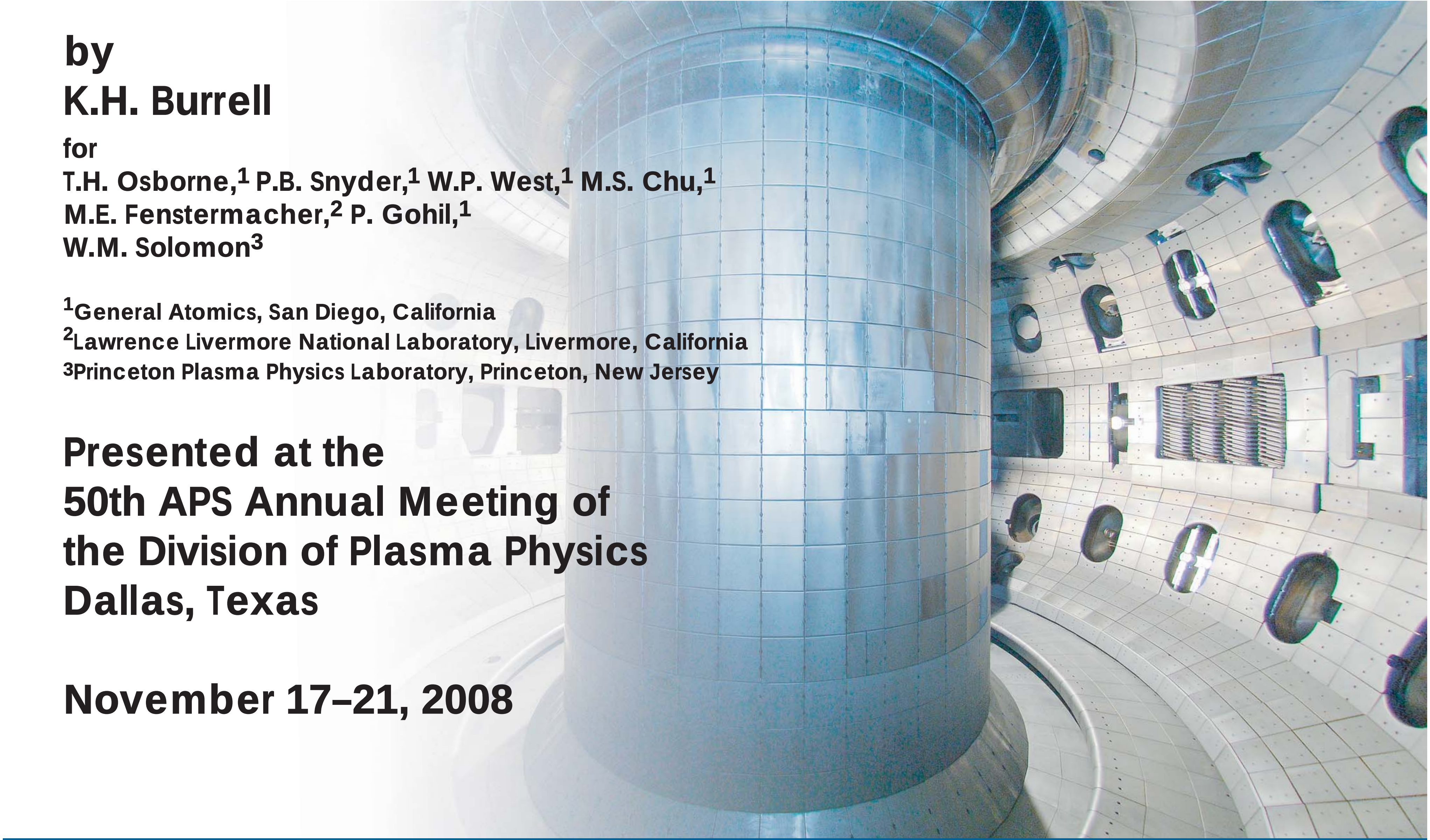
Edge Pedestal Control in Quiescent H-Mode Discharges in DIII-D Using Co Plus Counter Neutral Beam Injection



by

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for

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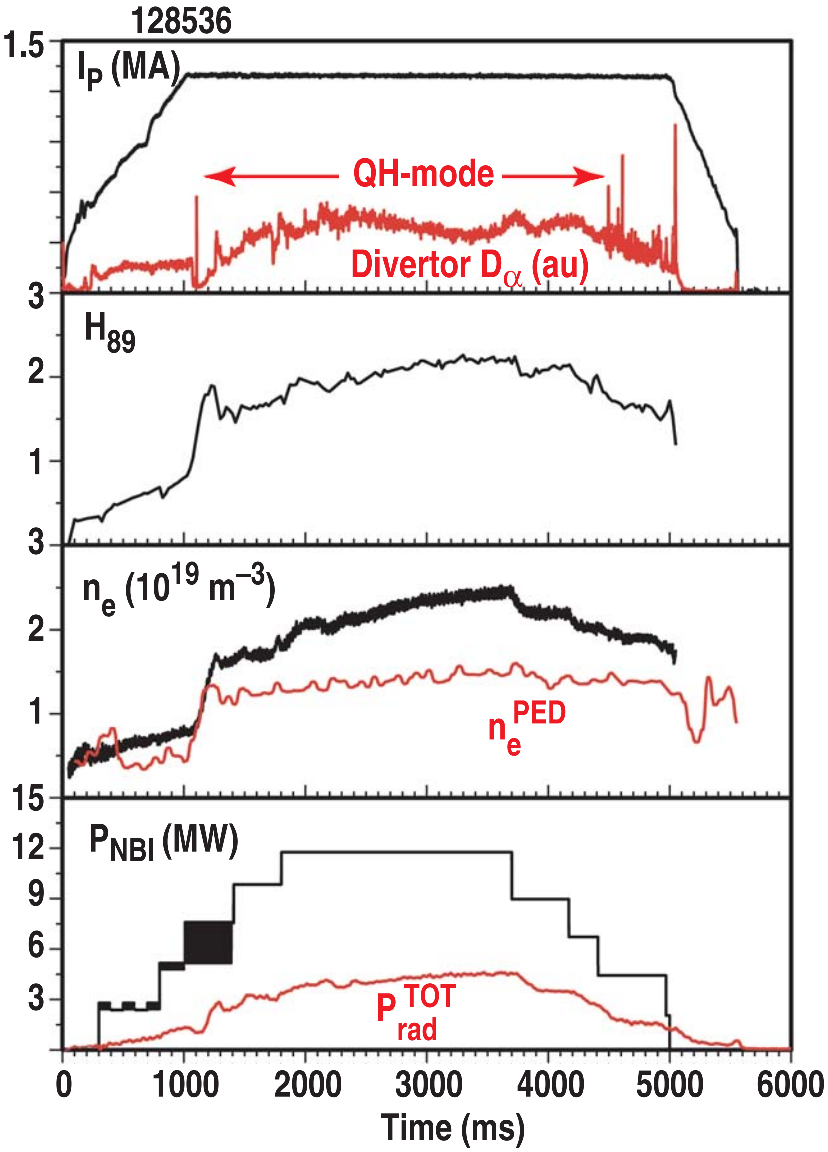
DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

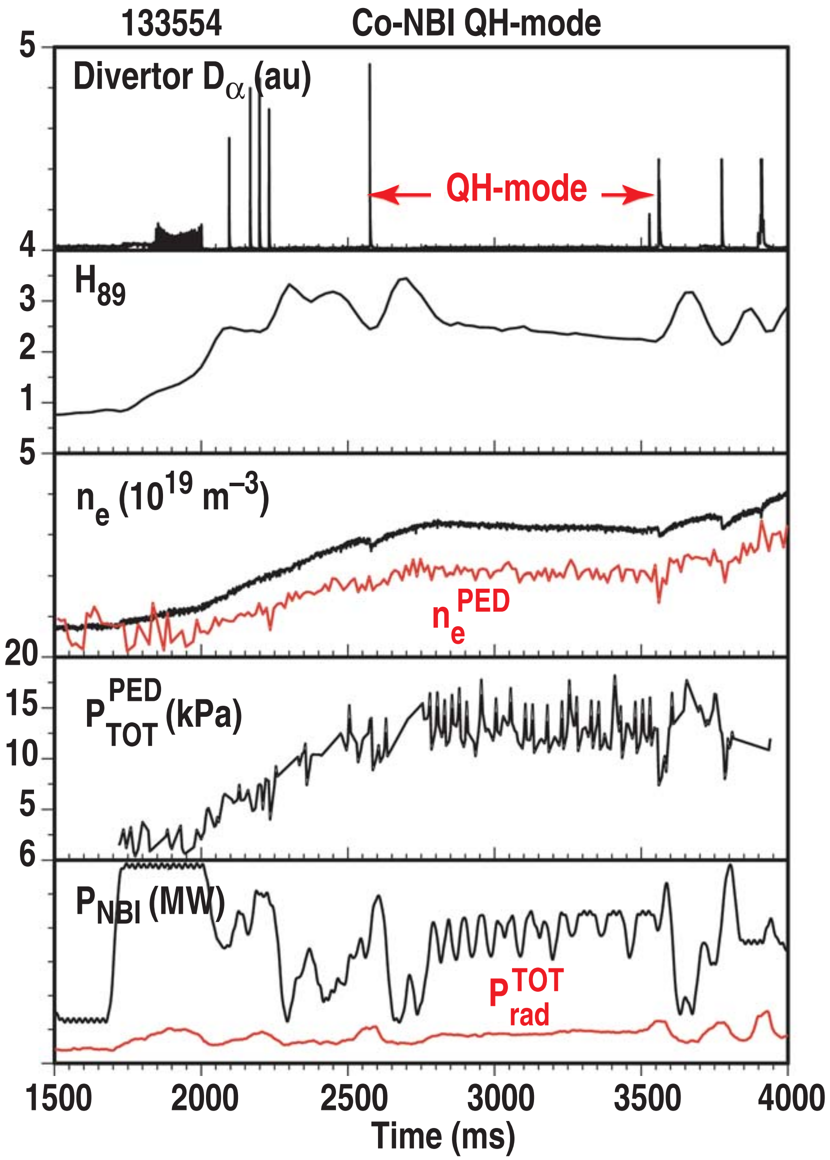
Quiescent H-Modes are the Ideal H-mode Plasmas

- **Quiescent H-modes (QH-mode) exhibit H-mode confinement and operate ELM-free with**
  - Constant density and radiated power
  - Long duration (> 4 s or 30 τ_E) limited only by hardware constraints
- **No ELMs means no pulsed divertor heat loads**
  - Quite important for next step devices such as ITER
- **Time-averaged edge particle transport is faster than in ELMing H-mode**
  - Facilitates He ash exhaust
- **QH-mode seen from 3 MW to over 15 MW**
  - Maximum power limited by core beta limit
- **QH-mode discovered in DIII–D**
  - Subsequently seen in JT-60U, ASDEX–U and JET



Recent Experiments Investigated Effects of Plasma Rotation on QH-mode

- **Achieved QH-mode operation over a continuous torque range, from all counter-injection to near balanced injection**
- **Demonstrated QH-mode operation with all co-injection**
- **Discovered that edge particle transport can be continuously adjusted by varying edge rotation**
  - Achieved maximum pedestal density and pressure possible without ELMs
- **Experiments test peeling-ballooning mode stability theory**
  - Theory provides ELM stability limits; shape dependence is quite important
  - Provides basis for theory of edge harmonic oscillation, which controls edge particle transport in QH-mode



Outline

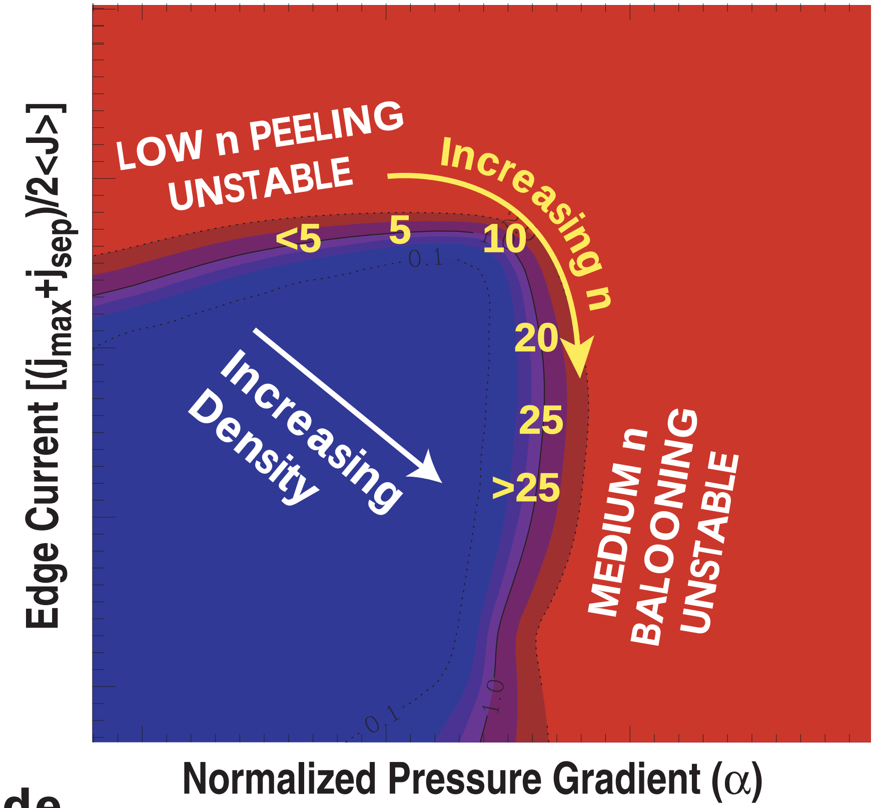
- Peeling-ballooning mode stability theory and edge harmonic oscillation (EHO)
- Effect of edge rotation on pedestal density and EHO
- Shape optimization: QH-mode with higher pedestal density and pressure
- Simultaneous shape and rotation optimization
- QH-mode with 100% co-injection

Edge Peeling-Ballooning Mode Stability Theory Guides QH-Mode Experiments

- **Peeling-ballooning mode stability theory is embodied in codes such as ELITE [P.B. Snyder, Phys. Plasmas (2002)]**

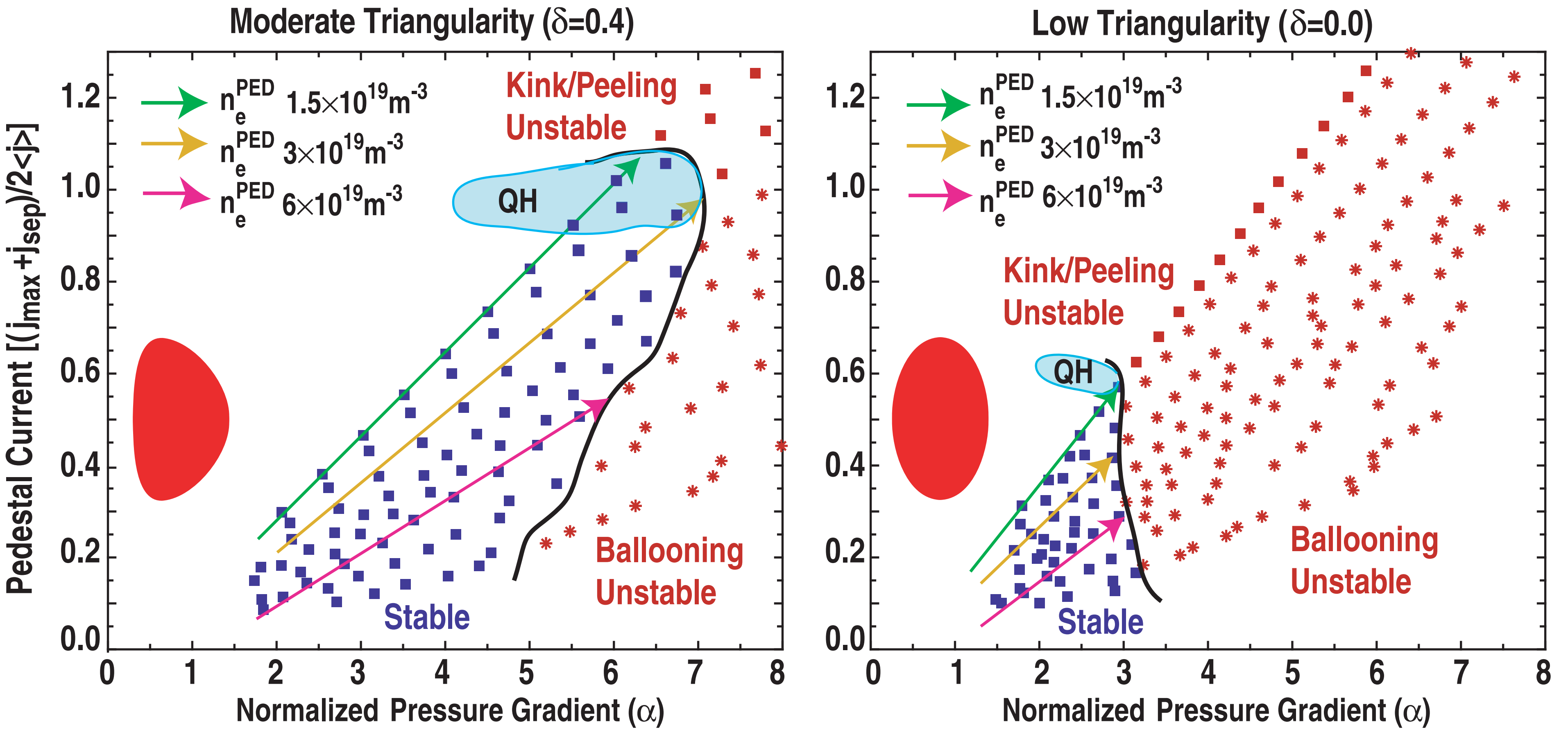
- **Modes are driven unstable by edge pressure gradient and by edge current**
  - Simplified, 2 D stability diagram can be plotted using these parameters

- **As density and collisionality increase, most unstable modes move from low toroidal mode number n < 5 on peeling boundary to high n > 25 on ballooning boundary**



Stable Region is Much Broader in More Highly Shaped (Triangular) Plasmas

- **Experimental results show QH-mode exists along peeling boundary**

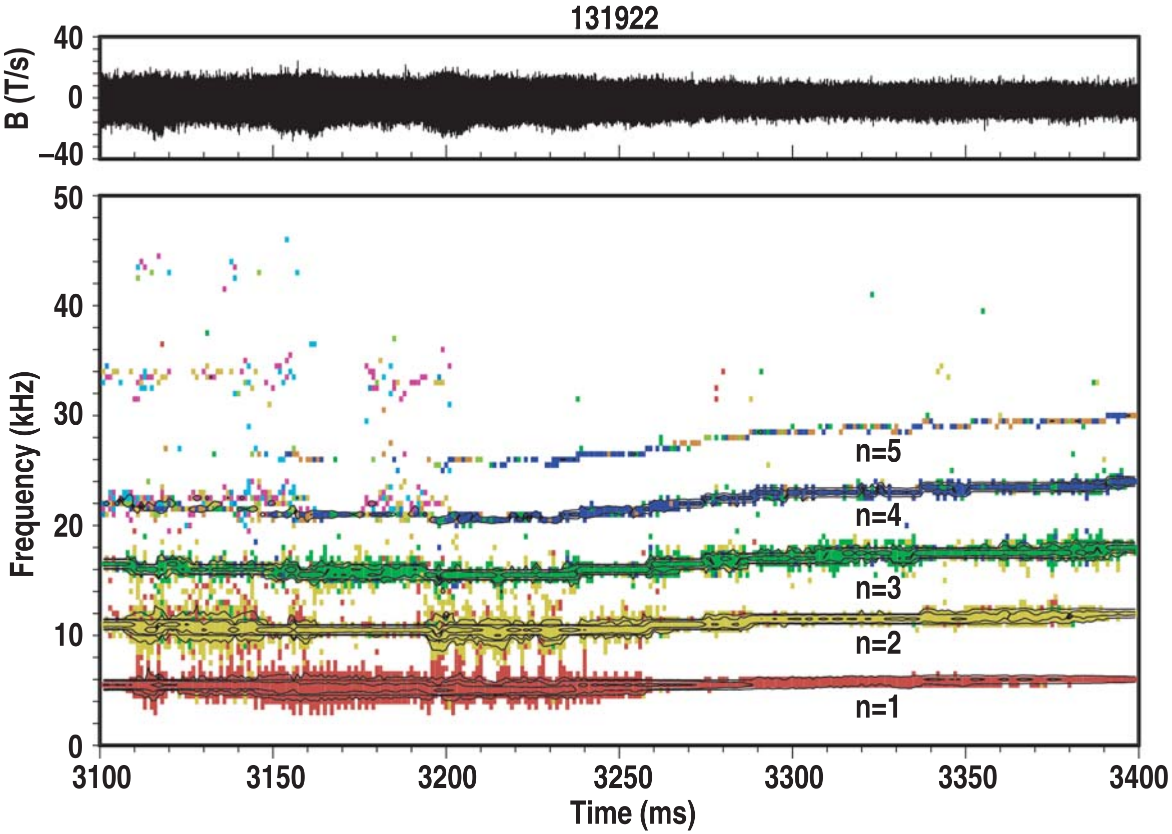


Moderate Triangularity (δ=0.4)

Low Triangularity (δ=0.0)

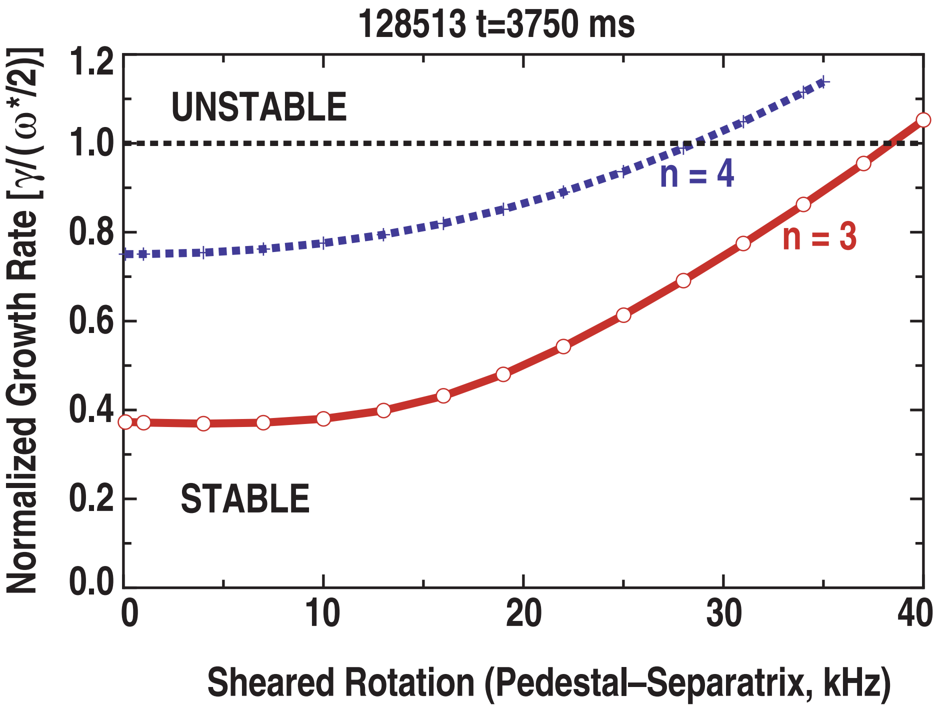
Edge Harmonic Oscillation (EHO) is Key to QH-Mode Operation

- **Edge harmonic oscillation (EHO) is an edge localized, electromagnetic oscillation**
  - Waveform is typically nonsinusoidal with multiple toroidal harmonics n
- **Previous work showed the EHO enhances edge particle transport [K.H. Burrell et al., Phys. Plasmas (2005)]**
- **Edge transport enhancement allows transport equilibrium at edge parameters just below peeling-ballooning mode limit**



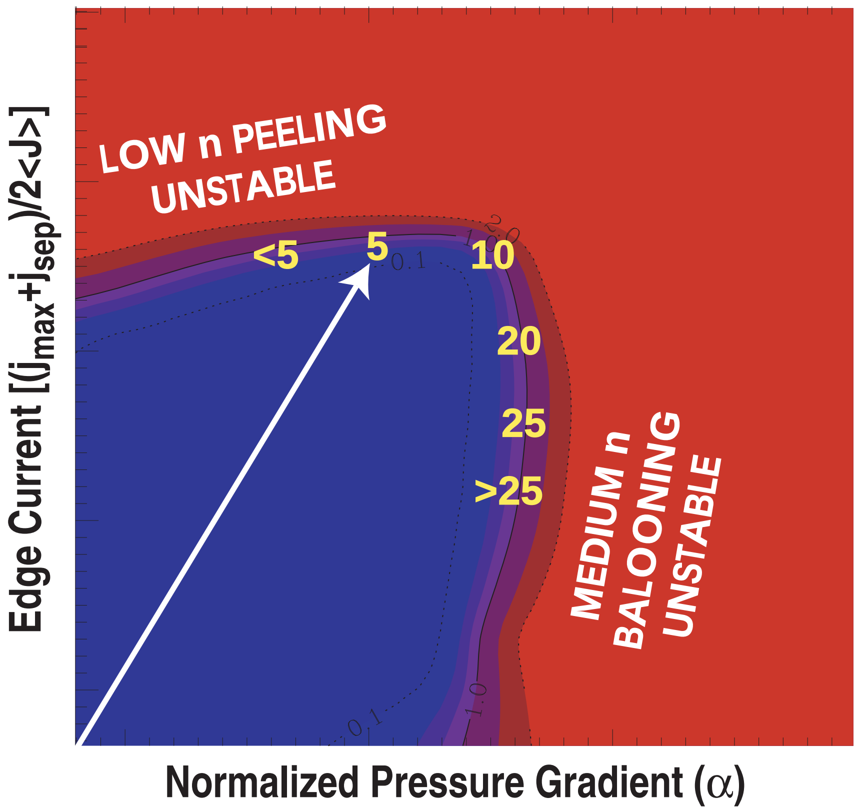
Theory of Edge Harmonic Oscillation Based on Effect of Rotational Shear on Peeling-Ballooning Stability

- **ELITE calculations show low n kink-peeling modes are destabilized by shear in the edge rotation**
- **Theory posits that EHO is low-n peeling-ballooning mode destabilized by rotational shear just before edge plasma reaches the zero-rotation stability boundary [P.B. Snyder, Nucl. Fusion(2007)]**
- **Theory predicts that rotational shear effect is independent of direction of plasma current — QH-mode should be possible with both co and counter injection**



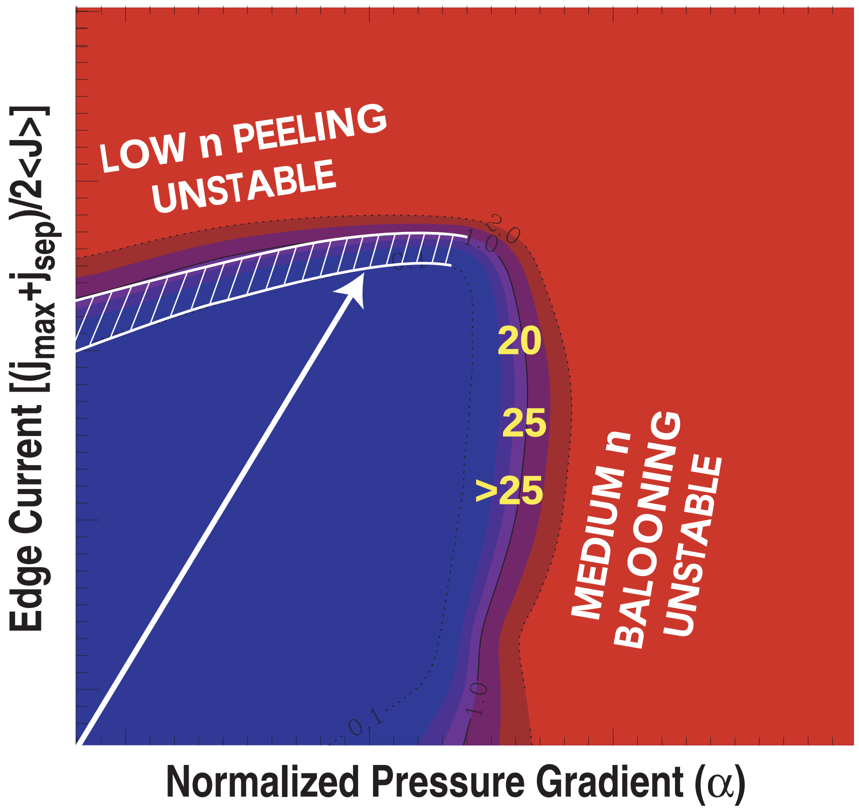
Without Edge Rotational Shear, ELM Occurs When Edge Operating Point Crosses Peeling Boundary

- **After L to H transition edge operating point moves up towards peeling boundary for low density shots**
- **Without rotation, once stability boundary is crossed, peeling mode grows to very large amplitude ELM before it finally drops edge current density**
  - Instability growth rate >> rate of change of edge current because of plasma inductance



Edge Rotational Shear Allows EHO to Grow Up and Saturate Before Plasma Edge Reaches Peeling Boundary

- **After L to H transition edge operating point moves up towards peeling boundary for low density shots**
- **With sufficient edge rotational shear, stability boundary moves down and EHO turns on before edge operating point reaches the hard, current-driven boundary**
- **With finite amplitude EHO enhancing edge transport, plasma reaches transport equilibrium at operating point near but below the no-rotation peeling boundary**



- **Multiple feedback loops allow EHO to reach steady state**
  - EHO driven by rotational shear but reduces shear by drag on wall
  - EHO enhances particle transport, reducing edge pressure gradient and edge bootstrap current drive of mode

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- Peeling-ballooning mode stability theory and edge harmonic oscillation (EHO)
- **Effect of edge rotation on pedestal density and EHO**
- Shape optimization: QH-mode with higher pedestal density and pressure
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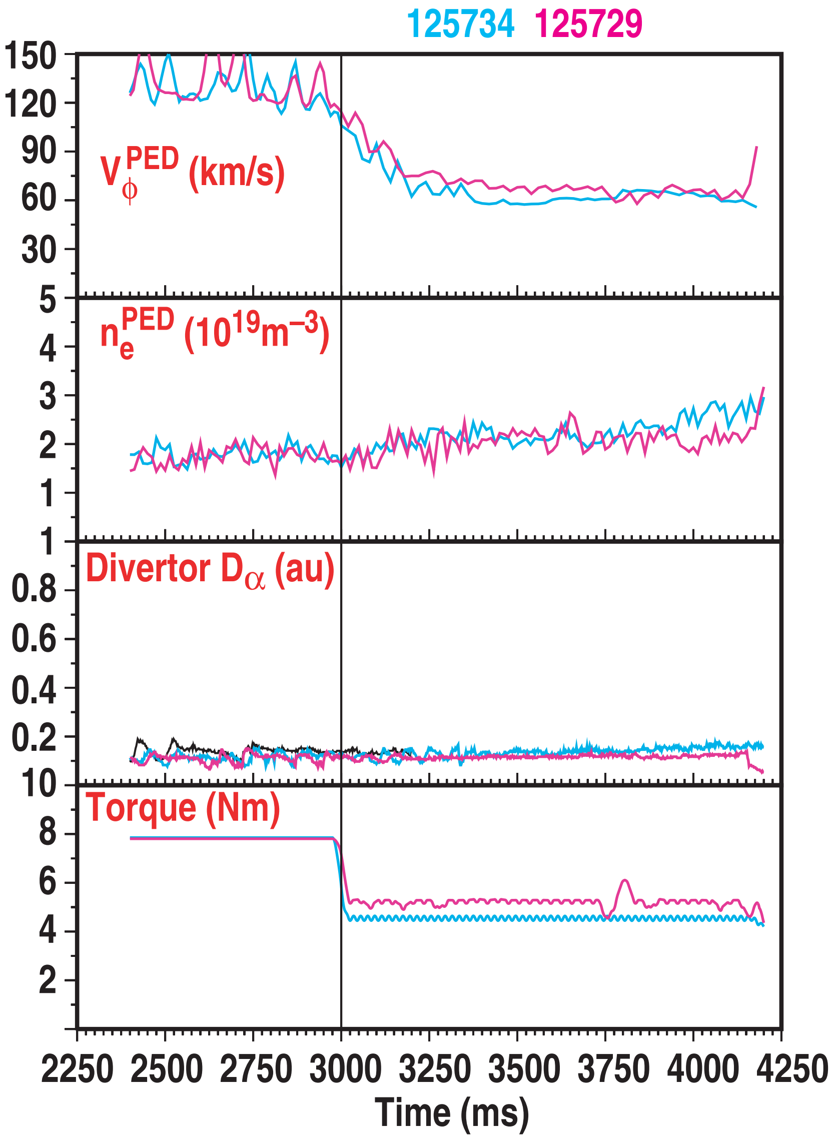
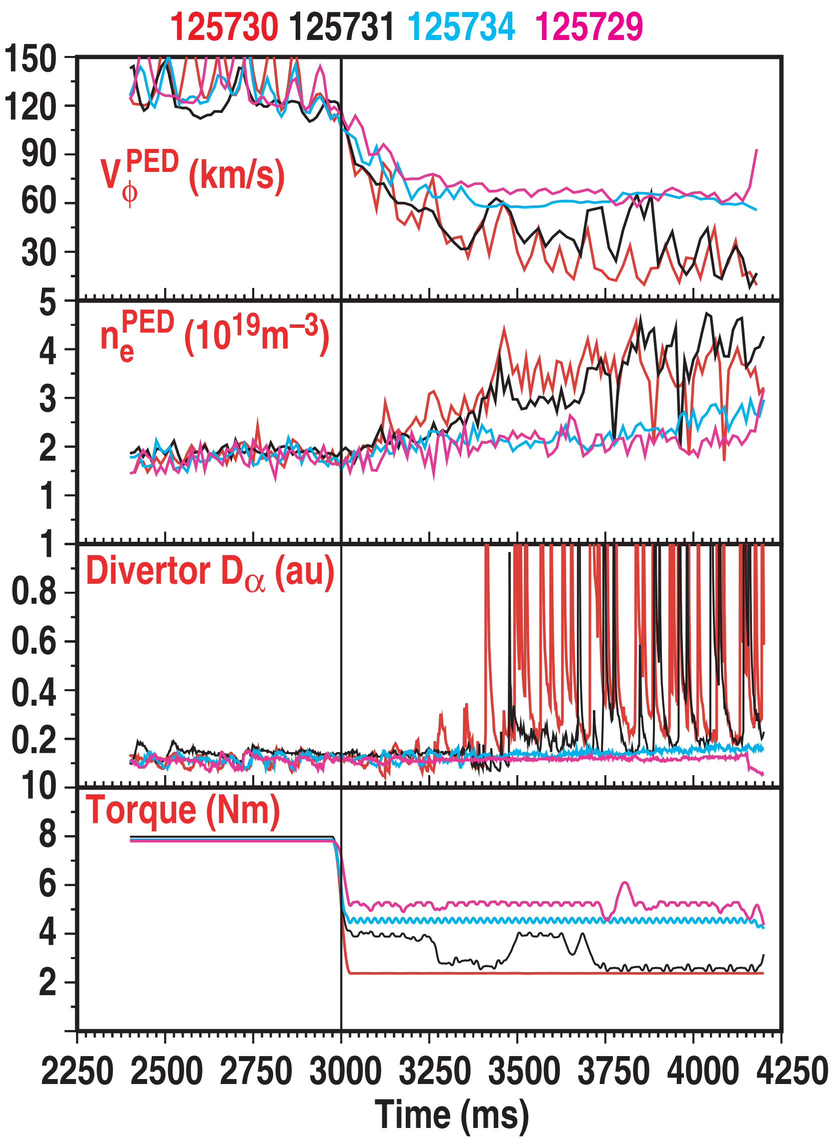
H-Mode Pedestal Density Increases as Net Torque is Reduced at Constant Input Power



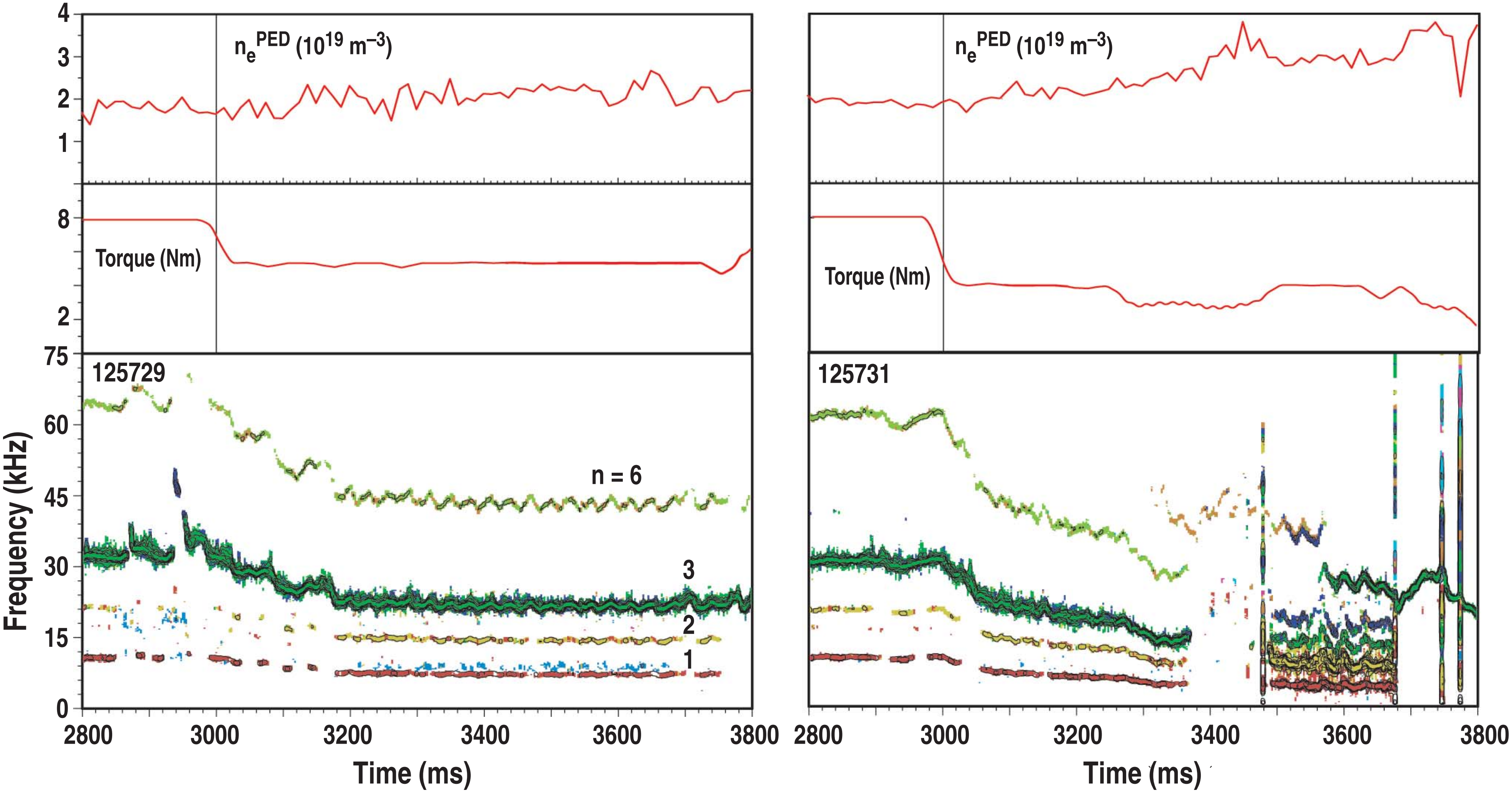
- **In 2006, DIII-D was equipped with simultaneous co plus counter NBI capability**
- **QH-mode pedestal density increases as input torque is reduced at constant input power**

H-Mode Pedestal Density Increases as Net Torque is Reduced at Constant Input Power



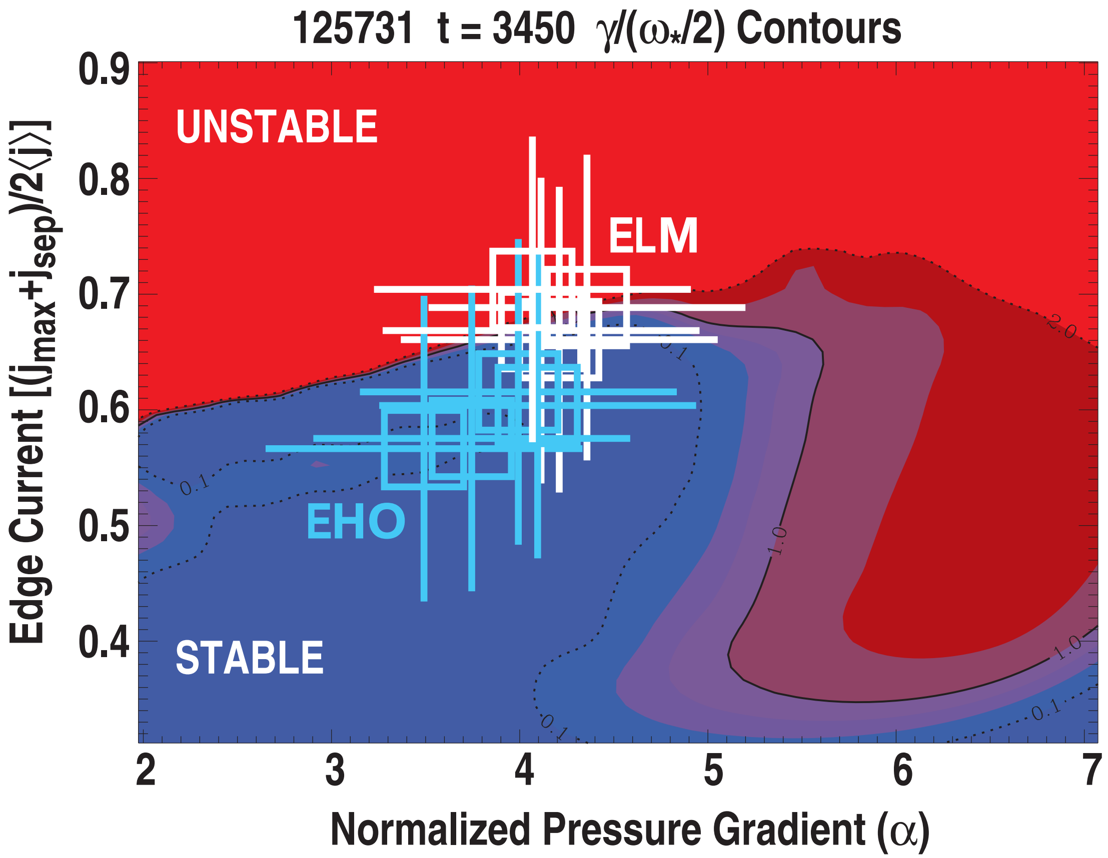
- In 2006, DIII-D was equipped with simultaneous co plus counter NBI capability
- QH-mode pedestal density increases as input torque is reduced at constant input power
- ELMs return at lower rotation and higher density
- Speculation: EHO-induced particle transport changes with changing rotation

Decreased Rotation Drops EHO Frequency
EHO Ceases When Rotation is Too Low



Operating Points of Shots at Various Torques Are Consistent with Edge Peeling-Ballooning Stability Theory

- **Stability calculations performed with ELITE code**
- **QH-mode plasma with EHO operates near but below peeling stability boundary**
- **ELMing shots are closer to peeling boundary**



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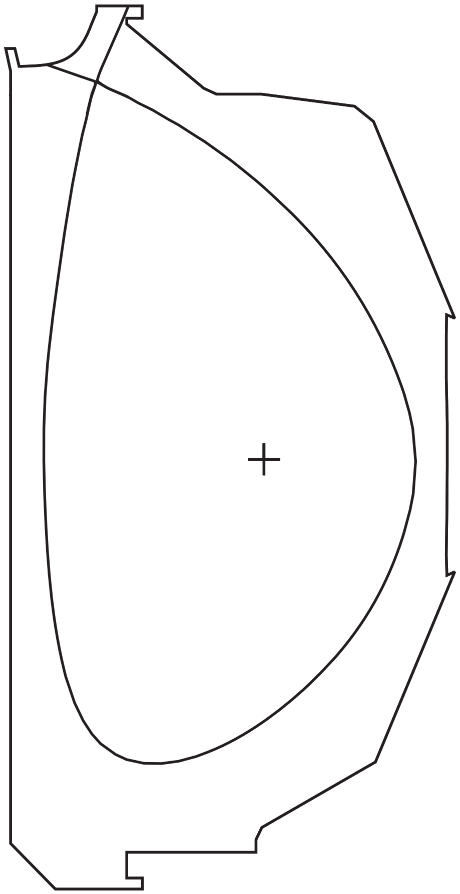
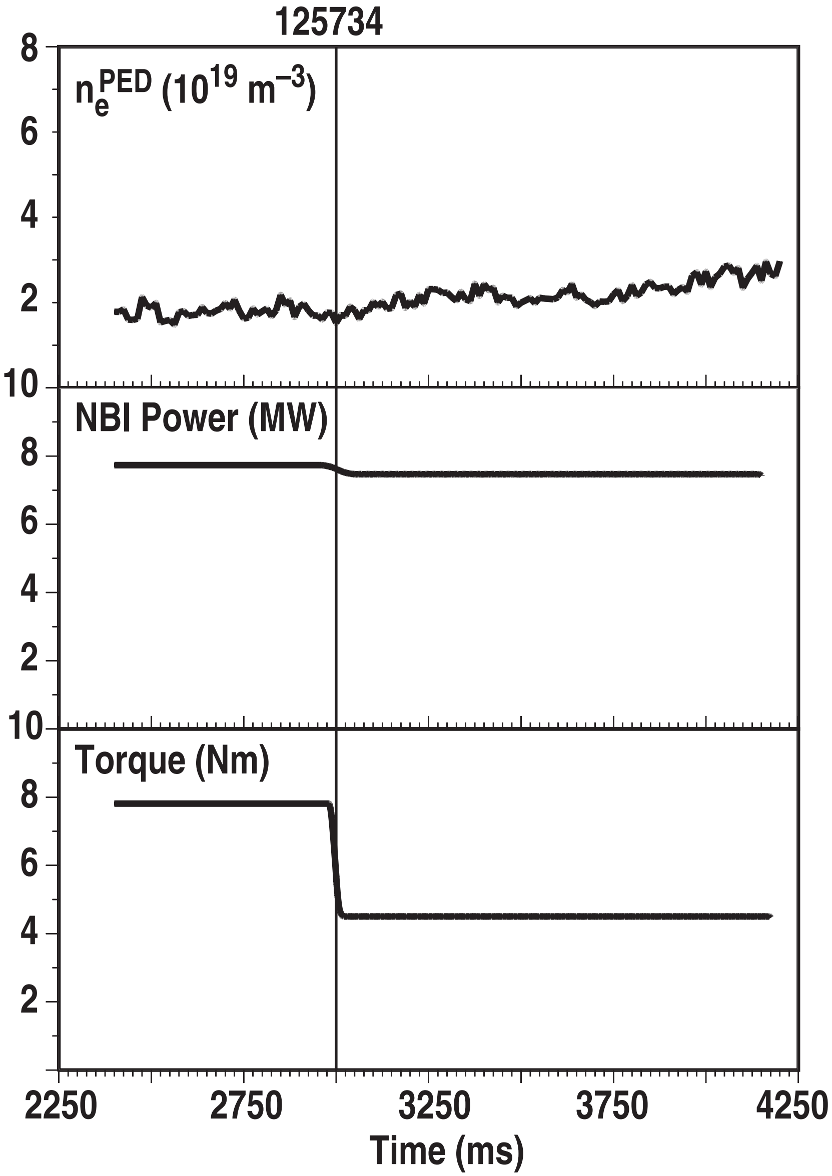
Higher Triangularity Allows QH–Mode Operation At Much Higher Pedestal Density





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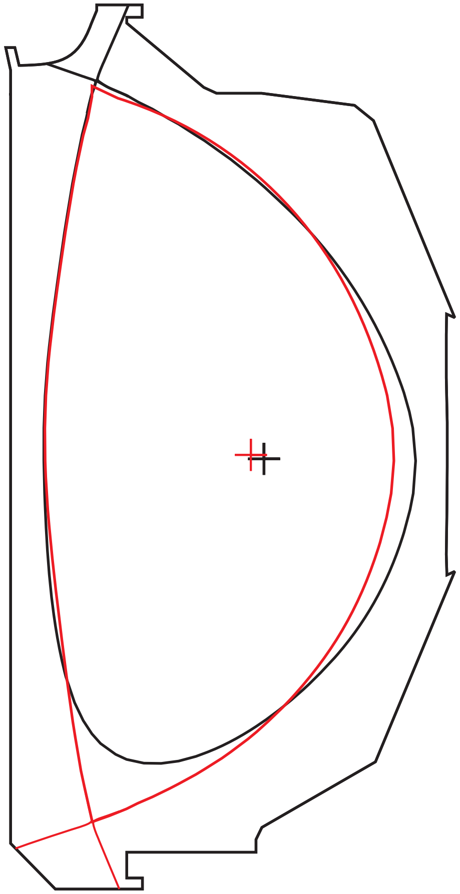
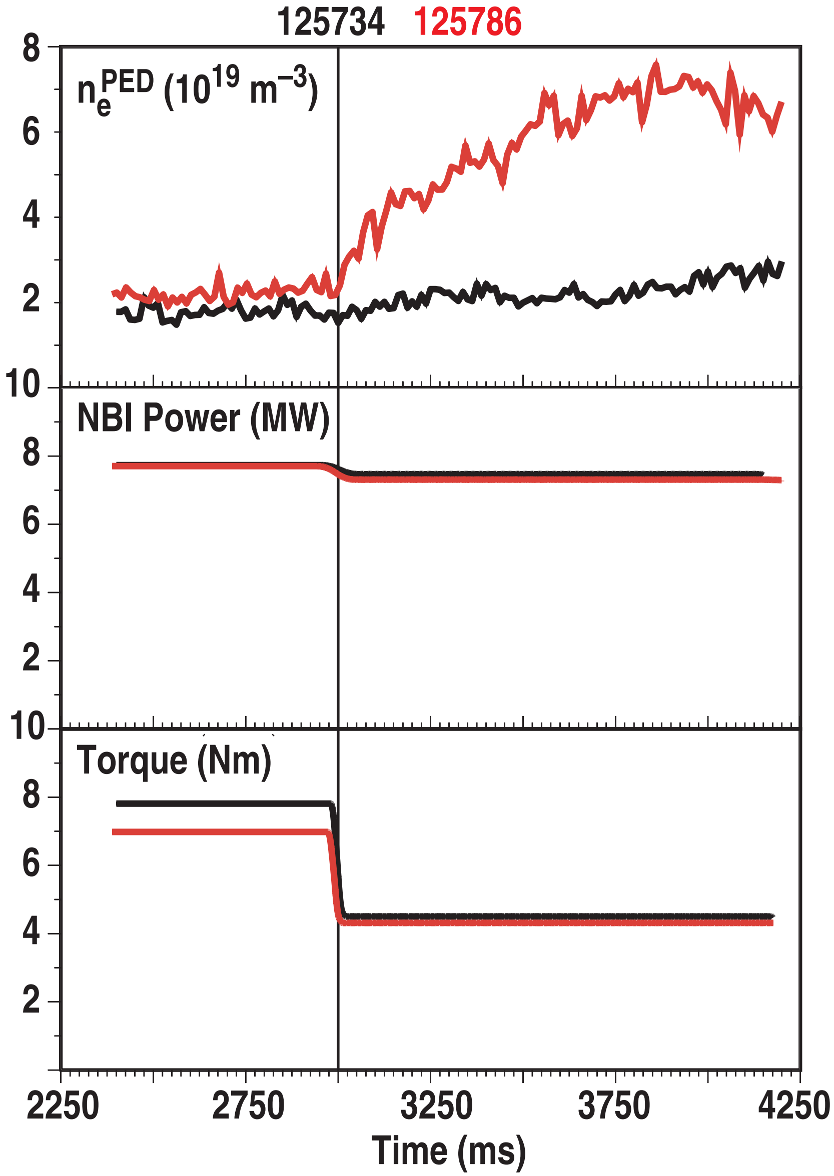
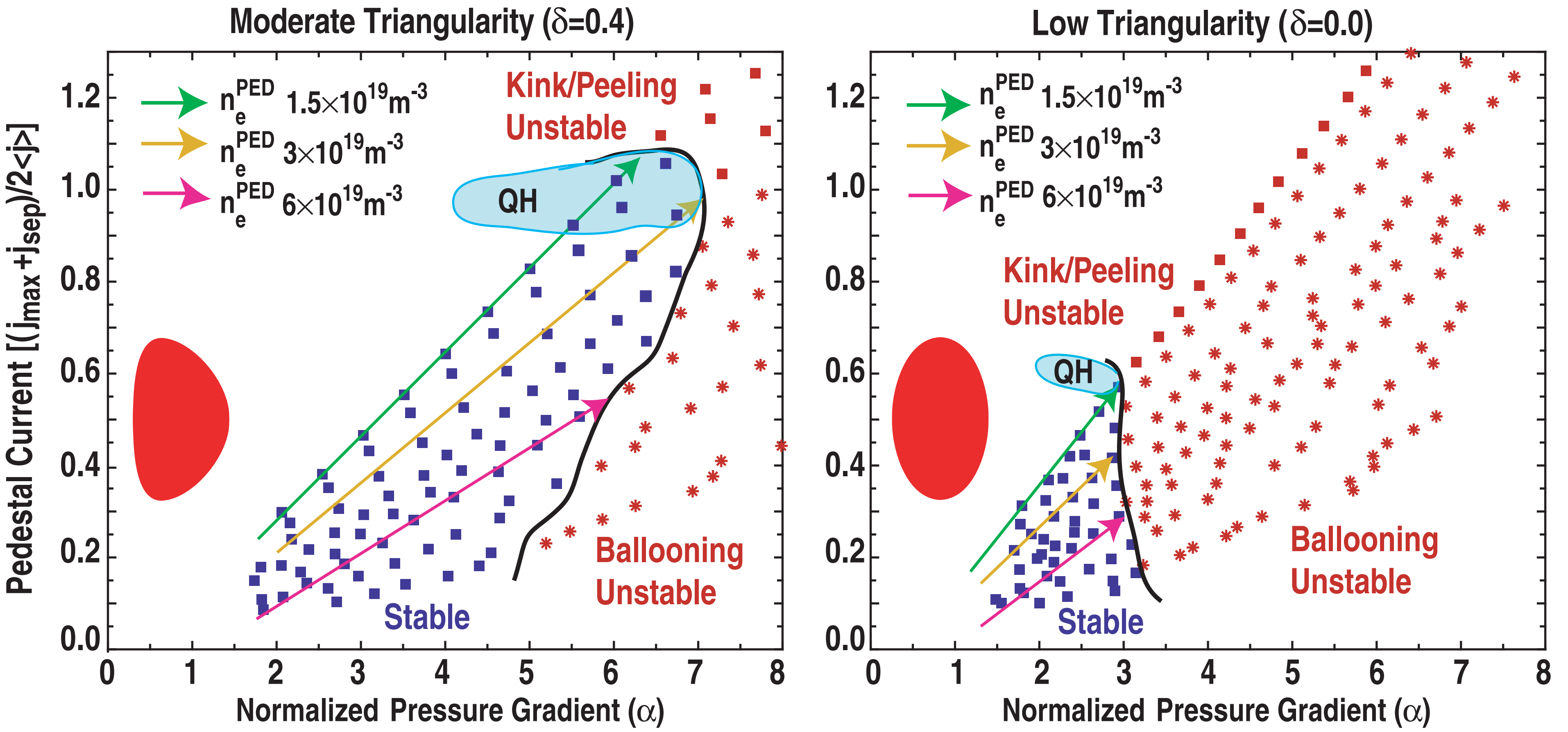




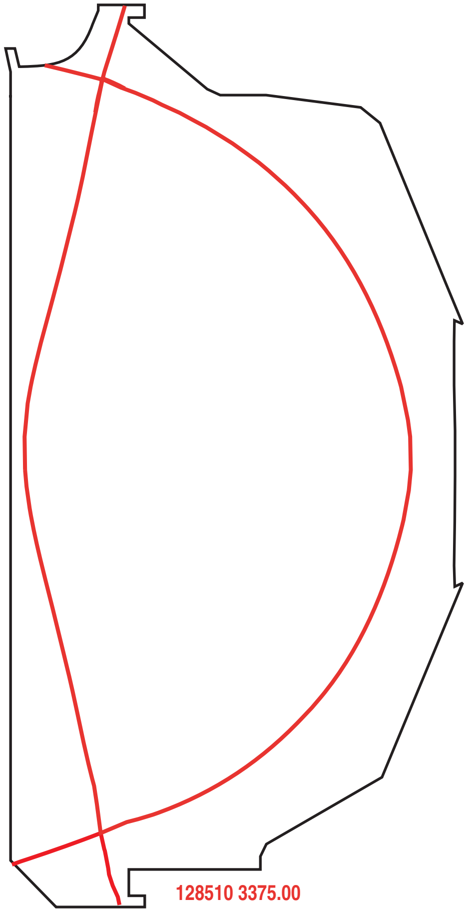
- n_e^{PED} up to $0.5\ n_{GW}$

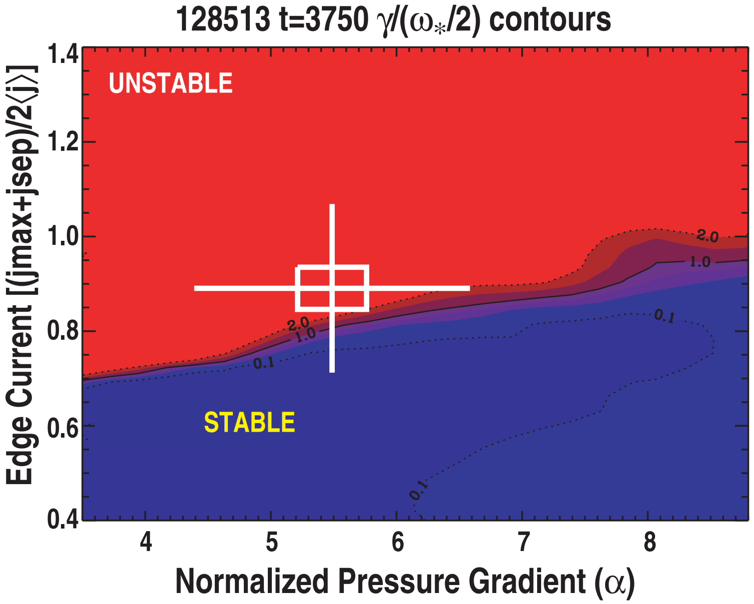
Higher Pedestal Density Consistent with Peeling-ballooning Stability

- **Theoretical prediction consistent with experimental observation of higher pedestal density in double null plasma**



Plasma Shape With Improved Edge Stability Developed for 2007 Campaign





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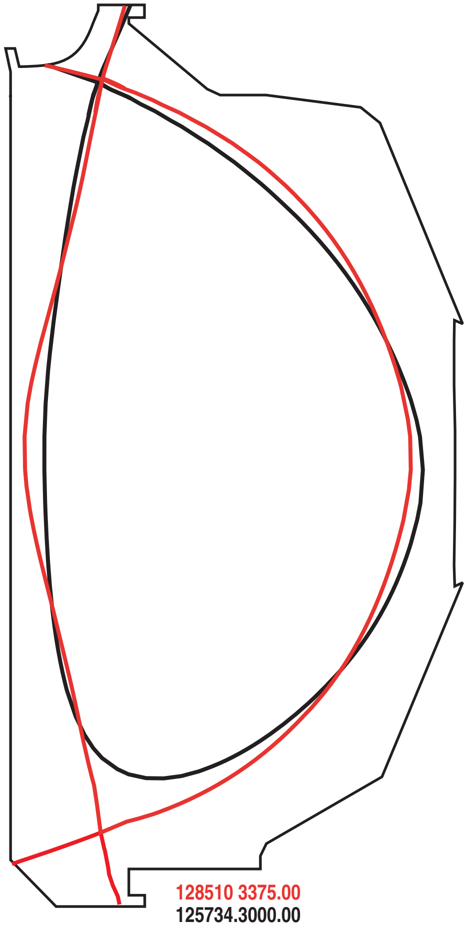

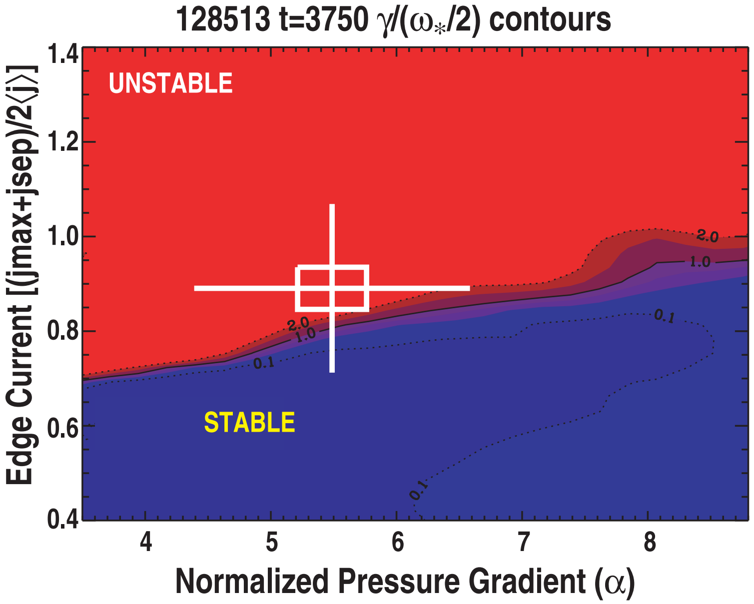

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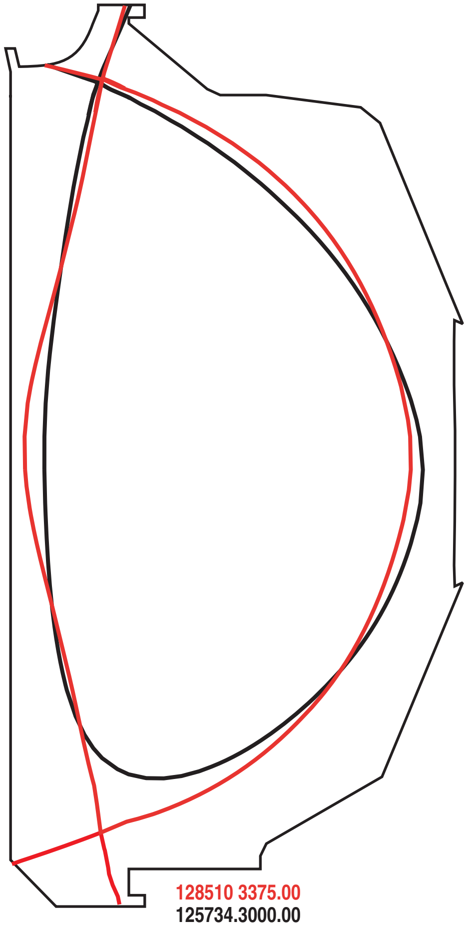
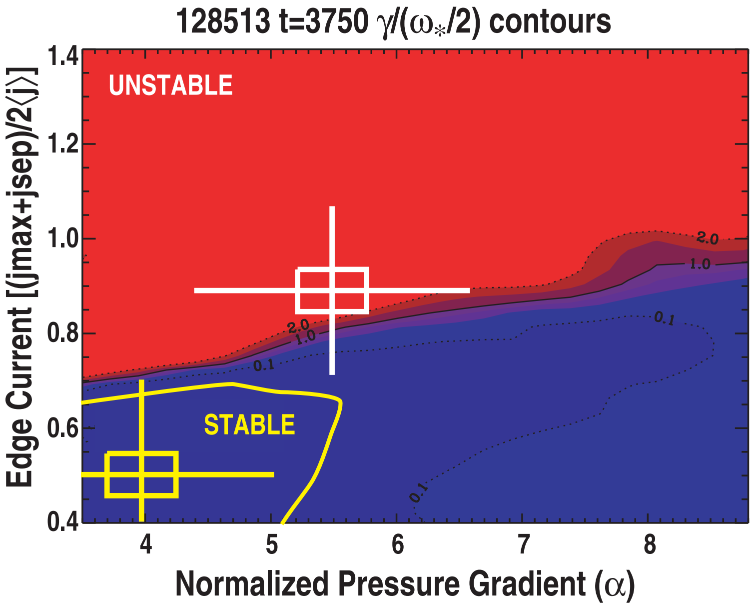


- **Improved operating point and broader stable region seen for double null shape**



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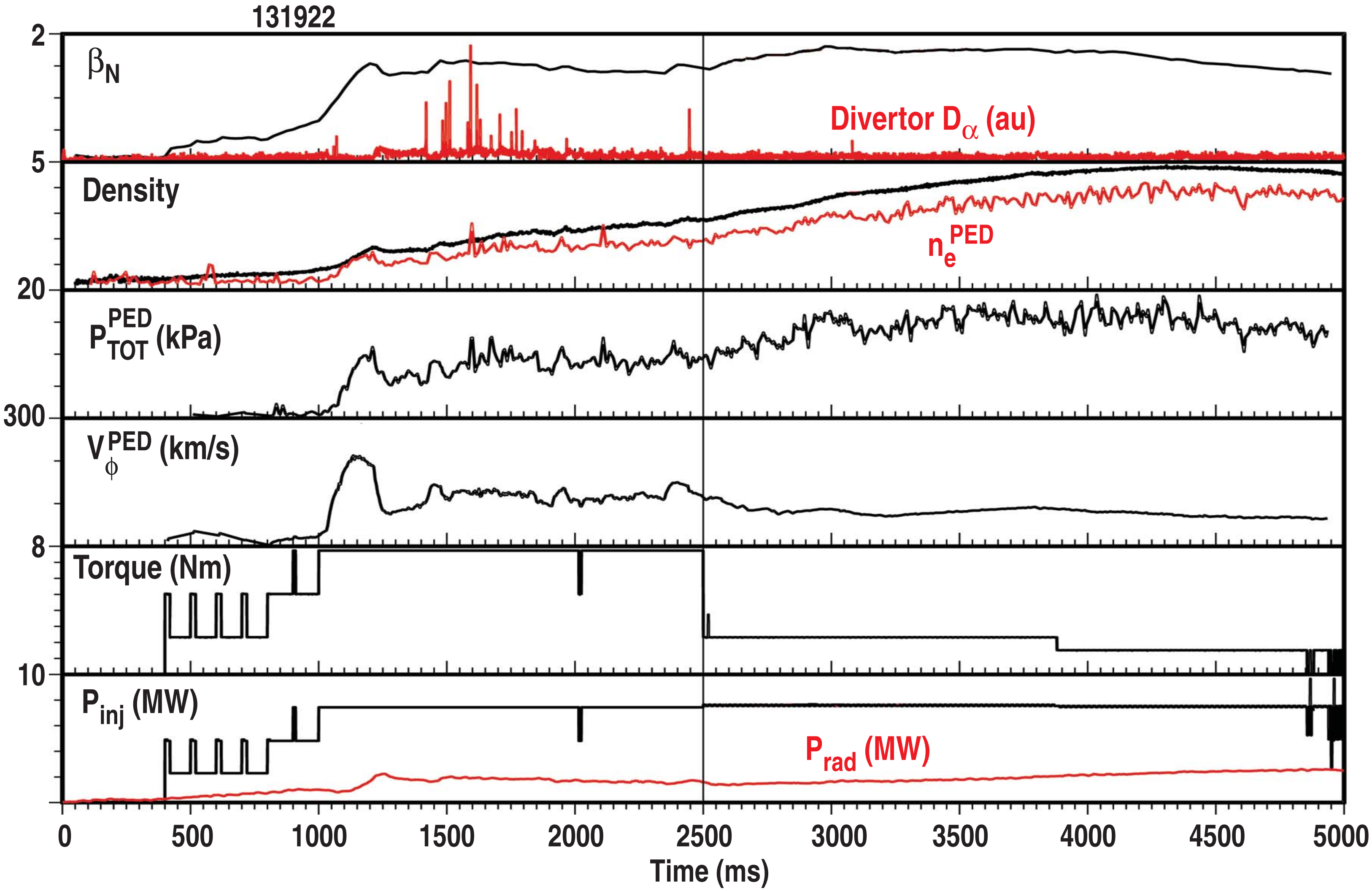
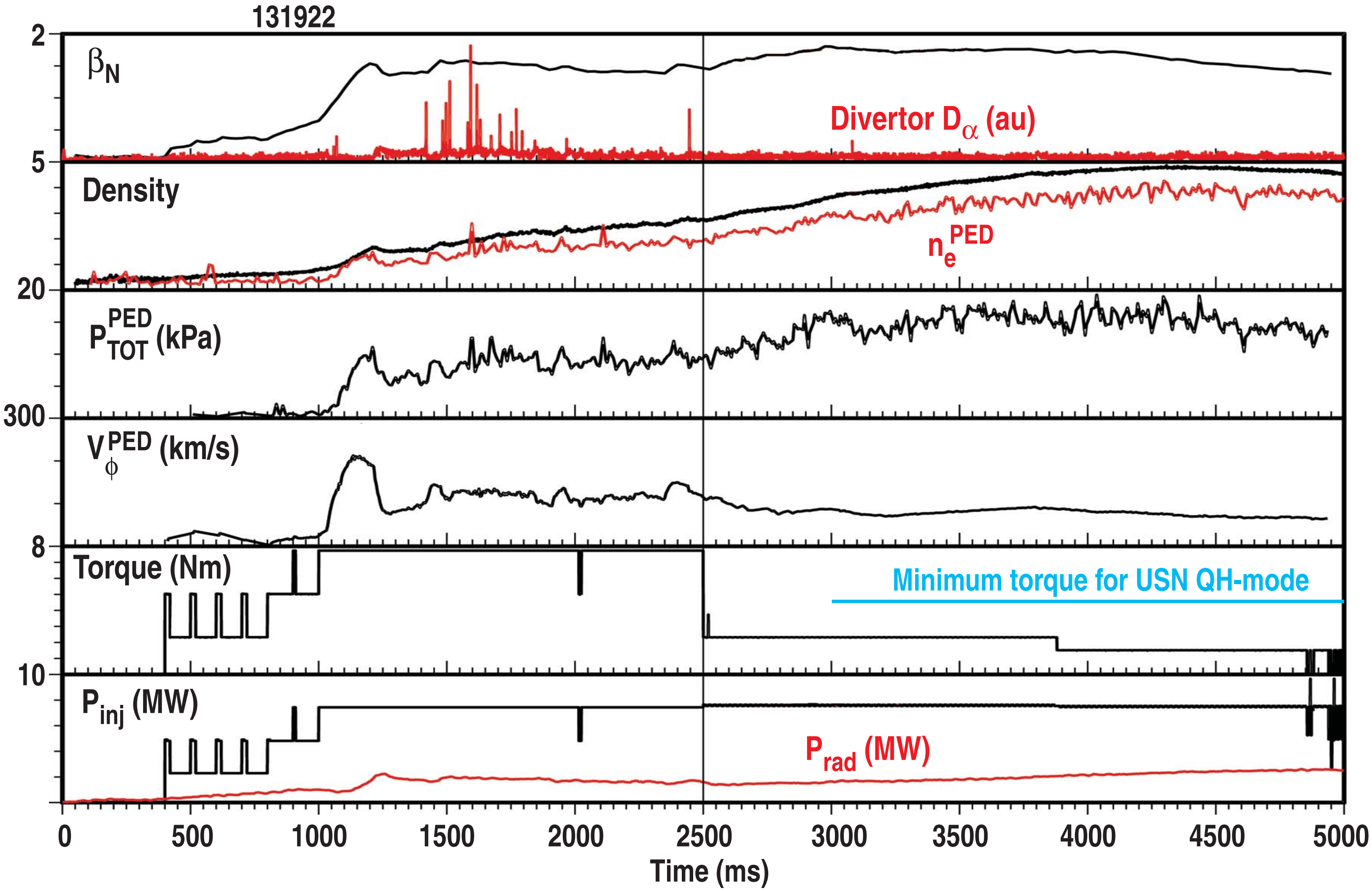
Rotation Control of Density and Improved Shape Allow QH-Mode Operation at Higher Pedestal Pressure and Higher Stored Energy



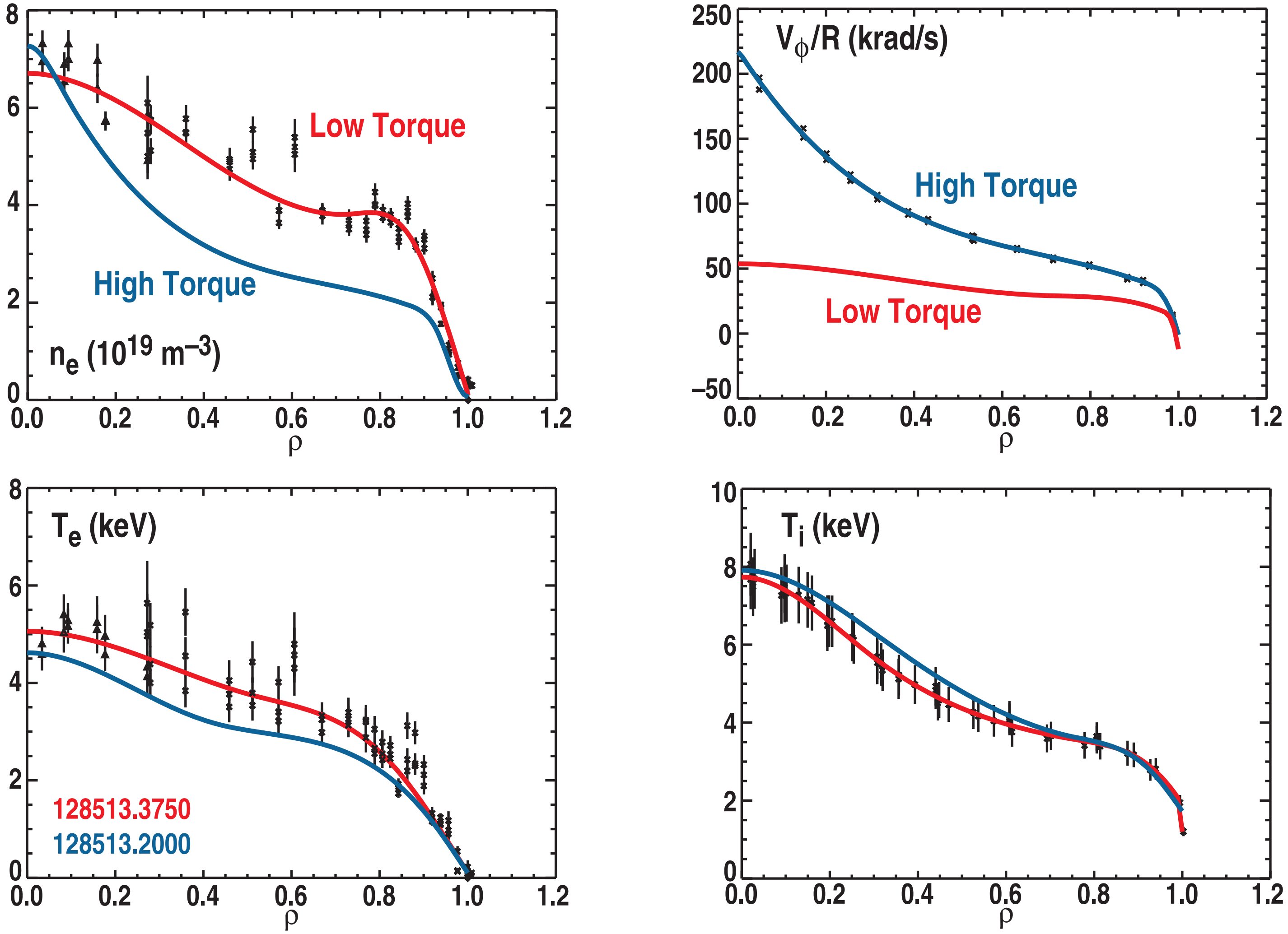
Rotation Control of Density and Improved Shape Allow QH-Mode Operation at Higher Pedestal Pressure and Higher Stored Energy

- Compared to upper single null shape, optimal shape allows QH-mode at factor 2.5 lower input torque



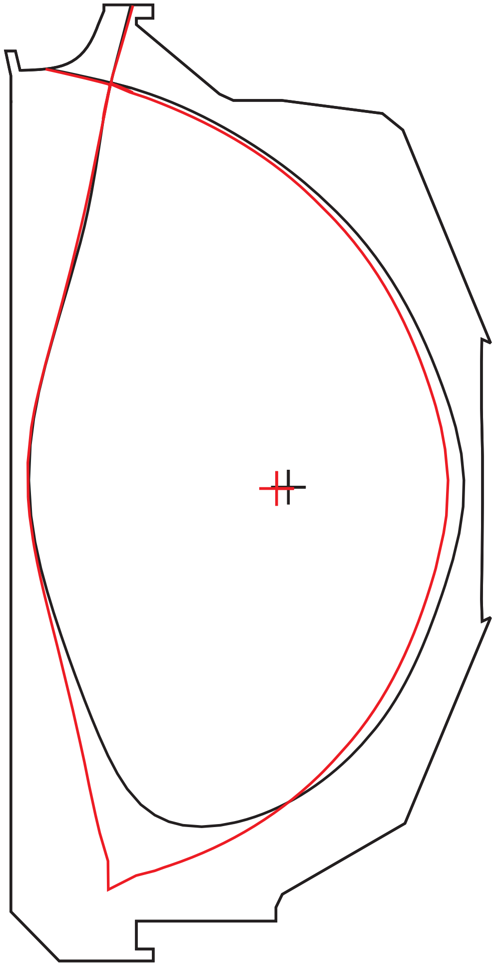
Edge Density Increases as Toroidal Rotation Decreases

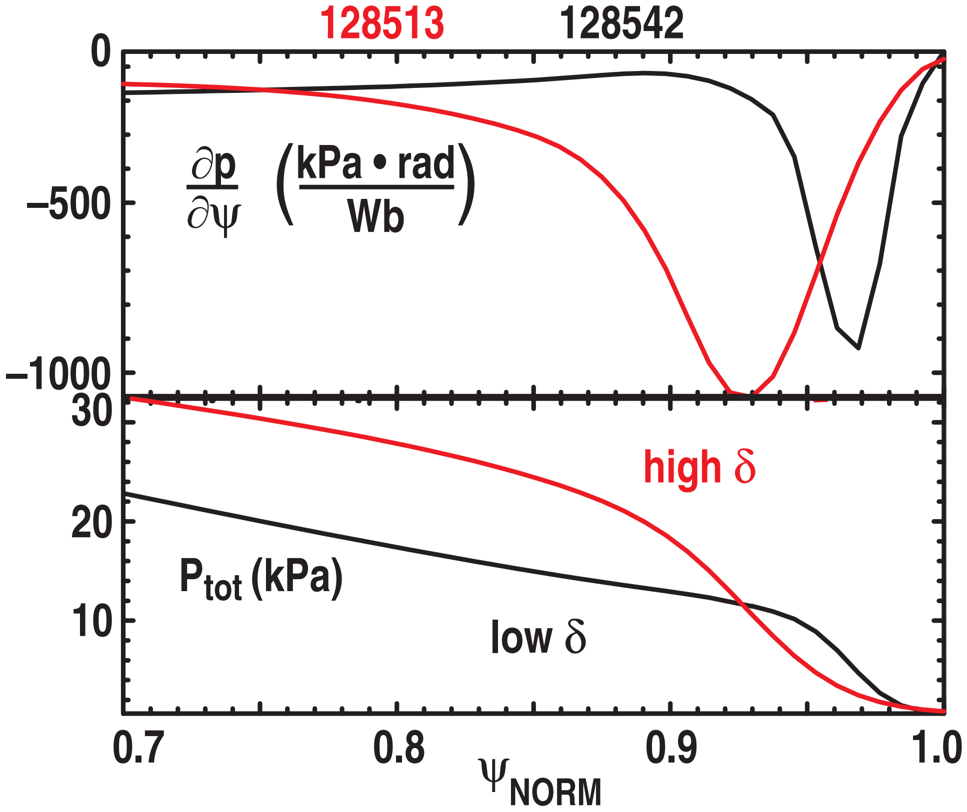
- **Global stored energy and energy confinement time increase 35% at lower rotation**



Stronger Plasma Shaping Allows QH-mode Operation with Higher Pedestal Pressure

- Higher triangularity gives higher stable p′ and broader pedestal width





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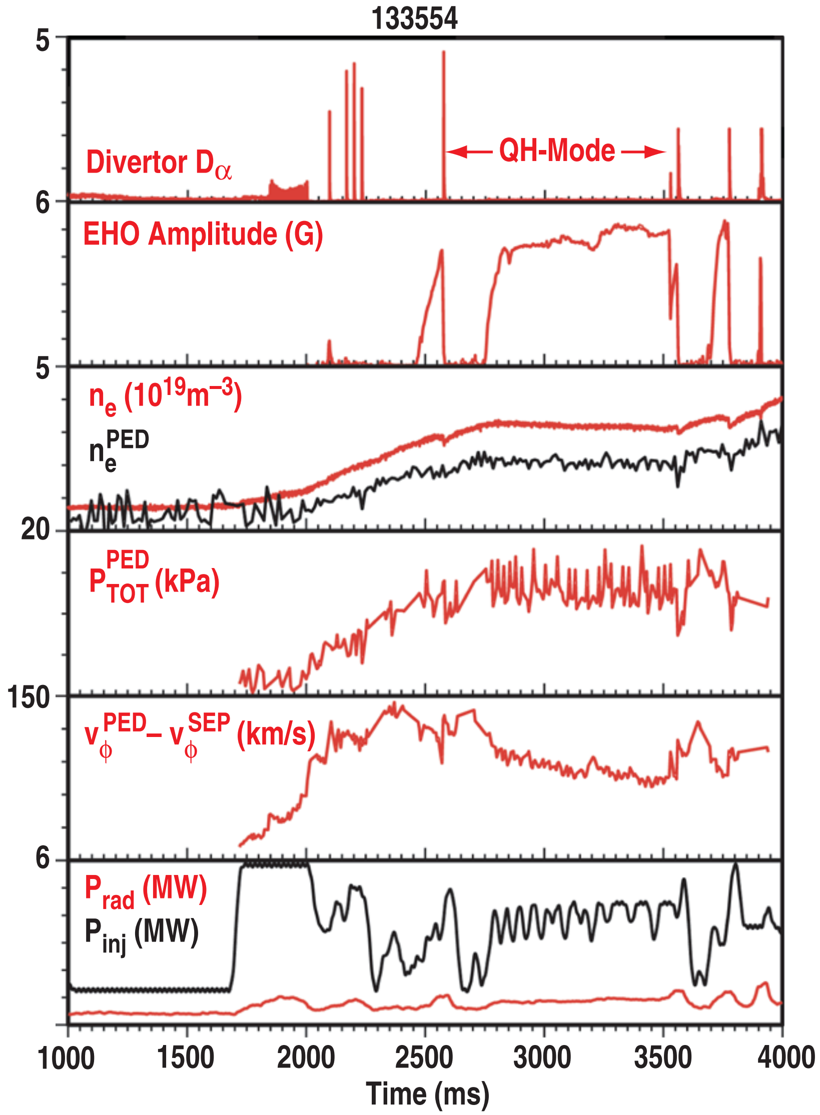
QH-Mode Operation with All Co-Injection Confirms Theoretical Prediction that Co-NBI QH-Mode is Possible



- **QH-mode created with 100% co-injection using**
  - Low target density
  - Feedback control of beam power to regulate stored energy

- **In preliminary experiments, see all usual features of QH-mode for periods up to 1 second long**
  - H-mode edge pedestal
  - Constant density and radiated power
  - EHO providing extra edge particle transport

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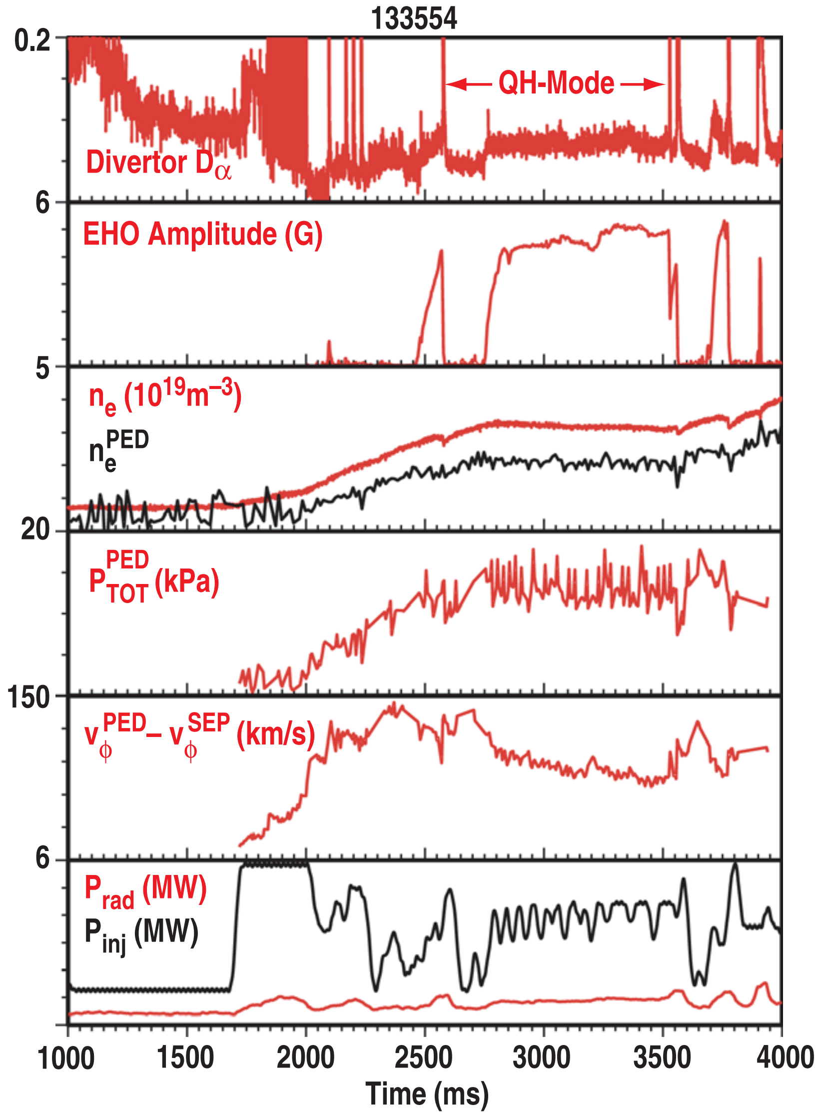

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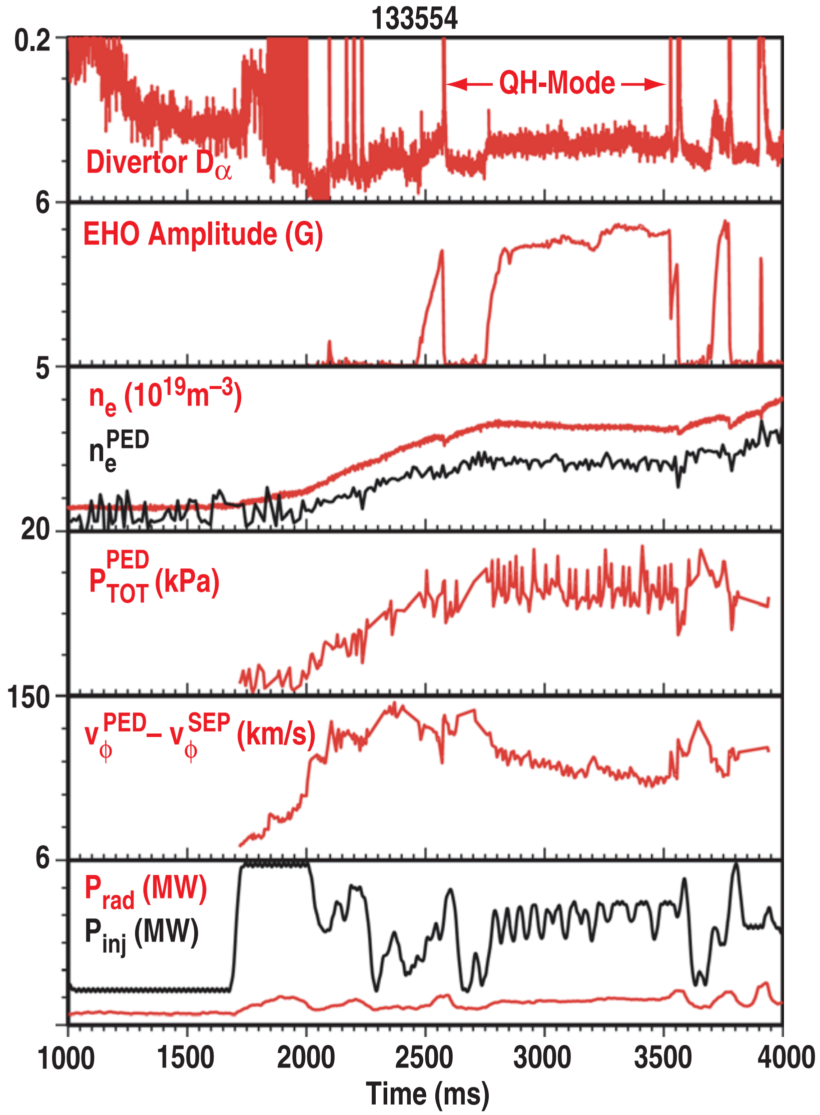

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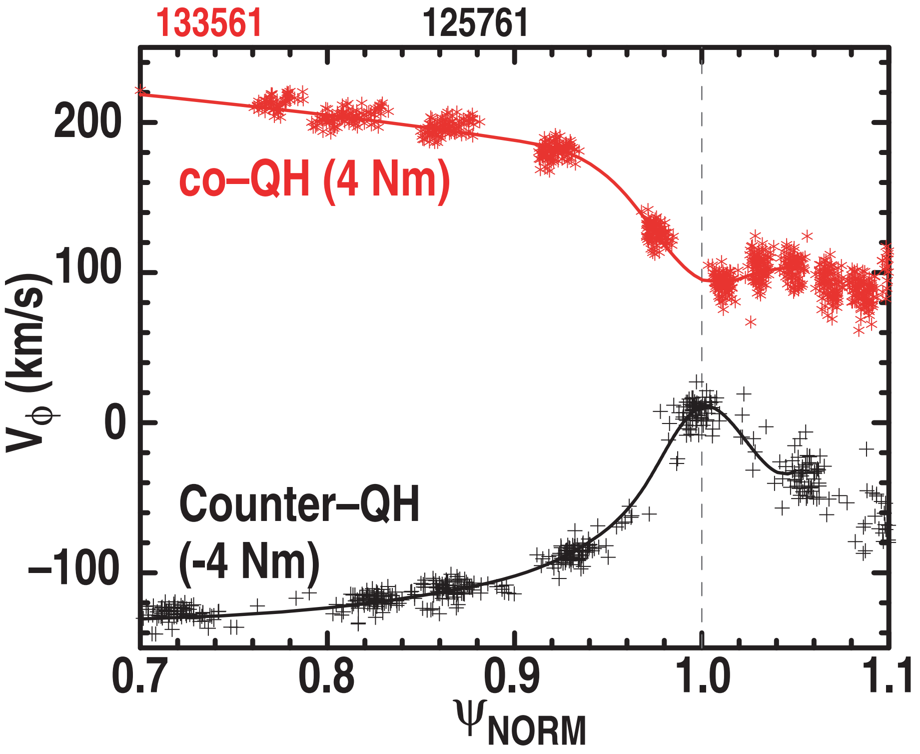
- **In preliminary experiments, see all usual features of QH-mode for periods up to 1 second long**
  - H-mode edge pedestal
  - Constant density and radiated power
  - EHO providing extra edge particle transport
- **Termination of QH-mode may be due to slow decay of edge rotation shear**
  - Input power and torque are at low end of what has been used in counter-NBI QH-mode

Edge Rotation Shear is Similar in Co-NBI and Counter-NBI QH-Modes at Similar Input Torque

- Theory predicts that magnitude of edge rotation shear is important but sign is not

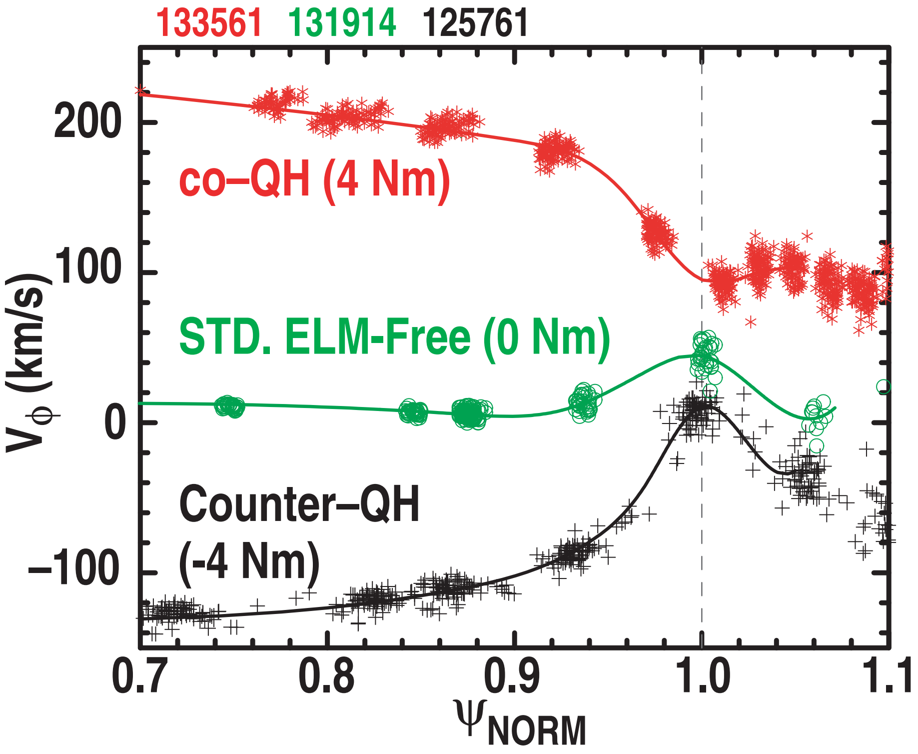
- Both co-NBI and counter-NBI QH-mode are predicted to exist if magnitude of rotation shear is large enough



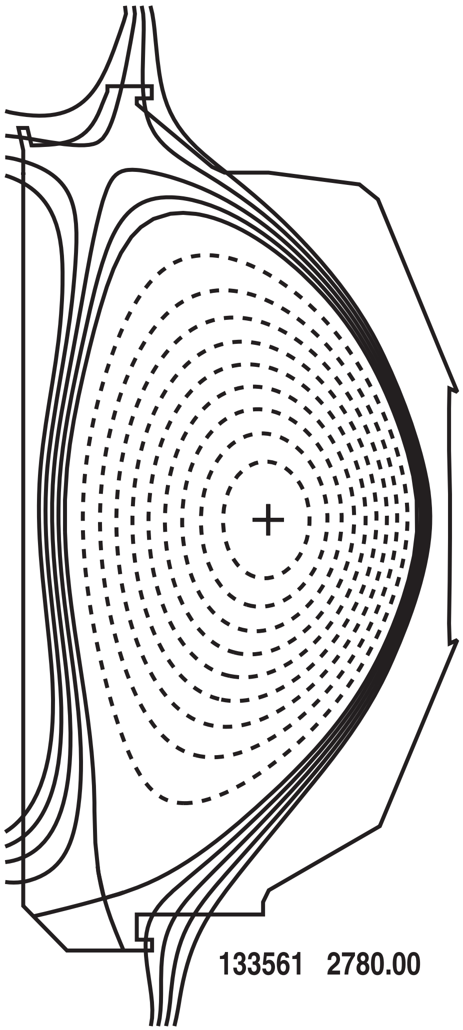
QH-Mode is Lost if Edge Rotation Shear is too Small

- **Balanced beam injection results in low edge rotation shear**

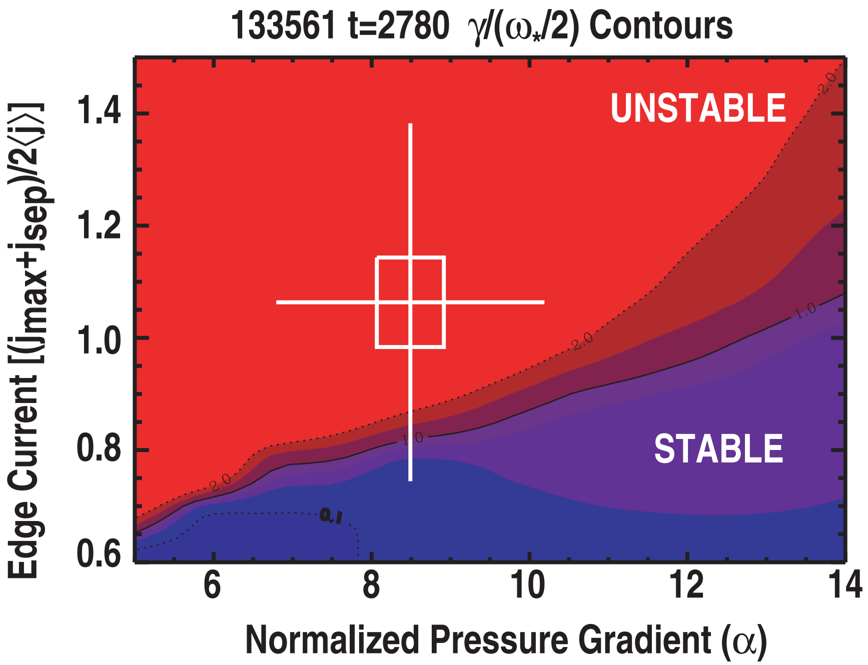
- **EHO is absent and plasma is standard ELM-free H-mode in shot with low rotation shear**
  - Standard ELM-free has monotonically rising density and radiated power



Peeling-Ballooning Stability Analysis Shows Excellent Edge Stability in Co-NBI QH-Mode Shots



- **Co-NBI QH-mode also operates near peeling stability boundary**



Can QH-mode be Used in Burning Plasmas?

- **In order to utilize QH-mode in burning plasmas such as ITER, the edge plasma must simultaneously reach the conditions needed for sufficient fusion power and the conditions needed to create the EHO**
  - Pedestal density and edge rotational shear are key issues
- **Pedestal density needed to operate at peeling stability boundary in ITER is close to that needed to meet fusion goal [Snyder, Nucl. Fusion (2007)] depending on density peaking factor**
- **More research is needed to determine whether necessary edge rotational shear can be obtained**
  - Rotation predictions for ITER are extremely uncertain
  - Incompletely understood effects of intrinsic rotation and neoclassical toroidal viscosity due to RMP coils lead to wide range of predictions (–100 km/s to + 200 km/s core rotation)

Conclusions

- **Demonstrated QH-mode operation with all co-injection and strong edge co-rotation**
  - Counter-NBI and counter rotation of plasma edge are not essential for QH-mode
- **Achieved QH-mode operation over a continuous torque range, from all counter-injection to near balanced injection**
  - More highly shaped plasmas allow QH-mode operation at lower input torque and lower edge rotation
- **Discovered that EHO-induced transport can be continuously adjusted by varying edge rotation**
  - Allows optimization of H-mode pedestal density and pressure
- **Peeling-ballooning mode theory used to guide experiments**
  - Effect of rotational shear on edge modes provides basis for theory of the EHO
  - Theory predicted existence of co-NBI QH-mode prior to experiments