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

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TTF Meeting
San Antonio
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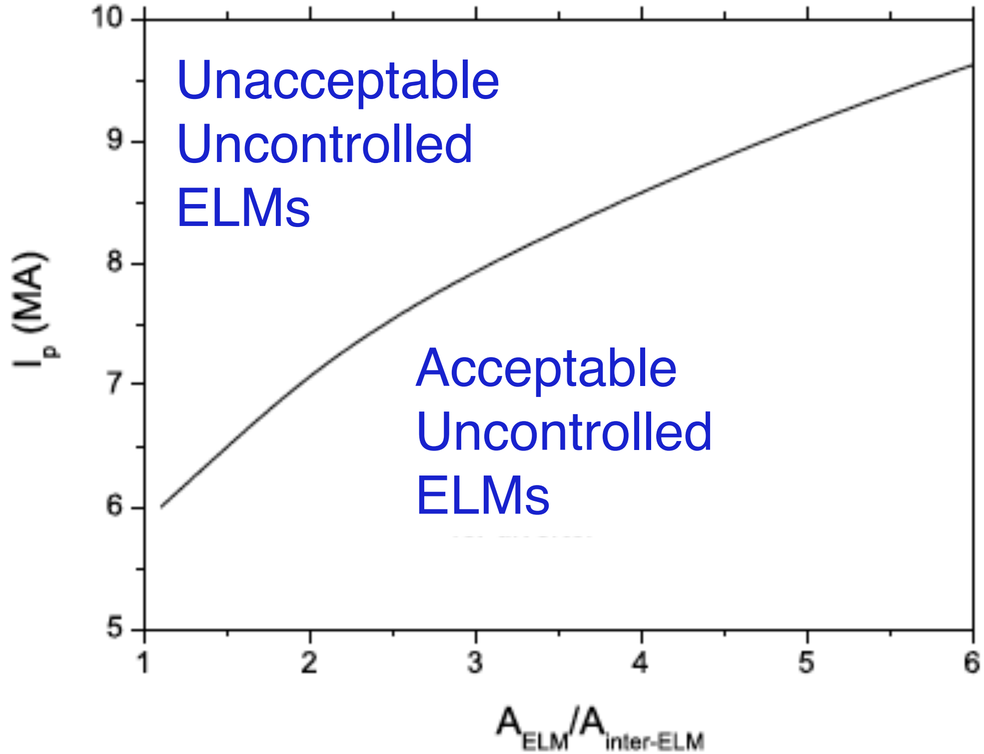
ITER Needs To Operate Without Uncontrolled Type-I ELMs

- 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

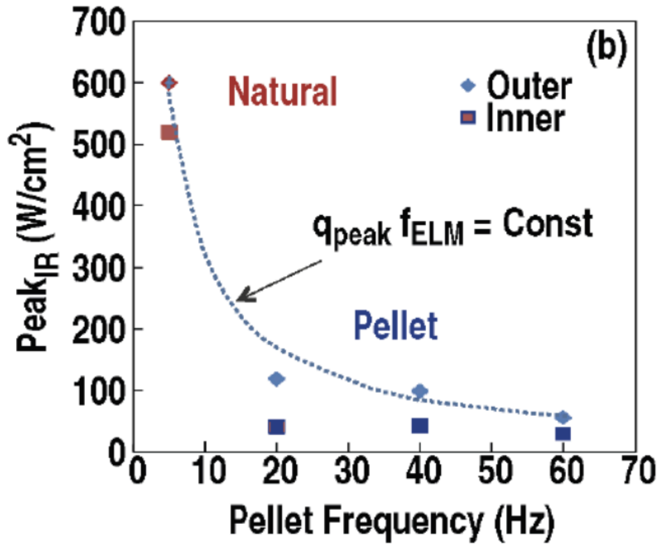


*A. Loarte, NF **54**, 033007 (2014)*

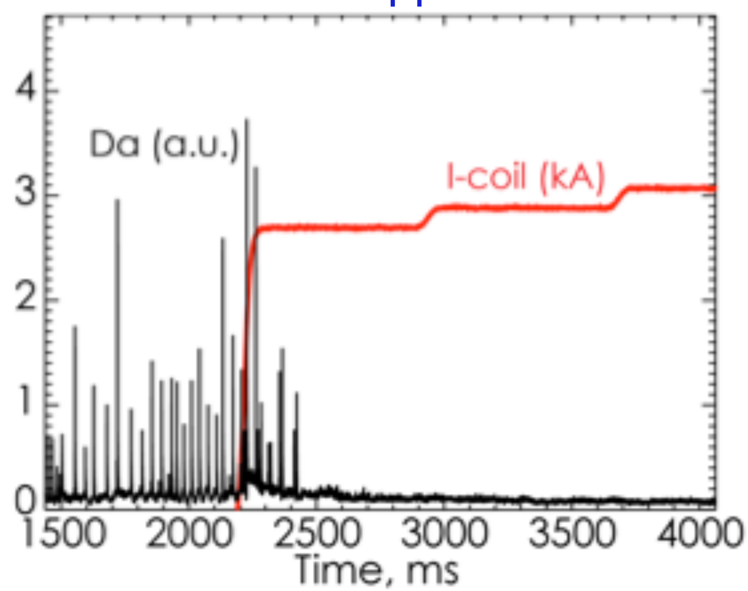
Numerous Strategies Are Under Development for Managing ELMs in ITER

- Achieve rapid ELMs via pacing techniques.
  - Pellet pacing most prominent example…
    - …but also vertical jogs
  - Relies on the peak heat flux to decrease as ~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



*L. Baylor, PRL **110** (2013), D. Orlov, APS Invited 2013*

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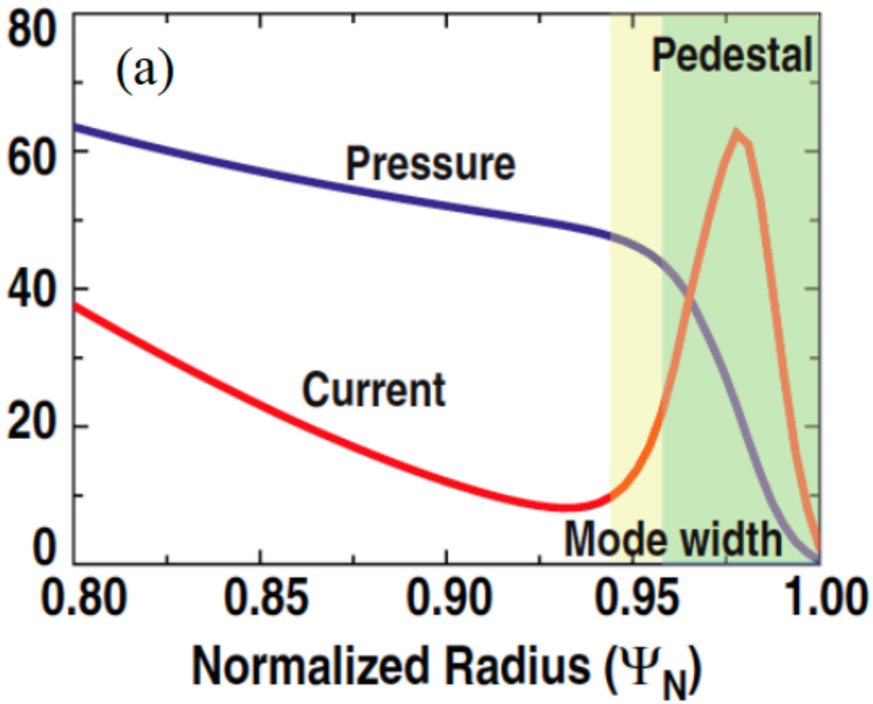
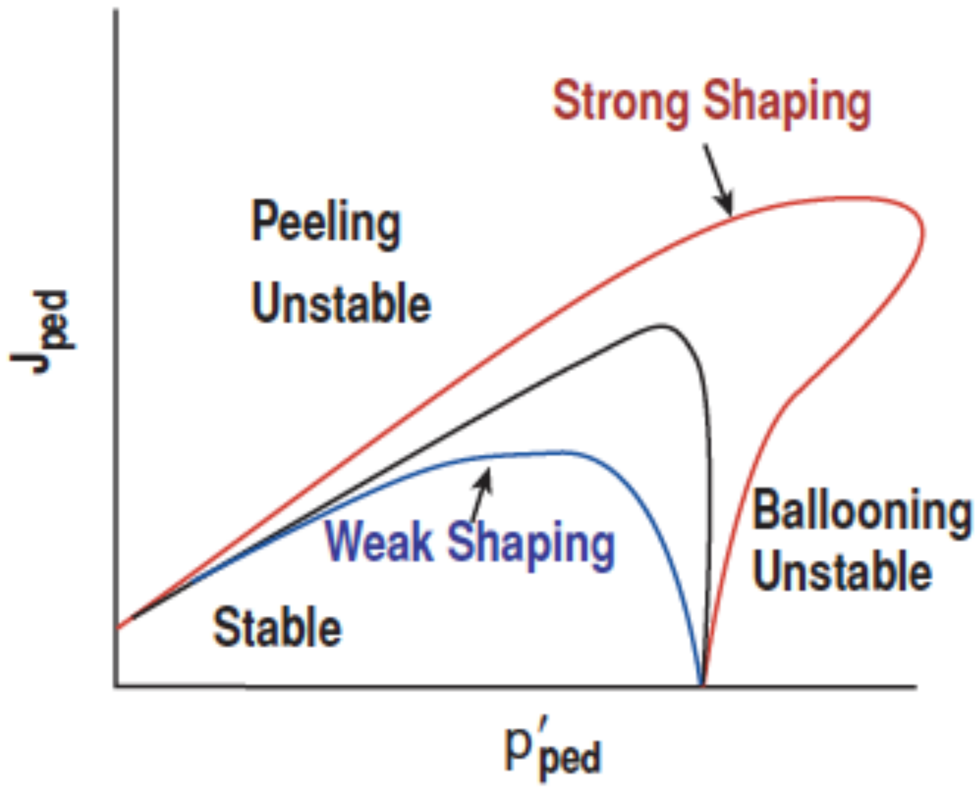
Type-I ELM Dynamics Often Understood In Terms of Peeling-Ballooning Stability

- 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 $\beta_{ped} \sim \Delta^{3/4}$



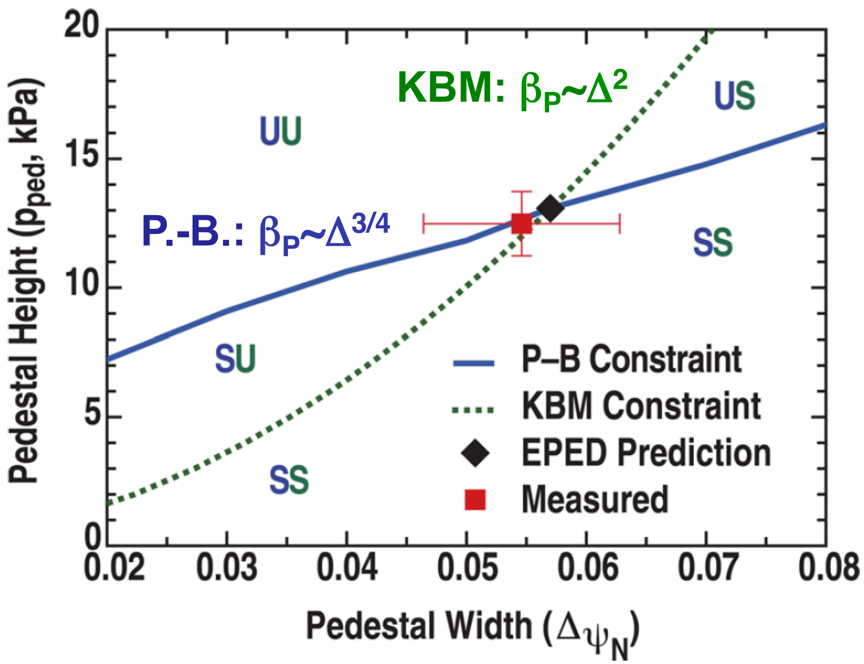
*P. Snyder, Nuclear Fusion **51** 1 (2011)*



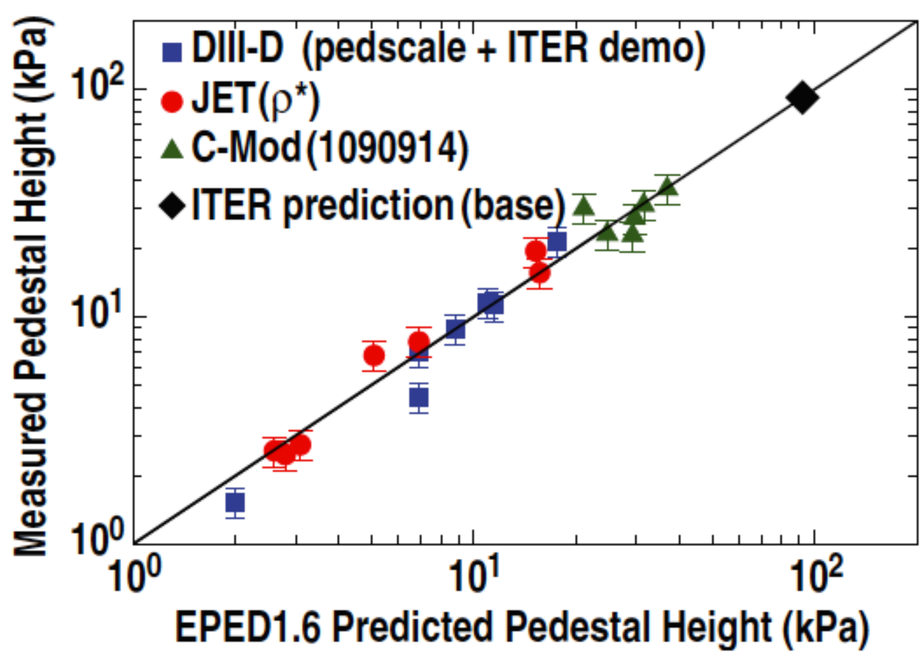
*P. Snyder, PPCF **46** A131 (2004)*

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 (KBMs)
  - 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 β



*P. B Snyder, PoP **19** 056115 (2012)*



*P. B Snyder, NF **51** 103016 (2011)*

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- Regimes with continuous edge fluctuations
  - Quiescent H-mode
  - The I-Mode Regime
- Recent research on RMP H-mode
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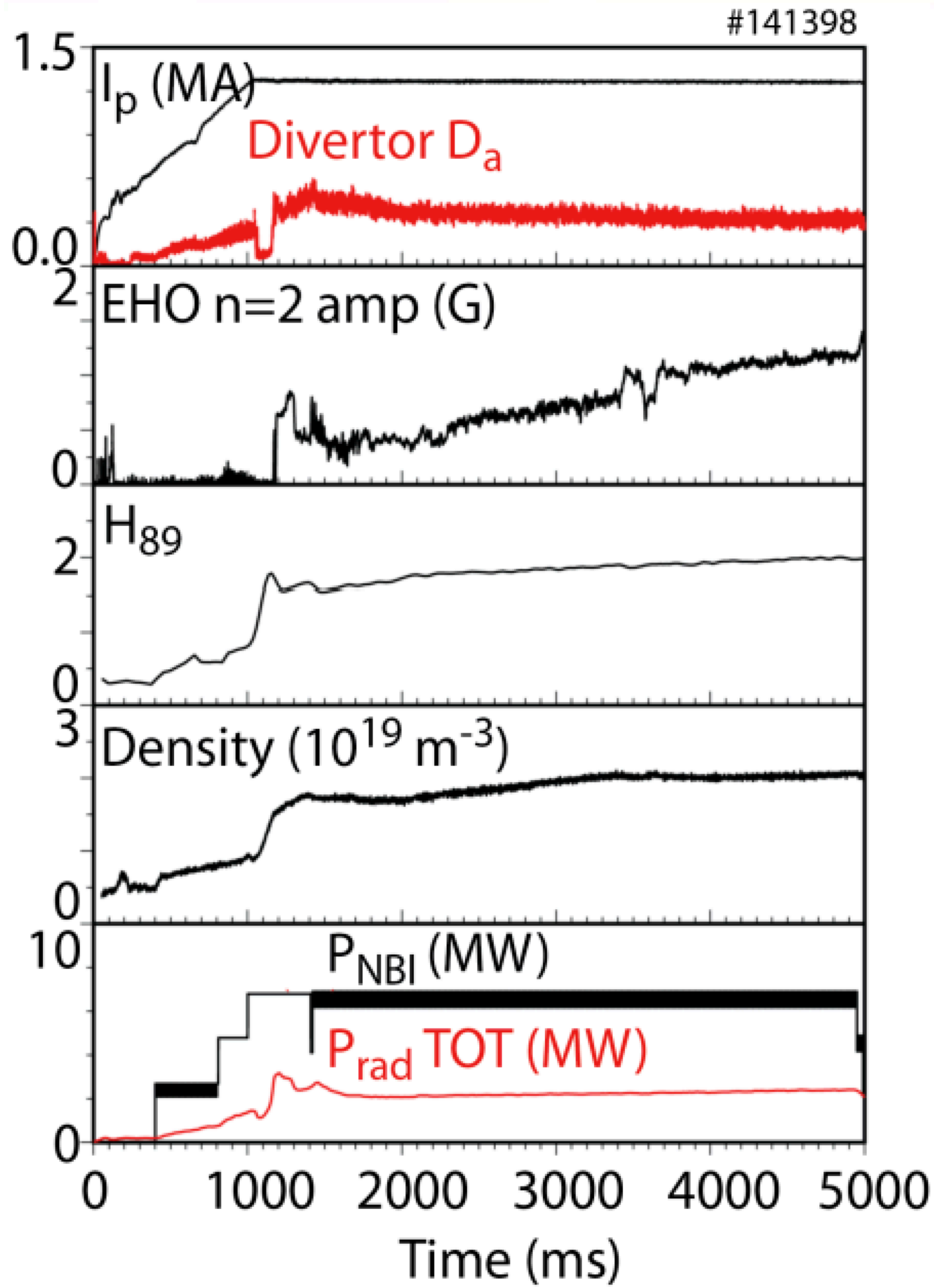
The Quiescent H-Mode Provides Particle Control Through an Edge Fluctuation Called the Edge Harmonic Oscillation

- 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



W. Solomon, et al, APS-DPP 2013

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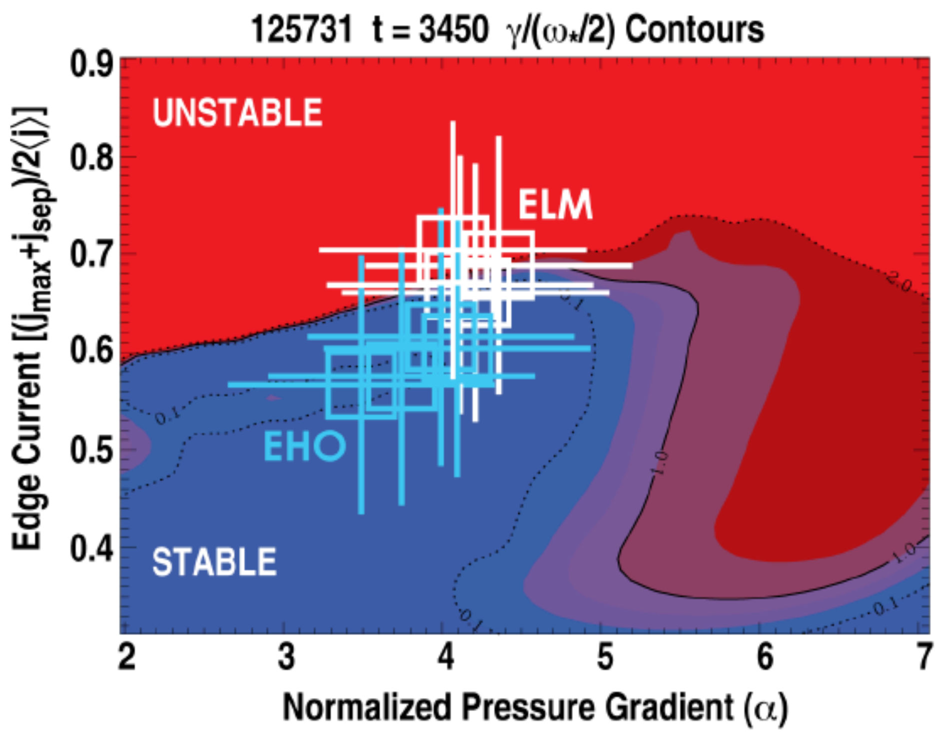
- QH-mode operates on the peeling boundary
  - EHO is thought to be a saturated peeling mode



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

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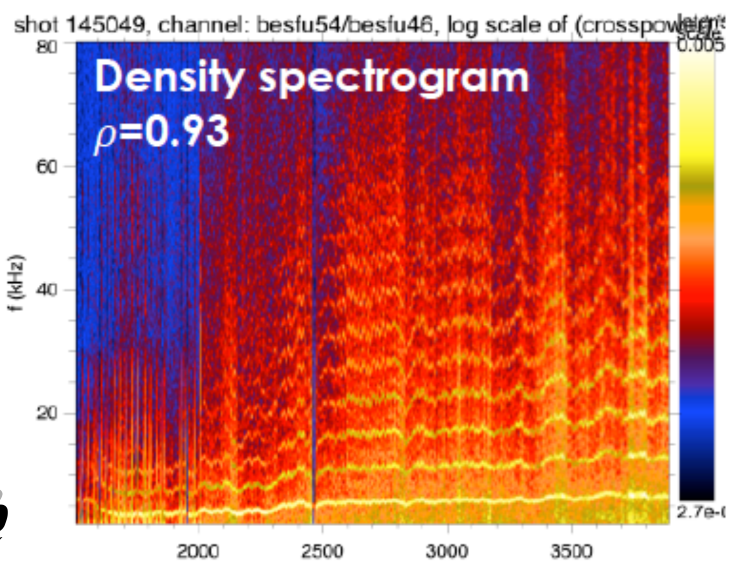
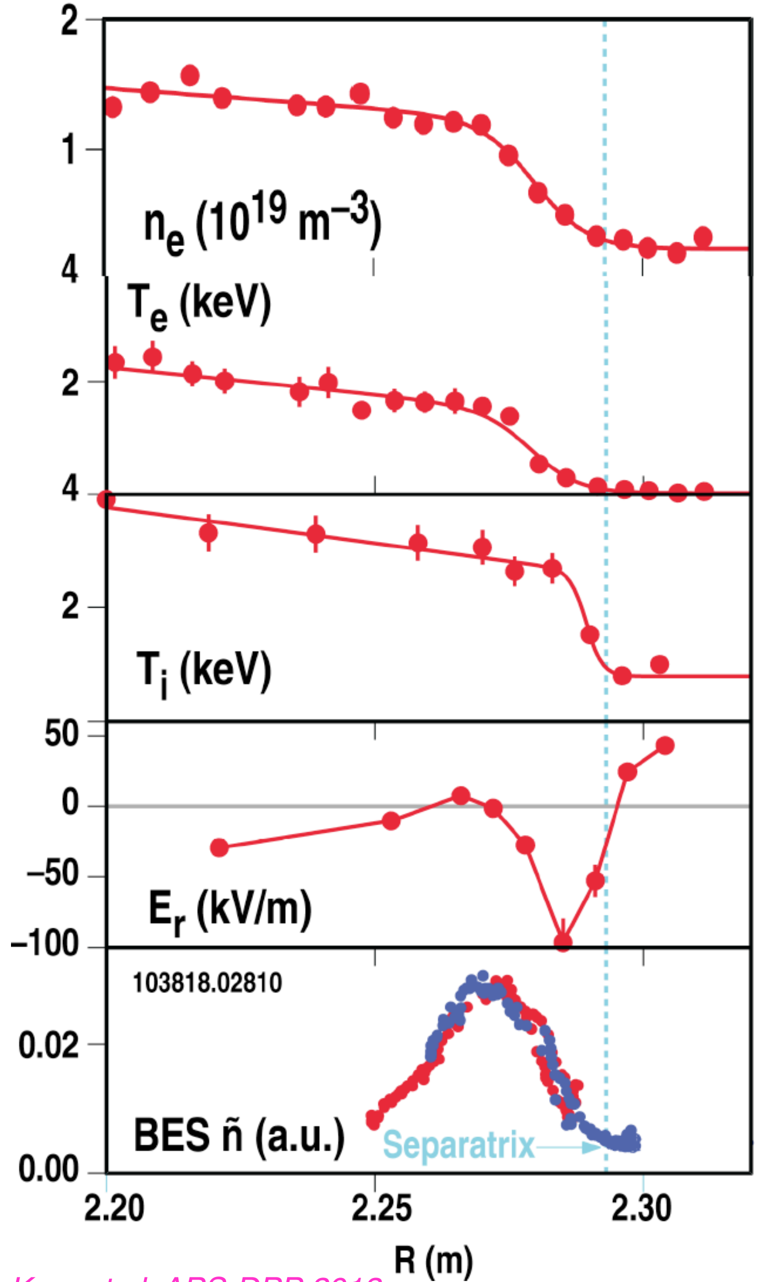
  - EHO is thought to be a saturated peeling mode
- EHO spans the width of the pedestal.
  - Many harmonics visible with BES



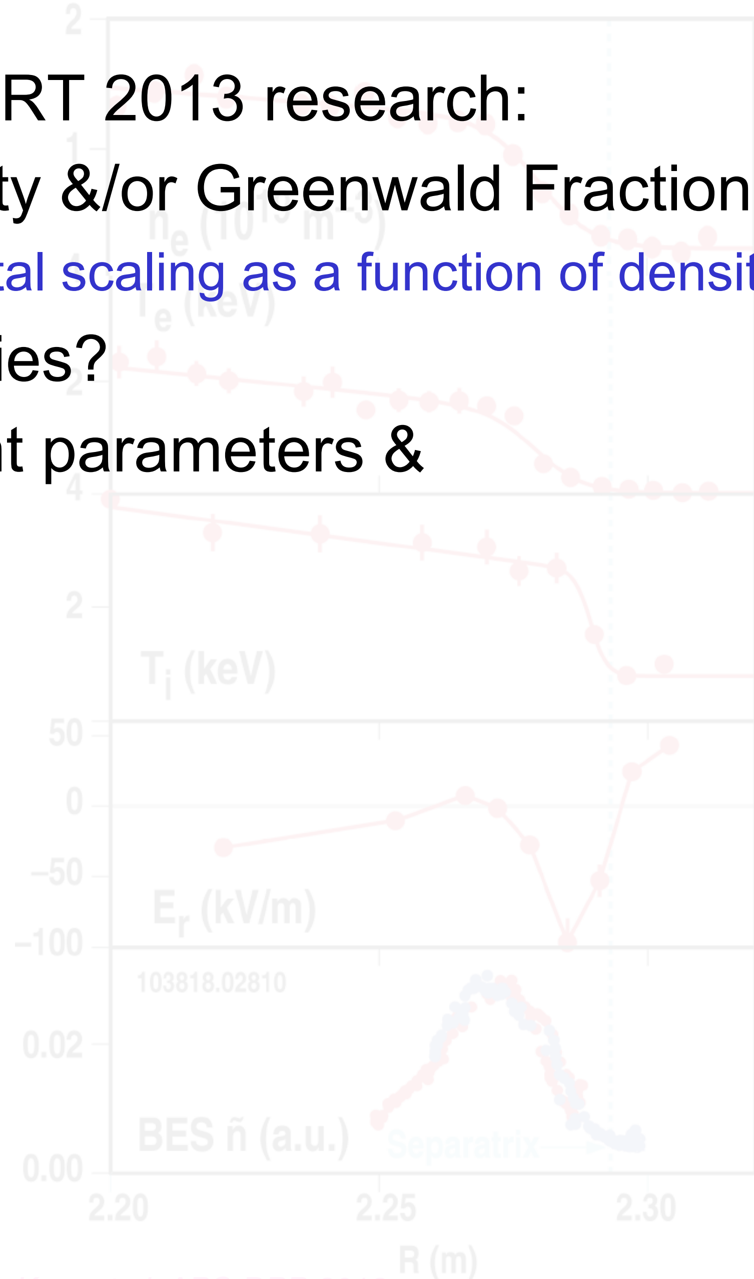


G. McKee, et al, APS-DPP 2013

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

Key questions addressed in JRT 2013 research:

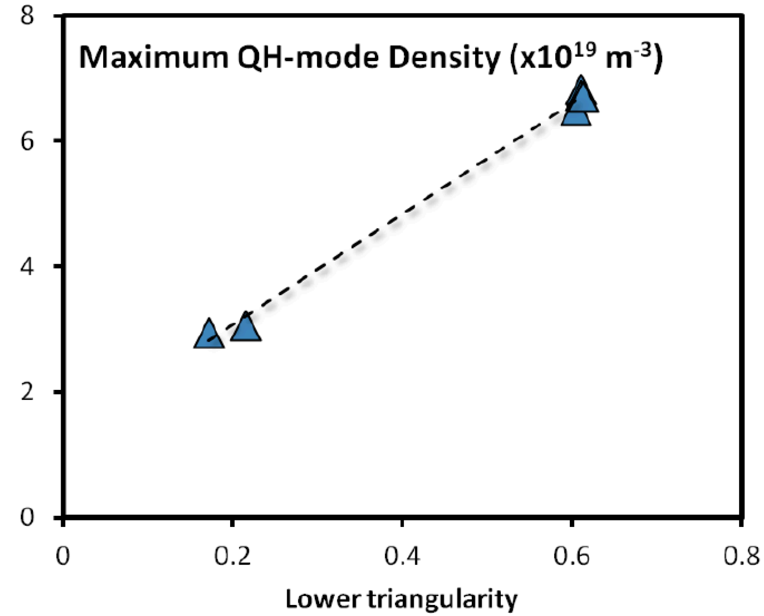
- Is QH mode accessible at high density &/or Greenwald Fraction?
  - How well does EPED capture the pedestal scaling as a function of density?
- How well does the EHO flush impurities?
- Can it be achieved with ITER relevant parameters & performance?

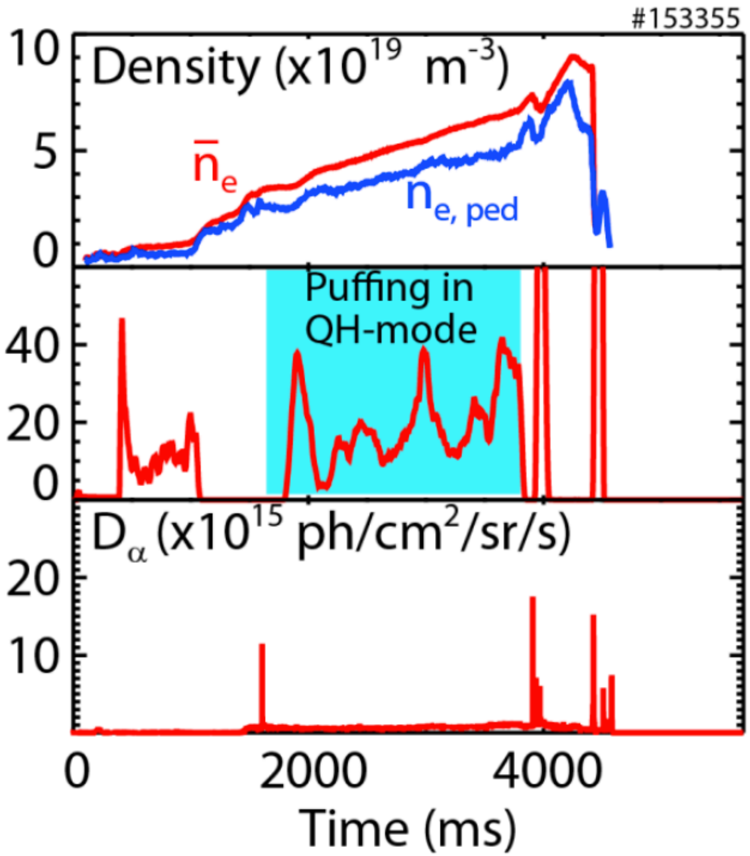


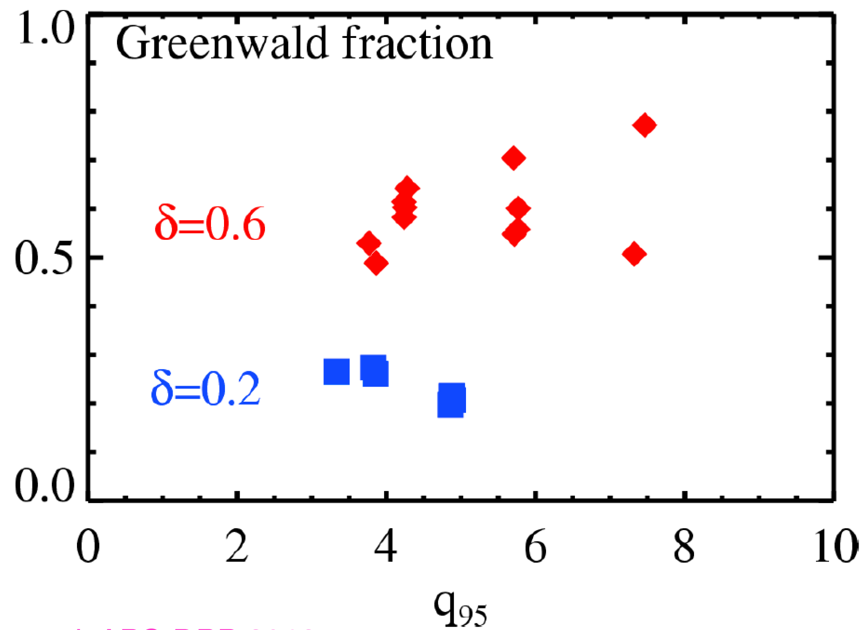
G. McKee, et al, APS-DPP 2013

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





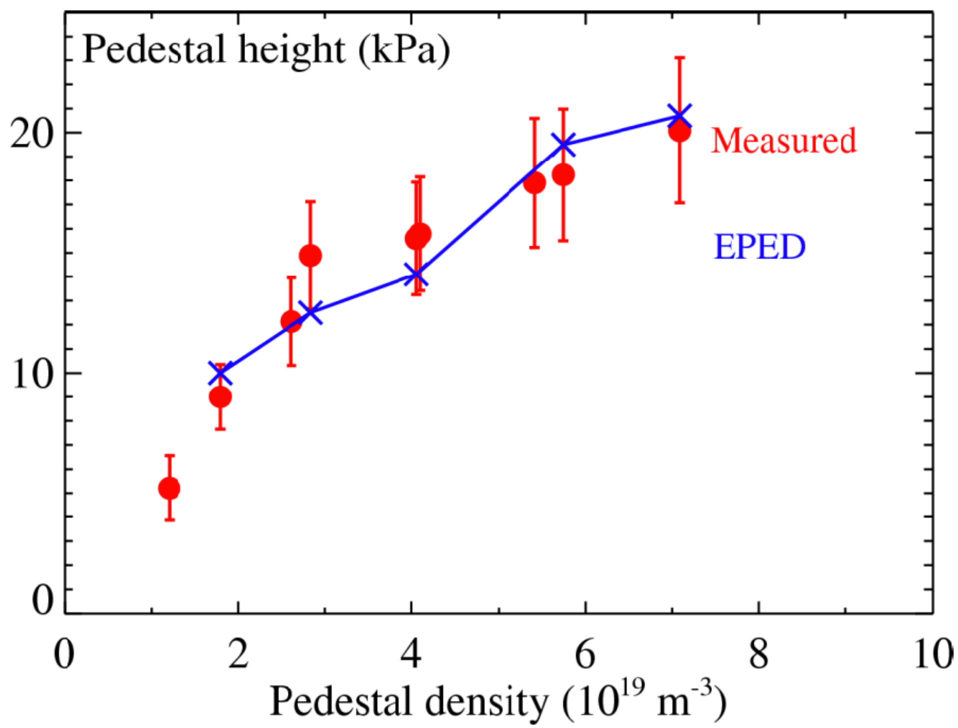


W. Solomon, et al, APS-DPP 2013

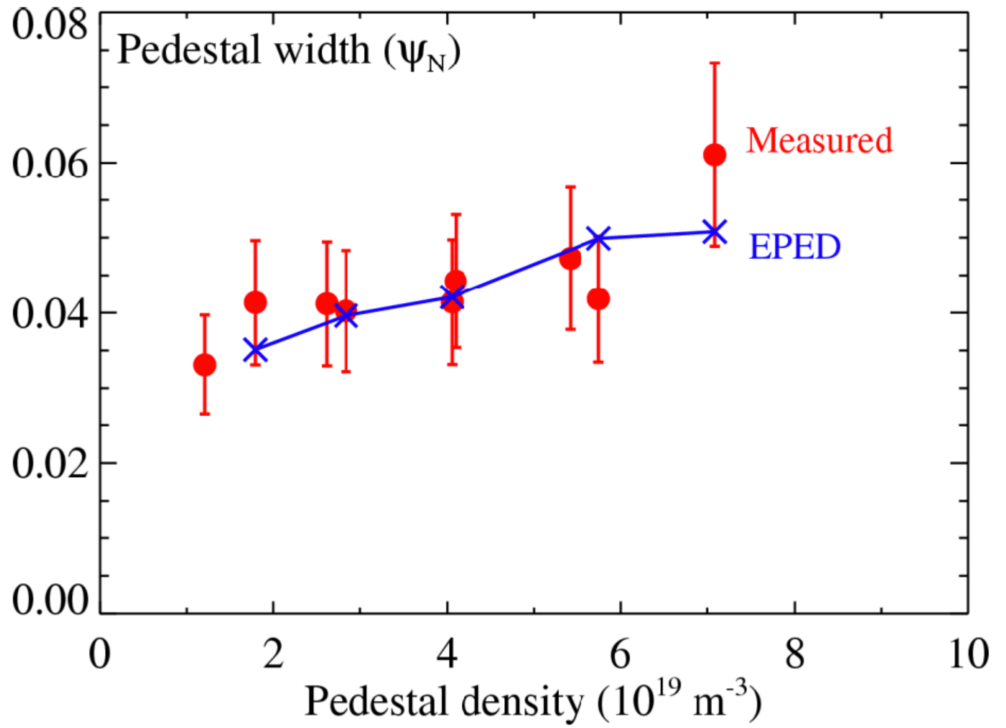
EPED Modeling Can Reproduce the Pedestal Trends in QH-Mode as a Function of Density

- 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

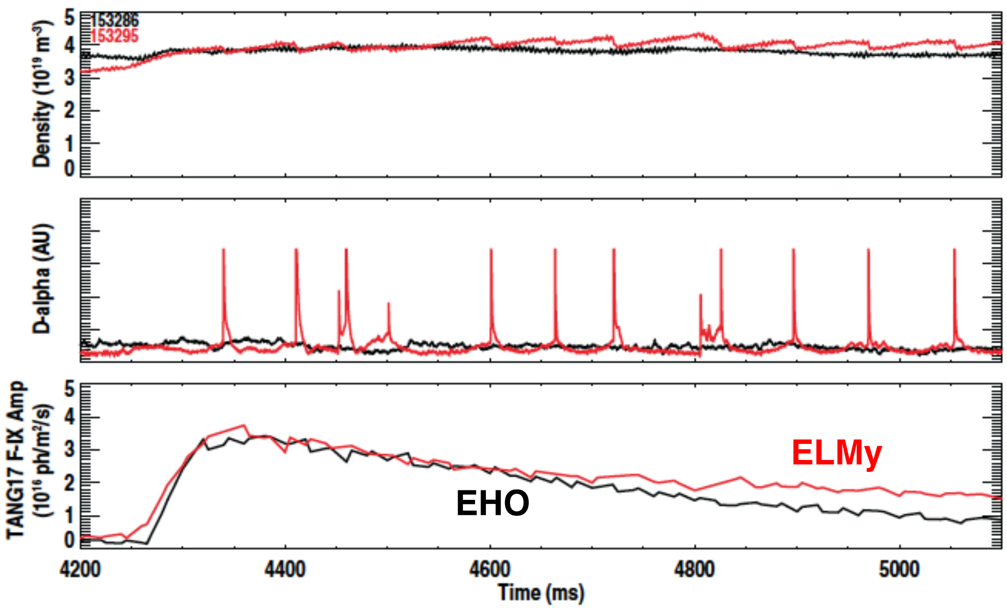


W. Solomon, et al, APS-DPP 2013

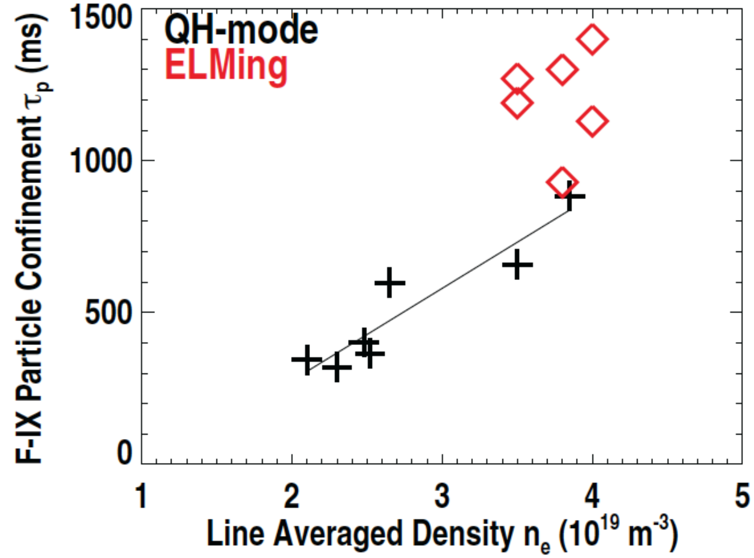
The EHO Can Exhaust Impurities Just as Well as Type 1 ELMs

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

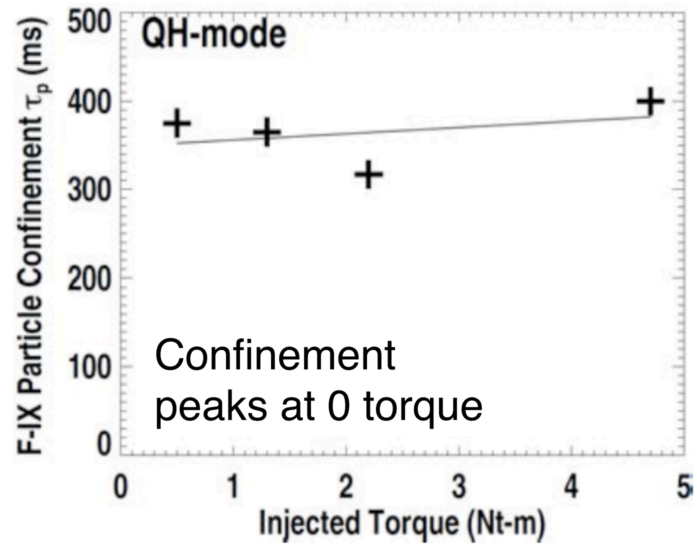
Impurity Confinement in QH-Mode vs. ELMing H-Mode



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

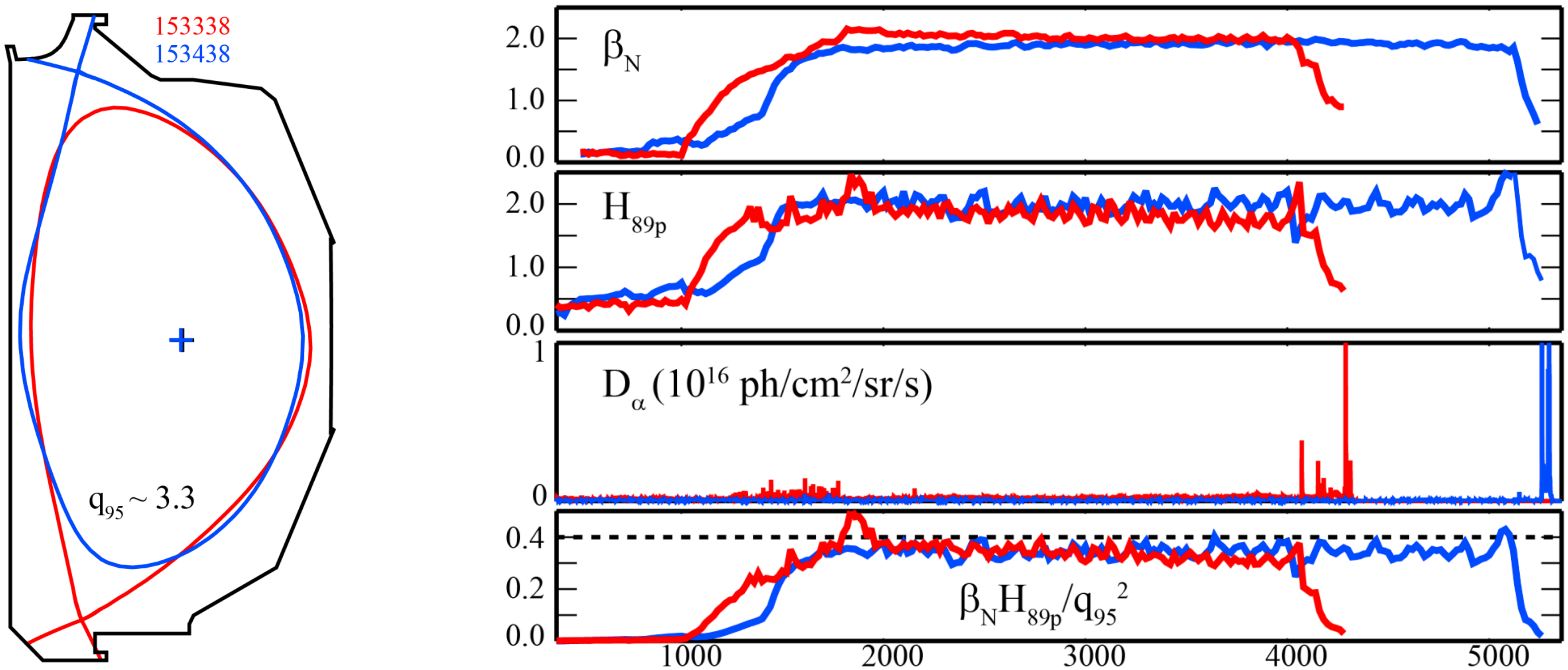


QH-Mode impurity confinement independent of torque



B.A. Grierson, et al., submitted to Nuclear Fusion

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

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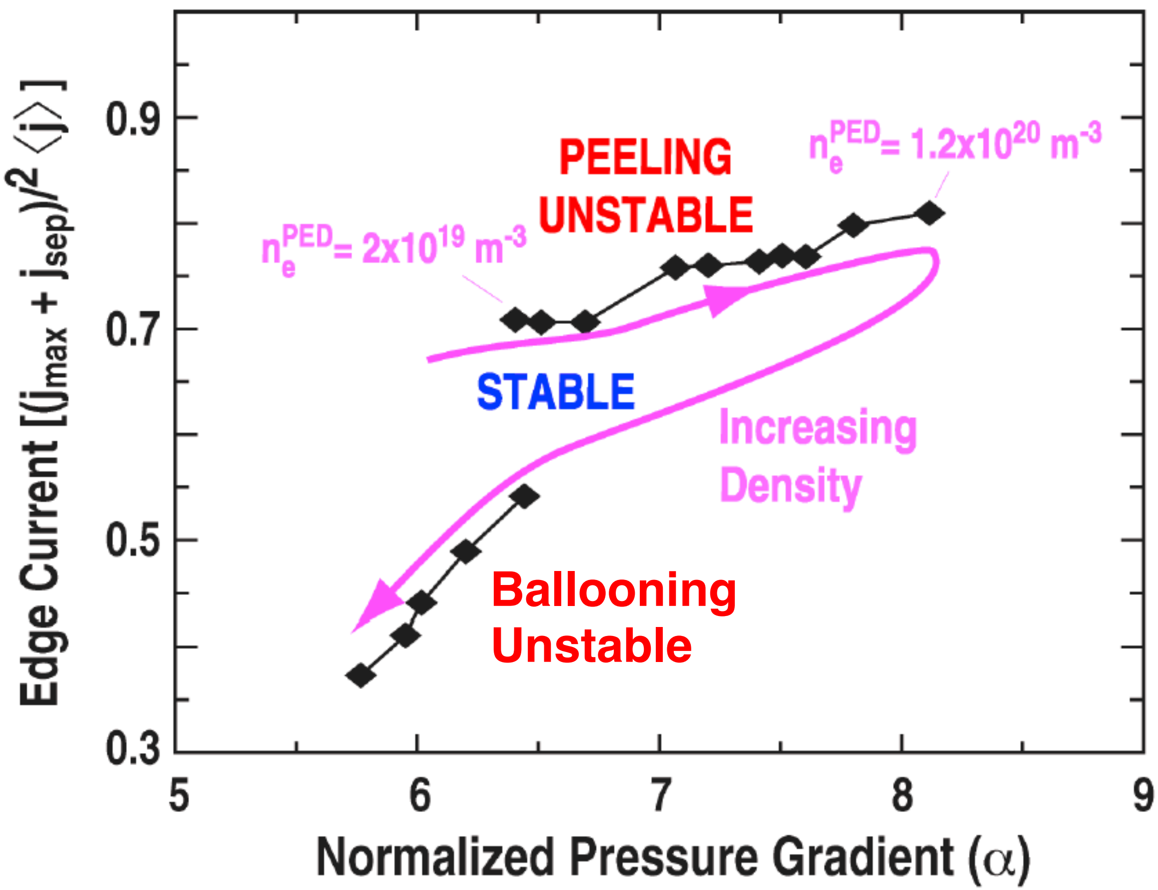
W. Solomon, et al, APS-DPP 2013

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 1.2×10^{20} m^{-3}

- ITER's pedestal will be in the collisionality and density range for QH-mode operation



Burrell et al, Phys Plasmas, 19, 056117 (2012)

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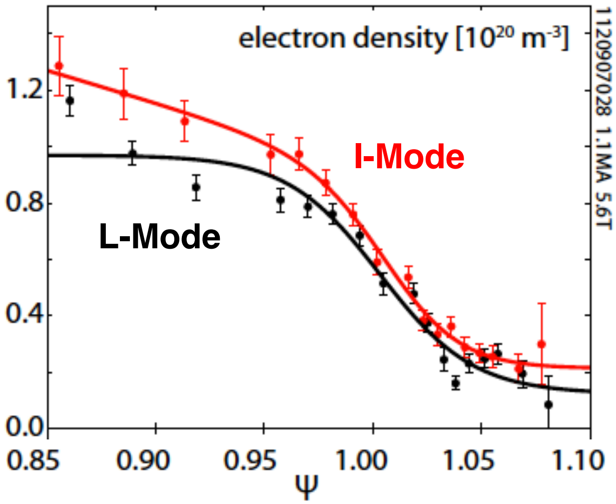
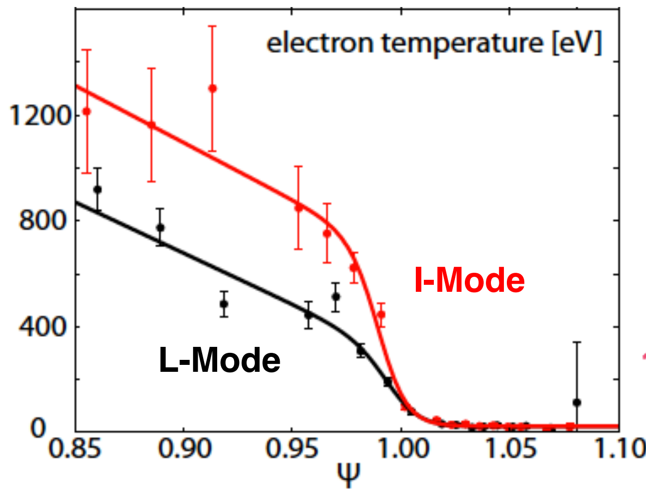
The C-MOD I-Mode Regime Combines an H-mode Temperature Profile w/ an L-mode Density Profile

Similar Density Profiles in L- and I-modes.



J. Walk, APS 2013

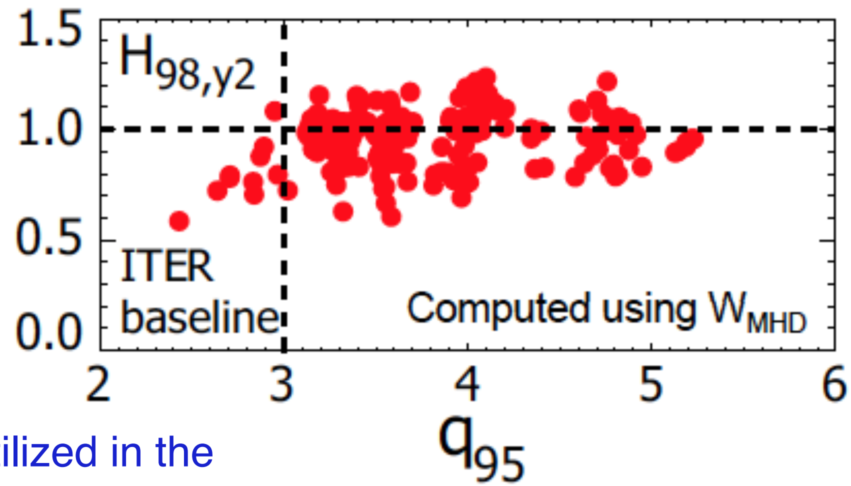
Higher T_e in I-mode, with Formation of Edge Pedestal

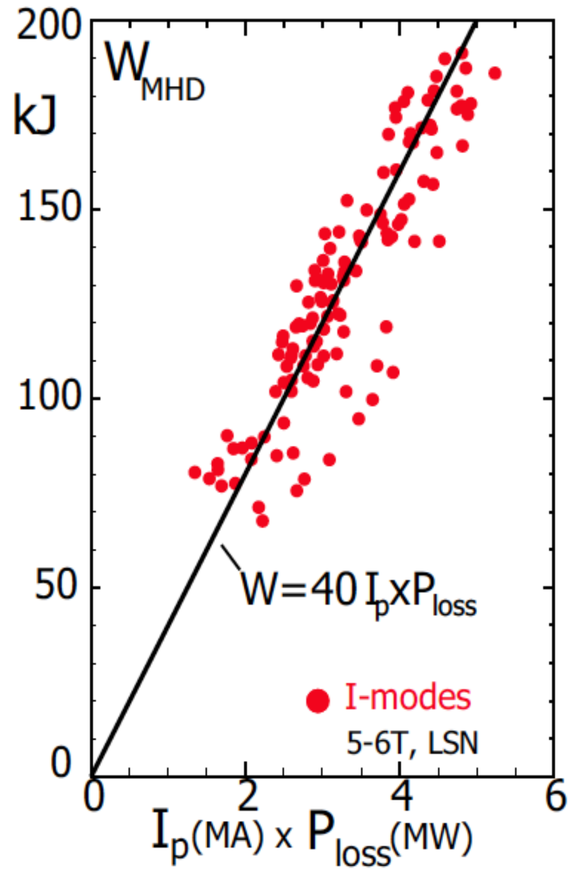


- I-mode exhibits minimal/no power degradation
  - In contrast to $\tau_{98} \sim I_P P^{-0.7}$ (or $W \sim I_P P^{0.3}$)

A. Hubbard, et al., 2012 FEC

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

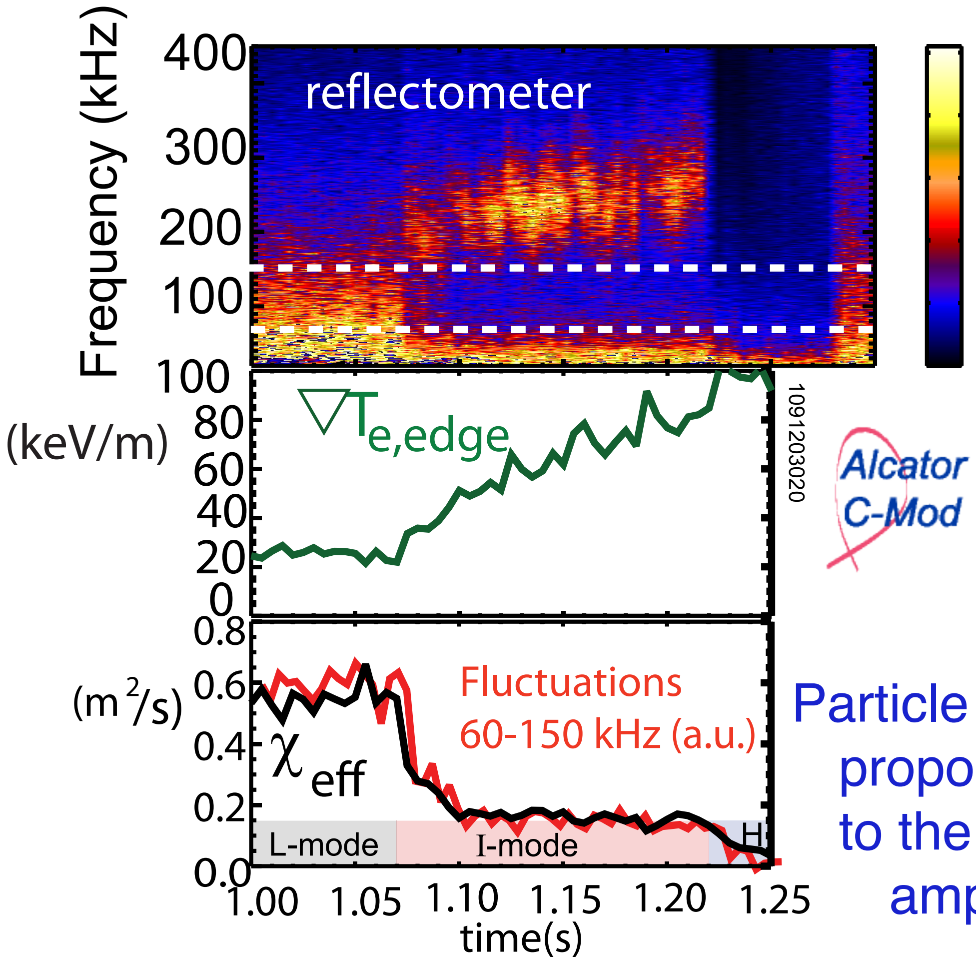




Note: the scaling exponents utilized in the ITER-98(y,2) scaling expression do not capture the I-mode dependencies

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

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



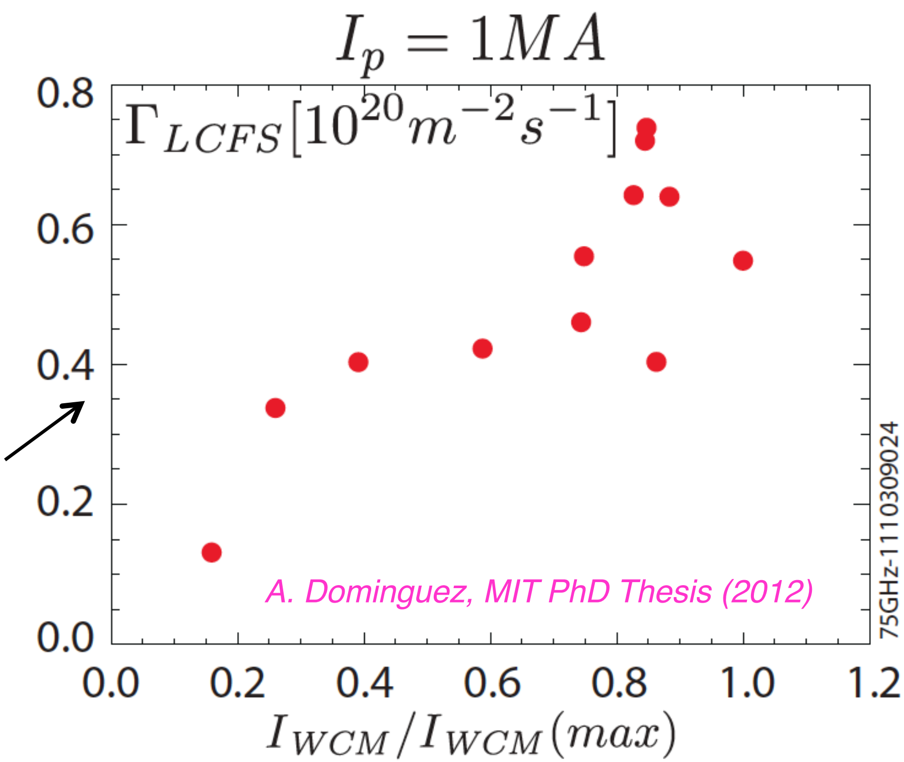
$\chi_{i,eff}$ evaluated for $0.95 < \psi_N < 1.0$

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

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

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

Particle flux is proportional to the WCM amplitude



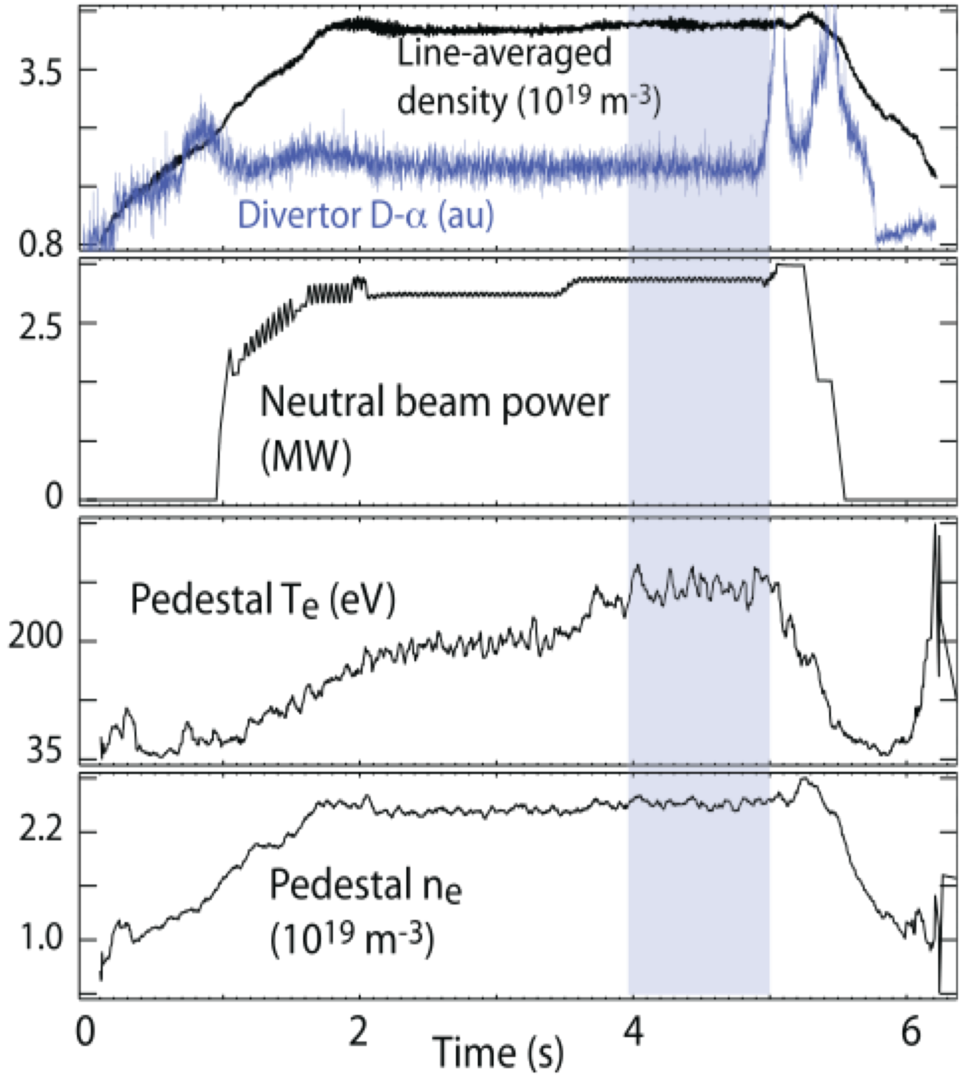
Weakly Coherent Mode Provides Density Control in C-MOD I-Modes

Questions Addressed by Recent Research

- 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?

I-Modes Have Been Found in DIII-D

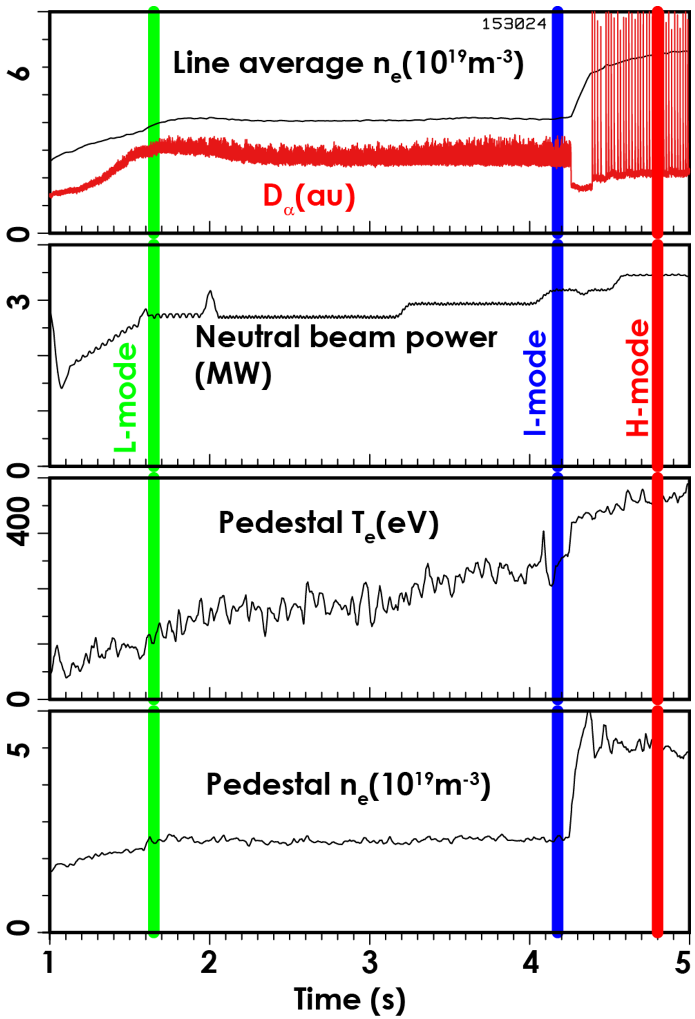
- Experiments with power ramps in configuration with unfavorable grad-B drift direction.
  - Increased power required to access H-mode, helps open the I-mode access window.



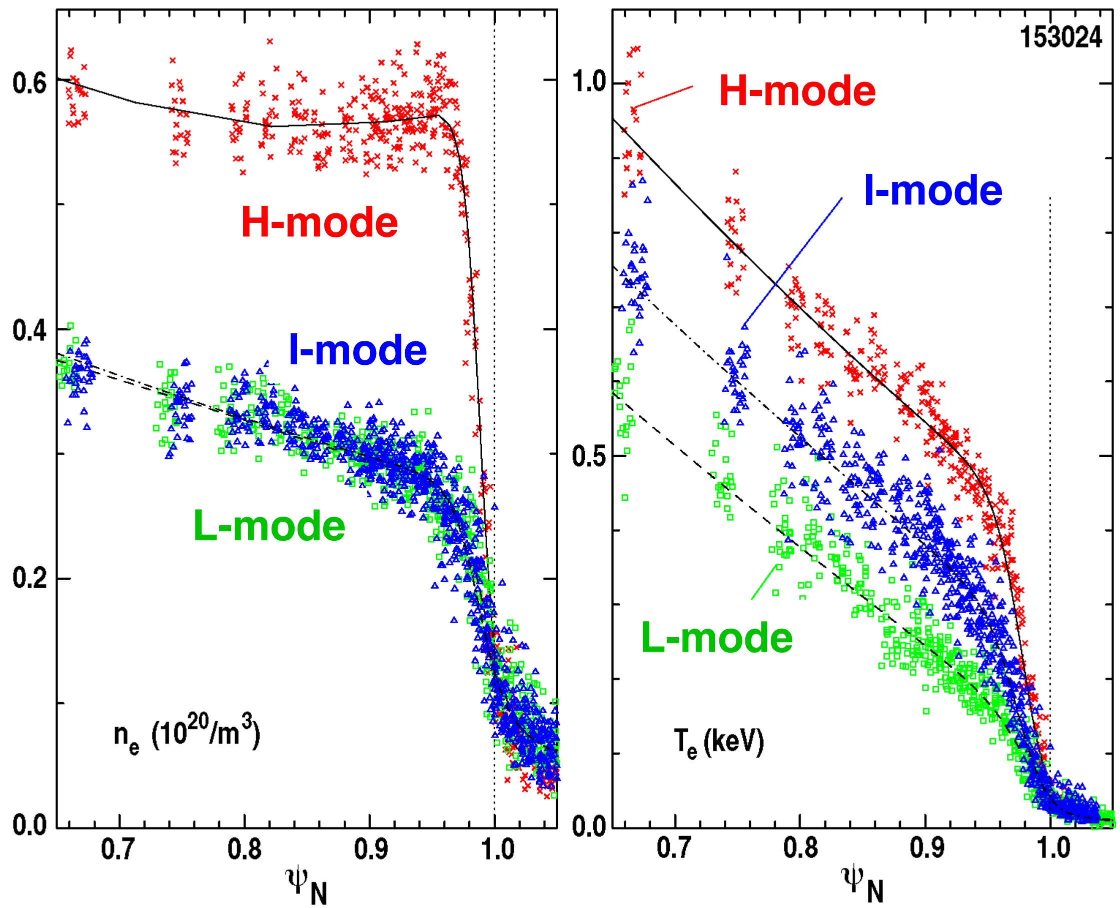
Temperature increases by a larger fraction than the heating power

JRT 2013 Report

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

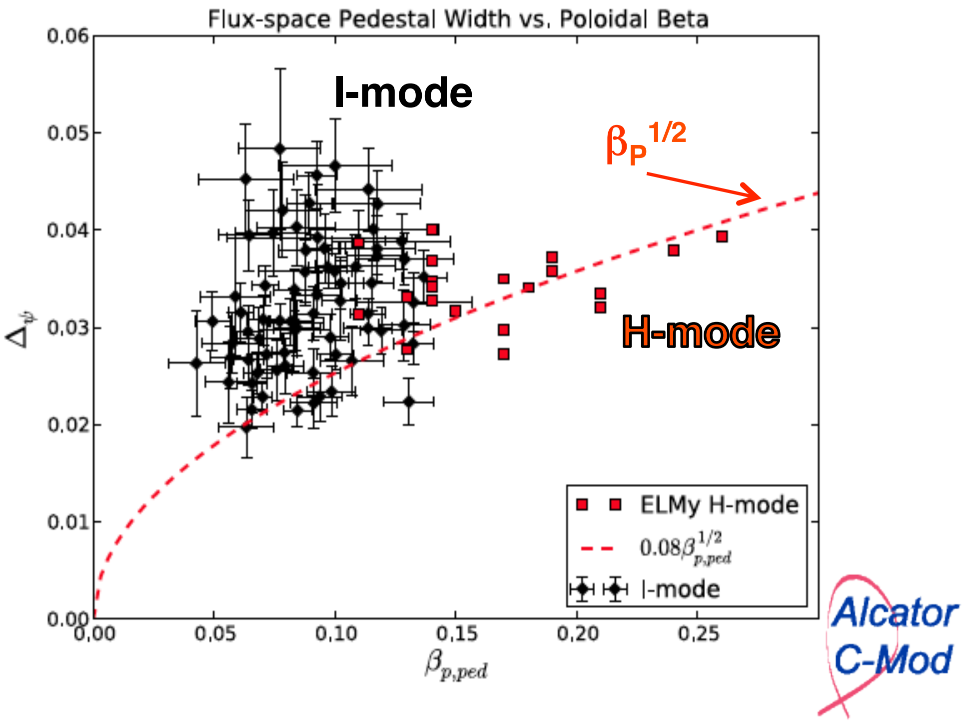


JRT 2013 Report

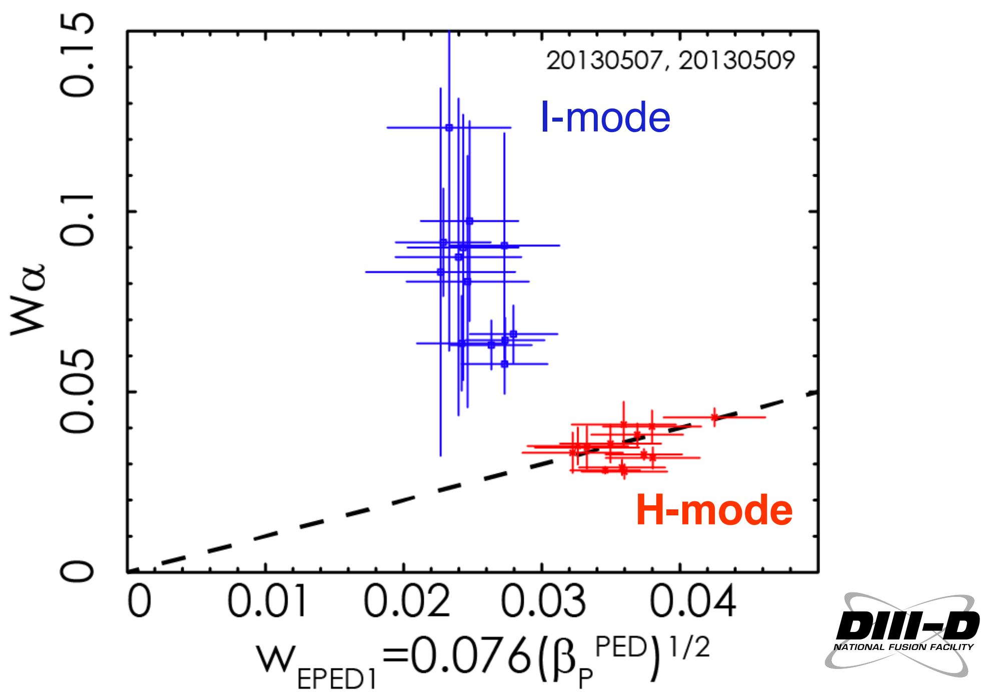
Pedestal Widths are Typically Broader than in H-Mode

- 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. β_P



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



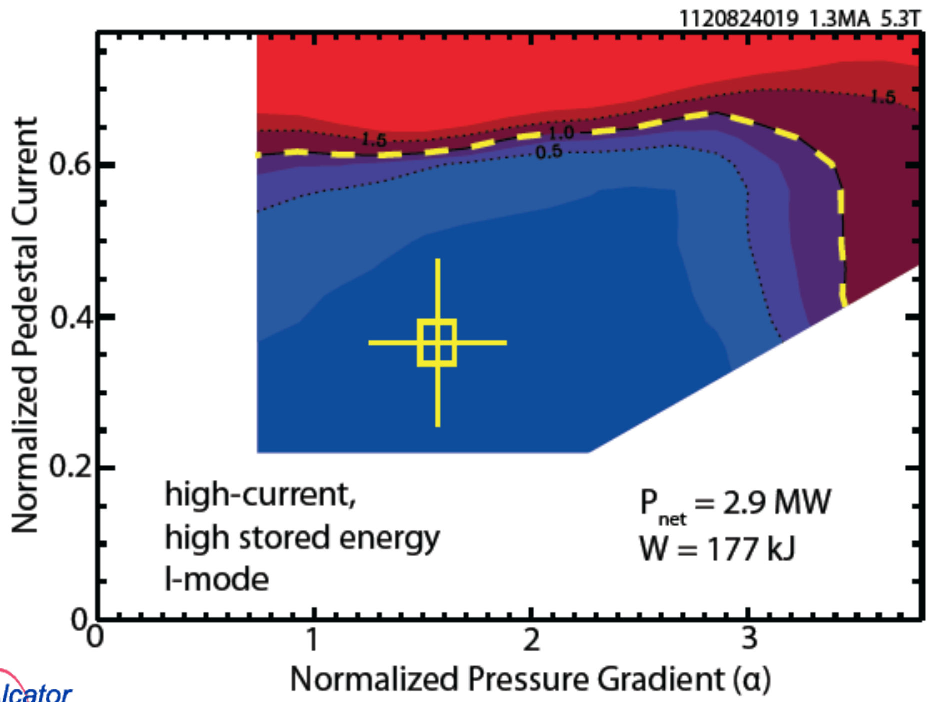
J. Walk, APS 2013

T. Osborne

I-Mode Pedestal Gradients Are Consistently Found To Be Beneath Pedestal Macrostability Limits

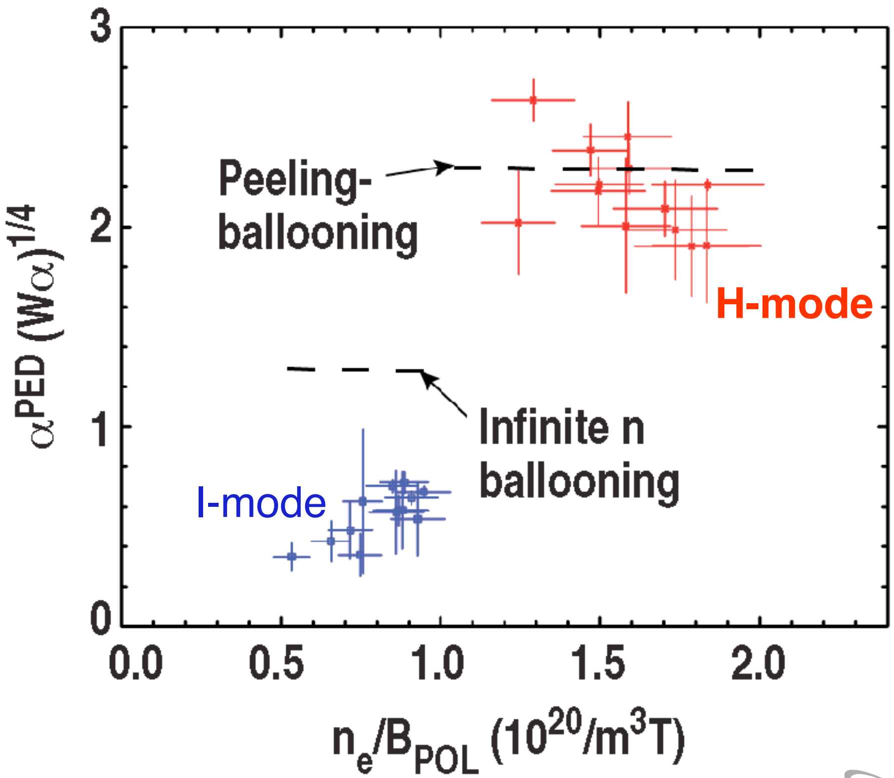
C-MOD

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



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.

J. Walk, APS 2013

T. Osborne

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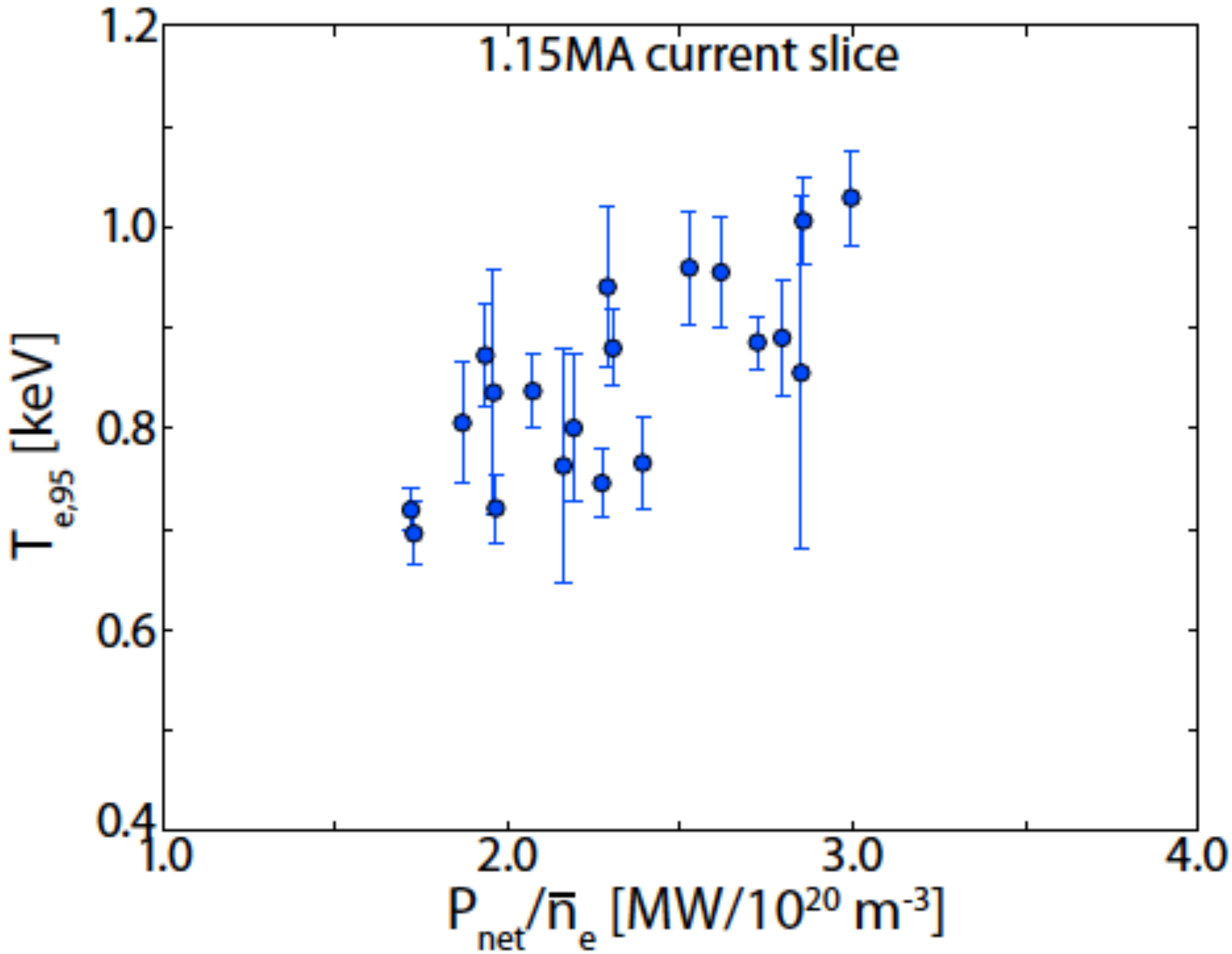
Recent Analysis of C-MOD Data Shows a Potential Path to I-Mode Performance Optimization

J. Walk, APS 2013, PoP 2014

- Power/particle sets the pedestal temperature
  - Pedestal pressure ~ P_{net}
- I-modes plasma can be “densified” following the L->I transition
- Pedestal pr
  - Fueling ca … sufficient power is a
  - Adjust the … es



Alcator C-Mod

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

J. Walk, APS 2013, PoP 2014

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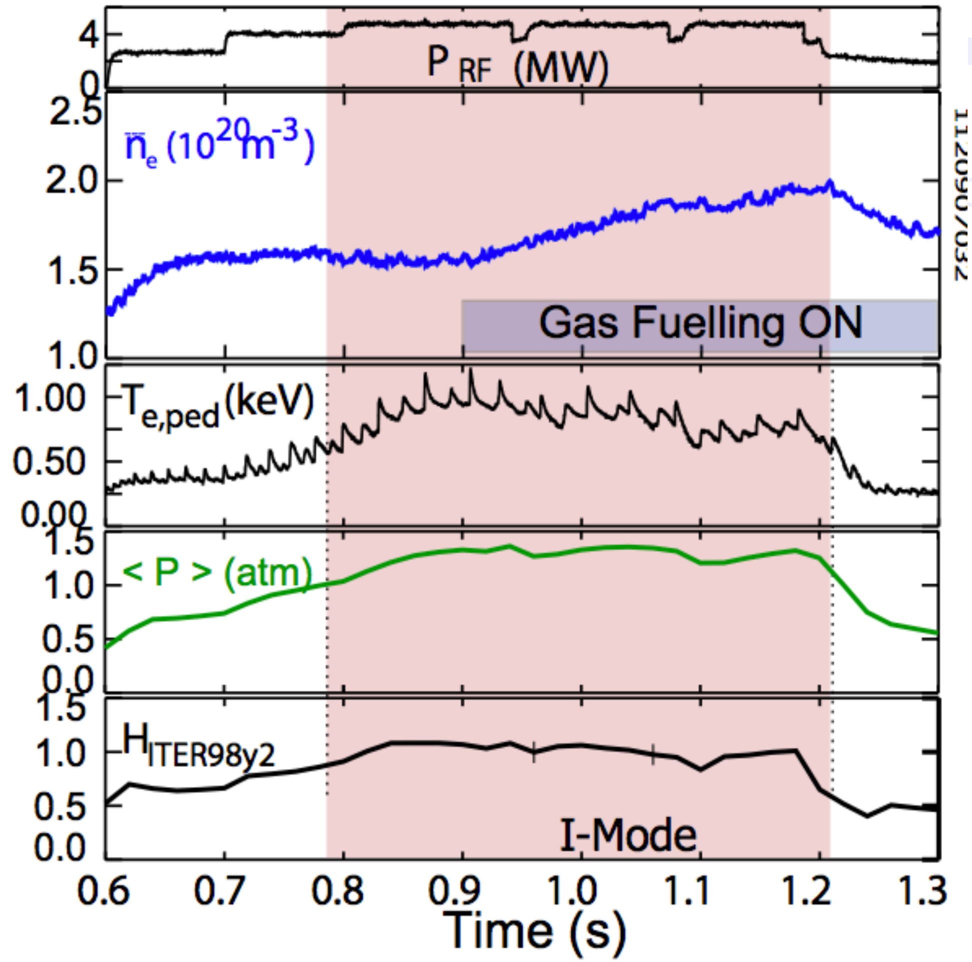

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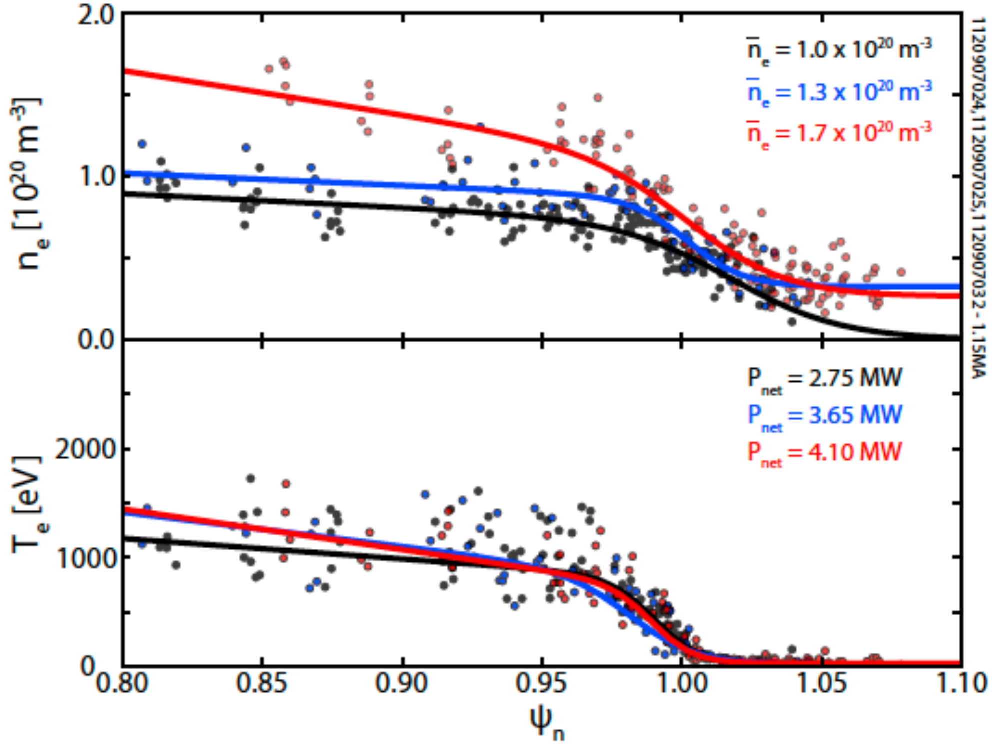
  - Fueling can be used to increase the pedestal pressure, provided sufficient power is available
  - Adjust the power level to achieve the same pedestal temperatures



Line Average Density [m^{-3}]

1.0×10^{20}

1.3×10^{20}

1.7×10^{20}

Net Power [MW]

2.75

3.65

4.10

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J. Walk, APS 2013, PoP 2014

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  - Adjust the power level to achieve the same pedestal temperatures

<u>Potential Recipe:</u>

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

<u>Caveat:</u>

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

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

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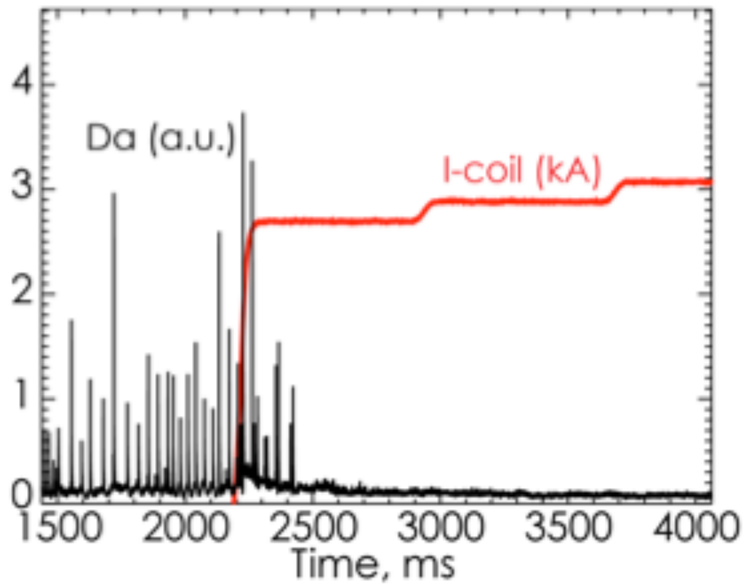
Complete Suppression of ELMs Has Been Observed in DIII-D RMP Experiments

- 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

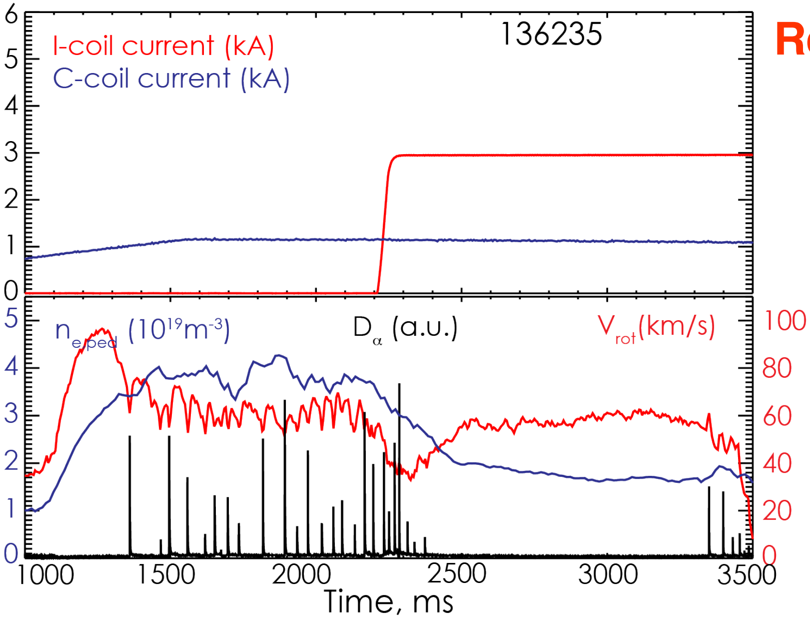


DIII-D I-Coil

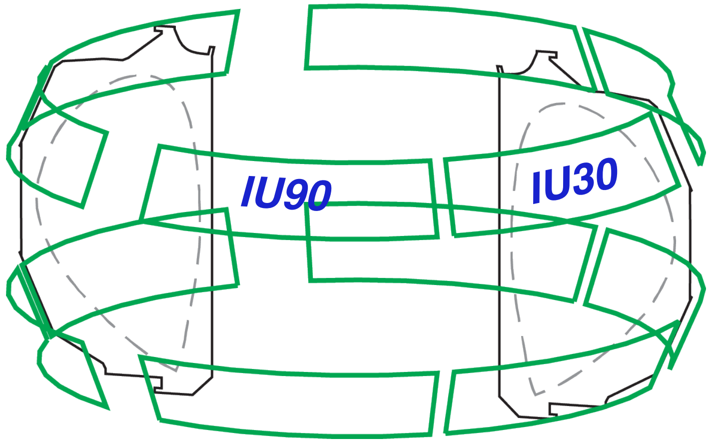
D. Orlov, APS Invited 2013

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



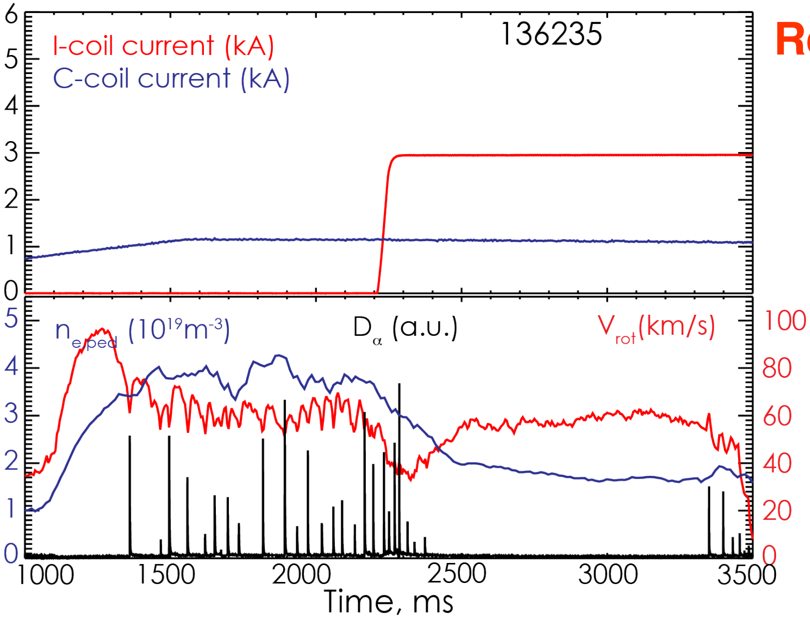
Reference 12 Coil Example: Suppression @ $I_{I\text{-}coil}$=2.9 kA



P_{inj} = 4.5 MW

D. Orlov, APS Invited 2013

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



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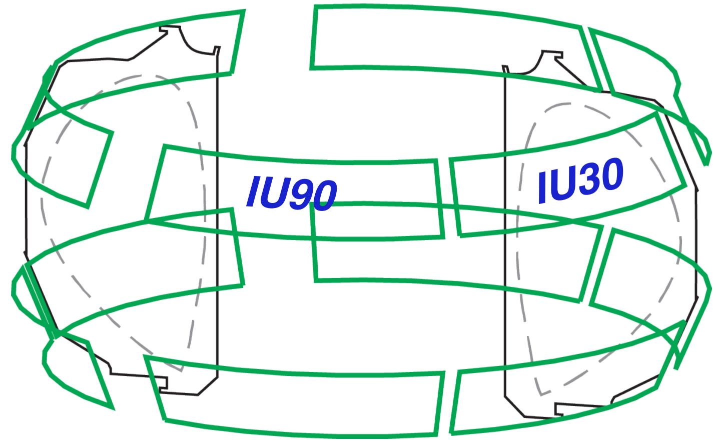

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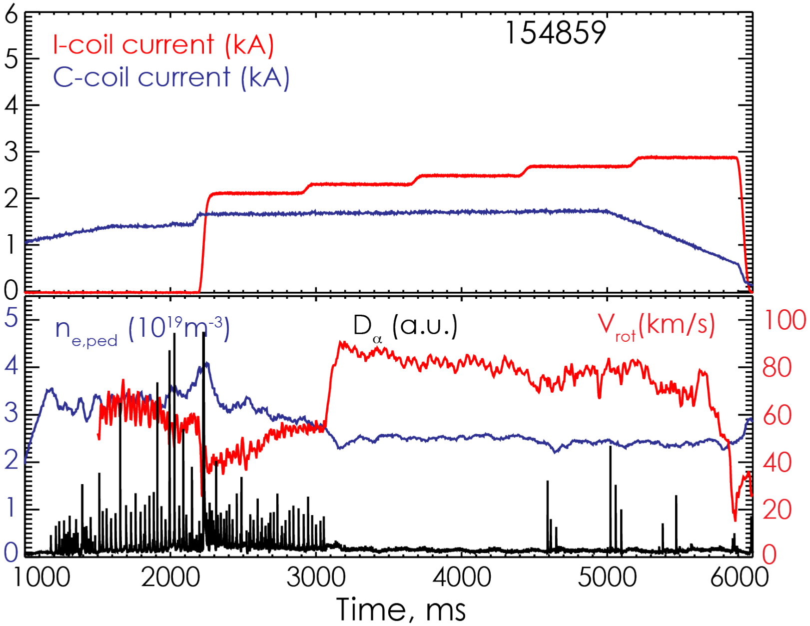
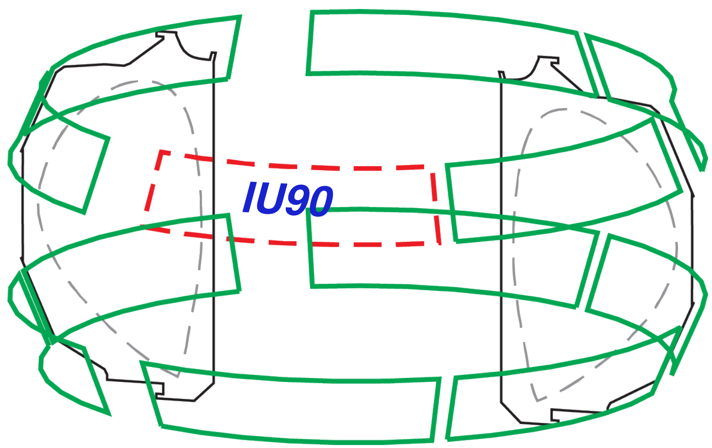


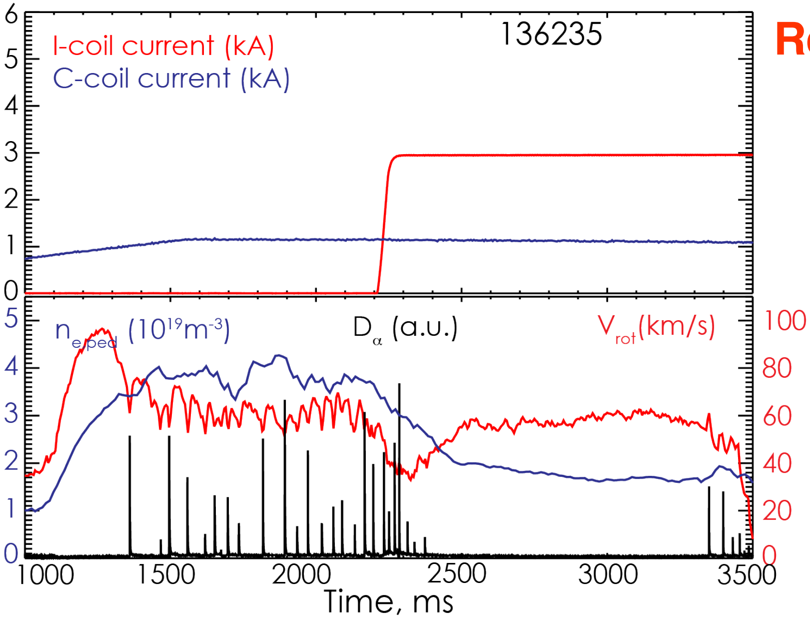
11 Coil Example: Suppression @ $I_{I\text{-}coil}$=2.3 kA



P_{inj} = 5.9 MW

D. Orlov, APS Invited 2013

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



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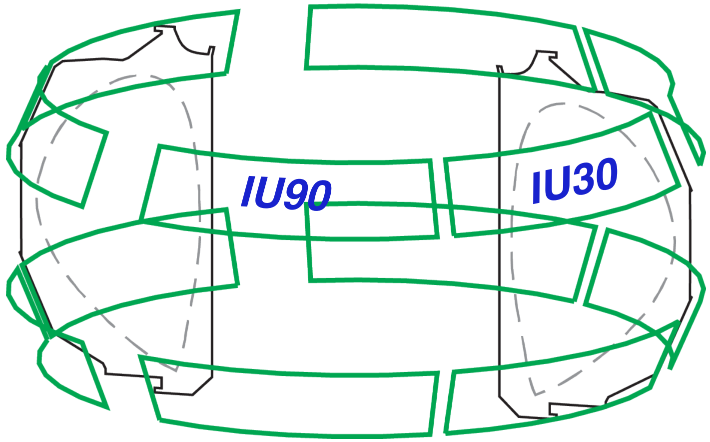

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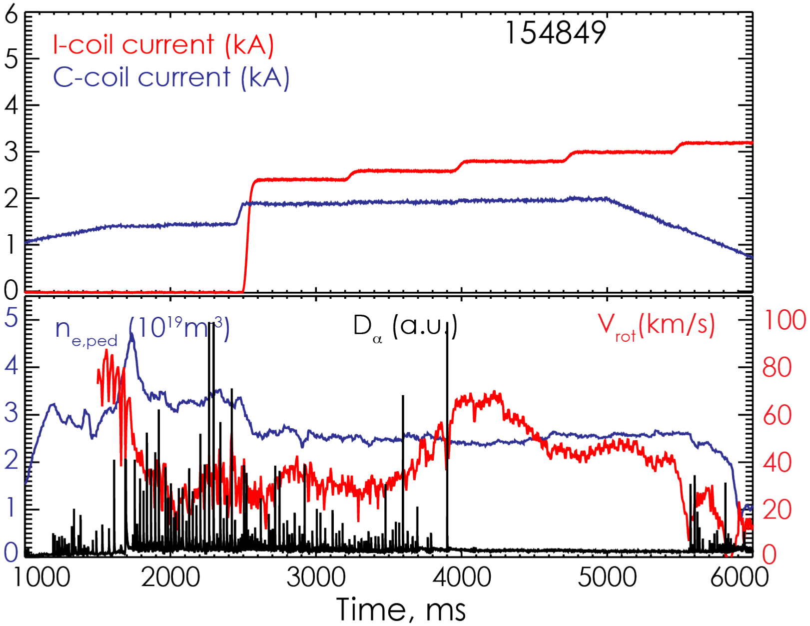
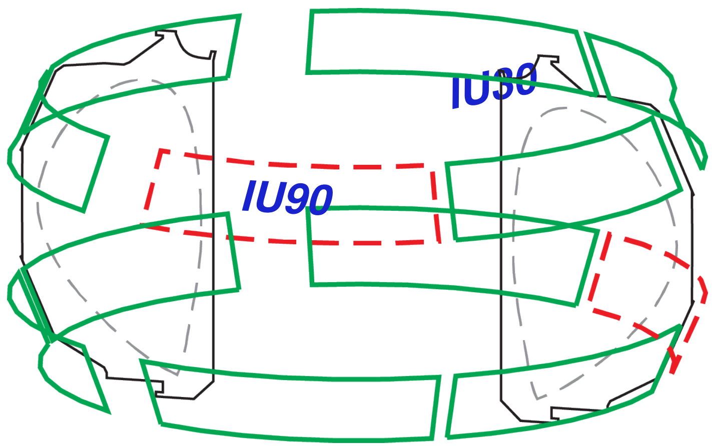


10 Coil Example: Suppression @ $I_{I\text{-}coil}$=2.8 kA



Coils turned off pseudo-randomly

P_{inj} = 7.7 MW

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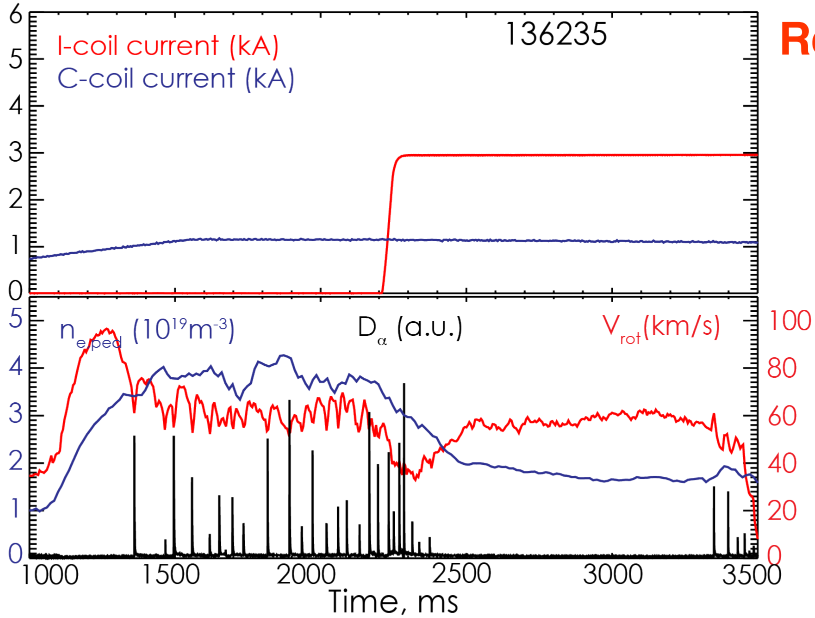
ELM Suppression Can Be Achieved in DIII-D With Fewer than 12 I-Coils



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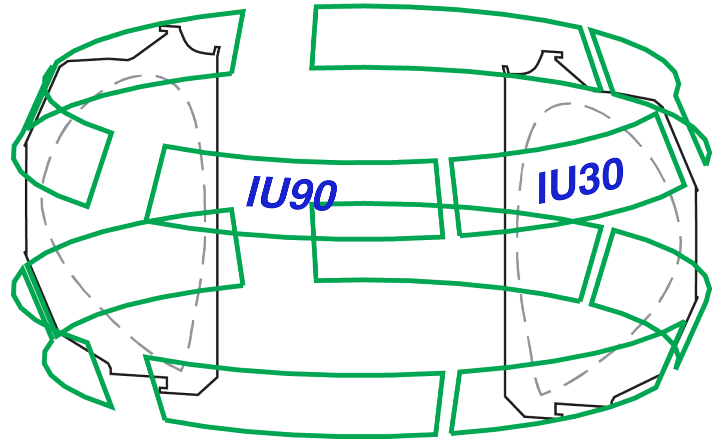
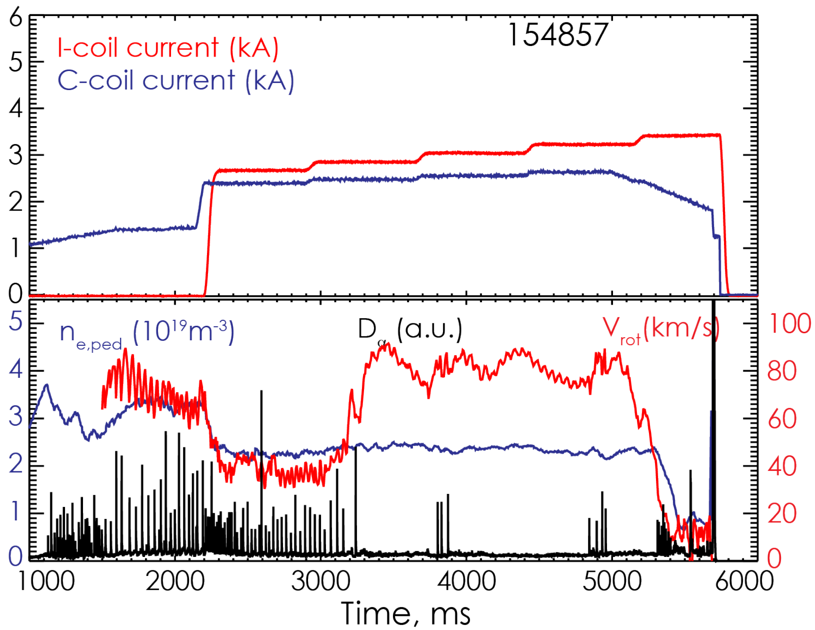
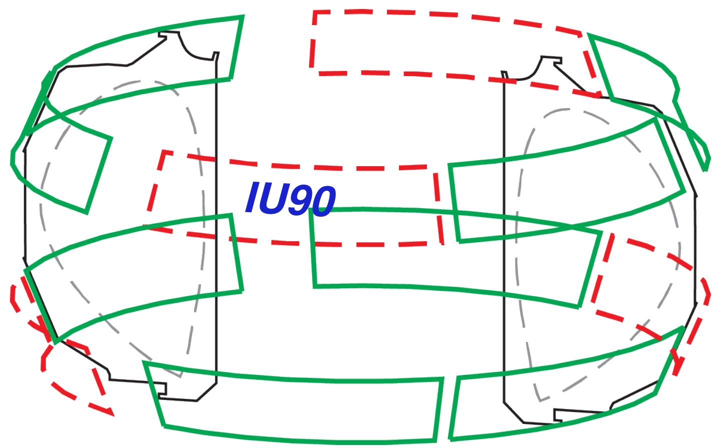


P_{inj} = 4.5 MW



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

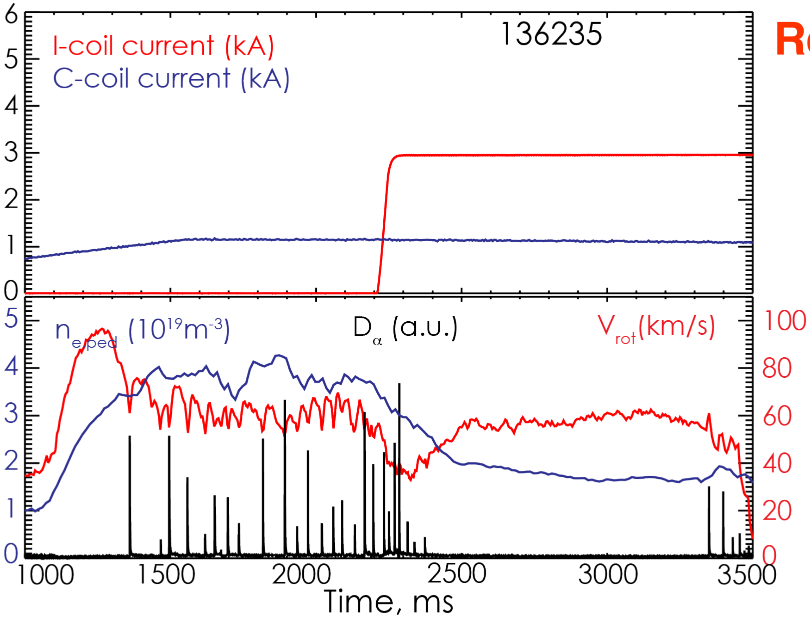
Coils turned off pseudo-randomly



P_{inj} = 5.9 MW

D. Orlov, APS Invited 2013

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



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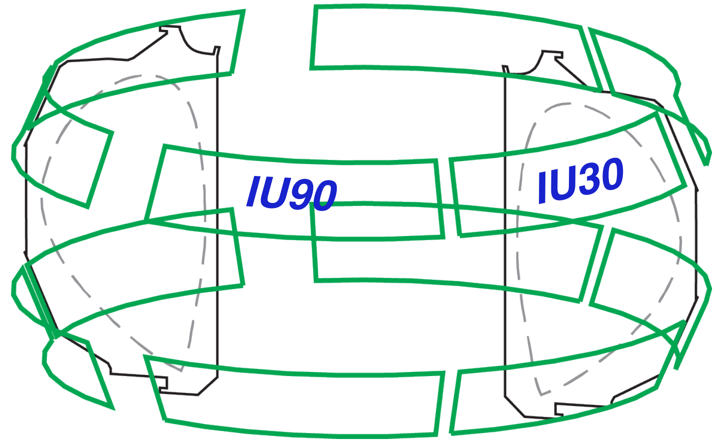

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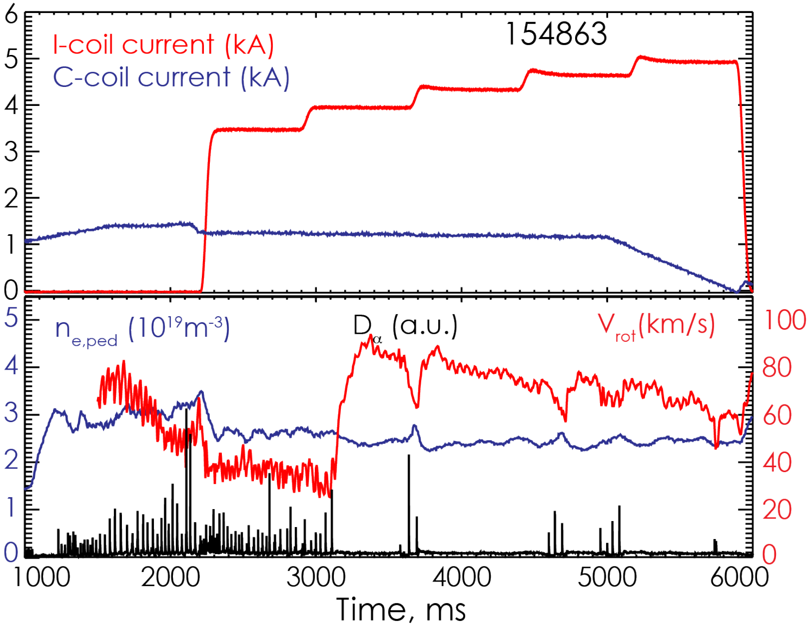
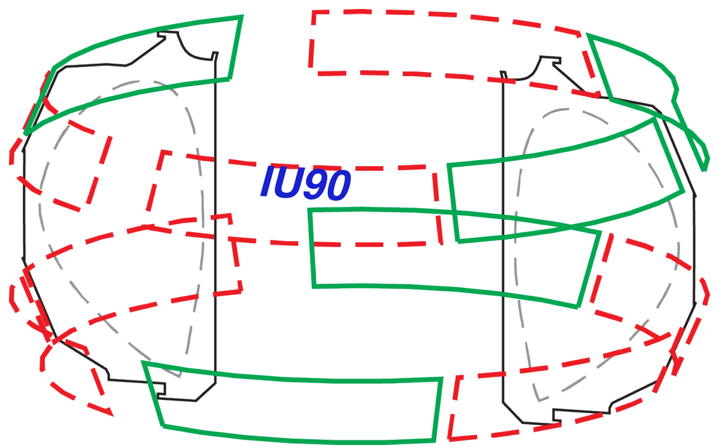


5 Coil Example: Suppression @ $I_{I\text{-}coil}$=3.95 kA

Coils turned off pseudo-randomly



P_{inj} = 5.9 MW

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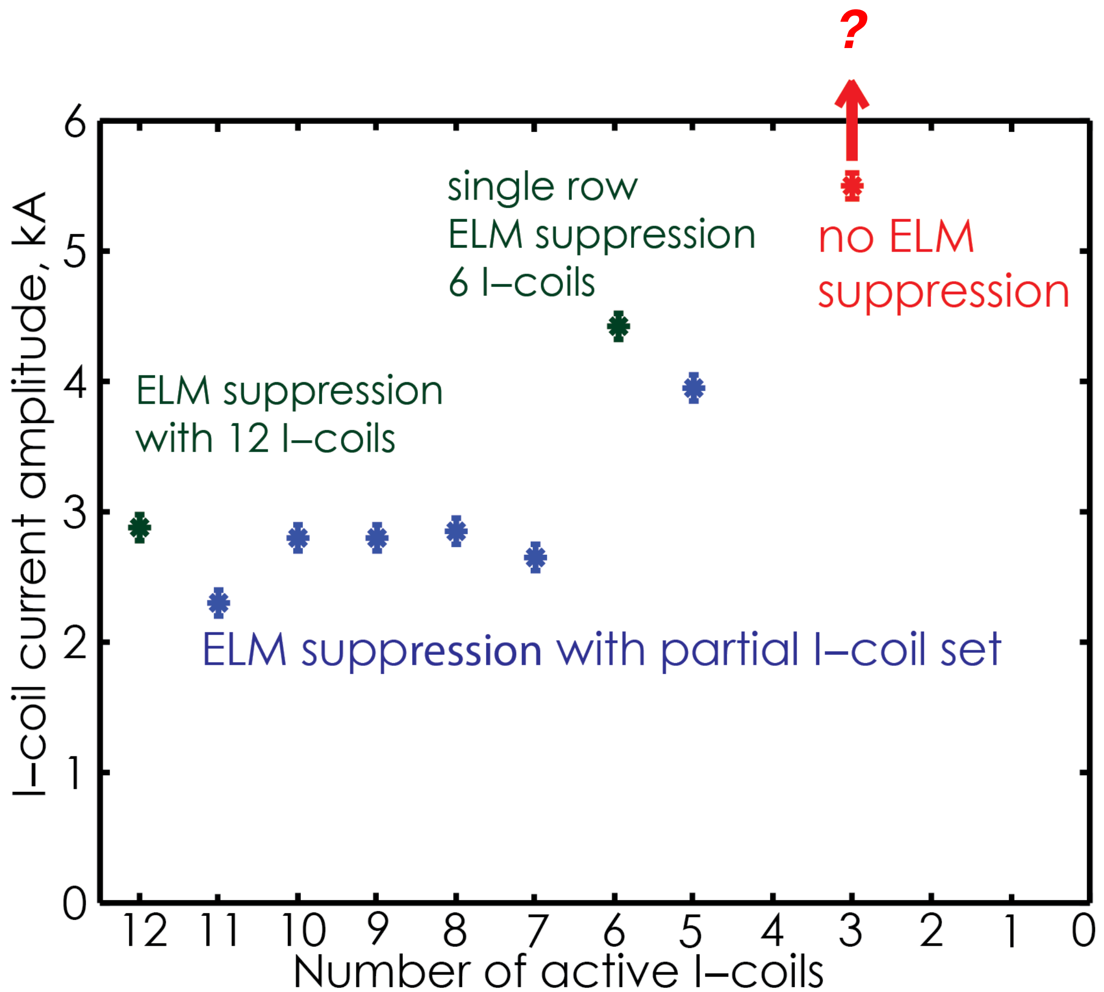
Minimal Variation in Current Amplitude Required For ELM Suppression with 5-12 I-Coils in DIII-D



- Elimination of coils results in n≠3 sidebands…do these sidebands play a role in increasing the edge stochasticity?

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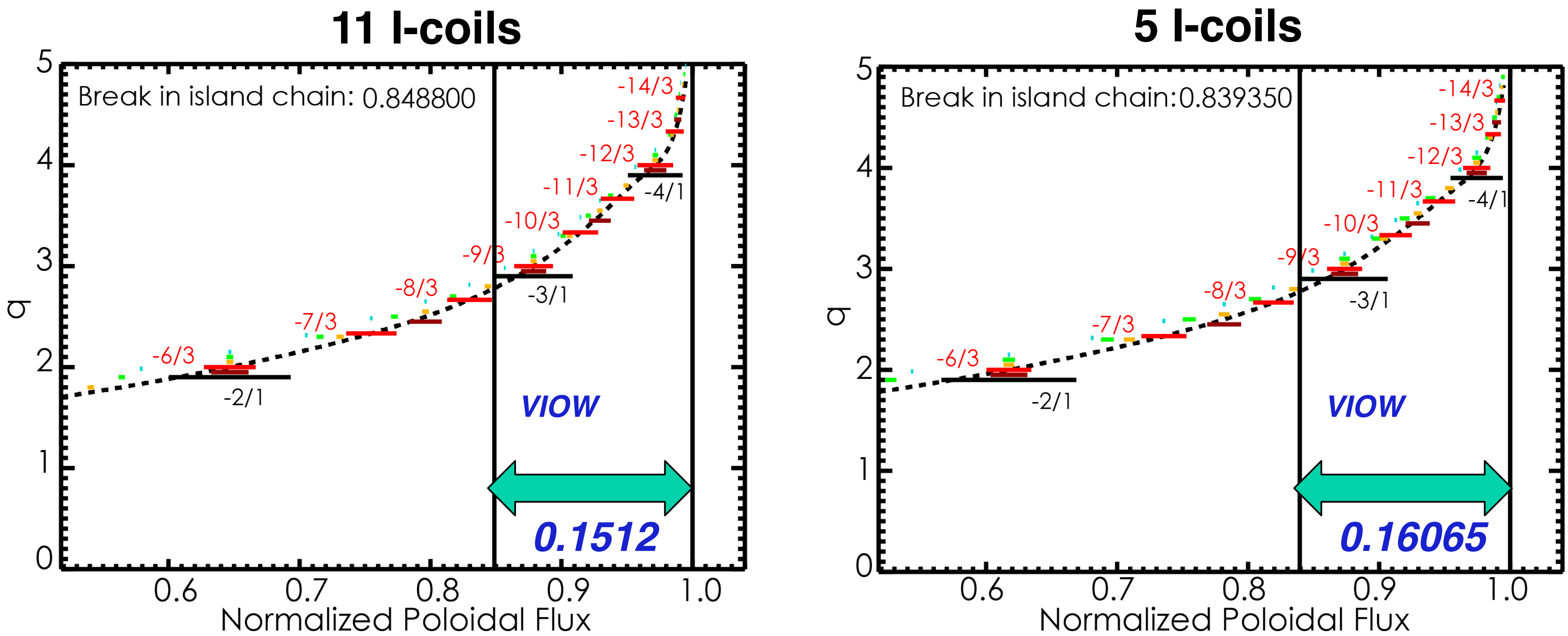
Vacuum Approximation Modeling Indicates that the Sidebands Help Maintain a Stochastic Boundary



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

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

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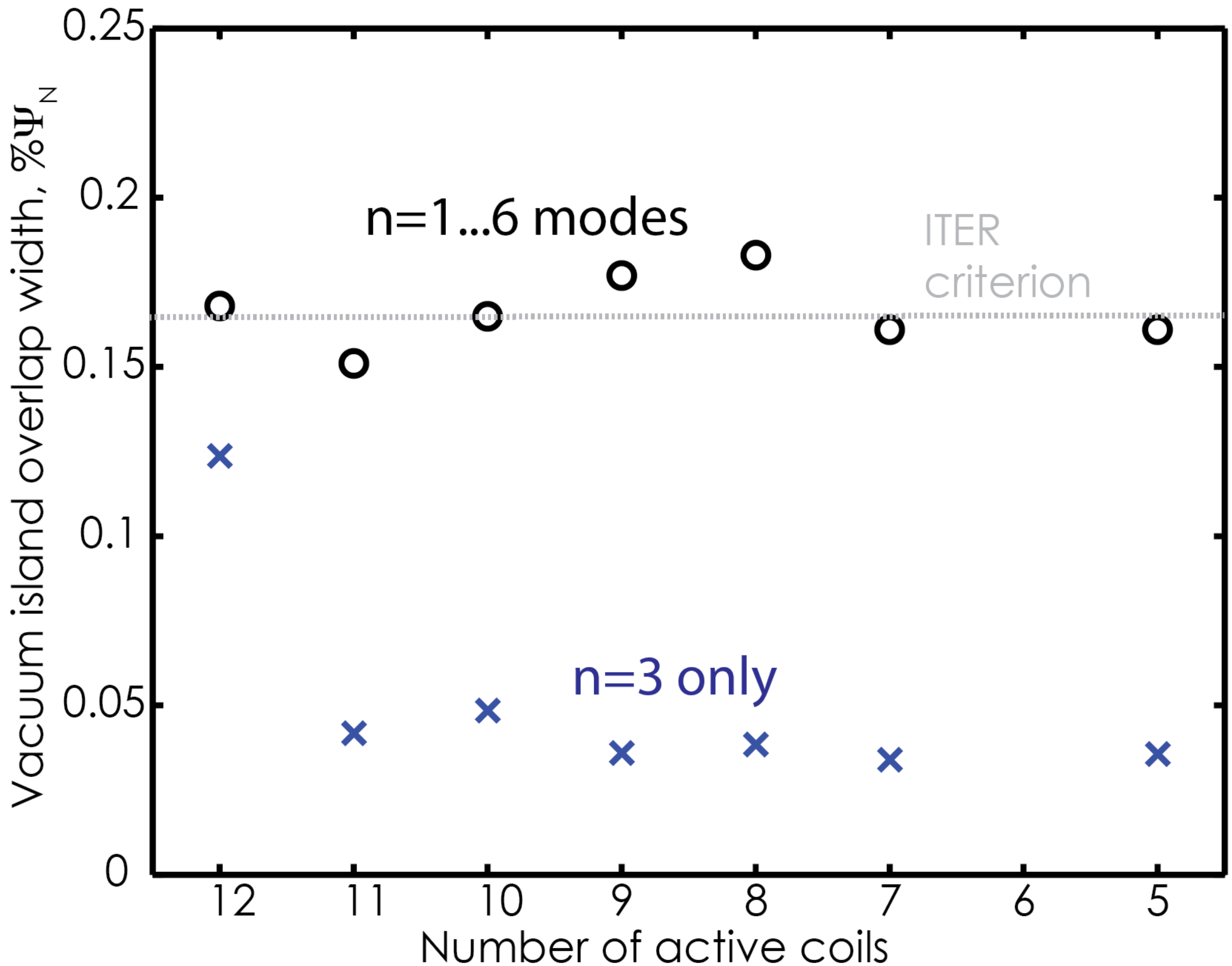
Vacuum Calculations Show that the Island Overlap Width is Similar in All Cases with ELM Suppression

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



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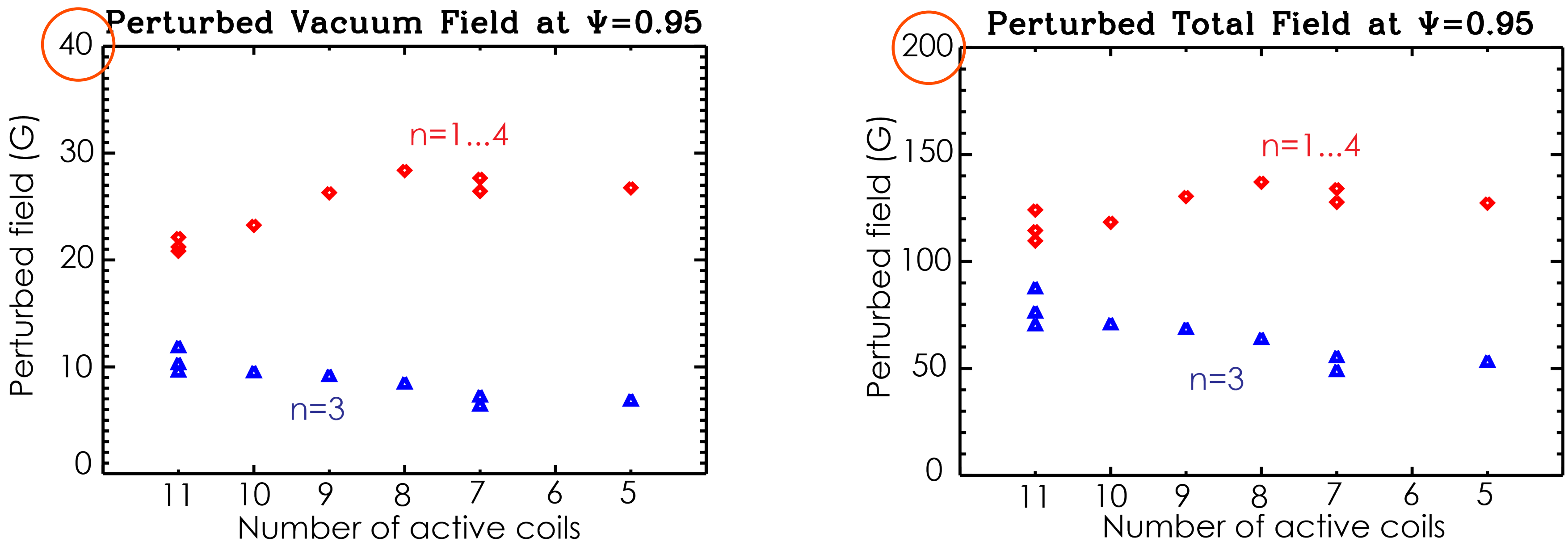
Two-Fluid MHD Calculations with M3D-C^1 Indicate the Importance of n≠3 Sidebands

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



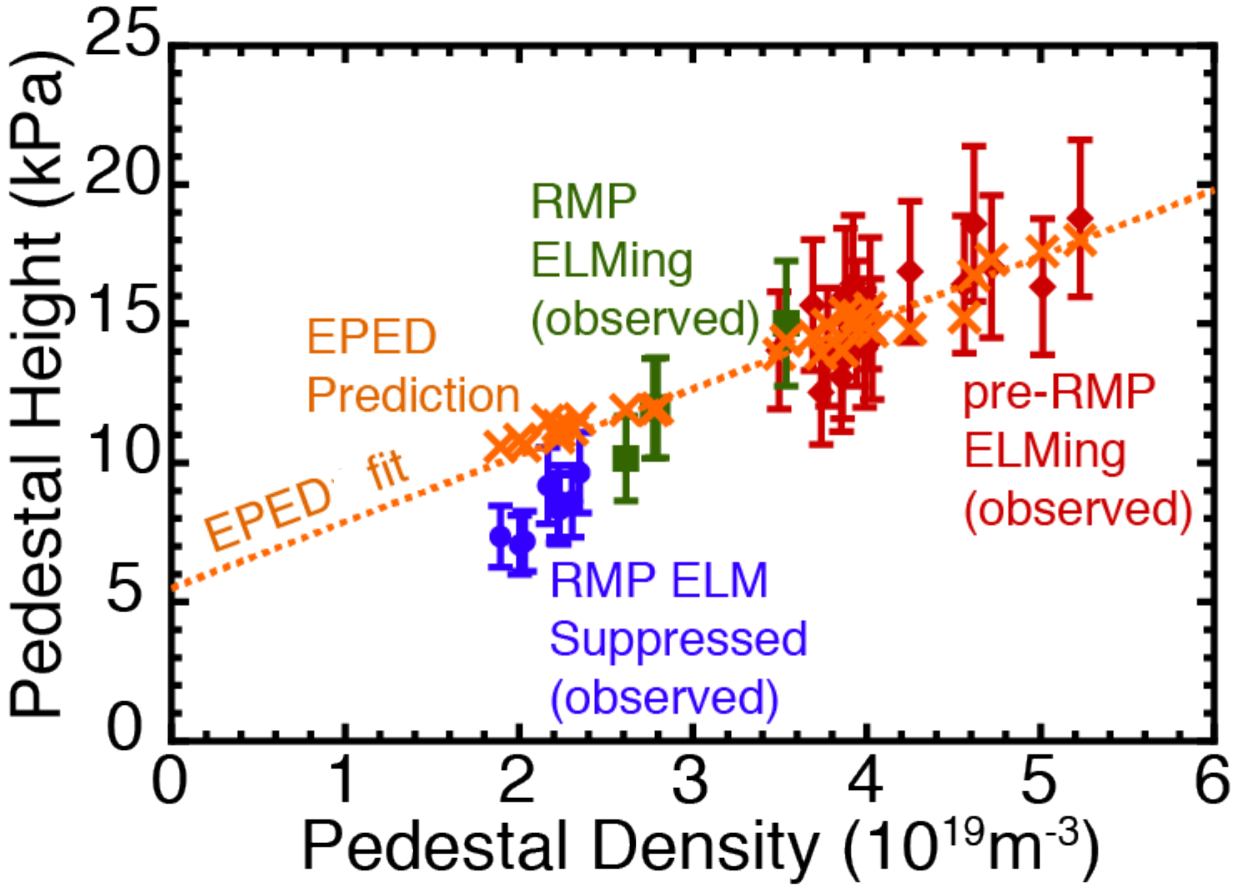
Calculations testing the limit of linear model

- $|\delta B|_{n=3}$ 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

N. Ferraro, D. Orlov, APS Invited 2013

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

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

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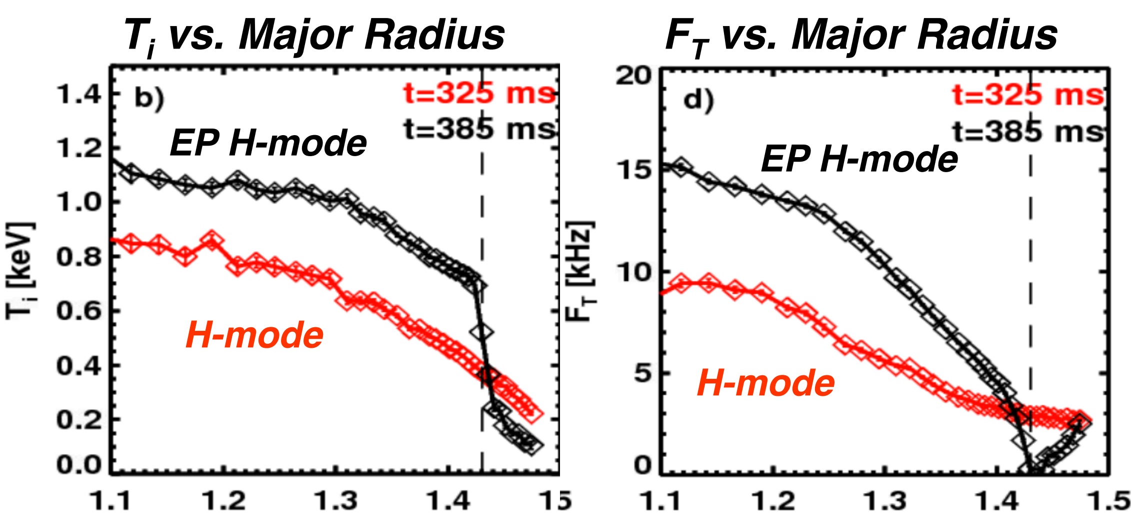
The Enhanced Pedestal H-mode is a High-Confinement Regime in the Spherical Torus

<u>Characteristics of the Enhanced Pedestal (EP) H-mode.</u>

- 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.



NSTX Upgrade

<u>Questions to be Addressed by Recent Research</u>

- 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

NSTX Upgrade

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

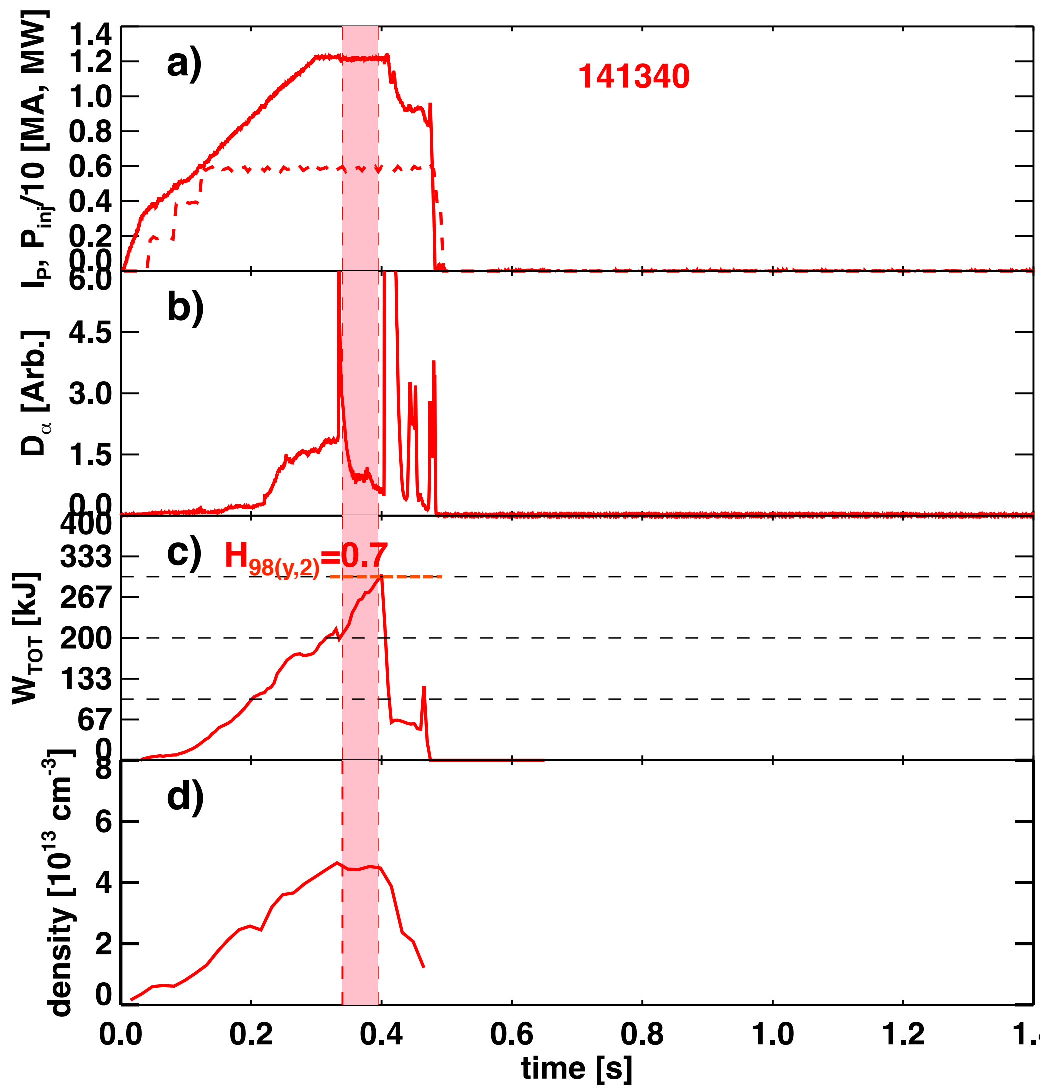
(R. Maingi, et al, Phys. Rev. Lett., 2010)

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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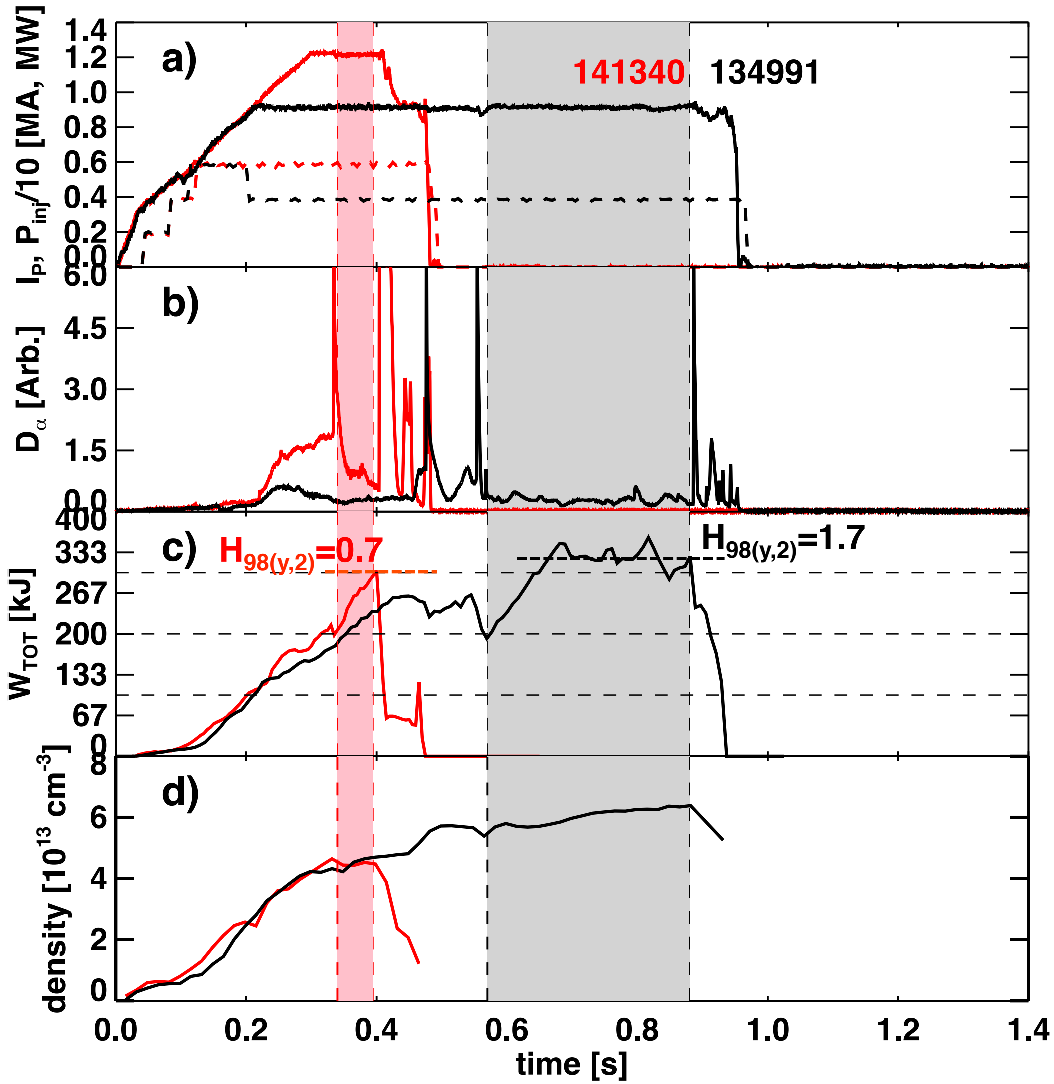

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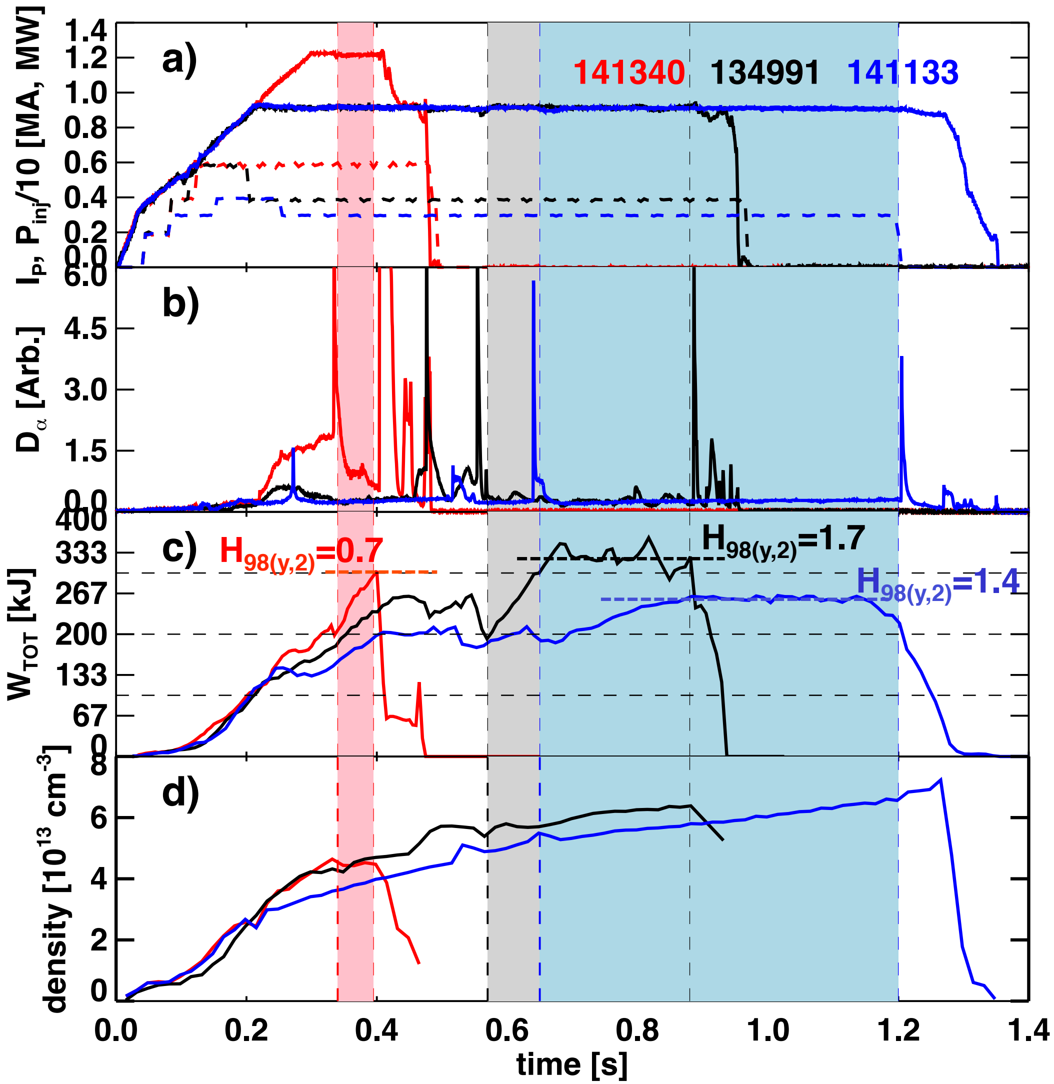


Density rise typically due to accumulation of C impurities in these cases

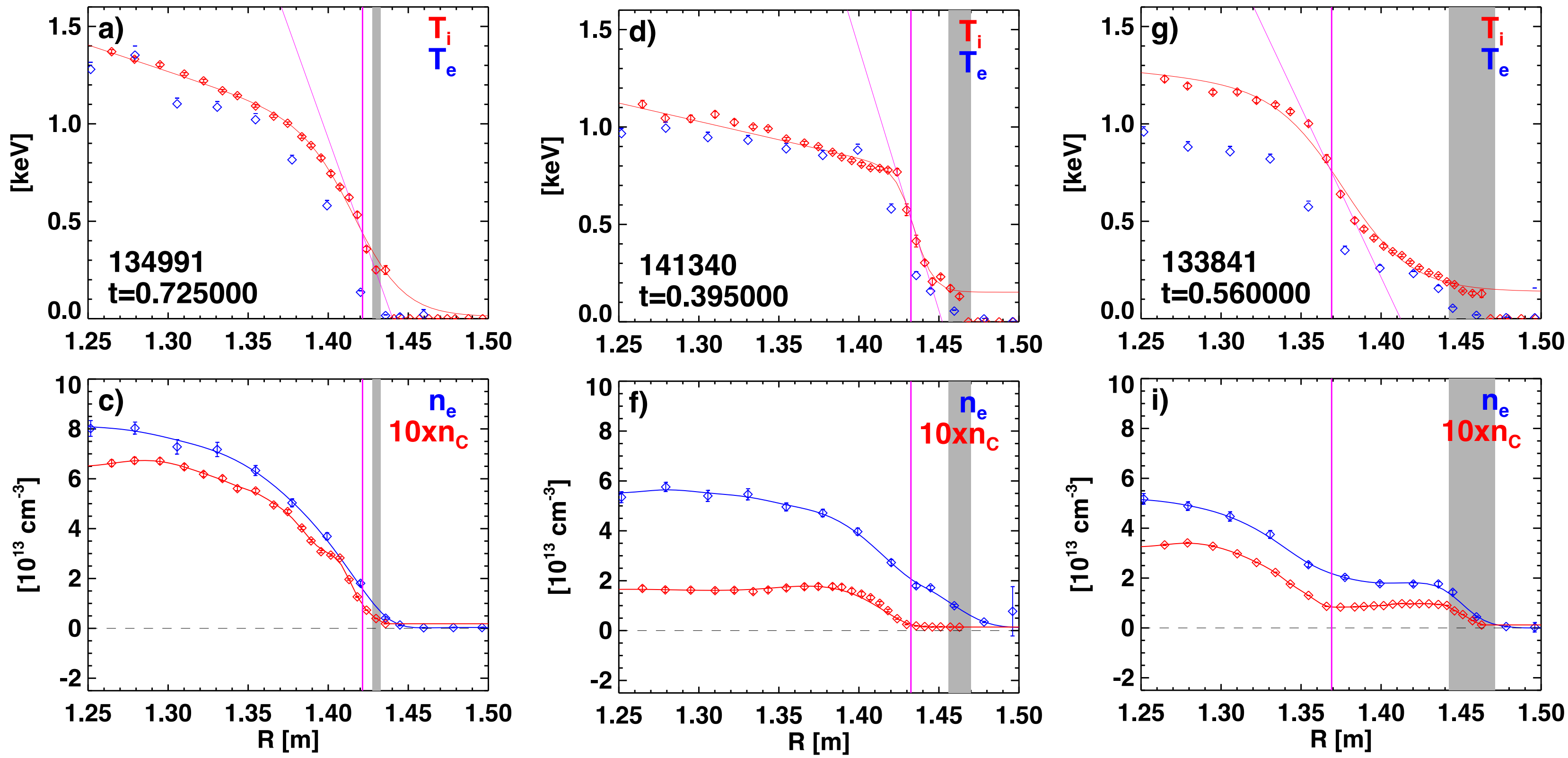
Stationarity typically not achieved in NSTX discharges

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

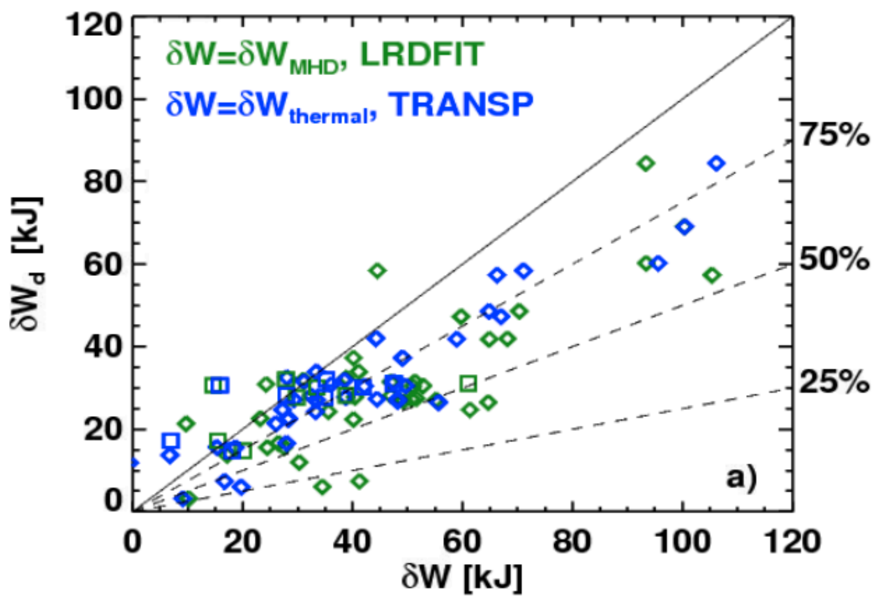


NSTX Upgrade

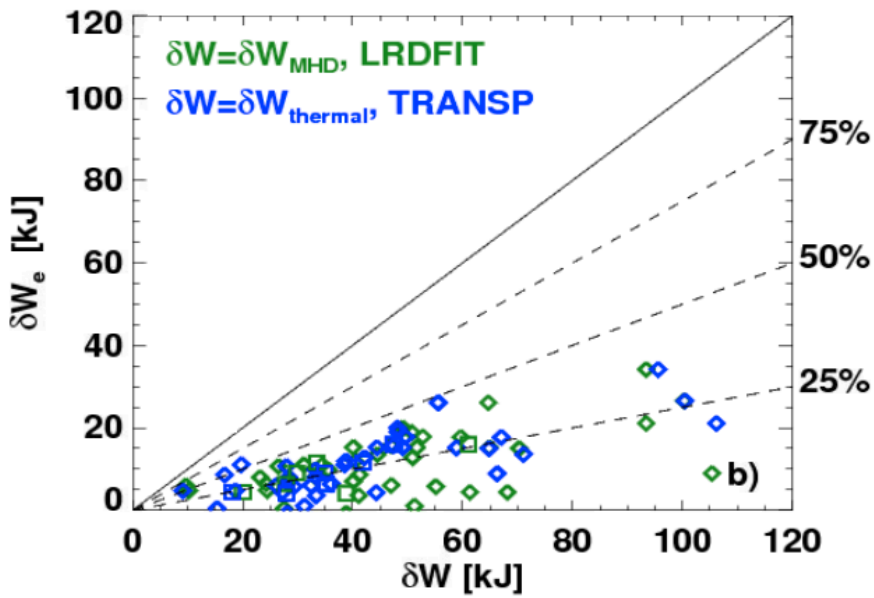
Most of the Energy Increment in EP H-mode is Contained in the Ions

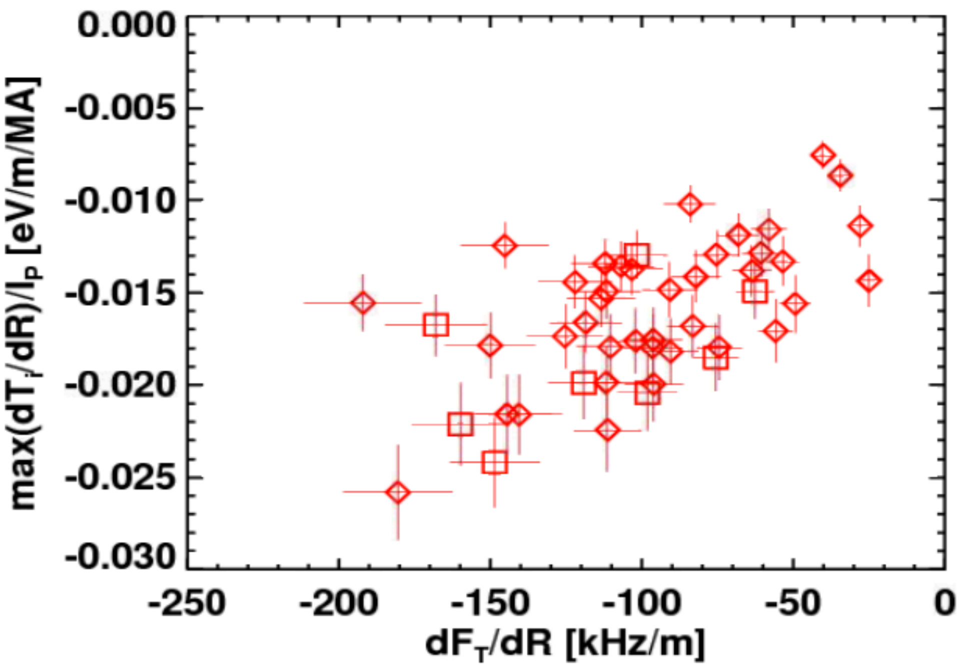
- Compare electron and ion energy increases following the EP H-mode transition
  - ~75% of the stored energy increase is in the ion channel.
- Maximum temperature gradient scales with the rotation gradient.
  - Speculate: rotation shear is quenching the residual ion-scale turbulence?

Ion Energy Increment vs. Total Energy Increment



Electron Energy Increment vs. Total Energy Increment

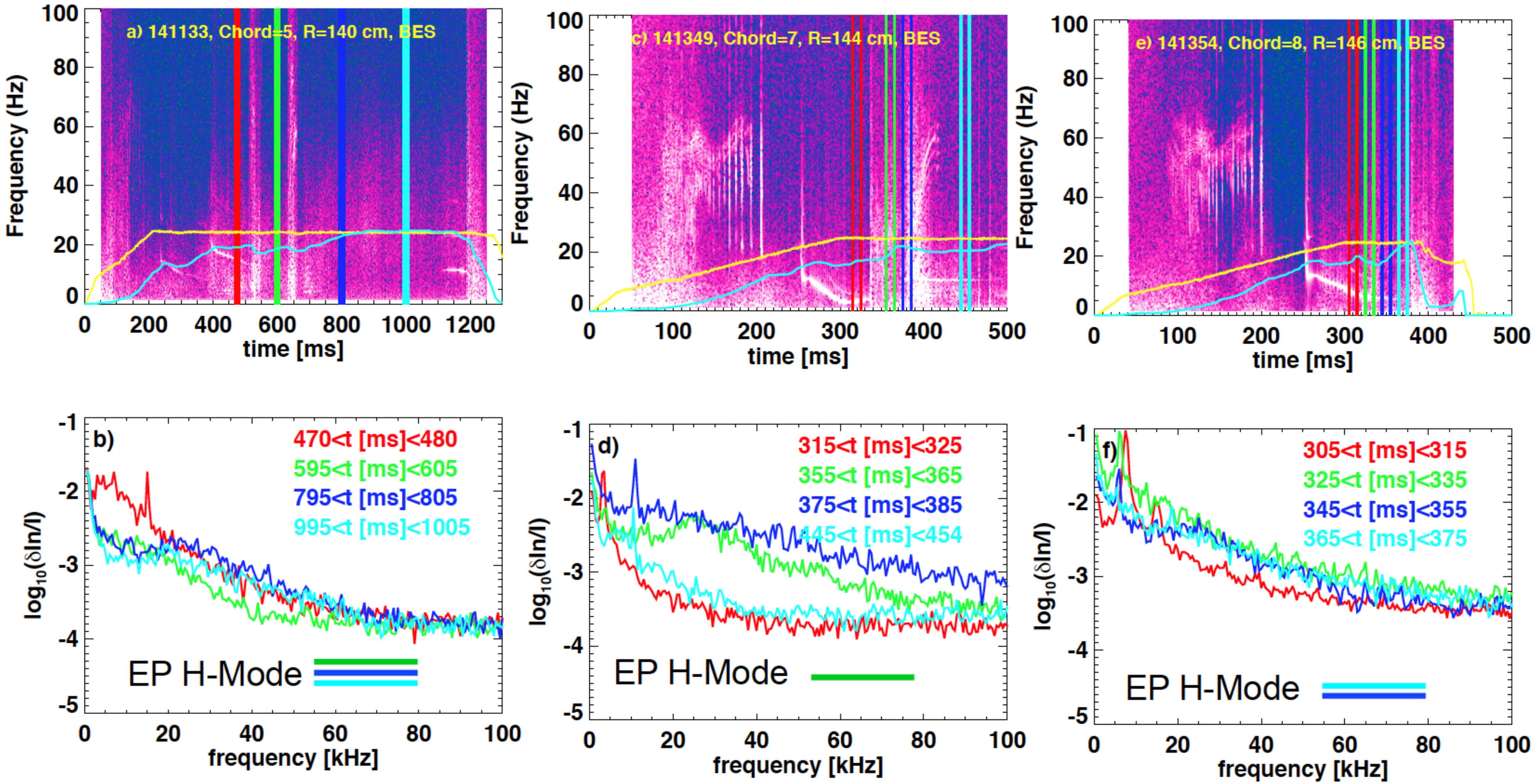




S.P. Gerhardt, et al., submitted to Nuclear Fusion (2014)

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



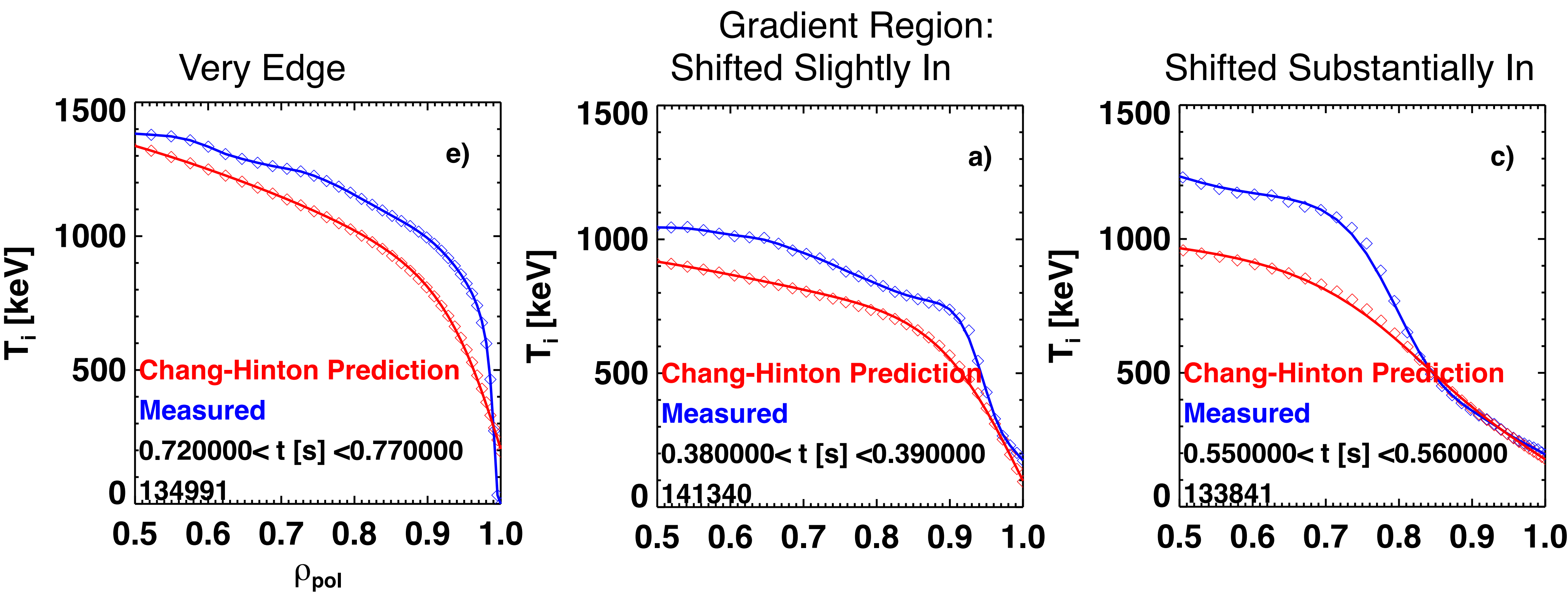
NSTX Upgrade

S.P. Gerhardt, et al., submitted to Nuclear Fusion (2014)

BES data provided by D.R. Smith

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_Φ
  - 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

S.P. Gerhardt, et al., submitted to Nuclear Fusion (2014)

NSTX Upgrade

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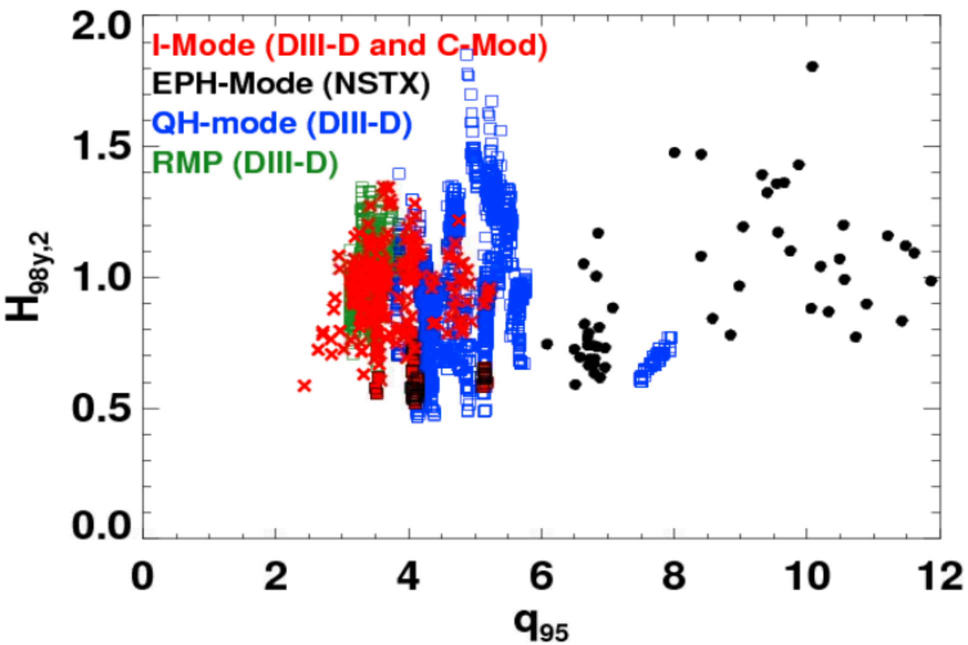
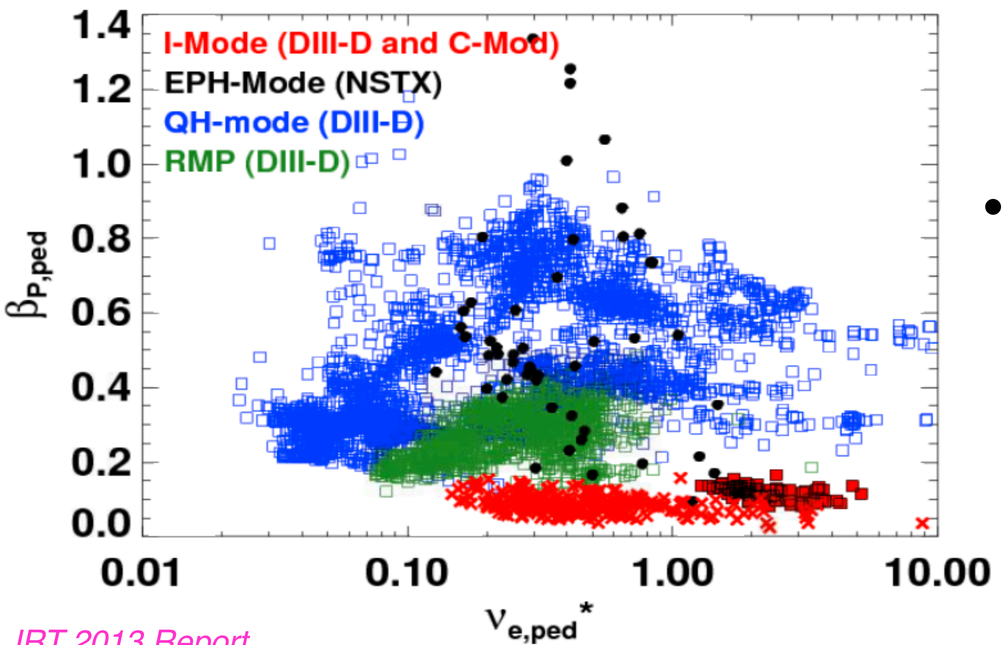
All Regimes Under Consideration Have Shown Good Confinement and Access to Low Collisionality





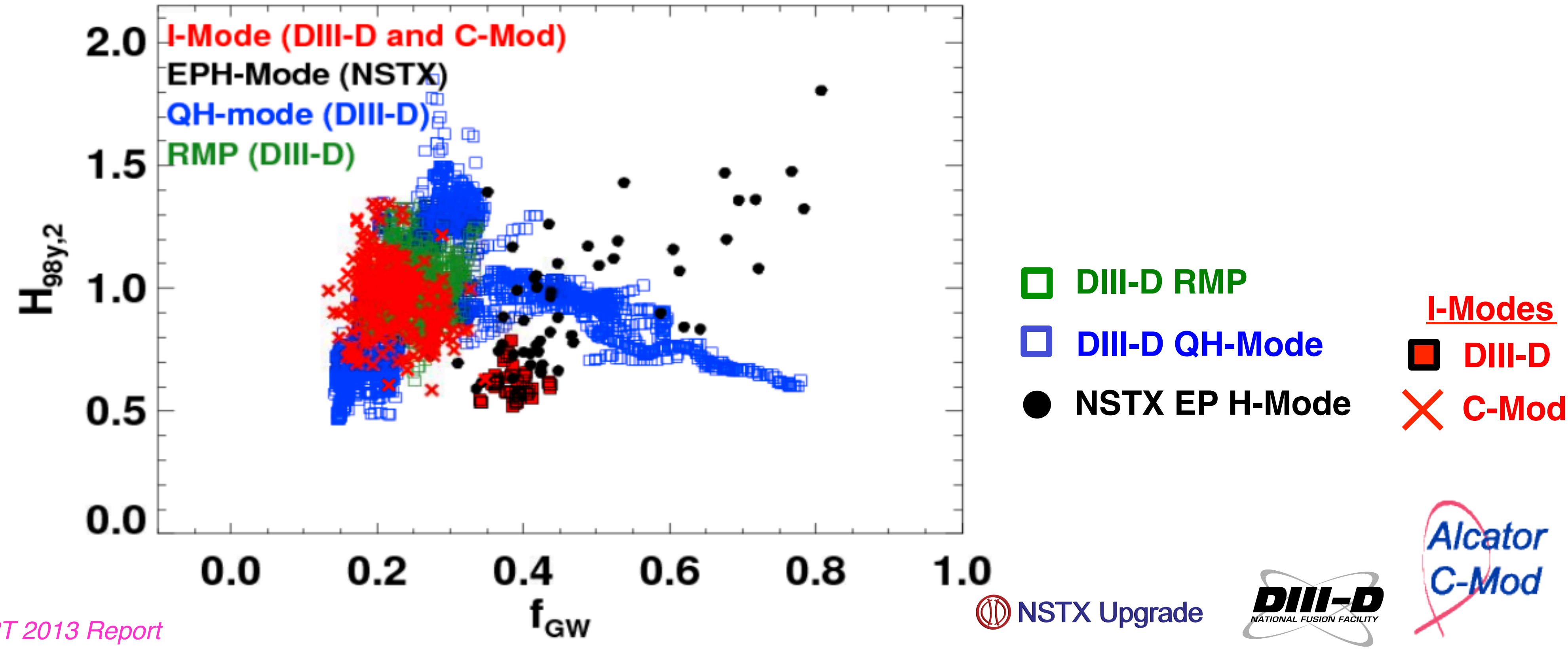
JRT 2013 Report

- Representative but incomplete data sets shown.
- Symbols for machines and colors for regimes:
  - DIII-D RMP
  - DIII-D QH-Mode
  - NSTX EP H-Mode
  - I-Modes: DIII-D, C-Mod
- RMP, QH-mode, and C-Mod I-mode have achieved $H_{98(y,2)}$~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)

NSTX Upgrade · DIII-D National Fusion Facility · Alcator 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 2×10^{14} cm^{-3} in absolute units, so still quite high
- NSTX EP H-mode cases have high confinement at high f_{GW}



JRT 2013 Report

NSTX Upgrade DIII-D NATIONAL FUSION FACILITY Alcator C-Mod

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
    - similar result found in VH-mode experiments in 2013.

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Thanks for your attention!