



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

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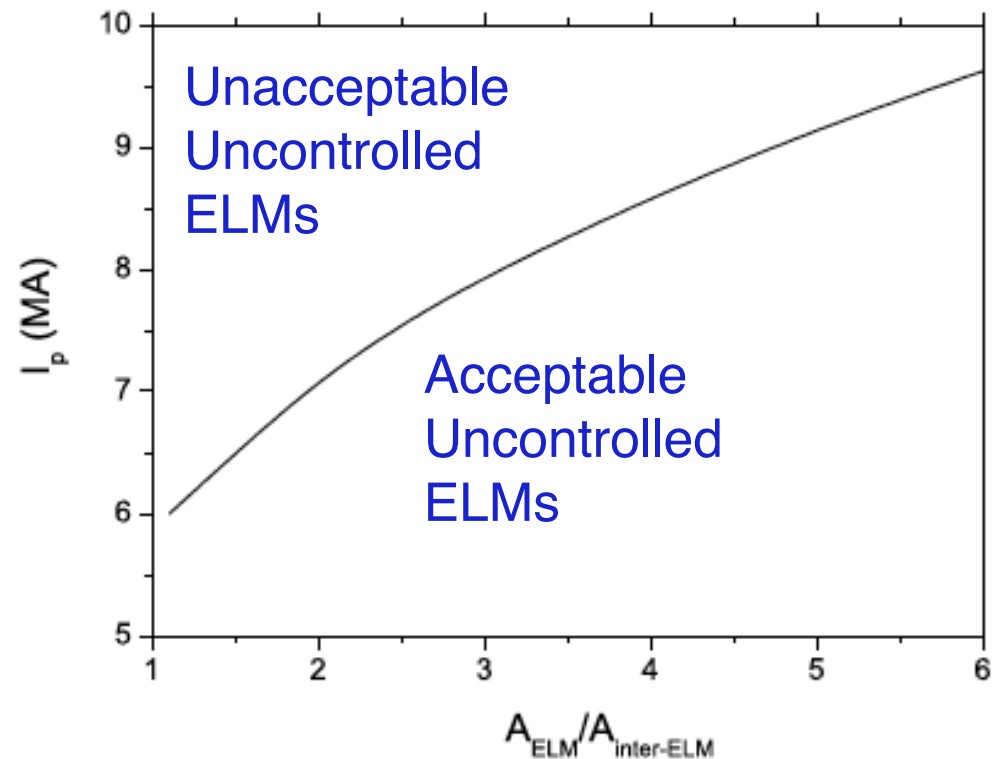
D.R. Smith, G. McKee, Zheng Yan, *University of Wisconsin-Madison, USA*

TTF Meeting, April 23, 2014

ITER Needs To Operate Without Large Type-I ELMs

- Good confinement H-modes are typically accompanied by type-I ELMs
- These 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

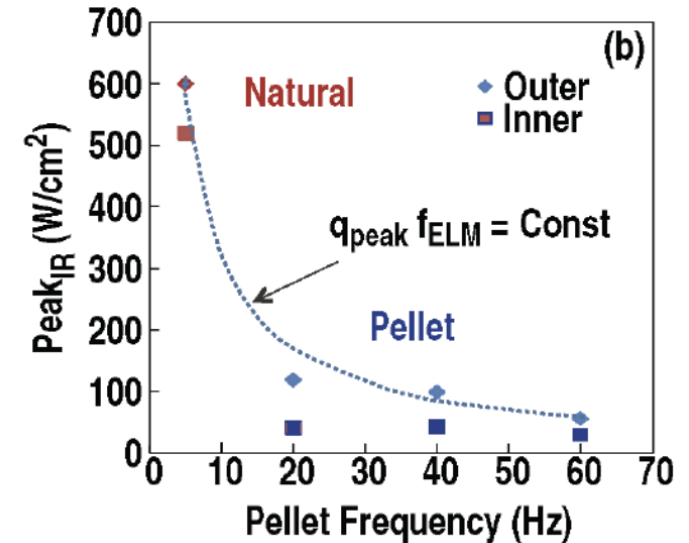


A. Loarte, NF 54, 033007 (2014)

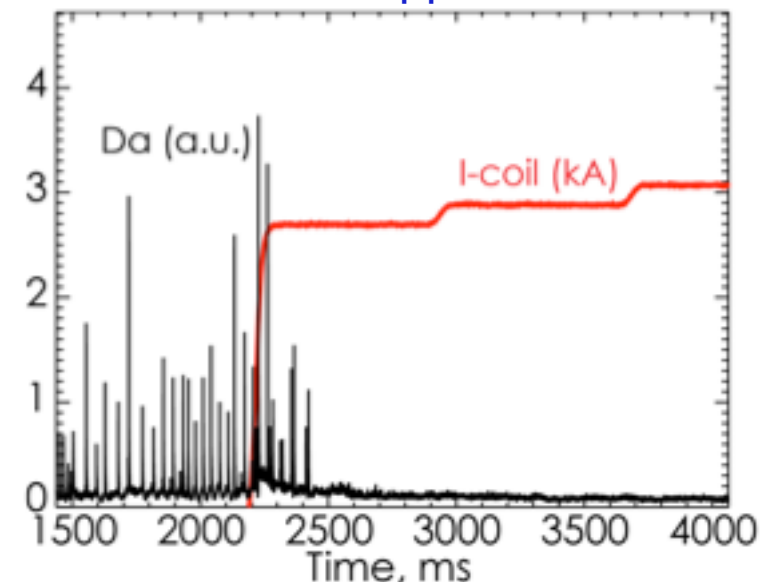
Numerous Strategies Are Under Development for Managing ELMs in ITER

- 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
 - RMP H-mode 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.

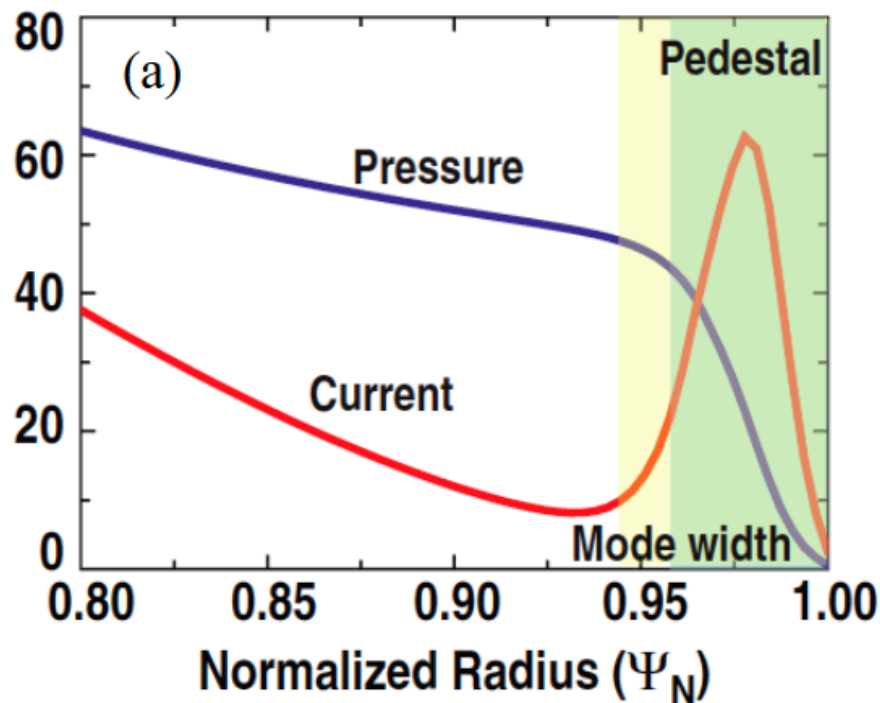
Presentation will Concentrate on Results Collected as Part of the Milestone Research
Only DIII-D Operated During FY-2013; Analysis of Existing Data from C-MOD and NSTX
was a Key Component of Research Exercise

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

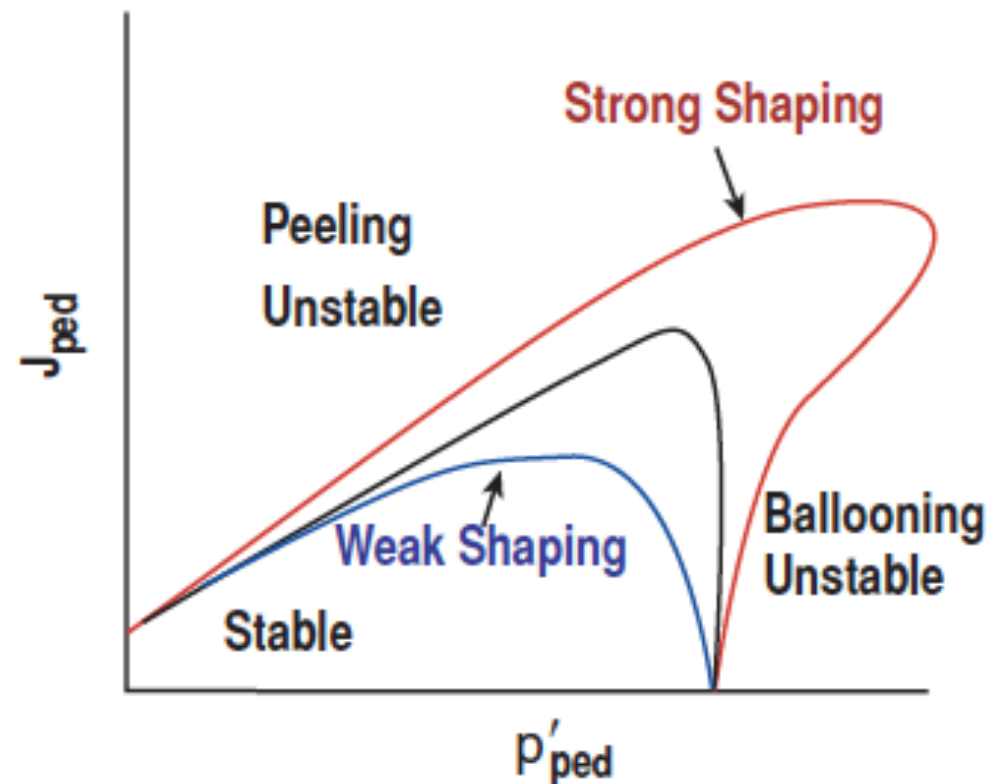
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Type-I ELM Dynamics Often Understood In Terms of Peeling-Ballooning Stability

- 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
- Global modes spanning the full pedestal
 - Typically yields a stability boundary as $\beta_{\text{ped}} \sim \Delta^{3/4}$



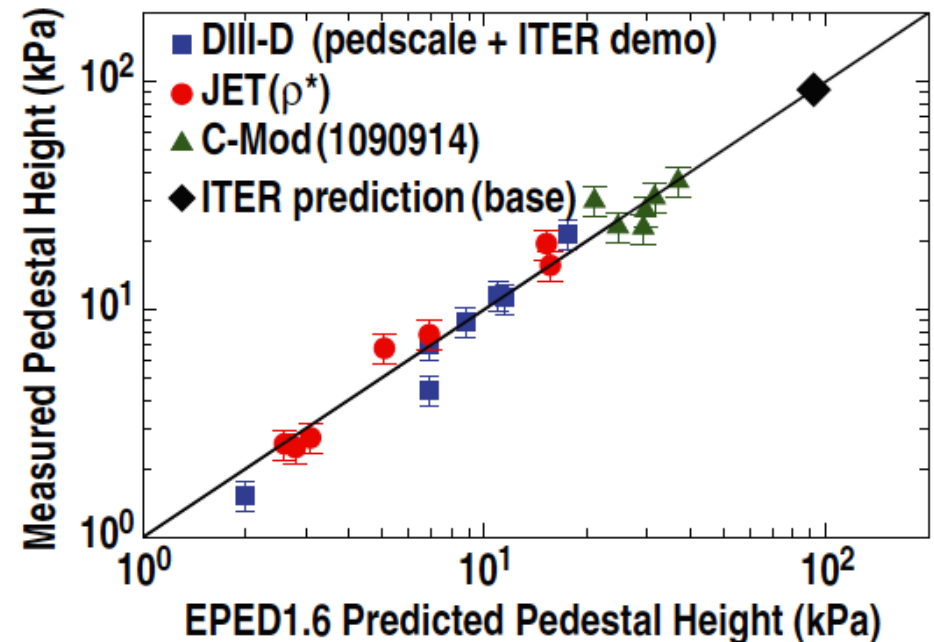
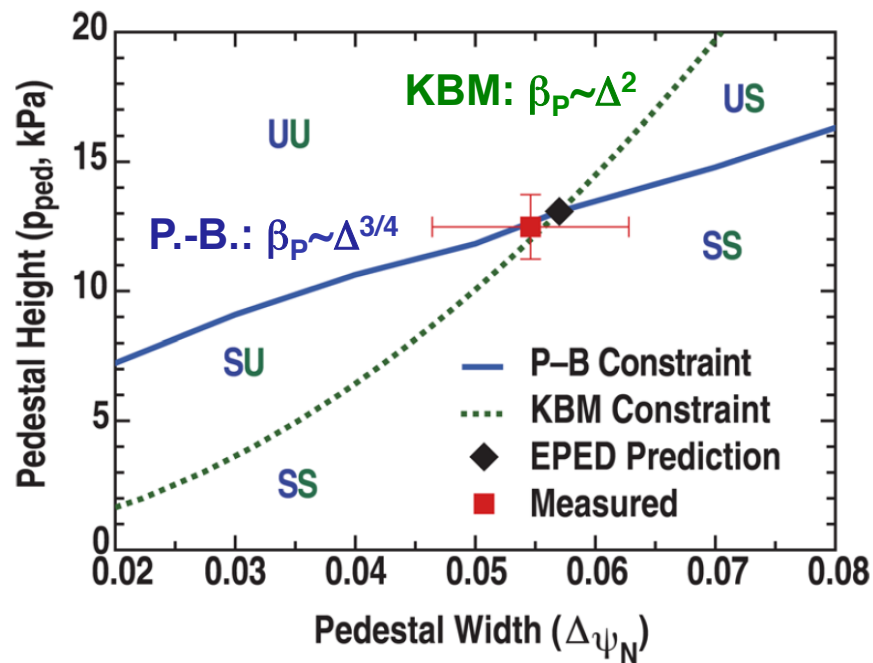
P. Snyder, *Nuclear Fusion* 51 1 (2011)



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 β

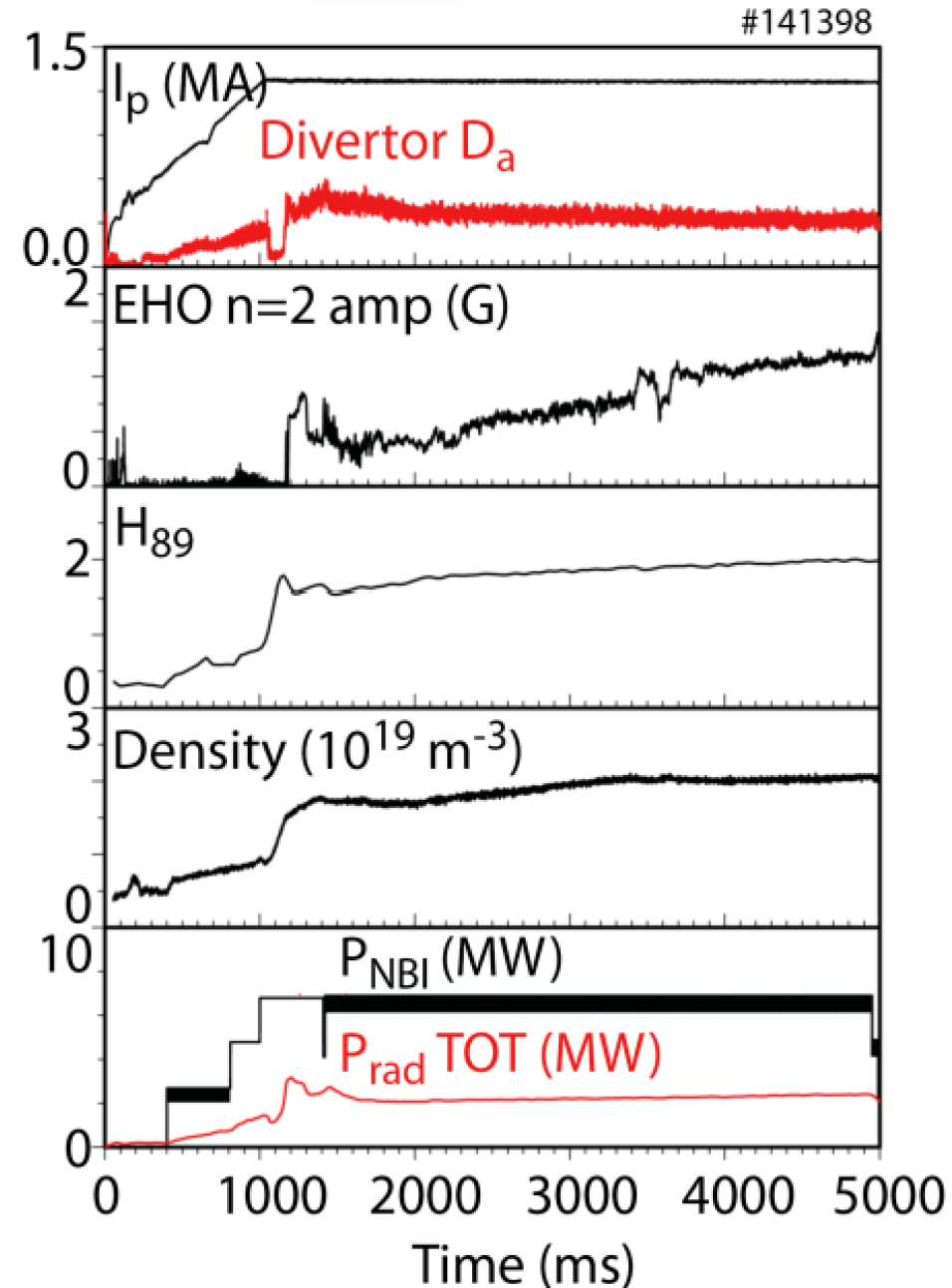


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- Reminder: Key pedestal physics considerations
- **Regimes with continuous edge fluctuations**
 - Quiescent H-mode and regimes with edge harmonic oscillations
 - The I-Mode Regime
- Recent research on RMP H-mode
- A very high confinement regime: the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

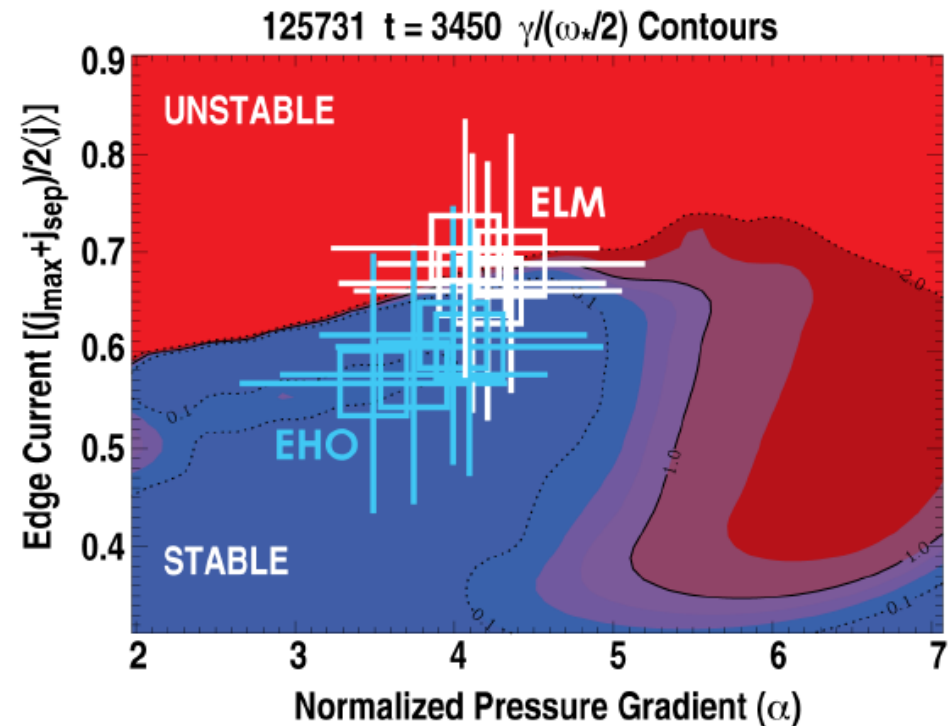
The Quiescent H-Mode Provides Particle Control Through an Edge Fluctuation Called the Edge Harmonic Oscillation

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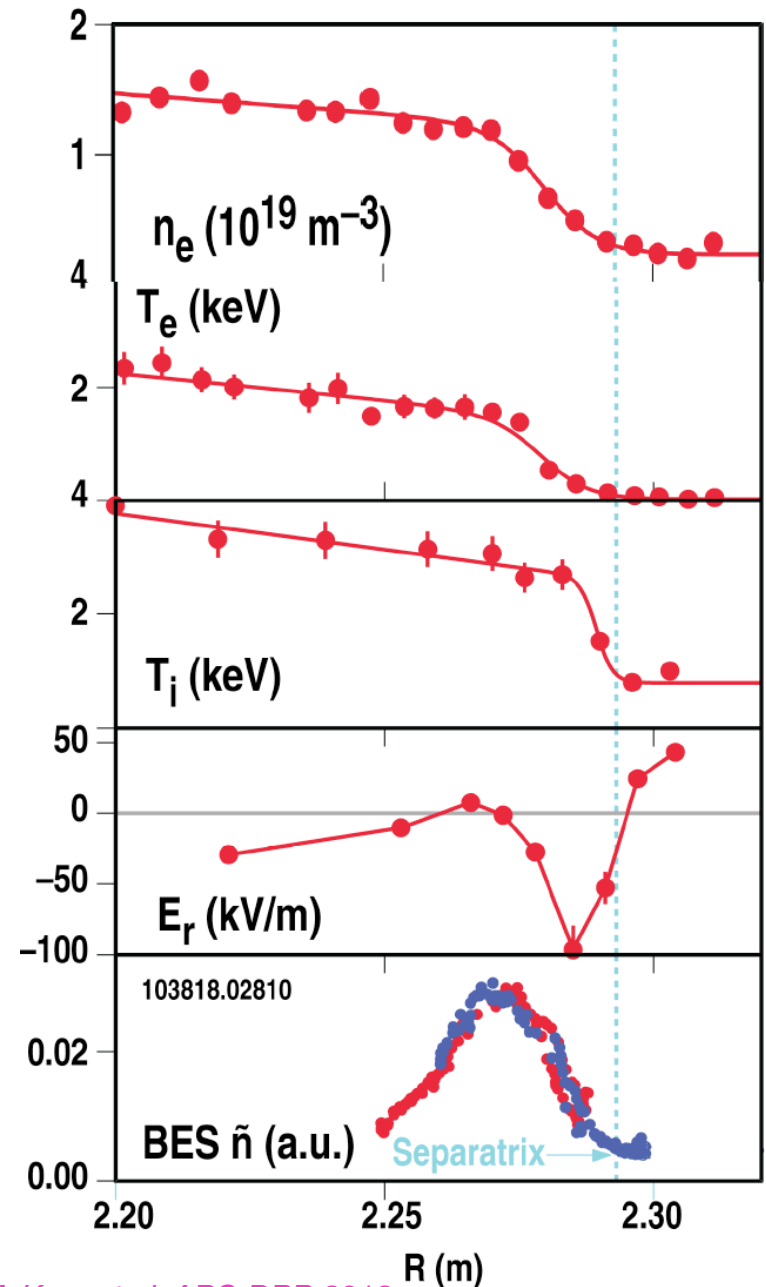
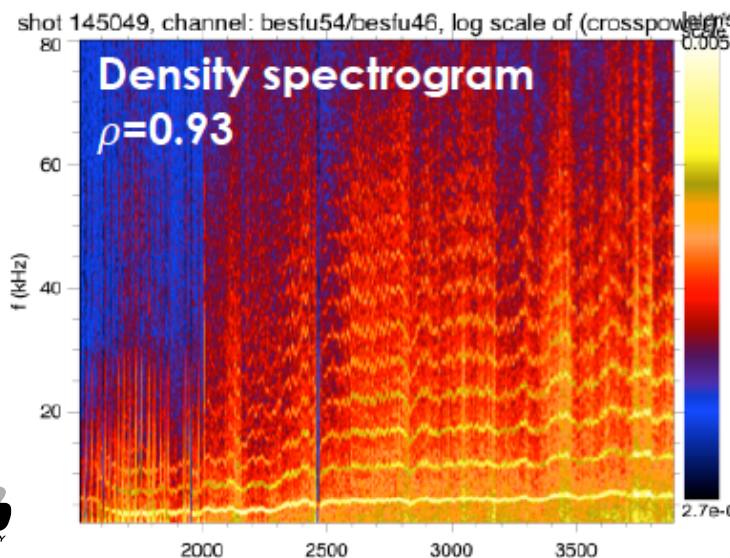
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- QH-mode operates on the peeling boundary
 - EHO is thought to be a saturated peeling mode



W. Solomon, et al, APS-DPP 2013

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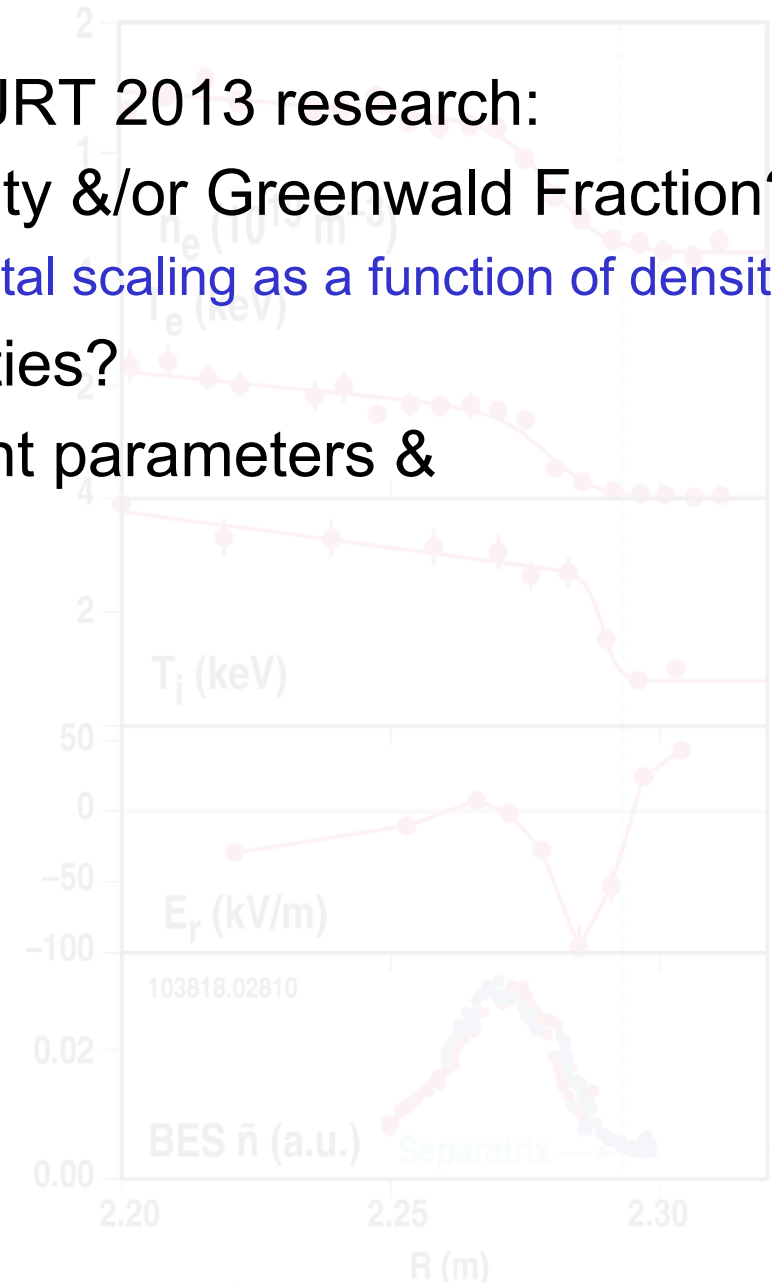
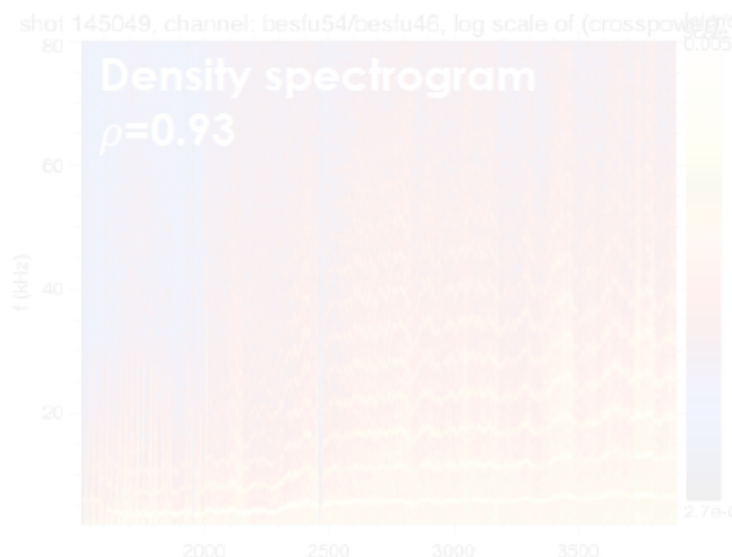
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- QH-mode operates on the peeling boundary
 - EHO is thought to be a saturated peeling mode
- EHO spans the width of the pedestal.
 - Many harmonics visible with BES



G. McKee, et al, APS-DPP 2013

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

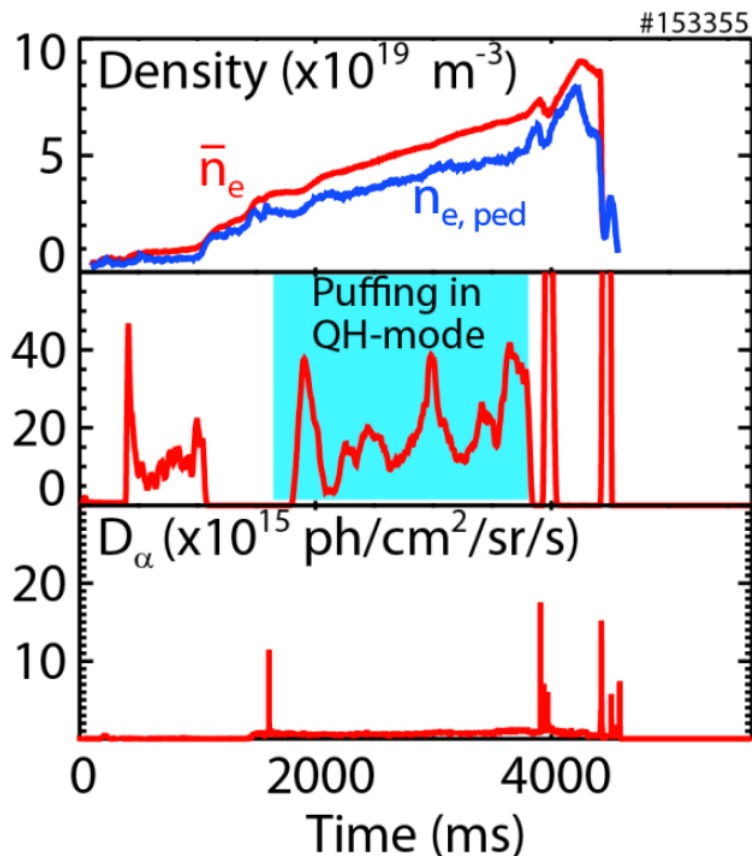
- Key QH-Mode characteristics
 - ELMS are controlled by the edge oscillation.
- Key questions addressed in JRT 2013 research:
 - Is QH mode accessible at high density &/or Greenwald Fraction?
 - How well does EPED capture the pedestal scaling as a function of density?
 - How well does the EHO flush impurities?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



G. McKee, et al, APS-DPP 2013

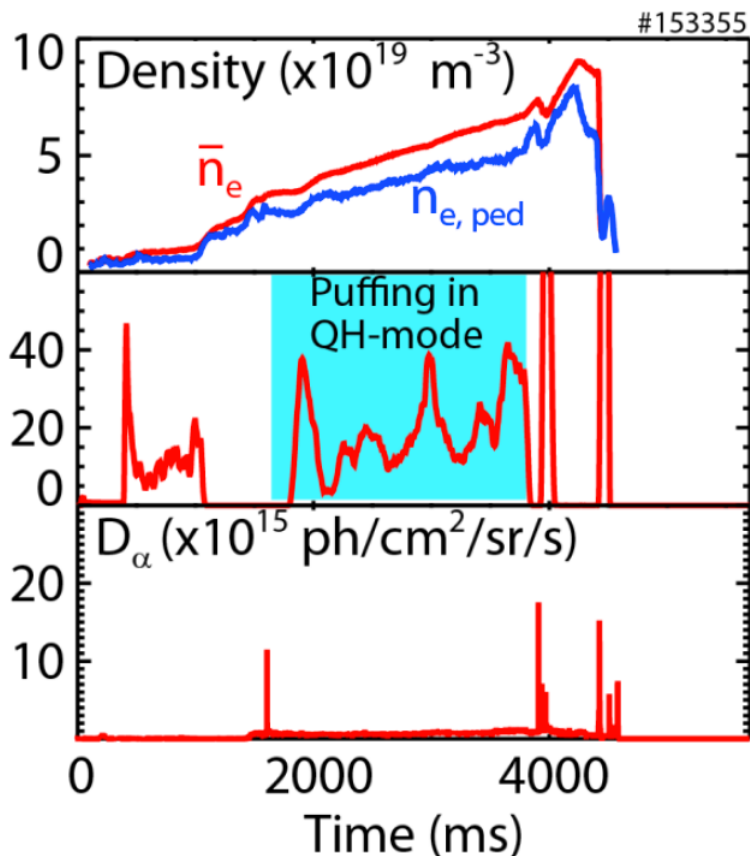
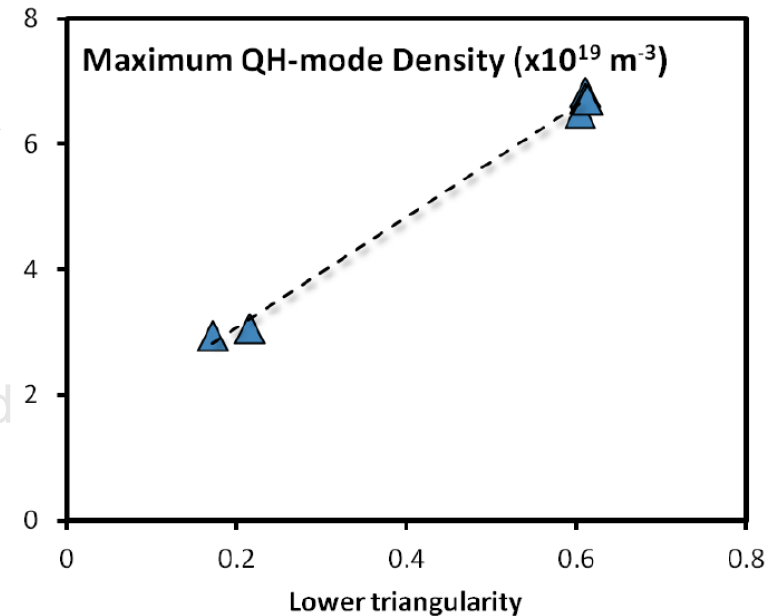
Stronger Shaping Allows Access to Higher Density QH-Modes

- P.-B. theory indicated that increasing the triangularity could raise the QH-mode density limit
- Plasma density raised by gas puffing
- Higher absolute density achieved with stronger shaping
- Greenwald fractions up to 0.8 have been achieved



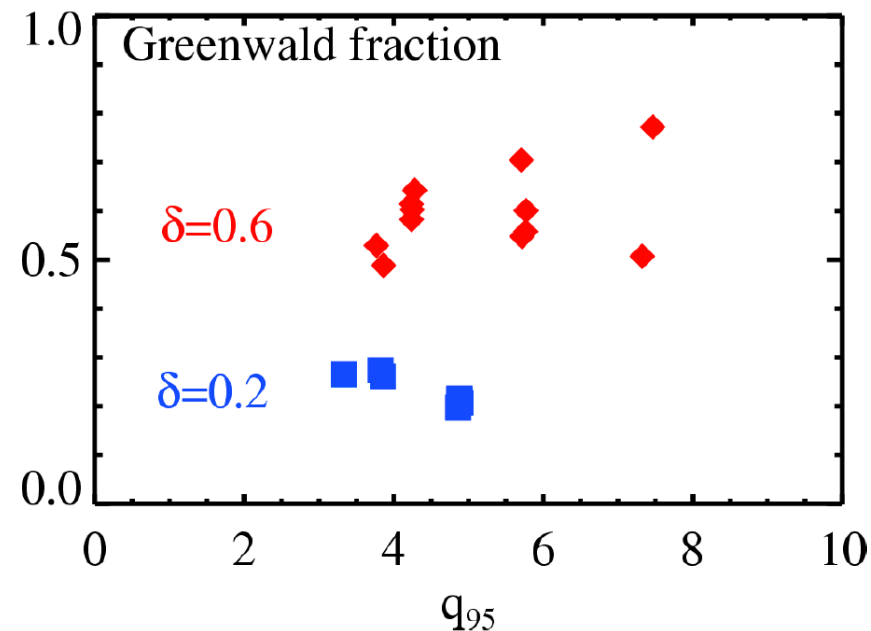
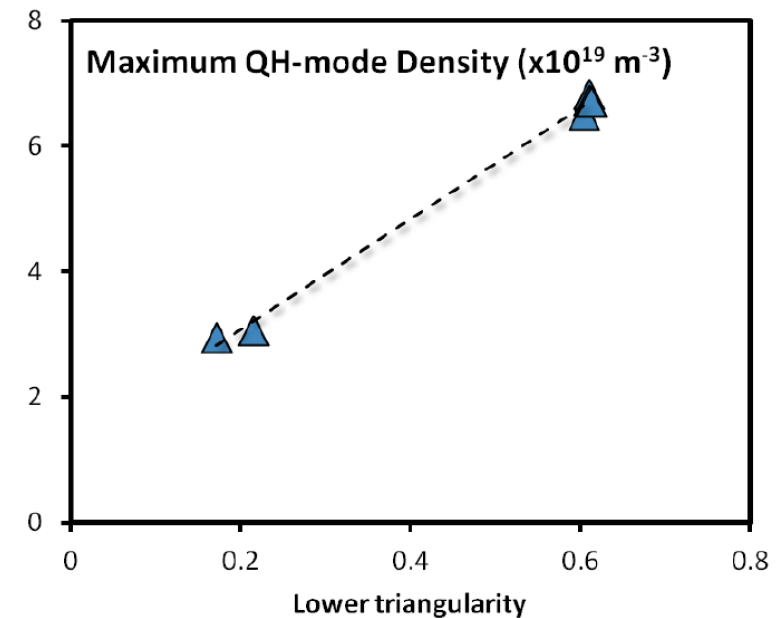
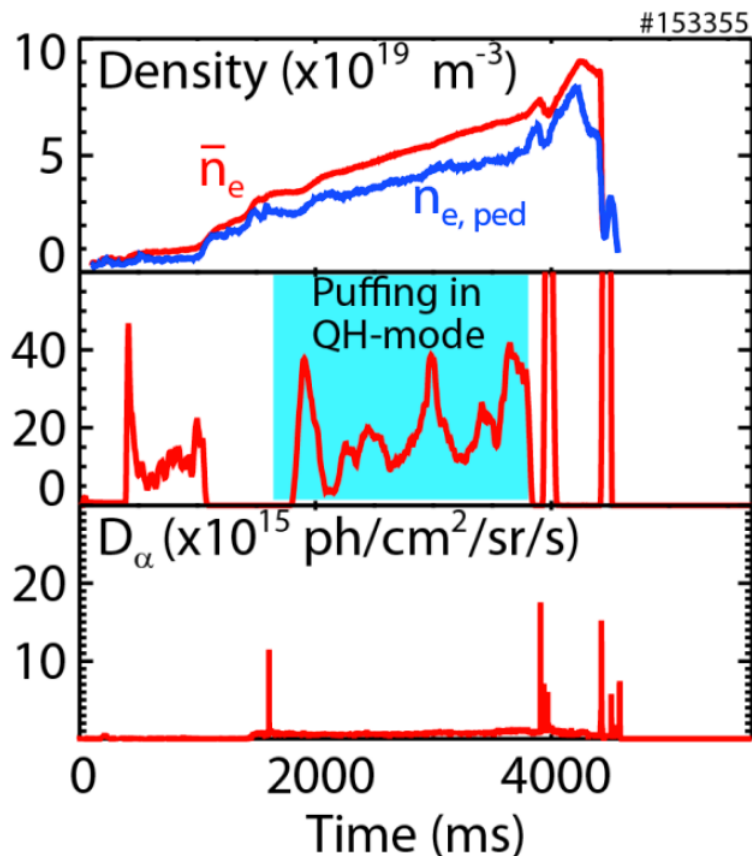
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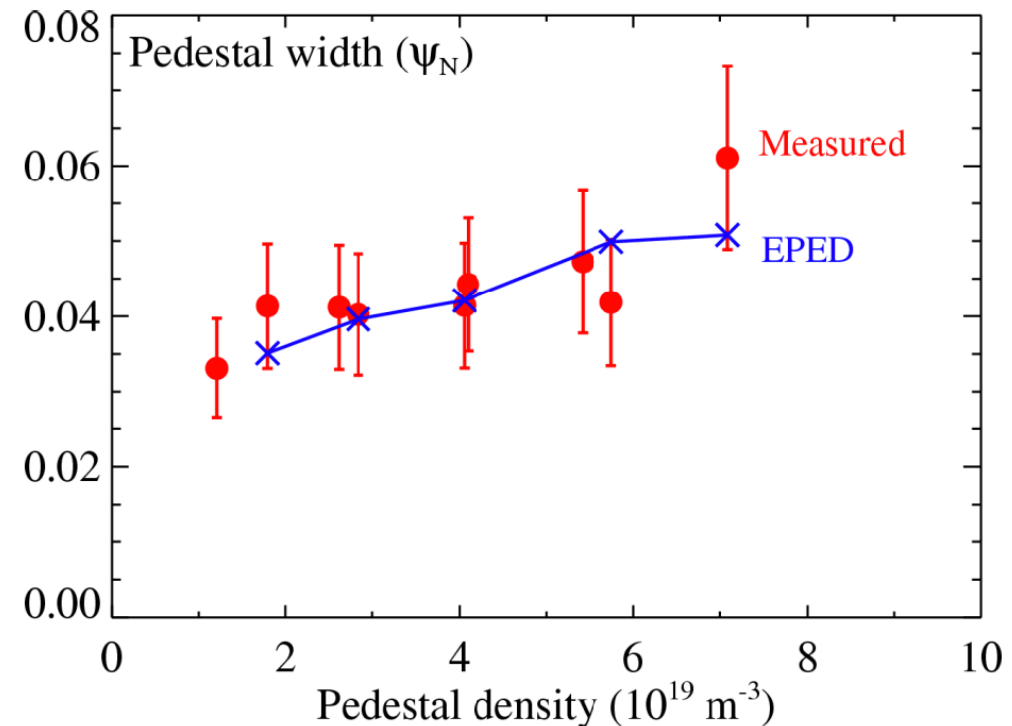
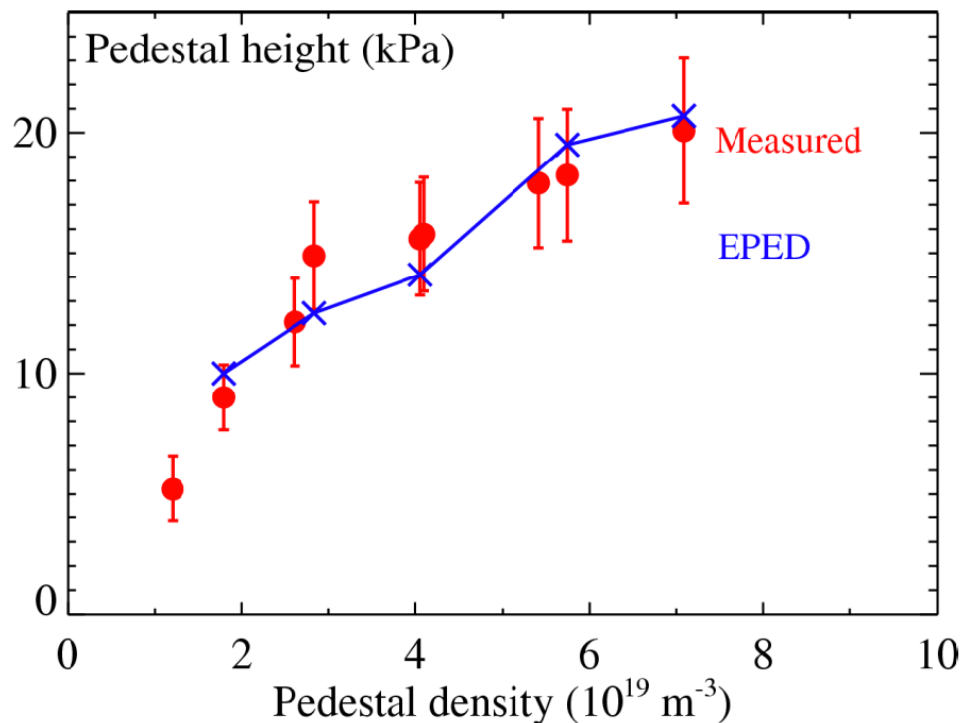
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EPED Modeling Can Reproduce the Pedestal in QH-Mode Trends as a Function of Density

- Recall: EPED is based on simultaneous constraints from transport and stability
- EPED accurately predicts the increase in pedestal height as a function of density.
- Also reproduces the trend in the pedestal width.

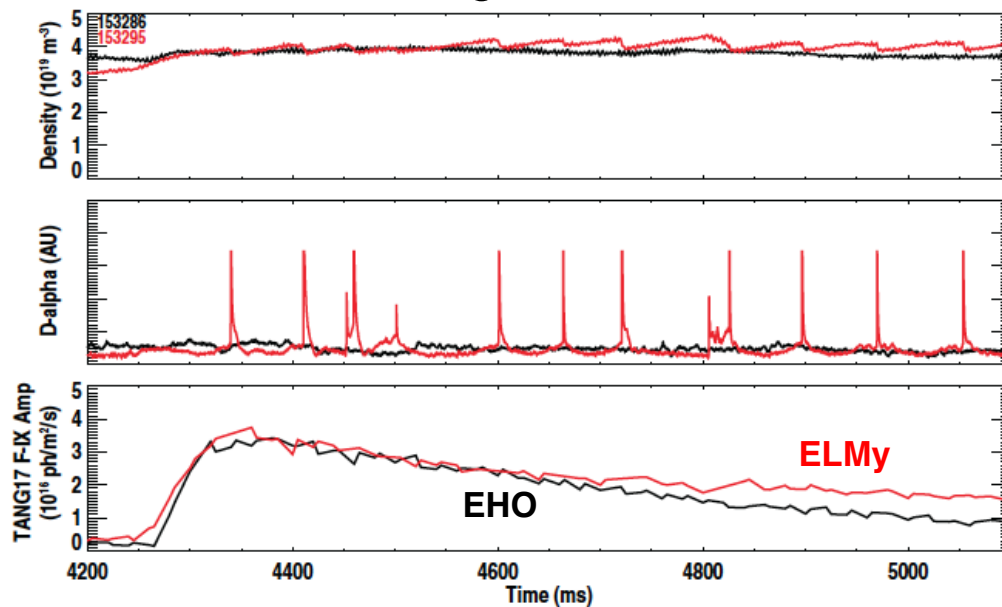


The EHO Can Exhaust Impurities Just as Well as Type 1 ELMs

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

- 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

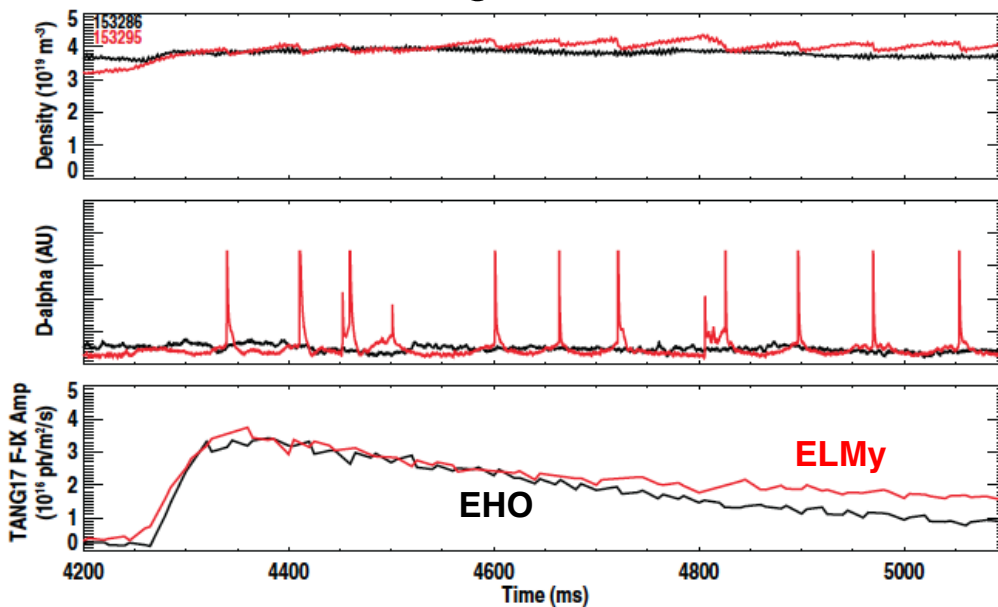


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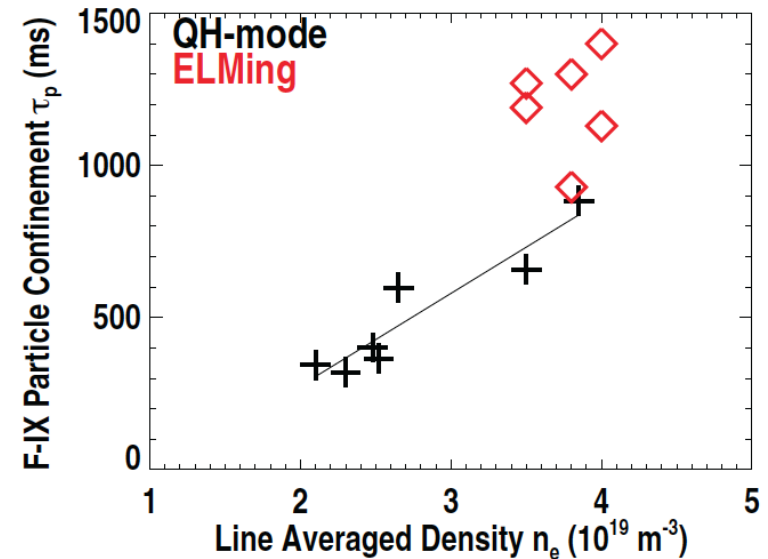
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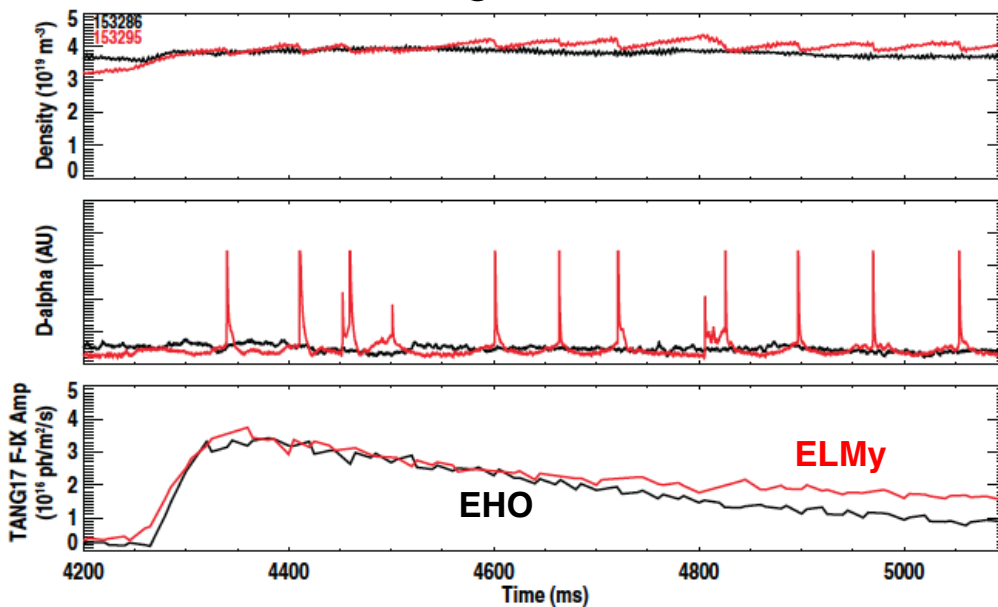


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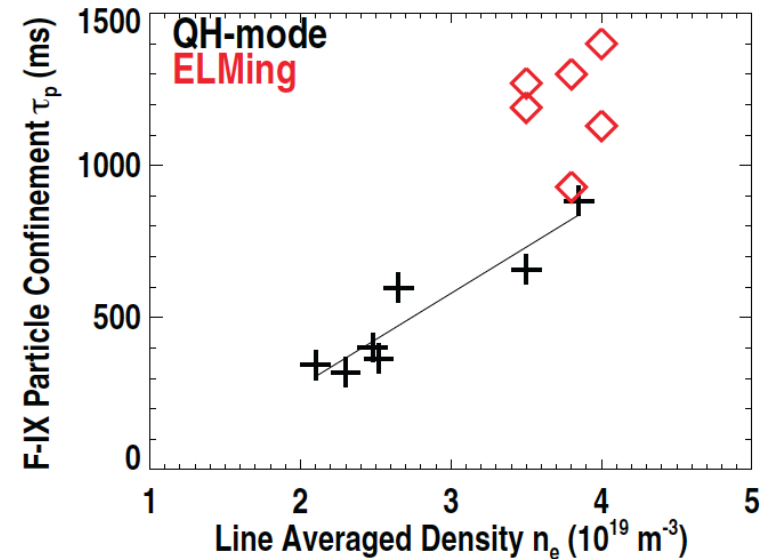
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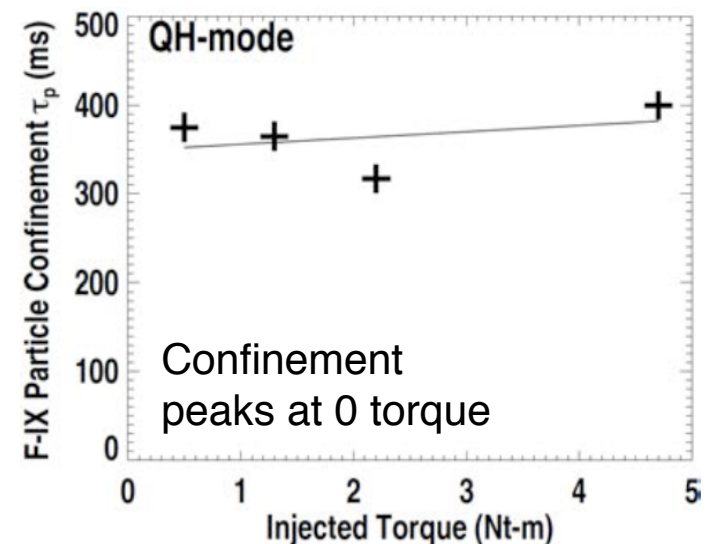
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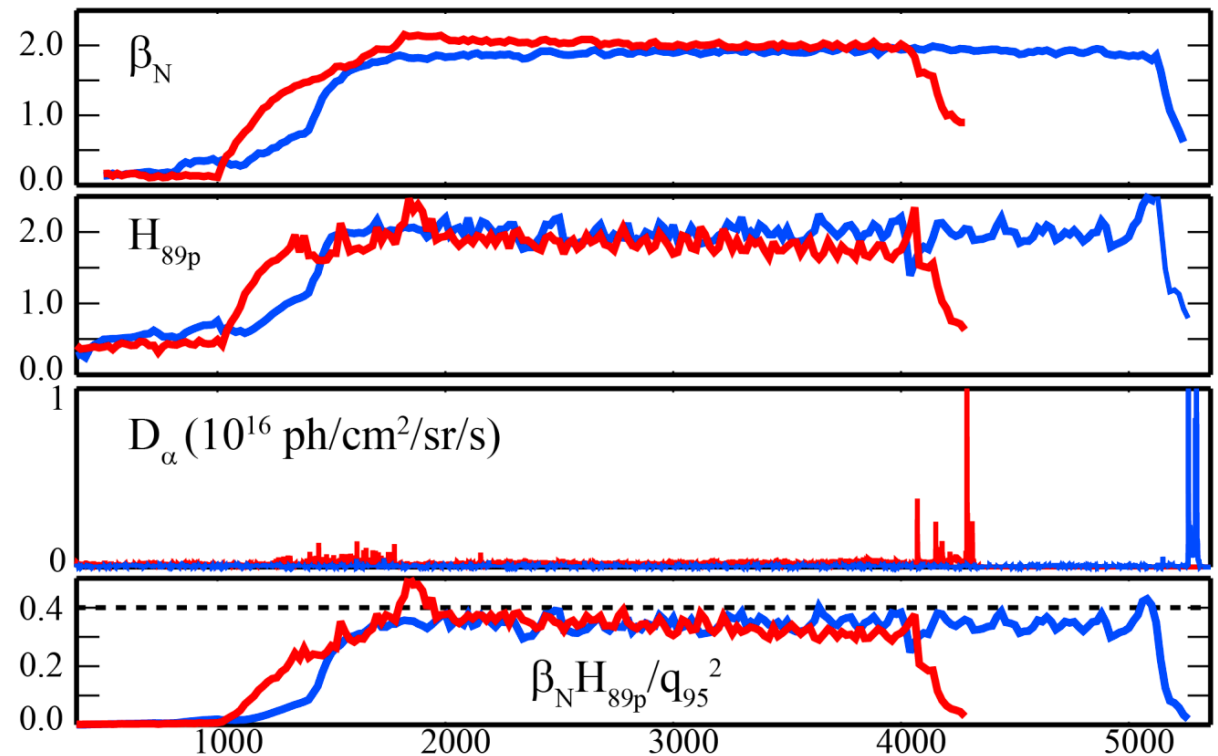
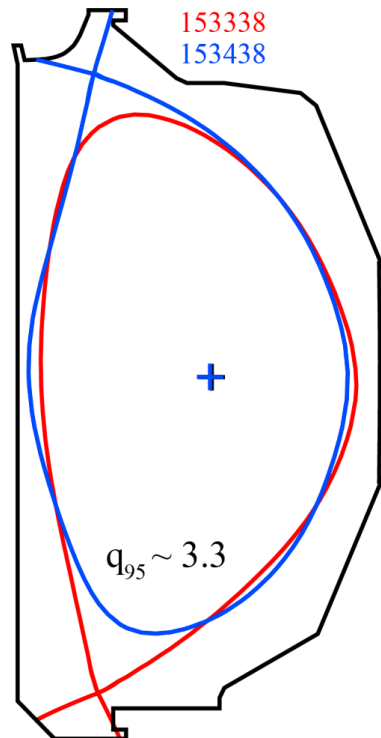
QH-Mode impurity confinement independent of torque



Confinement peaks at 0 torque



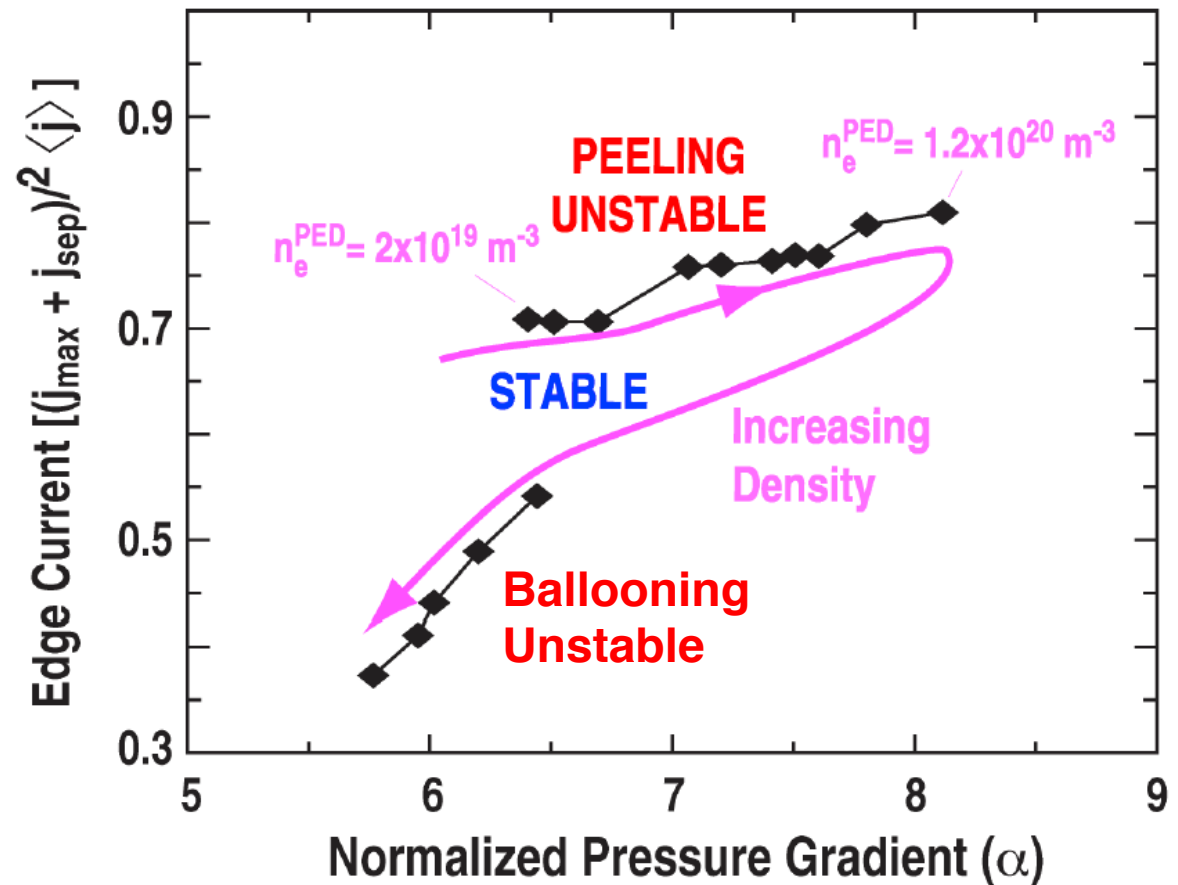
QH-Mode Has been Sustained at the ITER q_{95} in Recent DIII-D Research



- 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

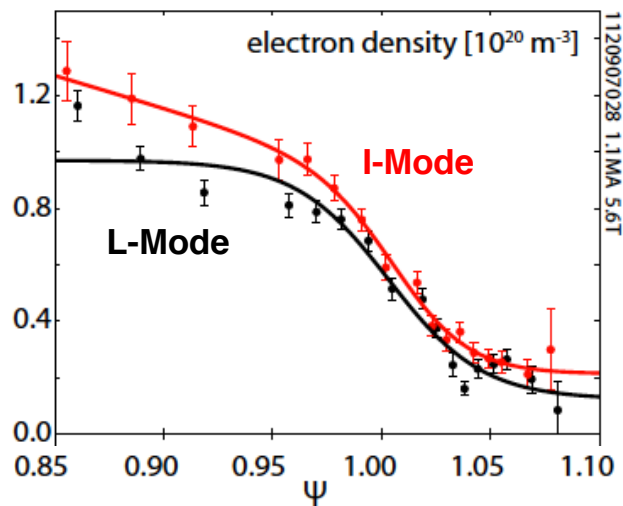


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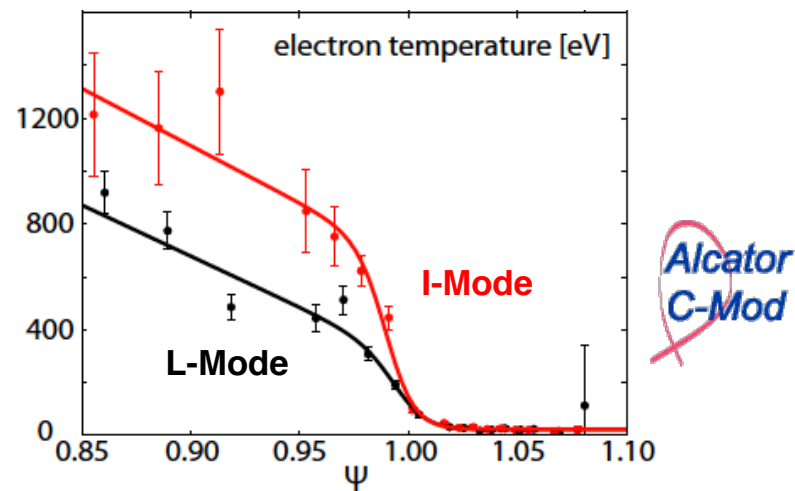
The I-Mode Regime Combines an H-mode Temperature Profile w/ and L-mode Density Profile

Similar Density Profiles in L- and I-modes.



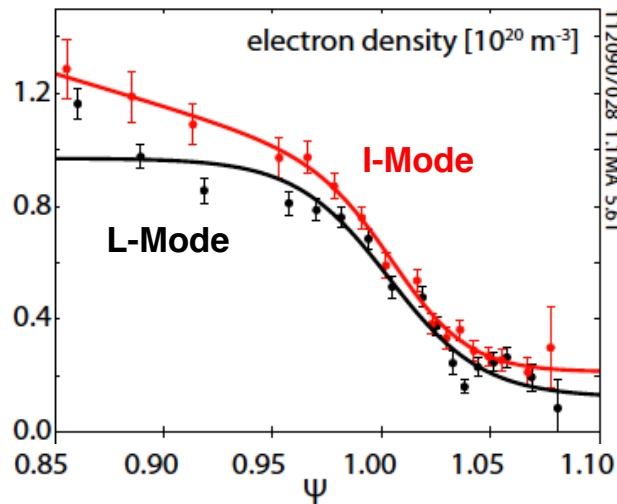
J. Walk, APS 2013

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



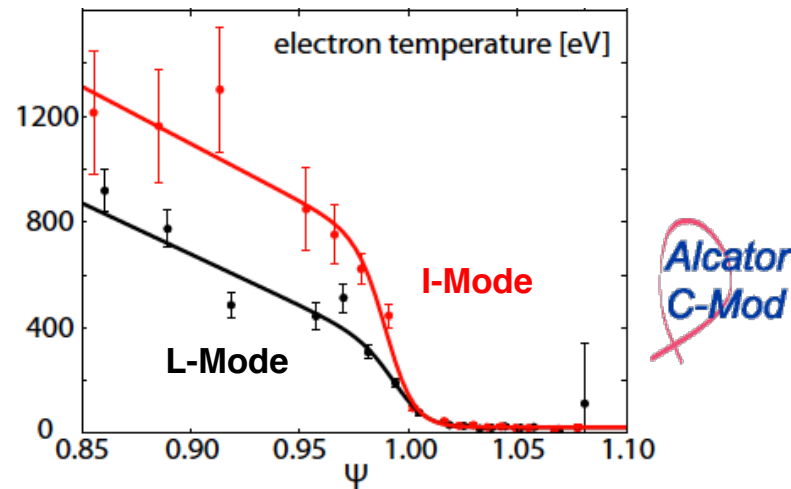
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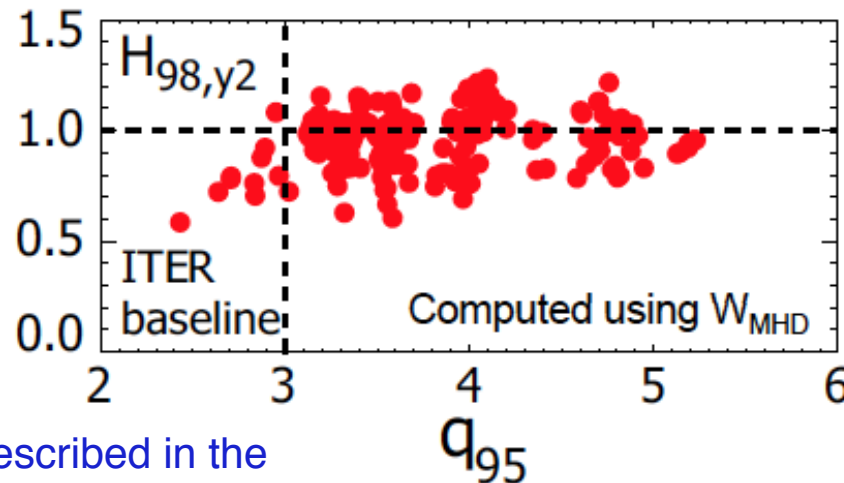
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A. Hubbard, et al., 2012 FEC

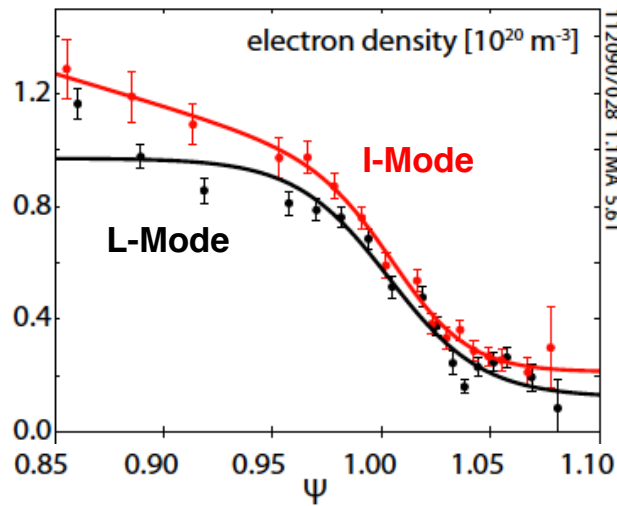
- Can access ITER-relevant confinement at the correct q_{95}



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

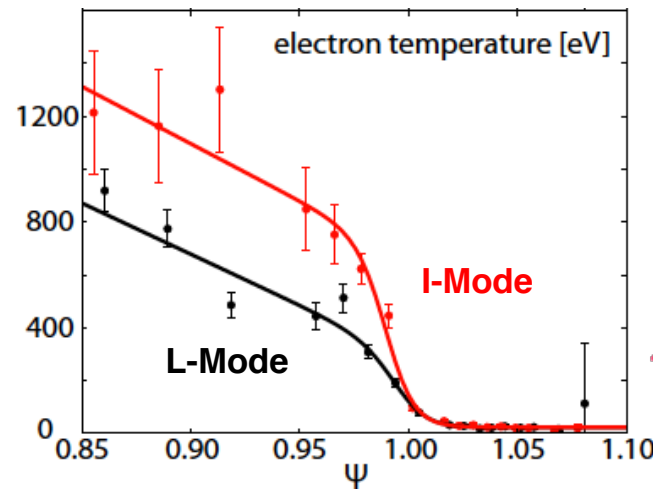
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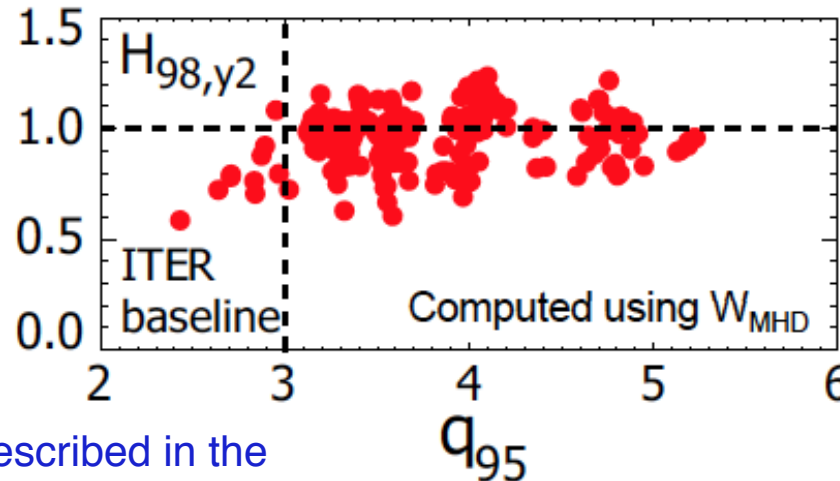
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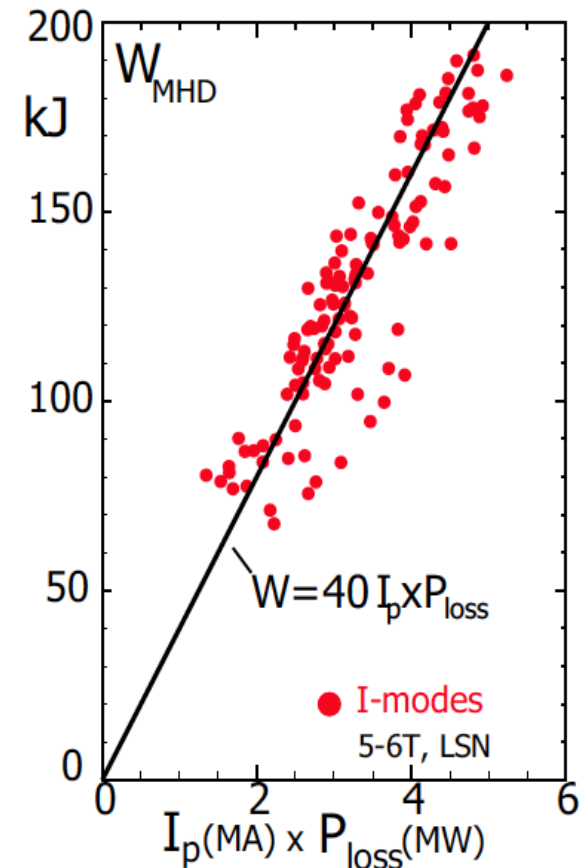
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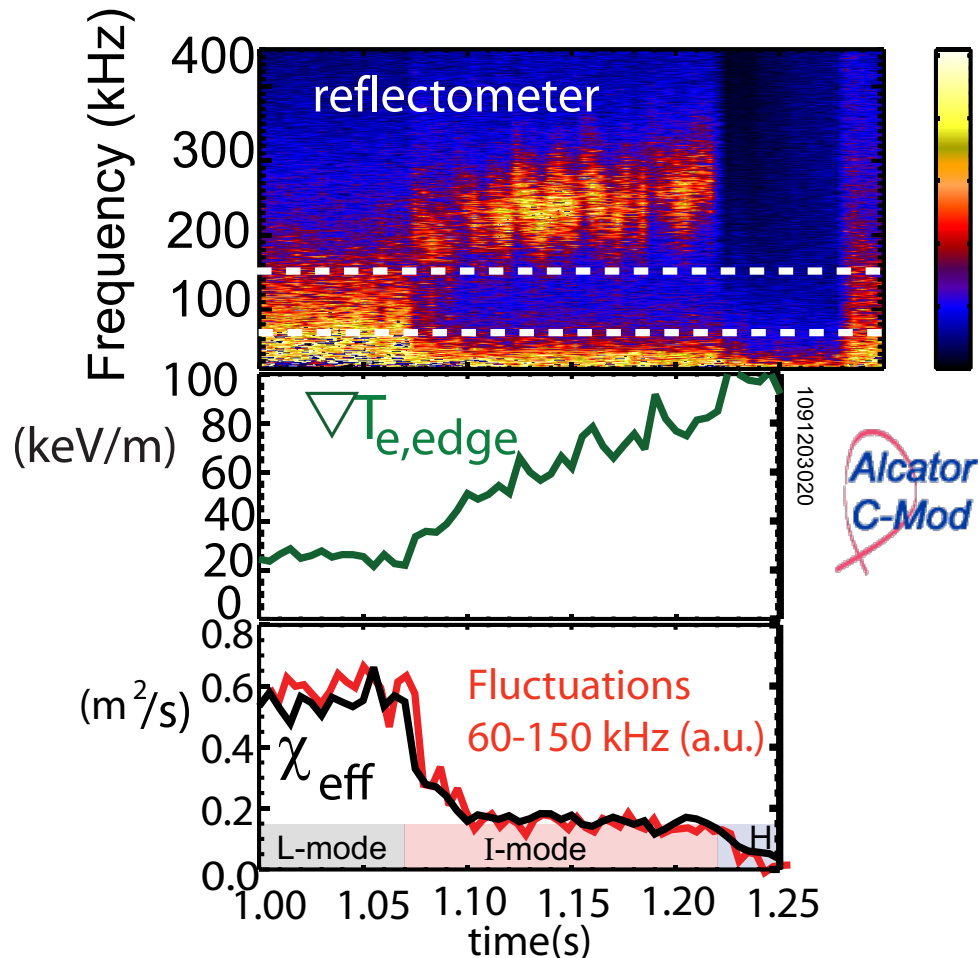
- I-mode exhibits minimal/no power degradation
 - In contrast to $\tau_{98} \sim I_p P^{-0.7}$ (or $W \sim I_p P^{0.3}$)

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.

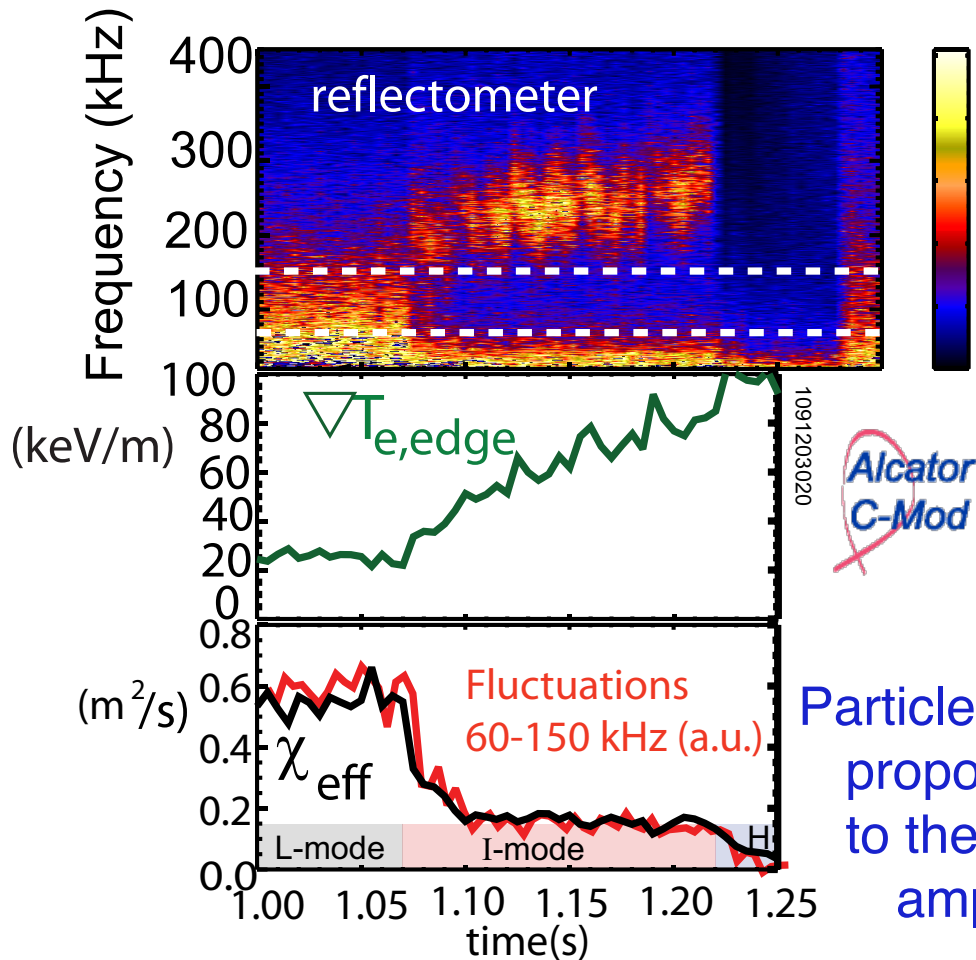


Frequency	100-400 kHz
Spread ($\delta f/f$)	$\sim 0.25-0.5$
Peak amplitude dn_e/n_e	$\sim 5-10\%$
Peak amplitude dT_e/T_e	$\sim 1-2\%$

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

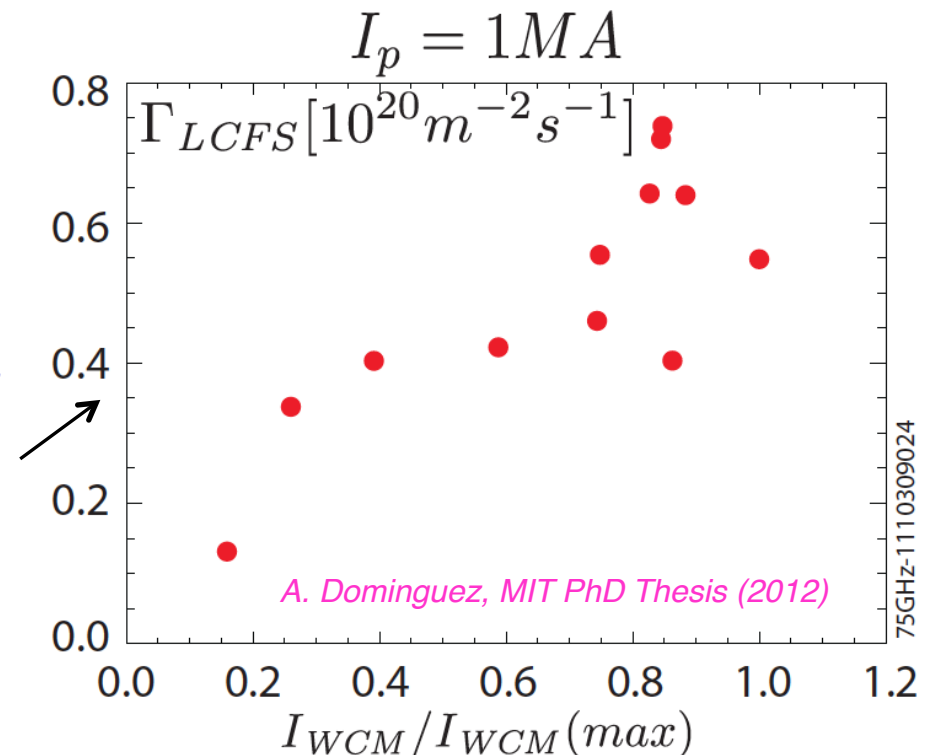
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A. Hubbard, et al., Phys. Plasmas 18, 056115 (2011)

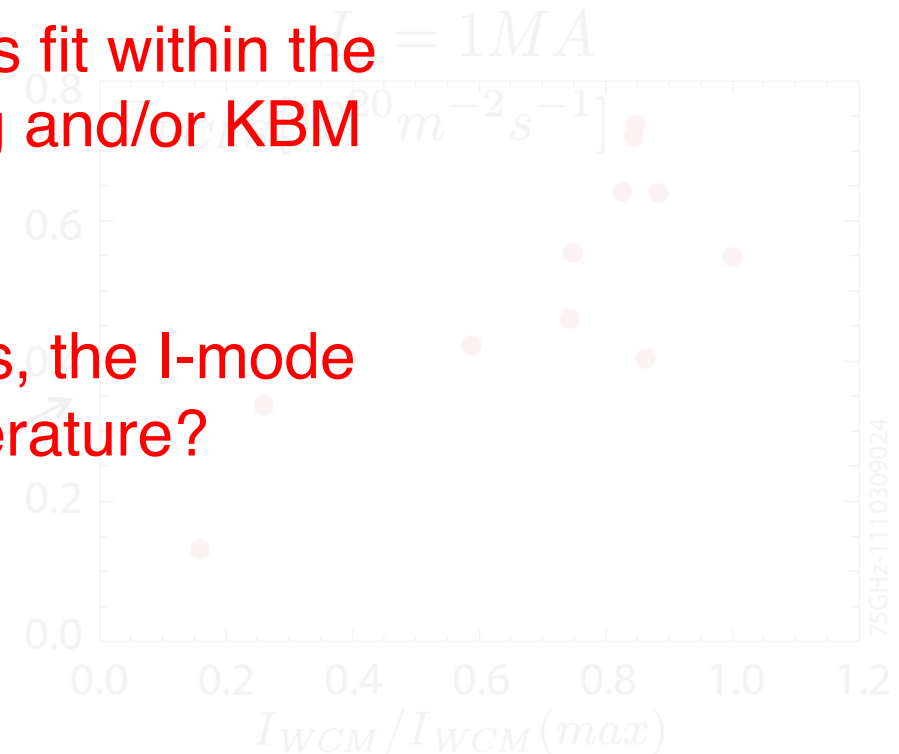
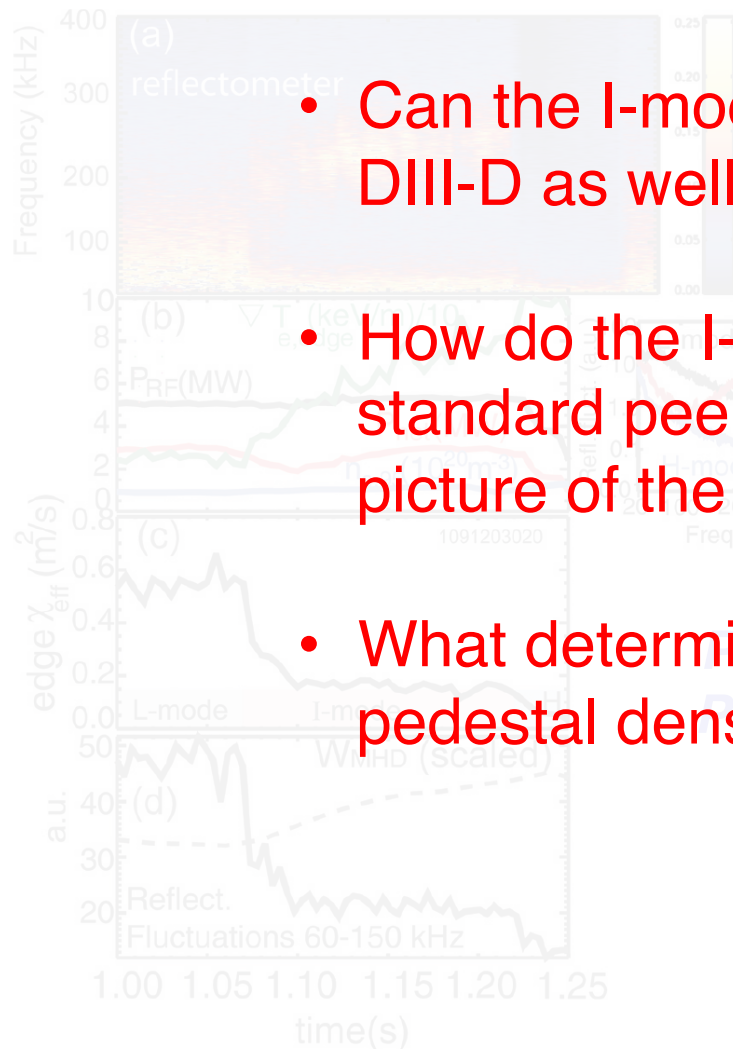
Weakly Coherent Mode Provides Density Control in C-MOD I-Modes

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

Questions Addressed by Recent Research

- Can the I-mode regime be accessed in DIII-D as well as 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?

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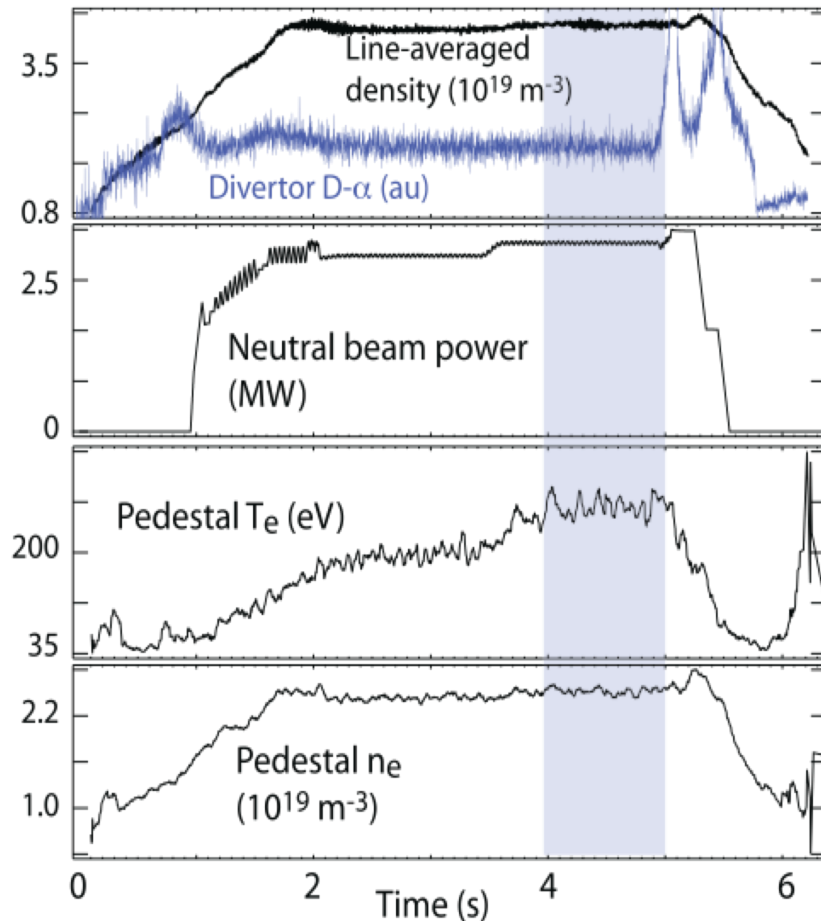
A. Hubbard, et al., Phys. Plasmas 18, 056115 (2011)

A. Dominguez, MIT PhD Thesis (2012)

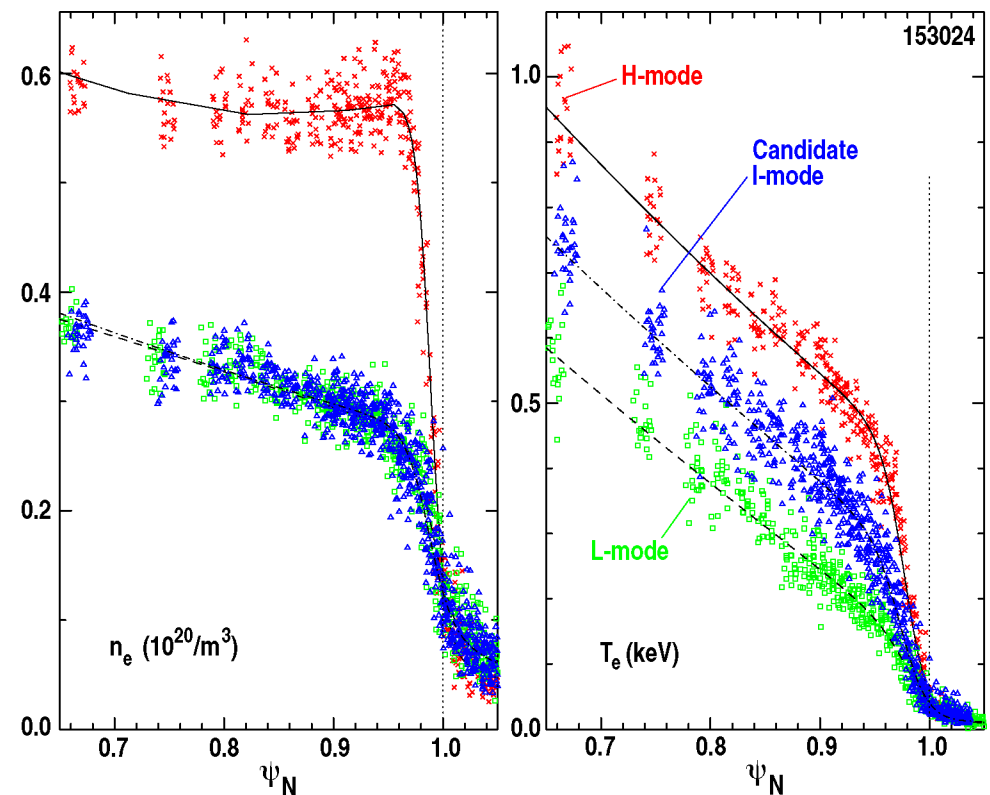
I-Modes Have Been Found in DIII-D

- 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



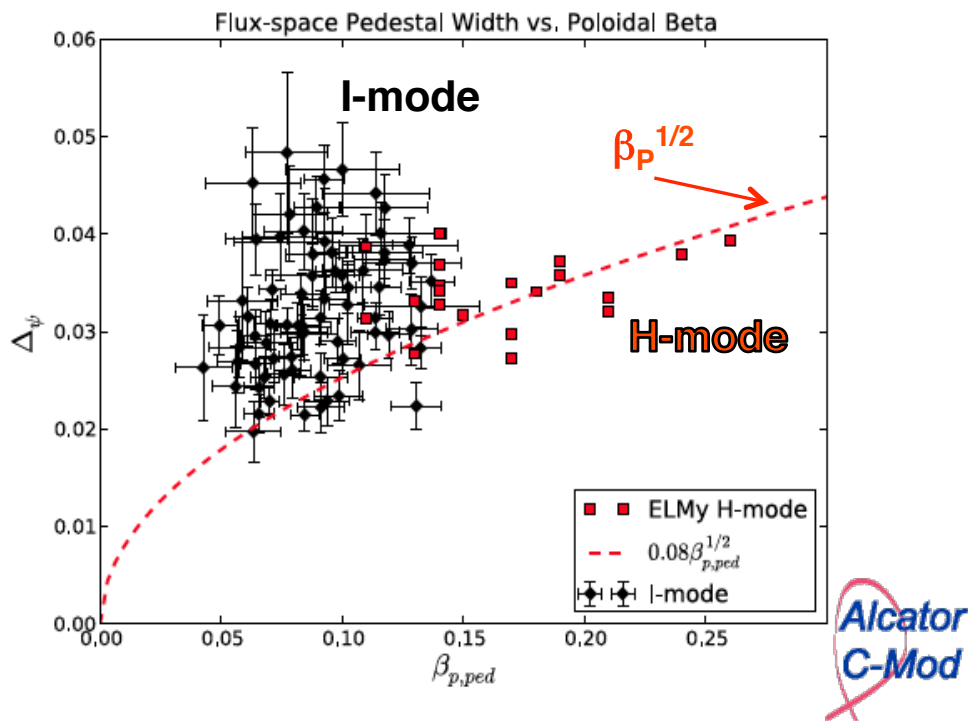
T_e pedestal forms w/o an increased density pedestal



Pedestal Widths are Typically Broader than in H-Mode

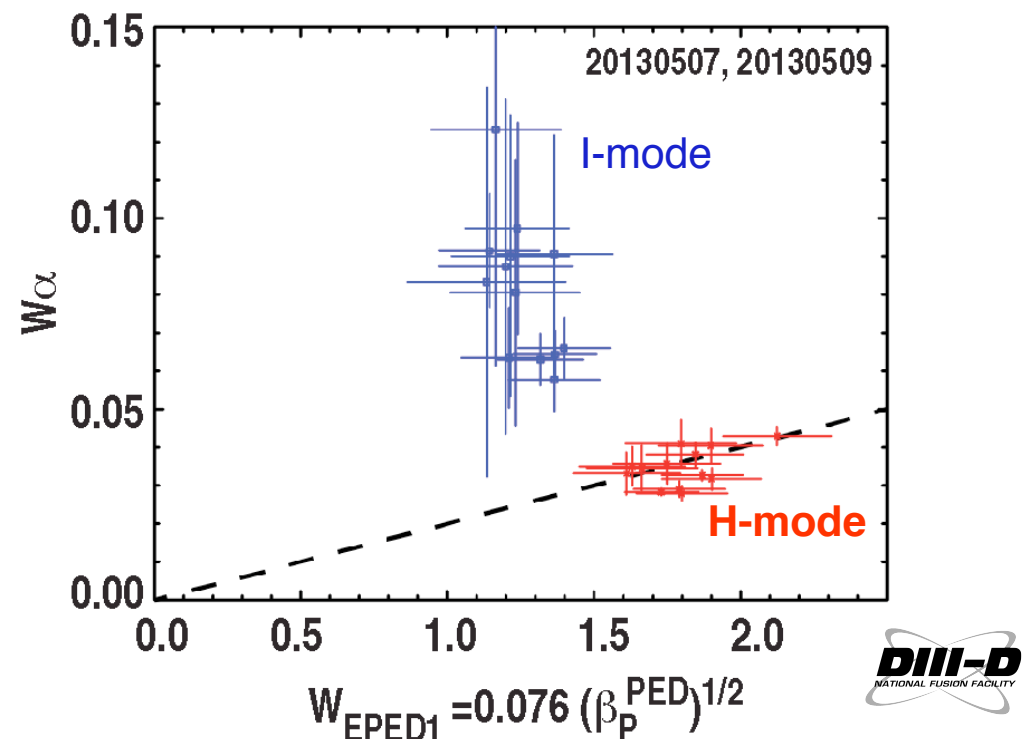
- Type-I ELMy H-mode typically shows pedestal width scaling as $\beta_p^{1/2}$
- I-mode pedestals are consistently broader than predicted for KBM limited pedestals
 - Breaks a fundamental assumption of the EPED model, suggesting I-modes are not limited by the same physics as H-modes.

C-MOD: Pedestal width vs. β_p



J. Walk, APS 2013

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

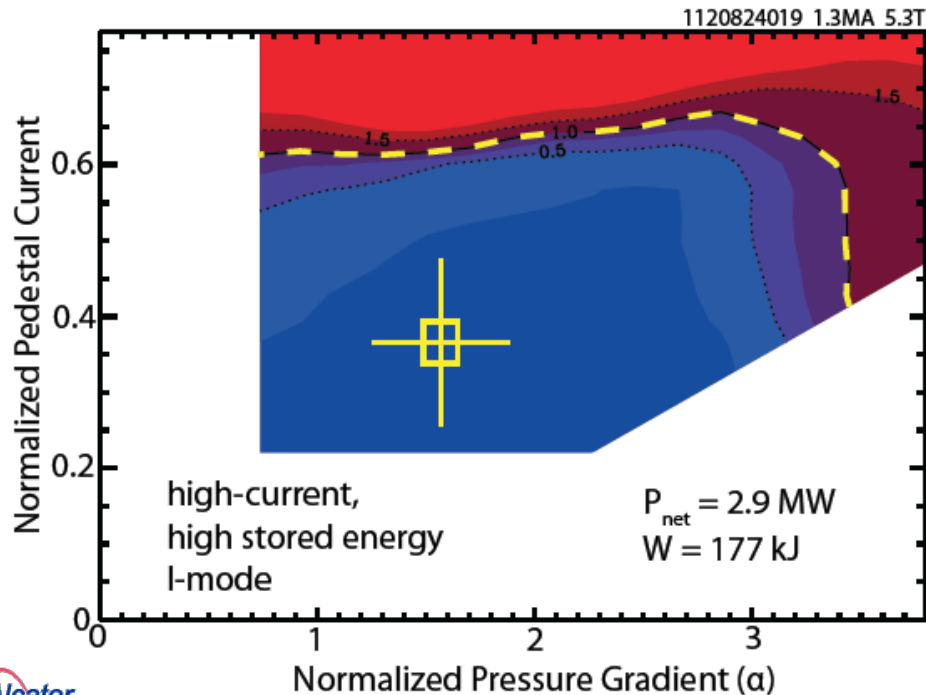


T. Osborne

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

C-MOD

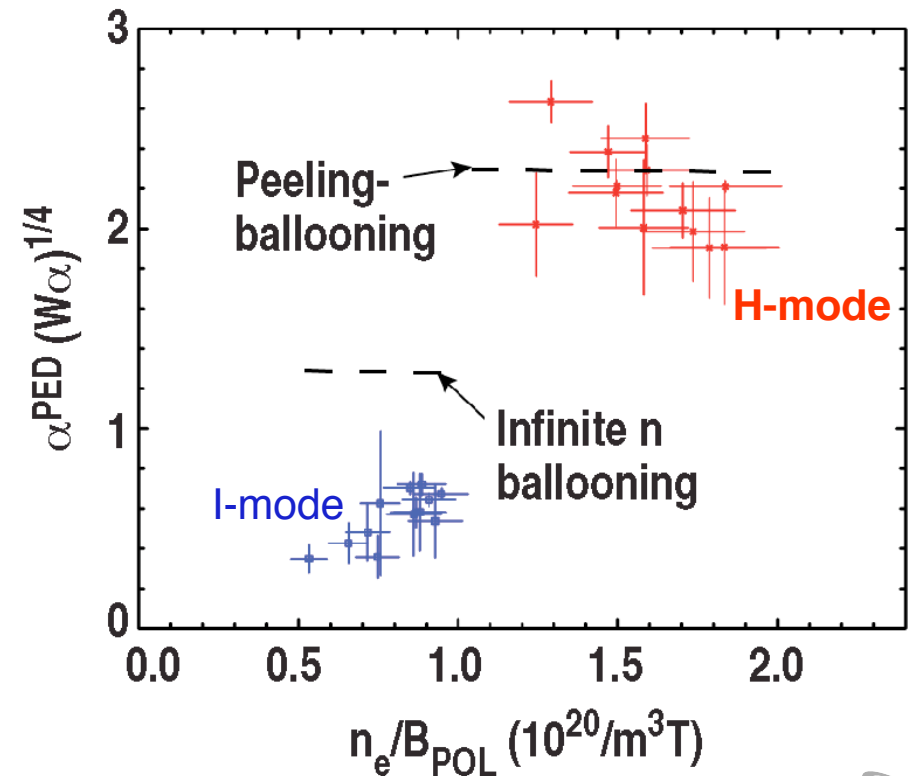
ELITE calculations show that the pedestal is well away from the computed peeling/ballooning boundaries



Alcator
C-Mod

DIII-D

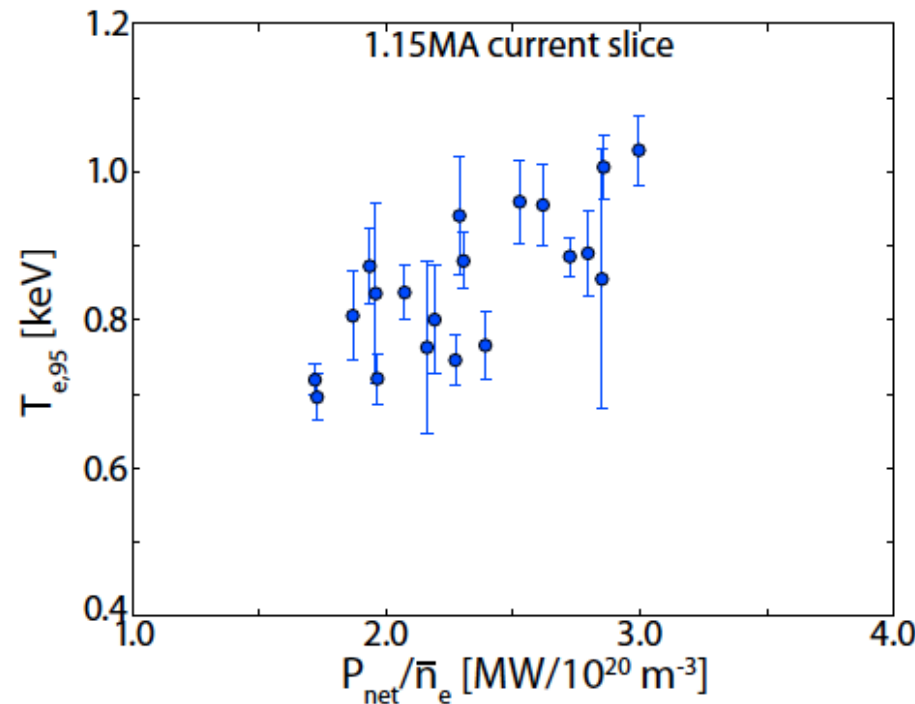
I-mode pedestals evaluated to be well below the peeling/ballooning & infinite-n stability limits



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 $\sim P_{\text{net}}$
- Density level can be controlled as in L-mode.
 - Adjust the power level to achieve the same pedestal temperatures
 - Fueling can be used to increase the pedestal pressure, provided sufficient power is available
- I-modes plasma can be “densified” following the L->I transition

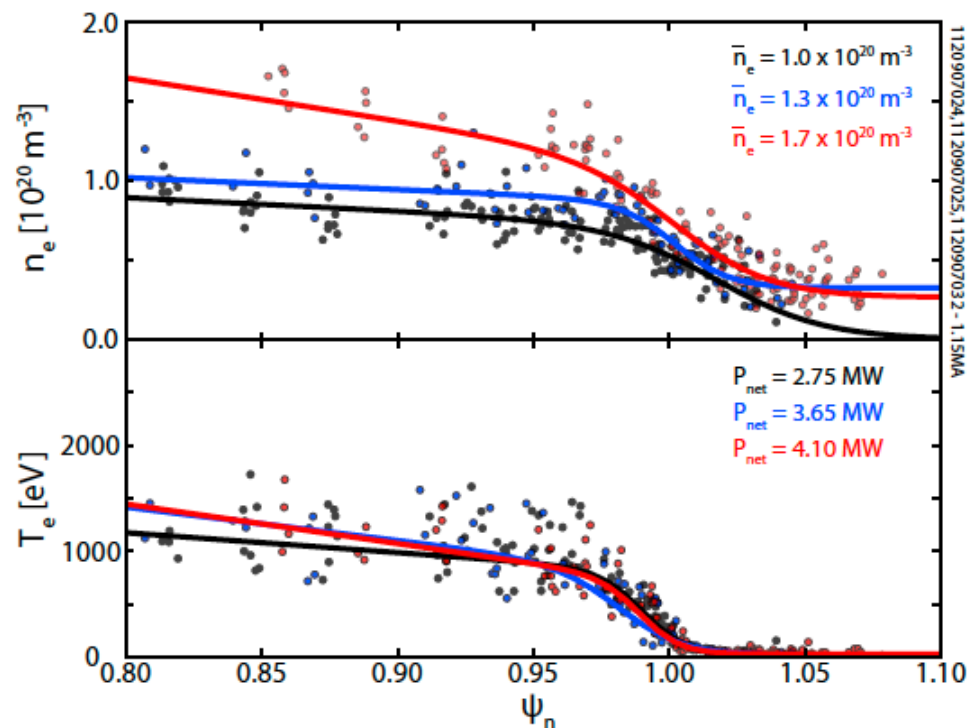


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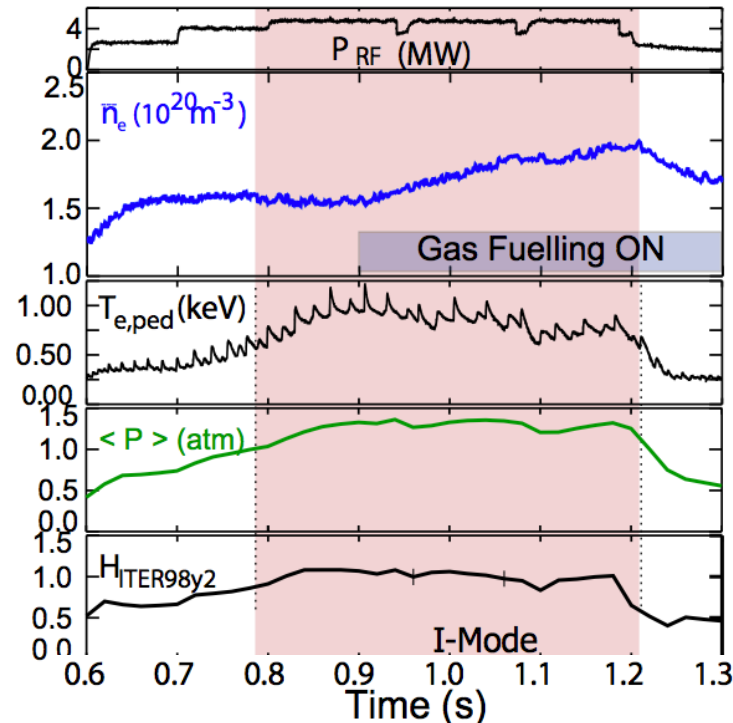


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Potential Recipe:

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

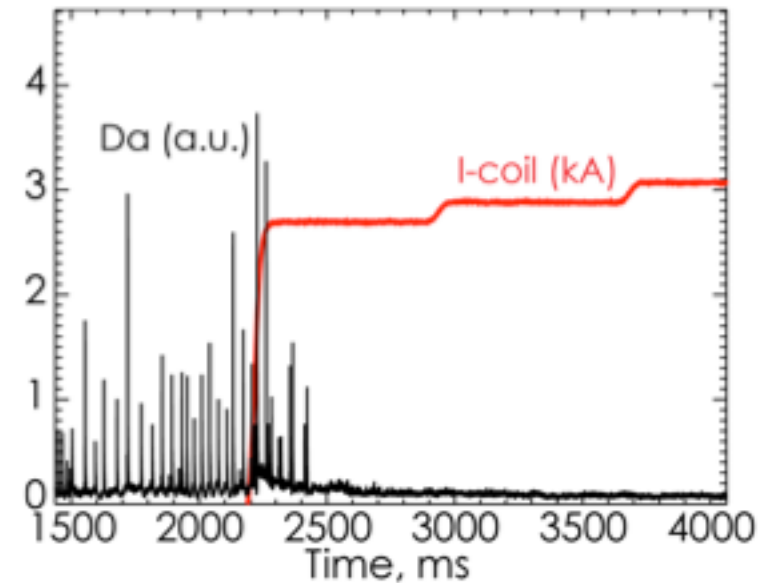
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- Introduction
- Reminder: Key pedestal physics considerations
- Regimes with continuous edge fluctuations
 - Quiescent H-mode
 - I-Mode
- **Recent research on RMP ELM Suppression**
- A very high confinement regime: the EP H-mode in NSTX
- Regime comparisons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

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 edge 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

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



DIII-D I-Coil

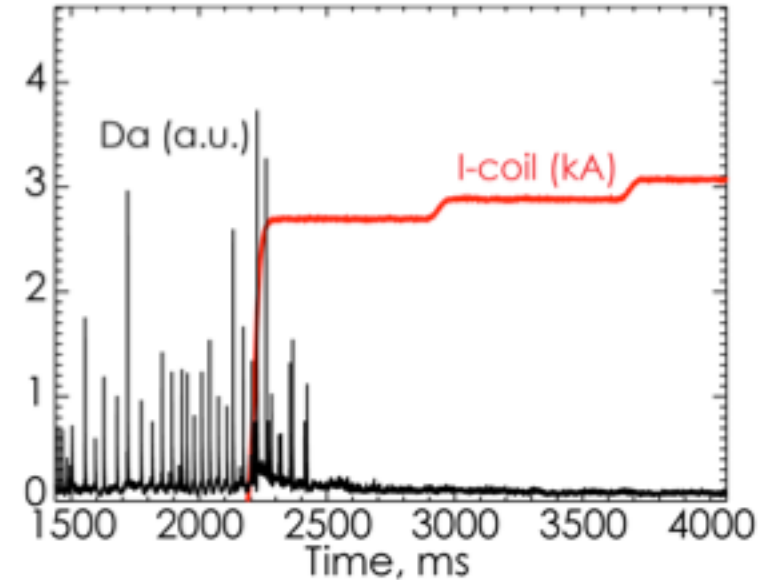


For a more general discussion of RMP issues, see recent BPO webinar by T. Evans.

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 - 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

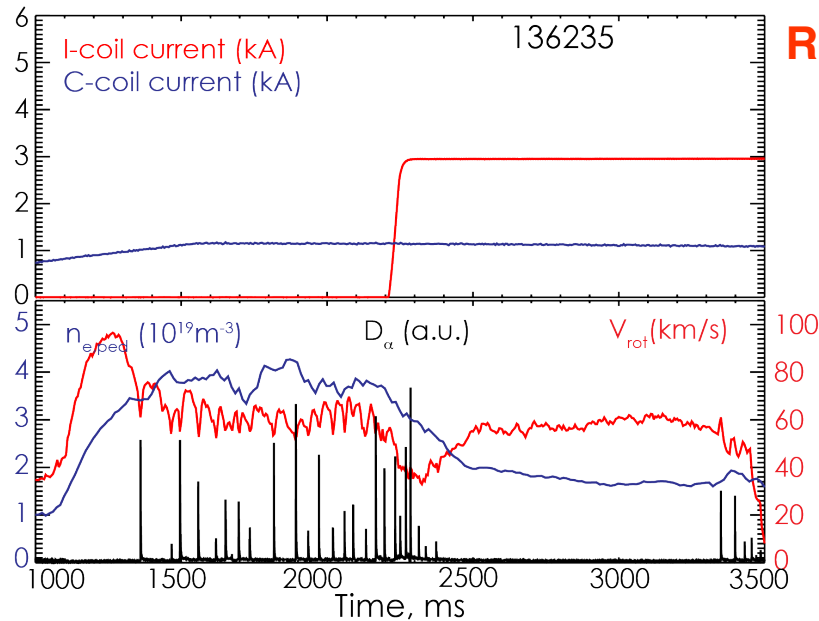


DIII-D I-Coil

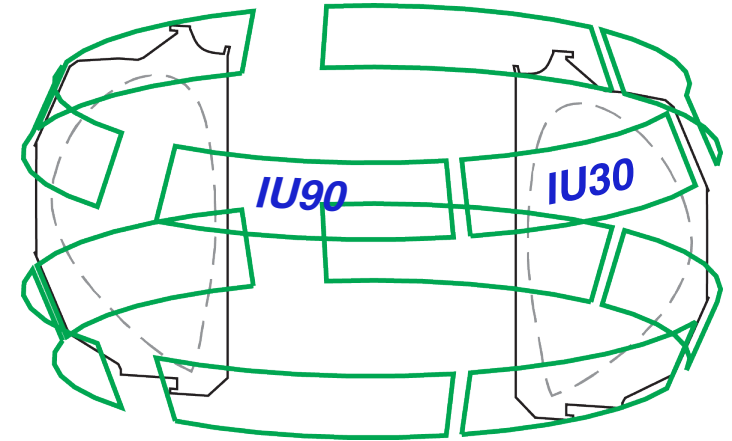


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ELM Suppression Can Be Achieved in DIII-D With Fewer than 12 I-Coils



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

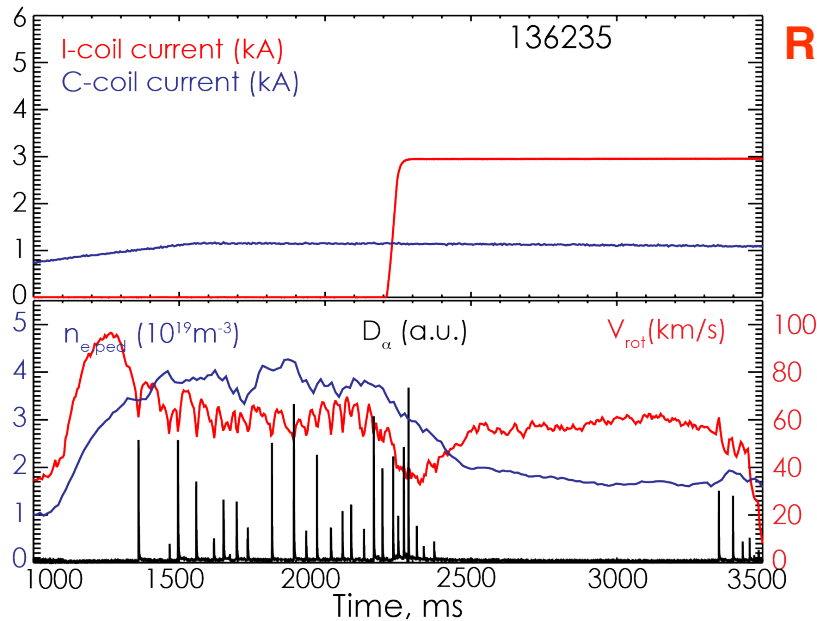


$P_{inj} = 4.5$ MW

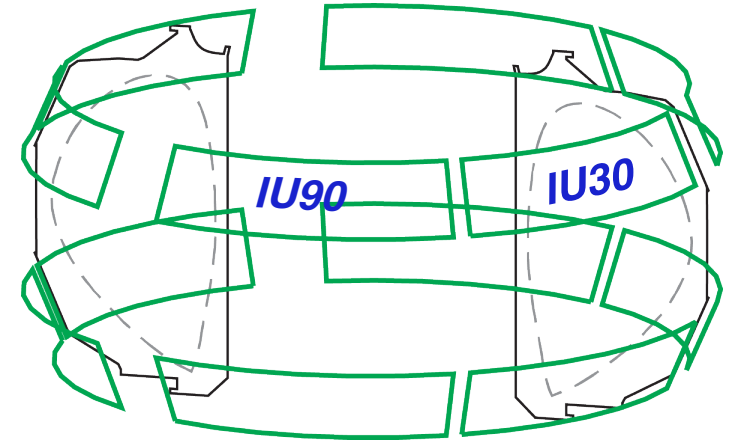


D. Orlov, APS Invited 2013

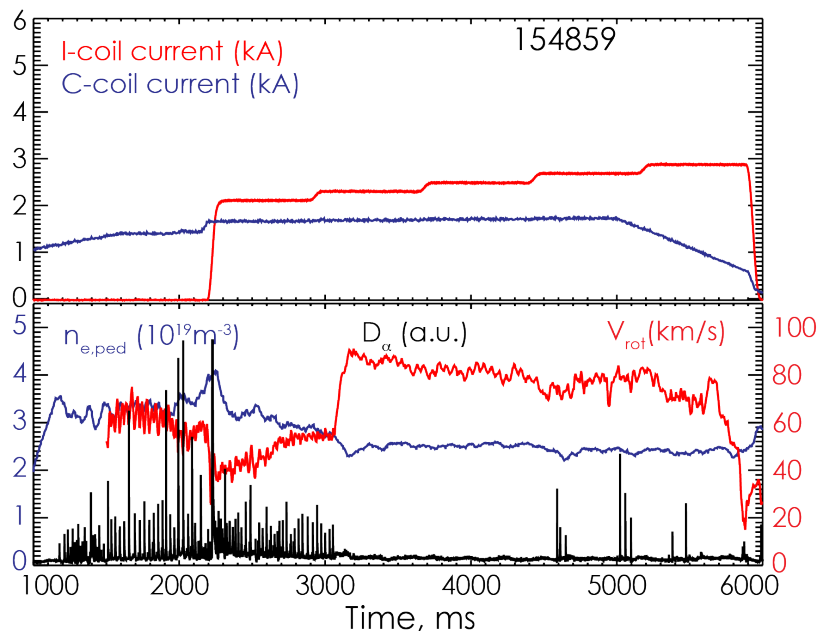
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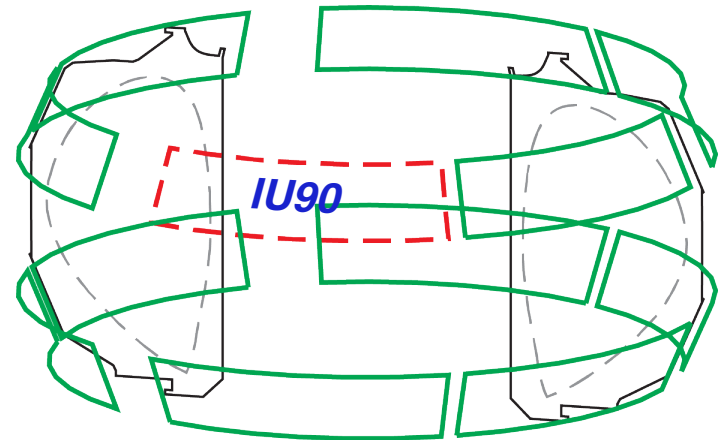
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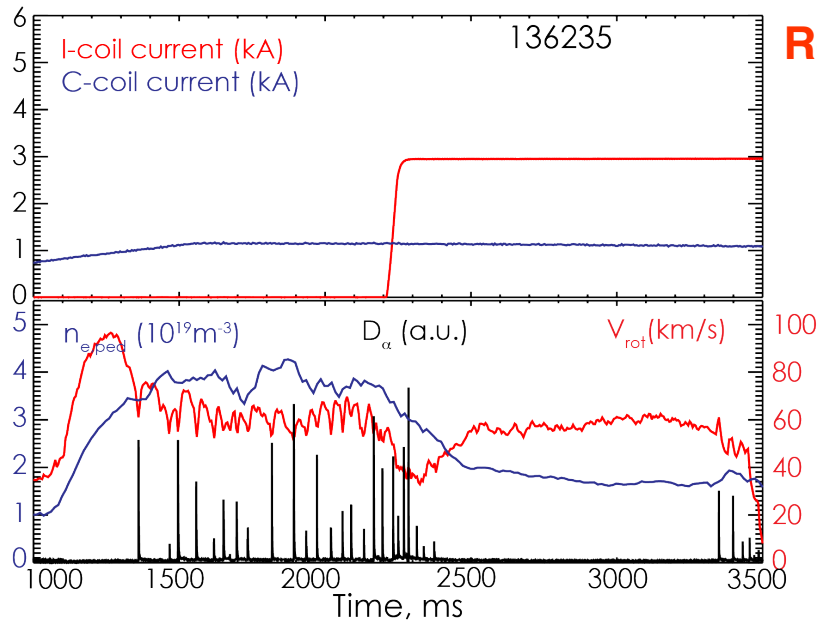
11 Coil Example: Suppression @ $I_{I-coil}=2.3$ kA



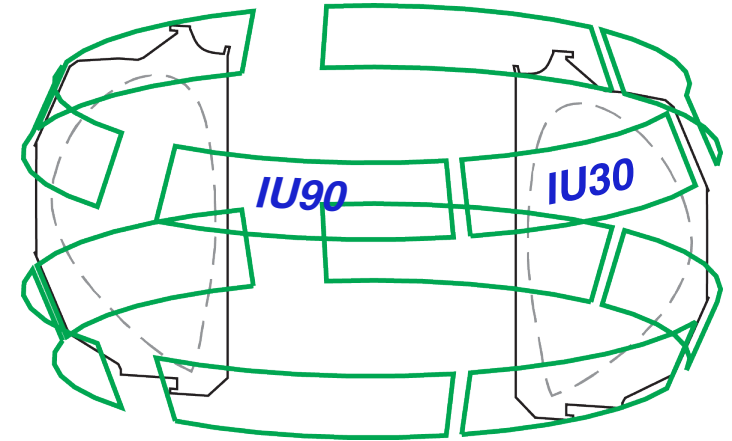
$P_{inj} = 5.9$ MW

D. Orlov, APS Invited 2013

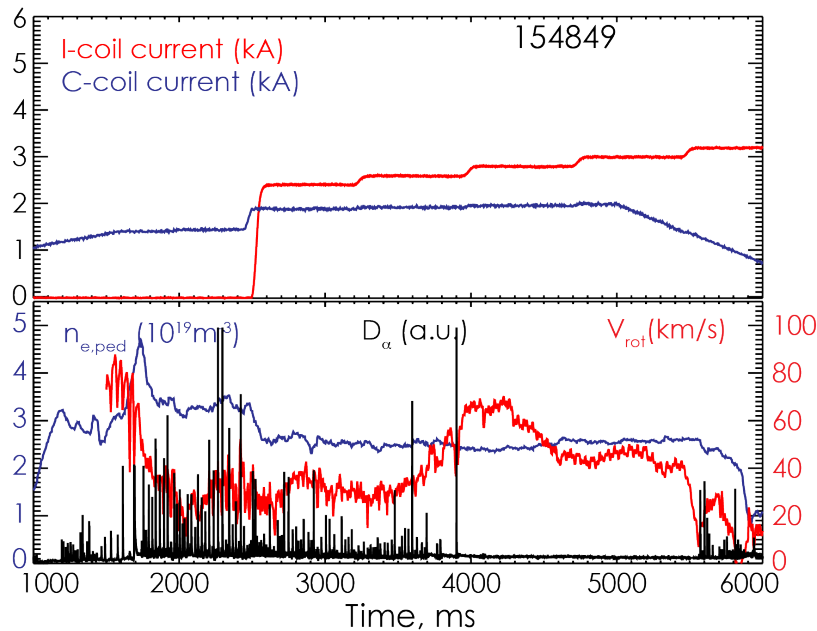
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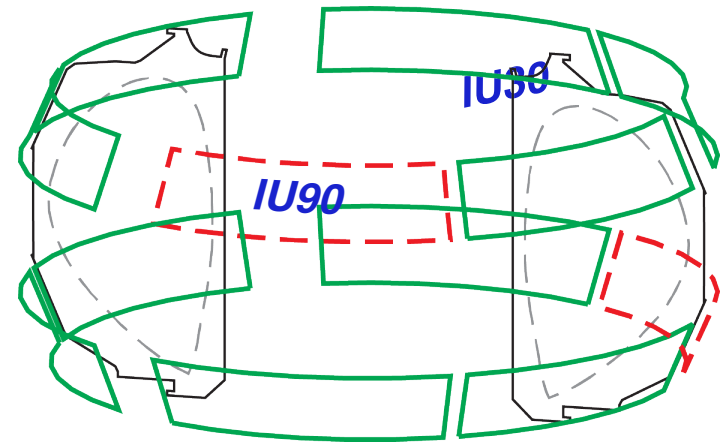
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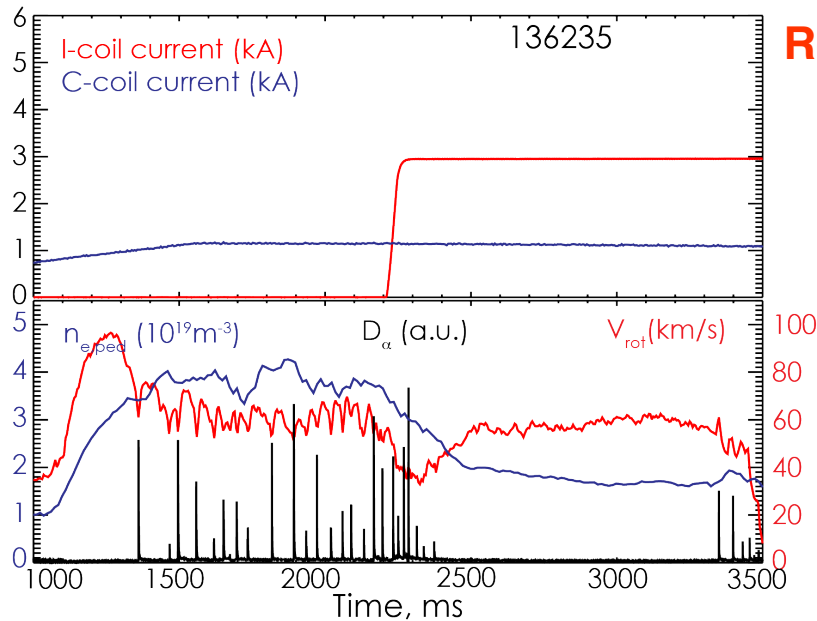
10 Coil Example: Suppression @ $I_{I-coil}=2.8$ kA



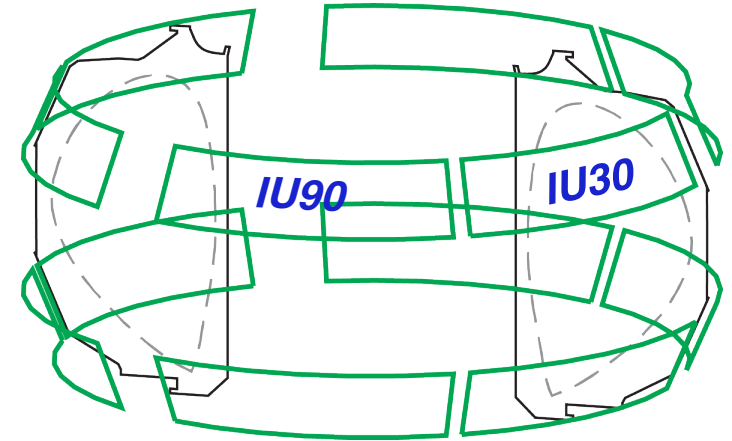
$P_{inj} = 7.7$ MW

D. Orlov, APS Invited 2013

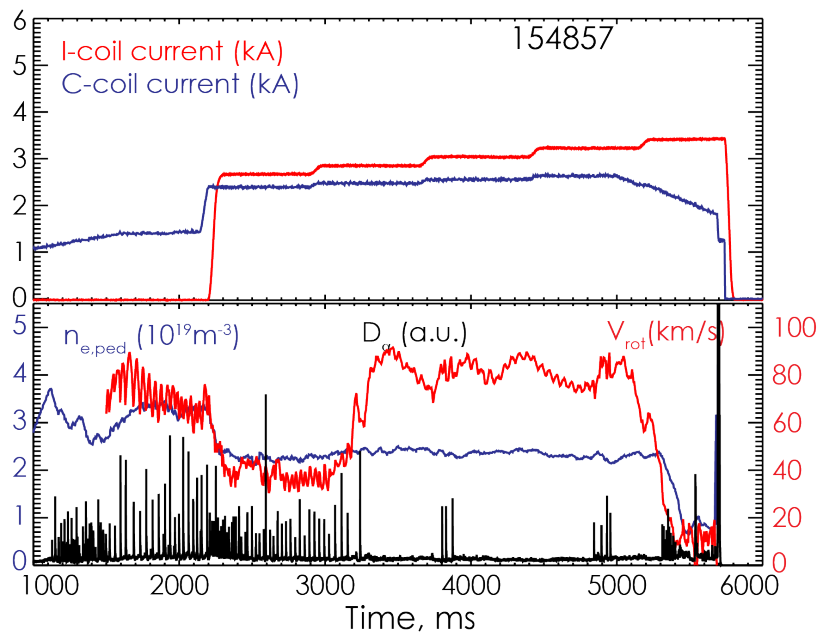
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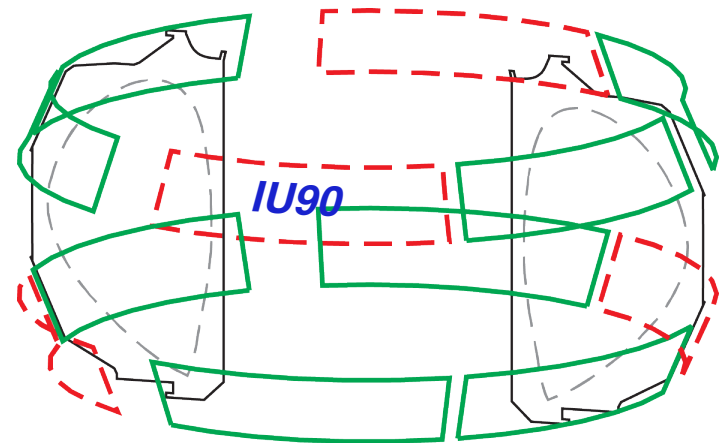
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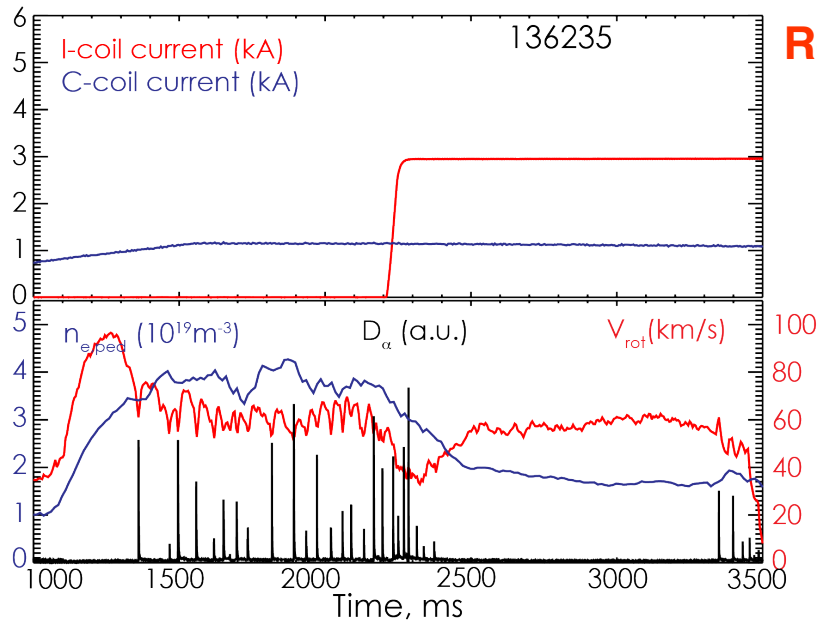
8 Coil Example: Suppression @ $I_{I-coil}=2.85$ kA



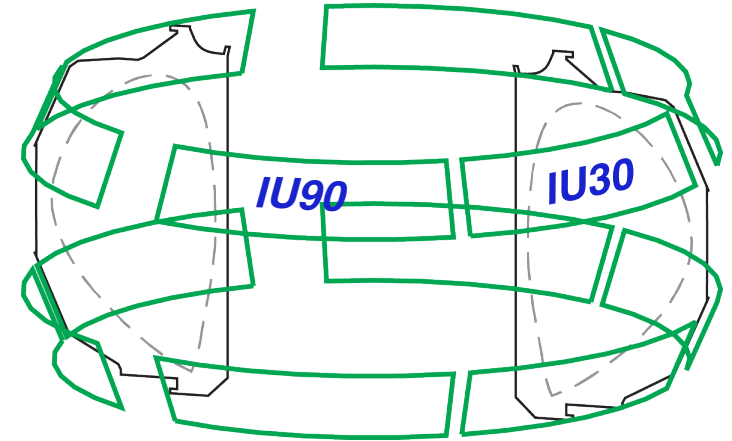
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D. Orlov, APS Invited 2013

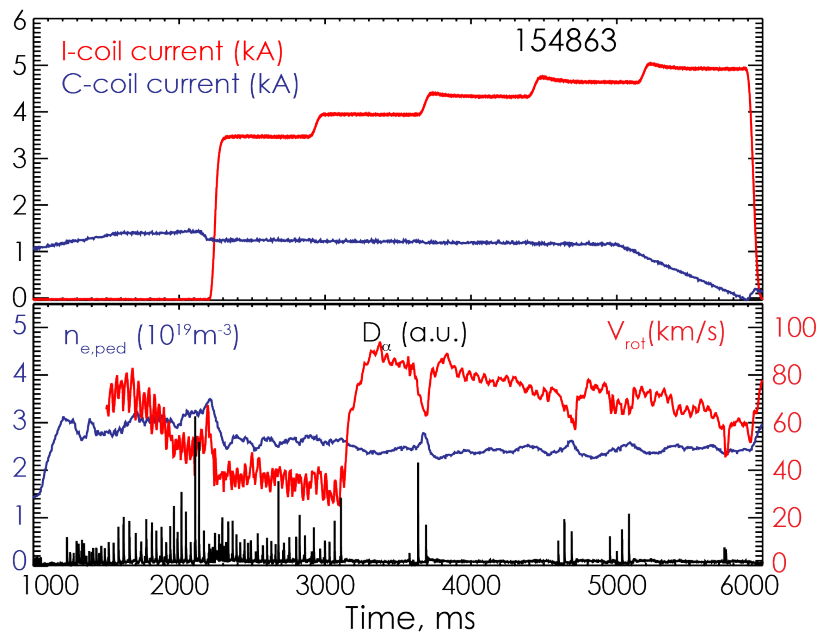
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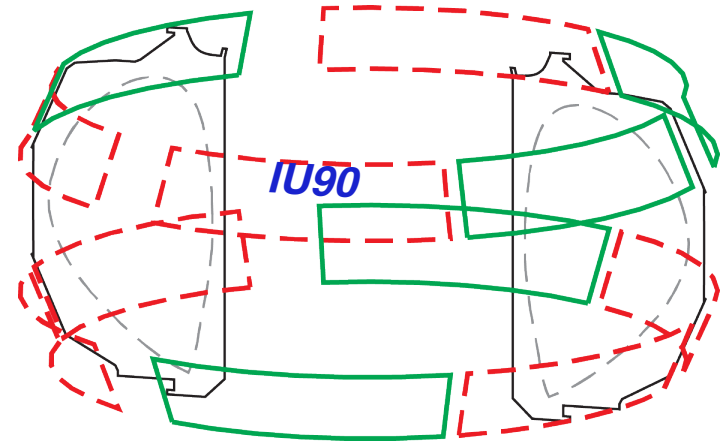
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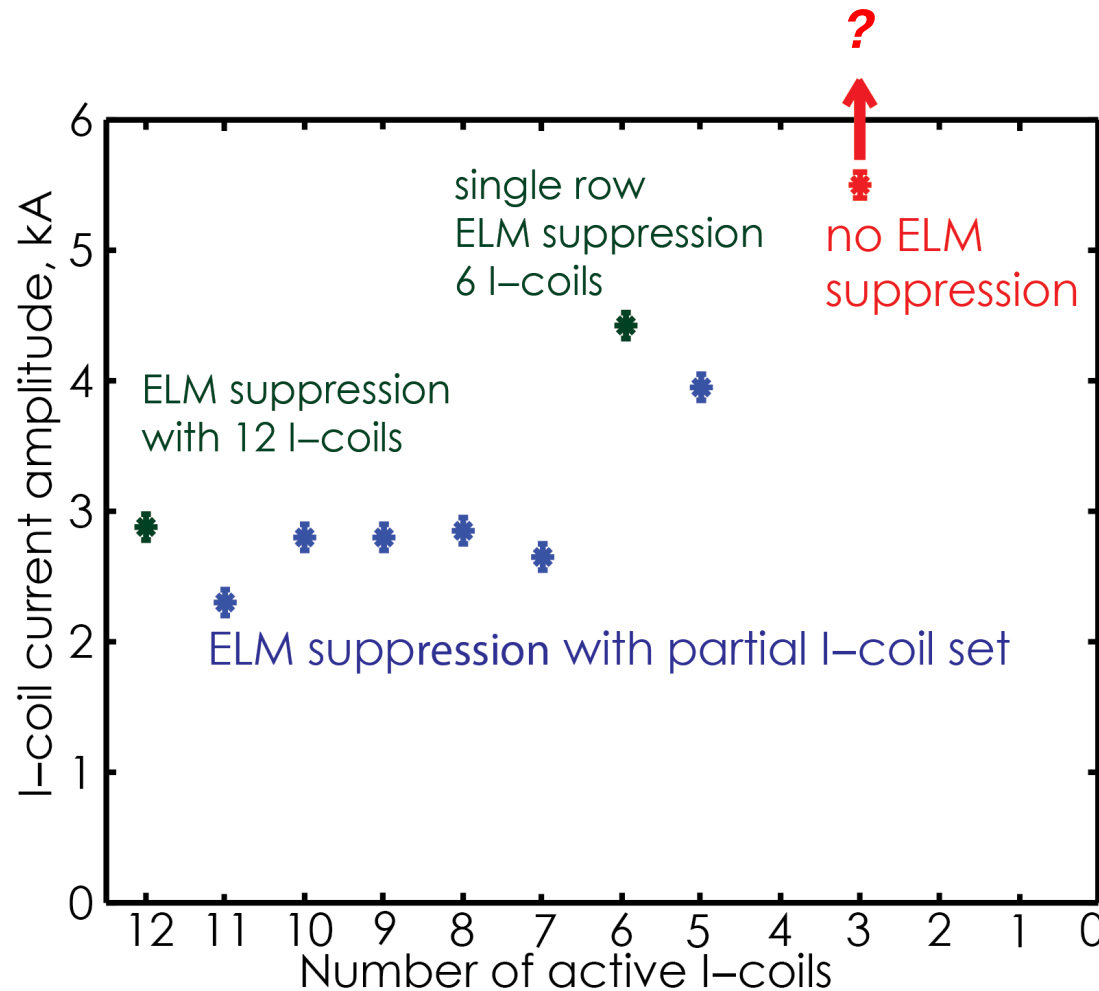
5 Coil Example: Suppression @ $I_{I-coil}=3.95$ kA



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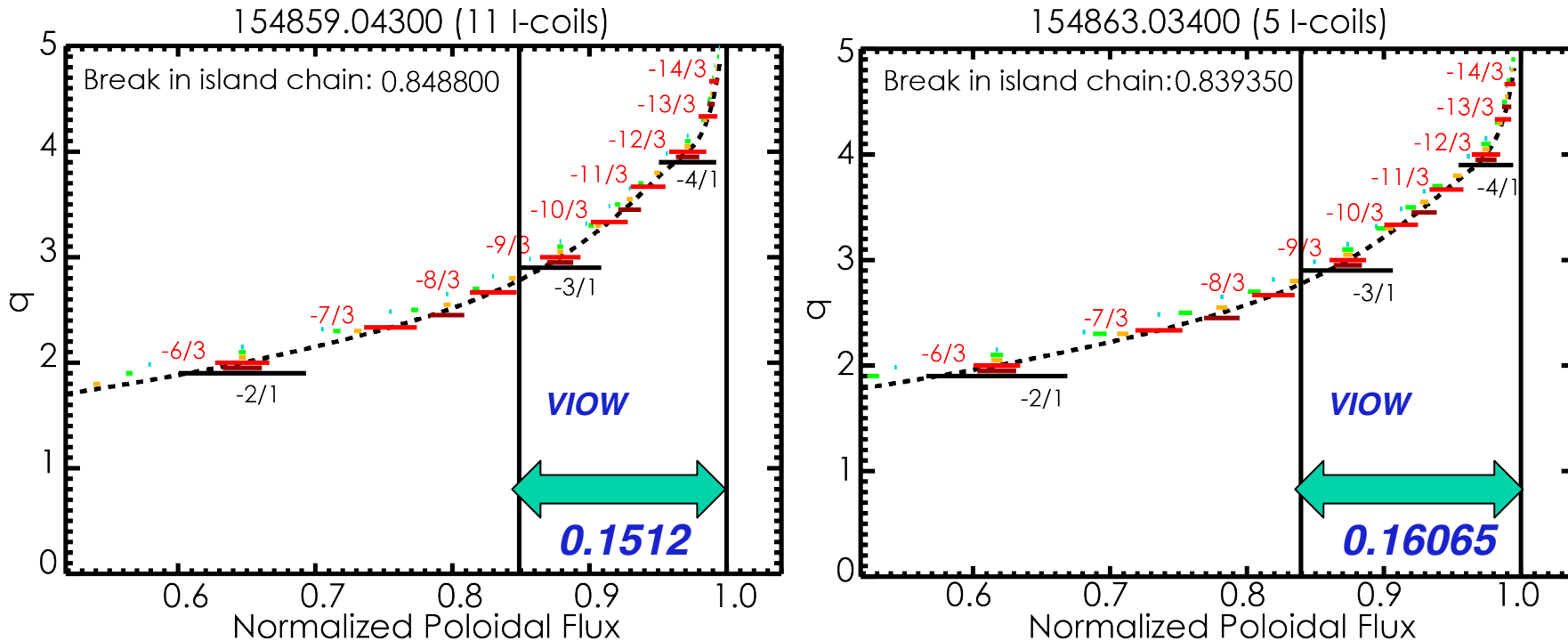
D. Orlov, APS Invited 2013

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

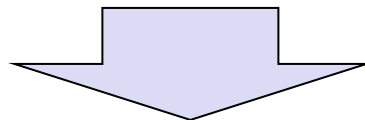


- Elimination of coils results in $n \neq 3$ sidebands...do these sidebands play a role in increasing the edge stochasticity?

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



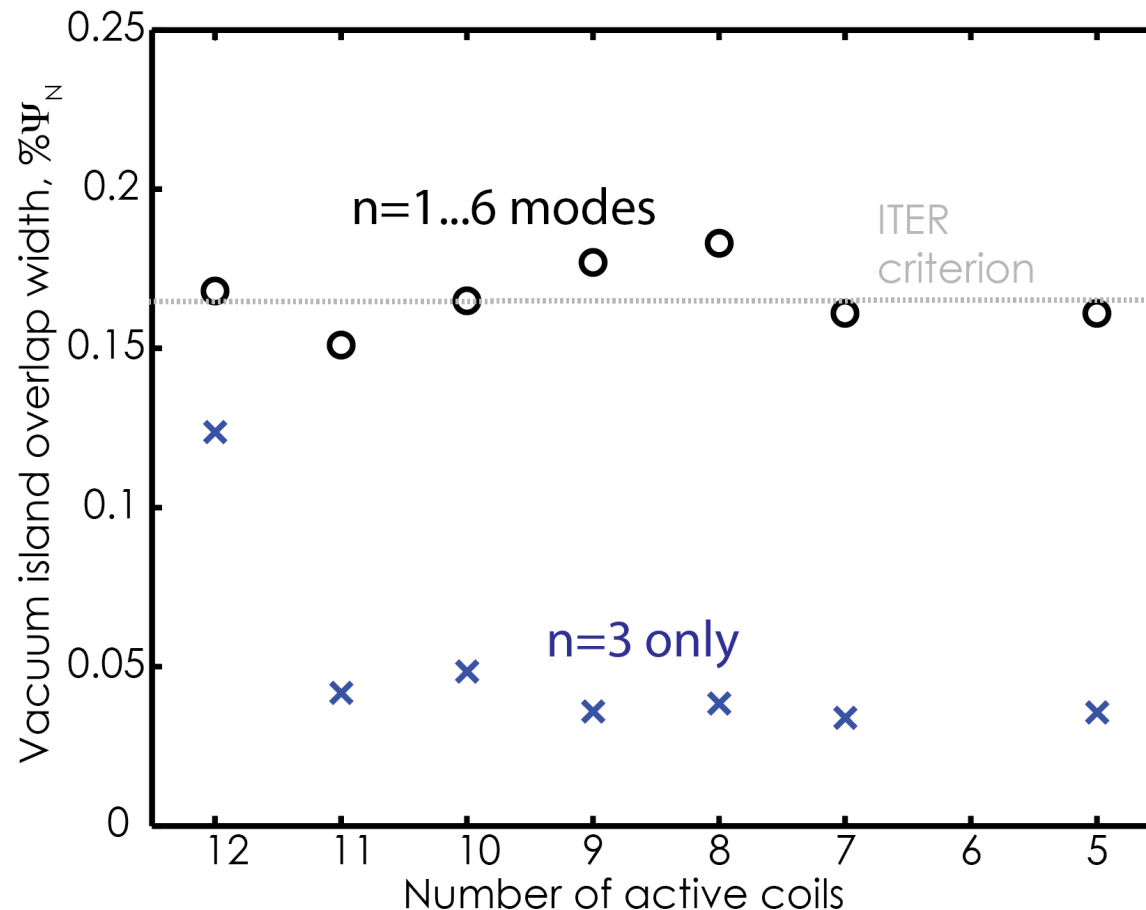
$n=3$ vacuum islands decrease when coils are turned off
Other n ($n=1,2,4,\dots$) islands grow in size



Vacuum Island Overlap Width value stays close to ITER criterion
of VIOW $\sim$ 0.17 in all configurations

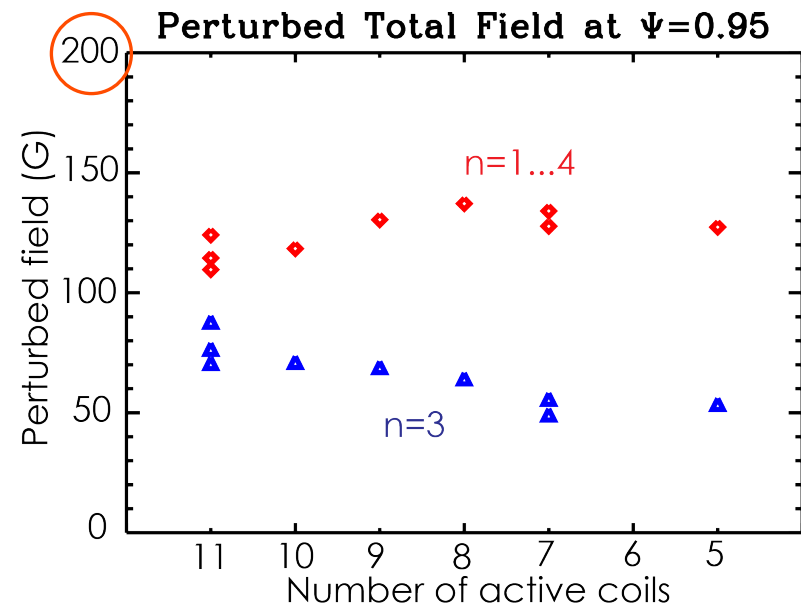
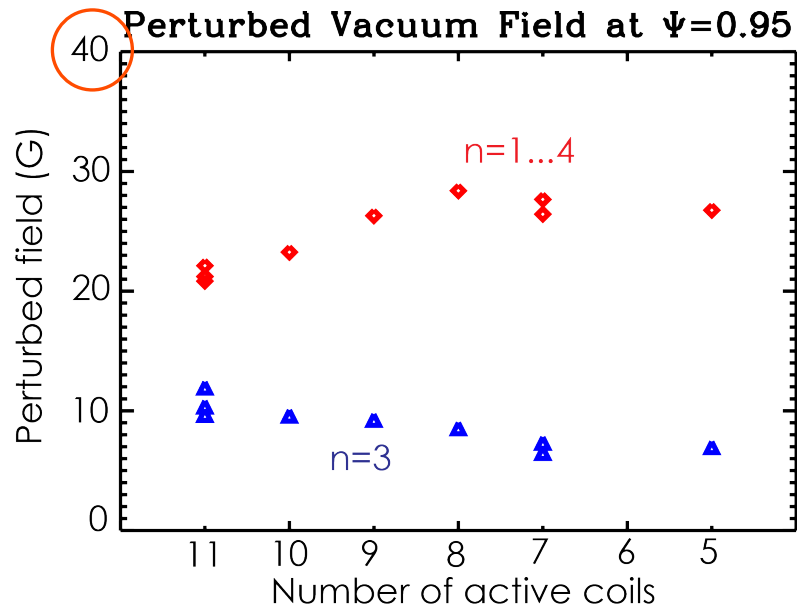
Vacuum Calculations Show that the Island Overlap Width is Similar in All Cases with ELM Suppression

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



Two-Fluid MHD Calculations with M3D-C¹ Indicate the Importance of $n \neq 3$ Sidebands

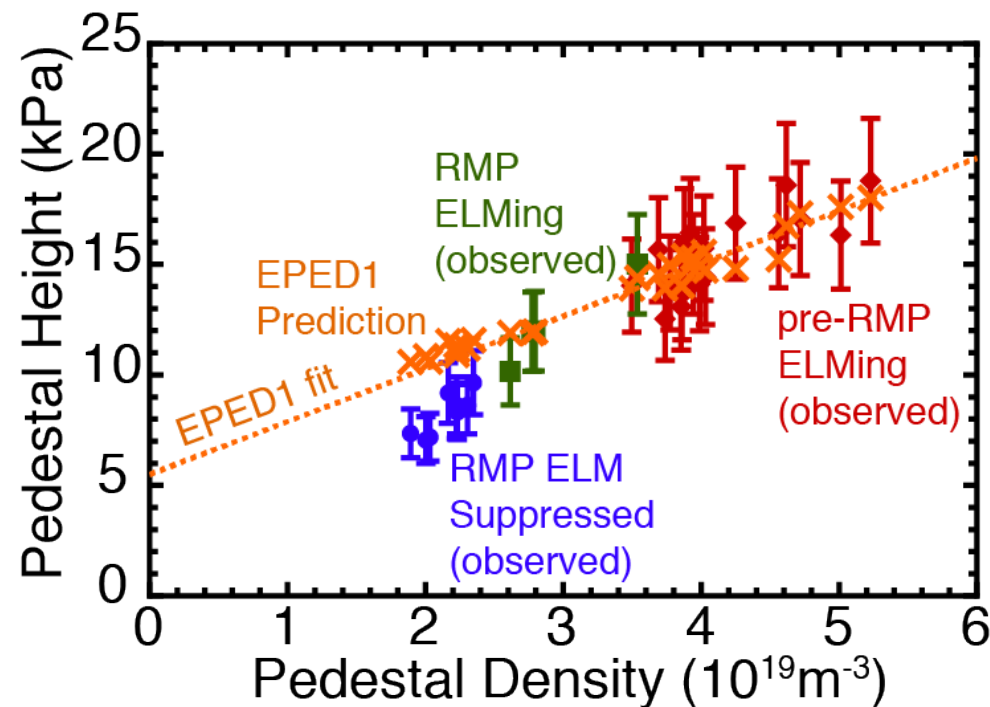
- M3D-C¹ calculates linear 2-fluid MHD response including rotation
- Shows both screening and amplification of the resulting perturbations



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

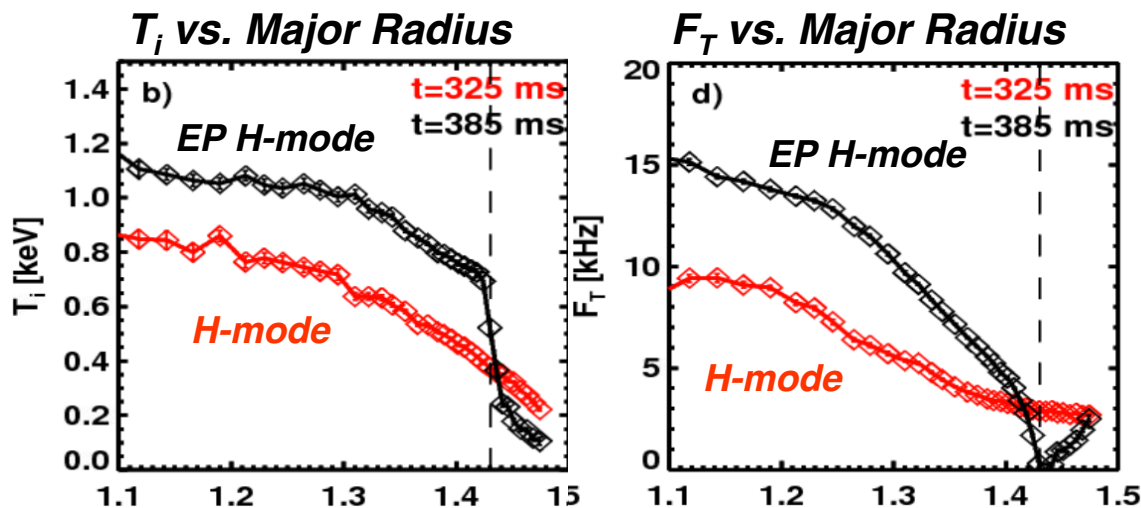
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The Enhanced Pedestal H-mode is a High-Confinement Regime in the Spherical Torus

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

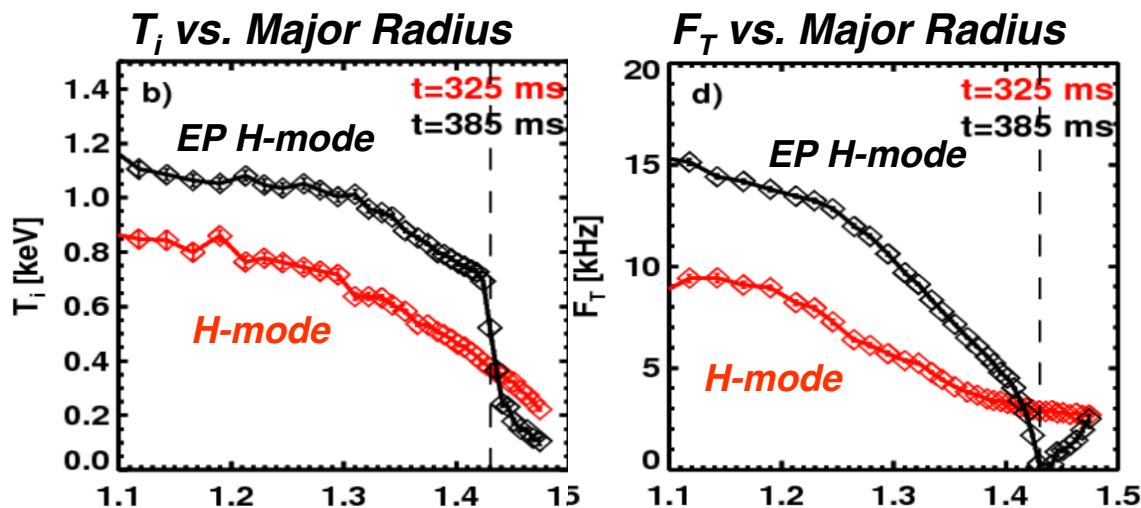
- Edge region where the T_i gradient is much steeper than in H-mode.
- T_i gradient associated with a region of strong toroidal flow shear
 - often a very narrow minima in the flow.
- The transition to this regime occurs after the L->H transition.
 - often follows on ELM.



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 - 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)

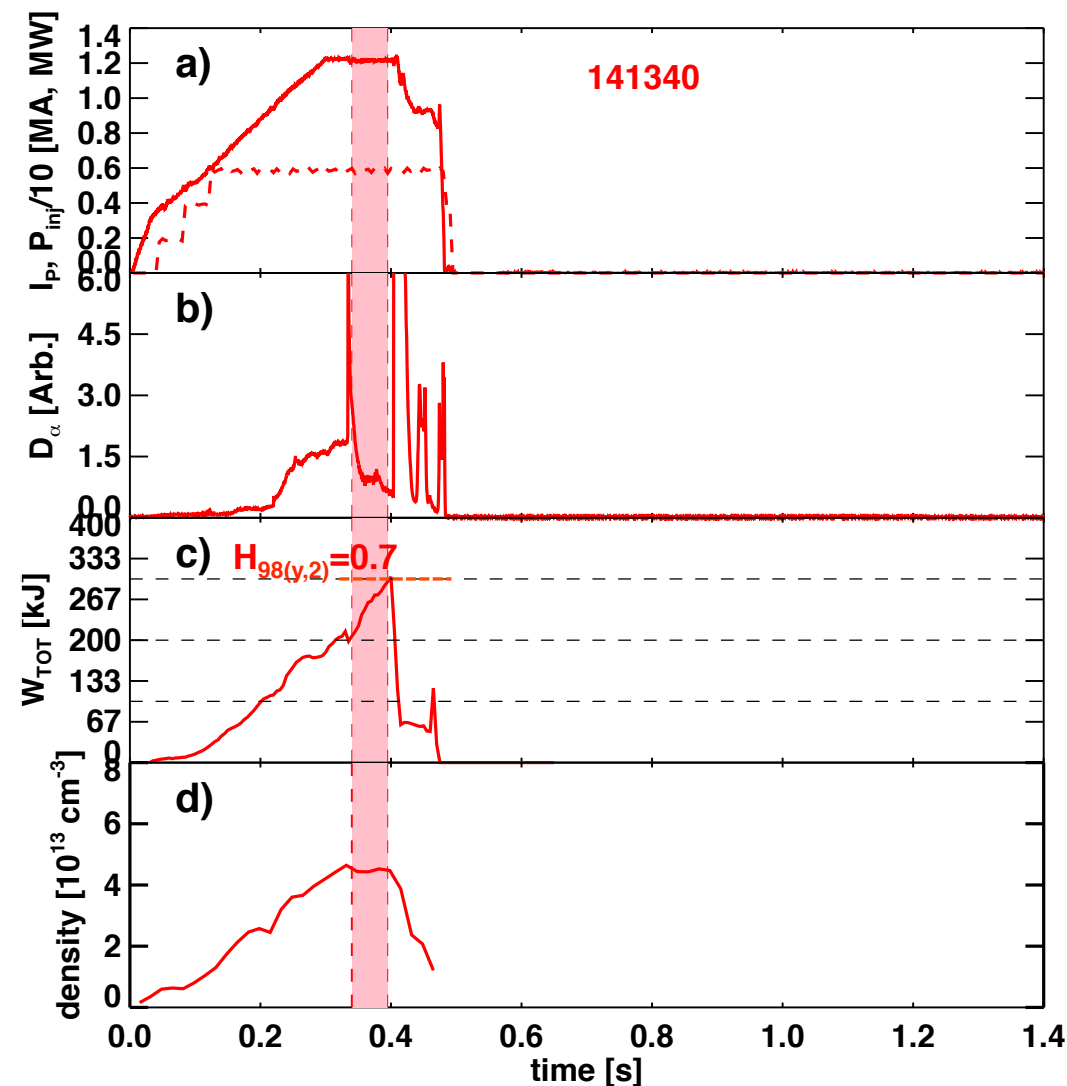
First Extended EP H-mode

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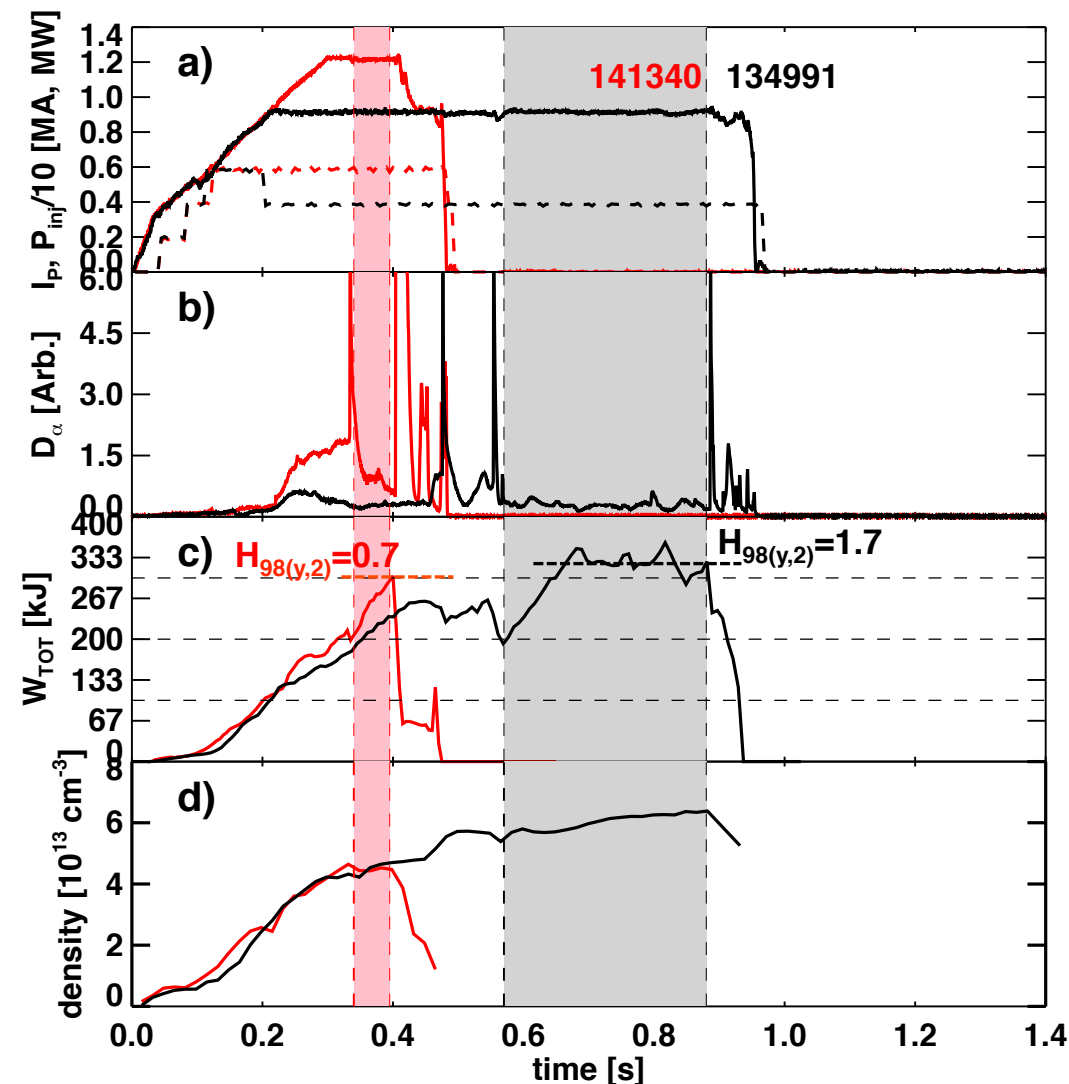
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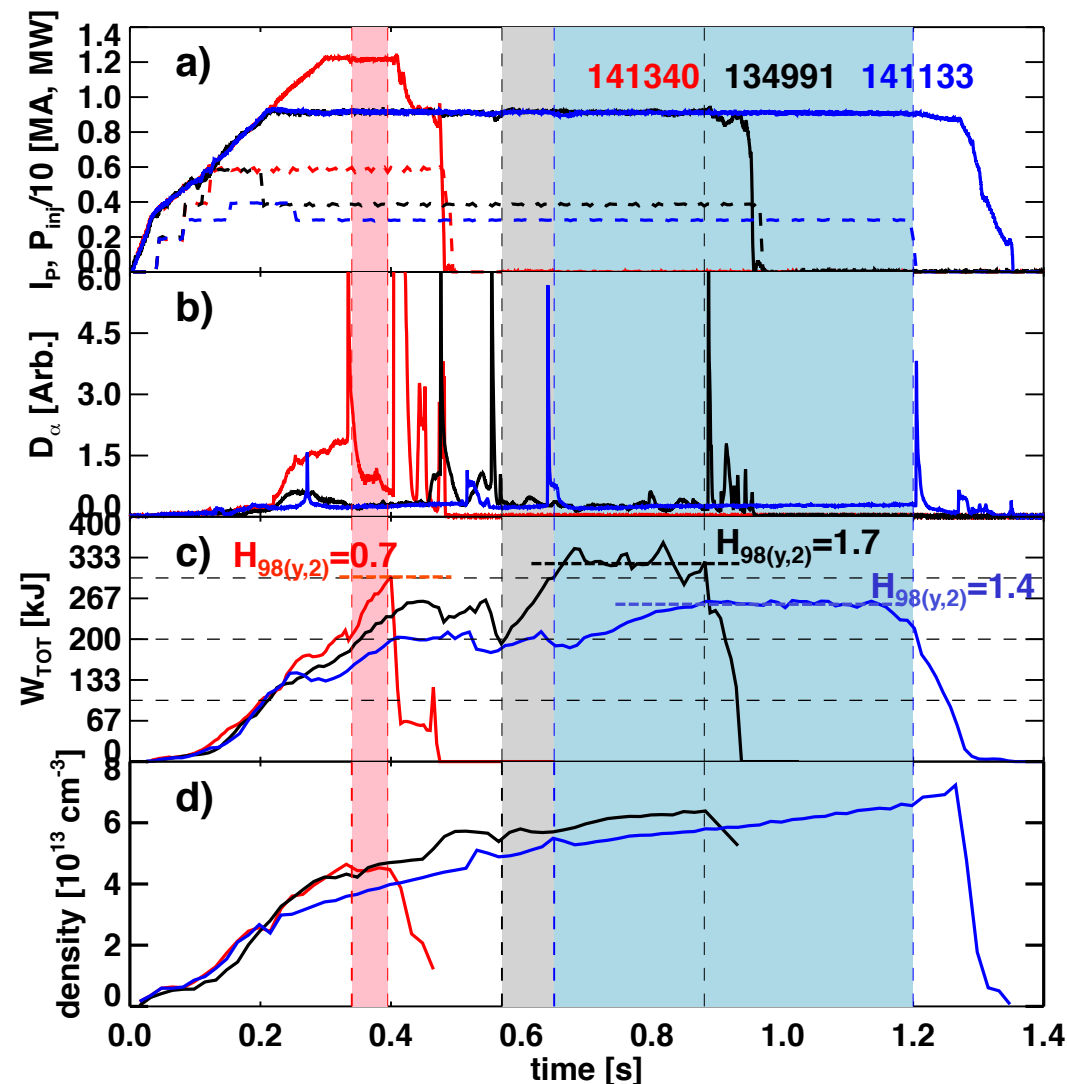
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Density rise typically due to accumulation of C impurities in these cases
Stationarity typically not achieved in NSTX discharges



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

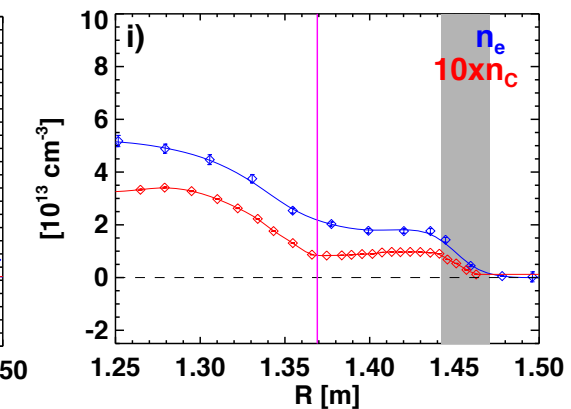
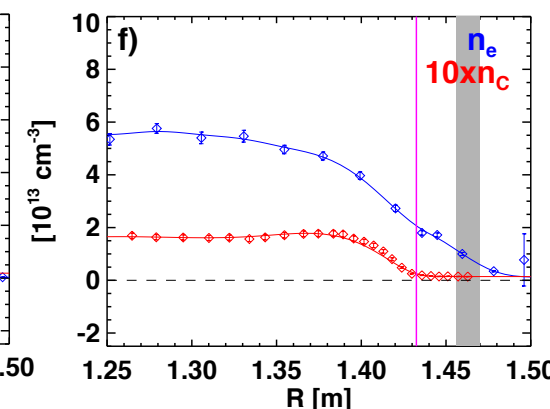
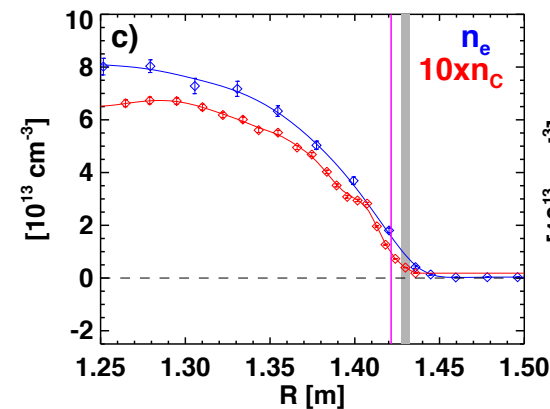
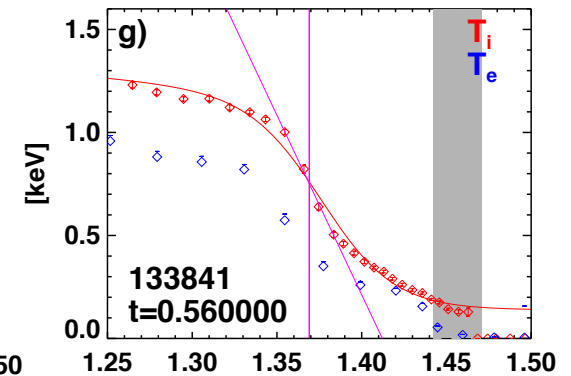
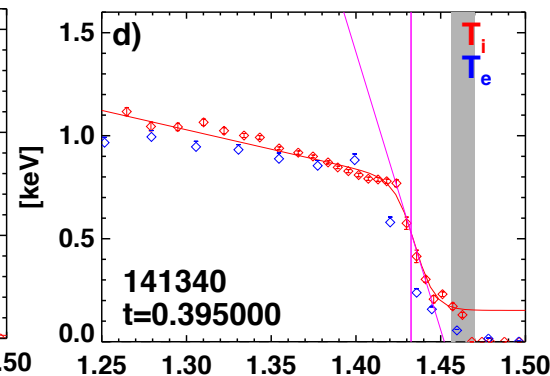
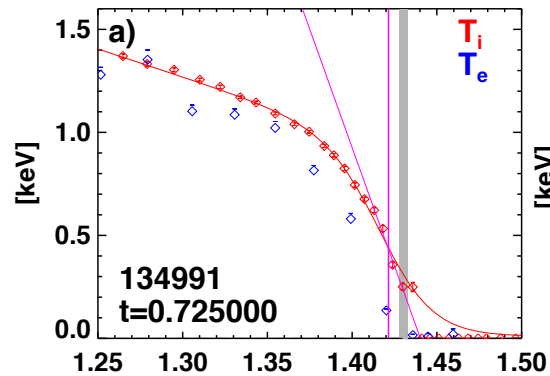
Steep Gradient: Near Separatrix

Shifted Slightly In

Shifted Significantly In

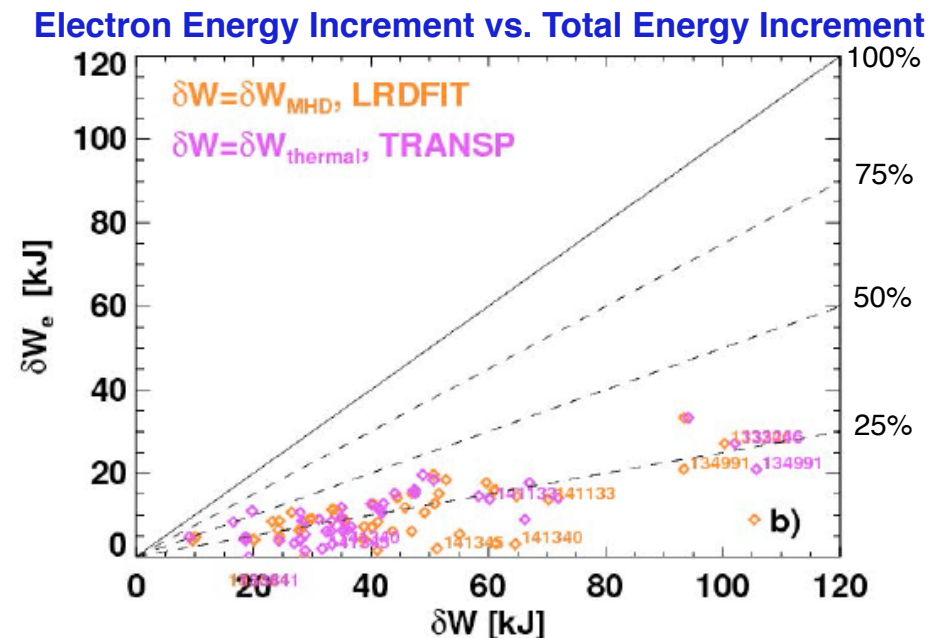
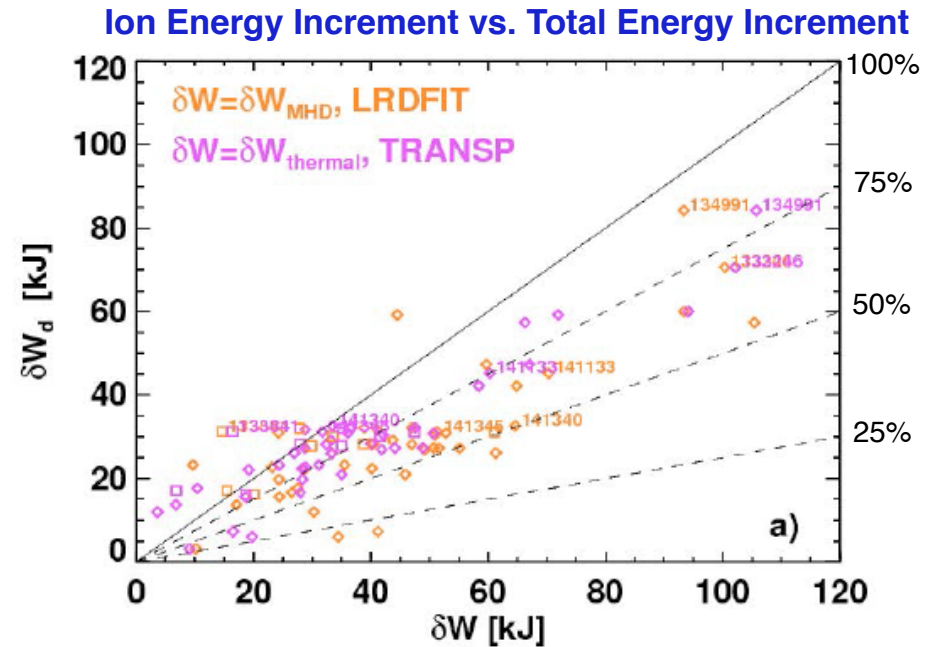
Electron temperature and ion temperature

Electron and carbon density



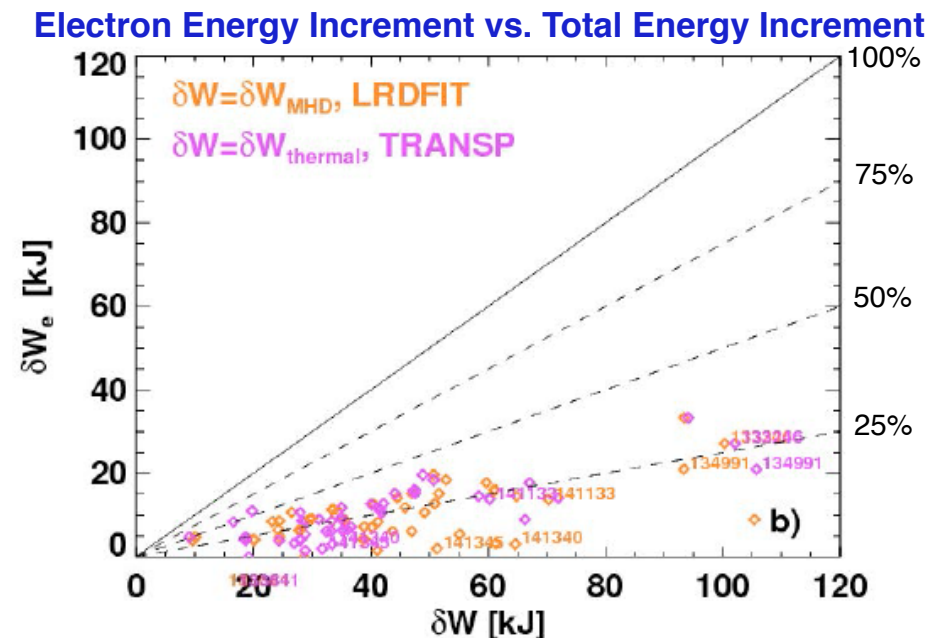
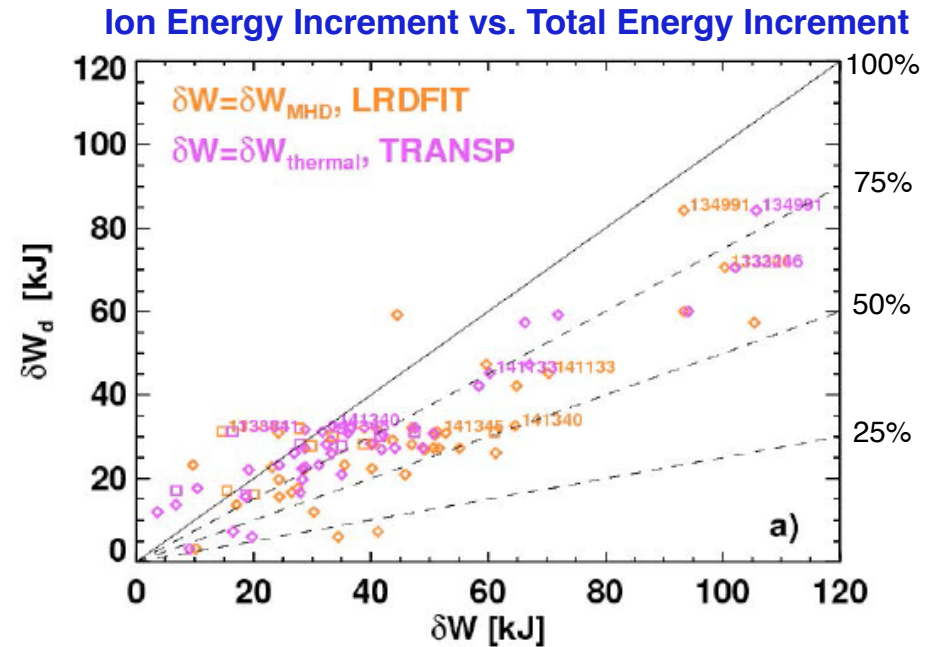
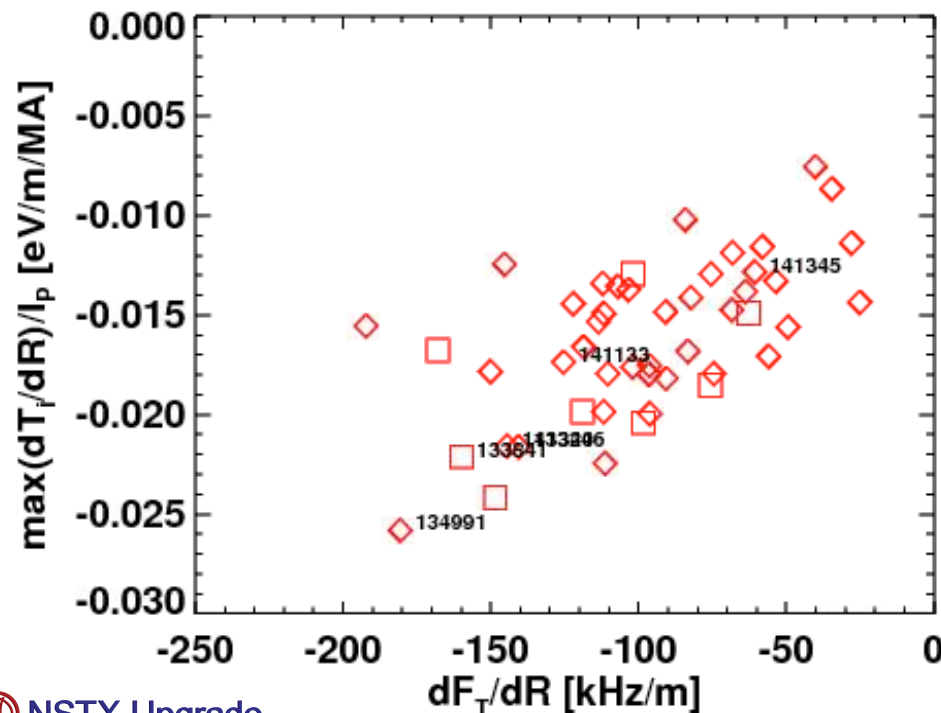
Most of the Energy Increment in EP H-mode is Contained in the Ions

- Compare electron and ion energy increases following the EP H-mode transition
 - ~75% of the stored energy increase is in the ion channel.



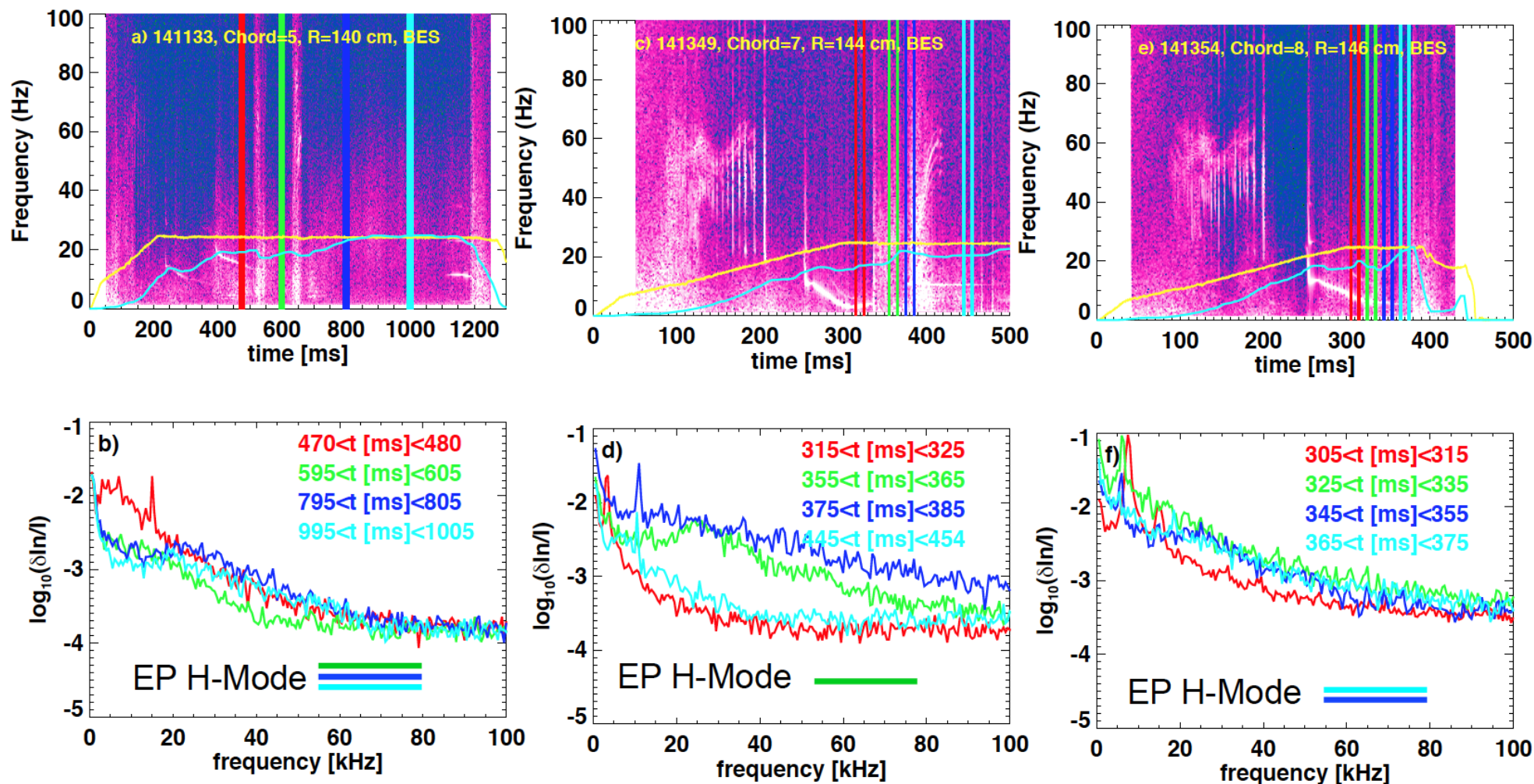
Most of the Energy Increment in EP H-mode is Contained in the Ions

- 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?



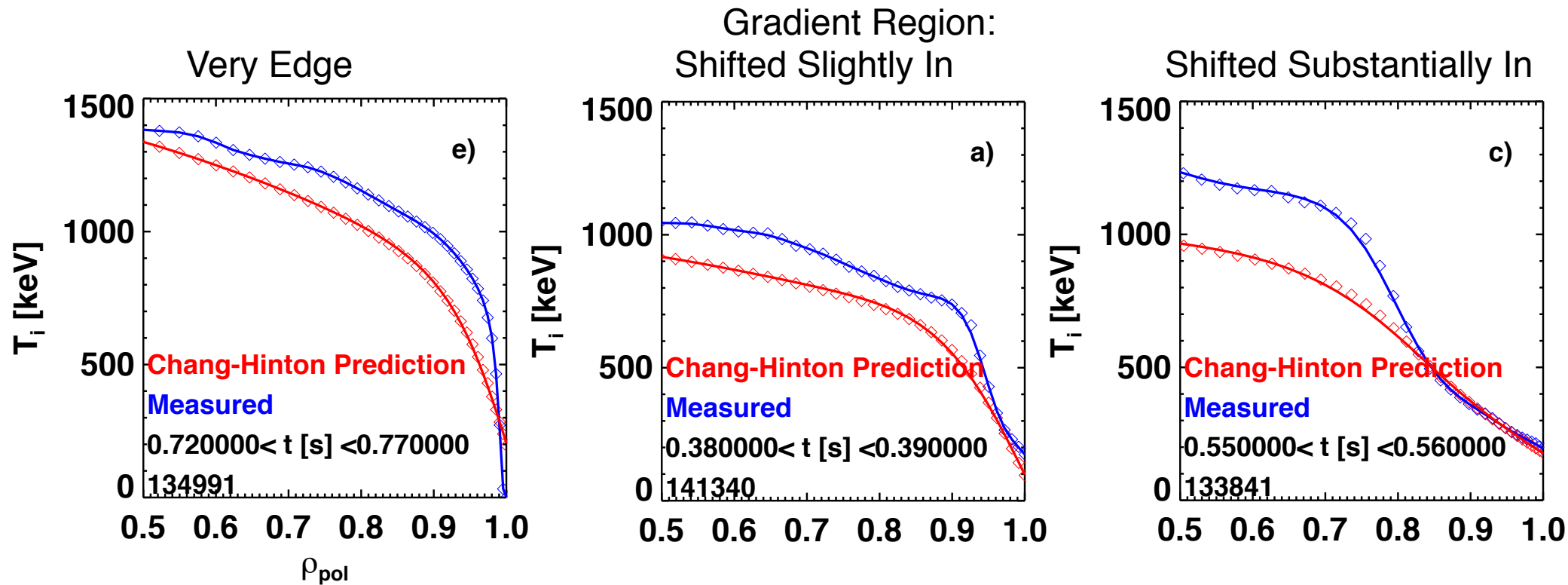
Measured Density Fluctuation Amplitude Does Not Decrease Following the EP H-mode Transition

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



Simple Neoclassical Transport Calculation Under-predicts T_i 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

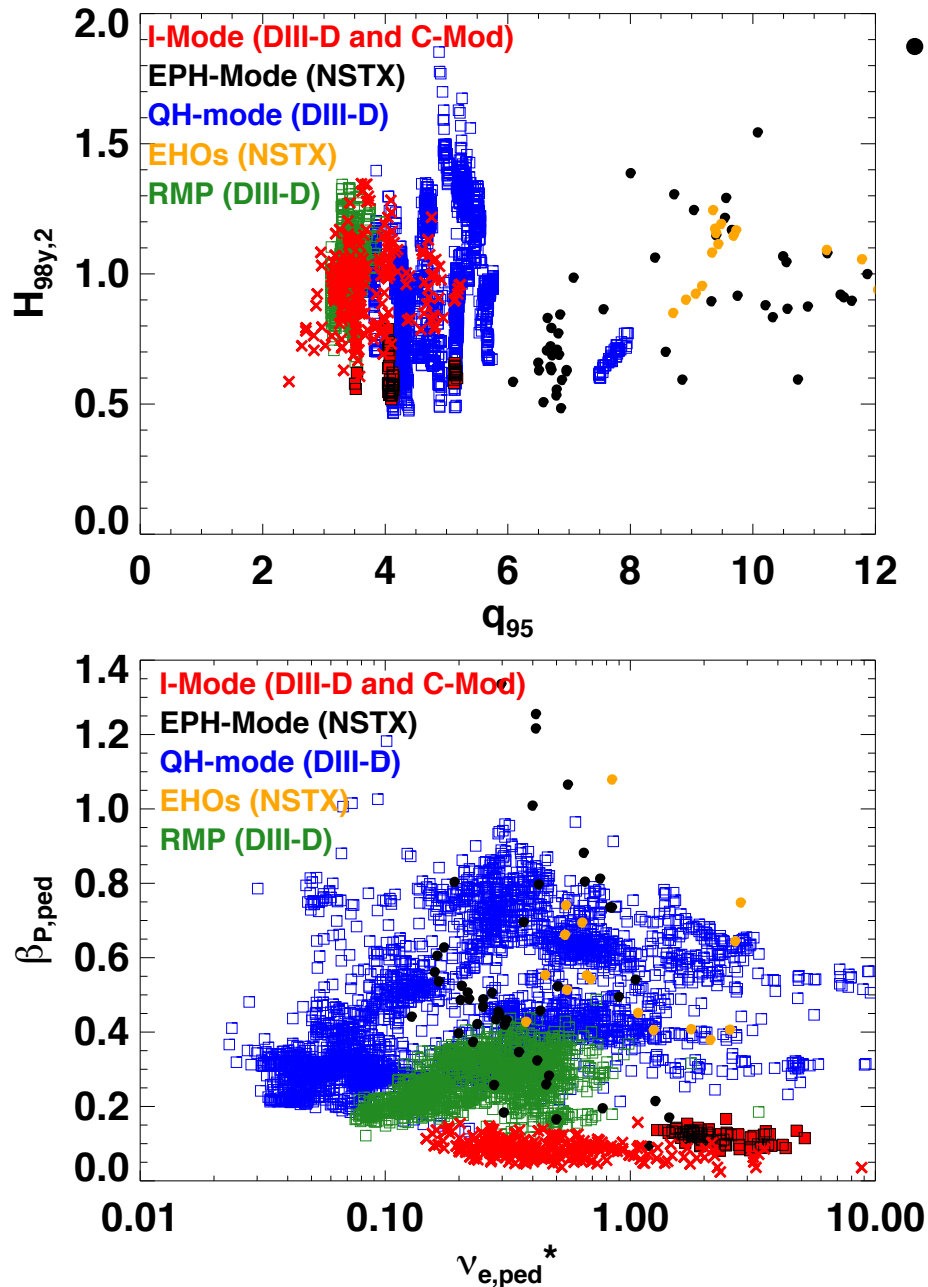


- T_i (and its gradient) is underestimated in all three cases.
 - Working on repeating this comparison with full neoclassical physics using XGC-0

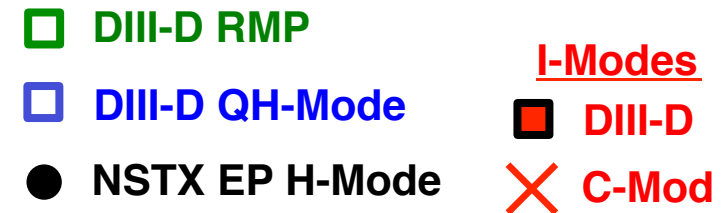
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All Regimes Under Consideration Have Shown Good Confinement and Access to Low Collisionality



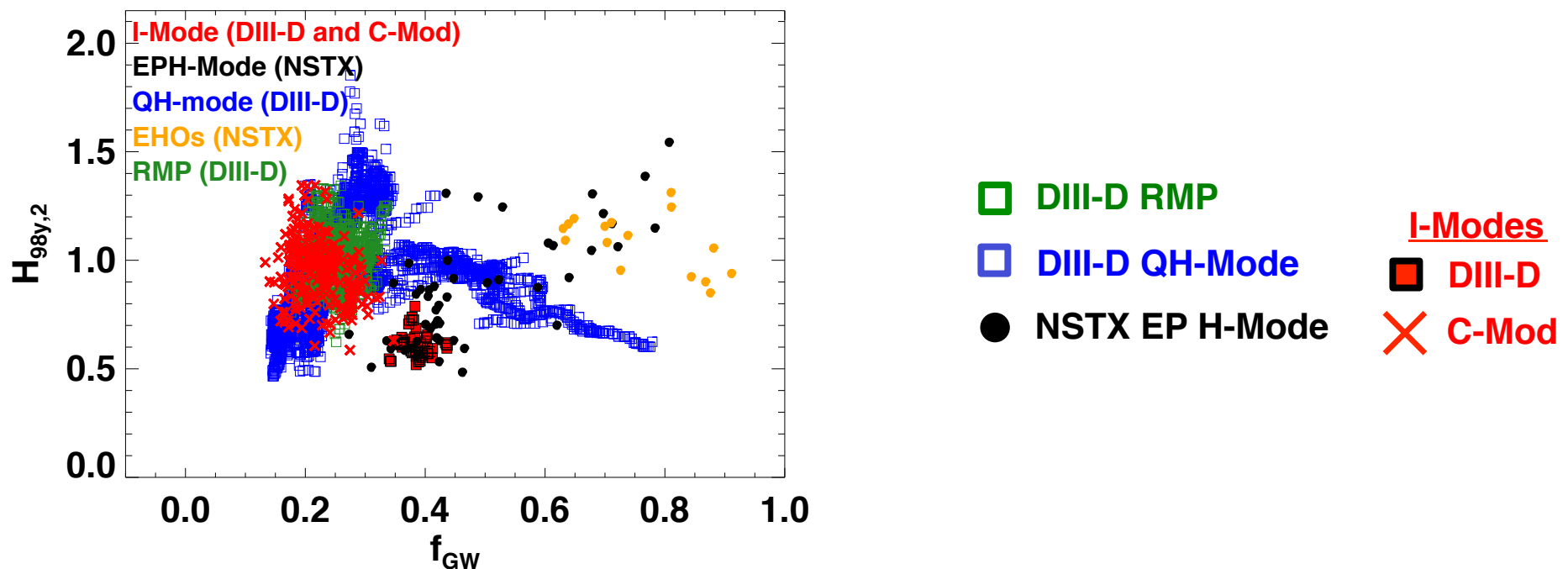
- Symbols for machines and colors for regimes:



- 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)

Targeting Higher Density is a Common Theme Among Recent Experiments

- QH-mode densities up to $f_{GW}=0.8$.
 - Facilitated by strong shaping
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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
 - NSTX cases with weak EHOs also near the peeling boundary
 - 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: Correlation between WCM amplitude and particle transport in I-mode
 - QH-mode: EHO can flush impurities better than ELMs
 - While maintaining excellent thermal transport.
 - 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 or the primary spectral component

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

- 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 to increase in EP H-mode compared to H-mode
 - similar result found in VH-mode experiments in 2013.

Thanks for your attention!

BACKUP

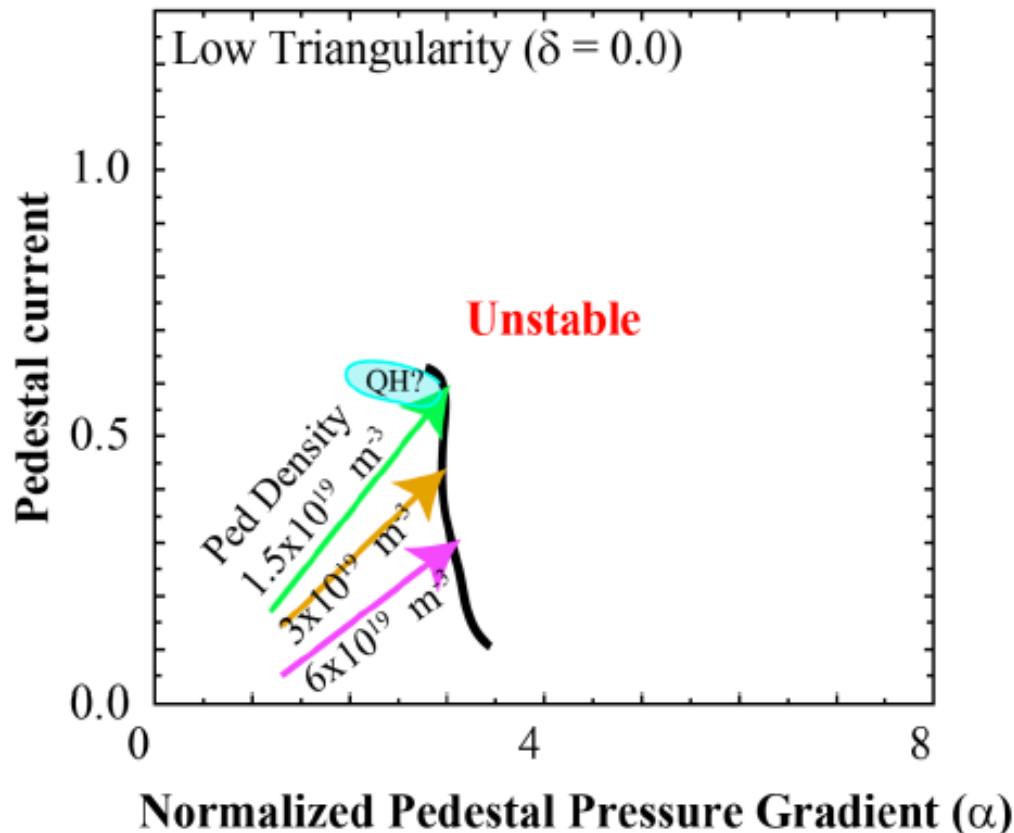
A Path to Raising the QH-Mode Density via Shaping Was Projected...

Working Hypothesis:

QH Mode Accessible When the Pedestal is at the Kink/Peeling Boundary

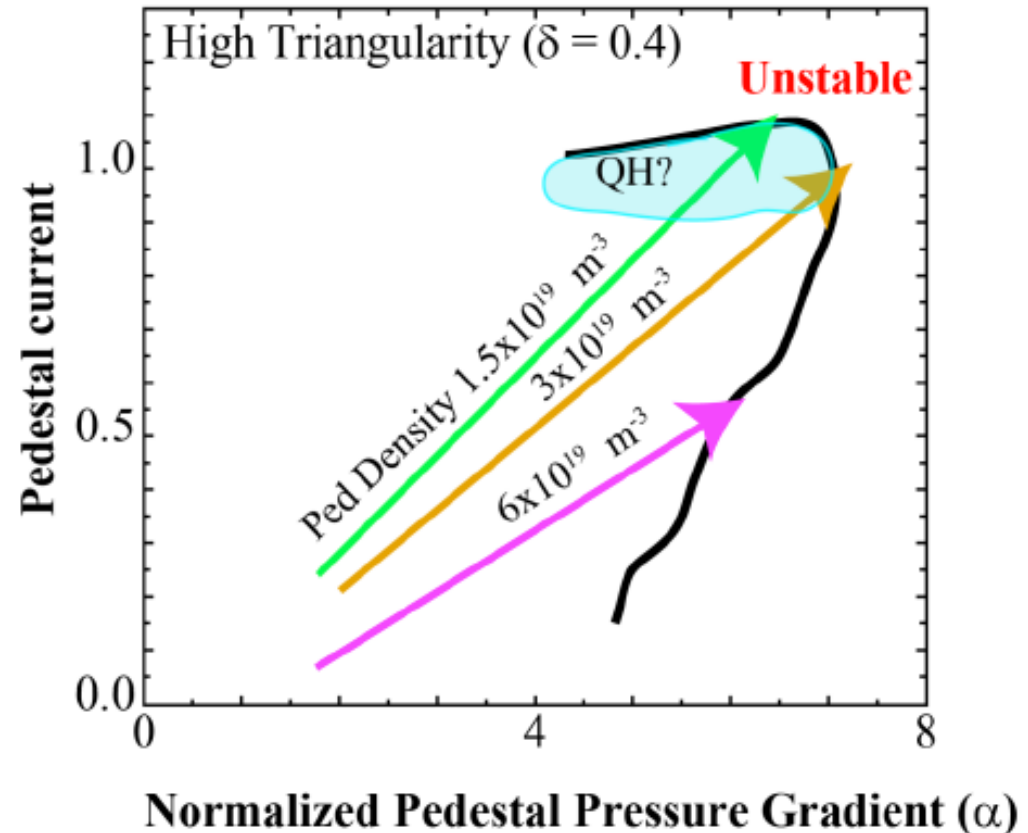
Low Triangularity

Kink/Peeling Boundary Only Accessible at Lower Density



High Triangularity

Kink/Peeling Boundary Accessible at Higher Density

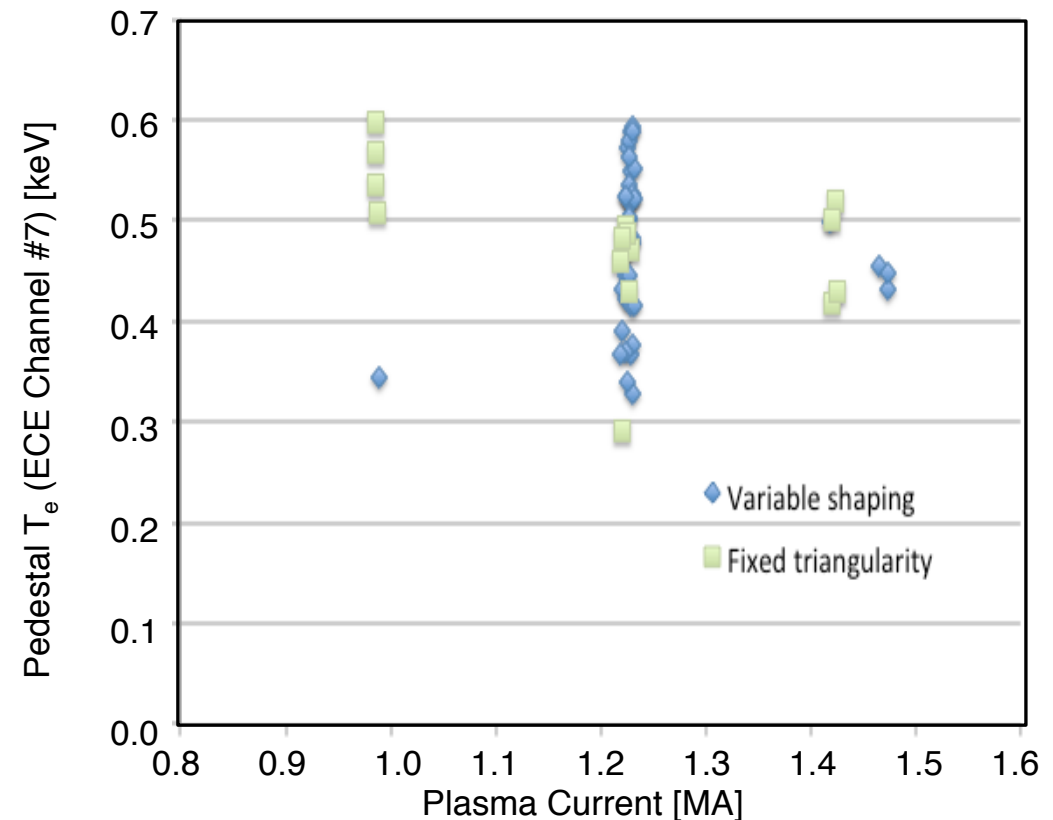


Simplified versions of predictions from Snyder, et al., NF 2007

Control of Sawtooth Cycle is Critical For Future Optimization in DIII-D

- Sawtooth driven heat pulses typically triggered I->H transition
 - Sawtooth triggered L->H transitions not uncommon.
- These transition limit the evolution of the T_e pedestal.
- Heat pulse smaller at lower current, resulting in highest $T_{e,ped}$ at lower current.
 - Opposite the experience in C-MOD!
- Improved sawtooth control likely necessary to fully exploit the regime in DIII-D.

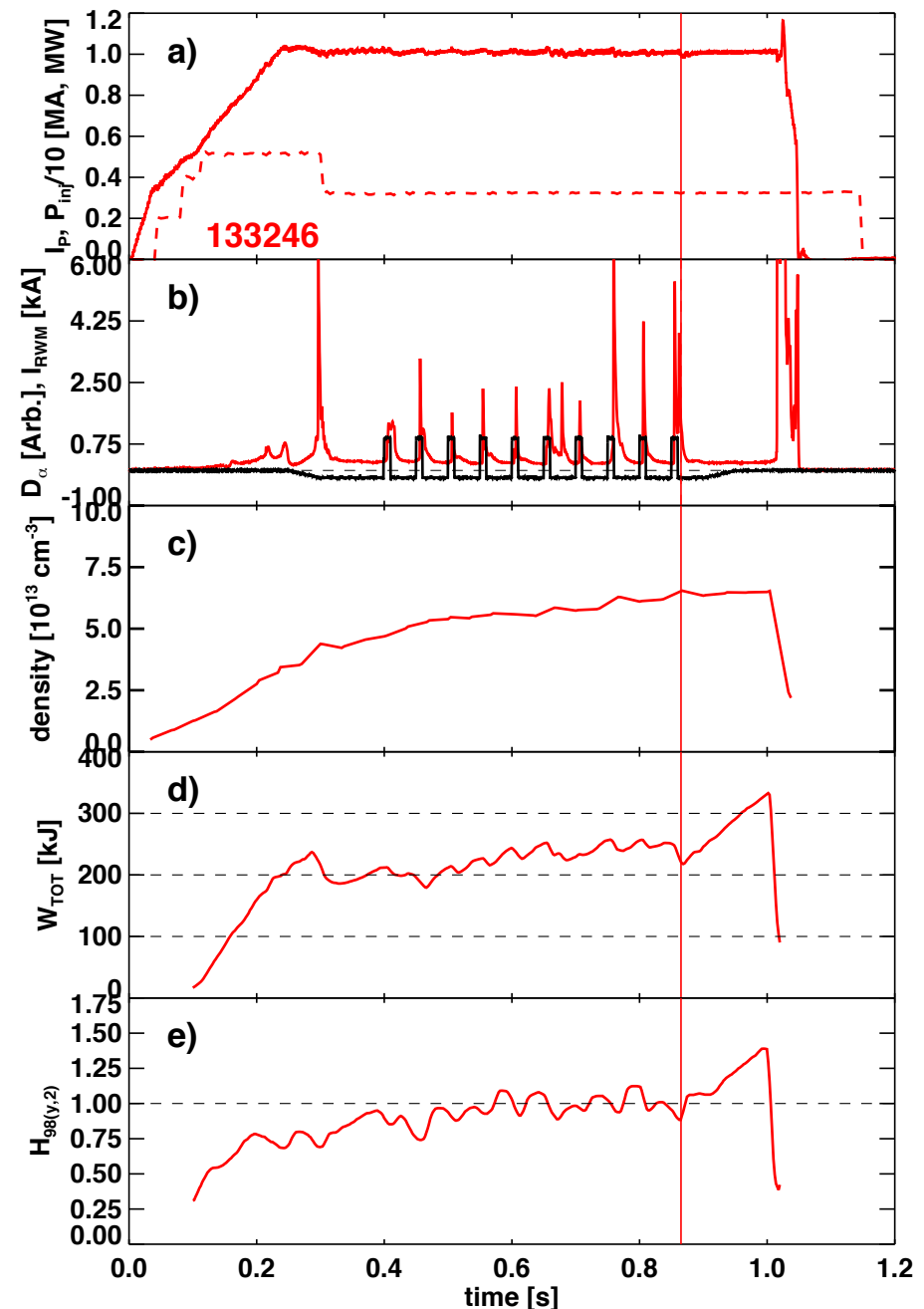
Pedestal Electron Temperature vs. Plasma Current for DIII-D I-Mode Regime Discharges



We May Be Able to Drive the EP H-mode Transition by Triggering ELMs

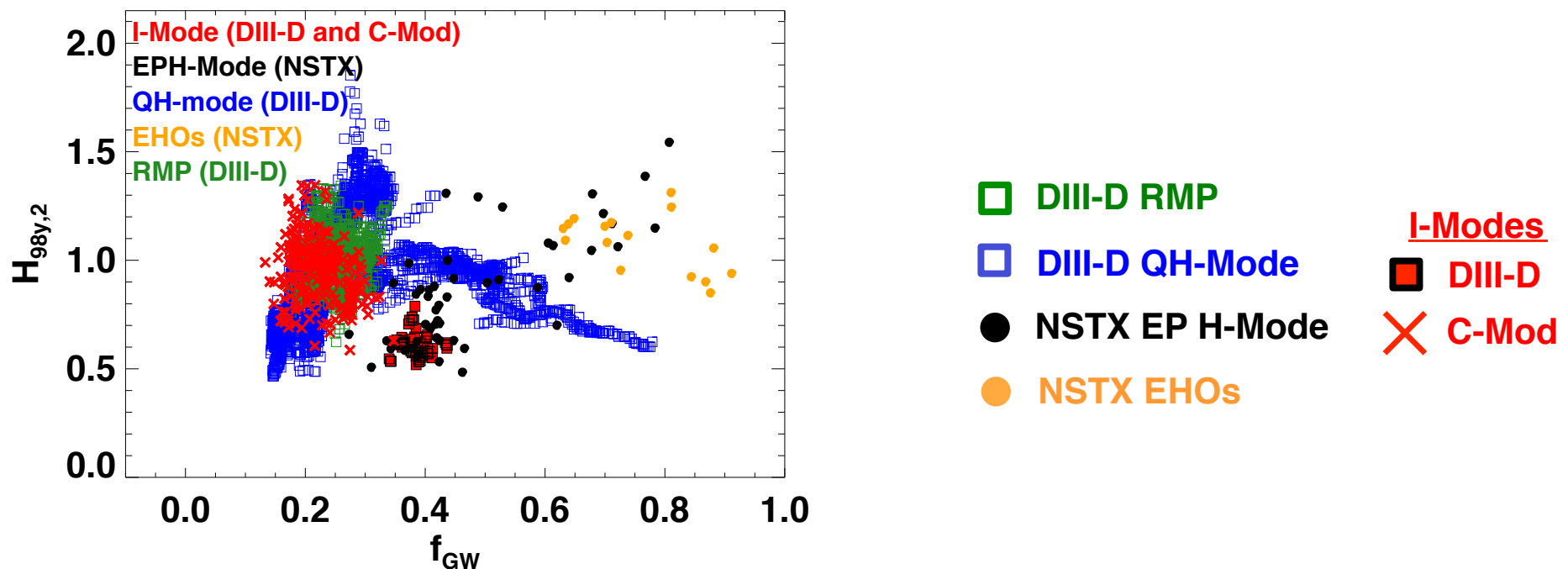
- Pulse n=3 fields used to trigger ELMs.
- Final triggered ELMs leads to an EP H-mode transition.

Also possible to achieve reliable EP H-mode transitions in low- q_{95} scenarios with highly repeatable timing of the first ELM.

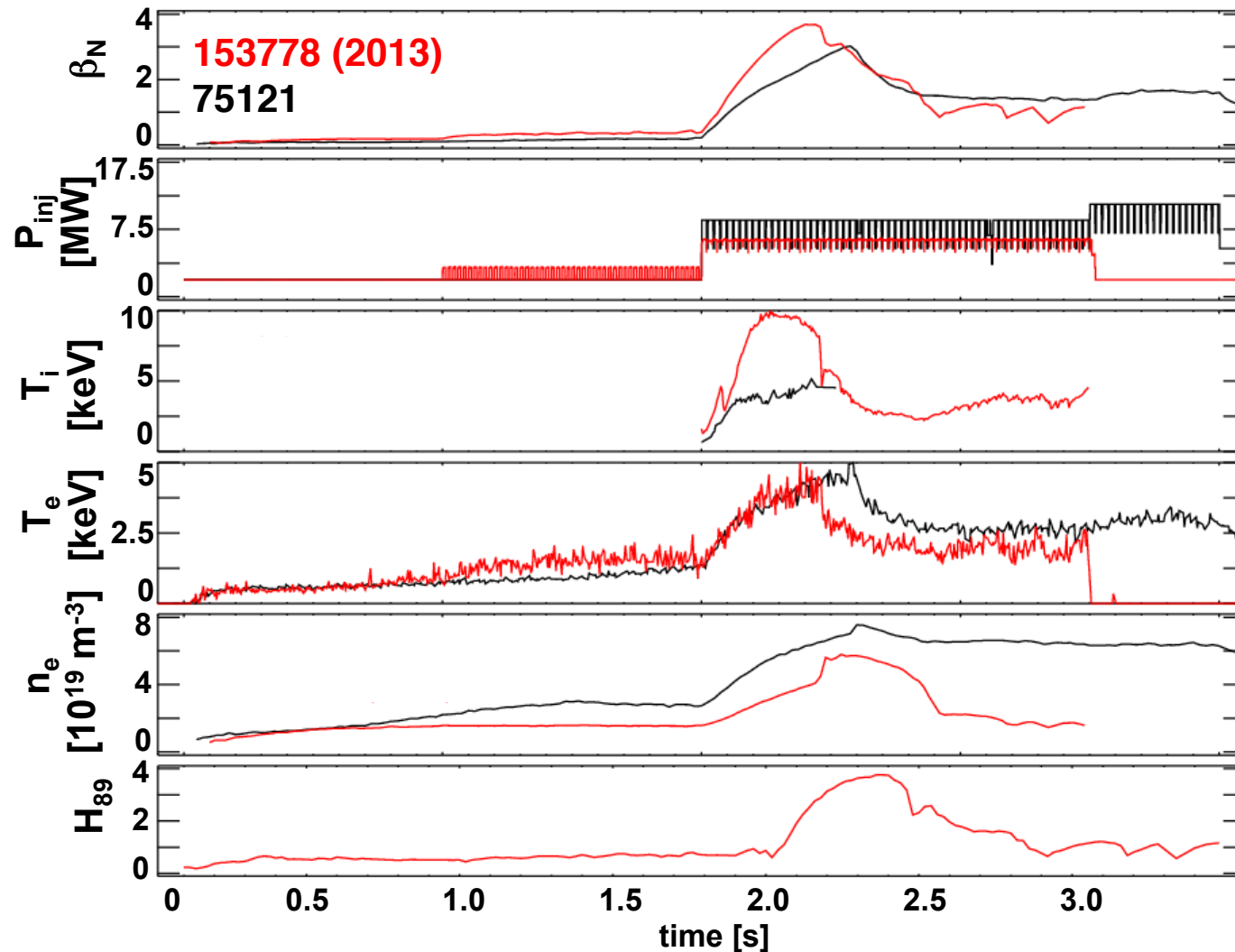


Targeting Higher Density is a Common Theme Among Recent Experiments

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 - Facilitated by strong shaping
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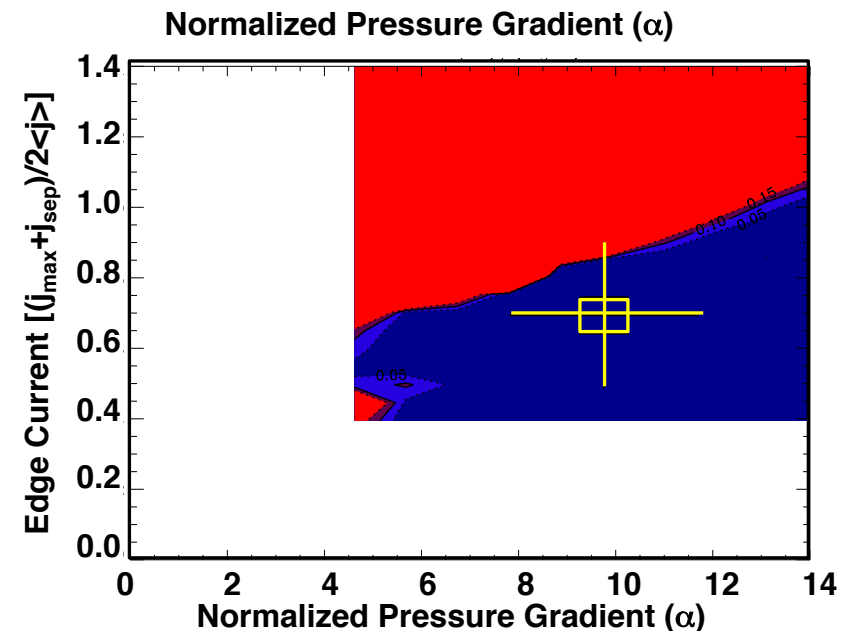
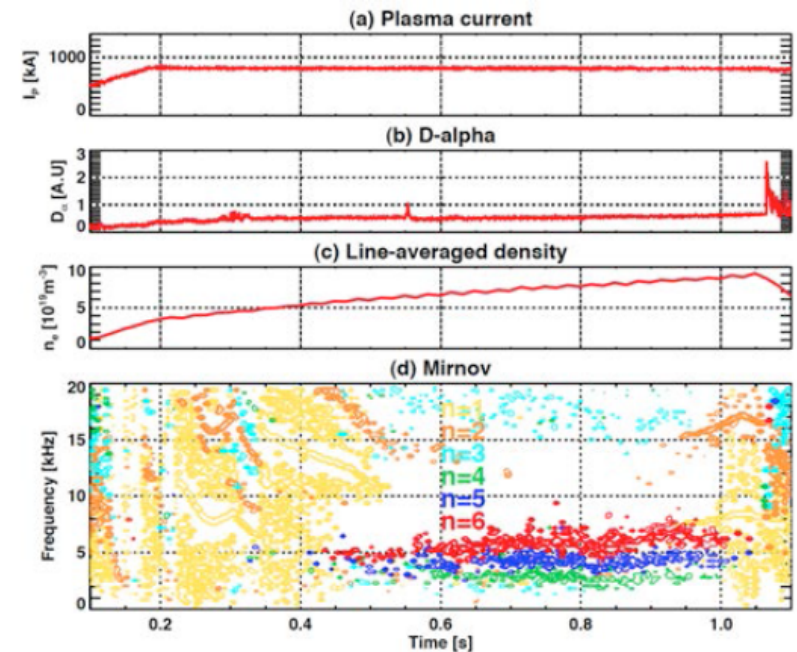
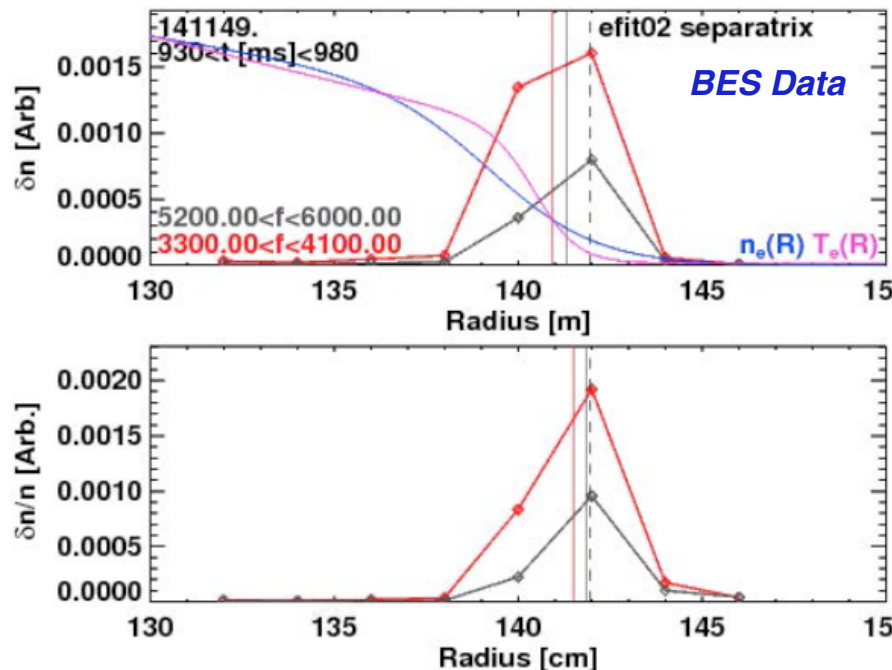
Recent VH-Mode Experiments Able to Match Performance of Previous Examples



- Goal of experiment: use $n=3$ fields and beta feedback to control the VH-mode evolution

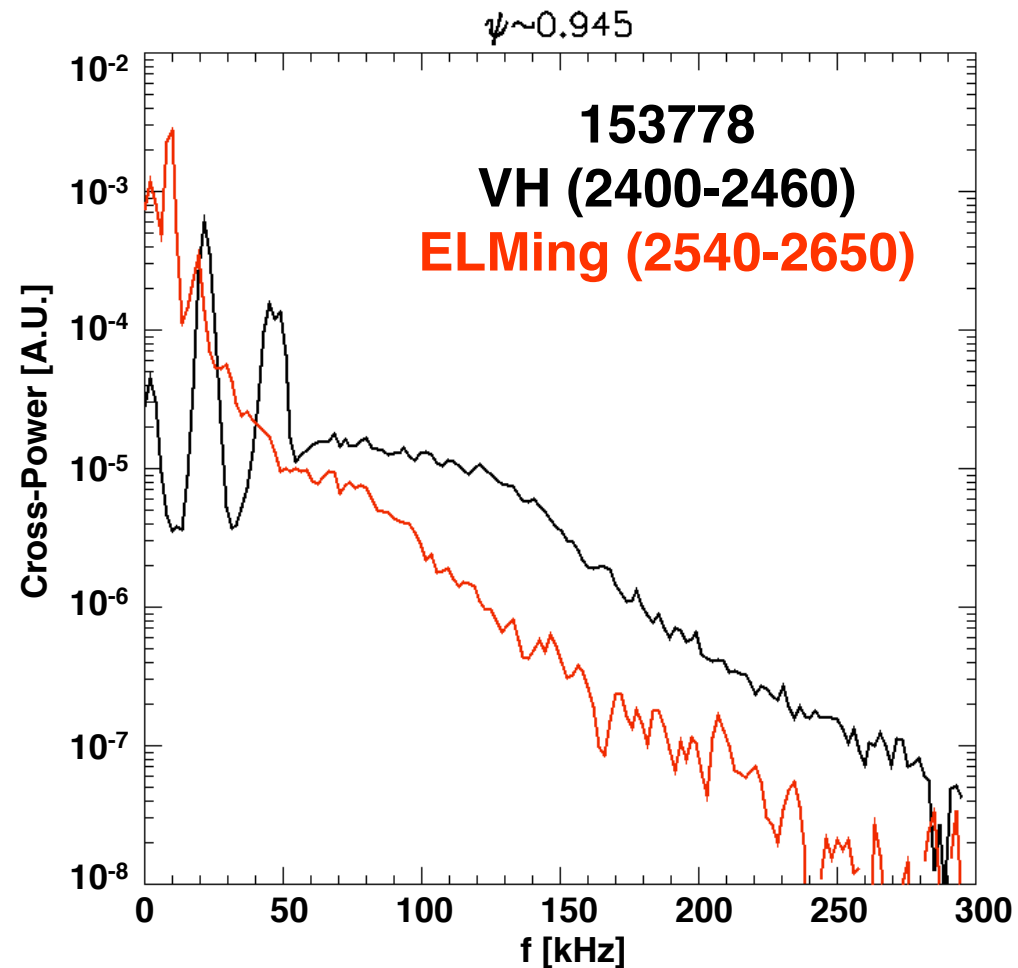
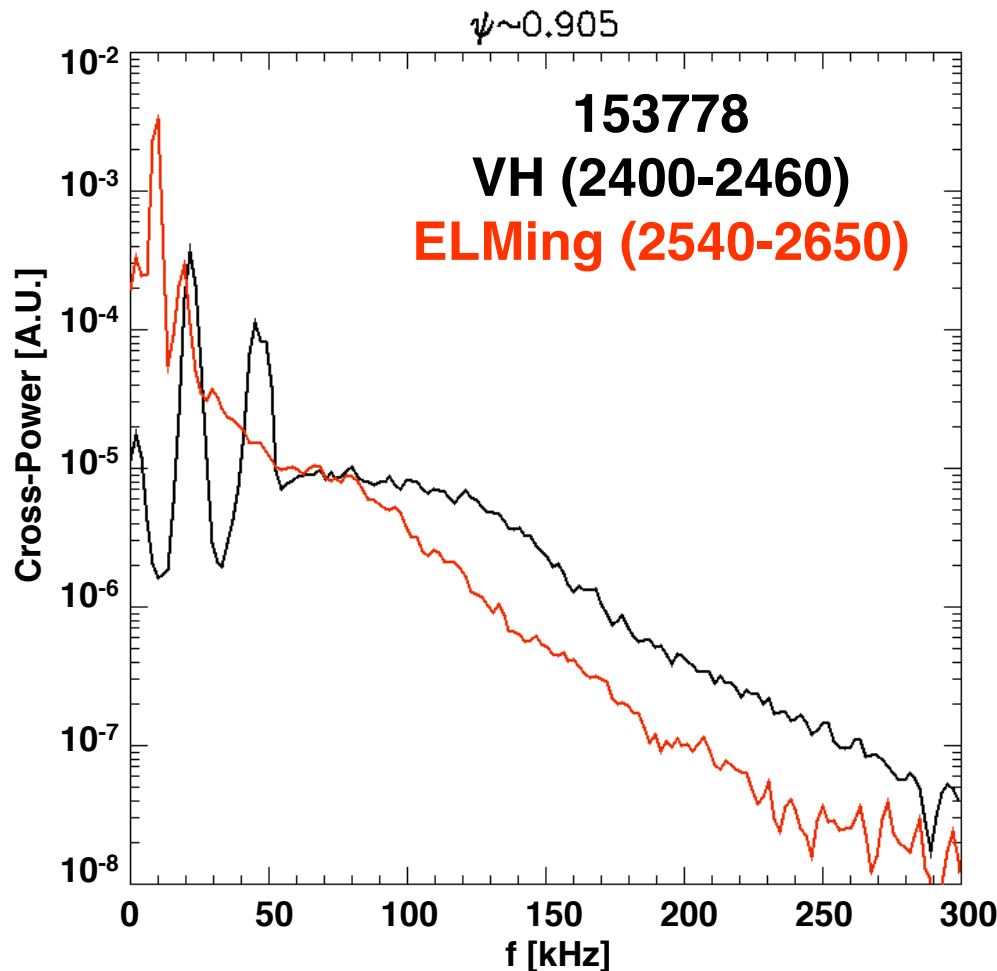
Low Amplitude EHOs Have Been Observed in NSTX-U As Well

- NSTX-U EHOs too weak to cause transport.
 - Physics assessment only.
- BES and reflectometer analysis show that the modes are very edge localized.
- ELITE calculations show that the pedestal resides near the peeling boundary.



Recent VH-Mode BES Data Also Shows No Reduction in Turbulence Compared to H-Mode

- Data collected from 2013 VH-mode experiments in DIII-D



VH-mode phase, like EP H-mode, has consistently larger fluctuations in the pedestal.

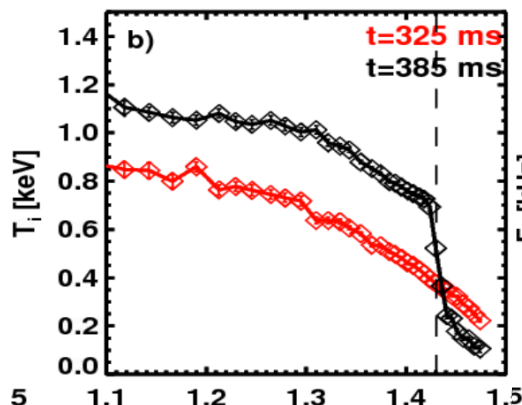
Confinement Regimes With Taller Pedestals than in H-Mode May Be Promising for Next-Step Devices

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

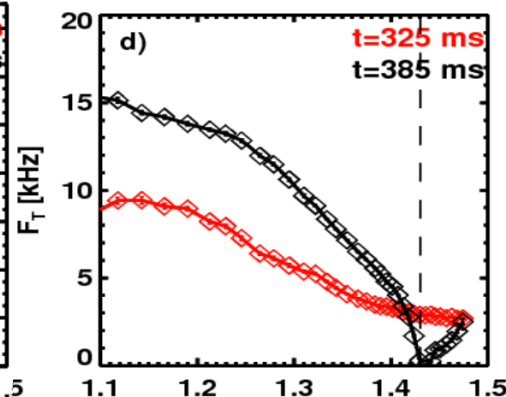
- Develops a region at the edge where the ion temperature gradient is much steeper than in H-mode.
- This region is associated with a region of strong toroidal flow shear, and often a very narrow minima in the flow.
- The transition to this region occurs after the L->H transition, and often follows on ELM.

H-mode *EP H-mode*

T_i vs. Major Radius

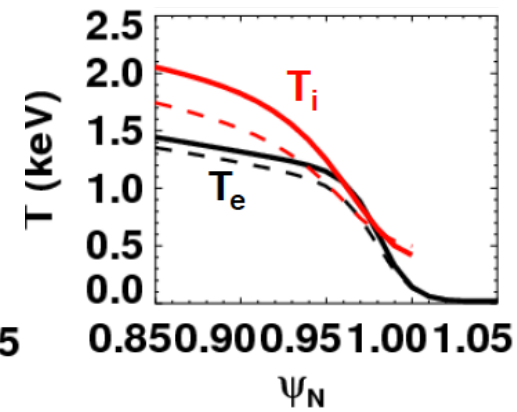
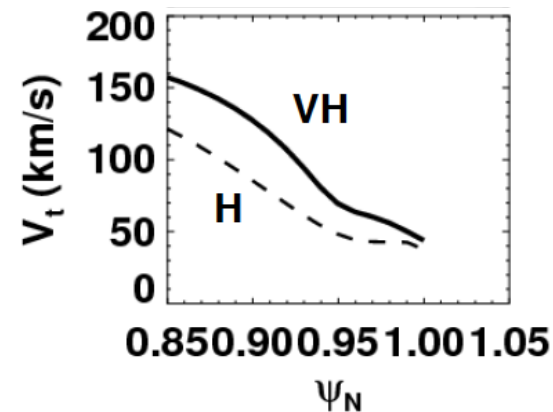


F_T vs. Major Radius



Characteristics of VH-Mode

- Obtained with very good vessel conditioning.
- Region of good confinement moves inward, resulting in a broader edge confinement barrier.
- Region of large ExB velocity shear extends inwards from the plasma edge.

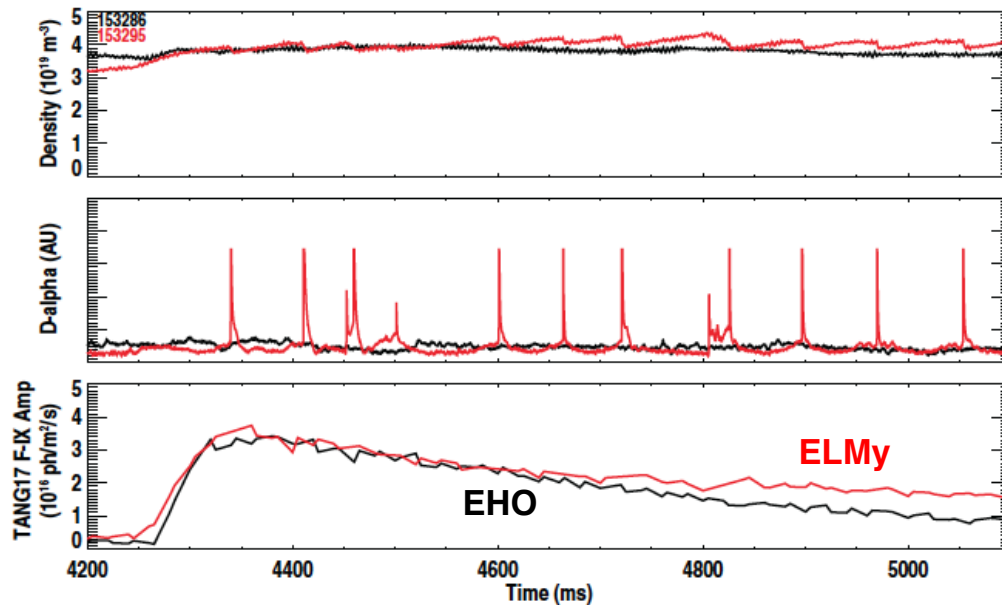


The EHO Can Exhaust Impurities Just as Well as Type 1 ELMs

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

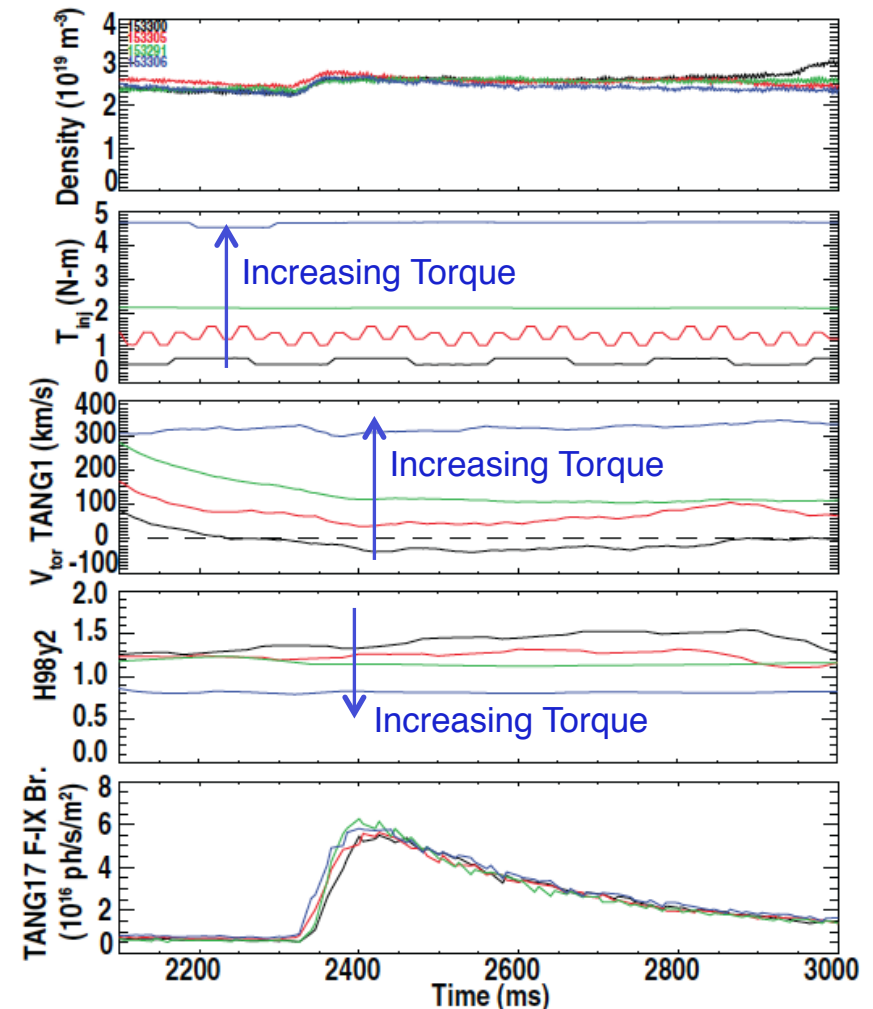
- Mixture of 90% deuterium and 10 % carbon-tetrafluoride introduced through a gas valve.
- Charge exchange emission from F-IX used to monitor impurity content.

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



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

Impurity confinement time as a function of input torque



QH-Mode confinement maximizes at low torque, but impurity confinement does not increase