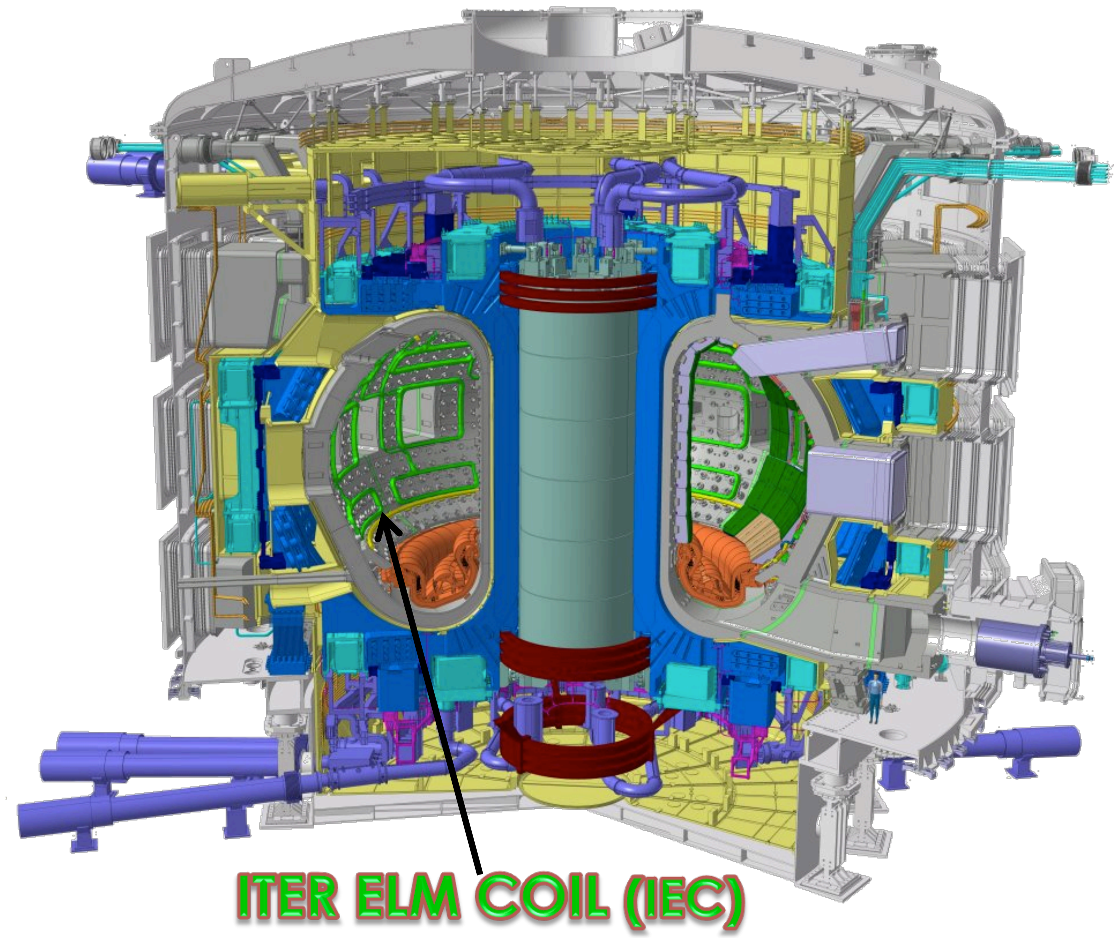
A Current Perspective on RMP ELM Mitigation

by

T.E. Evans

ITER Tokamak Cutaway



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Webinar

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Note: Many international facilities, scientist, engineers and technicians, too numerous to list here, have contributed to this area of research. Their contributions are gratefully acknowledged.

Edge Localized Mode Control is Essential for Accomplishing ITER's Mission Without Costly Delays and Expenses

Objective

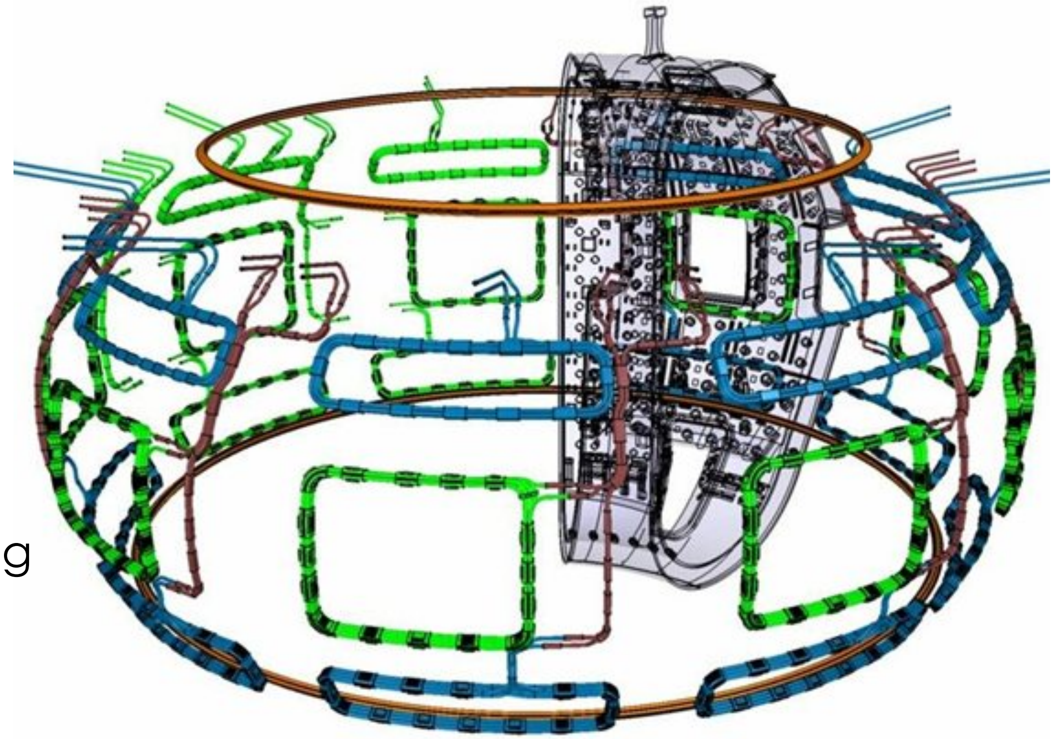
- Resolve key physics issues needed for ELMs control with Resonant Magnetic Perturbation (RMP) fields in ITER

Outline

- ITER ELM control requirements
- Summary of DIII-D result on key issues for RMP ELM control in ITER
- Progress on RMP ELM control research in Europe and Asia
- Summary and conclusions

Particle and Energy Bursts due to ELMs Must be Strongly Mitigated or Suppressed in ITER

- **Uncontrolled ITER ELMs will:**
  - Crack and melt tungsten divertor plates
  - Release impurities from solid surfaces that can cool the plasma and:
    - Degrade fusion performance
    - Trigger a radiative collapse leading to a plasma current disruption
- **RMP ELM control coils are included in the ITER baseline design**
  - Final engineering design review currently scheduled for March 2014

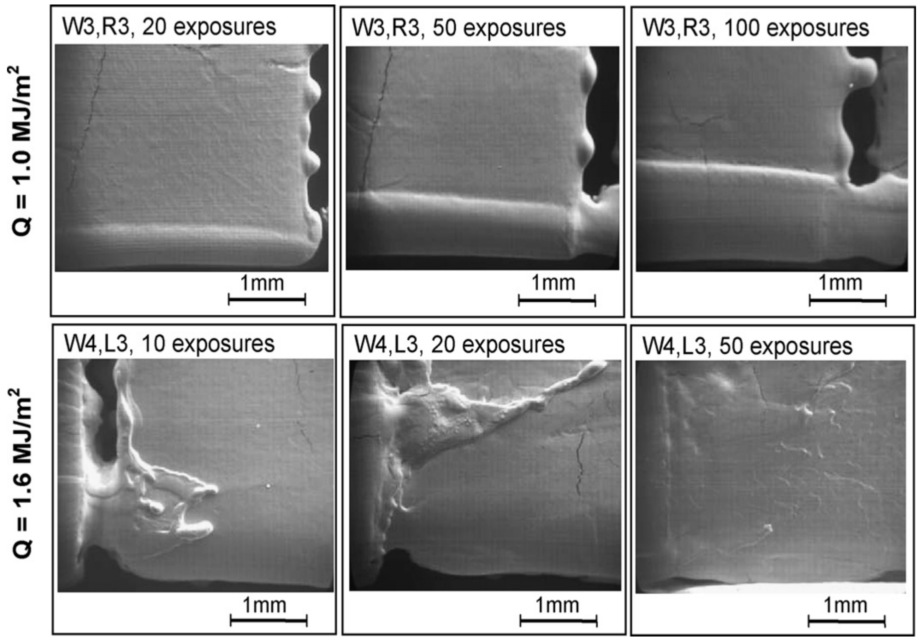


E. Daly, et al., *Fusion Sci. Technol.* **64** (2013) 168

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
    - $\Delta W_{ELM} = 0.2 W_{ped} = 0.2 * 0.3 W_{th} = 0.06 * 350$ MJ = 21 MJ
    - Assuming an ELM footprint area:
      - $A_{ELM} = A_{steady\_state} = A_{s.s.} \sim 1.4$ m^2
    - Uncontrolled ITER ELM energy density $\Delta W_{ELM}/A_{ELM} \sim 15$ MJ/m^2
- **ITER ELM energy density must be reduced to ≤ 0.5 MJ/m^2 to prevent melting of tungsten**
  - At this limit a divertor lifetime of ~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

ELM energy density limit in a 15 MA, Q_{DT} = 10 ITER plasma is:

➔ $\Delta W_{ELM}/A_{ELM}$ = 0.5 MJ/m^2

assuming $A_{ELM} = A_{s.s.}$ (ΔW_{ELM} = 0.7 MJ)

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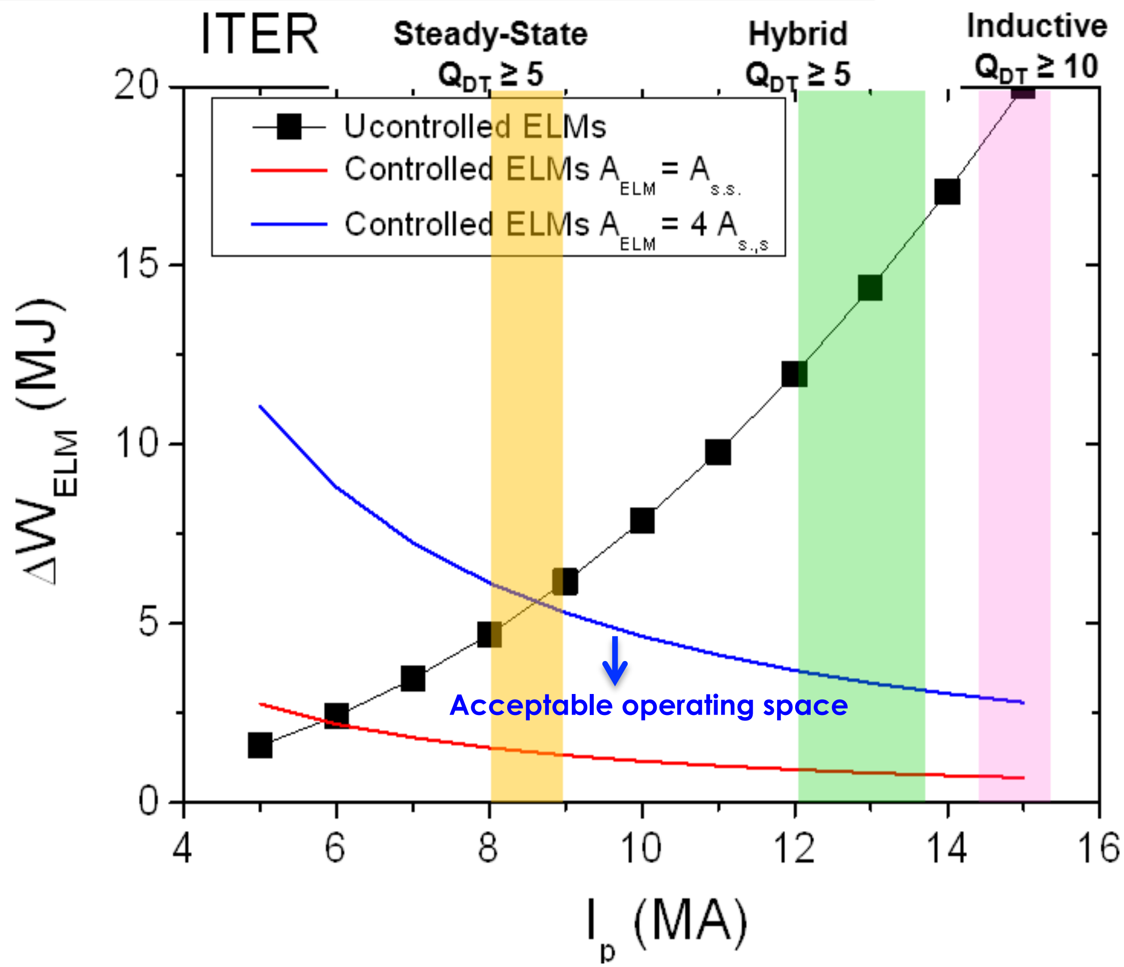
Acceptable Operating Space with Uncontrolled ELMs in ITER Depends on A_{ELM} Scaling With ELM Energy (ΔW_{ELM})

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

A Wide Range of ELM Control Techniques are Being Developed Worldwide

Technique	Impact on ELMs, physics mechanism (ITER baseline)
RMP fields	Mitigation or suppression, particle transport increased
Pellet pacing	Mitigation, small ELMs triggered by increased edge ∇p
QH- & I-mode	Suppression, transport specific to operating space
Impurity seeding	Mitigation, pedestal ∇p reduced by impurity radiation
Vertical kicks	Mitigation, dynamic perturbations of pedestal ∇p
SMBI (Supersonic Molecular Beam Injection)	Mitigation, transport increased by edge neutral fueling
Li walls	Suppression, ELM-free similar transport, increased P_{rad}
Edge ECH	Mitigation, energy confinement reduced by edge ECH
TF ripple	Mitigation, main ion stochastic transport
Small ELM regimes	Mitigation, pedestal ∇p reduced, small ELM transport

Key ITER ELM Control Requirements Span a Wide Range of Operational Issues

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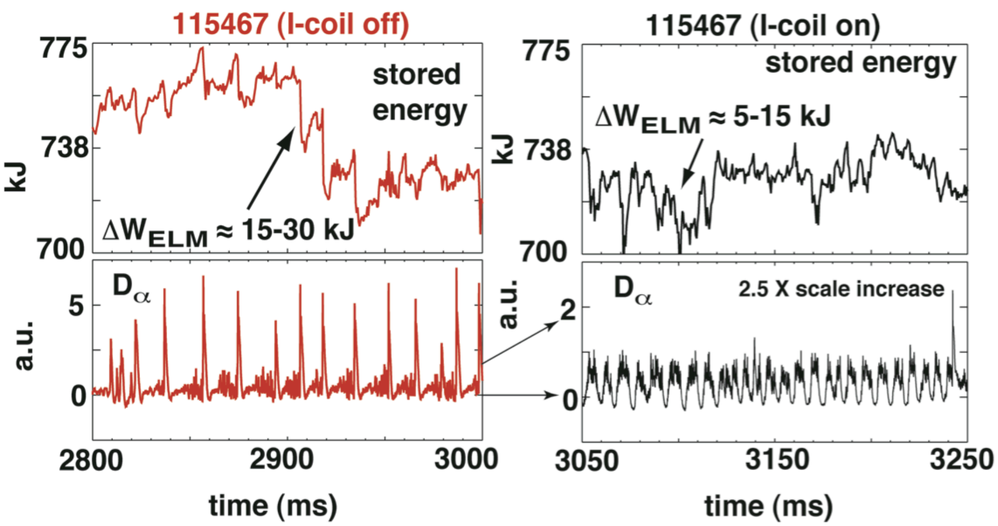
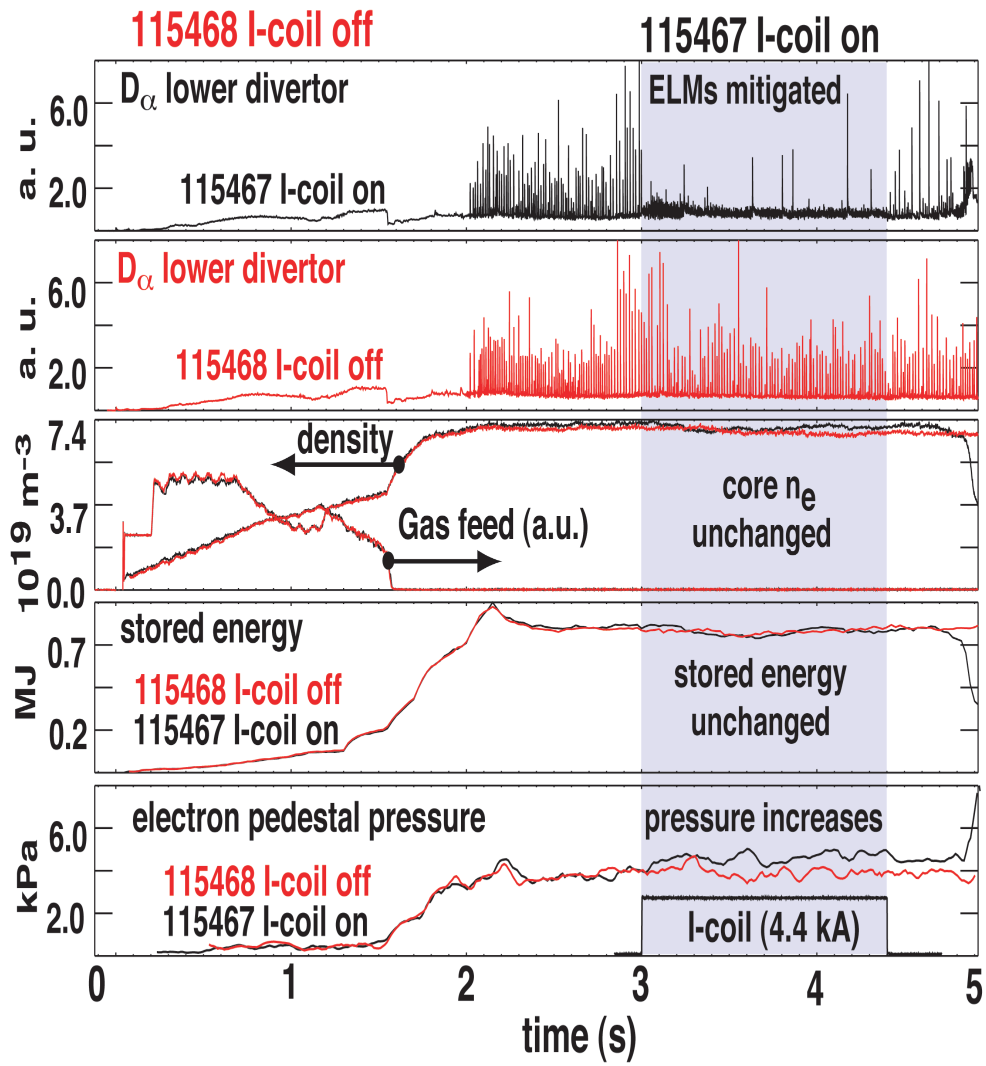
Goal → Minimize Divertor Heat and Particle Flux: ΔW_{ELM} Reduced by ~ 3x in $\nu_e^* \geq 1$ Plasmas

- **ELM mitigation in high pedestal collisionality $\nu_e^* \geq 1$ plasmas**
  - Reduces fast stored energy transients (ΔW_{ELM}) by 30-50%
  - Suppresses fast D_α spikes
  - Drives small D_α modulations with slow rise times relative to ELMs

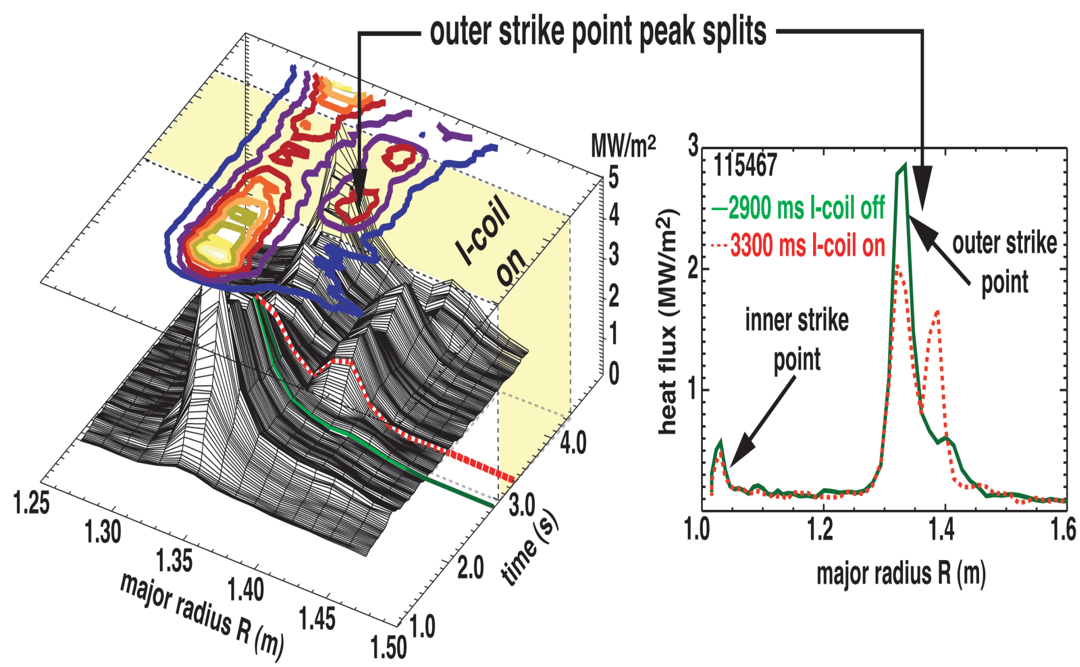


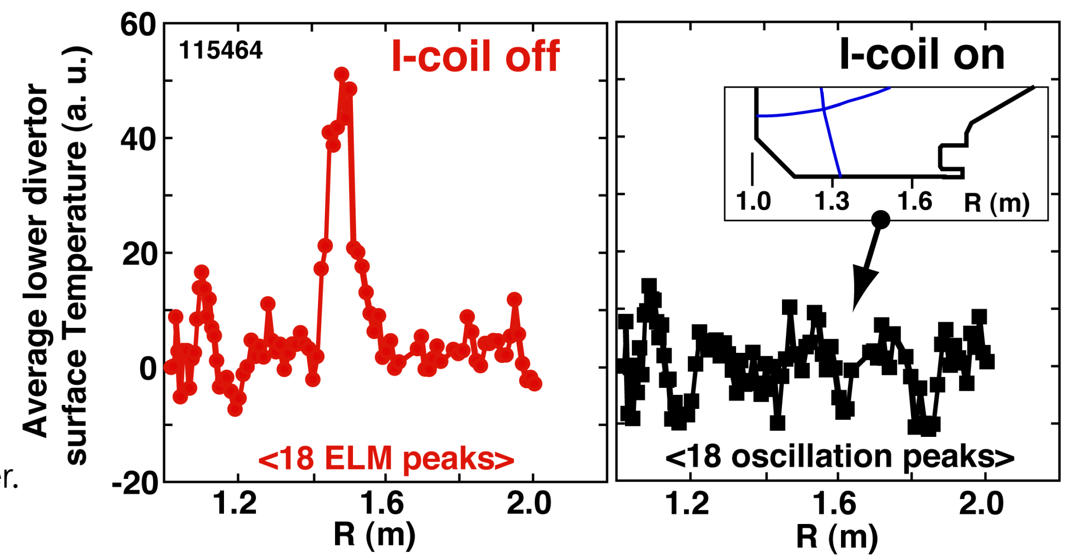


T. Evans, et al., Nucl. Fusion **45** (2005) 595

Goal → Minimize Divertor Heat and Particle Flux: Peak Divertor $q_{||}$ Reduced by ~ 2x in $\nu_e^* \geq 1$ Plasmas

- **Divertor heat flux profile splits into distinct peaks during $\nu_e^* \geq 1$ ELM mitigation**
  - Amplitude of peaks evolve with constant I-coil current
  - Additional experiments needed to understand time dependent heat flux splitting
  - Can MHD modeling reproduce this physics?
- **Target plate temperature transients due to ELMs reduced by ~ 5x**

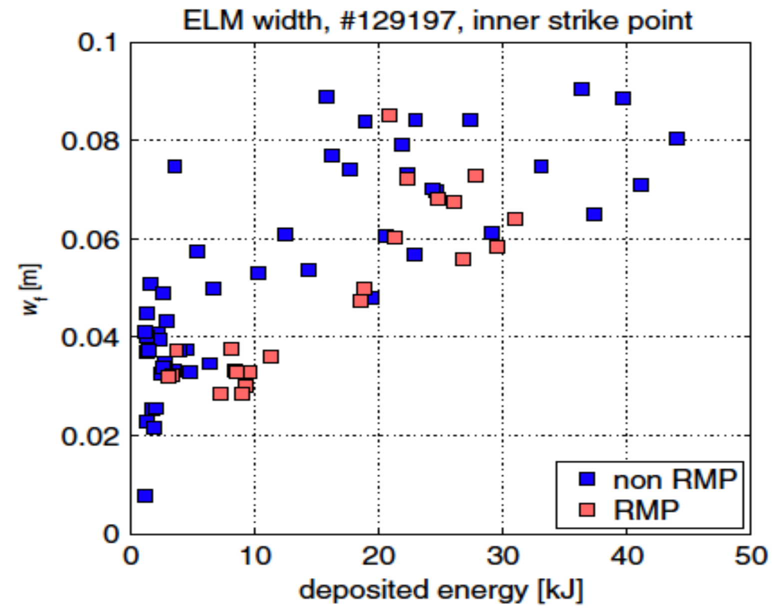


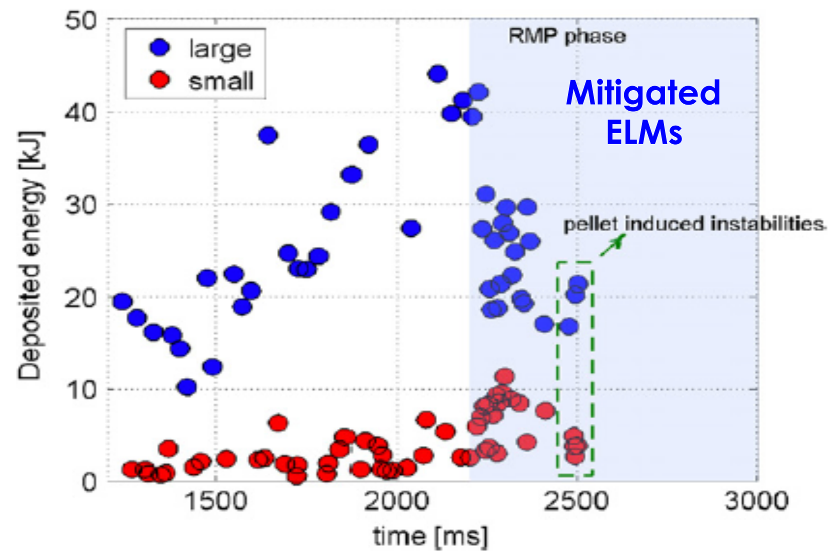


T. Evans, et al., J. Phy. Conf. Ser. **7** (2005) 174

Goal → Minimize Divertor Heat and Particle Flux: Mitigated A_{ELM} and ΔW_{ELM} Somewhat Reduced in $\nu_e^* \leq 0.35$ Plasmas

- **ELM mitigation in $\nu_e^* \leq 0.35$ plasmas:**
  - Reduces peak ΔW_{ELM} from ~ 40 kJ to ~ 30 kJ
  - Width of ELM footprint (W_f) inversely proportional to ΔW_{ELM}
  - Width of W_f and ΔW_{ELM} distributions are slightly reduced
- **ELM suppression in $\nu_e^* \leq 0.35$ plasmas:**
  - Reduces peak ΔW to < 5 kJ
- **Weak $q_{||}$ splitting during suppression is observed in $\nu_e^* \leq 0.35$ plasmas**





M. Jakubowski, et al., Nucl. Fusion **49** (2009) 0950013

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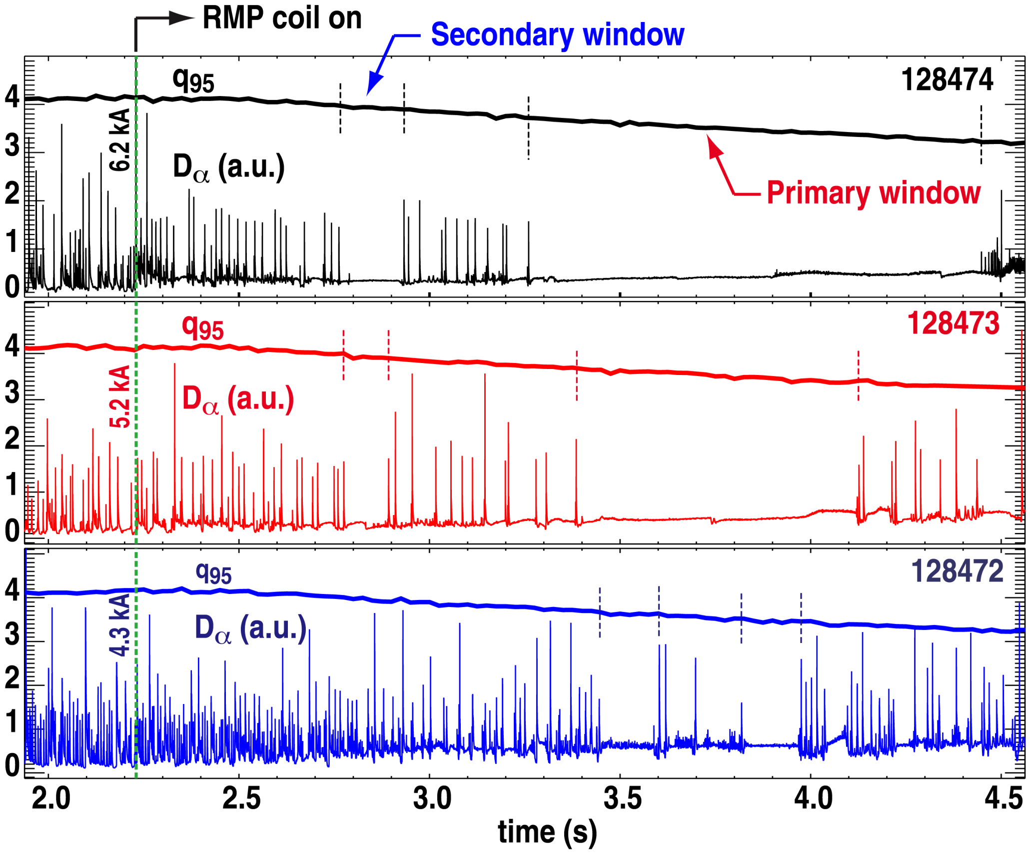
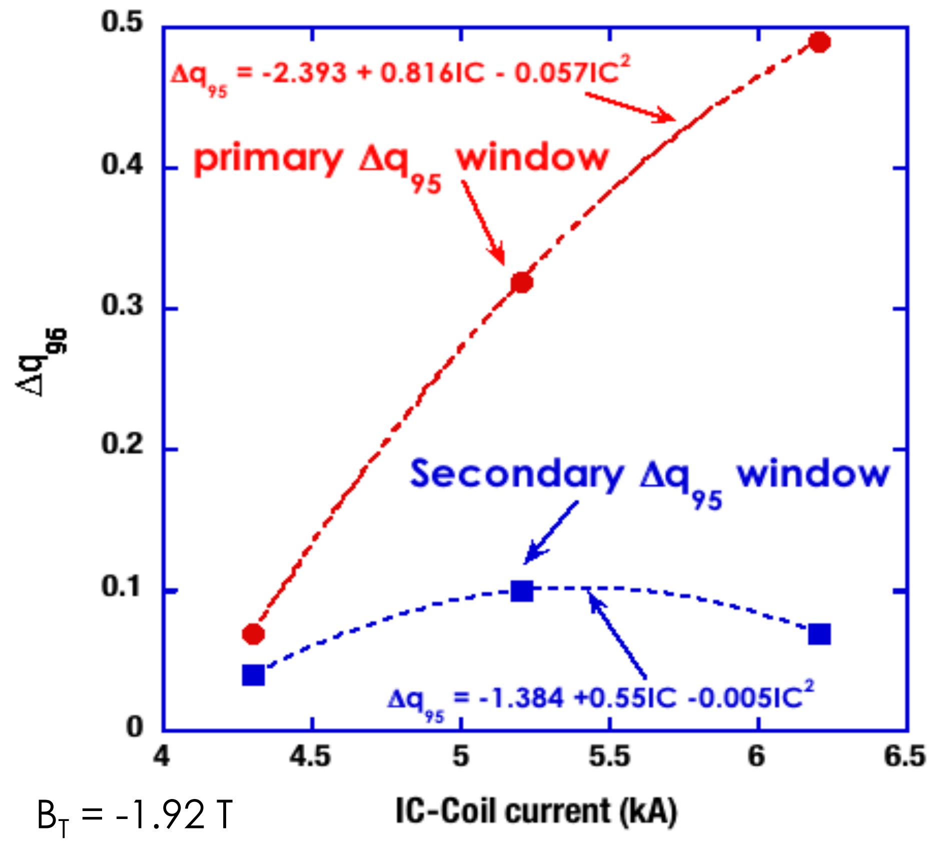
Goal → Obtain ELM Control Over Large q_{95} Range: q_{95} Suppression Window Increased with Multi-mode RMP





- **Increasing n=3 I-coil and n=1 C-coil currents expands q_{95} suppression window by ~7x**
- **Additional experiments with multi-mode RMPs may lead to improved coils designs with larger q_{95} suppression windows**

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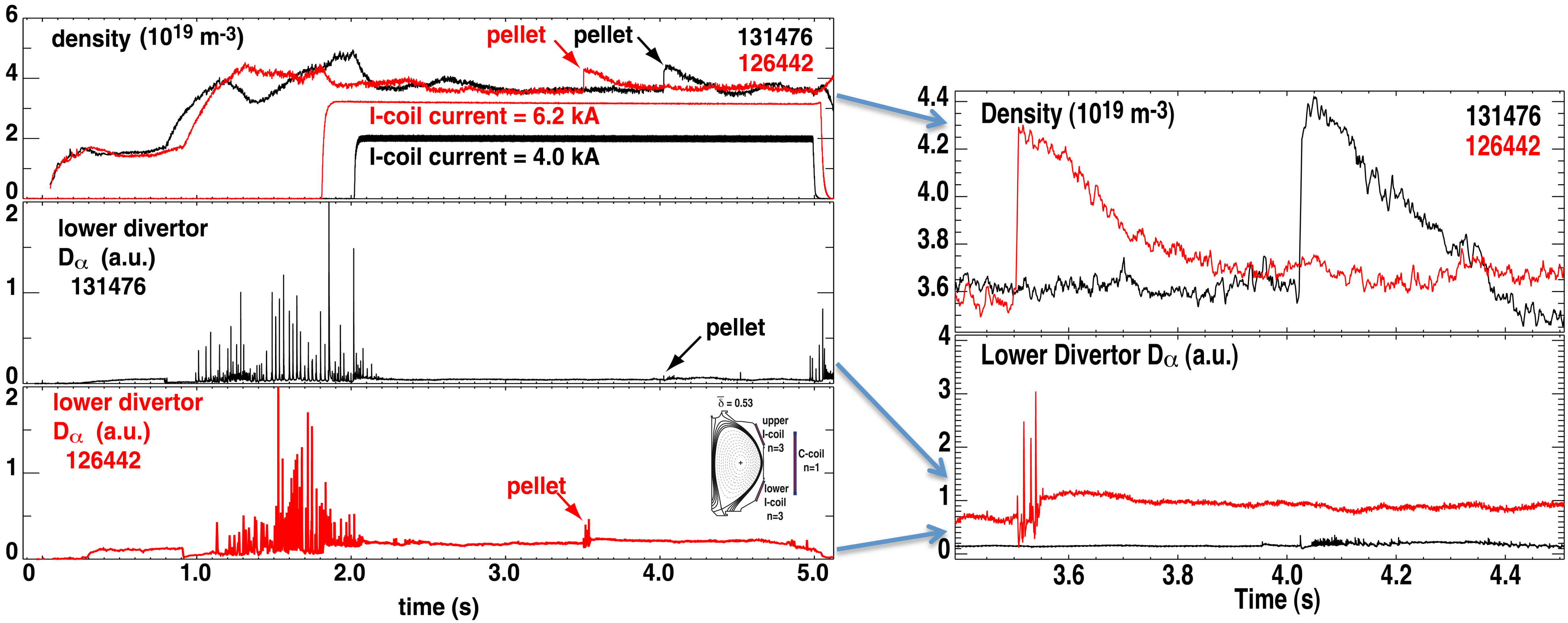
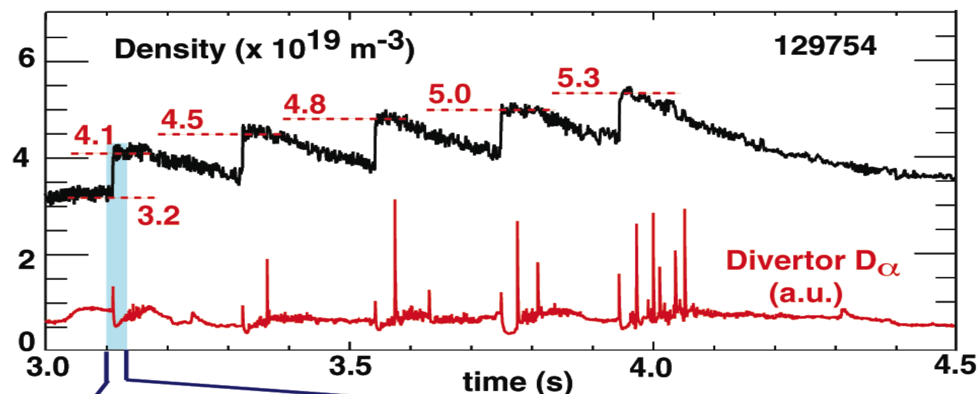
Goal → Maintain Efficient Core Pellet Fueling: Suppression Unaffected by Pellets Under Some Conditions

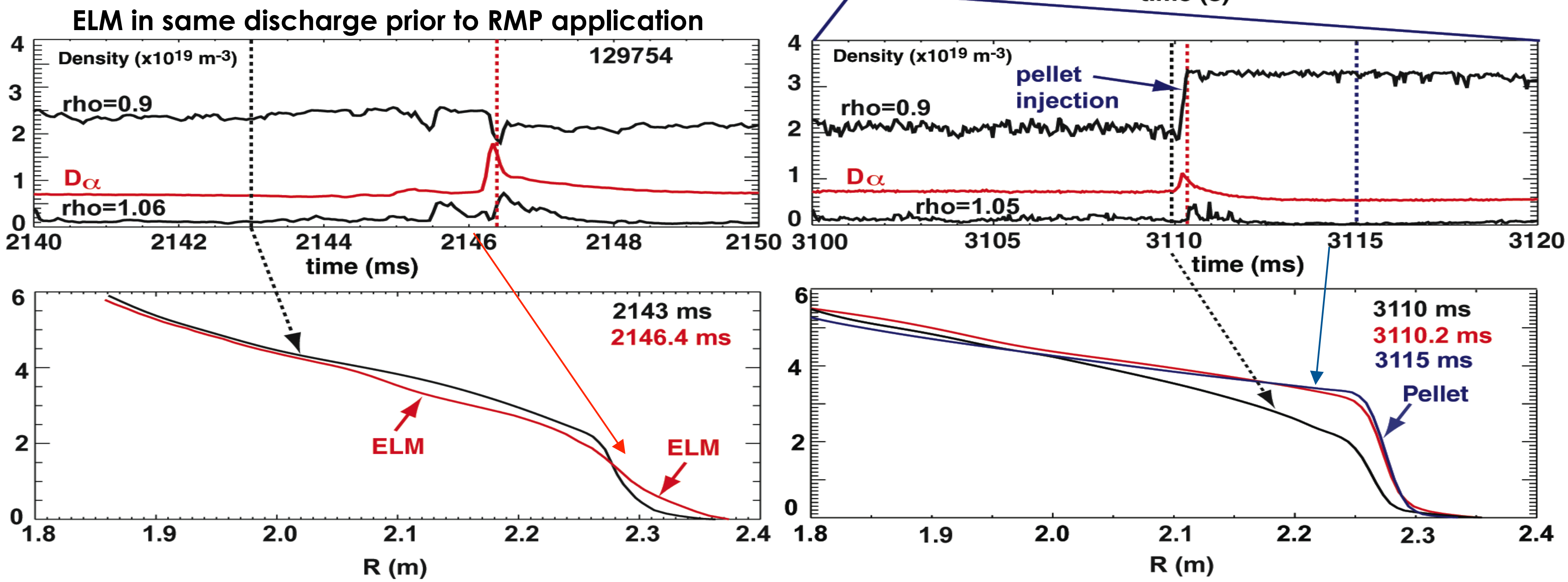


- **Suppression maintained during pellet fueling with 4 kA I-coil current**
- **Three small D_α spikes triggered with 6.2 kA I-coil current**
  - D_α spikes triggered when pellet hits plasma edge

Goal → Maintain Efficient Core Pellet Fueling: Repetitive Pellets Trigger ELMs Above Density Threshold

- **First D_α caused by pellet hitting the plasma edge - 5 Hz pellets**
  - ELM persistence increases with increasing density
  - Measurements needed to determine ΔW_{ELM} and A_{ELM}





L. Zeng, UCLA

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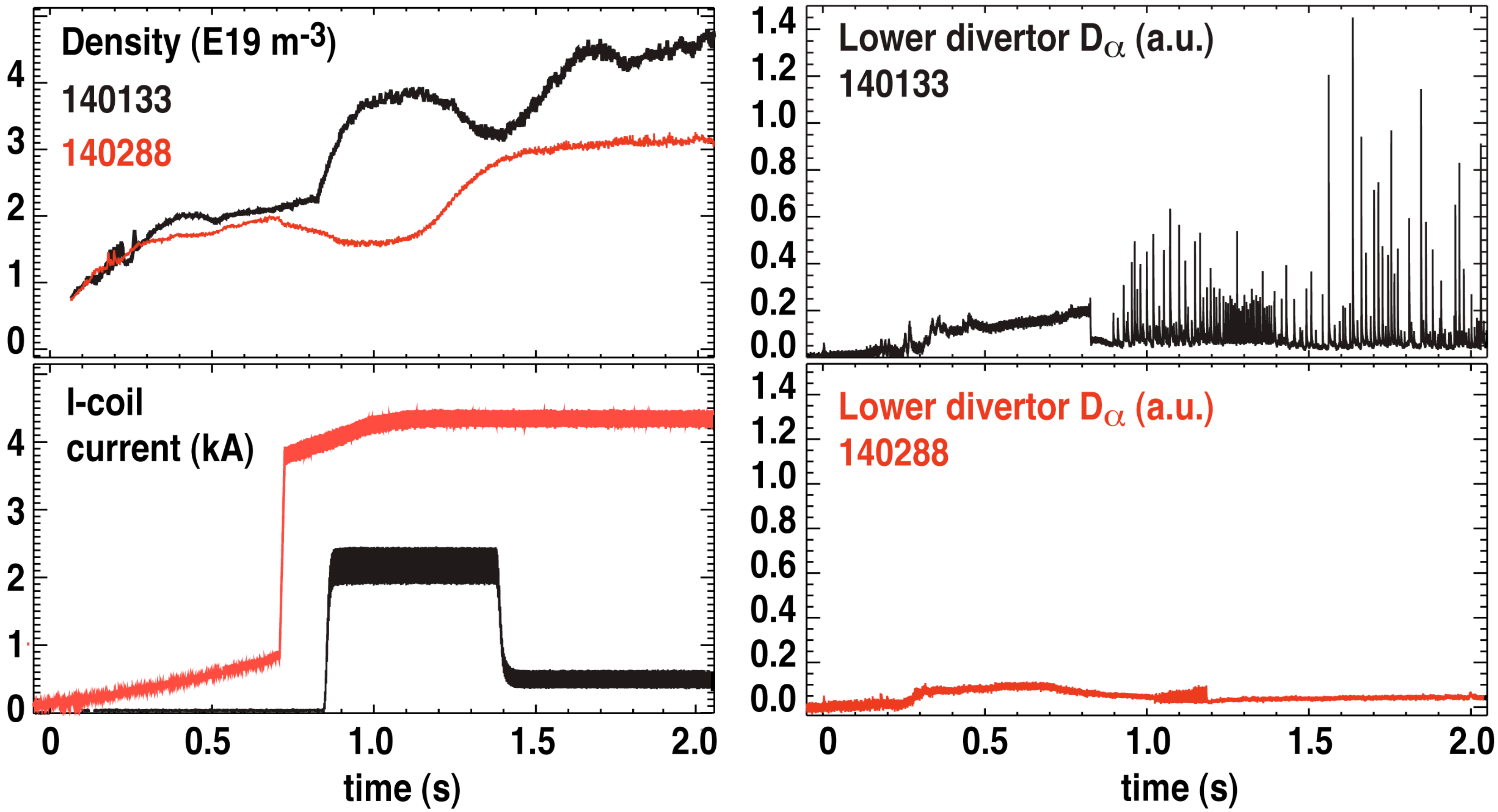
Goal → Control First ELM After L-H transition: First ELM Suppressed by Applying Early RMP Field



- **Applying large n = 3 RMP field before the L-H transition suppresses 1st ELM**
  - Large impact on density pump-out prior to L-H transition
  - Experiments needed to investigate density feedback control

T. Evans, et al., Plasma Fusion Res. **7** (2012) 2402046

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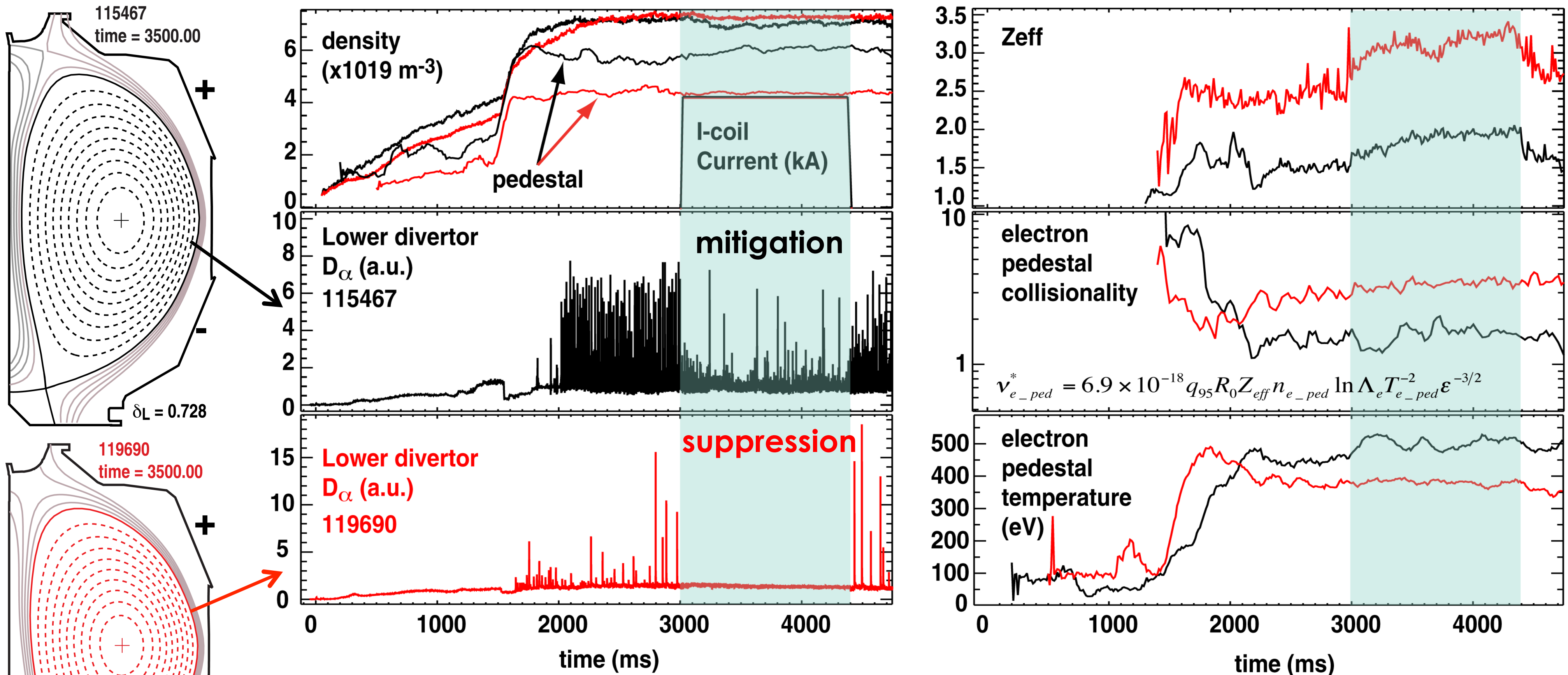
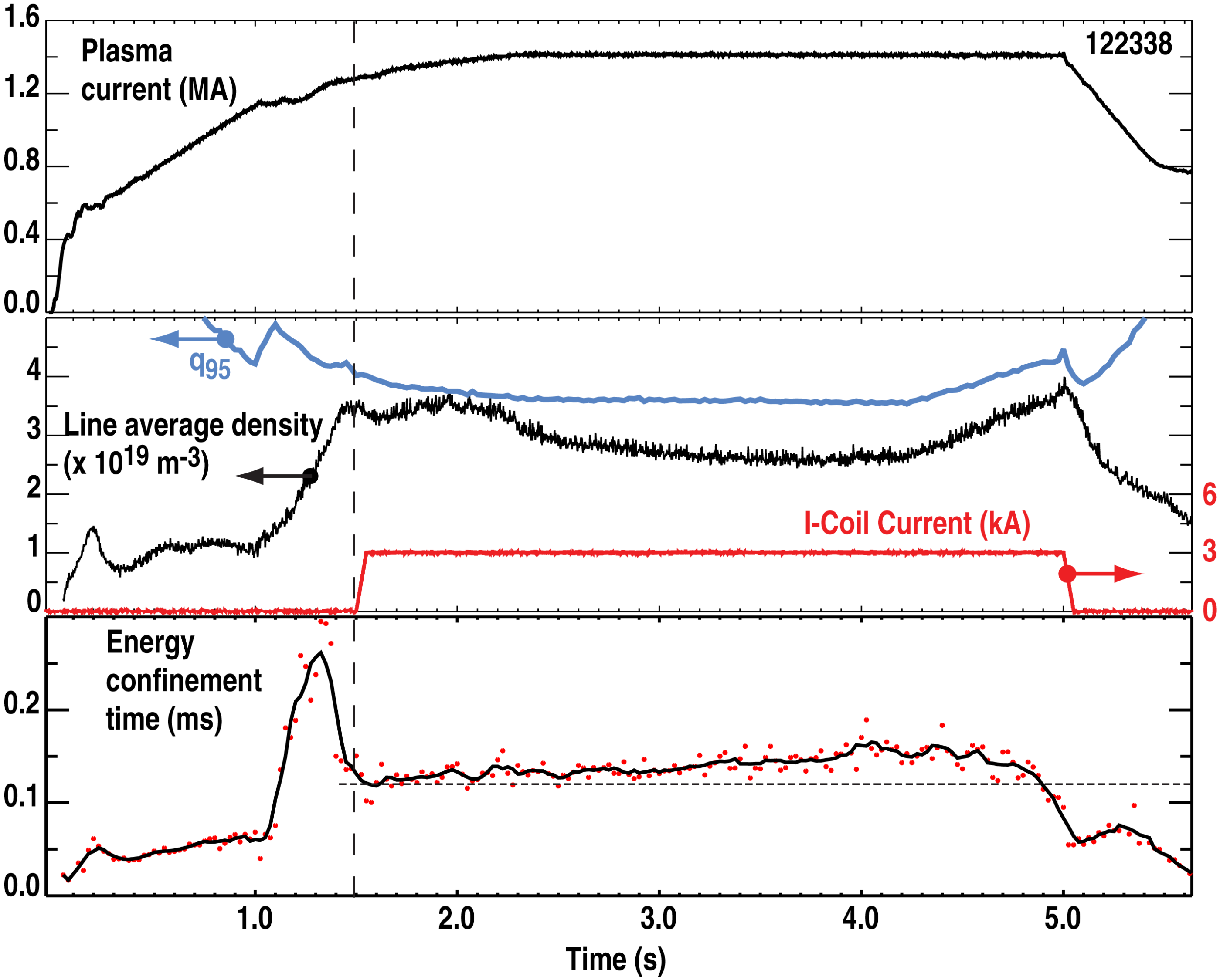
Goal → Minimize Impact to Core and Pedestal Performance: Density Unaffected during ELM Control in $\nu_e^* \geq 1$ Plasmas

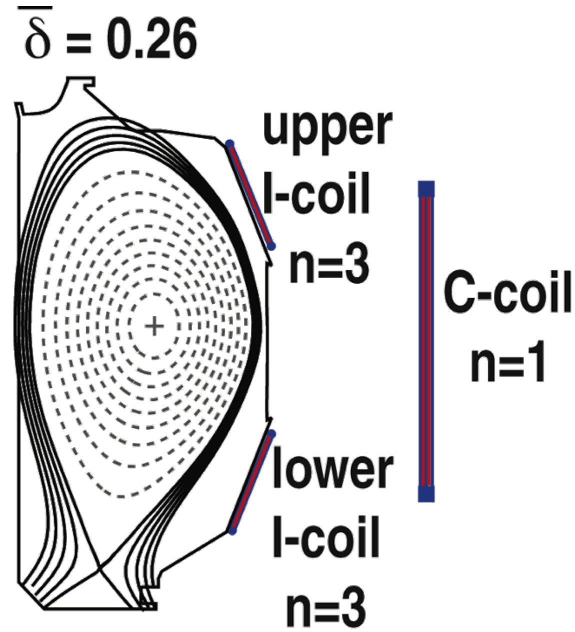


- **Line averaged and pedestal density unaffected by RMP**
  - Pedestal n_e and T_e profiles unaffected by RMP field
  - Pedestal carbon density increases slightly
    - Pedestal Z_{eff} increases from 2.5 to ~ 3.4 during ELM suppression

T. Evans, et al., Plasma Fusion Res. **7** (2012) 2402046

Goal → Minimize Impact to Core and Pedestal Performance: Small n_e Change seen in LSN Low δ, $\nu_e^* \leq$ 0.35 Plasmas

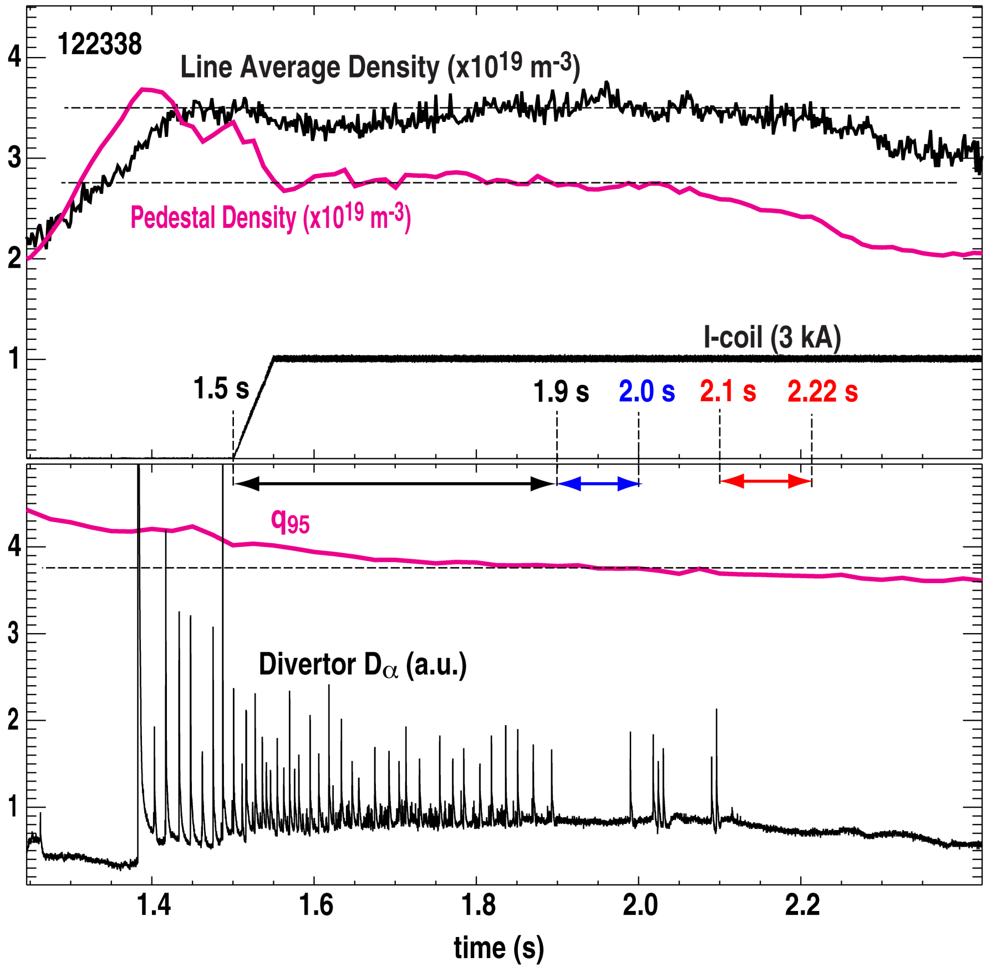


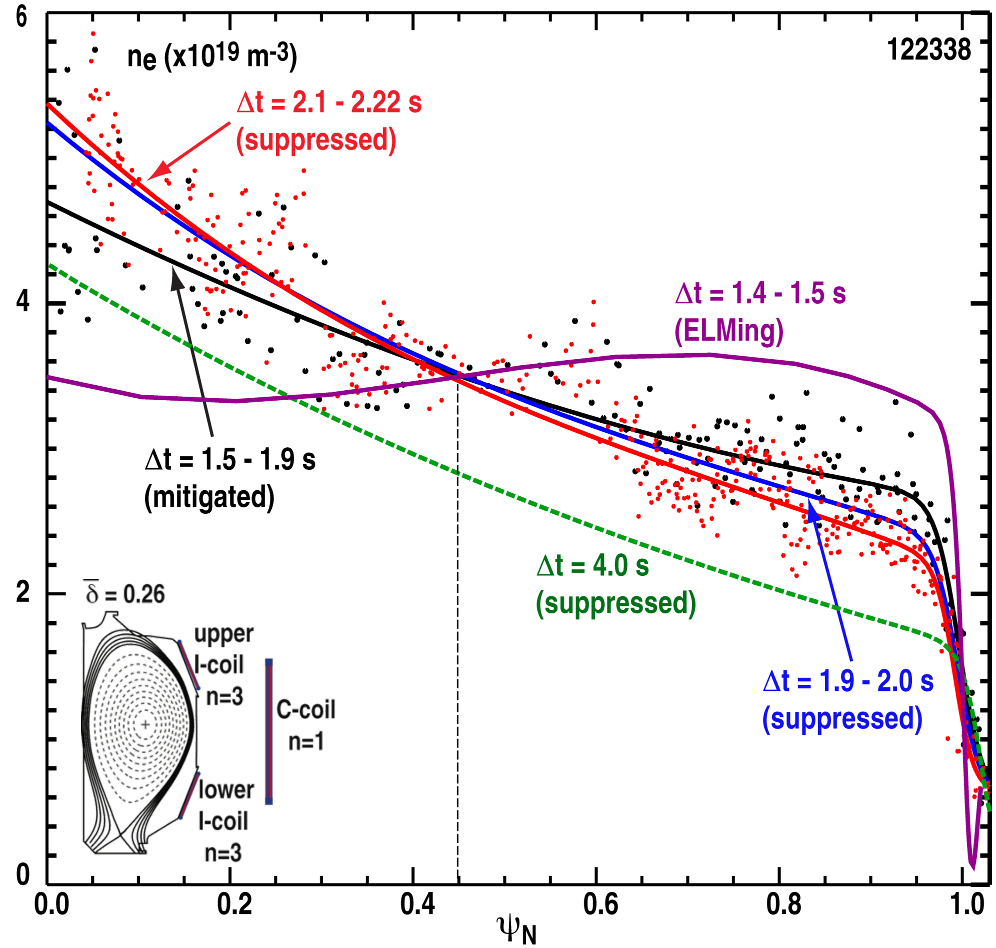


Low triangularity LSN

RMP fields reduce particle inventory and increases energy confinement time in some discharges

Goal → Minimize Impact to Core and Pedestal Performance: Density Response to RMP Evolves Slowly During Discharge





- **Evolution of global particle balance is consistent with time varying plasma response to RMP field**
  - Active feedback of RMP coil needed to improve core and pedestal performance

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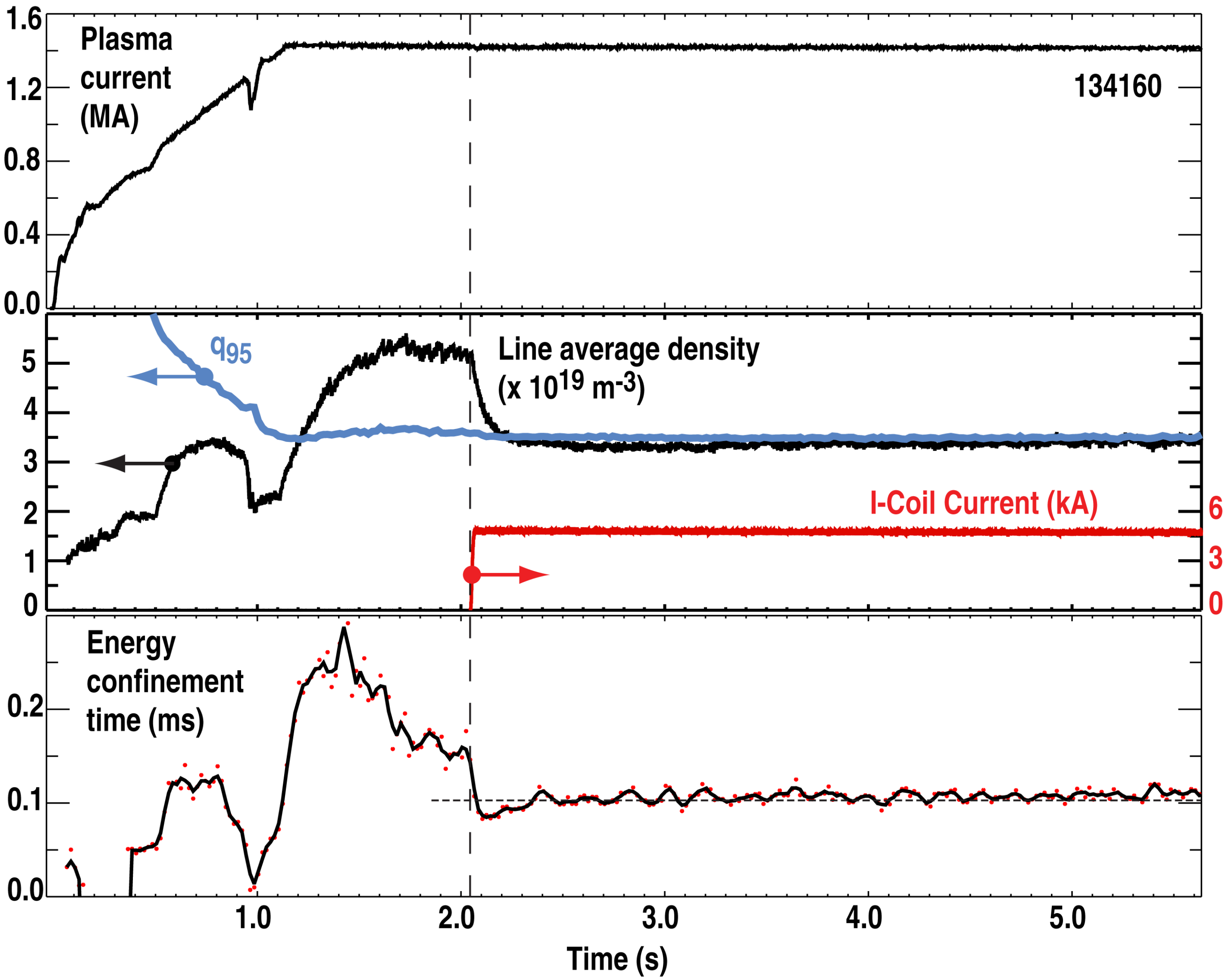
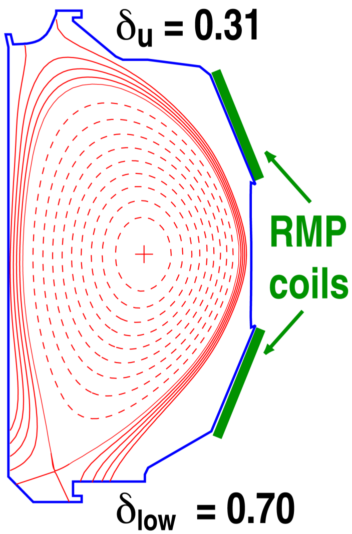
Goal → Minimize Impact to Core and Pedestal Performance: Larger Changes Observed in LSN High δ, $\nu_e^* \leq$ 0.35 Plasmas





ITER Similar Shape

134160 3500 ms

High triangularity LSN

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

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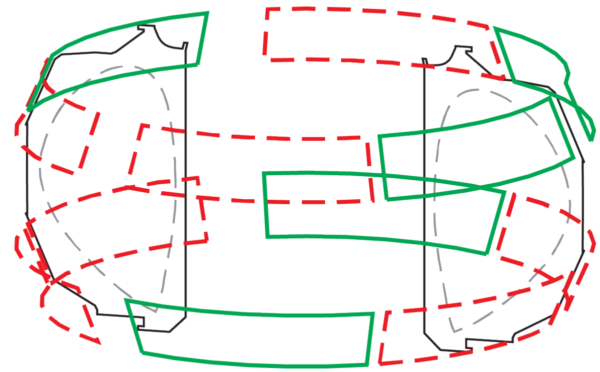
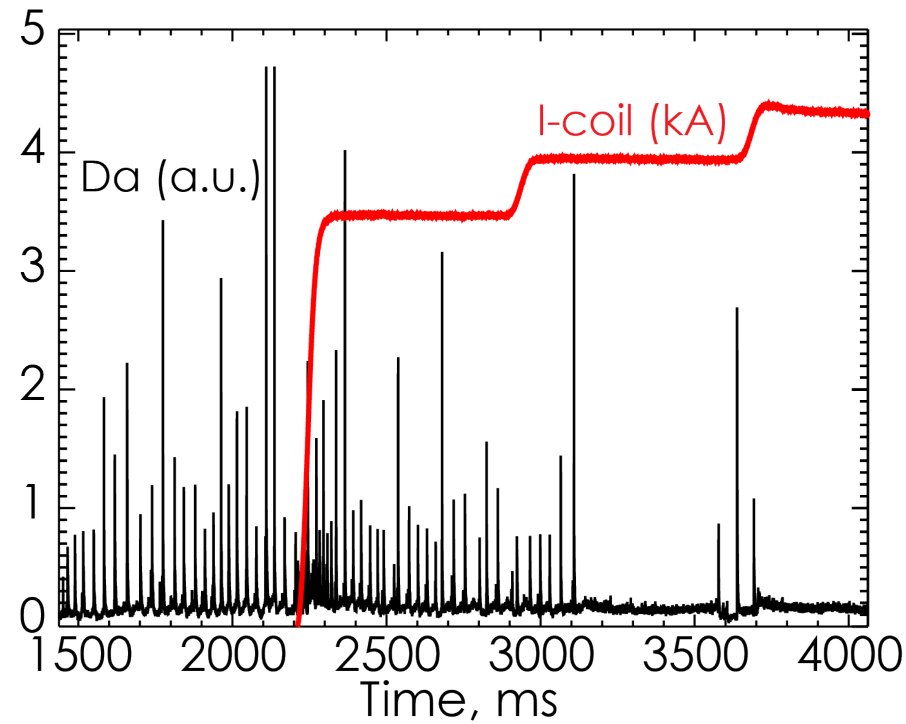
Goal → Ensure sufficient tolerance to Control System Malfunctions: ELM Suppression Obtained with Missing Coils

- **Suppression obtained with Individual I-coil loops turned off**
  - Loops turned off psudo-randomly form shot-to-shot
  - Small I-coil current steps used to identify suppression threshold
  - Suppression obtained with 7 of the 12 loops turned off
- **Result suggest that toroidal sidebands generated by missing loops assist with suppression**
  - Consistent with vacuum RMP field modeling predictions





D. Orlov, et al., APS invited (2014)

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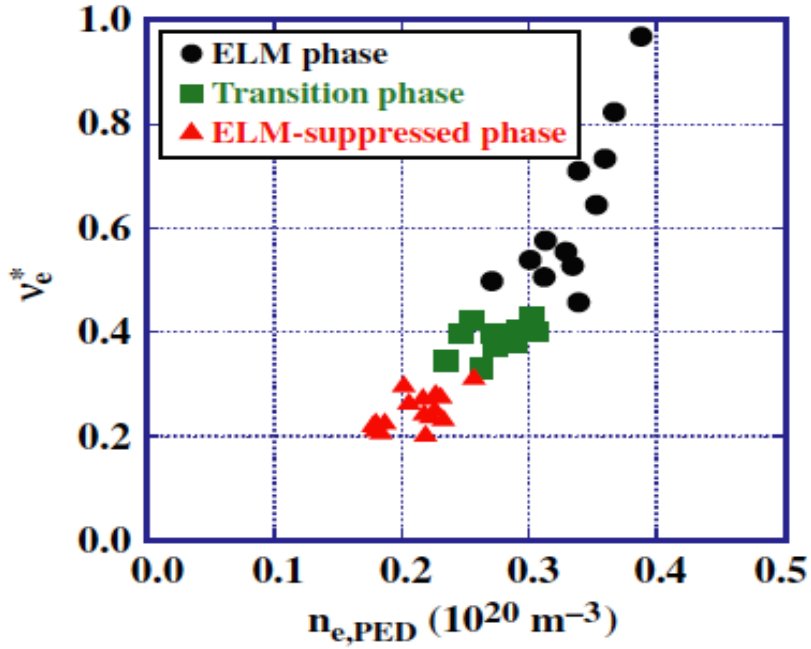
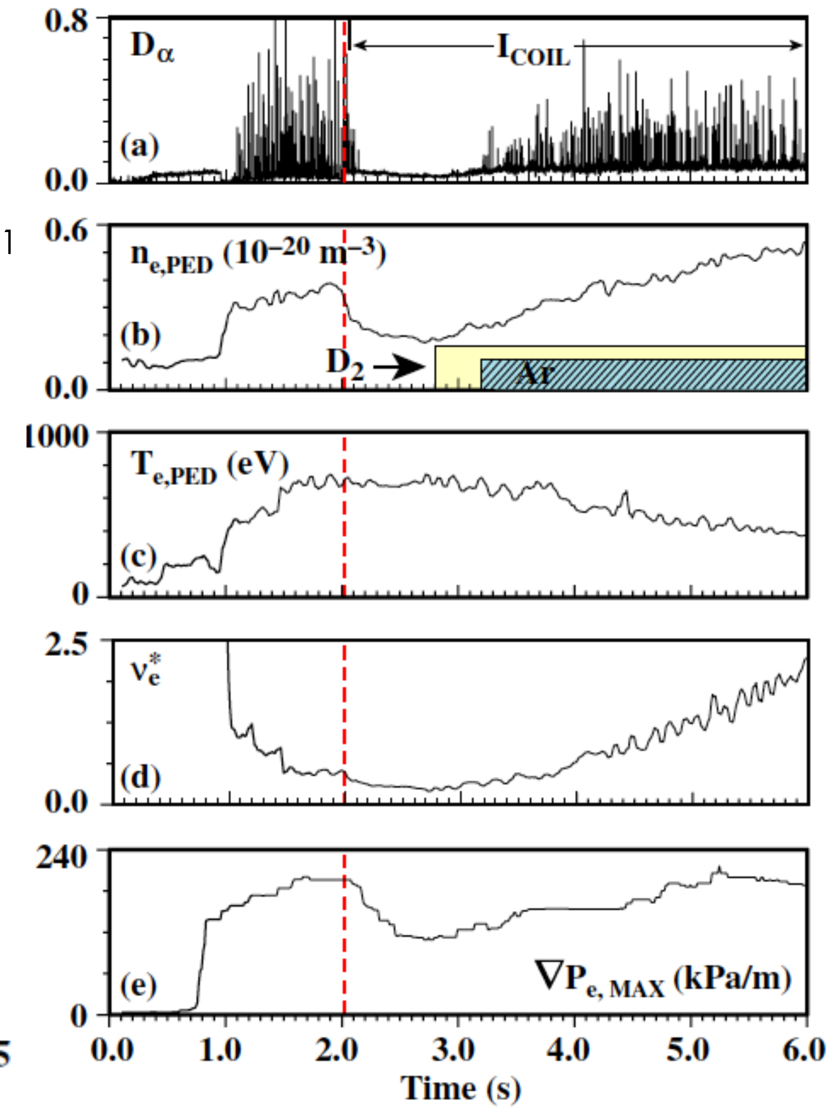
Goal → Maintain Detached Divertor During ELM Control: Obtained Detached Divertor with RMP but ELMs Return

- **Combined neutral D_2 and Ar gas flow increase ν_e^* above ELM suppression threshold (ν_e^* ~0.35)**
  - Γ_{D_2} = 0-10 Pa m^3 s^{-1} and Γ_{Ar} = 0.05 Pa m^3 s^{-1}
  - ELMs return prior to divertor detachment
  - More Experiments needed





T. Petrie, et al., Nucl. Fusion **51** (2011) 073003

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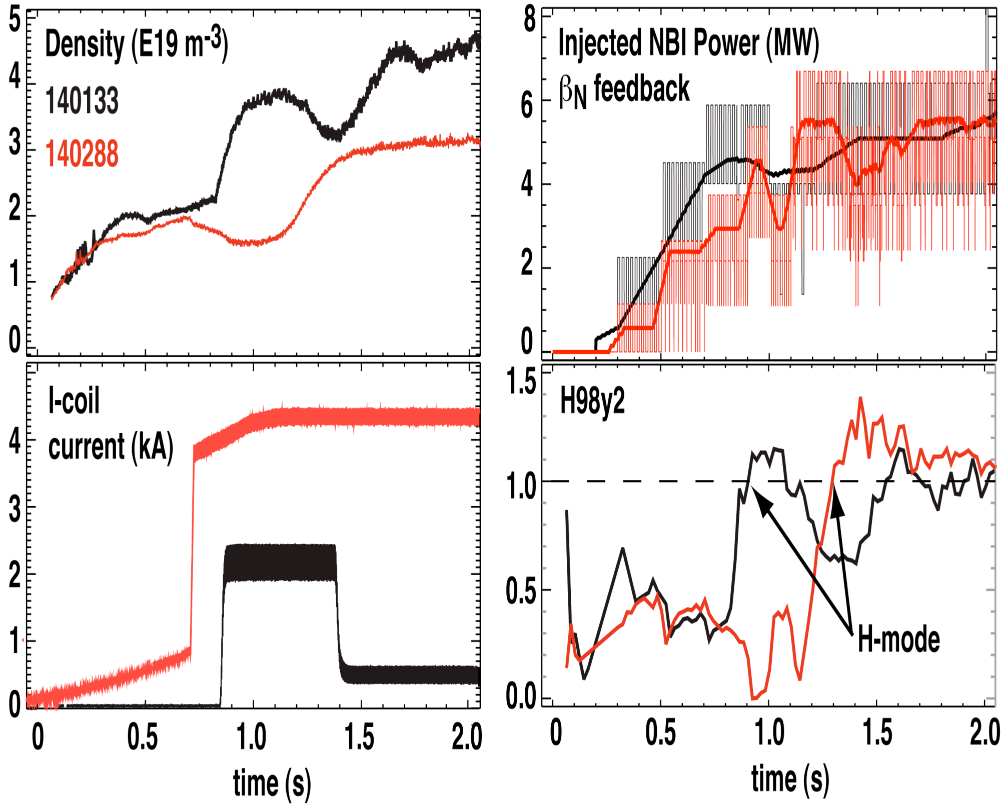
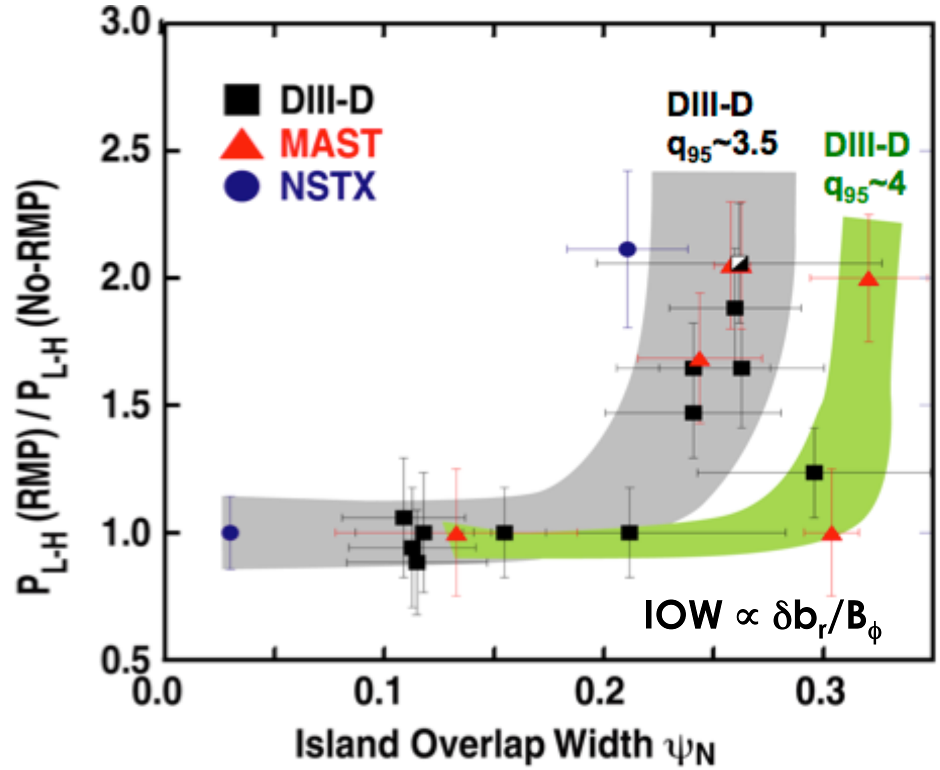
Goal → Minimize Impact on L-H Power Threshold: RMP Effect on L-H Power Threshold Increases with $\delta b_r/B_\phi$



T. Evans, et al., Plasma Fusion Res. **7** (2012) 2402046



M. Fenstermacher, et al., 23rd IAEA (2010) Daejeon, Korea

- **$P_{L\text{-}H}$ is unaffected with Island Overlap Widths (IOWs) less that ~0.25**
  - ELM suppression is correlated with an IOW ~0.165 in DIII-D
- **The RMP effect on $P_{L\text{-}H}$ also appears to depend on q_{95} in DIII-D**

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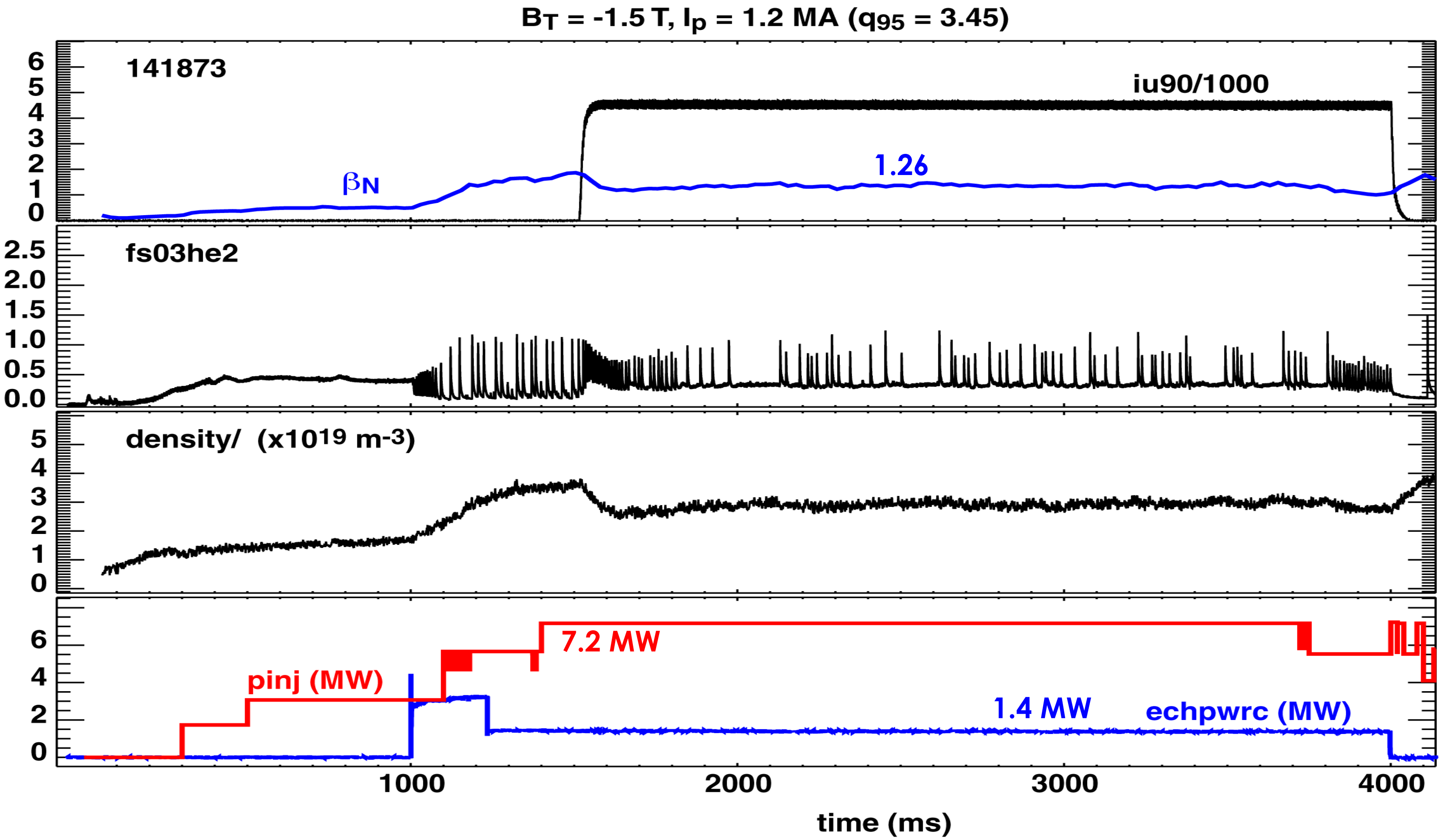
Goal → Control in He Plasmas: Marginal Suppression Obtained in He Plasmas



- **Pedestal collisionality exceeded $\nu_e^* \leq$ 0.35 threshold found in deuterium**
  - Need higher P_{inj} and lower pedestal density

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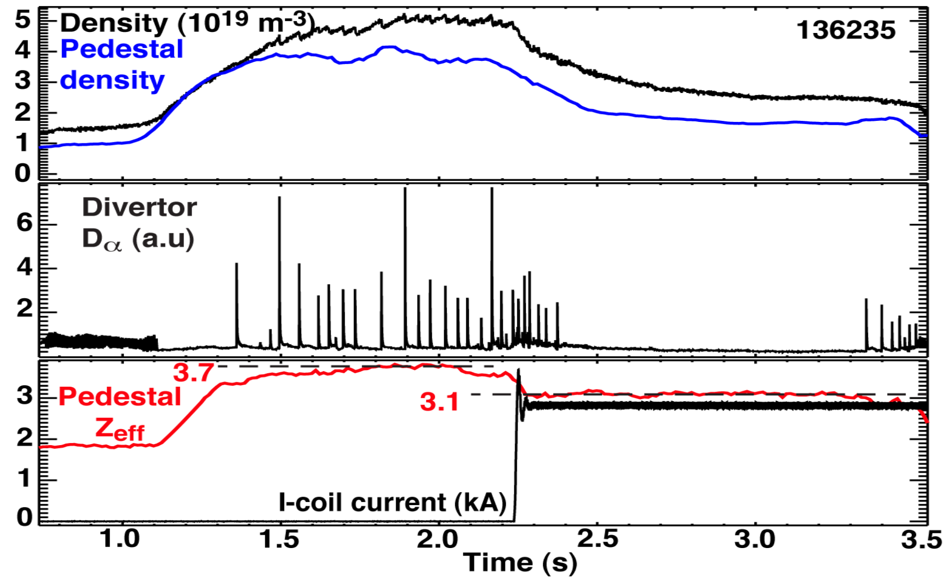
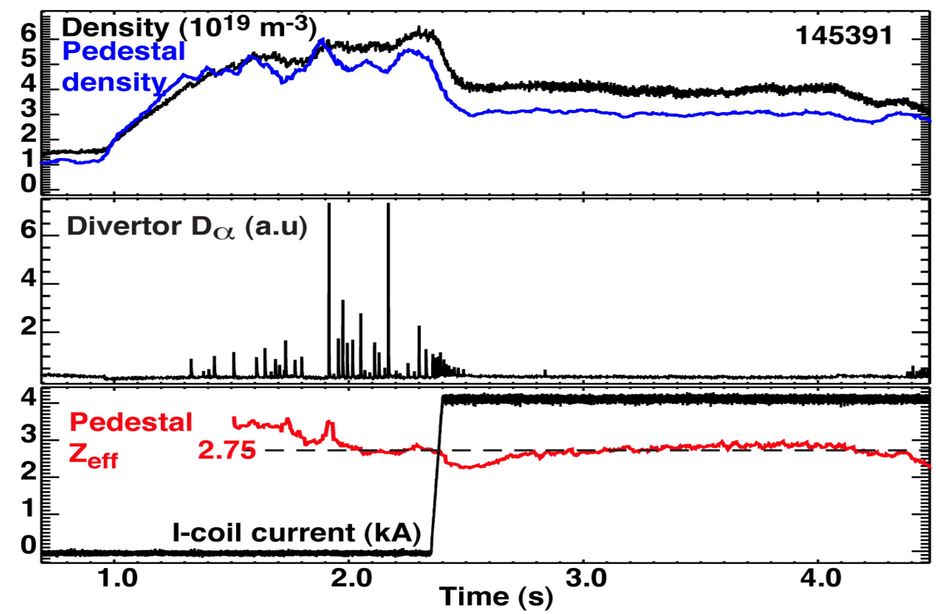
Goal → Minimize Impurity Influx: Z_{eff} due to Carbon is Sometimes Unaffected During Low ν_e*

- **Pedestal carbon response during suppression is unpredictable**
  - In low ν_e* plasmas carbon can be either unchanged, slightly increased or reduced
  - In high ν_e* discharges carbon typically increases by ~ 50%
- **Possible sources of carbon include:**
  - Increased divertor sputtering
  - Loss of energetic ion to main chamber walls
  - Energetic neutrals due to modified charge exchange rates





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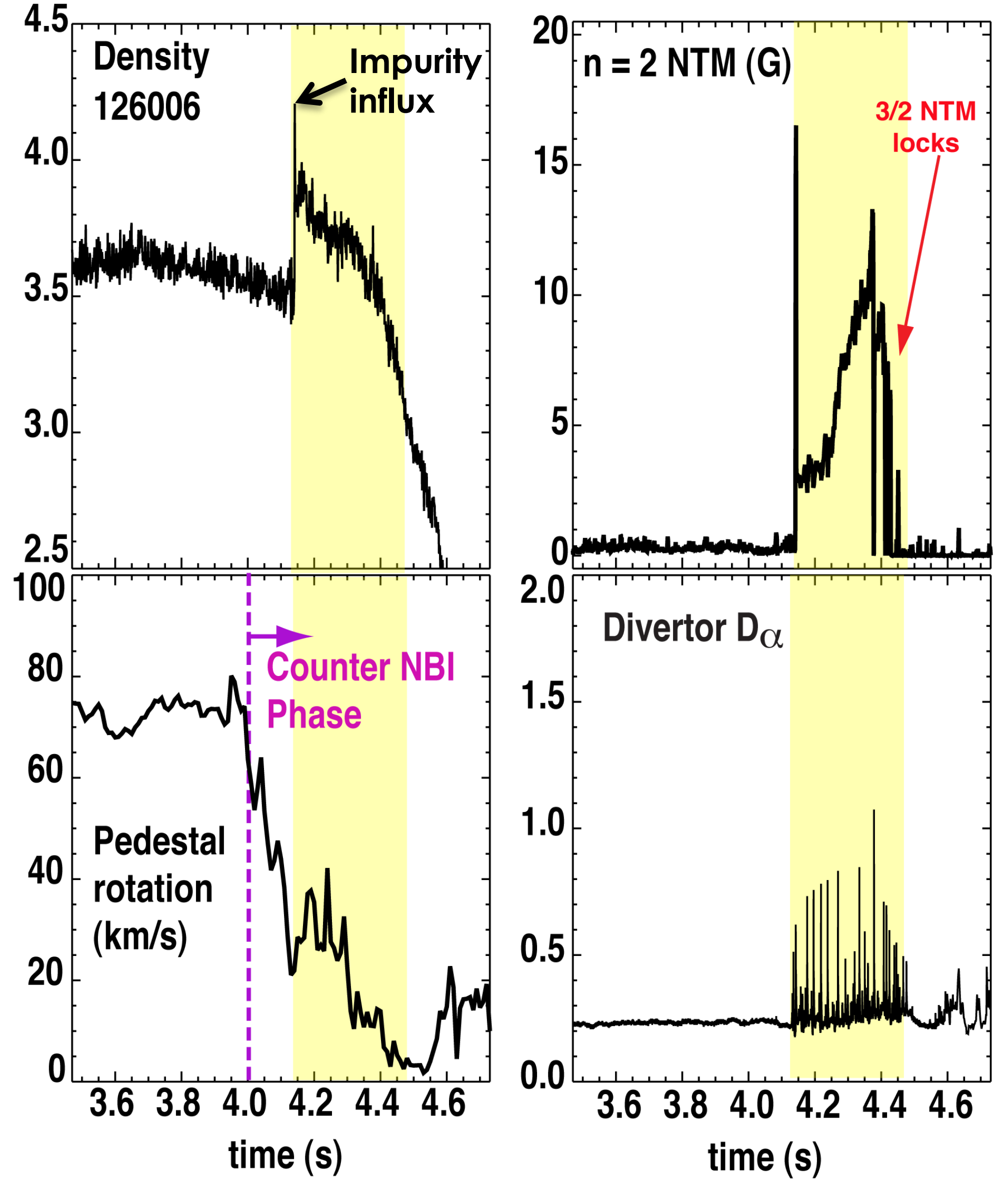
- Maintain efficient core pellet fueling
- Control of first ELM after L-H transition
- Minimize impact on core and pedestal performance
- Ensure sufficient tolerance to control system malfunctions
- Maintain detached divertor during ELM control
- Minimize impact on L-H power threshold
- Obtain ELM control 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

Goal → Obtain ELM Control at Low Rotation Without Locked Modes: Low Rotation Suppression Sometimes Triggers NTMs

- **Applying counter-NBI torque to reduce rotation during suppression sometimes:**
  - Triggers 3/2 NTMs which lock and degraded confinement
  - Produces ELM-like D_α bursts during 3/2 NTMs
- **Interactions between NTMs and RMP fields at low rotation difficult to interpret**
  - More experiments needed



T. Evans, et al., Nucl. Fusion **56** (2008) 015009

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Key ITER ELM Control Requirements Span a Wide Range of Operational Issues

- Minimize divertor heat and particle flux
- Obtain ELM control over Large q_{95} range
- Maintain efficient core pellet fueling
- Control of first ELM after L-H transition
- Minimize impact on core and pedestal performance
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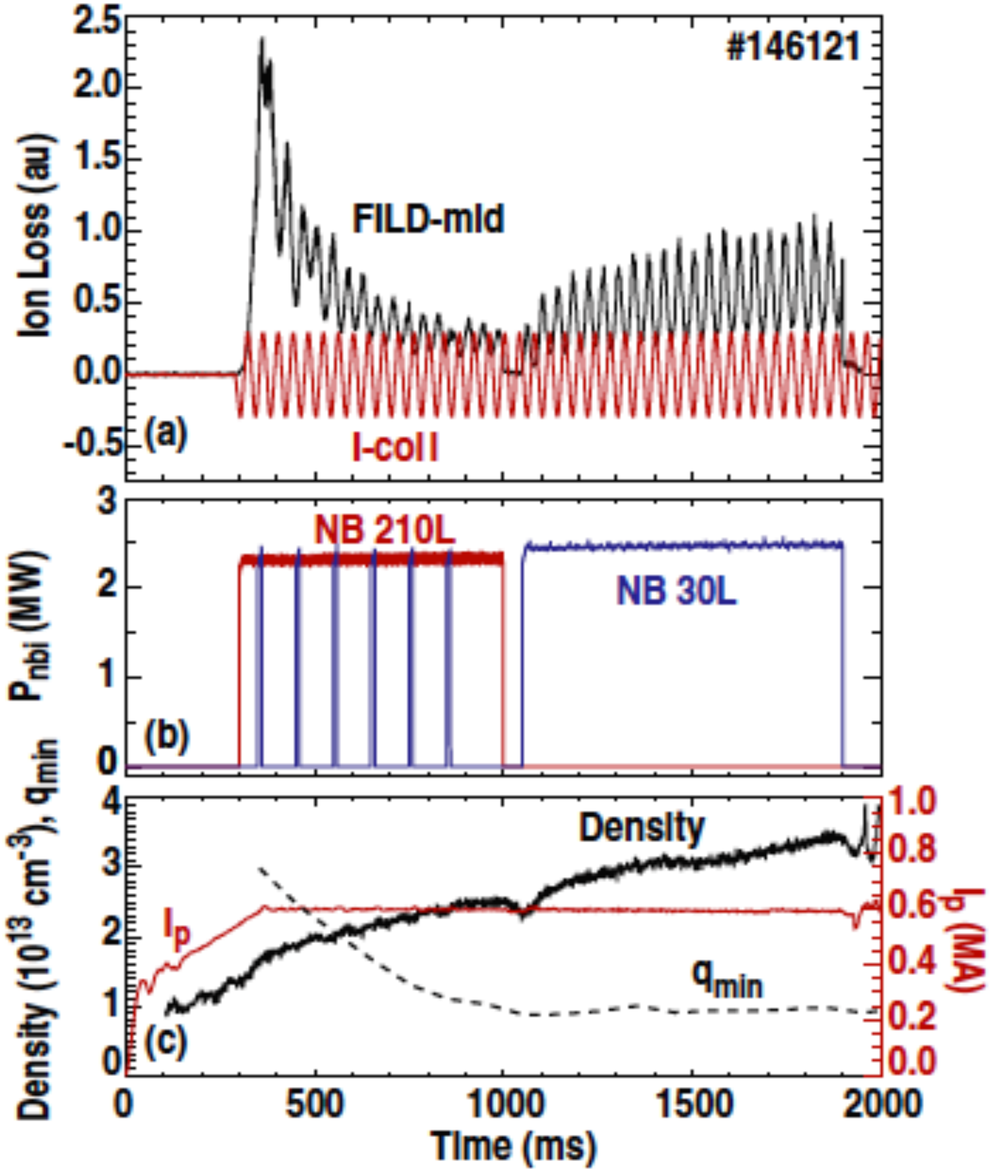
Goal → Minimal Impact on Energetic Particles: Energetic Particle Orbits Perturbed by n = 2 RMP Field

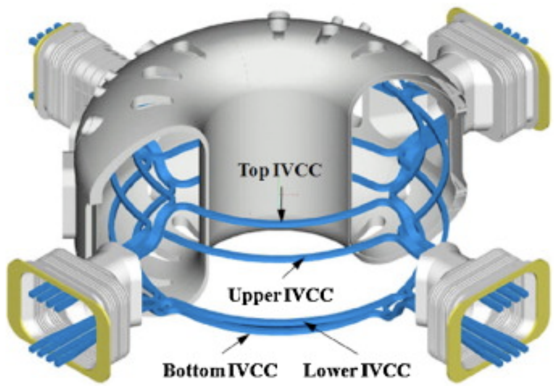
- **Loss of prompt 80 keV NBI ions observed during 25 Hz rotating n = 2 RMP field in L-modes**
  - Fast beam ion losses correlated with Plasma surface modulations
    - Possible affect on beam ion birth profile
- **Confinement improves with current penetration (q_{min} ↘) in (NB 210L) counter-NBI phase**
  - Density increase shifts NBI birth profile



M. Van Zeeland, et al., Plasma Phys. Control. Fusion **56** (2014) 015009

International RMP ELM Control Research is Addressing ITER Issues using Both In-vessel and Ex-vessel Coils

KSTAR



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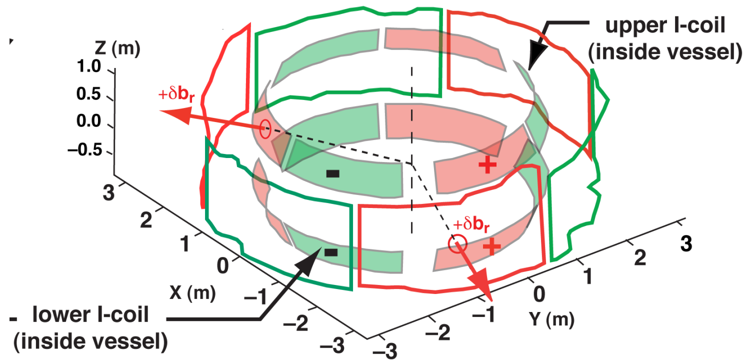
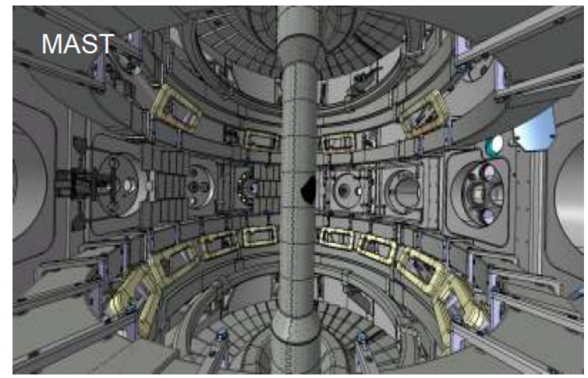
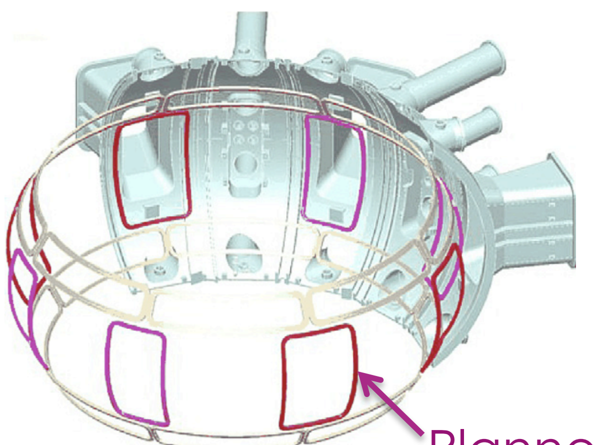


MAST



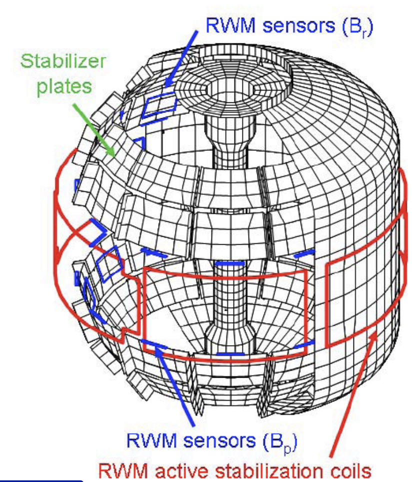
ASDEX-Upgrade



In-vessel RMP coils

JET

NSTX

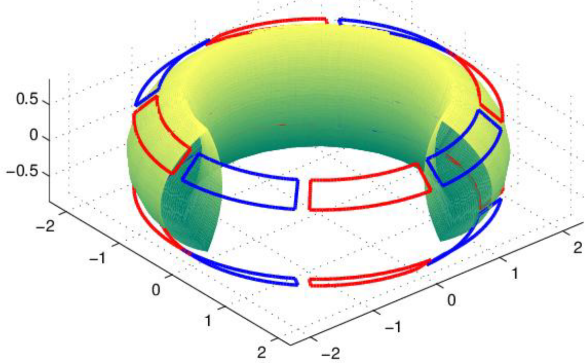


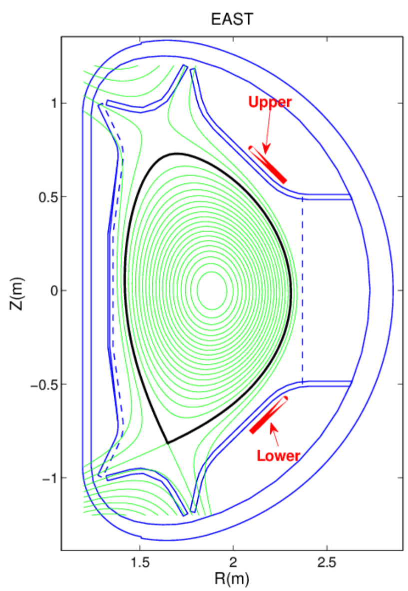
Ex-vessel RMP coils

Results from Machines in Europe and Asia are Contributing to a Rapidly Growing Database of RMP Physics Effects

- **ELM suppression obtained in KSTAR**
  - KSTAR: n = 1 (ϕ = +90°) and n = 2
- **ELM mitigation obtained in JET, AUG, MAST and KSTAR**
  - AUG: n = 1, n = 2 and n = 4, high density (ν_e*)
  - MAST: n = 3, n=4, n = 6 in LSN and DN
  - KSTAR: n = 1 (ϕ = 0°)
- **ELM triggering and ELM enhancement in KSTAR**
  - KSTAR: n = 1

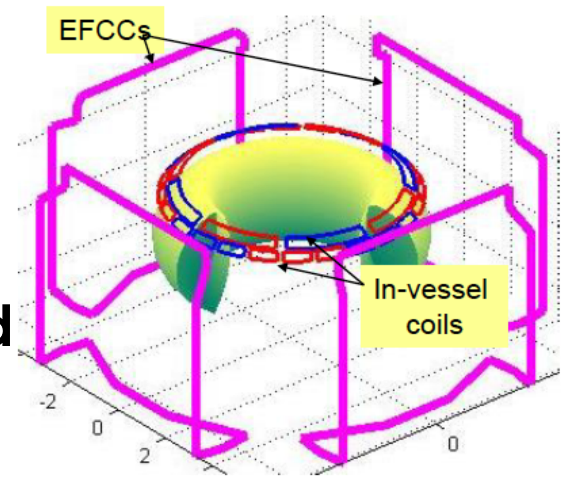
New RMP Experimental Capabilities Continually Being Added or Considered on a Variety of Tokamaks Worlwide





- EAST 3D Experiments start in April

- JET considering a design with 8 upper and 24 mezzanine in-vessel coils
- NSTX proposing a staged 2 x 12 upper and lower in-vessel coil set
- JT60-SA will have 3 x 6 coil array
- TCV considering 3 x 6 coil set
- COMPASS will initially have 4 coils and upgrade to 8 later



Summary

- **ELMs (ΔW_{ELM}) must be mitigated or suppressed to satisfy ITER's mission without triggering costly expenses or delays**
  - Mitigation requires $\Delta W_{ELM}/A_{ELM} \leq 0.5$ MJ/m^2
  - Scaling of the divertor target ELM area (A_{ELM}) with is ΔW_{ELM} uncertain
- **Twelve key operational issues need to be resolved to achieve successful RMP ELM control in ITER**
  - Significant progress made in DIII-D on resolving each of the key operational issues
  - None of these issues have been satisfactorily resolved yet
- **RMP ELM control research in Europe and Asia is contributing to progress in several key areas**

Conclusion

More emphasis on RMP ELM control research is needed in the U.S.

- **Highly focused experiments designed to specifically resolve each of the key ITER operational issues**
- **High priority RMP hardware upgrades**
  - Individually controlled power supplies on each loop of the 3D coil
  - 3D coils designed specifically for ELM control research
- **New and improved 3D diagnostic systems**
- **Development of a 3D coil active feedback control system**
- **Increased theory and modeling funding**
  - Emphasis on validating ELM control models with experimental data