Beneficial Effects of the Edge Harmonic Oscillation in Quiescent H-mode Plasmas

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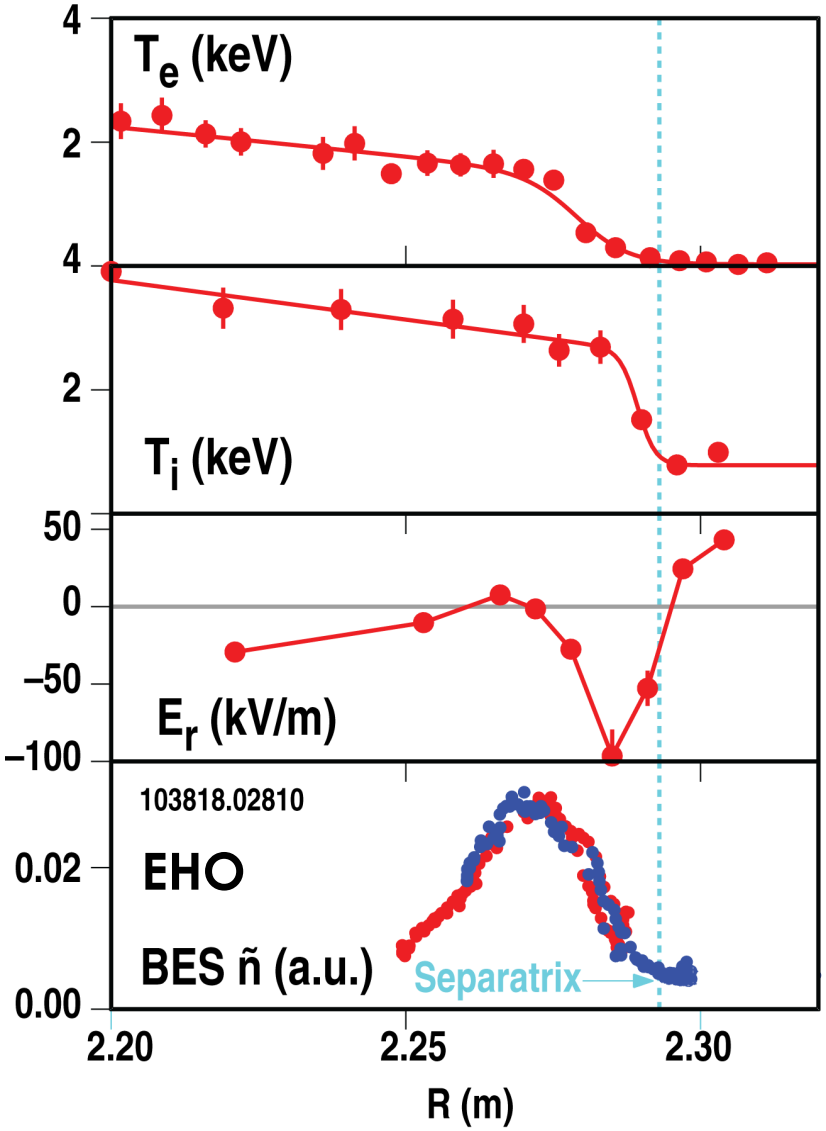
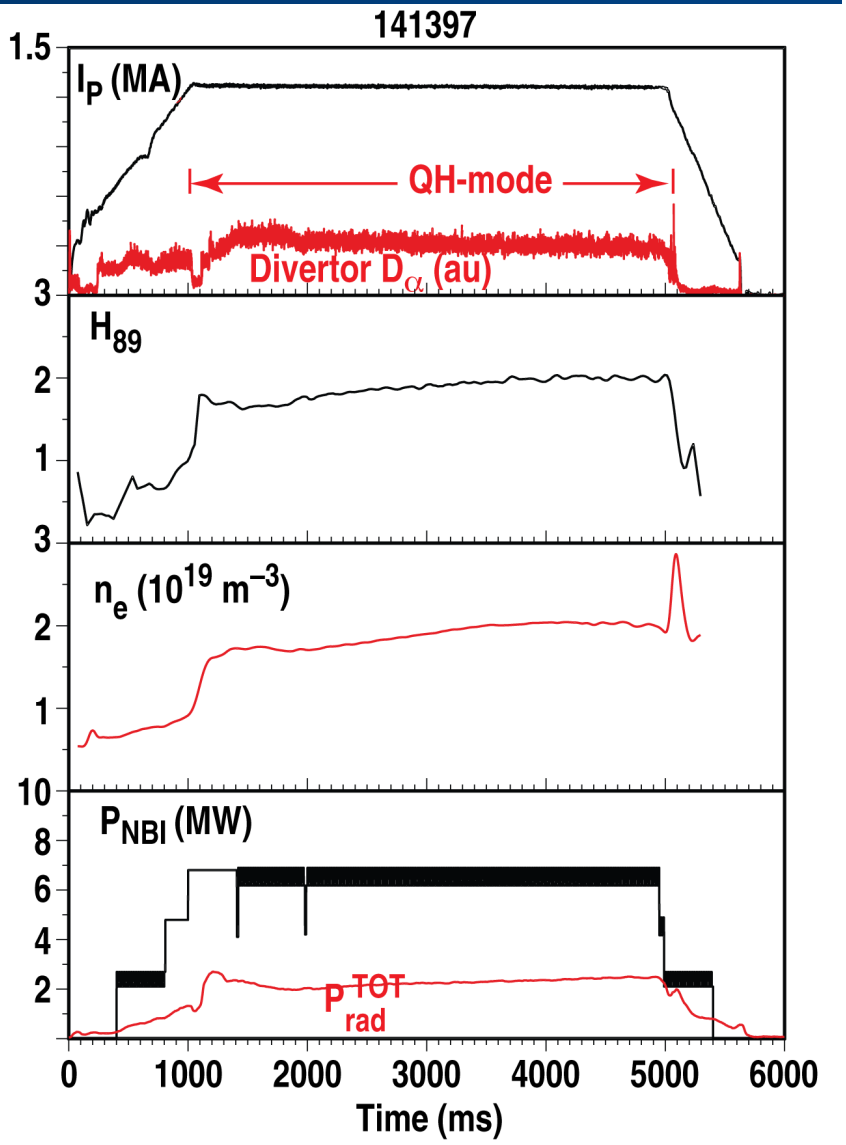


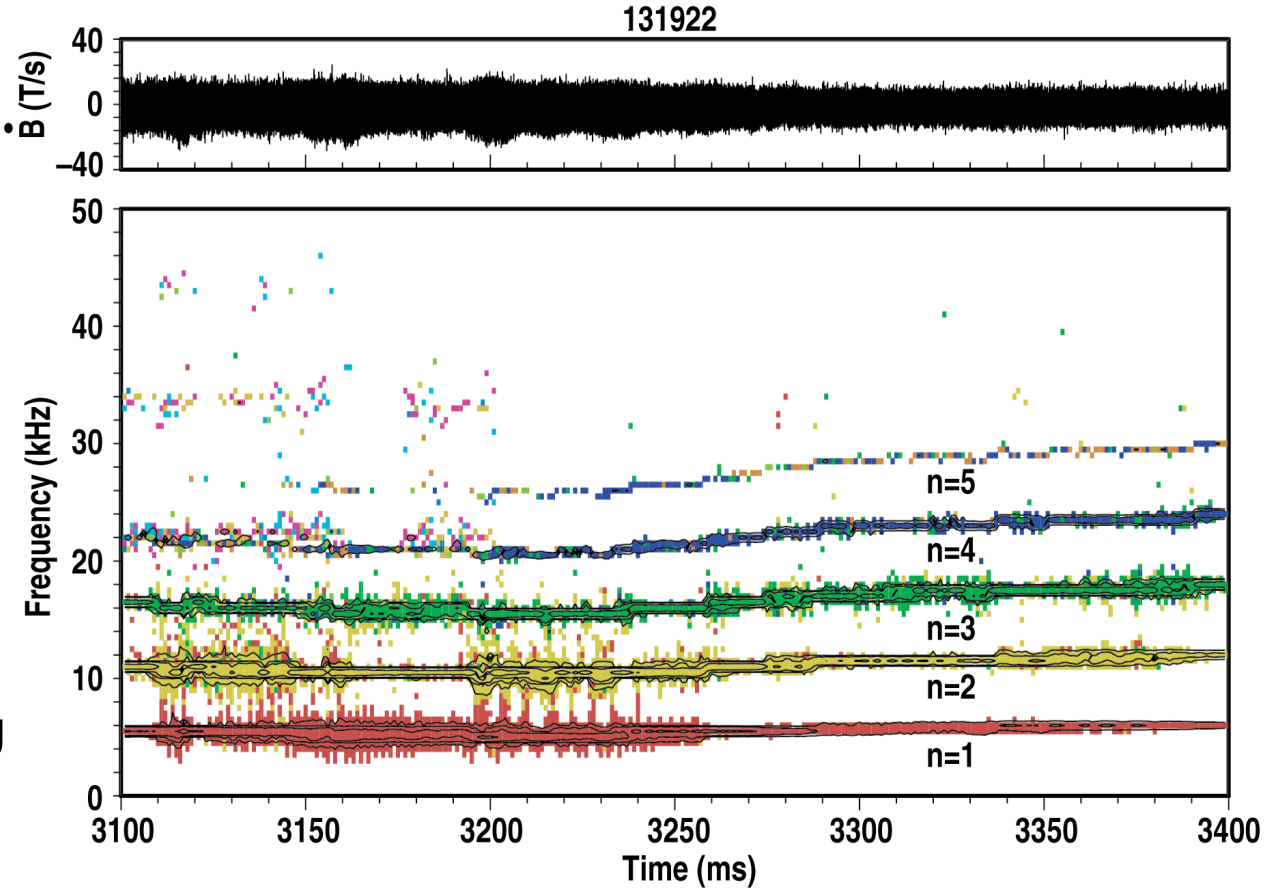
Quiescent H-Modes are the Ideal H-mode Plasmas

- **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
- **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
- **Time-averaged edge particle transport is faster than in ELMing H-mode**



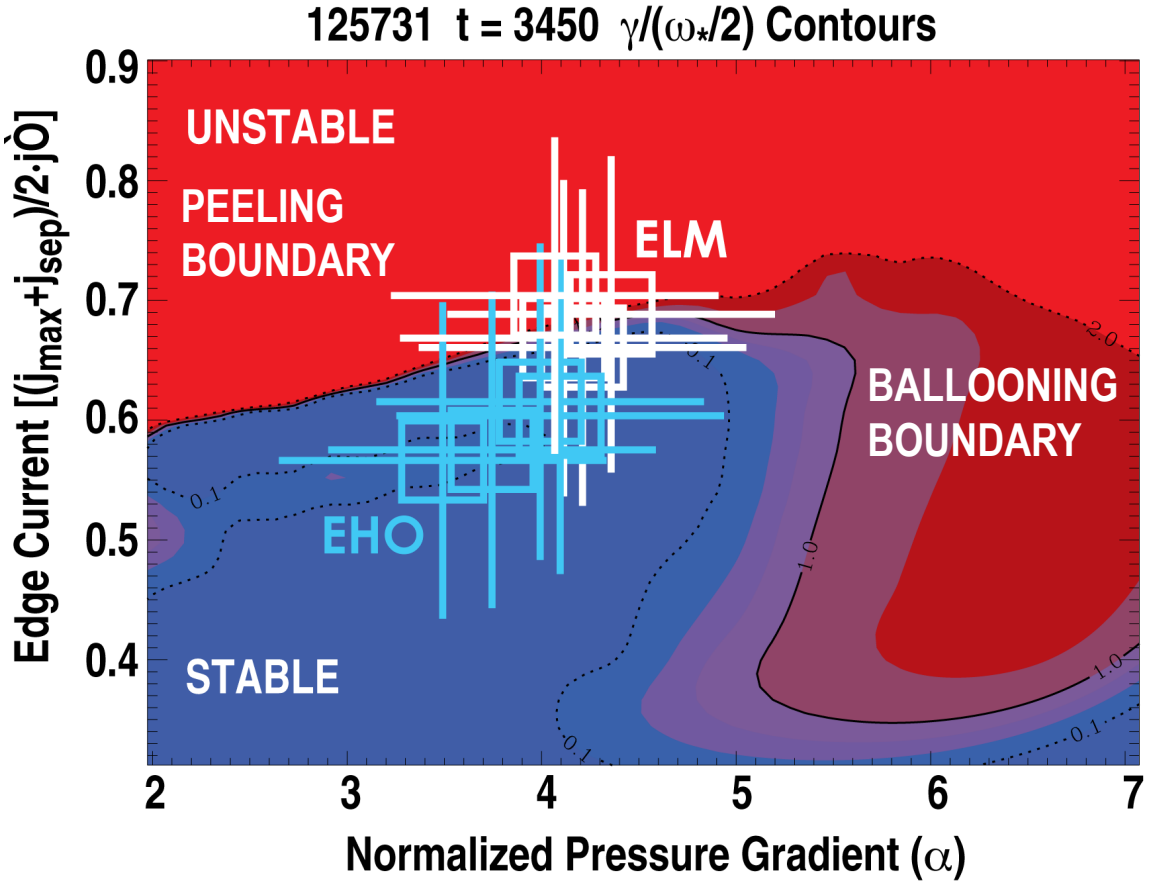
Edge Harmonic Oscillation (EHO) is Key to QH-Mode Operation

- **Edge harmonic oscillation (EHO) is an edge localized, electromagnetic oscillation**
  - Waveform is typically nonsinusoidal with multiple toroidal harmonics n
- **EHO enhances edge particle transport**
- **Edge transport enhancement allows transport equilibrium at edge parameters just below peeling-ballooning mode limit**



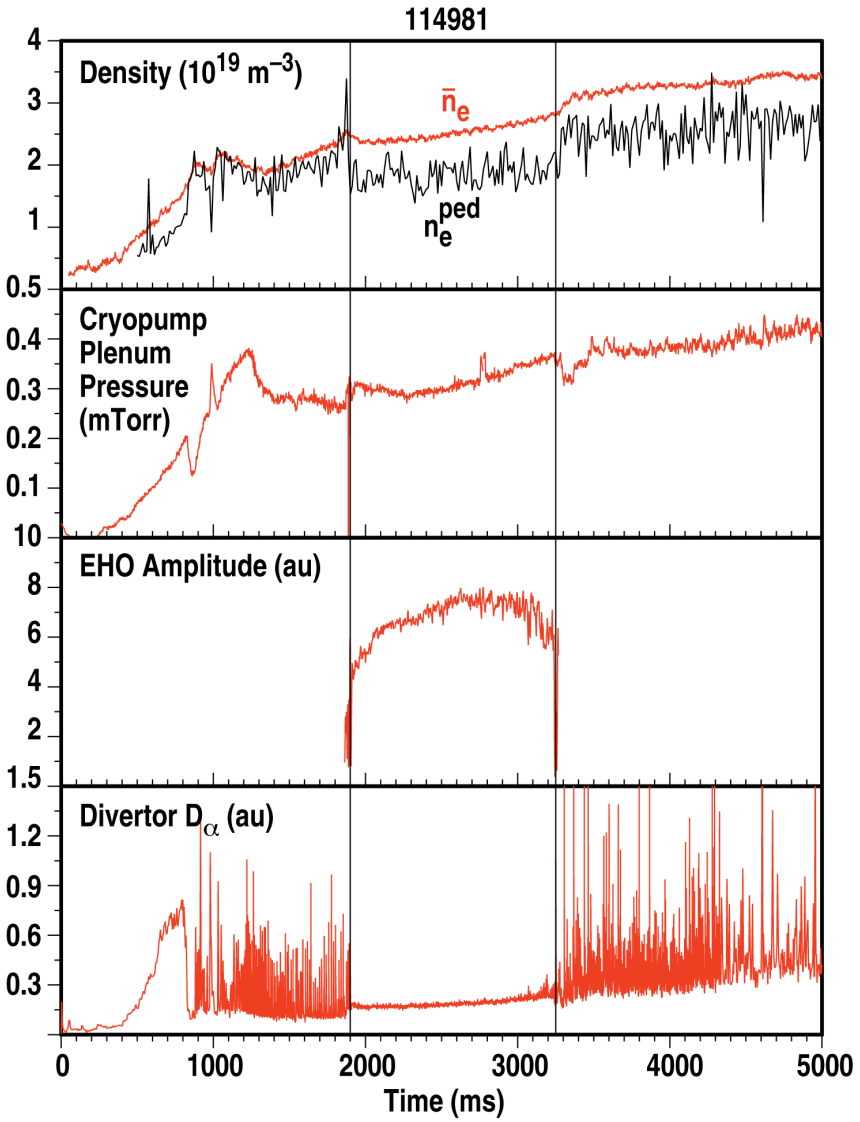
Operating Points of Shots at Various Torques Are Consistent with Edge Peeling-Ballooning Stability Theory

- 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

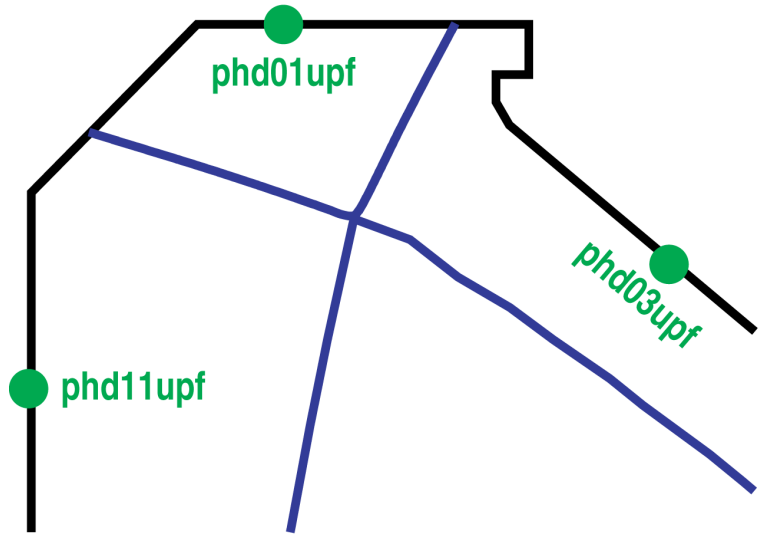


EHO Transports Particles More Rapidly Than ELMs

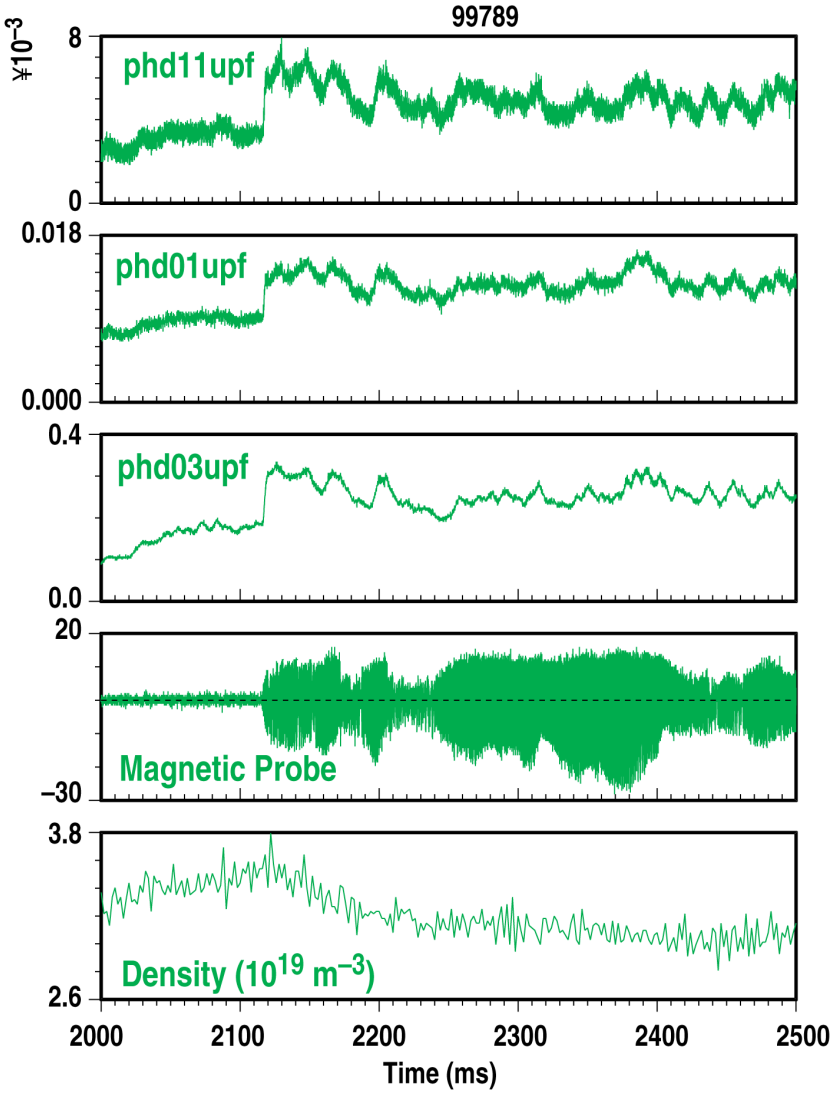
- **Density drops when EHO turns on and rises when it ceases**
  - Particle input constant
- **Pressure in pumping plenum rises when EHO turns on, consistent with particle exhaust from plasma**



D_α Radiation Rises Throughout Divertor and $\bar{n}_e$ Drops When Edge Harmonic Oscillation Starts

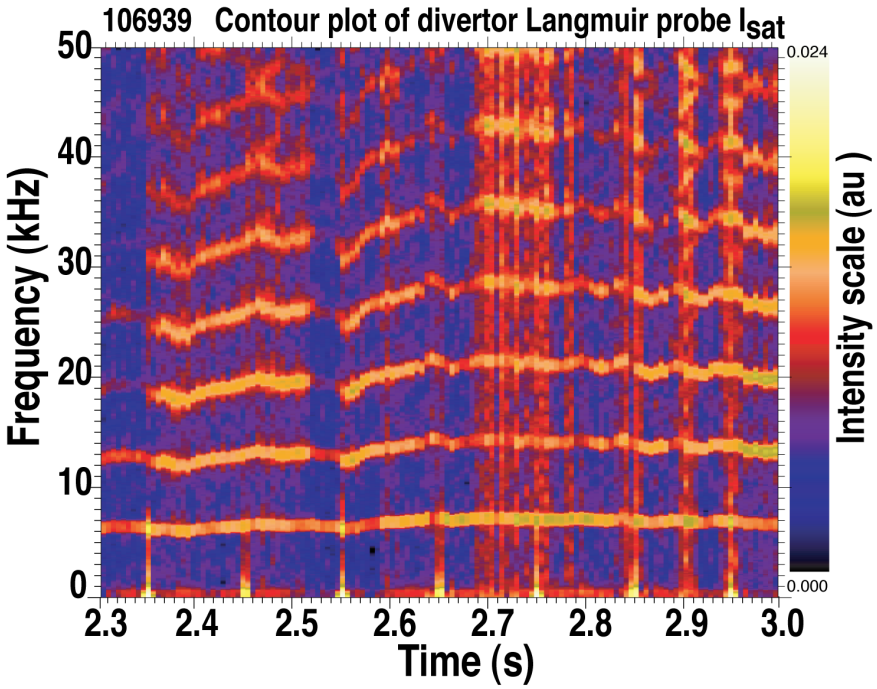


- Divertor shape for 1999 campaign

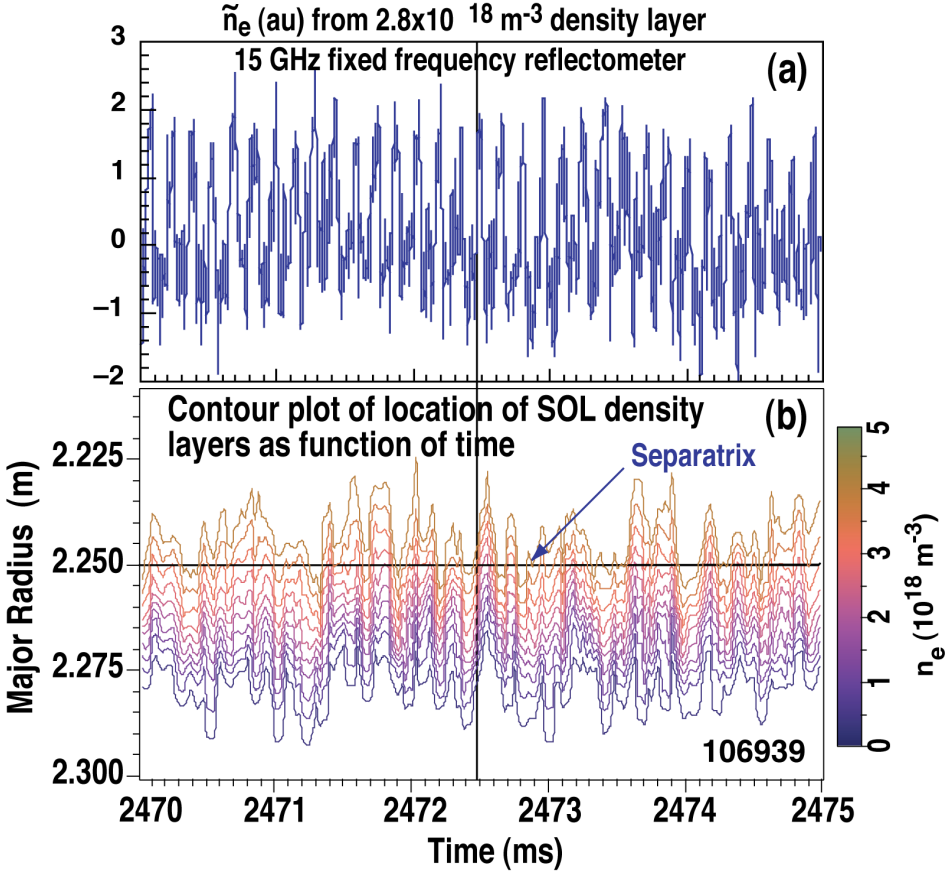


The EHO Causes Particle Transport — EHO Modulates Both Particle Flux to Divertor and SOL Density Profile

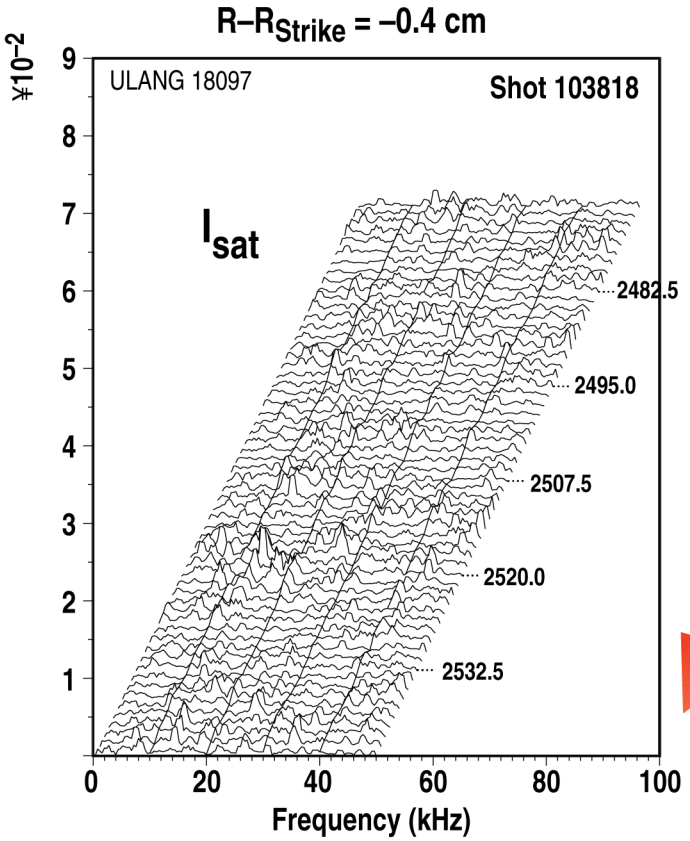
- **Divertor Langmuir probe I_{sat} signal shows particle flux is modulated at EHO frequencies**
  - EHO harmonics account for ~100% of the total flux to the probe

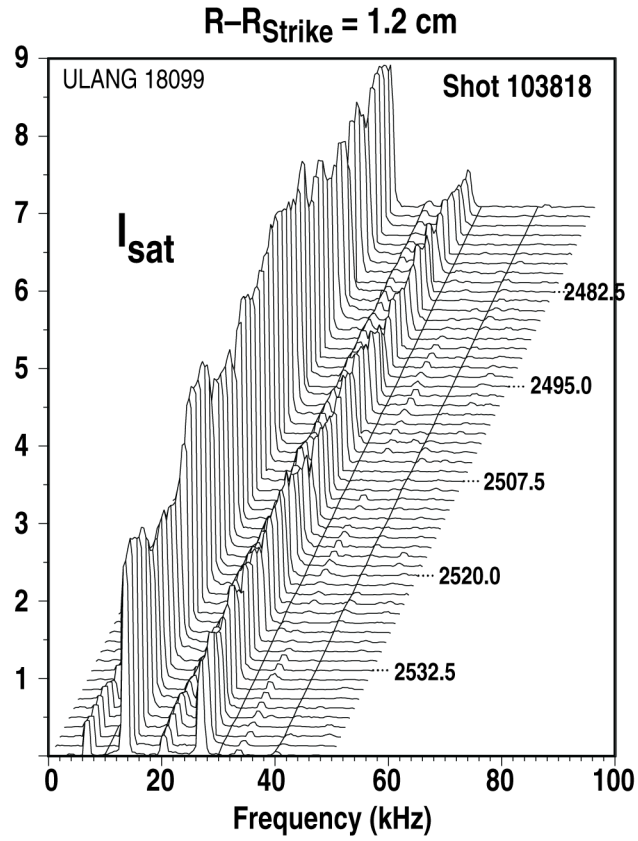


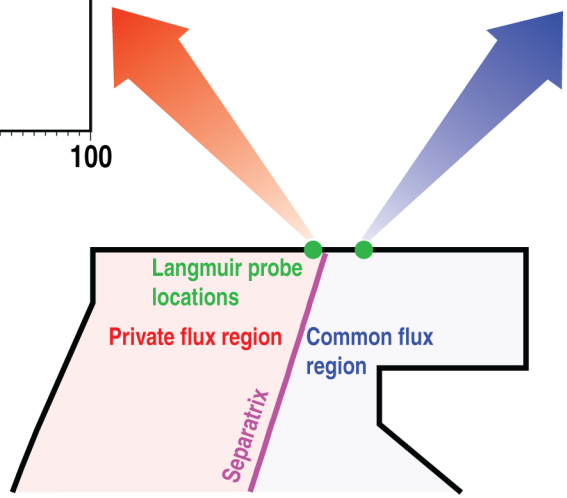
- **High resolution profile reflectometer system shows scrape-off layer (SOL) density profile is modulated at EHO frequency**



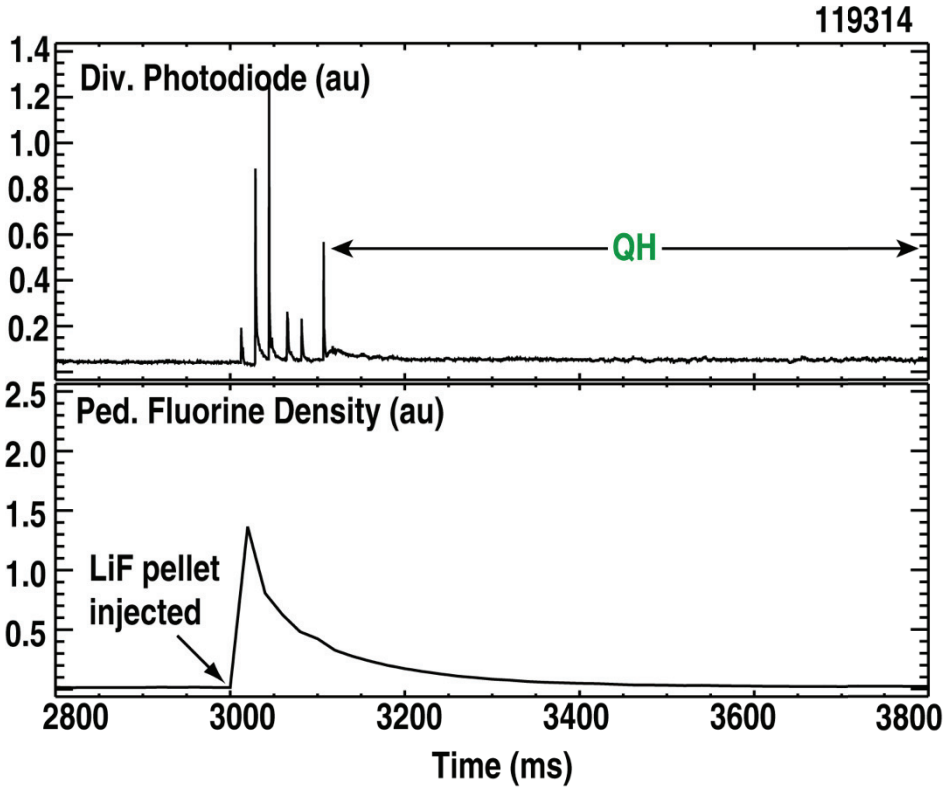
Divertor Langmuir Probes Show Edge Harmonic Oscillation Modulates Particle Flux to Divertor Plate from Common Flux Region





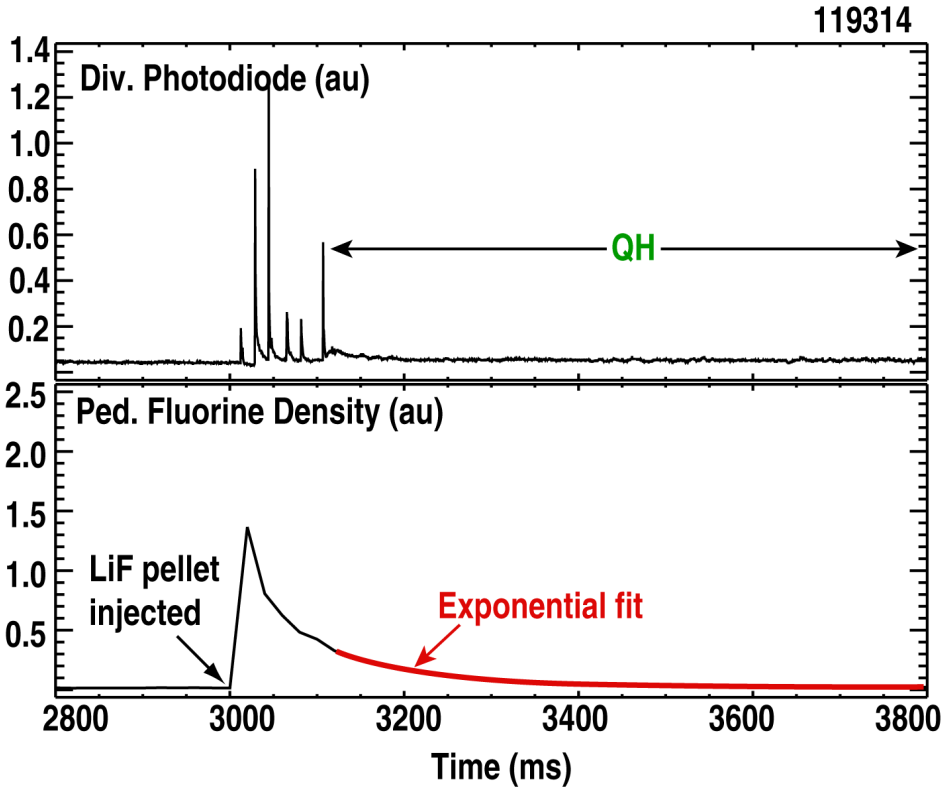


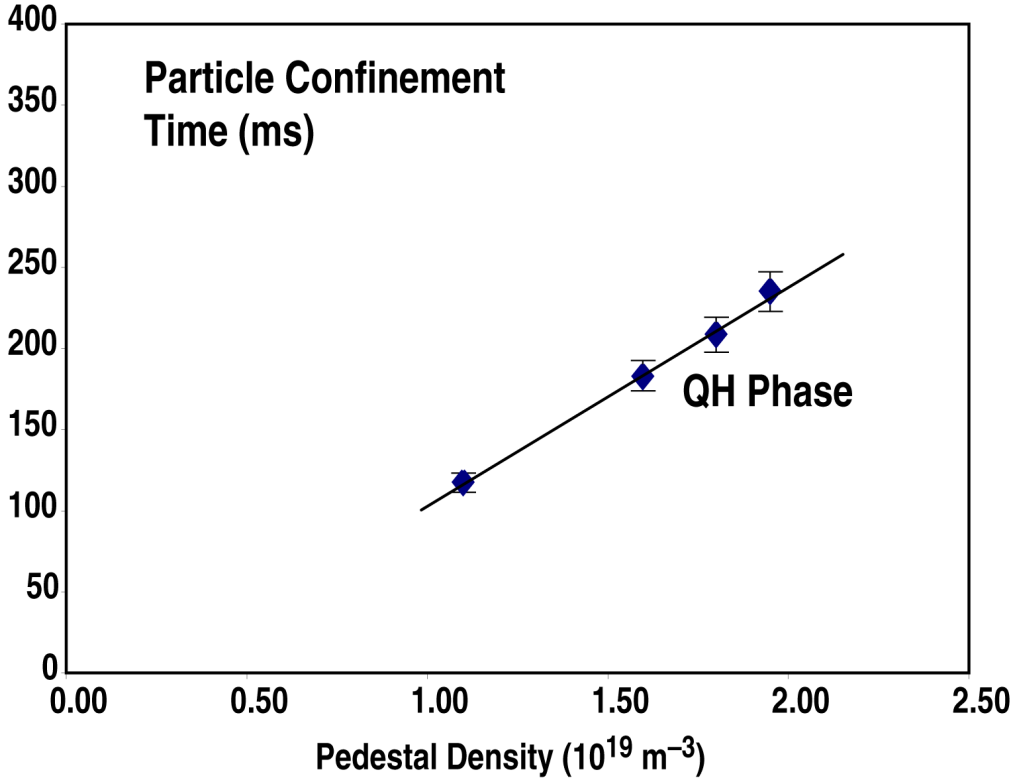
Impurities at the Plasma Edge Are Exhausted Faster in the QH-mode Phase than in the ELMing Phase



Impurities at the Plasma Edge Are Exhausted Faster in the QH-mode Phase than in the ELMing Phase

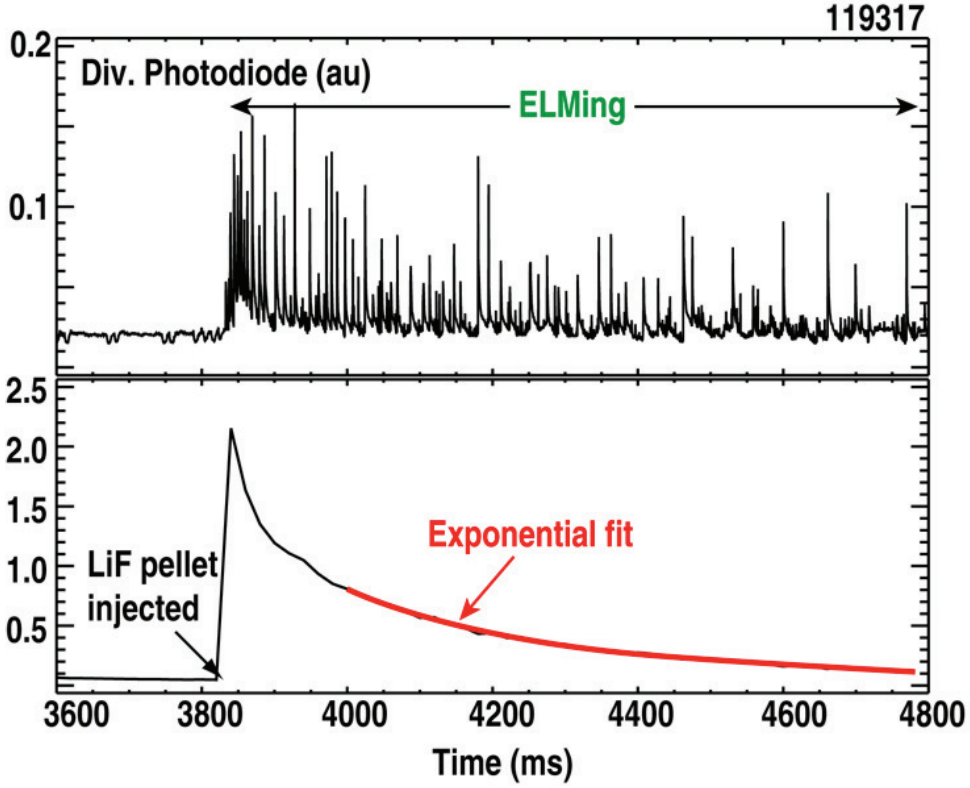
- The impurity particle confinement time at the plasma edge increases with the pedestal density

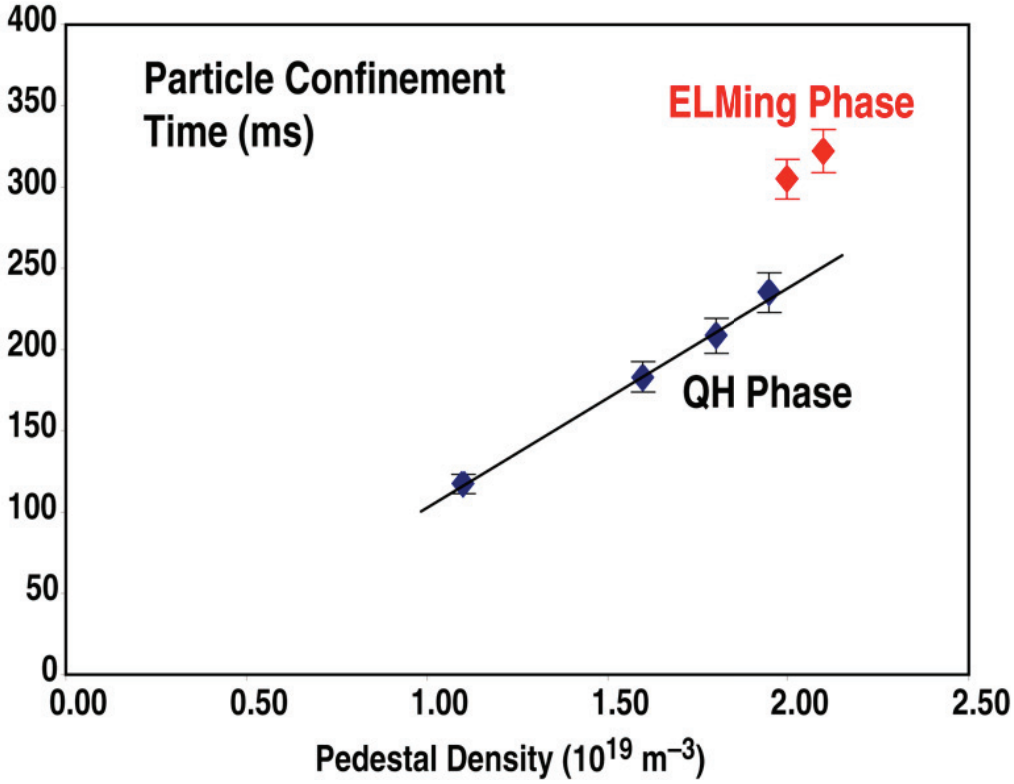




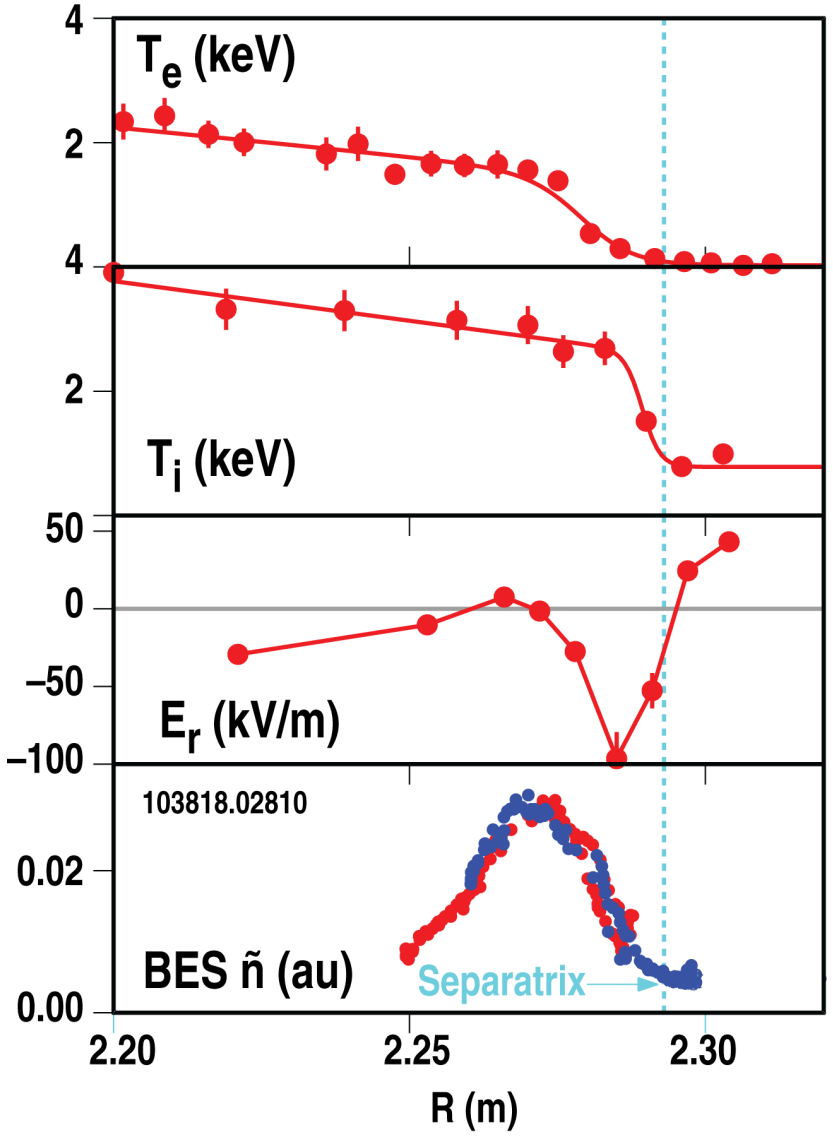
Impurities at the Plasma Edge Are Exhausted Faster in the QH-mode Phase than in the ELMing Phase

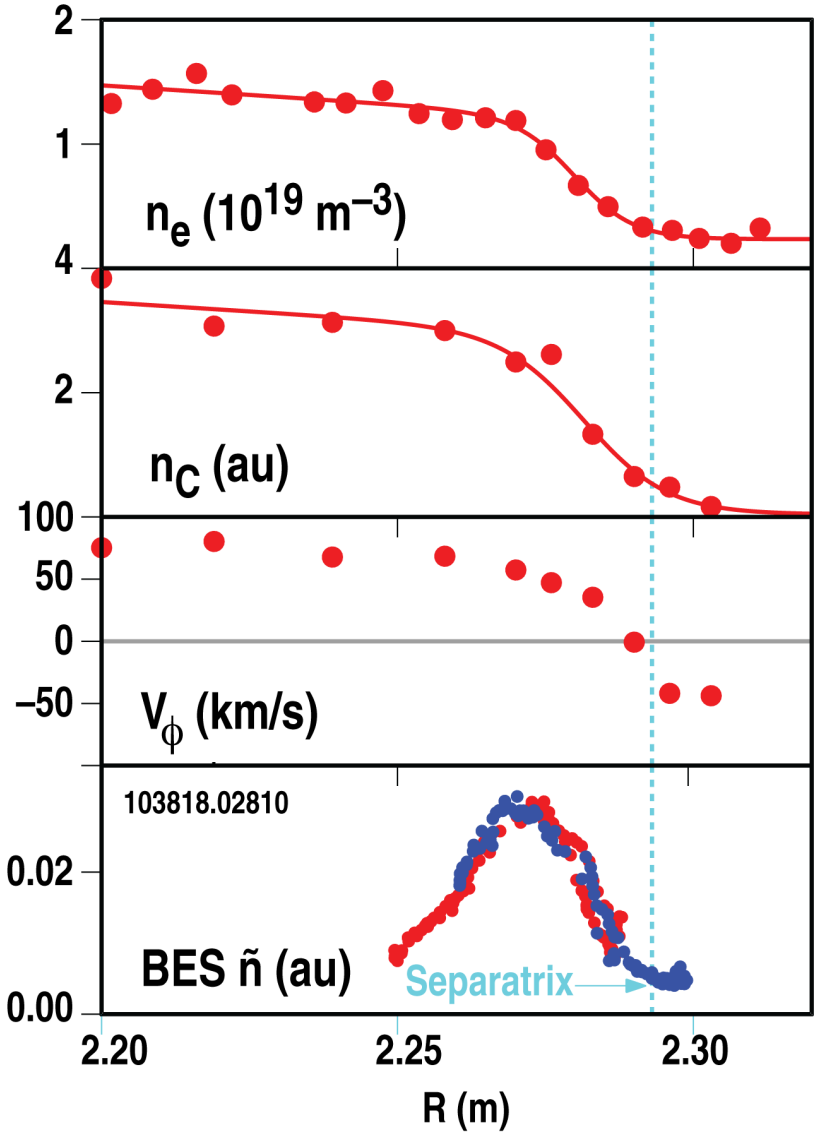
- The impurity particle confinement time at the plasma edge increases with the pedestal density
- EHO exhausts impurities faster than ELMs





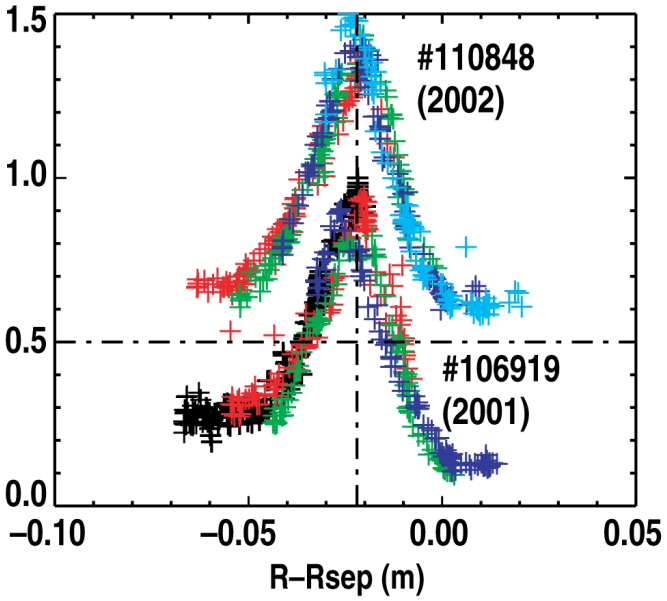
Maximum in ñ from EHO Located Near Top of Pedestal



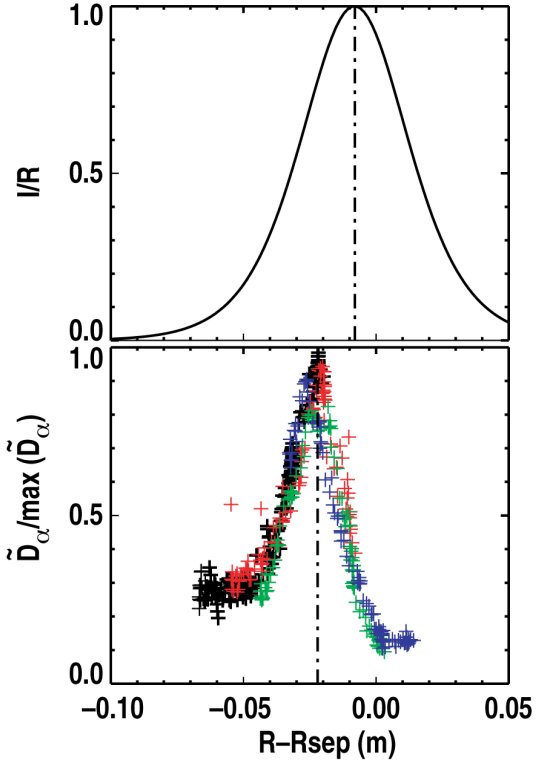


Edge Sweep Used to Improve Spatial Cross Calibration of CER and BES Systems [W. Solomon et al., RSI, 2003]

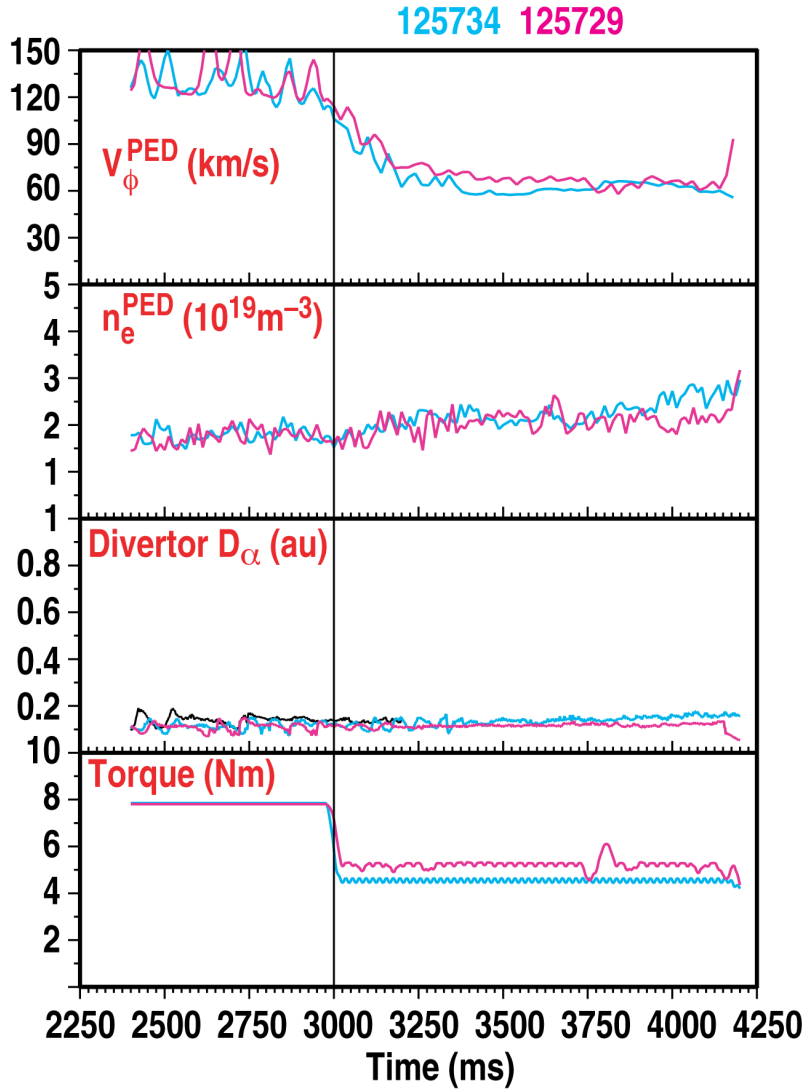
- Improved calibration shows peak of EHO ñ fluctuation is 2 cm inside separatrix
- Calibration gives reproducible location from year to year



- Peak of EHO ñ fluctuation is inside maximum gradient in BES emission profile
- EHO is not just a rigid motion of plasma edge

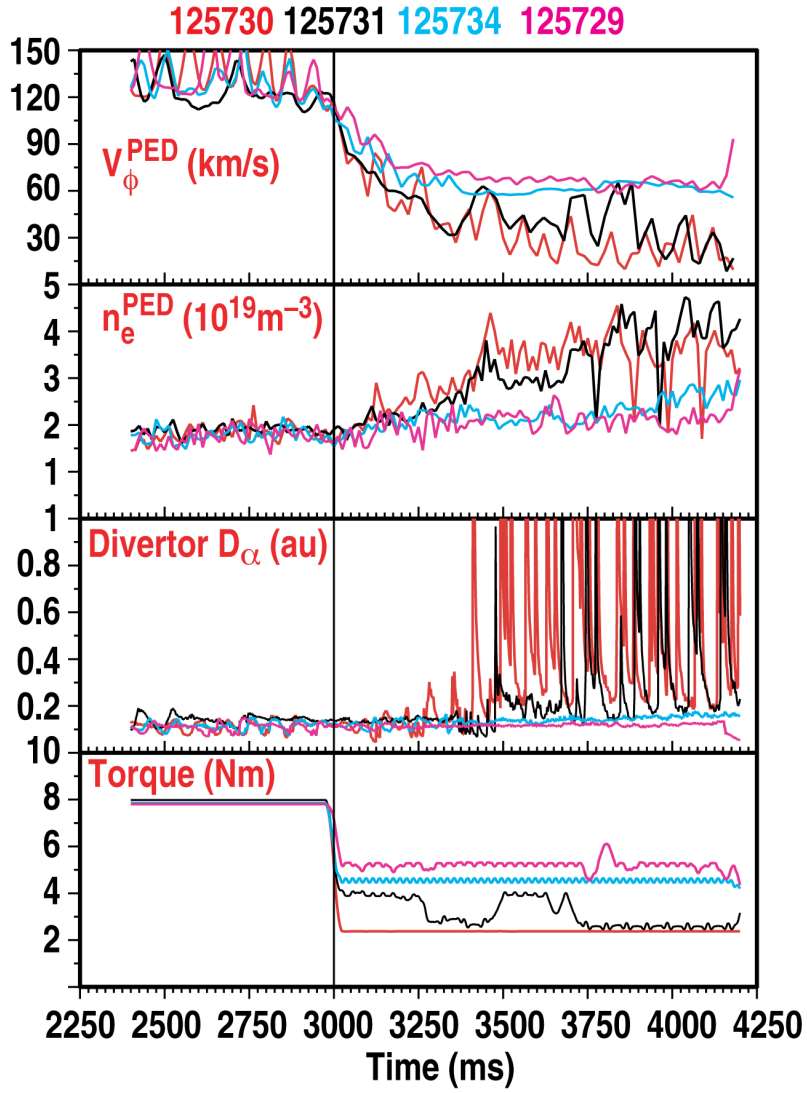


H-Mode Pedestal Density Increases as Net Torque is Reduced at Constant Input Power



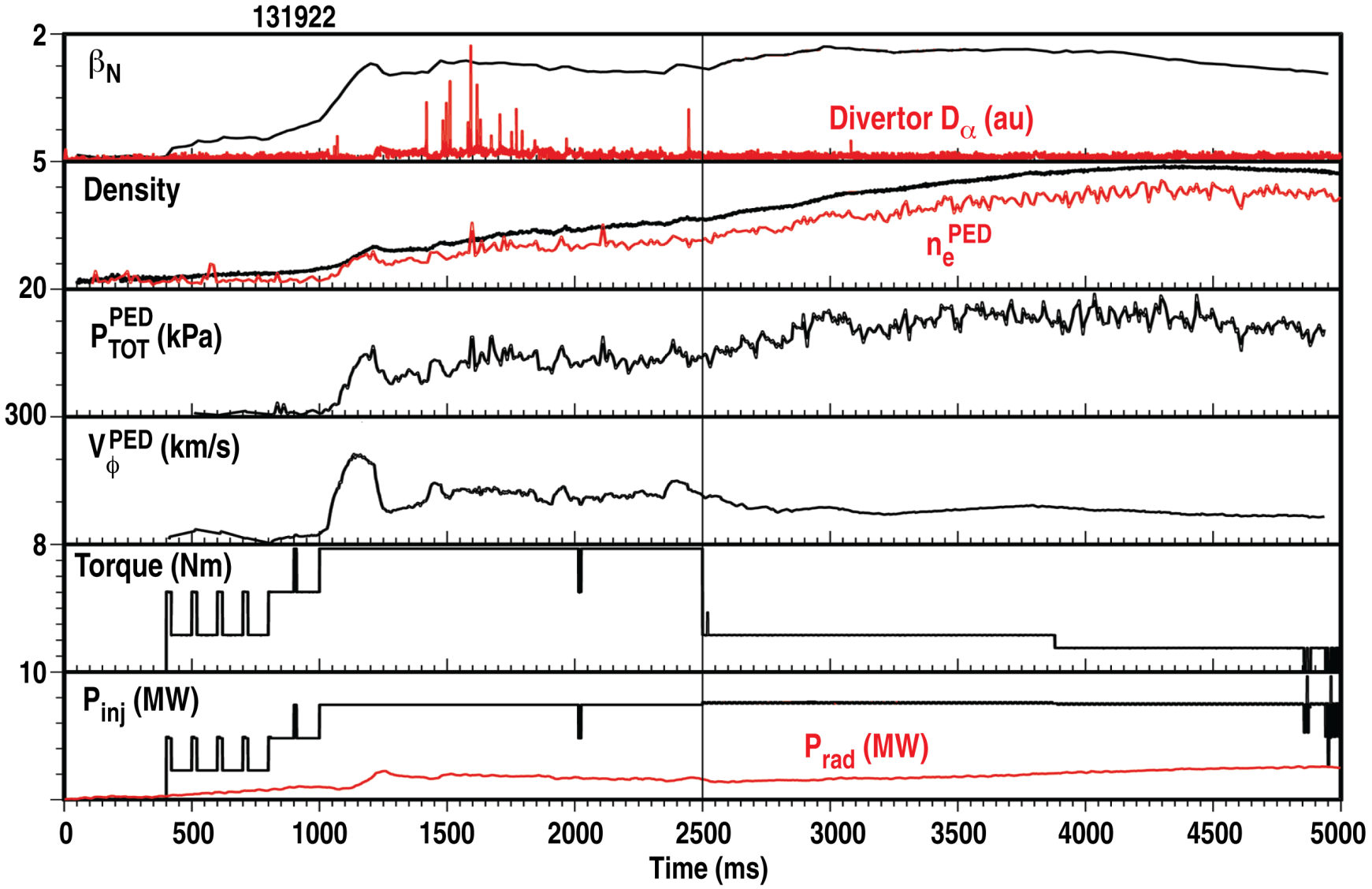
- In 2006, DIII-D was equipped with simultaneous co plus counter NBI capability
- QH-mode pedestal density increases as input torque is reduced at constant input power

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



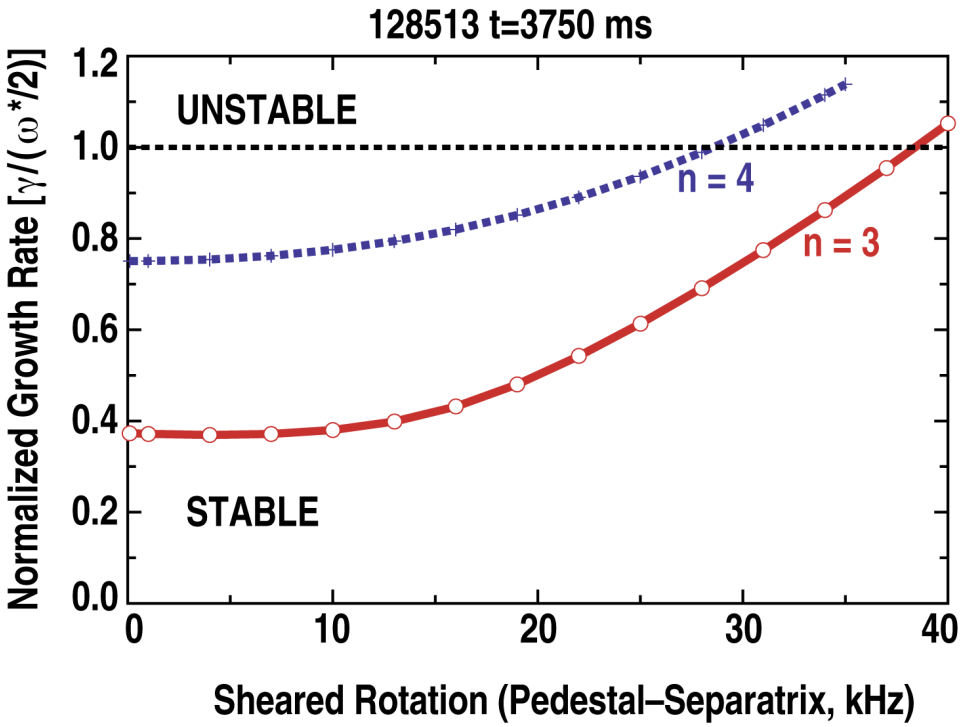
- In 2006, DIII-D was equipped with simultaneous co plus counter NBI capability
- QH-mode pedestal density increases as input torque is reduced at constant input power
- ELMs return at lower rotation and higher density
- Speculation: EHO-induced particle transport changes with changing rotation

Rotation Control of Density and Improved Double Null Shape Allow QH-mode at Higher Pedestal Pressure and Higher Stored Energy



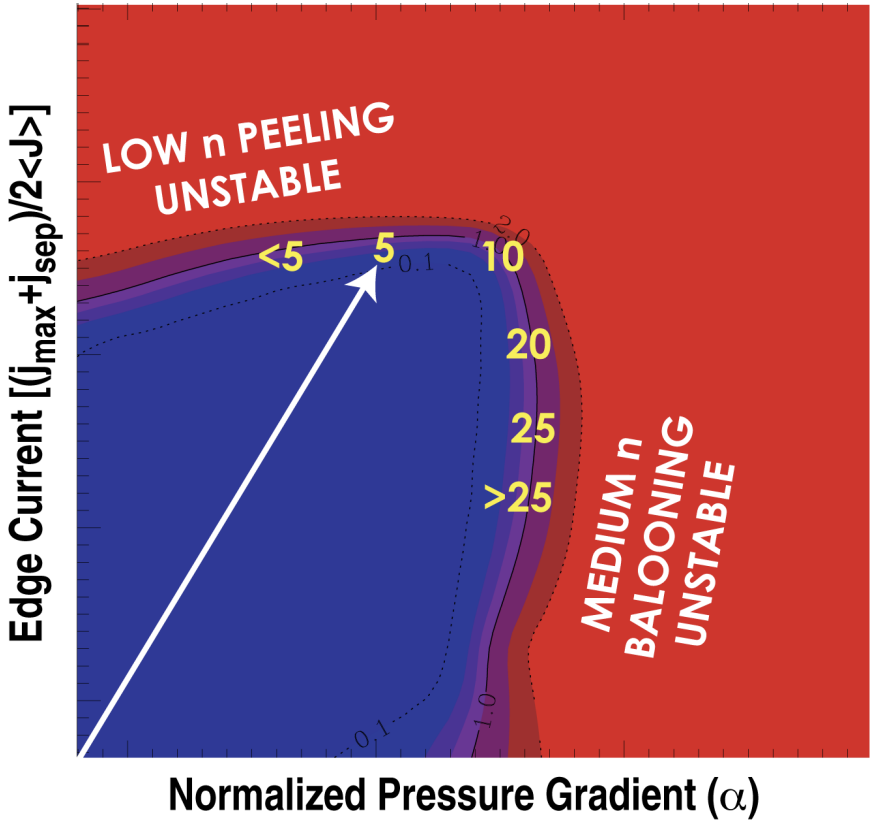
Theory of Edge Harmonic Oscillation Based on Effect of Rotational Shear on Peeling-Ballooning Stability

- 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



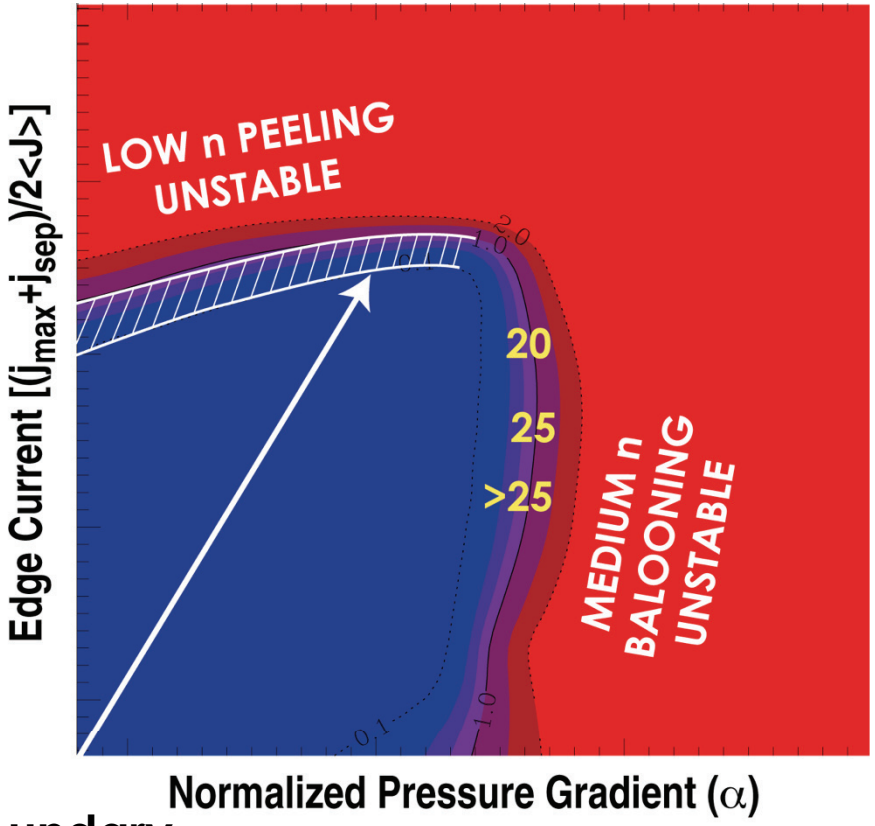
Without Edge Rotational Shear, ELM Occurs When Edge Operating Point Crosses Peeling Boundary

- **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



Missing: Theory to Explain How EHO Enhances Particle Transport

- **Basic concept of EHO as a saturated kink-peeling mode fits much of the data but does not translate into a theory of particle transport**
- **It would be elegant if we could find one theory which explains**
  - EHO induced particle transport
  - Additional particle transport from tearing modes
  - Additional particle transport from static, non-axisymmetric magnetic fields
- **For EHO, the change in particle transport with rotation suggests that toroidal friction between EHO, plasma and wall plays a role**
  - In neoclassical theory, there is a deep connection between radial particle transport and toroidal torque
- **If toroidal torque plays a role, we need to understand how plasma maintains ambipolar transport**
  - Torque induced by non-axisymmetric magnetic fields is different for electrons and ions

Summary

- **Additional particle transport caused by the EHO is the key to ELM-free operation in QH-mode**
  - Additional transport allows plasma to reach transport steady state at edge parameters just below the ELM stability boundary
- **EHO causes extra transport for electron, main ions and impurities**
- **EHO induced particle transport is faster than the time-averaged edge transport in ELMing discharges**
  - Important for helium exhaust in future devices
- **Theory of EHO as saturated kink-peeling mode explains several aspects of the data**
- **Still need to develop theory explaining enhanced particle transport**