Edge Stability of Steady-State ELM-Suppressed Regimes on DIII-D

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DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

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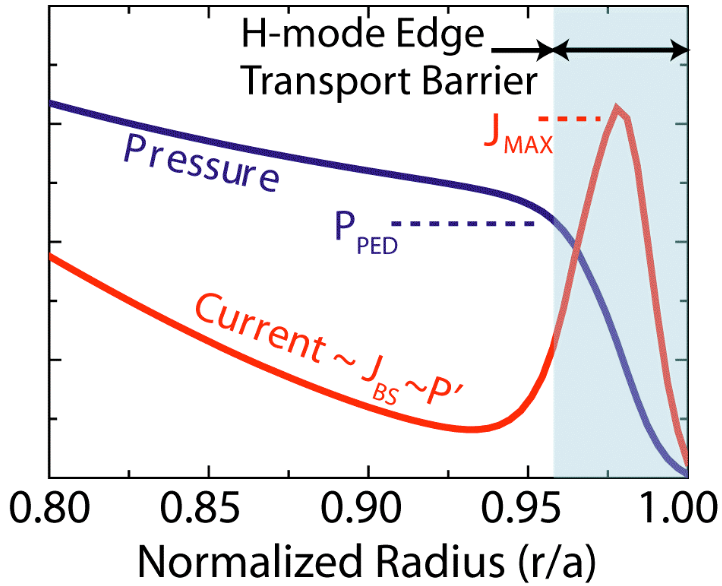
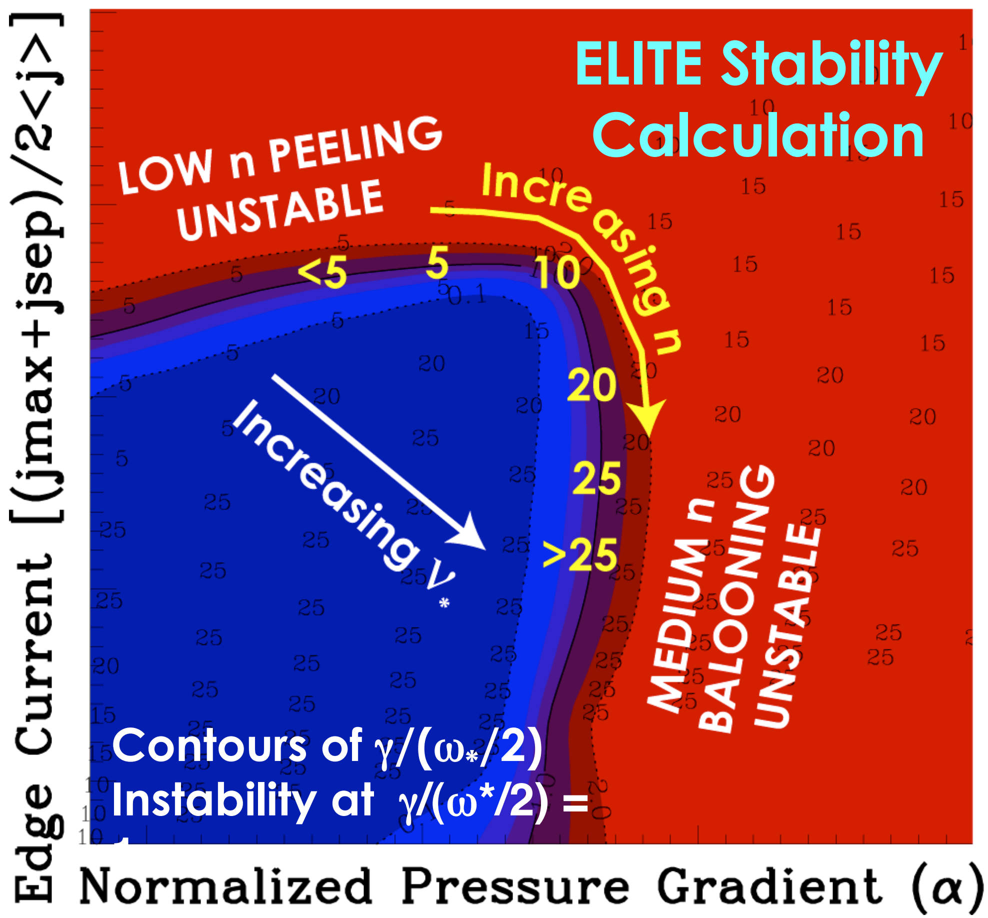
Introduction

- **An H-mode based reactor will require high H-mode pedestal pressure**
  - High n_e^{PED} required for high fusion power
  - High T^{PED} for high energy confinement ⇒ Q, with expected stiff T profiles
- **ETB low transport ⇒ ELMs instabilities driven by high J and dP/dR**
  - ELMs provide density and impurity control, but can erode plasma facing surfaces at reactor scale (ELM energy loss ∝ P_{PED})
- **Two ELM-free regimes on DIII-D, QH-mode and RMP-H-mode, with good energy confinement, high pedestal pressure, and no density or impurity accumulation**



High Pressure Gradient and Current Density in H-mode Edge Drives Peeling-Ballooning Instability



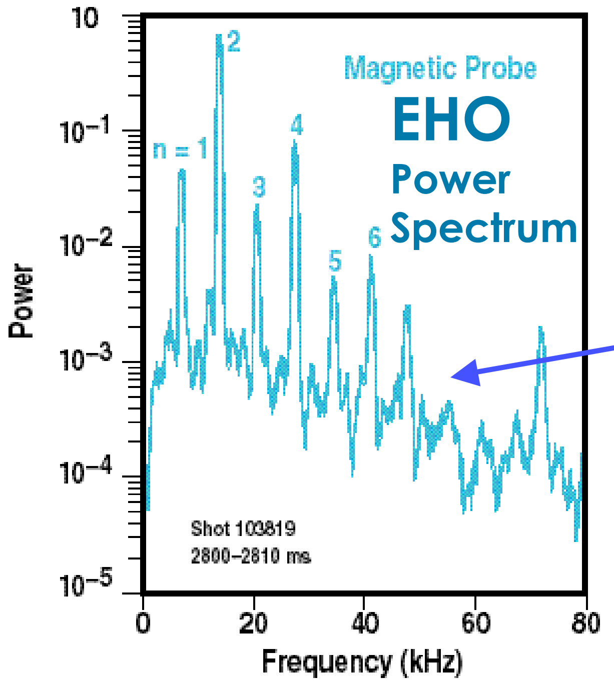
- p´ driven ballooning mode and J driven peeling mode main large scale instabilities in ETB
- Modes merge near n=10 giving low n, n ≲ 5, in the J driven regime and n ≳ 20 in the p´ driven regime
- ELMs triggered along either peeling or ballooning boundary
- J is dominated by bootstrap current ($J_{BS} \propto p´$) and $J_{BS}/p´$ decreases with ν_* moving from J drive at low n, to p´ drive at intermediate n
- Stability limit depends on plasma shape, collisionality, pedestal width, q, etc. ⇒ need an efficient code = ELITE[1]

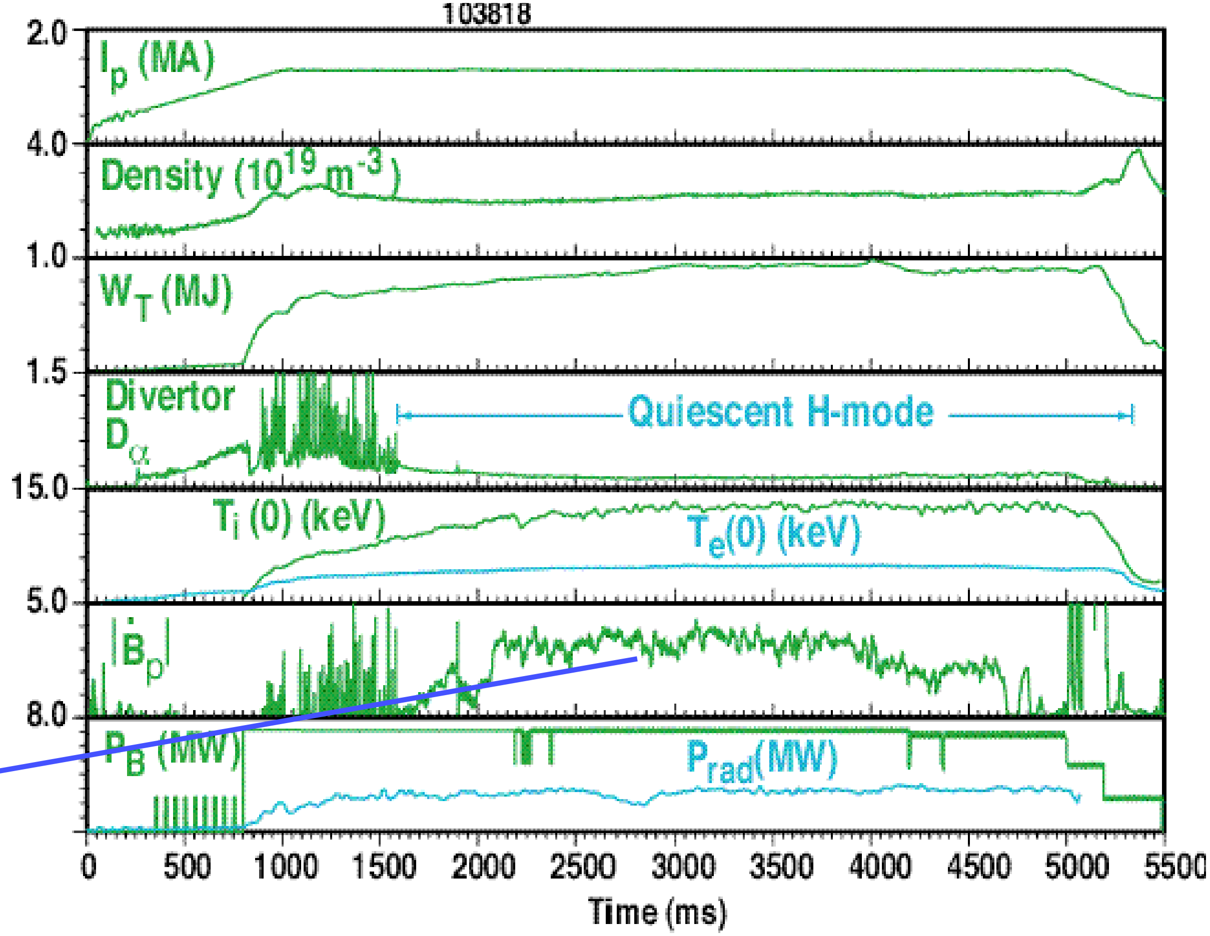
[1]H.R. Wilson, P.B. Snyder, et al., Phys. Plasmas 9 (2002) 2037.

QH-MODE RESULTS

ELM-free QH-mode With Edge Harmonic Oscillation (EHO) Has High Energy Confinement and No n_e Accumulation

- Counter injection
- Low density with divertor pumping
- H_{89P} to 2.4
- β_N to 2.9, $\beta_N H$ to 7
- $\nu_{*e} \approx 0.1$
- No max P_{inj} to 14MW

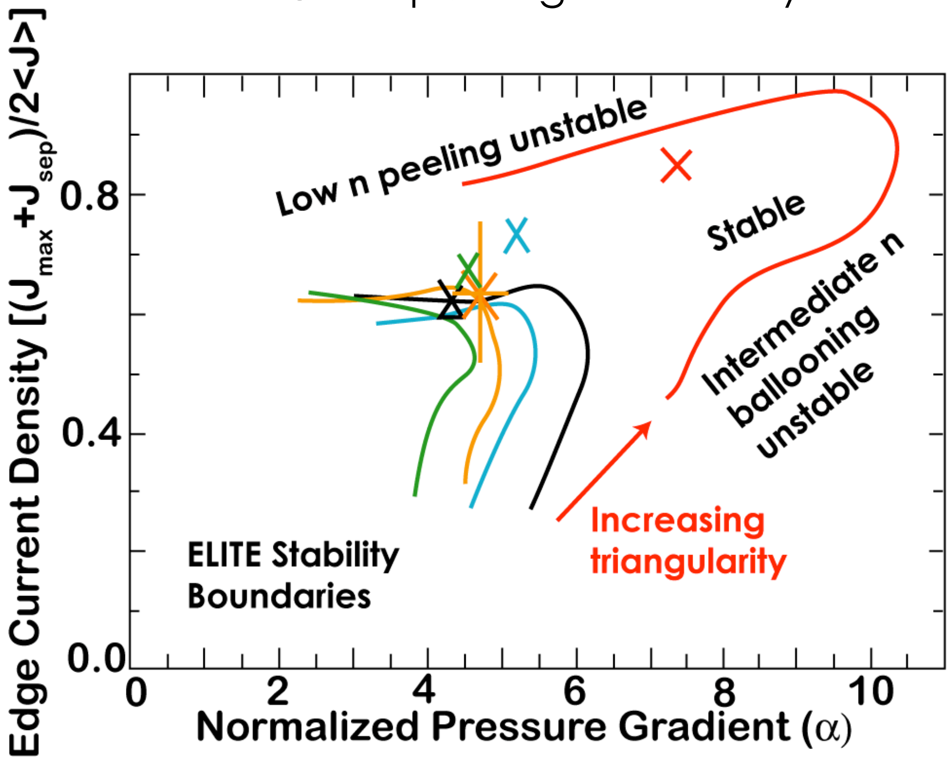


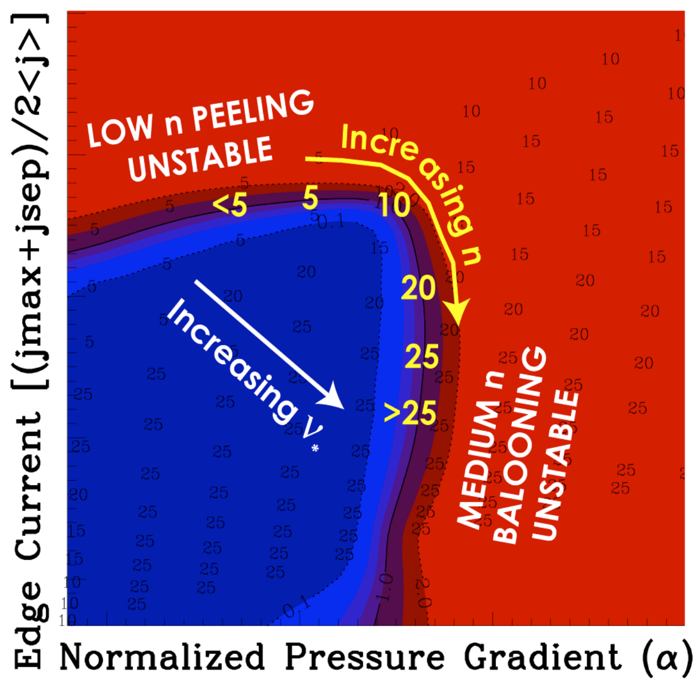


- EHO is typically dominated by n=1,2,3 or 4, in or near ETB, rotating in direction of beam injection

QH-mode Operation is Associated With the Edge Being Near the Low n Peeling Mode Stability Threshold

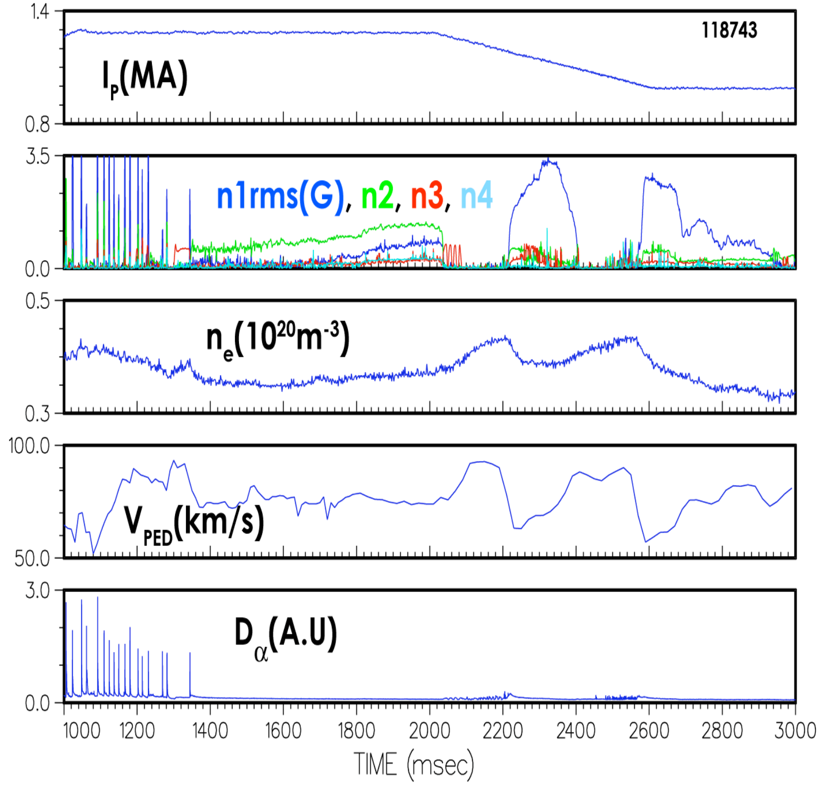
- **The QH-mode edge is always near the peeling mode stability limit where n ≤ 5 consistent with the observed n values for the EHO**
- **Low ν_* requirement for QH-mode operation suggests Low n peeling instability may be a necessary condition for QH-mode**
- **ELMs can occur along either the peeling or ballooning limits ⇒ Peeling instability not a sufficient condition for QH-mode**
  - If the EHO is a peeling mode why does it saturate in QH-mode ?



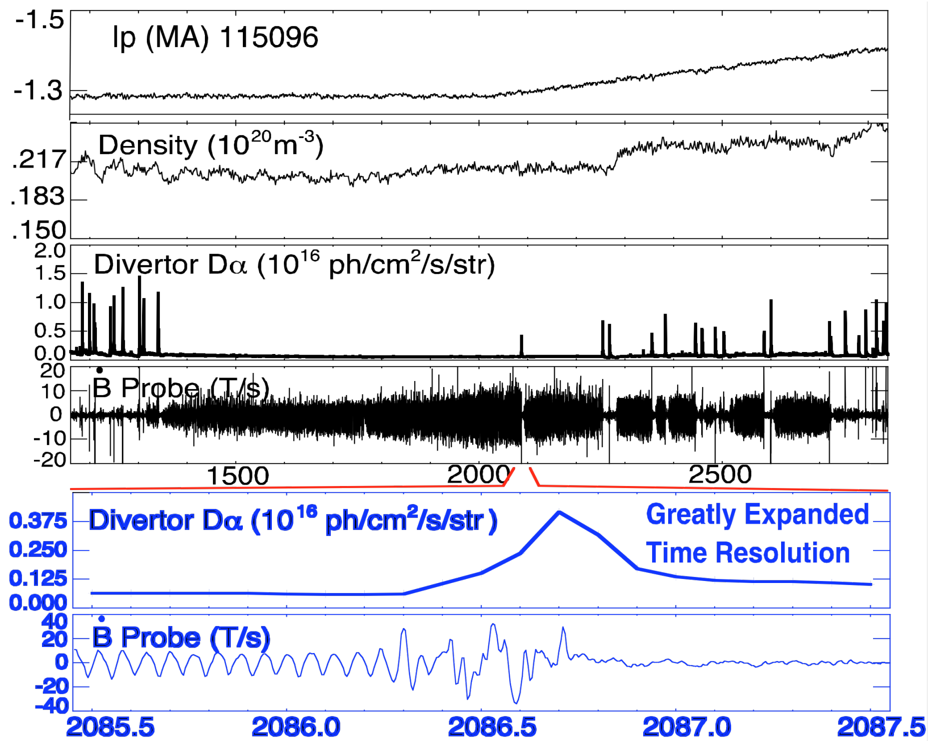


Current ramp experiments also suggest QH-mode is near peeling limit and EHO is destabilized with J below what is required for ELM

- EHO turns off as I_p is ramped down ⇒ EHO is current driven
- n_e rises with EHO off ⇒ EHO is source of n_e control; without EHO standard ELM free
- Rotation rises with EHO off ⇒ EHO

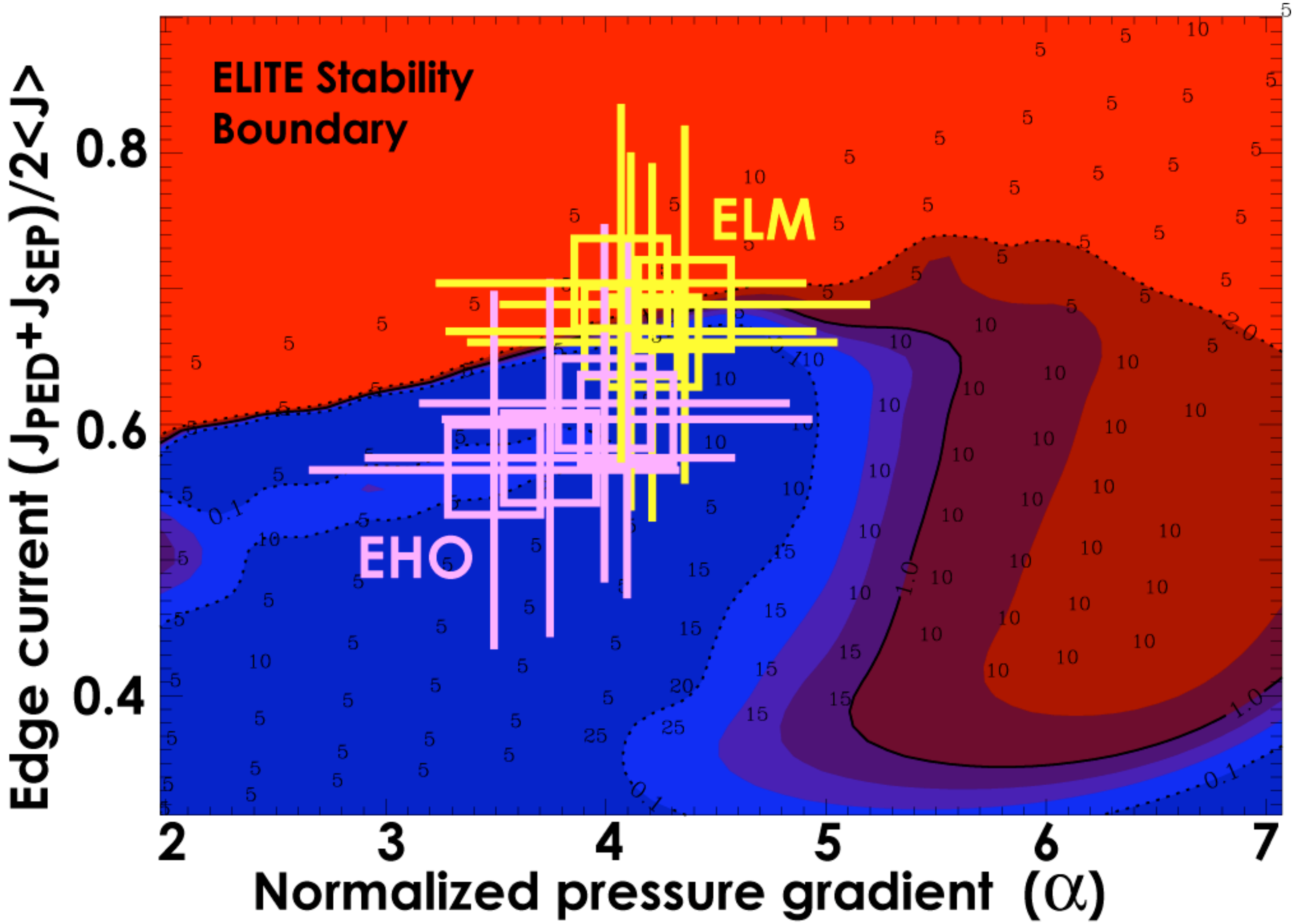


- ELMs return when I_p is ramped up ⇒ Stability threshold for ELM is at higher current than that required for EHO
- EHO disappears after ELM, but ELM precursor is more complex – higher n or nonlinear phase



Discharges Where Only CO-NBI Power Fraction Was Varied Also Show EHO Occurs Just Below Peeling Stability Threshold for ELM

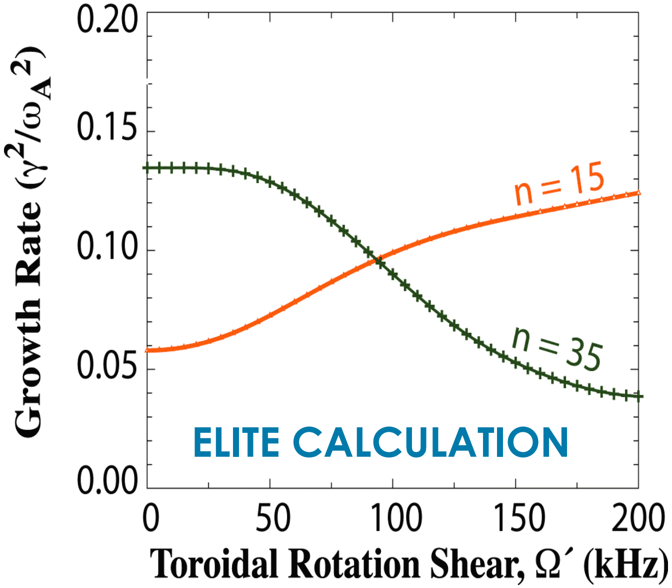
- **Data suggest there may be an additional drive for the peeling-ballooning instability in QH-mode which is more susceptible to saturation than the current drive**



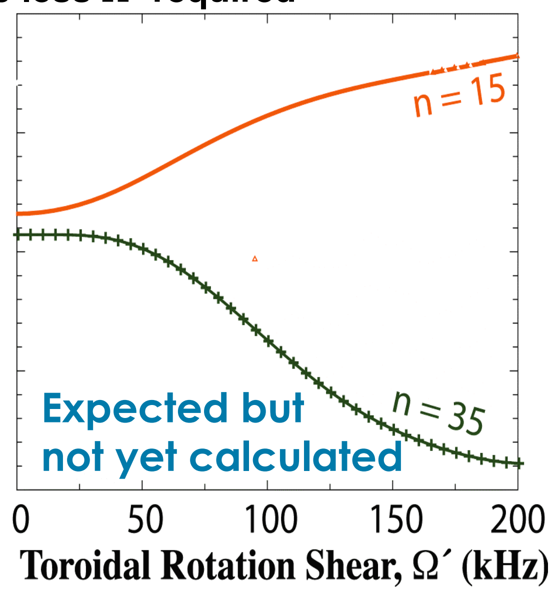
Rotational Shear Drive for Modes at Low n Suggests a Possible Saturation Mechanism for the EHO (P. Snyder)

- **Sheared toroidal flow incorporated into ELITE**
- **Rotational shear is destabilizing at low n and stabilizing at higher n**
- **For mode driven by Ω´, if mode growth reduces Ω´ this would reduce the drive and possibly saturation the mode**
  - Wall drag, or momentum transport

Along ballooning boundary where higher n modes dominate at Ω´ = 0 access requires high Ω´



Along peeling boundary where low n modes dominate at Ω´ = 0 less Ω´ required

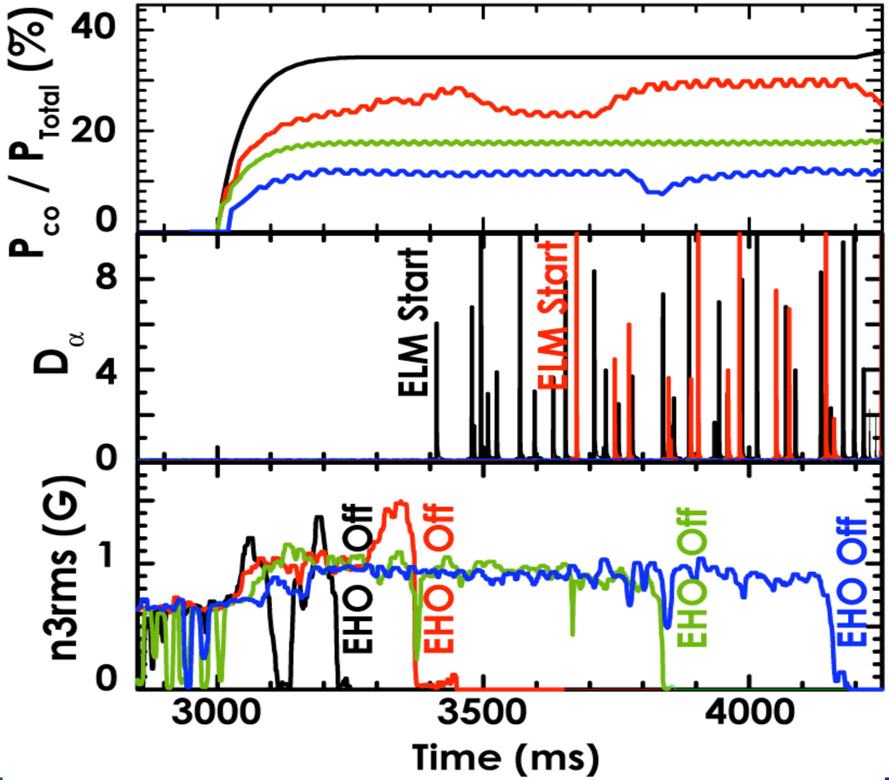


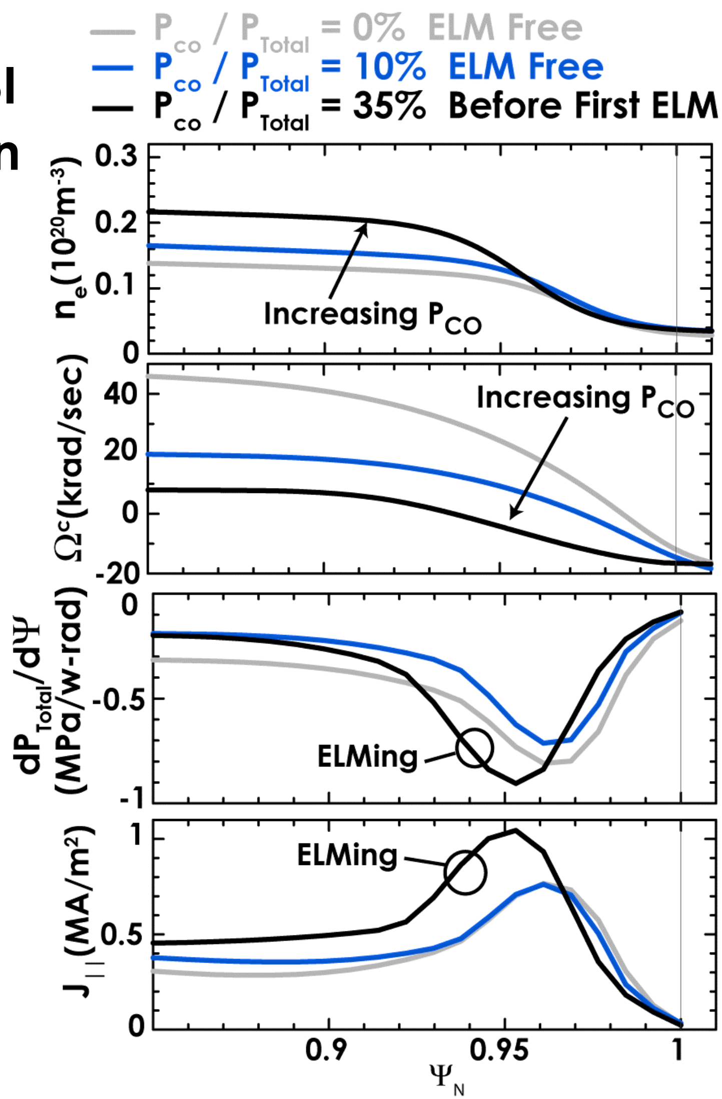
Saturation Requirements

- **Low n ⇒ along peeling boundary**
  - Ω´ drive at lower Ω´
  - Stronger wall drag
- **High rotational shear**
  - Ω´ drive dominates j drive
- **Small plasma wall gap**
  - Stronger wall drag

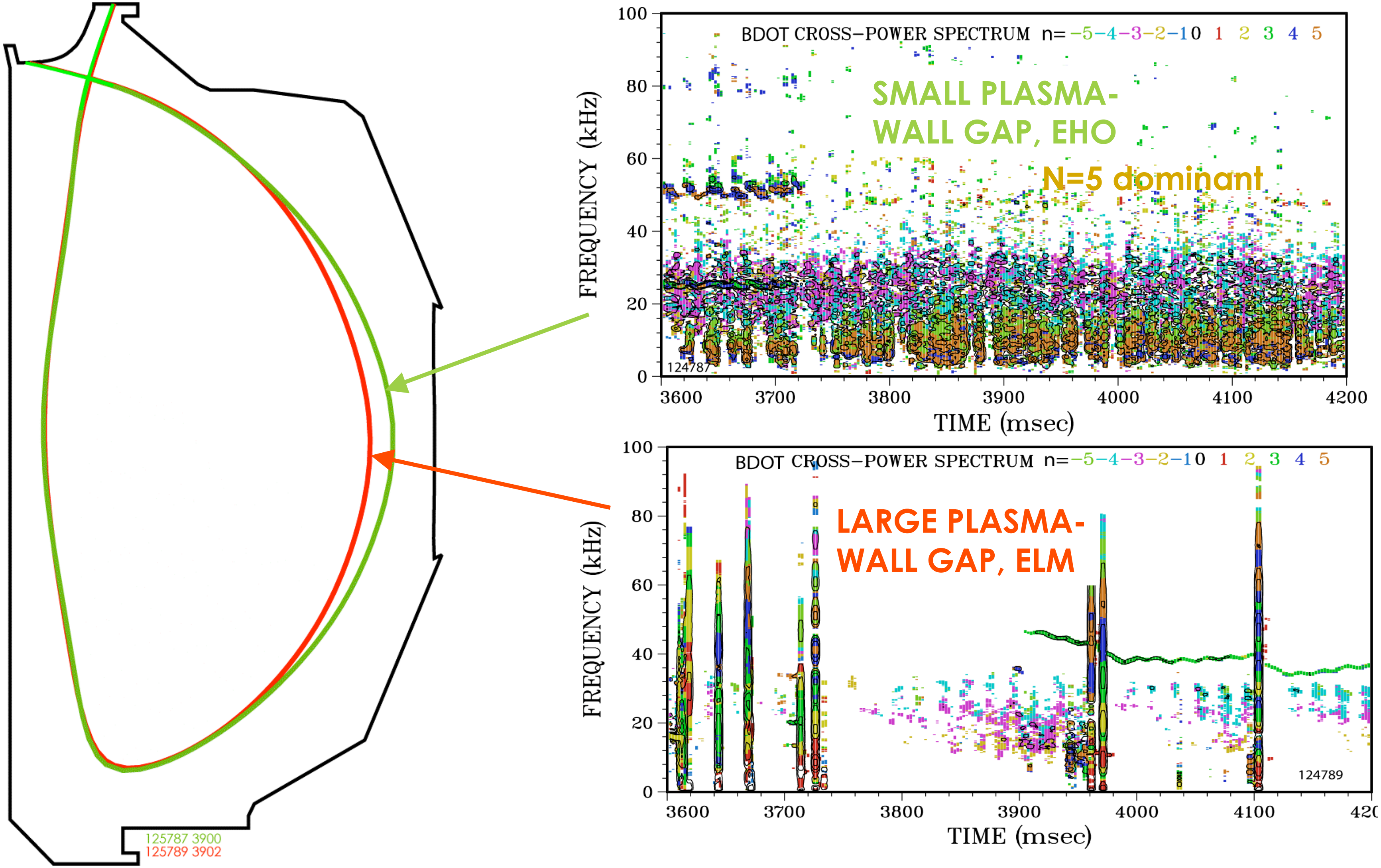
CO-NBI Injection Experiment Consistent With Importance of Rotation in EHO Saturation

- ELMs start earlier with increasing CO-NBI
- EHO shuts off earlier with increasing CO-NBI
- Ω´ reduced with increasing CO-NBI fraction
- P′ and J rise to ELM limit through an increase in n_e^{PED} and Δn_e^{PED}



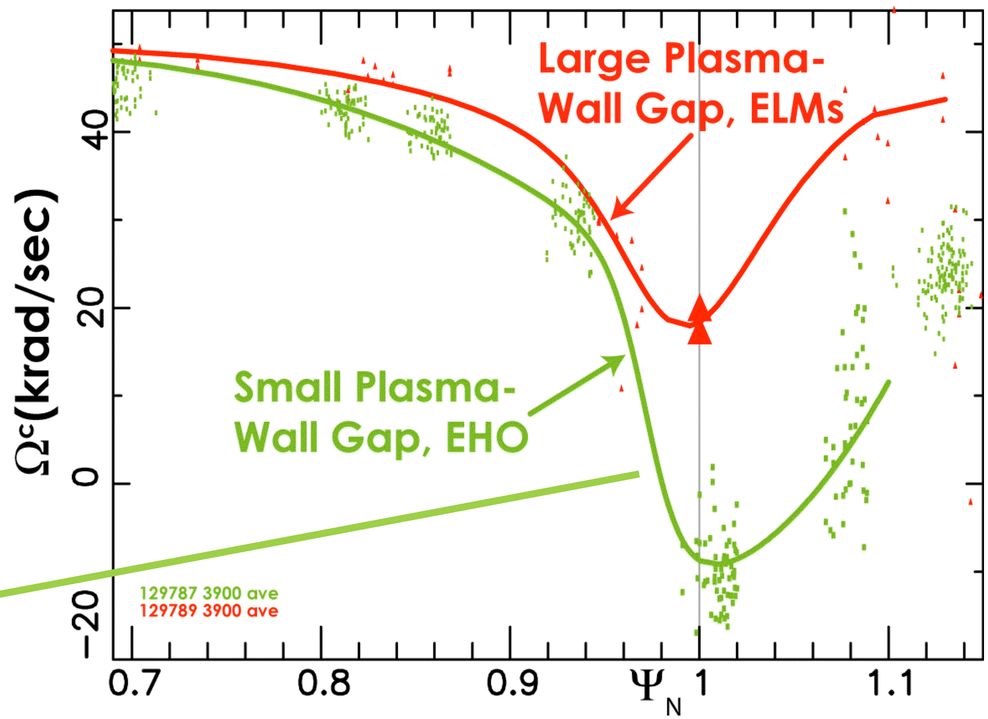


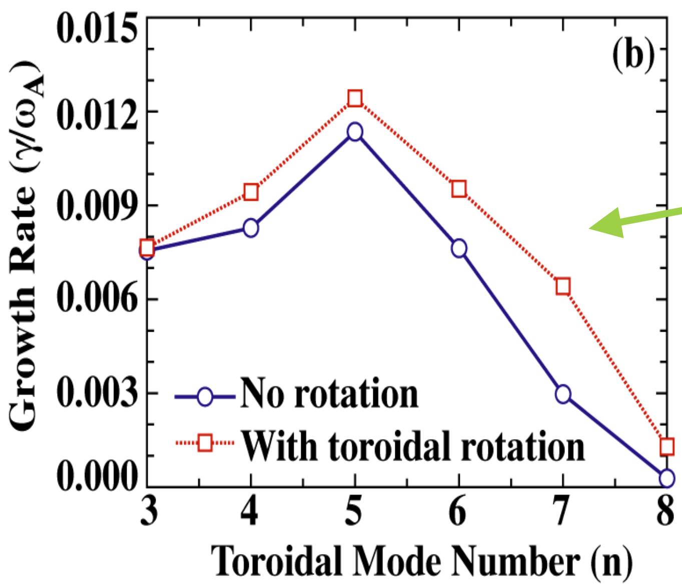
ELMs Return in Discharge With Large Plasma-wall Gap Consistent Importance of Wall Drag in EHO Saturation



Rotational Shear is Also Smaller in the ELMing Discharge With Smaller Plasma-wall Gap

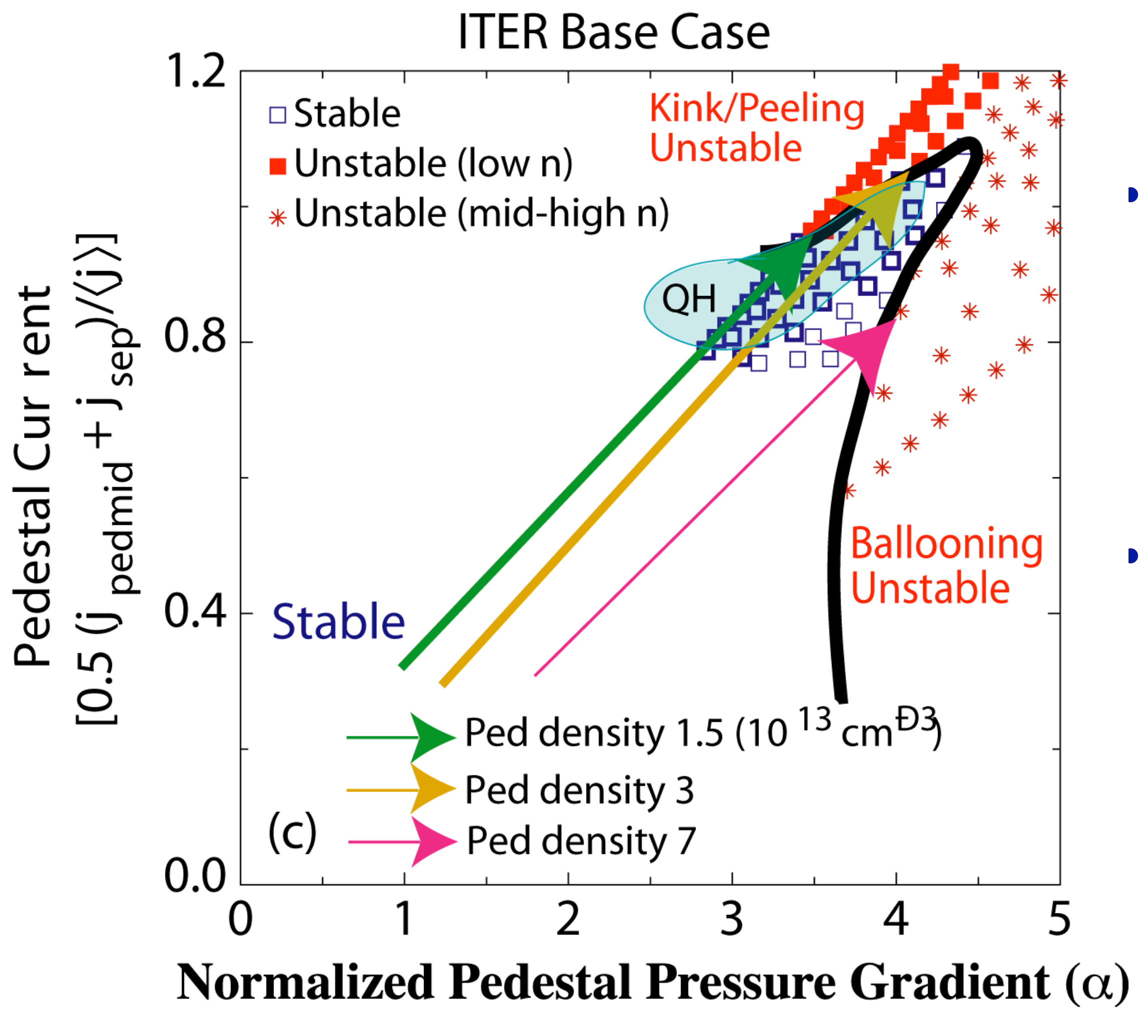
- **Saturation hypothesis for EHO requires Ω´ drive and wall drag (or other) rotational damping**
  - Less Ω´ and likely less wall drag with large gap





- ELITE calculation for ELM free case shows increase in growth rate with rotational shear
- Most unstable mode, n=5, agrees with observed dominant mode

Access to the Low n Peeling Mode Unstable Regime and Therefore Also QH-mode is Possible in ITER at Lower n_e^{PED}

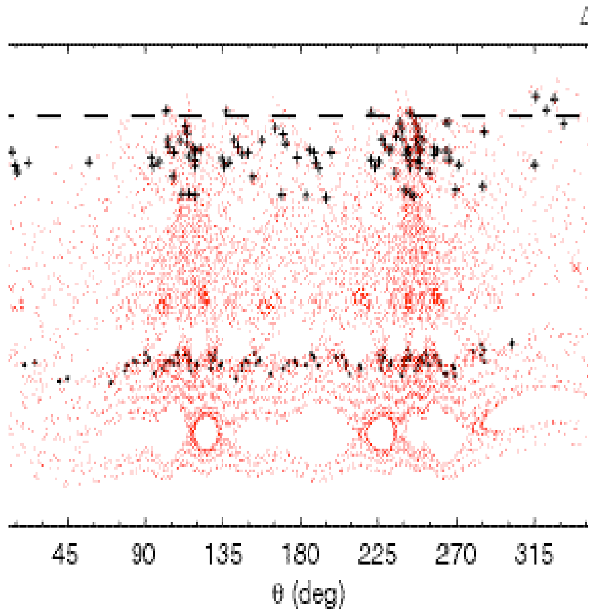


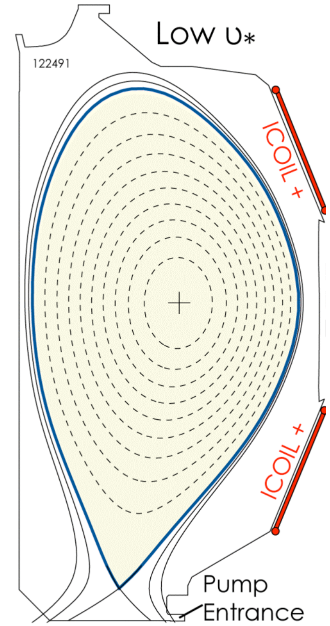
- ELITE calculations show ITER could access low n peeling unstable regime with $n_e^{PED} < \sim 0.3\times10^{20}m^{-3}$
- Rotational and wall effects yet to be determined

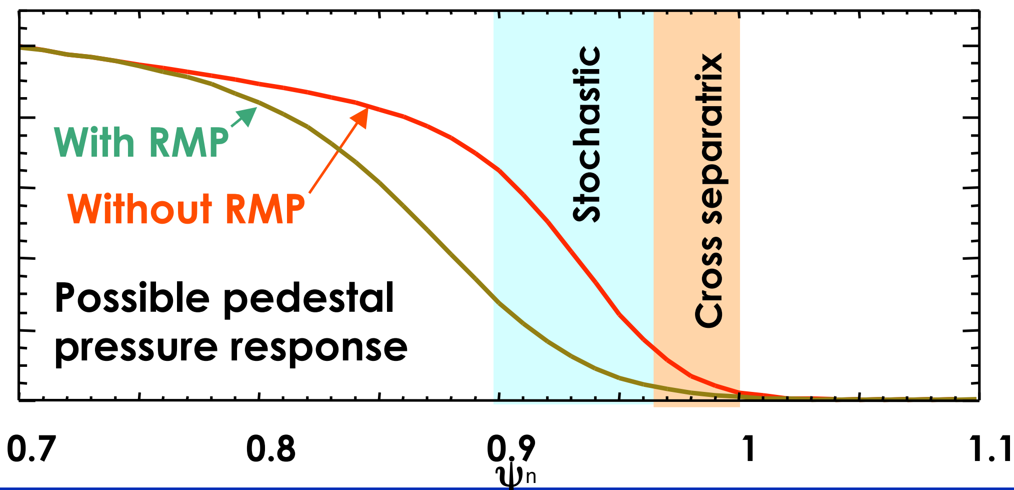
RMP H-MODE RESULTS

RMP Coil Expected to Give Control Over P_{PED} by Breaking Up Magnetic Surfaces in ETB Region

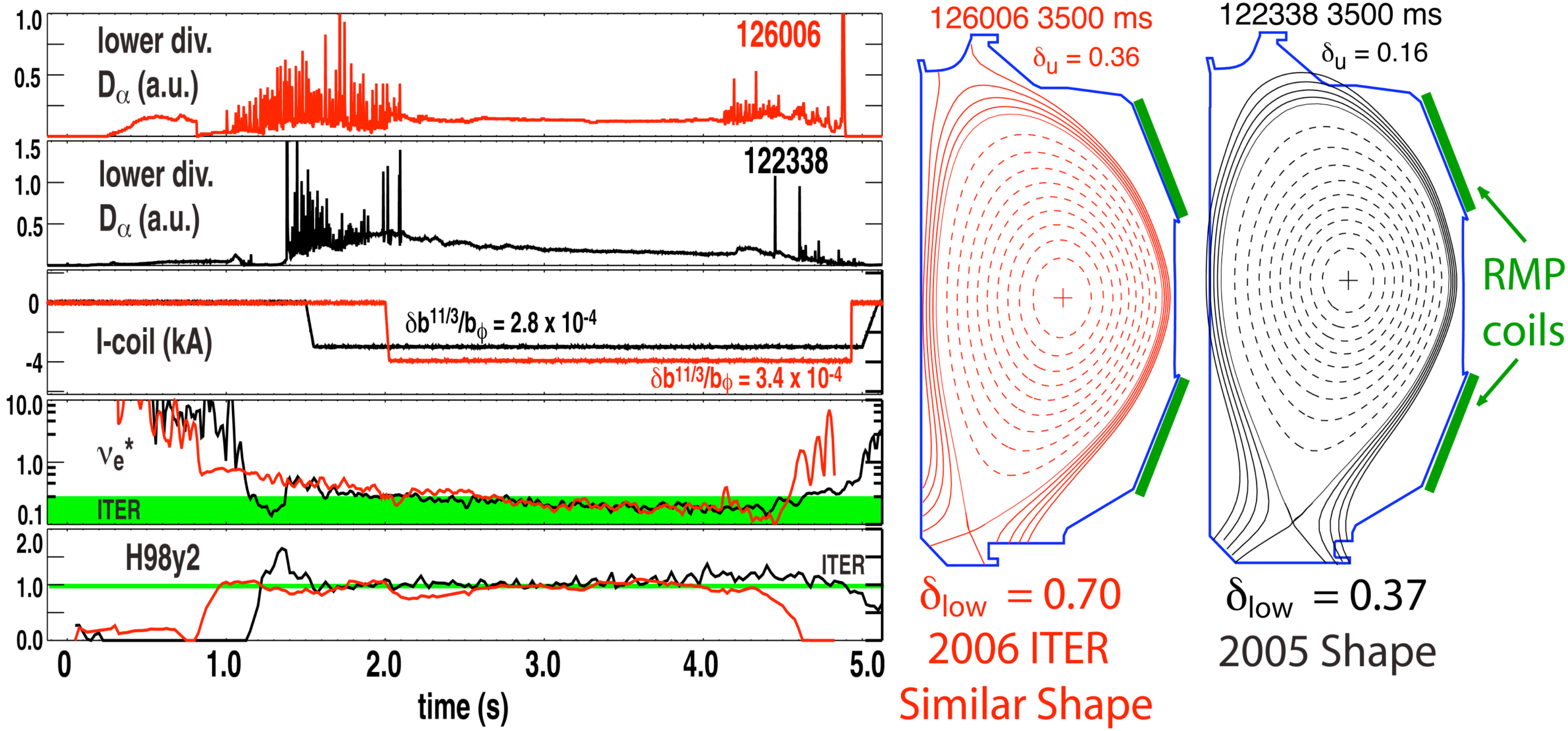
- External n=3 coils create Resonant Magnetic Perturbation in ETB, breaking up magnetic surfaces
- Very near the separatrix field lines cross separatrix and intersect vessel wall
- Further from the separatrix a region of stochastic field







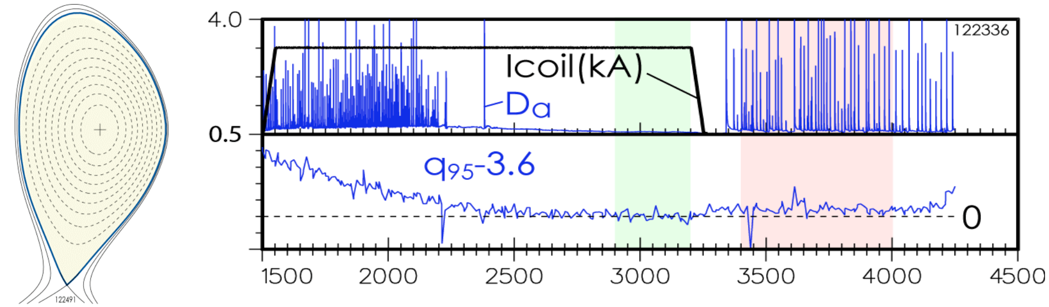
ELMs are Completely Eliminated With n=3 RMP in ITER Similar Shapes With ITER Pedestal Collisionalities

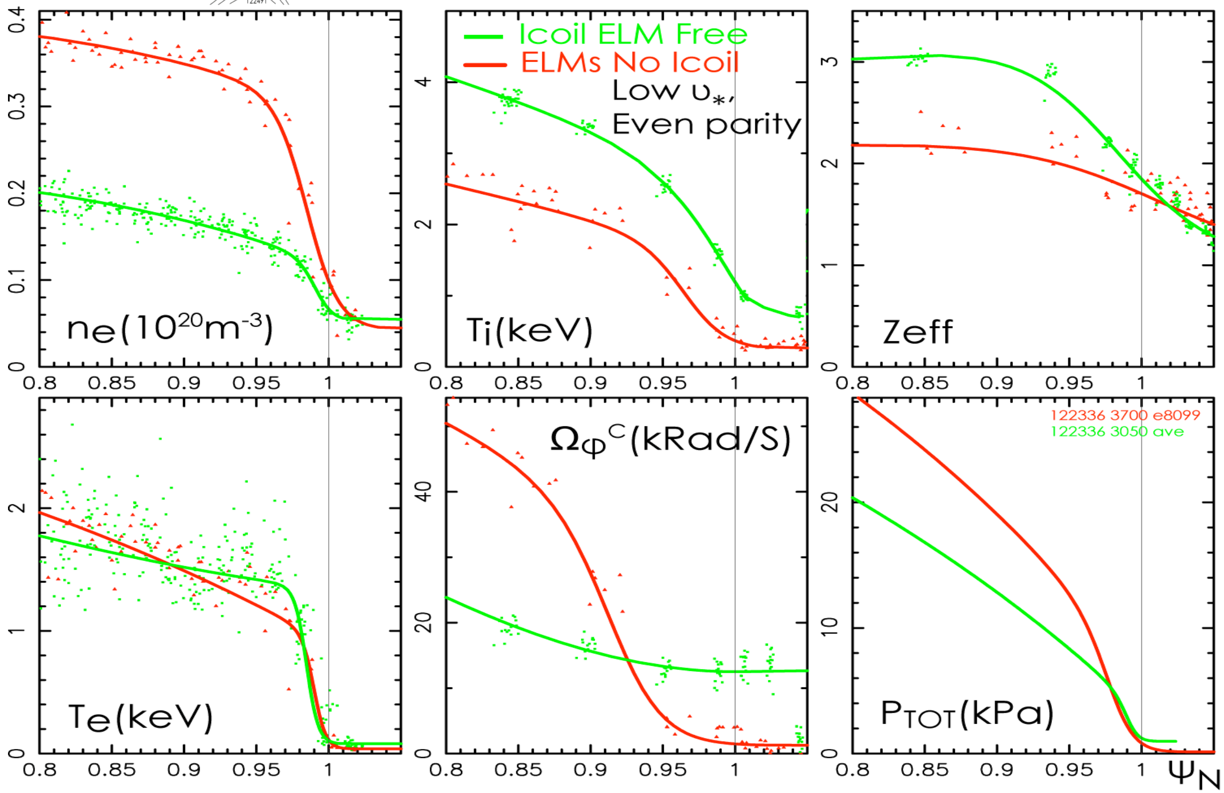


- **2006 lower divertor reconfiguration allows collisionality control (pumping) in ITER Similar Shape (ISS)**

P_{PED} is Strongly Reduced With RMP but Mainly Due to Reduction in n_e^{PED} and Width of High ∇n_e Region

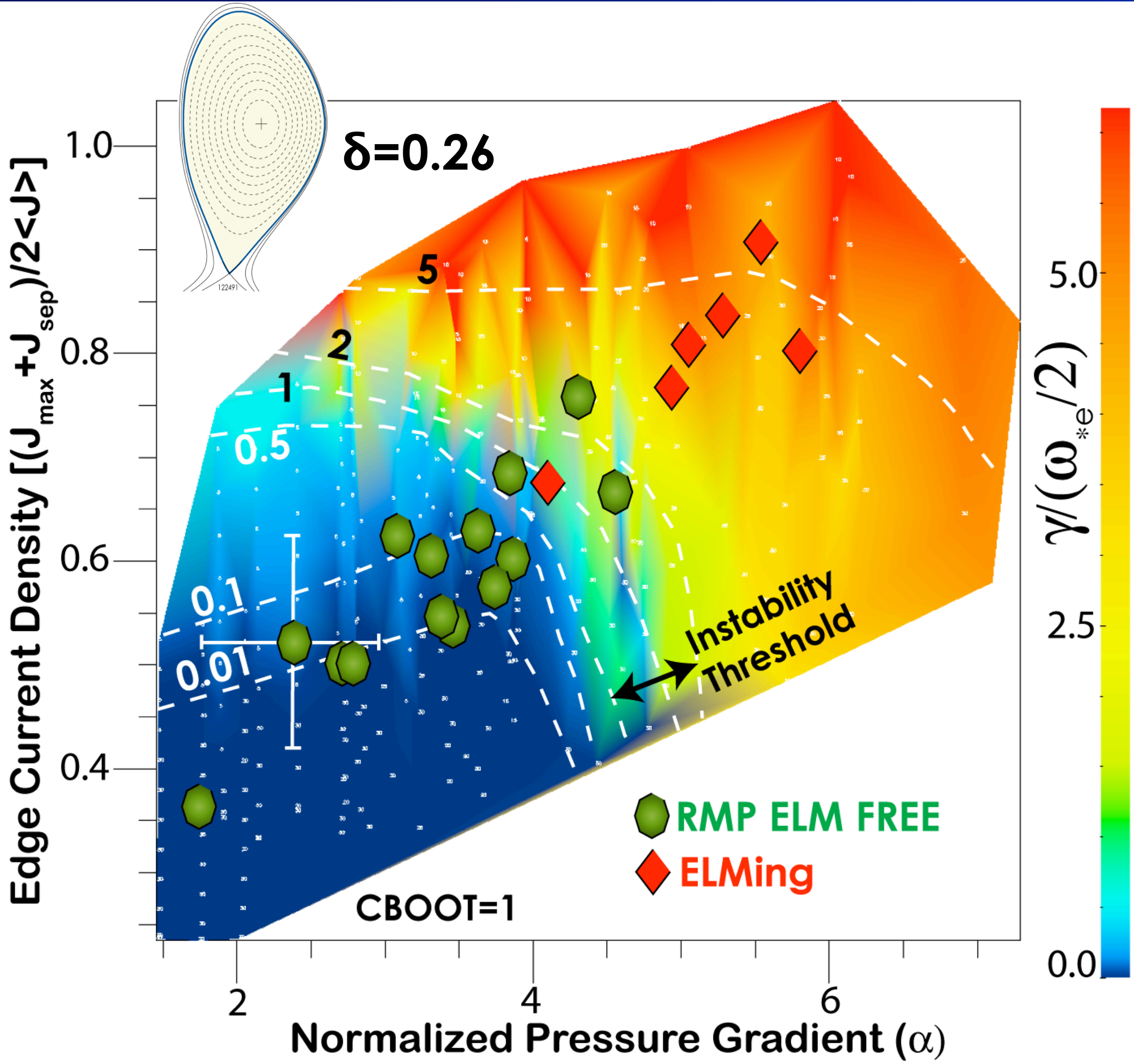
δ=0.26





- ELMs eliminated **only** in q window where RMP field is resonant with equilibrium field
- n_e and Δn_e strongly reduced with RMP
- T_e surprisingly relatively unchanged
- T_i increases (less coupling to electrons)
- Ω´ strongly reduced
- Z_{EFF} increased
- P_{PED} and ΔP_{PED} strongly reduced

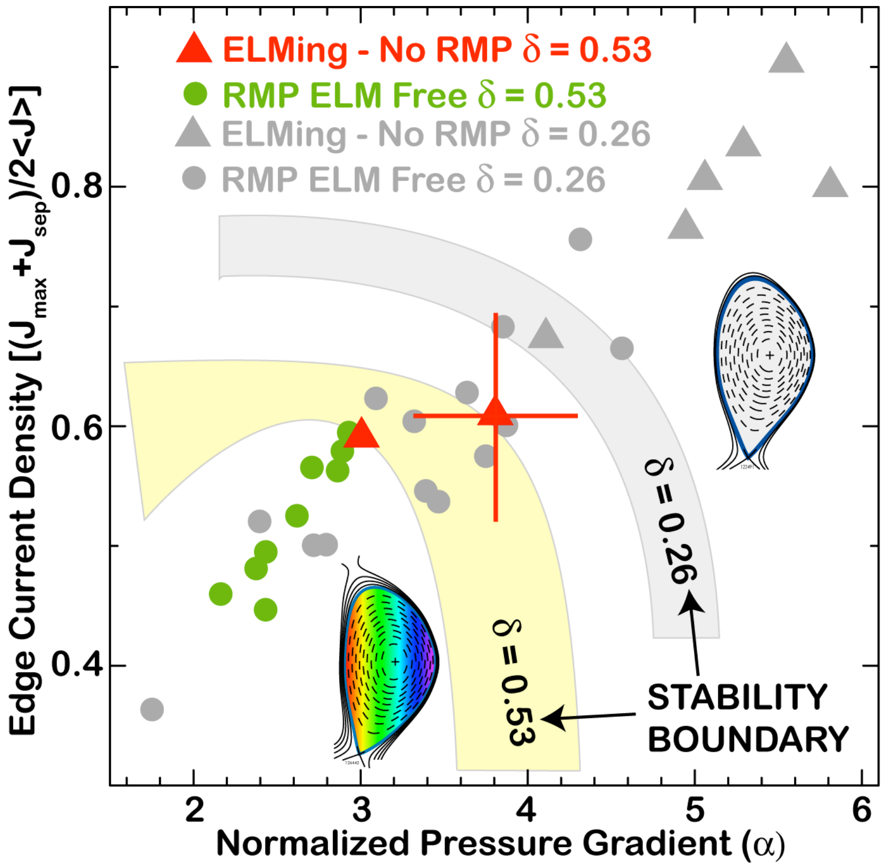
RMP Eliminates ELMs by Reducing Edge p´, j Below Peeling-Ballooning Stability Threshold

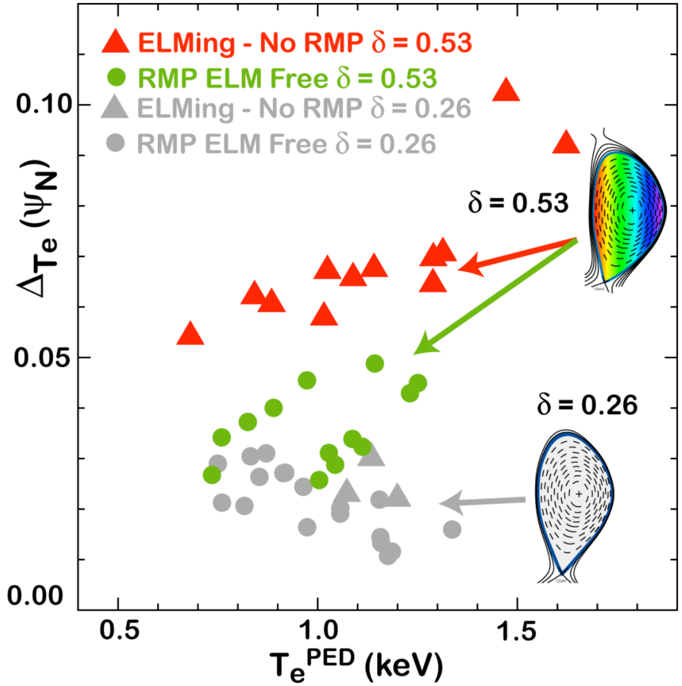


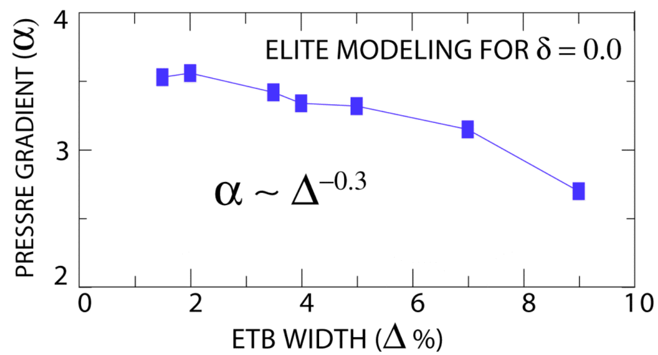
- **I-Coil ELM suppressed discharges at low triangularity generally have peeling – ballooning growth rates below stability threshold ($\gamma=\omega_{*e}/2$)**

Higher δ RMP ELM-free Discharges Also Lie Below PB-mode Threshold But at Lower p´, J

- **p´ reduced, but pedestal width increased at high triangularity**
  - p´ ∝ $\Delta^{-0.3}$ expected for peeling-ballooning stability (fixed **δ**)

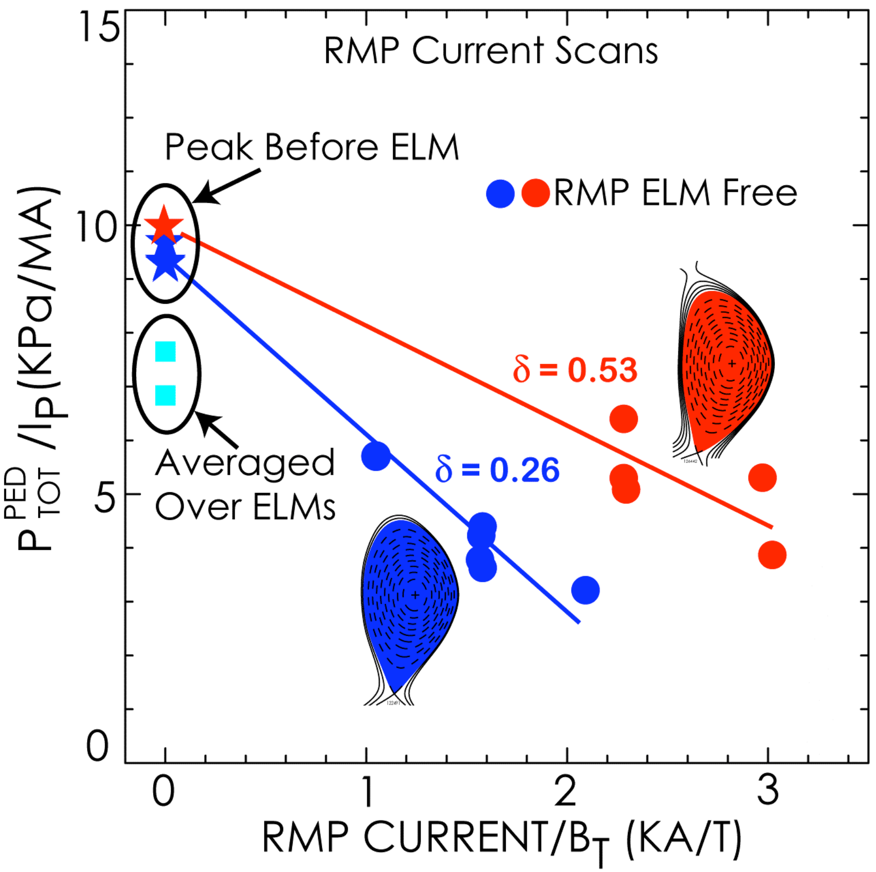




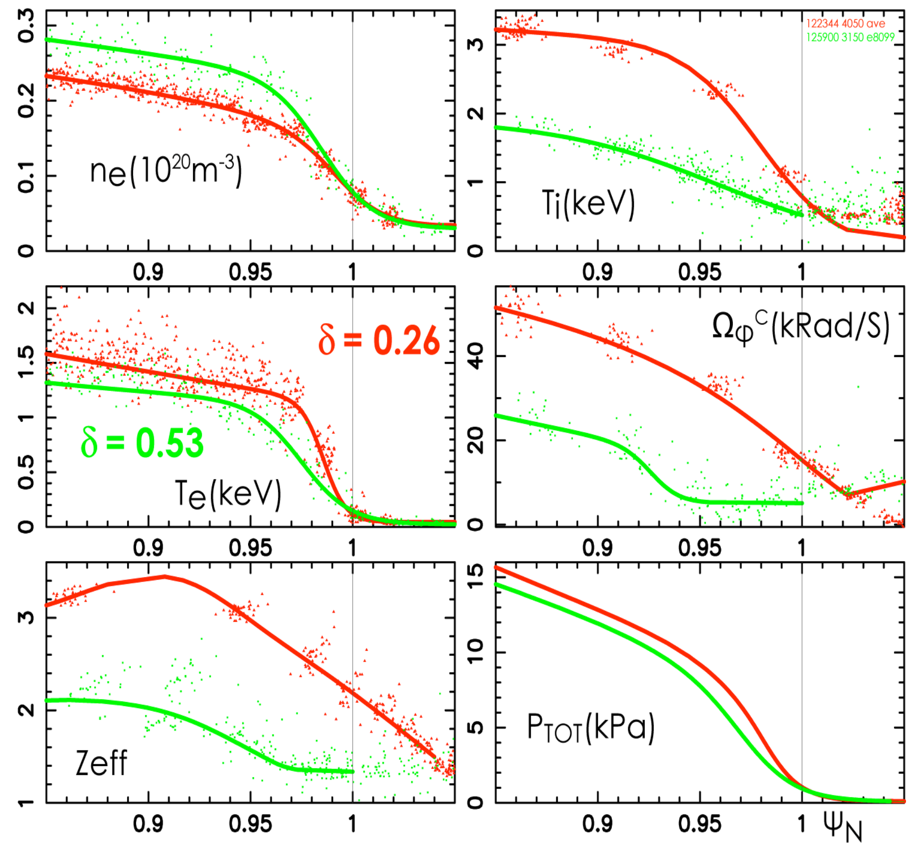


Maximum P_{PED} With RMP ELM Suppression Did Not Change Significantly With Triangularity

- Increased Δ offsets reduced P´ at high triangularity
- More RMP current needed to suppress ELMs at higher δ (Evans C01.00008)
- Although P_{PED} with RMP < peak P_{PED} before ELM, P_{PED} with RMP nearly as high as P_{PED} averaged over ELMs

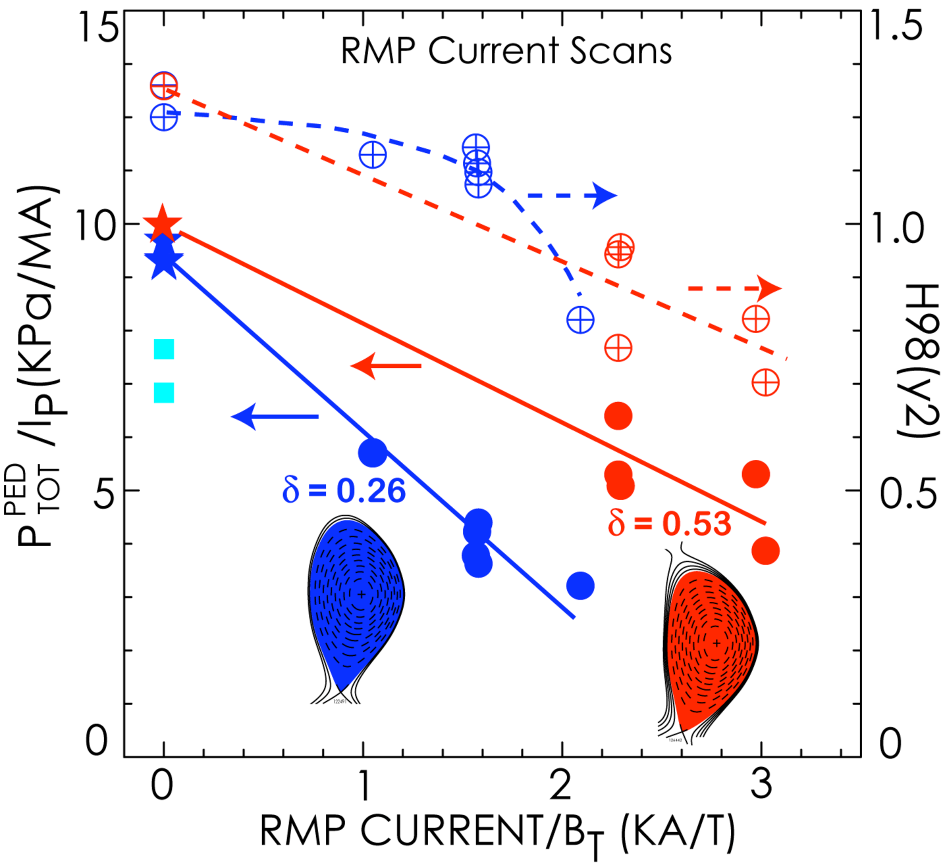


Profiles at min RMP current for ELM Suppression

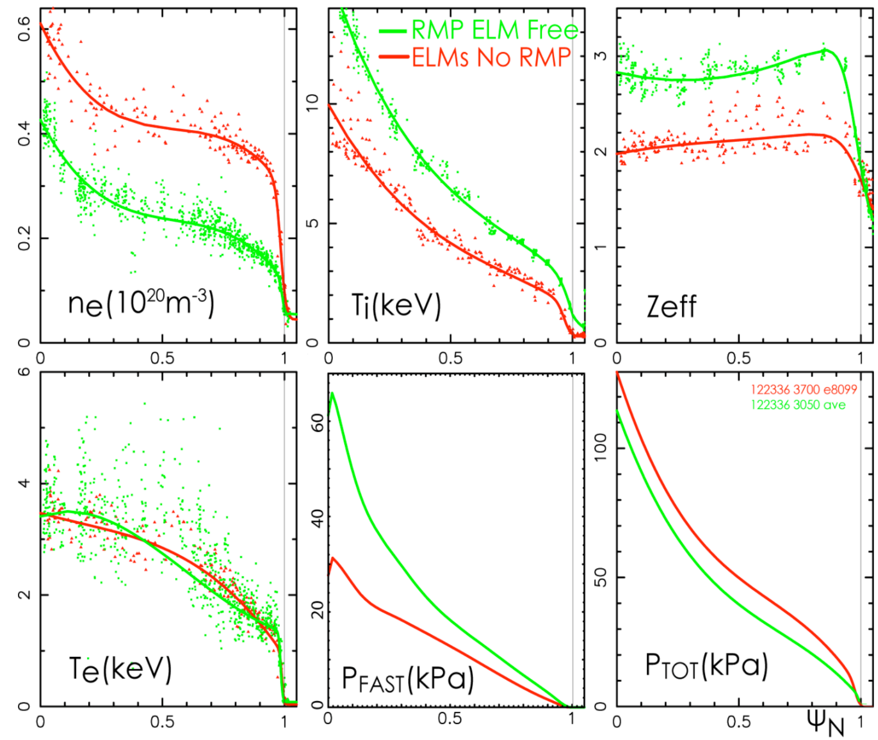


Energy Confinement Remains Good in RMP ELM Suppressed Discharges, Somewhat Worse at Higher δ

- **Reduction in P_{PED} at low δ offset by peaking of n_e profile, increase in T_i and fast ion pressure, and $n_e^{0.41}$ dependence of ITER98y2 scaling**
- **Differences with δ related to difference response of Z_{eff} and T_i (Evans CO1.00008)**

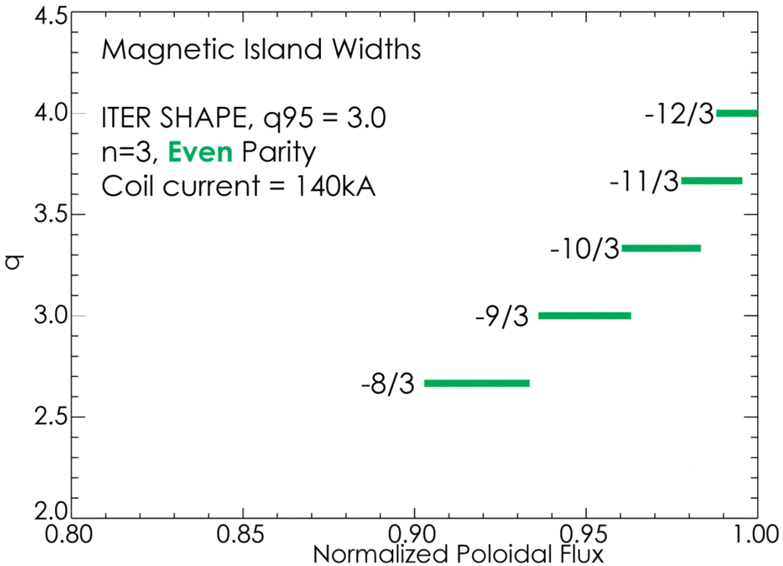


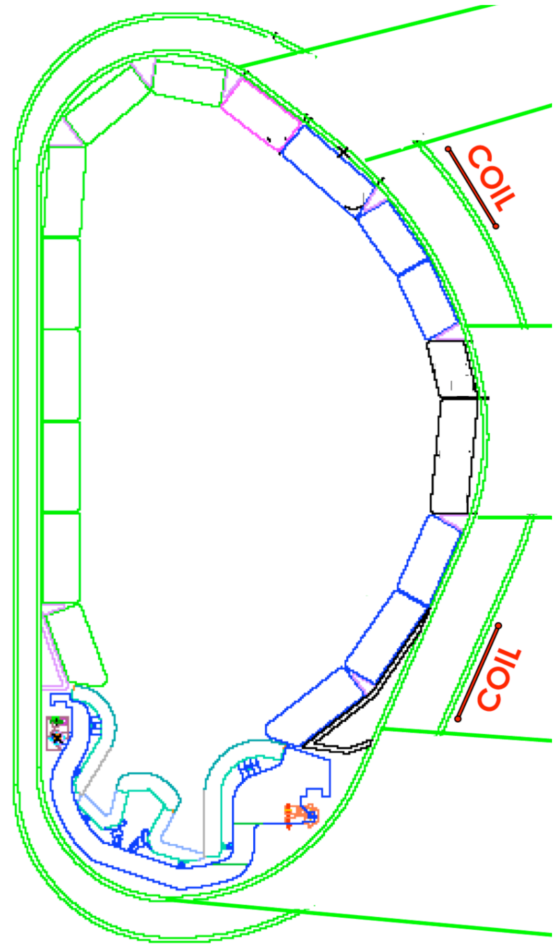
Profiles with and without RMP, δ=0.26



RMP ELM Suppression Might be Possible for ITER

- **Older study using 6 segment n=3 coil, like DIII-D, placed on outside of ITER vacuum vessel indicated 140kA would be required to produce the save island overlap required for suppression on DIII-D**





- **Work by M. Bécoulet* indicates currents could be reduced to 25 kA by mounting inside the vacuum vessel closer to the plasma**

***M. Bécoulet, et al., *Modeling of Edge Control by Ergodic Fields in DIII-D, JET, and ITER*, IAEA 2006, IT/P1-29**

Summary, Conclusions

- **RMP is an effective ELM suppression and density control technique applicable at ITER relevant shape, q, and collisionality**
  - An RMP coil for ITER is difficult but perhaps possible
- **A detailed understanding of the plasma response to the RMP is not complete, but coil acts to reduce edge P′ and J below peeling-ballooning mode stability threshold suppressing ELMS, while still allowing the pedestal pressure to stay relatively high**
- **QH-mode is also an attractive ELM suppressed regime which requires operation near the low n peeling stability limit where rotational shear drive coupled with wall drag may result in the saturated EHO that gives QH-mode its density control**
  - Access to the low n peeling unstable regime would be possible in ITER up to densities of ~ $0.3x10^{20}m^{-3}$
  - The counter injection requirement for QH-mode is yet to be understood