Progress in Quantifying the Edge Physics of the H-mode Regime in DIII-D

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Boundary Physics is Key to Performance of a Next Step Tokamak

- H-mode is baseline operating scenario for future machines
- H-mode access set by physics near separatrix
- Global confinement correlated with height of pressure pedestal
- Density and impurity control provided by edge transport, normally ELMs
    - However, heat pulses from ELMs are undesirable

H-mode Boundary Physics is Being Quantified in DIII-D

- Transition criterion not simply a critical value of T_e
- Gradients of temperature and pressure increase in L-mode and may play a causal role
- Evidence for threshold in terms of temperature or pressure gradients
- Edge pressure gradient limited by MHD stability
- Width of pressure barrier scales with $(\beta_{pol})^{1/2}$

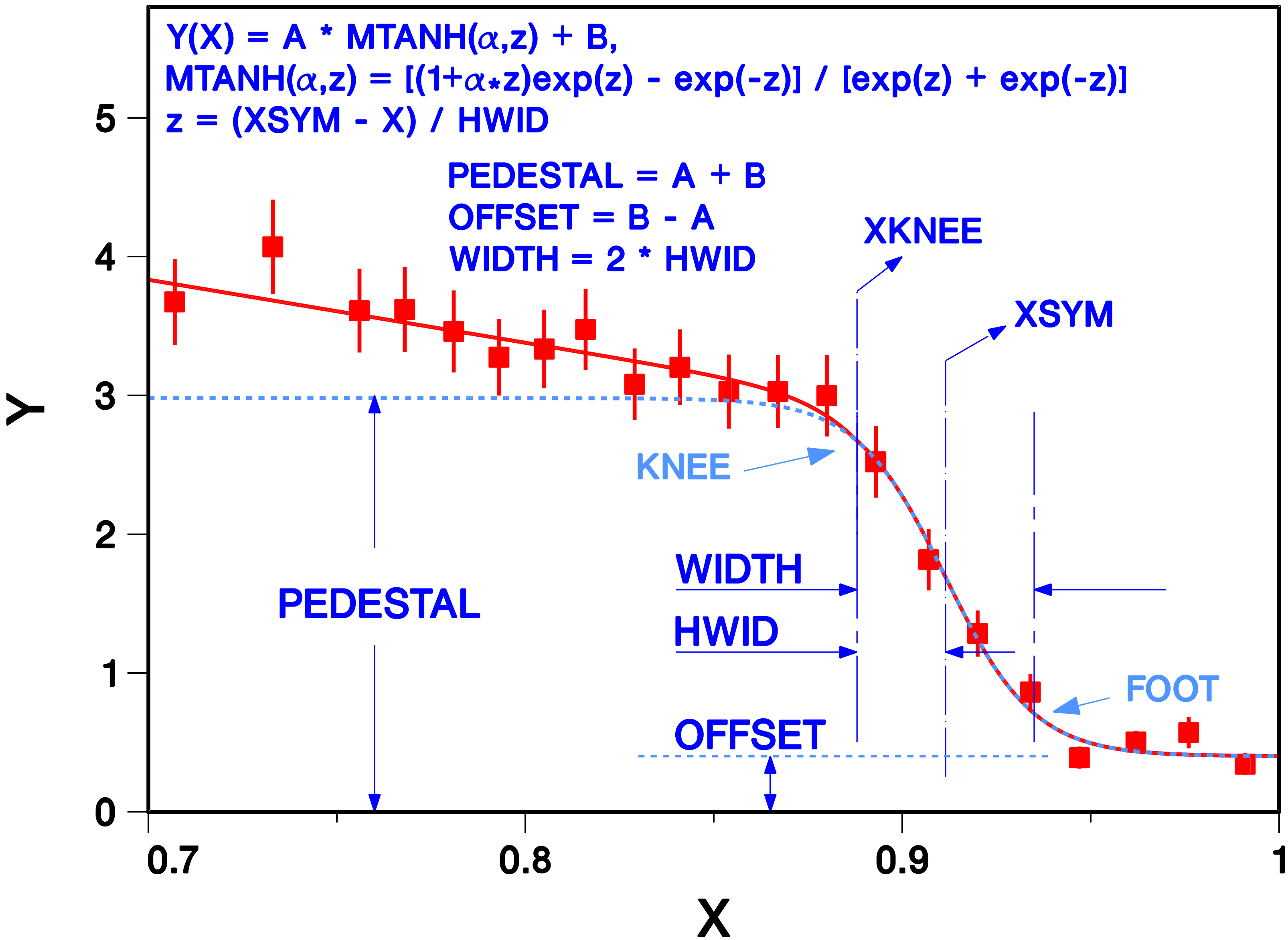
Steady-state, Non-ELMing H-mode Discharge Discovered -- *Quiescent H-mode*

- **Steady state density**
- **Low impurity content and radiated fraction**
- **Standard H-mode confinement**
- **No pulsed heat load to divertor plates**
- **Edge particle confinement may be controlled by continuous coherent mode**

Edge Parameters Measured Very Near Separatrix

- Edge profiles of T_e, n_e, p_e, T_i measured with spatial resolution of less than 1 cm
- Data fit with modified tanh function
  - Continuous first derivatives everywhere
  - Suitable for database and time evolution analysis
- Edge parameters normally evaluated where density gradient is steepest - the "symmetry point"
- This location is typically less than 1 cm inboard of separatrix

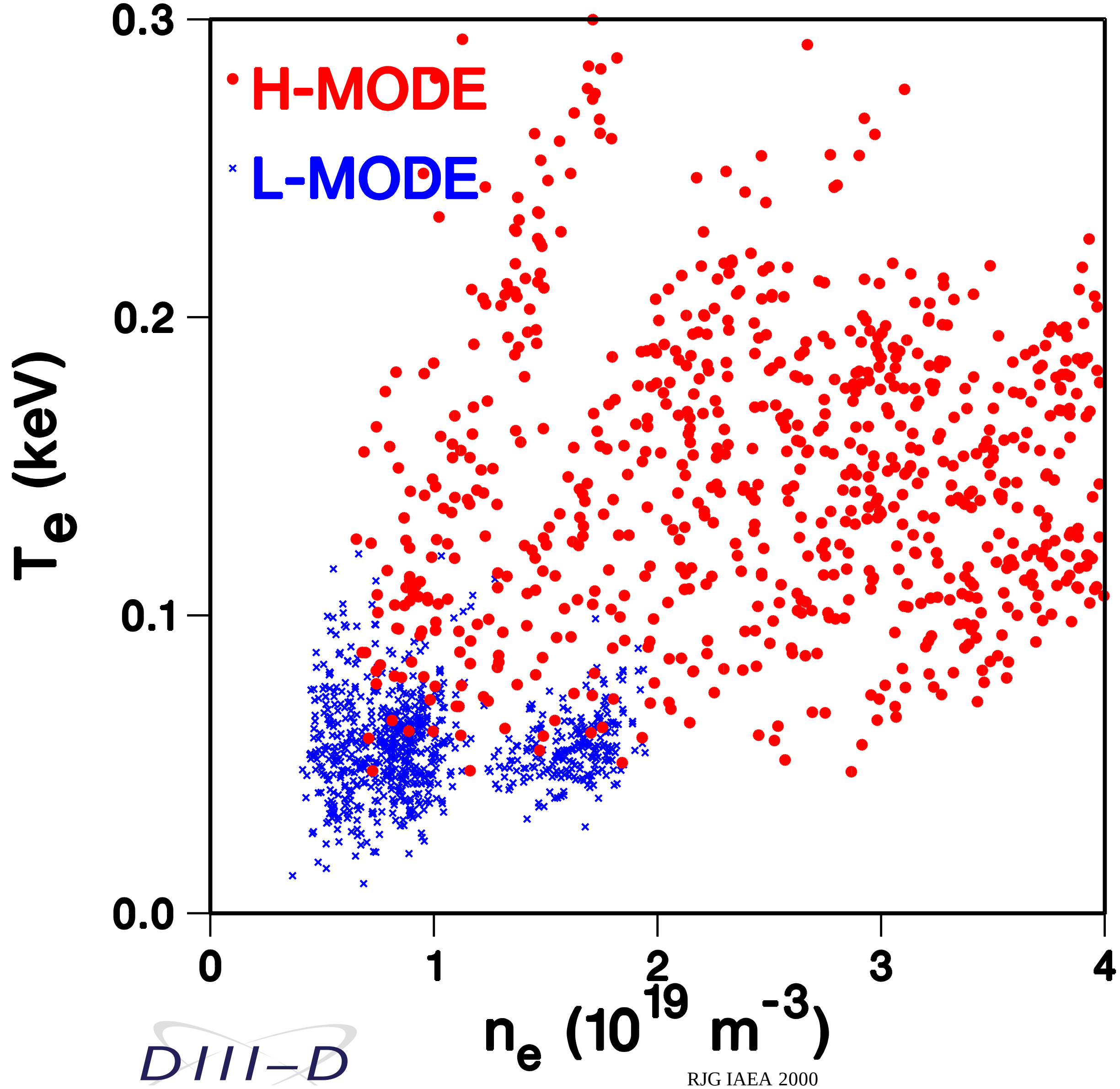
DEFINITION of MODIFIED TANHFIT



H-mode Transition *NOT* Controlled by Electron Temperature Alone

- **Operational space diagrams of T_e - n_e do not show clear distinction between L-mode and H-mode points**
- **Studies of Ion ∇B drift show that for same values of T_e, plasma can be close to or far from threshold**
  - **Depending on sign of B_t**
- **Pellet reduces edge temperature - yet, it causes an L-H transition**

T_e Does Not Show Boundary Between L-mode and H-mode States



- Operational space diagram from density scan
- Plasma current and toroidal field fixed
- SND discharges with ion ∇B drift in favorable direction

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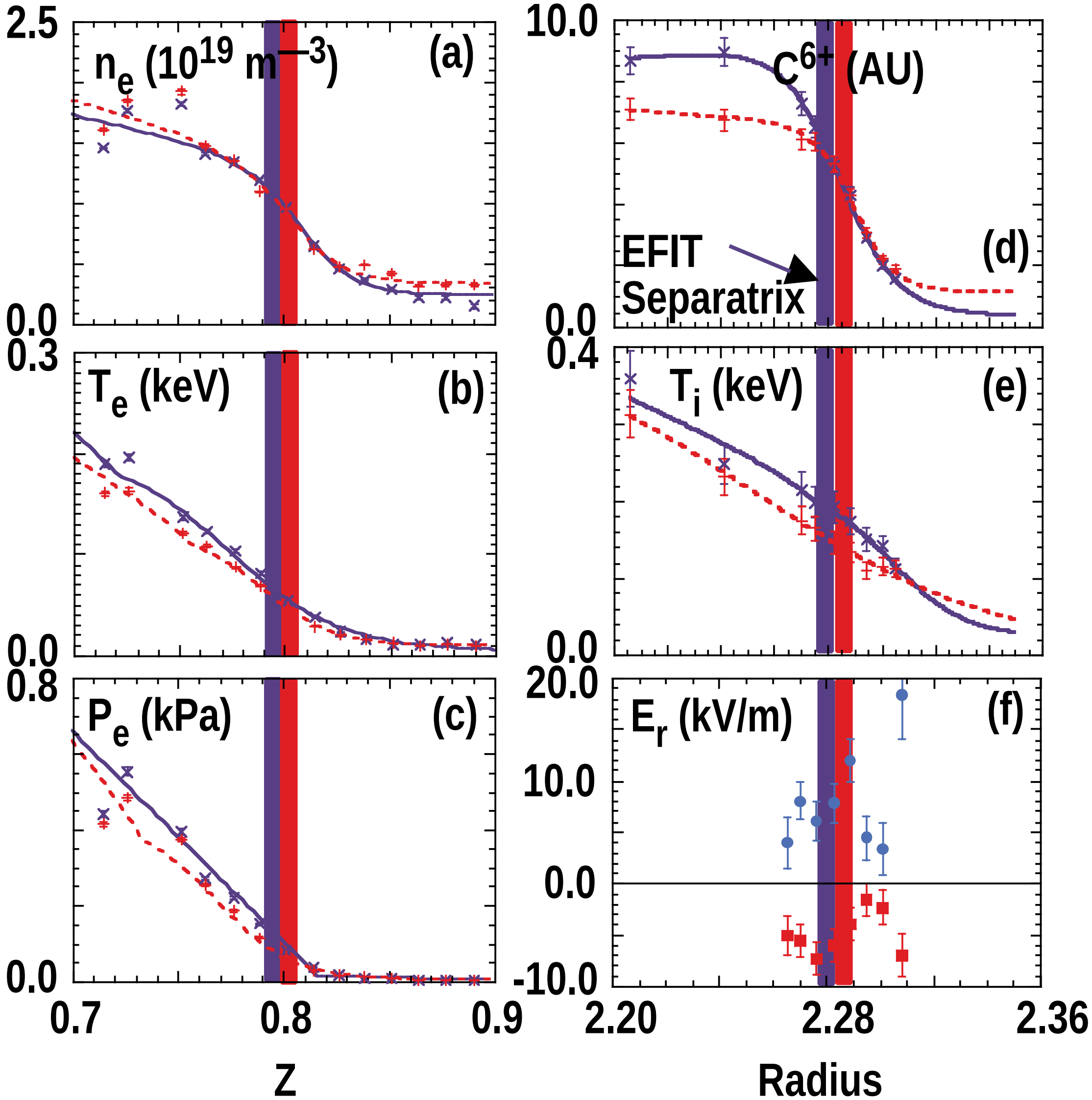
"Critical" T_e Not Observed for Ion ∇B Drift



- Blue data are from Ion ∇B drift towards x-point. Data are just prior to transition.
- Red data are from Ion ∇B drift away from x-point. Plasma is far from transition.
- T_e similar for both cases. Thus, T_e is not the control.
- *From T.N. Carlstrom, 2000 EPS*

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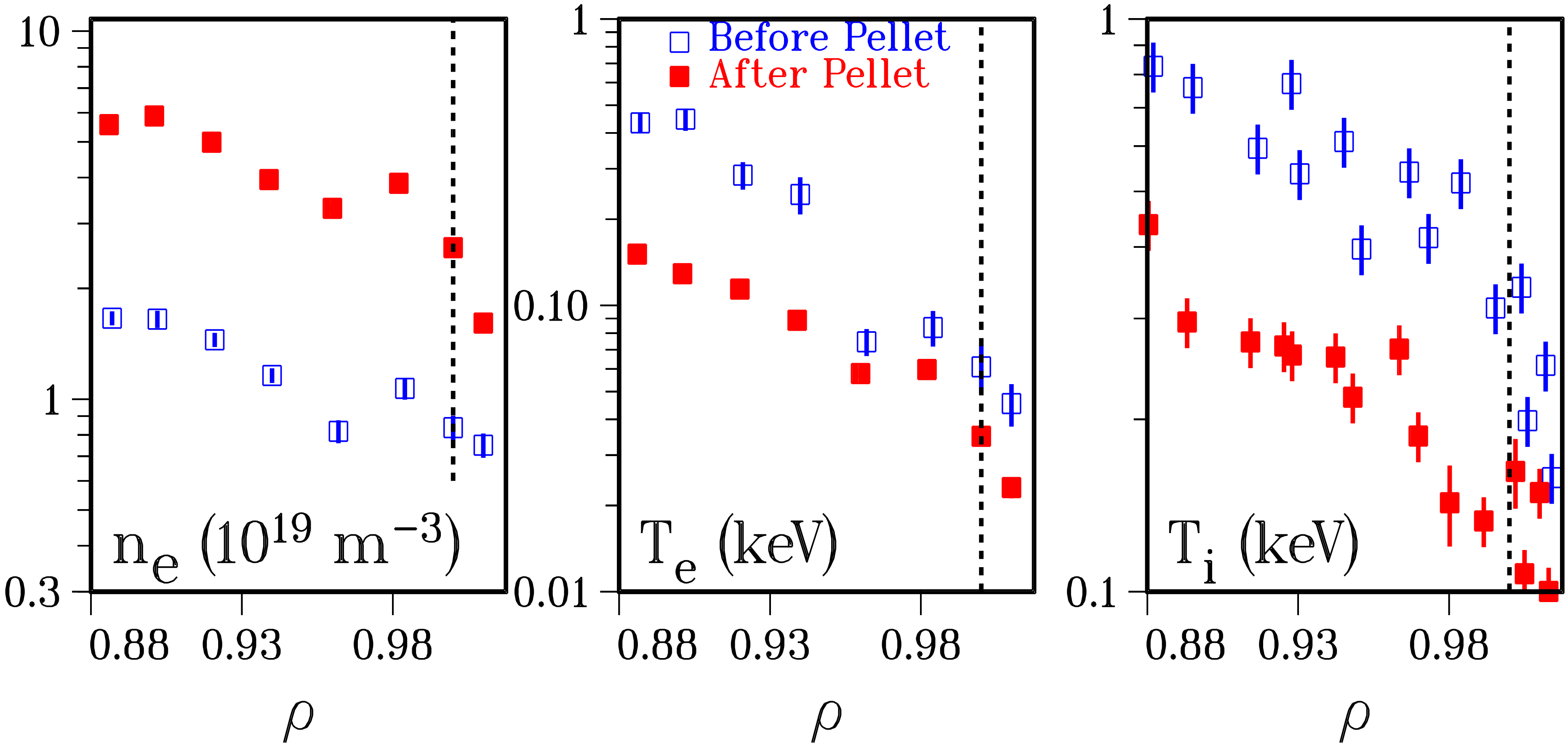
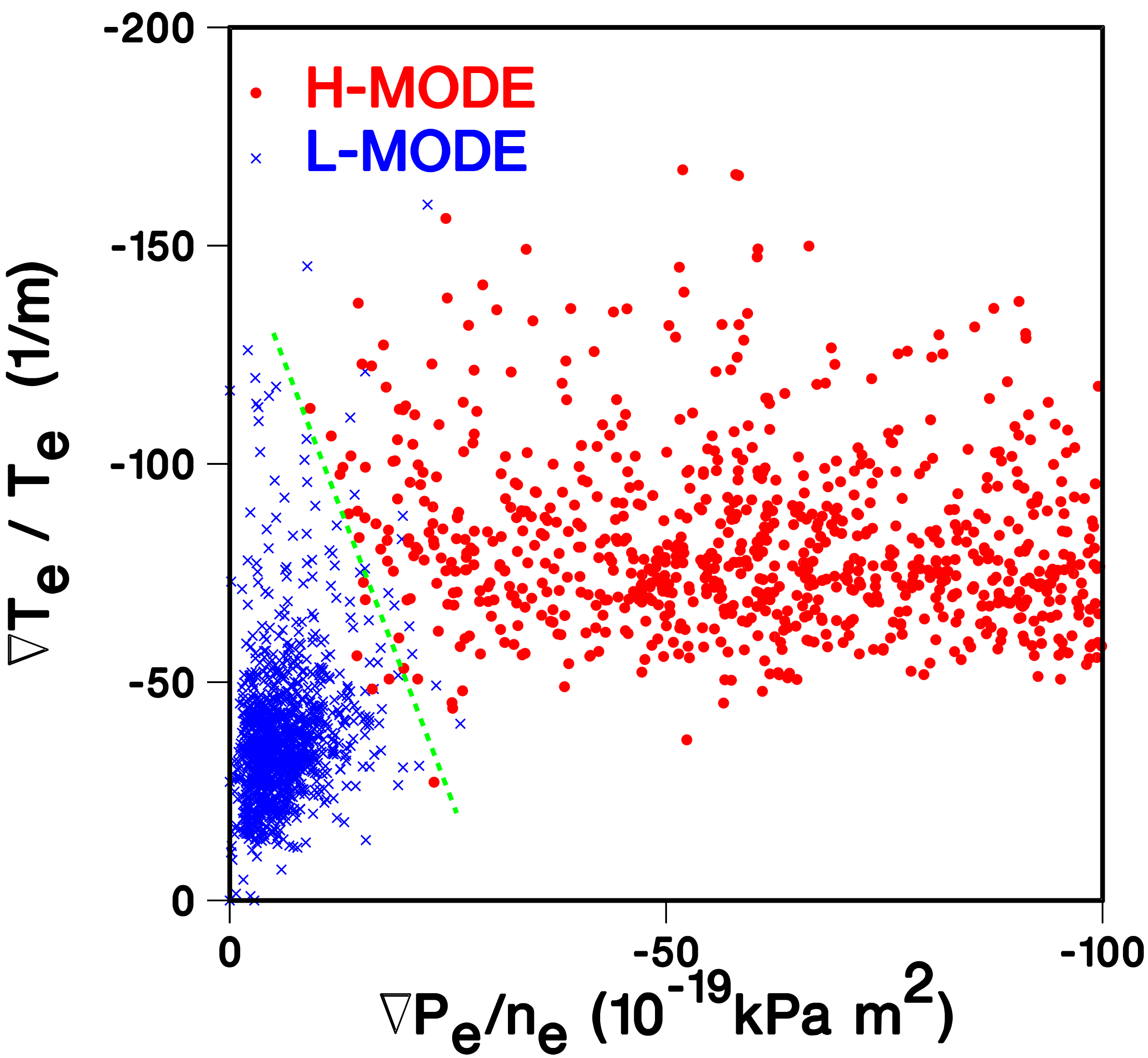
Pellet Reduces Edge Temperature But Still Causes an L-H Transition



Gradients of temperature and pressure increase in L-mode and may play a causal role

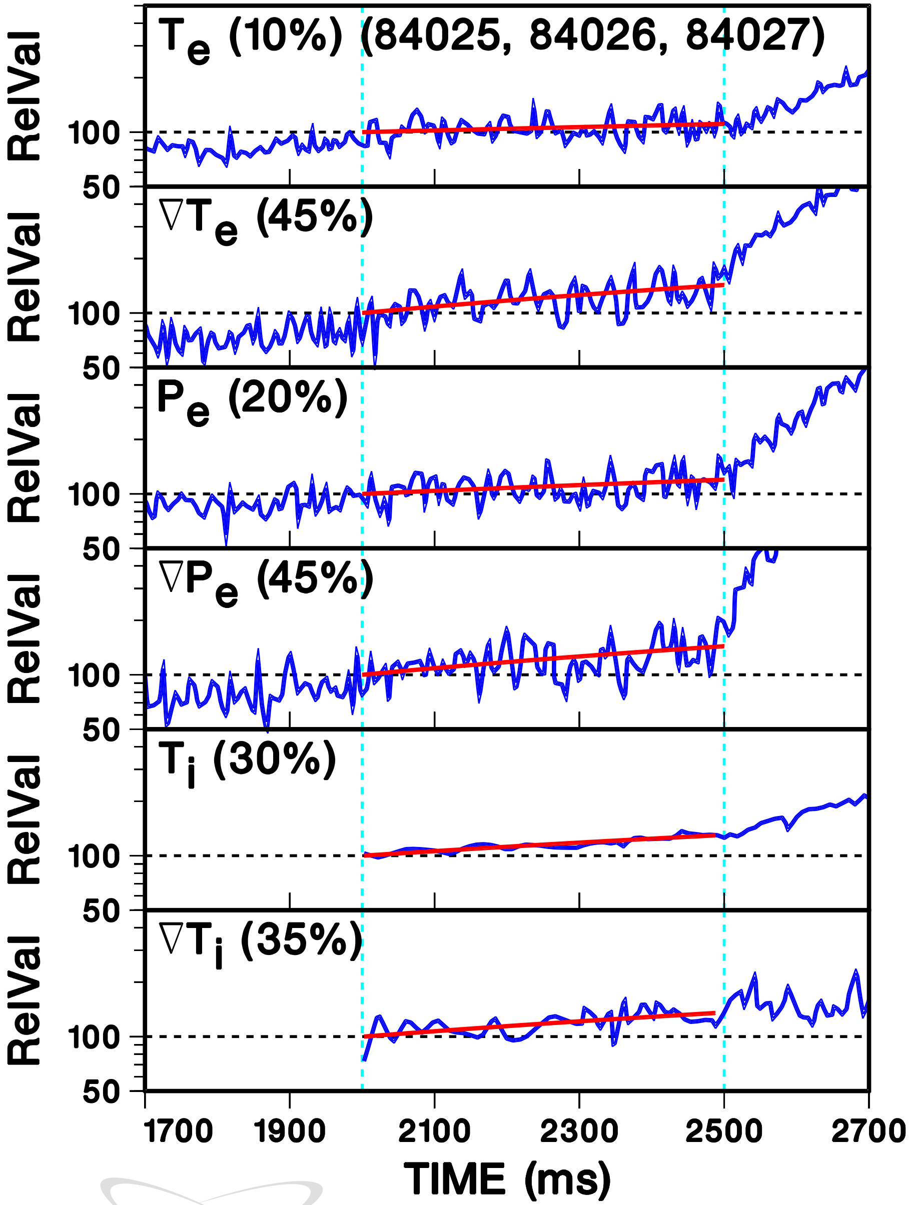
- Edge ∇T_e, ∇P_e, ∇T_i, ∇P_i routinely increase during L-mode prior to L-H transition
  - Changes are usually larger than changes in underlying parameters
- For a wide class of discharges, transition occurs when ∇T_e and ∇P_e approach a well-defined boundary
- If ohmic discharge is close to H-mode boundary, gradients evolve by small amount in L-phase
- If ohmic discharge is far from H-mode boundary, gradients evolve by large amount in L-phase

Gradients Classify L- and H-mode States Well



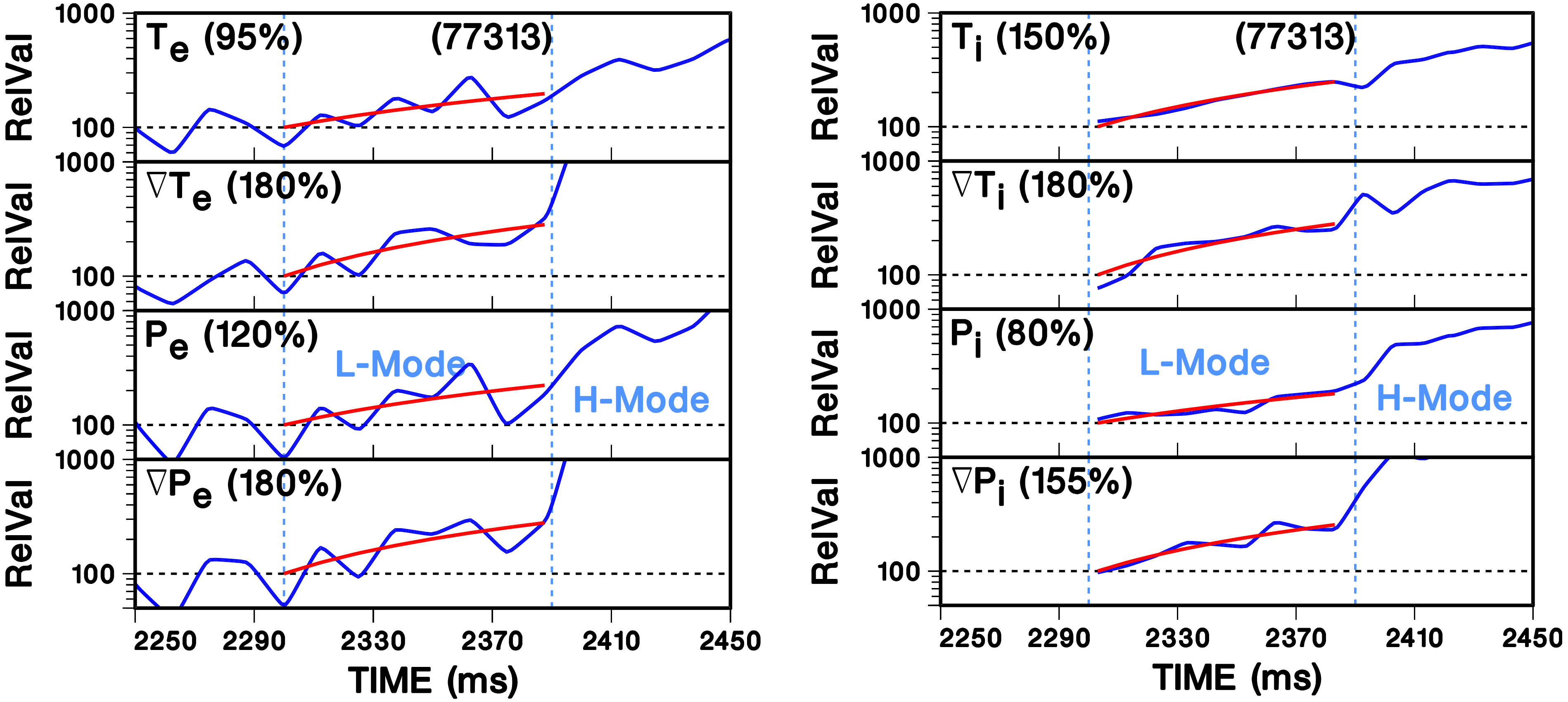
- Evaluated at point of largest density gradient
- Includes scans of n_e, I_p, B_t
- Also includes pellet-injected H-modes
- These data are a superset of data shown in T_e-n_e diagram

Gradients Increase During L-mode



- Average of 3 discharges with low power threshold
  - Ohmic discharge is close to H-mode threshold
- Increase in gradients is moderate during L-mode
- Increase in T_e is small during L-mode
- Percentages are relative changes of a parameter during L-mode phase

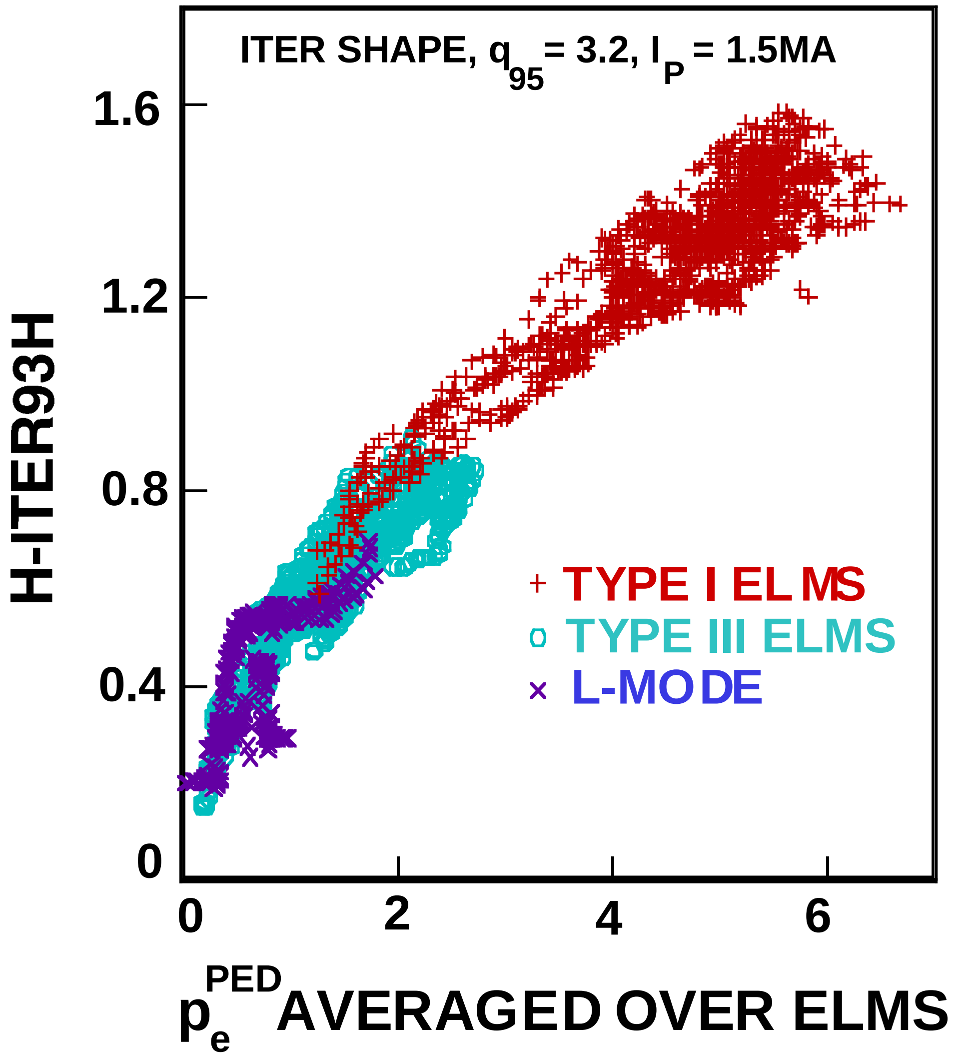
Gradients Increase Markedly In L-mode with High Power Threshold



Global Confinement Correlated with Pressure Pedestal

- **New observations exhibit this correlation**
- **Confinement degradation in gas-fuelled, high n_e discharges correlated with drop in T_{ped} and P_{ped}**
- **High density, gas-fuelled discharges which do not degrade in confinement, also show no degradation in P_{ped}**
- **Increase of confinement with triangularity δ is correlated with increase in P_{ped}**

H-Mode Energy Confinement Correlated with Height of Pressure Pedestal



- **Discharges with large H-mode pedestals have high energy confinement enhancement,** H**.**
  - **Type 1 ELM discharges have large pedestals due to high edge pressure gradient.**
  - **Low n_e Type 3 ELM discharges have limited gradient α and therefore poor** H.
  - **Low T_e Type 3 ELM discharges may reach higher** H **if α increases at high n_e**
- ***From T.H. Osborne, 1997 H-mode Workshop***

Edge Pressure Gradient Consistent with MHD Limits

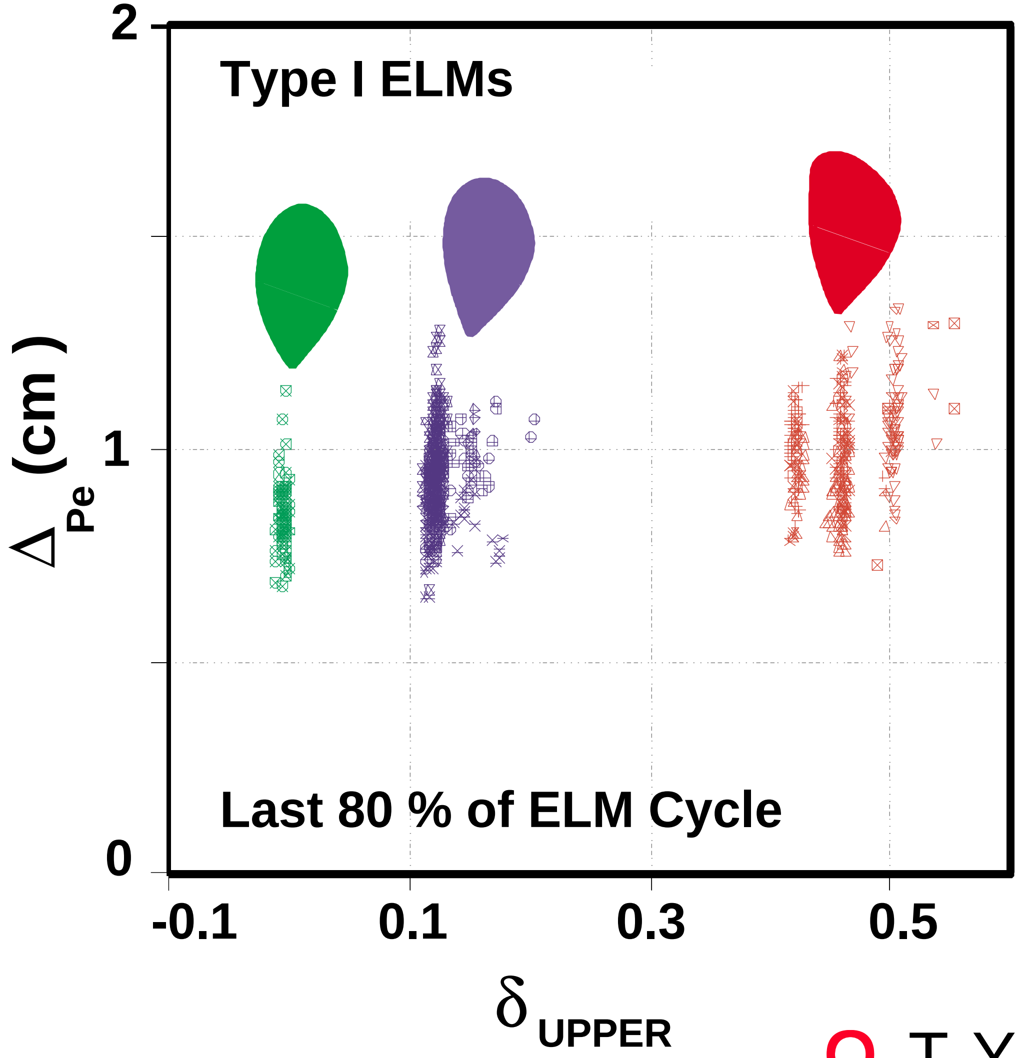
- **Under some conditions, pressure gradient is consistent with infinite-n ballooning modes, 1st regime limit**
- **However, edge bootstrap current often provides stability against these modes**
  - **Resulting pressure gradients in 2nd stable regime**
- **Then, observed pressure gradients are consistent with limits due to ideal medium-n kink/ballooning modes**

Increase of confinement with triangularity δ is correlated with increase in P_{ped}

- **Due primarily to increase in ∇P with δ**
  - **MHD stability improves with δ**
- **Observed pressure gradient consistent with medium-n ideal kink/ballooning modes**
- **Width of pressure barrier Δ_{pe} increases very weakly with δ**
- **Δ_{pe} has approximately value expected from established scaling relationship based on $(\beta_{pol})^{1/2}$**

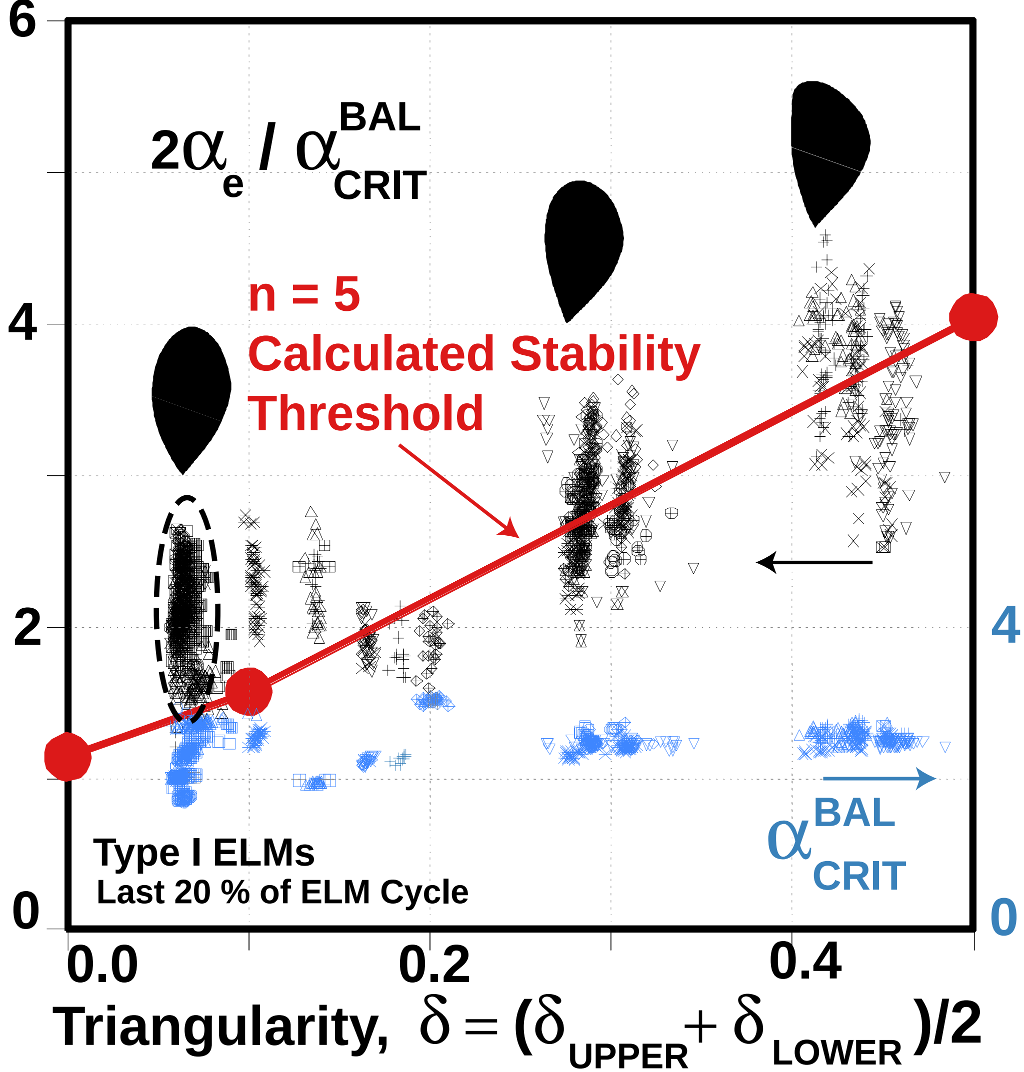
Width of Pressure Barrier Varies Weakly with Triangularity

(T.H. Osborne, 1999 H-mode Workshop)



Threshold for n=5 MHD Modes Increases with Triangularity as Does Measured Edge ∇P

(J.R. Ferron, 1999 APS)



- Modes are ideal kink/ballooning
- Calculations from GATO
- Calculations for symmetric up-down shape
- Thus, there may be slight change in quantitative results for actual non-symmetric shapes

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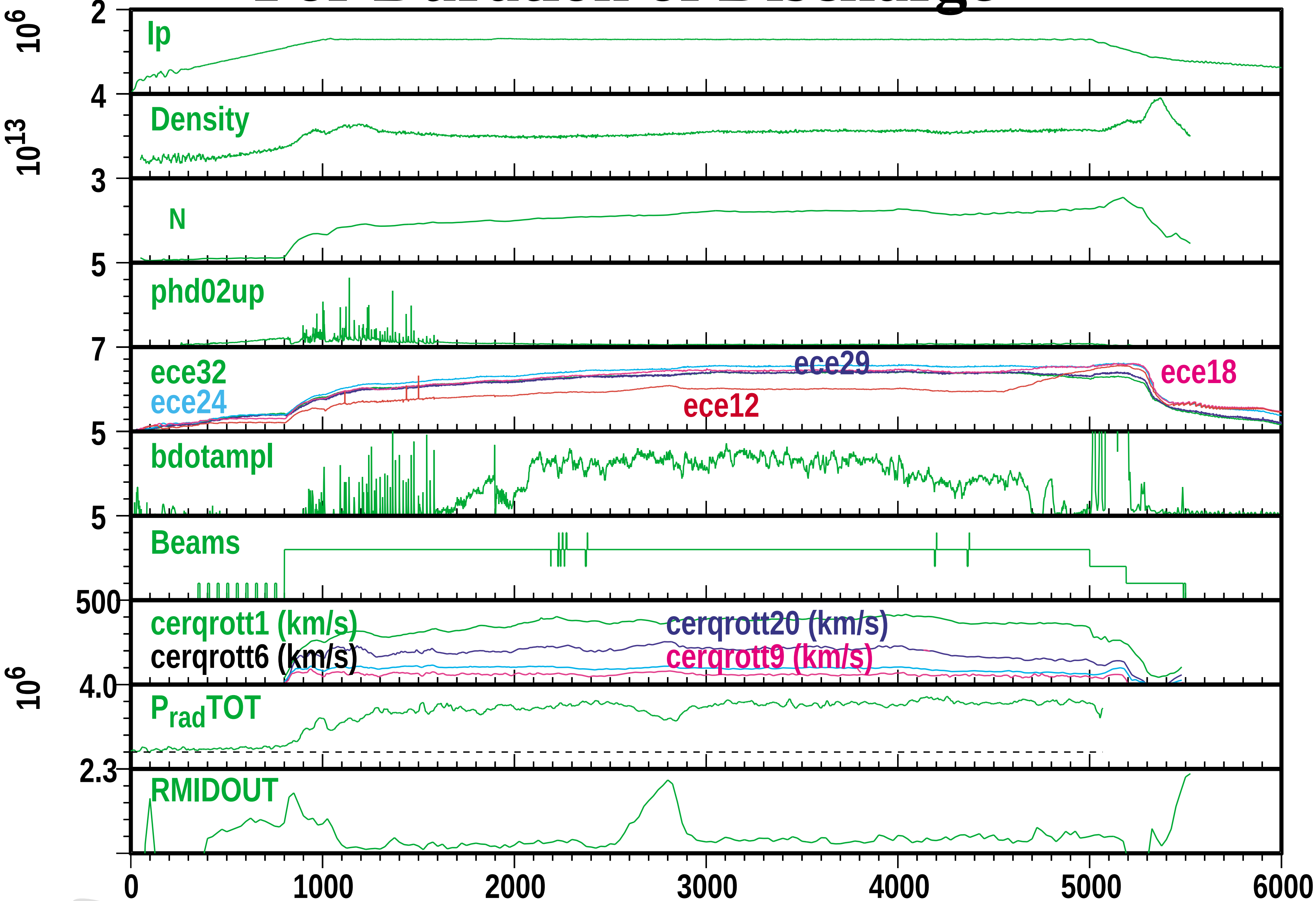
New Steady State H-mode Regime Discovered
- Called Quiescent H-Mode

- **Steady-state density and impurity levels**
- **Low radiated power**
- **ELM-free operation (no pulsed heat to divertor)**
- **Standard H-mode confinement quality**
- **Normal H-mode edge pressure gradient**
- **Discharge duration limited only by power supplies**
- **These discharges obtained with counter-injection, cryopumping and sufficient outer gap**

QH Mode Provides Steady State Operation For Duration of Discharge



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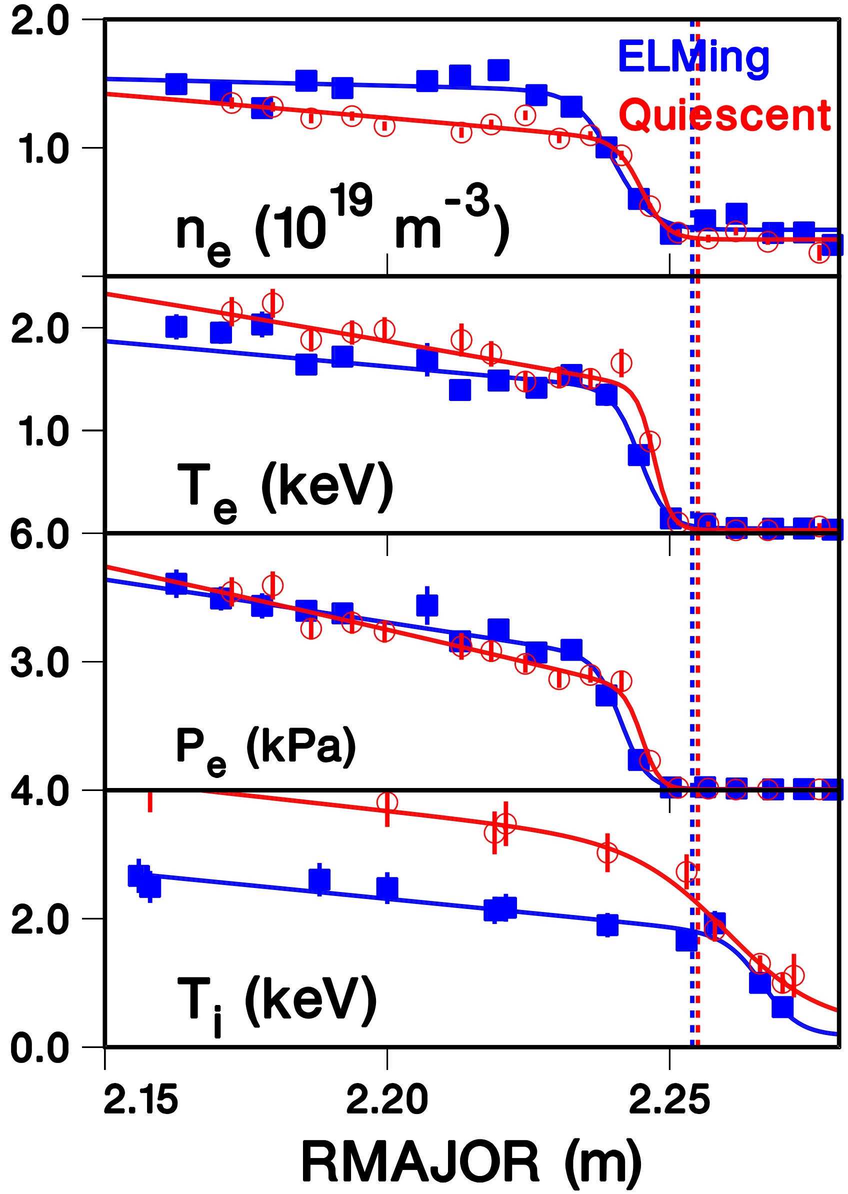
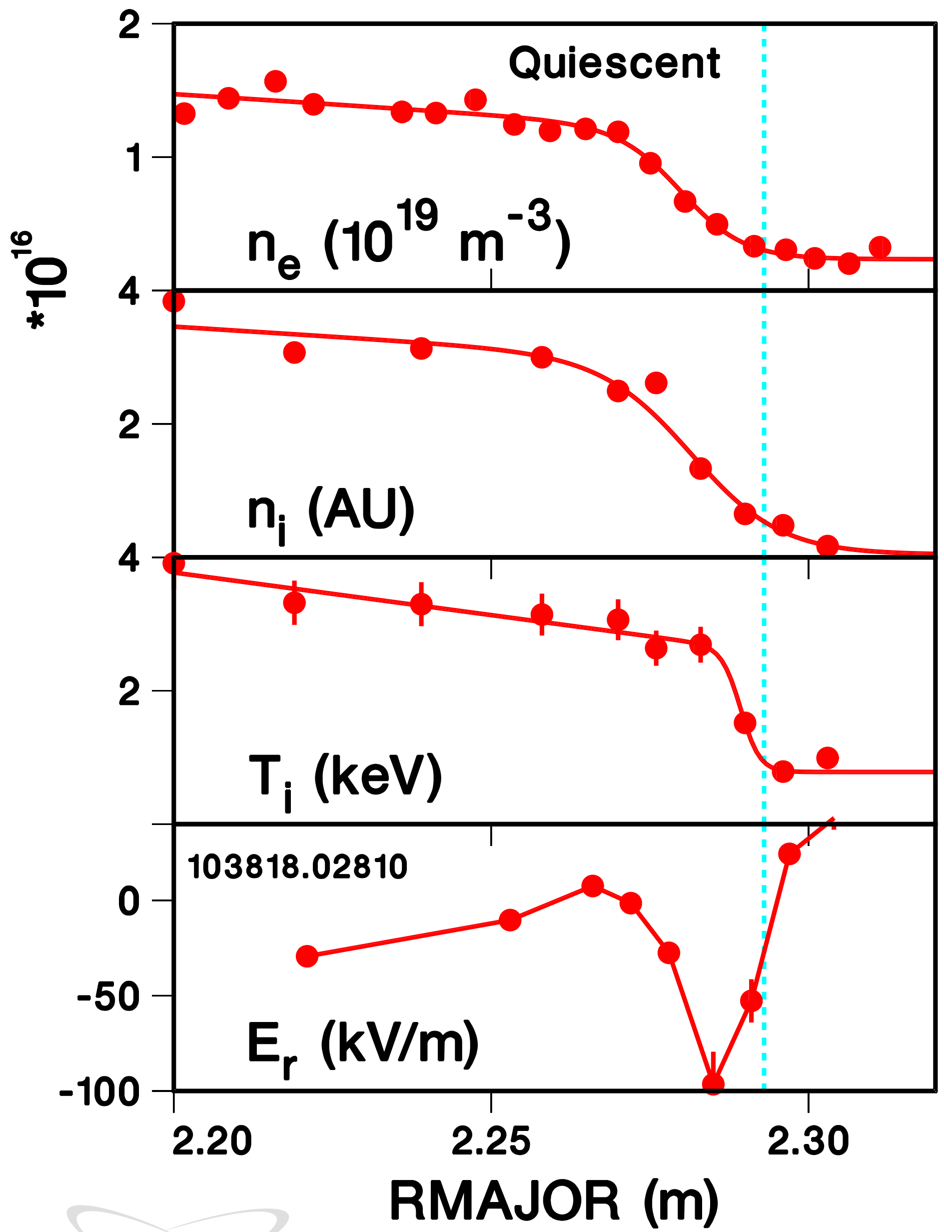
QH Mode Has Normal H-mode Pressure Gradient



- Electron profiles are very similar in ELMing and QH phases of same discharge
- ∇P_e is same in ELMing and QH phases
- Pedestal T_i is higher in QH phase

Very Deep E_r Well May Facilitate QH Mode

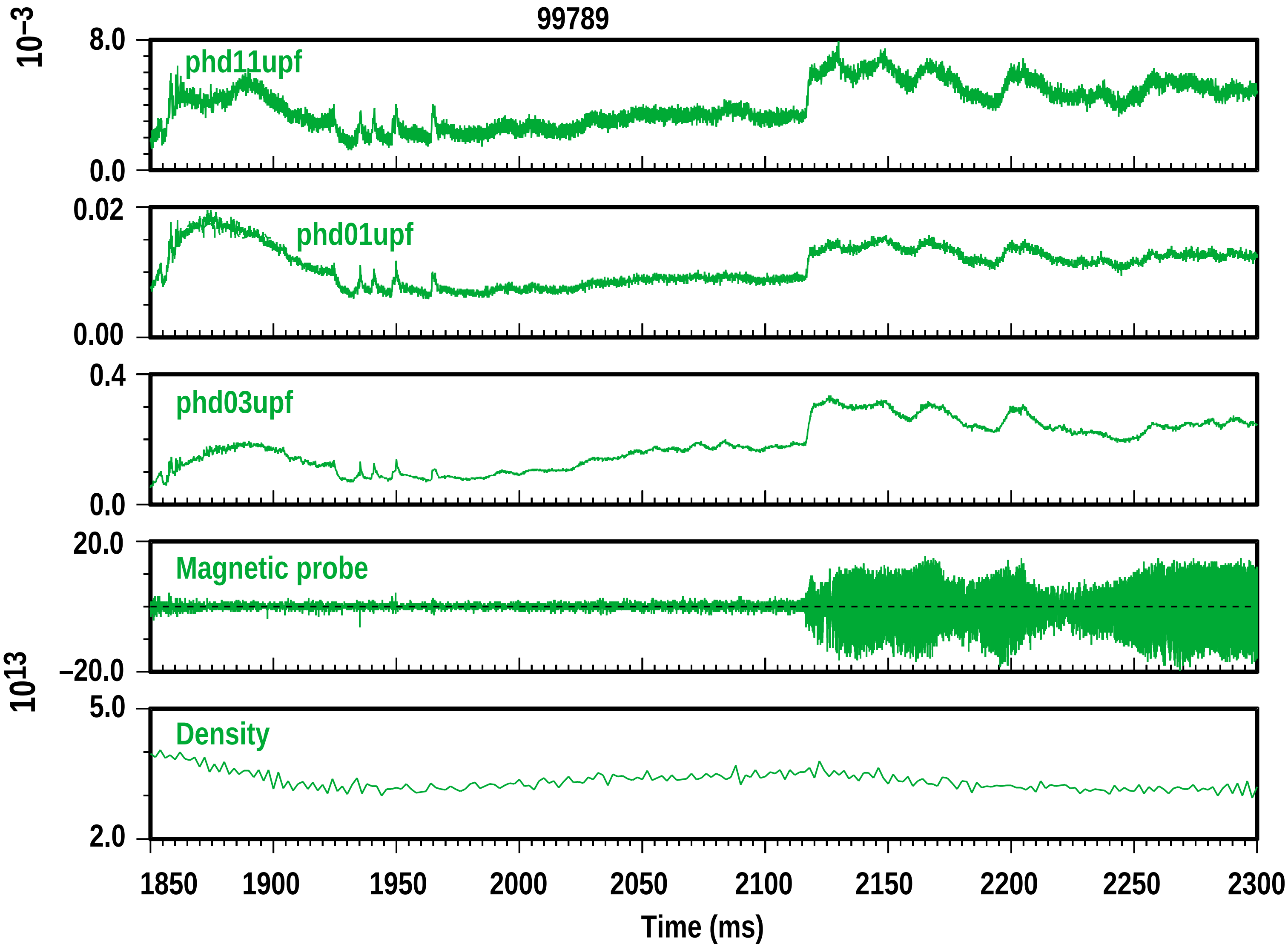


- Reversed plasma current modifies radial electric field
- $V_\Phi \times B_\theta$ term in radial force balance changes sign
- H-mode E_r well is deeper than for normal direction of plasma current
- Also, E_r is negative, rather than positive, in core

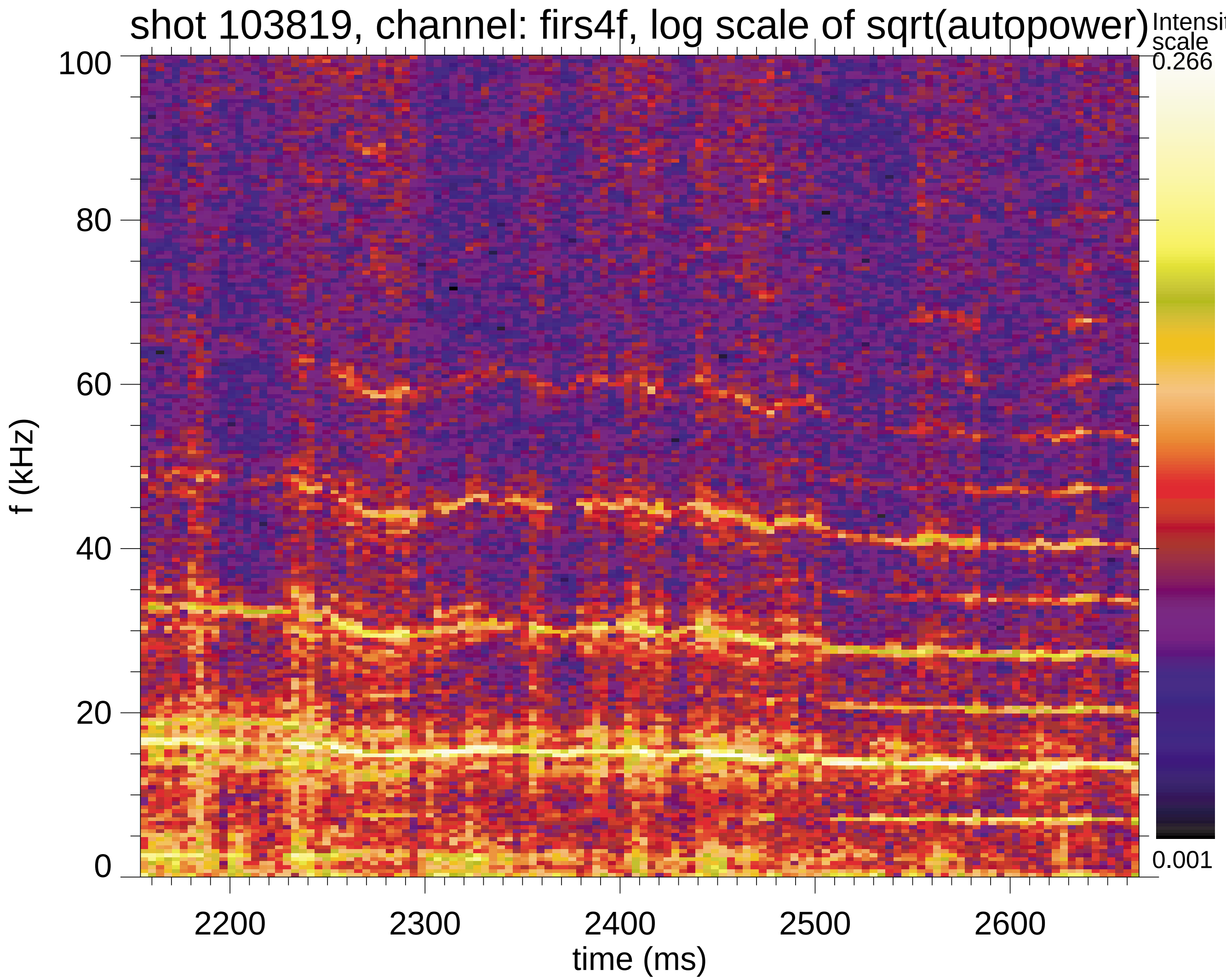
Multi-Harmonic MHD Mode (MHM) May Be the Key to Controlled Edge Transport

- **A continuous, coherent mode is observed on all fluctuation diagnostics during QH phase**
- **Mode has several harmonics with n typically in range 1-9**
- **Mode exists very near the separatrix**
- **This mode provides sufficient transport to exhaust particles**
  - **Thus, giving particle control**

ONSET OF MULTI-HARMONIC EDGE MODE INCREASES DIVERTOR D_α AND REDUCES n_e



Reflectometer Shows Multiple Harmonics of Coherent Mode



Summary and Conclusions

- Transition criterion not simply a critical value of T_e
- Gradients of temperature and pressure increase in L-mode and may play a causal role
- Edge pressure gradient limited by MHD stability
- Width of pressure barrier scales with $(\beta_{pol})^{1/2}$
- Quiescent H-mode provides steady-state particle control
  - Results in high quality H-mode discharge
- QH operation has very desirable reactor features