



# Recent Research On High-Confinement, Stationary Operating Scenarios Without ELMs for ITER and Beyond

**S.P. Gerhardt (PPPL)**

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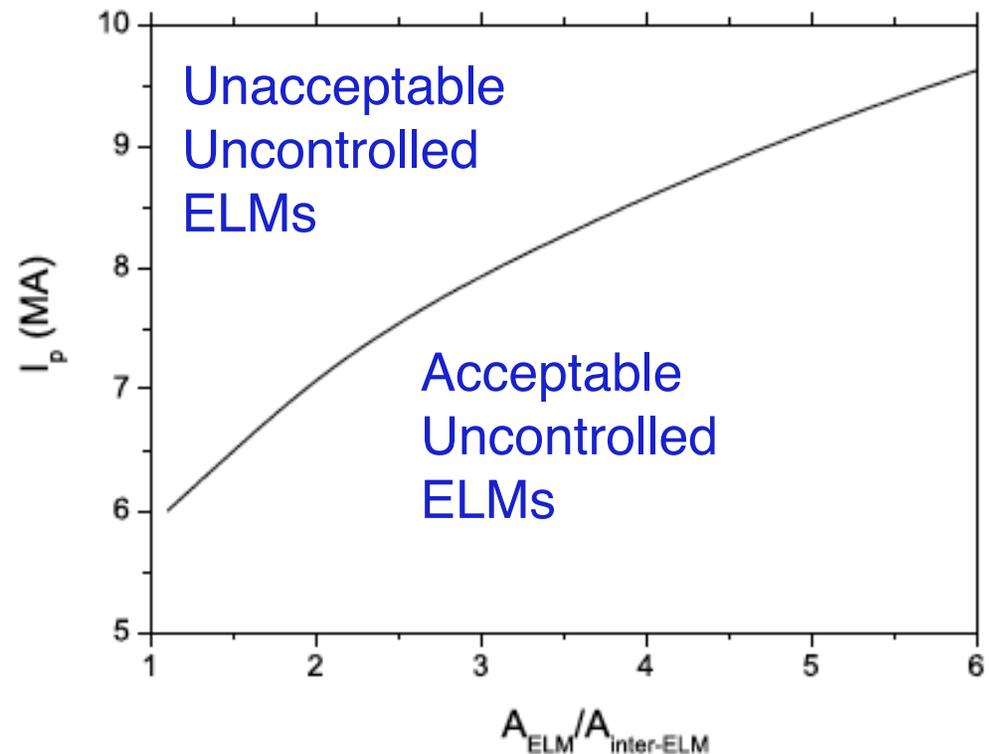
D.R. Smith, G. McKee, Zheng Yan *University of Wisconsin-Madison*

**TTF Meeting  
San Antonio  
April 22, 2014**

# ITER Needs To Operate Without Uncontrolled Type-I ELMs

- Good confinement H-modes are typically accompanied by type-I ELMs
- Uncontrolled ELMs are projected to limit the lifetime of the divertor
- However, must maintain the impurity flushing qualities of ELMs
  - Otherwise, the particle confinement in H-mode will result in unacceptable core impurity content

Domain of acceptable uncontrolled ELMs as a function of ELM wetted area and plasma current

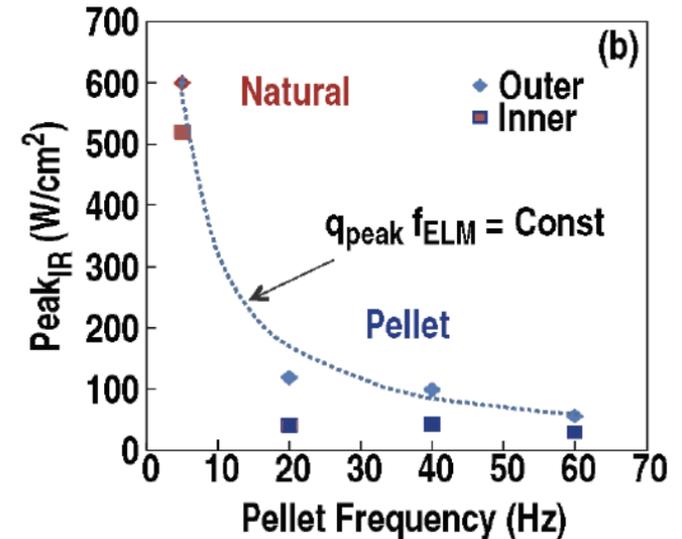


A. Loarte, NF 54, 033007 (2014)

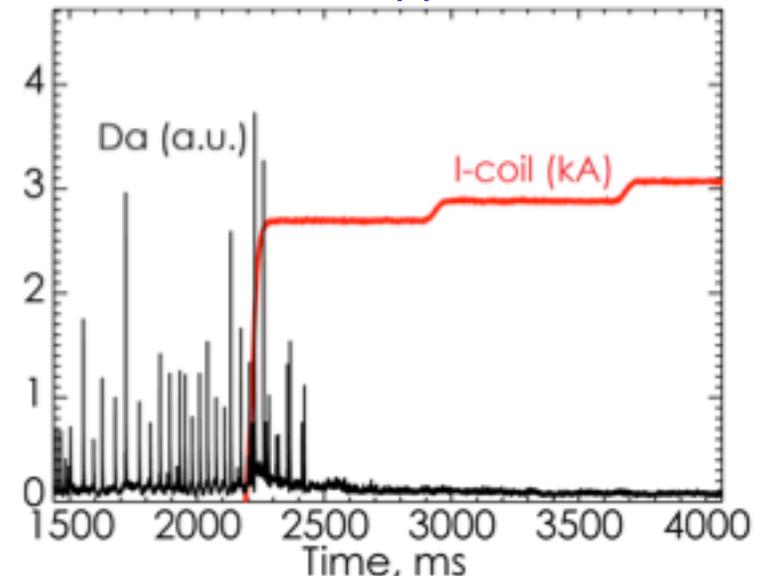
# Numerous Strategies Are Under Development for Managing ELMs in ITER

- Achieve rapid ELMs via pacing techniques.
  - Pellet pacing most prominent example...
    - ...but also vertical jogs
  - Relies on the peak heat flux to decrease as  $\sim 1/f$
- Replace ELMs with quasi-continuous edge fluctuations that drive particle transport
  - Achieve a beneficial separation between particle and energy transport
    - bad particle confinement is good
  - QH-mode, I-mode
- Suppress ELMs entirely
  - ELM suppression via RMP in DIII-D

## Rapid Pellet Injection Can “Pace” ELMs



## Resonant Magnetic Perturbations Suppress ELMs



# Some Common Questions Link the Various ELM Control Schemes

- Q1: Can these regimes be understood in terms of the standard peeling-ballooning & KBM models?
  - These models work well for ELMy H-mode
- Q2: Can these regimes be achieved at high(er) density?
- Q3: Can they provide the required particle and impurity transport in future tokamak systems?
- Q4: Access with ITER relevant parameters and constraints?
- Q5: Can we understand and control regimes with edge thermal confinement significantly better than H-mode?

And of course each scheme has a specific list of questions, which will be addressed throughout the talk

# Outline: Multi-Facility Research Milestone in 2013 Addressed Stationary High-Performance Regimes w/o Large ELMs

- Introduction
- Reminder: Key pedestal physics considerations
- Regimes with continuous edge fluctuations
  - Quiescent H-mode
  - I-Mode
- Recent research on RMP ELM Suppression
- A very high confinement regime: the EP H-mode in NSTX
- Regime comparisons and answers to the five broad questions

Presentation will Concentrate on Results Collected as Part of the Milestone Research

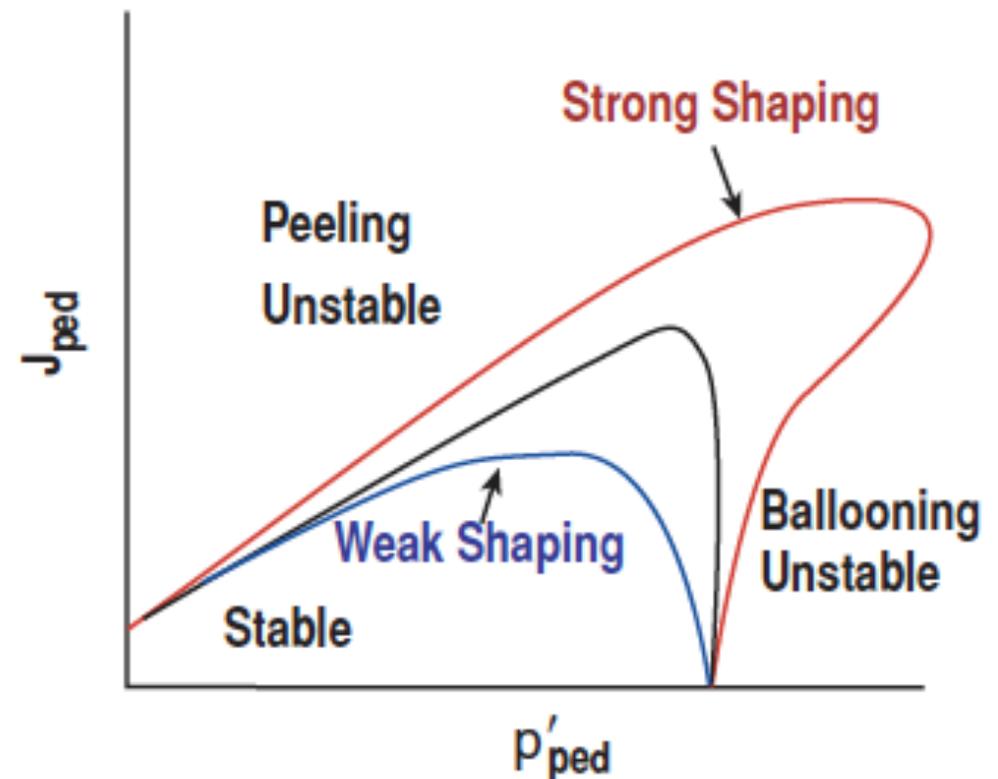
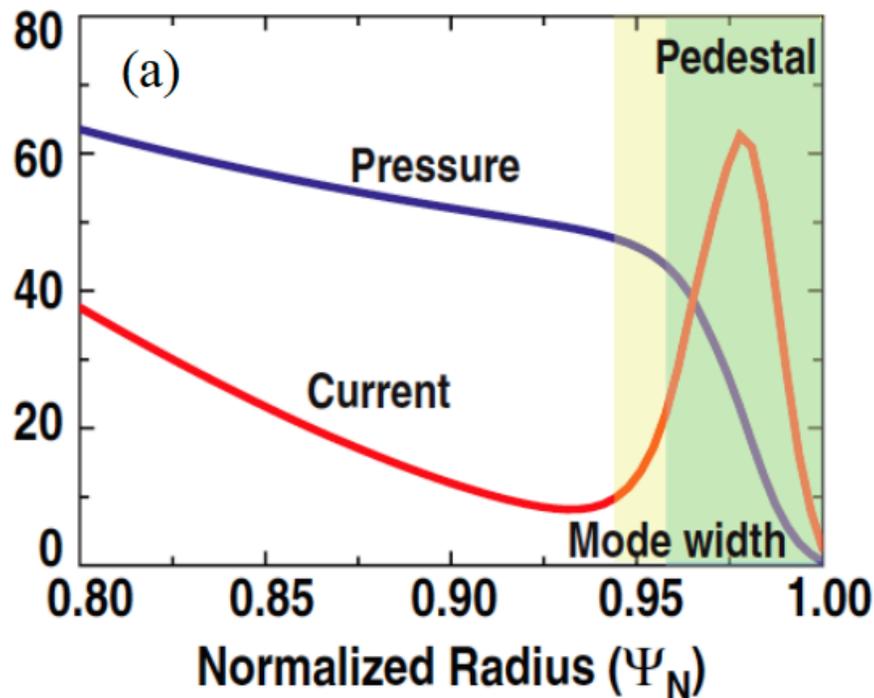
Only DIII-D Operated During FY-2013; Analysis of Existing Data from C-MOD and NSTX was a Key Component of Research Exercise

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# Type-I ELM Dynamics Often Understood In Terms of Peeling-Ballooning Stability

- Edge pedestal has steep gradients in the kinetic profiles located just inside the separatrix
  - Steep gradients result in localized currents
- Localized currents and pressure gradients destabilize MHD modes in the pedestal
- Modes span the full pedestal
  - Typically yields a stability boundary as  $\beta_{ped} \sim \Delta^{3/4}$

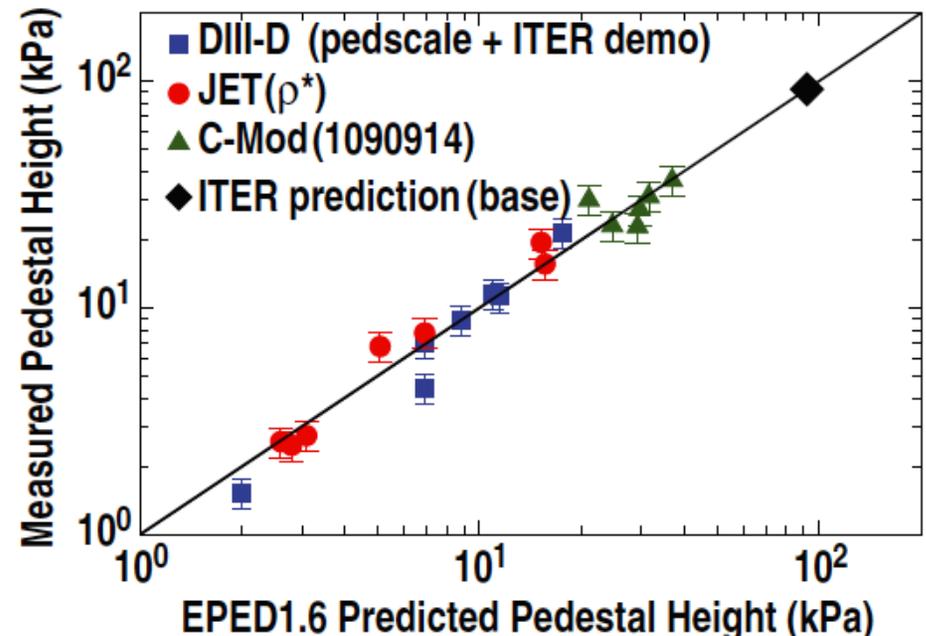
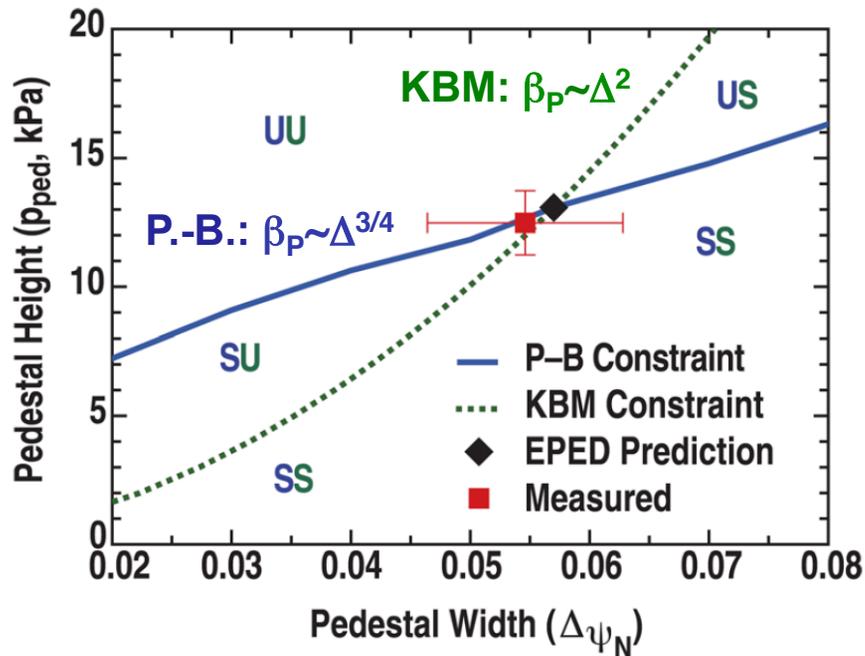


P. Snyder, Nuclear Fusion 51 1 (2011)

P. Snyder, PPCF 46 A131 (2004)

# When a Transport Constraint is Added, a Predictive Model for the Pedestal Can be Derived

- Postulate that pedestal transport between ELMs is determined by Kinetic Ballooning Modes (KBM)
  - Yields a dependence as  $\Delta \sim \beta_p^{1/2}$ , or  $\beta_p \sim \Delta^2$
  - Consistent with many experiments
- Combine the peeling ballooning constraint, the KBM constraint, and predefined profile shapes to make a model for the pedestal height
  - Inputs are field and current, shape parameters, pedestal density, global  $\beta$

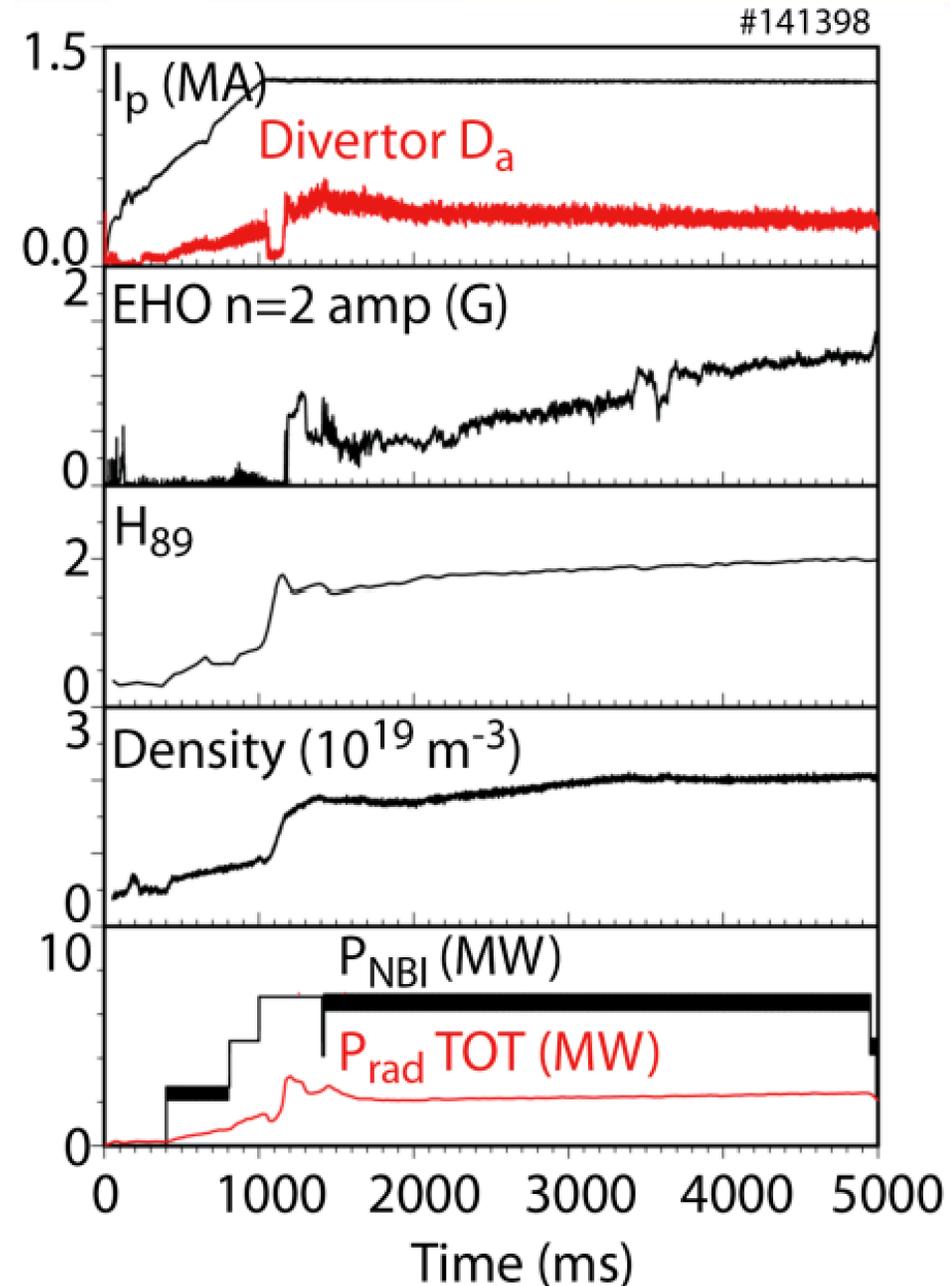


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  - The I-Mode Regime
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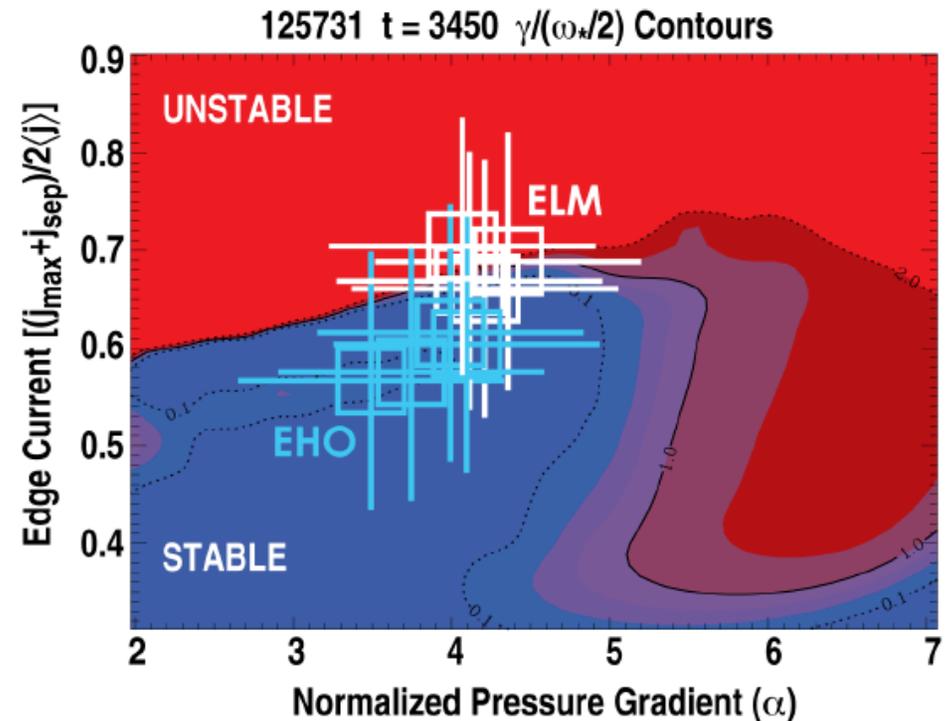
# The Quiescent H-Mode Provides Particle Control Through an Edge Fluctuation Called the Edge Harmonic Oscillation

- Key QH-Mode characteristics
  - ELMs are replaced by a continuous edge oscillation
  - Good confinement is maintained
  - Density and radiated power is controlled
  - Achieved with co- or counter- torque



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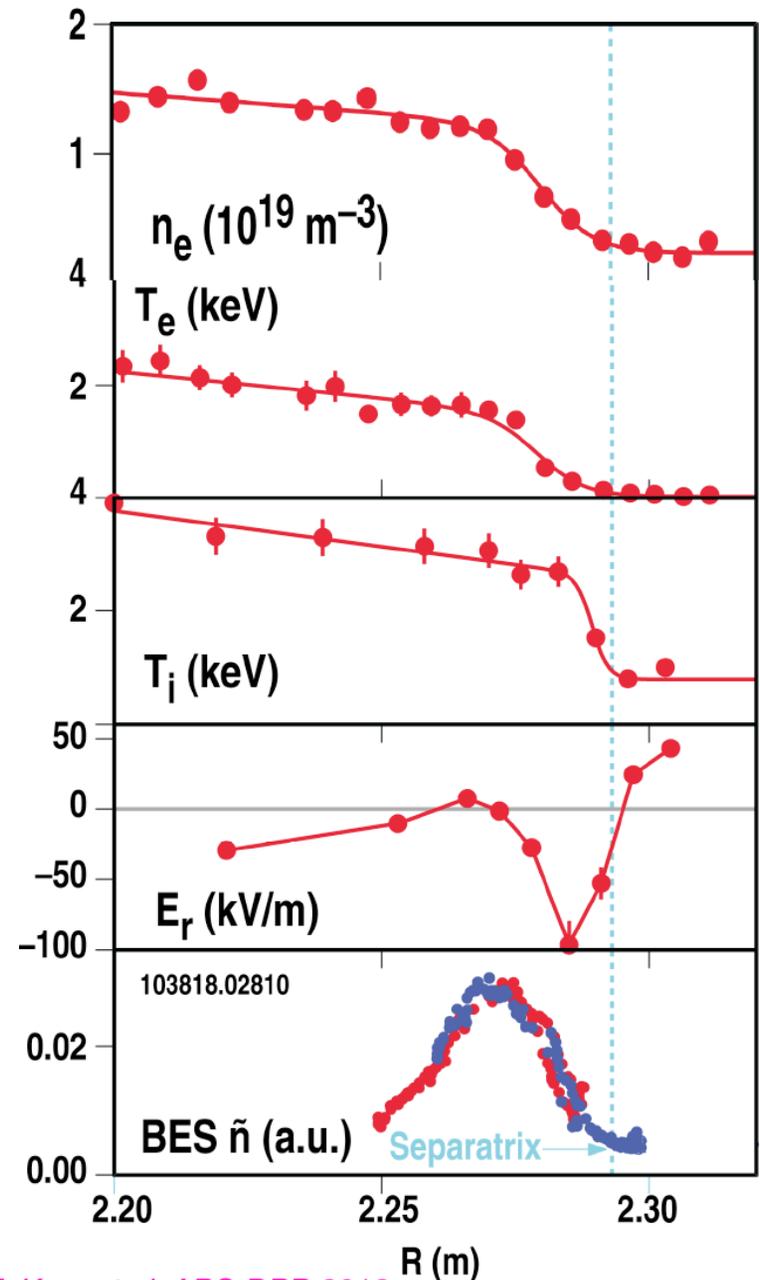
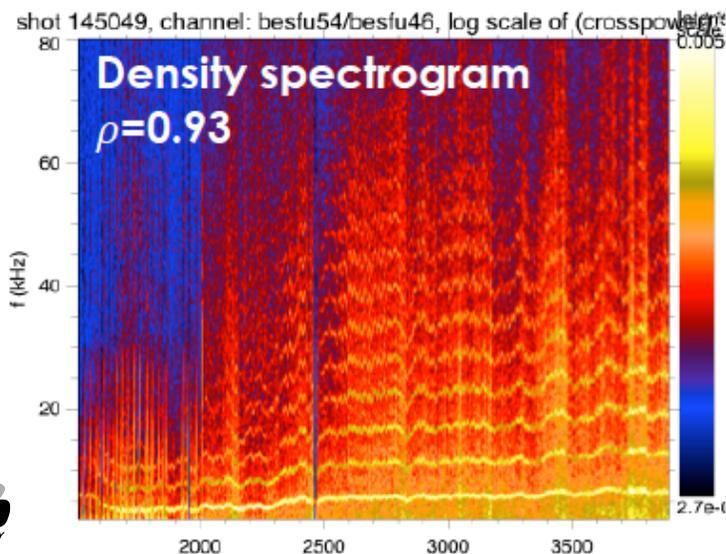
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  - EHO is thought to be a saturated peeling mode



Osborne et al, J. Physics: Conf. Series 123, 012014 (2008).

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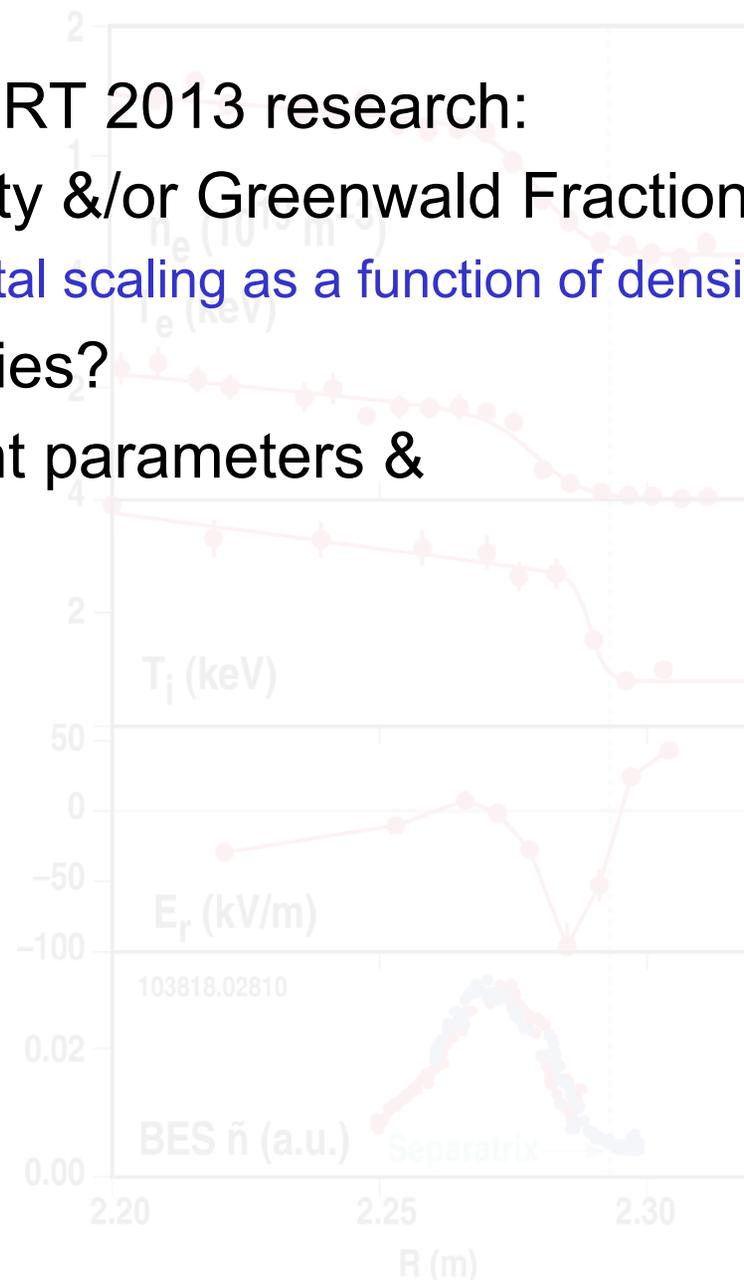
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  - EHO is thought to be a saturated peeling mode
- EHO spans the width of the pedestal.
  - Many harmonics visible with BES



G. McKee, et al, APS-DPP 2013

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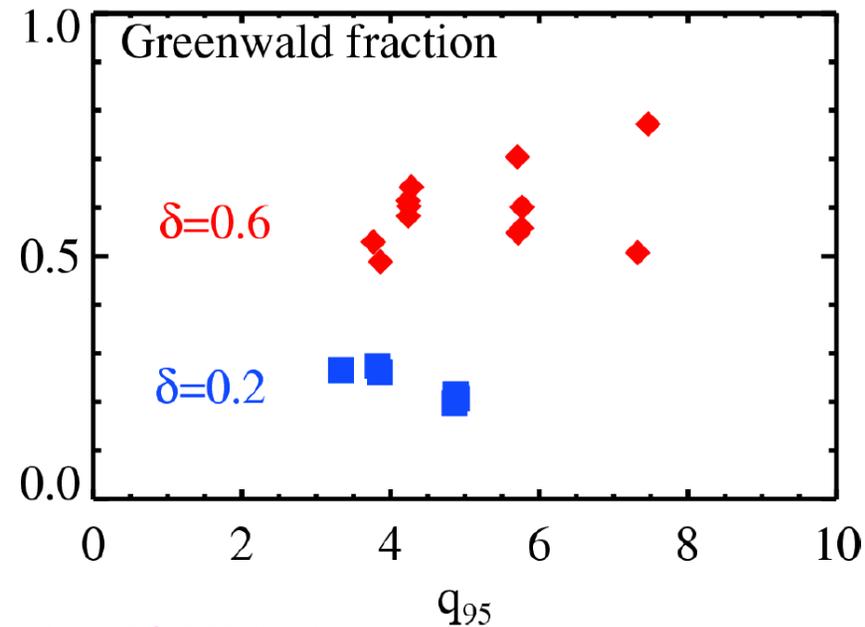
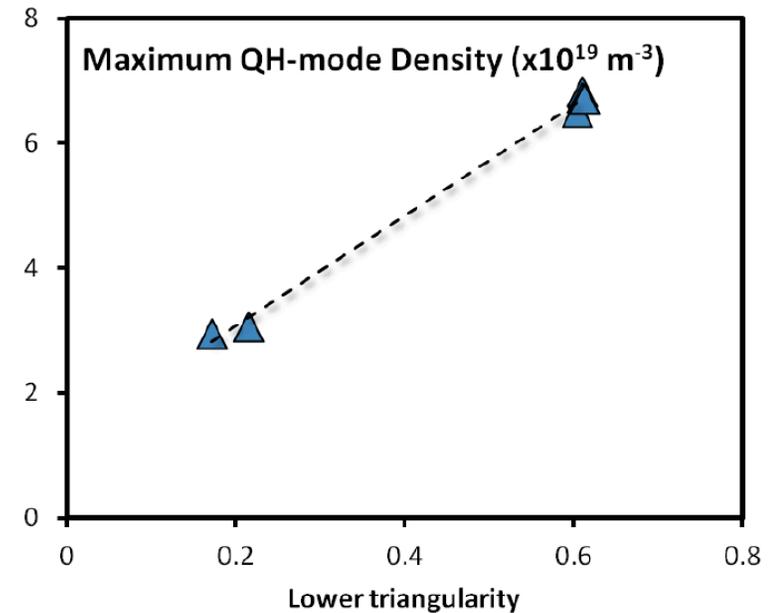
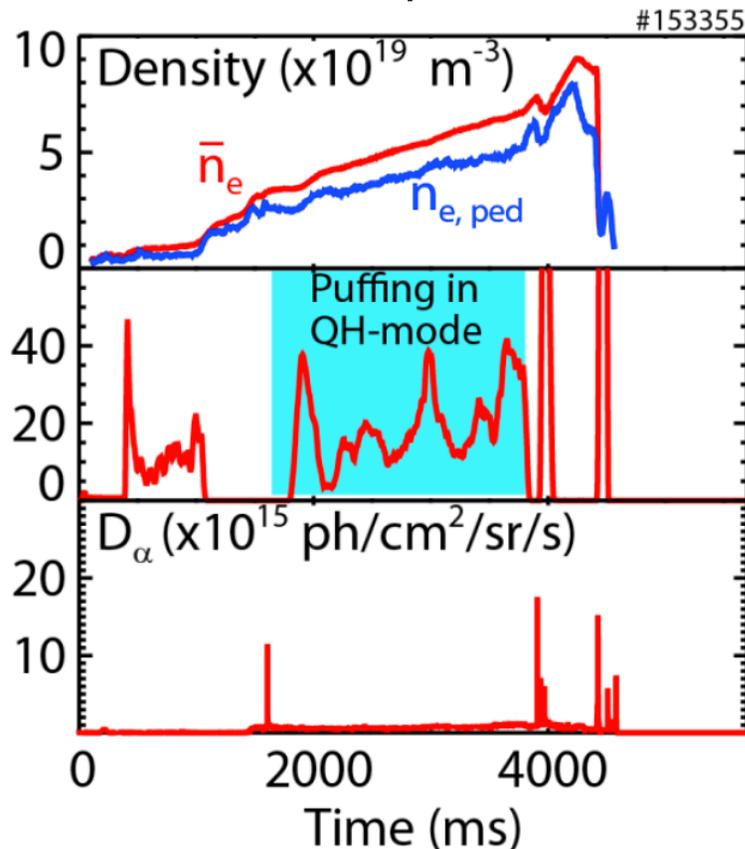
- Key QH-Mode characteristics
  - ELMs are suppressed
  - Edge oscillation controlled.
- Key questions addressed in JRT 2013 research:
  - Is QH mode accessible at high density &/or Greenwald Fraction?
    - How well does EPED capture the pedestal scaling as a function of density?
  - How well does the EHO flush impurities?
  - Can it be achieved with ITER relevant parameters & performance?
- EHO is a global mode peaked near the pedestal top.
  - Many harmonics visible with BES



G. McKee, et al, APS-DPP 2013

# Stronger Shaping Allows Access to Higher Density QH-Modes

- P.-B. theory showed that increasing triangularity could make more of the peeling boundary accessible
- Plasma density raised by gas puffing
- Higher absolute density achieved with stronger shaping
- Greenwald fractions up to 0.8 have been achieved

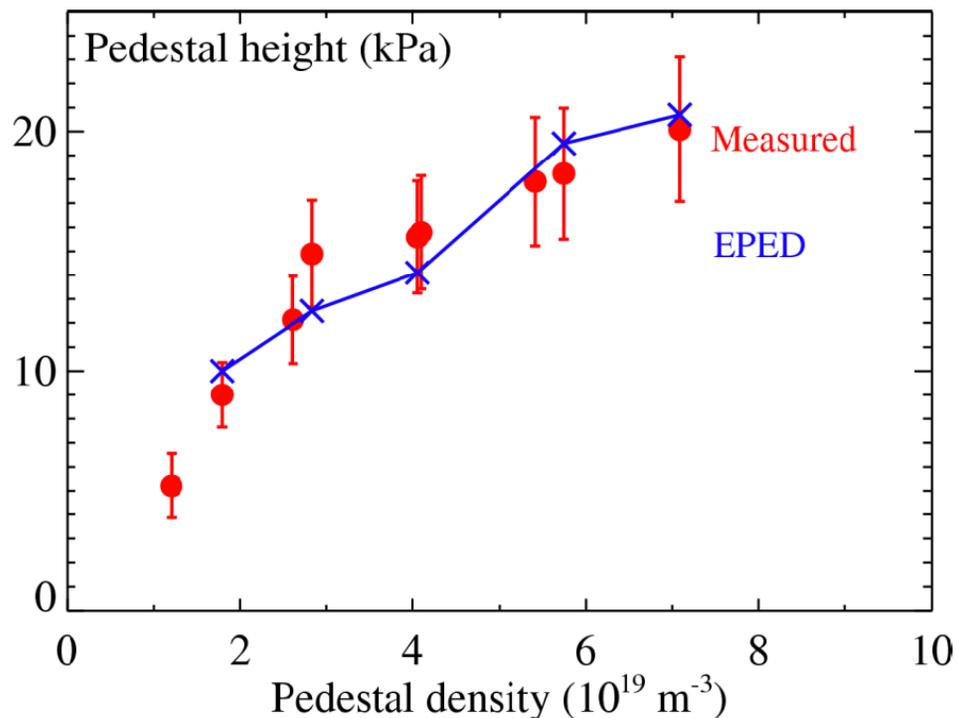


W. Solomon, et al, APS-DPP 2013

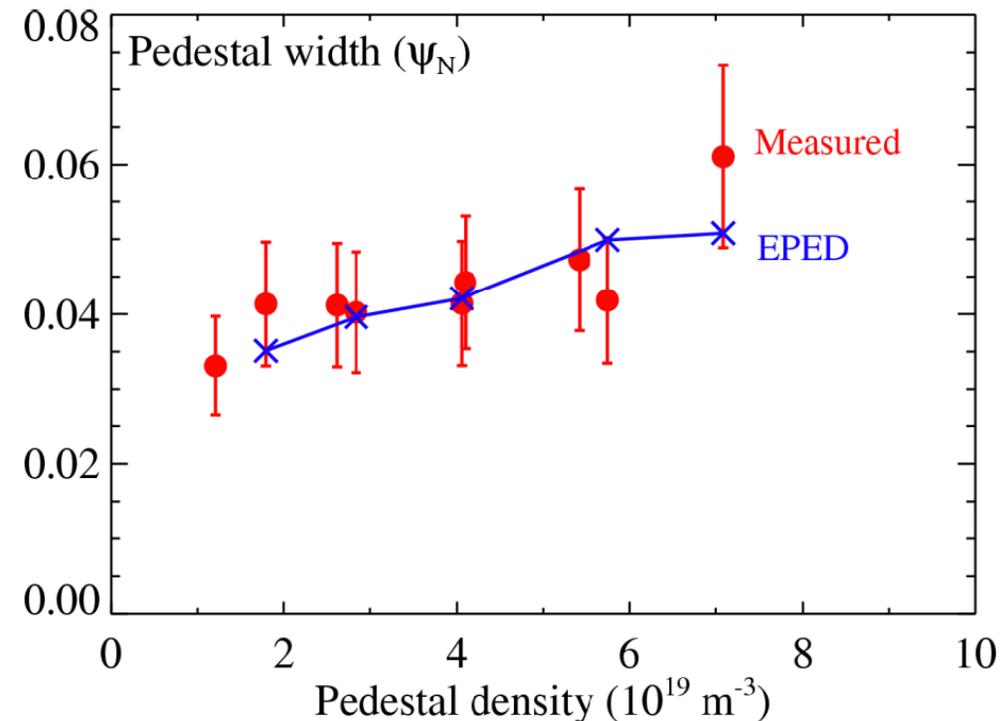
# EPED Modeling Can Reproduce the Pedestal Trends in QH-Mode as a Function of Density

- Recall: EPED is based on simultaneous constraints from transport and stability

EPED accurately predicts the increase in pedestal height as a function of density



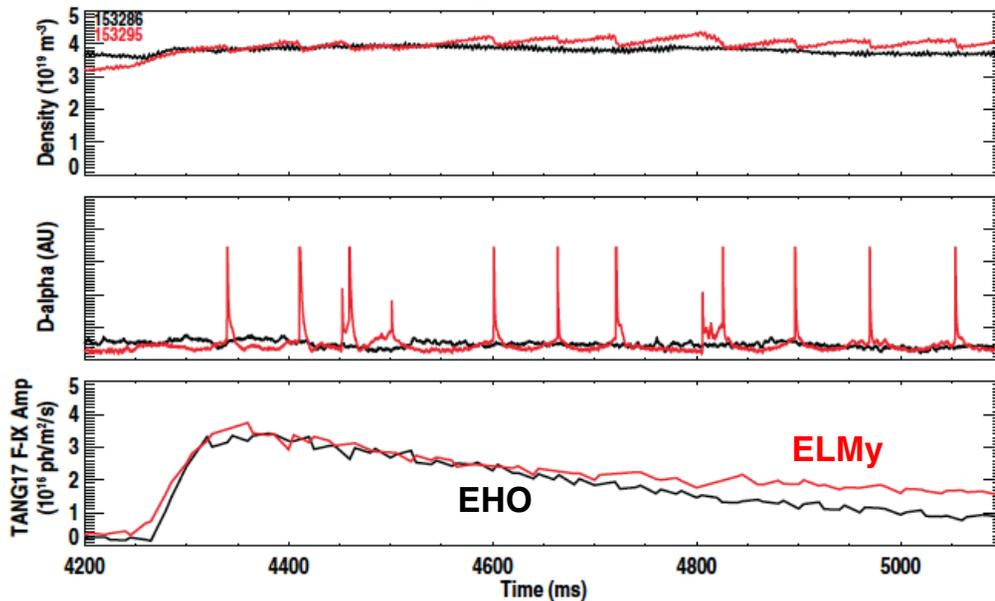
EPED accurately predicts the trend in the pedestal width as a function of density



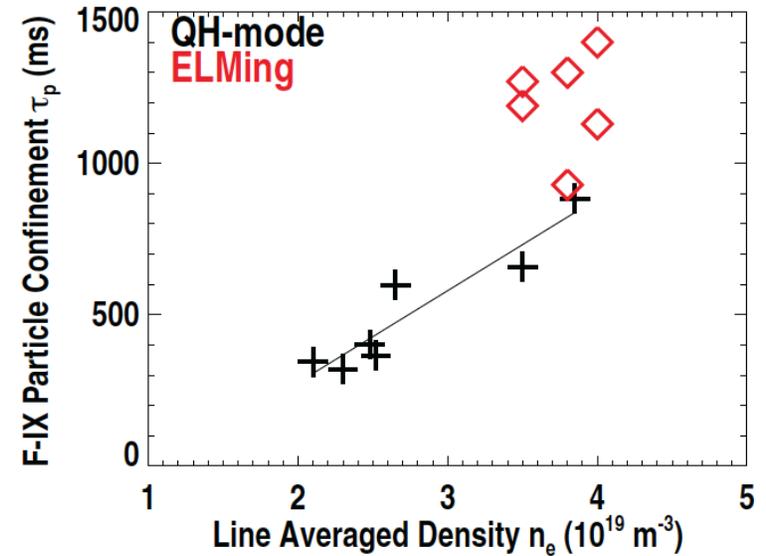
# The EHO Can Exhaust Impurities Just as Well as Type 1 ELMs

- Mixture of 90% deuterium and 10 % carbon-tetrafluoride introduced through a gas valve
- Charge exchange emission from F-IX used to monitor impurity content

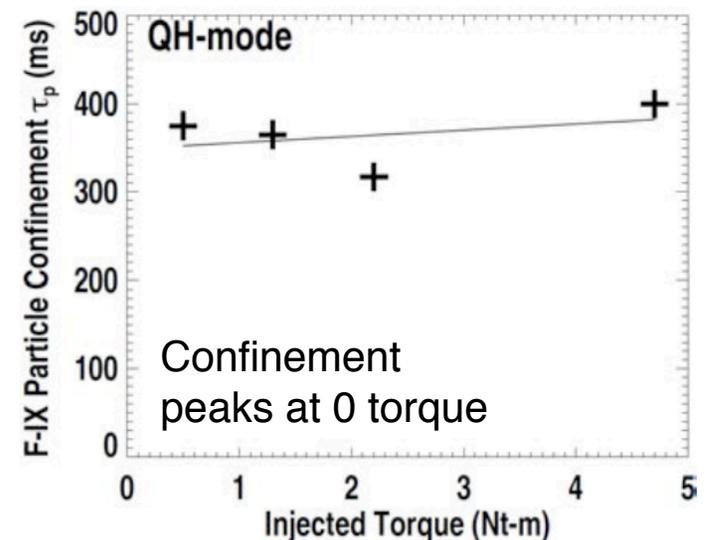
## Impurity Confinement in QH-Mode vs. ELMing H-Mode



QH-mode case, with an EHO, exhausts impurities more rapidly

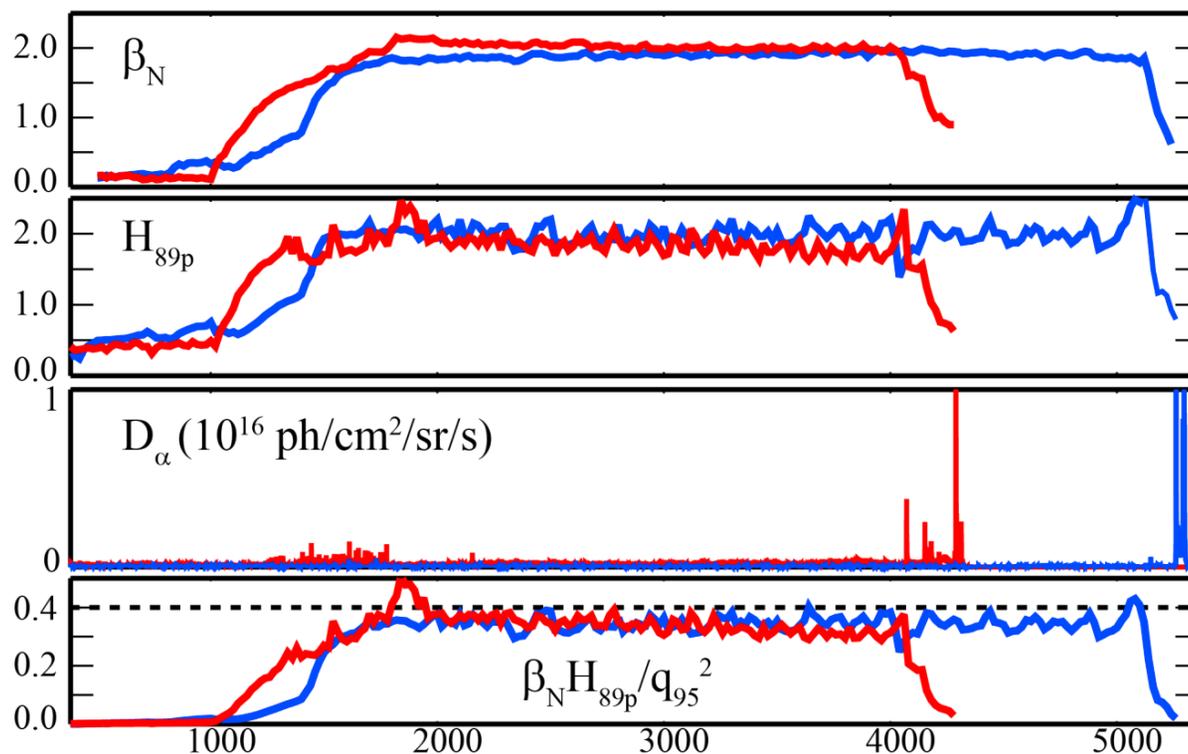
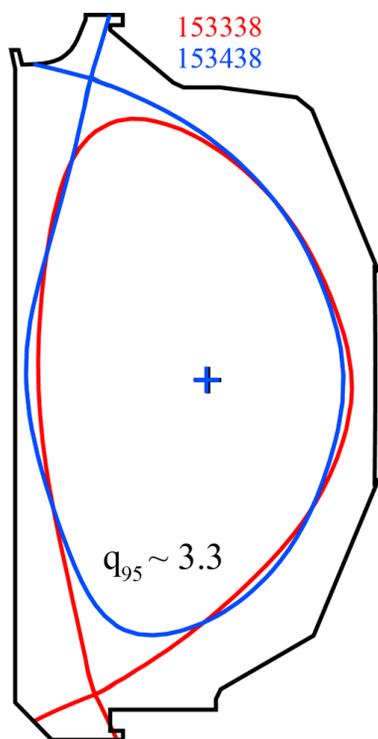


QH-Mode impurity confinement independent of torque



Confinement peaks at 0 torque

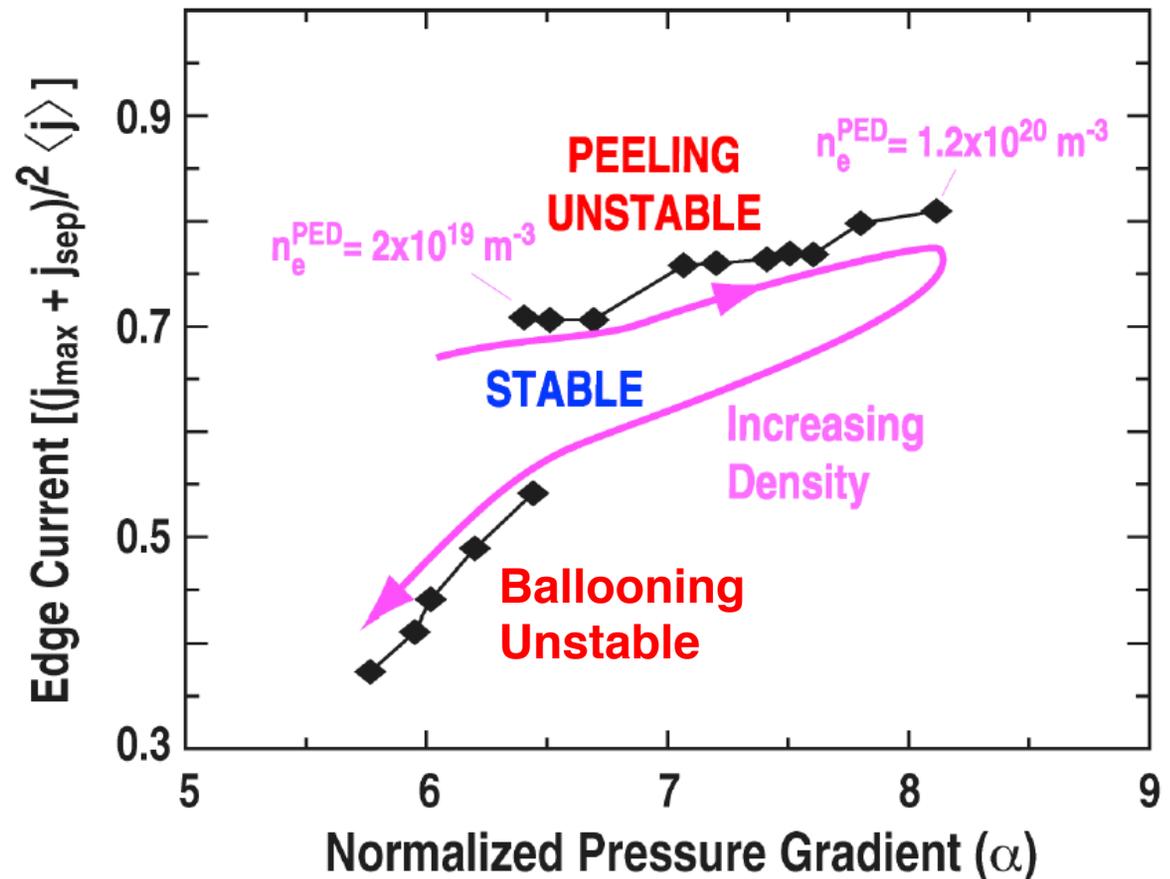
# QH-Mode Has been Sustained at the ITER $q_{95}$ in Recent DIII-D Research



- But required some counter-torque to avoid locked-modes
  - Raising  $q_{95}$  allowed for a reduction in the counter-torque w/o locked modes
- Both raising the density and improved error field correction are promising for allowing low- $q_{95}$  high performance QH-mode

# Pedestal Stability Calculation Indicate ITER Will Operate on the Peeling Boundary

- Calculations indicate that ITER will be on the peeling boundary for densities up to  $1.2 \times 10^{20} \text{ m}^{-3}$
- ITER's pedestal will be in the collisionality and density range for QH-mode operation

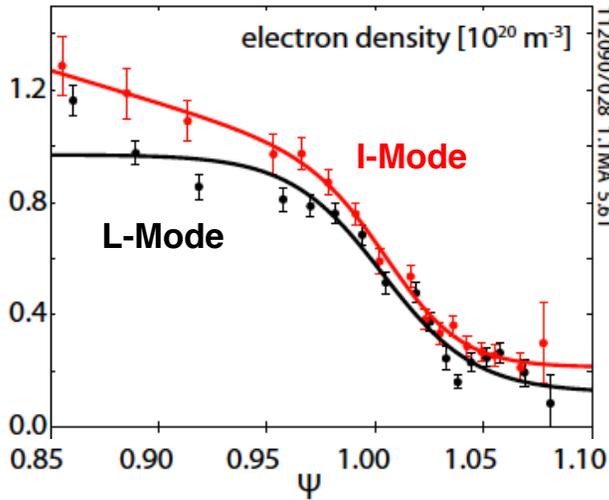


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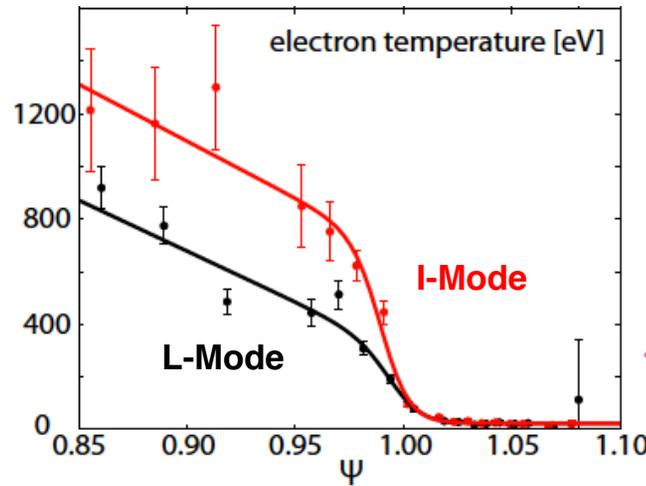
# The C-MOD I-Mode Regime Combines an H-mode Temperature Profile w/ an L-mode Density Profile

Similar Density Profiles in L- and I-modes.



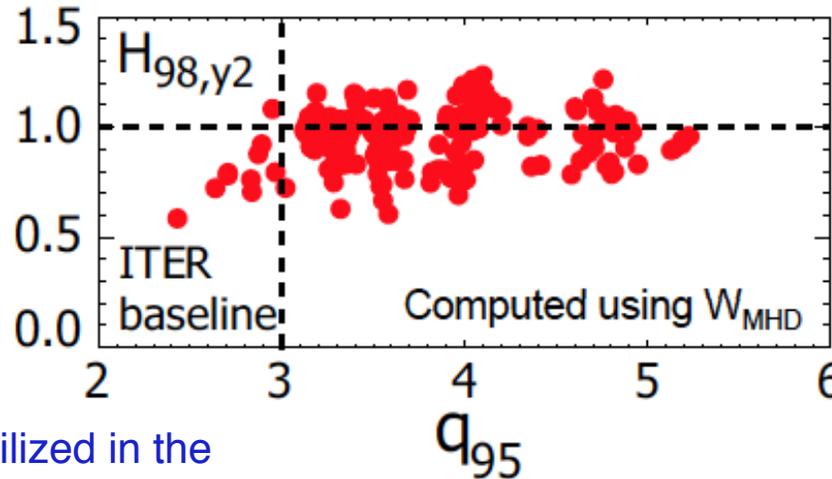
J. Walk, APS 2013

Higher  $T_e$  in I-mode, with Formation of Edge Pedestal



A. Hubbard, et al., 2012 FEC

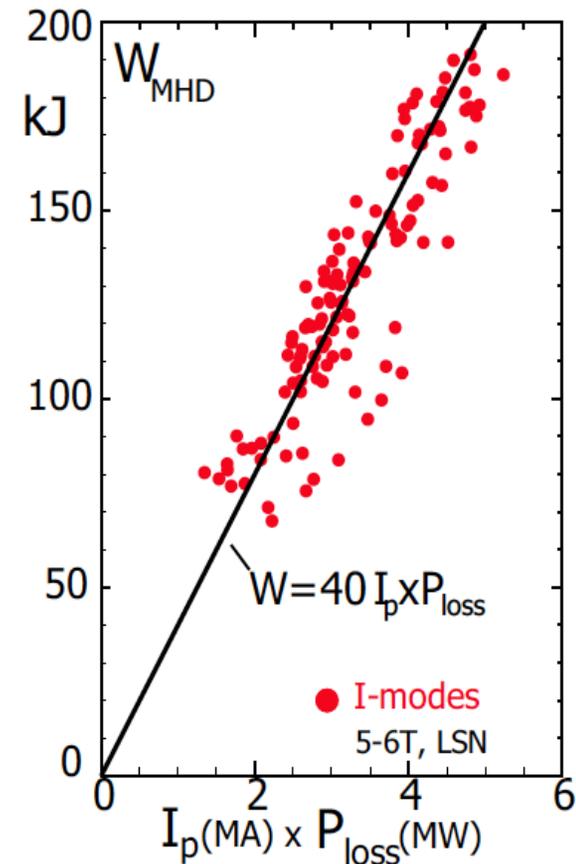
- Can access ITER-relevant confinement at the correct  $q_{95}$



Note: the scaling exponents utilized in the ITER-98(y,2) scaling expression do not capture the I-mode dependencies

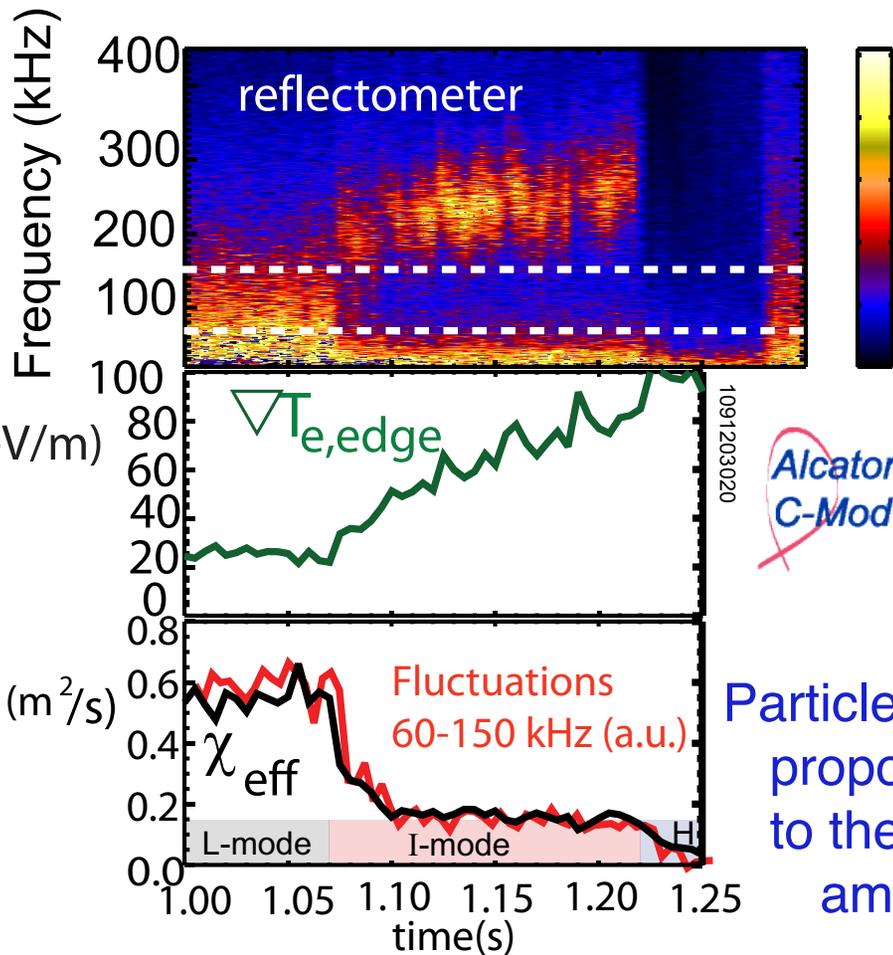
- I-mode exhibits minimal/no power degradation
  - In contrast to  $\tau_{98} \sim I_p P^{-0.7}$  (or  $W \sim I_p P^{0.3}$ )

Alcator C-Mod



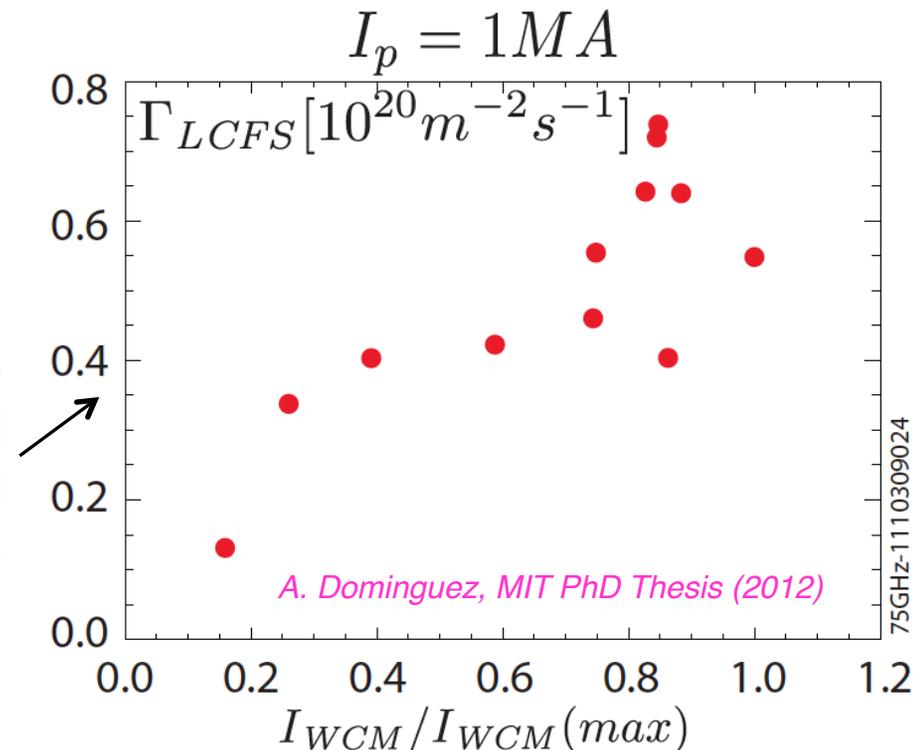
# Weakly Coherent Mode Provides Density Control in C-MOD I-Modes

- Low frequency fluctuations reduced at L-I, but mid-frequency fluctuations increase.



Frequency	100-400 kHz
Spread ( $\delta f/f$ )	$\sim 0.25-0.5$
Peak amplitude $\delta n_e/n_e$	$\sim 5-10\%$
Peak amplitude $\delta T_e/T_e$	$\sim 1-2\%$

Both higher frequency, and less coherent, than the EHO observed in QH-mode



$\chi_{i,eff}$  evaluated for  $0.95 < \psi_N < 1.0$

A. Hubbard, et al., Phys. Plasmas 18, 056115 (2011)

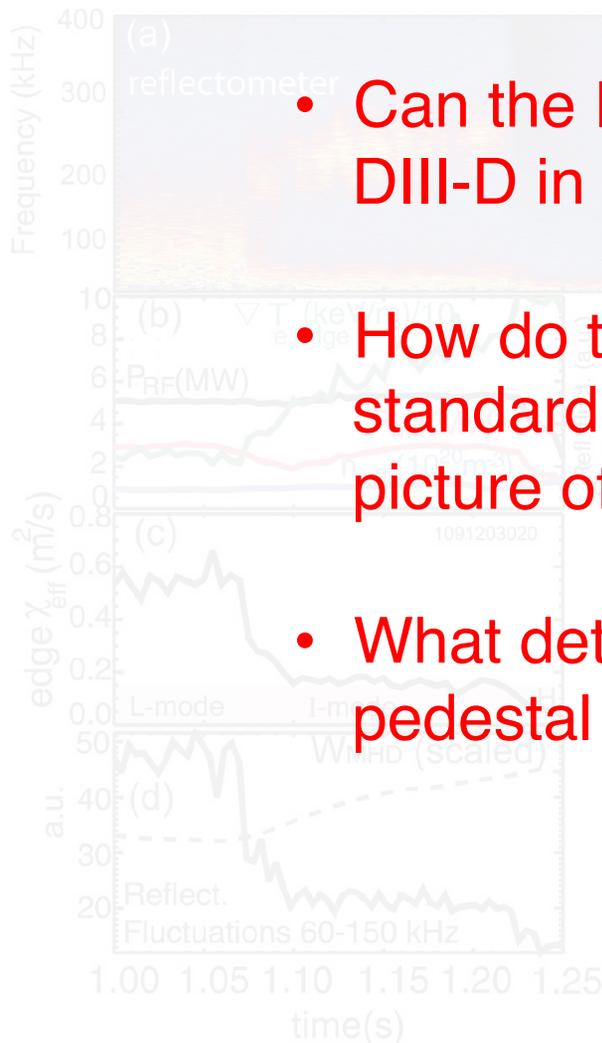
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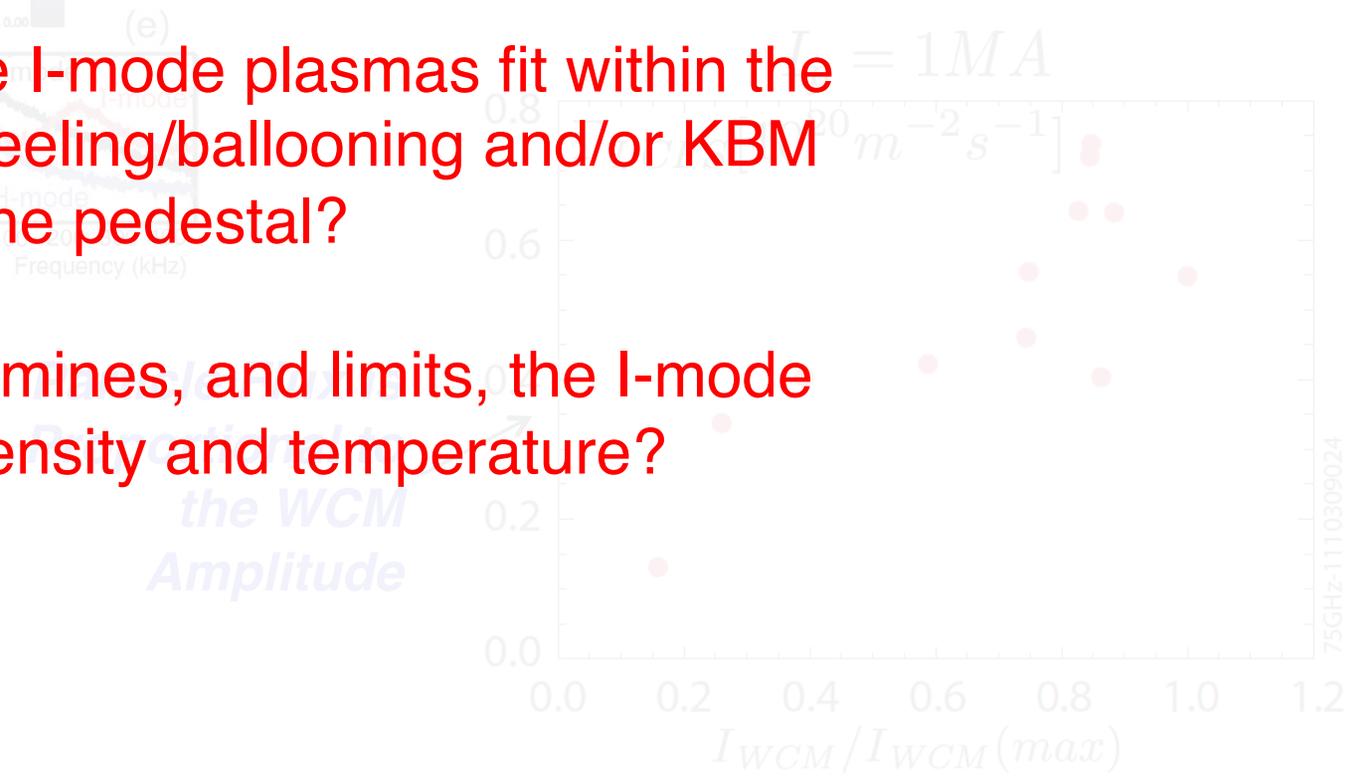
## Questions Addressed by Recent Research

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Peak amplitude $\Delta n_e/n_e$	$\sim 5-10\%$
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- Can the I-mode regime be accessed in DIII-D in addition to C-Mod and AUG?
- How do the I-mode plasmas fit within the standard peeling/ballooning and/or KBM picture of the pedestal?
- What determines, and limits, the I-mode pedestal density and temperature?



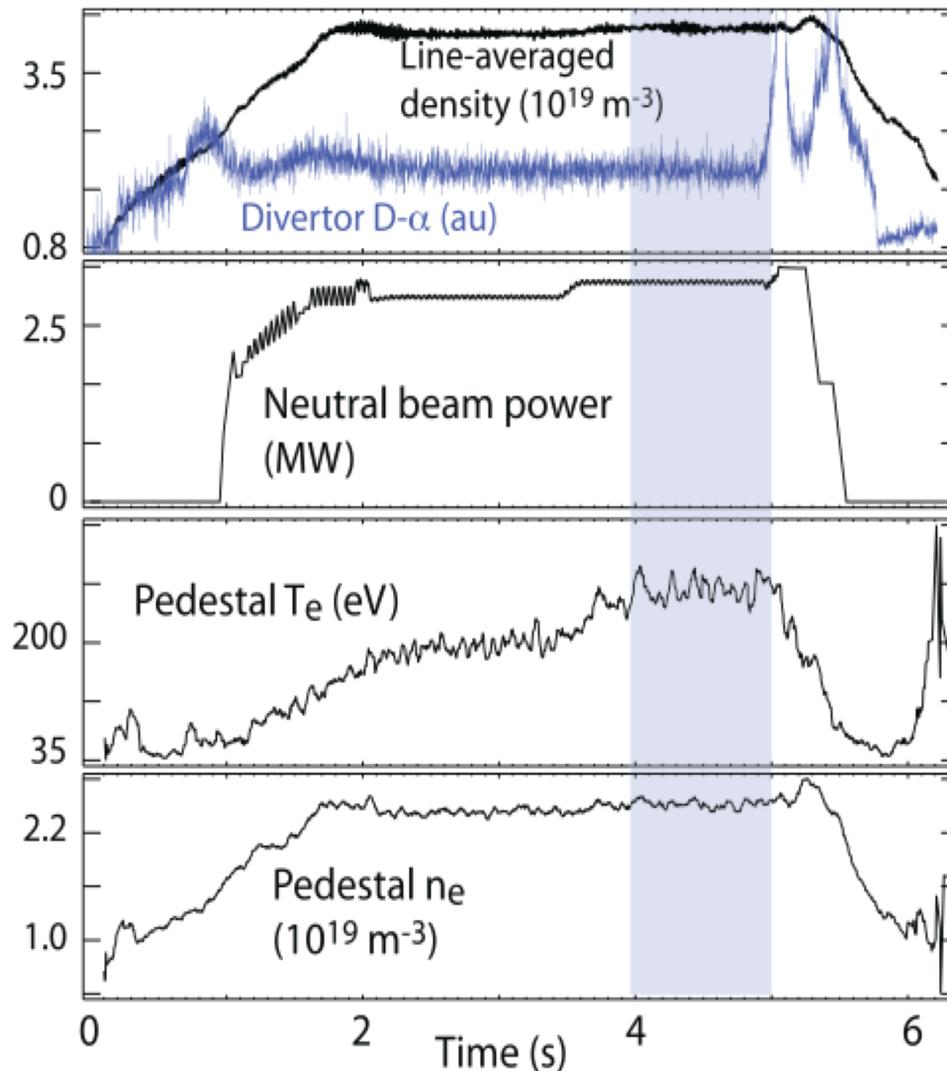
A. Hubbard, et al., Phys. Plasmas 18, 056115 (2011)



A. Dominguez, MIT PhD Thesis (2012)

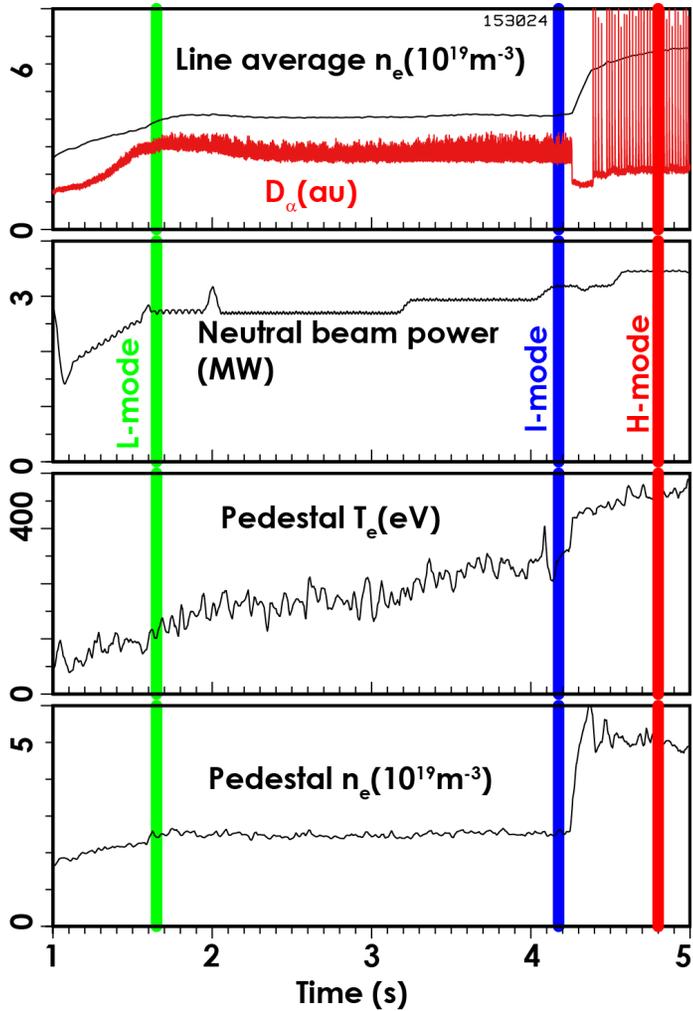
# I-Modes Have Been Found in DIII-D

- Experiments with power ramps in configuration with unfavorable grad-B drift direction.
  - Increased power required to access H-mode, helps open the I-mode access window.

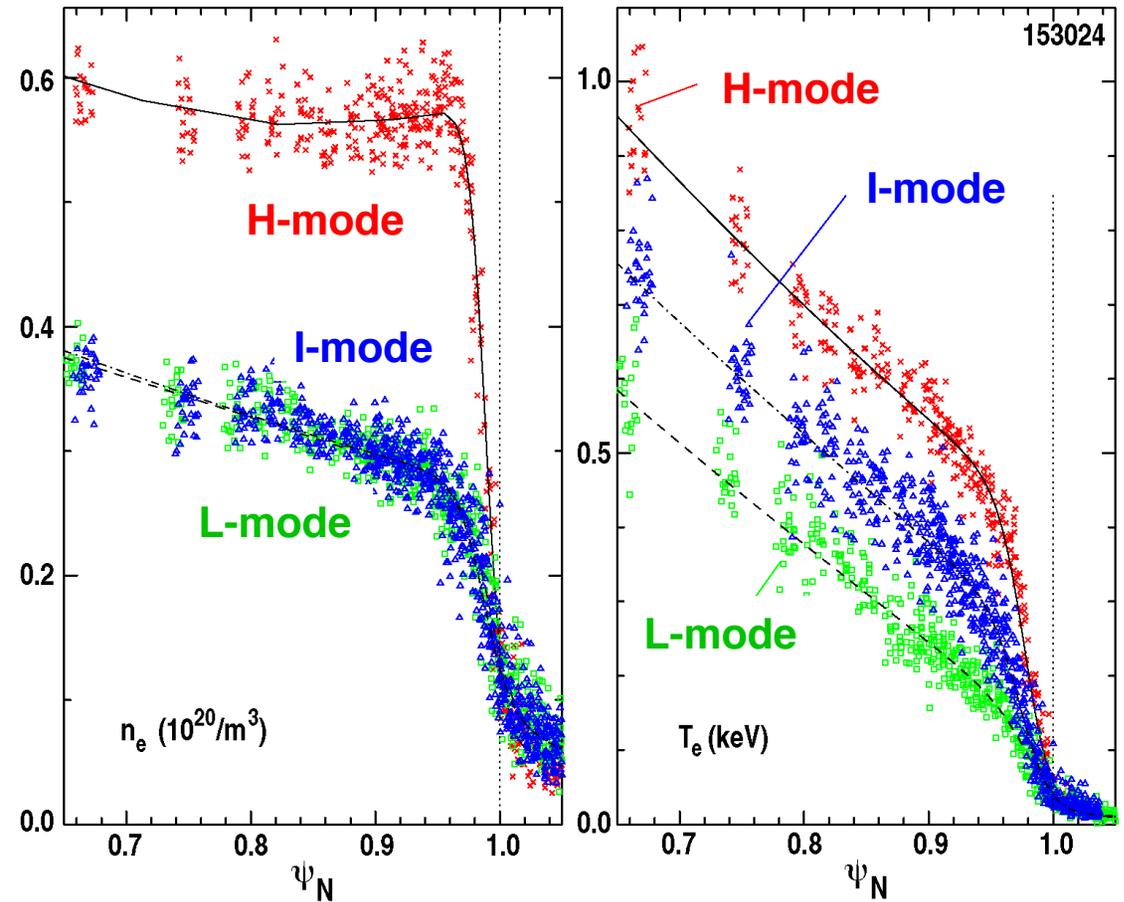


Temperature increases by a larger fraction than the heating power

# DIII-D I-mode Profiles Show L-mode Like Density Profiles, but Increases in $T_{e,ped}$



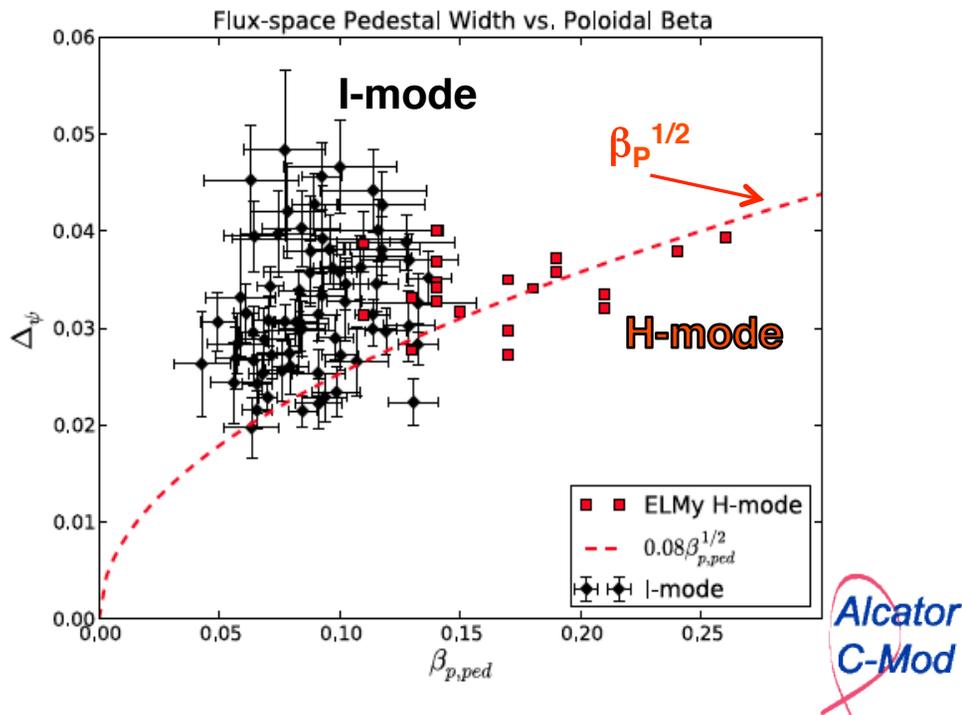
$T_e$  pedestal forms w/o an increased density pedestal



# Pedestal Widths are Typically Broader than in H-Mode

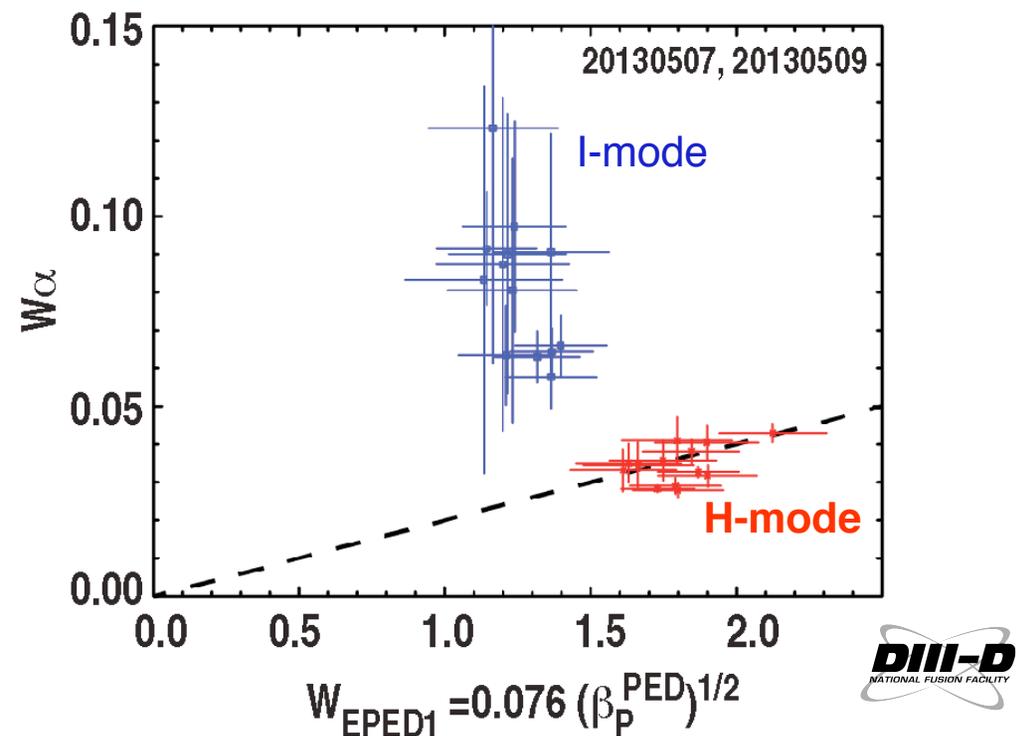
- Type-I ELMy H-mode typically shows pedestal width scaling as  $\beta_P^{1/2}$
- I-mode pedestals are consistently broader than predicted for KBM limited pedestals
  - Breaks a fundamental assumption of the EPED model, suggesting that these I-modes are not determined by the same physics as H-modes

C-MOD: Pedestal width vs.  $\beta_P$



J. Walk, APS 2013

DIII-D: Pedestal width vs.  $\beta_P^{1/2}$

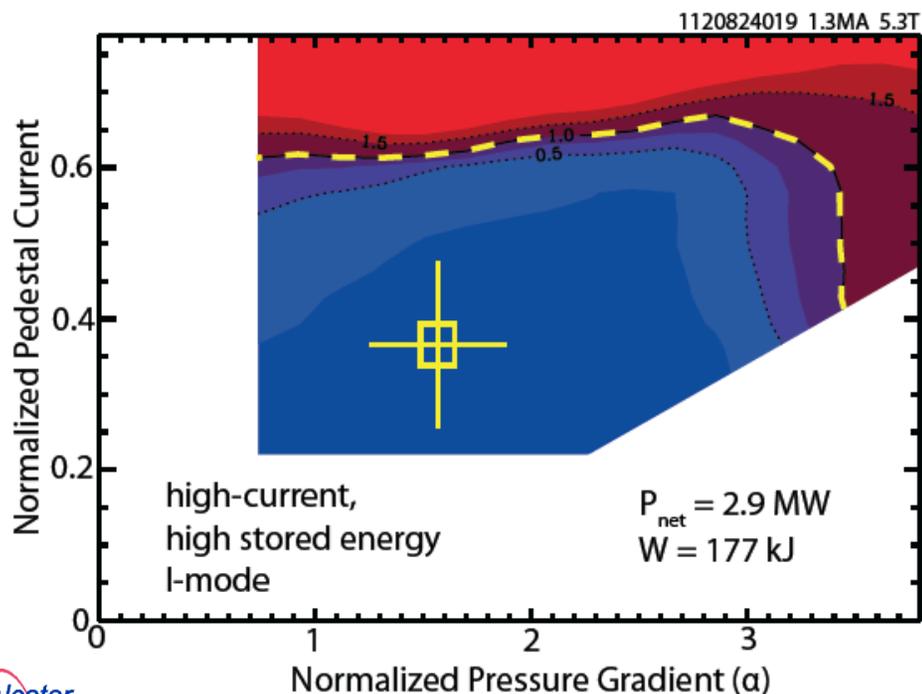


T. Osborne

# I-Mode Pedestal Gradients Are Consistently Found To Be Beneath Pedestal Macro-stability Limits

## C-MOD

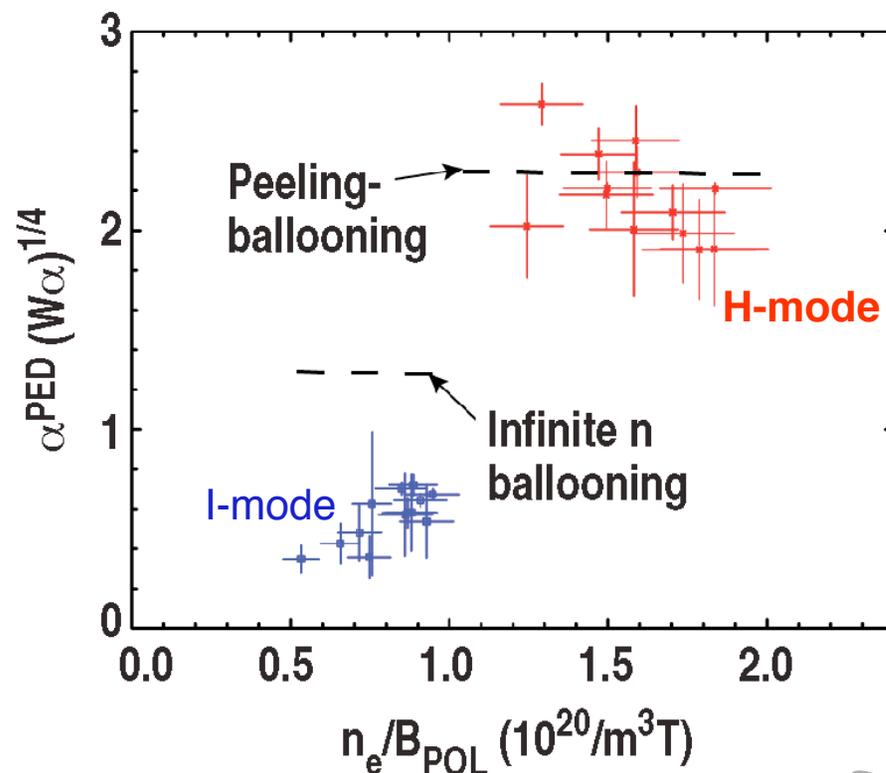
ELITE calculations show that the pedestal is well away from the computed peeling/ballooning boundaries



Alcator C-Mod

## DIII-D

I-mode pedestals evaluated to be well below the peeling/ballooning & infinite-n stability limits



It may be possible to further optimize the I-mode confinement regime for higher pedestal pressure.

# Recent Analysis of C-MOD Data Shows a Potential Path to I-Mode Performance Optimization

- Power/particle sets the pedestal temperature

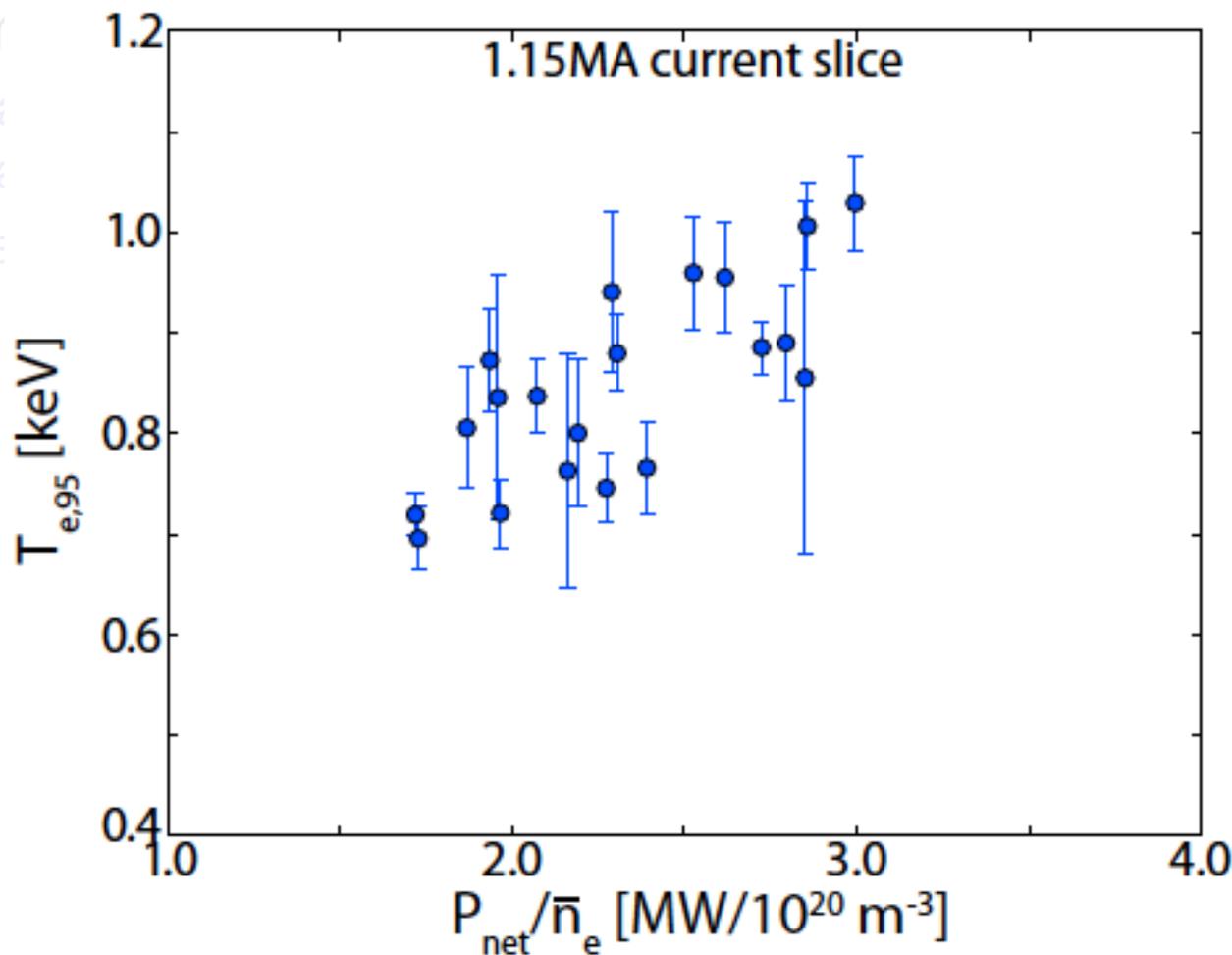
- Pedestal pressure  $\sim P_{\text{net}}$

*J. Walk, APS 2013,  
PoP 2014*

- I-modes plasma can be “densified” following the L->I transition

- Pedestal pr

- Fueling ca
  - power is a
  - Adjust the



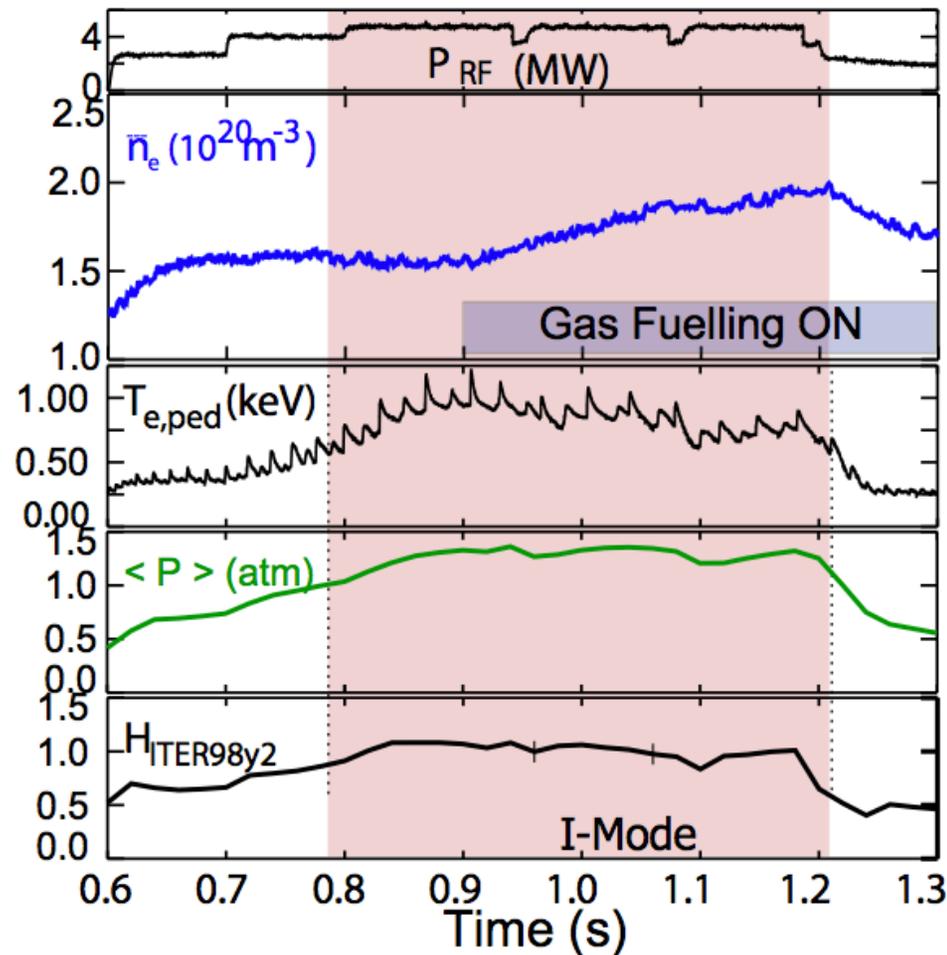
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- Pedestal pressure can be controlled by these actuators

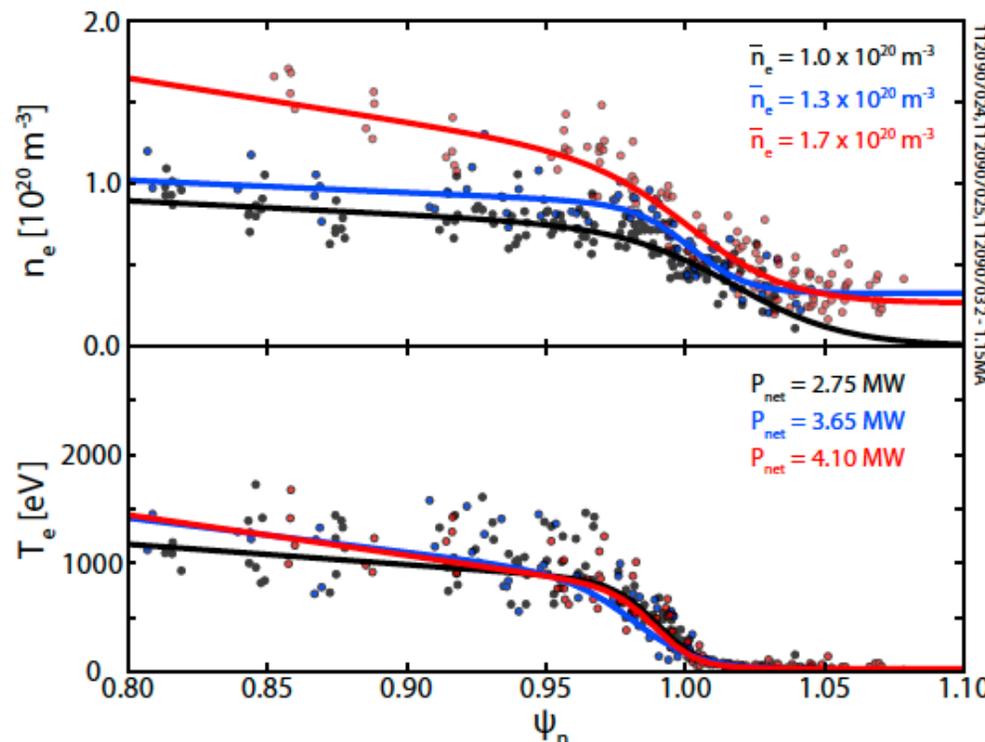
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  - Fueling can be used to increase the pedestal pressure, provided sufficient power is available
  - Adjust the power level to achieve the same pedestal temperatures

*J. Walk, APS 2013,  
PoP 2014*



**Line Average Density [m<sup>-3</sup>]**

**1.0x10<sup>20</sup>**

**1.3x10<sup>20</sup>**

**1.7x10<sup>20</sup>**

**Net Power [MW]**

**2.75**

**3.65**

**4.10**

*Alcator  
C-Mod*

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*J. Walk, APS 2013,  
PoP 2014*

## Potential Recipe:

- Transition to I-mode at lower density
- Fuel to higher density, using sufficient external/internal heating to maintain high  $T_{e,\text{ped}}$
- Use these actuators to control the pedestal beneath the low-n peeling/ballooning boundary

## Caveat:

- Power limit set by transition to H-mode, not global stability
  - Avoiding the transition to H-mode is a topic of present research

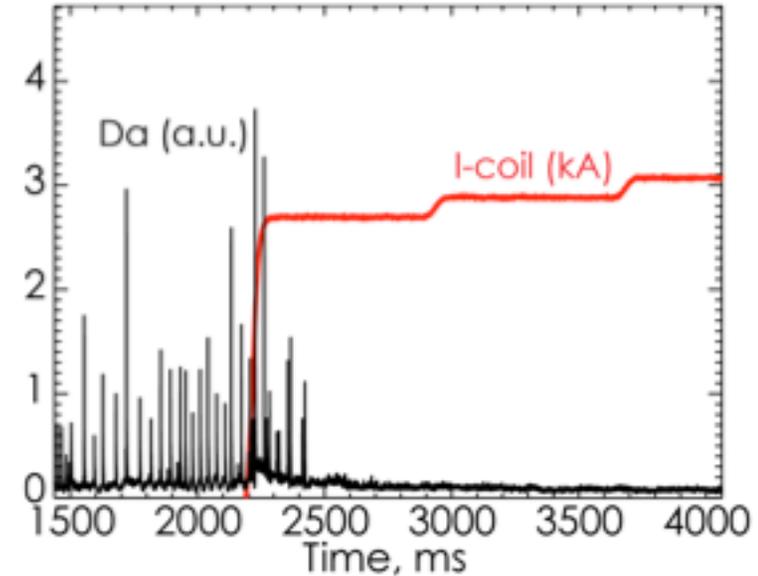
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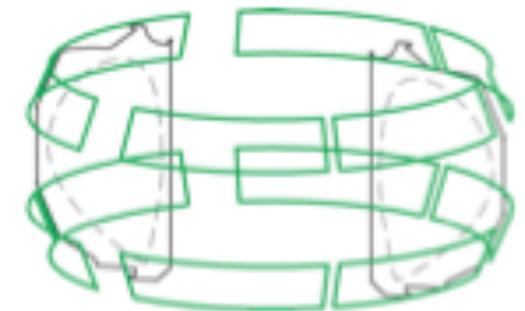
# Complete Suppression of ELMs Has Been Observed in DIII-D RMP Experiments

- RMP = resonant magnetic perturbations
- Have been observed to suppress ELMs in ITER-relevant low collisionality
  - Hypothesized to generate islands and/or stochastic regions at the pedestal top that limit the growth of the pedestal
- ITER coil designed assuming that the resulting region of island overlap is larger than some minimum value
  - Incomplete understanding of the physics elements
- Fields applied in DIII-D using off-midplane internal coils, typically with  $n=3$  toroidicity
- Key question addressed in recent research:
  - What is the impact of missing coils on the ability to control ELMs w/ RMP?
  - Motivated by possibility of failure of internal coil in ITER

ELM Suppression with  $n=3$  RMP in DIII-D

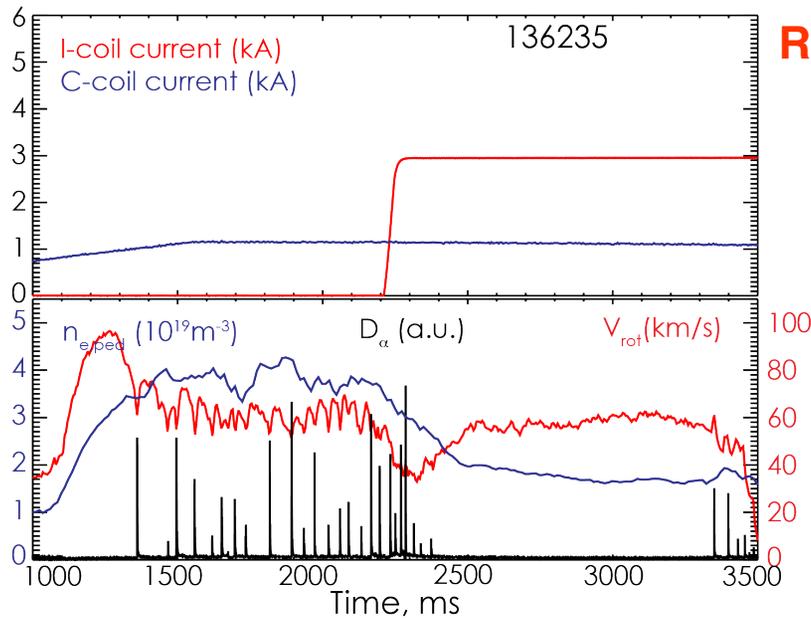


DIII-D I-Coil

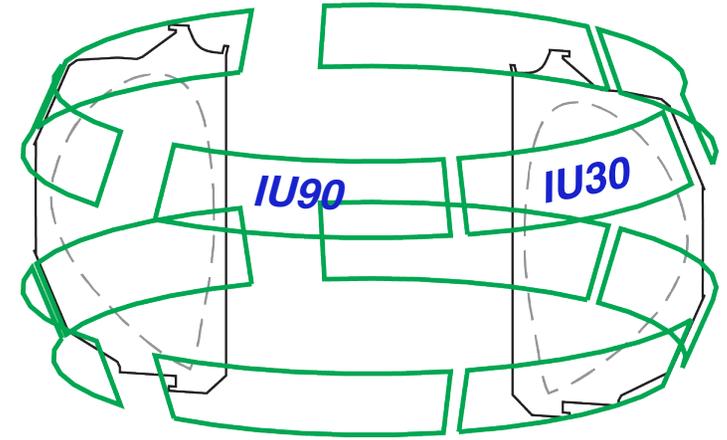


For a more general discussion of RMP issues, see recent BPO webinar by T. Evans.

# ELM Suppression Can Be Achieved in DIII-D With Fewer than 12 I-Coils



Reference 12 Coil Example: Suppression @  $I_{I-coil}=2.9$  kA

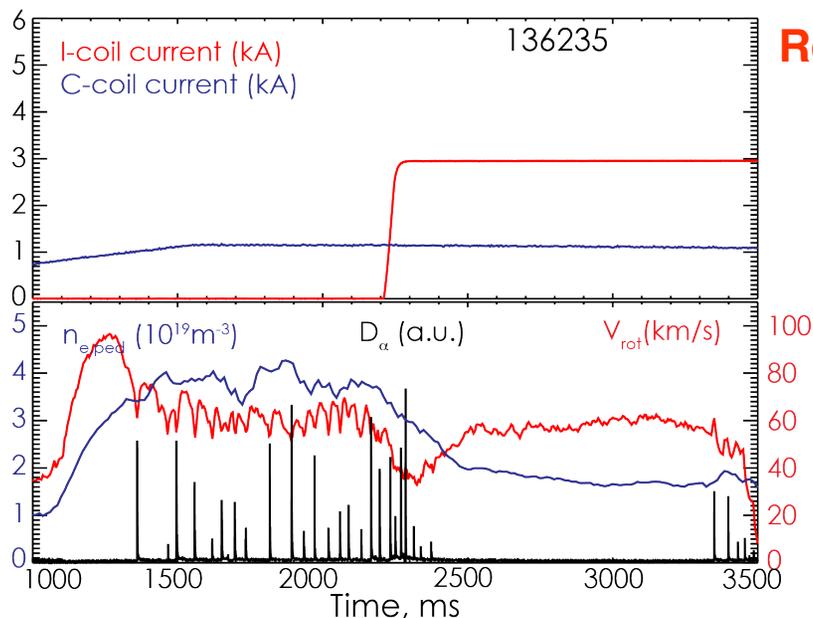


$P_{inj} = 4.5$  MW

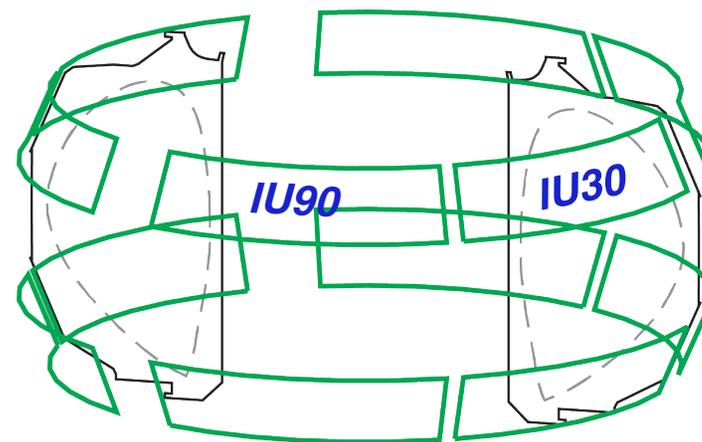


D. Orlov, APS Invited 2013

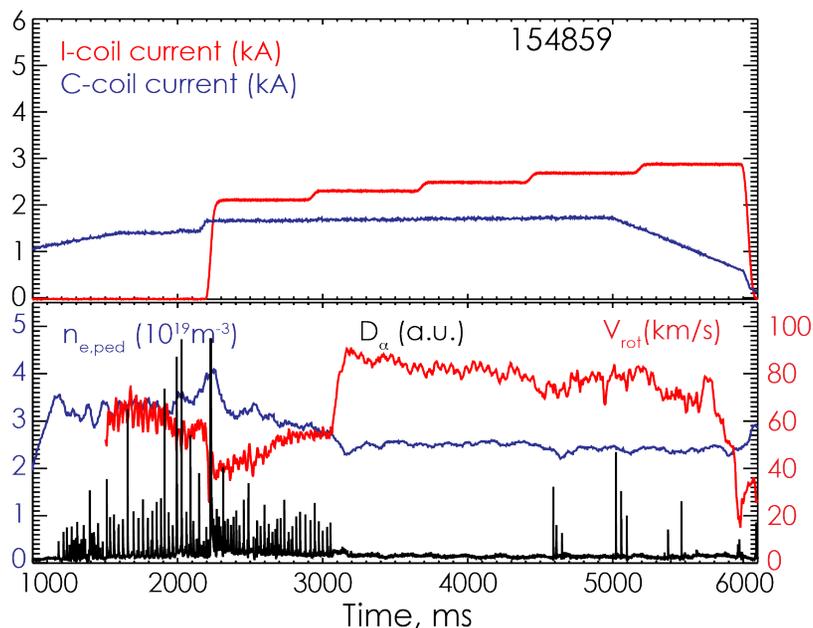
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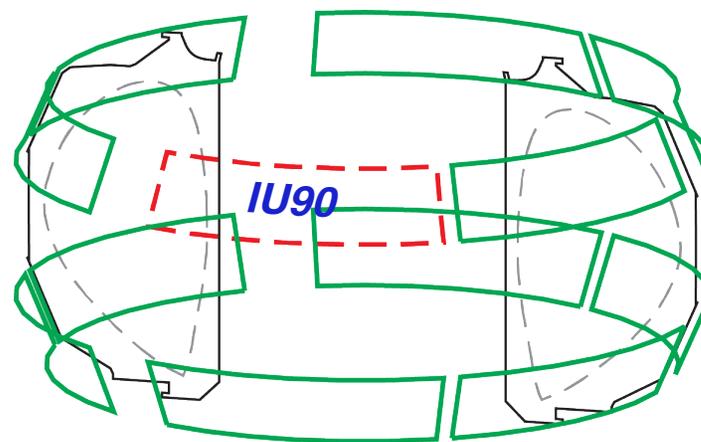
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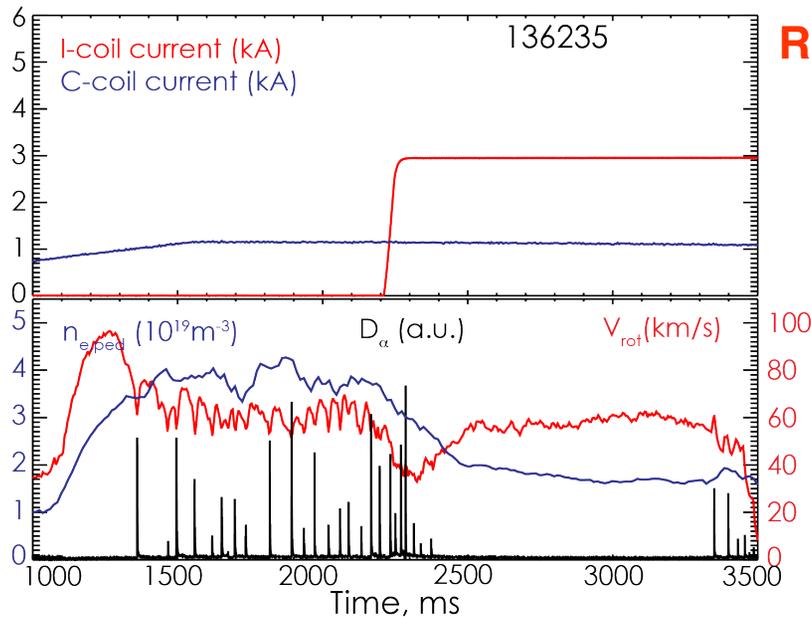
11 Coil Example: Suppression @  $I_{I-coil}=2.3$  kA



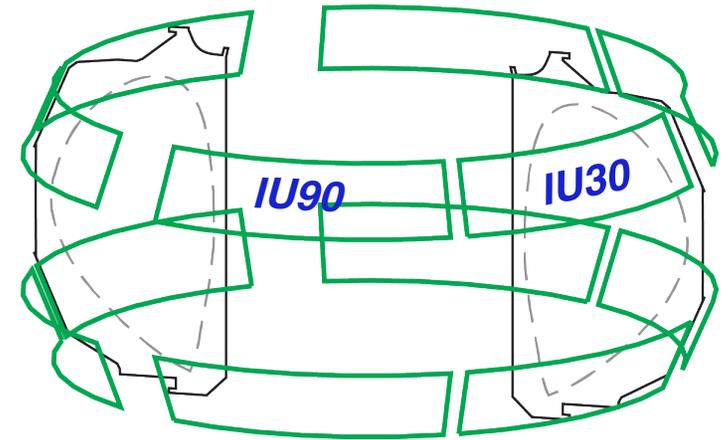
$P_{inj} = 5.9$  MW

D. Orlov, APS Invited 2013

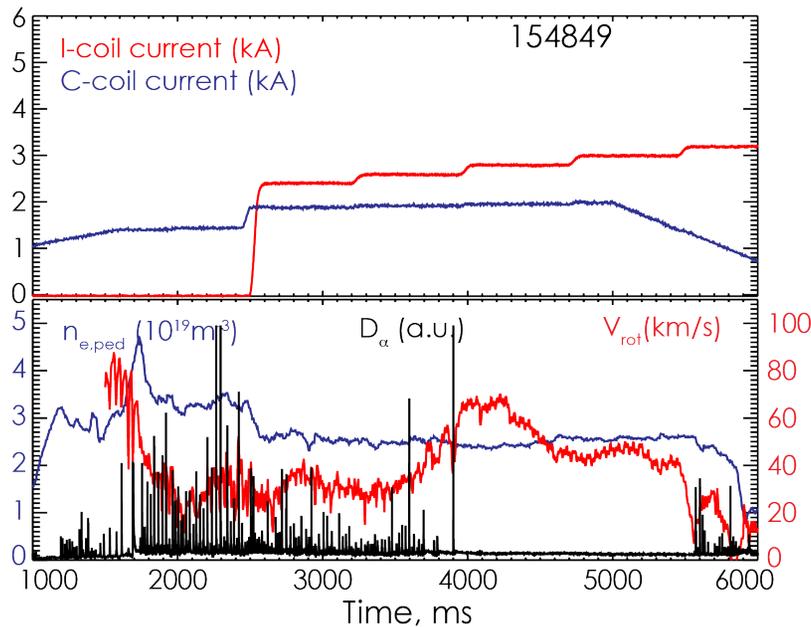
# ELM Suppression Can Be Achieved in DIII-D With Fewer than 12 I-Coils



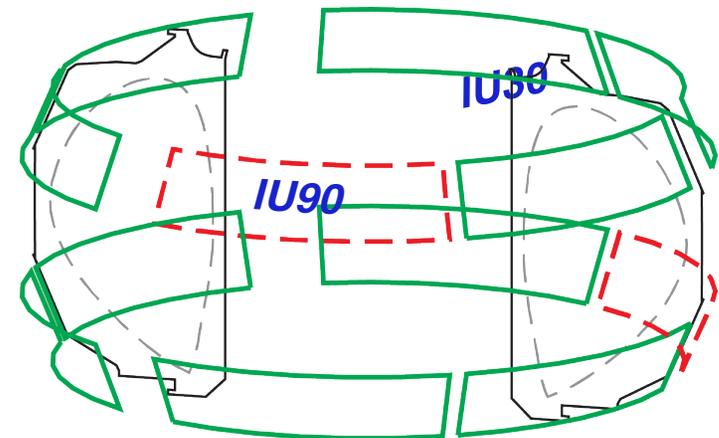
Reference 12 Coil Example: Suppression @  $I_{I-coil}=2.9$  kA



$P_{inj} = 4.5$  MW



10 Coil Example: Suppression @  $I_{I-coil}=2.8$  kA

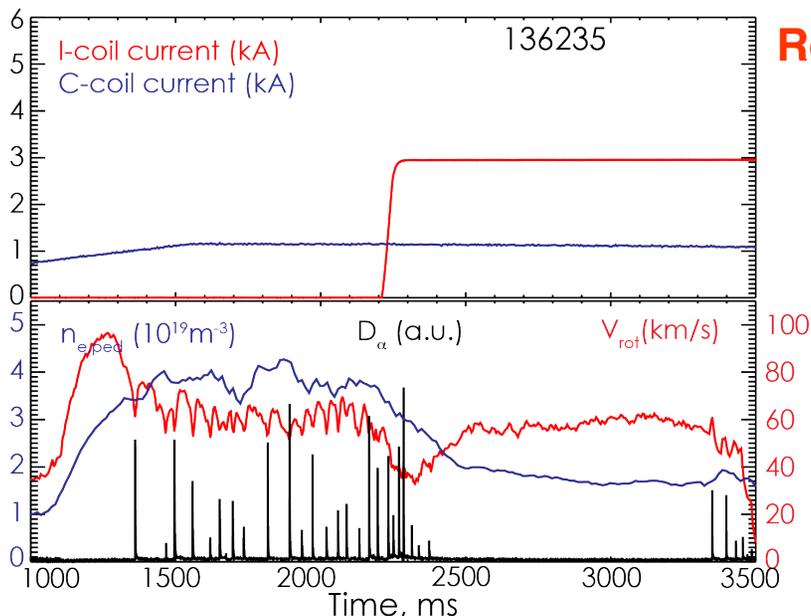


Coils turned off pseudo-randomly

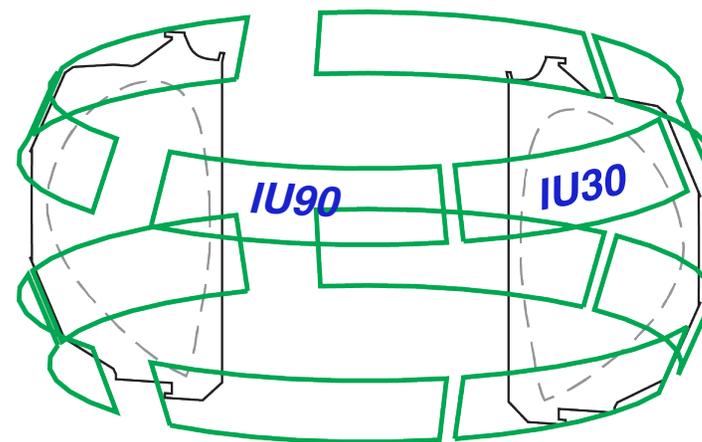
$P_{inj} = 7.7$  MW

D. Orlov, APS Invited 2013

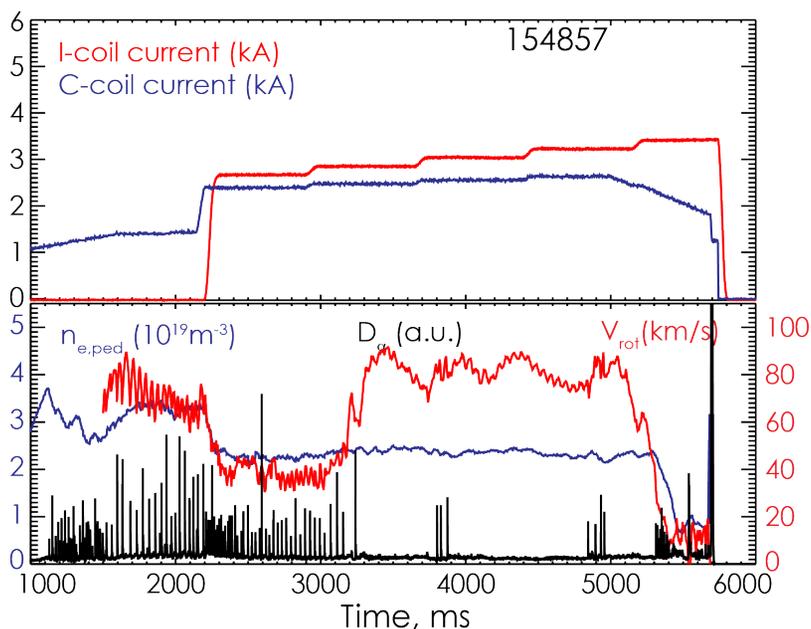
# ELM Suppression Can Be Achieved in DIII-D With Fewer than 12 I-Coils



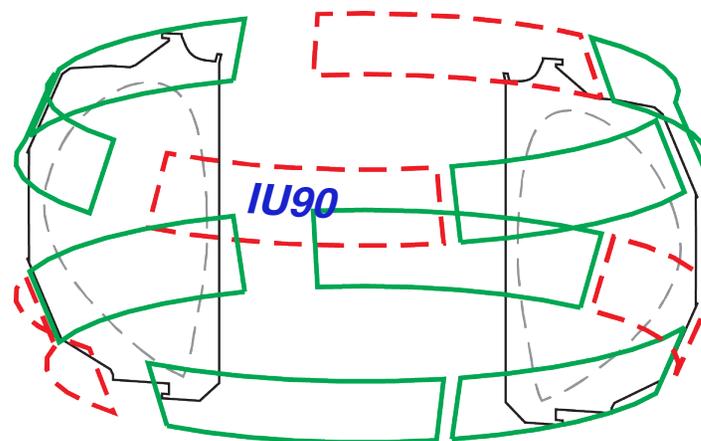
Reference 12 Coil Example: Suppression @  $I_{I-coil}=2.9$  kA



$P_{inj} = 4.5$  MW



8 Coil Example: Suppression @  $I_{I-coil}=2.85$  kA

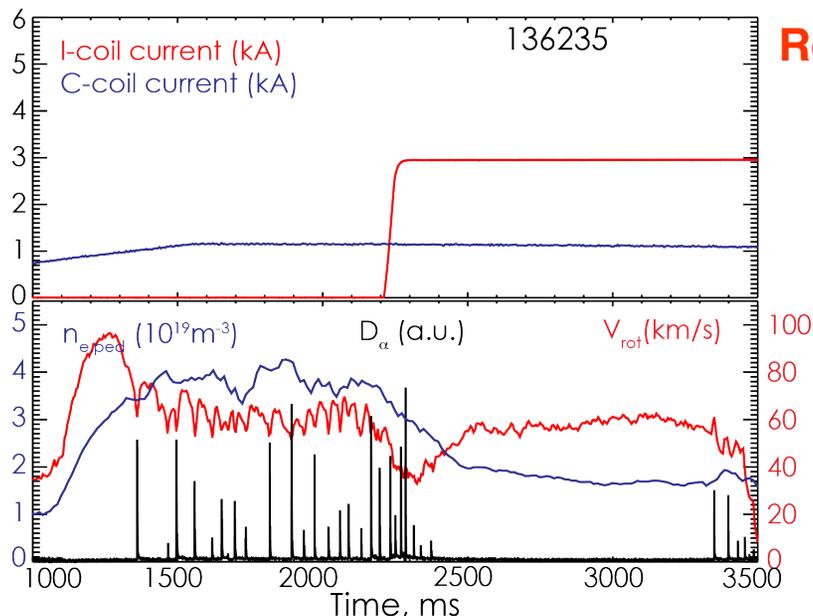


Coils turned off pseudo-randomly

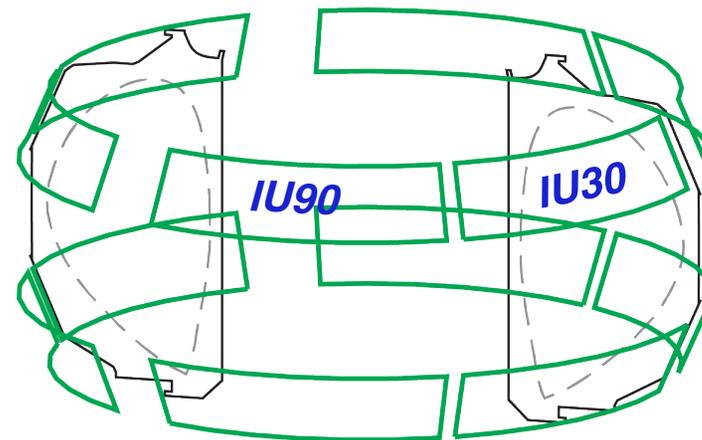
$P_{inj} = 5.9$  MW

D. Orlov, APS Invited 2013

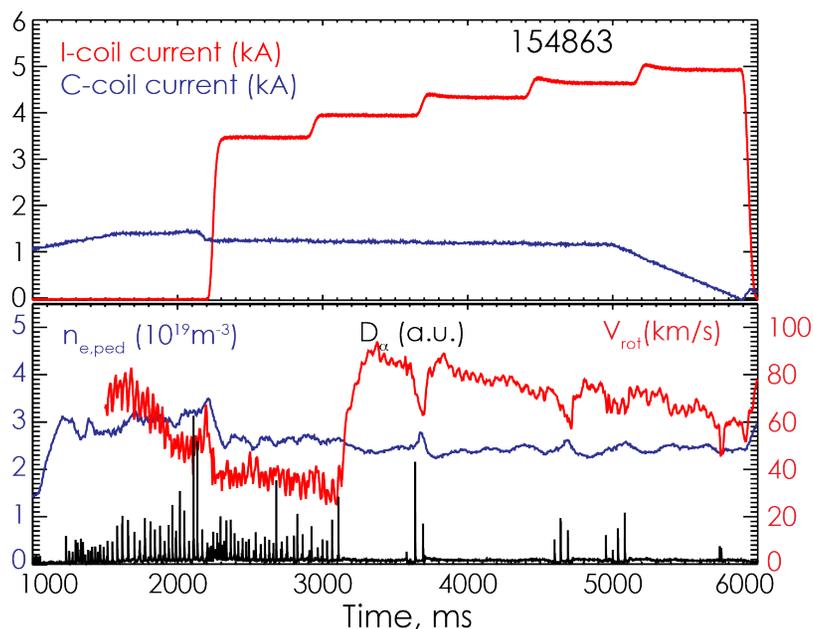
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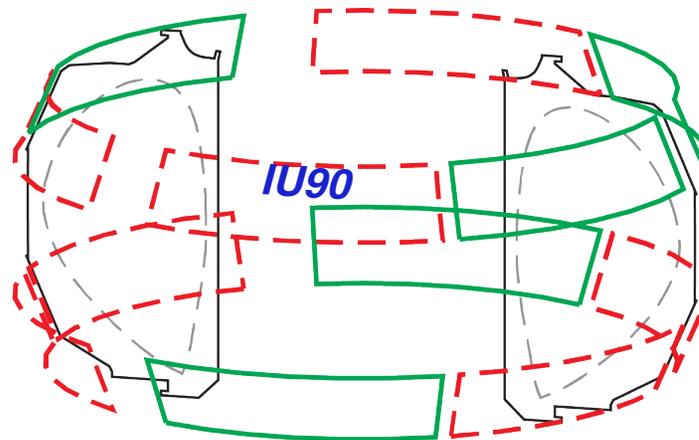
Reference 12 Coil Example: Suppression @  $I_{I-coil}=2.9$  kA



$P_{inj} = 4.5$  MW



5 Coil Example: Suppression @  $I_{I-coil}=3.95$  kA

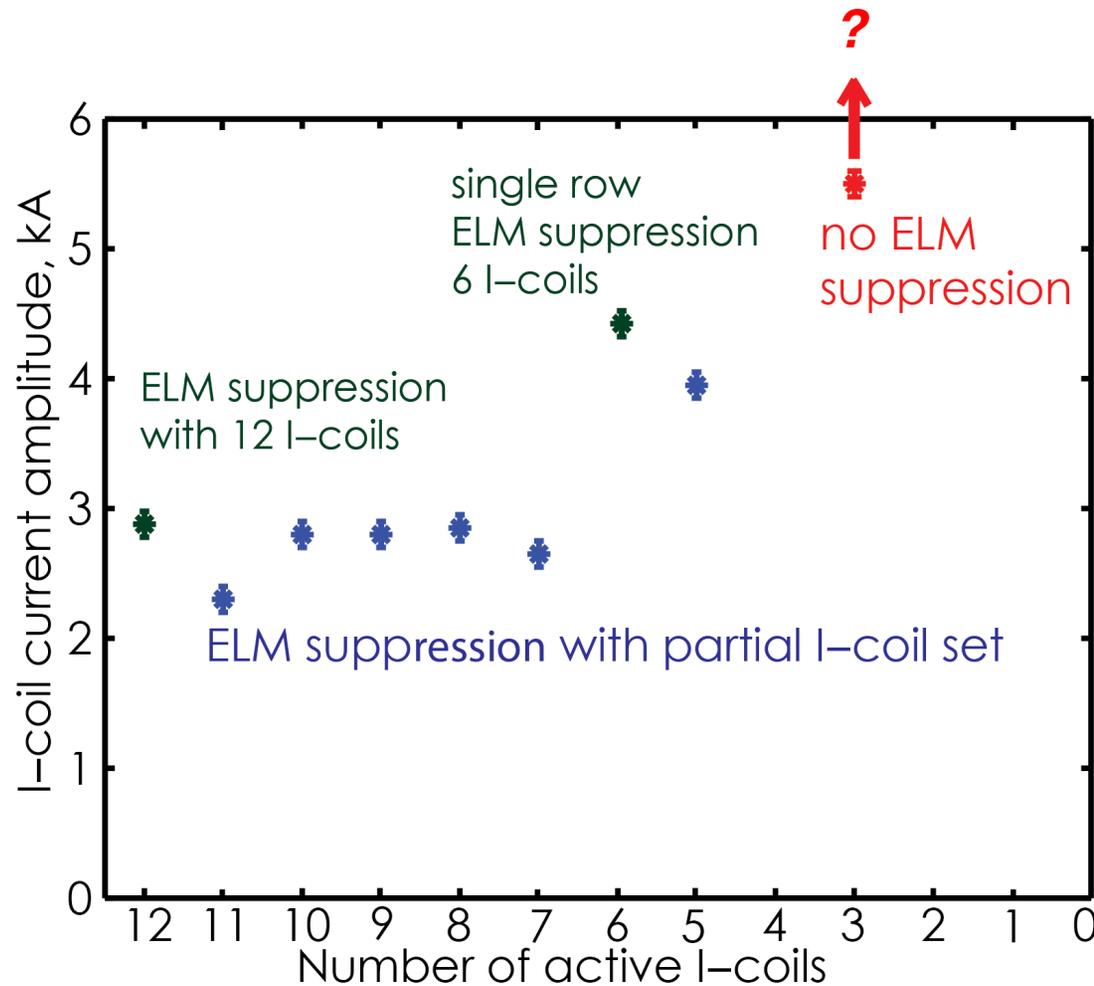


Coils turned off pseudo-randomly

$P_{inj} = 5.9$  MW

D. Orlov, APS Invited 2013

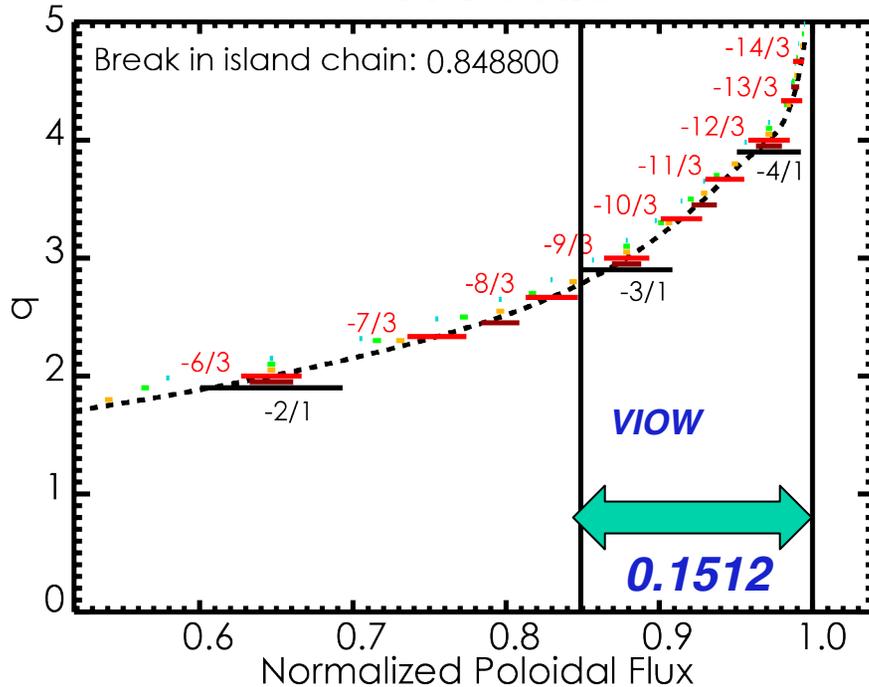
# Minimal Variation in Current Amplitude Required For ELM Suppression with 5-12 I-Coils in DIII-D



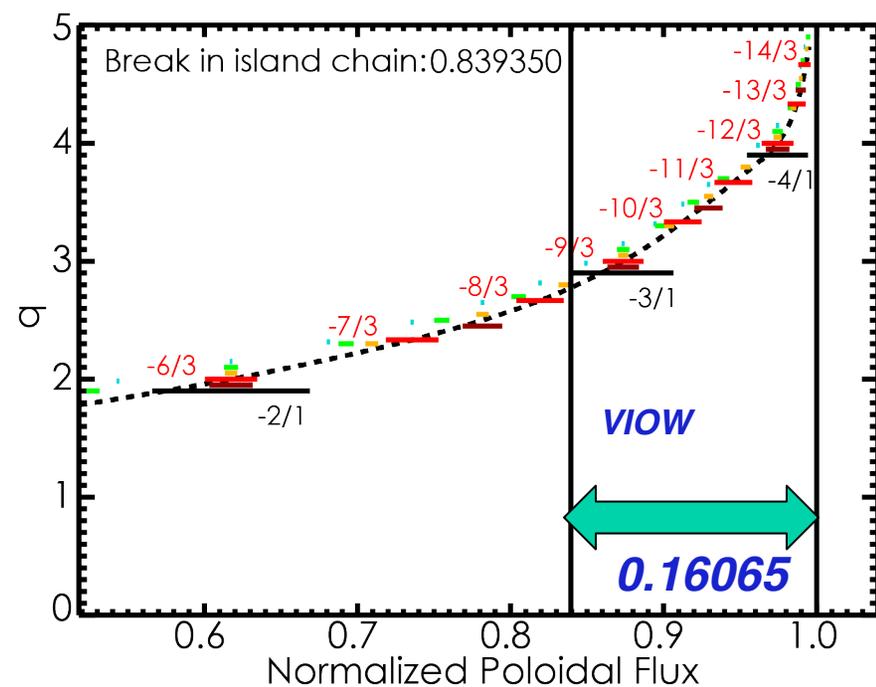
- Elimination of coils results in  $n \neq 3$  sidebands...do these sidebands play a role in increasing the edge stochasticity?

# Vacuum Approximation Modeling Indicates that the Sidebands Help Maintain a Stochastic Boundary

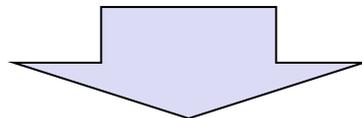
## 11 I-coils



## 5 I-coils



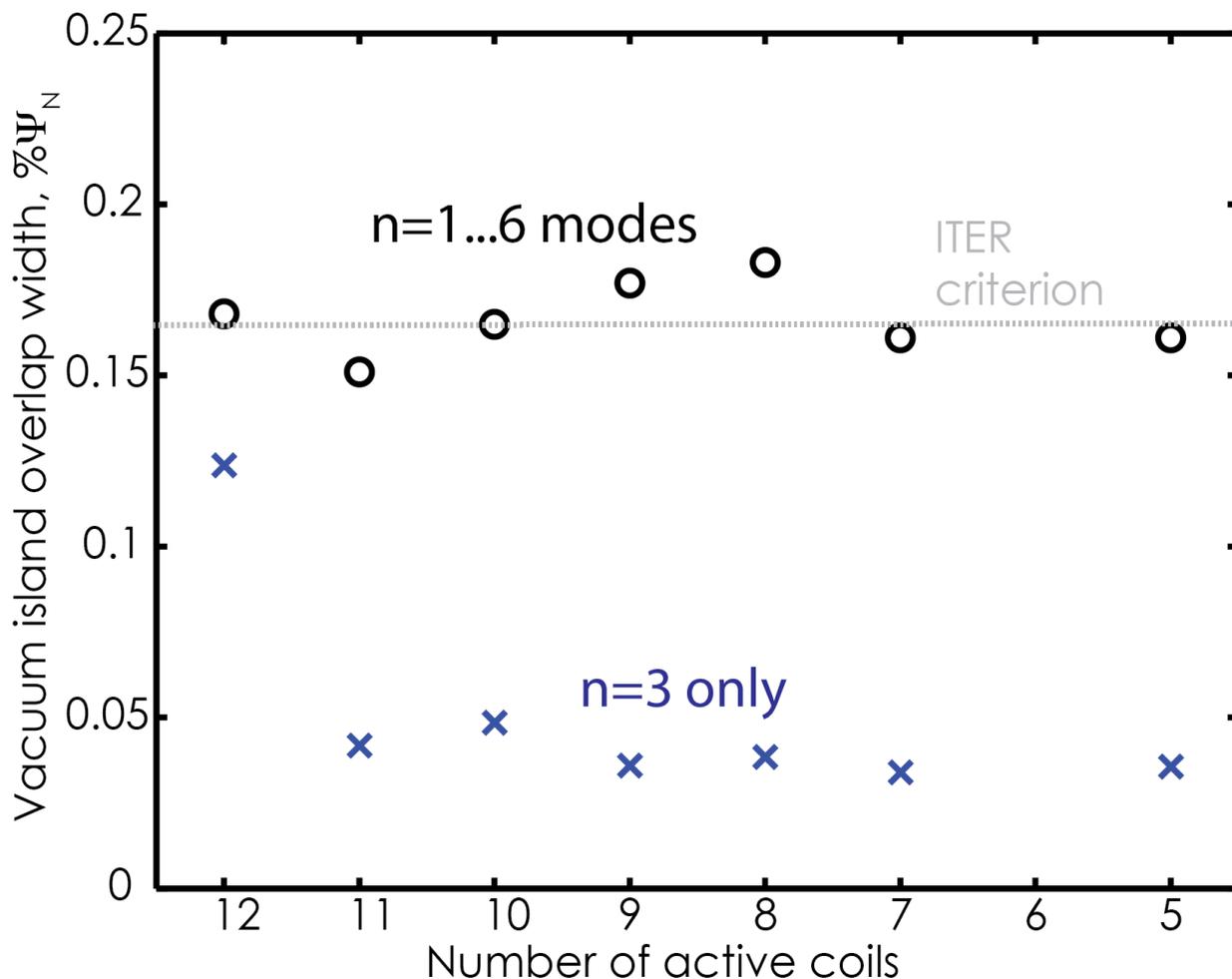
$n=3$  vacuum islands decrease when coils are turned off  
Other  $n$  ( $n=1,2,4\dots$ ) islands grow in size



Vacuum Island Overlap Width value stays close to ITER criterion of  $VIOW \sim 0.165$  in all configurations

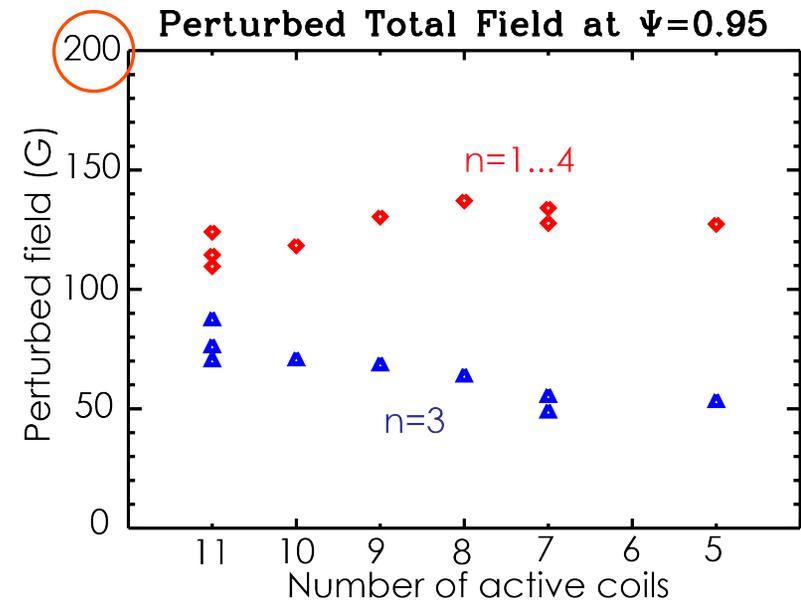
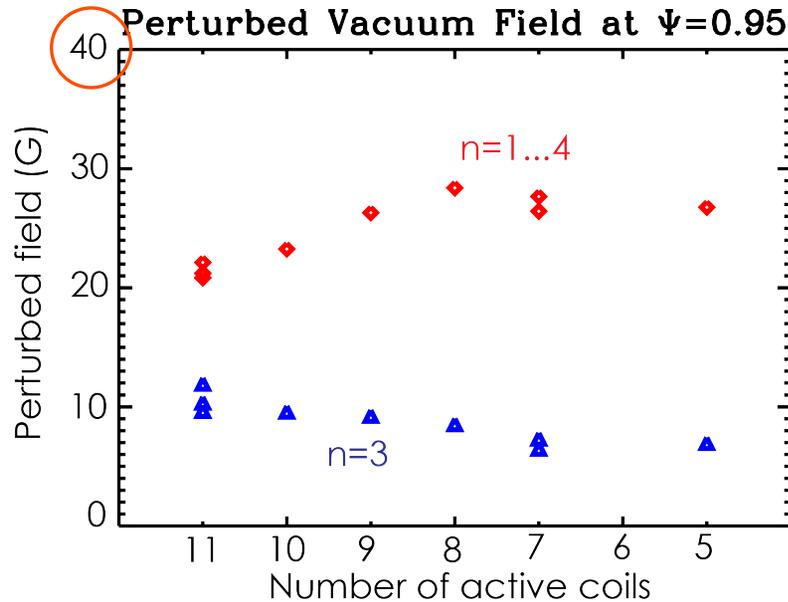
# Vacuum Calculations Show that the Island Overlap Width is Similar in All Cases with ELM Suppression

- Inclusion of sidebands is critical in determining the full overlap width



# Two-Fluid MHD Calculations with M3D-C<sup>1</sup> Indicate the Importance of n≠3 Sidebands

- M3D-C<sup>1</sup> calculates linear 2-fluid MHD response including rotation
- Shows both screening and amplification of the resulting perturbations



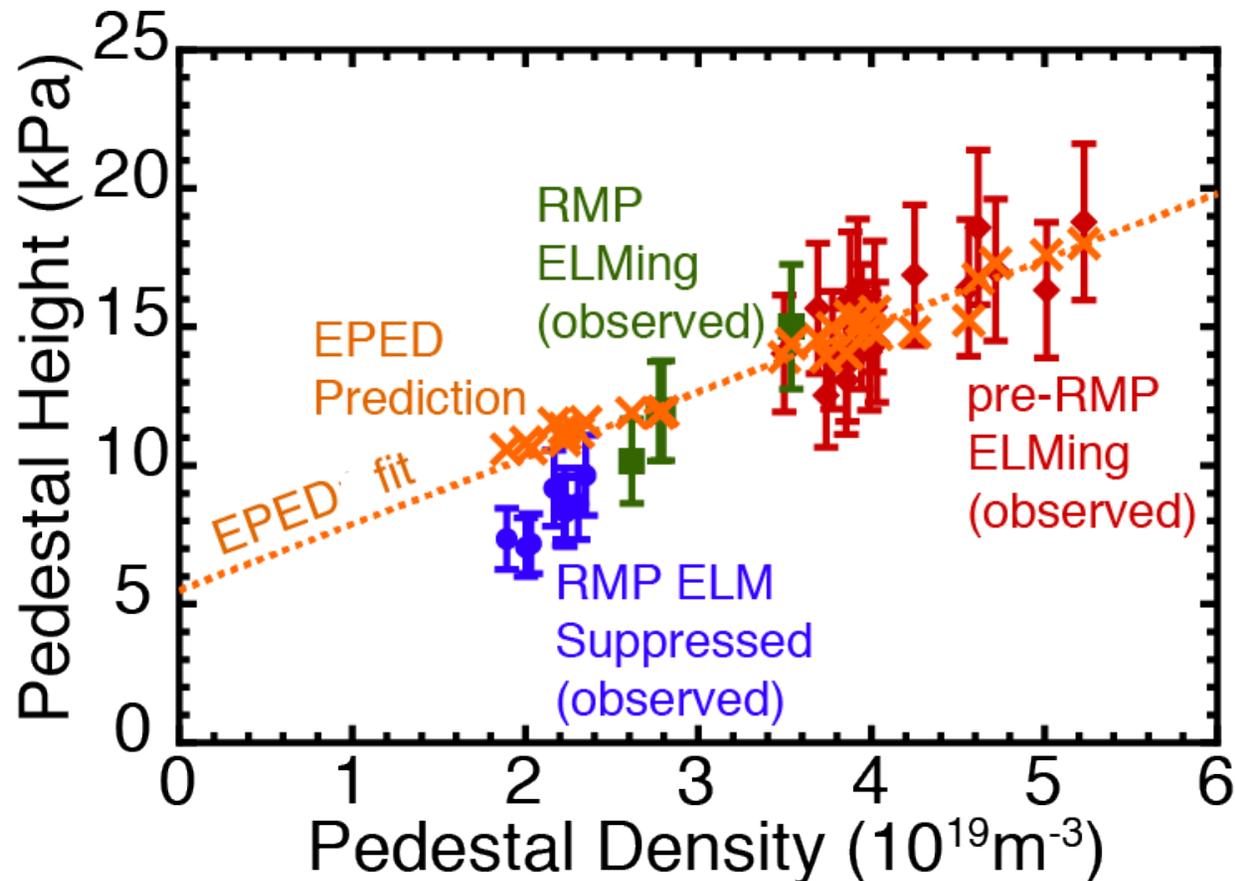
Calculations testing the limit of linear model

- $|\delta B|_{n=3}$  field decreases as coils are removed
- $|\delta B|_{n=1} + |\delta B|_{n=2} + |\delta B|_{n=3} + |\delta B|_{n=4}$  increases with number of coils



# Cases With ELM Suppression Show Pedestal Heights Beneath the EPED Prediction

- No (or small) RMP current → pedestal height matches EPED prediction
- ELM suppression → pedestal height beneath EPED prediction



Note: Density pump-out results in lower pedestal density with RMP application

Consistent with model where the RMP limits the pedestal width

P. Snyder, et al., Phys. Plasmas **19** (2012)

R. Nazikian, APS 2013  
D. Orlov, APS Invited 2013

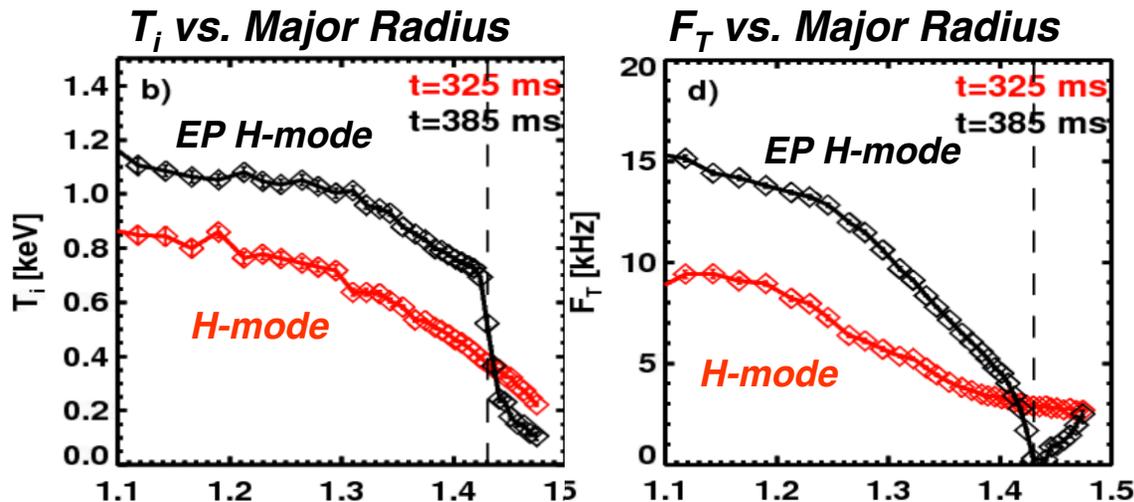
# Outline: Multi-Facility Research Milestone in 2013 Addressed Stationary High-Performance Regimes w/o Large ELMs

- Introduction
- Reminder: Key pedestal physics considerations
- Regimes with continuous edge fluctuations
  - Quiescent H-mode
  - I-Mode
- Recent research on RMP ELM suppression
- **A very high confinement regime: the EP H-mode in NSTX**
- Regime comparisons and answers to the five broad questions

# The Enhanced Pedestal H-mode is a High-Confinement Regime in the Spherical Torus

## Characteristics of the Enhanced Pedestal (EP) H-mode.

- Edge region where the  $T_i$  gradient is much steeper than in H-mode.
- $T_i$  gradient associated with a region of strong toroidal flow shear
  - often a very narrow minima in the flow.
- The transition to this regime occurs after the L->H transition.
  - often follows on ELM.



## Questions to be Addressed by Recent Research

- Can the configuration be sustained?
- Is there a reduction in turbulence during this phase?
- Is the transport dominantly neoclassical in this phase?

# Long-Pulse, Quiescent EP H-modes Have Been Observed

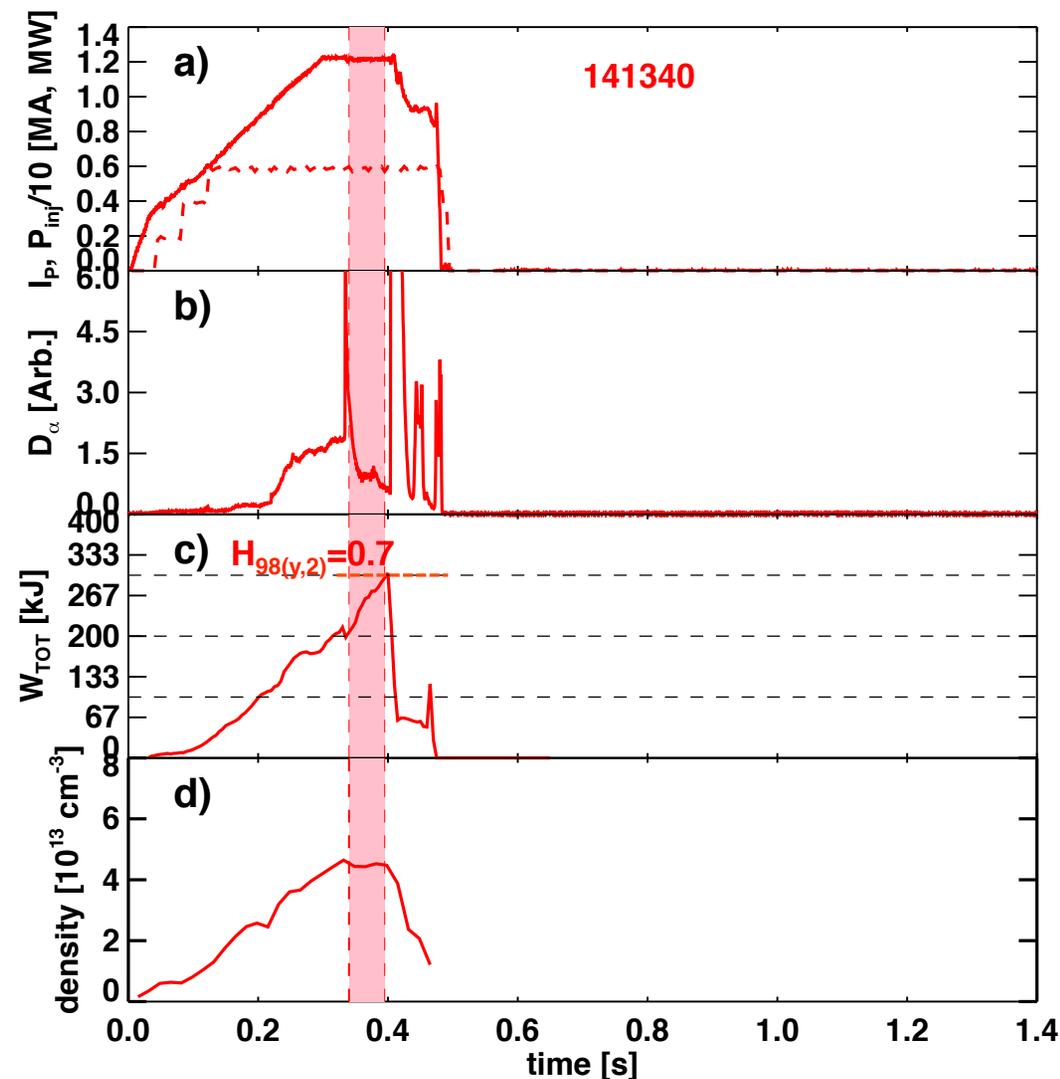
## Early Examples

Strong stored energy ramps following transition, but short lived  
(R. Maingi, et al., JNM 2009)

First Extended EP H-mode  
Demonstrated high confinement for many confinement times  
(R. Maingi, et al, Phys. Rev. Lett., 2010)

## Quiescent Long-Duration EP H-mode

Configuration maintained for duration of NB heating  
Very quiescent  
(S.P. Gerhardt, et al., submitted to Nuclear Fusion, 2014)



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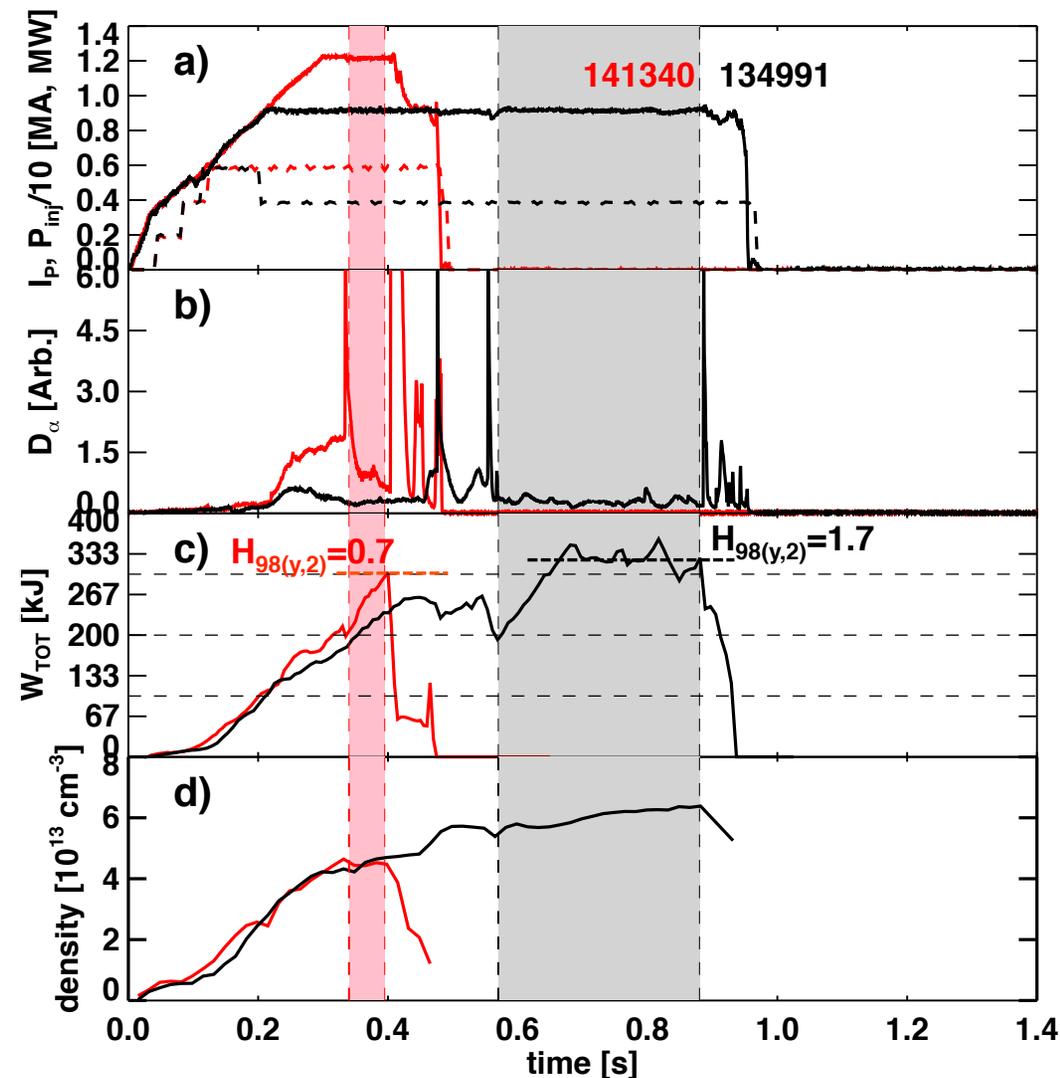
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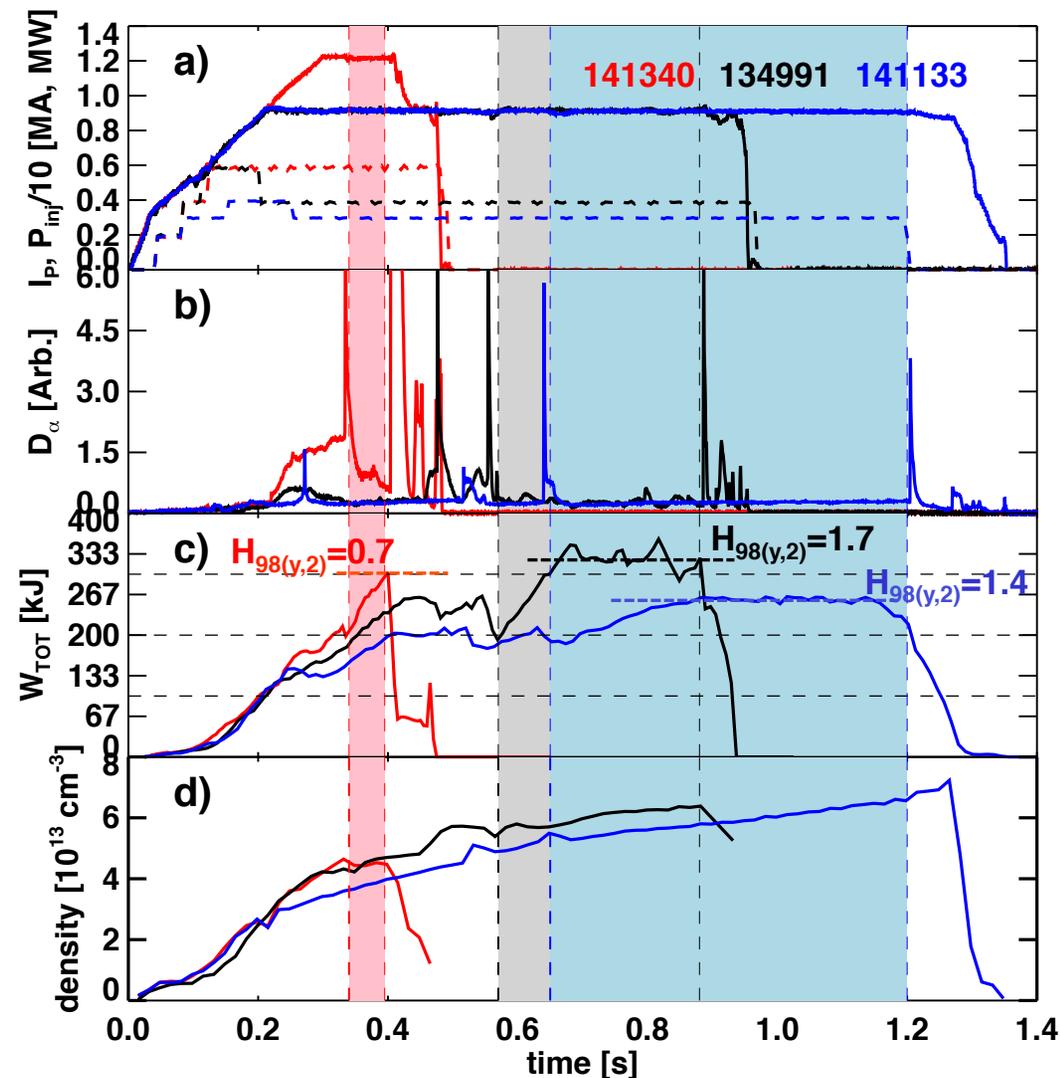
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Density rise typically due to accumulation of C impurities in these cases  
Stationarity typically not achieved in NSTX discharges



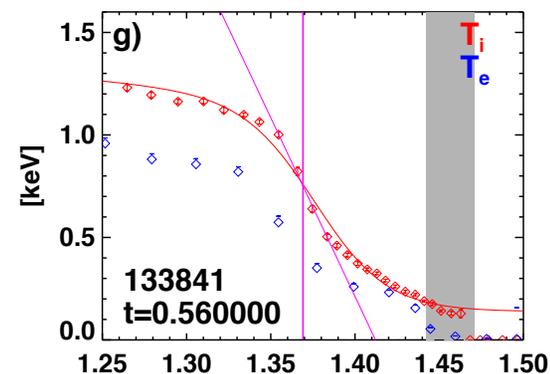
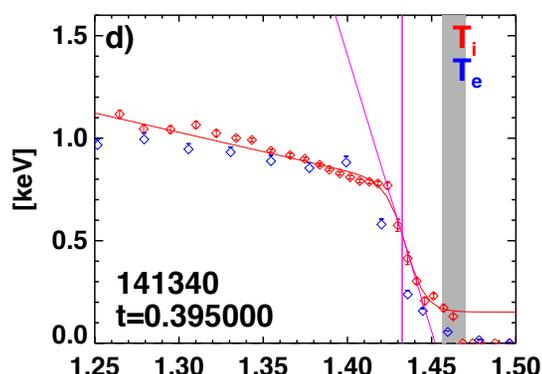
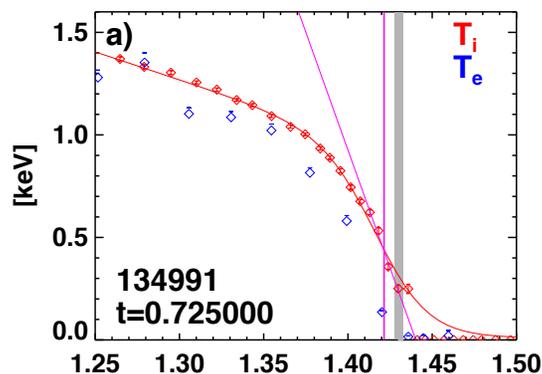
# JRT Research Demonstrated That a Wide Variety of Profile Shapes Can Fit in the “EP H-mode” Category

Steep Gradient: Near Separatrix

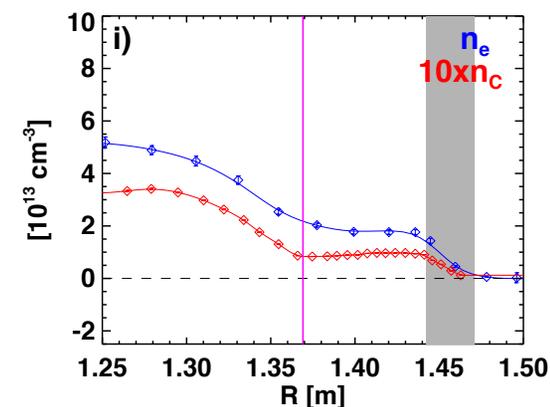
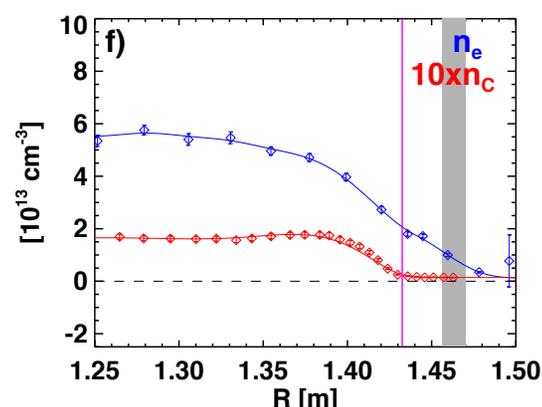
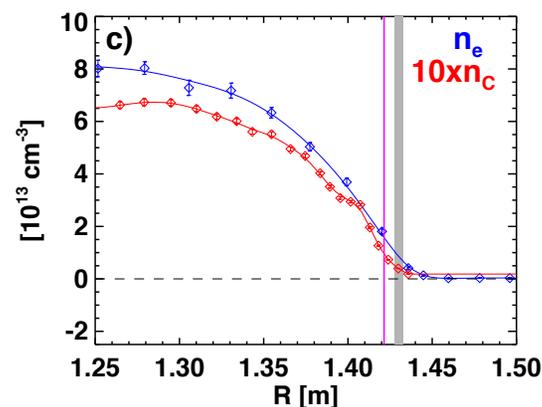
Shifted Slightly In

Shifted Significantly In

Electron temperature and ion temperature



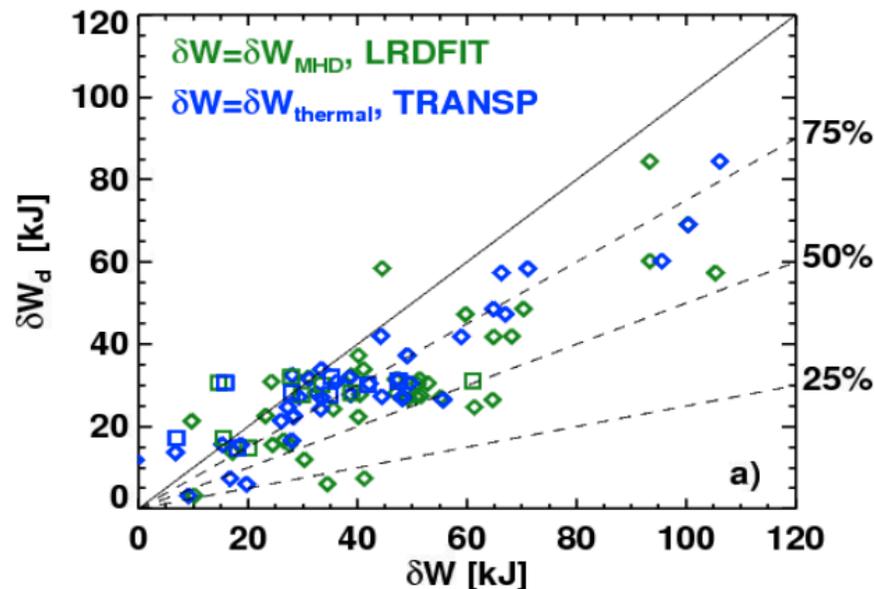
Electron and carbon density



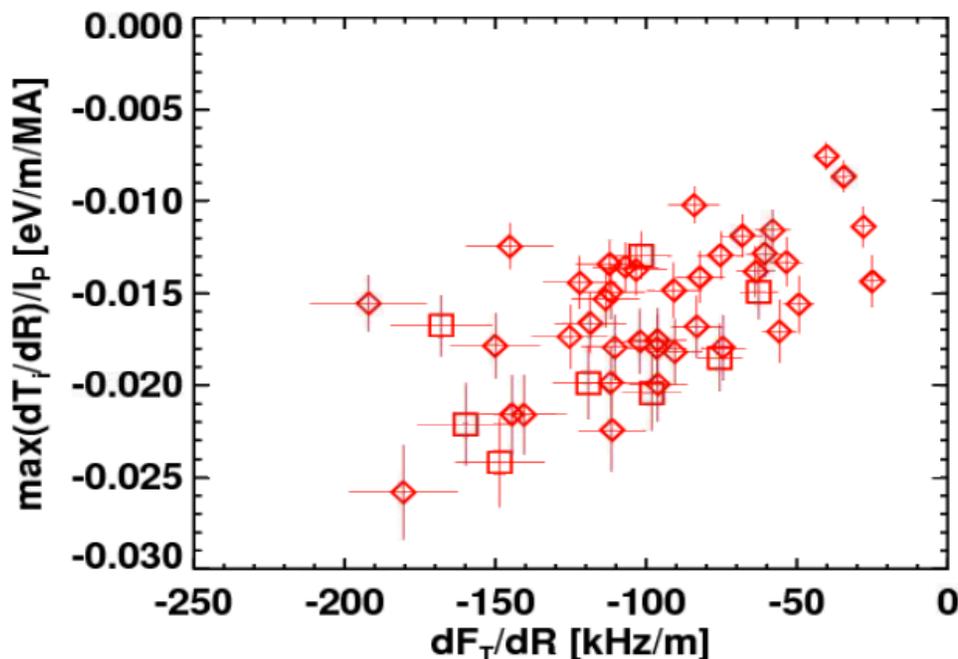
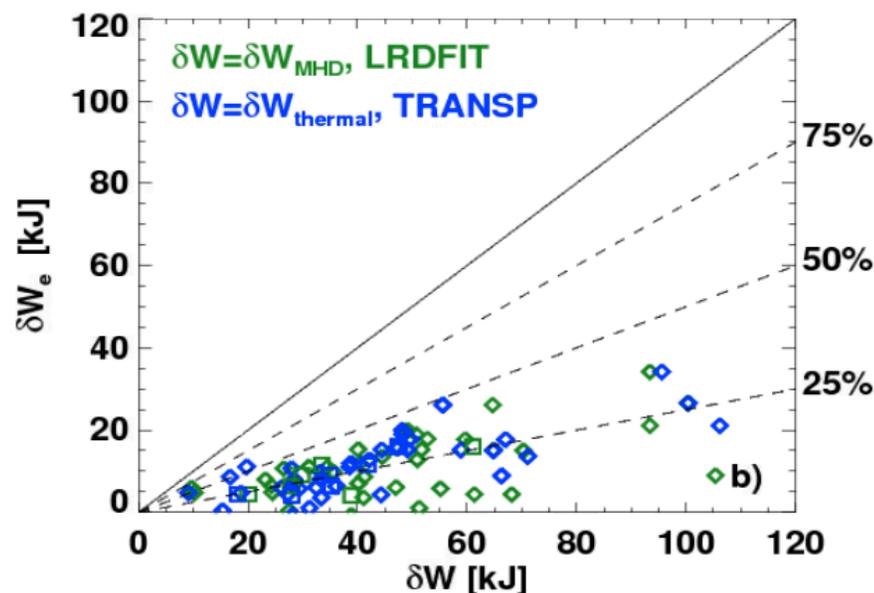
# Most of the Energy Increment in EP H-mode is Contained in the Ions

- Compare electron and ion energy increases following the EP H-mode transition
  - ~75% of the stored energy increase is in the ion channel.
- Maximum temperature gradient scales with the rotation gradient.
  - Speculate: rotation shear is quenching the residual ion-scale turbulence?

Ion Energy Increment vs. Total Energy Increment

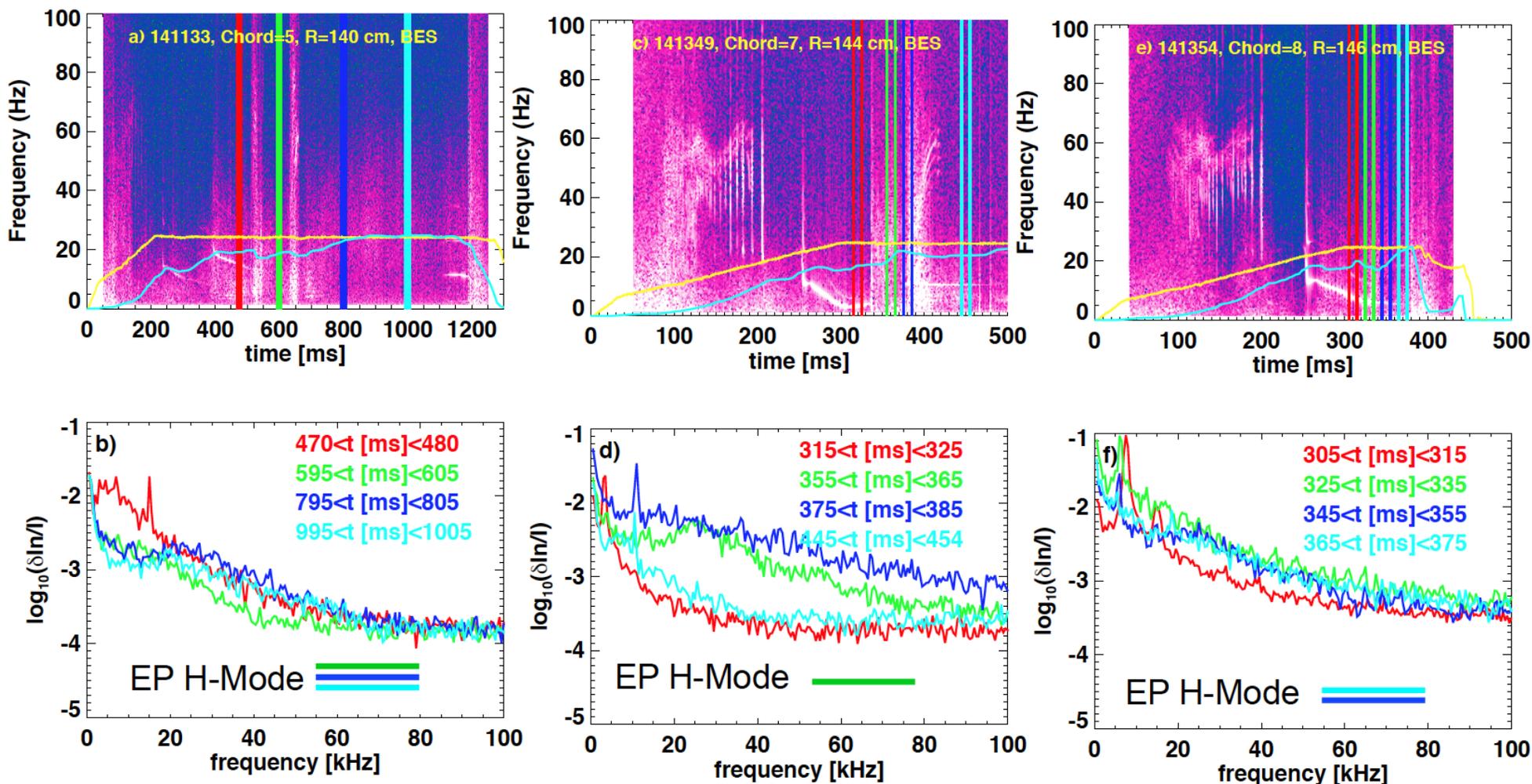


Electron Energy Increment vs. Total Energy Increment



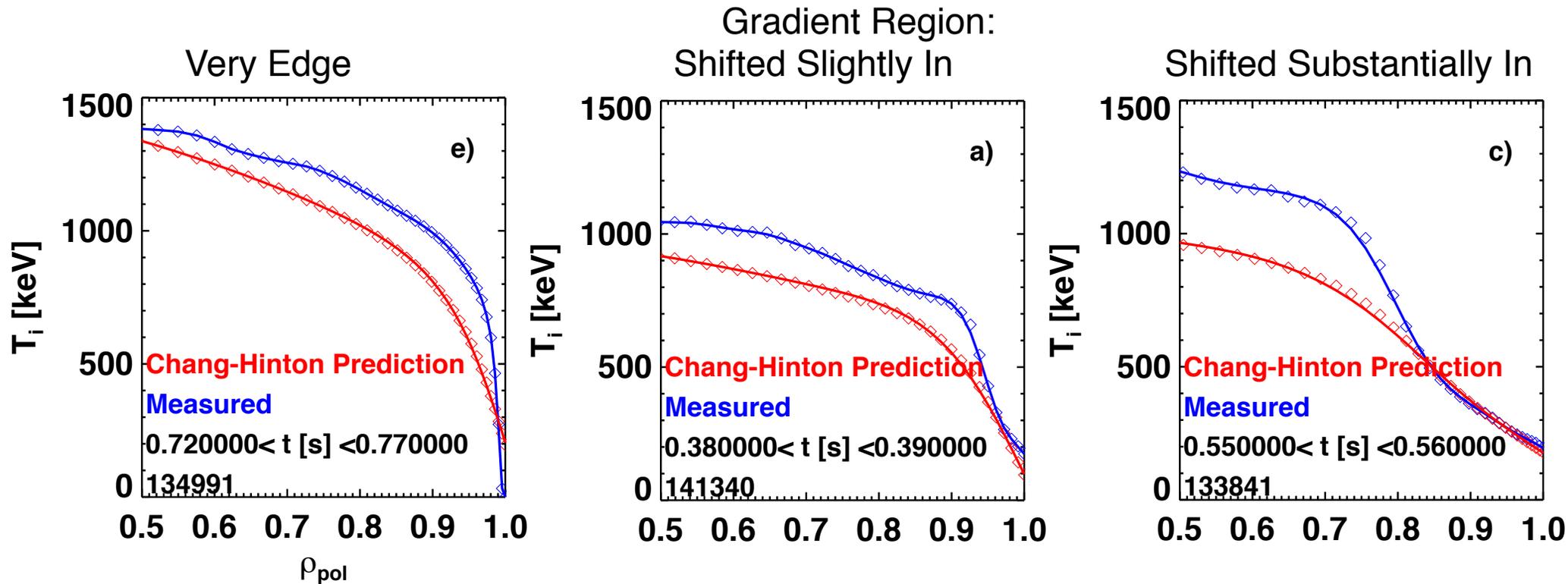
# Measured Density Fluctuation Amplitude Does Not Decrease Following the EP H-mode Transition

- Density fluctuations measured with Beam Emission Spectroscopy (BES) channel in the steep  $T_i$  gradient region



# Simple Neoclassical Transport Calculation Under-predicts $T_i$ Gradient in the Steep Gradient Region in EP H-mode

- Method
  - Use measured profiles of  $T_e$ ,  $n_e$ ,  $n_C$ ,  $n_D$ ,  $V_\Phi$
  - Use the Chang-Hinton model within TRANSP to predict the  $T_i$  profile

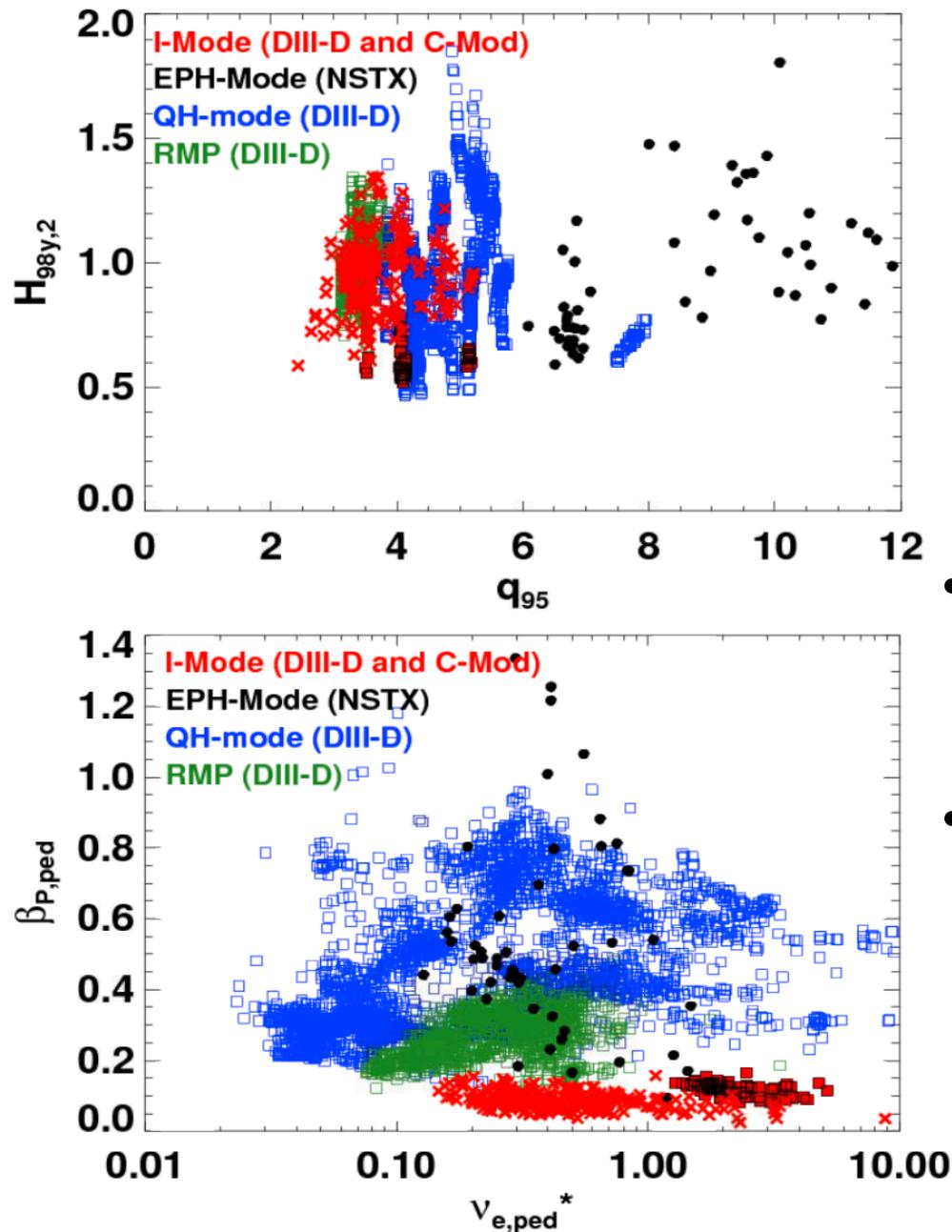


- $T_i$  (and its gradient) is underestimated in all three cases.
- Working on repeating this comparison with full neoclassical physics using XGC-0

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- **Regime comparisons and answers to the five broad questions**

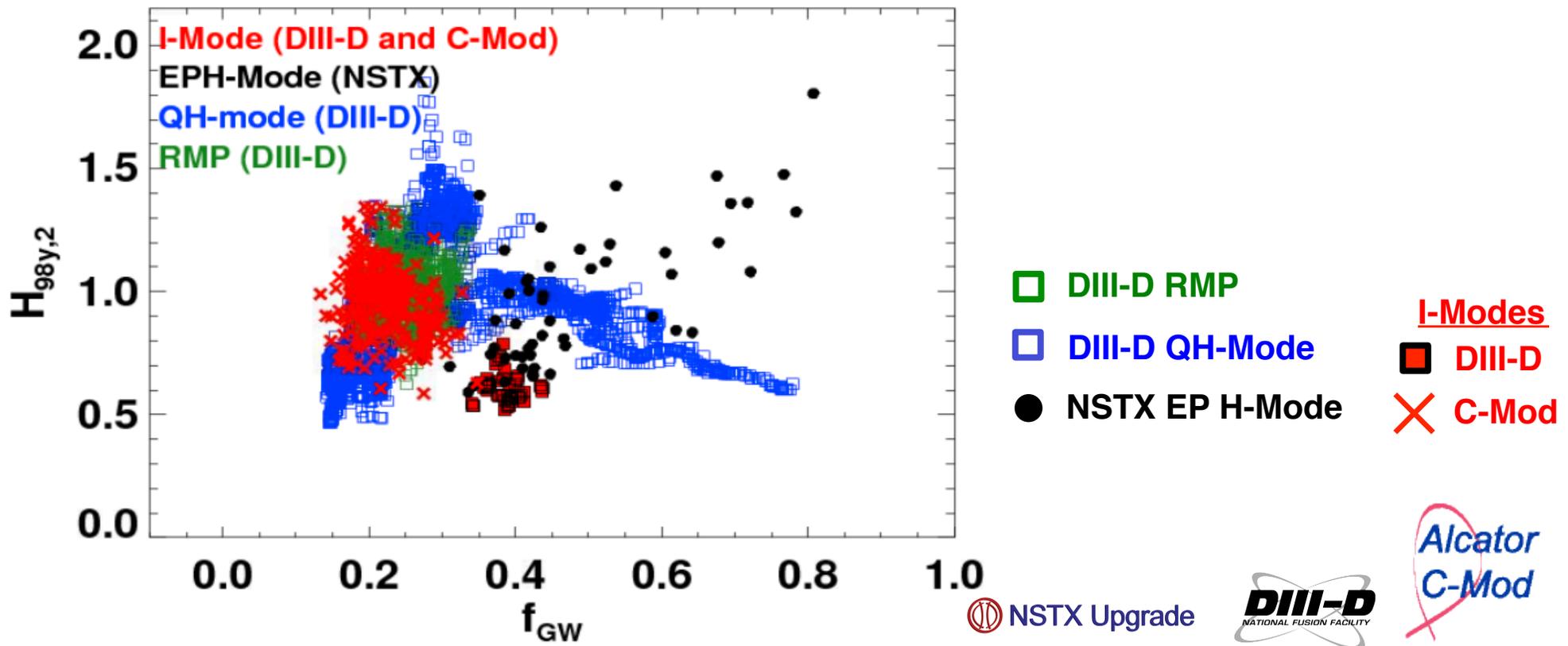
# All Regimes Under Consideration Have Shown Good Confinement and Access to Low Collisionality



- Representative but incomplete data sets shown.
  - Symbols for machines and colors for regimes:
- |   |   |
|---|---|
| <span style="color: green;">□</span> DIII-D RMP     | <span style="color: red;">□</span> I-Modes  |
| <span style="color: blue;">□</span> DIII-D QH-Mode  | <span style="color: black;">■</span> DIII-D |
| <span style="color: black;">●</span> NSTX EP H-Mode | <span style="color: red;">×</span> C-Mod    |
- RMP, QH-mode, and C-Mod I-mode have achieved  $H_{98(y,2)} \sim 1$  at ITER-relevant  $q_{95}$
  - All regimes have demonstrated compatibility with low-collisionality pedestals
    - Unlike type-V ELMs (NSTX), EDA H-mode (C-Mod)

# There has been Success at Raising the Density in These Regimes

- QH-mode densities up to  $f_{GW}=0.8$ 
  - Facilitated by strong shaping, used strong ramps and were not optimized
- C-Mod I-modes at  $f_{GW}=0.35$ 
  - Is  $2 \times 10^{14} \text{ cm}^{-3}$  in absolute units, so still quite high
- NSTX EP H-mode cases have high confinement at high  $f_{GW}$



# Present Results Have Answered Many of the Original Questions (I)

- Q1: Can these regimes be understood in terms of the peeling-ballooning & KBM models?
  - I-modes far from both the kink/peeling and KBM boundaries
    - Provides room for performance extension
  - DIII-D QH-modes near the peeling boundary
    - EPED does a good job of predicting the pedestal parameters
  - DIII-D RMP pedestals are just beneath the EPED predictions during ELM suppression
- Q2: Can these regimes be achieved at high(er) density?
  - Densification of QH-mode possible for strongly shaped plasmas
    - Consistent with stability theory
  - Densification following the transition to I-mode is possible
    - And provides part of the recipe for optimizing the I-mode regime

# Present Results Have Answered Many of the Original Questions (II)

- Q3: Can they provide the required particle and impurity transport in future tokamak systems?
  - I-mode: Impurity transport at L-mode levels, correlation found between WCM amplitude and particle transport
  - QH-mode: EHO can flush impurities better than ELMs
  - While a working physics hypothesis exists for the origin of the EHO, gyrokinetic modeling is ongoing in order to understand the WCM
- Q4: Access with ITER relevant parameters and constraints?
  - All the regimes have demonstrated compatibility with low collisionality
  - I-mode demonstrated with both no external torque (C-Mod) and co-injection (DIII-D)
    - With graphite and Mo PFCs.
  - QH-mode operated at ITER relevant  $q_{95}$  and fusion gain parameters
    - Increasing density, error field correction may be powerful tools to allow operation at simultaneous ITER torque and  $q_{95}$
  - Successful RMP ELM suppression with less than the full set of coils:
    - Harmonic sidebands serve to mitigate loss of the primary spectral component

# Present Results Have Answered Many of the Original Questions (III)

- Q5: Can we understand and control regimes with edge thermal confinement much better than H-mode?
  - Long-duration EP H-mode examples have been documented
  - Rotation shear appears to play a role in determining the confinement in EP H-mode
    - and in VH-mode
  - Turbulence (or at least density fluctuations) appear comparable in EP H-mode and H-mode
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***Thanks for your attention!***