NSTX-U

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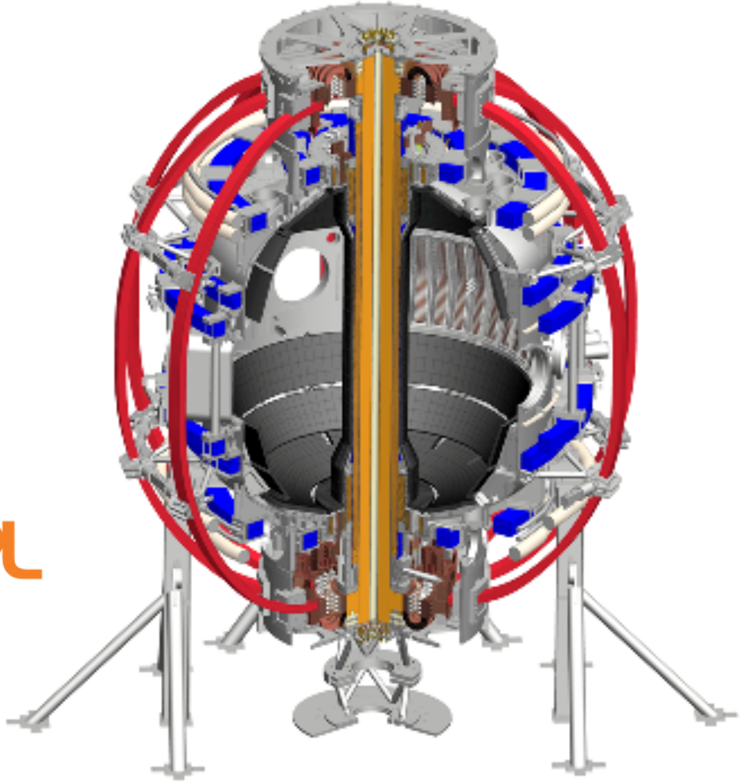
Enhanced Pedestal H-mode Regime on NSTX

D.J. Battaglia,

W. Guttenfelder, R.E. Bell, S.P. Gerhardt, S.M. Kaye, R. Maingi and D.R. Smith



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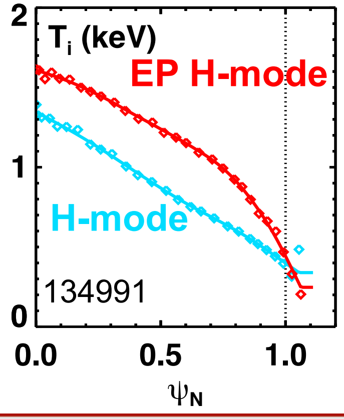
Largest normalized confinement on NSTX achieved in the Enhanced Pedestal (EP) H-mode regime

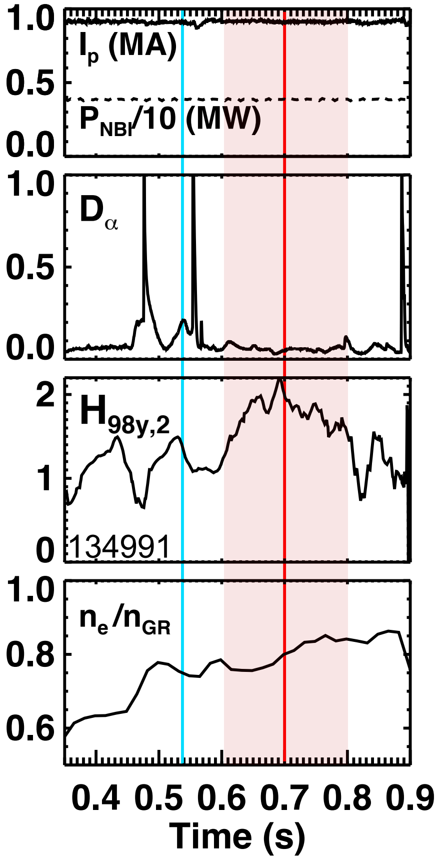
- Steady-state compact tokamak concepts require large normalized confinement
  - CFPP target: $H_{98y,2}$ > 1.5 with small or no ELMs

B. N. Sorbom et al. Fusion Eng. Des. 100, 37 (2015)
J. E. Menard et al. Nucl. Fusion 56, 106023 (2016)
R.J. Buttery et al. 46th EPS Conference (2019)

- EP H-mode is an ELM-free regime on NSTX
  - Often following a large ELM
  - Slower density rise compared to standard ELM-free regimes
  - Defining feature is large edge ∇T_i

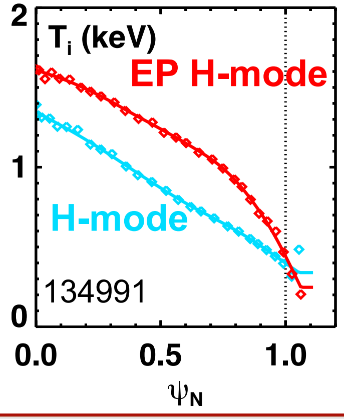
R. Maingi et al., J. Nucl. Mat. 390-1, 440-3 (2009)
R. Maingi et al., PRL 105, 135004 (2010)
S. Gerhardt et al., NF 54, 083021 (2014)

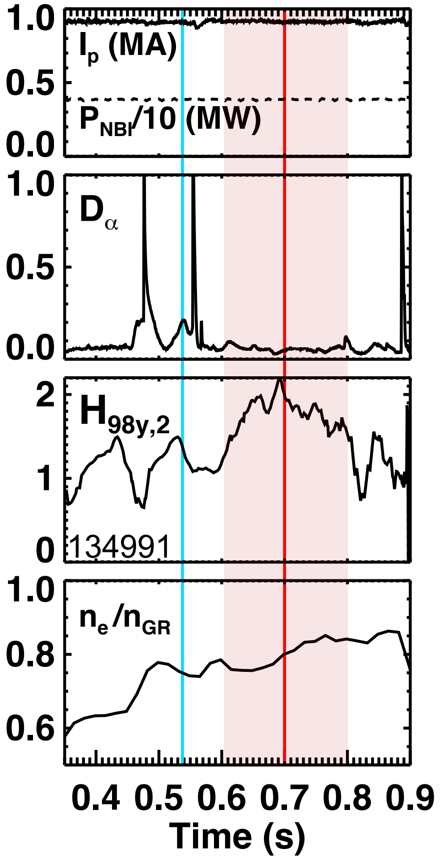




This talk aims to show …

- EP H-mode occurs in conditions that achieve low edge ion collisionality
- Enhanced edge ∇T_i consistent with neoclassical scaling
- Temporary reduction of neutral fueling during the ELM recovery can lead to a new pedestal state





Outline

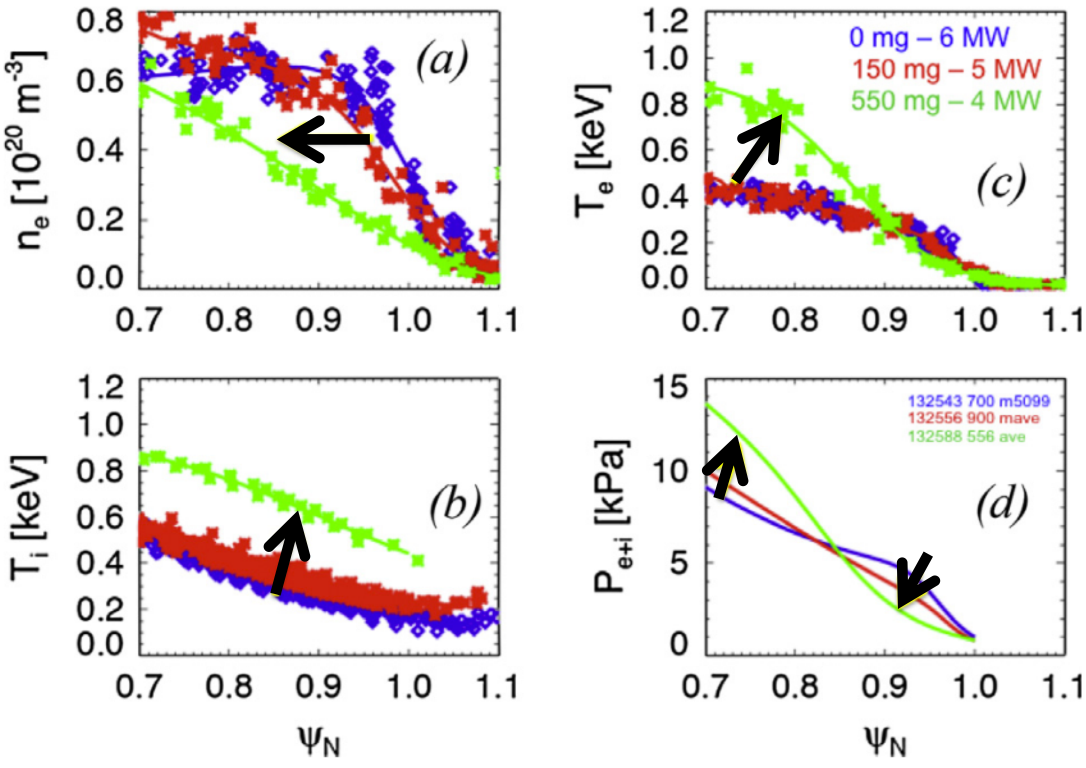
- Characteristics of EP H-mode
- Enhanced edge ∇T_i consistent with neoclassical scaling
- Role of ELM and turbulent transport in establishing lower edge collisionality

NSTX achieved wide pedestal H-mode via reduction in recycling with lithium wall coatings

- Reduction in recycling changes ∇n_e
  - Increase in χ_e at bottom of pedestal, decrease at top
  - Improved confinement in ELM-free regime

J. M. Canik, et al. Nucl. Fusion 53 (2013)
R. Maingi, et al. Phys. Rev. Lett. 103 (2009)
M. Coury et al. Phys. Plasmas 23 (2016)

	P_{NBI}	Lithium
ELMy H-mode	6 MW	0 mg
ELM-free H-mode	5 MW	150 mg
Wide ped. H-mode	4 MW	550 mg



R. Maingi, et al. J. Nucl. Mater. 463 (2015)

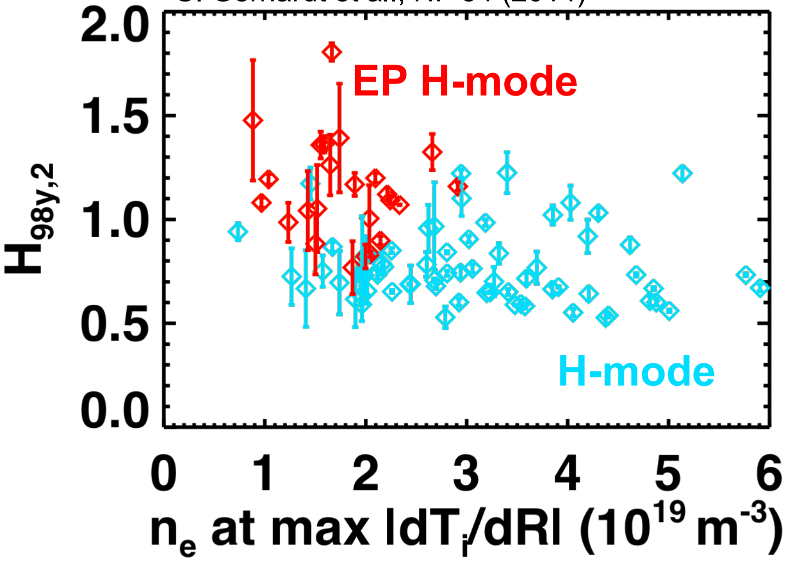
EP H-mode occurs in conditions that achieve the lowest edge density

- EP H-mode observed over a wide range of shapes, I_p, B_T, q_{95}, P_{NBI}, 3D fields, lithium conditioning

- Common feature is reduced edge density using …
  - The super-sonic gas injector, or …
  - Extra thick lithium coating, or …
  - Impurity control via boronization, triggered ELMs or 3D fields, or …
  - Operations following helium experiments

- Largest $H_{98y,2}$ observed with q_{95} ~ 8 - 10
  - EP H-mode limited by MHD at low q_{95} and global stability at high q_{95}

Adapted from
S. Gerhardt et al., NF 54 (2014)



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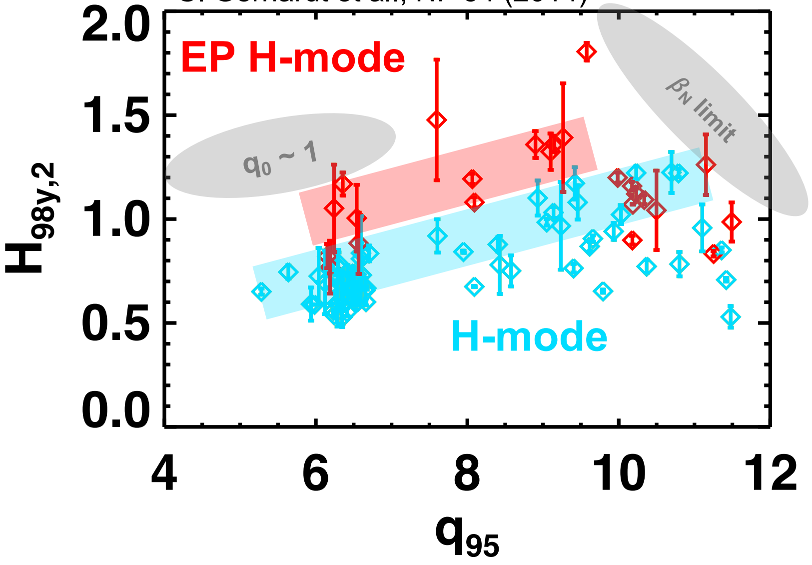


Outline

- Characteristics of EP H-mode
- **Enhanced edge ∇T_i consistent with neoclassical scaling**
- Role of ELM and turbulent transport in establishing lower edge collisionality

Ion thermal transport is typically consistent with neoclassical predictions for H-modes on NSTX

- ITG stabilized by high-β and large Shafranov shift
  - Independent of the rotation and E × B shear
  - Supported by NSTX observations where inferred $\chi_\mathrm{i} \approx \chi_\mathrm{i,neo}$
  - Consistent with ion-scale turbulence core calculations showing $\chi_\mathrm{i,neo} \gg \chi_\mathrm{i,anom}$ for typical collisionality regime on NSTX
  - Wide orbits in STs enhance neoclassical transport

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

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

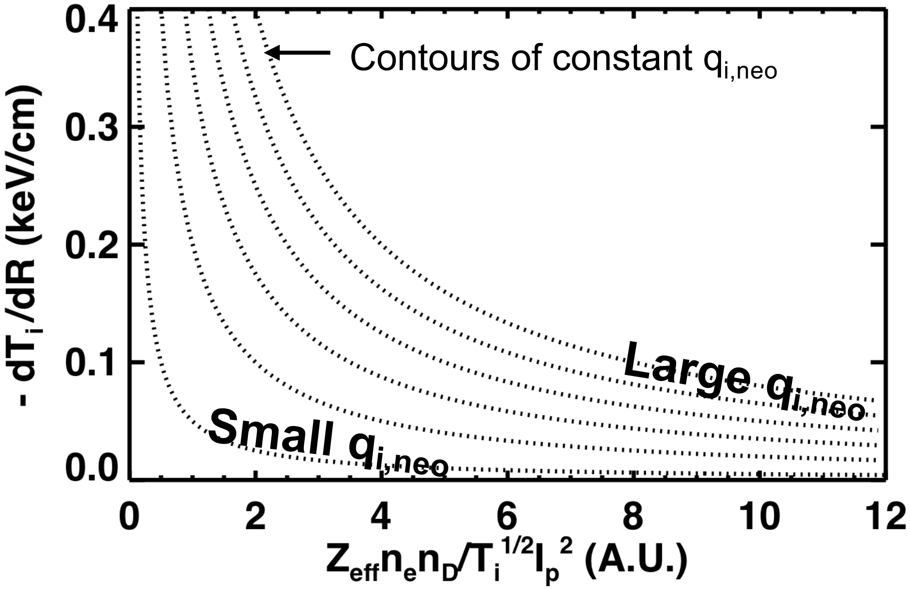
$$-\frac{dT_i}{dr} \sim q_{i,neo} \left(\frac{I_p^2 \sqrt{T_i}}{Z_{eff} n_e n_i} \right)$$

Constant shape

- ∇T_i increases inversely with density at constant $q_{i,neo}$

$-\nabla T_i$ expected to increase rapidly at low density with constant $q_{i,neo}$

- Rapid rise in ∇T_i as density and Z_{eff} decrease to low values



$$-\frac{dT_i}{dR}\frac{Z_{eff}n_en_i}{I_p^2\sqrt{T_i}} \sim q_{i,neo}$$

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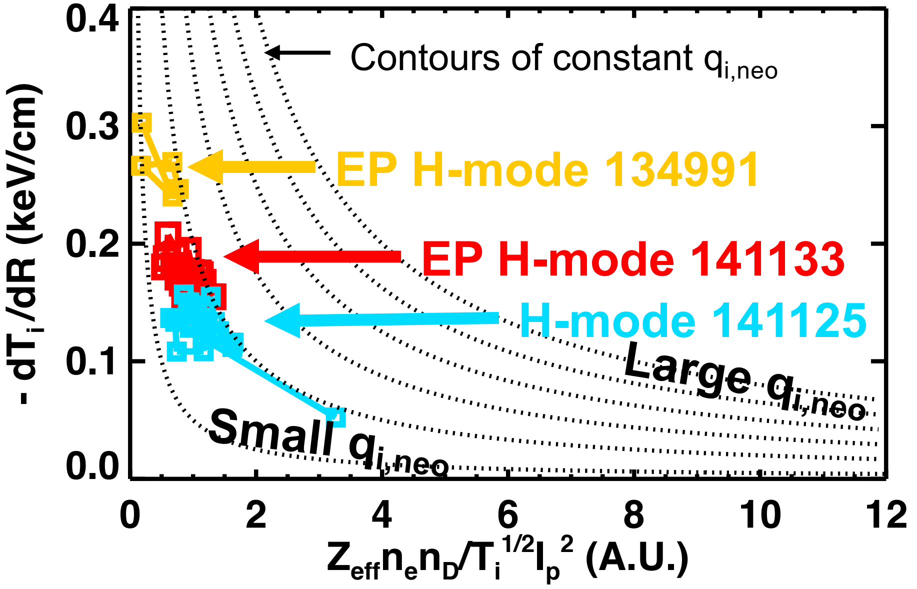
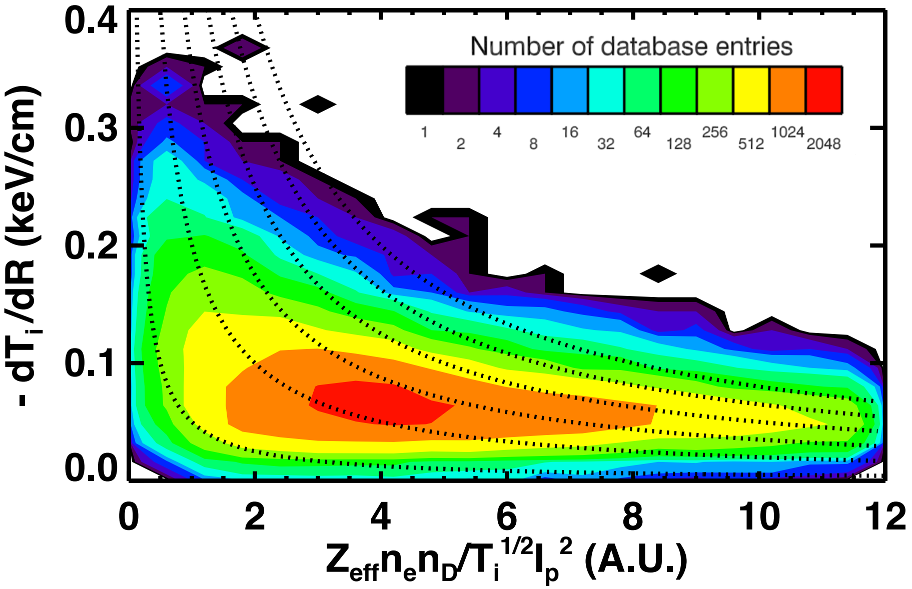


$$-\frac{dT_i}{dR}\frac{Z_{eff}n_e n_i}{I_p^2\sqrt{T_i}} \sim q_{i,neo}$$

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

- Rapid rise in ∇T_i as density and Z_{eff} decrease to low values
- Database of all NSTX CHERS profiles with P_{NBI} > 2 MW
  - Identify max $-\nabla T_i$ for each profile in edge region
  - Colors represent number of database entries



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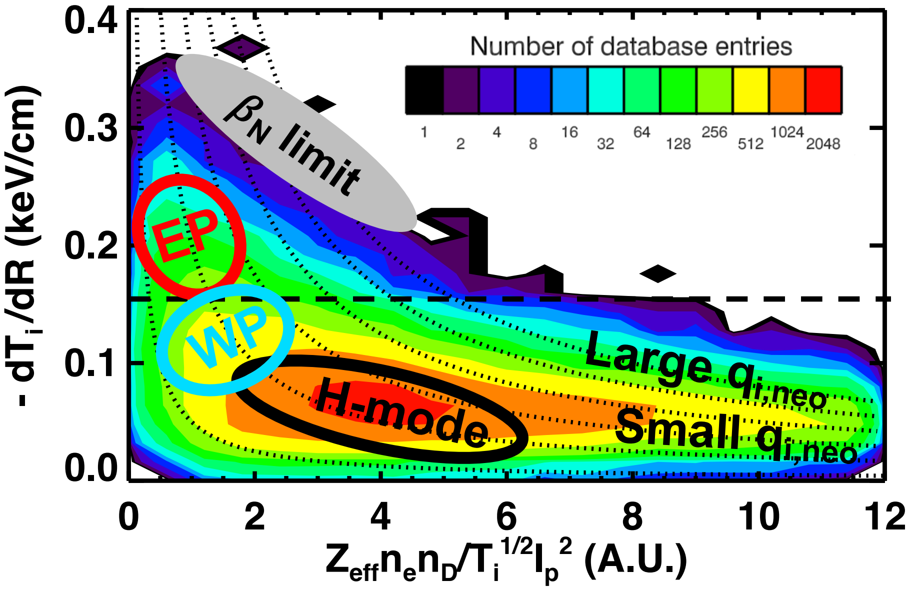
- Largest ∇T_i achieved at lower P_{NBI} (lower $q_{i,neo}$) and n_e
  - Remain below global stability limit



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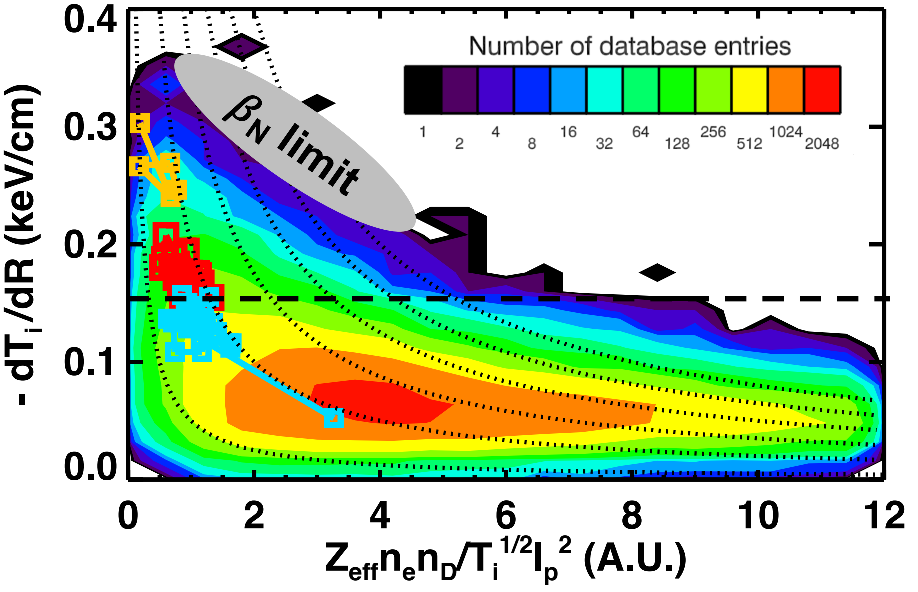
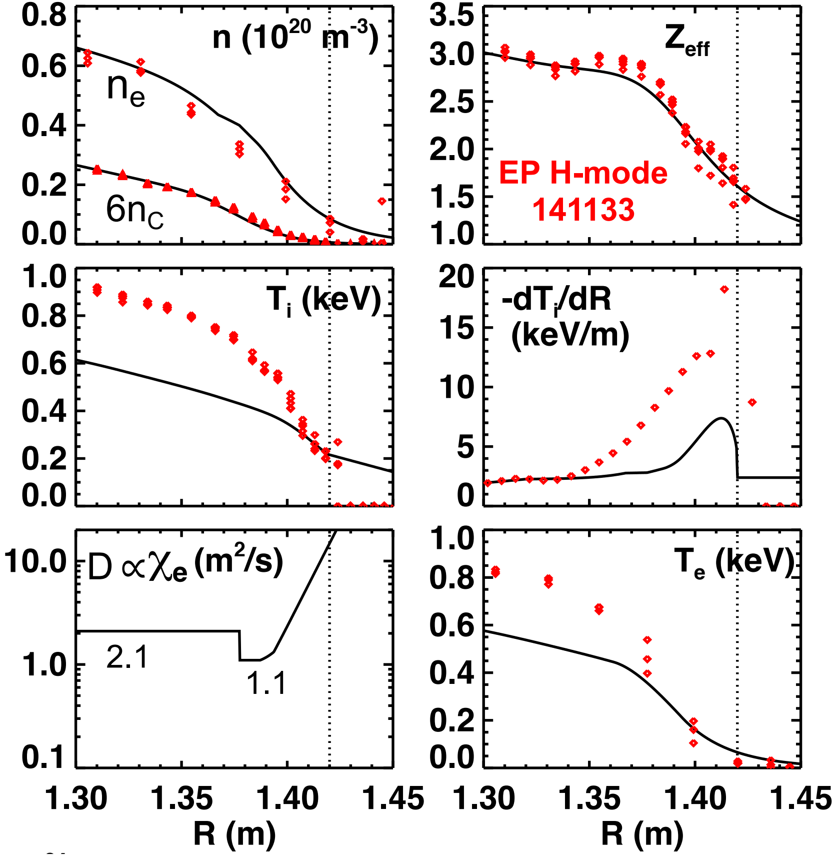


$$-\frac{dT_i}{dR}\frac{Z_{eff}n_e n_i}{I_p^2\sqrt{T_i}} \sim q_{i,neo}$$

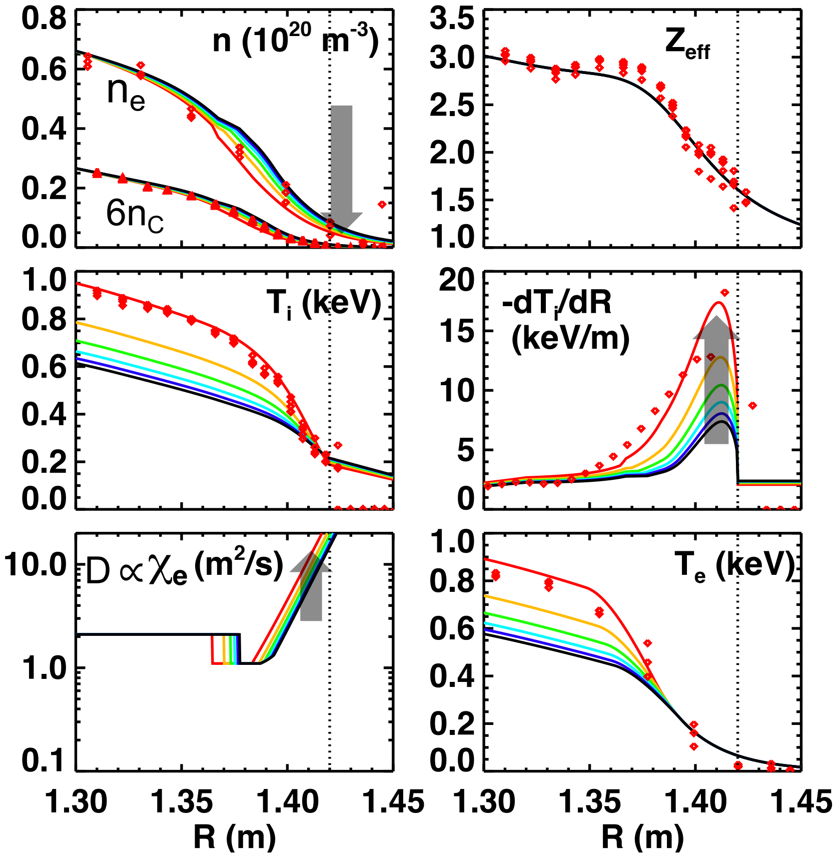
Simple model solving coupled particle and energy transport captures sensitivity to edge density

- Fixed heating profile, electron source rate profile, Z_{eff}, n_{el}, $T_{e,sep}$
  - Fixed $\nabla T_e/T_e$ from separatrix up to when χ_e reaches a minimum
  - Min χ_e = 2.1 (core) and 1.1 (edge)
  - Core: T_e/T_i = 0.94
- D profile $\propto \chi_e$ profile
- $q_{i,neo}$ (Wesson)
  - $T_{i,sep} \propto q_{i,sep}$
- Find self-consistent profiles for given $n_{e,sep}$
  - Particle source scaled to maintain constant line-averaged density

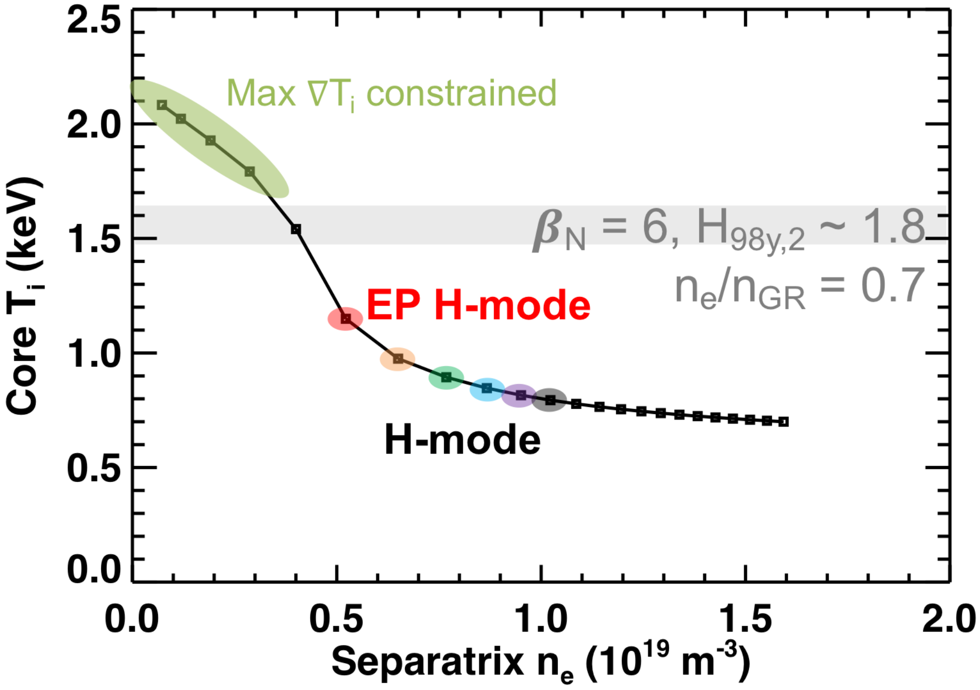


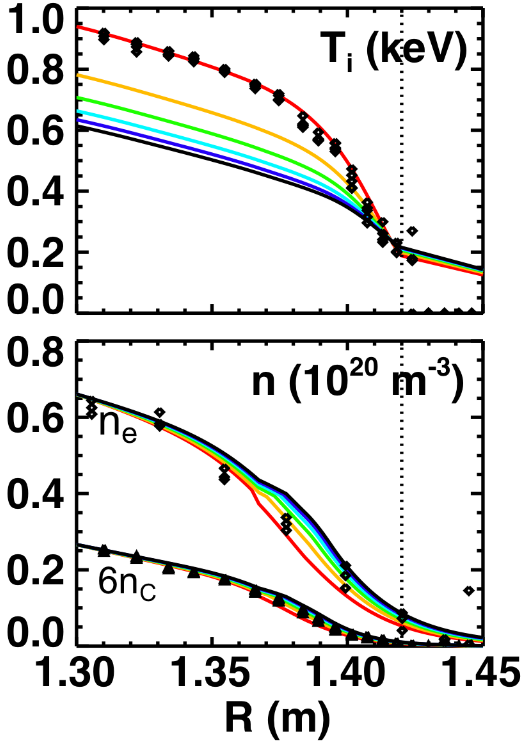
Simple model solving coupled particle and energy transport captures sensitivity to edge density

- $n_{e,sep}$ decreases black → red
- Edge ∇T_i increases rapidly with small changes in n_e
  - Leads to large change in core T_i
- Edge χ_e increases to maintain Q_e at lower n_e with fixed ∇T_e
  - Increased D_e reduces n_e gradient
  - Amplifies sensitivity to $n_{e,sep}$



Simple model solving coupled particle and energy transport captures sensitivity to edge density





Outline

- Characteristics of EP H-mode
- Enhanced edge ∇T_i consistent with neoclassical scaling
- **Role of ELM and turbulent transport in establishing lower edge collisionality**

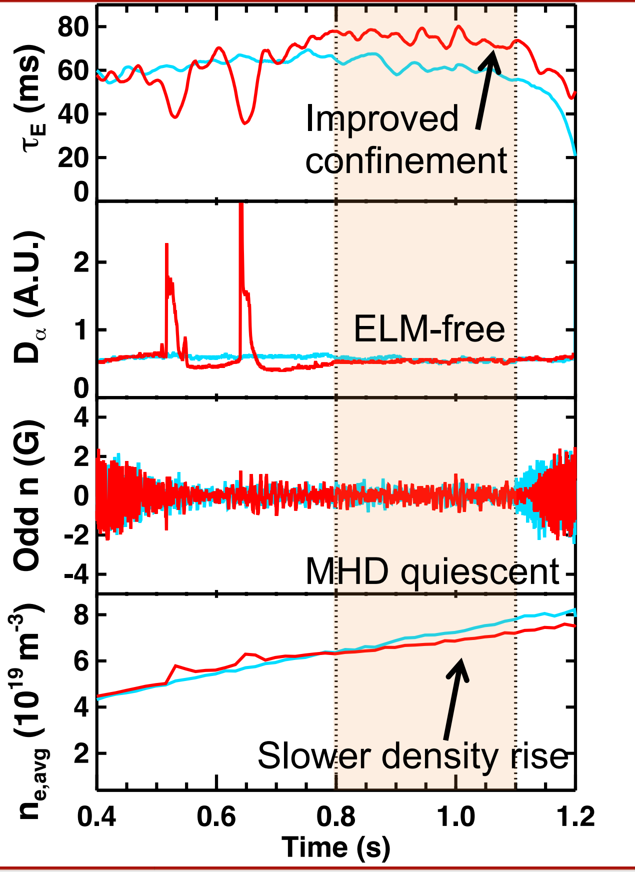
Matched discharges provide the opportunity to compare wide pedestal and EP H-mode regimes

- Compare matched H- and EP H-mode discharges on NSTX
  - Extended periods of ELM-free, MHD quiescence
  - **H-mode**: typical wide-pedestal H-mode ($H_{98y,2} = 1.2$)
  - **EP H-mode**: 300ms EP period, but "marginal" improvement ($H_{98y,2} = 1.35$)

- EP H-mode discharge had two ELM events

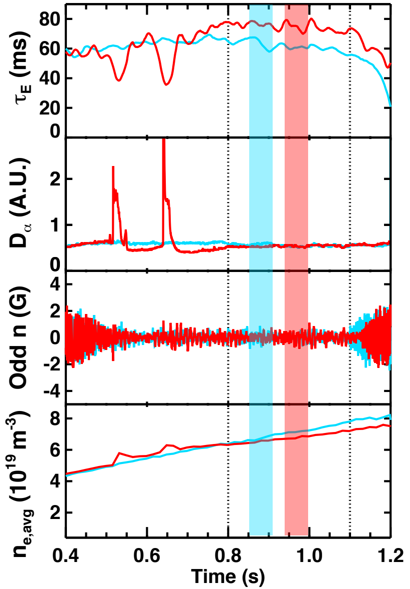
- Demonstrates increase in thermal confinement with a reduction in particle accumulation

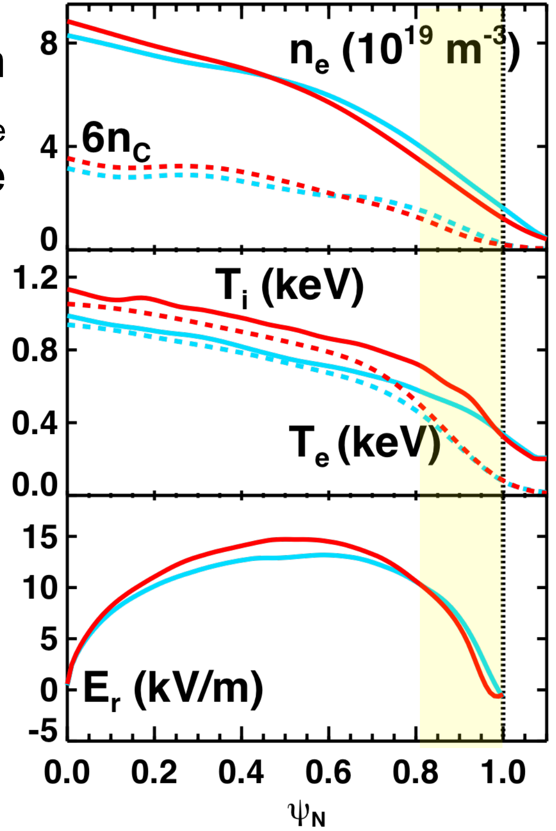
EP H-mode 141133
H-mode 141125



Transport changes in edge region ($\psi_N > 0.8$) impact core confinement during EP H-mode phase

Comparing periods with matched line-averaged n_e during saturated phase





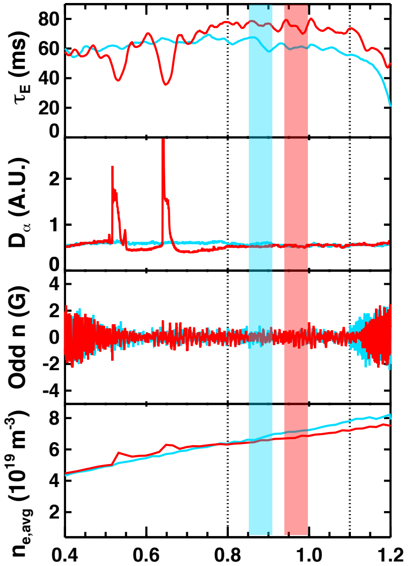
EP H-mode 141133
H-mode 141125

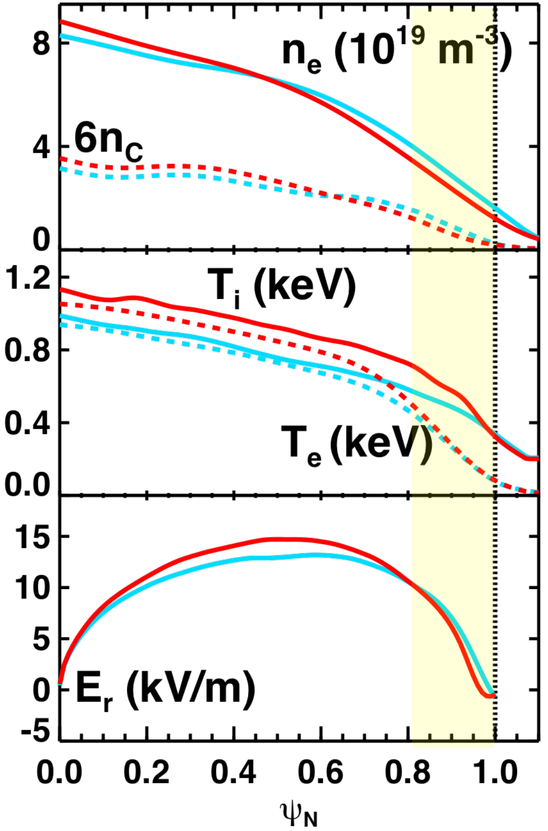
Small change in edge density leads to 15% increase in core T_i

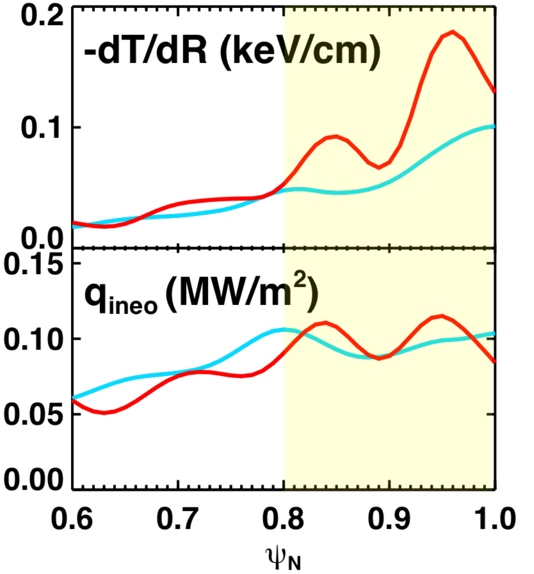
Subtle differences in E_r

Transport changes in edge region ($\psi_N > 0.8$) impact core confinement during EP H-mode phase

Comparing periods with matched line-averaged n_e during saturated phase







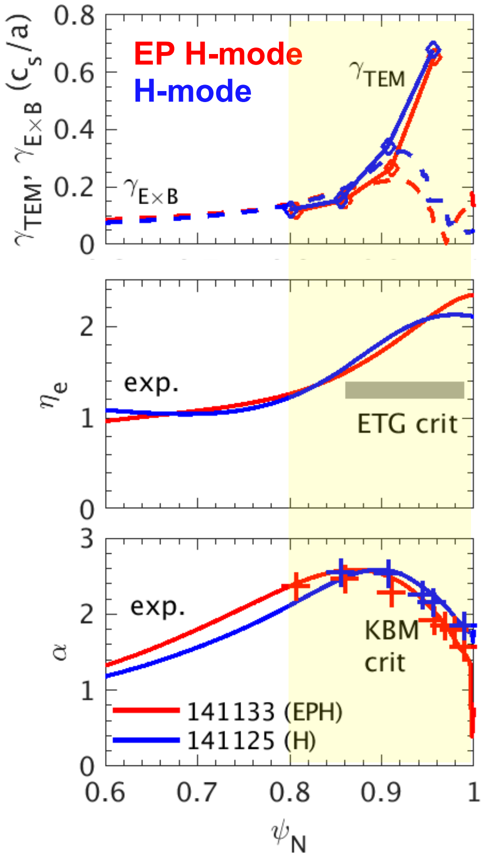
KBM, ETG and TEM predicted to contribute to edge transport $\psi_N \sim 0.95$

- Linear CGYRO* calculations for saturated EP and wide-pedestal H-mode phases
  * J. Candy, E.A. Belli, JCP (2016)

- TEM contributes to thermal and particle transport
  - Stabilized $\psi_N < 0.9$ by E x B shear
  - Broad spectrum predicted unstable at bottom of pedestal

- ETG contributes to χ_e for $\psi_N > 0.85$
  - Consistent with region with stiff T_e
  - MTM not as likely: $\gamma_E \sim \gamma_{lin}$

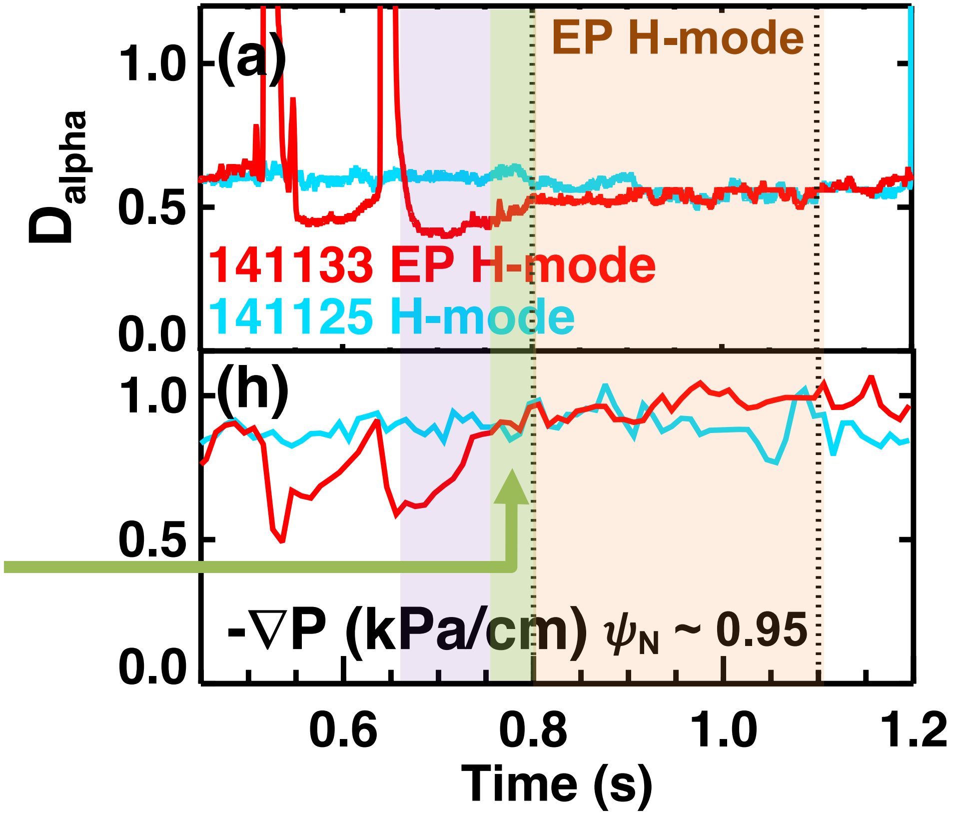
- KBM contributes to thermal and particle transport
  - Normalized pressure profiles close to KBM onset $\psi_N > 0.8$



A period of reduced neutral fueling occurs during the ELM recovery

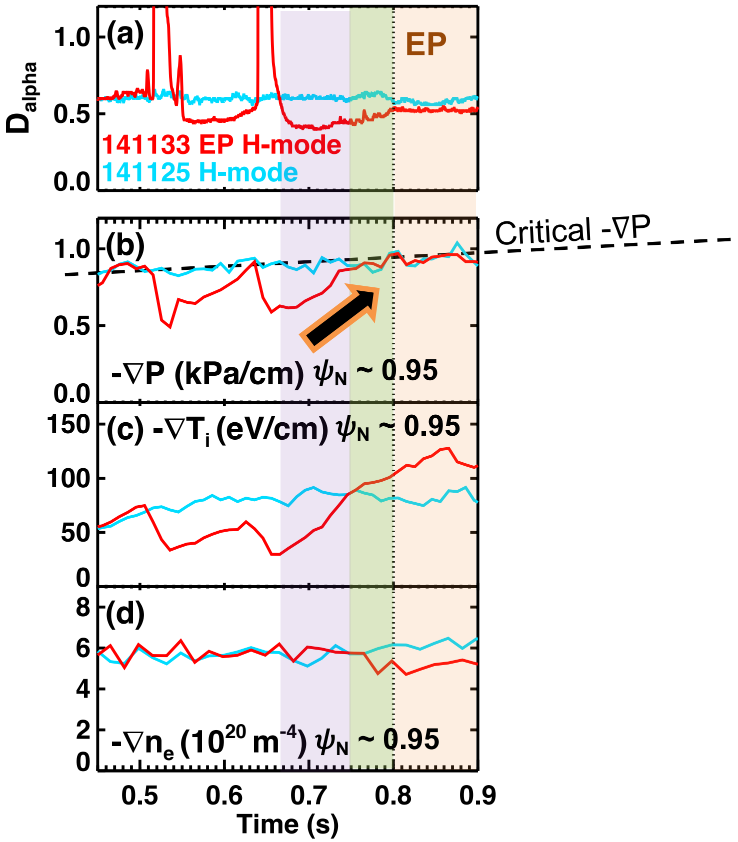
- Divertor heat flux from ELM liberates neutrals from the wall
  - Neutral recycling reduced while wall inventory recovers

- Key feature: slower neutral recovery compared to the rebuild of the pedestal pressure



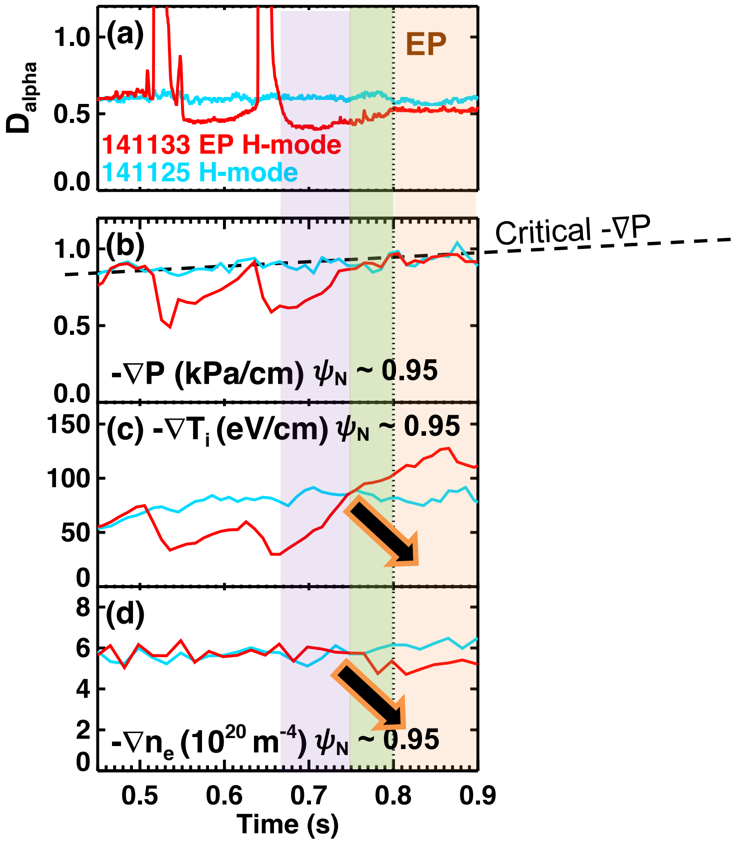
Period of reduced neutral fueling can lead to lower ∇n

- After ELM, ∇P recovers back to ∇P_{crit}
  - ∇P clamped by KBM onset



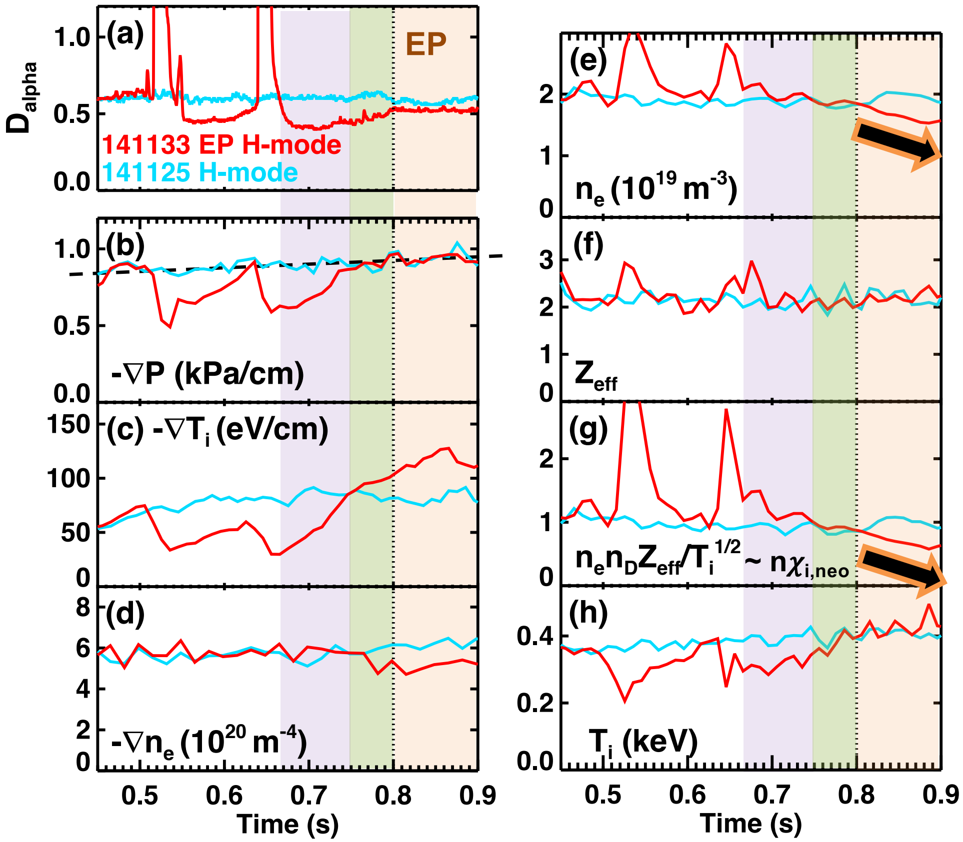
Period of reduced neutral fueling can lead to lower ∇n

- After ELM, ∇P recovers back to ∇P_{crit}
  - ∇P clamped by KBM onset
- KBM increases transport, acts to reduce ∇n, ∇T
  - ETG adjusts to maintain stiff T_e
- Yet, ∇T_i keeps increasing during KBM period
  - Larger q_i to make up for lower charge-exchange losses from reduced neutral density



A new balance between $\chi_{i,neo}$ and $\chi_{i,KBM}$ is established

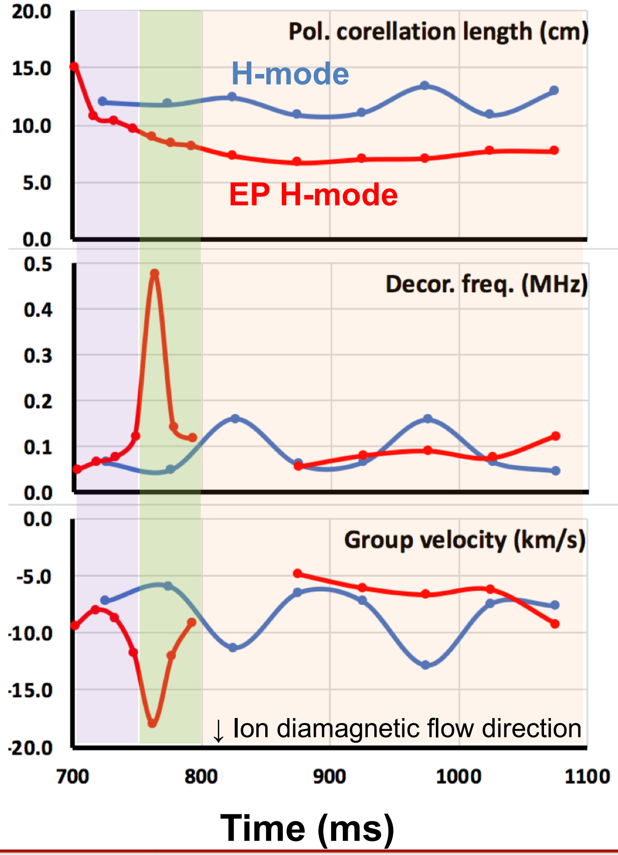
- ∇T_i "overshoot" drives anomalous energy and particle transport
  - Leads to a reduction in local n_e
  - Impacts both impurity and main ion density
- Lower density reduces $\chi_{i,neo}$
- Reduction in $\chi_{i,neo}$ can offset increase in $\chi_{i,KBM}$
  - "Lock in" larger ∇T_i, smaller ∇n



Characteristics of ion scale modes evolves during ELM recovery

- BES measurements of low-k modes $\psi_N \sim 0.9$
  - Intermediate toroidal mode number
  - dn/n ~ 2% rapidly increasing to 10% near separatrix
- Reduction in the poloidal correlation length (L_C) in the pedestal during the EP H-mode phase
  - Consistent with work demonstrating inverse scaling of L_C with ∇T_i in wide-pedestal H-mode on NSTX

    D.R. Smith et al. Phys. Plasmas 20 (2013)
  - Concurrent development of broad peak in dn/n spectrum around 30 kHz
- Poloidal decorrelation frequency increases when ∇P saturates prior to EP phase
  - Group velocity (no doppler shift correction) shifts toward ion diamagnetic drift direction (KBM-like)



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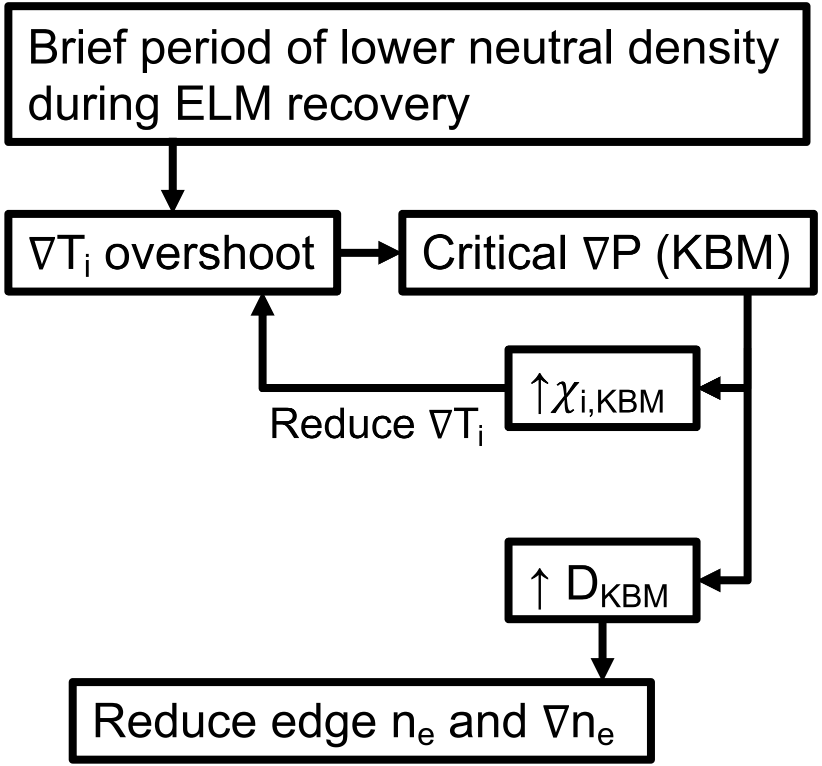
Positive feedback when reduction of neoclassical ion thermal transport exceeds increase in KBM transport



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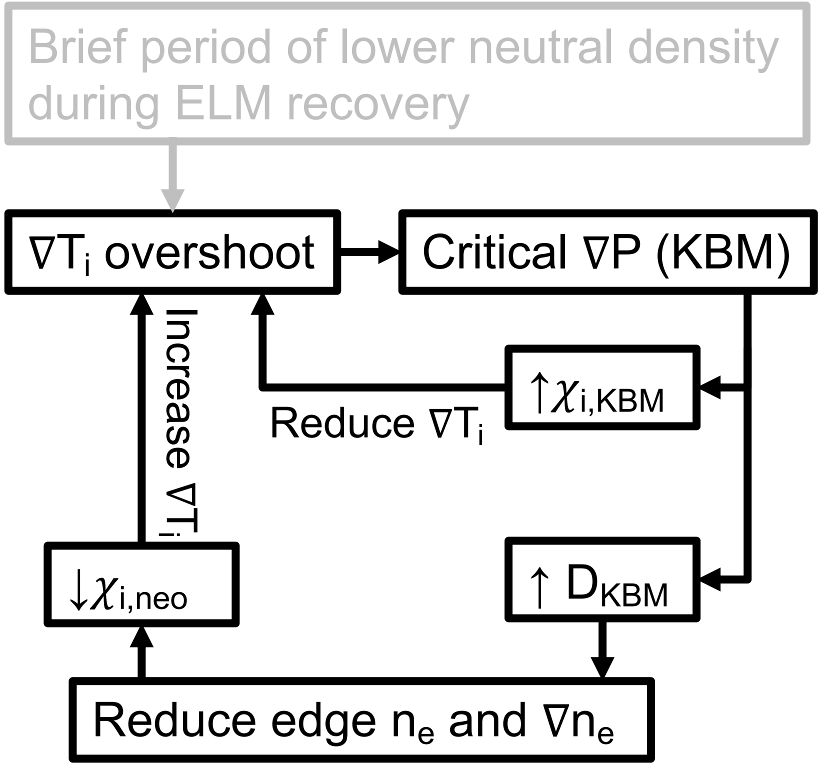
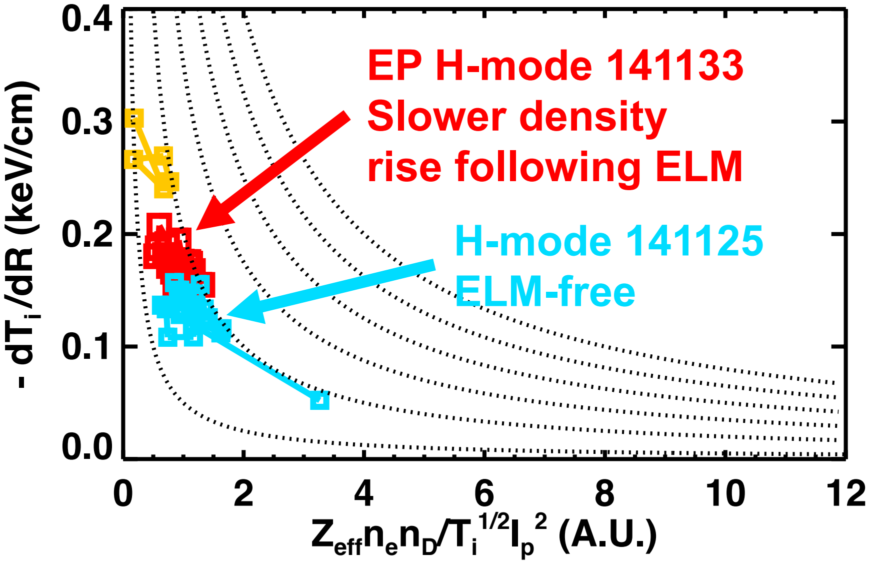




EP H-mode: Improved energy confinement and increased particle transport at low collisionality

- EP H-mode occurs at low edge ion collisionality where $\chi_{i,neo}$ is sensitive to small changes in density
  - Increase in core T_i at with decreasing $n_{e,sep}$ consistent with neoclassical scaling

- Temporary reduction in neutral recycling during an ELM recovery can trigger transition to lower ion collisionality state
  - KBM maintains constant ∇P, ultimately reducing ∇n as ∇T_i increases

- Motivates accessing low edge density that is compatible with $n/n_{GW} \rightarrow 1$ and heat flux mitigation in high-β regimes
  - Baffled divertor in MAST-U, lithium research on NSTX-U and LTX-β

Open questions

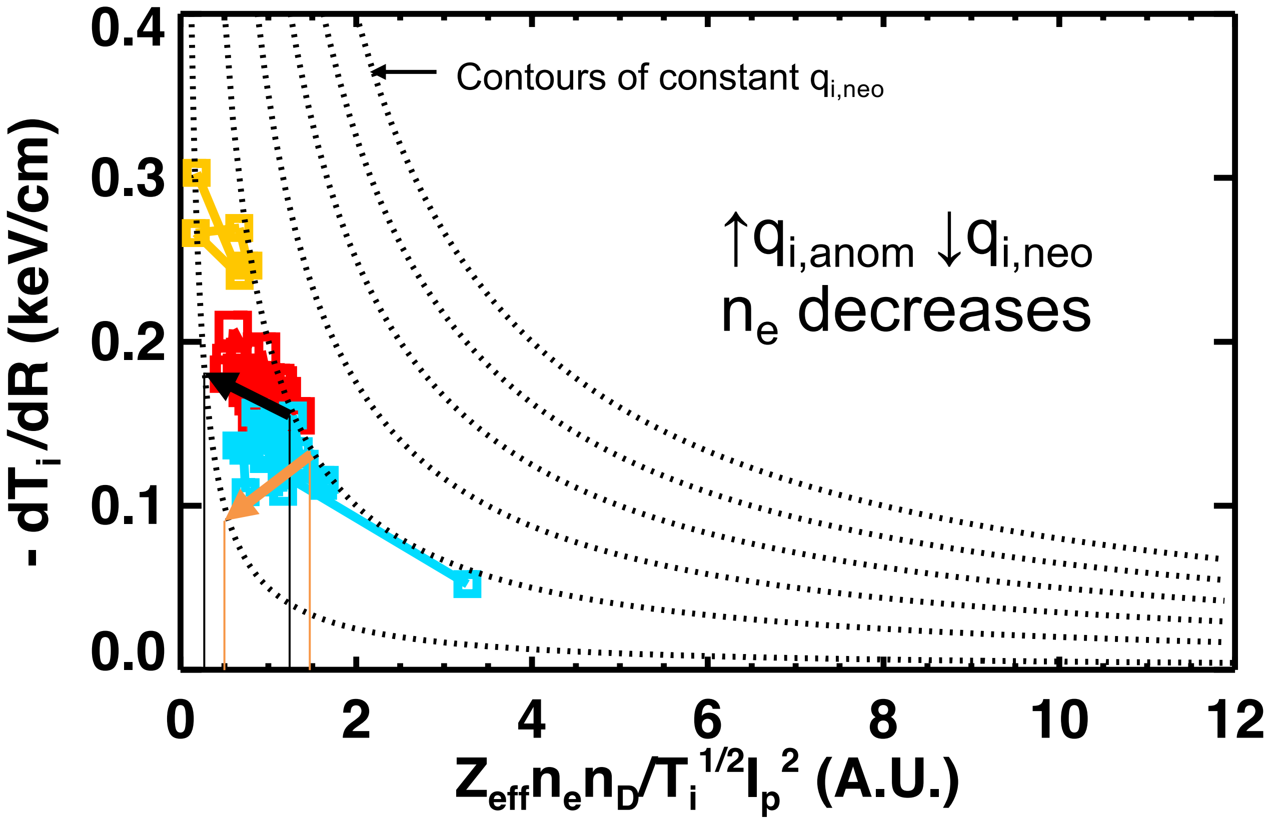
- Work remains to demonstrate quantitative agreement between transport calculations and observations
  - Example: Measured ∇T_i exceeds ∇T_i predicted from neoclassical calculations using inferred q_i
  - NSTX-U FY20 research milestone aims to better quantify edge transport and stability mechanisms in low collisionality NSTX regimes

- Quantitative model required to determine potential for EP H-mode regimes in CPP concepts
  - New diagnostic capabilities on NSTX-U will provide critical data to constrain models

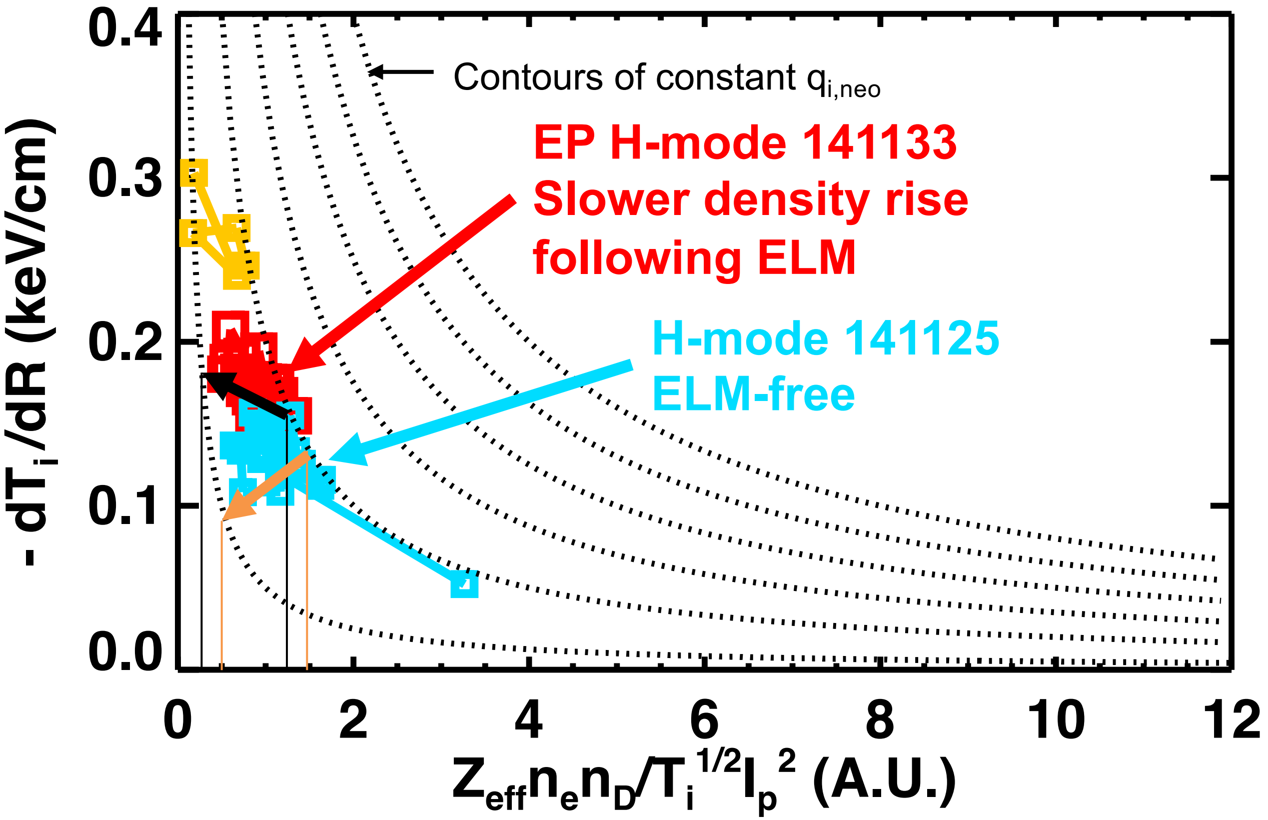
- Can the edge density be sufficiently controlled to produce a stationary, high-β, $H_{98y,2}$ = 1.8 regime?
  - Improved actuators and expanded operating space on NSTX-U will provide critical data

Backup

Tipping point for ELM triggered EP H-mode occurs at low edge ion collisionality



Consistent with observed improvement in energy confinement with slower density accumulation



Transport changes in edge region (ψ_N ~ 0.95) impact core confinement during EP H-mode phase

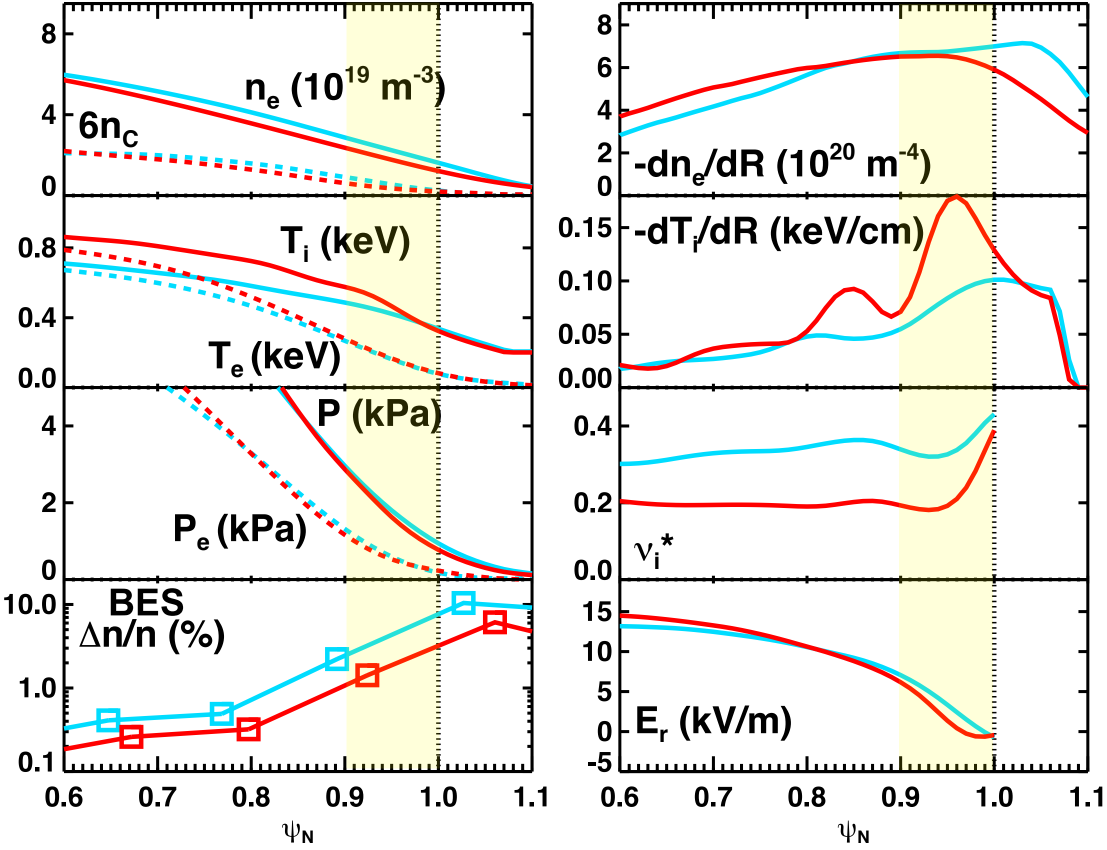
Lower $n_{e,sep}$

EP H-mode 141133

H-mode 141125

"Stiff" T_e and thermal pressure

Intensity of low-k modes increasing toward edge



Similar $-\nabla n_e$

(except near separatrix)

Larger $-\nabla T_i$

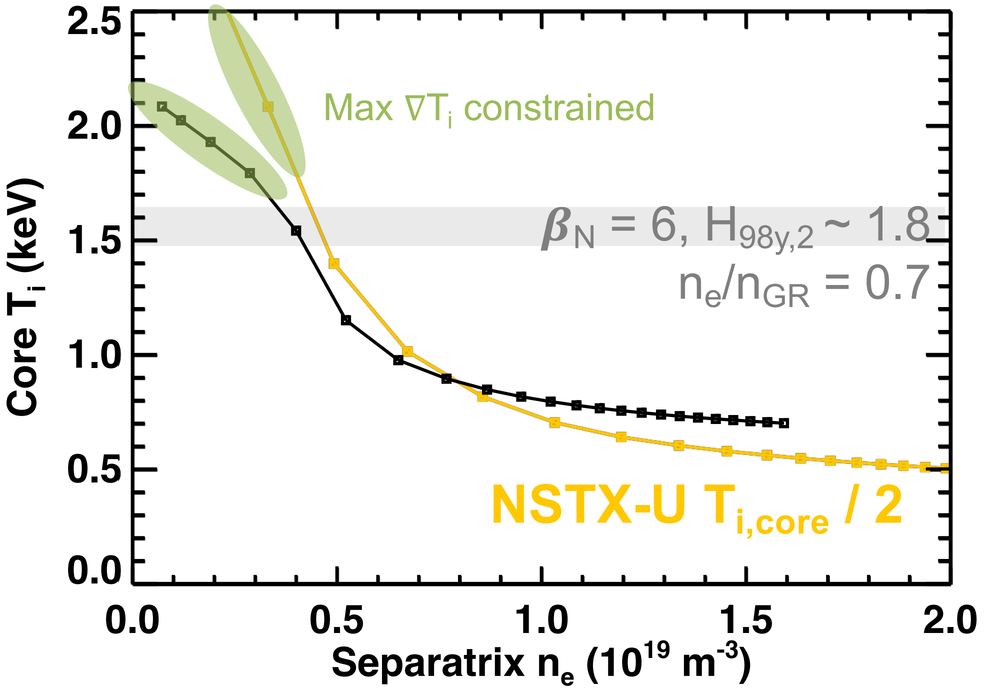
Big difference in ν_i^*

Subtle difference in E_r

Simple model predicts similar threshold in $n_{e,sep}$ for NSTX-U to access EP H-mode

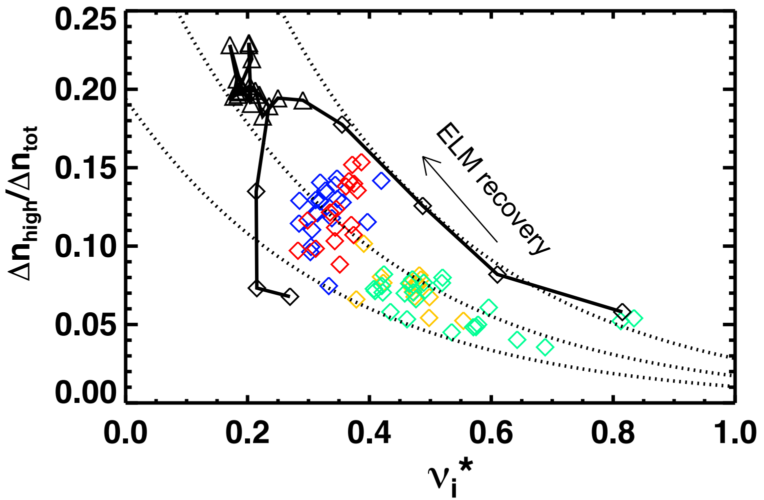
- Double I_p, B_T, P_{heat}, $n_{e,avg}$ & change R,a
  - $\tau_{e,ITPA98y,2}$ doubles
  - Core T_i twice as large gives similar $H_{98y,2}$ and β_N

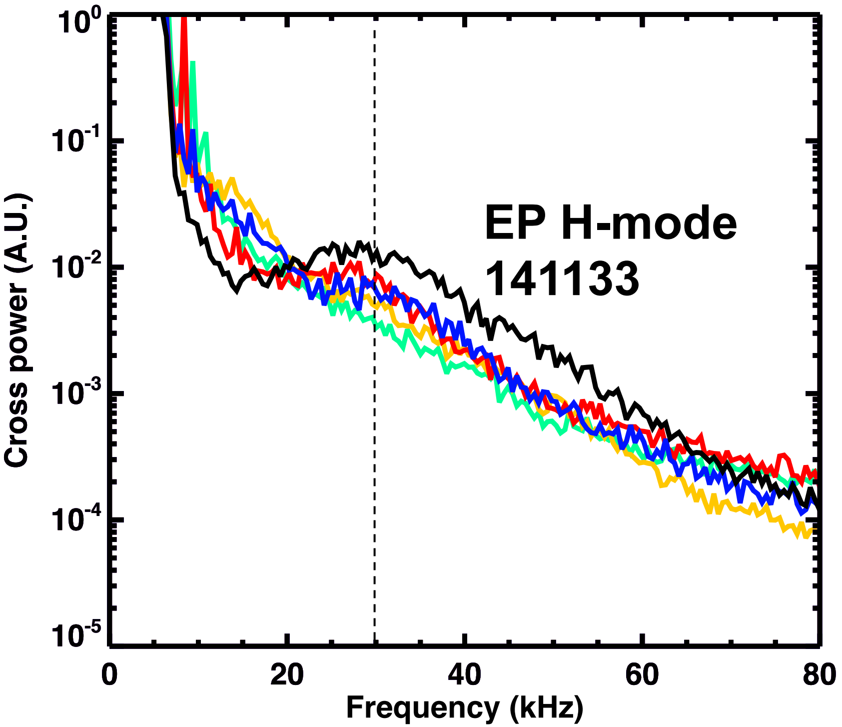
- Caveats to result
  - Did not change min χ_e, & T_e assumptions
    - May improve at lower ν_e^*
  - $n_{e,sep}/n_{e,avg}$ half as large compared to NSTX
  - Increased max ∇T_i by factor of 4



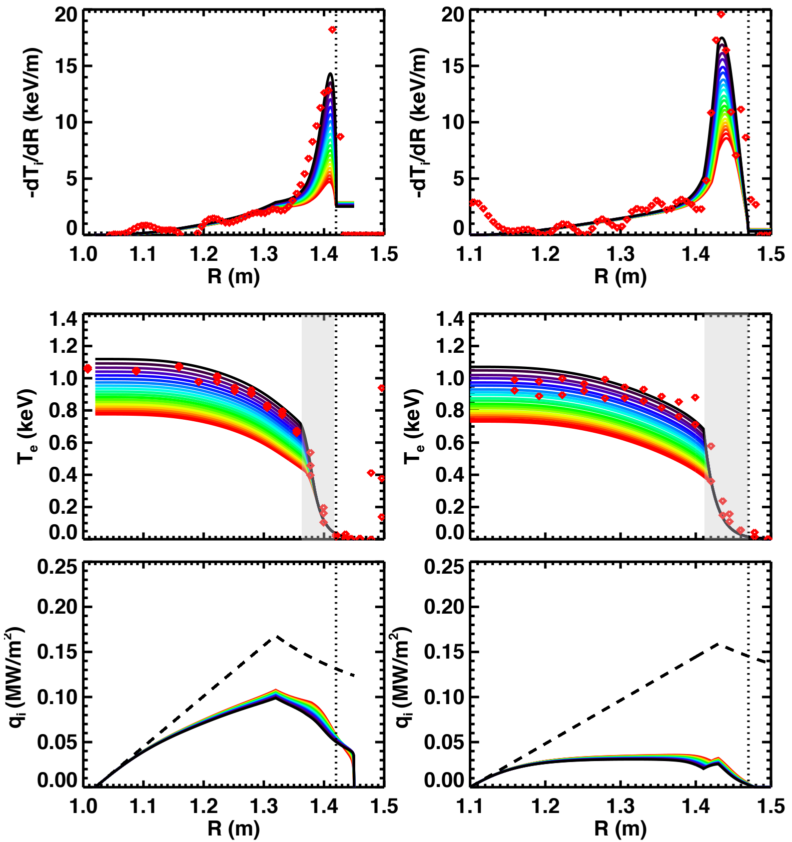
Nature of edge turbulence may change as indicated by shift to higher frequency

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





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