NSTX-U

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# Progress in Understanding the Enhanced Pedestal H-Mode in NSTX


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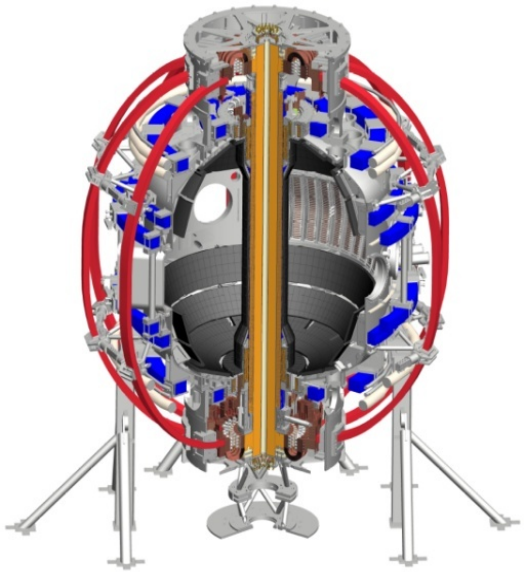
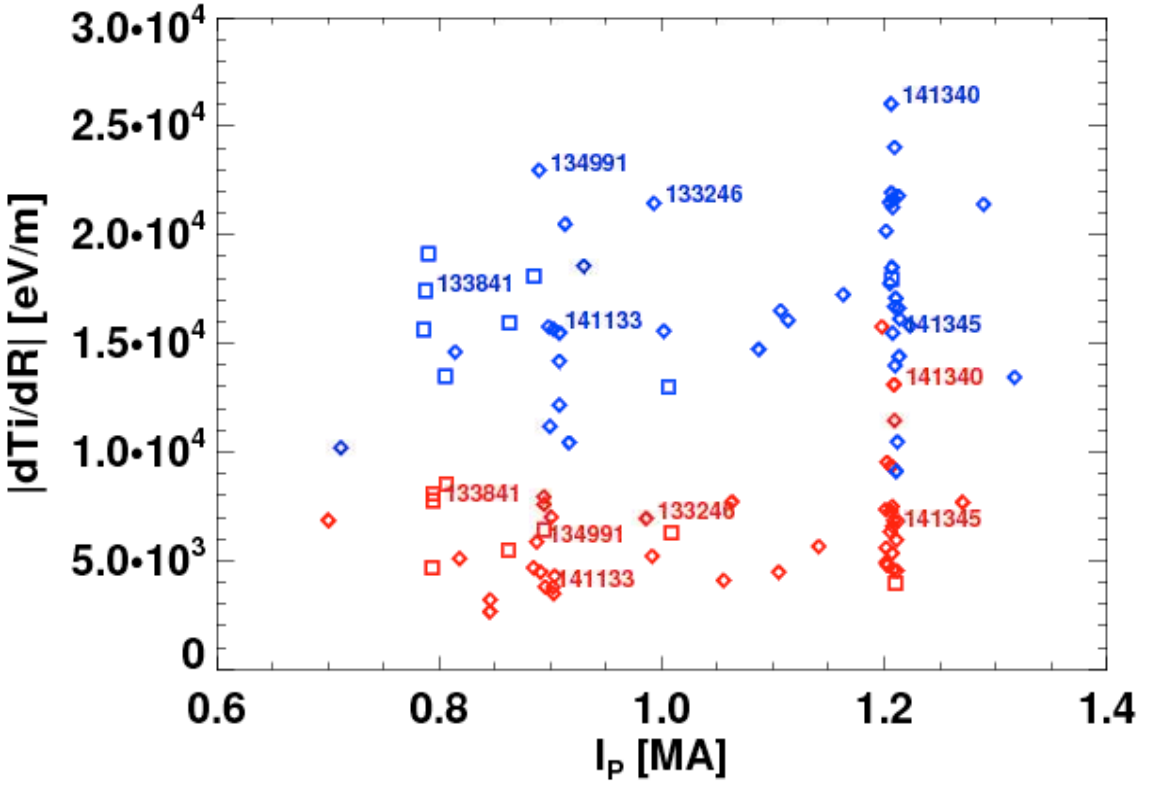


# How Do We Identify an Enhanced Pedestal (EP) H-mode?

- Should have a discrete transition to a higher confinement regime after the L->H transition.
- Should have a very steep gradient in the ion temperature, somewhere in the outer region of the plasma.
  - Which often, but not always, translates to improved global confinement.
- Should have a region of sharp rotation shear in the vicinity of the $T_i$ gradient

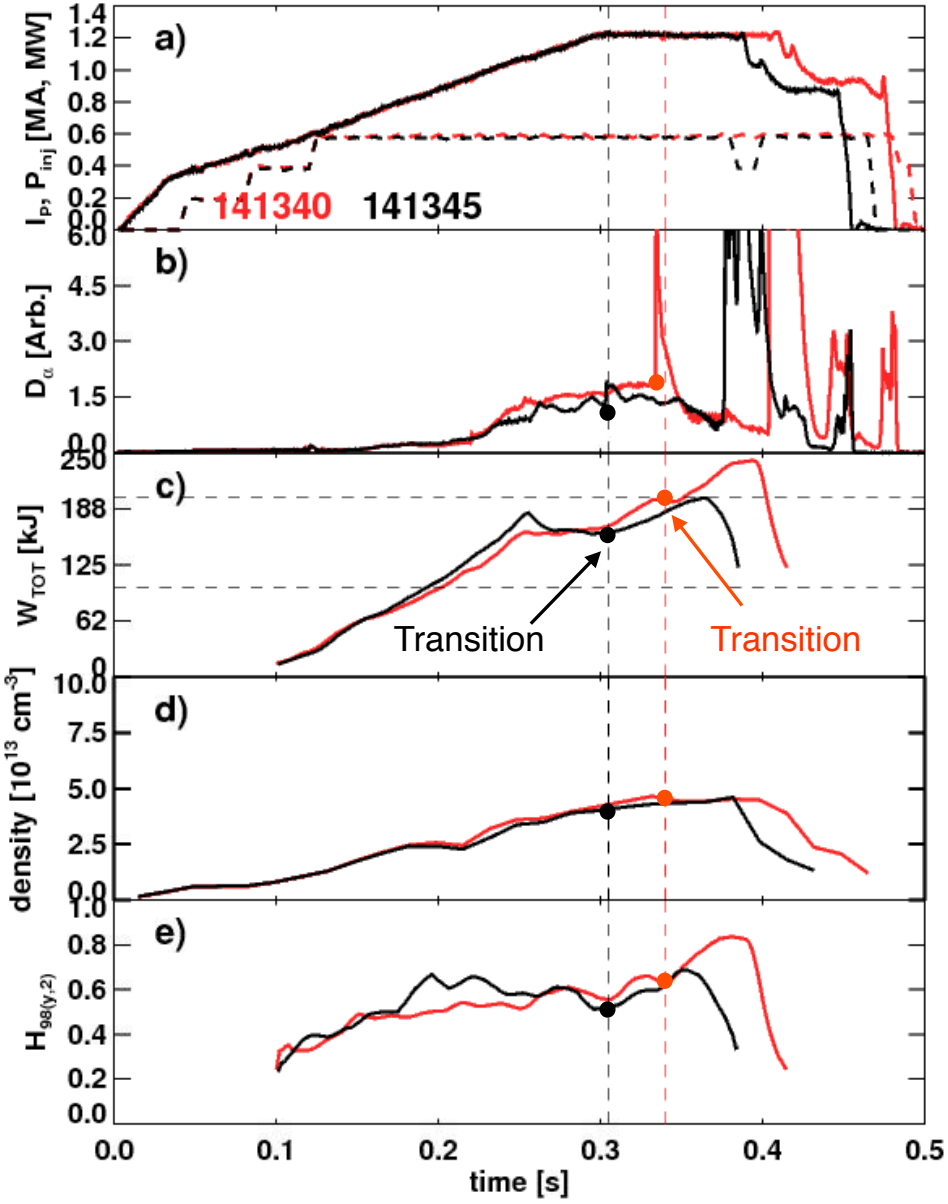
***H-mode phase EP H-mode phase.***




EP H-mode transition have been observed both “early” and “late” in the discharge.

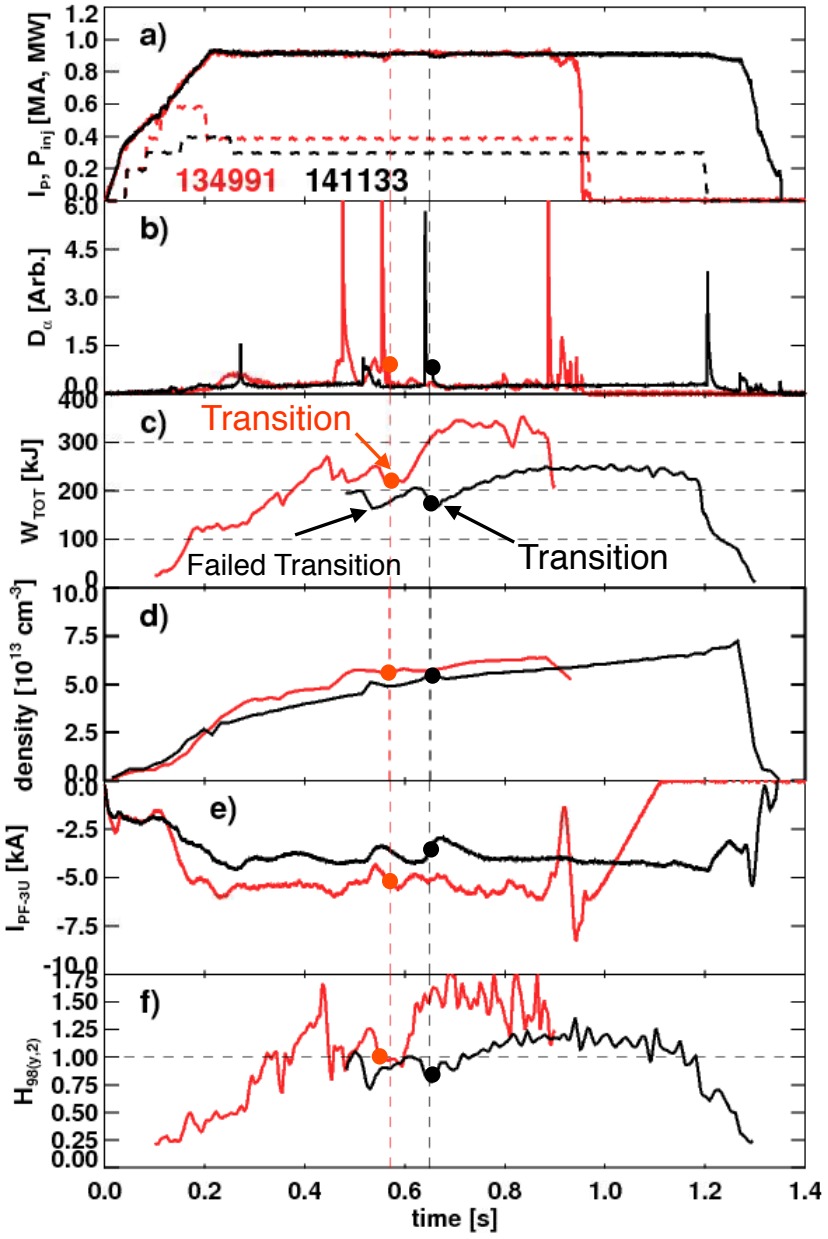
# "Early" EP H-mode Transitions Tend to Result in Short Lived Discharges

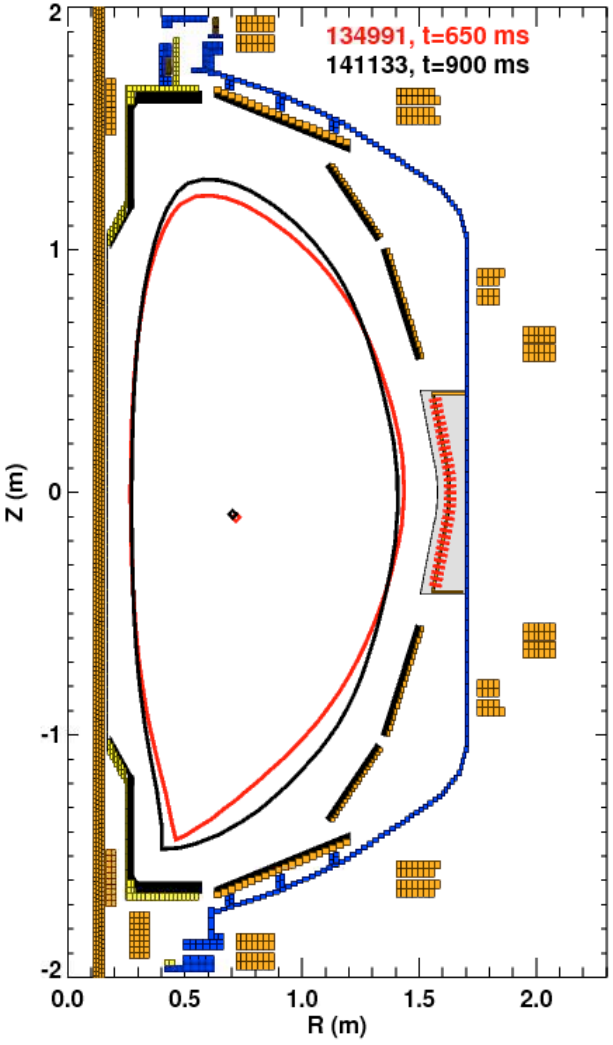
- "Early" refers to transitions that occur at or just after start of flat top.
  - Current profile is typically still evolving rather rapidly.
- Transitions often associated with ELMs
- Typically do not have time to achieve high confinement before the disruption occurs.



# "Late" EP H-Mode Examples Show That the Regime an Be Supported For Longer Periods

- 134991:
  - Very high confinement.
  - Considerable dynamics (partially related to unrefined outer-strikepoint controller).
  - Ultimately disrupts.
  - Described in Maingi PRL
- 141133:
  - Newly observed.
  - Attempted transition at t=0.57, truncated by ELM.
  - Final transition at t=0.65
  - High confinement, with minimal core dynamics.
    - Only terminated by heating power ramp-down.
    - Demonstrates nearly quiescent EP H-mode.
  - Described in 2013 JRT report.



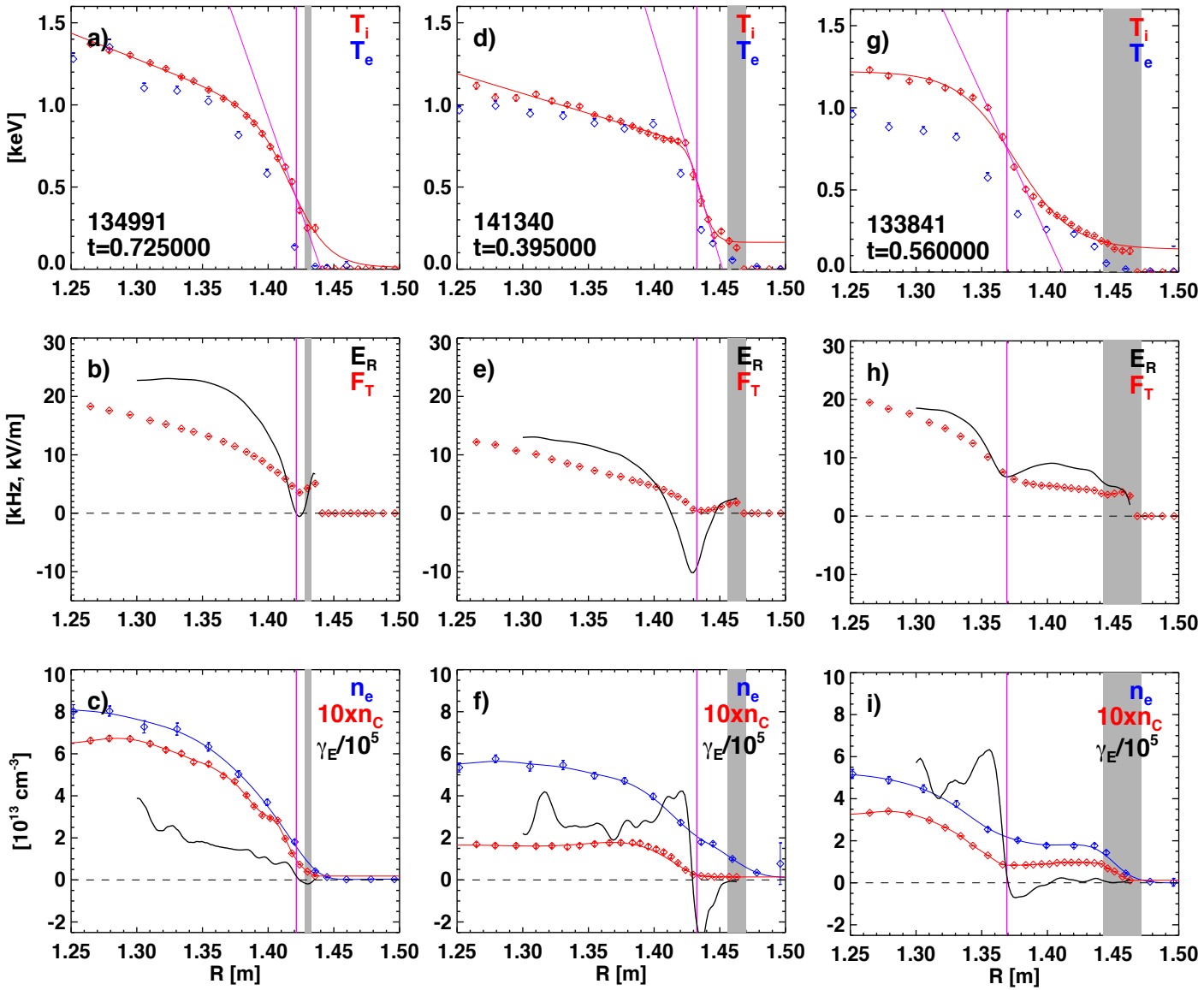
# Region of Strong $T_i$ Gradient Can Be Near Separatrix, or Shifted Substantially Inward

**Steep Gradient:** | **Near Separatrix** | **Shifted Slightly In** | **Shifted Significantly In**

**Electron temperature and ion temperature**

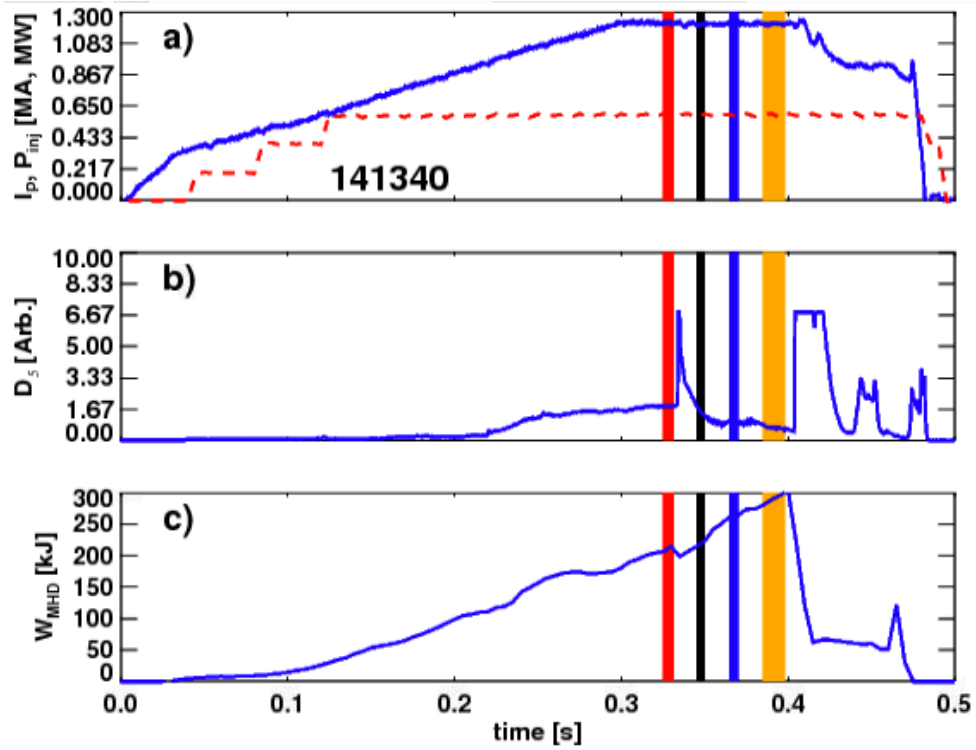
**Toroidal rotation and the radial electric field**

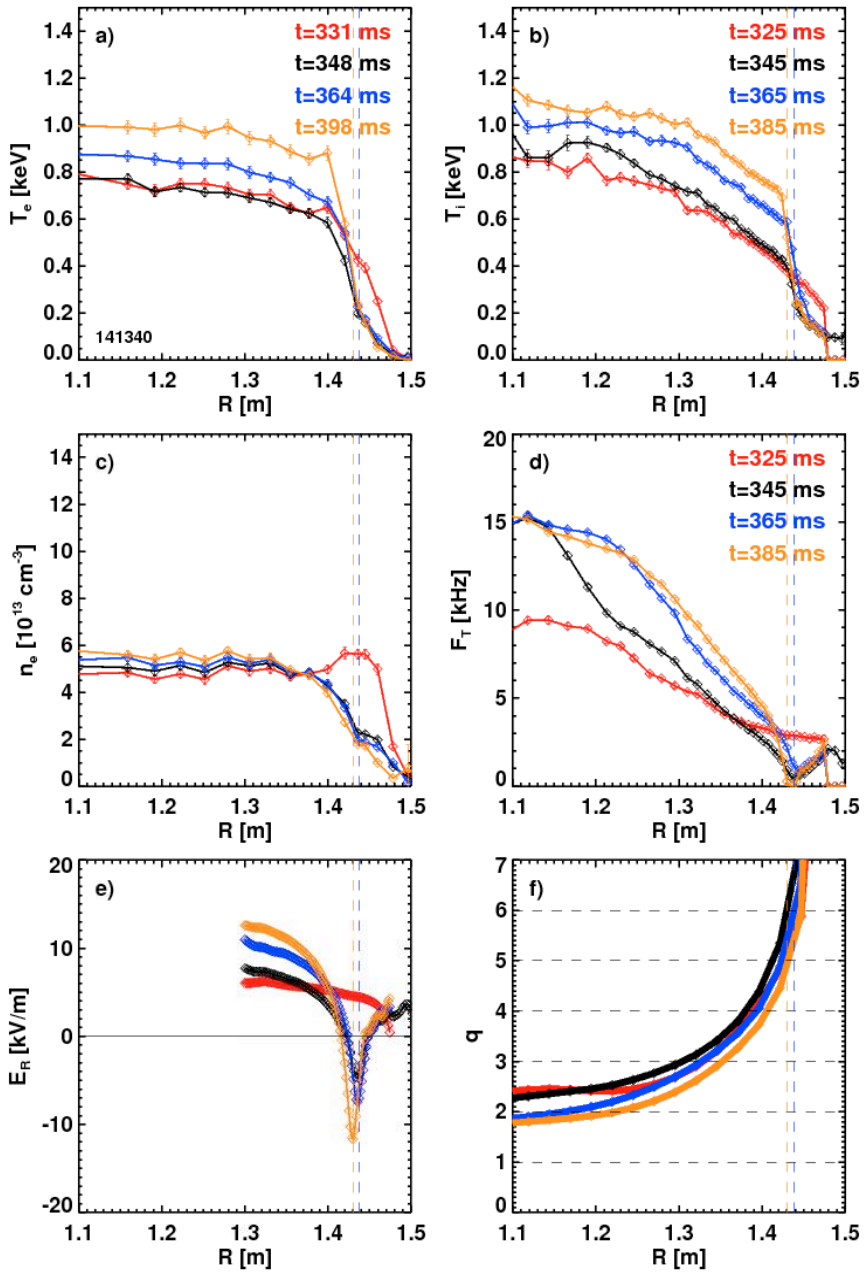
**Electron density, carbon density, and ExB shearing rate.**



# Profiles Evolve During Early EP H-mode State at Roughly Fixed Gradient

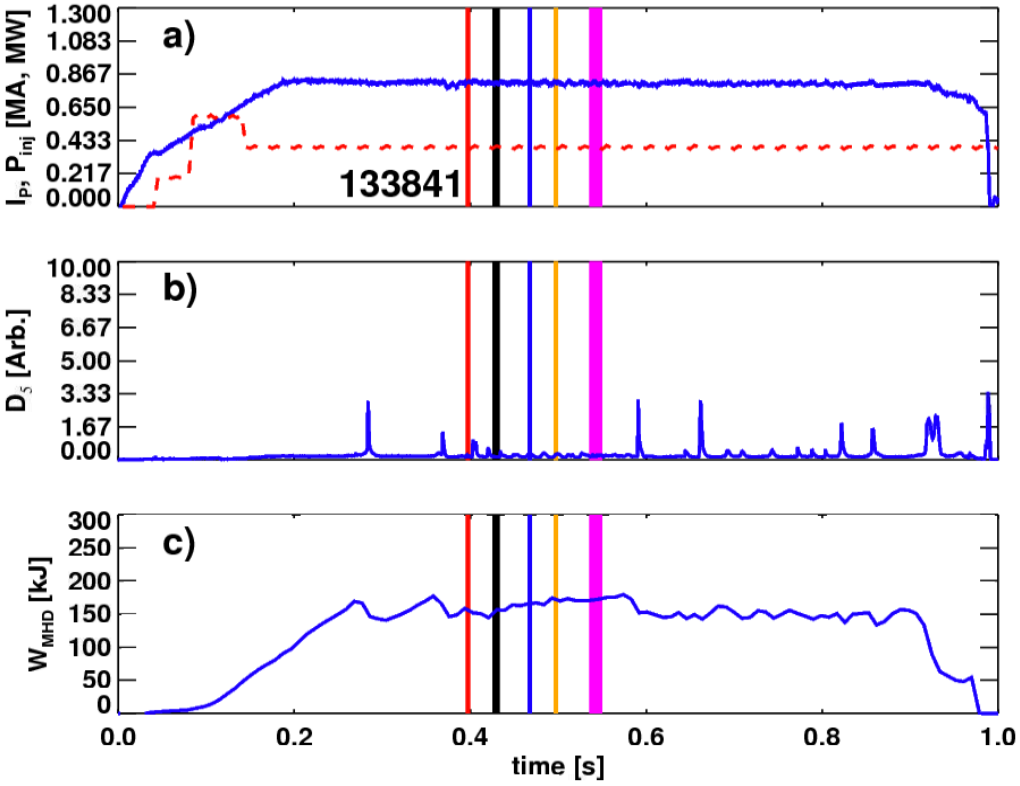
- Edge $T_i$ is dropped during the ELM.
  - Gradient increases.
  - Local minima in $T_i$ appears.
  - Large local $E_R$ shear develops
- $T_i$ at the pedestal top increases at roughly fixed gradient.

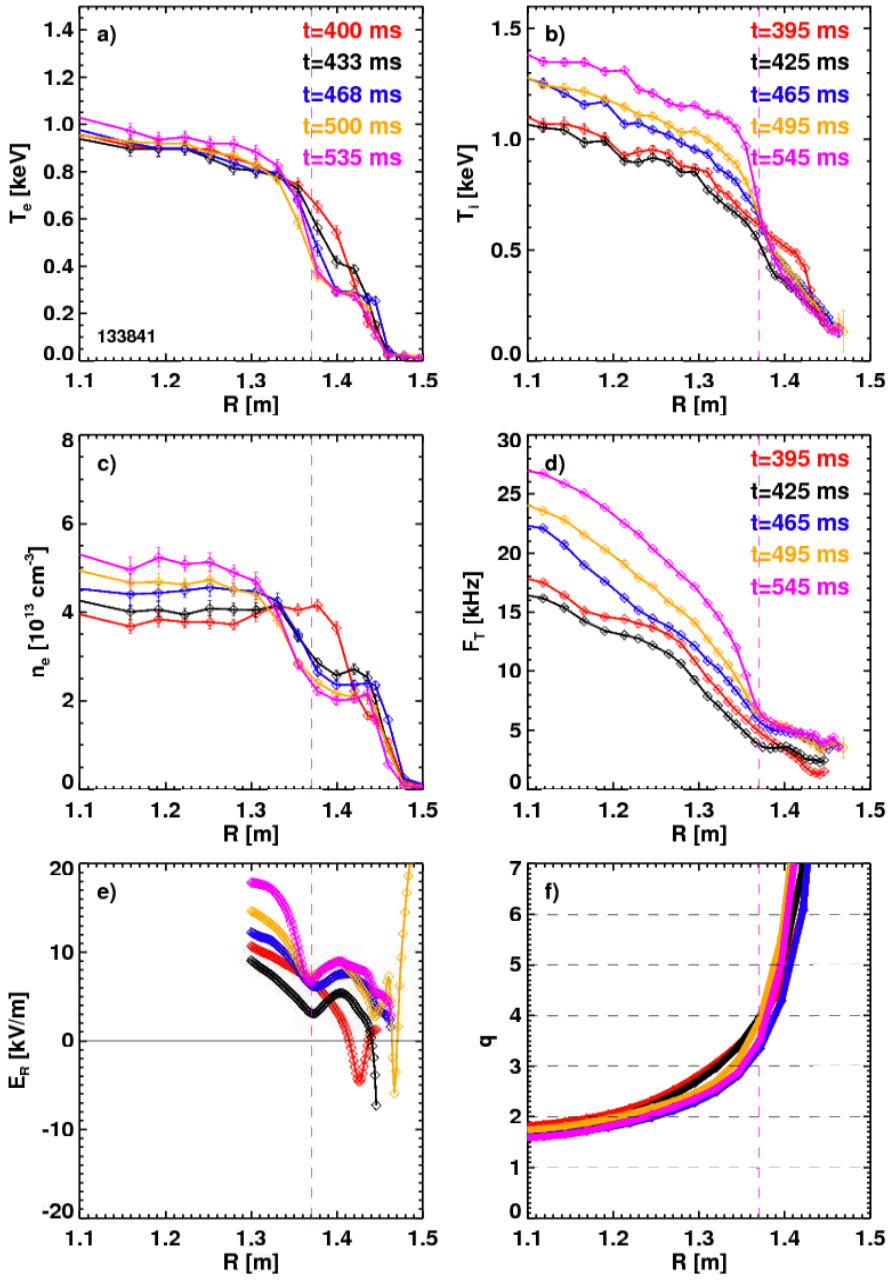


# Case With Inward Shifted Gradient Shows a Similar Evolution

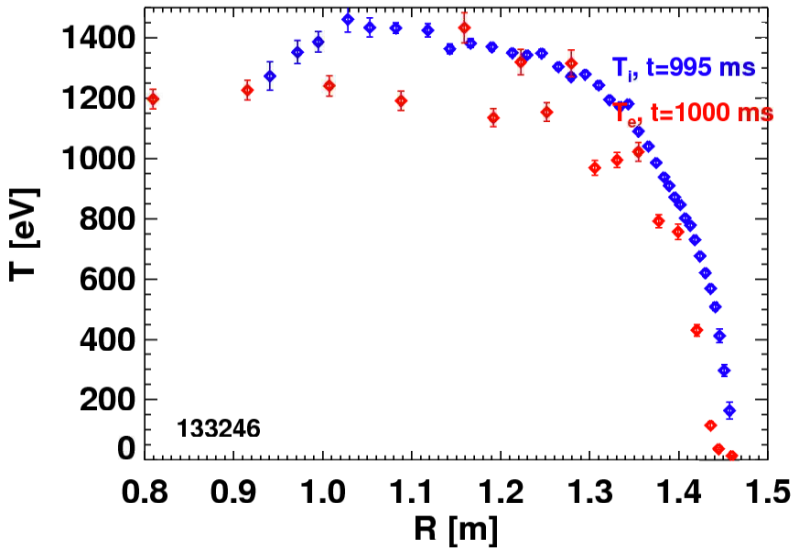
- Small ELM at t=0.4 triggers transition.
  - Rotation and temperature reduced to substantially larger radius
- Clear double-barrier structure formed in the electron density and temperature.
- Further analysis: is there a systematic correlation between depth of ELM perturbation and location of $T_i$ gradient.

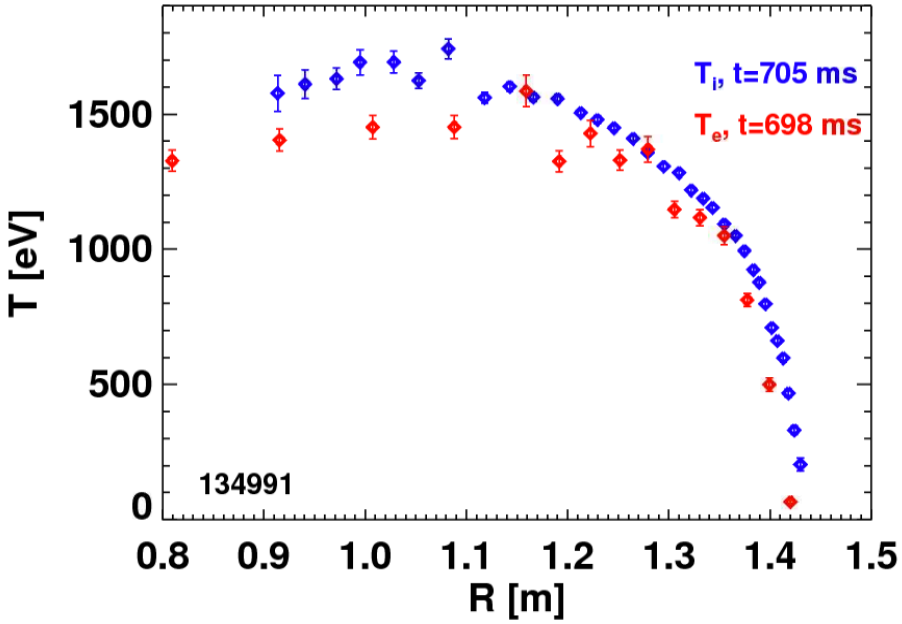


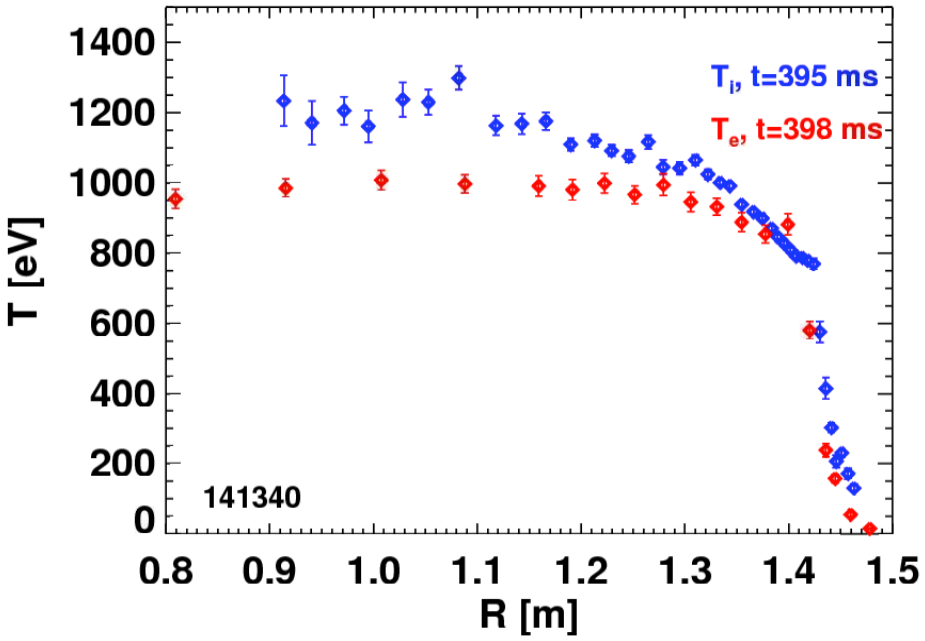



# Radial Separation of the $T_e$ and $T_i$ Gradient Is Commonly Observed in EP H-Mode Phases

- $T_i$ gradient typically shifted out with respect to the $T_e$ gradient.
- 3-4 cm shift not uncommon
- Not a diagnostic calibration issue… profiles line up well in other phases of the discharge.

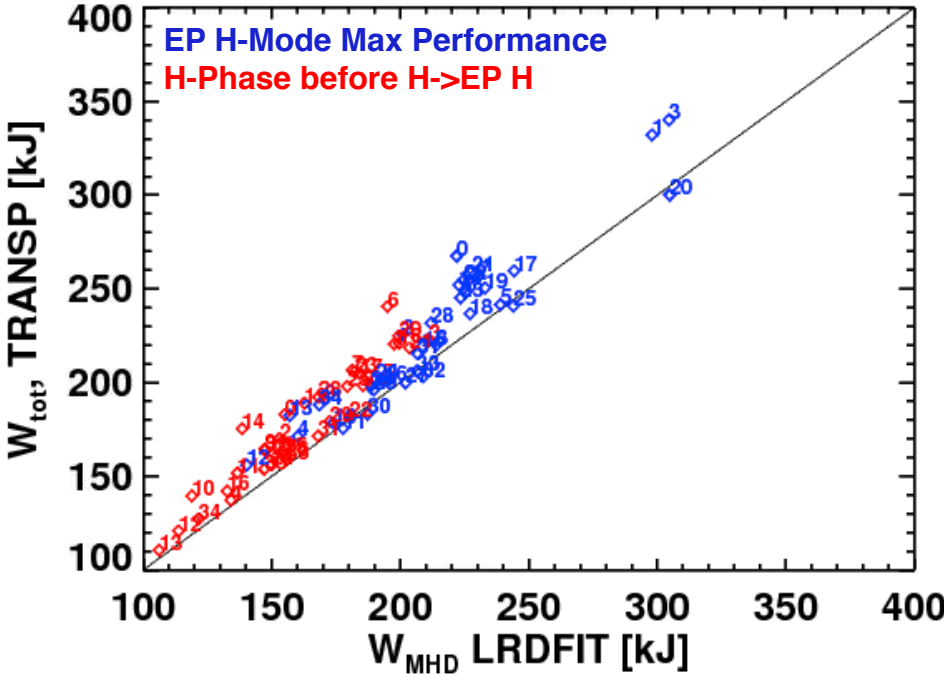


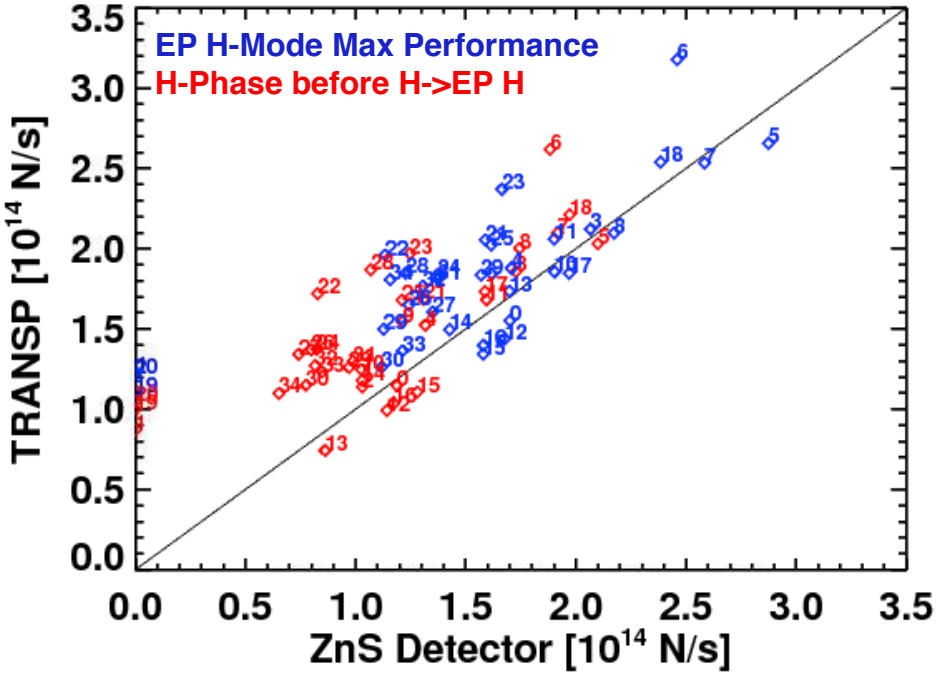



# Database of EP H-Modes Has Been Checked For Consistency Amongst TRANSP, Equilibrium Reconstructions, Neutron Emission.

- "Robot" code used to find promising EP H-mode cases by identifying discharges with large $T_i$ gradients.
  - Cases so identified used in a more comprehensive database.
- Comprehensive database includes:
  - pedestal fits,
  - TRANSP confinement results,
  - Equilibrium quantities computed by EFIT and LRDFIT (the latter often "partial kinetic")
- Consistency check: Match of both the total energy and neutron emission between TRANSP and EFIT/LRDFIT, and neutron emission measurements.



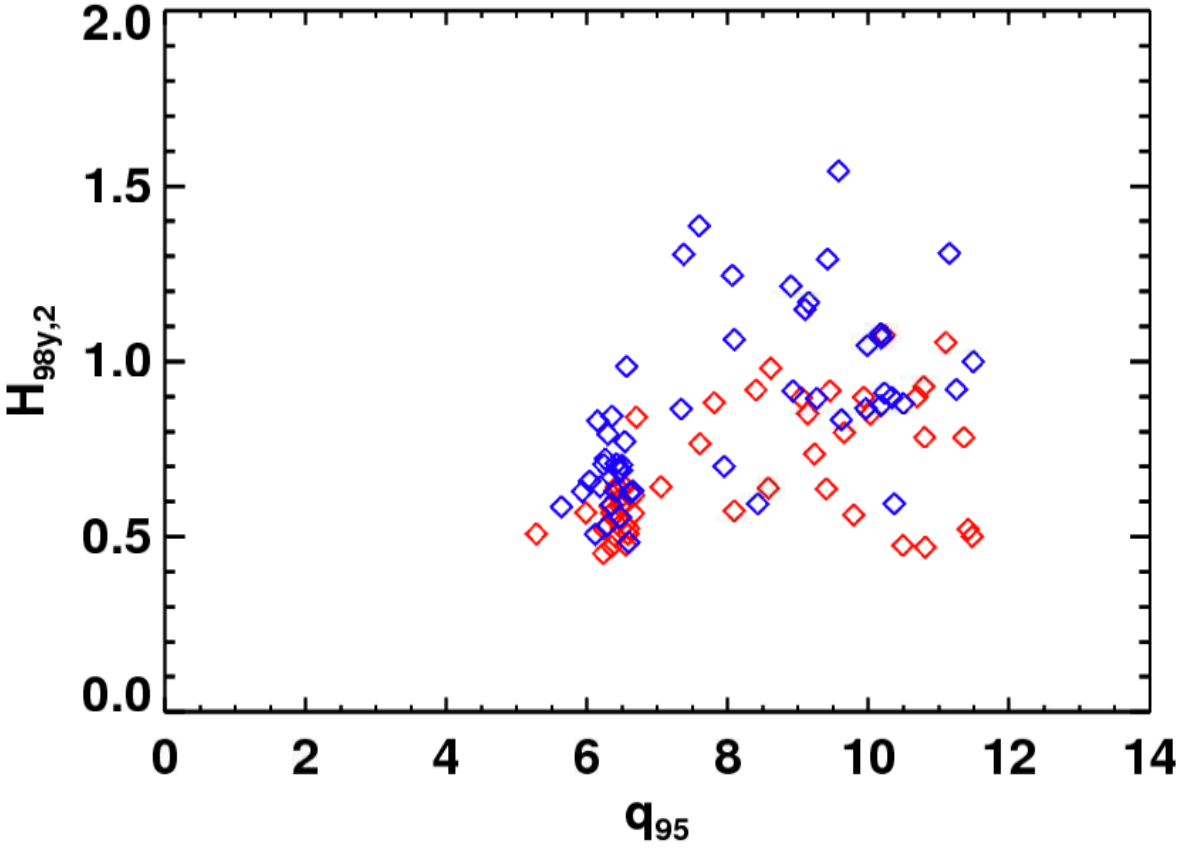



# High-Confinement EP H-mode Cases Identified Over a Range of $q_{95}$

- "Early Transition" EP H-mode cases favor low $q_{95}$
  - or higher $I_P$
  - Typically disrupt before achieving high performance.
- High confinement examples observed for $7<q_{95}<12$.

***H-mode phase before the EP H-mode transition.***

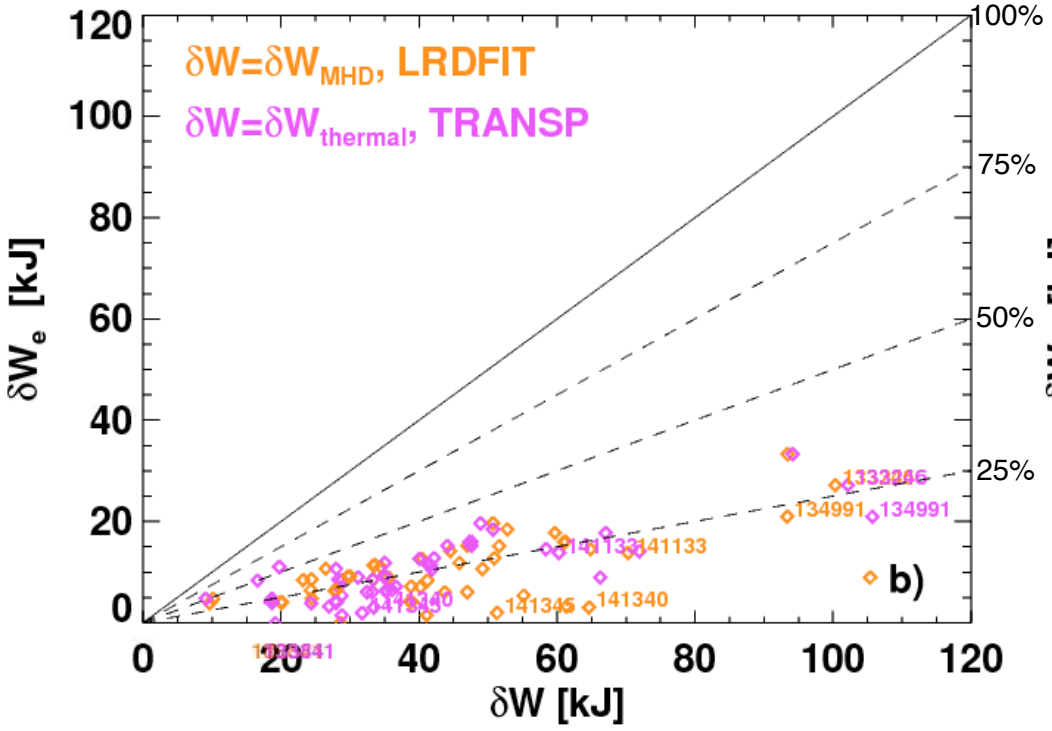
***Peak performance of EP H-mode phase.***



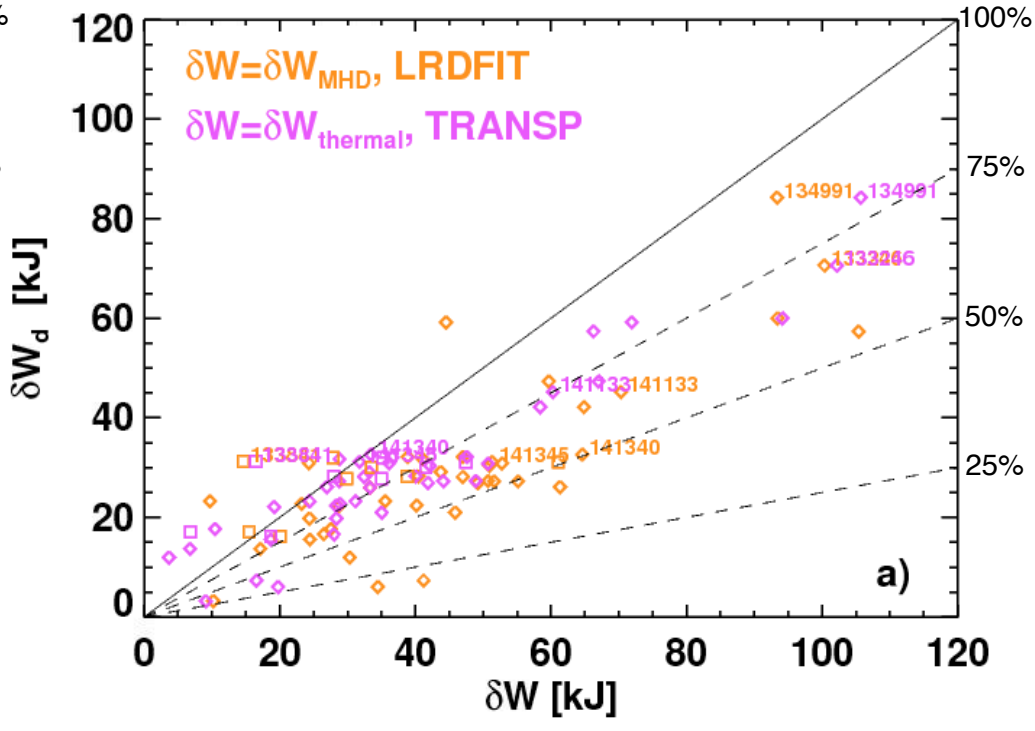
# The Stored Energy Increment is Mostly in the Ions

- Compute change in stored energy between the H-mode phase before the transition, and the peak performance of the EP H-mode phase…call it δW
  - $\delta W_{MHD}$: Change in the total stored energy, from MHD equilibrium reconstruction.
  - $dW_{thermal}$: Change in the total thermal energy (TRANSP).
  - $dW_e$, $dW_d$: Changes in the electron and deuterium thermal energies (TRANSP).

***~25% of the Stored Energy Increment to Electrons***

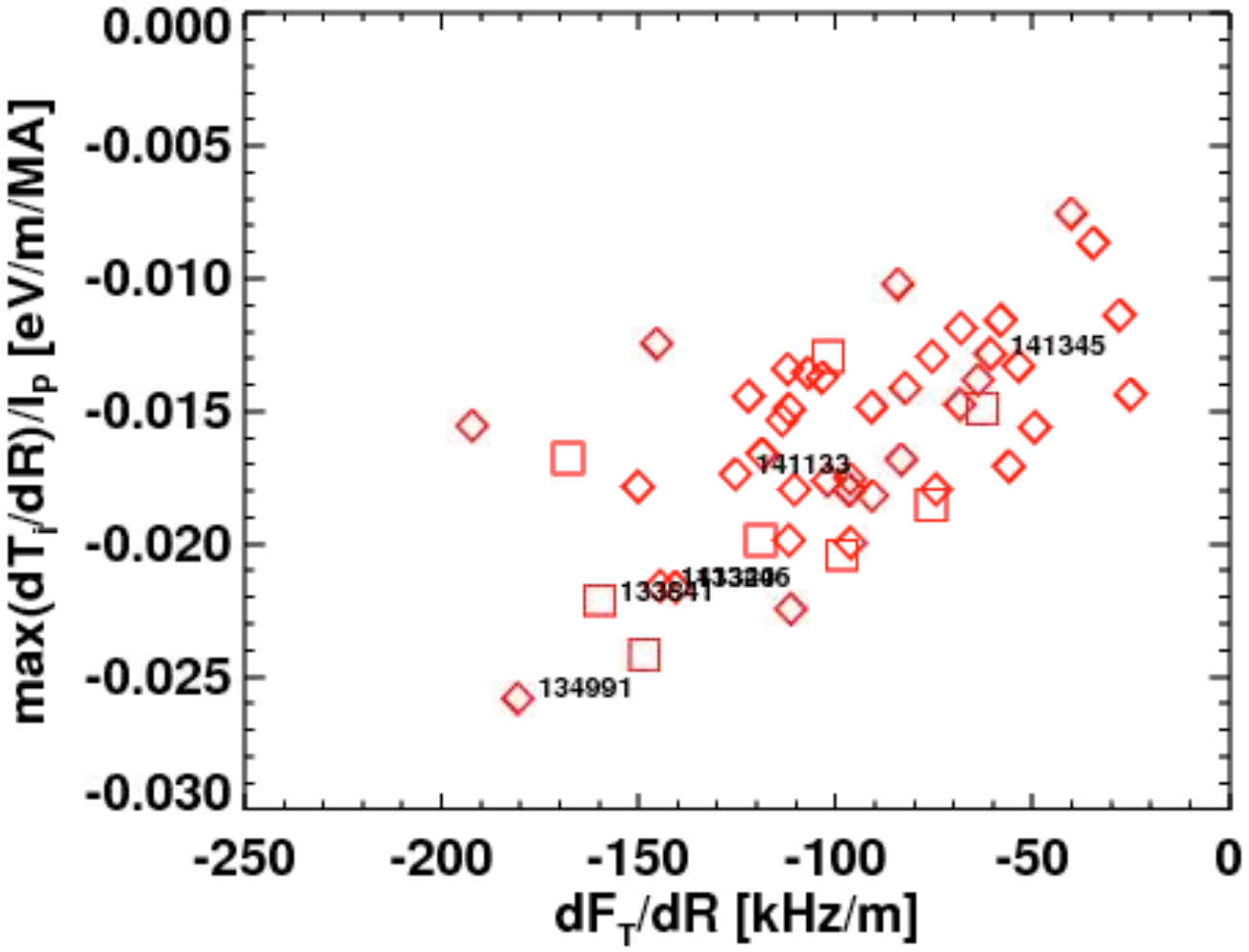



***~75% of the Stored Energy Increment to Ions***



# Ion Temperature Gradient Appears to Scale with the Nearby Gradient in the Toroidal Rotation

- Consider the rotation gradient just inside the point of maximum $dT_i/dR$.
- Clear scaling of the $I_P$ normalized $T_i$ gradient with the rotation gradient.
- Eliminating the $I_P$ normalization makes the trend less clear.



# EP H-Modes Can Sometimes Show a Reduction in Density or Impurity Accumulation: Early EP H-Modes

*The two examples of "longish" duration (141345 & 138169) both show density ramping.*

**Black is $P_{rad}$:**
Solid: Core
Dotted: ~135 cm

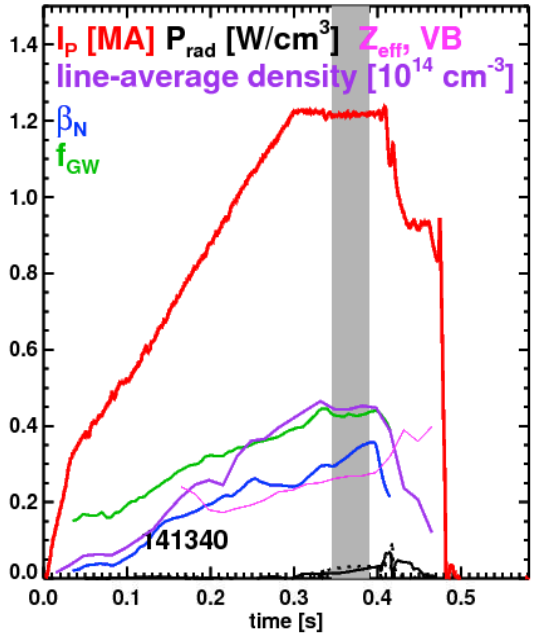
**Line Average Density**

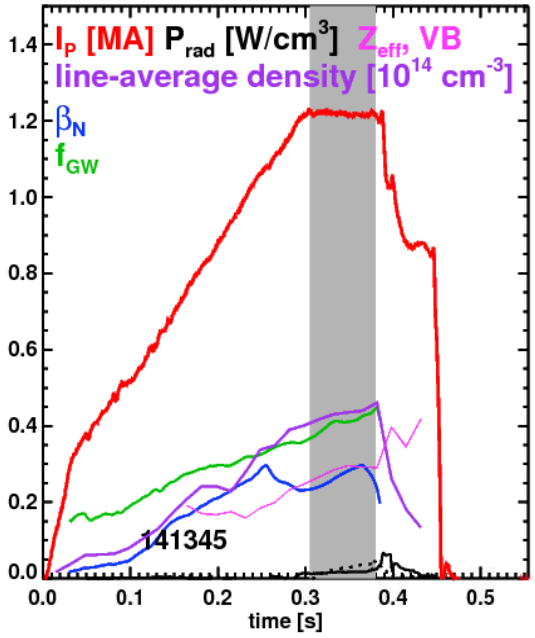
$I_P$

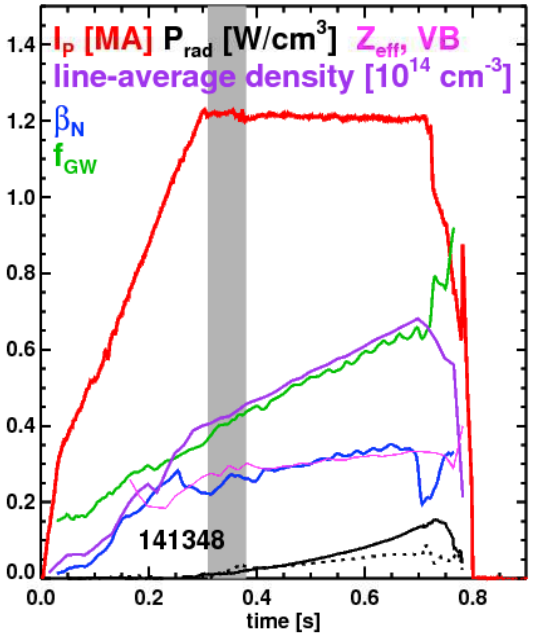
$\beta_N$

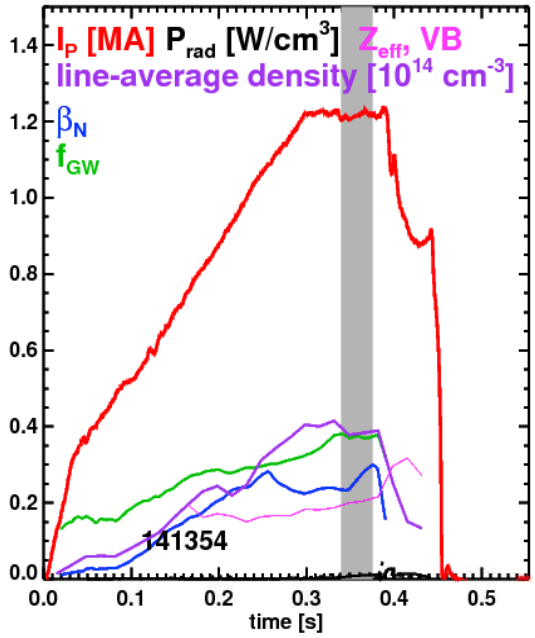
$f_{GW}$

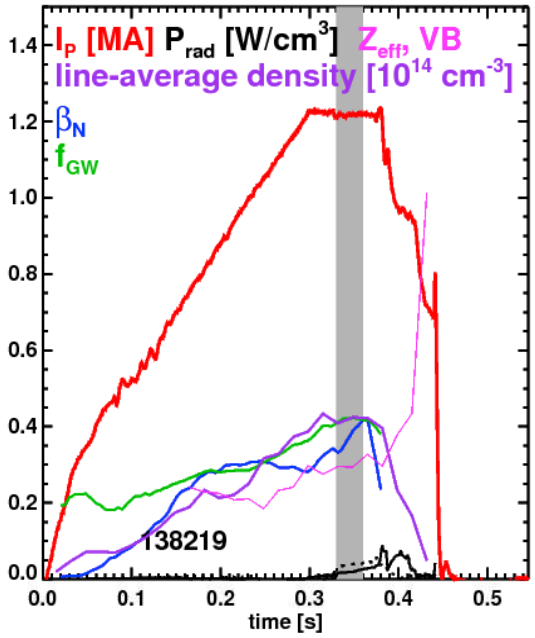
$Z_{eff}$ (from VB)

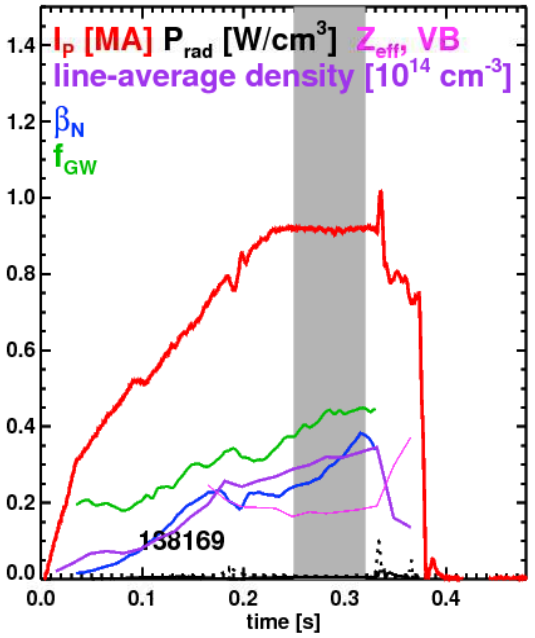


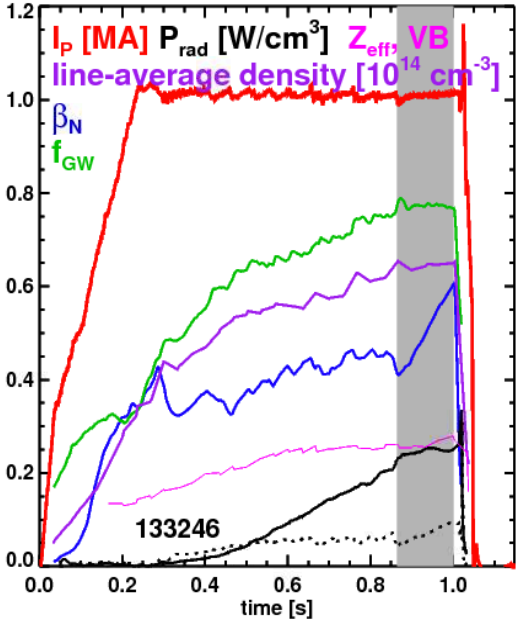
# EP H-Modes Can Sometimes Show a Reduction in Density or Impurity Accumulation: Late EP H-Modes

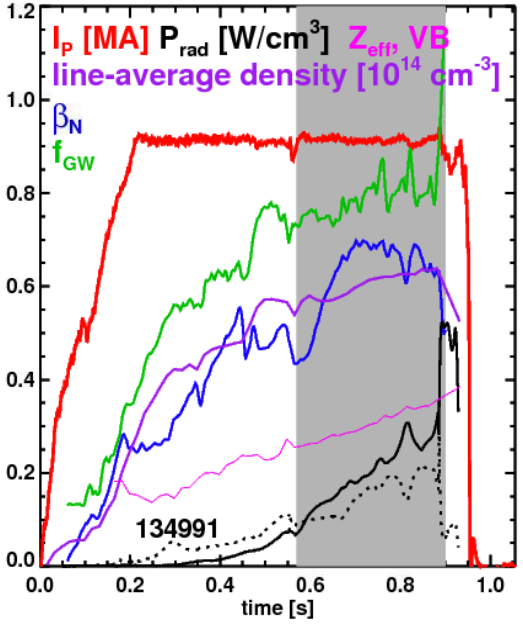
133246 and 133905 are the only examples here where the density & impurities both actually stop ramping.

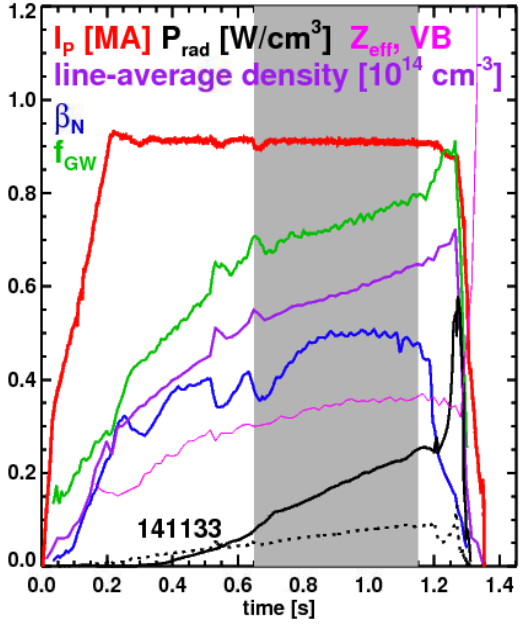
**Black is $P_{rad}$:**
**Solid: Core**
**Dotted: ~135 cm**
**Line Average Density**
**$I_P$**
**$\beta_N$**
**$f_{GW}$**
**$Z_{eff}$ (from VB)**

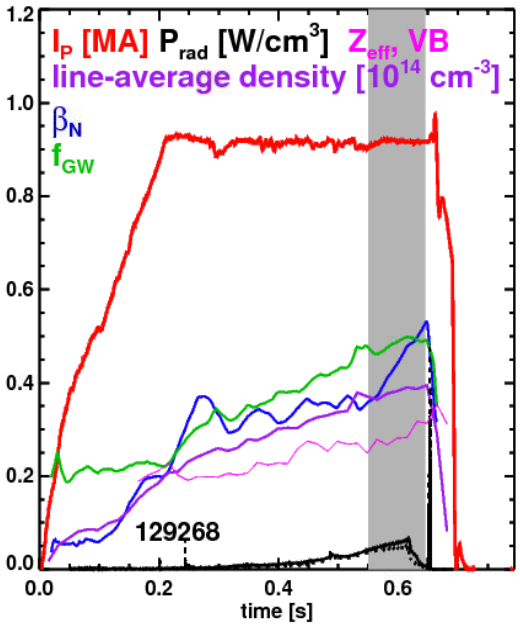
*"Old" Long Pulse Demo*

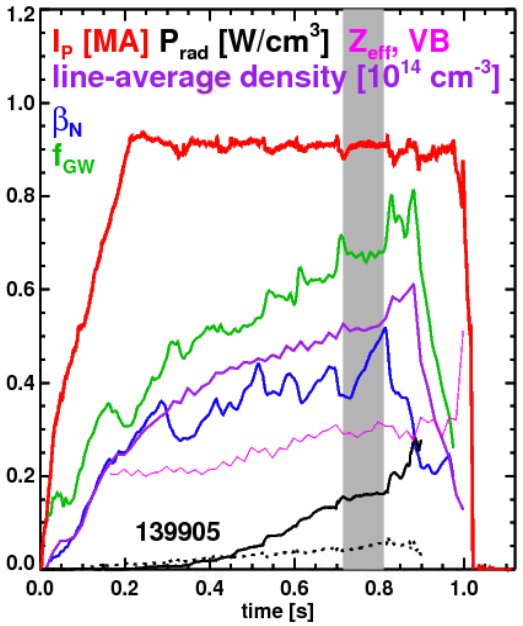
*"New" Long Pulse Demo*

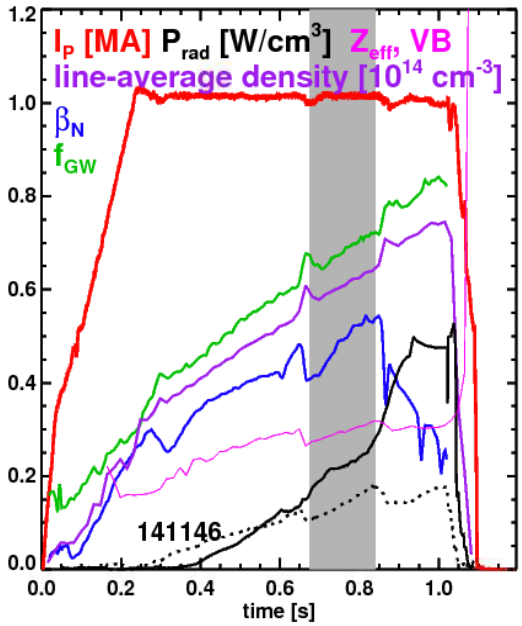


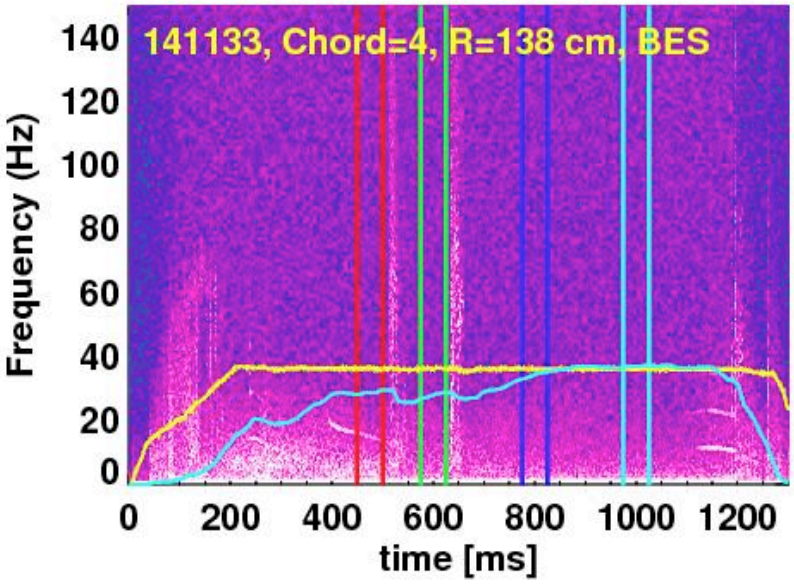



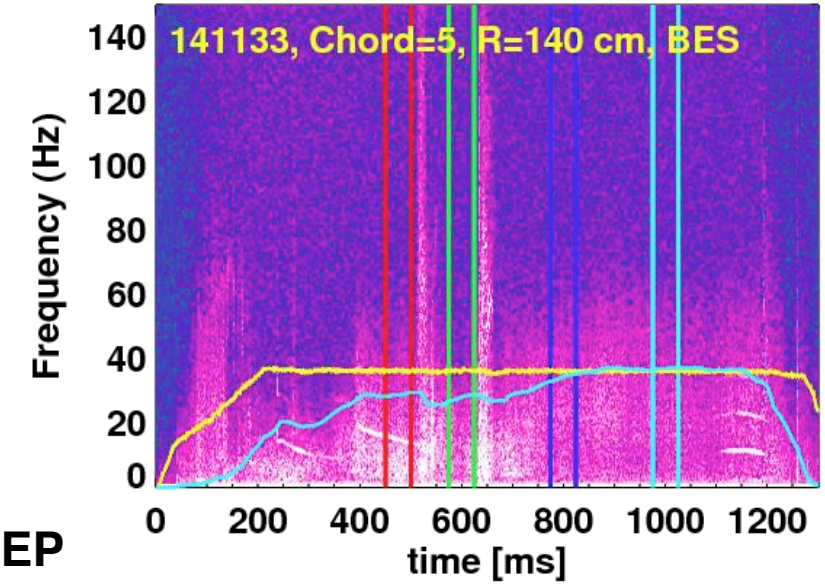



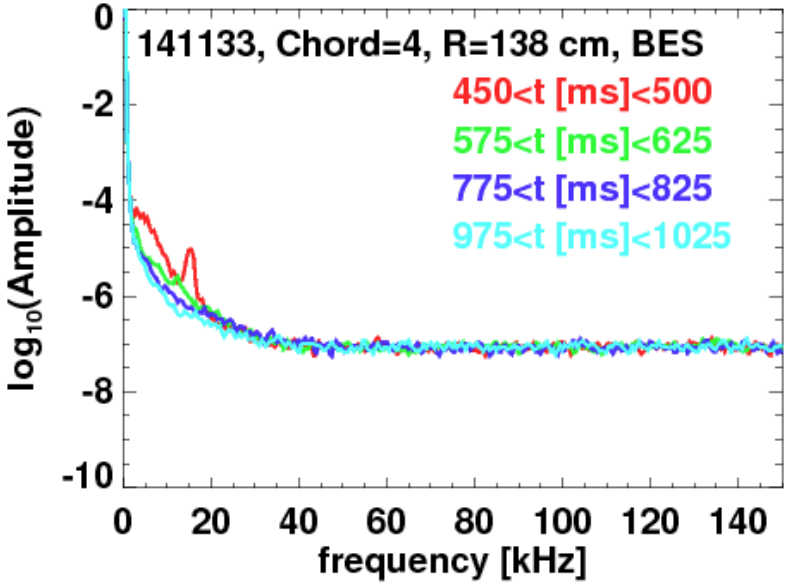
# BES Data in this Regime Shows No Major Changes in the Low-k Turbulence

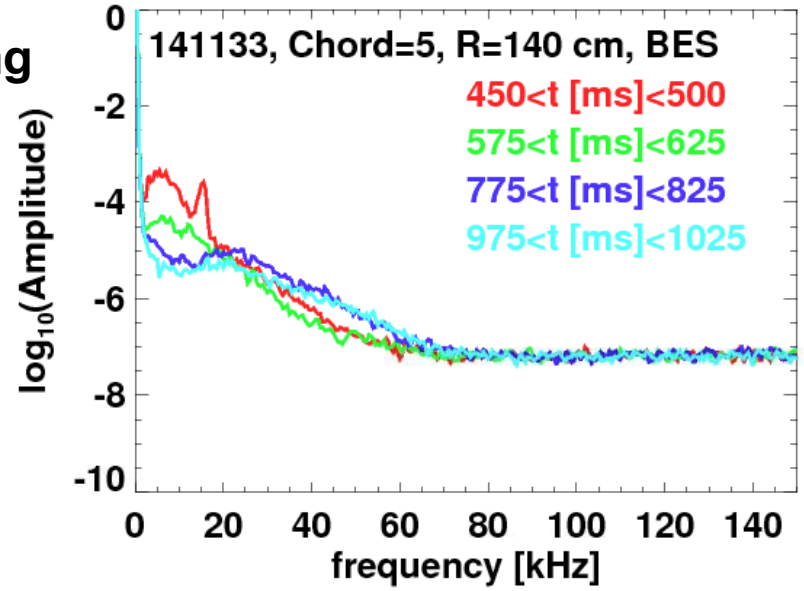


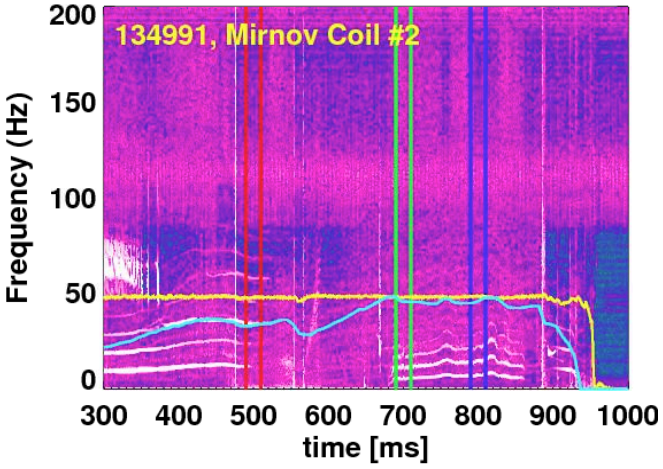

**Red**, **Green**: **Pre-EP H-mode**

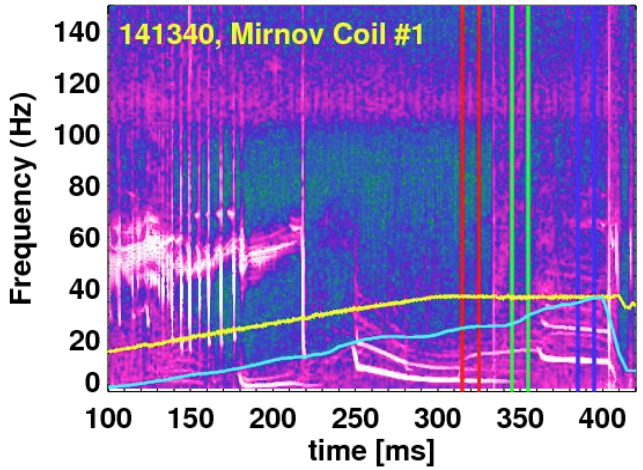
**Blue**, **Cyan**: **During EP H-mode**

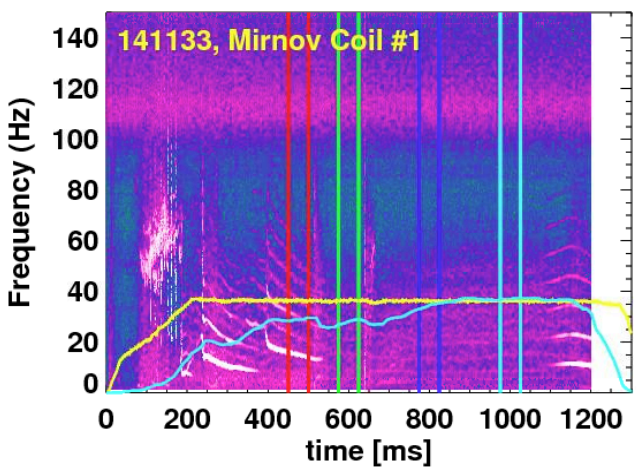


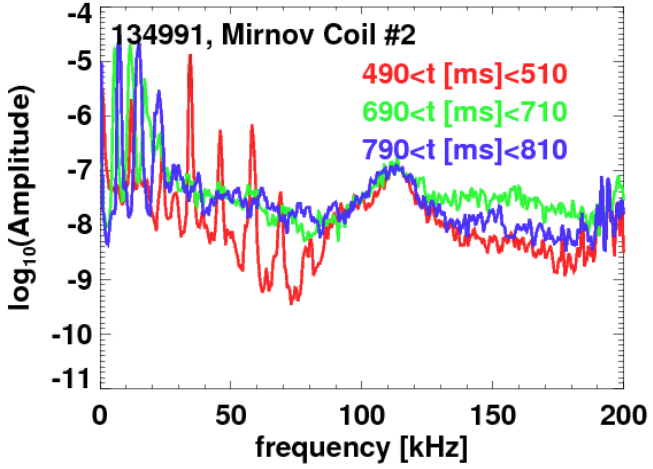



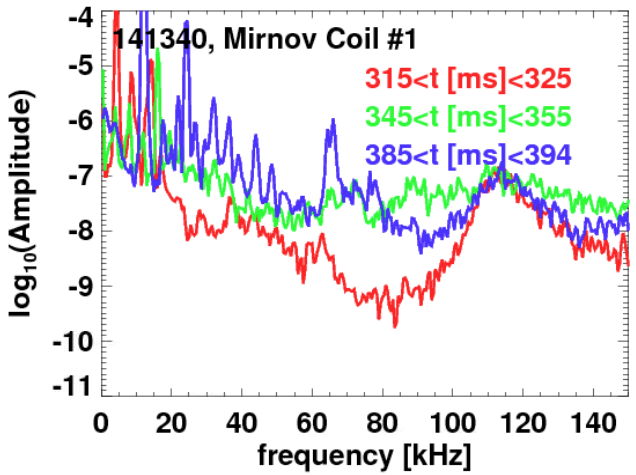
# There May be Hints of a Change in the Magnetic Fluctuation Level During the EP H-Mode Phase

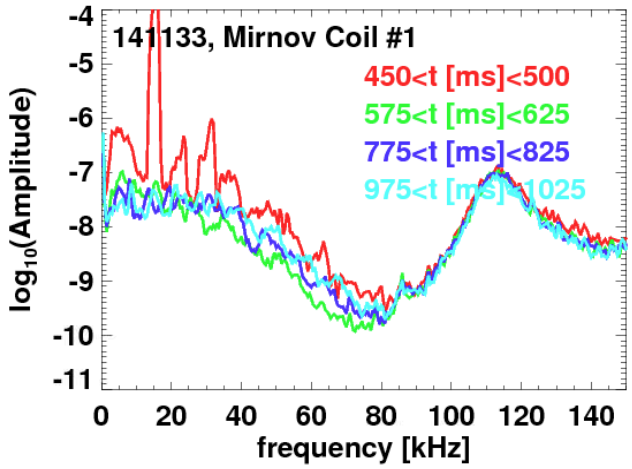


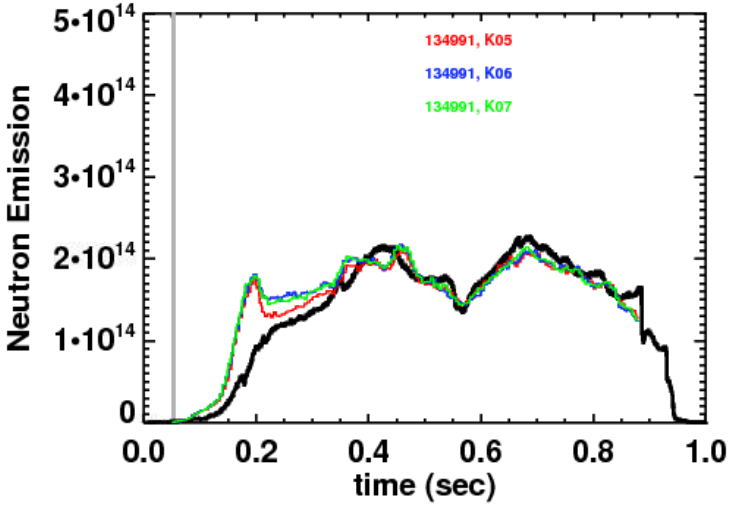



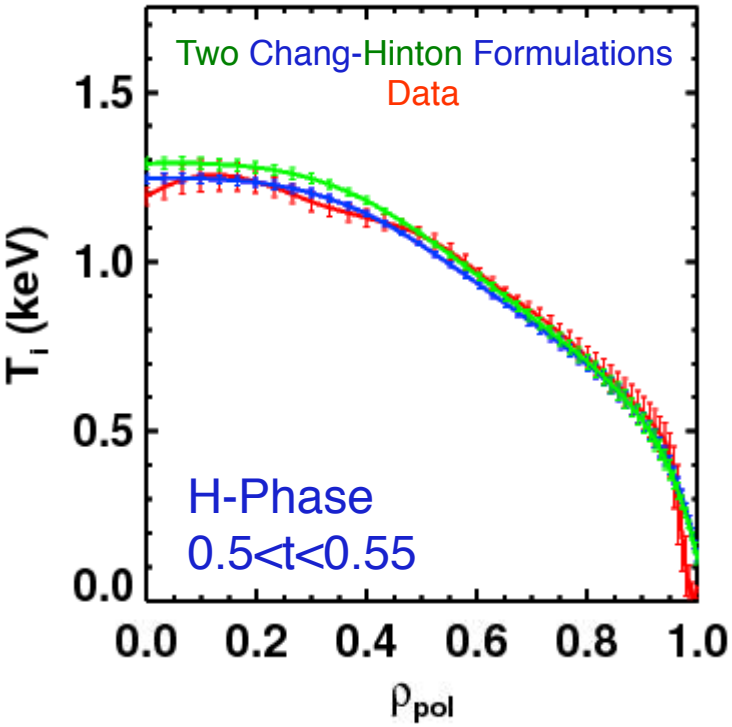

***If there are no changes in turbulence, does it imply that EP H-mode is a neoclassical effect?***

# $T_i$ Predictions Using the Chang-Hinton Model Show That the Ion Transport is (Apparently) Less than Neoclassical

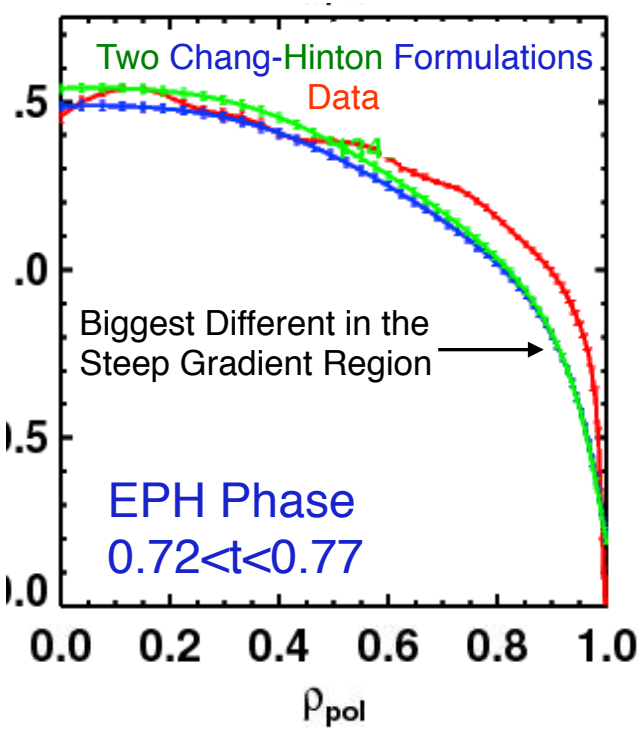
- Use experimental $n_e$, $n_C$, $T_e$ profiles.
  - Critical to get the plasma boundary right
- Use experimental equilibria, injected powers
- Predict Ti profile using two formulations of the Chang-Hinton model.
  - These in blue ('K06') and green ('K07') below

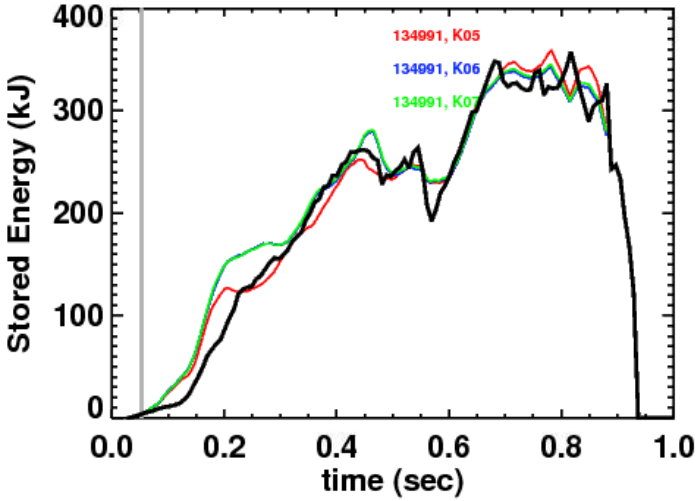



***Profiles Match Well***




***Profiles Don't Match Well***

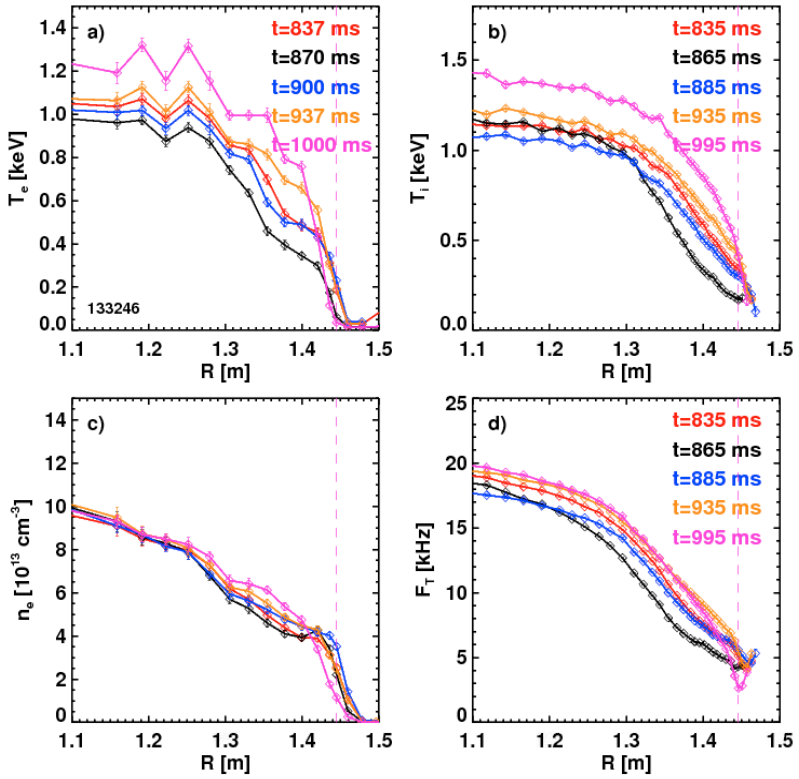


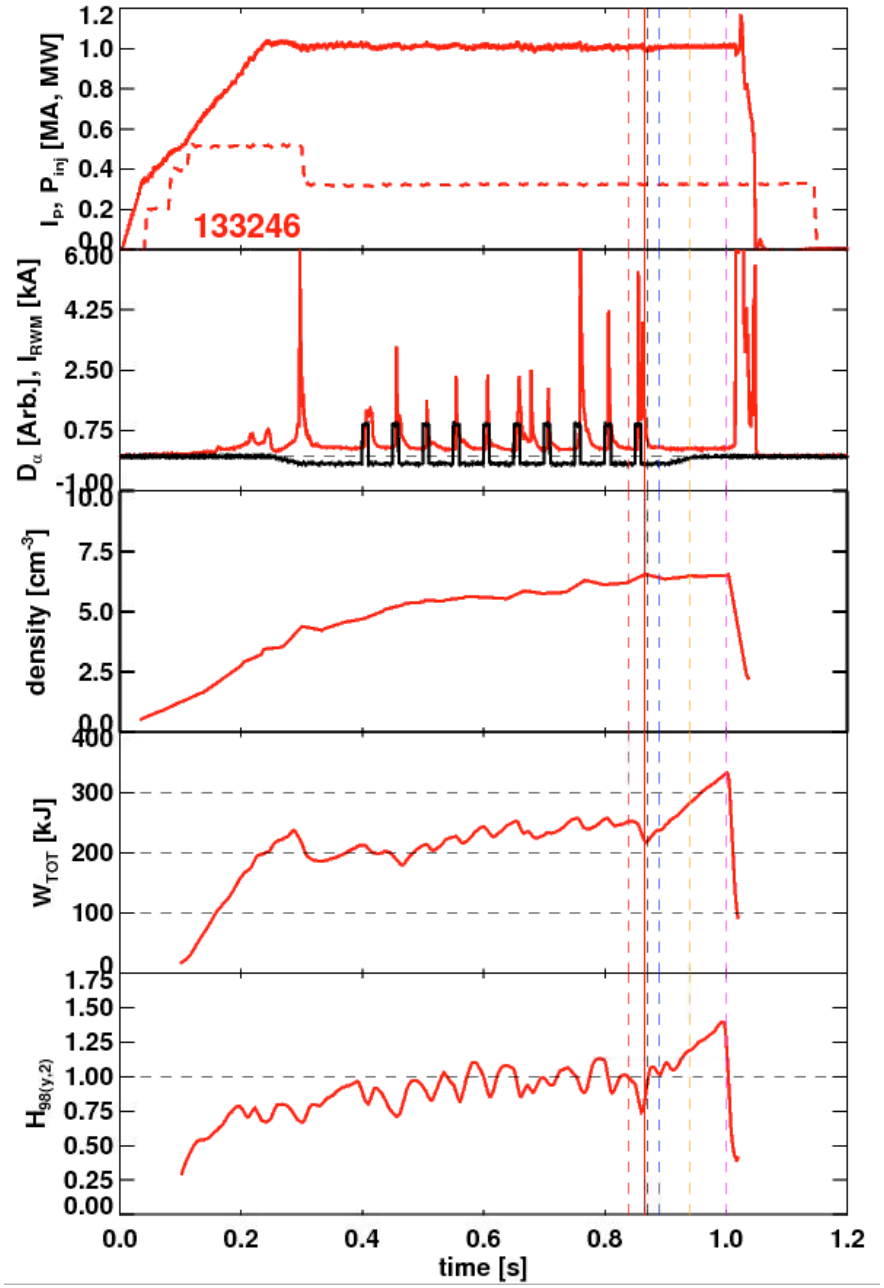




Presently using XGC-0 to fully understand the neoclassical transport in H-mode and EP H-mode.

# Reliable Triggering Required For Use in Future Devices

- Discharge with ELMs triggered by pulsed 3D fields.
- Discharge enters EP H-mode phase following final triggering ELM.



# Summary

- Expanded number of EP H-mode cases recently found.
- Region of steep $T_i$ gradient can vary from the very edge to many cm inside the separatrix.
- Primary source of stored energy increase in EP H-mode is through the ion channel.
- The steepness of the $T_i$ gradient is correlated with the local rotation shear.
- No strong changes in the turbulence have been observed at the transition.
- Ion transport appears to be sub-neoclassical, when compared to predictions using the Chang-Hinton model.
- Appears that it may be possible to trigger EP H-modes with triggered ELMs.