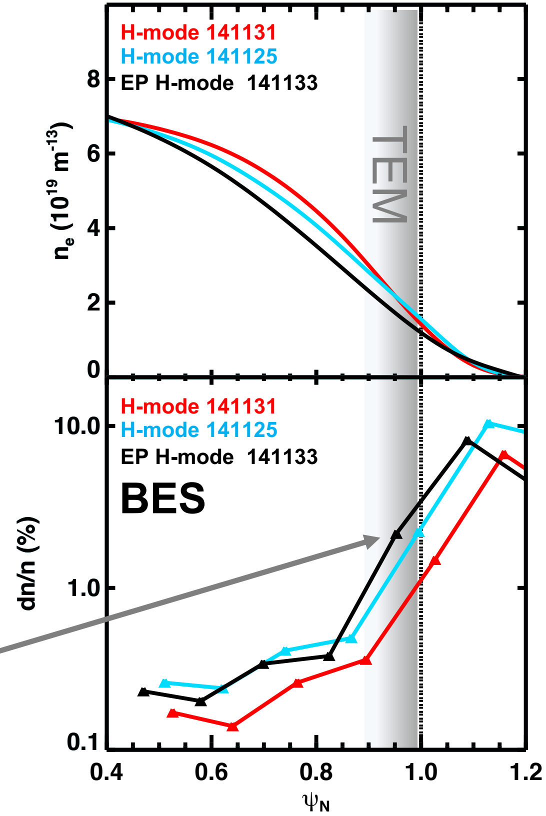
- Wide pedestal on NSTX: predominantly TEM driven by ∇T_e
  - Growth rates larger than E×B shearing rates (γ_E) for $\psi_N > 0.9$
  - Weak low-k_θ MTM at at top of pedestal

- BES fluctuation measurements and linear CGYRO calculations are similar for both H-mode and EP H-mode
  - Ion-scale fluctuations shift to higher frequency in large ∇T_i region
    - Qualitatively consistent with CGRYRO predicted $\Delta\omega_r$ due to larger ∇T_i



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





EP H-mode: Improved energy confinement and increased particle transport at low collisionality

- Accessed at low-collisionality where $\chi_{i,neo}$ is sensitive to small changes in density and Z_{eff}
  - EP H-mode occurs when edge anomalous transport increases, but reduction in $\chi_{i,neo}$ exceeds increase in $\chi_{i,anom}$

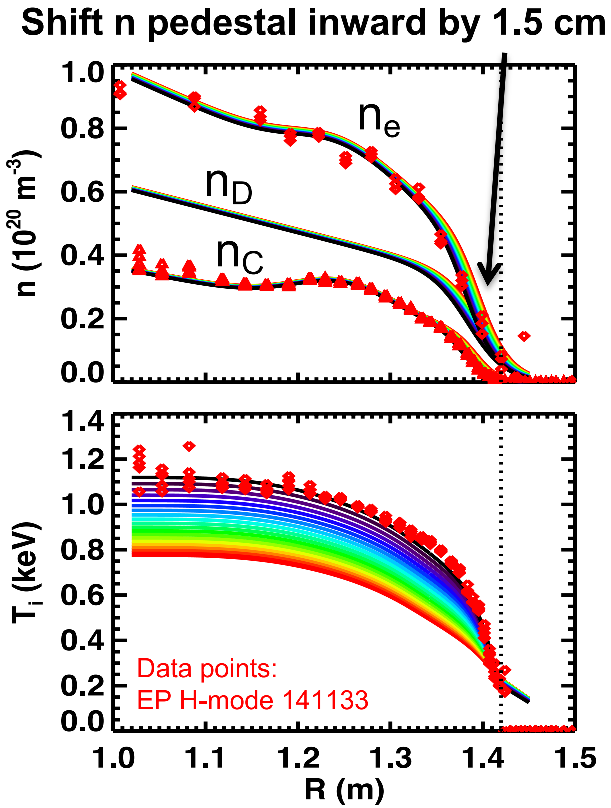
- Temporary reduction in neutral recycling during an ELM recovery can trigger EP H-mode

- Motivates edge density control that is compatible with $n/n_{GW} \rightarrow 1$ and heat flux mitigation
  - Baffled divertor in MAST-U, lithium research on NSTX-U
  - Increased field in Upgrade STs will access lower collisionality regimes

Backup

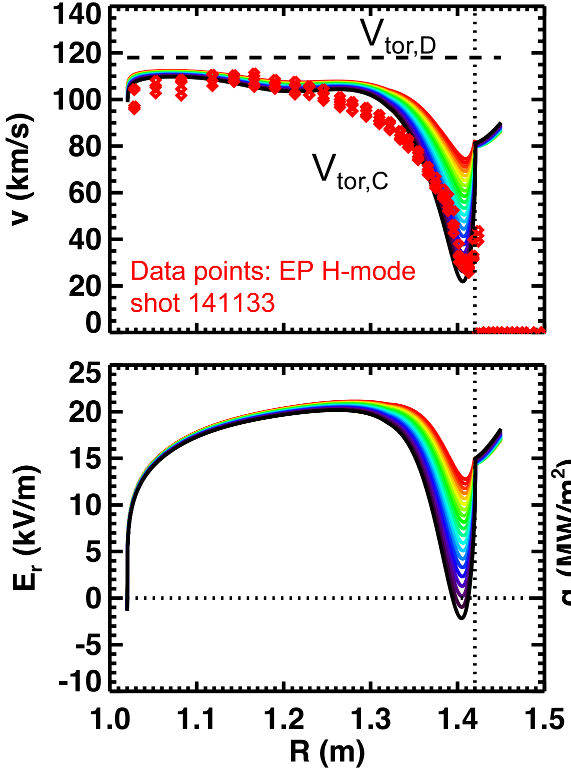
Reduced transport model illustrates large impact edge density has on T_i profile with $\chi_{i,neo} > \chi_{i,anom}$

- Reduced 1D transport model illustrates impact of density on energy confinement
  - Fixed geometry, q-profile & volumetric heating
  - Density profiles are an input
  - Neoclassical ion transport (Wesson)
  - Fixed T_{esep}
  - Fixed T_e gradient scale length when $T_e < T_i$
  - Fixed χ_e when $T_e = T_i$
  - Ion-electron coupling
  - Separatrix T_i proportional to q_i
- Small change in edge density, large change in edge ∇T_i and core T_i



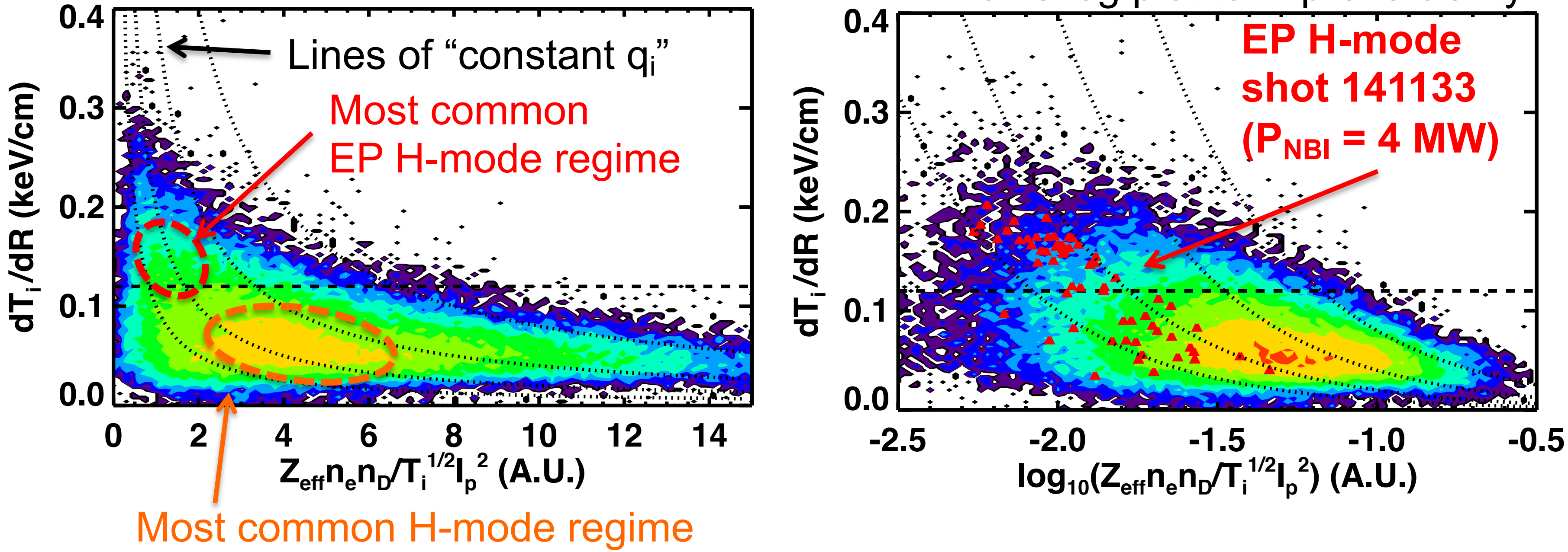
Differences in ion species v_{dia} may describe concurrent increase in ∇v_{ϕ} with ∇T_i

- 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}



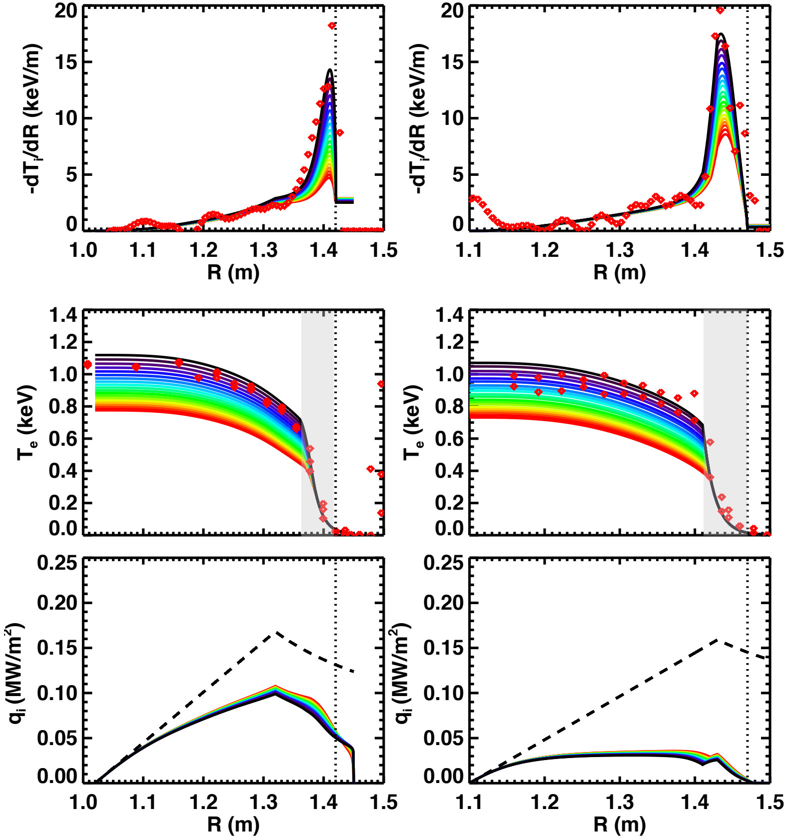
Edge gradients increase and location of maximum gradient shifts inward

Max -∇T_i increases at decreasing density and increasing I_p, consistent with neo model



$$-\frac{dT_i}{dr} \sim q_i \left(\frac{Z_{eff} n_e n_i}{I_p^2 \sqrt{T_i}} \right)^{-1}$$

Position of max -∇T_i in model sensitive to the T_e profile



Two EP H-mode discharges

141133 (left):

max -∇T_i is near separatrix

141340 (right):

max -∇T_i is 4 cm inside separatrix

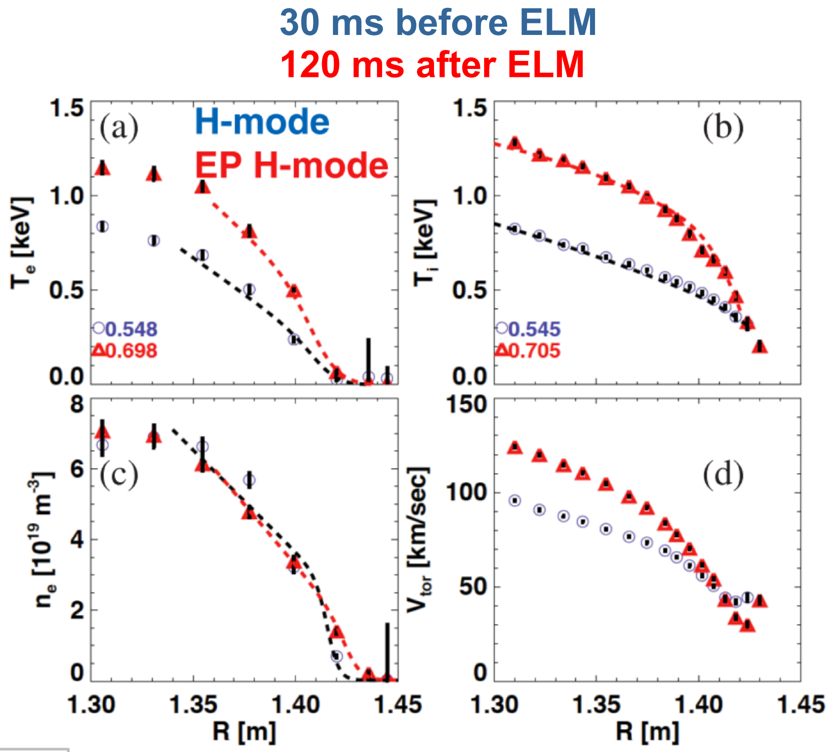
Top of T_e pedestal shifted inward compared to 141133

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

Characteristics of EP H-mode

- 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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