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New Insights into the Enhanced Pedestal H-mode Regime on NSTX

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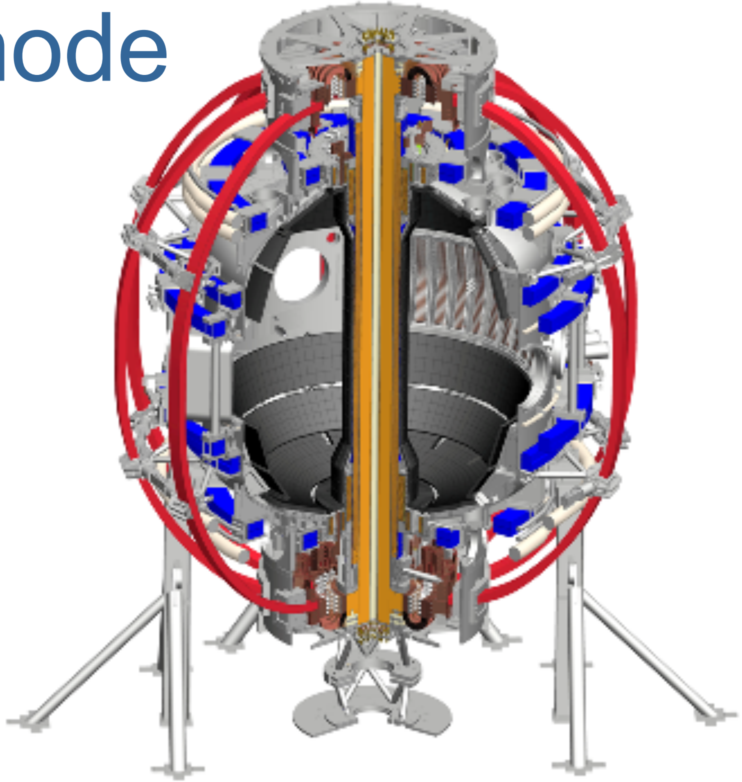
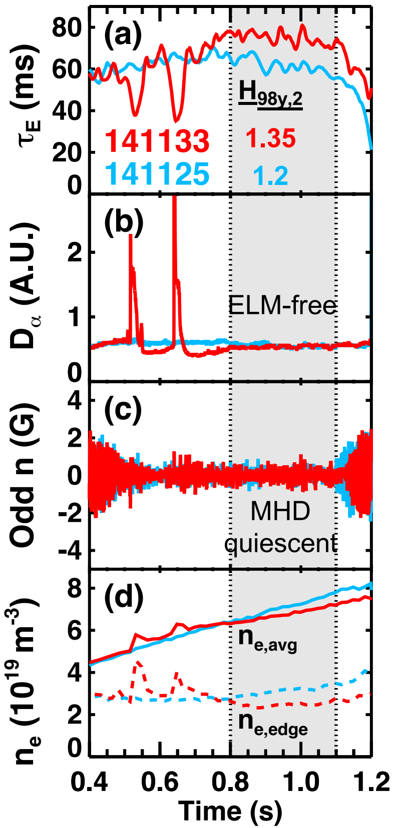


Largest confinement time on NSTX achieved in the Enhanced Pedestal (EP) H-mode regime

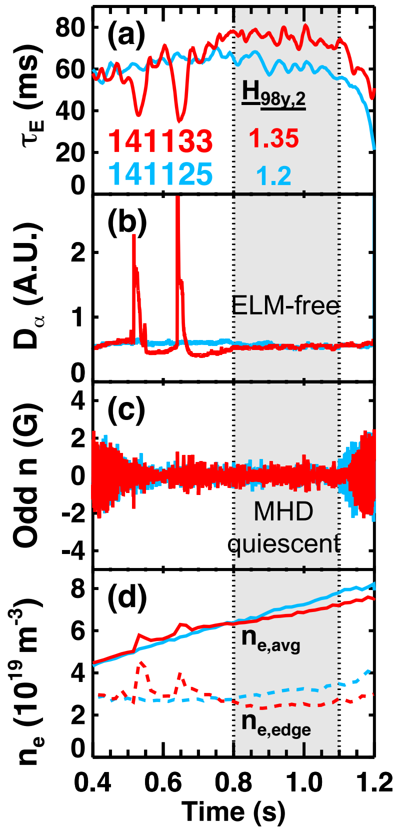
- NSTX-U mission: develop solutions for a tokamak compact fusion pilot plant (CFPP)
  - Compact designs: $H_{98y,2}$ > 1.5 with small or no ELMs
  - AT approach: steady-state, high β_N at large f_{GW} and f_{BS}
- EP H-mode on NSTX is attractive for a CFPP
  - Enhanced confinement ($H_{98y,2}$ as large as 1.8)
  - ELM-free with slower density accumulation
  - $\beta_N \sim 6 - 7$, $f_{GW} > 0.7$, $f_{BS} > 0.6$, $q_{min} \sim 2$, $q_{95} \sim 9$
  - 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 transition: positive feedback between neoclassical ion energy transport and anomalous particle transport
  - Evolves to new state with improved energy confinement, reduced particle confinement
- Large ELM can trigger positive feedback
  - Due to temporary reduction in edge neutral density
- Anomalous particle transport changes in character in EP H-mode
  - Transport becomes more MHD-like (KBM, kink-peeling)



Outline

- Comparison of wide-pedestal and EP H-mode
- Neoclassical ion thermal transport at low ν_i^*
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- Anomalous transport in ELM-free pedestal
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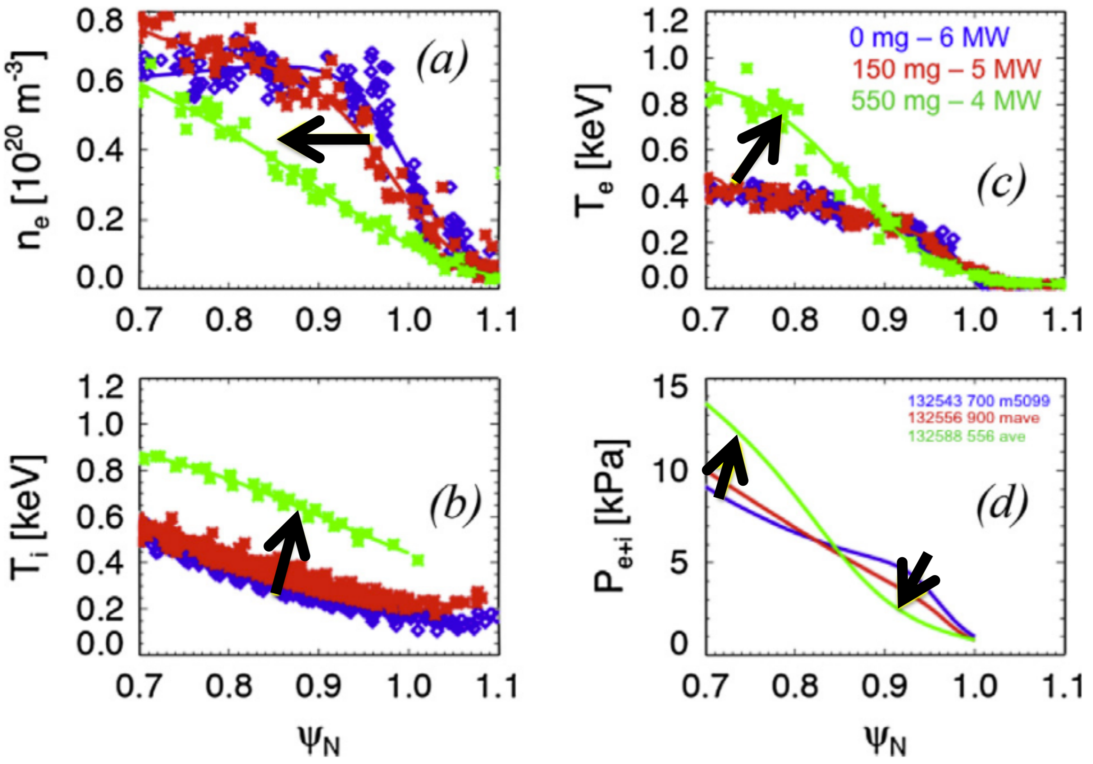
NSTX achieved wide pedestal H-mode via reduction in recycling with lithium wall coatings

- Lower recycling reduces $n_{e,sep}$ and ∇n_e
  - Improved confinement in ELM-free regime
  - Stabilize MTM $\psi_N < 0.9$
  - Enhanced χ_e $\psi_N > 0.9$

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



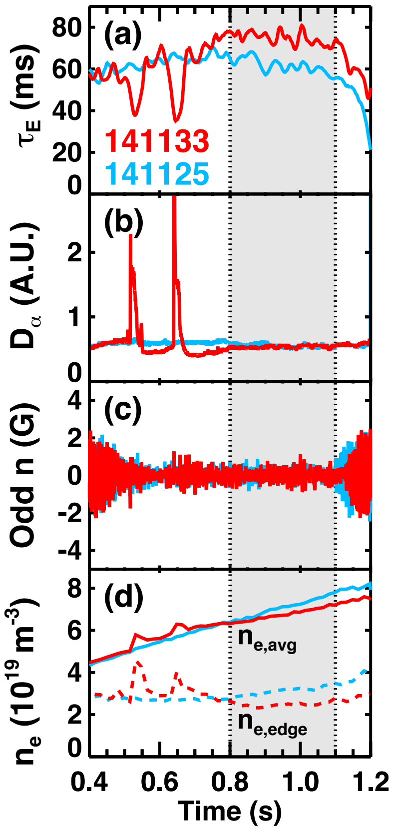
R. Maingi, et al. J. Nucl. Mater. 463 (2015)

Matched discharges provide good comparison for wide-pedestal and EP H-mode

- WP → EP H-mode via further reduction in edge n_e
- Compare MHD-quiescent periods at matched $n_{e,avg}$
  - B_T = 0.45T, I_p = 0.9MA, 3 MW NBI, q_0 < 2, q_{95} ~ 9, near DN

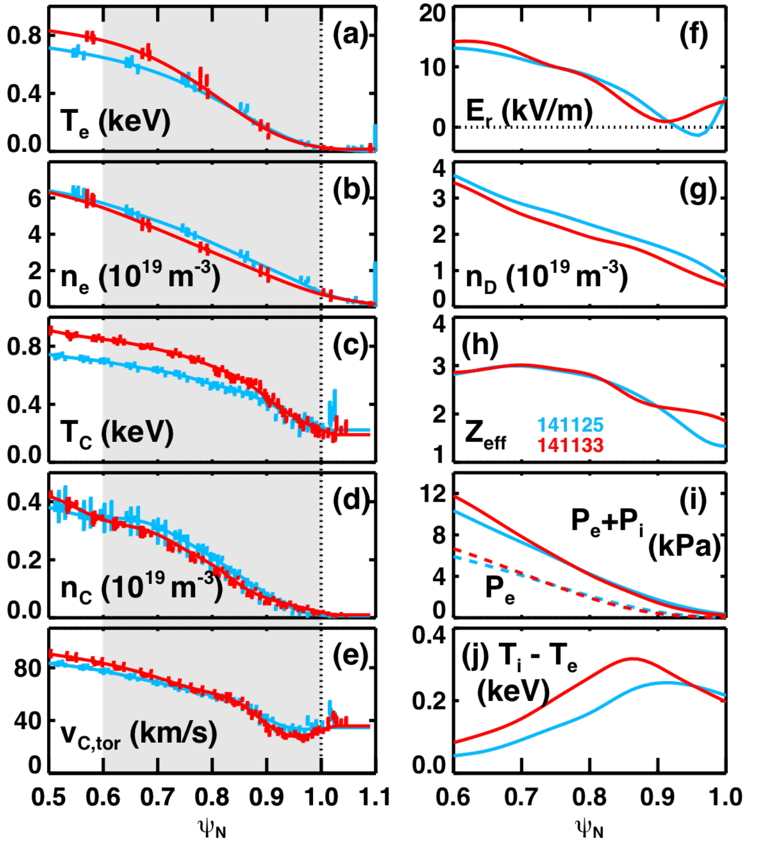
WP H-mode 141125 EFC + 400A n=3
EP H-mode 141133 EFC + 500A n=3

- Long ELM-free periods with lithium wall conditioning
  - Non-resonant 3D field alters edge, induces ELMs
  - 600A current in 3D coils induces regular ELMs
  - EP H-mode discharge has 2 ELMs, then ELM-free
- $H_{98y,2}$ = 1.2 in WP, $H_{98y,2}$ = 1.35 in EP
  - Modest EP H-mode with β_N = 5.5



EP H-mode has lower edge n_e, larger core T_i and T_e

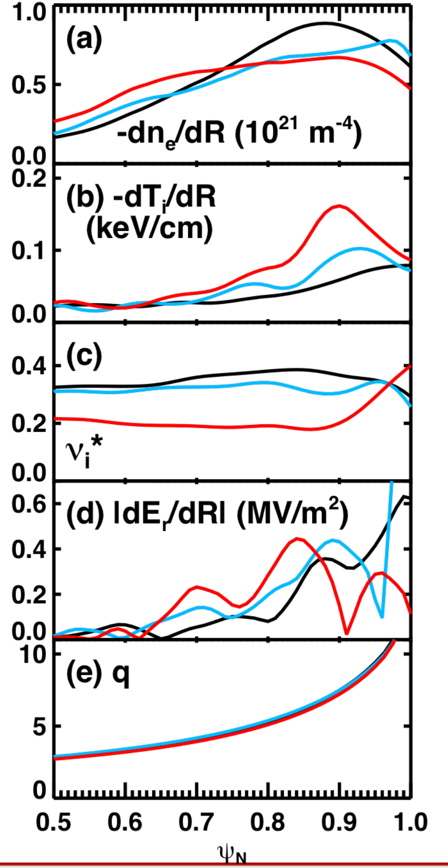
- Edge n_e, n_D is reduced
  - Z_{eff} larger for $\psi_N > 0.9$
- Location of minimum E_r shifts inward
- Pressure similar for $\psi_N > 0.8$
- Characteristic increase in edge ∇T_i
  - Larger core T_i and T_e
  - Bigger increase in core T_i



WP H-mode 141125 EFC + 400A n=3
EP H-mode 141133 EFC + 500A n=3

EP H-mode realized with more peaked density profile and lower ν_i*

- EP H-mode: smallest $-\nabla n_e$ for $\psi_N > 0.9$, largest for $\psi_N < 0.7$
  - Density profile is more peaked
- EP H-mode profiles have largest edge $-\nabla T_i$
- $\nu_i^* < 0.3$ near $\psi_N = 0.9$ due to lower density
  - Farther in, smaller ν_i^* due to larger T_i
- E_r shear peaks inside location of maximum $-\nabla T_i$
  - Max $-\nabla T_i$ typically close to E_r minimum in EP H-mode profiles
- Enhanced thermal confinement without reverse q-shear



WP H-mode 141131 EFC only
WP H-mode 141125 EFC + 400A n=3
EP H-mode 141133 EFC + 500A n=3

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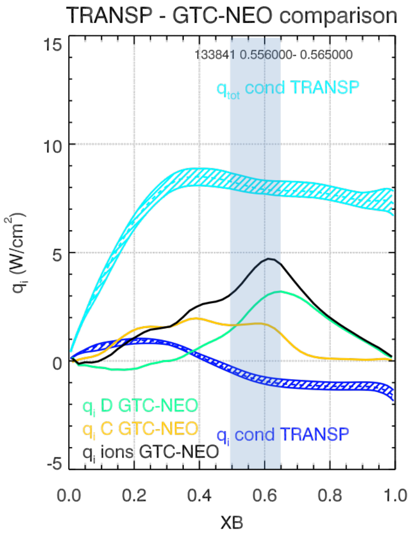
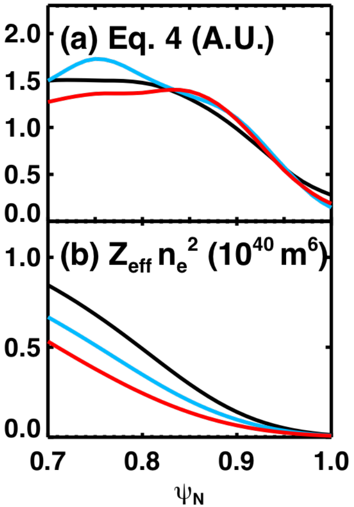
Improved ∇T_i consistent with neoclassical scaling

- Experimental q_i from **interpretive analysis** *smaller* than **neoclassical** q_i
  - Resolving quantitative discrepancy is an on-going task

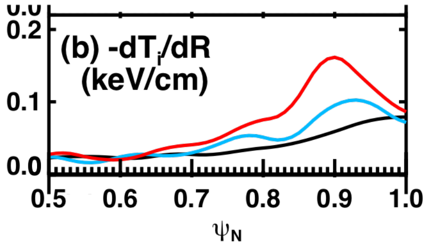


- This work focuses on demonstrating ∇T_i agrees with *scaling* of neoclassical banana transport

$$q_{i,neo} \propto -\frac{dT_i}{dR}\frac{Z_{eff}n_e^2}{I_p^2\sqrt{T_i}} \qquad \text{(eq. 4)}$$



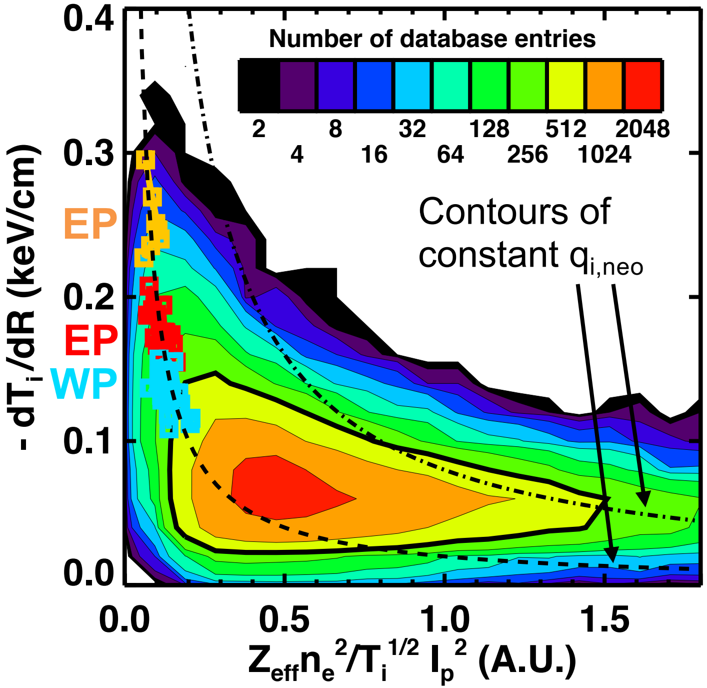
- EP H-mode has smaller edge $Z_{eff}n_e^2$
  - Leading terms of $q_{i,neo}$ similar despite differences in ∇T_i



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, Z_{eff} < 3
  - Identify max $-\nabla T_i$ for each profile
    - Form database of local parameters
  - Colors represent number of entries
    - 83% of entries reside inside thick black contour (yellow, orange, red)

- Largest $-\nabla T_i$ achieved at small values along x-axis
  - Rapid increase in $-\nabla T_i$ at constant $q_{i,neo}$
  - Colored points are shots of interest



$$-\frac{dT_i}{dR} \propto \frac{1}{q_{i,neo}} \frac{Z_{eff} n_e^2}{I_p^2 \sqrt{T_i}}$$

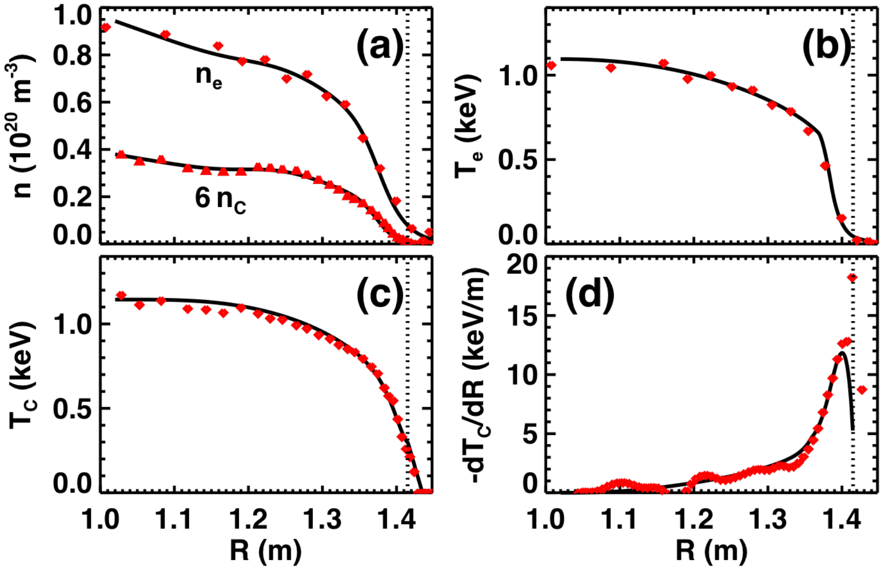
Simple model developed to illustrate impact of edge density on core temperatures

- Use fixed equilibrium (B_T, I_p, q, κ …)
- Define n_e, n_C that match EP H-mode
- Solve time-independent energy transport

$$q_{i,neo} = Q_i - n_D \nu_\varepsilon^{e/i}(T_i - T_e)$$

$$-n_e\, \chi_e\, \nabla T_e = Q_e + n_D \nu_\varepsilon^{e/i}(T_i - T_e)$$

- Q_i, Q_e approximated using TRANSP
- $q_{i,neo}$ proportional to analytic neoclassical
- Core χ_e = 2.9 m^2/s

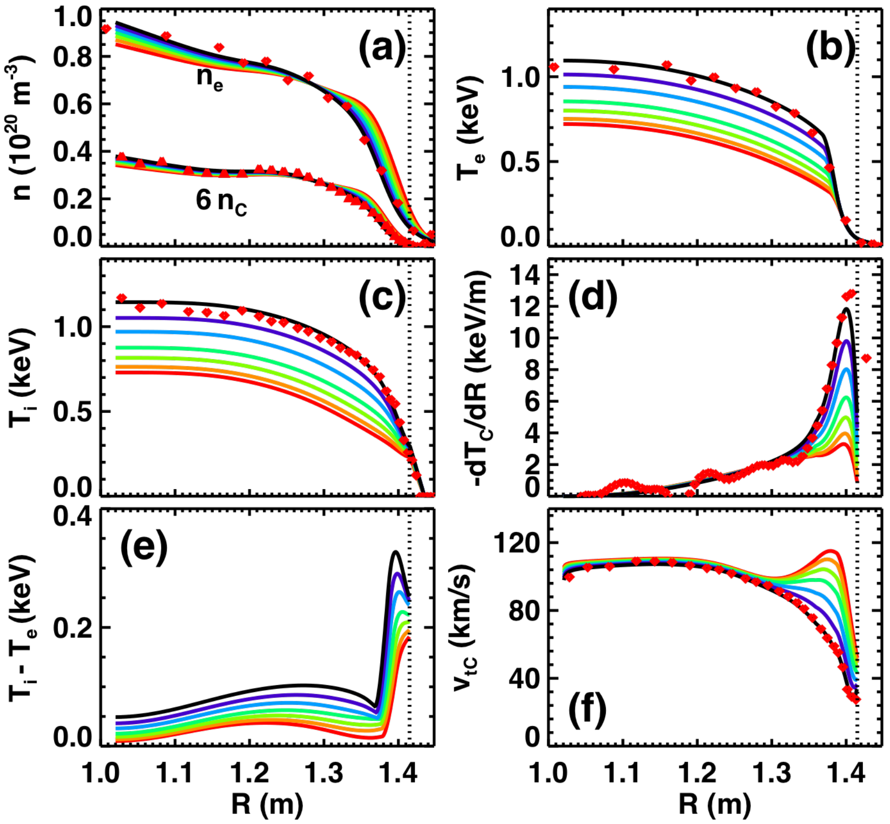


- Iterate to find T_i and T_e profiles with separatrix conditions:
  - $T_{i,sep}$ proportional to $q_{i,neo}$ at separatrix
  - $T_{e,sep}$ = 60 eV with fixed a/L_{Te} until T_e/T_i = 0.9

Core temperature decreases as density profiles become broader

- Broaden n_e profile (Black→red)
  - Maintain same line-averaged n_e
  - Keep Z_{eff} profile constant
  - All other free parameters are the same
  - Repeat calculation of self-consistent temperature for each choice n_e profile

- Edge $-\nabla T_i$ and core T decrease as edge n_e increases
  - Region of stiff T_e becomes narrower
  - T_i - T_e becomes smaller
  - With fixed E_r (and v_{pol} = 0) edge toroidal carbon rotation becomes more positive

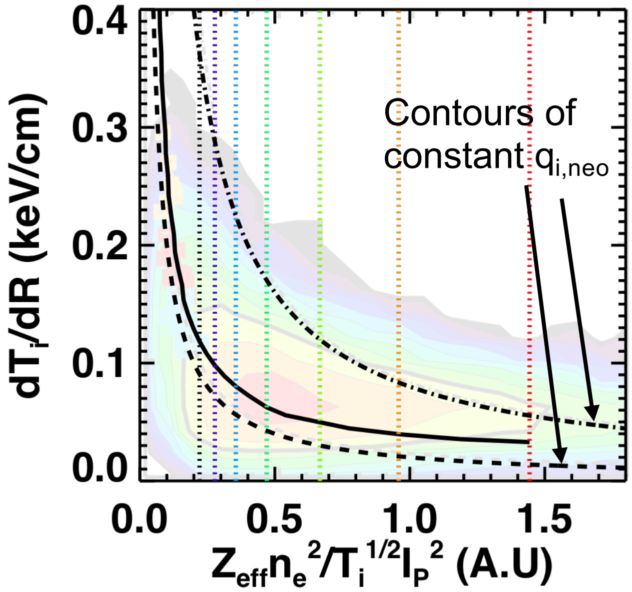


Simple model demonstrates relationship between edge density and core temperature

- Reproduces rapid increase in edge ∇T_i as $n_{e,sep}$ decreases
  - Due to $\nabla T_i \propto 1/n_e^2$ at constant $q_{i,neo}$

- Increasing difference in core T_i and T_e at lower $n_{e,sep}$
  - Reduces edge $q_{i,neo}$ as more ion energy is transferred to electrons via collisions

$$q_{i,neo} = Q_i - n_D \nu_\varepsilon^{e/i} (T_i - T_e)$$



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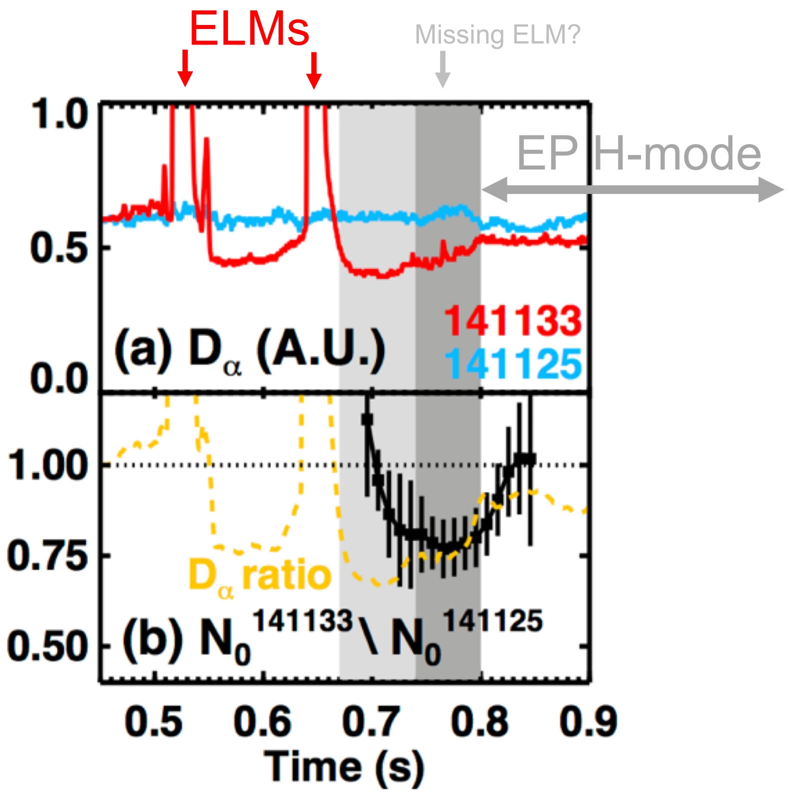
A period of reduced neutral fueling occurs during the ELM recovery

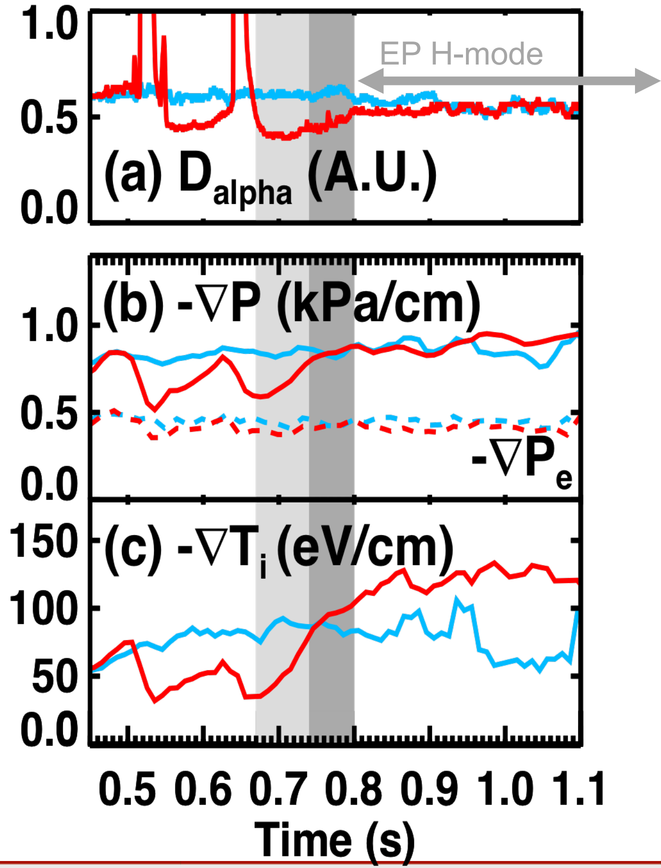
- Divertor heat flux from ELM liberates neutrals from the wall
  - Neutral recycling reduced while wall inventory recovers
- Ratio of neutral density at T_e = 100eV between two shots (black) similar to ratio of divertor D_α (gold)
  - Lower neutral density facilitates entry into EP H-mode
  - Measurement from passive CHERs



Proposed trigger mechanism: Pressure gradient saturates prior to neutral density recovery

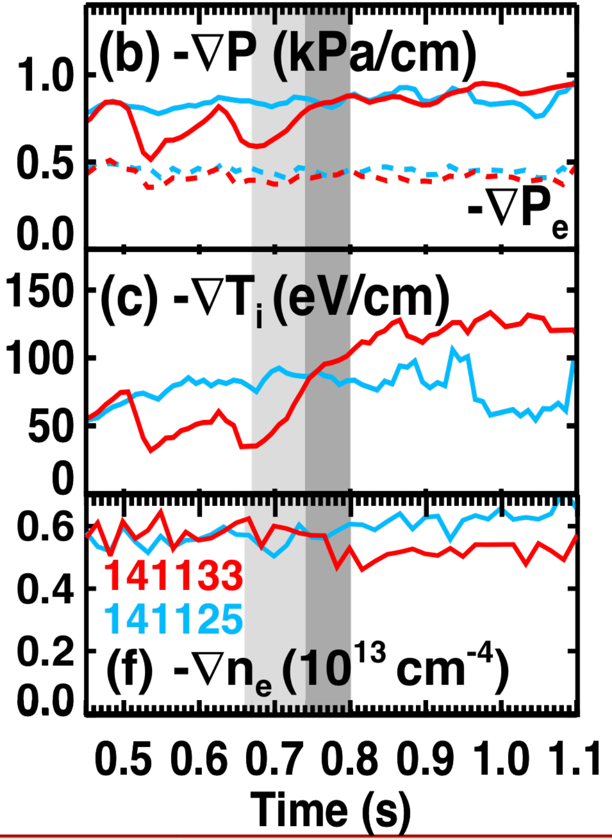
- KBM and/or saturated kink-peeling instability clamp ∇P
  - Dark gray phase

- Lower neutral density leads to a "T_i overshoot" in this phase
  - Reduced charge-exchange losses

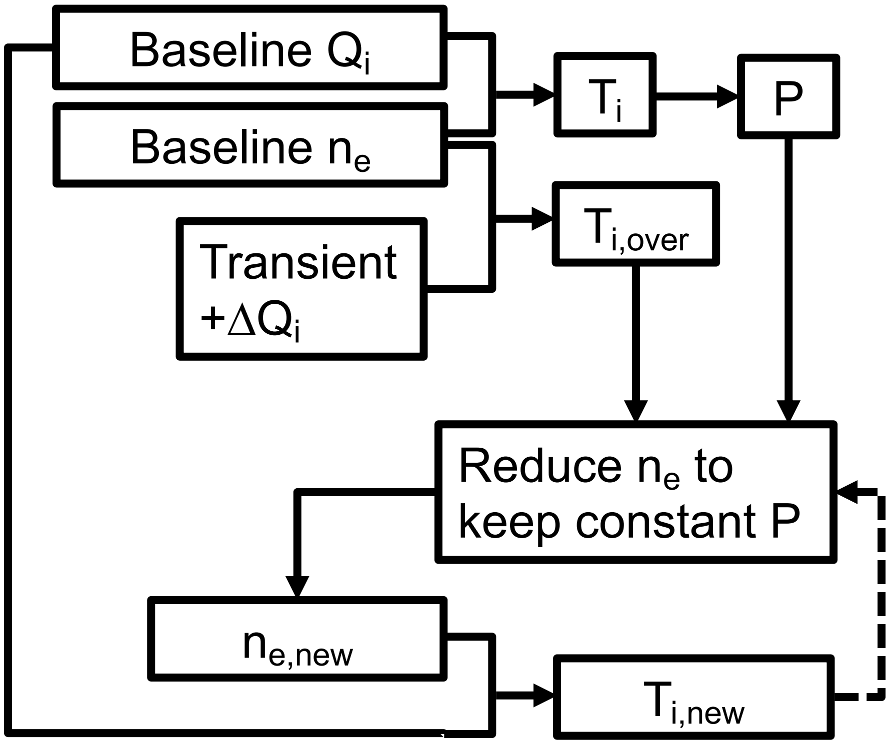


Proposed trigger mechanism: pressure gradient saturates prior to neutral density recovery

- MHD-like instability reduces edge density gradient to maintain ∇P during T_i overshoot
  - MHD-modes have a larger impact on the total particle transport than the total energy transport in the pedestal
    - $D/\chi \sim 1$ for MHD-like transport
    - $D/\chi \ll 1$ for ETG, MTM
    - $D/\chi < 0.1$ in pedestal
- Increased ∇T_i gets "locked in" by reduction in edge density
  - Maintain neoclassical heat flux at lower edge density
  - Persists after full recovery of neutral density



Simple model demonstrates positive feedback between neo. energy transport and MHD-like particle transport



- Use simple model for $0.85 < \psi_N < 1$

  $$q_{i,neo} = Q_i - n_D \nu_\varepsilon^{e/i}(T_i - T_e)$$

  - Fixed T_e profile (constant a/L_{Te})
  - Simplify n_e profile
    - Two parameters: $n_{e,sep}$, ∇n_e
    - $Z_{eff} = 2$ with C^{6+} only impurity

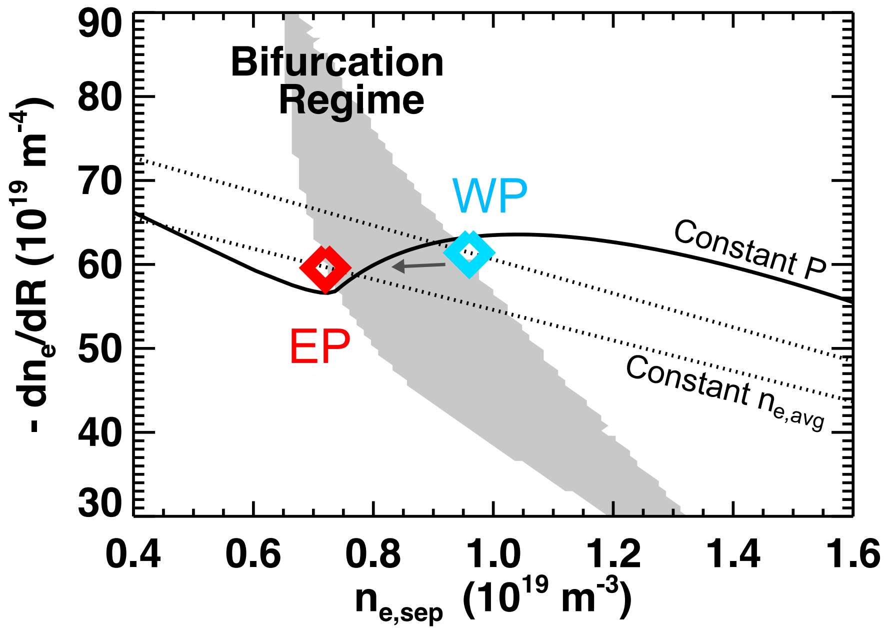
- Increase Q_i slightly
  - Recalculate T_i profile ($T_{i,over}$)
  - Reduce n_e to maintain constant P ($n_{e,new}$)

- Calculate T_i with lower n_e profile and original Q_i ($T_{i,new}$)
  - Is $T_{i,new} > T_{i,over}$?

Simple model demonstrates positive feedback between neo. energy transport and anomalous particle transport

- Lower $n_{e,sep}$ facilitates bifurcation with a constant $n_{e,avg}$ (dotted lines)
  - i.e. more peaked density profiles
- Left-side boundary of gray region (stable EP solutions) requires damping mechanism
  - Imposed in model by defining a max ∇T_i
  - Possible damping mechanisms include:
    - Growing T_i/T_e in core, reducing $q_{i,neo}$
    - Increasing $\chi_{i,anom} / \chi_{i,neo}$
    - Evolving equilibrium, Z_{eff}
- Simple model illustrates WP → EP bifurcation with $n_{e,sep} < 10^{19}$ m^{-3}
  - New state at constant P (solid line)

Gray region indicates n_e profiles where positive feedback is initiated ($T_{i,new} > T_{i,over}$)



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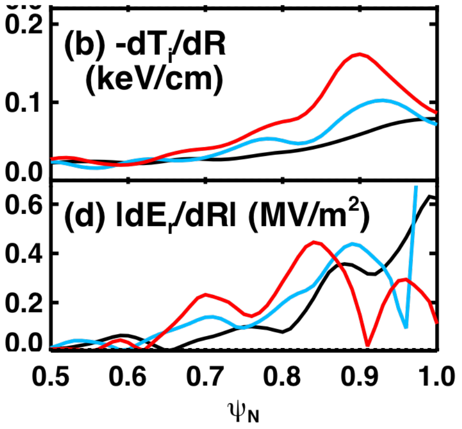
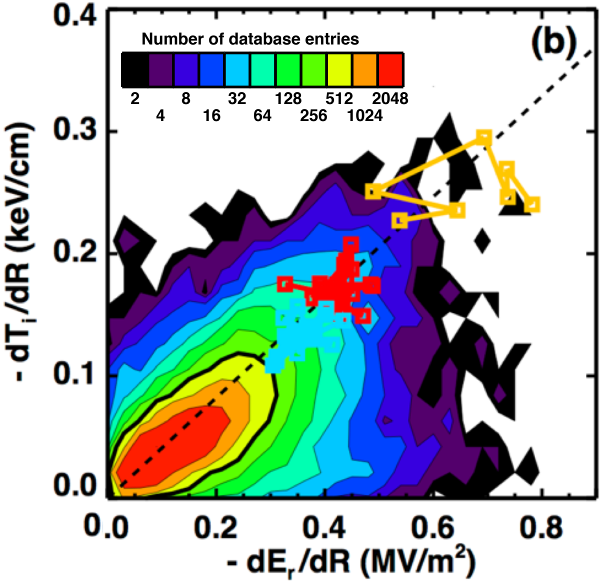
Maximum $-\nabla E_r$ and maximum $-\nabla T_i$ increase concurrently

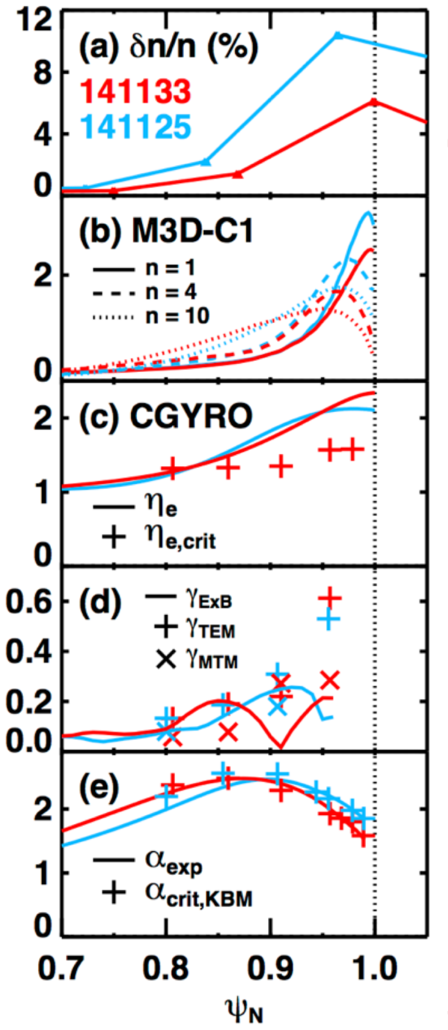
- Location of max $-\nabla E_r$ at smaller R compared to $-\nabla T_i$
  - Max $-\nabla T_i$ typically aligns with minimum in E_r ($\nabla E_r = 0$) in EP H-mode
- Magnitudes grow concurrently
  - Location of max $-\nabla E_r$ shifts inward with EP H-mode
- May impact anomalous transport
  - For example, improved electron energy confinement





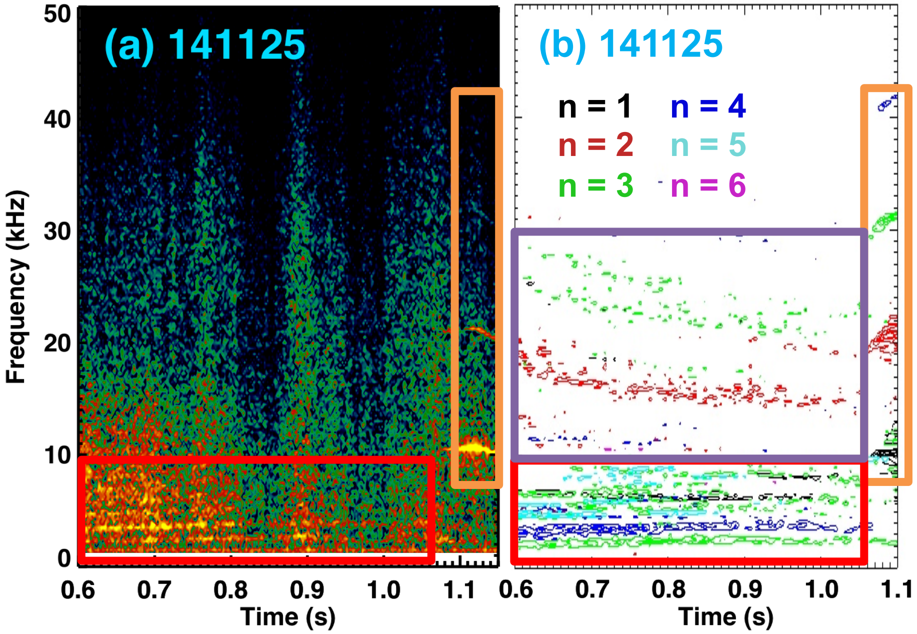
WP and EP phases have similar linear stability properties

- BES shows dn/n perturbations increasing toward separatrix
  - Large flux compression limits channel radial resolution ($\Delta\psi_N \sim \pm 0.1$)
  - Normalized density perturbations (dn/n) larger in WP than EP
- M3D-C1 predicts unstable kink-peeling modes
  - n =1 – 20 predicted to be linearly unstable in both discharges
  - Initial two-fluid calculations: co-I_p in lab frame with n x 11 kHz
- CGYRO linear results similar to previous WP analysis
  - ITG robustly stable across profile, ETG unstable in region of stiff ∇T_e
  - TEM unstable for $\psi_N > 0.9$, MTM subdominant in this region
  - TEM, MTM near marginal stability for $\psi_N < 0.9$
- Experimental profiles near critical onset for KBM (α_{crit})
  - Scale β and identifying rapid increase in γ and switch to ion-directed
  - No onset if local equilibrium scaled self-consistently (i.e. second-stability)



BES: Ion-scale fluctuations are predominately below 10 kHz in wide-pedestal H-mode

Wide pedestal H-mode



BES ψ_N ~ 0.84

Magnetics

- Core modes as $q_0 \rightarrow 1$
  - Coupled 1/1, 2/1

Gerhardt *et al. NF* **51**, 073031 (2011)

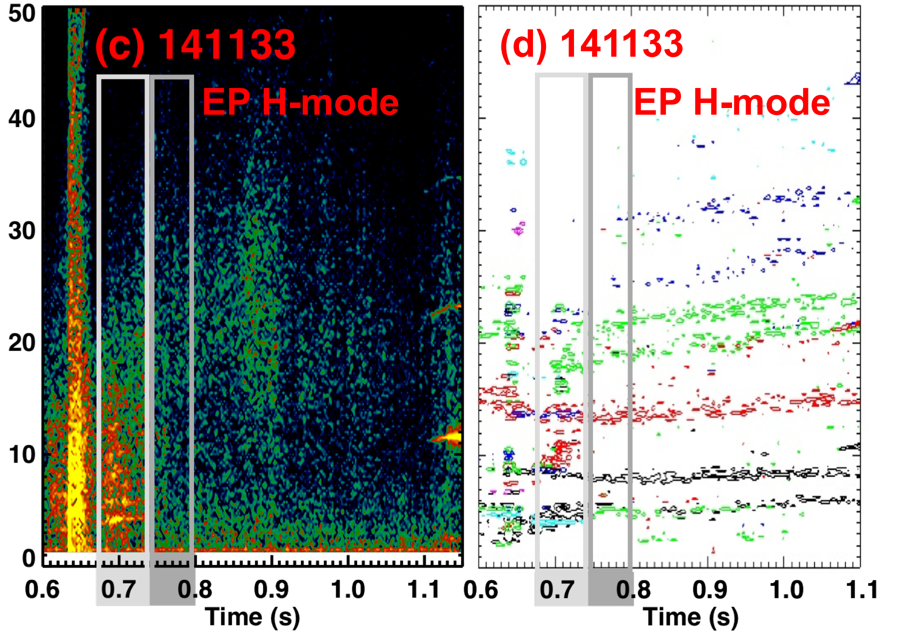
- Low frequency, coherent edge modes in ELM-free or small-ELM regimes
  - Peak in amplitude at separatrix but exist throughout pedestal
  - Sometimes observed with harmonics, Δf ~ 2 kHz
  - Shown to broaden heat flux

Sontag et al. *NF* **51**, 103022 (2011) Park et al. *NF* **54**, 043013 (2014)
Gan et al. *NF* **57**, 126053 (2017) Zweben et al. PoP, submitted (2020)

- Faint detection of EHO in mag.
  - Δf = 7 – 10 kHz co-I_p

Low-frequency modes appear early in ELM recovery, significantly reduced in EP H-mode phase

- Gray boxes correspond to two phases of ELM recovery
  - Saturation of ∇P in dark gray phase
- Low frequency, quasi-coherent edge modes reduced in EP phase
  - Observed early in recovery (light gray) at saturation of $1/L_{Te}$, $1/L_{ne}$
  - Onset of TEM and/or MTM (?)
  - Sharp reduction at saturation of ∇P
- Stronger detection of EHO
  - Δf = 6 – 7 co-I_p kHz
  - Resembles broadband EHO

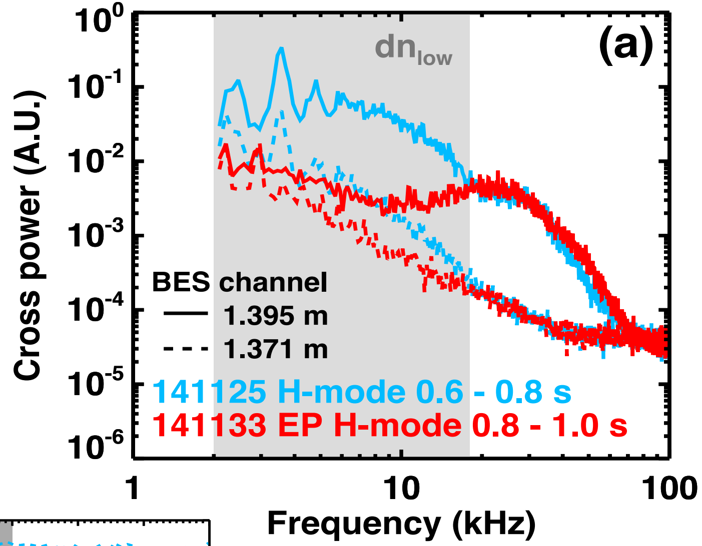


BES ψ_N ~ 0.87

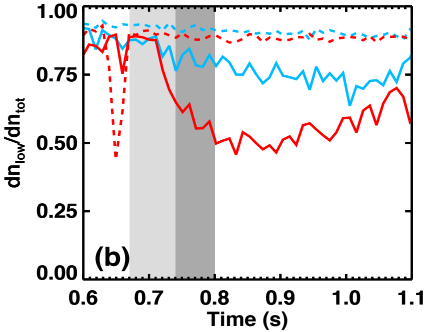
Magnetics

Biggest difference in BES spectra between WP and EP H-mode occurs below 20 kHz

- Average BES spectra over a 200ms time window for 2 edge channels
  - Broad modes from 2 – 80 kHz on channels imaging ψ_N > 0.8 (solid lines)
    - Not observed ψ_N < 0.8 (dashed lines)
  - Low frequency (2 – 18 kHz) modes suppressed in EP H-mode (red)
    - Including coherent modes



- Time evolution of ratio of low frequency spectra (2 – 18 kHz) to total spectra (2 – 80 kHz)
  - Suppression begins near ∇P saturation



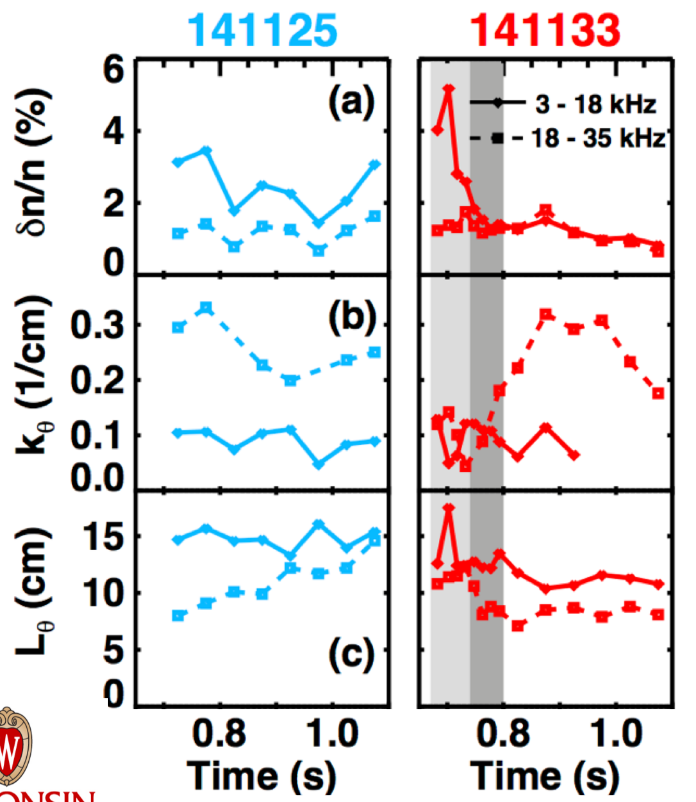
Poloidal BES array at ψ_N ~ 0.85 suggests the poloidal correlation of ion-scale modes is reduced in EP H-mode

- Single vertical array in BES system images above midplane $0.75 < \psi_N < 0.95$
  - Solid lines are low-f modes, dashed are mid-f modes

- Panel (a) shows drop in low-f (solid) dn/n for EP H-mode compared to WP

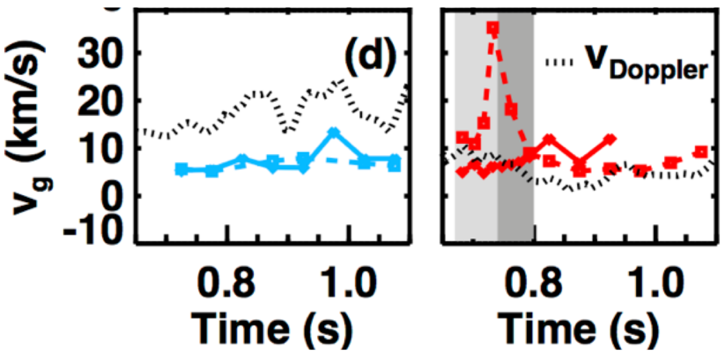
- Panel (b) shows mid-f k_θ about 2-3 times low-f except during ELM recovery

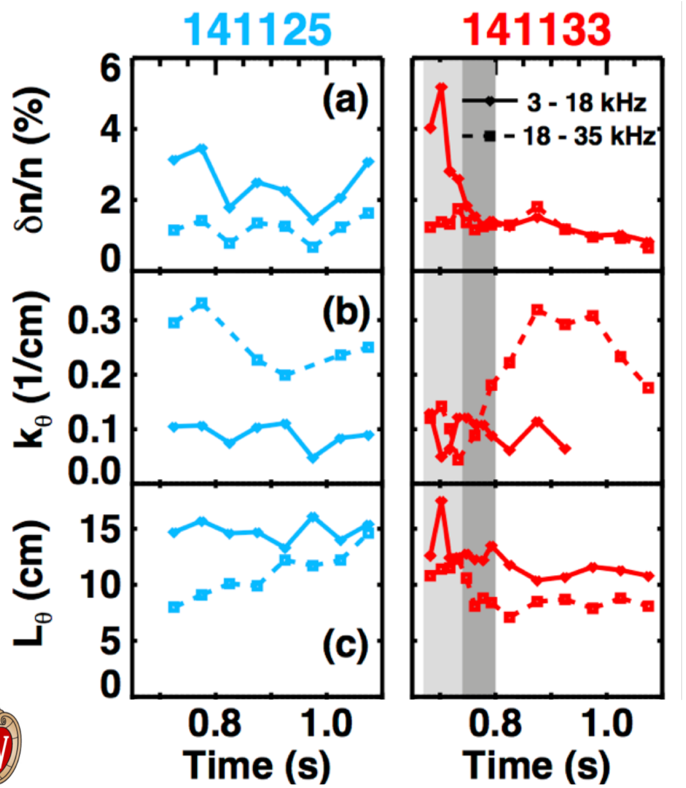
- Panel (c) shows poloidal correlation length lower in EP H-mode for all frequencies



Mode direction shifts from electron to ion diamagnetic directed in EP H-mode

- WP H-mode: group velocity is 10 km/s in e-dia direction in plasma frame
  - Consistent with TEM, MTM
- EP H-mode: v_g near Doppler velocity, slightly in i-dia direction
  - Large jump in v_g near onset of grad-P saturation
  - Consistent with MHD-like: KBM, kink-peeling





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Characterizing edge instabilities and associated transport is an ongoing activity (R20-1 milestone)

- Hypothesis is that MHD-like activity clamps ∇P by inducing transport, with outsized impact on total D

- WP and EP H-mode have similar linear stability thresholds
  - No "slam dunk" in terms of crossing a stability threshold

- BES shows lower dn/n, smaller poloidal correlation in EP H-mode
  - Appears to counter hypothesis of increased transport
  - Low-f modes impact SOL; suppression in EP H-mode may change SOL

- BES and magnetics suggest edge modes become more MHD-like
  - Propagation shifts toward ion-diamagnetic direction in the plasma frame
  - Stronger detection of EHO-like oscillations in magnetics with $\Delta f \sim 10$ kHz

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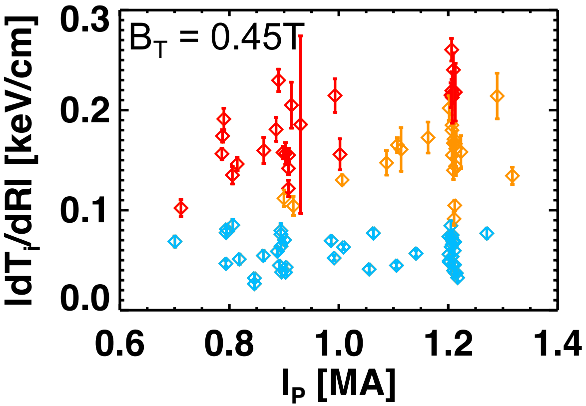
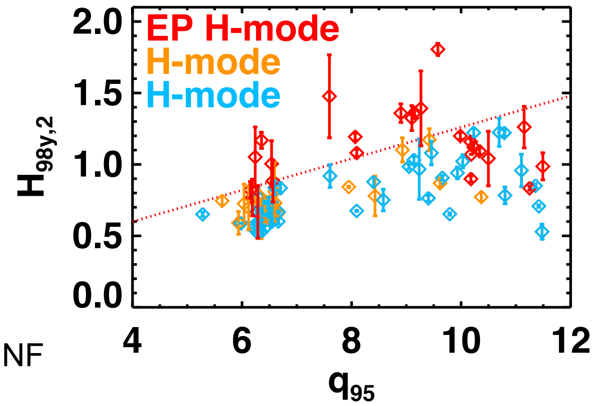
Best EP H-mode performance achieved on NSTX with I_p/B_T = 2MA/T at q_{95} ~ 9

- Highest normalized confinement achieved with q_{95} ~ 9, I_p ~ 0.9MA
  - Smaller q_{95} (larger I_p): easier to get steep edge ∇T_i,
    - $q_0 \rightarrow 1$ soon after entering EP H-mode
  - Larger q_{95} (smaller I_p): need a lower edge density and harder to get long ELM-free periods
- High performance target on NSTX-U is I_p = 2 MA, B_T = 1T with q_{95} ~ 9





Data set from:
S. Gerhardt et al., NF 54, 083021 (2014)

New tools on NSTX-U should improve access and sustainment of EP H-mode

- Double I_p, B_T, n_e, P_{NBI} (same n_{GR}) in simple models
  - Bifurcation regime accessed at larger edge n_{GR} due to $\chi_{i,neo} \propto T_i^{1/2}$
  - Saturated EP H-mode phase sensitive to assumed anomalous electron and ion thermal transport levels

- More tangential NBI + expanded control of non-axisymmetric fields will improve sustainment and provide actuator for optimizing discharges
  - Drive off-axis current to avoid $q_0 \rightarrow 1$
  - Increase edge rotation shear for modifying edge stability through E_r shear

- Expanded wall conditioning capabilities
  - Improved bake-out system and evaporative lithium coverage
  - Longer inter-shot helium GDC
  - Possible reduction in carbon production with fish-scaled tiles
  - Intra-shot conditioning with lithium injection (granule and dropper)

- Expanded diagnostic capability

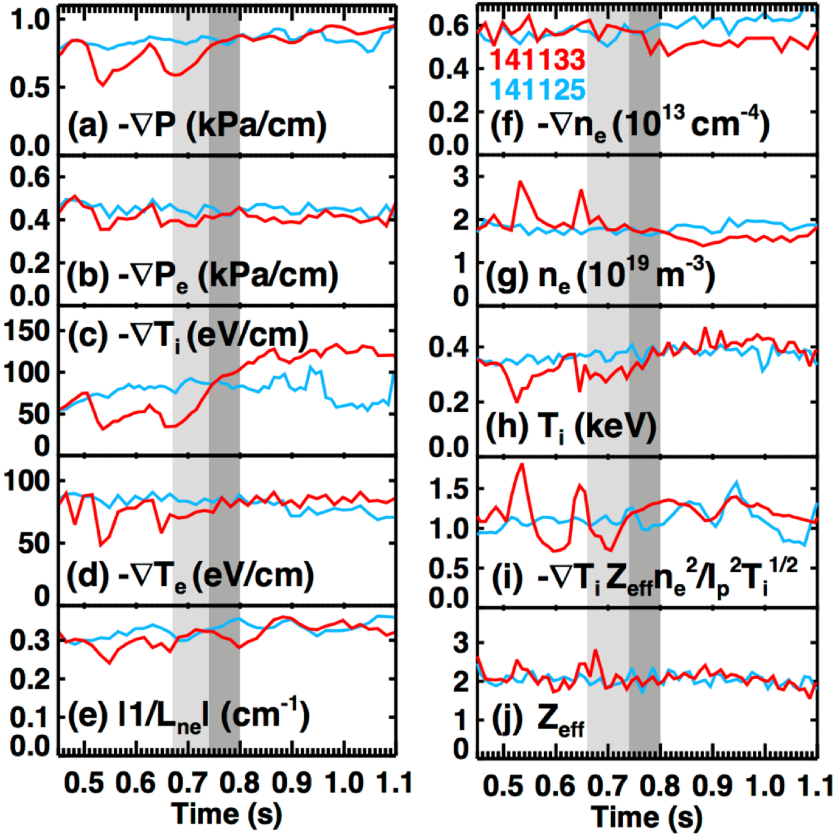
Summary

- EP H-mode is an attractive operating regime for compact fusion devices
  - ELM-free with enhanced edge particle transport (similar to wide-pedestal QH-mode)
  - Enhanced thermal confinement at high β_p with large f_{GW} and f_{BS}
  - NSTX-U will have new tools to sustain, optimize and understand scenario
- Improved thermal confinement and bifurcation following ELM consistent with neoclassical ion thermal transport
  - Simple models and database analysis demonstrates sensitivity to edge density and positive feedback between neo transport and pressure-driven particle transport
- Nature of anomalous transport changes in EP H-mode
  - ETG, MTM, TEM, KBM, K-P predicted to be linearly unstable in edge
  - BES and magnetic measurements suggest ion-scale density perturbations become more MHD-like (KBM, K-P) in EP H-mode
  - Low-frequency coherent perturbations are suppressed in EP H-mode

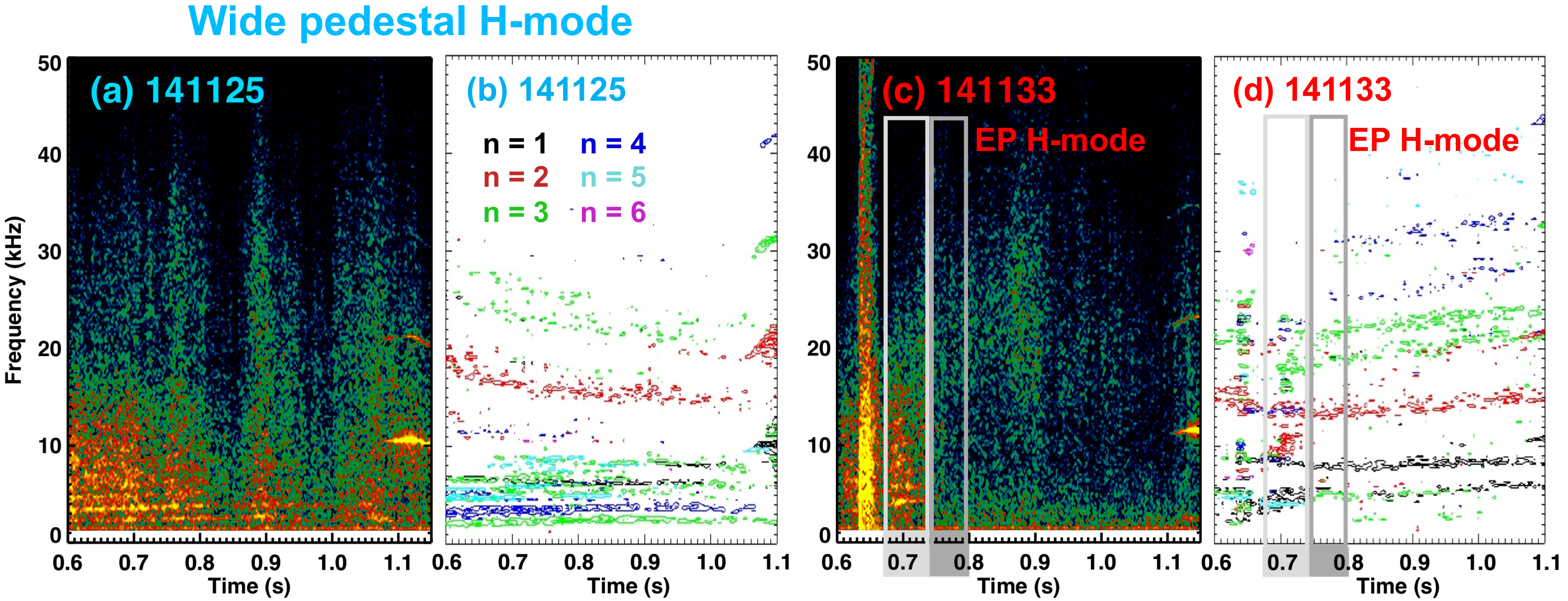
Backup and Extra material

Hypothesis: reduced neutral density leads to "∇T_i overshoot" during ELM recovery

- Plot shows time evolution of local parameters for ψ_N ~ 0.9 (T_e = 140 eV)
- At ∇P saturation (dark gray), ∇n_e decreases with ∇T_i overshoot
  - Assume onset of MHD-like instabilities (KBM, K-P) induce transport
    - Consistent with larger impact on total particle transport compared to total energy transport
  - Later (t > 0.8s) edge n_e decreases
- Larger $-\nabla T_i$ "locked in" after full D_α recovery by lower edge n_e
  - Consistent with neoclassical scaling

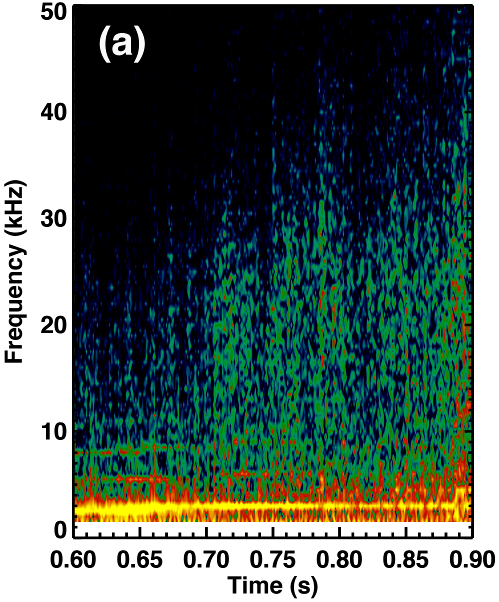


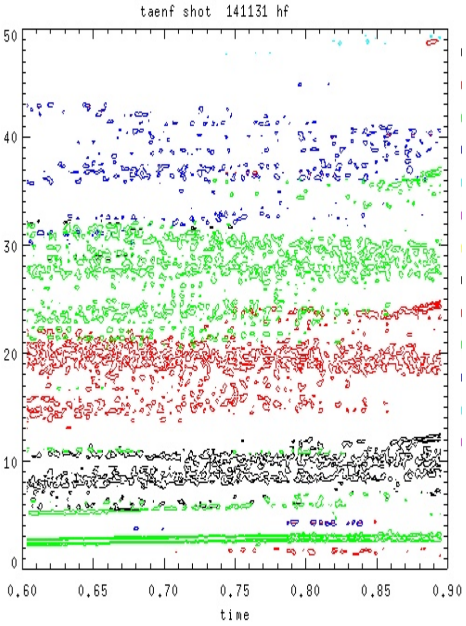
The biggest difference occurs below 10 kHz



BES $\psi_N \sim 0.84$ | Magnetics | BES $\psi_N \sim 0.87$ | Magnetics

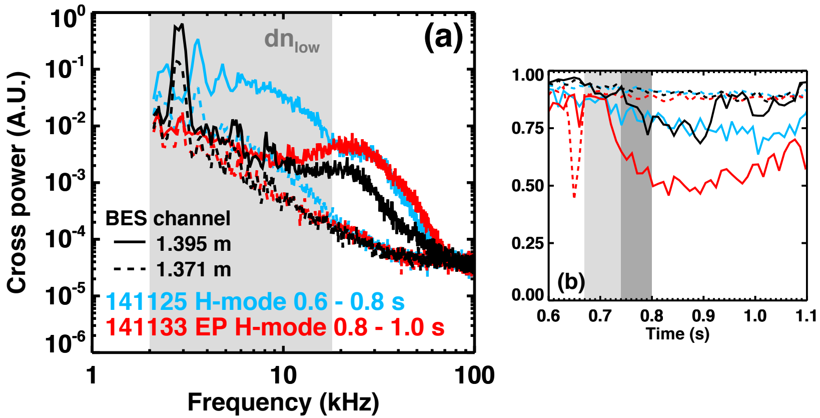
141131: H-mode with EFC only





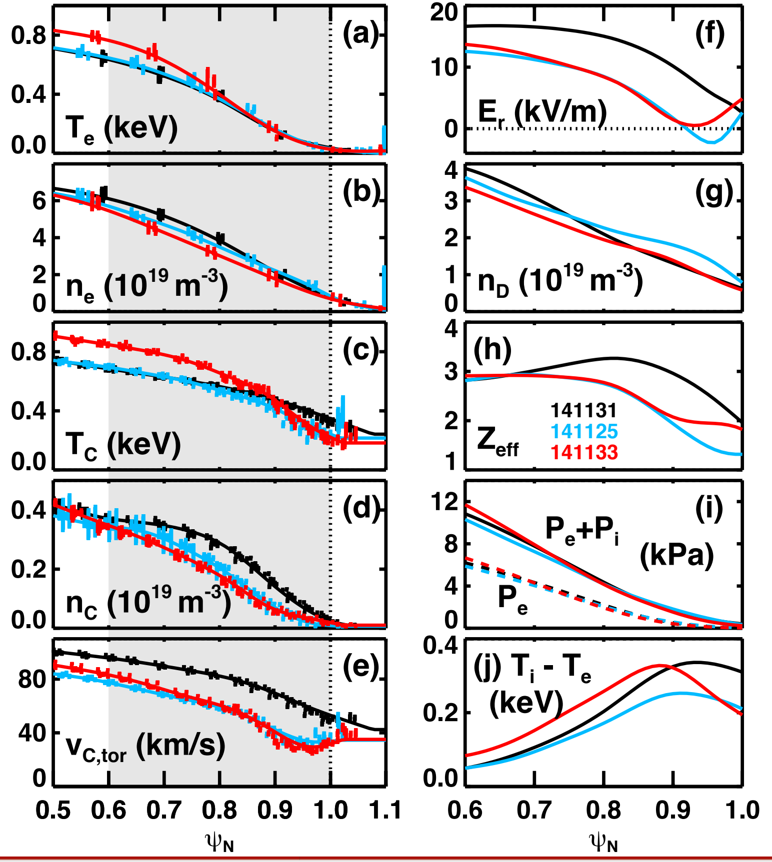
- Well defined 2.5 – 3 kHz edge mode
  - Fewer harmonic components detected
  - Similar frequency to 141125 despite differences in E_r, rotation
  - No broad spectra observed below 18 kHz, but dn_{low}/dn_{tot} similar to 141125

- Broadband EHO detected, but no broad spectra below 18 kHz

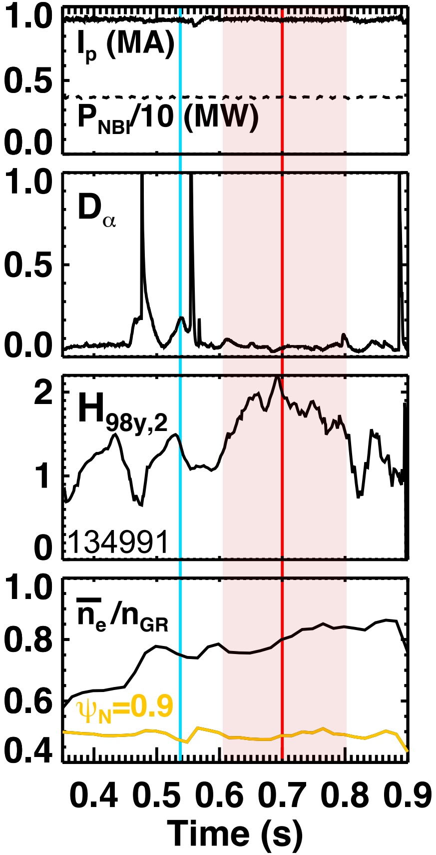


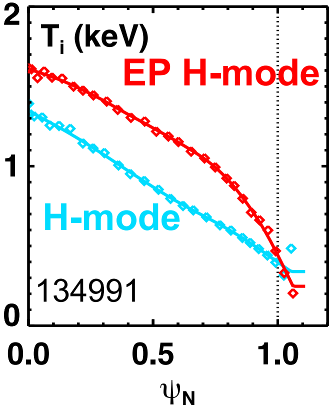
Three matched discharges provide good comparison for wide-pedestal and EP H-mode

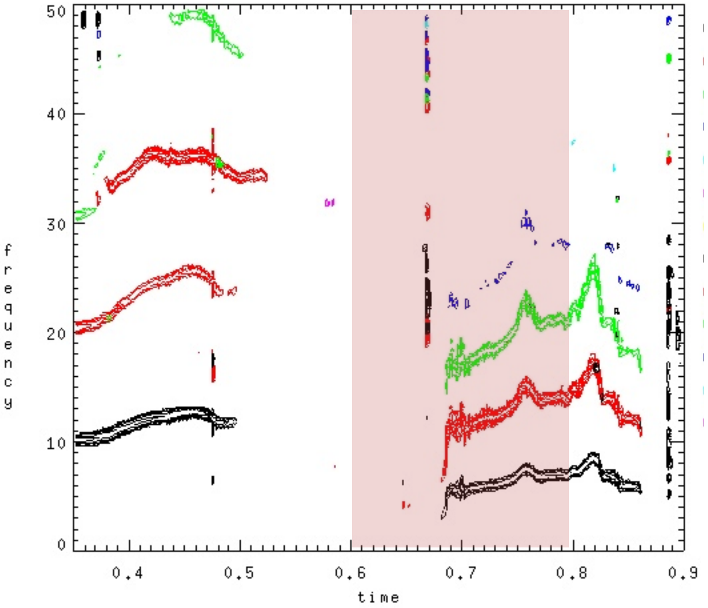
WP H-mode 141131 EFC only
WP H-mode 141125 EFC + 400A n=3
EP H-mode 141133 EFC + 500A n=3



Example of EP H-mode with higher normalized confinement (and a coherent EHO??)





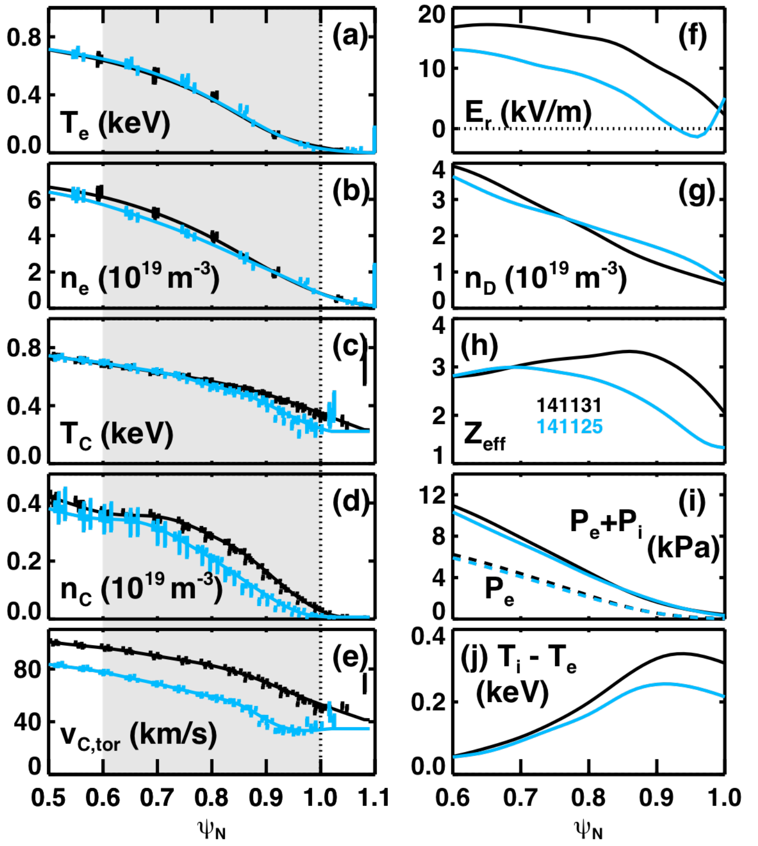


Preliminary hint that modes between 0.7 – 0.87s are edge localized (no BES available).
Observed when shaping comes closer to DN

Non-resonant 3D fields in WP regime alters edge E_r, Z_{eff}

- Small impact on electron profiles
  - Little change to T_e
  - n_e slightly broader in edge region
- Bigger impact on ion profiles
  - Rotation, E_r reduced via NTV
  - T_i smaller in edge, matched in core
  - n_D broader, n_C pedestal shifts inwards
    - Significant reduction in edge Z_{eff}
- Pressure profiles are similar

WP H-mode 141131 EFC only
WP H-mode 141125 EFC + 400A n=3
EP H-mode 141133 EFC + 500A n=3



Three matched discharges provide good comparison for wide-pedestal and EP H-mode

- Compare MHD-quiescent periods at matched $n_{e,avg}$
  - B_T = 0.45T, I_p = 0.9MA, 3 MW NBI, $q_0 < 2$, $q_{95} \sim 9$, near DN

WP H-mode 141131 EFC only
WP H-mode 141125 EFC + 400A n=3
EP H-mode 141133 EFC + 500A n=3

- Long ELM-free periods with lithium wall conditioning
  - Non-resonant 3D field alters edge, induces ELMs
  - 600A current in 3D coils induces regular ELMs
  - EP H-mode discharge has 2 ELMs, then ELM-free
- $H_{98y,2}$ = 1.2 in WP, $H_{98y,2}$ = 1.35 in EP
  - Modest EP H-mode with β_N = 5.5