Limits to H-mode Pedestal Pressure Gradient in DIII-D

R.J. Groebner, P.B. Snyder, T.H. Osborne, A.W. Leonard, T.L. Rhodes, L. Zeng, E.A. Unterberg, Z. Yan, G.R. McKee, C.J. Lasnier, J.A. Boedo, J.G. Watkins

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DIII-D
NATIONAL FUSION FACILITY

GENERAL ATOMICS

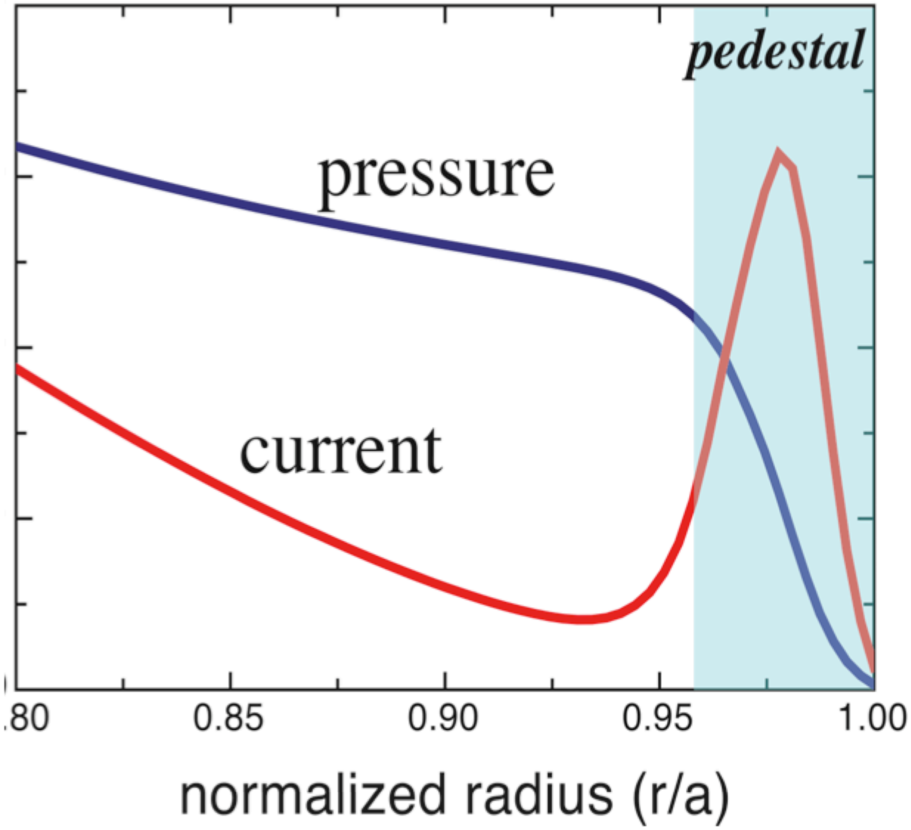
Long Term Goals of DIII-D Pedestal Physics Program

- **Validated model of pedestal height**
  - For ELMing and ELM-suppressed conditions
- **Optimized pedestal for ITER and beyond**
  - High pedestal (enabling good core confinement)
  - No ELMs or tolerable ELMs
  - Acceptable impurity influx into plasma
  - Compatible with divertor solutions for heat flux
  - Compatible with fueling methods (i.e. pellets)

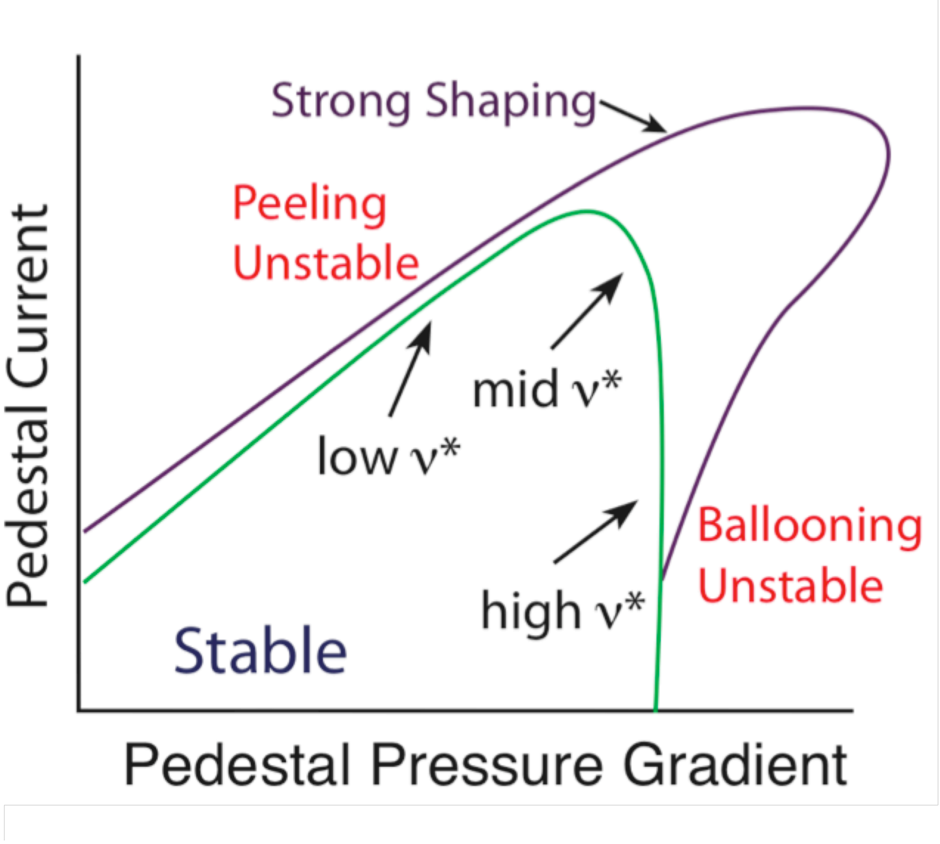
EPED1 Pedestal Model Successfully Describes a Wide Range of DIII-D Data

- **This model is based on two hypotheses:**
  - 1) Pedestal pressure limited by finite-n, ideal peeling-ballooning modes
  - 2) Pedestal pressure gradient and width are limited by kinetic ballooning modes (KBM)
  - KBM model predicts that pedestal width $\Delta \sim 0.1\ (\beta_\theta^{ped})^{1/2}\ G(\nu_*, \varepsilon, \ldots)$
  - From experiment, G determined to be ~ 0.76
  - EPED1 model uses ELITE to compute peeling-ballooning limit and implements width scaling $\Delta = 0.076 (\beta_\theta^{ped})^{1/2}$
  - (Snyder et al., Phys. Plasmas 16 (2008) 056118)
- **EPED1 code has made good quantitative predictions of pedestal height and width in DIII-D**
  - Pedestal pressure height was varied by more than 10X and width was varied by 3X
  - (Groebner et al., Nucl. Fusion 49 (2009) 085035)

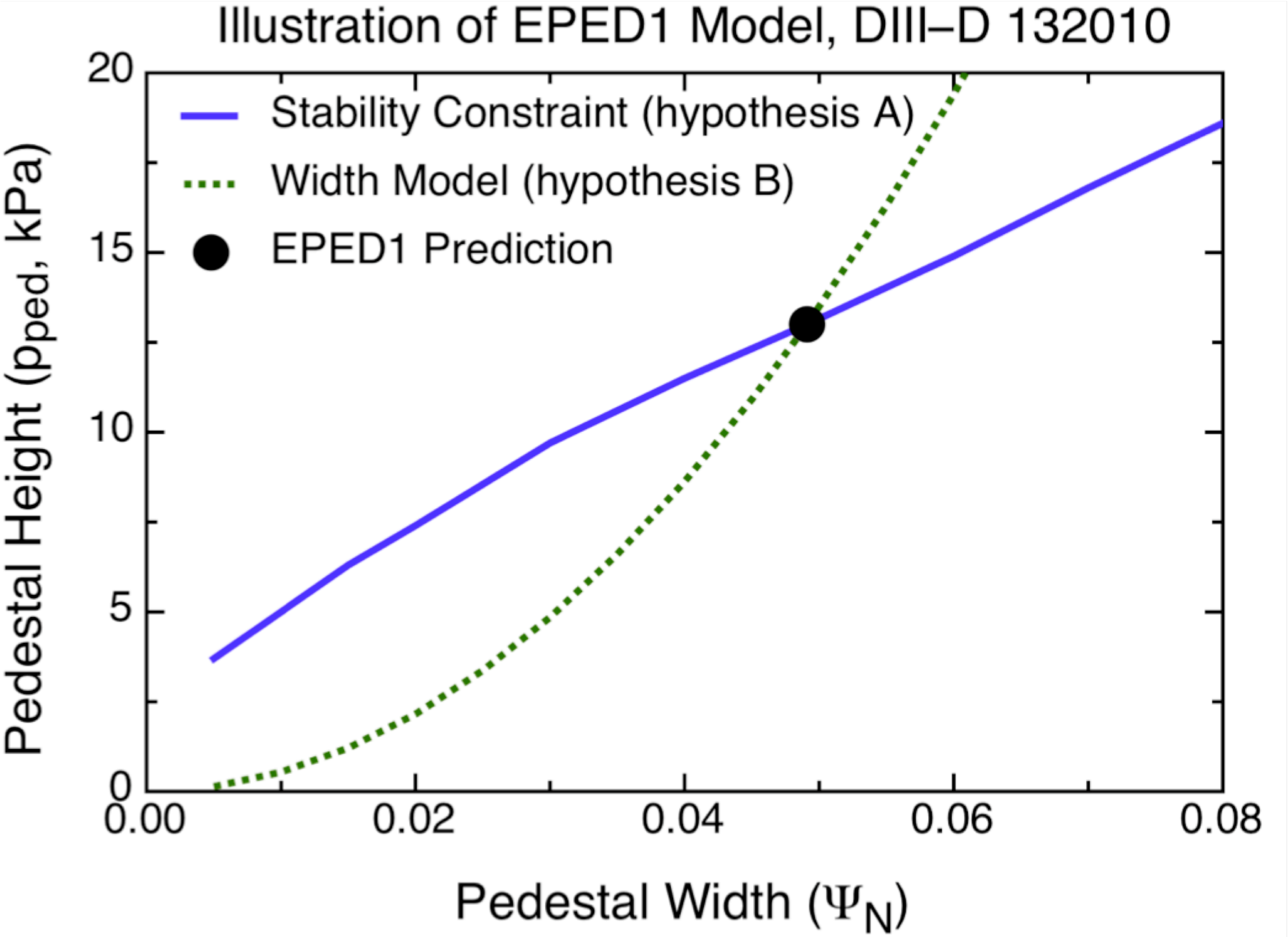
In Peeling-ballooning Theory, Pedestal Current and Pressure Gradient Control ELM Onset



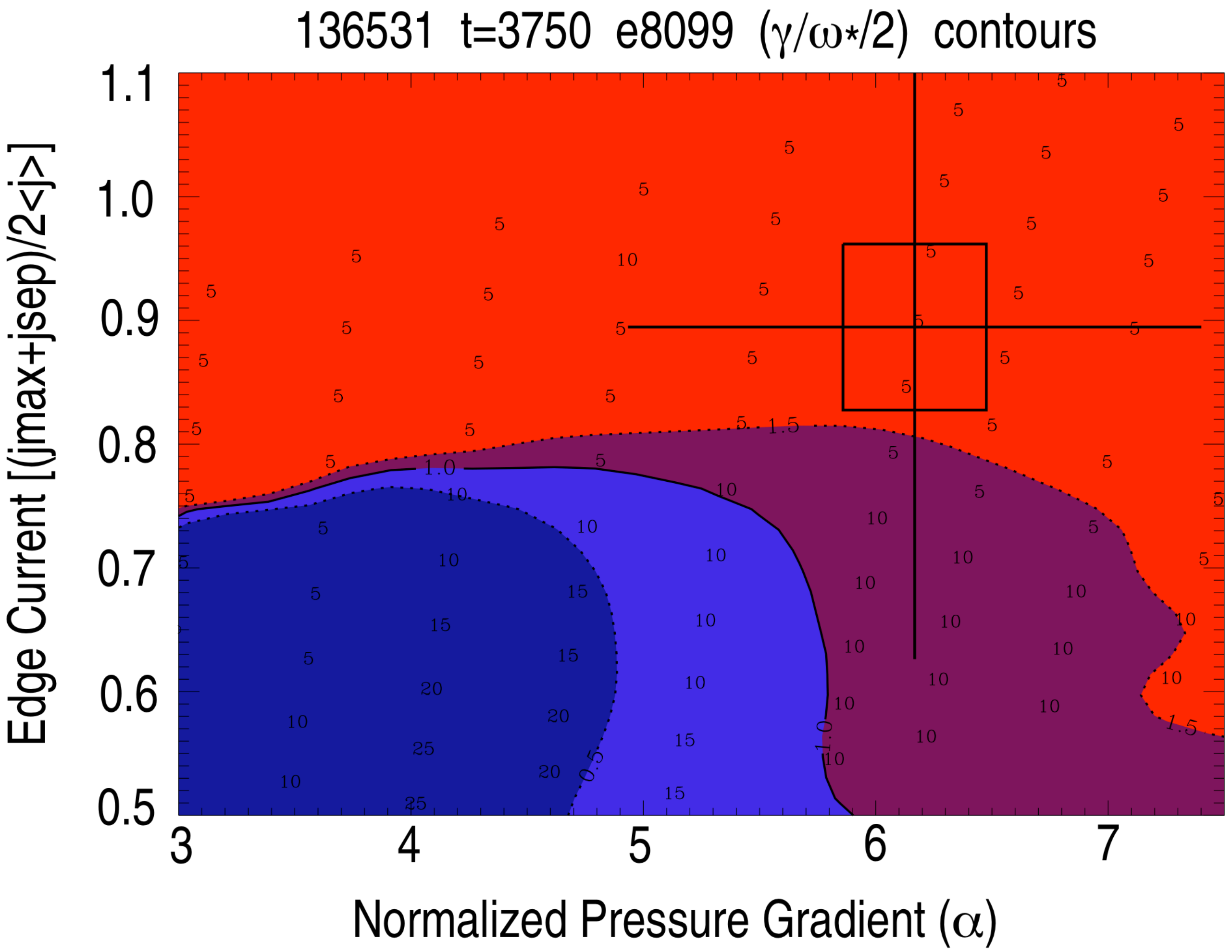
Schematic edge MHD stability diagram



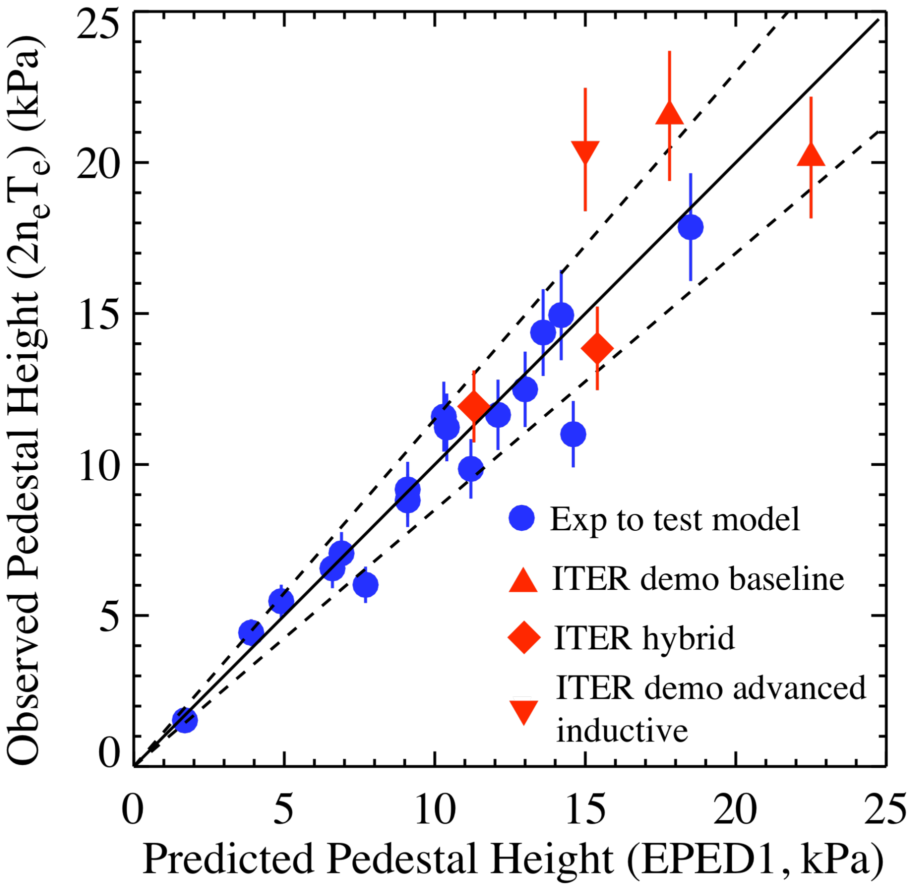
Pedestal Operating Point from EPED1 Given by Intersection of Two Equations

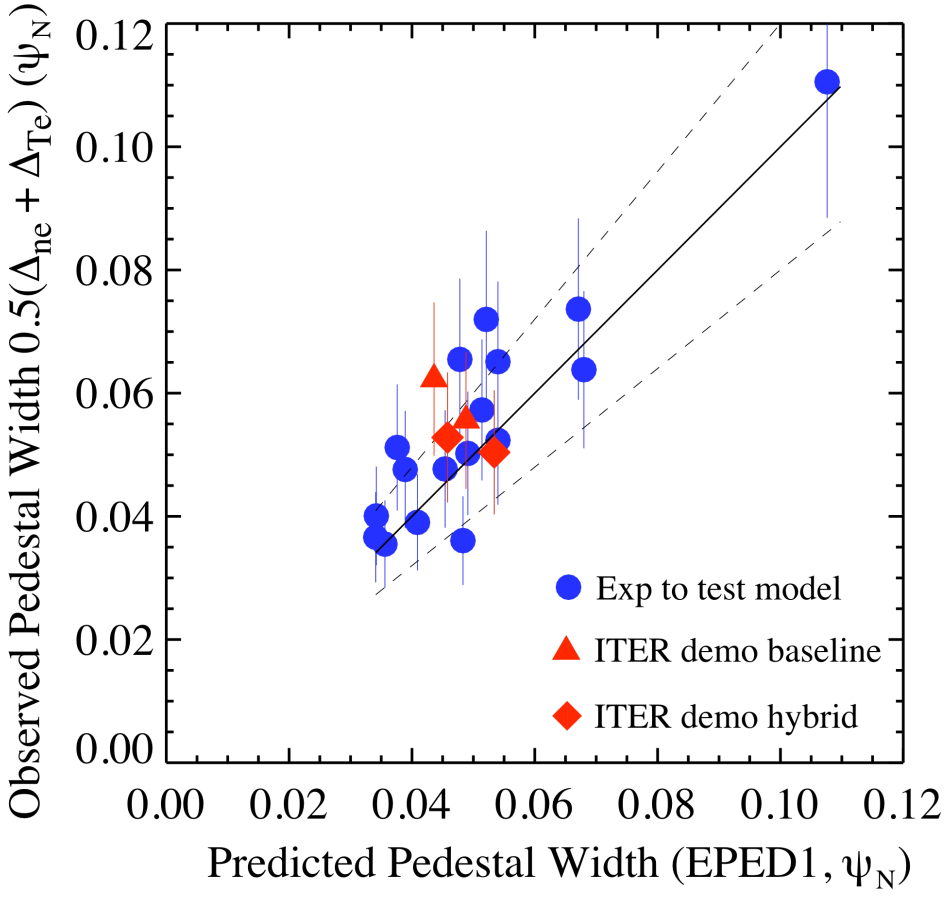


DIII-D Pedestal Operating Point at ELM Crash is Explained by Peeling-ballooning Theory



EPED1 Model Predicted Pedestal Height and Width Variation in a Dedicated Experiment

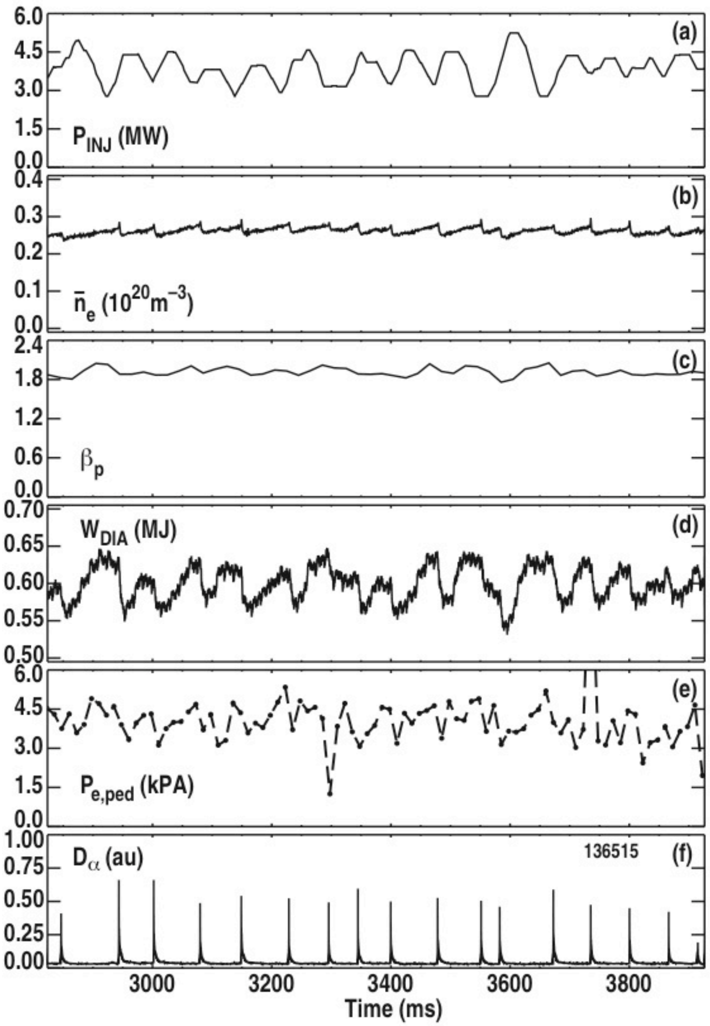




Motivated by Success of EPED1, Experiment Was Designed to Look for Evidence of KBM in Pedestal

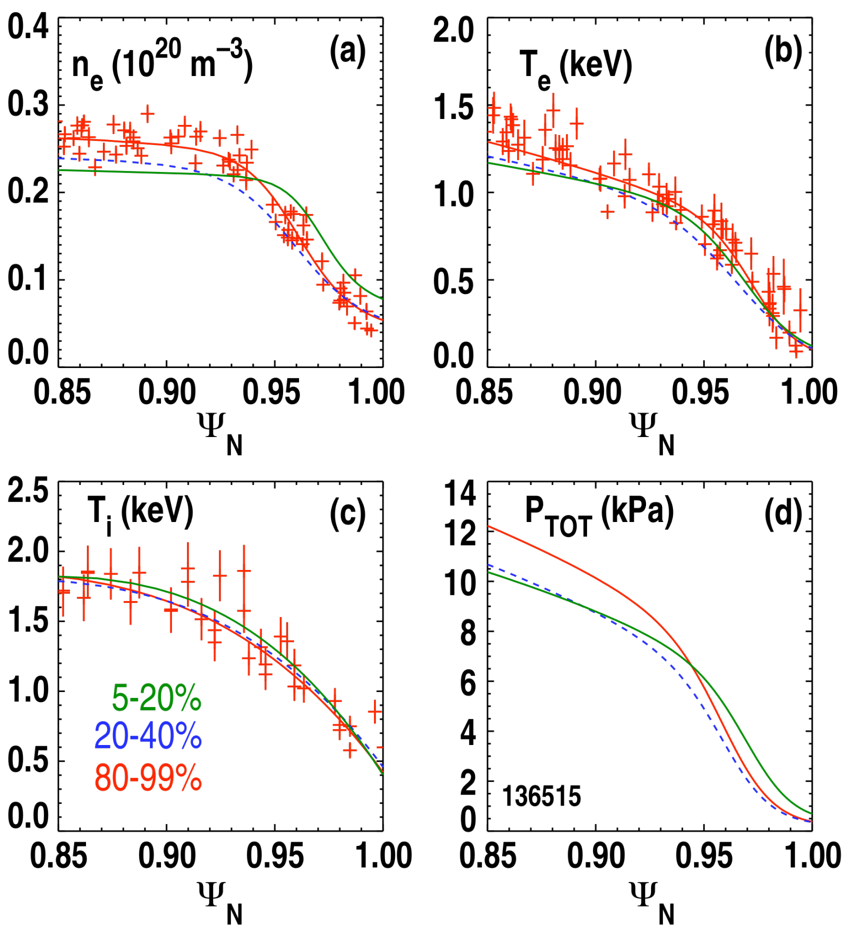
- **Key model parameters of KBM model are normalized pedestal pressure gradient and magnetic shear (α and *s*)**
  - Hypothesis of experiment was that KBM would turn on during ELM cycle when pedestal pressure gradient (α) reached a critical level
  - Onset of KBM would cause a halt or slow-down in rate of rise of GradP
- **This work presents results of pressure gradient variations in the experiment**
  - Total pressure gradient obtained from measurements on n_e and T_e (TS), of T_i and carbon density (CER) and computed beam pressure (ONETWO)
  - ELM cycle (interval between two ELMs) was divided into 5 intervals
  - Composite profiles obtained from these intervals during a quasi-steady state phase of each discharge
- **Key experiment parameters**
  - Current scan to look for evidence of GradP increasing with I_p
  - Density scan to look for evidence of pedestal height decreasing with increasing collisionality

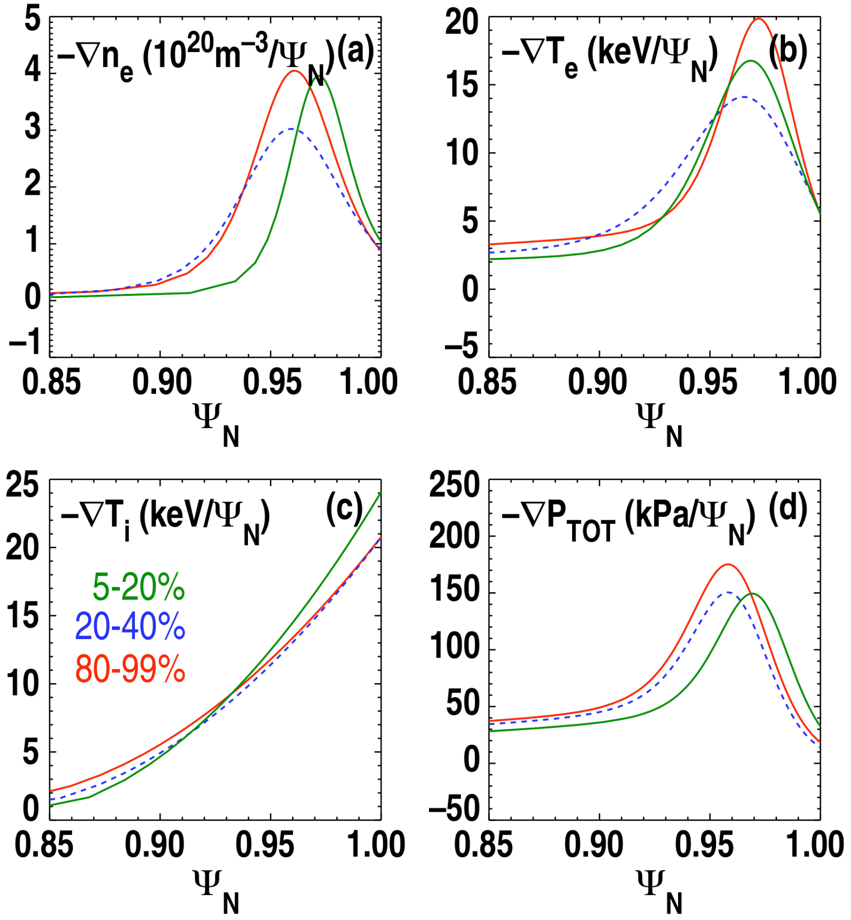
Data Accumulated in Low I_p, High β_p Discharge, Where Wide Pedestal Was Expected



- I_P = 0.7 MA
- B_T = 2.1 T
- β_P = 1.9
- Average ELM period ~ 62 ms
- ELMs were roughly periodic and of similar size

Pressure Gradient Shows Small Change During ELM Cycle for Low I_p, High β_p Discharge 136515





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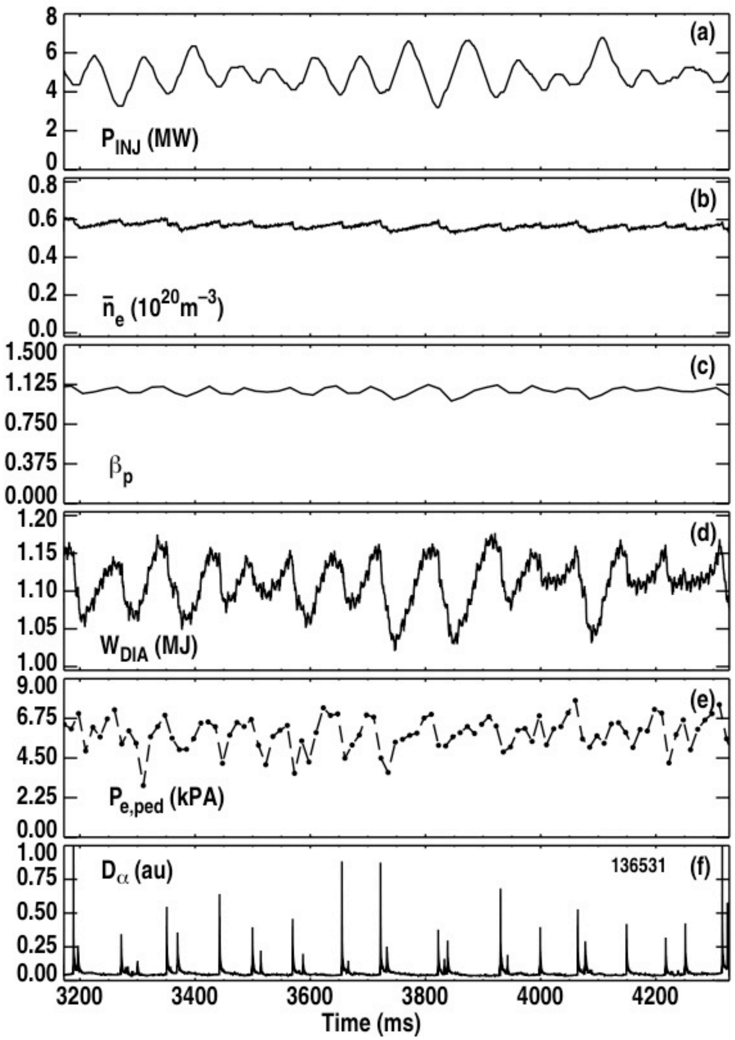
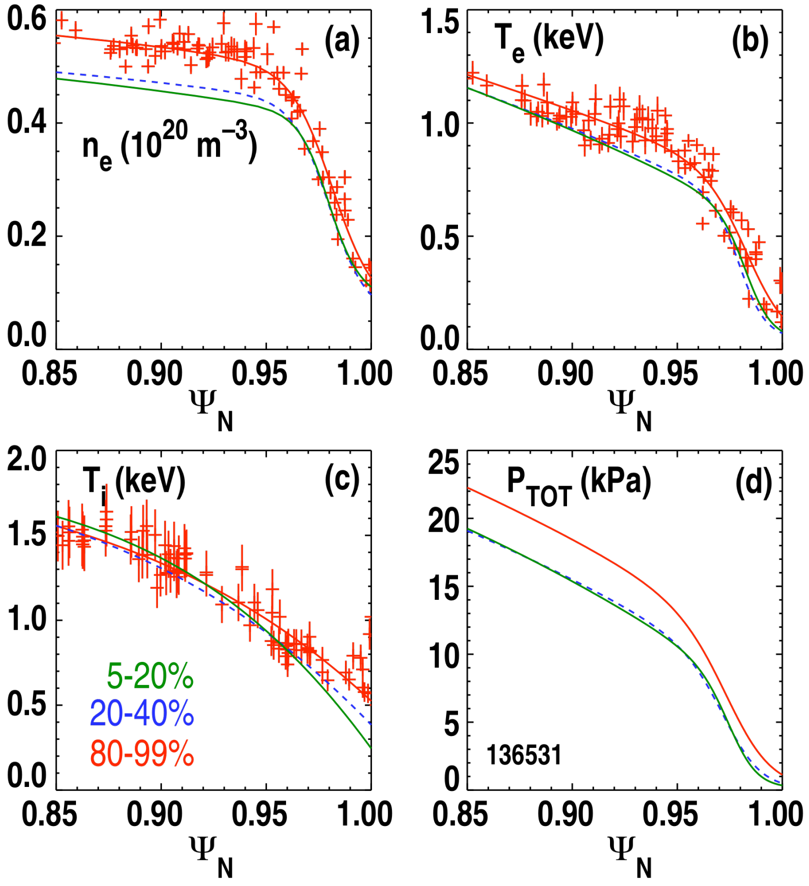
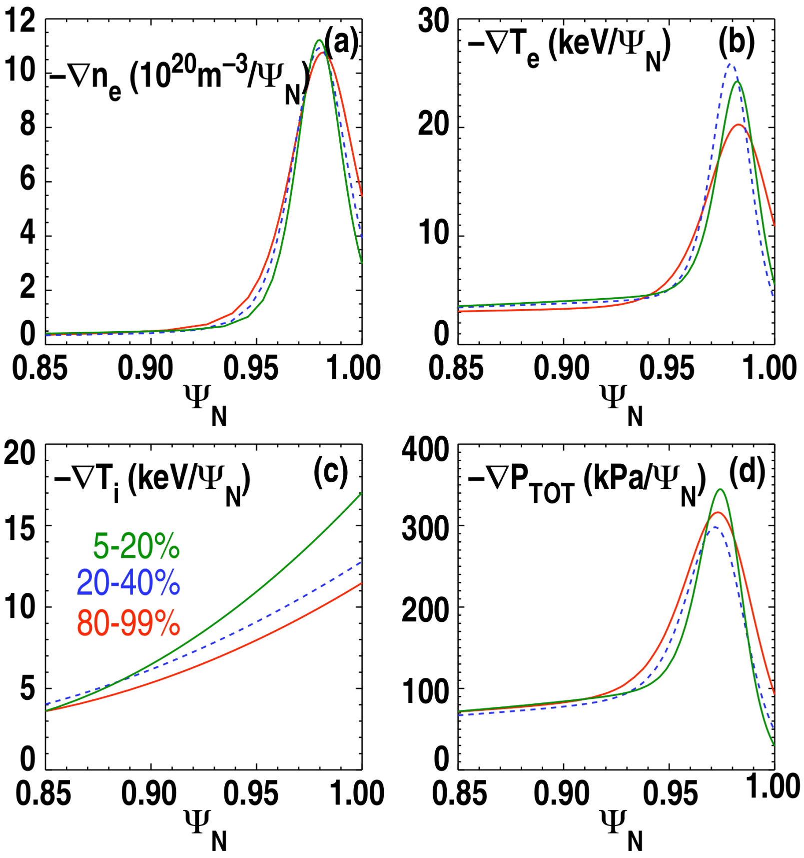
Data Obtained at High Current to Look for Effect of I_p on Pedestal Height and Gradient



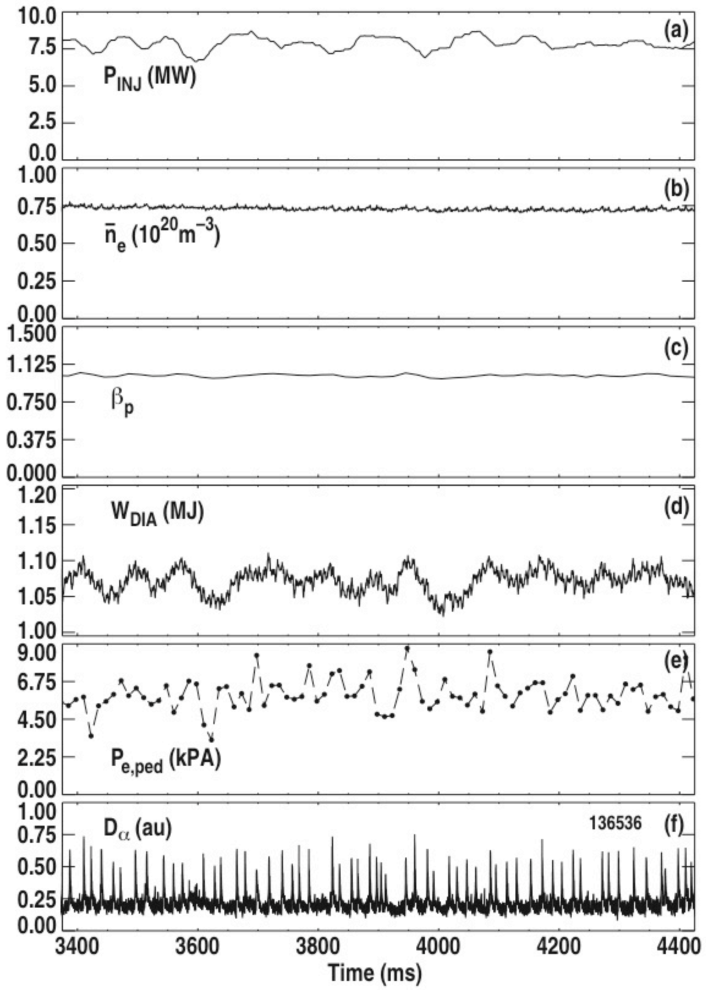
- I_P = 1.3 MA
- B_T = 2.1 T
- β_P = 1.05
- Average ELM period = 70 ms
- Mixture of large and small ELMs
- Filtering in analysis to reject ELM cycles related to small ELMs

Pressure Gradient Shows Slight Broadening During ELM Cycle of High I_p Discharge 136531



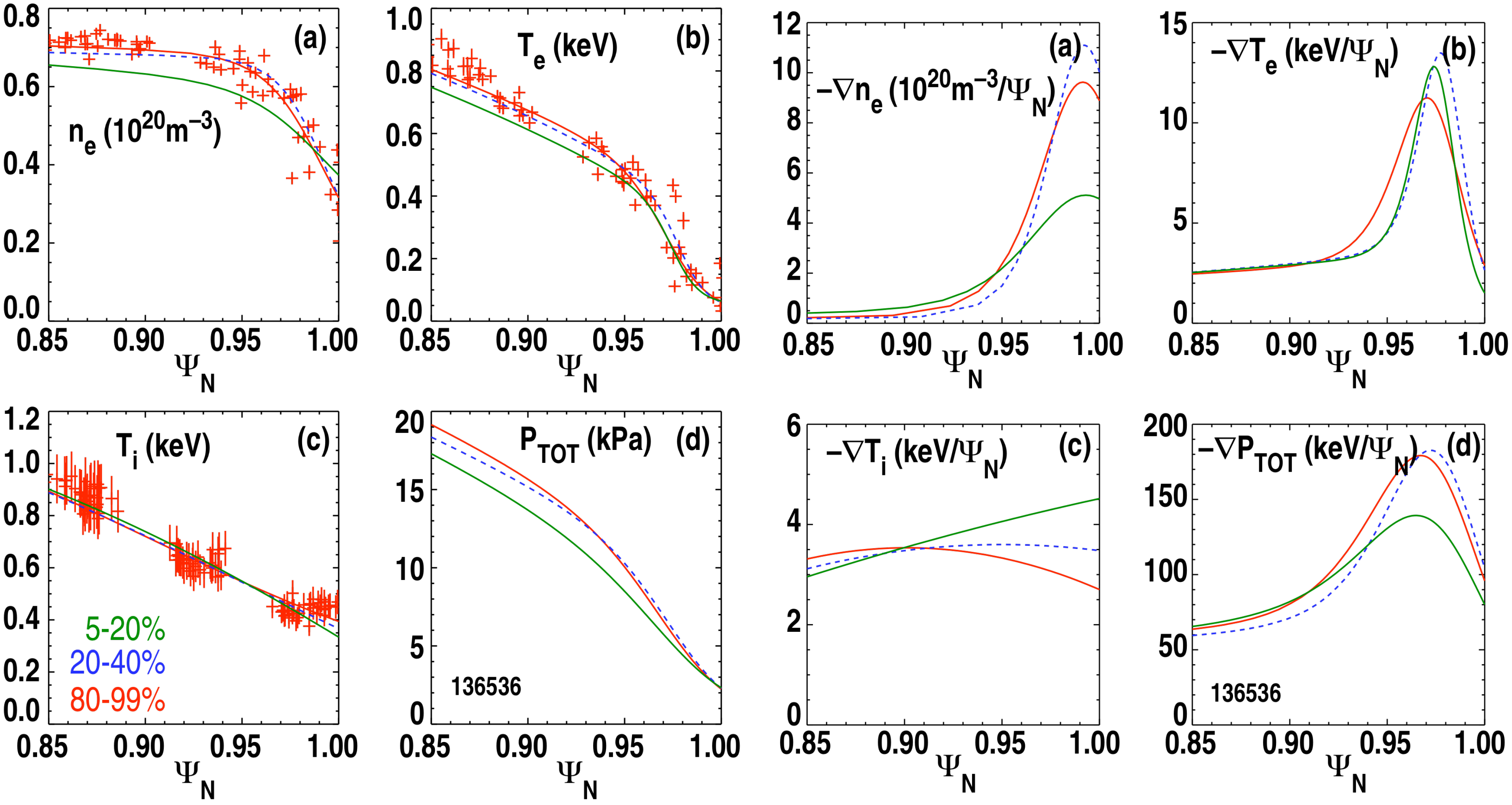


Density Scan Performed at High Current to Look for Effect of Collisionality on Pedestal Height



- I_P = 1.3 MA
- B_T = 2.1 T
- β_P = 1.01
- Average ELM period ~ 17 ms
- Mixture of large and small ELMs
- Filtering in analysis to reject ELM cycles related to small ELMs

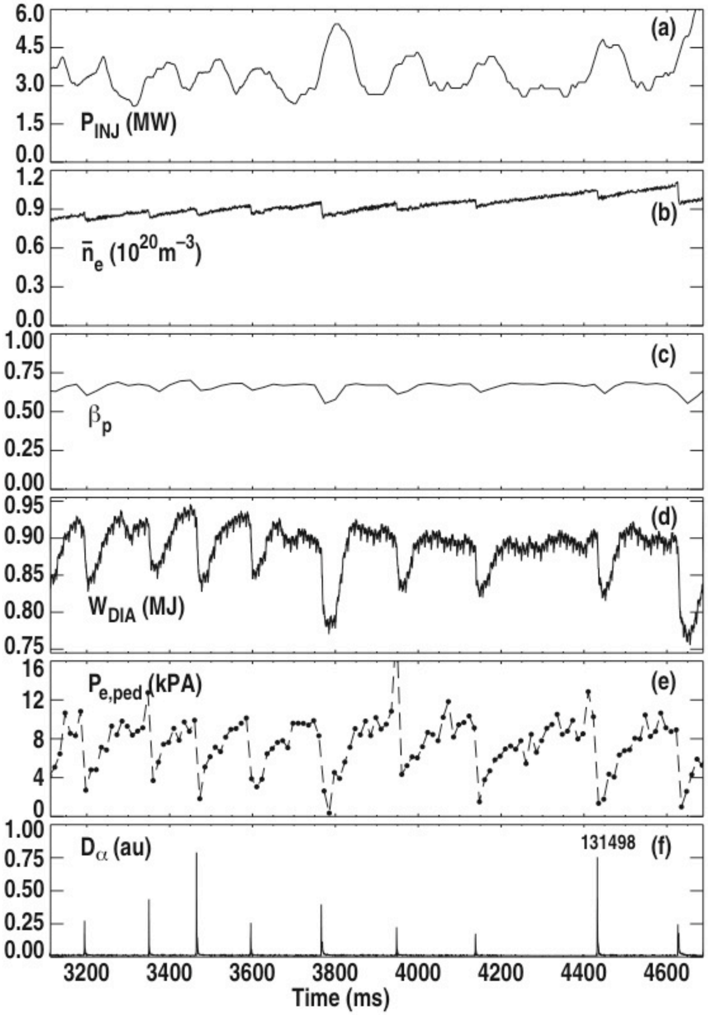
Pressure Gradient Shows Small Variation in ELM Cycle of High I_p, High Density Discharge



Small Variation of Pressure Gradient Observed During ELM Cycle of Discharges to Look for KBM

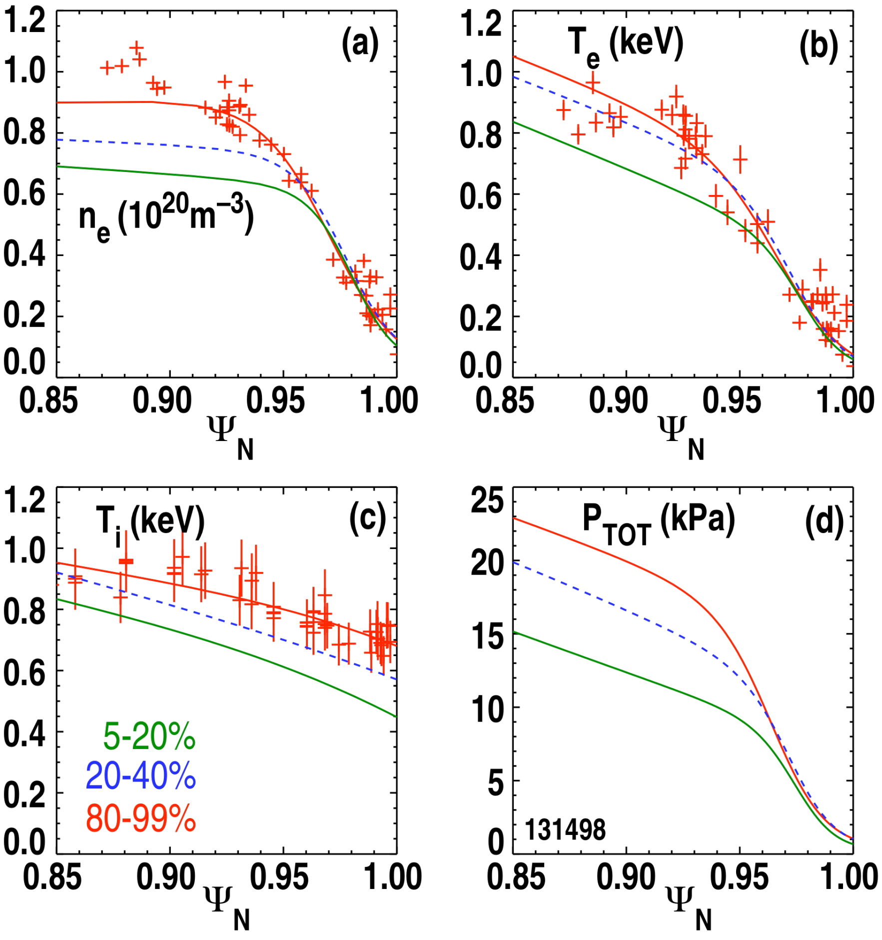
- **Some general conclusions about experiment to look for KBM:**
  - Large pressure gradients obtained early in ELM cycle
  - Small variation of maximum pressure gradient during ELM cycle
  - Some tendency for region of steep gradients to broaden during ELM cycle
- **There are many DIII-D discharges which exhibit more variation in ELM cycle than seen here in KBM experiment**
  - For instance, discharges to demonstrate baseline operation in ITER show a significant evolution of pedestal pressure during ELM cycle

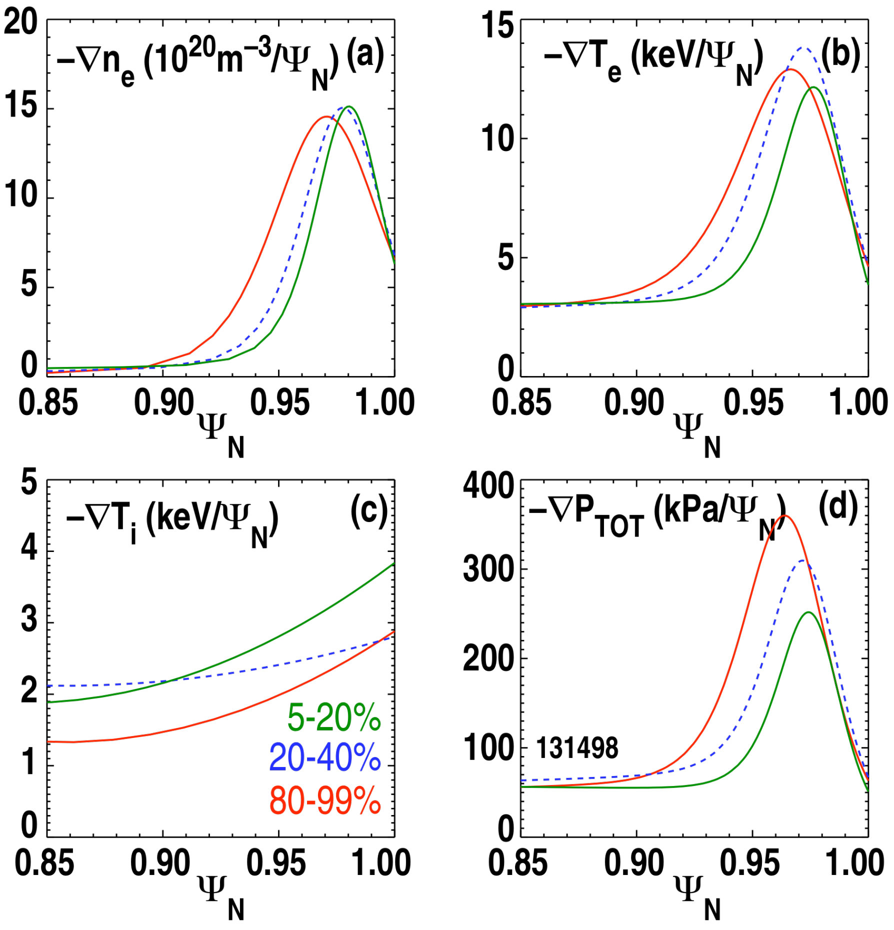
ITER Demonstration Discharge (131498) had Long ELM Cycle, Suitable for Good Measurements



- I_P = 1.5 MA
- B_T = 1.9 T
- β_P = 0.66
- Average ELM period ~ 180 ms
- $p_{e,ped}$ shows increase by ~5X during ELM cycle
- Rate of rise of $p_{e,ped}$ gradually slows during ELM cycle
  - Approaches a steady state

Pressure Gradient Broadens and Increases in Magnitude in ITER Demonstration Discharge





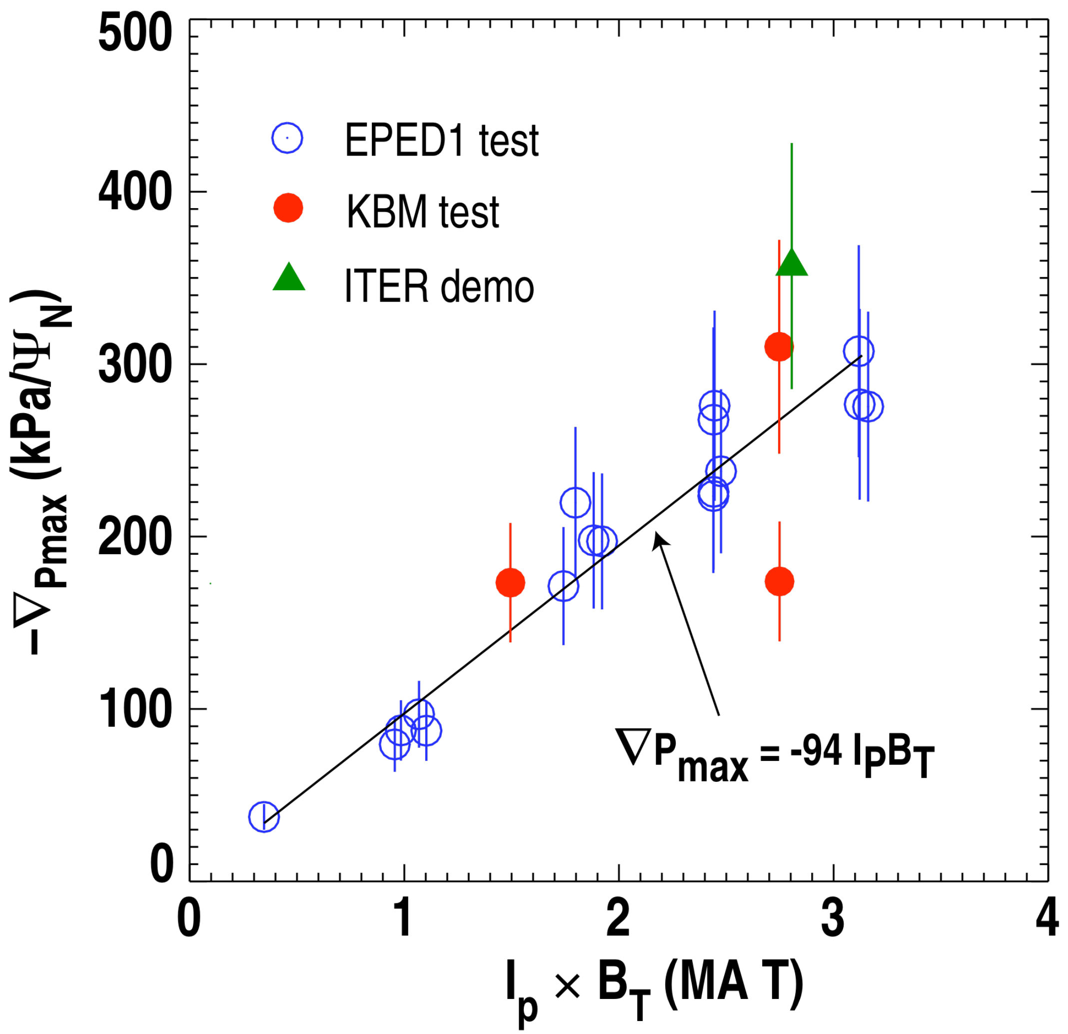
Peeling-ballooning Theory Make Predictions for Maximum Pressure Gradient Achieved at Type-I ELM

- **Model studies show that maximum pedestal pressure ∇p_{crit} increases with $I_P B_T$ for fixed pedestal width**
  - For fixed shape, geometry and collisionality
  - (Snyder et al., Plasma Phys Control. Fusion 46 (2004) A131)
- **These studies also show that** $\nabla p_{crit} \propto \Delta^{-1/4}$
- **Ignoring this weak dependence, theory implies that**

$\nabla p_{crit} \approx p_{ped}/\Delta$ **and therefore** $\nabla p_{crit} \sim I_p B_T$

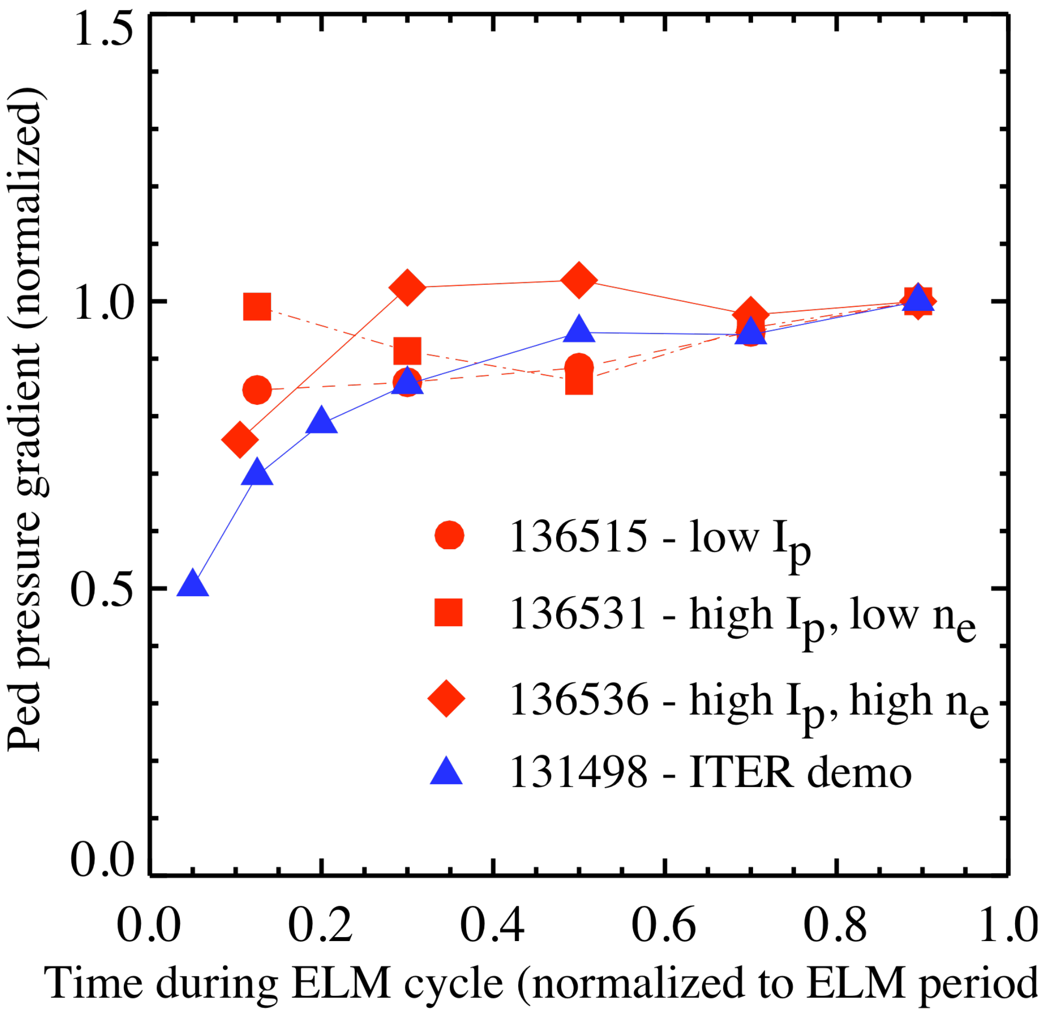
- **This scaling provides a good description of data previously obtained to test the EPED1 model**
  - (Groebner et al., Nucl. Fusion 49 (2009) 085037)
- **This prediction is also a good description of pressure gradients at ELM crash in the experiment to search for KBM**
- **Theory also predicts that** ∇p_{crit} **decreases at high collisionality**

Pressure Gradient at ELM Crash Shows Scaling Expected from Peeling-ballooning Theory



- Pressure gradients shown from 80-99% of ELM cycle
- Low solid circle at 2.7 MA T may show effect of increased collisionality
  - High I_p, high density
  - Expect lower bootstrap current, lower ELM threshold

Pressure Gradients in KBM Test Show Little Evolution During ELM cycle



- Gradients normalized to gradient for 80-99% interval of ELM cycle
- Time normalized to fraction of ELM period
- ITER demo shot has best time resolution early in ELM recovery
  - Show significant very early in ELM cycle
- All gradients have reached ~80% of maximum by 20-40% of ELM cycle

The Pressure Gradients Observed in ELM Cycle are Large Enough to Potentially Drive KBM

- **KBM modes are predicted to be driven unstable for normalized pressure gradients α in the range ~ 1-10**

$$\alpha = \mu_0 /(2\pi^2)(\partial p/\partial\psi)(\partial V/\partial\psi)(V/2/\pi^2/R)^{1/2}$$

- **Values of α ~ 2-8 are observed very early in the ELM cycle**

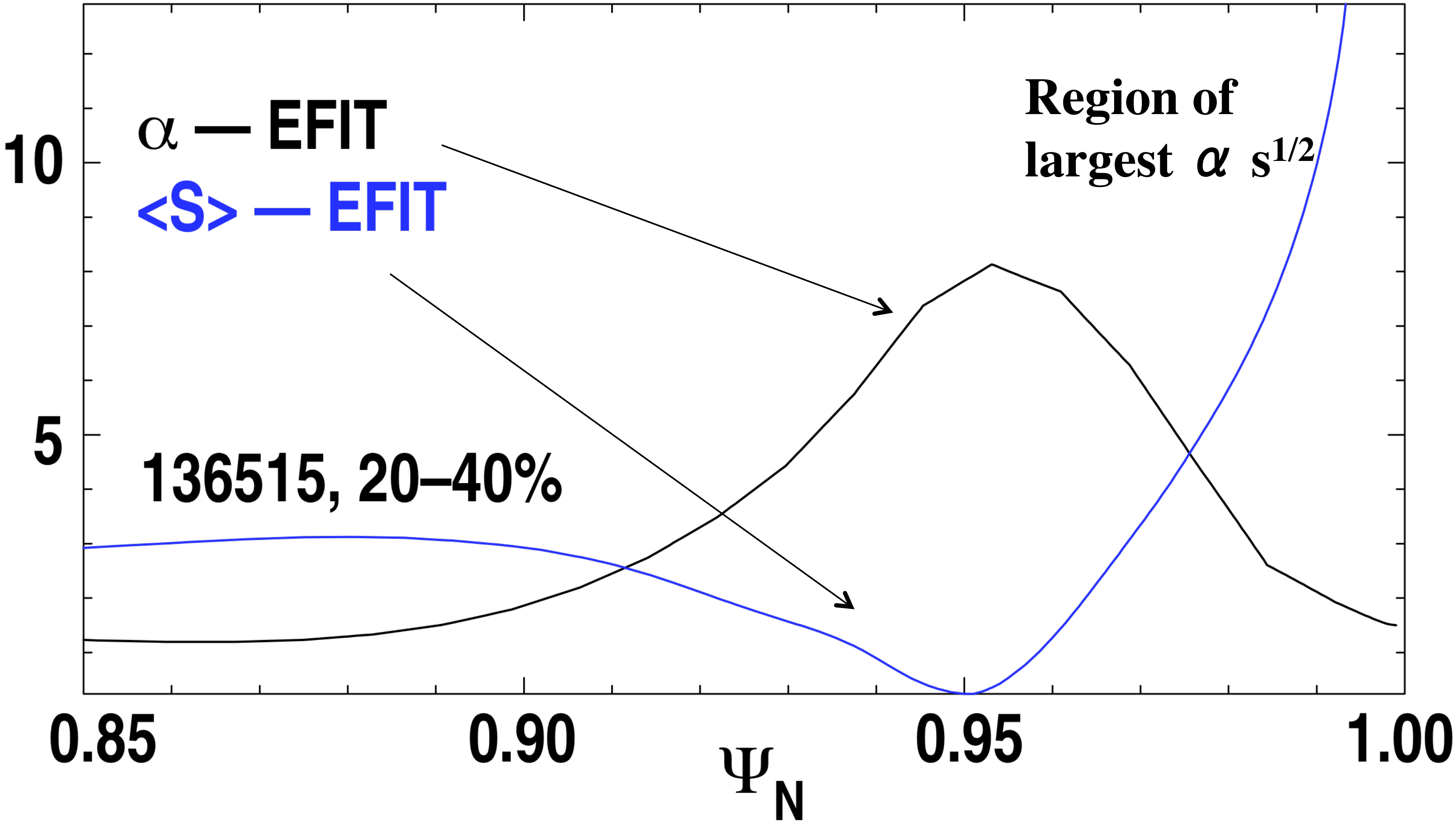
- **Thus, the experimentally observed pressure gradients are potentially large enough to drive KBM**

- **KBM model predicts threshold pressure gradient α_{crit} scales as α_{crit} ~ $s^{-1/2}$ where s is magnetic shear =** $s = 2(V/V')(q'/q)$

(Snyder et al., Phys. Plasmas 16 (2008) 056118)

- **These threshold conditions are most easily met in outer half of pedestal where $\alpha\ s^{1/2}$ achieves largest values**

Large Values of Normalized Pressure Gradient Observed Very Early in ELM Cycle

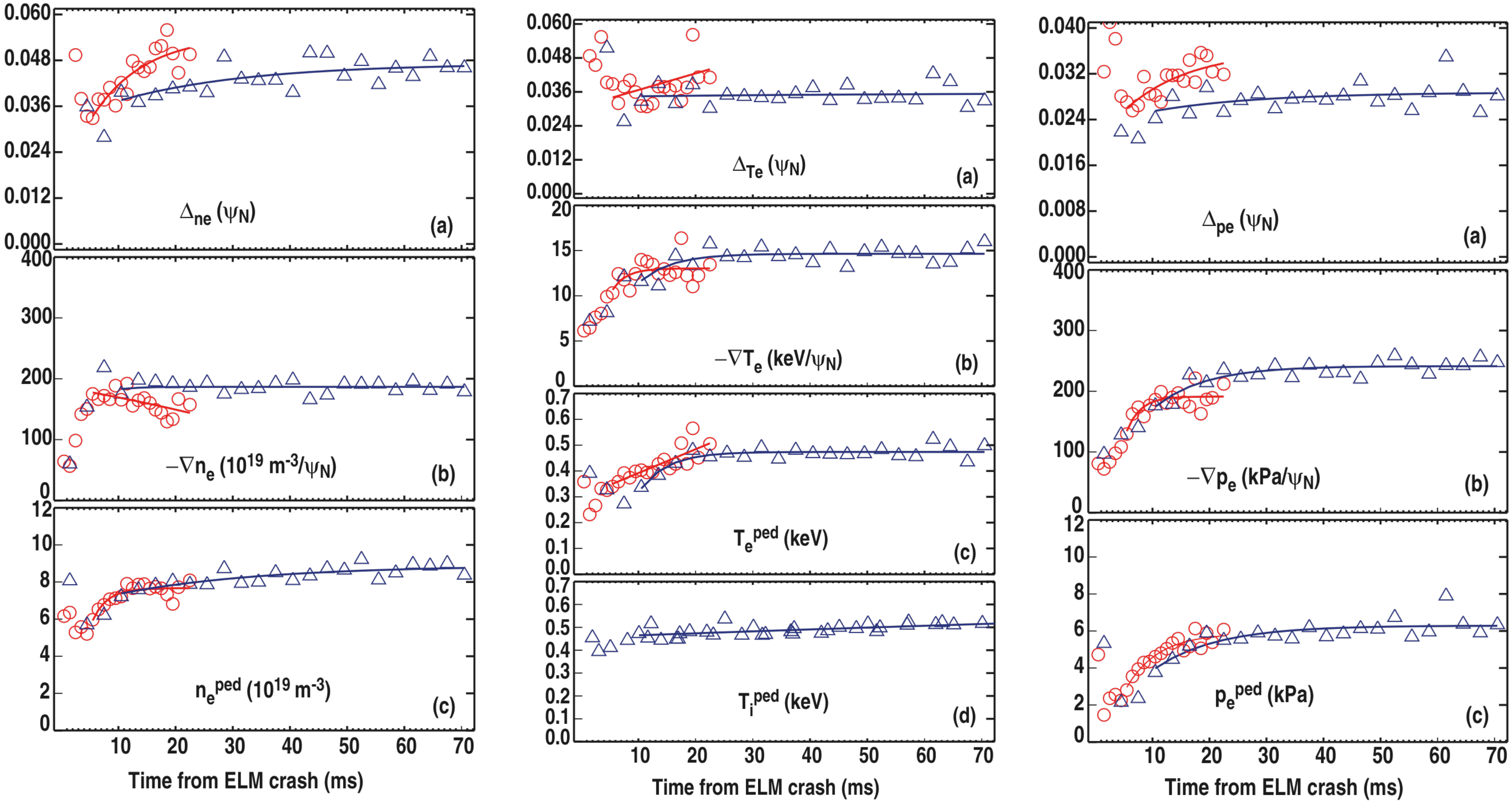


New Data are Consistent with Previous Studies of Inter-ELM Cycle on DIII-D

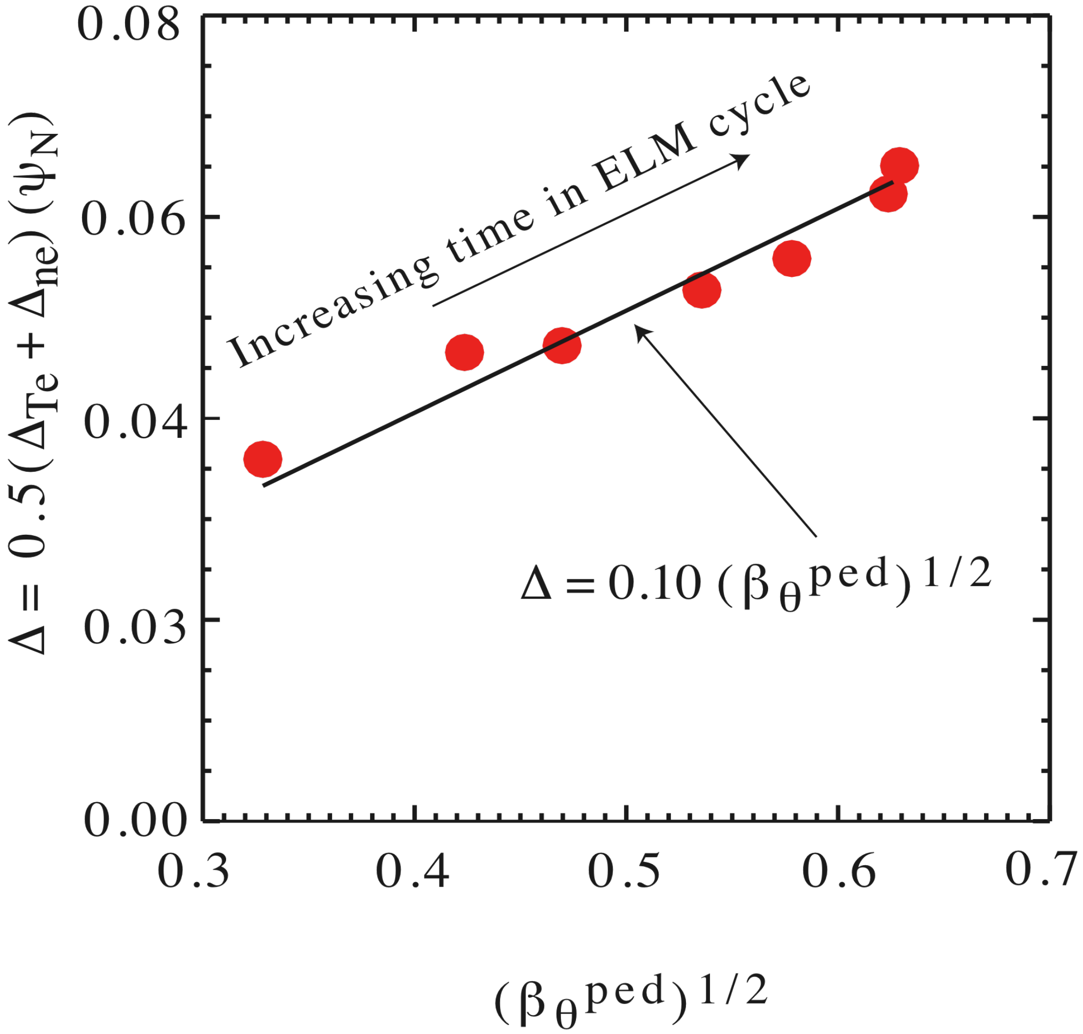
- **Fast initial recovery of pedestal parameters after ELM crash have been observed**
  - Electron pressure gradient recovers to nearly maximum value in ~ 10 ms for an ELM period of ~ 60 ms
    - Nucl. Fusion **49** (2009) 045013
- **Pedestal width increases during ELM cycle with $(\beta_\theta^{ped})^{1/2}$ scaling**
  - Observed in ITER demo discharge
    - Nucl. Fusion **49** (2009) 085037

Evidence for Fast Recovery of Pressure Gradient Observed in Two Different ELM Cycles

Red (blue) data from average ELM period of 20 (60) ms



Pedestal Width Exhibits KBM Scaling During ELM Cycle in ITER Demonstration Discharge



Experimental Data Have Been Used to Look for Evidence of KBM Limiting Pressure Gradient in Pedestal

- Pressure gradients are large enough to drive KBM
- If KBM is playing a role, it may turn on very early in the ELM recovery
- Threshold conditions for onset of KBM are most easily met in outside of pedestal
- It is plausible that KBM stiffness begins first in outside of pedestal and then builds in

Experimental Data Have Been Used to Test Scaling Prediction of PB Theory for Pressure Gradient

- **Theory predicts pressure gradient at ELM scales with $I_P B_T$**
  - With weaker dependencies on other parameters (shape, collisionality, width)
- **The $I_P B_T$ scaling is good description of the data**
- **Some evidence for reduction of pressure gradient with increased collisionality, as expected from theory**

Future Work

- Use gyrokinetic codes to improve quantitative thresholds for onset of KBM in pedestal
- Look at turbulence measurements for evidence of mode turning on during pedestal evolution
- Use fast profile reflectometer data to determine if time evolution of density gradient shows evidence that a mode turns on
- Look for evidence of pressure gradient saturation in shots where pedestal shows a slower evolution – such as in long ELM-free H-mode or in discharges with large ELM period
- Examine carefully the initial recovery of pedestal after an ELM