The Physics of Edge Resonant Magnetic Perturbation in Hot Tokamak Plasmas

Presented by
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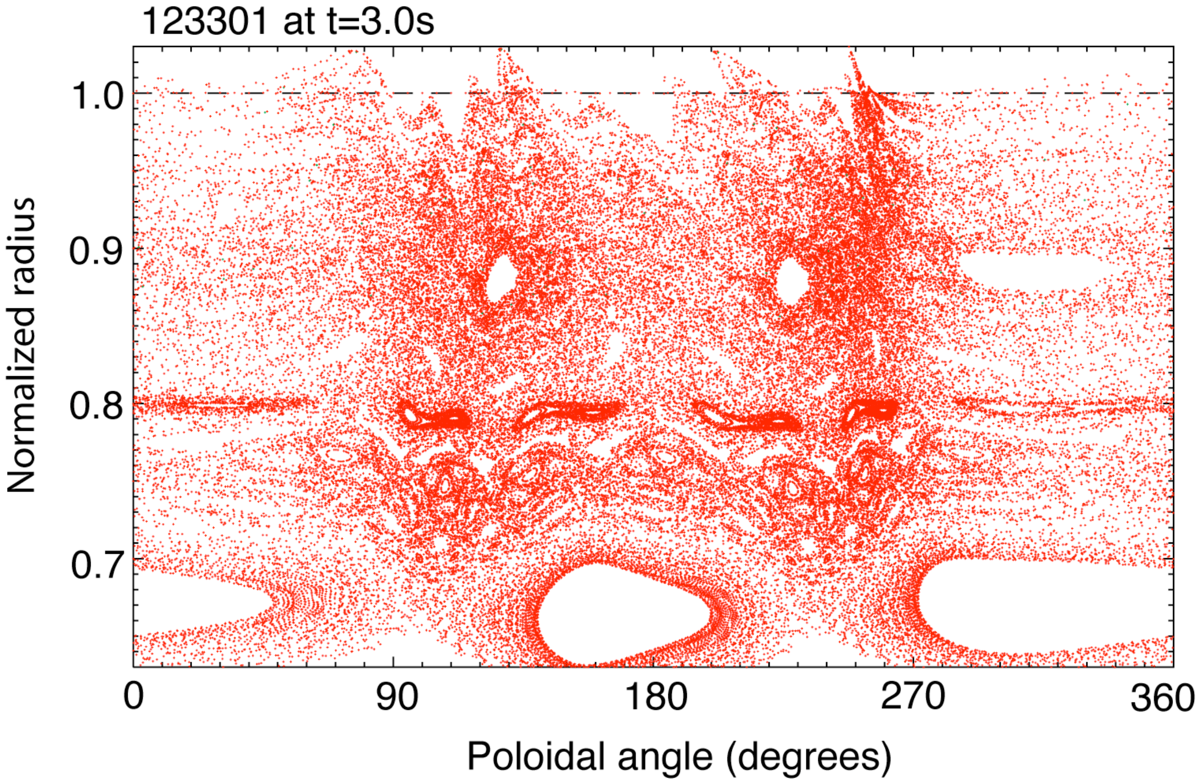

***In collaboration with:**
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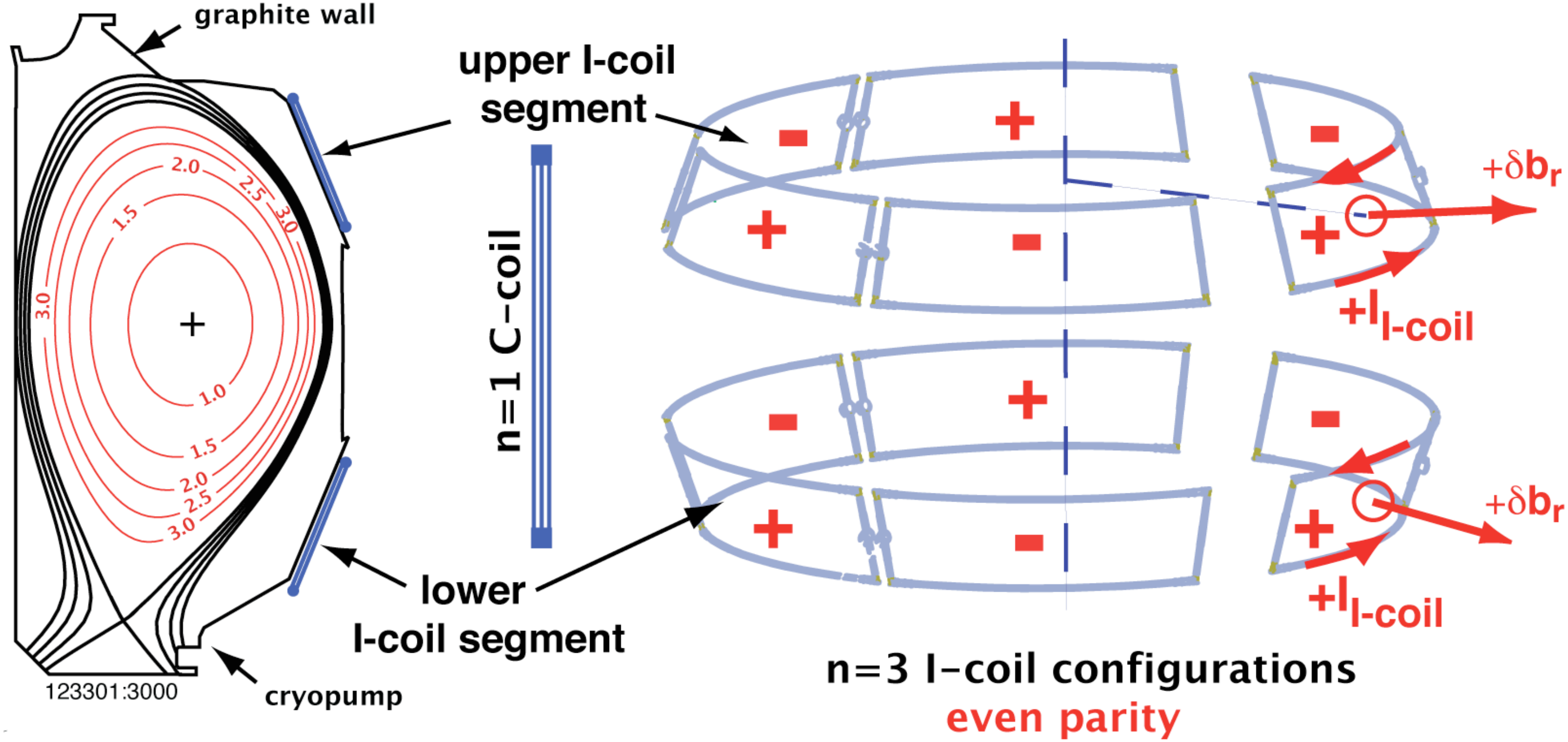
Edge resonant magnetic perturbations: a promising approach for pedestal control in burning plasmas

- Small edge *Resonant Magnetic Perturbations* (*RMPs*) used to:
  - Control pedestal profiles in high confinement plasmas
    - ∇p control → edge bootstrap current (j_{edge})control?
- Type-I ELMs completely eliminated in low collisionality (ν_e*) burning plasma relevant conditions:
  - Consistent with peeling-ballooning ∇p, j_{edge} stabilization for all cases tested to date
  - ∇p (j_{edge} ?) operating point controlled with *RMP* coil current
- ∇p changes primarily due to increased particle rather than energy transport:
  - Challenges stochastic transport theory
  - Suggests particle convection dominates stochastic open field thermal conduction in low ν_e* pedestal plasmas

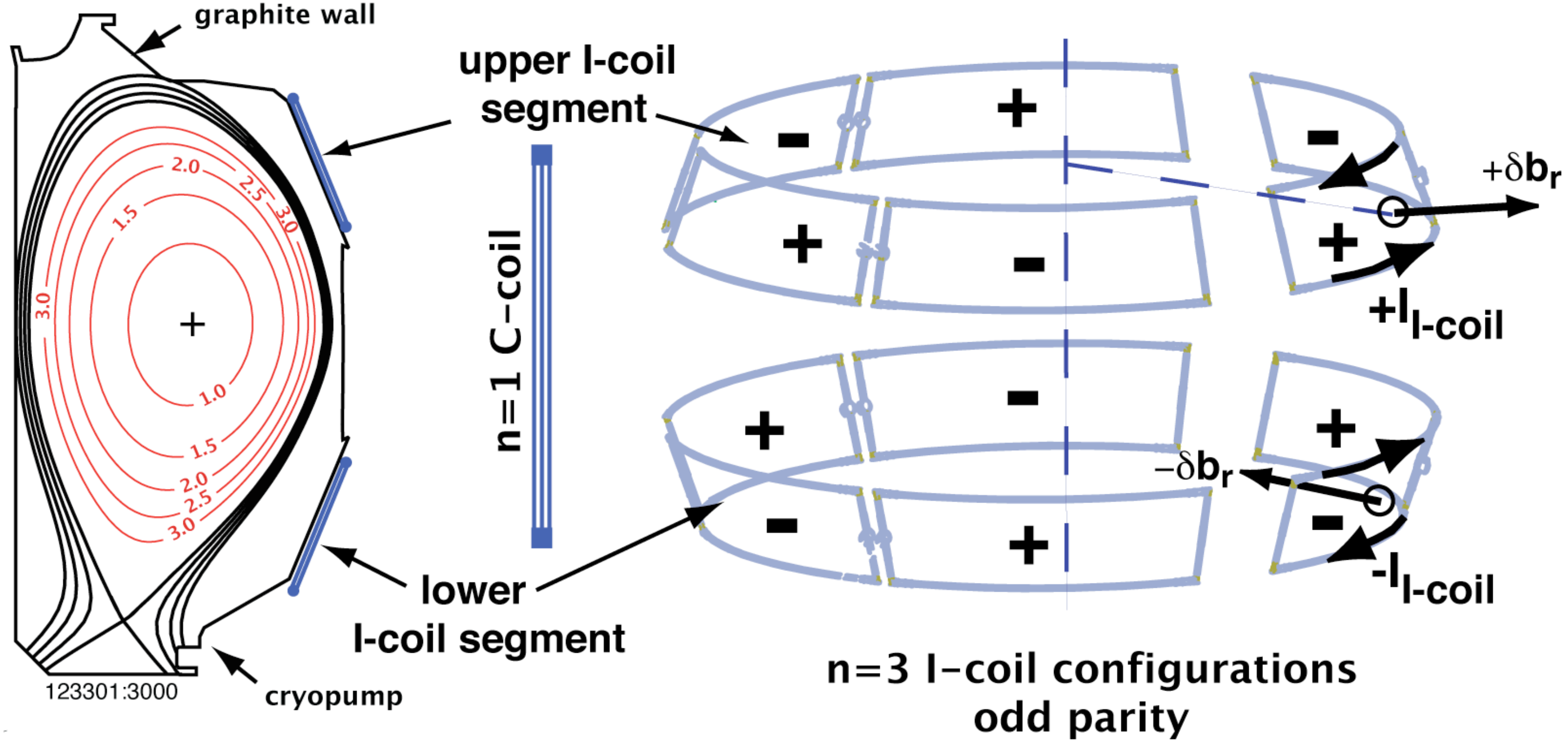
The DIII-D I-coil produces a variety of edge localized resonant magnetic perturbations (*RMPs*)



n=3 I–coil configurations
even parity

- Flexible control of poloidal (m) spectrum with n=3, **even** parity

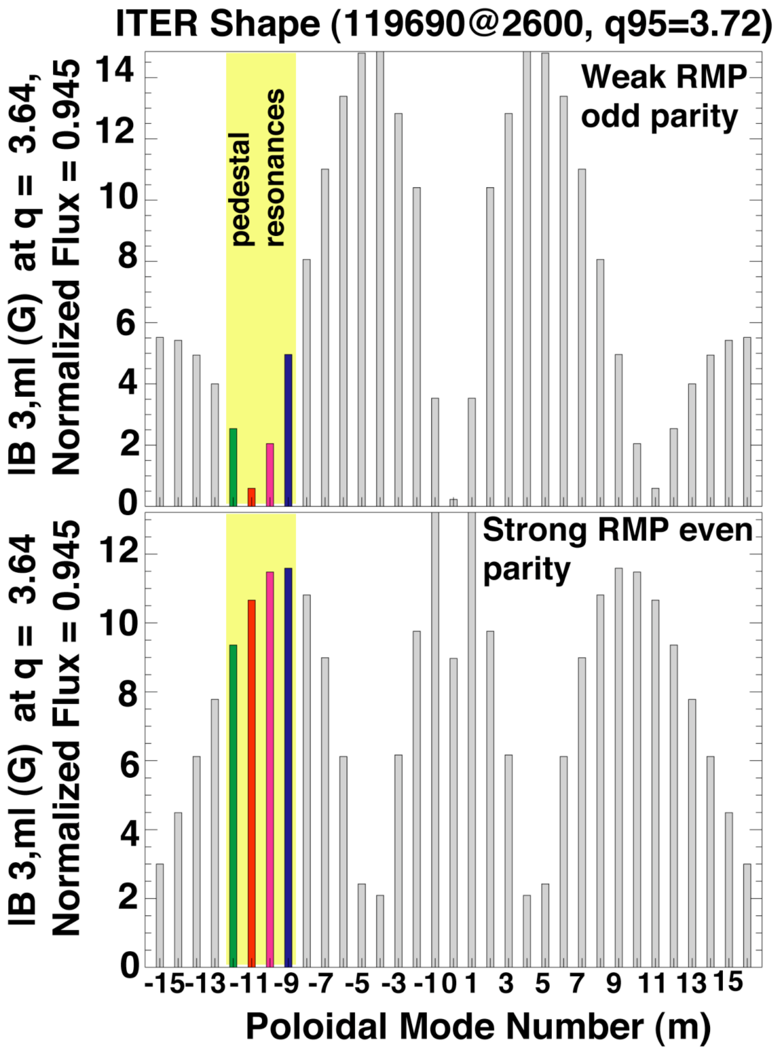
The DIII-D I-coil produces a variety of edge localized resonant magnetic perturbations (*RMPs*)



n=3 I–coil configurations
odd parity

- Flexible control of poloidal (m) spectrum with n=3, **even** and **odd** parity

I-coil parity sets maximum pedestal *RMP* amplitude



ITER Shape (119690@2600, q95=3.72)

2004 Results:

odd parity → weak edge *RMP*

$\delta b_r/B_T \sim 2\times10^{-5}$ ~ size of field-errors

ELMs suppressed by increasing fluctuations

little or no profile changes

high collisionality (ν_e*)

New 2005 Results:

even parity → strong edge *RMP*

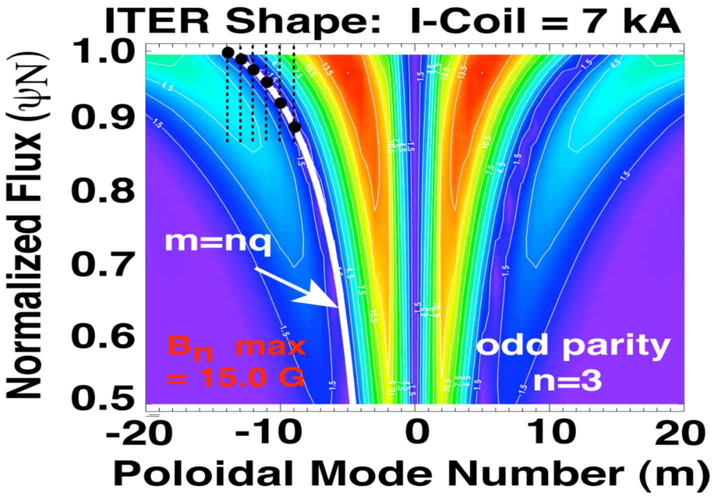
$\delta b_r/B_T \sim 3\times10^{-4}$ ~ 10-20× size of field-errors

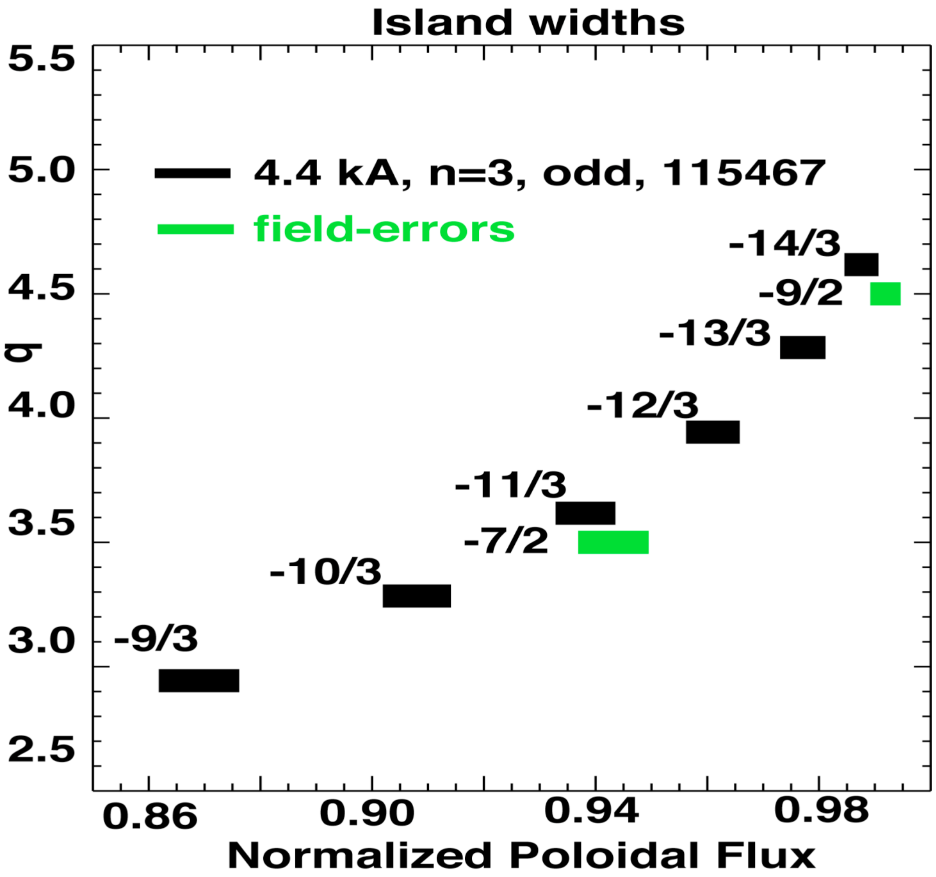
→ ELMs eliminated by controlling ∇p

low collisionality (ν_e*)

first burning plasma relevant experiments

I-coil parity controls pedestal island overlap

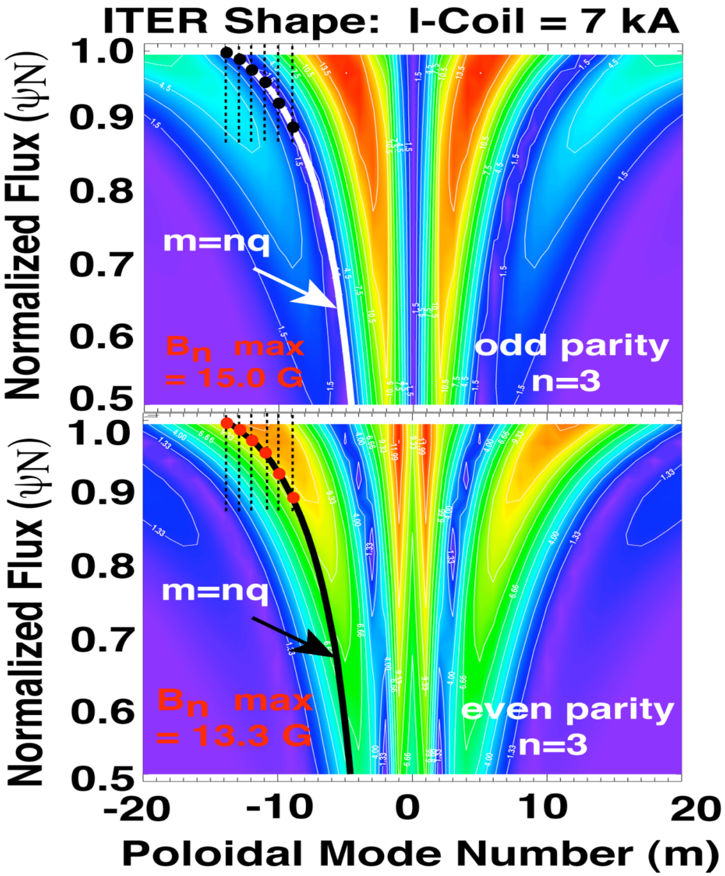


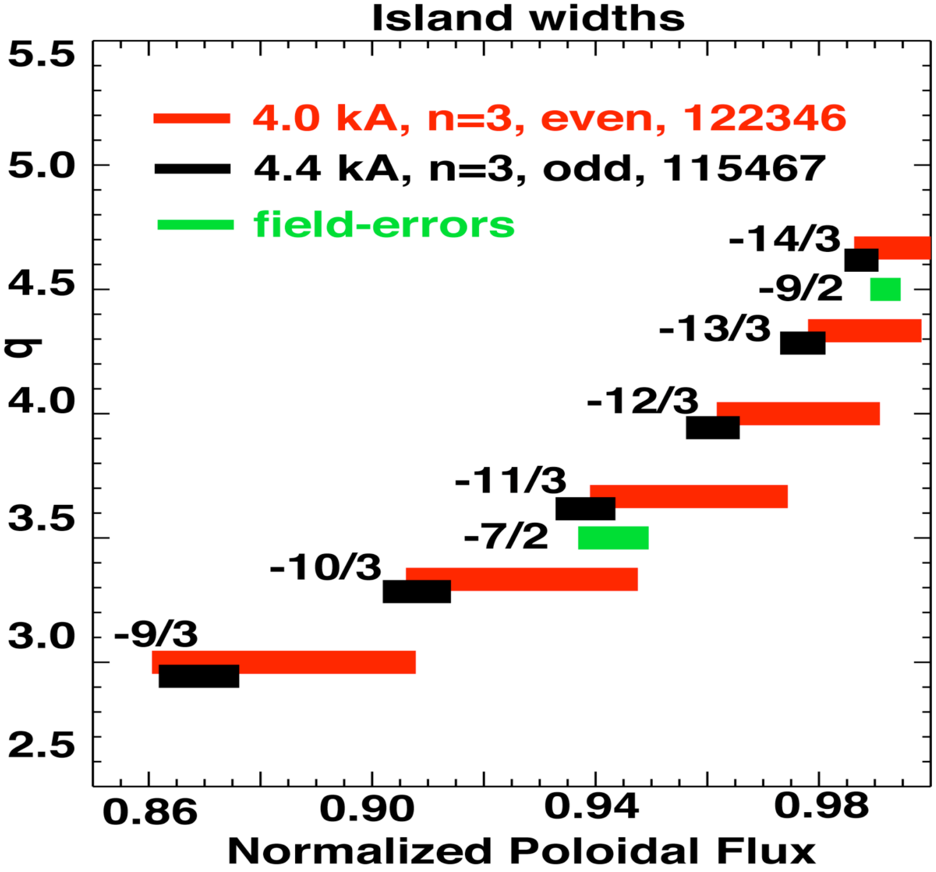


- Both parities suppress ELMs
  - Odd (weak *RMP*) → small islands → little or no change in pedestal

Odd parity, high ν_e^* (119690)

I-coil parity controls pedestal island overlap

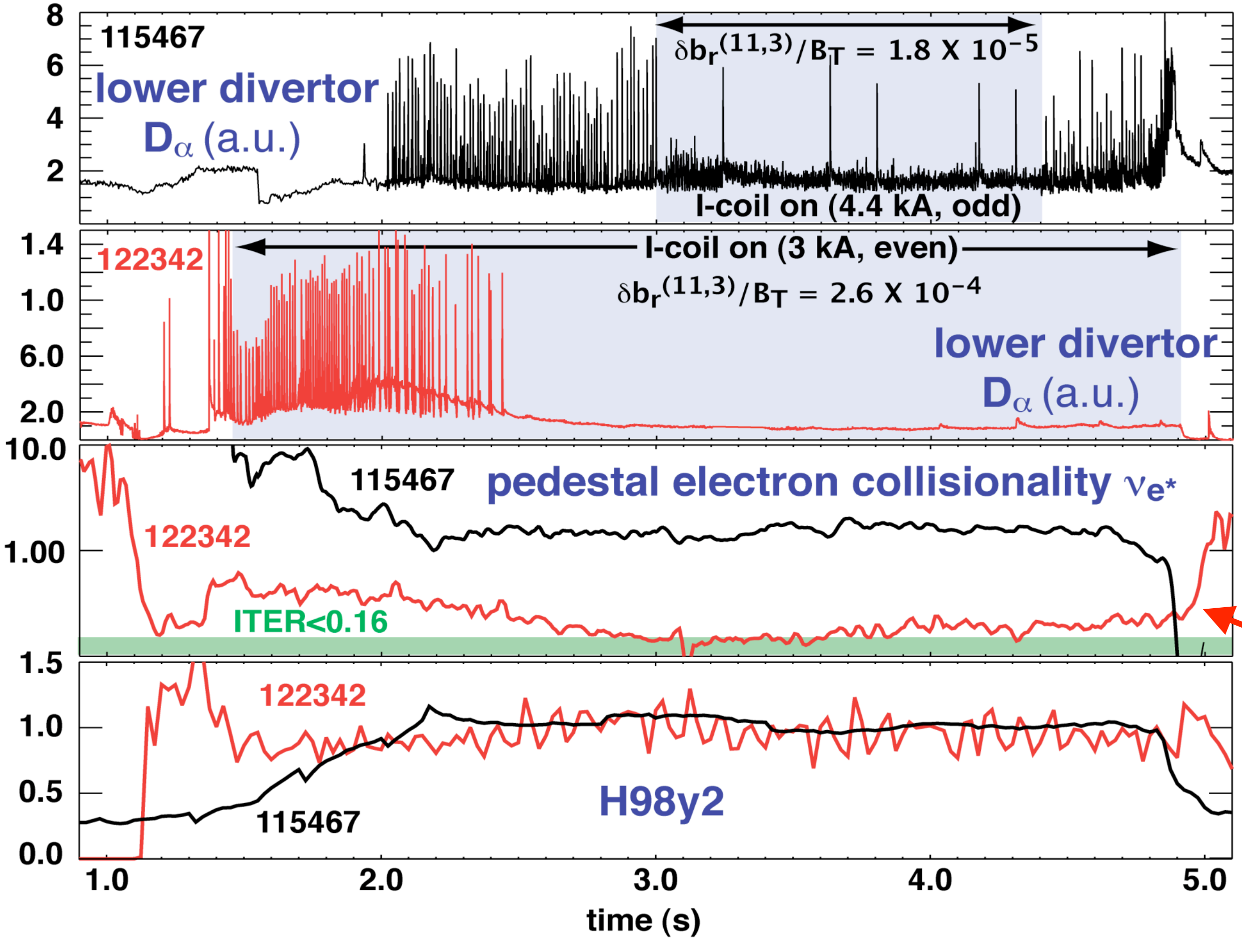




- Both parities suppress ELMs
  - Odd (weak *RMP*) → small islands → little or no change in pedestal
  - Even (strong *RMP*) → stochastic → transport / pedestal control

Odd parity, high ν_e^* (119690) and parity, low ν_e^* (122346)

Strong *RMP* configuration results in long quiescent ELM-free H-modes at ITER ν_e* operating point



2004: weak edge *RMP* (odd parity) results -
→ Some intermittent ELMs remain

New 2005: strong edge *RMP* (even parity) results
→ ELMs completely eliminated at low ν_e*

ν_e* at burning plasma target in strong (even parity) edge *RMP* case

- With ν_e* < 0.2 ELMs are eliminated for 2.6 s (~17τ_E) - limited only by hardware constraints

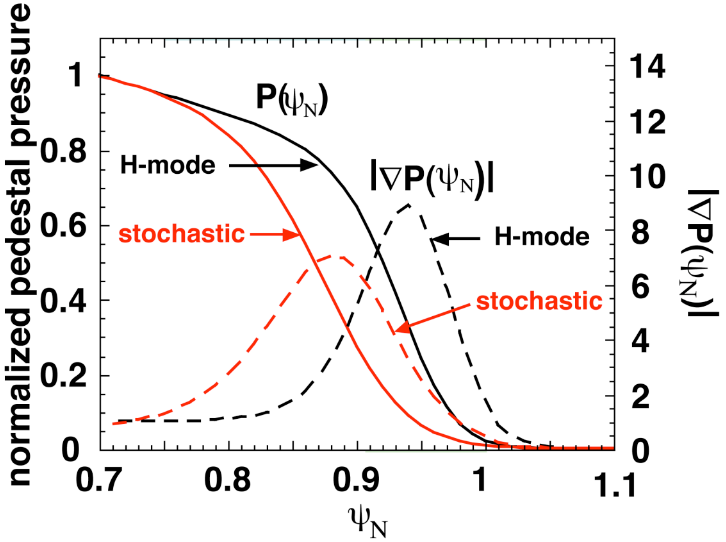
See: BO3.00008 - R. Moyer, et al.
and CP1.00003 - M. Fenstermacher, et al

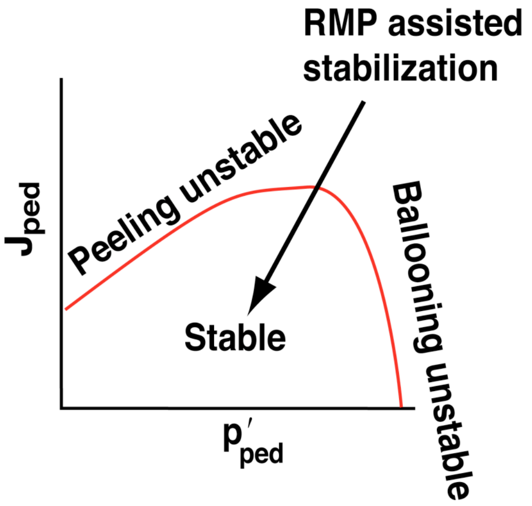
Original ELM control concept: *RMP* → stochasticity → increased energy transport → ELM stabilization

- Edge *RMP* → stochastic magnetic field across pedestal:
  - Increased electron energy transport → reduced pedestal T_e → reduced pedestal pressure gradient

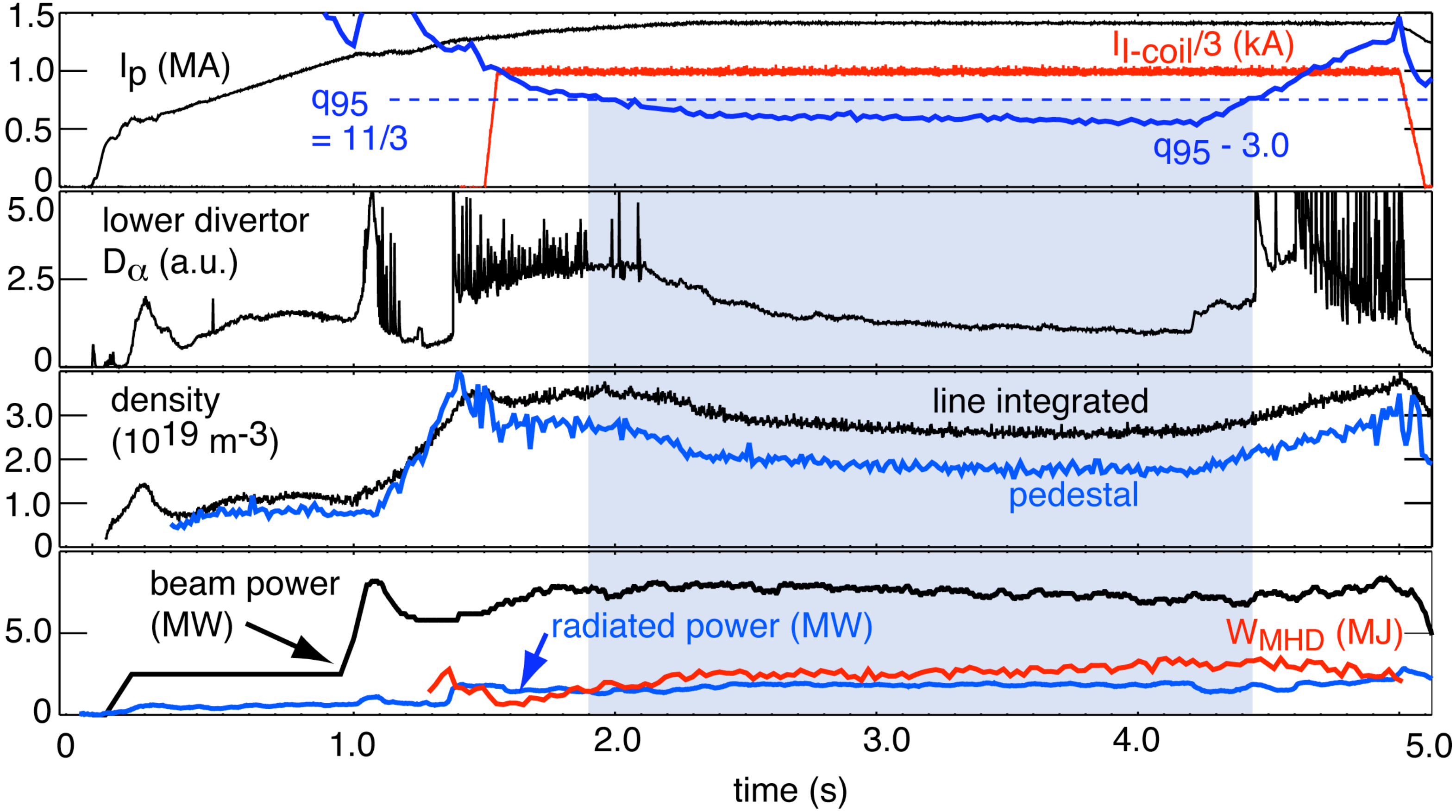
- Reduced pedestal pressure gradient → stable peeling-ballooning operating point
  - Operating point controlled with *RMP* amplitude
  - Maintain good H-mode confinement (wider T_e pedestal: comparable height)

- ELM impulses eliminated





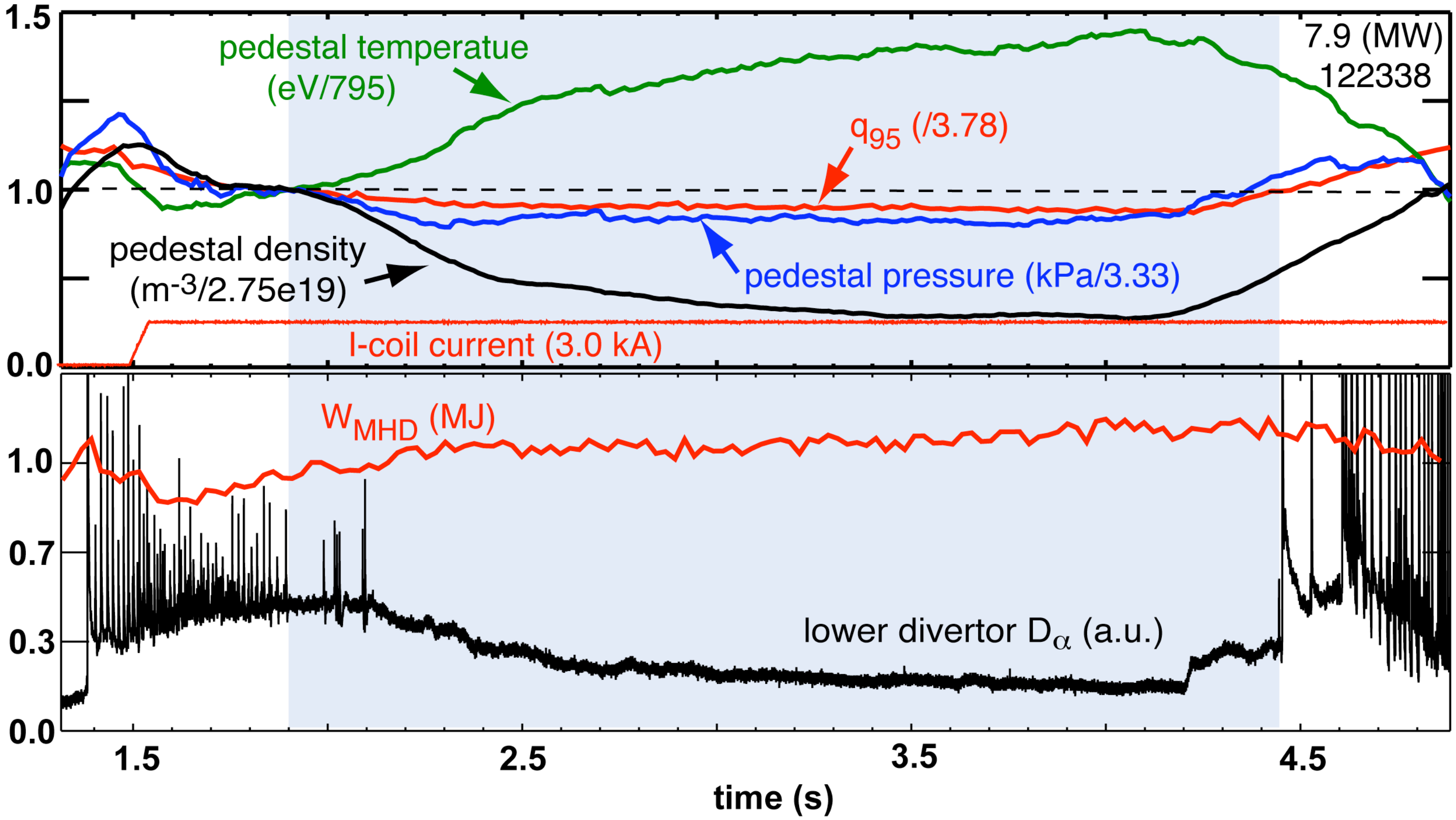
I-coil *RMPs* have the largest effect on pedestal and ELMs inside resonant window $11/3 \le q_{95} \le 7/2$



- NBI heating power, total radiated power and stored energy (W_{MHD}) remain relatively constant inside q_{95} resonant window

Even parity, low ν_e*, 7.9 MW (122338)

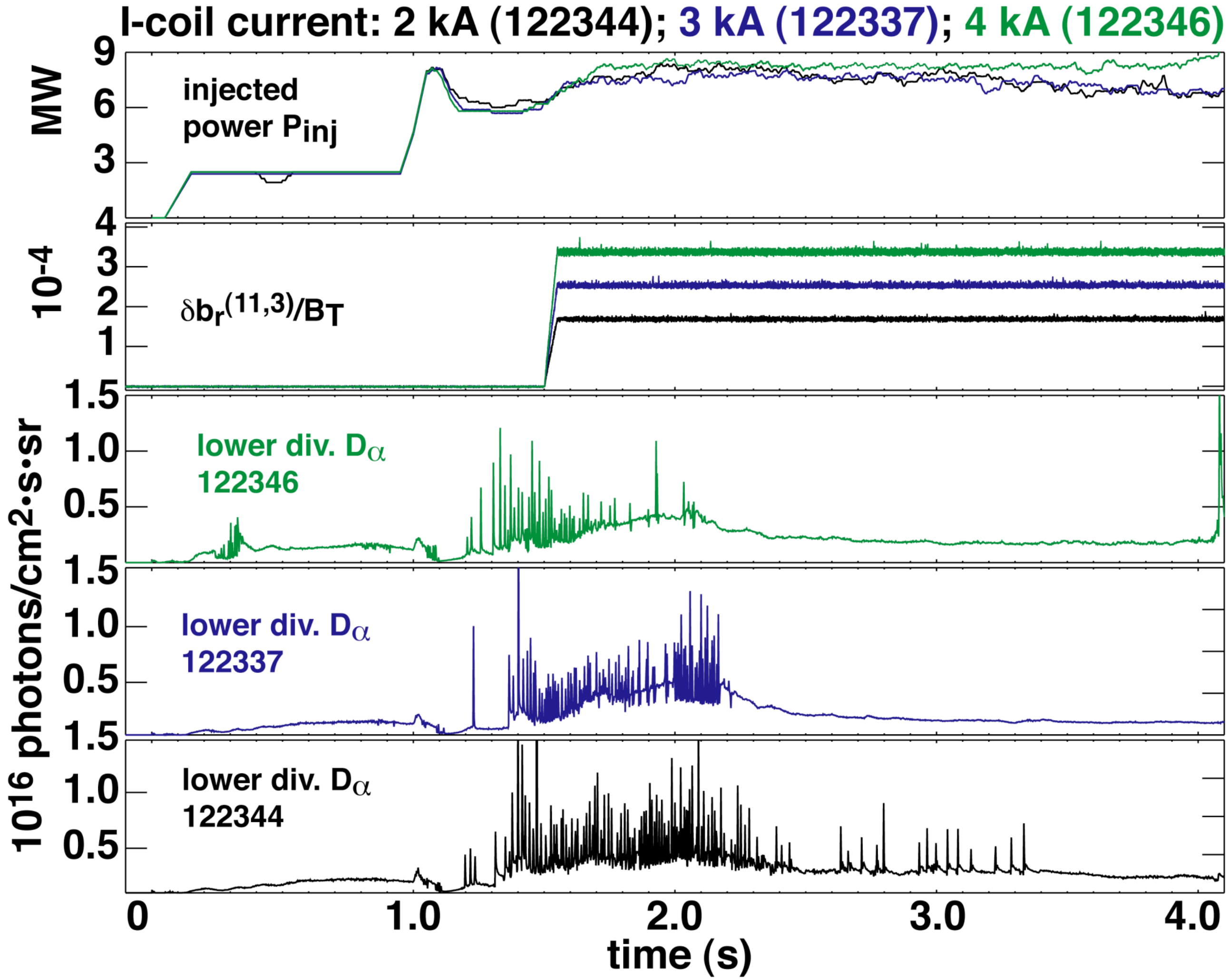
$T_{e,ped}$ increase with $n_{e,ped}$ decrease contradicts original expectation but ELMs are eliminated



- Energy confinement, stored energy (W_{MHD}), relatively unaffected by *RMP*
  - ELMs suppressed and particle confinement reduced when $q_{95} \leq 3.78$

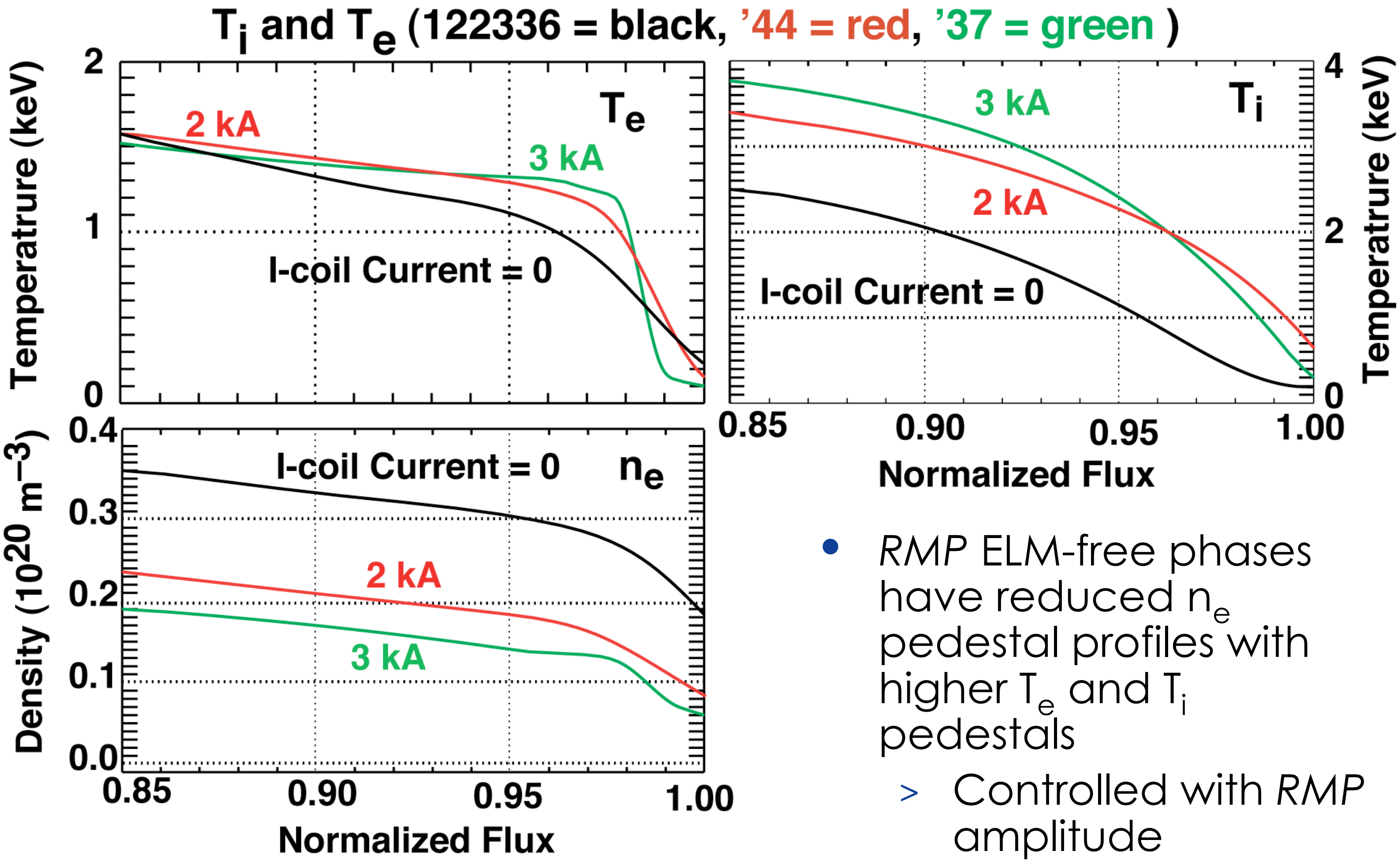
Even parity, low ν_e^*, 7.9 MW (122338)

ELMs completely eliminated above RMP amplitude threshold



Even parity, low ν_e^*, 2kA, 3 kA and 4 kA

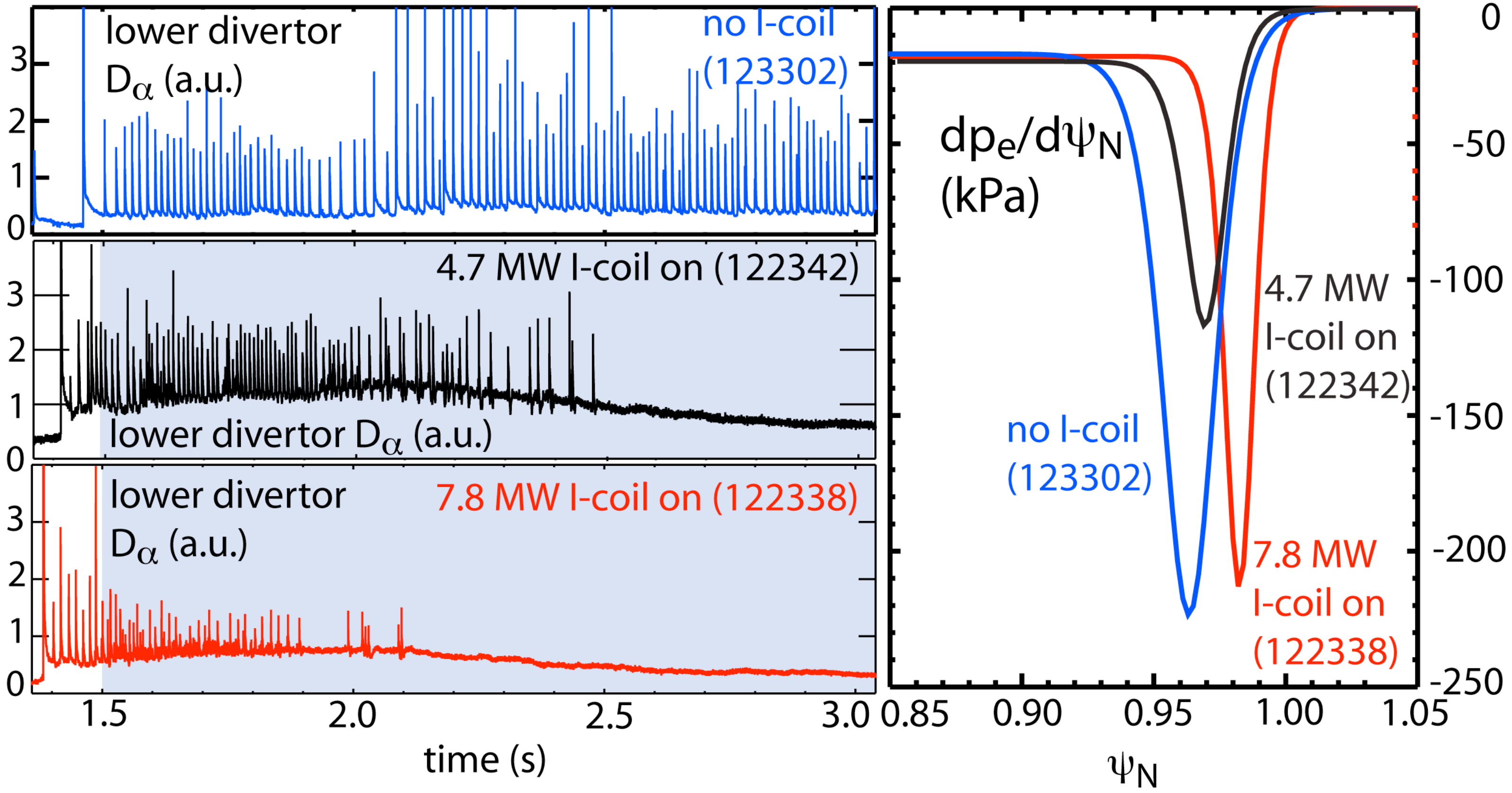
RMP controls pedestal without destroying H-mode



- *RMP* ELM-free phases have reduced n_e pedestal profiles with higher T_e and T_i pedestals
  - Controlled with *RMP* amplitude

Even parity, low ν_e^*, 0 kA, 2kA and 3 kA

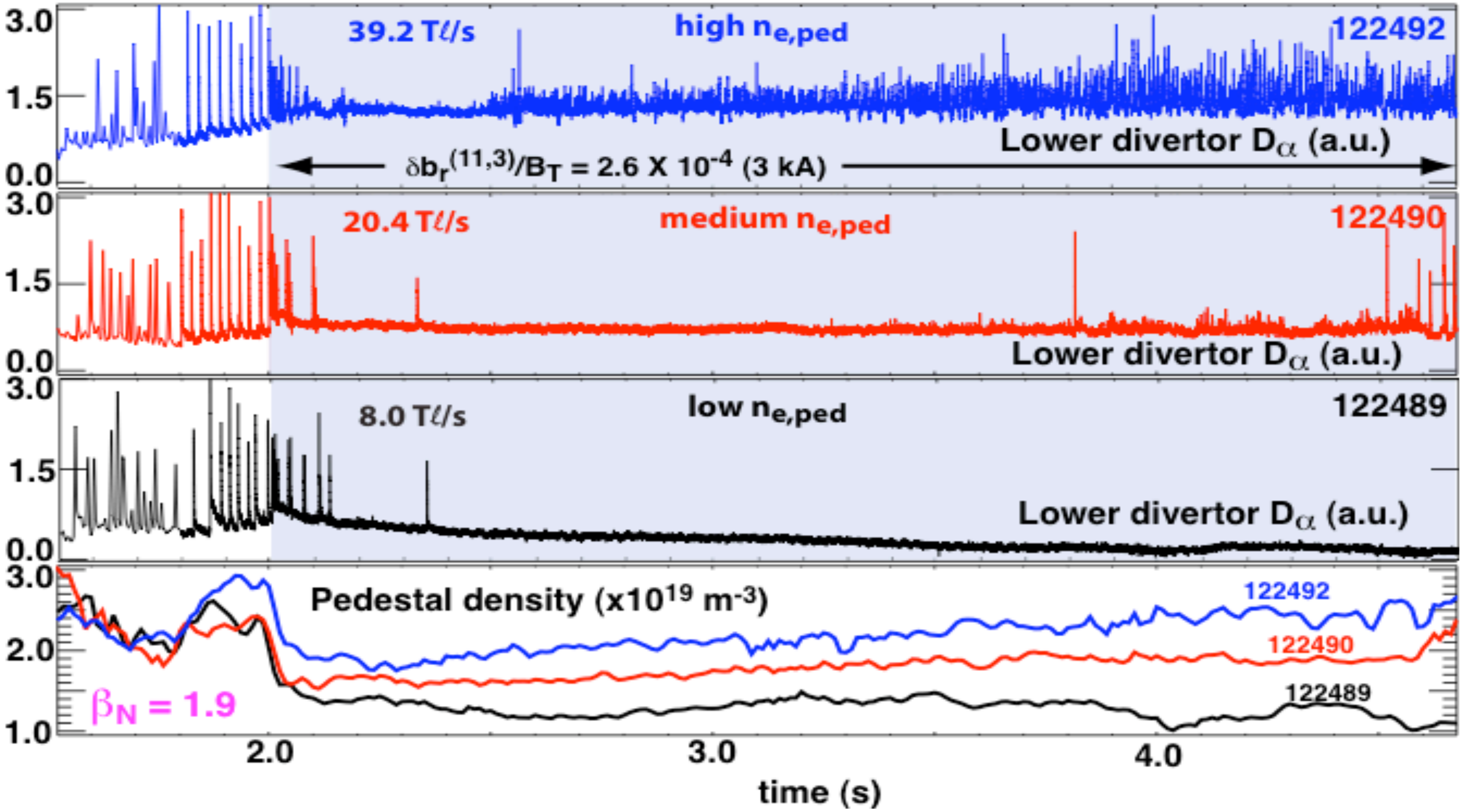
The amplitude, width and radial position of the pedestal ∇p_e are controlled with the *RMP* and P_{NBI}



- Complete ELM suppression is obtained with ∇p_e comparable to that in ELMing plasmas but narrower and shifted outward

Even parity, low ν_e*, no I-coil (123302),
4.7 MW (122342) and 7.9 MW (122338)

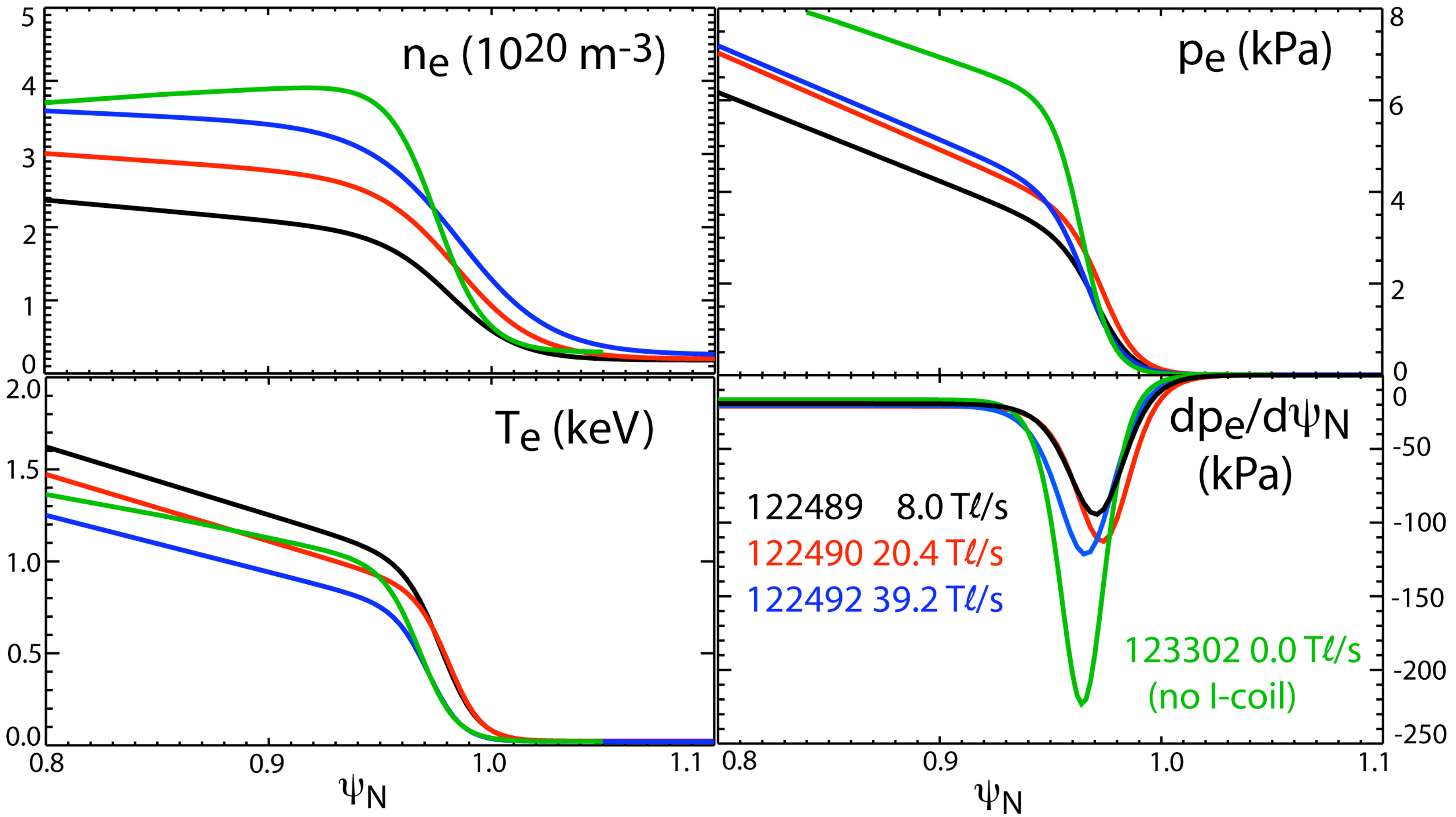
ELMs eliminated below a critical pedestal density



- Small, high frequency ELMs return as pedestal n_e increases
  - Similar to previous weak *RMP* (odd parity) with high n_e and ν_e*

Even parity, low ν_e*, high, medium and low $n_{e,ped}$
See: CP1.00008 - J. Watkins, et al.

$n_{e,ped}$ increases with increased fueling rate while ∇n_e, ∇T_e , ∇p_e remain approximately constant

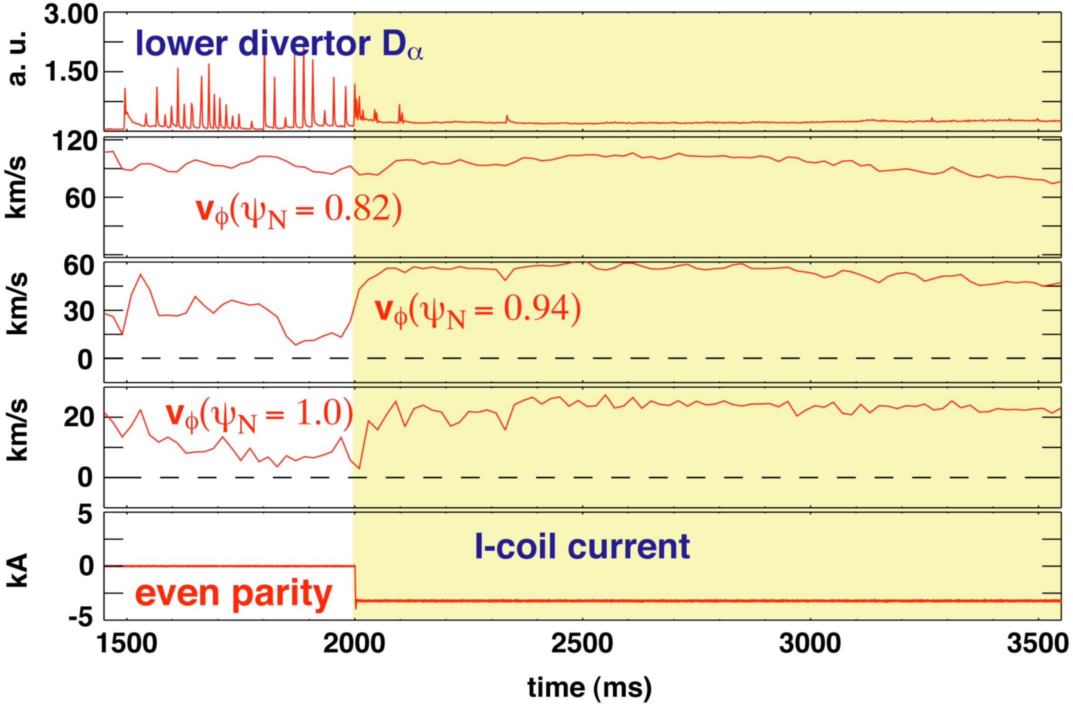


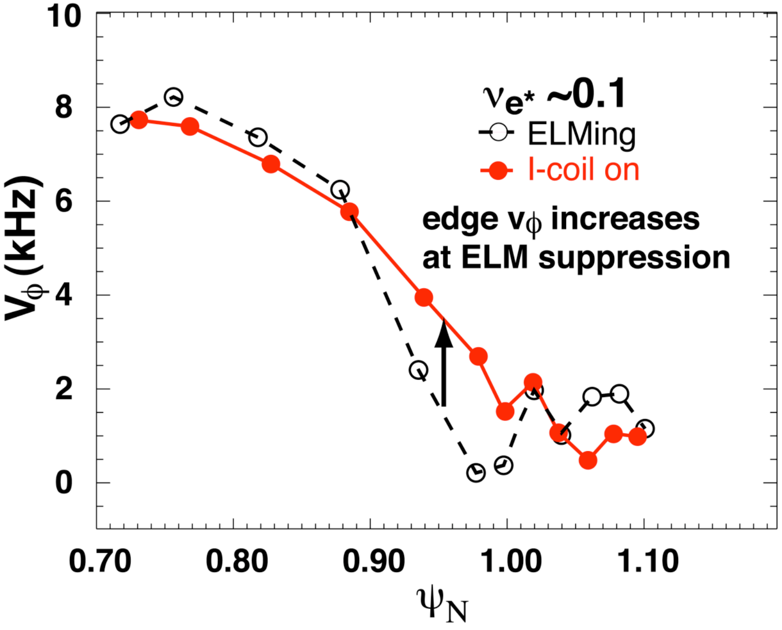
- $n_{e,ped}$ increases while $T_{e,ped}$ decreases → ν_e*~constant

Even parity, low ν_e*, high, medium and low $n_{e,ped}$

Edge rotation increases in low ν_e* *RMP* ELM-free phase

even parity/low ν_e*: 122490

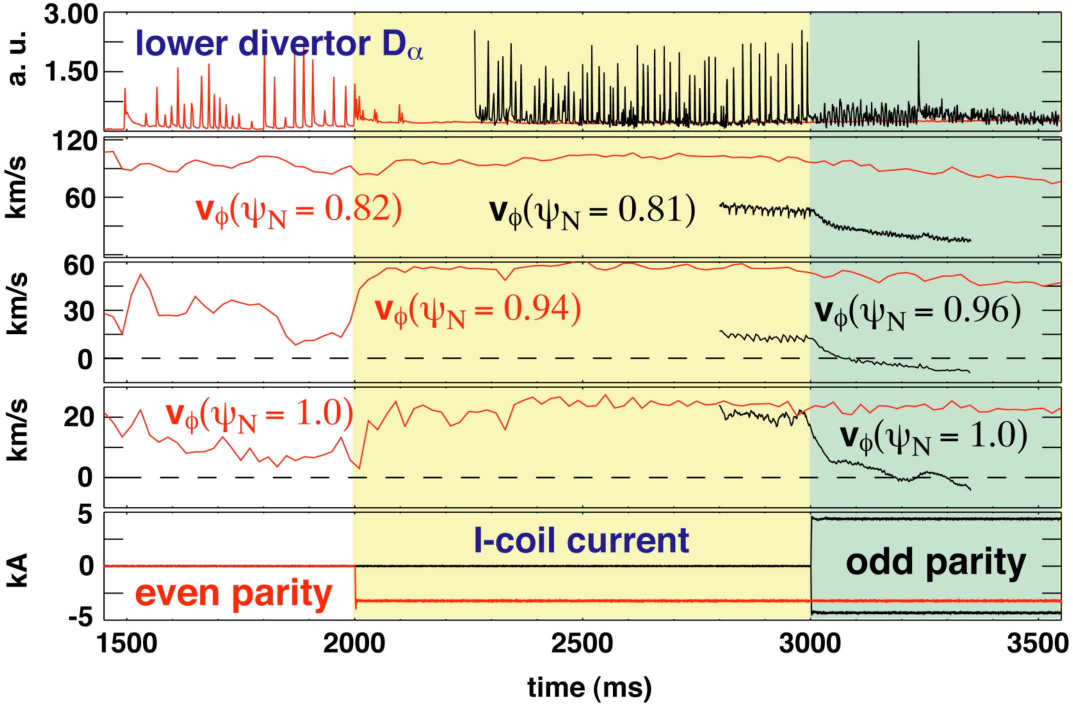


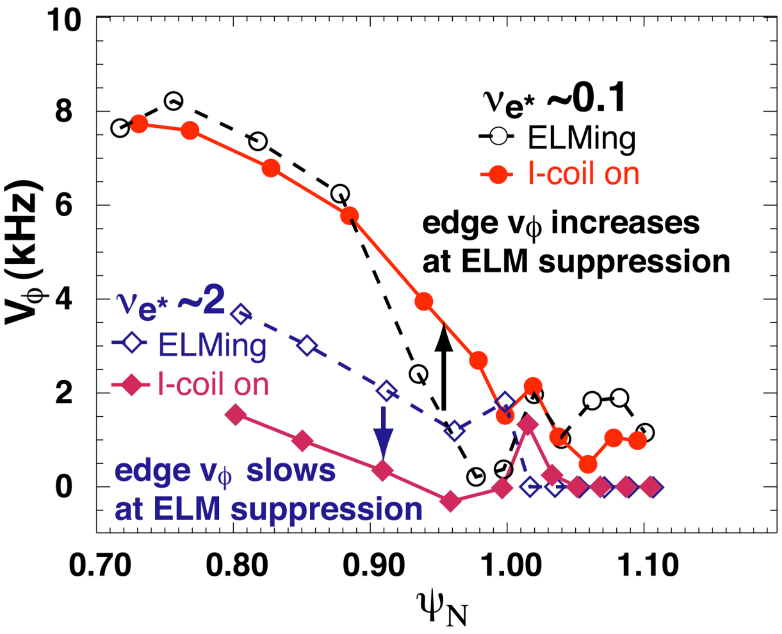


- Performance preserved in low ν_{e*} (high *RMP*) cases

Edge rotation increases in low ν_{e*} RMP ELM-free phase

even parity/low ν_e*: 122490 **odd parity/high ν_e*: 115467**

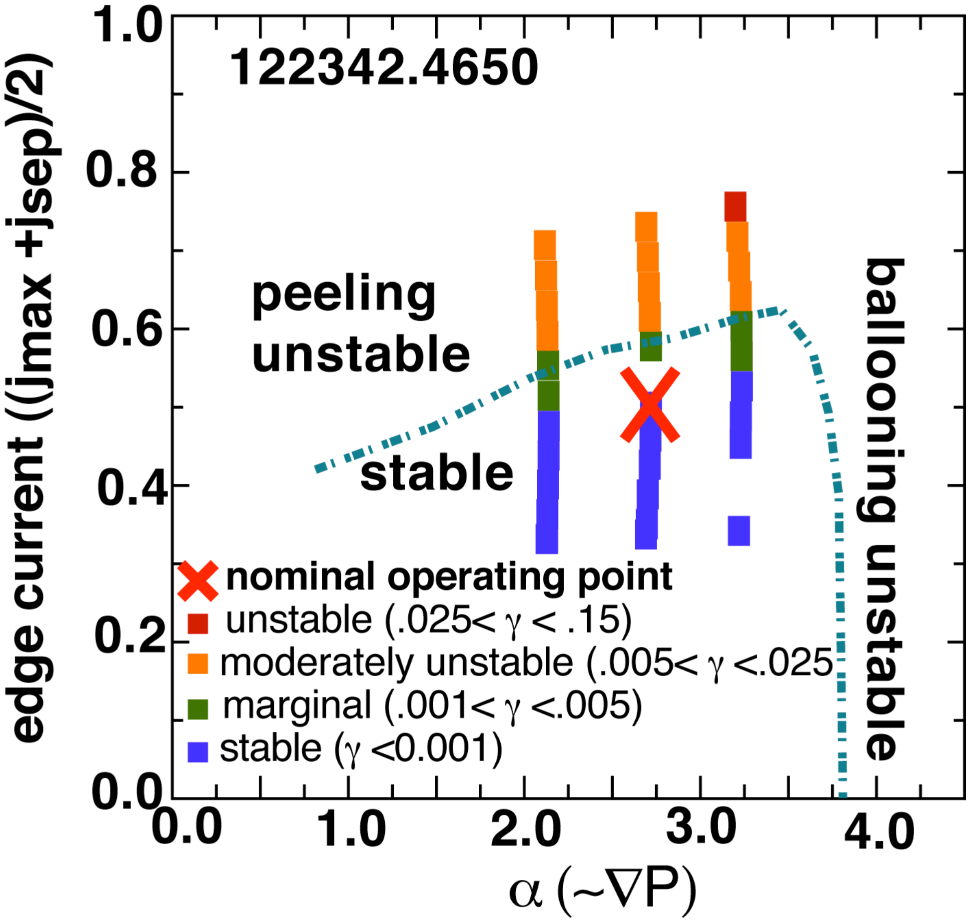




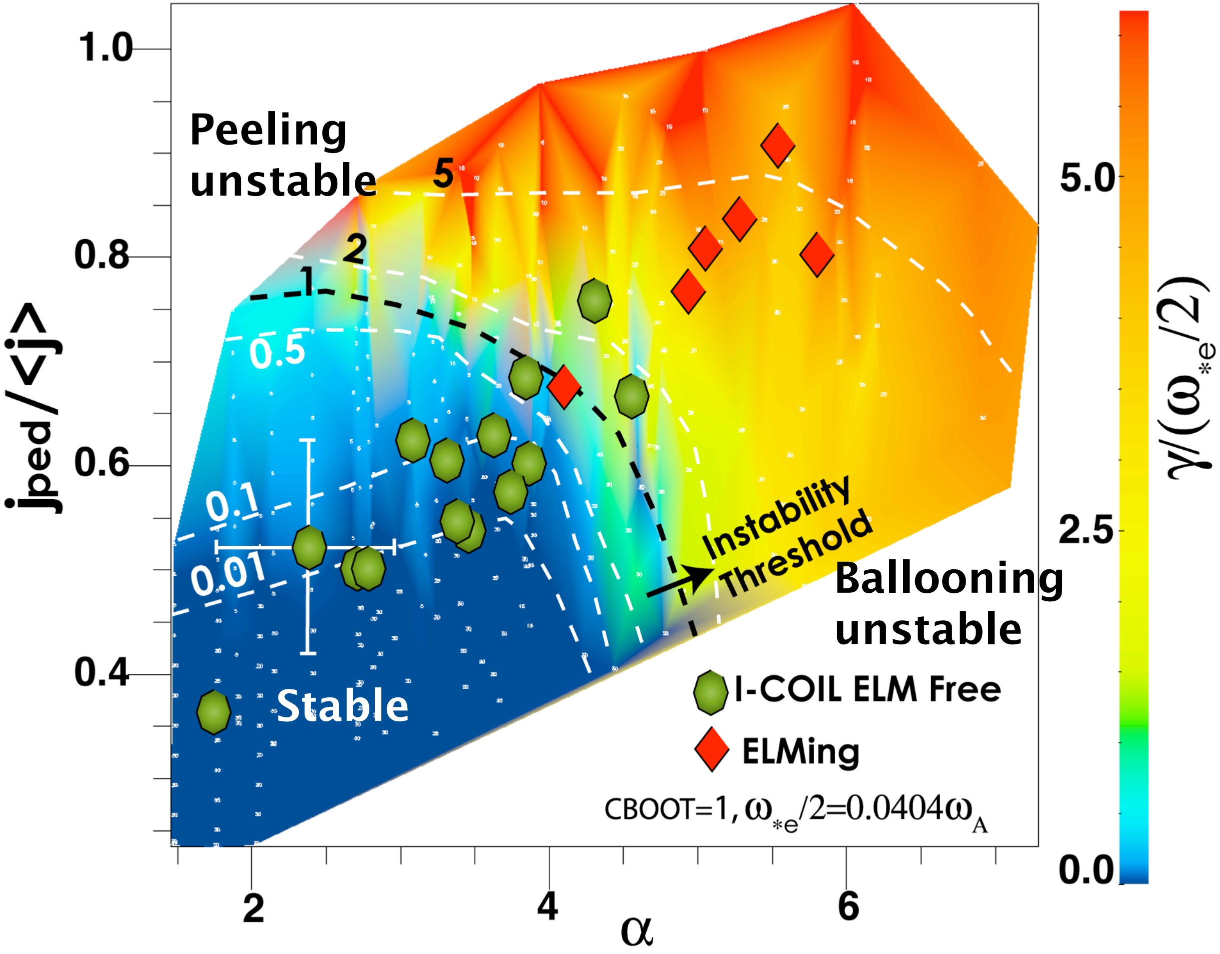
- Performance preserved in low ν_{e*} (high *RMP*) cases
- Previous high ν_{e*} (weak *RMP*, odd parity) cases had a large decrease in rotation

RMP ELM-free H-modes can be operated well away from the ELM instability boundary

- P-B Model: ELMs triggered by pedestal pressure gradient and current driven MHD modes
  - ELMing discharges go unstable across the ballooning or coupled P-B regions
- Stable RMP ELM-free point X well inside both the peeling and ballooning instability boundaries

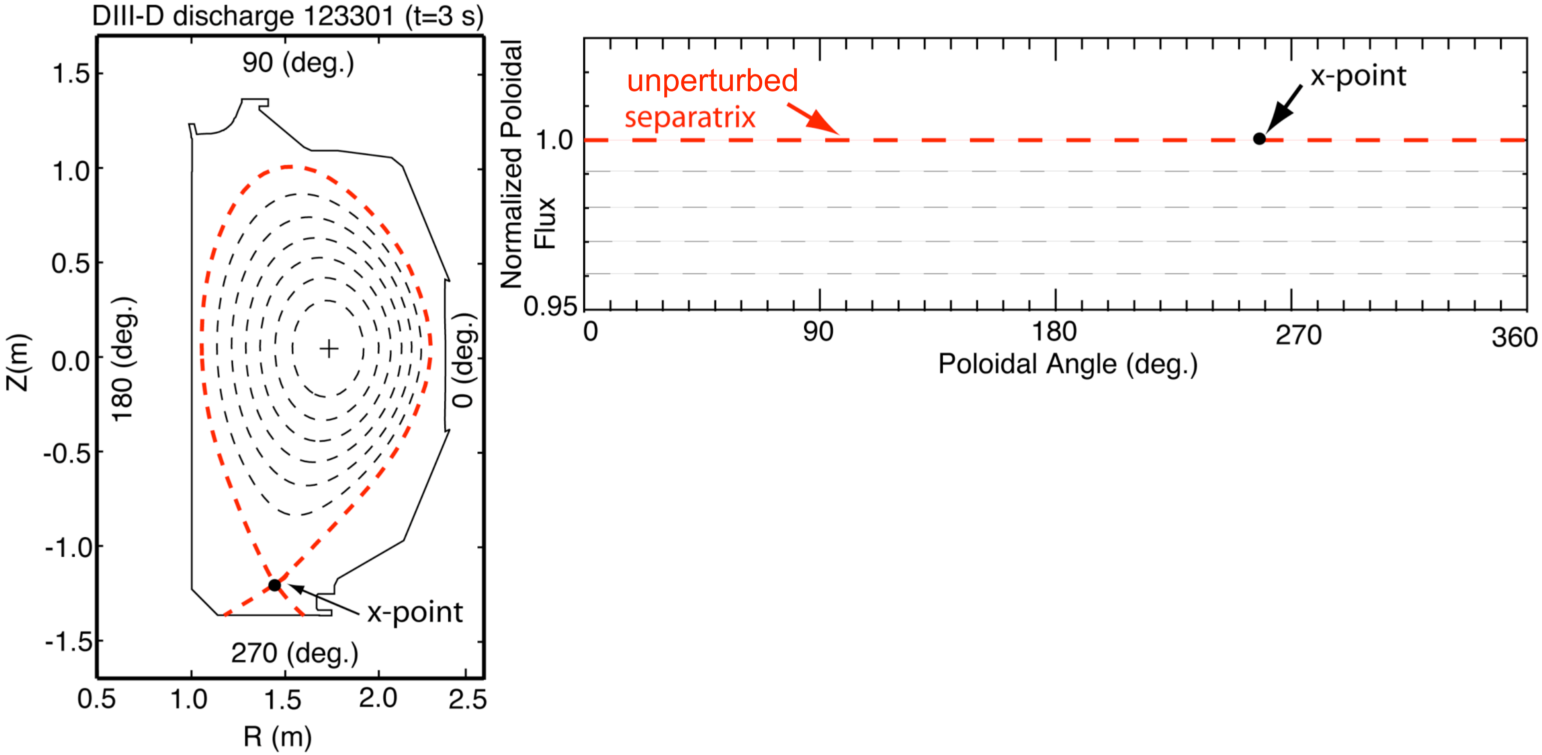


RMP ELM-free H-modes can be pushed deep into stable region by increasing the *RMP* amplitude



See T. H. Osborne, et al., 05 EPS (P4.012)

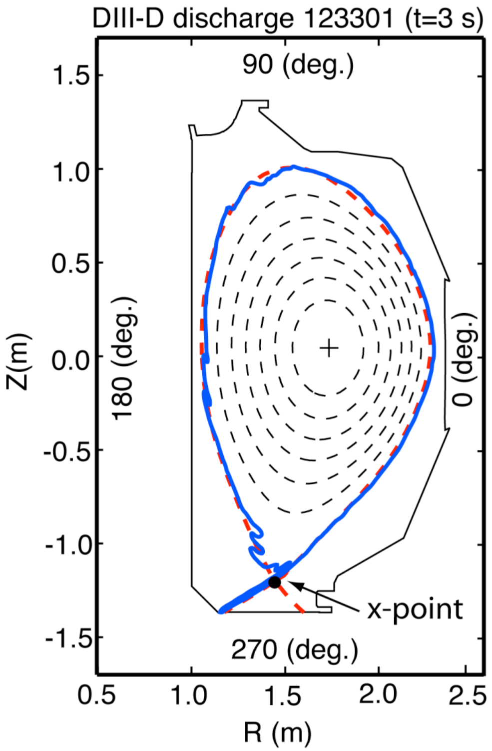
Small edge *RMPs* significantly alter the magnetic topology of the pedestal

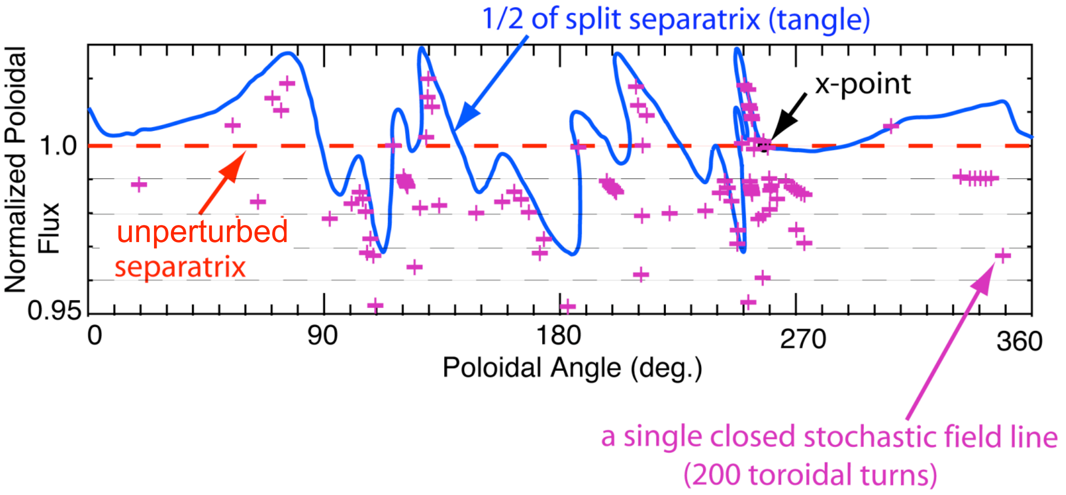


TRIP3D code results:
no plasma response

- Ideal axisymmetric separatrix and flux surfaces are smooth

Small edge *RMPs* significantly alter the magnetic topology of the pedestal





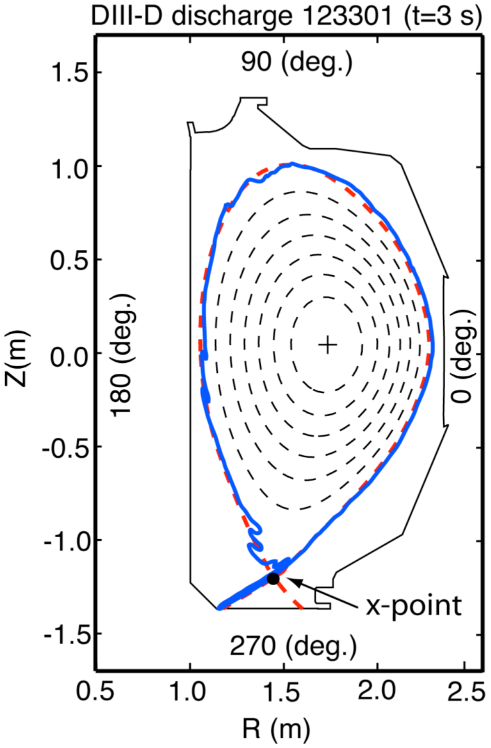
a single closed stochastic field line (200 toroidal turns)

TRIP3D code results:
no plasma response

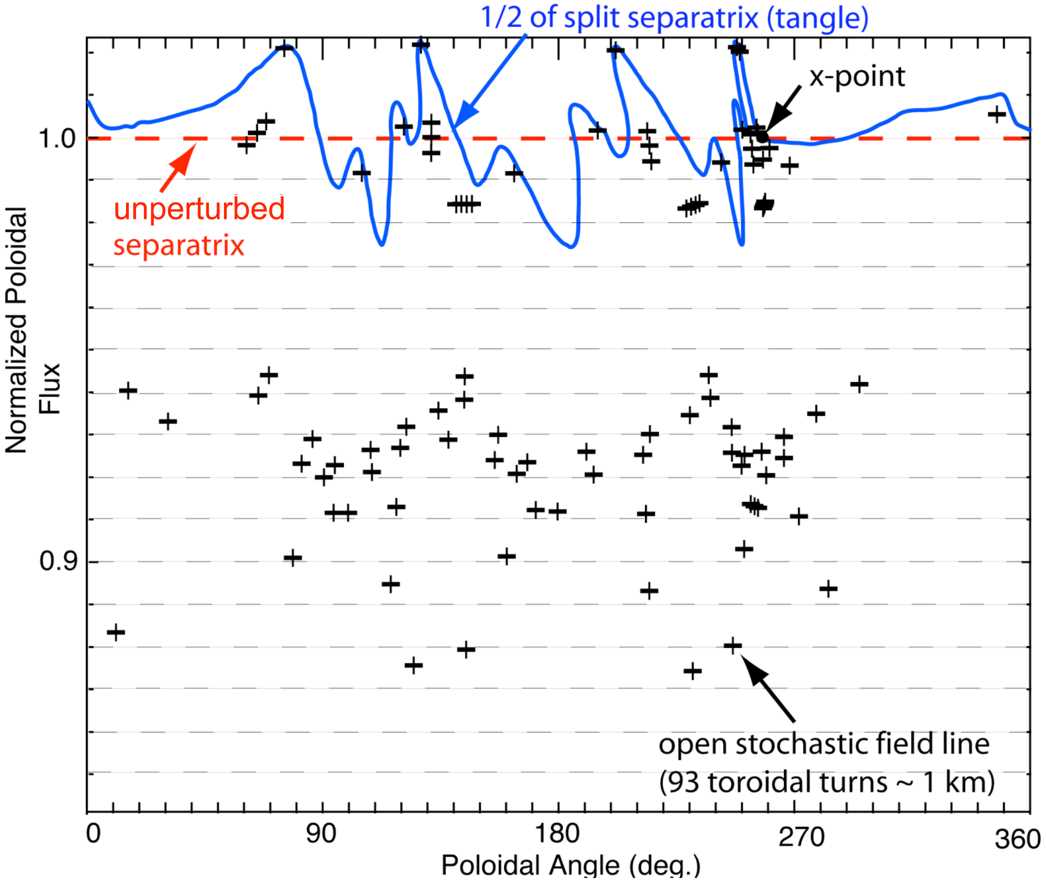
- Ideal axisymmetric separatrix and flux surfaces are smooth
- Non-axisymmetric perturbation split the separatrix → homoclinic tangle

Even parity, 3.2 kA I-coil current, C-coil and field-error

Small edge *RMPs* significantly alter the magnetic topology of the pedestal



TRIP3D code results:
no plasma response

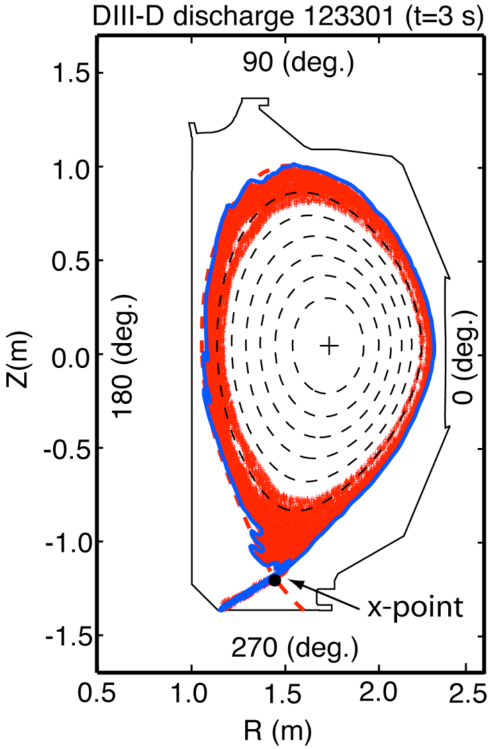


Open stochastic field lines connect to divertor through tangle at 240 deg.

- Ideal axisymmetric separatrix and flux surfaces are smooth
- Non-axisymmetric perturbation split the separatrix → homoclinic tangle
- Stochastic field lines cross the pedestal and hit solid surfaces

Even parity, 3.2 kA I-coil current, C-coil and field-error

Small edge *RMPs* significantly alter the magnetic topology of the pedestal



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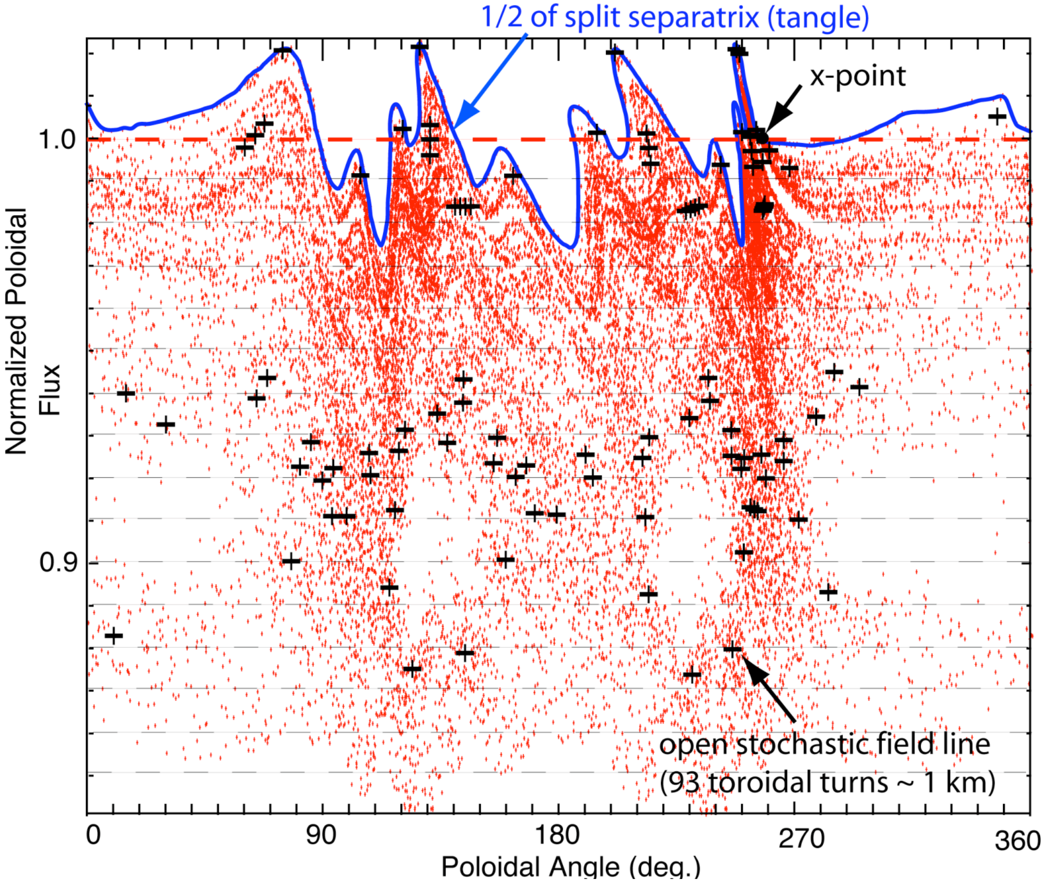


Open stochastic field lines connect to divertor through tangle at 240 deg.

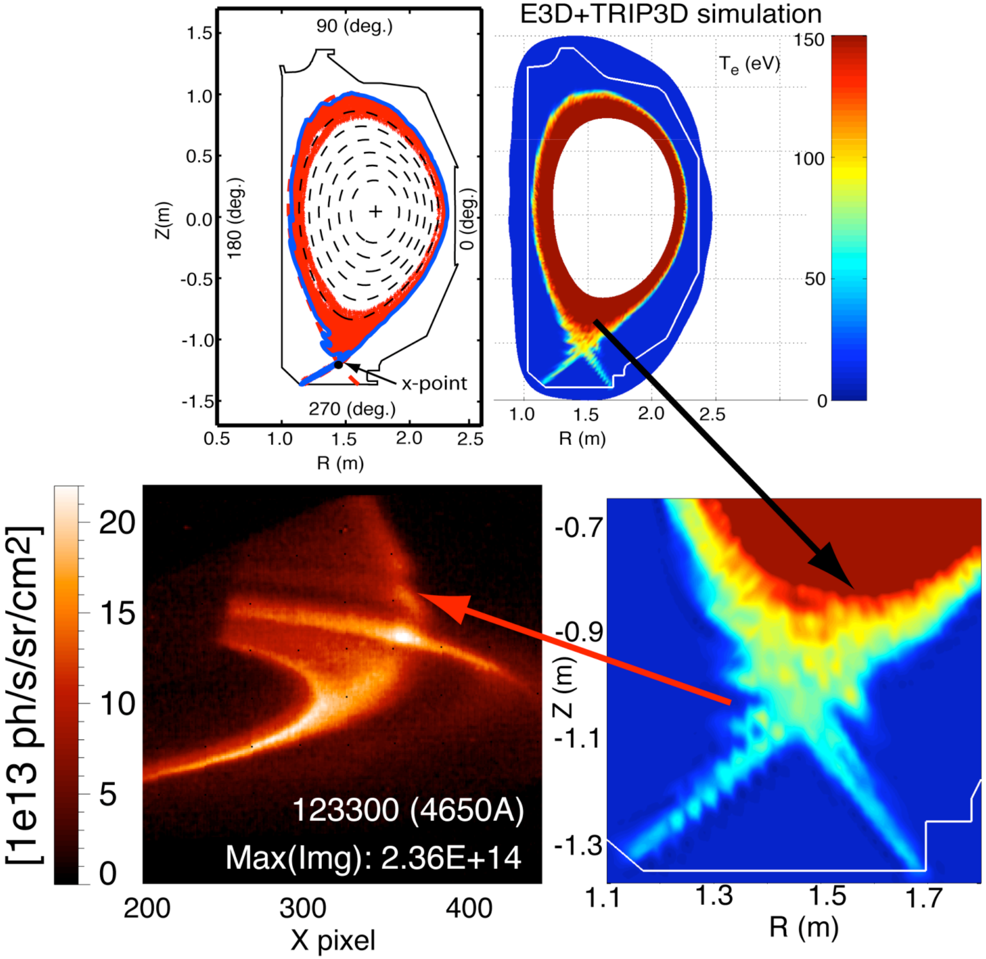
Open stochastic field lines circle islands: changes island potential and E_r, E_θ → increase convective particle transport?

- Ideal axisymmetric separatrix and flux surfaces are smooth
- Non-axisymmetric perturbation split the separatrix → homoclinic tangle
- Stochastic field lines cross the pedestal and hit solid surfaces - strong mixing

Even parity, 3.2 kA I-coil current, C-coil and field-error

3D energy transport modeling with E3D+TRIP3D codes shows heating of x-point tangle structure

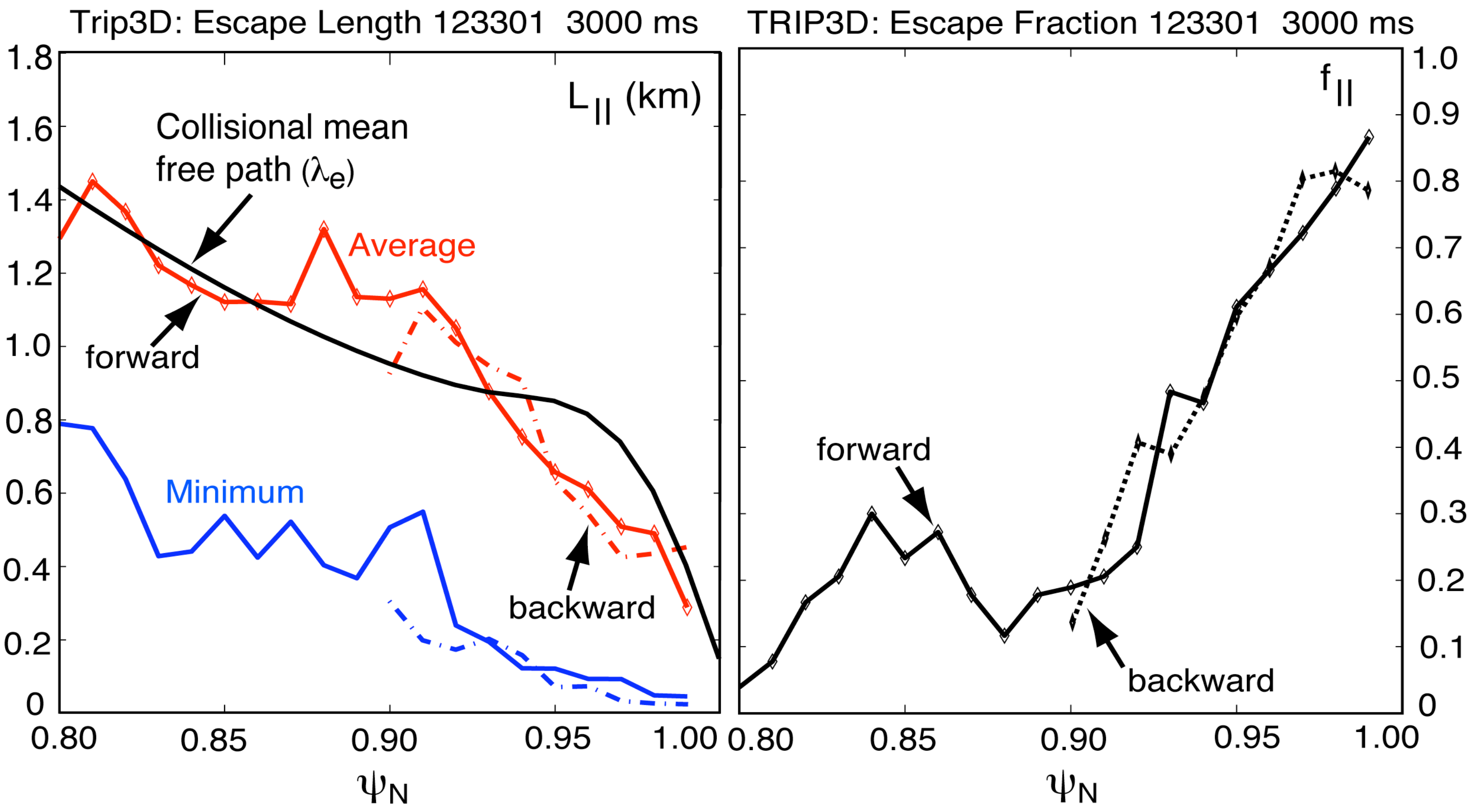
- Non-axisymmetric (homoclinic) tangle appears as a filament-like structure in 2D image
- E3D+TRIP3D heat transport simulations reproduce temperature distribution consistent with observed X-point carbon emission



E3D+TRIP3D heat transport results:
A. Runov, R. Schneider (MPI Greifswald), S. Kasilov (Kharkov IPT) and I. Joseph (UCSD)
- see CP1.00006 I. Joseph, et al.,

X-point carbon images:
- see CP1.00003 - M. Fenstermacher, et al.,

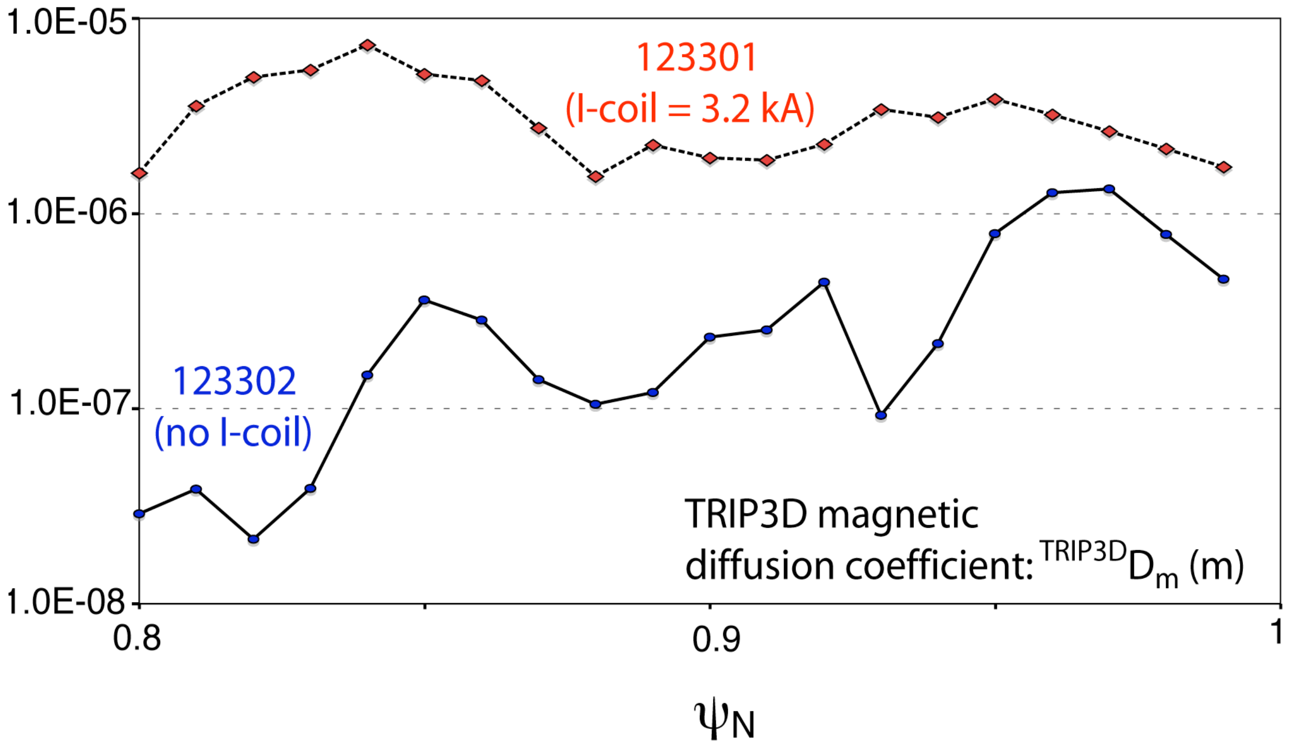
The field line escape fraction increases rapidly with ψ_N outside 0.9



- A significant number of escaping field lines have lengths exceeding the electron collisional mean free path length λ_e

Even parity, 3.2 kA I-coil current, C-coil and field-error

Calculated field line diffusion implies thermal diffusivity that is two orders of magnitude too large



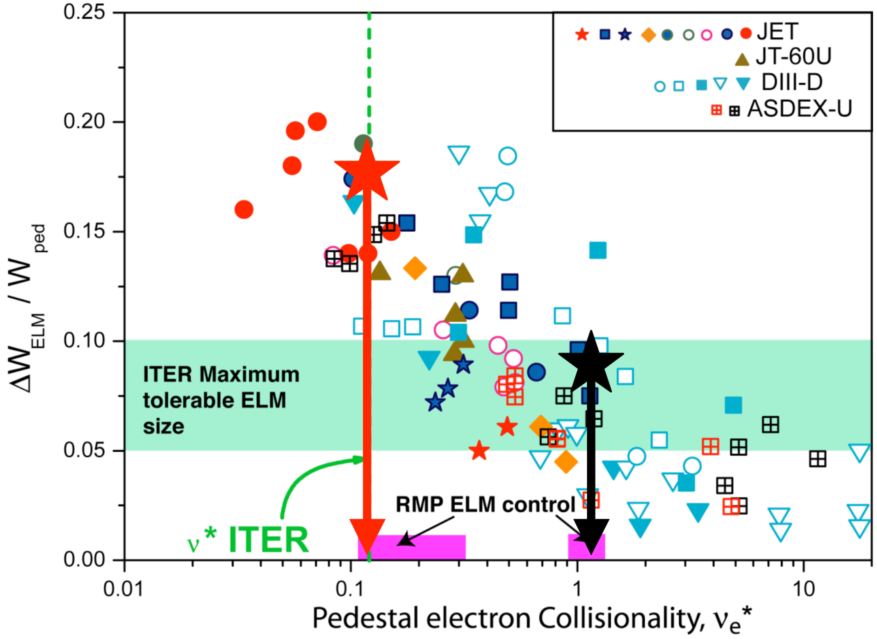
C-coil and field-errors included in each case:
I-coil = 3.2 kA (upper)
and
no I-coil (lower).

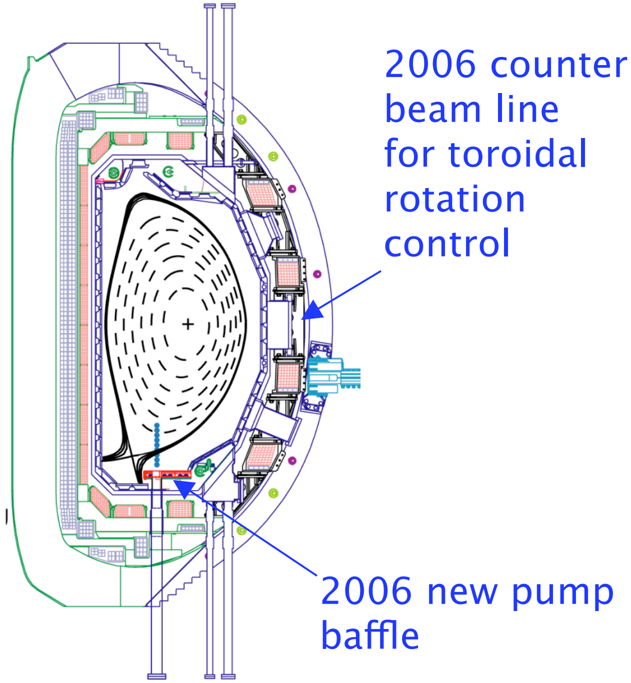
- At $\psi_N = 0.95$, $^{TRIP3D}D_m = 3.9E\text{-}6$ m and $^{quasi\text{-}linear}D_m = 3.5E\text{-}6$ m:
  - $^{quasi\text{-}linear}\chi_e = v_{Te} D_m \sim 49\ m^2/s$ but to match experimental $T_{e,ped}$ $^{simulation}\chi_e \sim 0.2\ m^2/s$
- Need more comprehensive edge *RMP* transport theory
  - Is *RMP* screening due to plasma rotation or pressure a significant factor?

Even parity, 3.2 kA I-coil current, C-coil
and field-error

Significant progress made toward burning plasma pedestal and ELM control in DIII-D using edge *RMPs*

- **2004 results** : n=3 *RMPs* suppress ELMs at high collisionality in ITER shape





2006 counter beam line for toroidal rotation control

2006 new pump baffle

- **New results in 2005** : n=3 ELM suppression at ITER relevant low collisionality using DIII-D pumping in low triangularity (δ) plasmas
- **Next year**: new DIII-D hardware allows pumping in higher δ, ITER-like, shapes → n=3 *RPMs* in low collisionality ITER-like shapes with low rotation

DIII-D NATIONAL FUSION FACILITY

See: CP1.00009 - L. Zeng, et al., and CP1.00005 - J. Boedo, et al.

Summary and Conclusions

- Small edge *R*esonant *M*agnetic *P*erturbations (*RMP*s) used to:
  - Control pedestal profiles in high confinement plasmas
    - ∇p control → edge bootstrap current (j_{edge})control?
- Type-I ELMs completely eliminated in low collisionality (ν_e^*) burning plasma relevant conditions:
  - Consistent with peeling-ballooning ∇p, j_{edge} stabilization for all cases tested to date
  - ∇p (j_{edge} ?) operating point controlled with *RMP* coil current
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