3D Magnetic Perturbation Effects on Confinement During ELM Control Experiments

by

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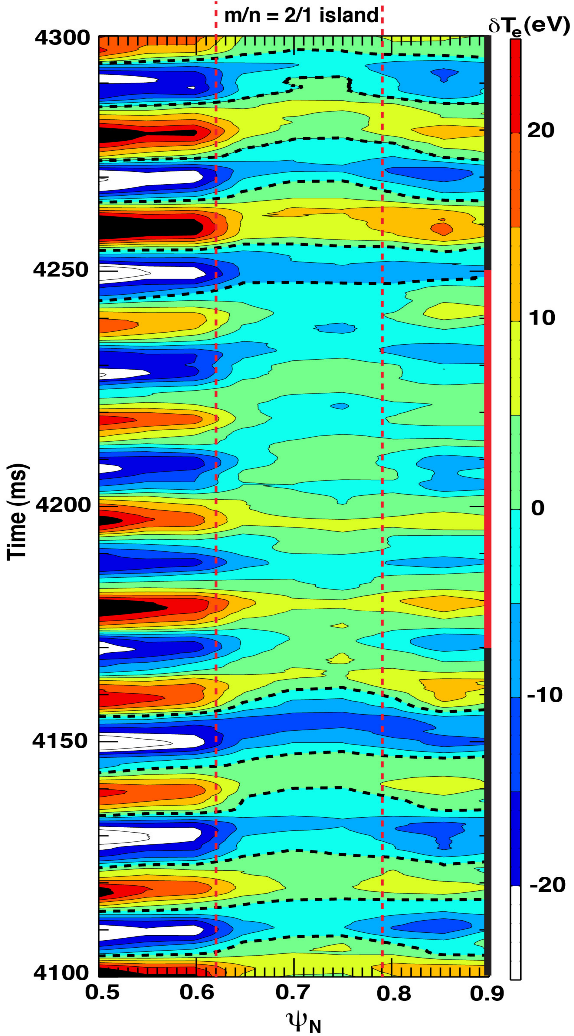
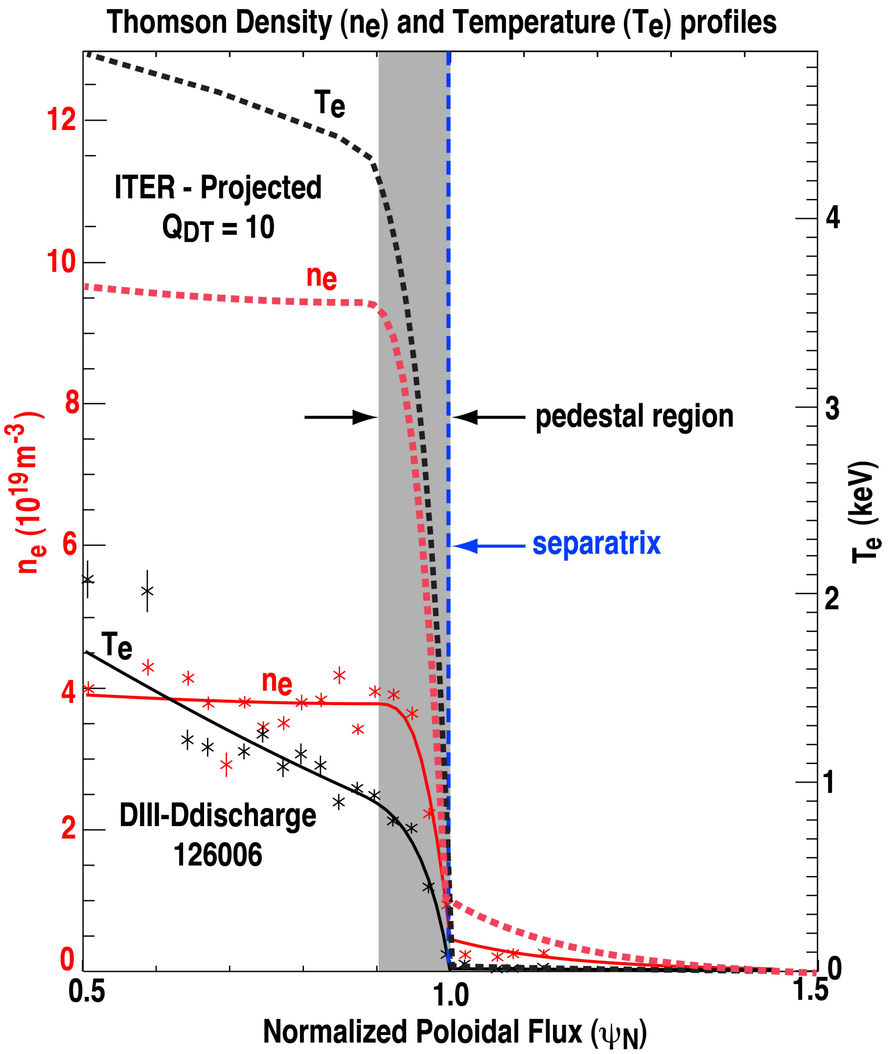


Spontaneous m/n=2/1 island bifurcations in DIII-D

ELM Control is Essential for Achieving High Fusion Gain in Burning Plasma

Outline

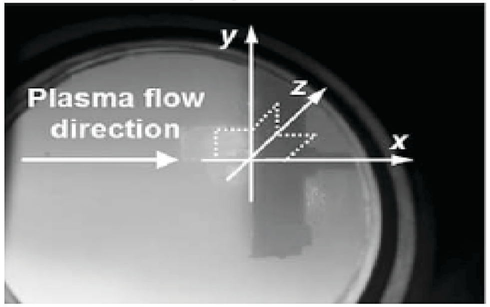
- **Implication of Edge Localized Modes (ELMs) in ITER**
- **Overview of Resonant Magnetic Perturbation (RMP) transport**
- **Transport during ELM suppression with RMP fields in DIII-D**
- **Summary and conclusions**



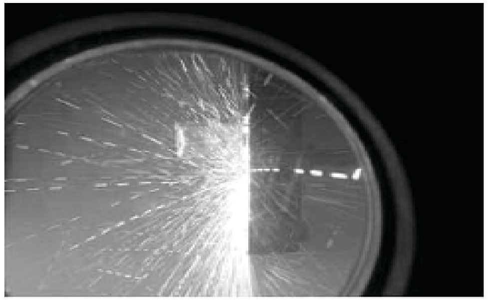
High Fusion Gain Requires Pedestal Pressures Resulting in Uncontrolled ELMs that Exceed Vessel Damage Thresholds

- **ELMs must be suppressed or strongly mitigated in burning plasma devices**
- **In ITER, ELM energy transients exceeding 0.5-1.0 MJ/m^2 will result in a:**
  - Significant reduction of plasma facing component lifetimes
- **Two ELM control options are currently planned in ITER:**
  - Triggering small, high frequency ELMs, with pellets – ***pellet pacing***
  - Maintaining MHD stable pedestal pressures with ***RMP fields***

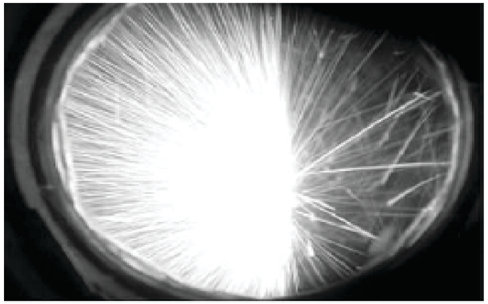
Droplets ejected from a tungsten surface by a plasma flow



Q = 1.1 MJ/m2, p = 1.5 atm



Q = 2.0 MJ/m2, p = 3.2 atm



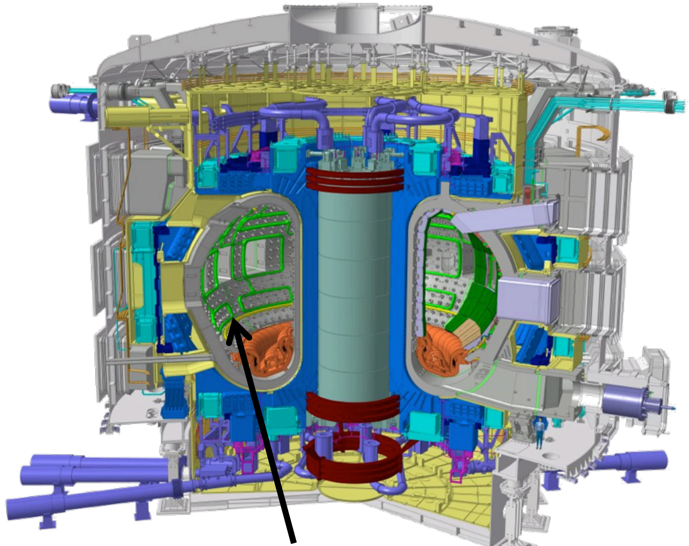
Q = 2.2 MJ/m2, p = 5.0 atm

N. Klimov, *et al.*, J. Nucl. Mater. **390–391** (2009) 721

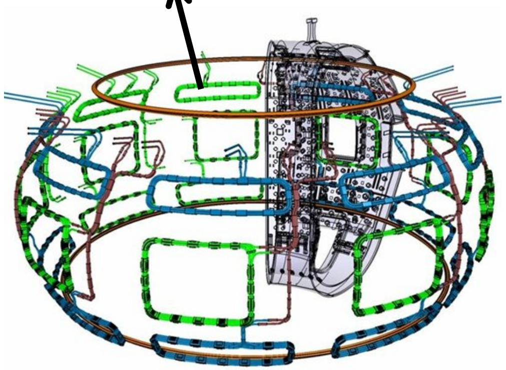
ELM Control is Essential for Achieving ITER's Q_{DT} = 10 Goal

- **Uncontrolled ITER ELMs will:**
  - Crack and melt tungsten divertor plates
  - Release impurities from plasma facing surfaces that:
    - Contaminate and cool the plasma
    - Degrade fusion performance
    - Trigger a radiative collapse leading to a plasma current disruption
- **RMP ELM control coils are included in the ITER baseline design**
  - Each of the 27 coil loops will be individually controlled
    - Maximum current 90 kAt

ITER Tokamak Cutaway



ITER ELM coil (IEC)

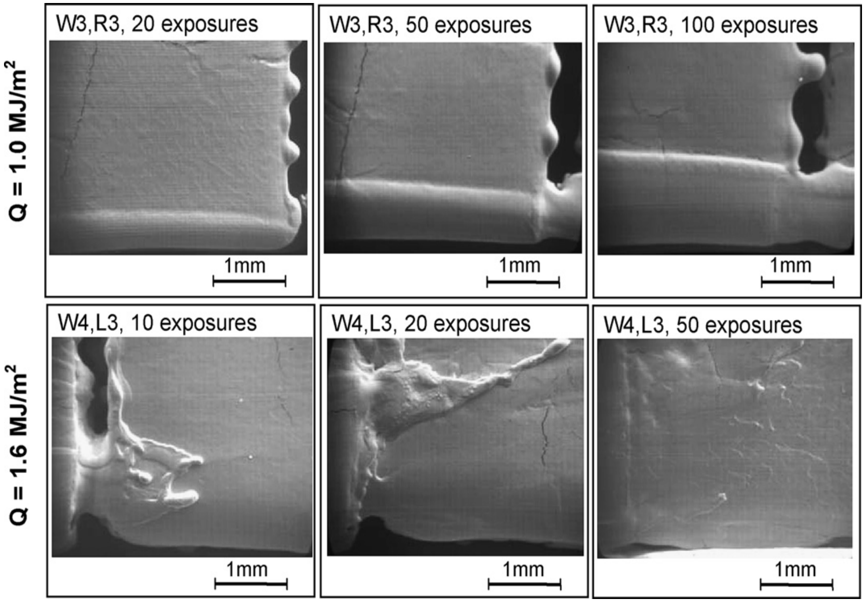


E. Daly, et al., *Fusion Sci. Technol.* **64** (2013) 168
T. E. Evans, et al., Nucl. Fusion **53** (2013) 093029

Uncontrolled ELMs are Expected to Exceed the ITER Tungsten Divertor Melt Limit by Approximately Factor of 30

- **ELM energy scales inversely with pedestal electron collisionality**
    - Implies a 20% loss of pedestal energy (W_{ped}) during each ITER ELM
        - $\Delta W_{ELM} = 0.2W_{ped} = 0.2{*}0.3W_{th} = 0.06{*}350\text{ MJ} = 21\text{ MJ}$
        - Assuming an ELM footprint area:
            - $A_{ELM} = A_{steady\_state} = A_{s.s.} \sim 1.4\text{ m}^2$
        - Uncontrolled ITER ELM energy density $\Delta W_{ELM}/A_{ELM} \sim 15\text{ MJ/m}^2$
- **ITER ELM energy density must be reduced to ≤ 0.5 MJ/m² to prevent melting of tungsten**
    - At this limit a divertor lifetime of $\sim 10^5$ ELMs is expected

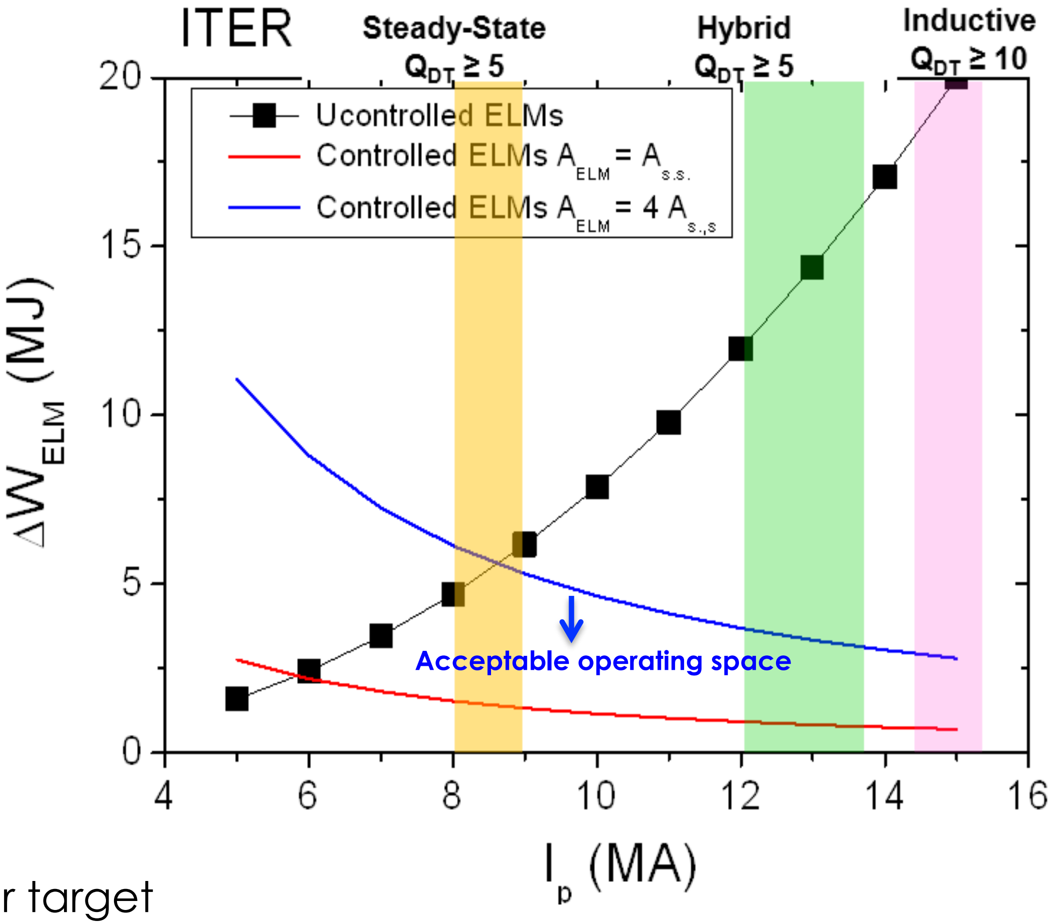
Evolution of tungsten samples during 0.5 ms simulated ELM pulses



A. Zhitlukhin, *et al.*, J. Nucl. Mater. **363–365** (2007) 301

Acceptable Operating Space with Uncontrolled ELMs in ITER Depends on A_{ELM} Scaling With ELM Energy (ΔW_{ELM})

- **Energy of uncontrolled ELMs (ΔW_{ELM}) increases with I_p**
- **A_{ELM} expected to increase with I_p in ITER during uncontrolled ELMs**
  - Limited by interaction with main chamber wall
- **Scaling of uncontrolled and controlled A_{ELM} is uncertain**
  - Additional research is a high priority

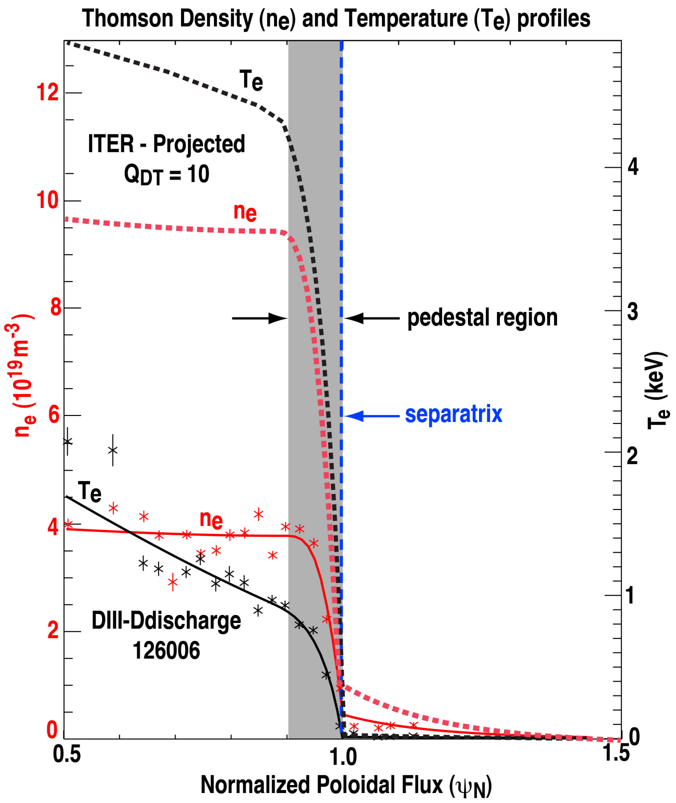


A_{ELM} = area of ELM footprint on divertor target

A. Loarte, et al., Nucl. Fusion **54** (2014) 033007

Understanding RMP Effects on Density and Neutral Fueling is Critical for Scaling ELM Control to ITER

- **ELM mitigation and suppression in DIII-D is linked to a reduction in the pedestal height and width**
  - RMP fields alter the edge density transport and/or neutral fueling efficiency
  - No significant change in edge energy transport
- **ITER Q_{DT} = 10 pedestal pressure is significantly Larger than in DIII-D**
  - Pedestal response to RMP fields likely to be different
  - Fueling due to neutral recycling will be ineffective
- **Validated transport and neutral fueling models* needed to assess viability of RMP ELM control in ITER**

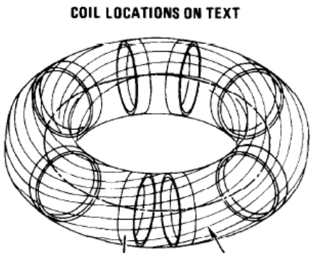


* **See 3/16 morning talk by:** H. Frerichs, et al., "Three-dimensional edge plasma and neutral gas modeling with the EMC3-EIRENE code on the example of RMP application in tokamaks - status and development plans"

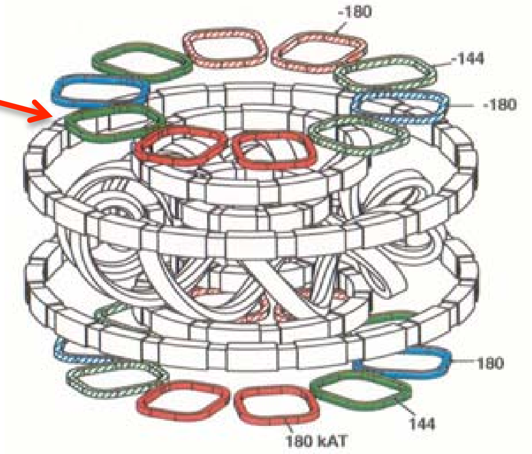
RMP Studies in Ohmic and L-mode Limiter Plasmas Have Provided Important Insight into Transport and Fueling Physics

TEXT

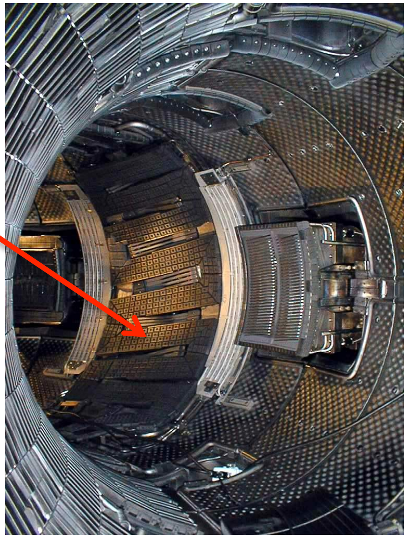
External RMP coils



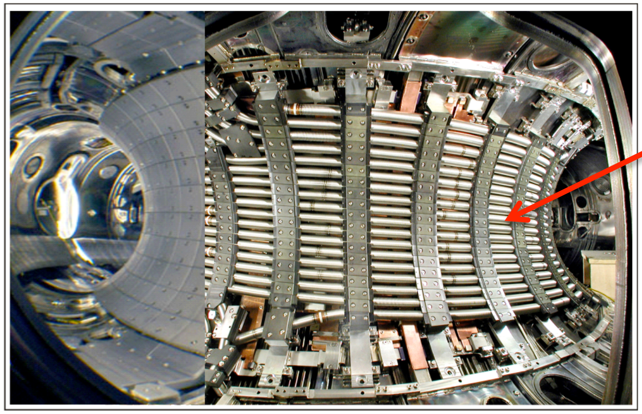
LHD



TORE SUPRA

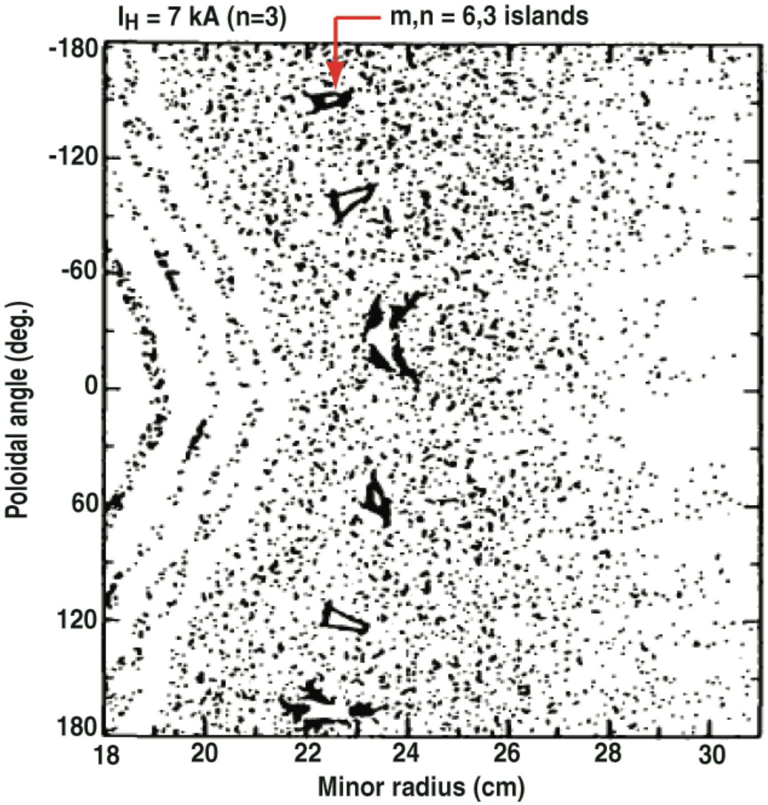


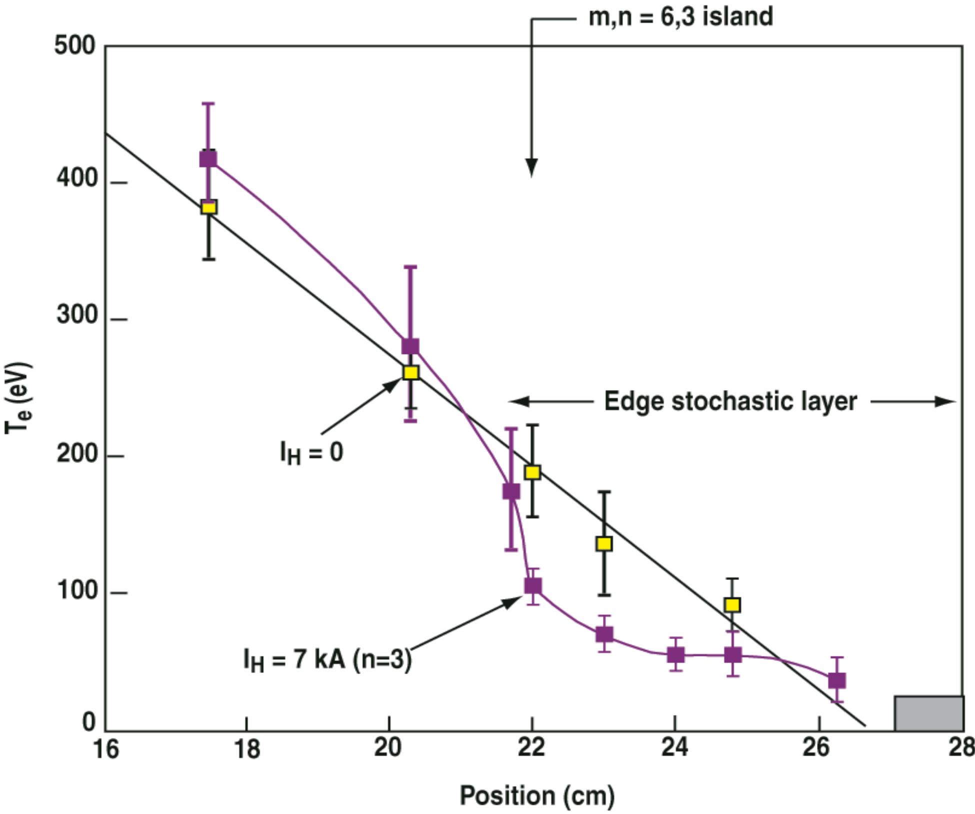
TEXTOR



Internal RMP coils

Large RMP Fields in TEXT Increase Electron Thermal Transport, but Only in the Edge Stochastic Layer

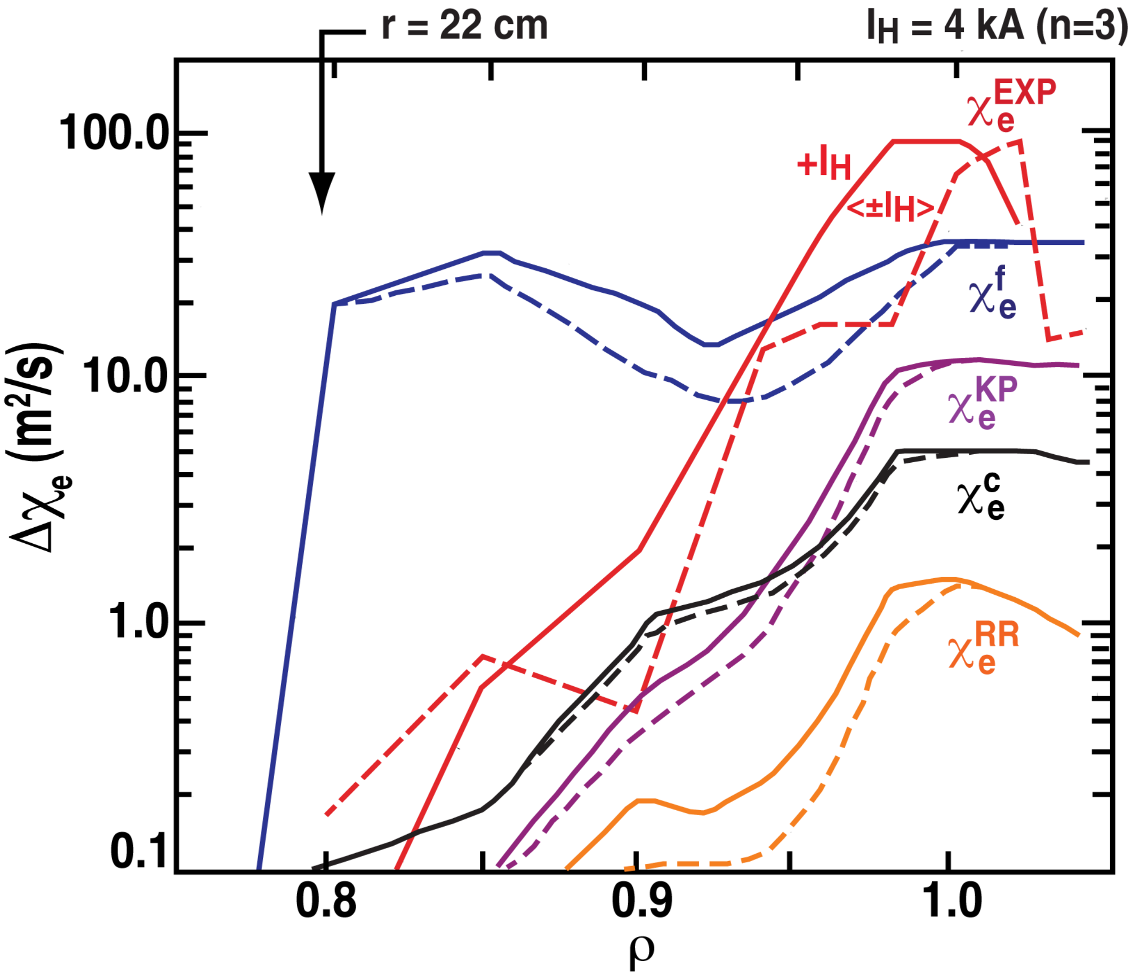




- **Electron thermal diffusivity (χ_e) at r_a = 27 cm increases from 20 m^2/s with no RMP to ~ 200 m^2/s with an RMP field of $\delta b_r/b_\phi = 1 \times 10^{-3}$**
  - Core thermal confinement improves inside r = 21 cm (∇T_e increases similar to ETB)

T. E. Evans, et al., *J. Nucl. Mater.* **145-147** (1987) 812

Stochastic Electron Thermal Diffusivity Exceeds Model Predictions in TEXT L-mode Plasmas



χ_e^{EXP} Power balance measurements

Models

$\chi_e^f = D_{||}\langle(b_r/B_\phi)^2\rangle$
Collisional fluid

$\chi_e^{KP} = (D_m/\delta_\perp)(D_{||}D_\perp)^{1/2}$
Collisional Kadomtsev-Pogutse

$\chi_e^c = D_m v_e$
Collisionless quasi-linear

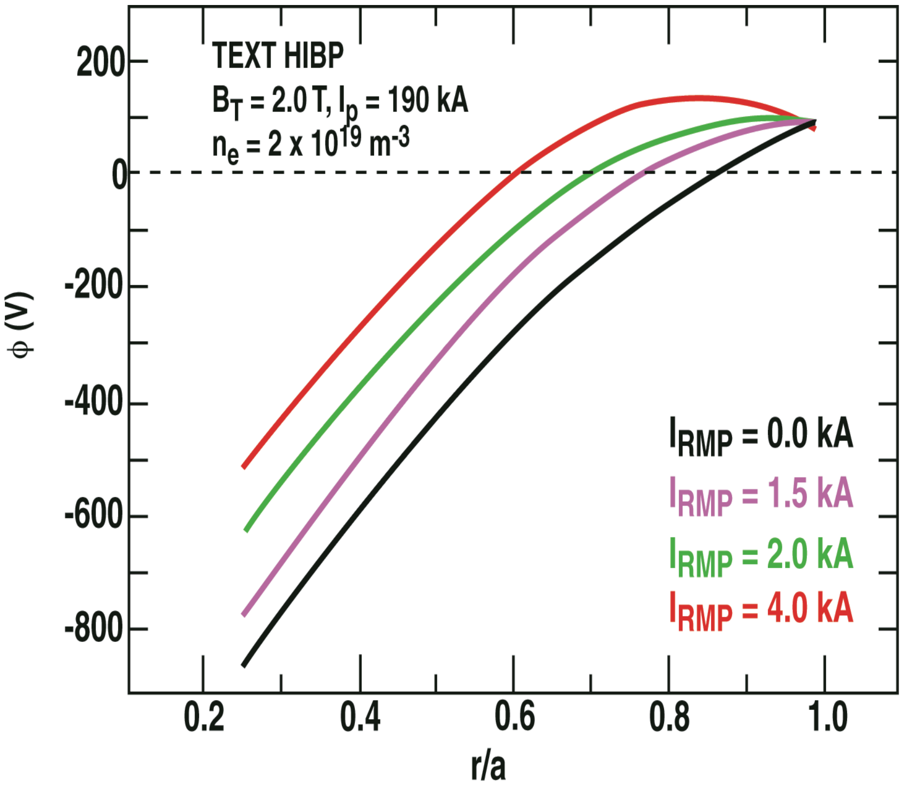
$\chi_e^{RR} = D_m D_{||}/L_K$
Collisional Rechester-Rosenbluth

- Electron thermal diffusivity at $\rho = 1.0$, $\chi_e(1) \sim 100$ m²/s with $\delta b_r/b_\phi = 5.7 \times 10^{-4}$

S.C McCool, et al., *Nucl. Fusion* **29** (1989) 547

Positive Edge Plasma Potential, Resulting in a Positive E_r, is a Signature of an Edge Stochastic Magnetic Field

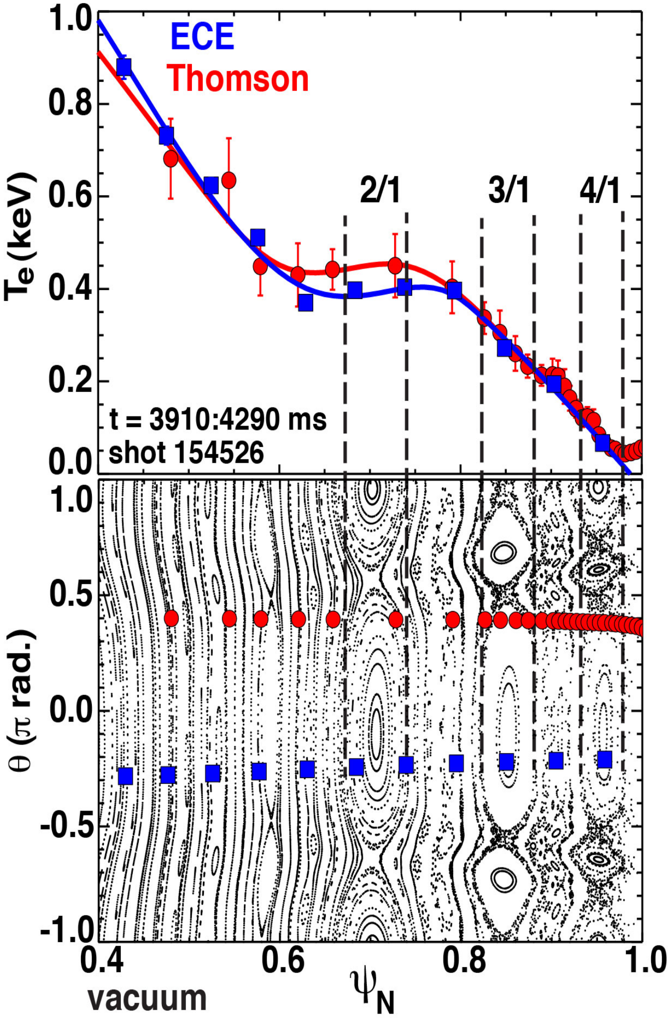
- **Experiments in Ohmic limiter plasmas have an edge plasma potential that increases with the width of the calculated vacuum stochastic layer**
  - Measured with a heavy ion beam probe in the TEXT tokamak



X. Z. Yang, et al., *Phys. Fluids,* **B3** (1991) 3448

- **Hypothesis:**
  - Non-ambipolar electron transport increased in stochastic layer
  - Increases positive plasma potential
  - Generates positive (outward) E_r
  - Alters macroscopic edge E x B flow, along with turbulence and transport

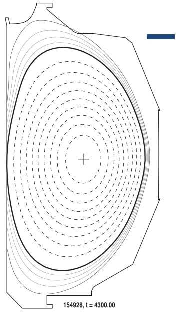
T_e Profiles do not Provide Definitive Information on the Plasma Response to RMP Fields



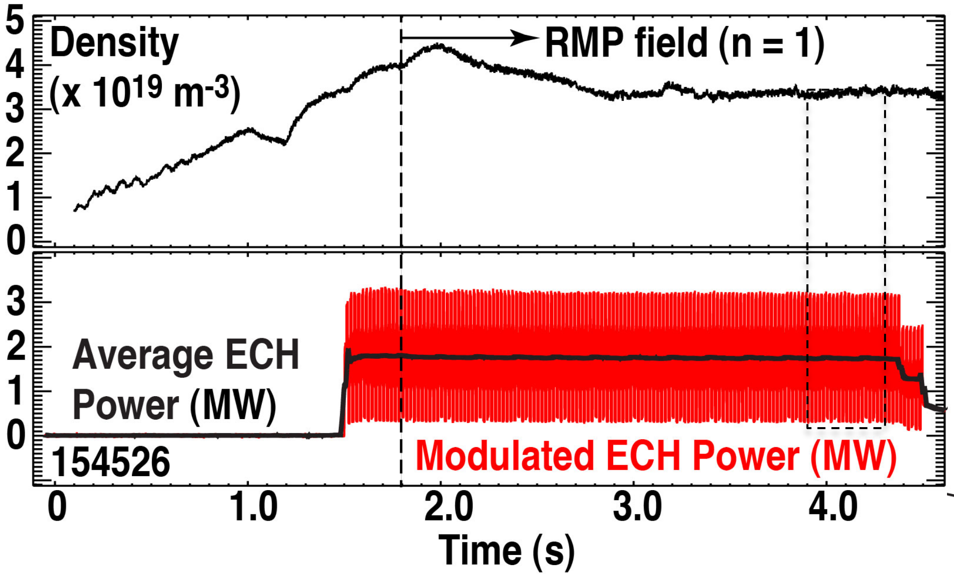
- **Flattening of T_e profiles in DIII-D due to RMP fields not consistent with vacuum island widths**

- **Wide T_e profile flattening across q = 2 surface could result from:**
  - An amplified m/n = 2/1 island
  - A partially stochastic m/n = 2/1 island
  - A fully stochastic layer
  - Turbulence spreading across island

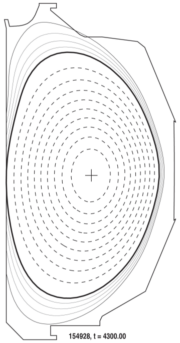
- **Additional diagnostic data needed to quantify RMP plasma response:**
  - Modulated Electron Cyclotron (MEC) heat pulse analysis used to resolve differences

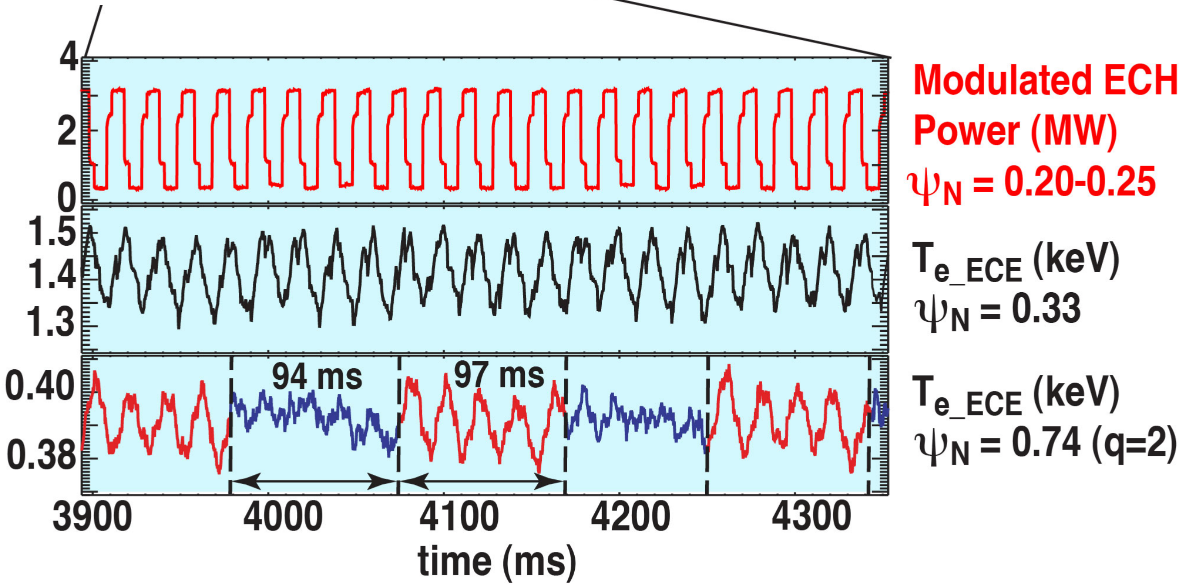


Modulated EC (MEC) Heat Pulse Analysis Provides Additional Information on Magnetic Topology



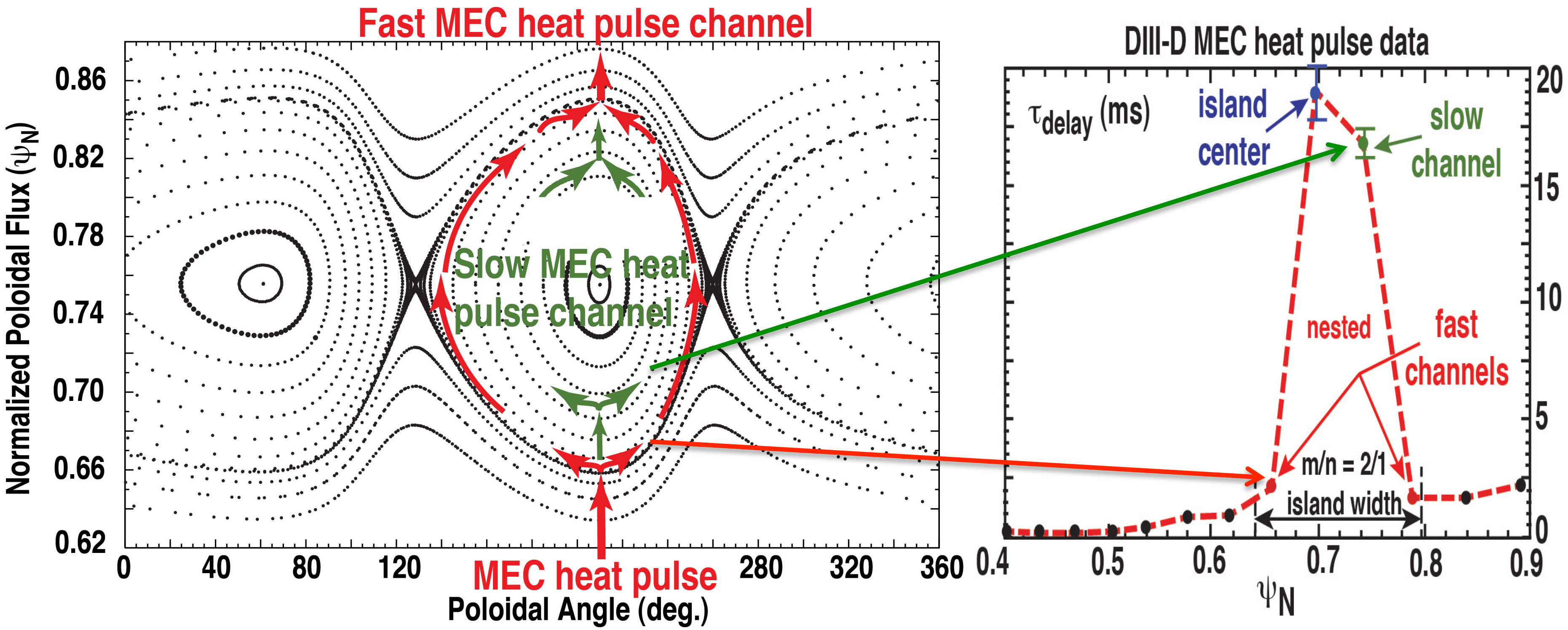
- **Plasma response to RMP field studied during stationary conditions (t = 3.9 to 4.35 s)**





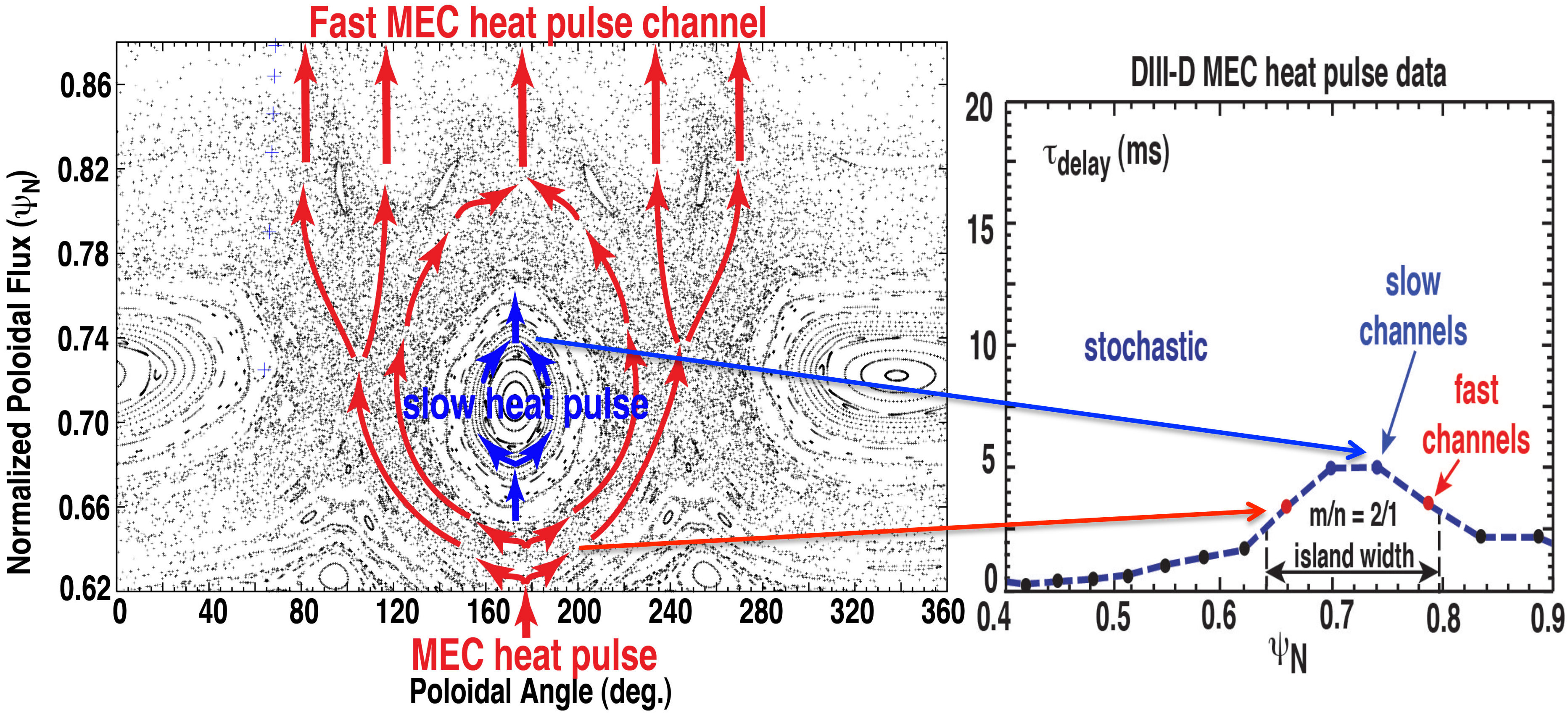
- **T_{e_ECE} response at q =2 shows spontaneous bifurcations**
  - Related to changes in m/n = 2/1 island transport

MEC Heat Pulse Delay Time Used to Determine Island Location and Width



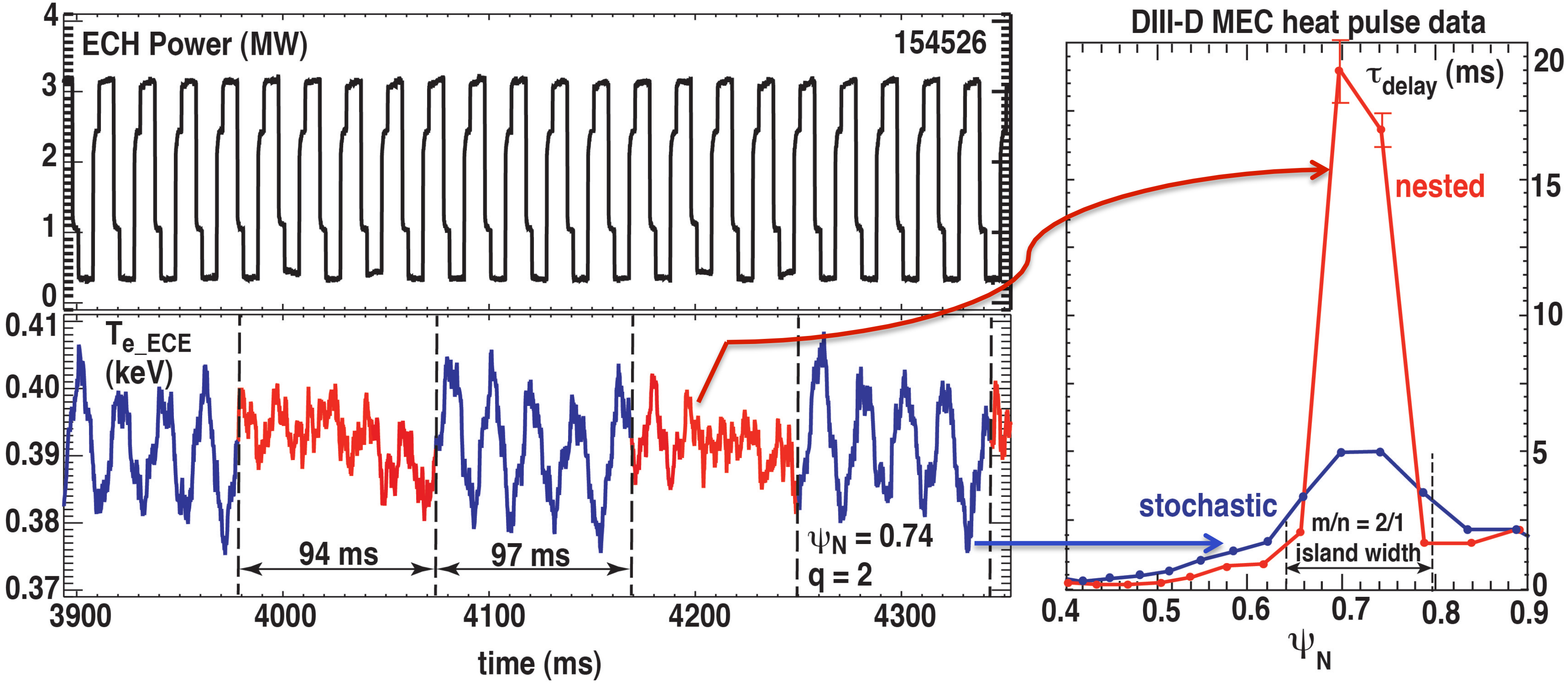
- Fast heat pulse shunted around outside of island ($\chi_{||} >> \chi_{\perp}$)
- Heat pulse delay time increases at island center
- Island width determined from delay time profile

MEC Heat Pulse Time Delay Determines Degree of Stochasticity and Transport Enhancement Around Islands



- **Heat pulse delay time reduced by partially stochastic island and/or changes in turbulence**
  - Nested flux surface in island center increases delay time

MEC Analysis May Imply a Bifurcation of the m/n = 2/1 Island from Nested Flux Surfaces to Partial Stochasticity



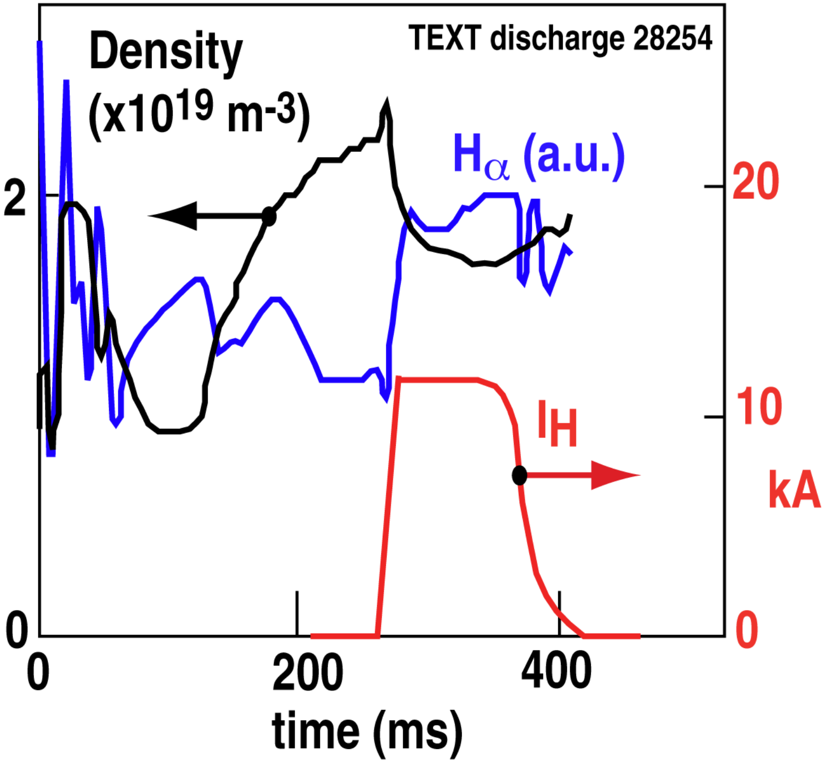
- **Periodic bifurcations of island observed during constant RMP field**
  - Hypothesis: island topology altered (nested -> partially stochastic -> nested)
    - May also involve changes in turbulent transport
- **Indicates importance of plasma response on island stability**

RMP Particle Transport and Neutral Recycling Studies in Limiter Plasmas Reveal Multiple Complex Physics Effects

Ohmic and L-mode RMP transport results

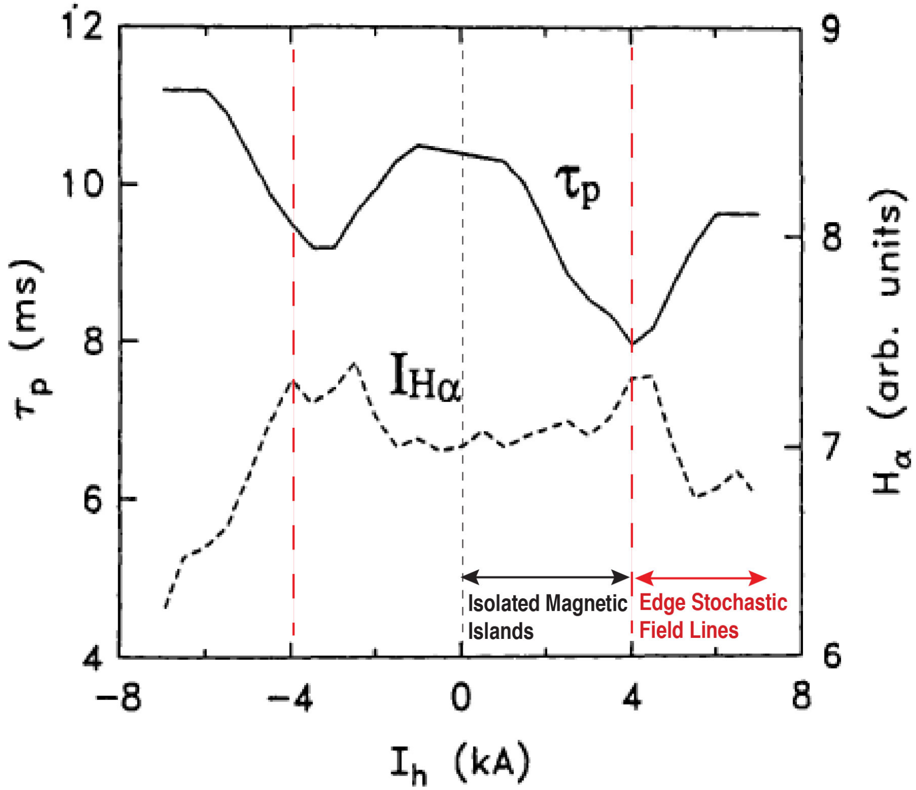
- **Particle transport scales with magnetic island widths**
  - Islands match applied vacuum field calculations (to within ±5%)
  - Island localized **E** x **B** convective cell dynamics contribute to transport
- **Particle confinement sensitive to plasma shape and recycling fueling efficiency**
  - Both degraded and improved τ_p (τ_p*) observed

TEXT: limiter discharge with RMP fields applied



N. Ohyabu, et al., *J. Nucl. Mater.* **121** (1984) 363

Particle Confinement Time in TEXT L-mode Plasmas is Proportional to Edge Magnetic Island Widths

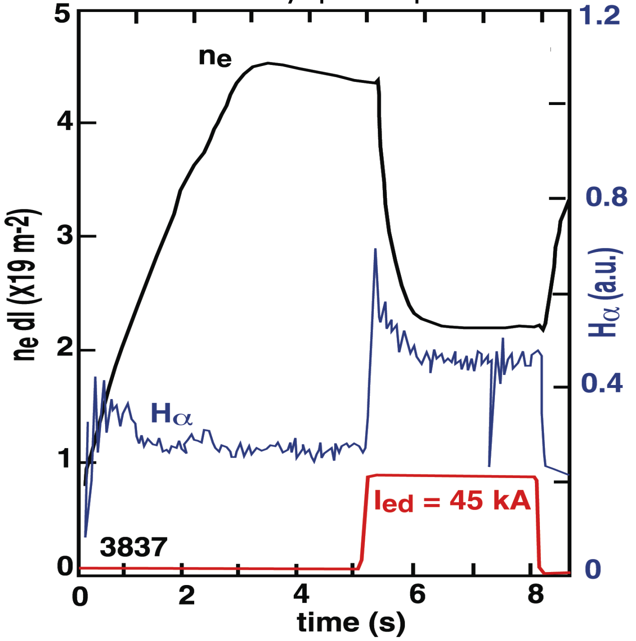


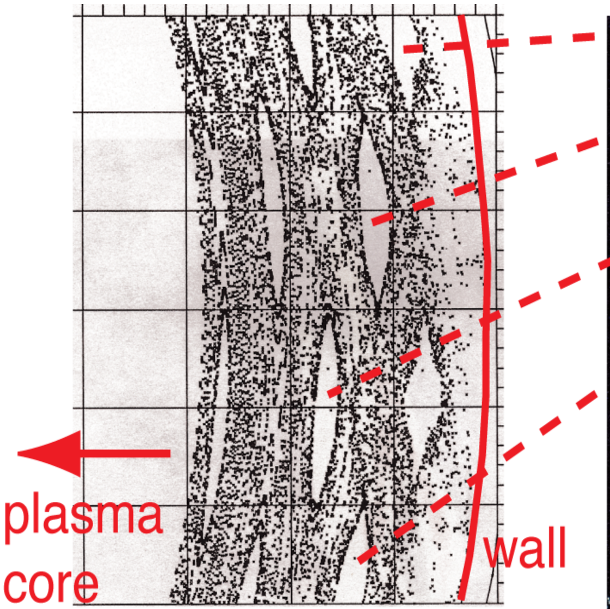
- **Particle confinement minimum seen at I_h ~ ± 4 kA**
  - Edge magnetic islands reach maximum width at I_h ~ ± 4 kA
  - I_h > ± 4 kA reduces island widths due to increased stochastic layer width

S.C McCool, et al., *Nucl. Fusion* **30** (1990) 167

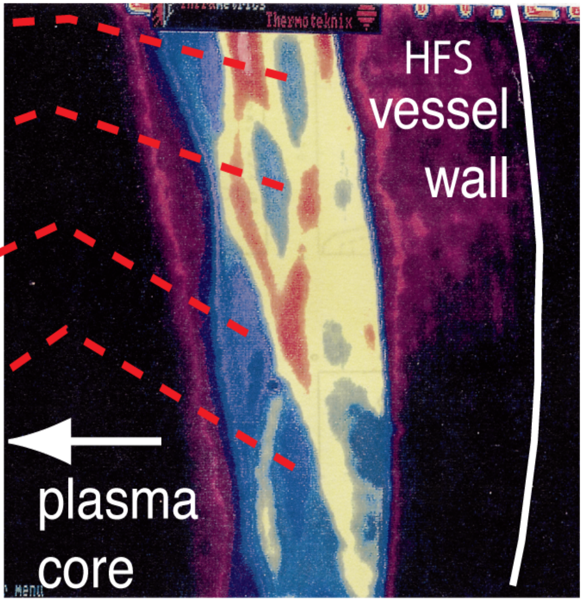
Increased Particle Transport In Limiter L-mode Plasmas Linked to Island Localized E x B Convection

Tore Supra Ergodic Divertor density pump-out



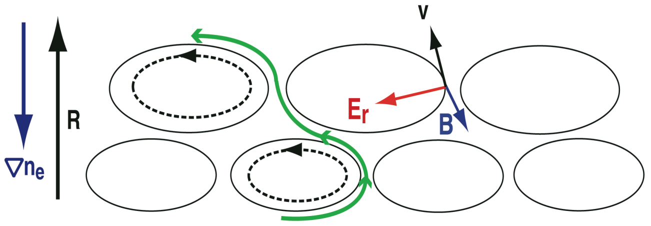


Vacuum field line calculation of islands in Tore Supra



Islands in Tore Supra (recycling light)

T. E. Evans et al., *Phys. Plasmas* **9** (2002) 4957

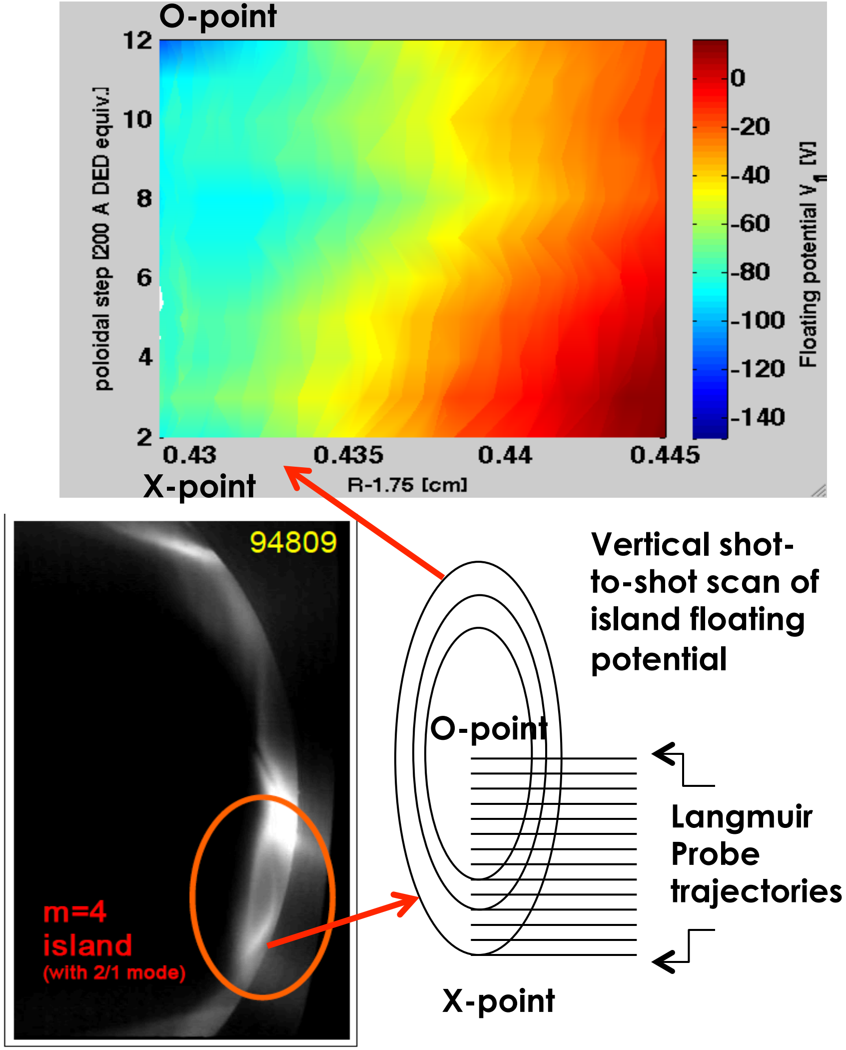


- **Island localized E x B convective cell transport hypothesis supported by data from**:
  - TEXT, CSTN-II, TEXTOR and Tore Supra

S. Takamura, et al., *Phys. Fluids* **30** (1987) 144,
S.C McCool, et al., *Nucl. Fusion* **30** (1990) 167 and
T. E. Evans, et al., *14th EPS Madrid, 1987, Vol.* ***11D****, p. 770*

Vertical Scan of Isolated Magnetic Islands in TEXTOR Shows Strong Floating Potential Gradients

- **Island floating potential distribution:**
  - Large negative region near O-point (~ -140 V)
  - Reduced potential near X-point (~ - 80 V)
  - Suggests electrons may be better confined than ions inside island
- **Implies local E_{island} across O-point could be as large as 15 kV/m**
  - Need T_e measurements to obtain plasma potential values
- **Consistent with island localized E x B convective transport hypothesis**
- **Introducing islands causes a 25% drop in τ_p**



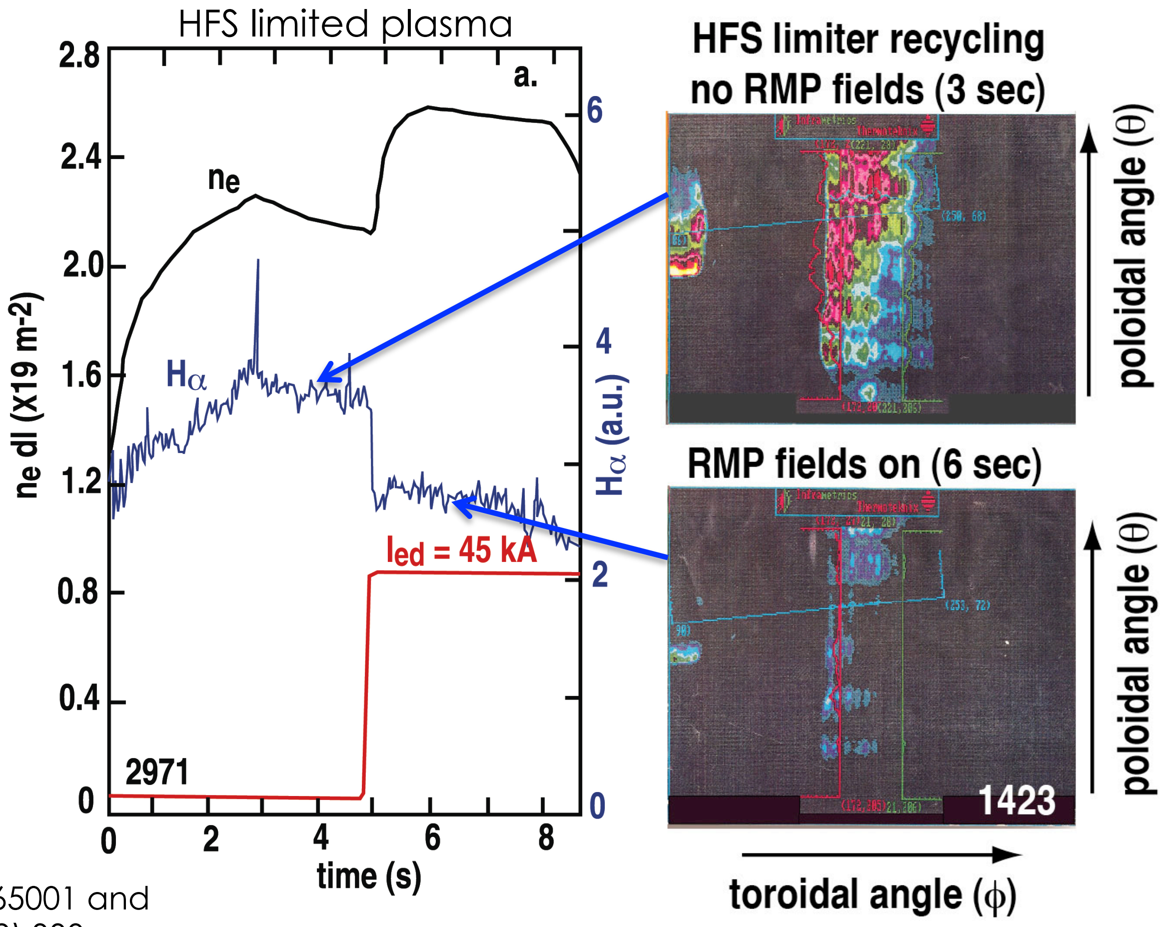
Vertical shot-to-shot scan of island floating potential

O. Schmitz, et al., J. *Nucl. Mater.* **415** (2011) S886

Improved Particle Confinement in Tore Supra with Applied RMP Fields Implies a More Complex Physics Picture

- **RMP fields in High Field Side (HFS) limited plasmas**
  - Increased density
  - Reduces recycling

- **Results reproduced in TEXTOR with HFS RMP coil**

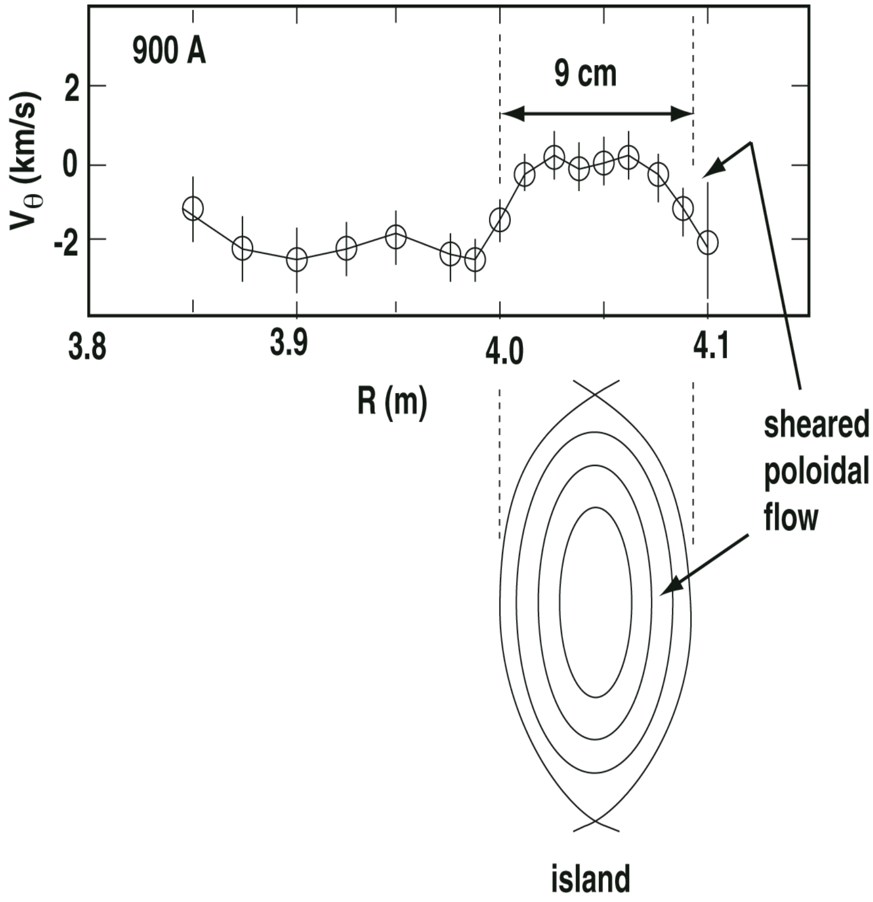


K. H. Finken, et al., *Phys. Rev. Lett.* **98** (2007) 065001 and
O. Schmitz, et al., *J. Nucl. Mater.* **390-391**(2009) 330

T. E. Evans, et al., *J. Nucl. Mater.* **196-198** (1992) 421 and T. E. Evans, Chaos, Complexity and Transport, World Scientific (2008) 147

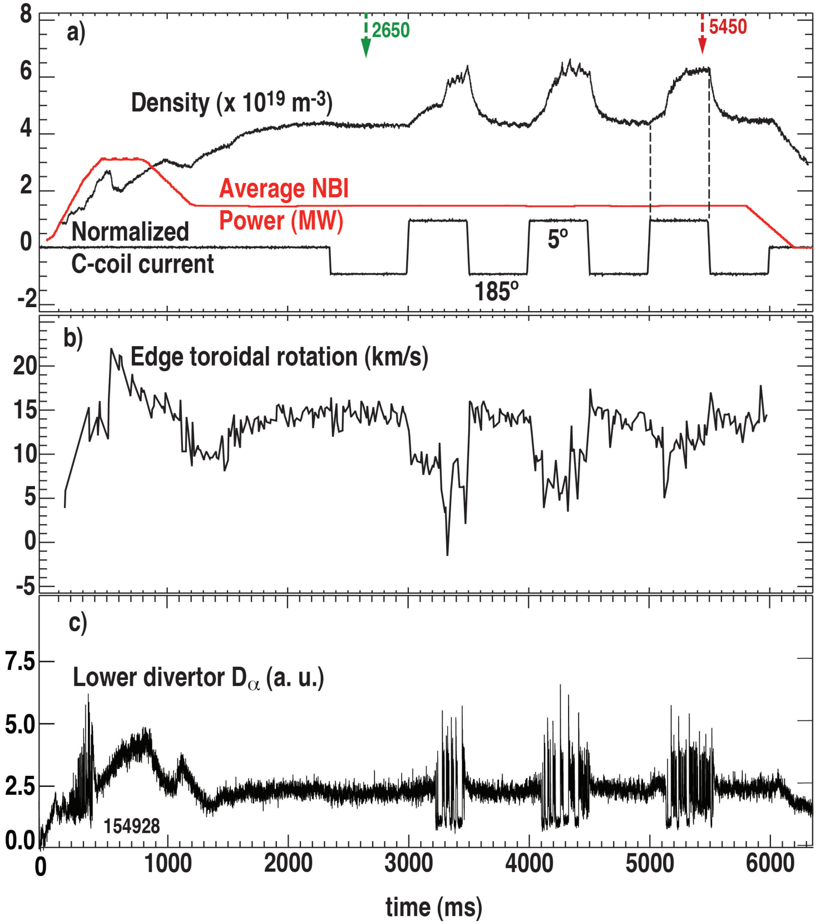
Isolated Magnetic Islands Produce Local Transport Barriers in LHD Heliotron Plasmas

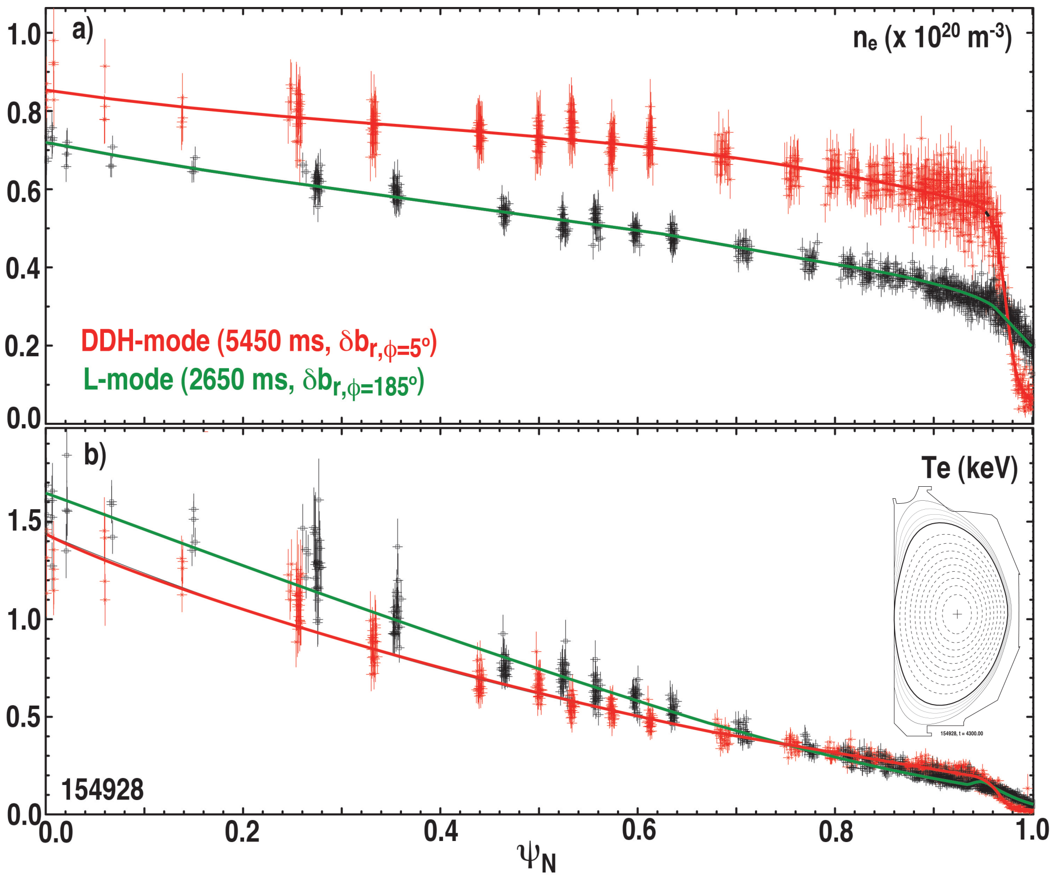
- **Sheared poloidal flows and plasma potential profiles peaked at the separatrix in large magnetic islands:**
  - Generates negative E_r profiles near the edge of the island
  - Reduces particle transport across the island separatrix
- **Radial variations in poloidal flows and E_r observed in LHD plasmas with large magnetic islands**



K. Ida, et al., *Phys. Rev. Lett.*. **88** (2002) 015002

RMP Field Triggers Improved Particle Confinement in Low Rotation DIII-D Limiter L-mode Plasmas



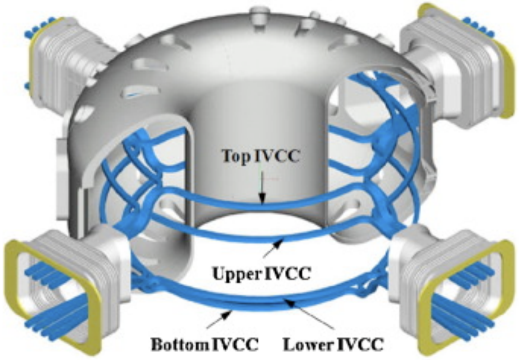


- **Divertor recycling shows dithering-like behavior without triggering ELMs**

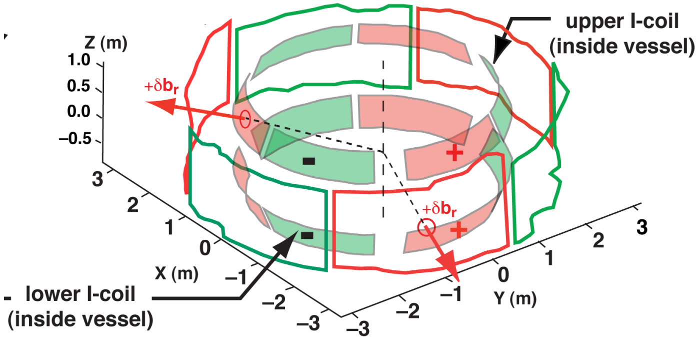
ELM Suppression and Mitigation is Obtained in Diverted Plasmas with Significantly Different RMP Coil Configurations

ELM Suppression has Only Been Obtained in KSTAR and DIII-D

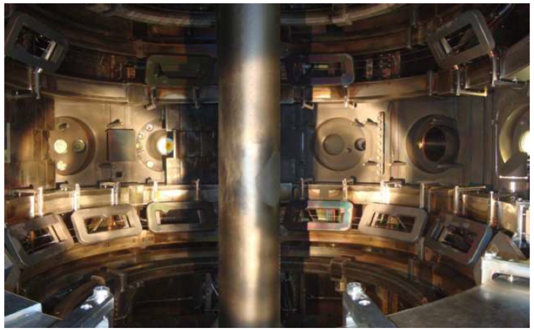
KSTAR



DIII-D

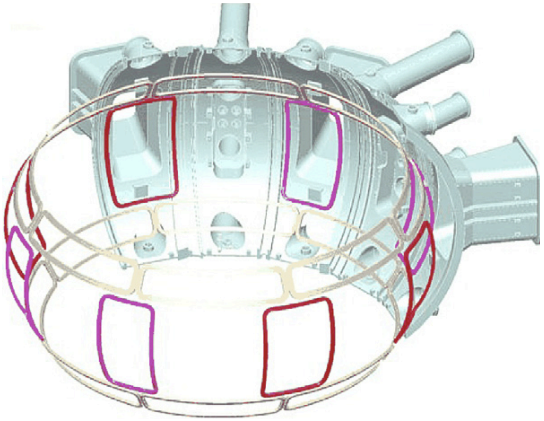


MAST



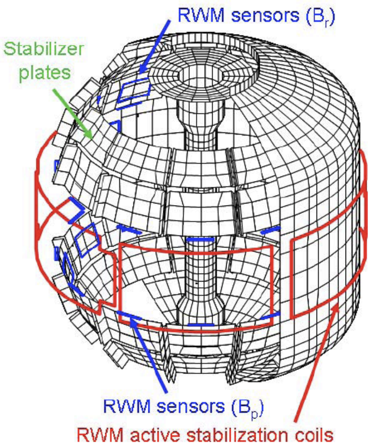
In-vessel RMP coils

ASDEX-Upgrade

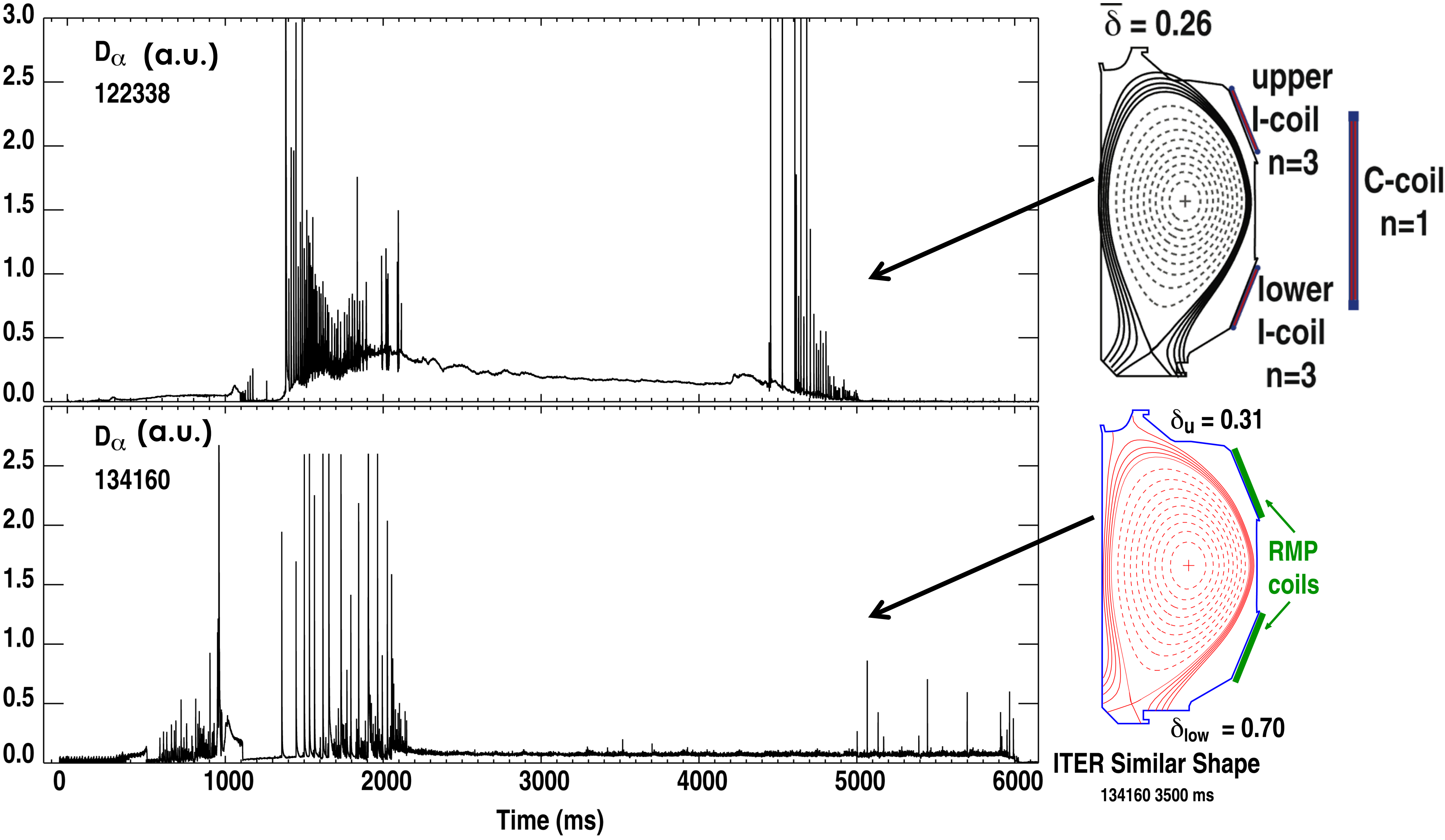


JET

NSTX

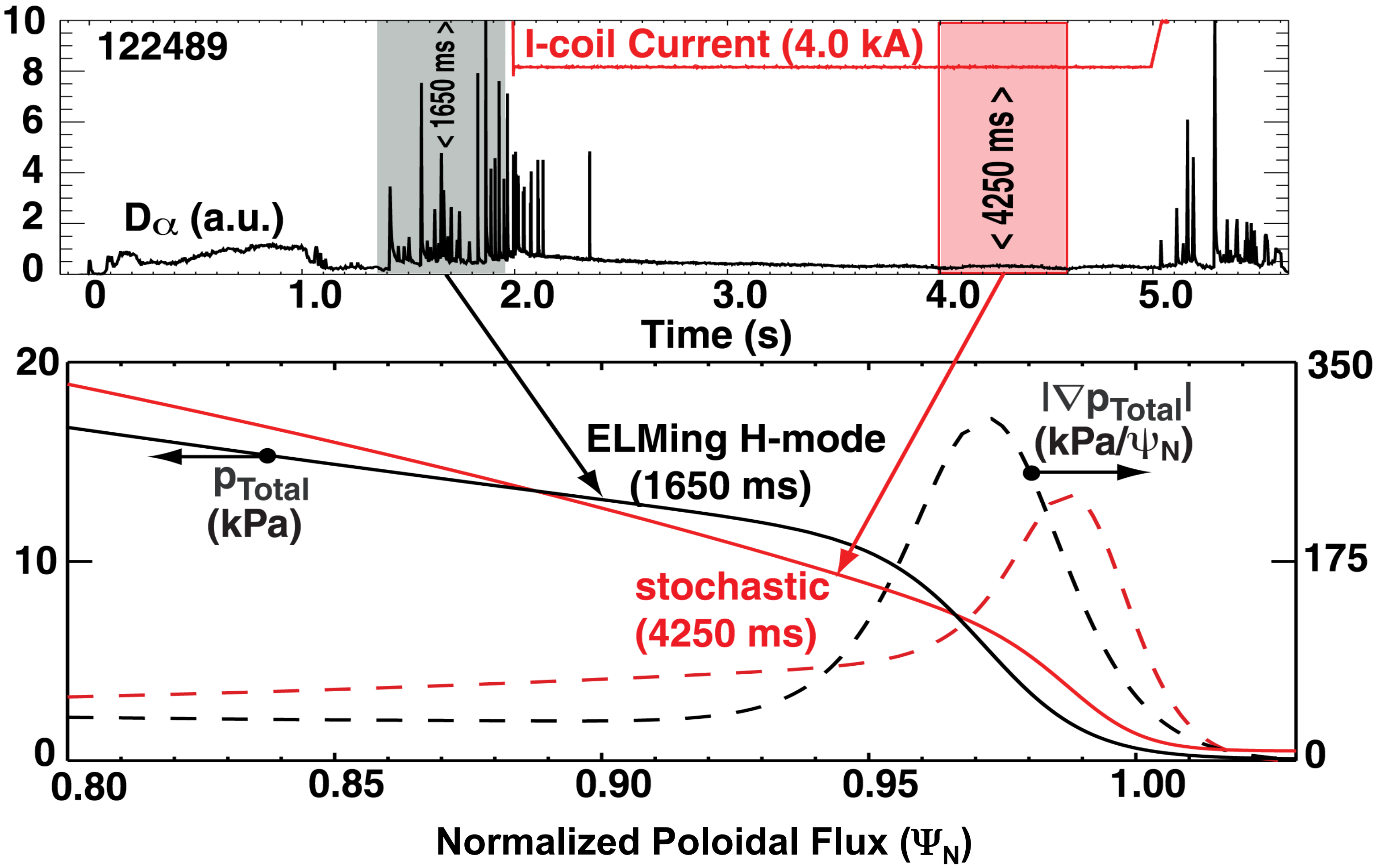


ELM Suppression is Obtained in DIII-D Over a Range of Plasma Shapes and Divertor Parameters

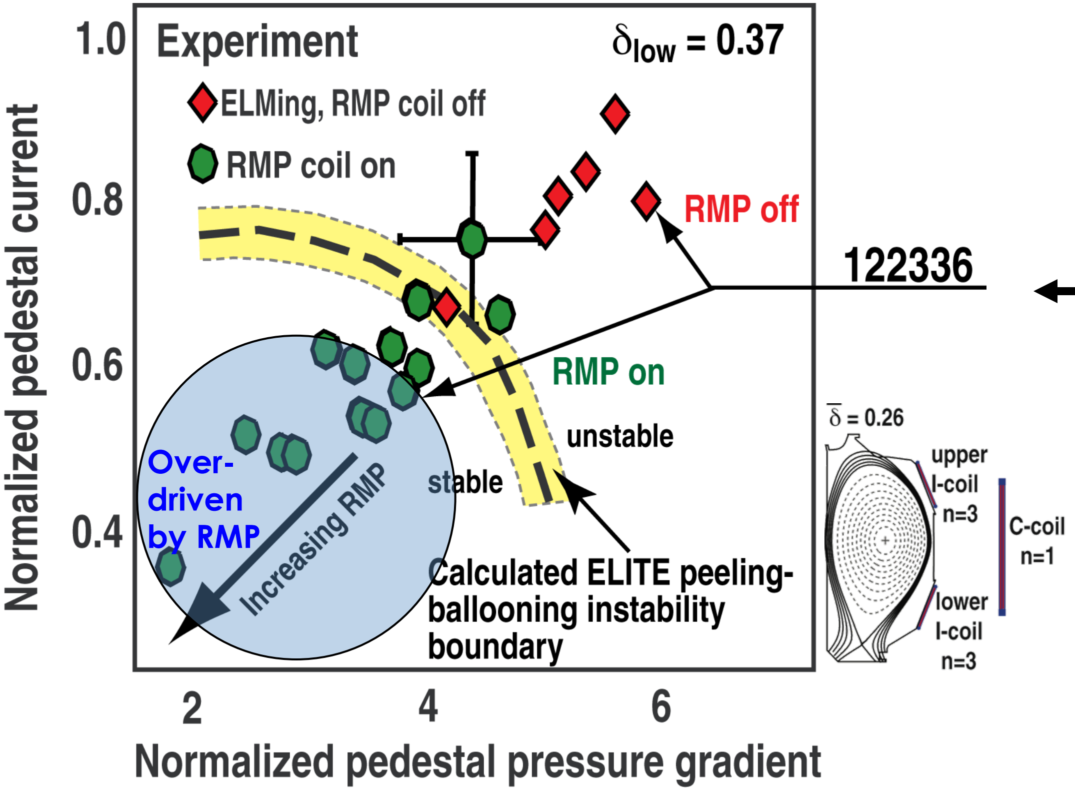


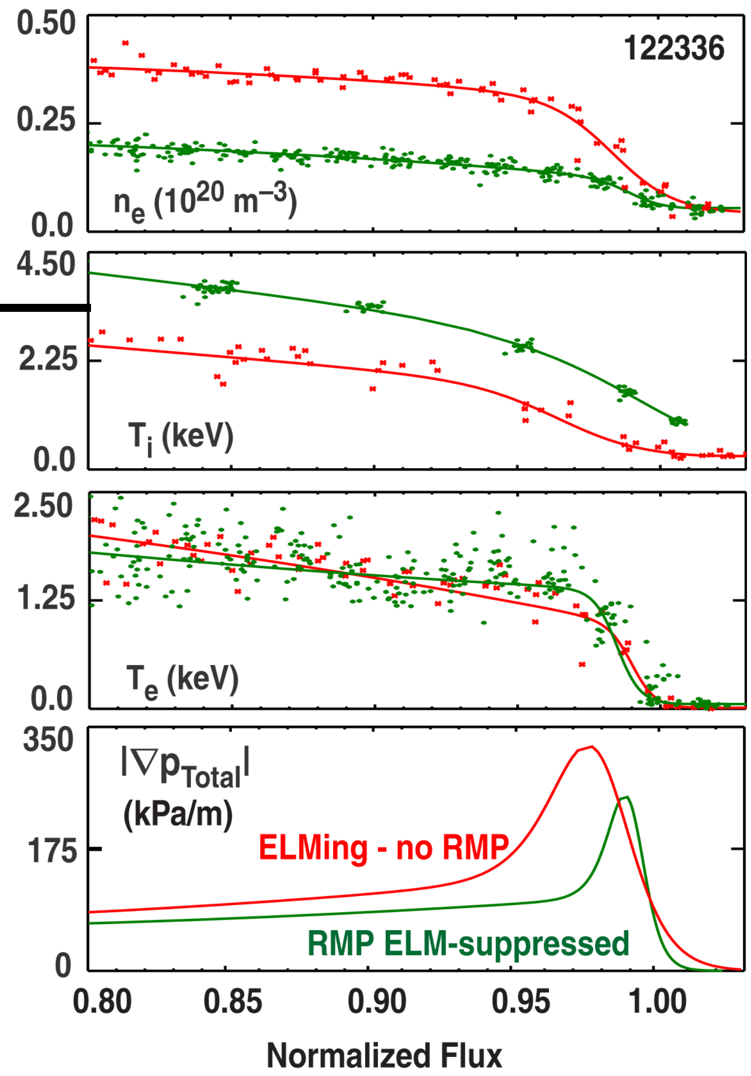
ELM Suppression Correlated with Pedestal Narrowing and Reduced ∇p_{Total}

DIII-D low δ ELM Suppression



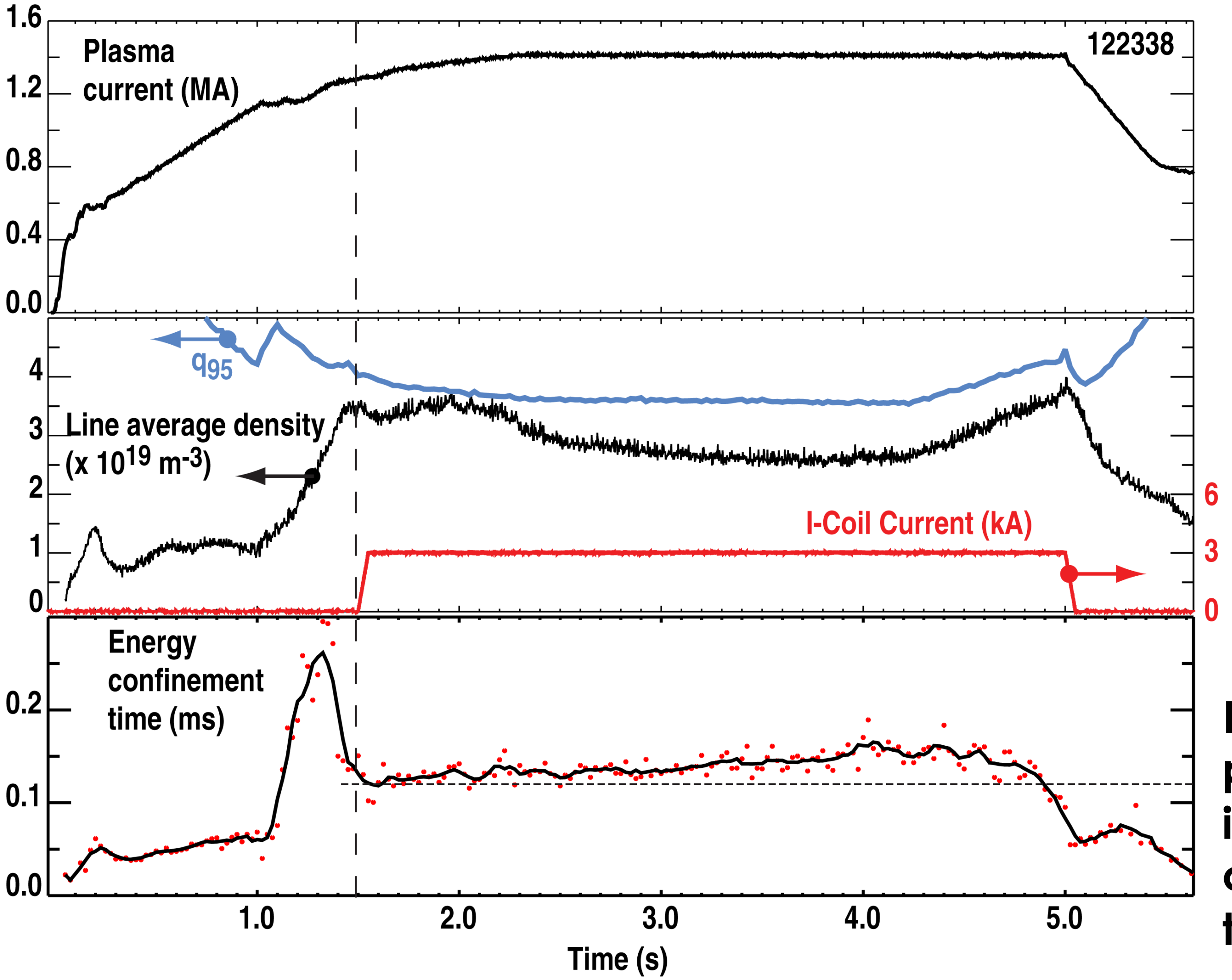
ELM Suppression Correlated With Crossing Peeling-Ballooning (P-B) ELM Stability Boundary Due to Reduced Pedestal Density

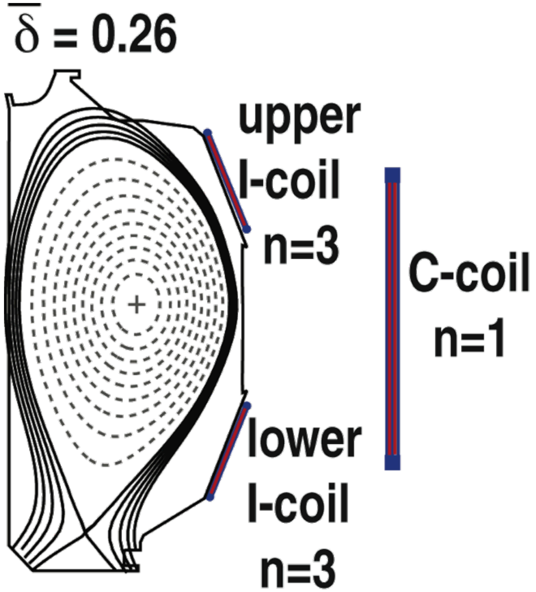




- **2D Peeling-Ballooning (P-B) stability calculations with ELITE code:**
  - Pressure and current reduced by RMP
  - Discharge moves to P-B stable region

Edge Transport Barrier (ETB) is not Destroyed During the Application of Small RMP Fields

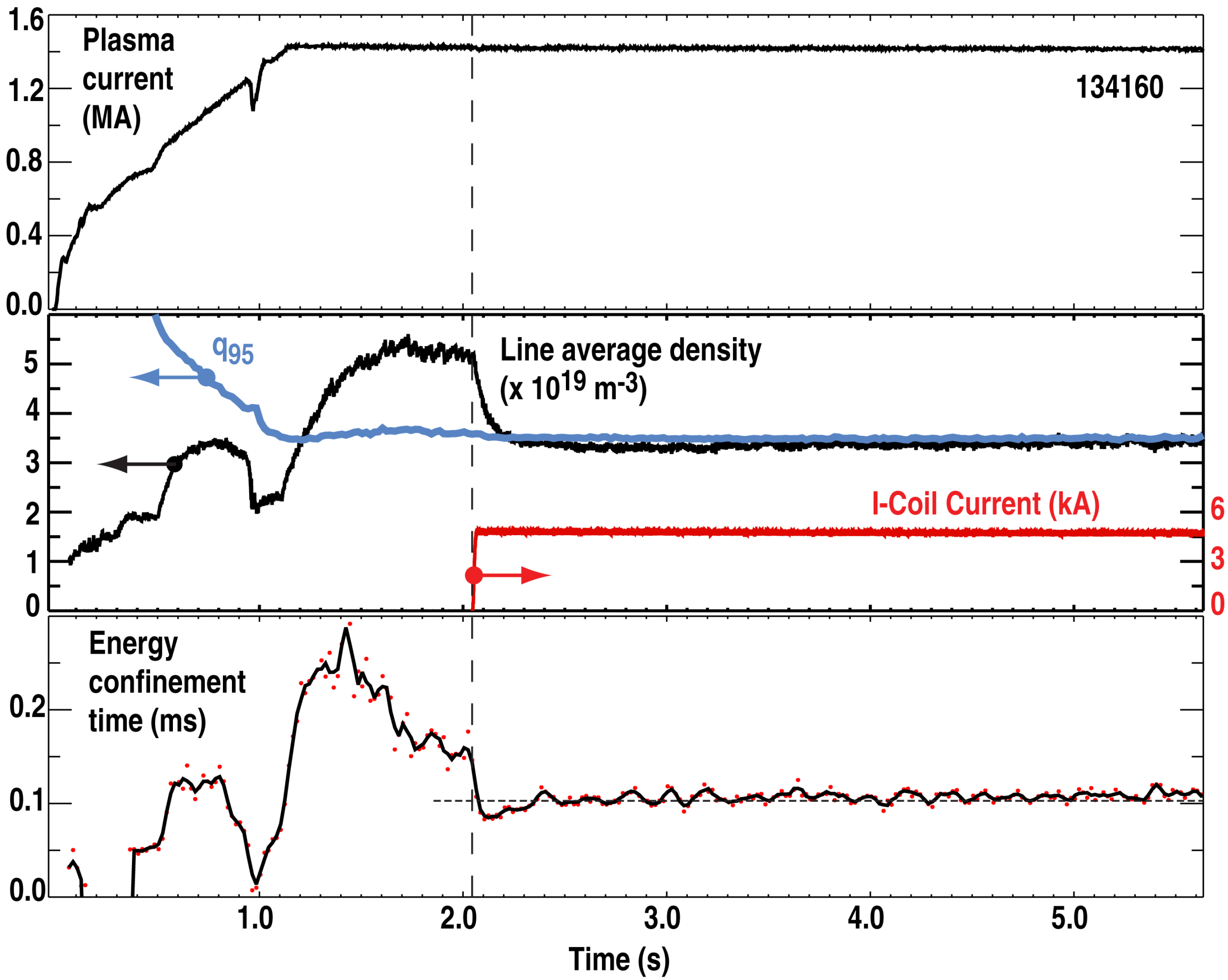


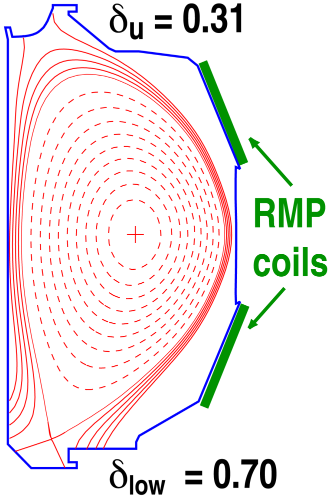


Low-triangularity LSN

RMP fields reduce particle inventory and increases energy confinement time low-triangularity discharges

RMP Fields Reduce H-mode Confinement in ITER Similar Shape Plasmas Compared to Low-Triangularity Plasmas





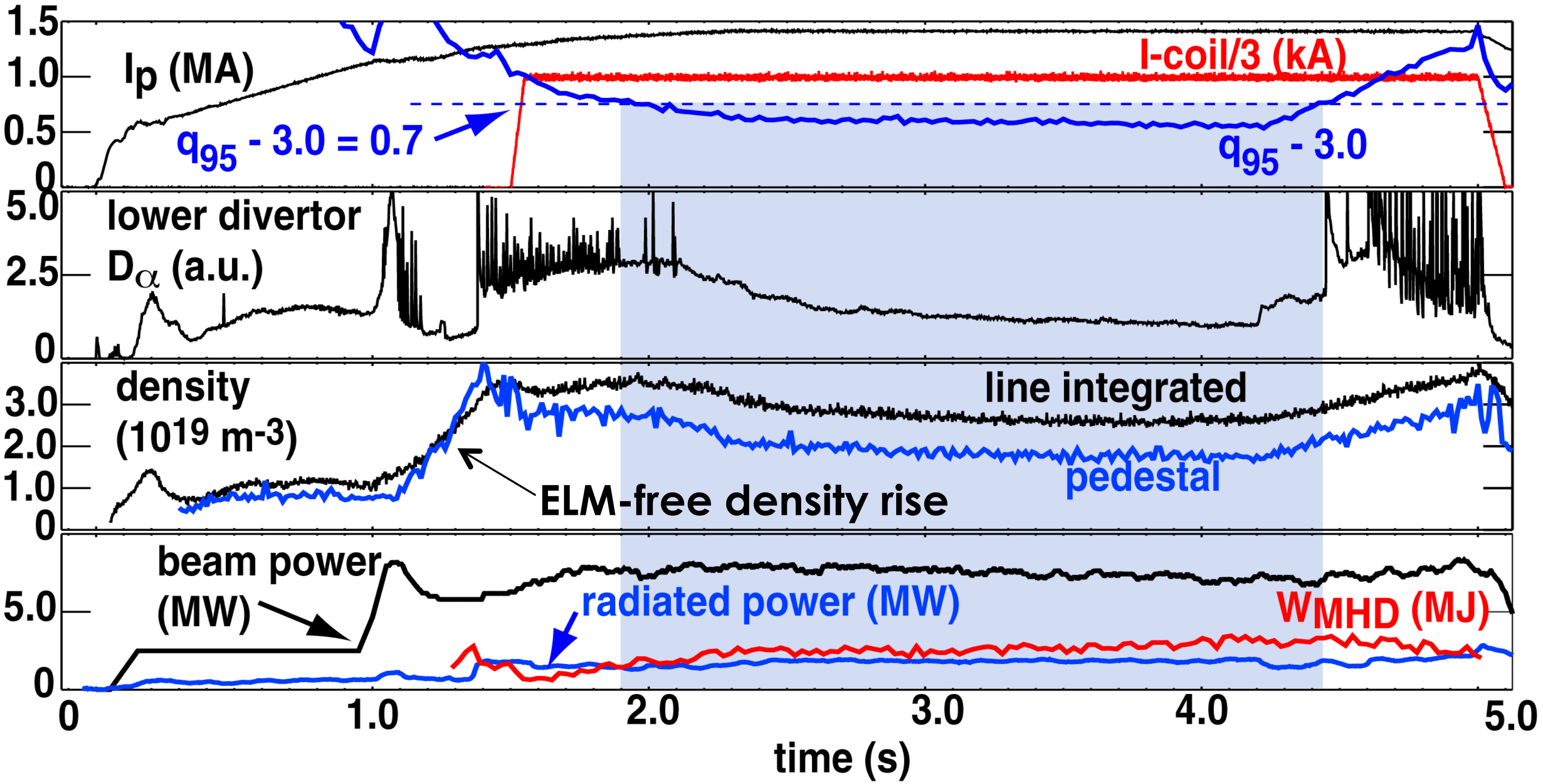
ITER Similar Shape

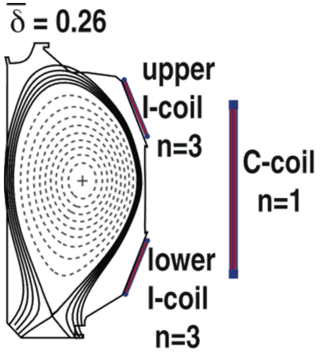
134160 3500 ms

High-triangularity LSN

RMP fields generally reduce particle inventory and energy confinement time in ITER Similar Shape discharges

ELM Suppression is Associated with a Reduction in the Pedestal Density Due to the RMP Field





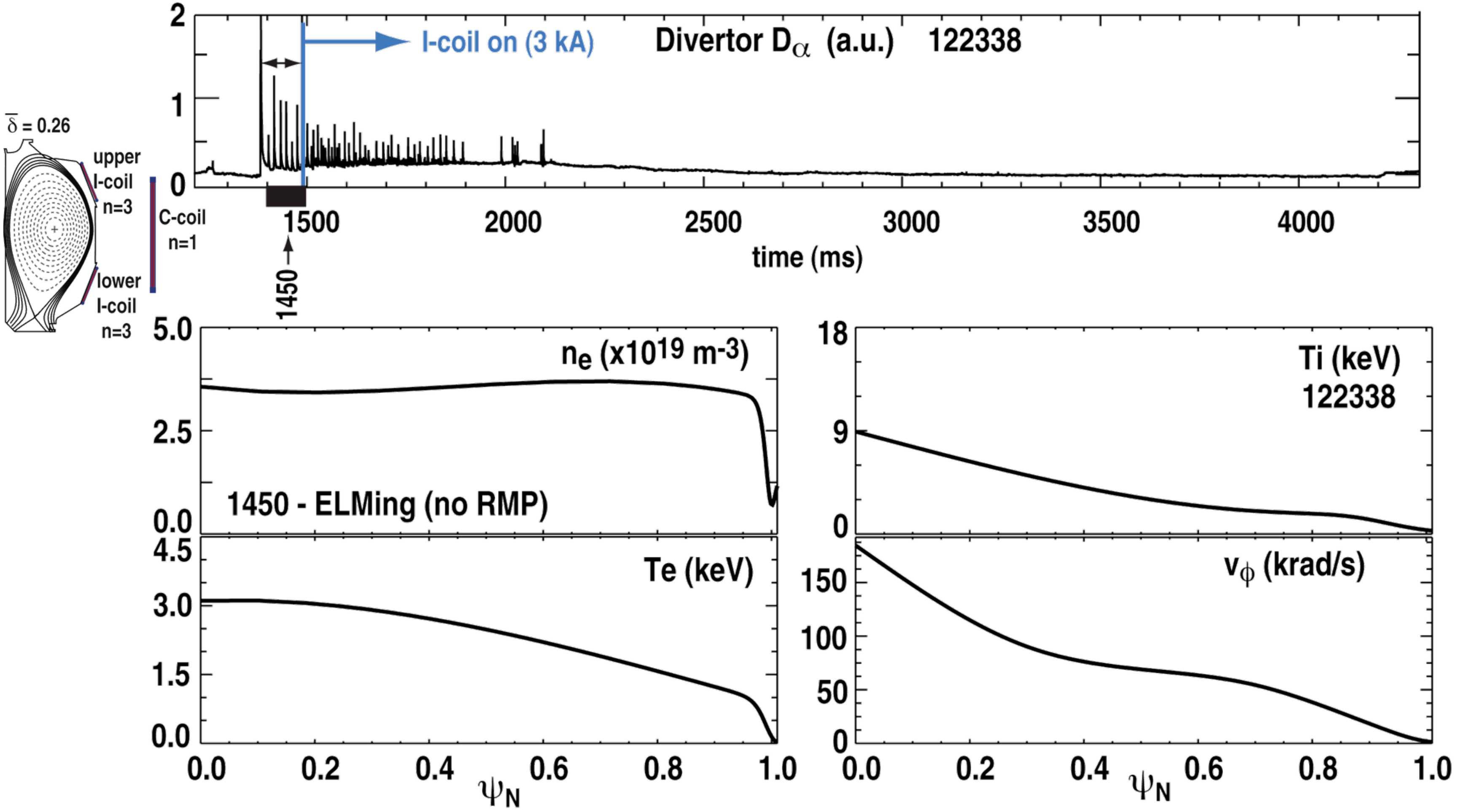
DIII-D Low-triangularity LSN shape

122338
7.9 MW

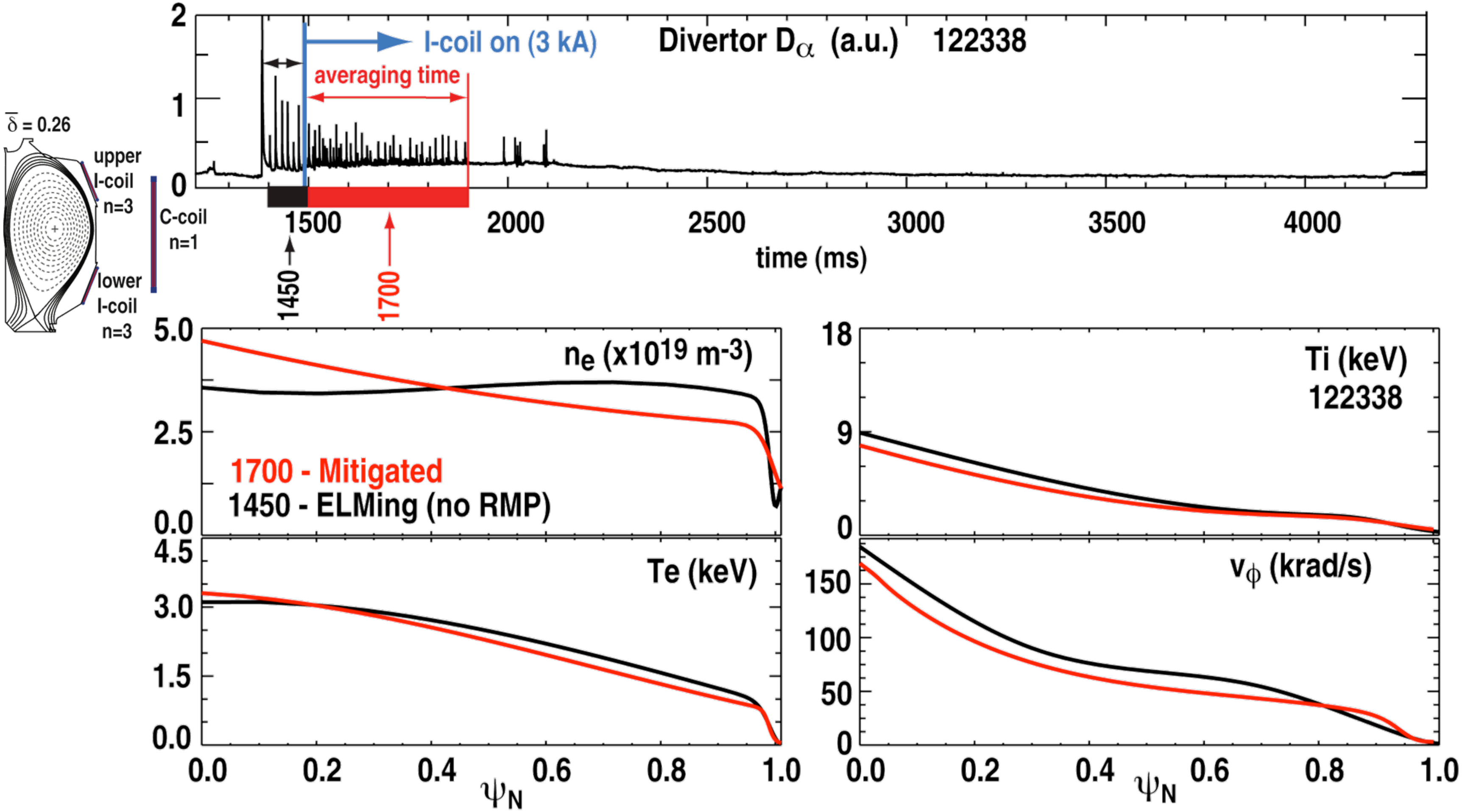
- **ELM suppression in $\nu_e^* \leq 0.3$ plasmas with average $\delta = 0.26$, $\delta b_r/b_\phi = 2.4 \times 10^{-4}$:**
  - Density, stored energy (W_{MHD}) and radiated power are well controlled by the RMP field - *unlike an ELM-free H-mode*
  - Requires a specific q_{95} range in DIII-D: e.g., $3.1 \leq q_{95} \leq 3.7$ low δ and ν_e^*

T. E. Evans, et al., *Nucl. Fusion* **48** (2008) 024002

Low-Triangularity DIII-D LSN ELMing H-mode Target Plasma has Flat Density Profile with Peaked Core T_i and v_ϕ

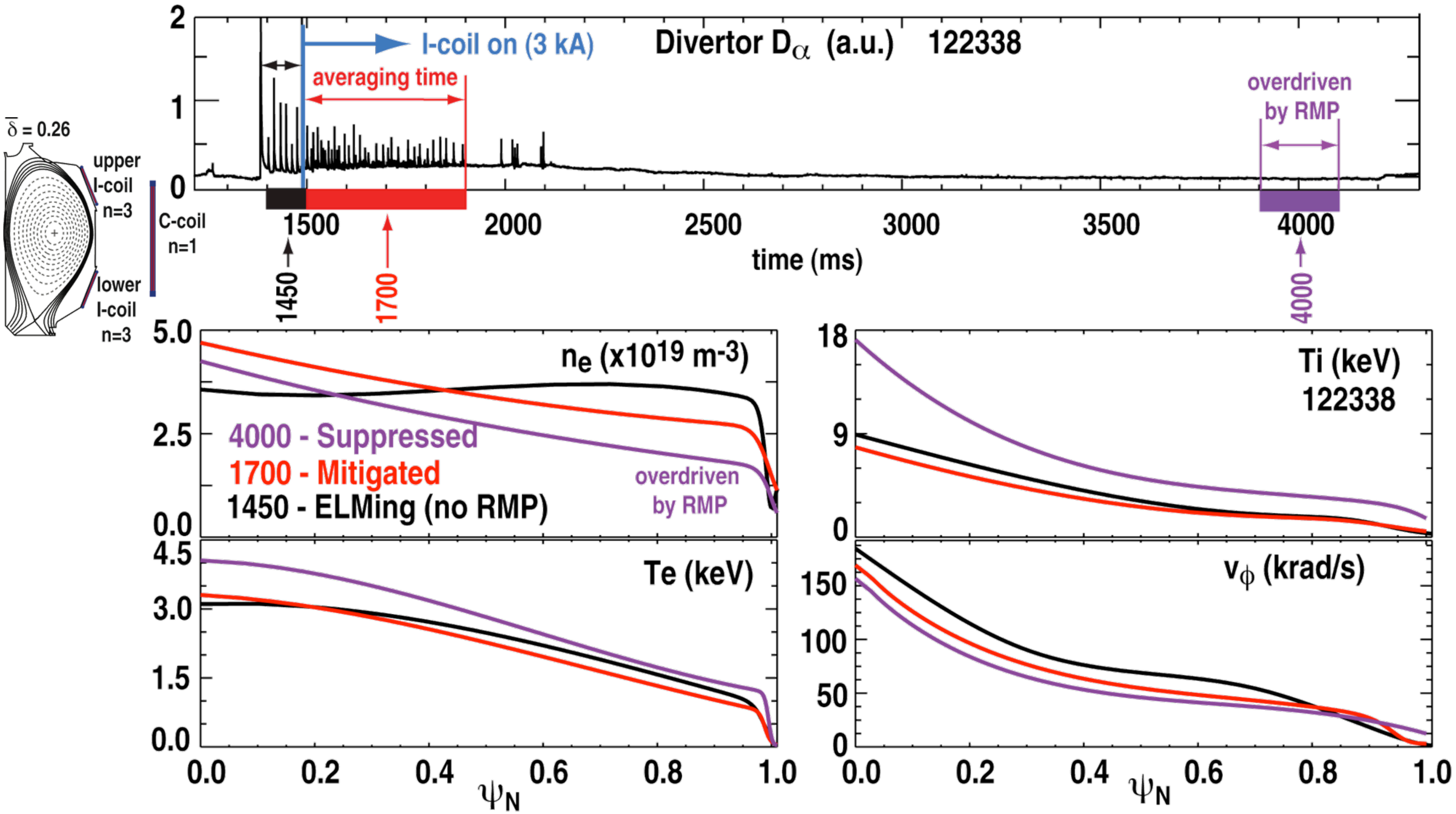


During ELM Mitigation Phase, RMP Fields Reduce Pedestal n_e and T_e while Increasing Core n_e and T_e



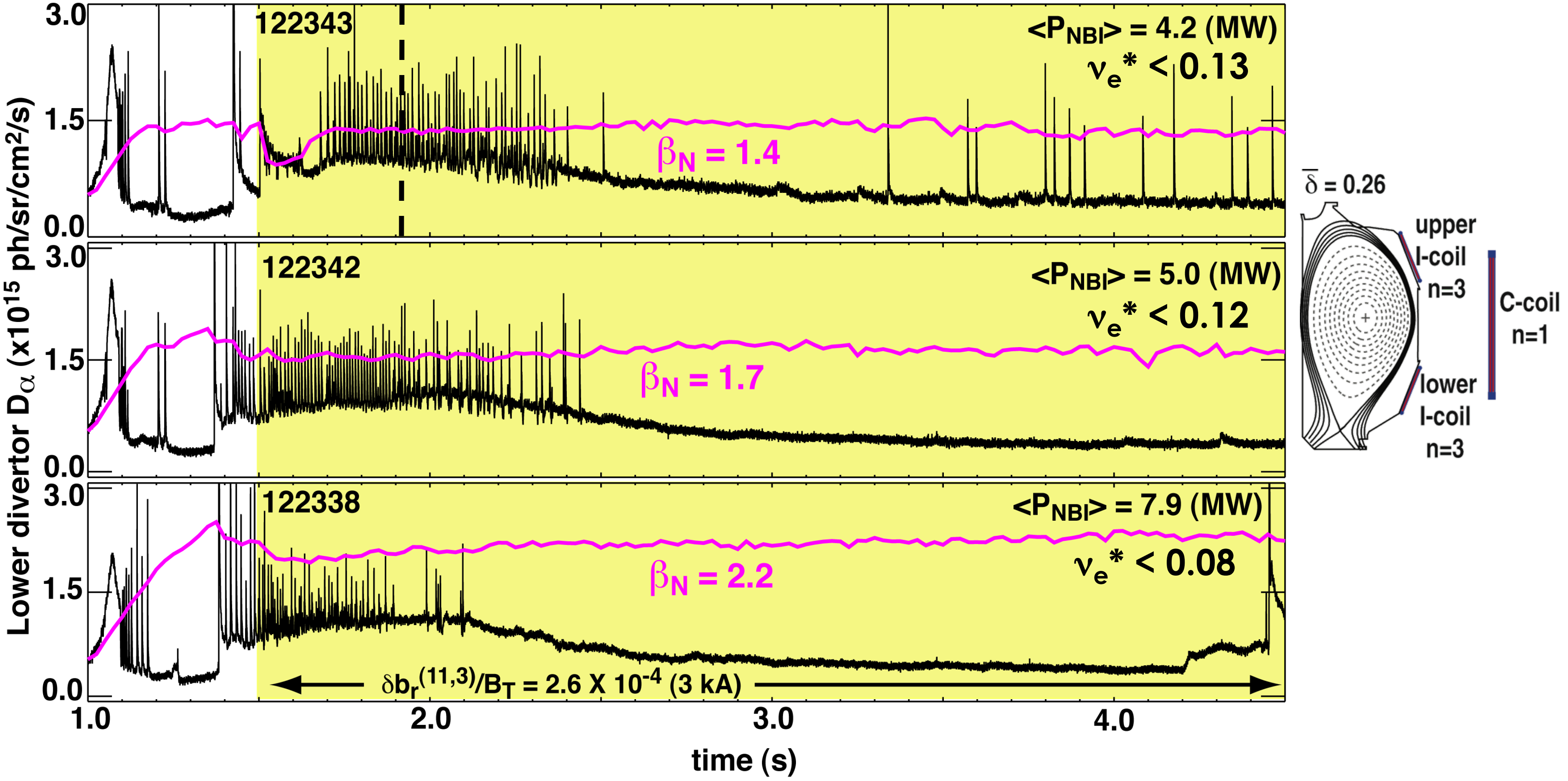
- Core rotation (v_ϕ) and T_i are reduced slightly during ELM mitigation phase

Particle and Energy Transport are Decoupled by the RMP Field During ELM Suppression



- **Most DIII-D ELM suppressed discharges have overdriven particle transport**
- **Core toroidal rotation is reduced while the edge rotation increases**

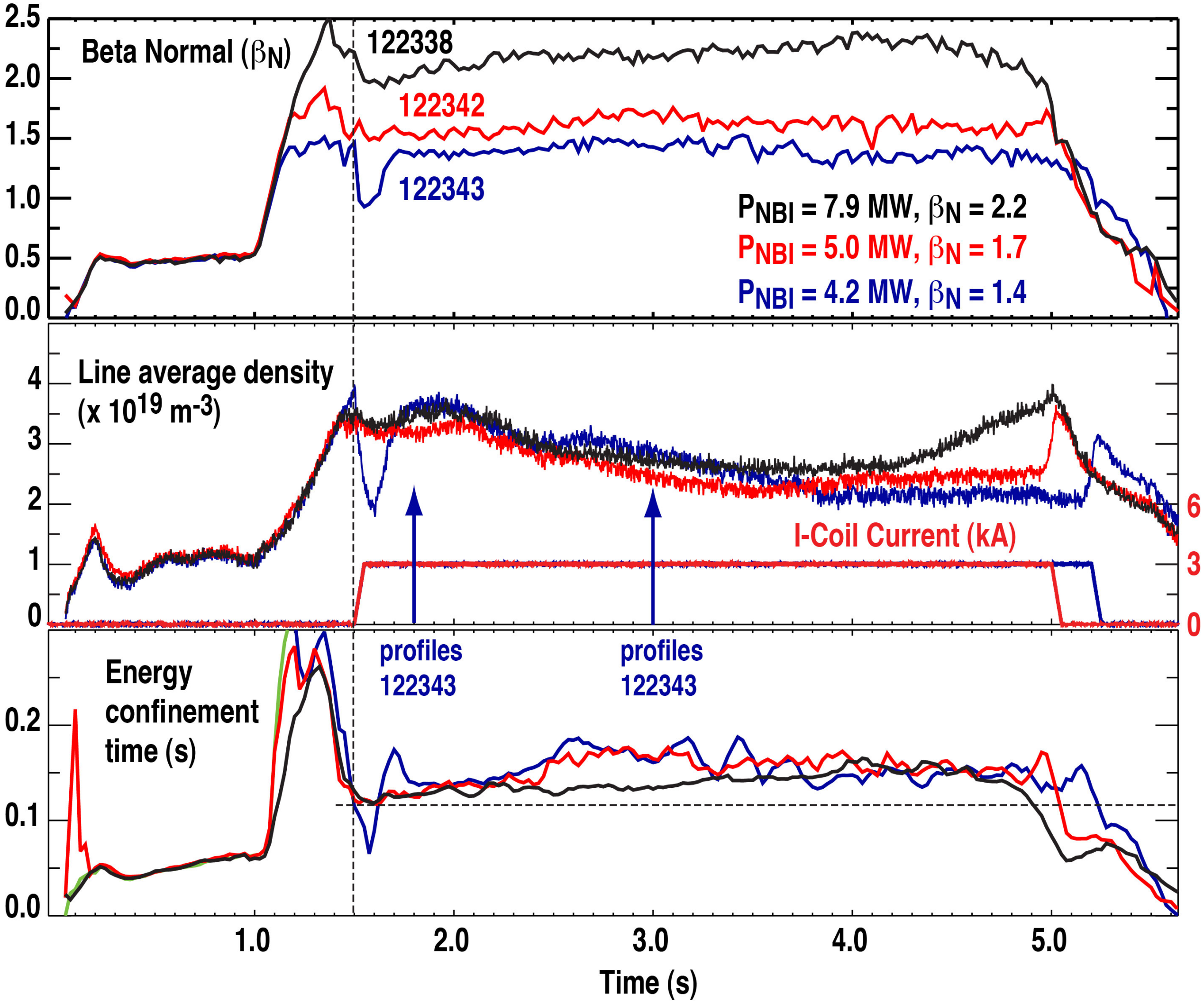
ELM Suppression Improves with an Increase in the NBI Heating Power (P_{NBI}) in DIII-D



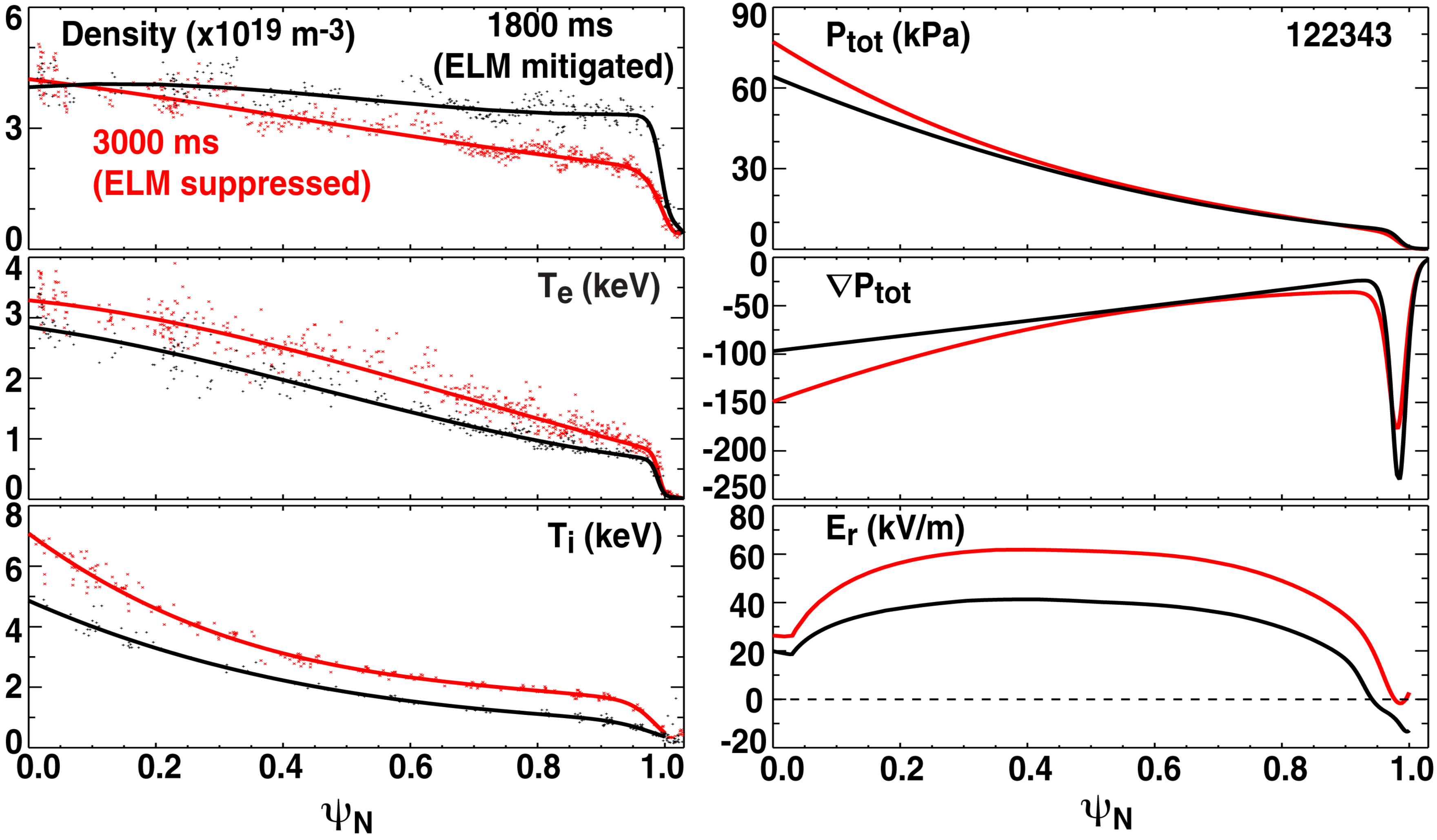
- Increasing P_{NBI} triggers earlier transition from ELM mitigation to suppression

RMP Related Changes in Particle Inventory and Energy Confinement Times do Not Scale with β_N

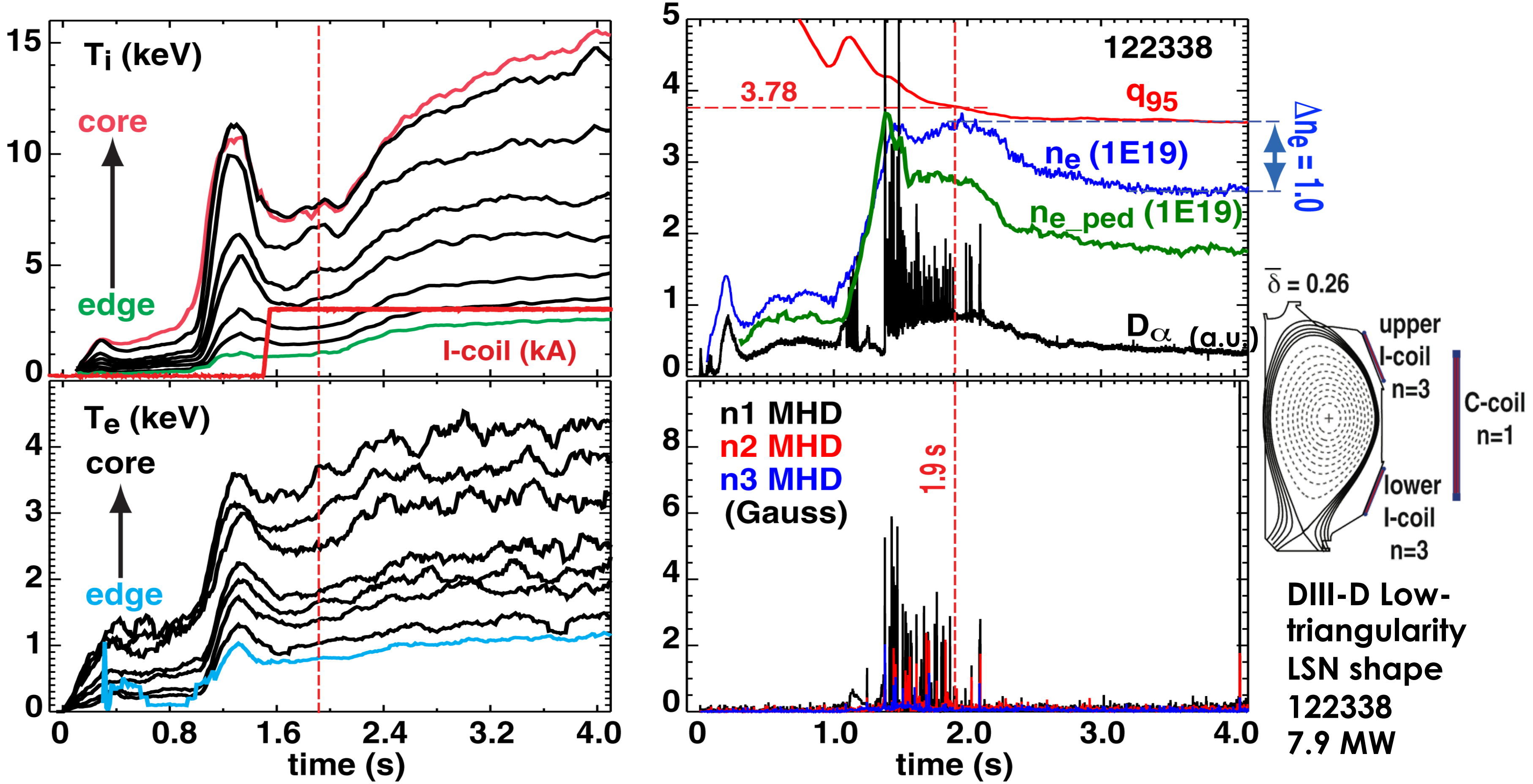
- **ELM suppression improves with P_{NBI}**
  - Marginal suppression at P_{NBI} = 4.2 MW
- **ELM suppression appears to be independent of confinement but:**
  - May depend on β_N



Edge Pressure Gradient Reduced During ELM Suppression Relative to ELM Mitigation Without Altering the Peak Location



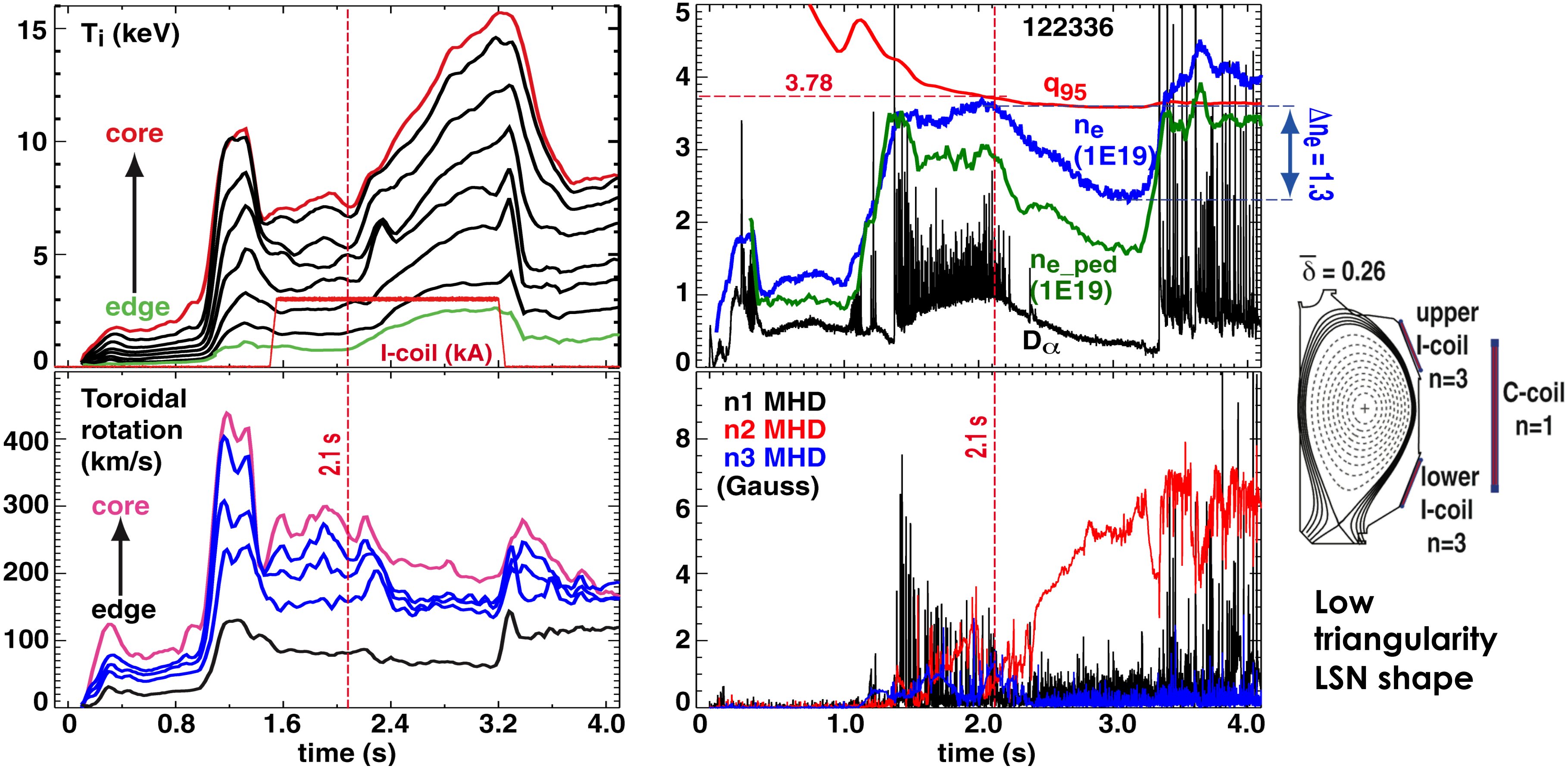
Both T_i and T_e Increase while n_e Decreases during ELM Suppression with RMP fields in Low-triangularity Plasmas



DIII-D Low-triangularity LSN shape 122338 7.9 MW

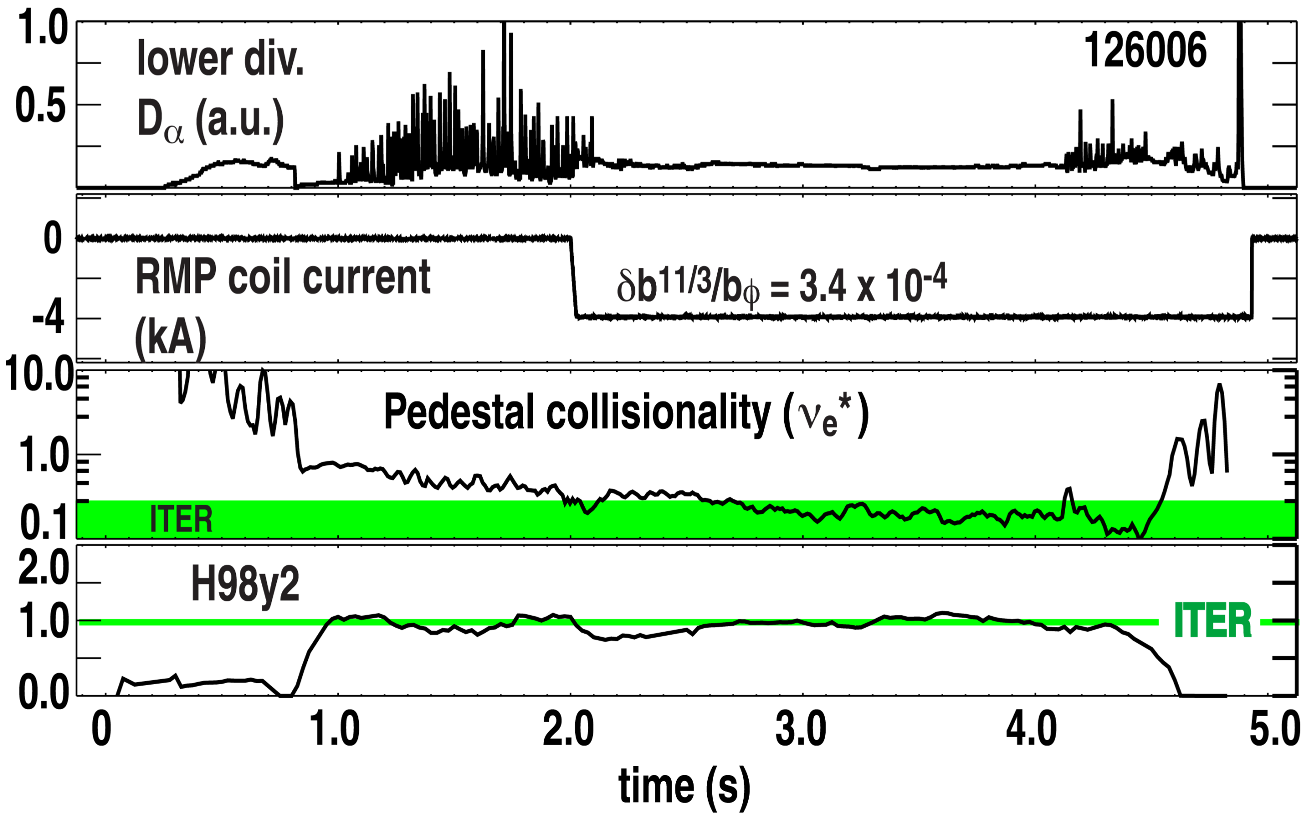
- Increase in τ_E is correlated with a large increase in T_i
- When q_{95} crosses 3.78 ELMs are suppressed

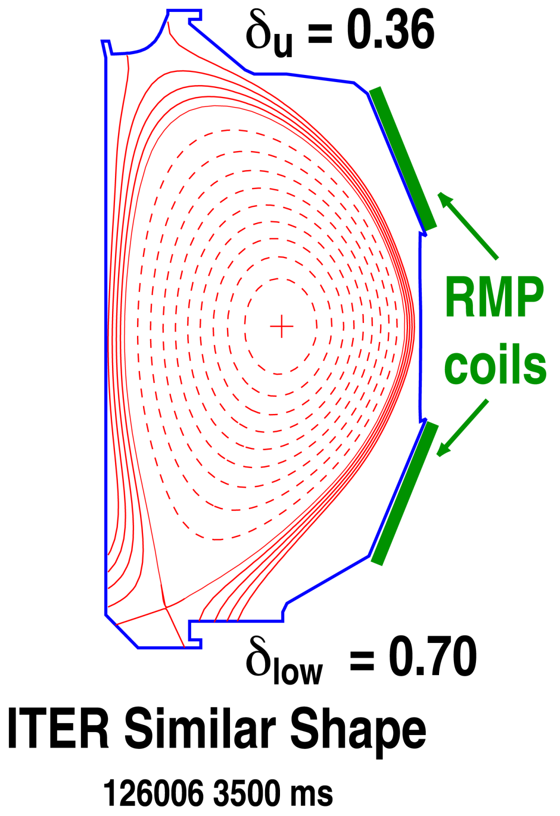
Core MHD Reduces Particle Inventory without a Significant Effect on Energy Confinement



- n = 2 MHD mode reduces toroidal rotation during the ELM suppressed phase

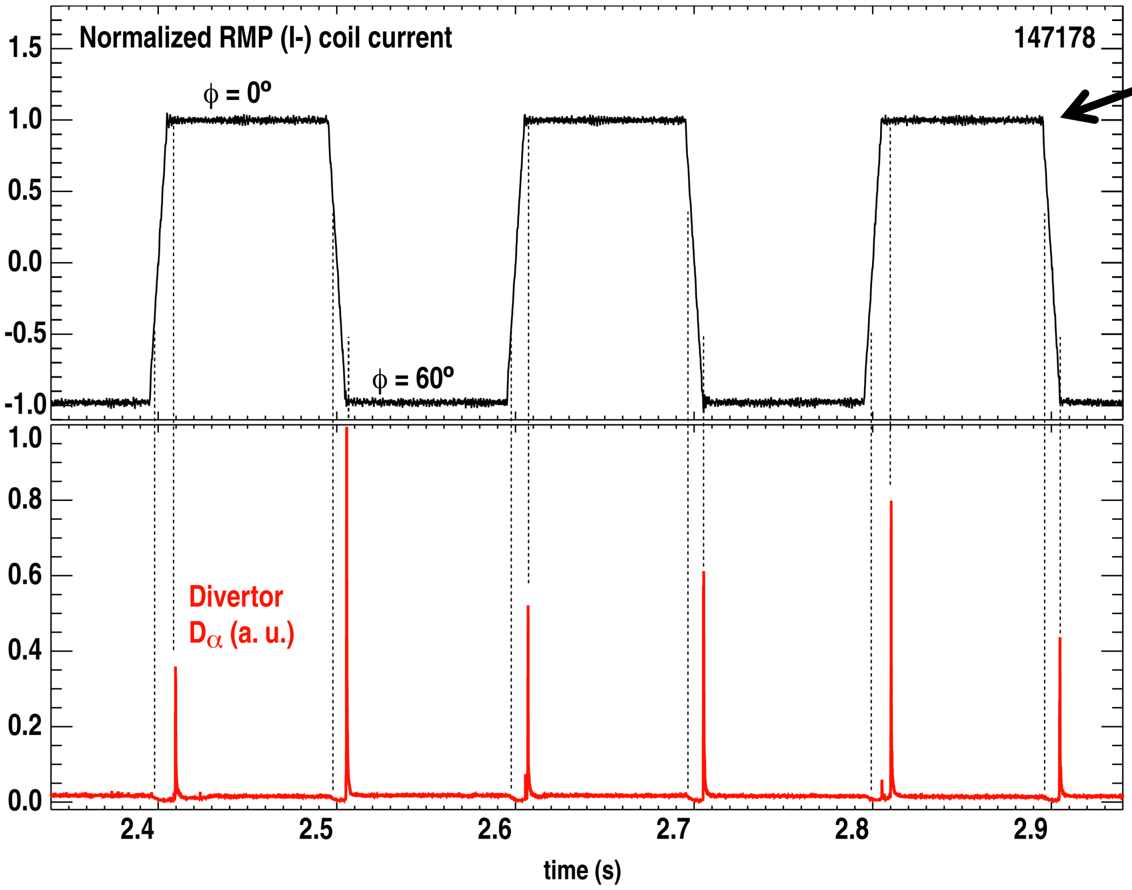
Reproducible ELM Suppression Obtained in DIII-D with ITER Similar Shape H-mode Plasmas

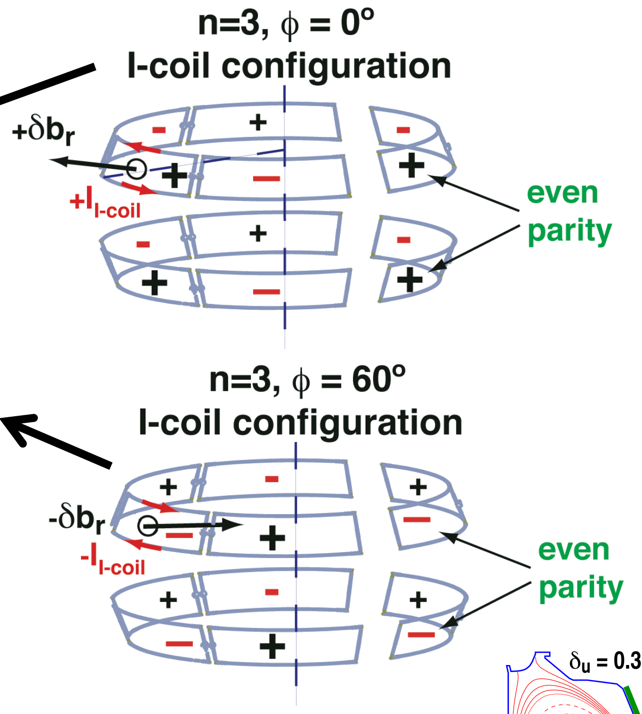




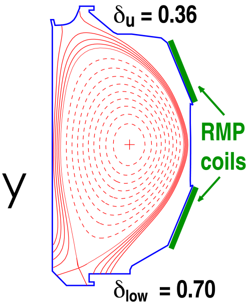
- **ITER Similar Shaped (ISS) plasmas used in DIII-D to match dimensionless ITER parameters**
  - pedestal collisionality (ν_e*) matched but not pedestal pressure

ELM Suppression is Unaffected by Changes in the Toroidal Phase of the n = 3 RMP Field





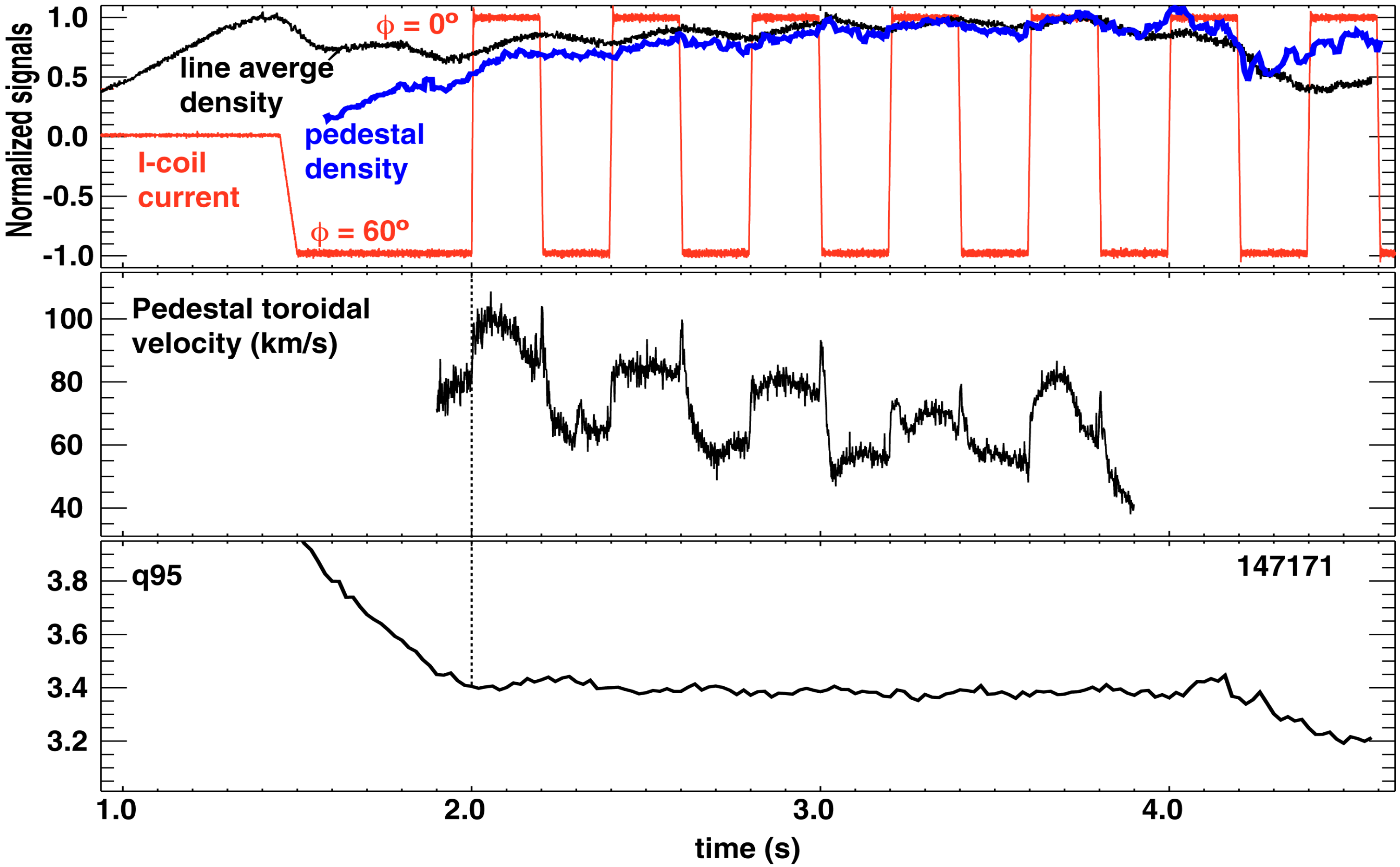
Low ν_e^*,
even parity

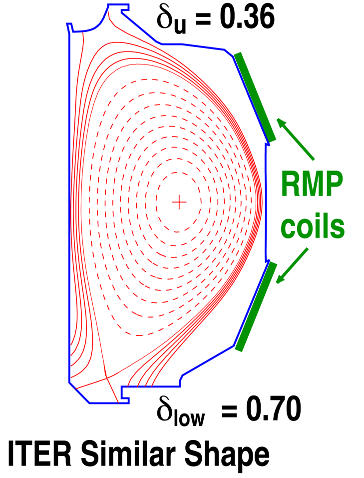


ITER Similar Shape

- Although ELM-like events are seen shortly after δb_r passes through 0, ELMs are suppressed for the remainder of both phases

Strong Particle and Momentum Transport Modulations are Observed During n = 3 RMP Toroidal Phase Flip Experiments

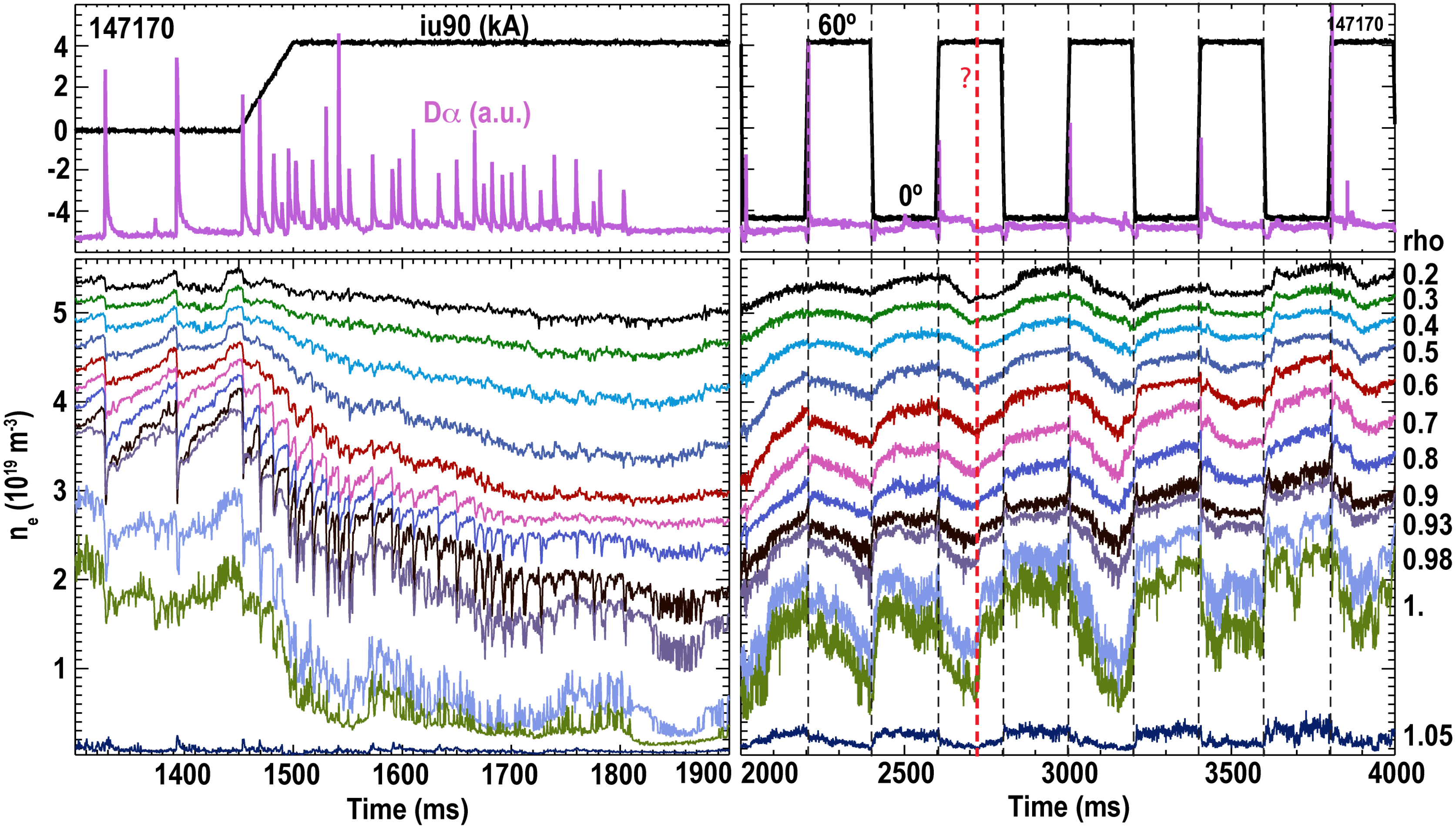




Low ν_e^*, even parity

- **Suggests intrinsic field-errors are important for understanding the transport response to RMP fields**

Increases in the $\phi_{n=3}$ = 0° Density are Larger than $\phi_{n=3}$ = 60° Decreases due to a Hysteresis of the Particle Transport

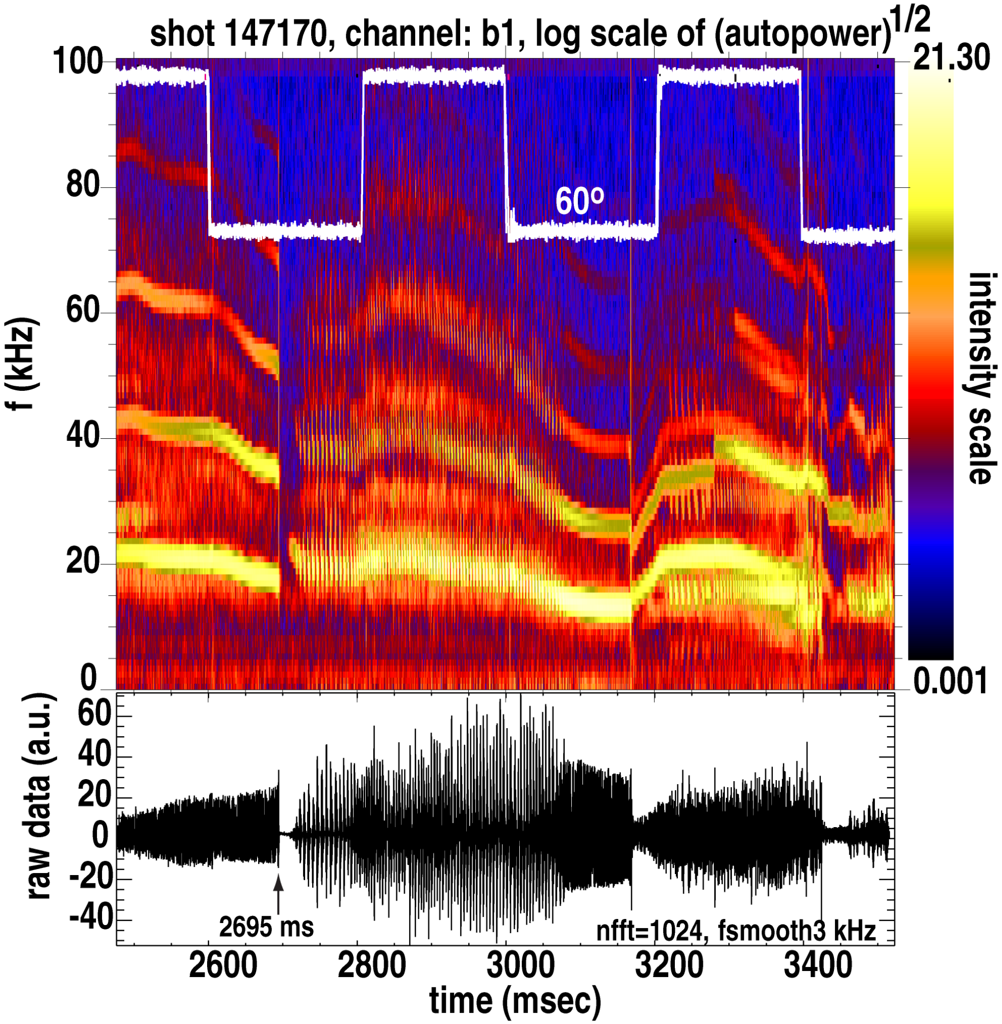


- **An "event" at t = 2720 ms reverses RMP effect on n_e causing it to suddenly increase in the middle of the $\phi_{n=3}$ = 60° phase**

Courtesy of L. Zeng, UCLA

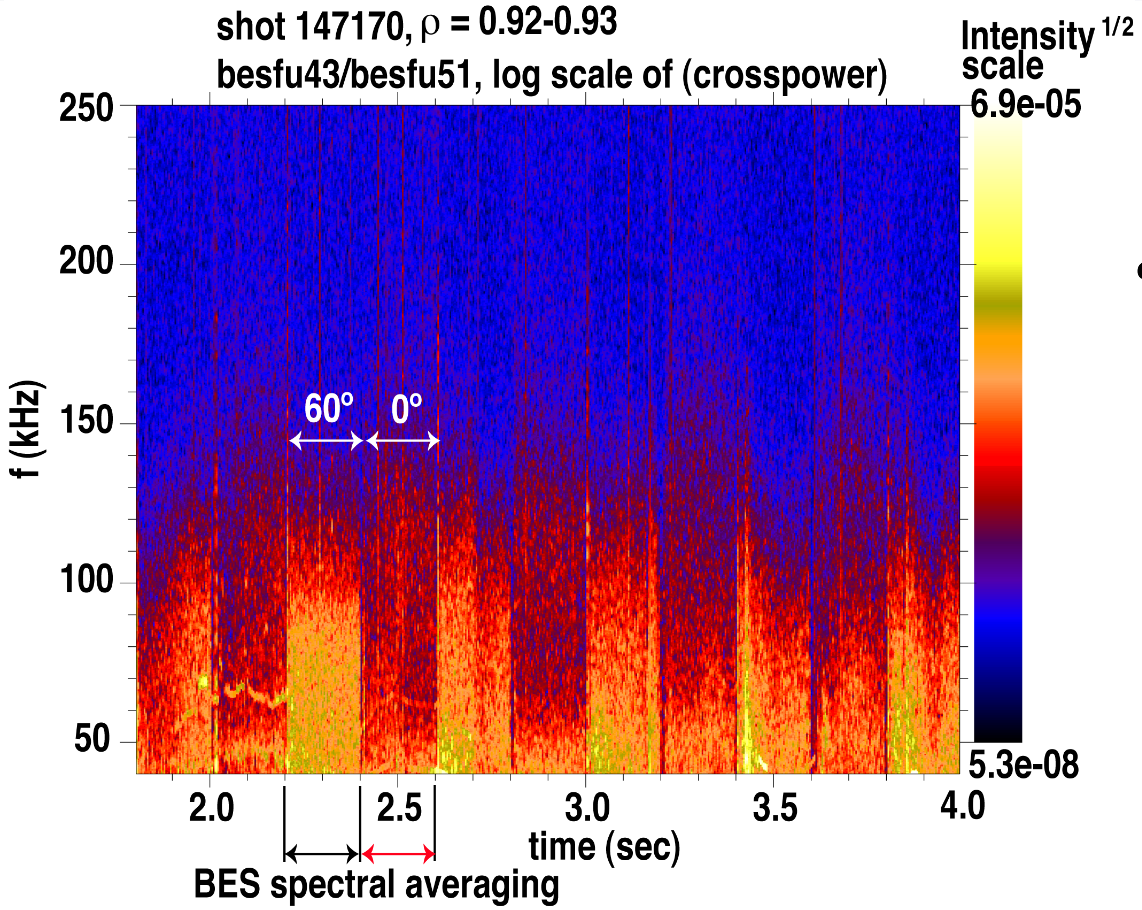
Reduced Particle Transport at 2720 ms, during the 60º RMP Coli Phase, is Correlated with a Stabilization of the Core MHD

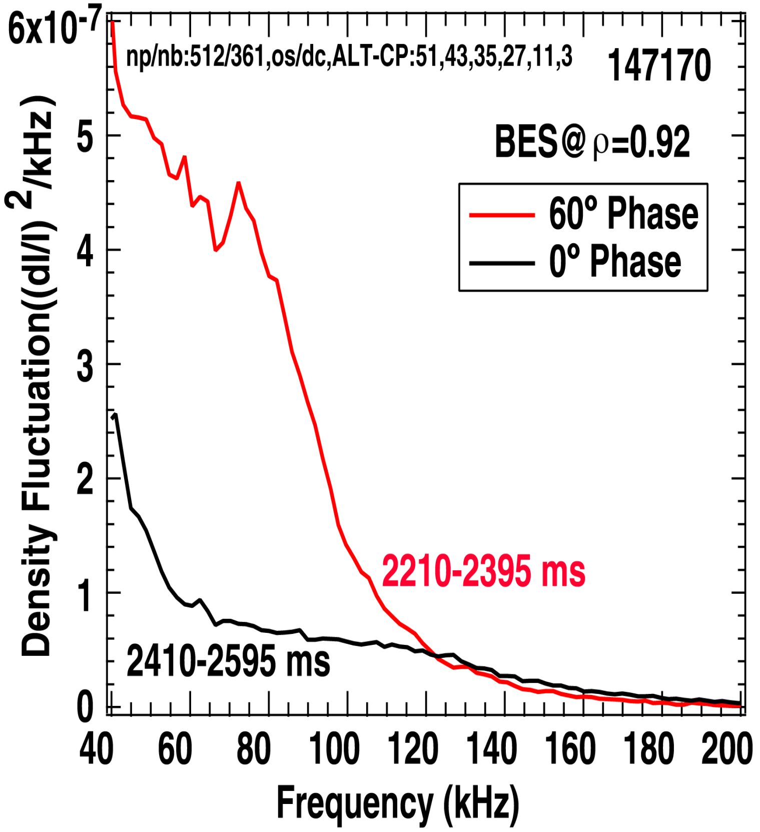
- **MHD mode appears with turn on of RMP coil**
- **Has a complex multi-harmonic structure**
  - Similar to QH-mode Edge Harmonic Oscillator (EHO) but:
    - Frequency is higher than EHO
  - Frequency and stability depends on RMP coil phase



Courtesy of T. Rhodes, UCLA

Beam Emission Spectroscopy Shows n=3 Phase Flip Modulation in Fluctuations near Pedestal Top



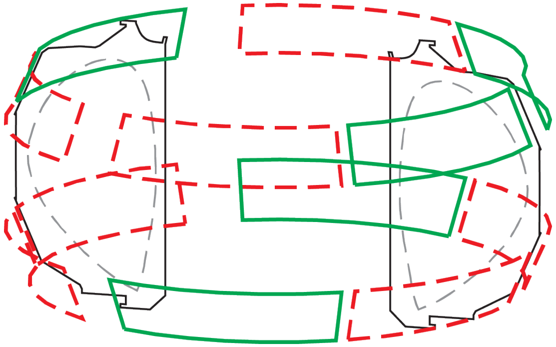


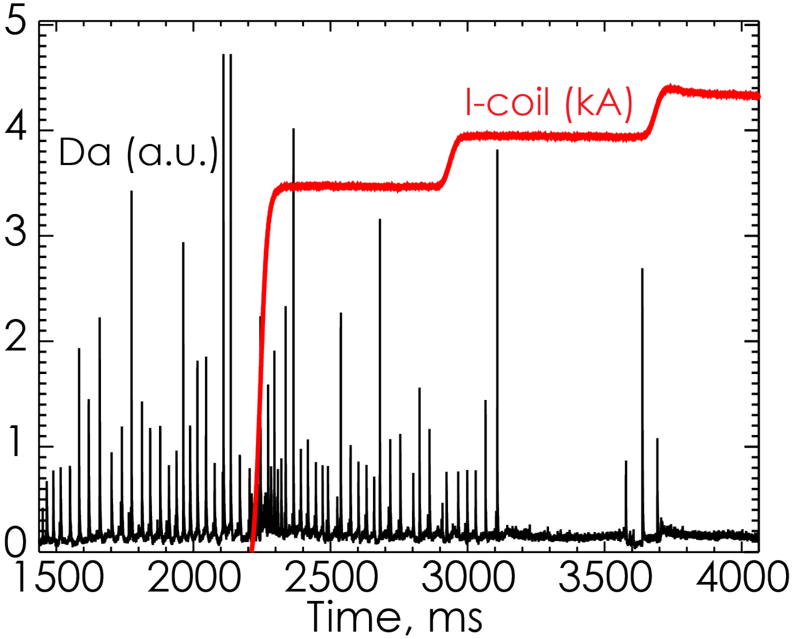
- **Fluctuations strongly reduced across the pedestal during ϕ = 0° n = 3 phase**
  - Correlated with positive dn_e/dt

Courtesy of G. McKee, Univ. Wisconsin

Transport and Stability Studies of ELM Suppression With Reduced Coils Sets Provide Insight into RMP Spectral Effects

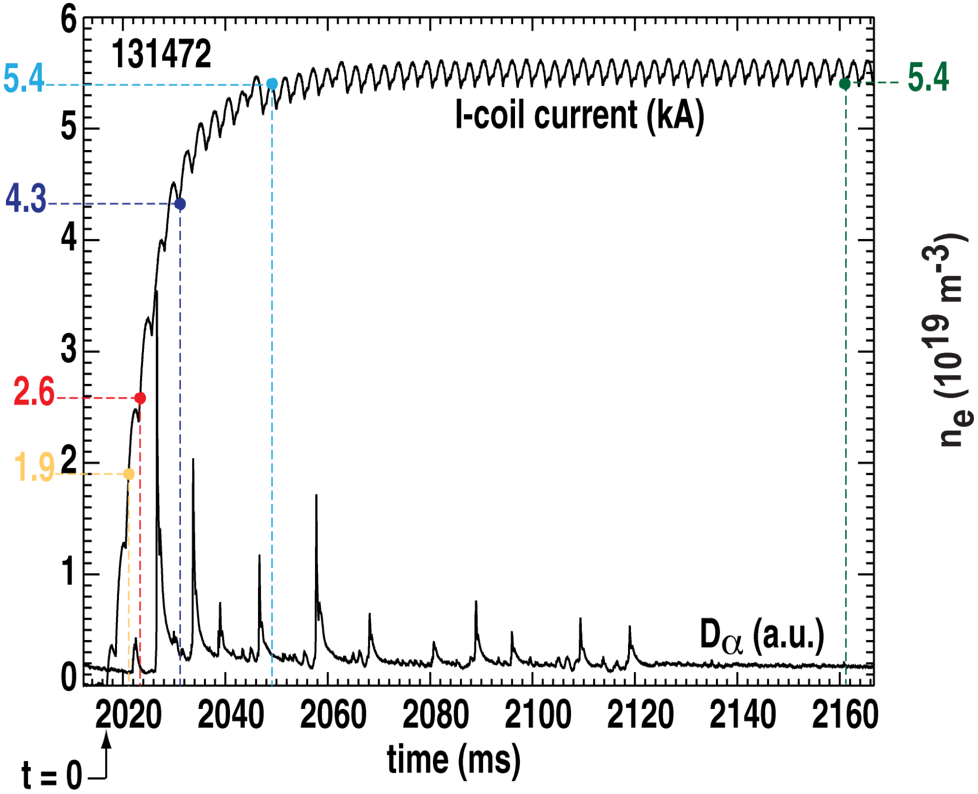
- **Suppression obtained with as few as 5 of 12 DIII-D RMP coils active**
  - Coils turned off psudo-randomly from shot-to-shot
  - Coil current threshold for suppression matched 12 coil case with 11 ⇒ 7 coil active
- **Result suggest that toroidal sidebands generated by missing loops assist with suppression**
  - Consistent with vacuum RMP field modeling predictions

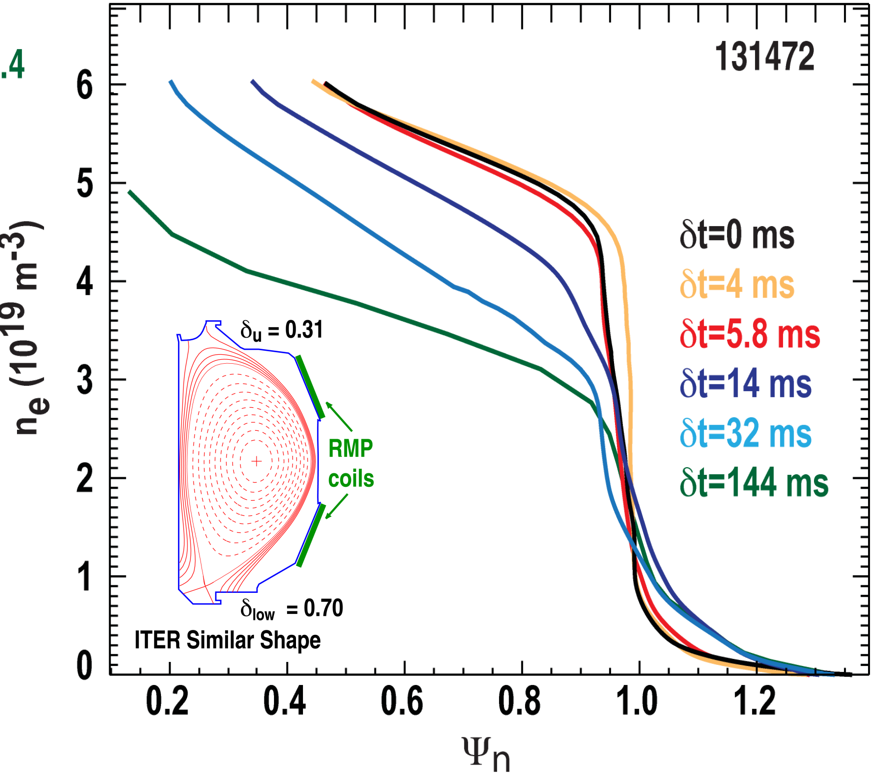




* **See** presentation P3.039 by D. Orlov, et al., "Numerical Modeling of RMP ELM Suppression with Incomplete I-coil set in DIII-D"

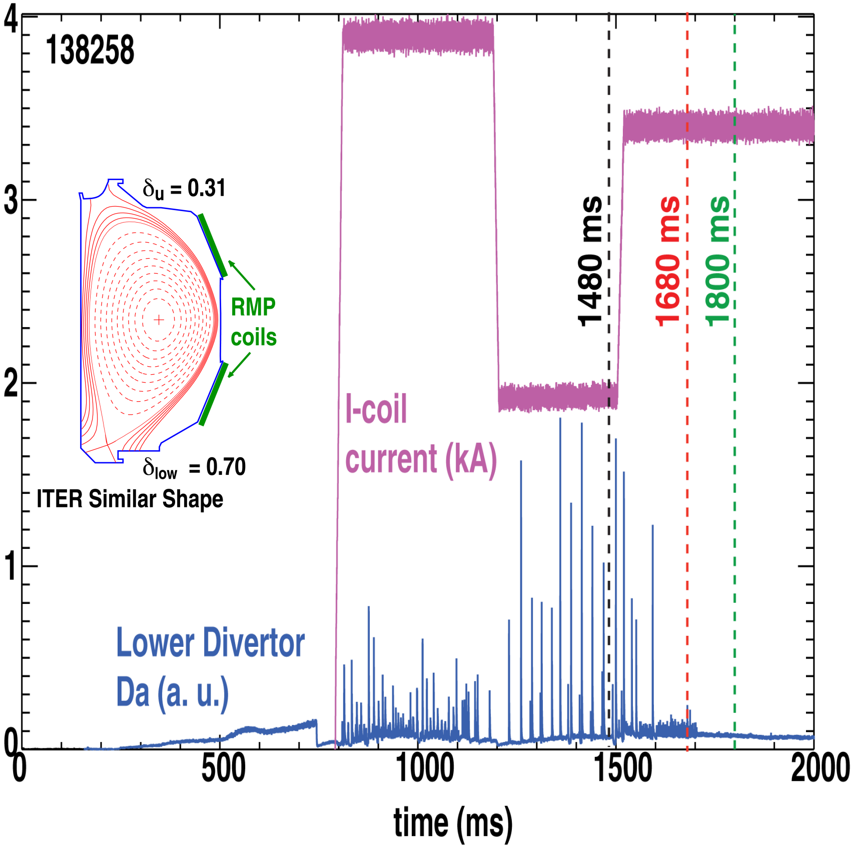
Density Drops Rapidly Between Pedestal and Separatrix as RMP (I-coil) Current Increases

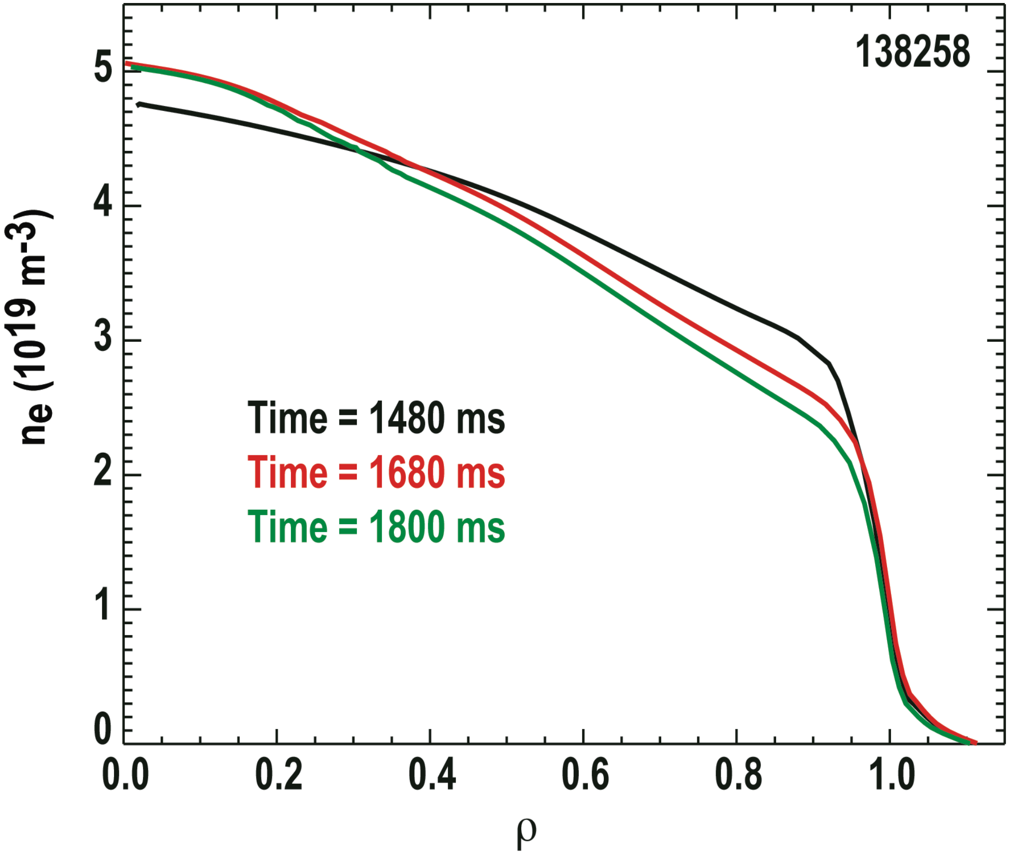




- **SOL density increases as the pedestal density drops**
- **ELM suppression observed with currents of ~ 2 kA in some discharges**
  - Uncertainties in RMP particle transport and recycling fueling efficiency tend to result in higher than needed RMP coil currents (overdrive)

Core Density Increases while Controlling Pedestal Density to Maintain ELM Suppression with Dynamic RMP Coil Control

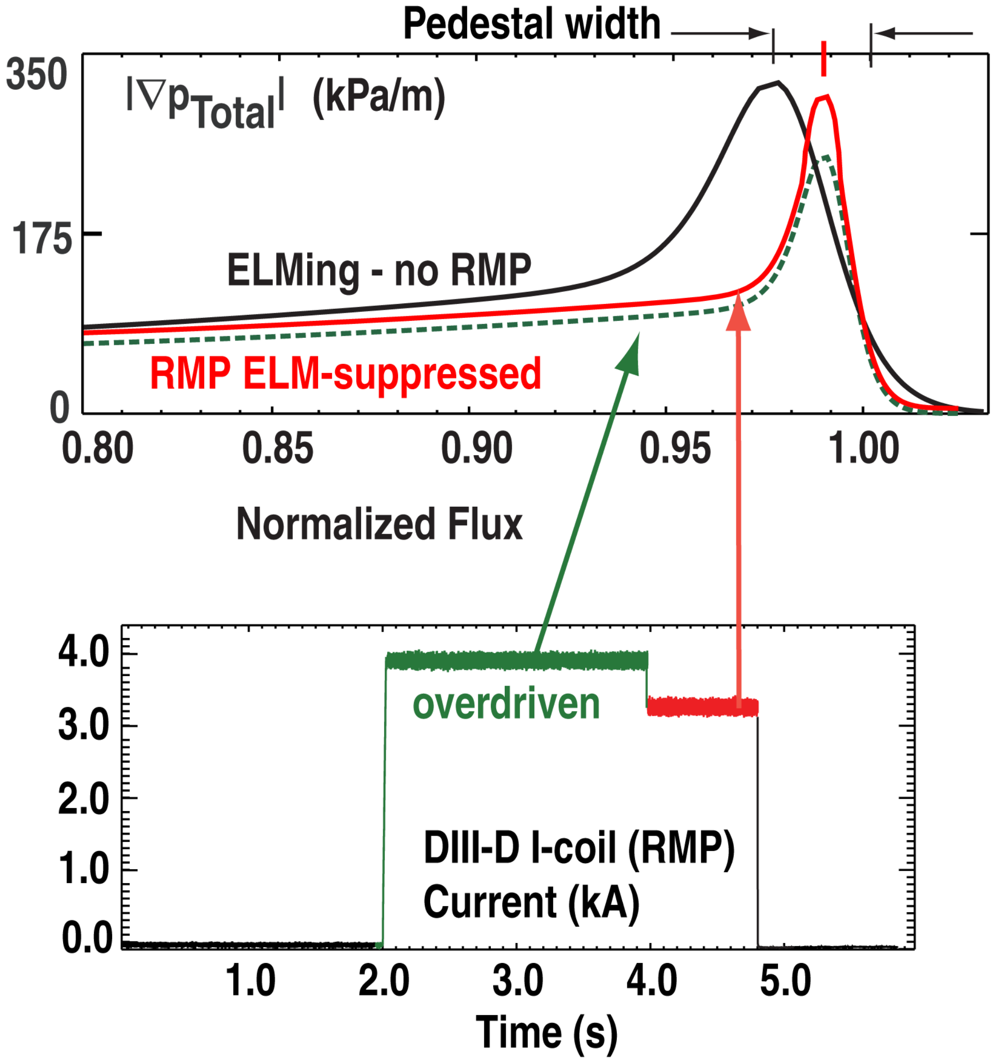




- **During ELM suppression (1680 ms and 1800 ms) core density peaking increases compared to ELMing phase (1480 ms)**

Active Feedback Control Required to Minimize Pedestal Pressure Reduction during RMP ELM Suppression

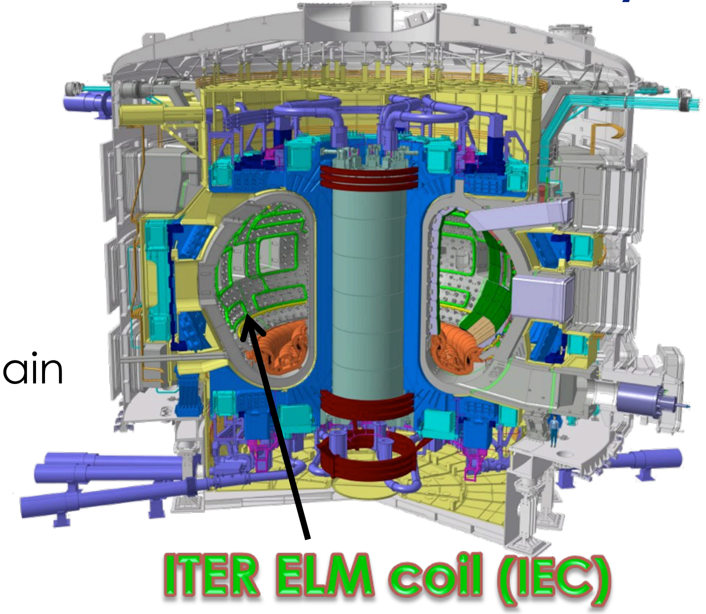
- **ELMs are stabilized by reducing the pedestal width (Δp_{ped})**
  - RMP reduces both Δp_{height} and Δp_{ped}
- **Active feedback control used to:**
  - Maintain reduce Δp_{ped} with increased ∇p_{Tota}
- **Requires real-time n_e and T_e profile measurements and**
  - RMP coil current and mode spectrum control with
  - Individually powered coil loops



Summary and Conclusions

- **ELM control is essential for $Q_{DT} = 10$ in ITER**
- **RMP effects on density and neutral fueling are critical for scaling ELM control to ITER**
  - ELM suppression in DIII-D linked to reduced pedestal height and width
  - Pedestal response to RMP fields in ITER is uncertain due to pressure profile differences with DIII-D
- **RMP experiments reveal complex particle transport and neutral recycling effects**

ITER Tokamak Cutaway

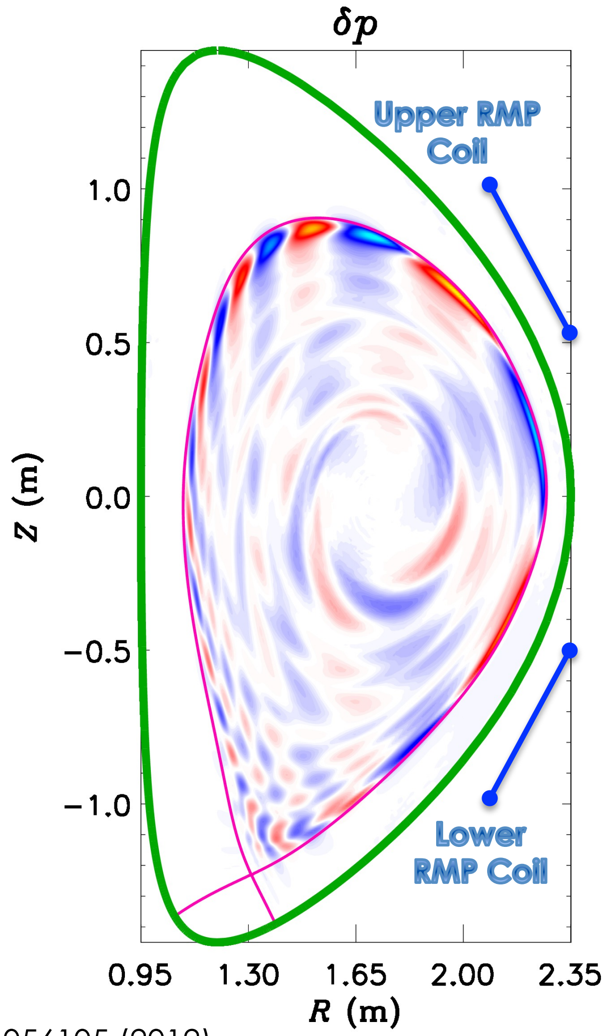


- **Need validated transport and neutral fueling models to assess viability of RMP ELM control in ITER**

Back-up

M3D-C1, a Two-Fluid MHD Code, is Used to Model the Plasma Response to RMP Fields

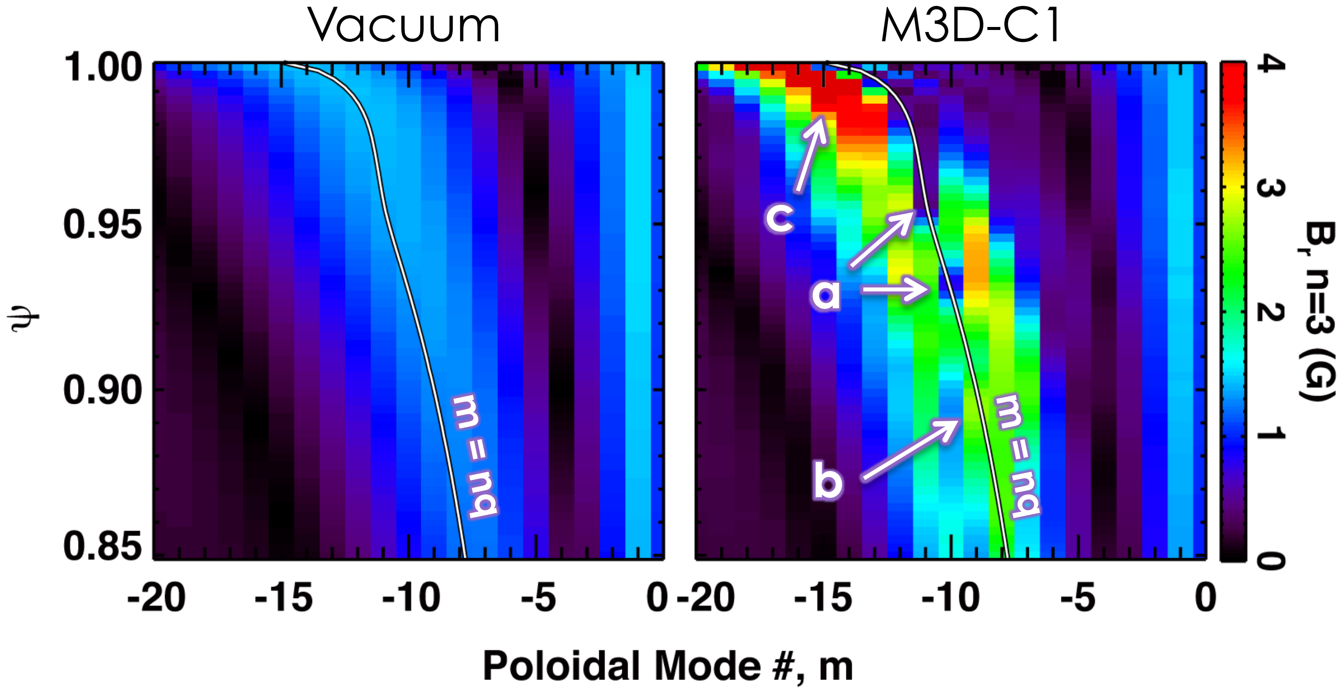
- **Linear, time-independent, equations solved subject to prescribed boundary conditions:**
  - Conservation of mass and energy
  - Force balance, pressure tensor
  - Generalized Ohm's Law
  - Maxwell's equations
  - Heat conduction



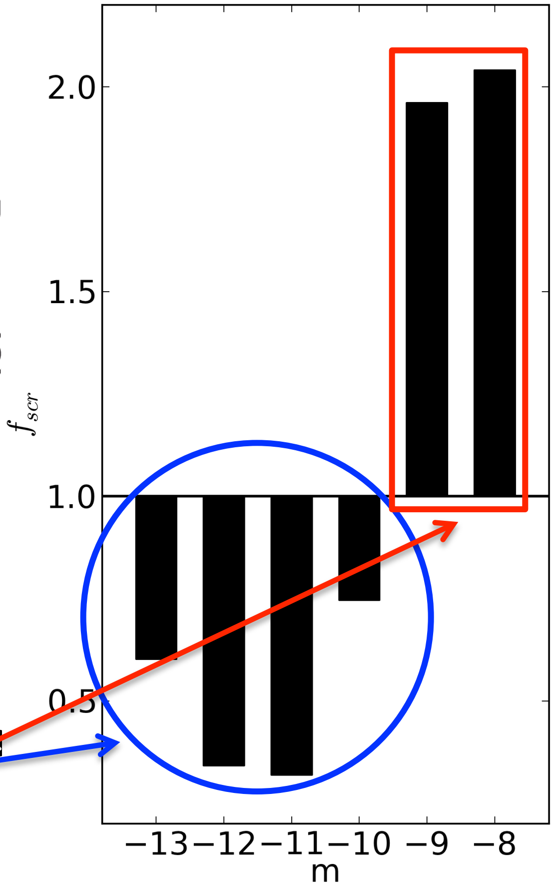
*** See:** presentation P2.0390 N. Ferraro, "Progress in Modeling Non-Axisymmetric Response in Tokamaks" and N.M. Ferraro, *et al.*, PoP **19**, 056105 (2012)

Simulations of Plasma Response to RMP Fields in Rotating DIII-D H-mode Plasmas Show Changes in Island Widths

Poloidal mode spectrum for 148712



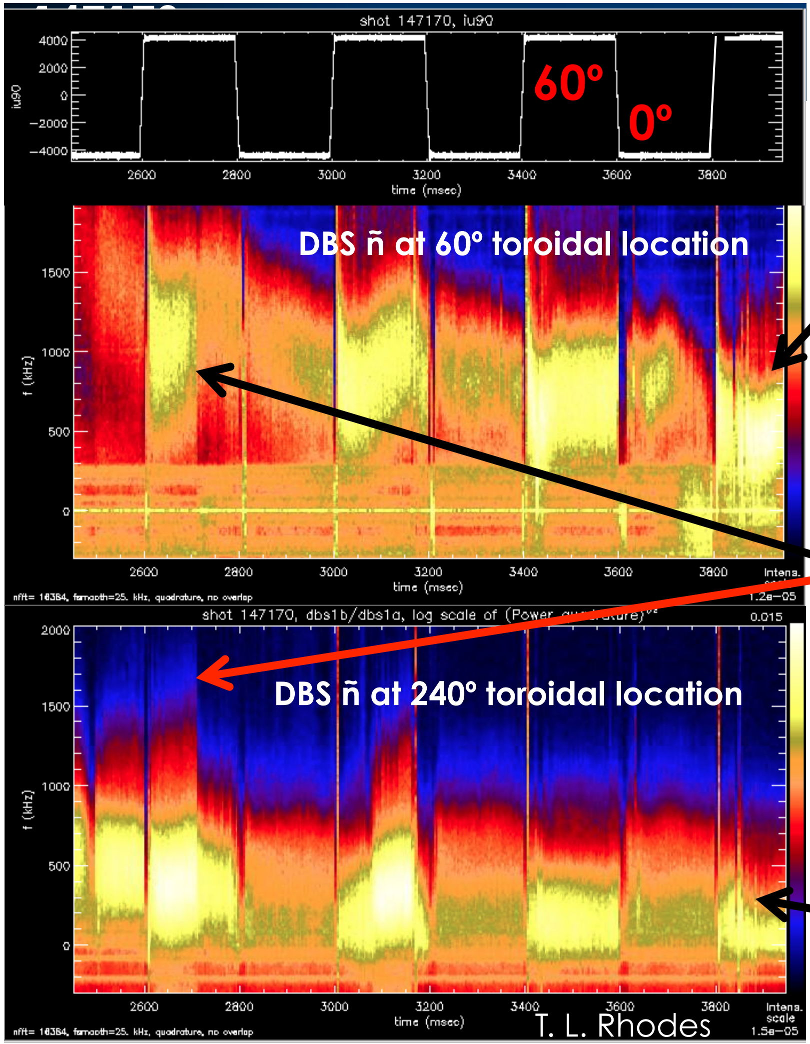
$$f_{\mathrm{scr}} = B_{r,\mathrm{pr}} / B_{r,\mathrm{vac}}$$



- **Linear 2-fluid M3D-C1 simulation produce 3 effects**
  a. resonant screening → Islands shrink
  b. resonant amplification → Islands grow
  c. non-resonant amplification → kinking of flux surfaces

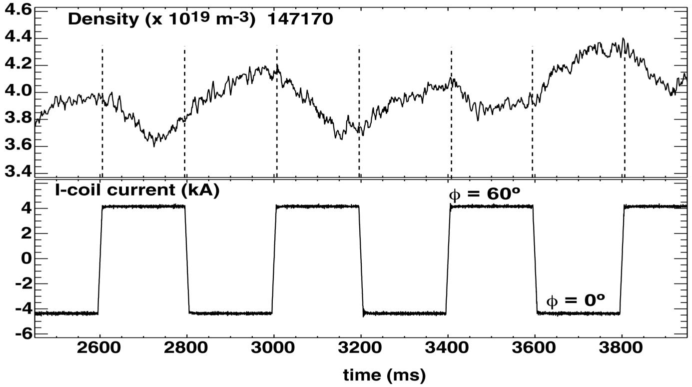
* **See:** presentation P2.0390 N. Ferraro, "Progress in Modeling Non-Axisymmetric Response in Tokamaks" and N.M. Ferraro, *et al.*, PoP **19**, 056105 (2012)

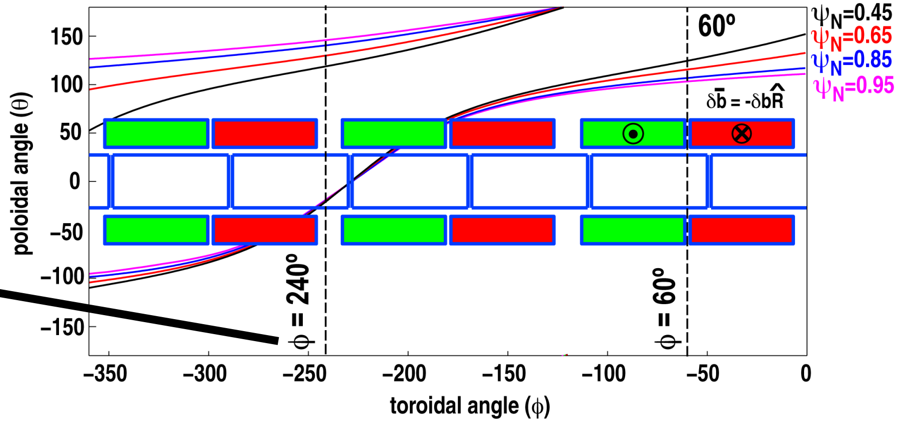
Reduced Particle Inventory Correlated with Increased Density Fluctuations during $\phi_{n=3}$ = 60° phase



- **DBS measurements at ρ = 0.9 separated by ϕ = 180°:**
  - Density fluctuations increase during n = 3, 60° toroidal phase

2720 ms "event"

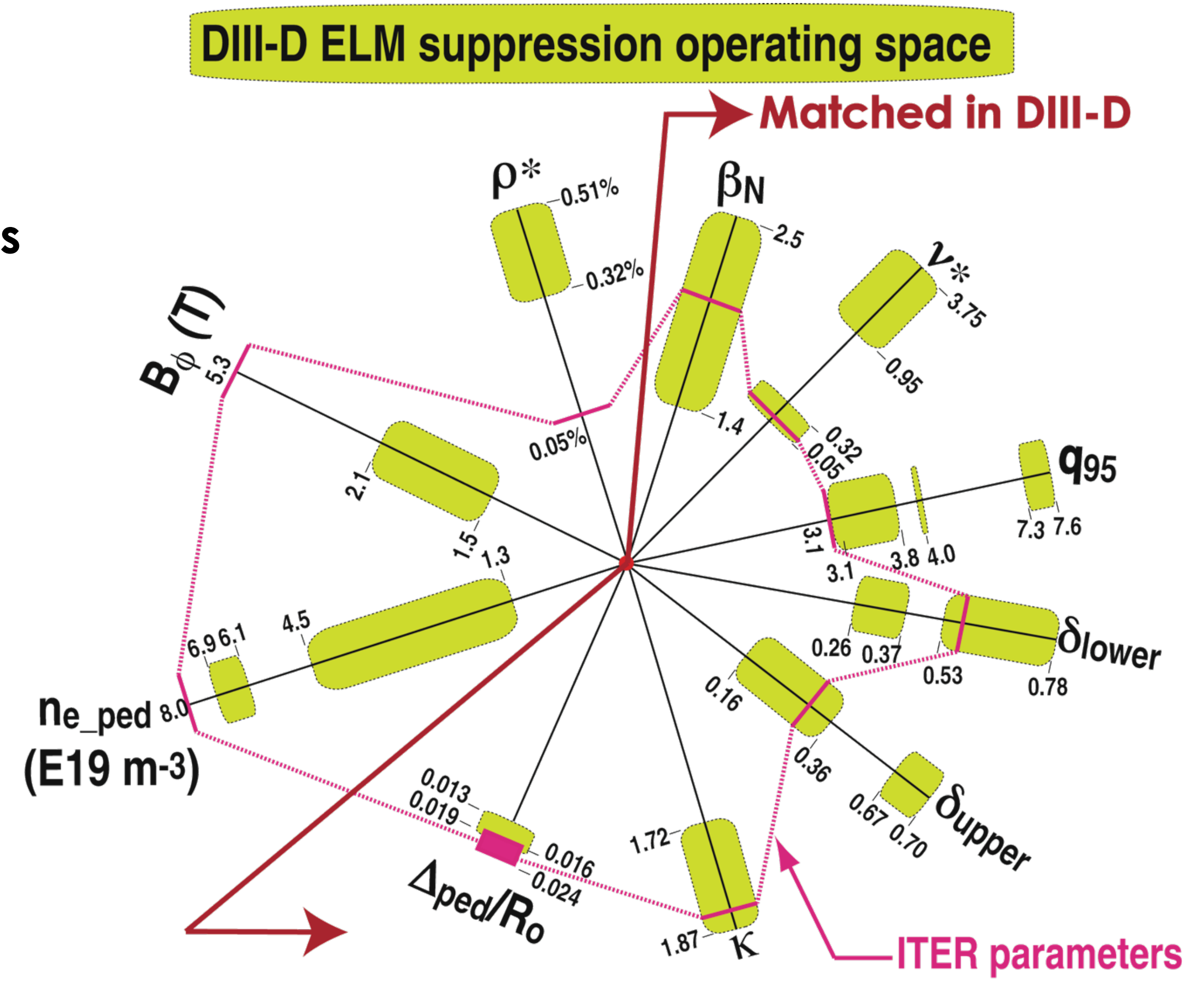




Courtesy of T. Rhodes, UCLA

ELM Suppression Obtained Over a Wide Range in DIII-D Operating Parameters

- **RMP ELM suppression obtained with all key ITER dimensionless parameters**
  - Except ρ^*
- **ITER dimensional parameters such as B_ϕ and p_{e_ped} are not accessible**
  - Models are needed to assess scaling to ITER



ITER ELM Control Requirements Span a Wide Range of Operational Issues

- Maintain detached divertor during ELM control
- Obtain ELM control over Large q_{95} range
- Maintain efficient core pellet fueling
- Able to suppress first ELM after L-H transition
- Minimal impact on core and pedestal performance
- Ensure sufficient tolerance to control system malfunctions
- Minimal impact on L-H power threshold
- Obtain ELM control in He plasmas
- Minimize core impurity influx relative to ELMing plasmas
- Obtain ELM control at low rotation without locked modes
- Minimize impact on energetic particles