NSTX-U

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Bifurcation to Enhanced Pedestal (EP) H-mode on NSTX

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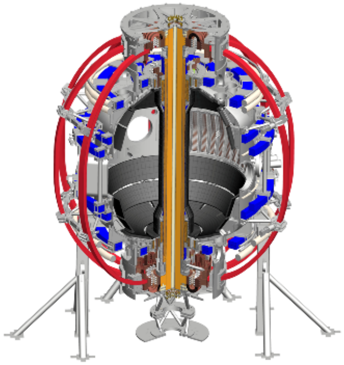
PPPL

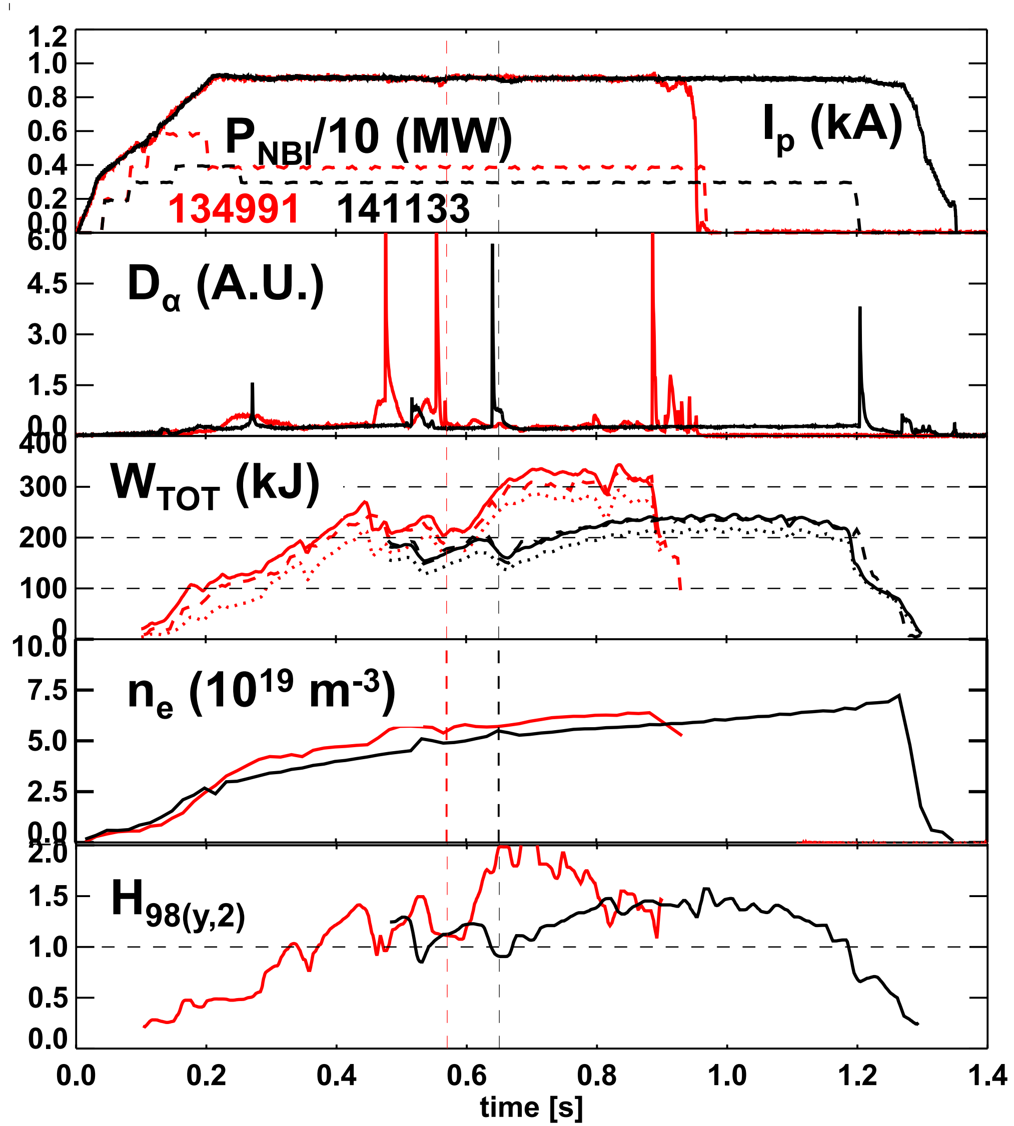


Outline

- Characteristics of the Enhanced Pedestal (EP) H-mode on NSTX
- Evidence for the role of ion collisionality in the bifurcation criteria
- Properties of neoclassical and anomalous transport in EP H-mode

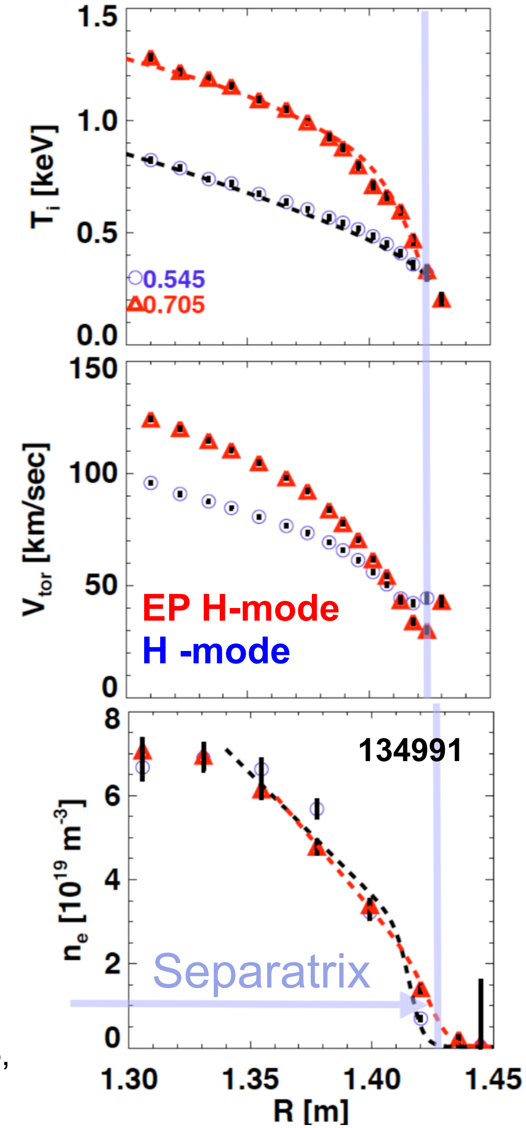
Enhanced Pedestal (EP) H-mode discharges on NSTX bifurcate to larger $H_{98(y,2)}$

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



Majority of gain in stored energy due to increase in T_i gradient

- EP H-mode: bifurcation to a significantly larger T_i gradient
  - Typically v_ϕ gradients increase concurrently with T_i gradient
  - Typically reduced gradient in n_e, n_C
- Impact on T_e pedestal can vary
  - Often the T_e pedestal becomes wider
  - Sometimes the T_e gradient increases
- Often E_r well shifts inward

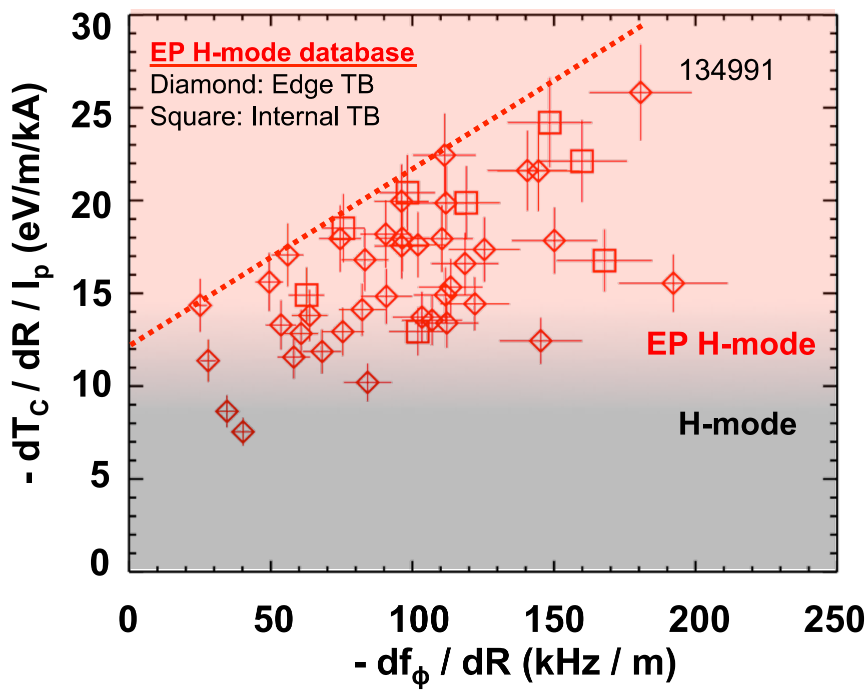


R. Maingi et al, PRL **105**, 135004 (2010)

Largest T_i gradients observed in discharges with large toroidal flow shear

- EP H-mode achieves largest local T_i gradients on NSTX
- Maximum dT_C/dR scales with rotation frequency gradient and I_p
  - Maximum T_i gradient tends to align with the minimum of a local E_r well

Local gradients in CHERs profiles



S. Gerhardt et al, NF **54**, 083021 (2014)

- Flow shear enables the best performance, but is not the sole requirement for EP H-mode
  - What other criteria must be met?

EP H-mode observed over a wide range of conditions on NSTX

- Transport barrier can occur at different locations
  - ITB-like or within H-mode pedestal
- Reduced neutral fueling is a common characteristic
  - Most often observed with lithium wall conditioning
- Transition most often occurs during an ELM recovery
  - Observed with both natural ELMs and triggered ELMs
  - Slow transition (unlike the L-H transition)
- Most often observed at low q_{95} (6 - 7)
  - Best performance at modest q_{95} ~ 10 that supports large $\beta_{p,ped}$ (~ 1)
- Observed over a wide range of shapes, I_p, B_T, q_{95}, β_p, P_{NBI}
  - EP H-mode has been observed with and without applied n=3 fields

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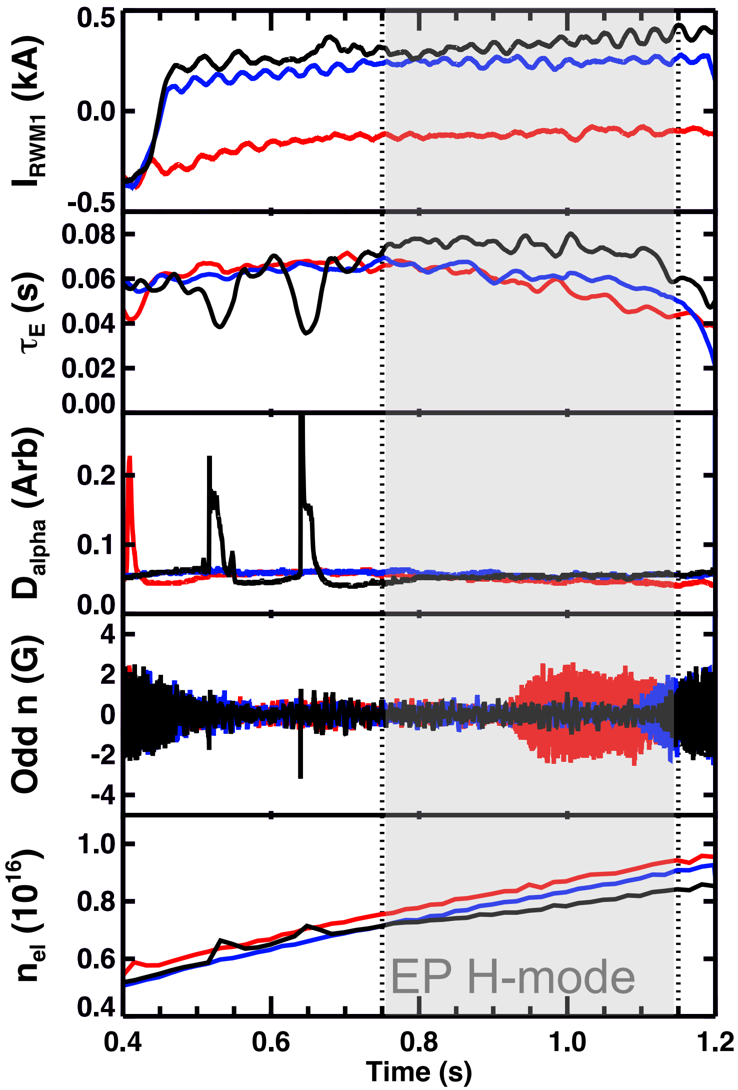
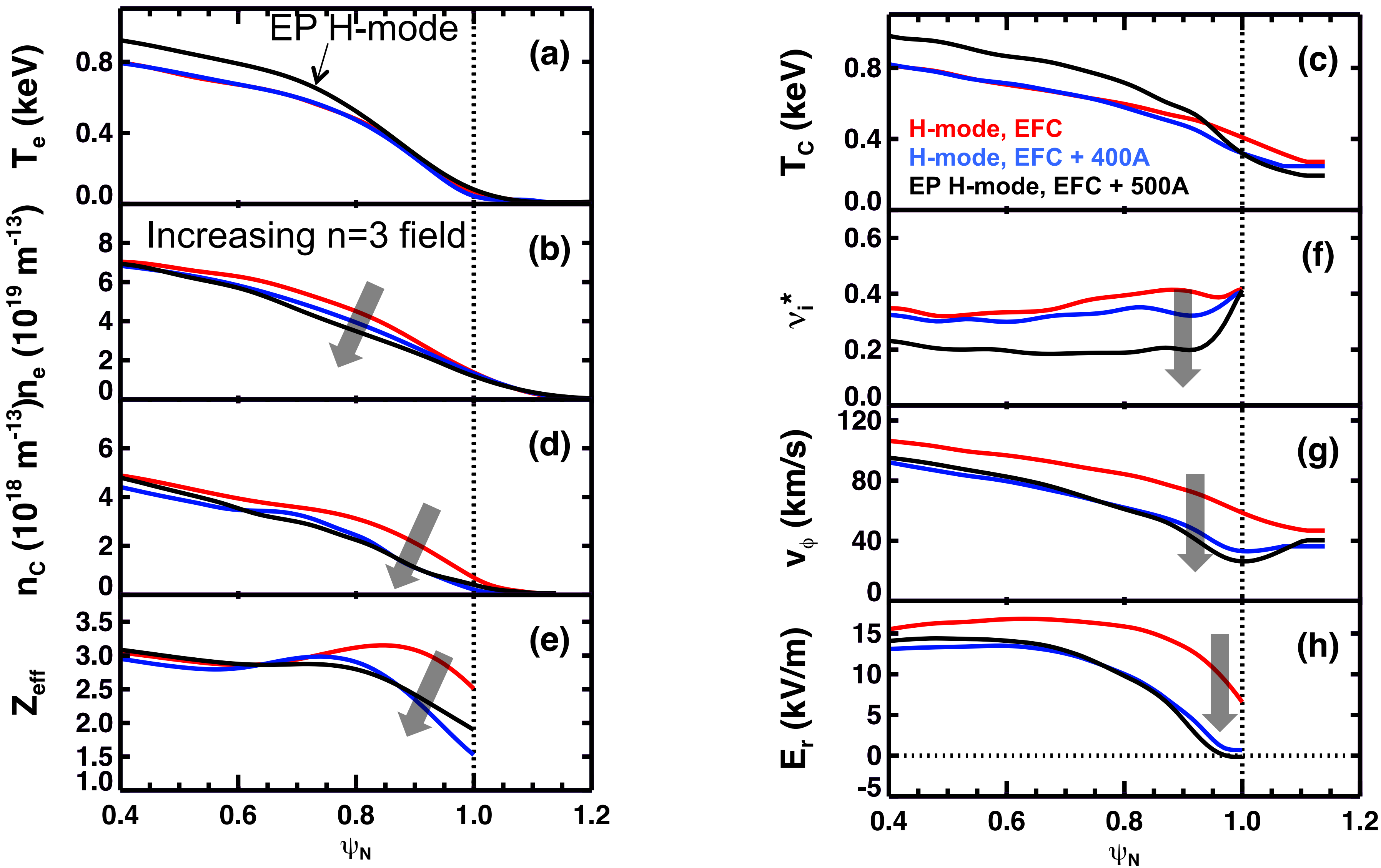
Scanning applied 3D field produced discharges around EP H-mode threshold



H-mode	EFC	141131
H-mode,	EFC + 400A	141125
EP H-mode	EFC + 500A	141133

- All discharges have a quiescent period to evaluate transport
  - Matched LSN high-triangularity shape
  - I_p = 900 kA, B_T = 0.45T, q_{95} ~ 9.5
  - P_{NBI} = 3 MW
  - Lithium wall conditioning
  - 100ms time windows for all profiles
- One EP H-mode shot (black)
  - Modestly larger τ_E
  - Reduced density rise

Applied n=3 field increases edge rotation and E_r shear and reduces edge Z_{eff}

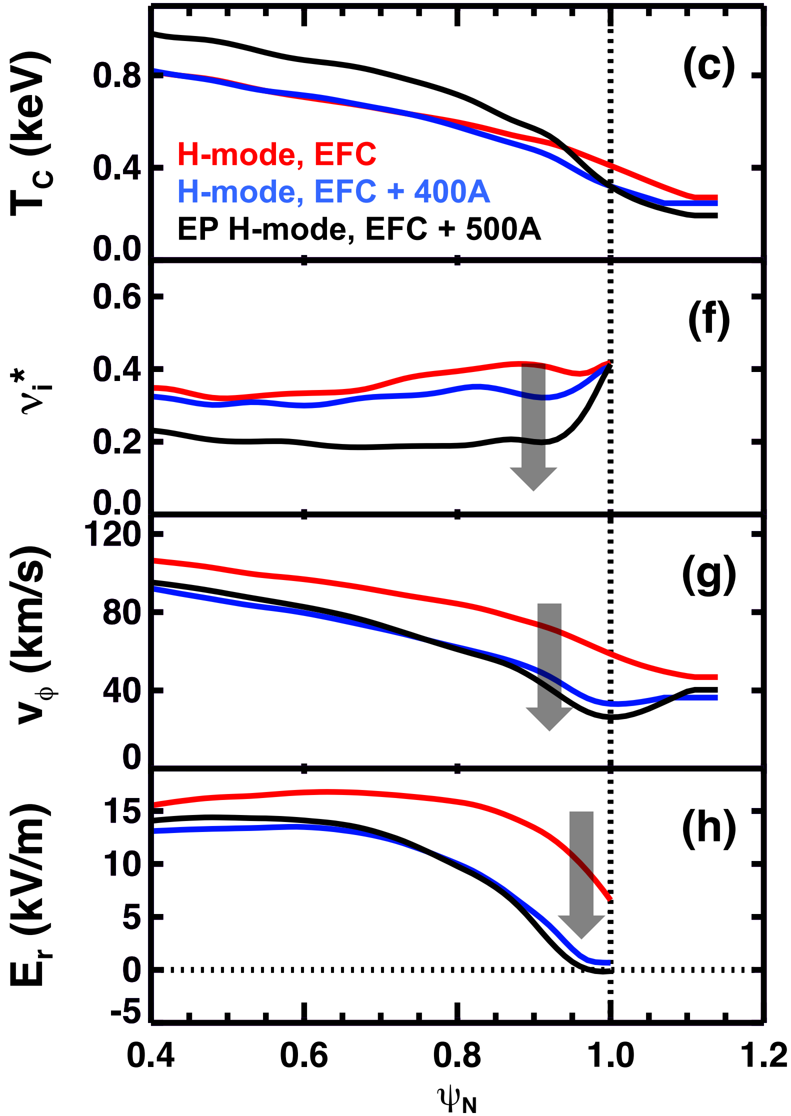


EP H-mode accesses significantly lower ion collisionality compared to H-mode

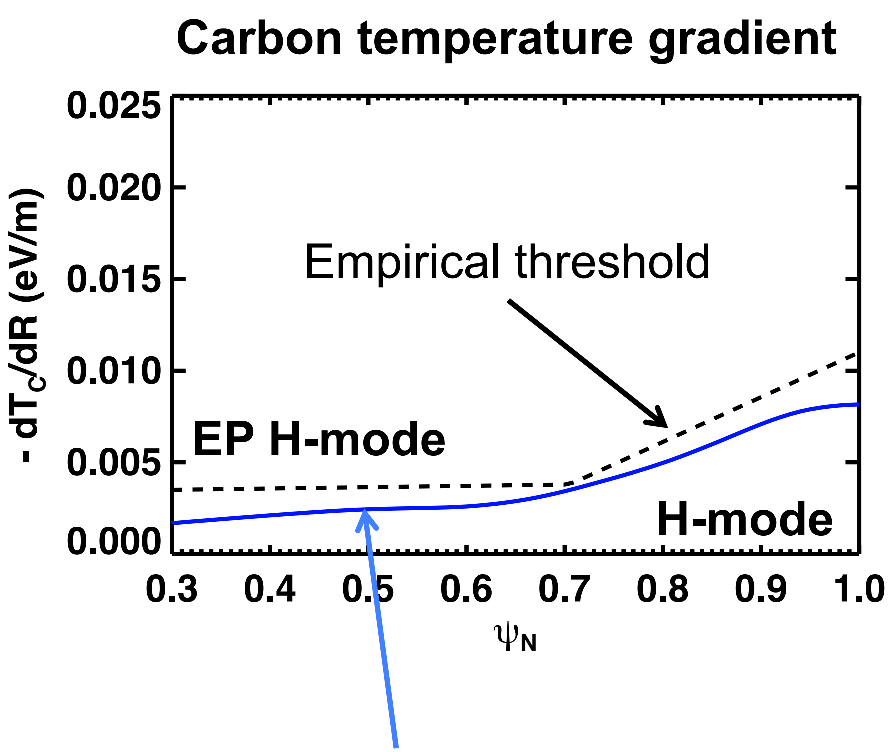
- Ion thermal transport changes with subtle change to v_ϕ and E_r

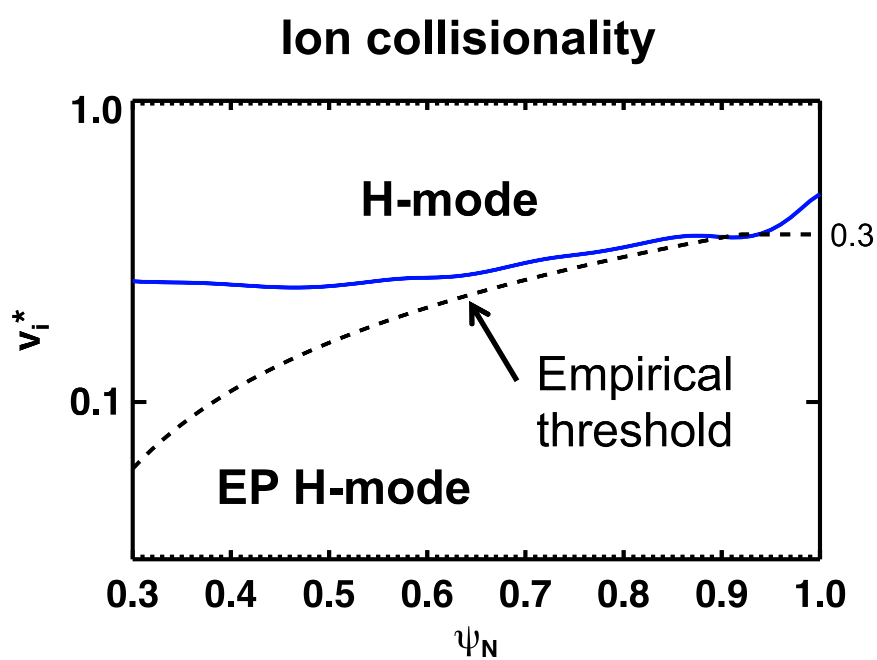
- Significant decrease in ion collisionality in EP H-mode

$$\nu_i^* \sim \frac{q R_0 n_e Z_{eff} \ln(\Lambda_{ii})}{T_i^2 (r/R_0)^{3/2}}$$



dT_i/dR exceeds H-mode levels when ν_i^* drops below a threshold

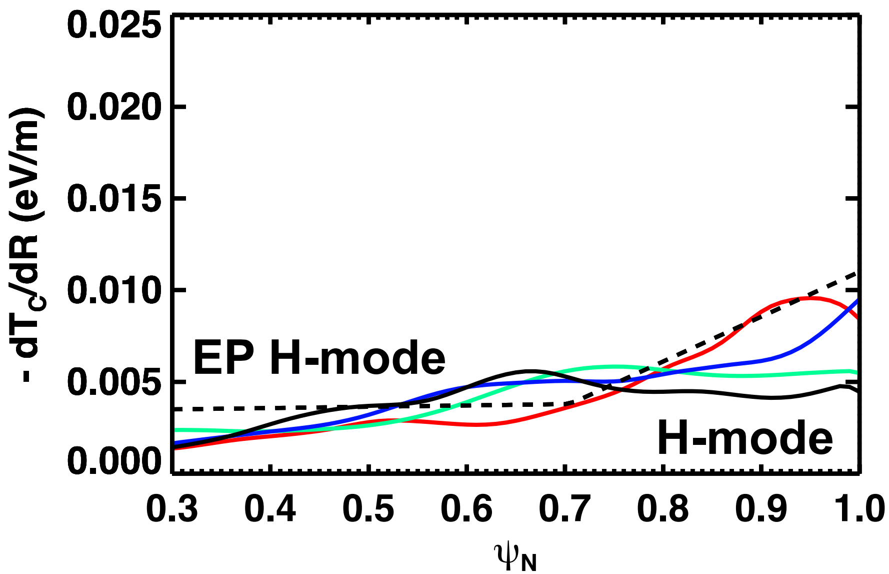




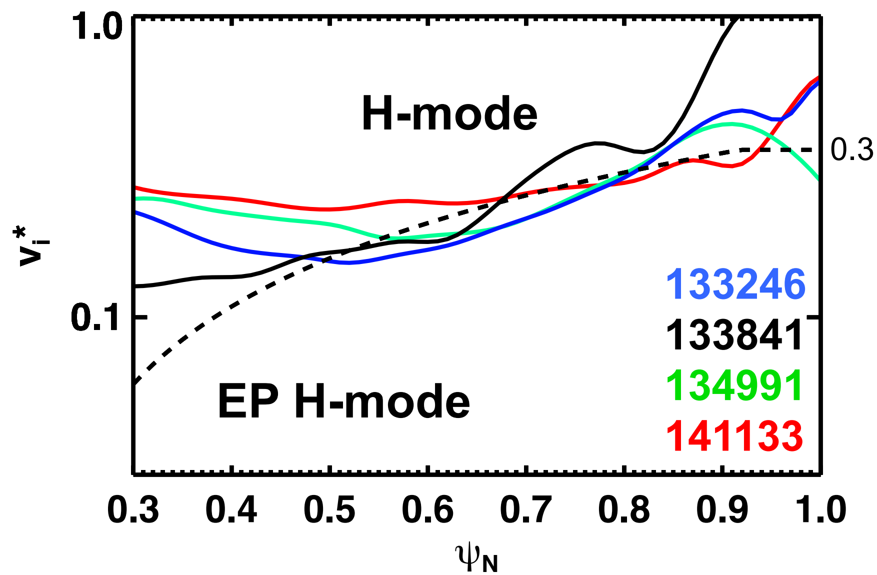
H-mode discharge close to EP H-mode threshold

dT_i/dR exceeds H-mode levels when ν_i^* drops below a threshold

Carbon temperature gradient



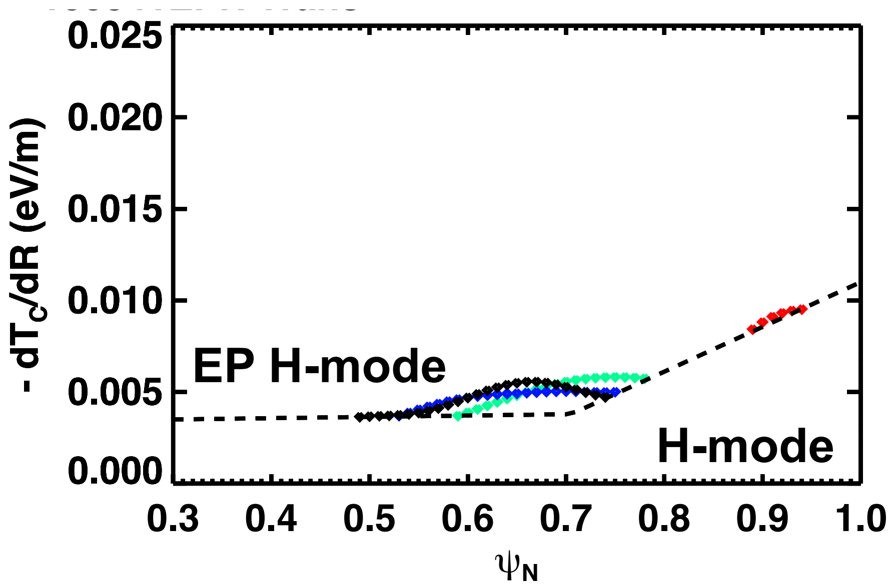
Ion collisionality



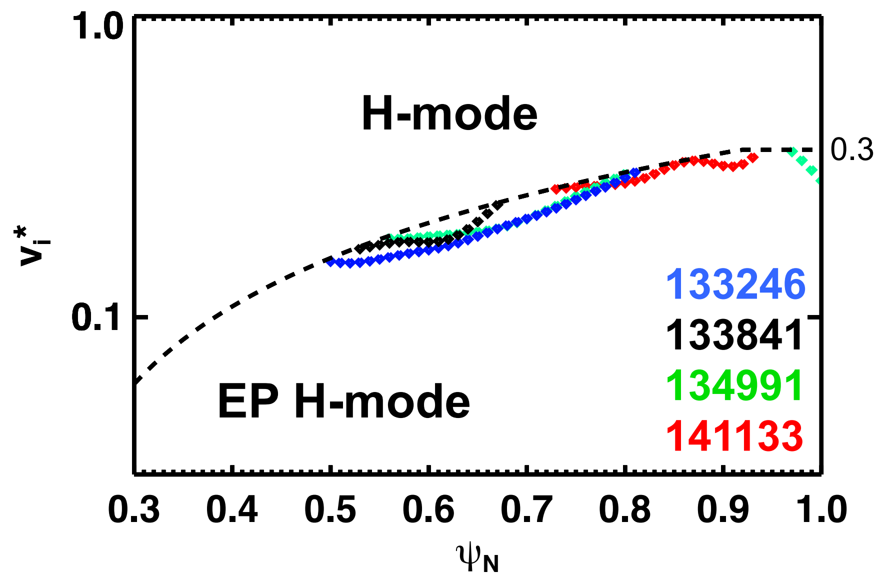
Four EP H-mode discharges at "bifurcation time"

dT_i/dR exceeds H-mode levels when ν_i^* drops below a threshold

Carbon temperature gradient



Ion collisionality



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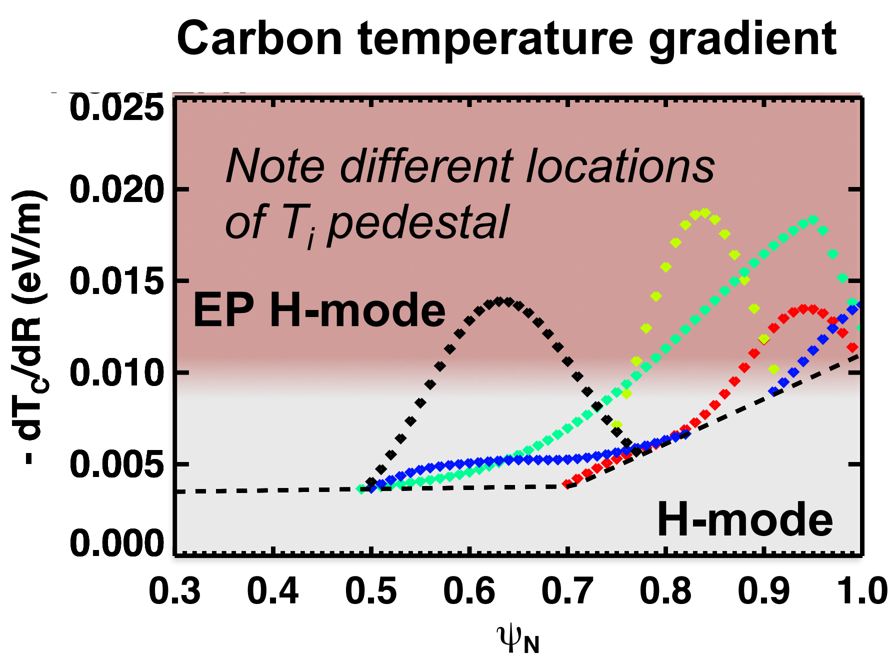

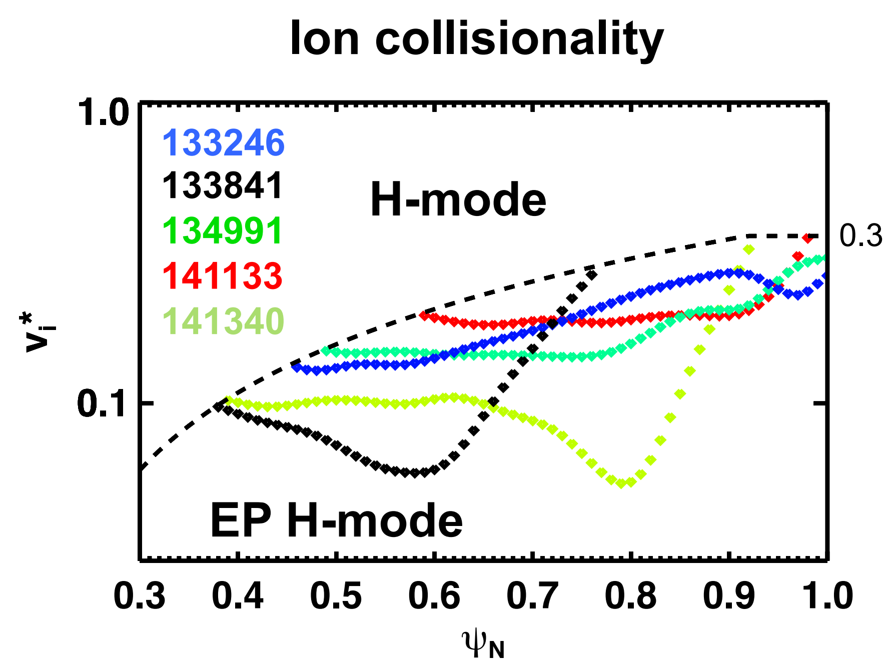

Period of maximum confinement in five EP H-mode discharges

Steep T_i gradients align with regions of low ion collisionality

New observations suggest low ion collisionality is a requirement for EP H-mode

- EP H-mode most often observed with …
  - Lower q_{95}
  - Lower neutral fueling
    → lower edge n_e, larger edge T_i

$$\nu_i^* \sim \frac{q\,R_0\,n_e\,Z_{eff}\,\ln(\Lambda_{ii})}{T_i^2\left(r/R_0\right)^{3/2}}$$

- ELM events are observed to …
  - Reduce edge n_e, Z_{eff}
  - Briefly achieve larger T_i after recovery

- Below a critical v_i*, ion thermal and momentum confinement improves in regions of moderate flow shear
  - Starts positive feedback loop, where T_i and v_ϕ gradients improve driving lower v_i* and more flow shear

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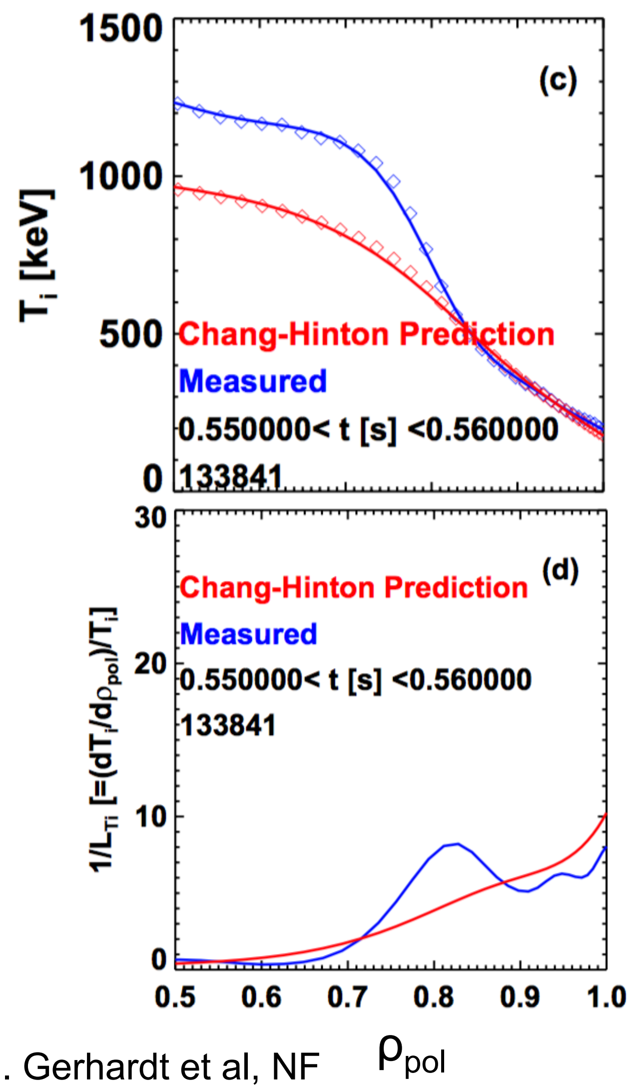
Non-local and kinetic neoclassical effects are important in EP H-mode

- Local neoclassical over-predicts χ_i in steep gradient region
  - Indicates non-local and kinetic effects must be included when evaluating NC transport
  - Future work will evaluate with neoclassical calculations (NEO, GTC-NEO, XGC0)

- Transport bifurcation at low ν_i^* may be due to neoclassical effects
  - For example, orbit-squeezing or non-linear changes to viscosity

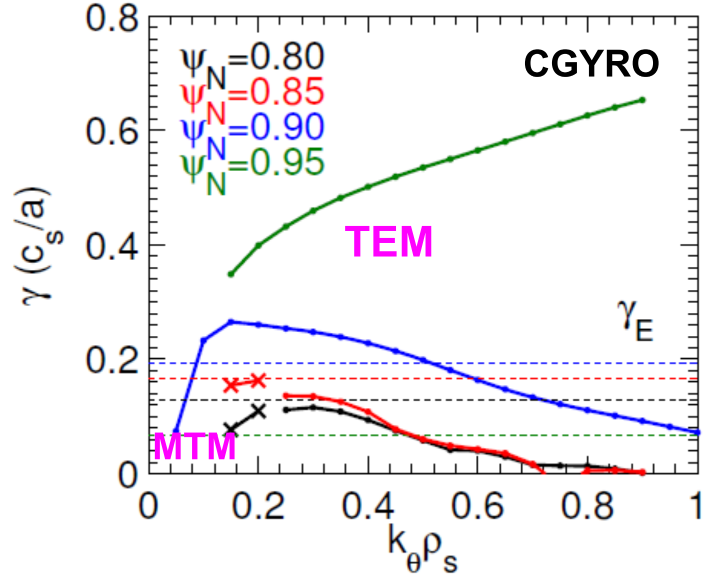


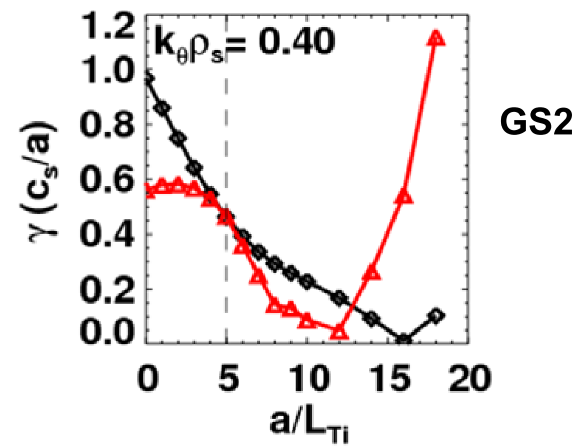
S. Gerhardt et al, NF **54**, 083021 (2014)

Linear CGYRO* simulations predict broad spectrum of electron drift waves in pedestal region

- Predominantly trapped electron modes (TEM) driven by ∇T_e ($a/L_{Te} > a/L_{ne} > a/L_{Ti}$)
  - Weak low-k_θ microtearing at some radii
- Growth rates larger than E×B shearing rates (γ_E) around steepest gradients ($\psi_N > 0.9$)
- Stabilized by ∇T_i – consistent with improved confinement?
  - Similar to previous EPH-mode calculation using GS2 [Gerhardt NF, 2014] and H-mode calculations using GEM [Smith NF, 2013]

Linear growth rates
141133 EP H-mode



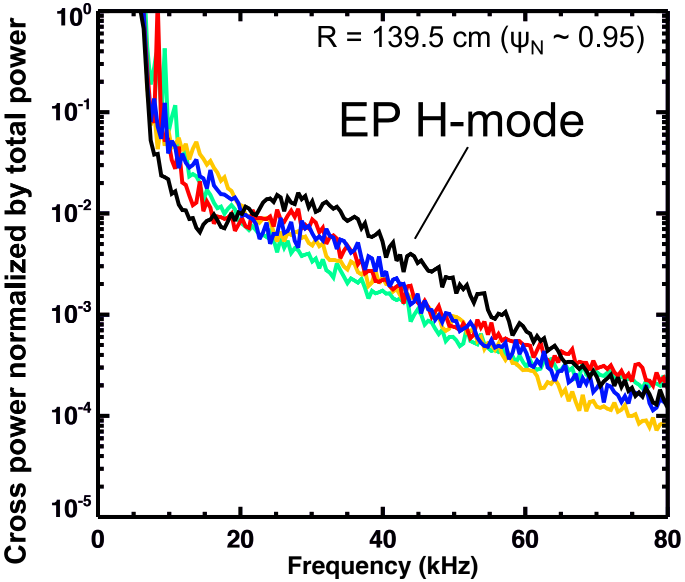


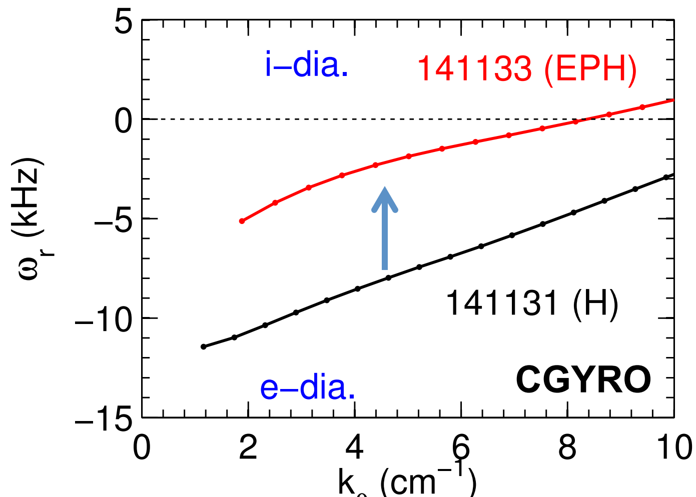
S. Gerhardt et al, NF **54**, 083021 (2014)

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

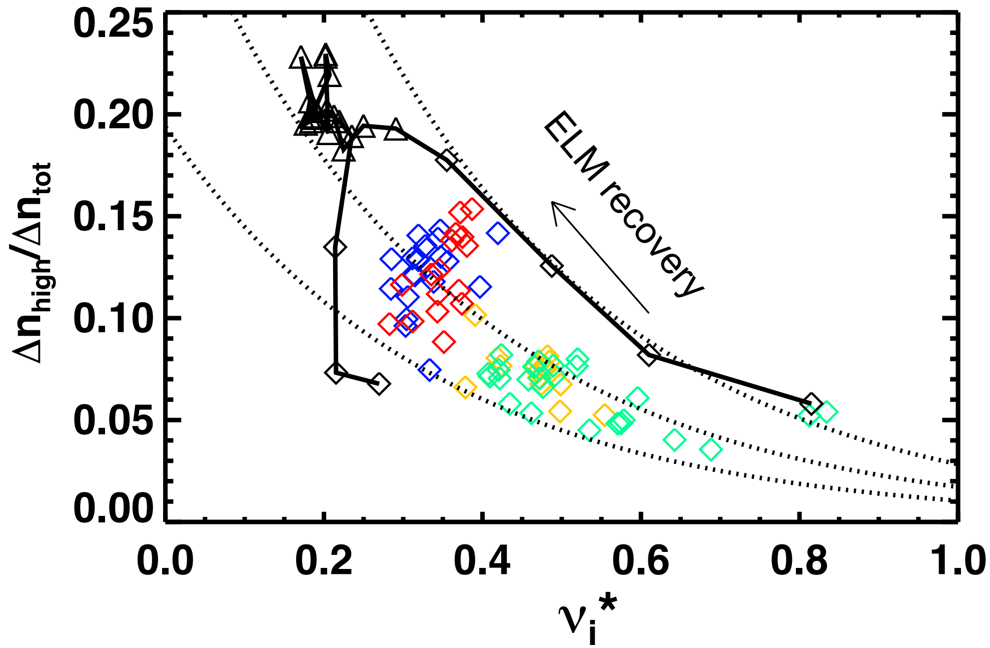
BES spectrum shifts to higher frequency in the region with the largest T_i gradient

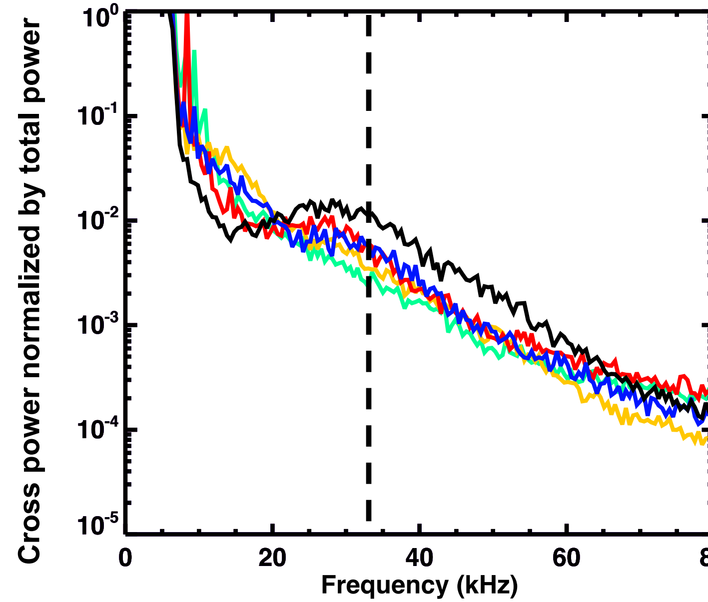
- BES cross power is suppressed below 30 kHz in EP H-mode
  - Largest change observed in region with large T_C gradient
  - Poloidal correlation length decreases in EP H-mode, consistent with shift to higher frequency
- Qualitatively consistent with predicted $\Delta\omega_r$ due to higher ∇T_i (opposite to change in $V_{doppler}$)





BES spectrum shifts to higher frequency, with lower ion collisionality





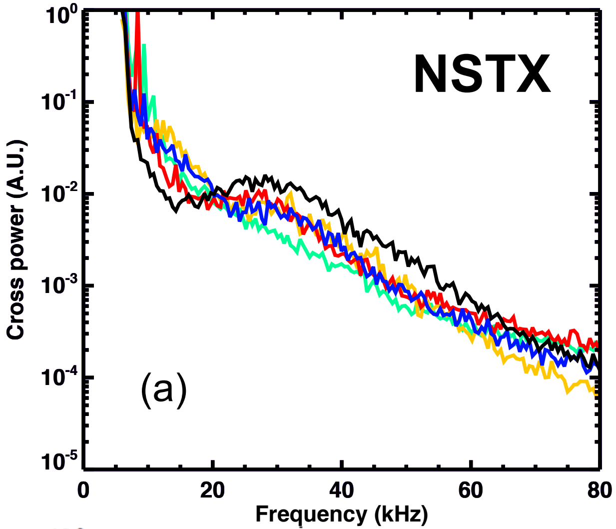
- Ratio of cross-power above 30 kHz increases as v_i^* decreases
  - Ratio does not scale as cleanly with other parameters, such as E_r or E_r'

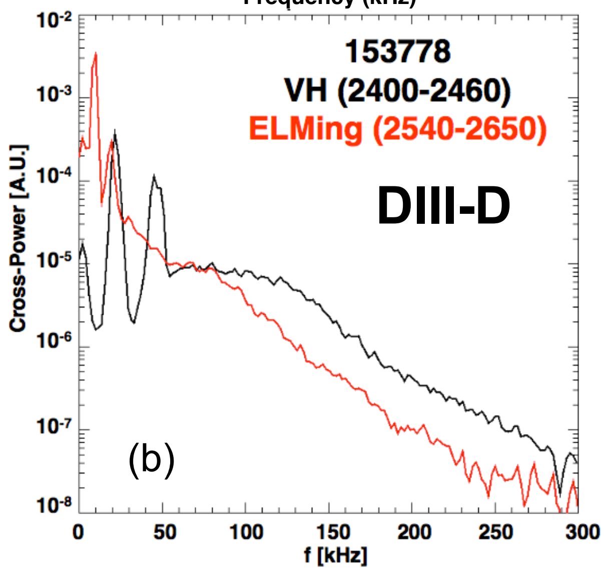
- Shift in BES is larger than H-mode discharges at similar v_i^* during ELM recovery in EP H-mode shot

Suppression of low-k modes at low ion collisionality could trigger EP H-mode

- Suppose low-n modes are stabilized at a critical ν_i^*
- Gyro orbits of trapped ions in the tail of the energy distribution average over higher-n perturbations
  - Ion thermal and momentum transport sensitive to transport of deuterium ions in the tail of the energy distribution
- Improved ion thermal and momentum confinement drives ν_i^* lower, initiating positive feedback mechanism
  - Inspired by quantitative description of the separation of thermal and particle transport in an ITB as described by G. Staebler [PoP, 2014]

Transport bifurcation in EP H-mode similar to other high confinement scenarios





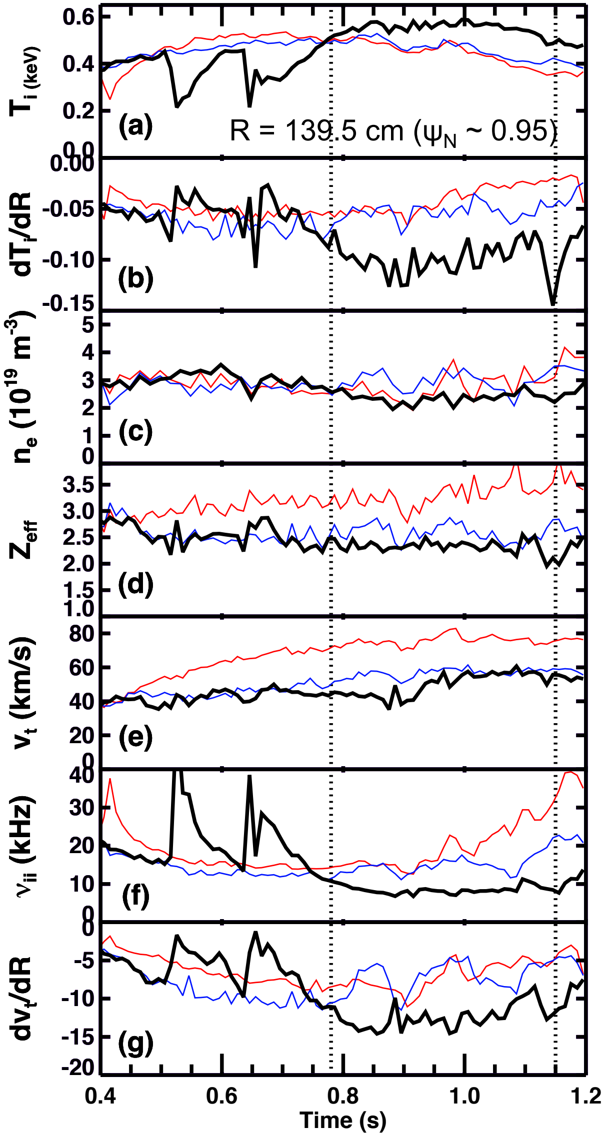
- VH-mode is a transient ELM-free scenario with large energy confinement on DIII-D
  - Most often observed following boronization
  - Broad pedestal with $H_{98y2} > 2$
  - Facilitated by large edge rotation shear
- Qualitative features in BES spectrum similar to EP H-mode
- EP H-mode transport barrier shares some characteristics with reverse shear ITBs

Summary

- EP H-mode is an attractive scenario for NSTX-U and future ST devices
  - Increase in ion energy and momentum confinement with beneficial increase in particle transport
- EP H-mode realized at low ion collisionality
  - Maximum dT_i/dR scales with toroidal flow shear (~ dE_r/dR)
  - Location of large dT_i/dR aligns with location of low ν_i^* in the edge profiles
- Neoclassical and gyrokinetic calculations are underway to investigate mechanisms that could trigger and/or sustain EP H-mode
  - NSTX-U will further explore physics via access to lower collisionality and greater control of v_ϕ shear compared to NSTX

Backup

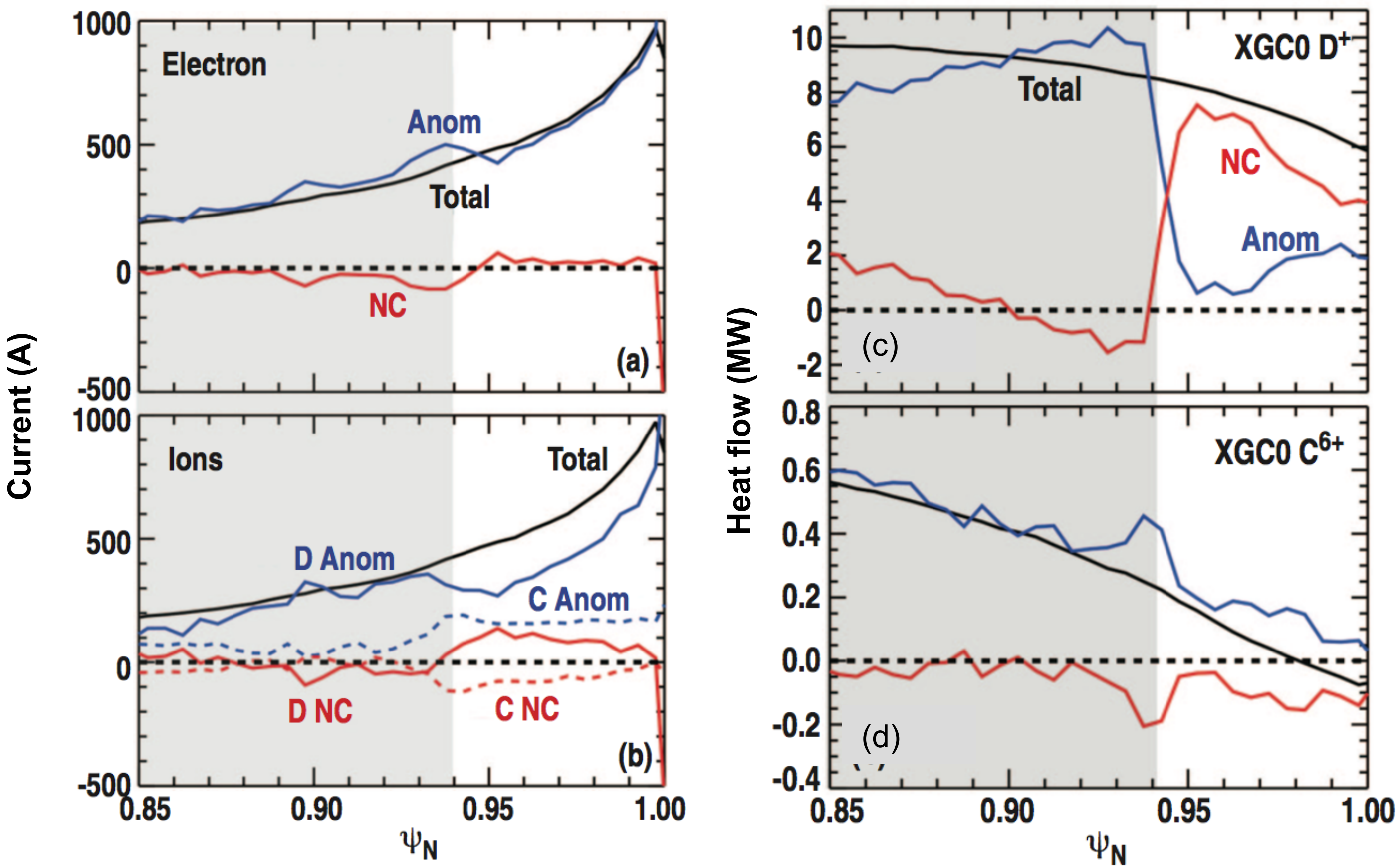
EP H-mode bifurcation occurs during the recovery of T_i after an ELM



- dTi/dR, dvt/dR and ν_{ii} concurrently deviate from H-mode levels
- Low ν_{ii} at time of bifurcation accessed via low edge n_e and Z_{eff}
- Collisionality for $\psi_N < 0.95$ driven lower by increase in T_i

Consistent with total thermal transport set by tail deuterium ions at low ν_{ii}

XGC0 simulation of transport in a low collisionality QH-mode discharge on DIII-D



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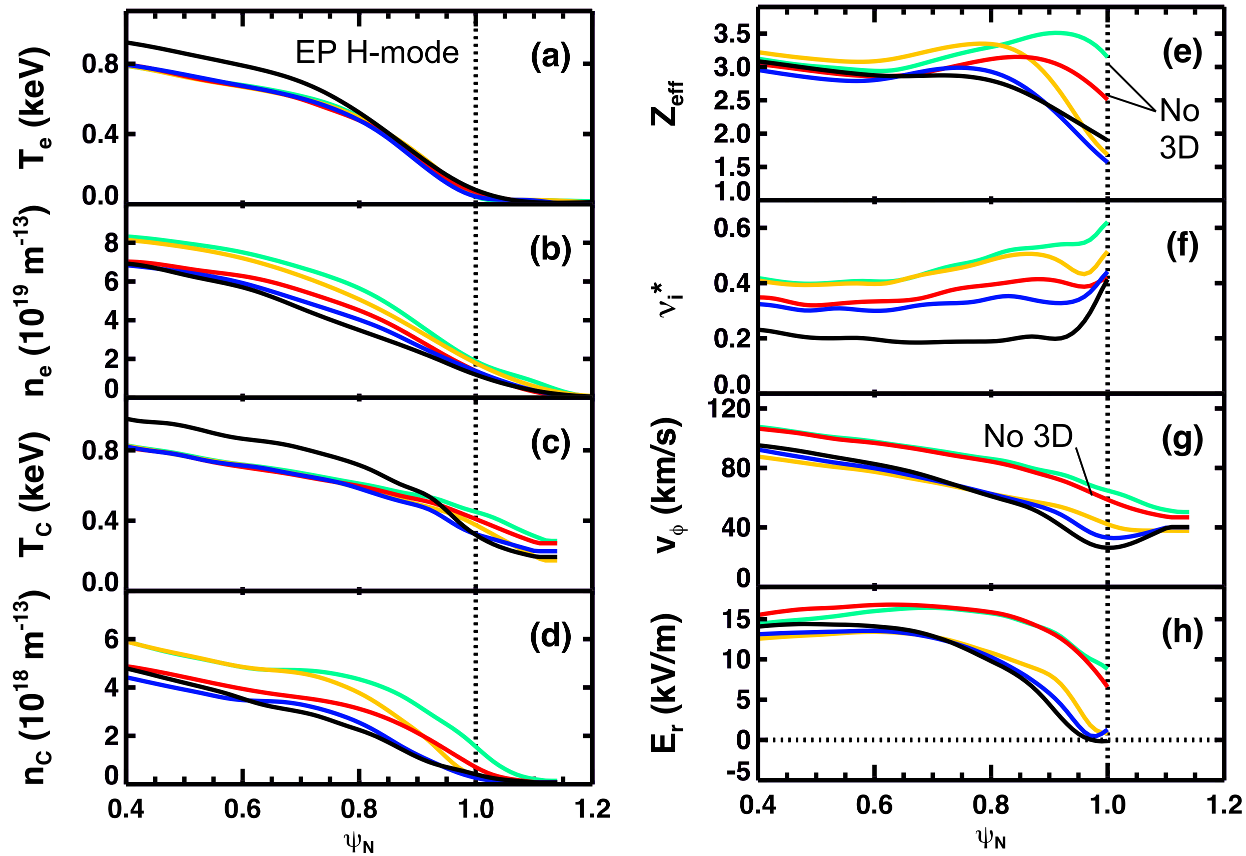
Particle transport (left column) dominated by anomalous transport, whereas energy transport (right column) dominated by kinetic neoclassical (NC) transport of deuterium ions via loss orbits of tail ions.

New capabilities on NSTX-U will advance understanding and utility of EP H-mode

- Edge rotation control with tangential NBI + 3D fields
  - Future: NCC coils provide additional edge rotation control
- ELM control with lithium pellet injector, 3D fields
- Expanded edge Thomson and BES capabilities
- Lower collisionality via higher fields
  - Also change in characteristic ion gyro and banana orbit size
- Edge instability characteristics at higher fields and aspect ratio

Applied n=3 field increases edge rotation shear and reduces edge Z_{eff}

- Increasing 3D field
  - Shallower n_e gradient
  - Reduces edge v_ϕ
  - Reduces E_r
  - Shifts n_C pedestal inwards
  - Reduces edge Z_{eff} and v_i*
- EP H-mode bifurcation
  - Wider T_e pedestal
  - Steeper T_C gradient
  - Much lower v_i*
  - Subtle change to v_ϕ and E_r



H-mode, EFC, 3.0 MW NBI
H-mode, EFC, 3.9 MW NBI
H-mode, EFC + 400A, 3.0 MW NBI
H-mode, EFC + 400A, 3.9 MW NBI
EP H-mode, EFC + 500A, 3.0 MW NBI