Dependence of Edge Turbulence Dynamics and the L-H Power Threshold on Toroidal Rotation

by

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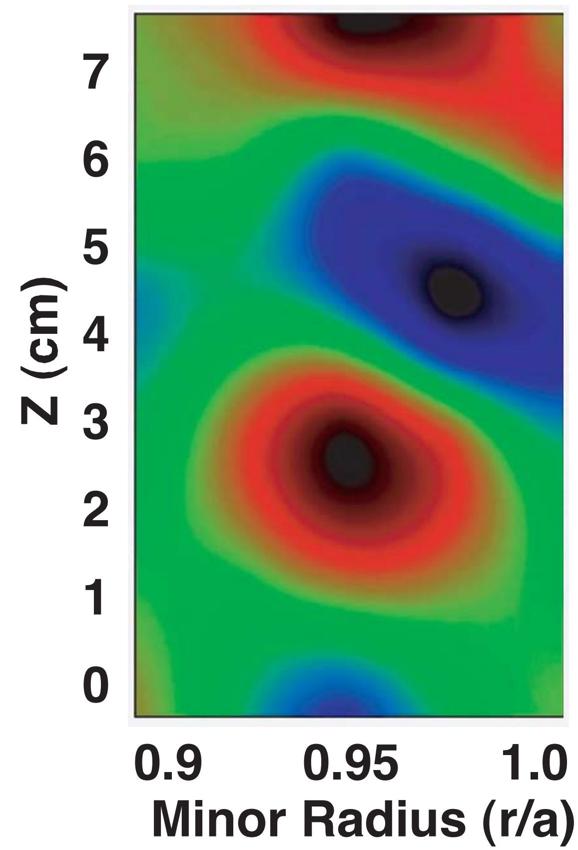

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MADISON

Dependence of Edge Turbulence Dynamics and the L-H Power Threshold on Toroidal Rotation

- **Power flux required to trigger an LH transition varies strongly on injected torque and toroidal rotation**
  - *Higher P_{LH} threshold at higher co-current rotation*
  - *Affects plasmas with ion ∇B drift towards and away-from X-point*
- **Edge turbulence characteristics change dramatically and consistently with toroidal rotation**
  - *Radially sheared poloidal flows strongly influenced by rotation*
  - *Turbulence mode structure depends on magnetic configuration & rotation*
  - *Zonal flow behavior strongly dependent on rotation*
- **Mechanism appears to depend on complex interplay of radial electric field, turbulence and zonal flow dynamics in edge region of plasma**
- **Beneficial implications for accessing H-mode in slowly rotating plasmas**

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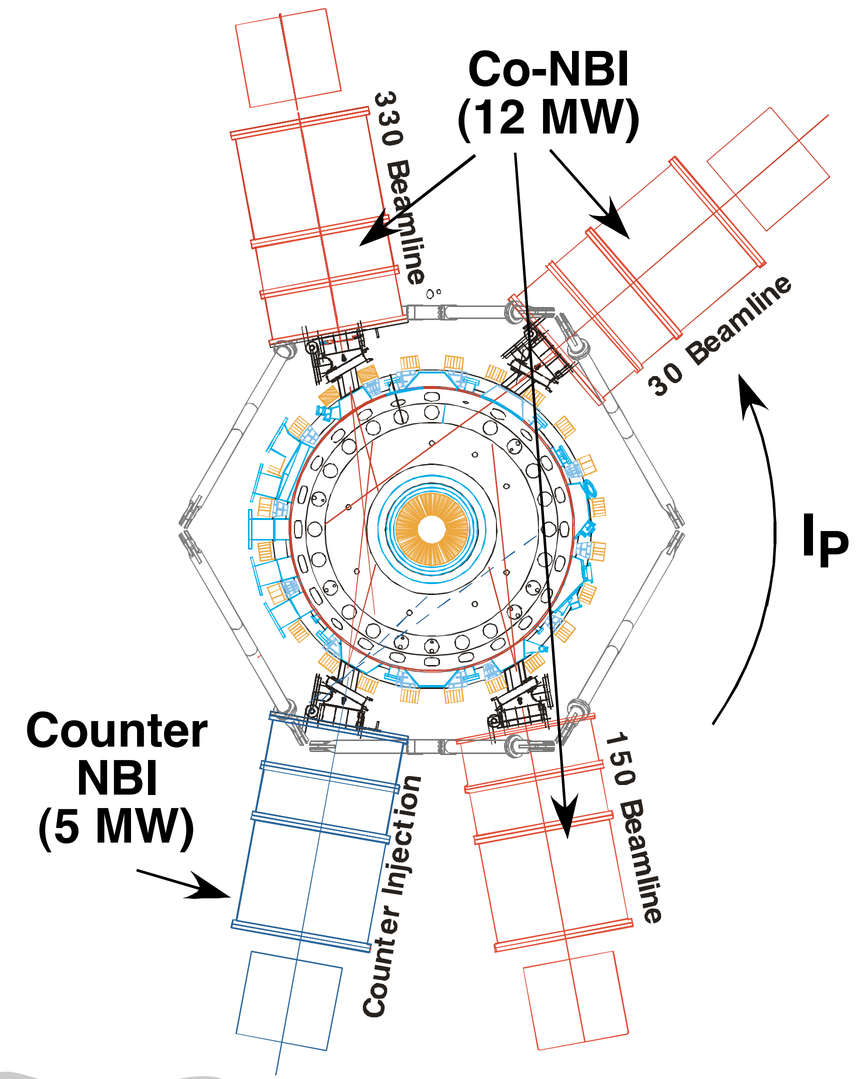
Outline

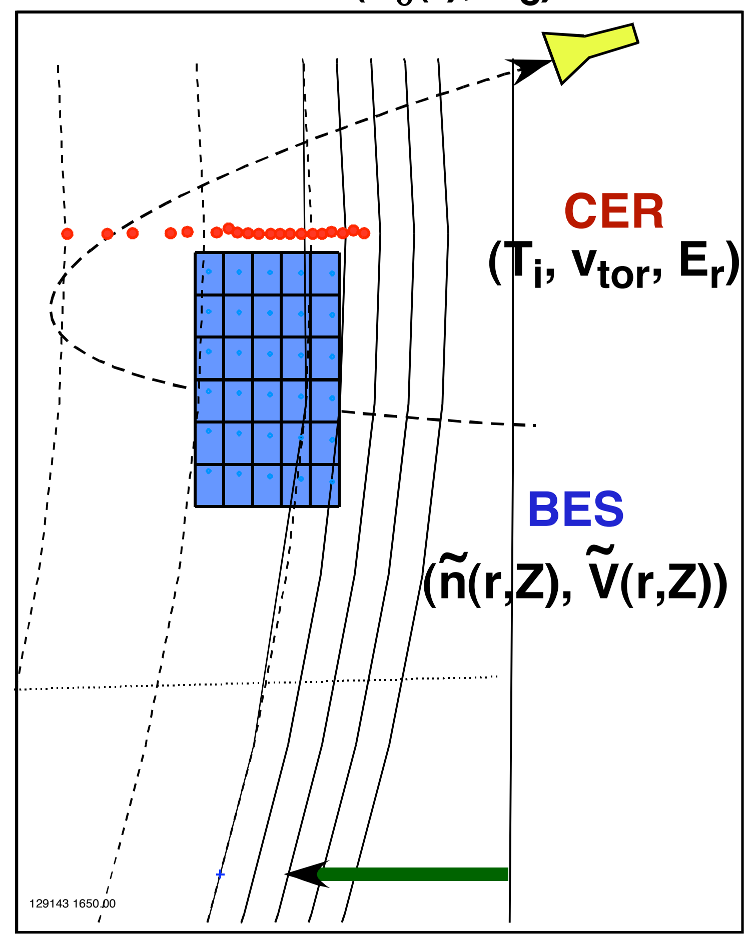
- Experimental observations and P_{LH} threshold dependence on torque
- Radial electric field variations
- Turbulence measurements
- Torque-Induced L-H Transition
- Zonal flow evolution
- Visualizations of Edge Turbulence
- Implications and Conclusions

CO-CURRENT AND COUNTER-CURRENT NBI INJECTION AND ARRAY OF FLUCTUATION DIAGNOSTICS FACILITATE DETAILED EXAMINATION

Plan View of the DIII-D Tokamak



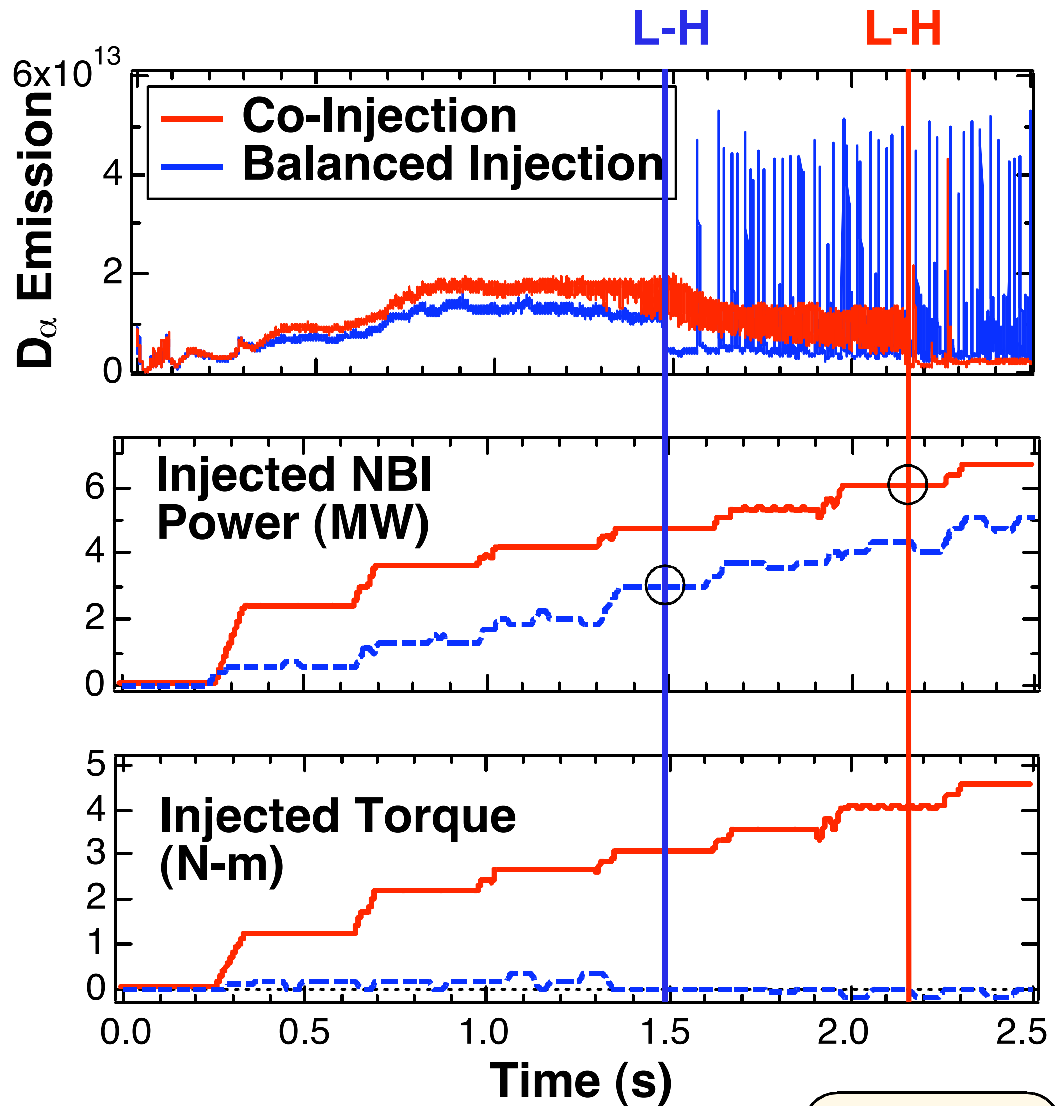
Doppler Reflectometer
$(v_\theta(t), \tilde{n}_e)$



Reciprocating Langmuir Probe
(M, ϕ, n)

CO-ROTATING DISCHARGE REQUIRES TWICE THE INJECTED POWER OF BALANCED INJECTION DISCHARGE TO UNDERGO LH TRANSITION

- **Upper-Single-Null plasmas: ion ∇B drift away from X-point**
  - *higher LH power threshold than with ion ∇B drift towards X-point*
- **Beam power ramped gradually**
- **Co and counter NBI sources control torque and power**
- **Fluctuating D_α determined to be in L-mode**
- **P_{LH}, co = 6 MW**
  P_{LH}, balanced = 3 MW



I_p = 1 MA
B_T = -2 T

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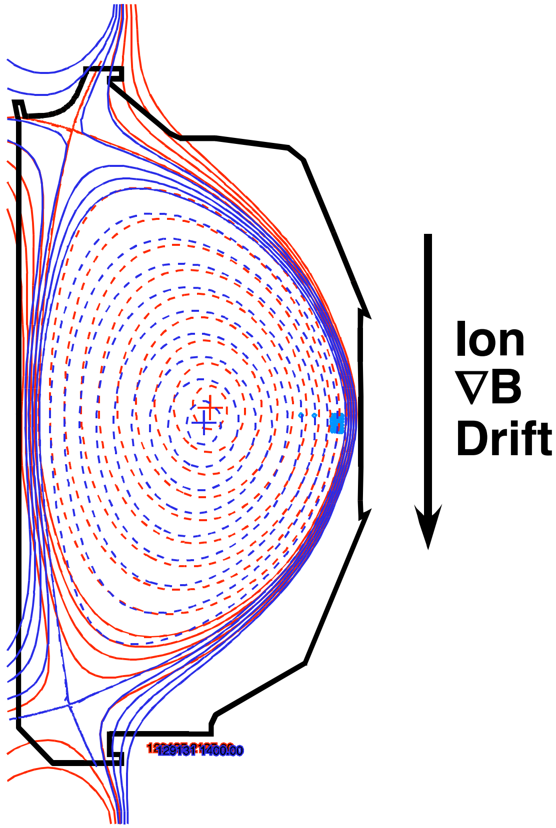
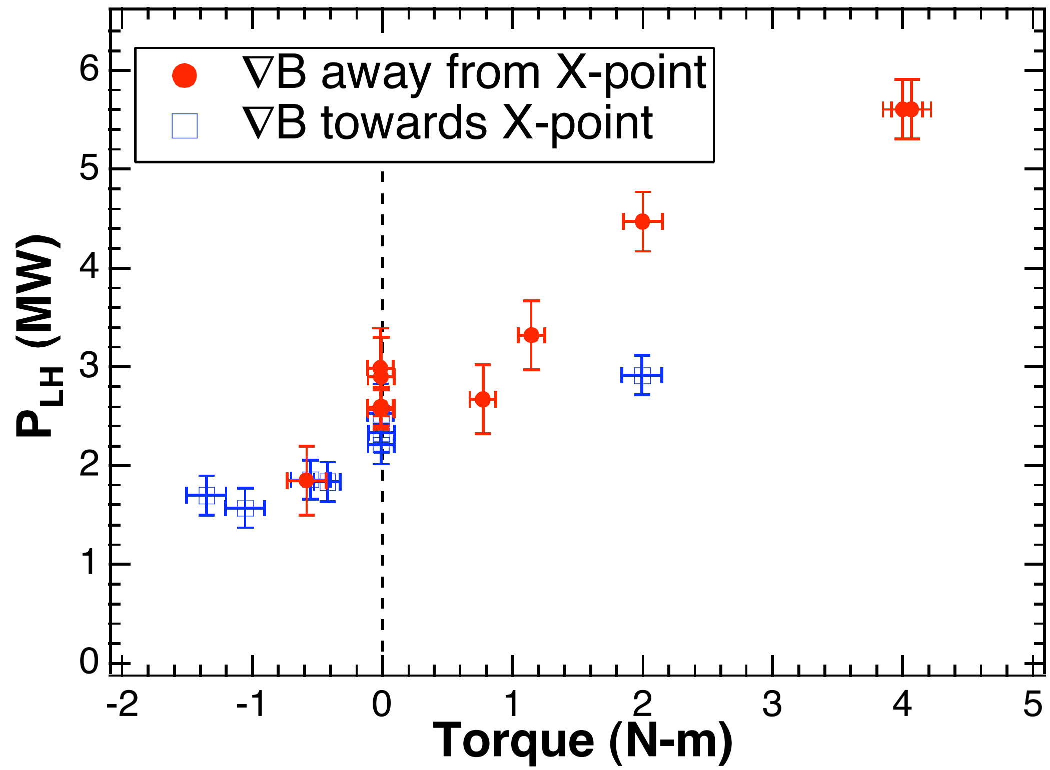
P_{LH} Increases Significantly with Torque





Lower Single Null:
∇B towards X-Point

Upper Single Null:
∇B away from X-Point

- Factor of 4 increase in P_{LH} with rotation with ∇B away from X-Point
- Factor of 2 increase with ∇B towards X-Point
- Difference in P_{LH} between ∇B drift directions increases with rotation

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Radial Electric Field Terms Favor Higher Edge E_R Shear in Balanced Injection Plasma, Facilitating L-H Transition

Radial Electric Field:

- **E_r in Co-Inj. discharges dominated by v_ϕ term**
- **E_r in Balanced-INJ discharges, ∇P term dominates Er and Er' near the plasma edge**

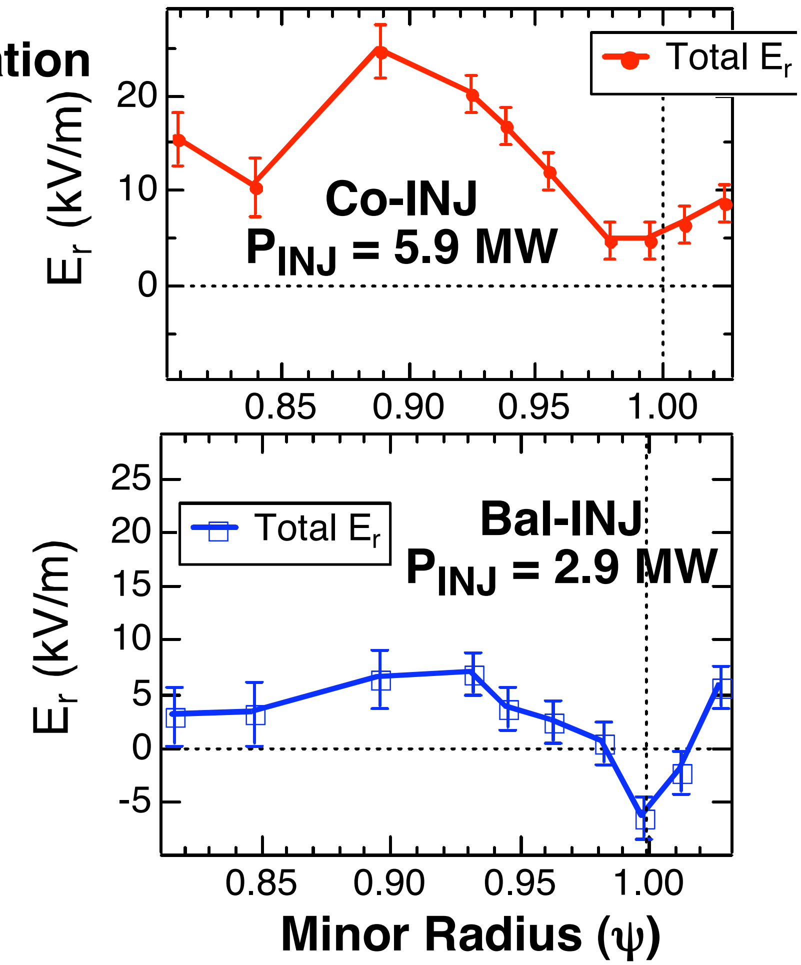
$$E_r = \frac{\nabla P_I}{Z_I e n_I} + v_{\phi,i} B_\theta - v_{\theta,i} B_\phi$$

Pressure Gradient

Rotation

∇B away from X-point

***E_r* prior to LH Transition**



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RADIAL ELECTRIC FIELD TERMS FAVOR HIGHER EDGE E_R SHEAR IN BALANCED INJECTION PLASMA, FACILITATING L-H TRANSITION

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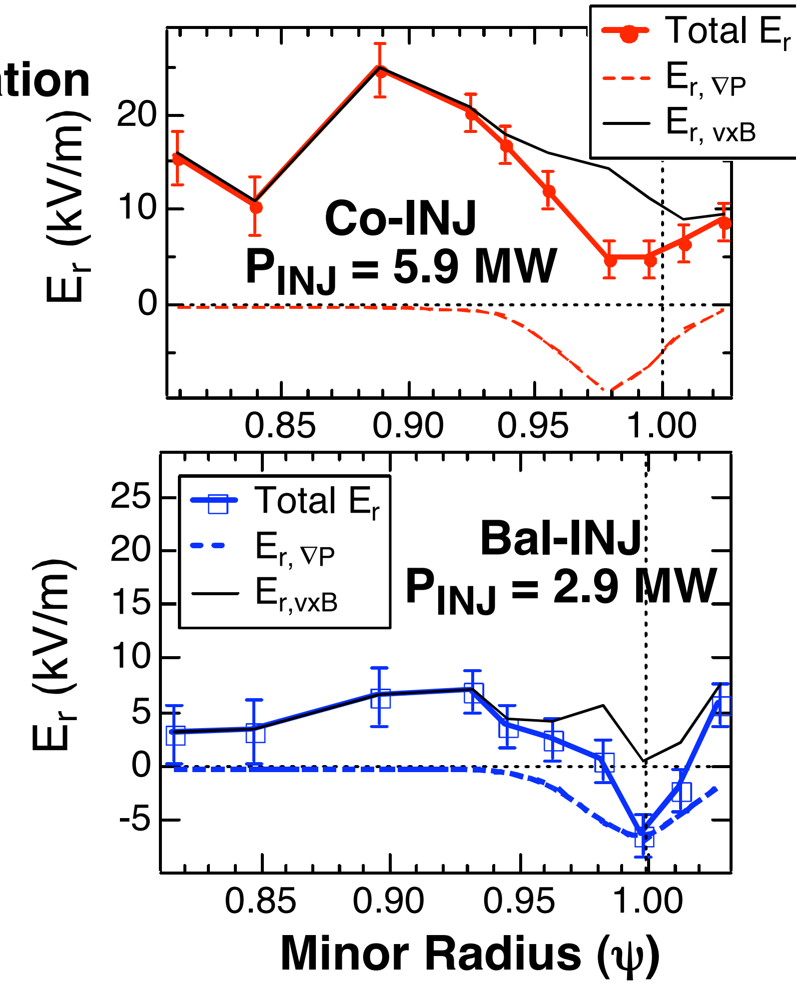
$$E_r = \underbrace{\frac{\nabla P_I}{Z_I e n_I}}_{\text{Pressure Gradient}} + v_{\phi,i}B_\theta - \underbrace{v_{\theta,i}B_\phi}_{\text{Rotation}}$$

∇B away from X-point

***E_r* prior to LH Transition**



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Radial Electric Field:

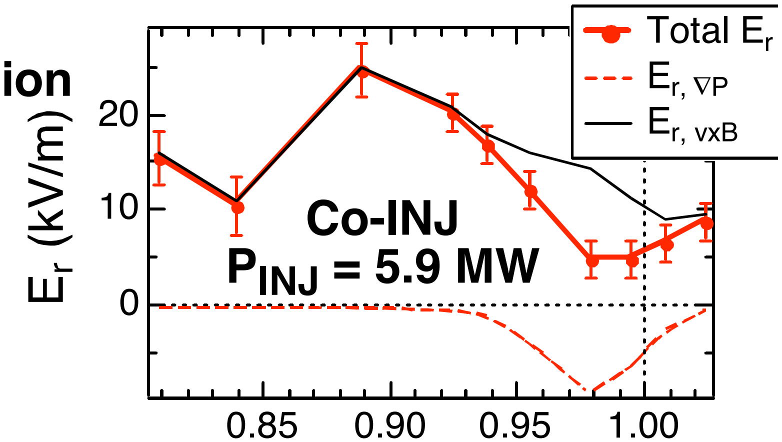
$$E_r = \frac{\nabla P_I}{Z_I e n_I} + v_{\phi,i} B_\theta - v_{\theta,i} B_\phi$$

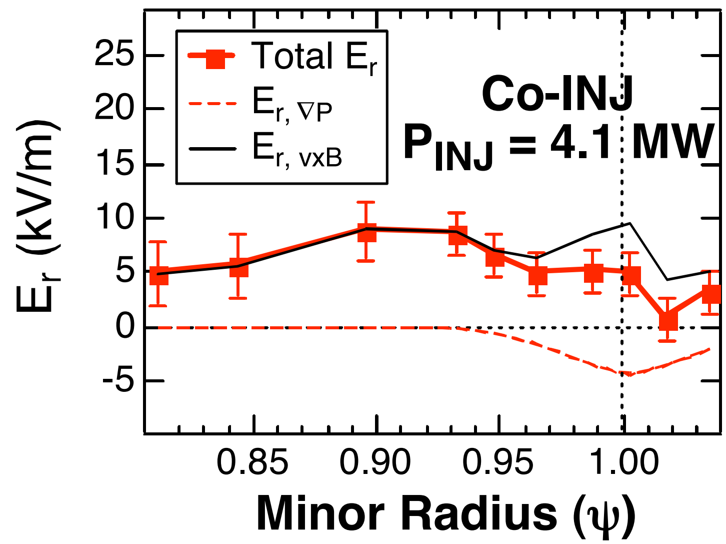
Pressure Gradient **Rotation**

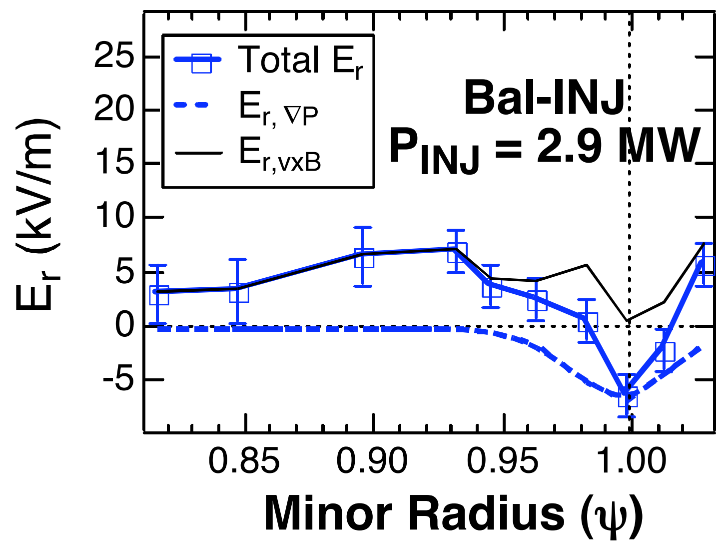
- **E_r in Co-Inj. discharges dominated by v_ϕ term**
- **E_r in Balanced-INJ discharges, ∇P term dominates Er and Er' near the plasma edge**
- **Co-Inj at lower power exhibit little Er' inside separatrix**

E_r prior to LH Transition

∇B away from X-point







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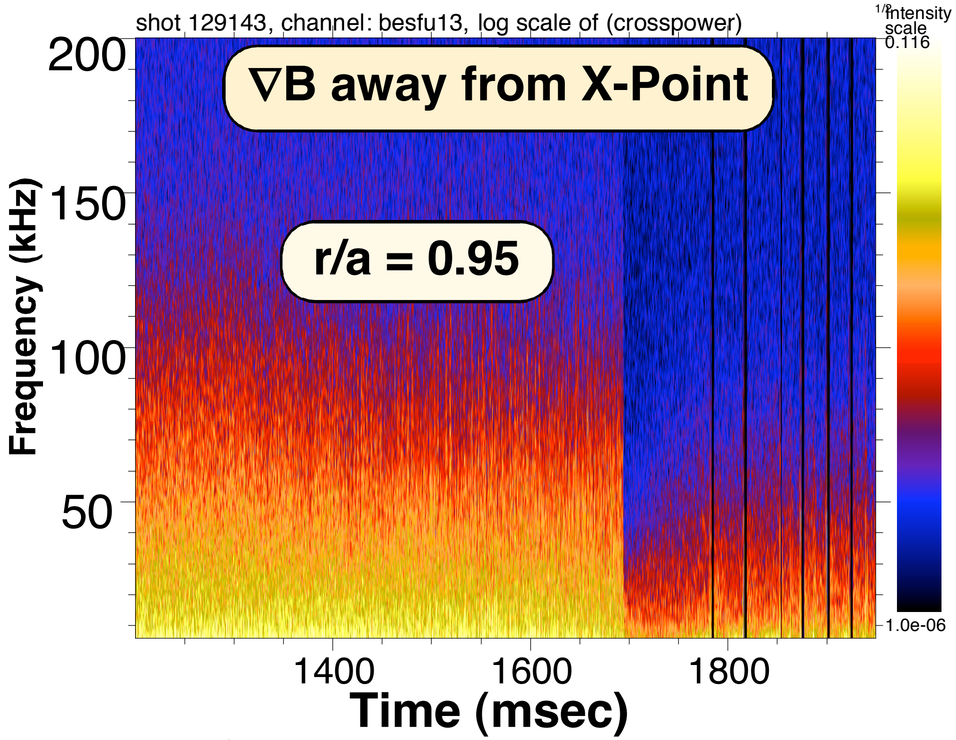
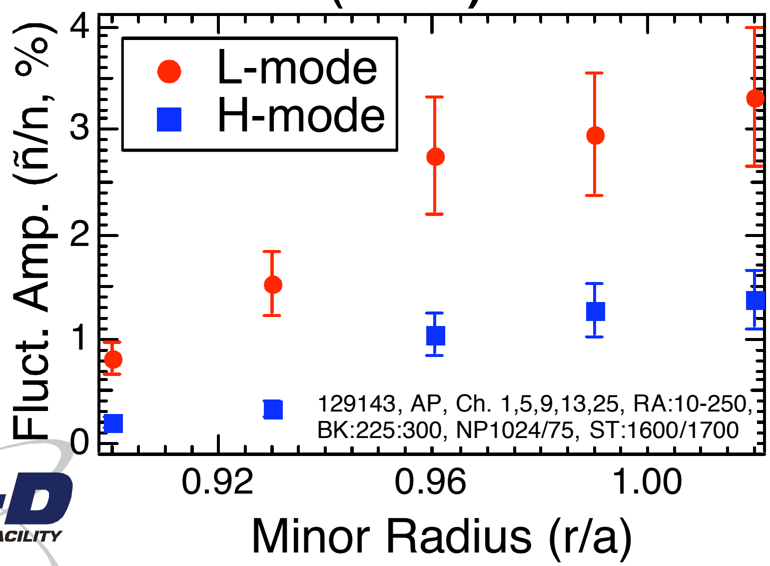
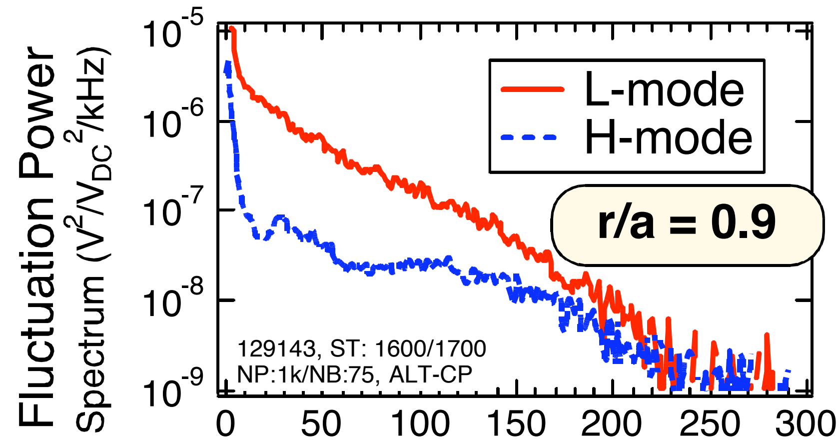
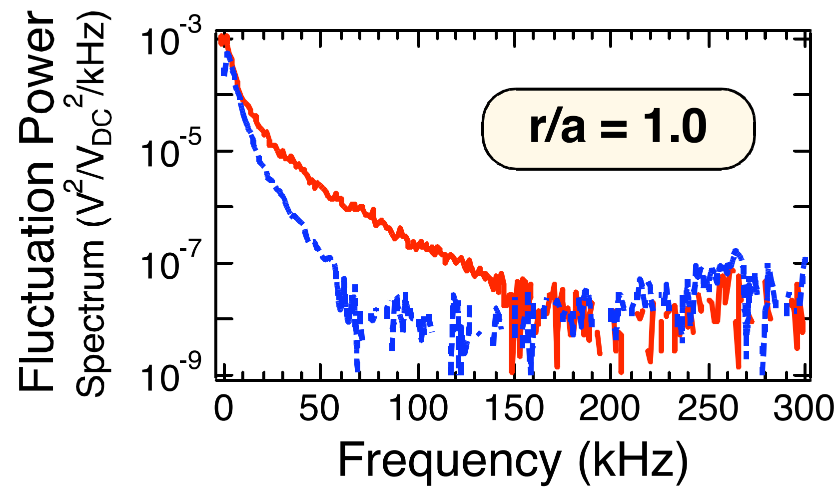
Rapid Fluctuation Suppression Observed In Edge at LH Transition





BES Measurements of density fluctuation spectra





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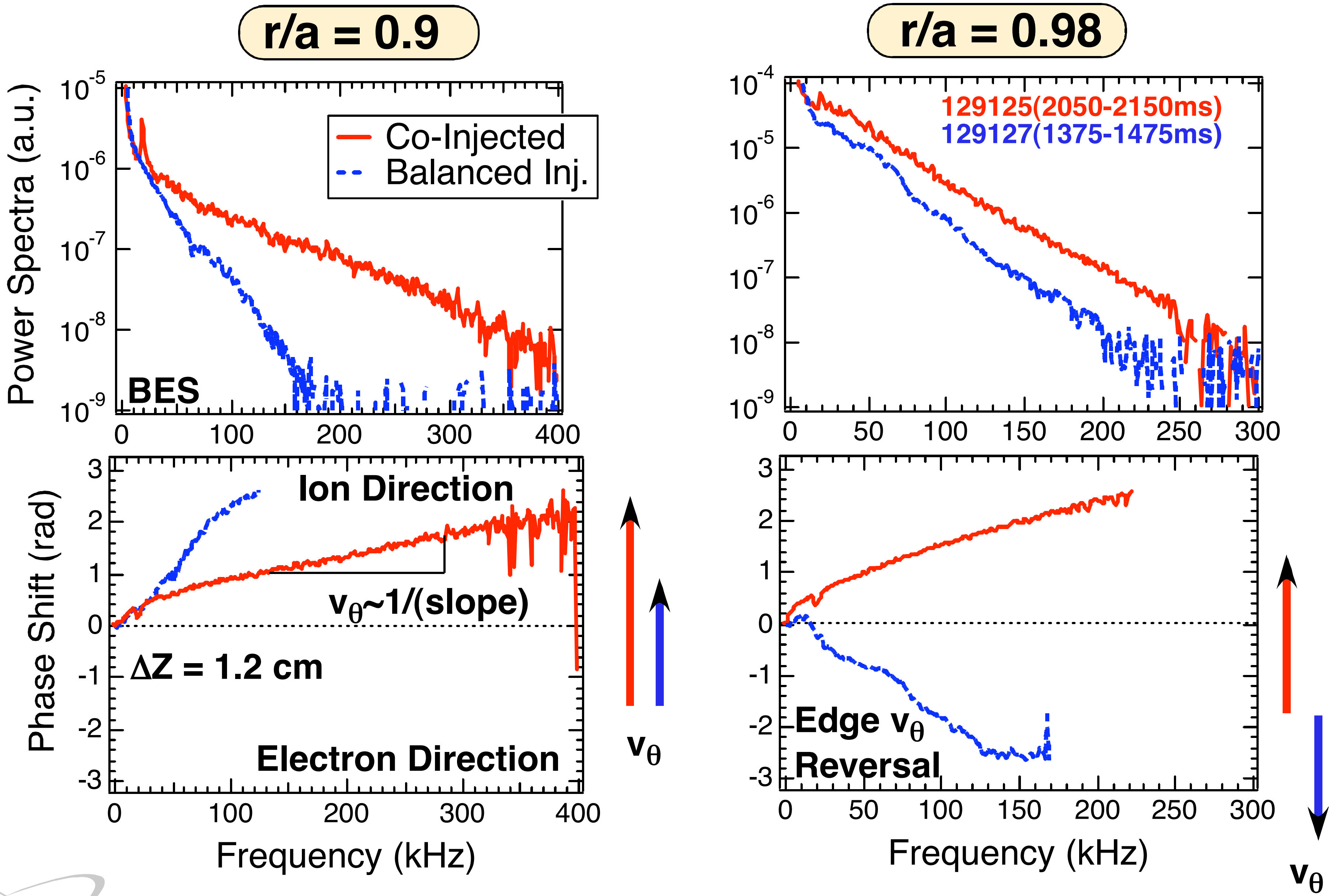
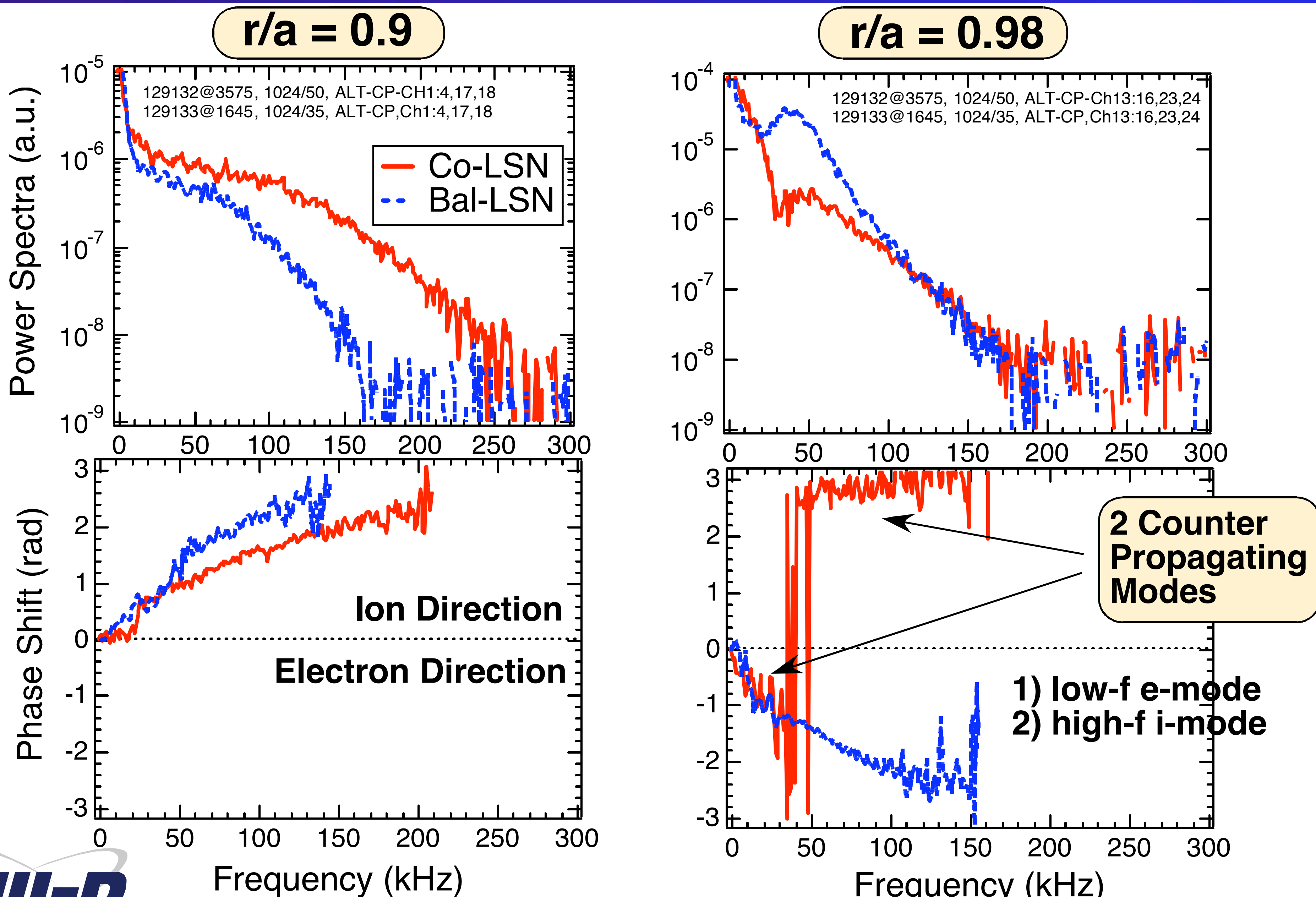
Significant Difference in Edge Turbulence & Flows Between Co-Injection & Balanced Injection (∇B *away from* X-Point)



Plasmas with Ion ∇B *Towards* X-Point Exhibit Similar Flows as well as Multiple Turbulence Modes



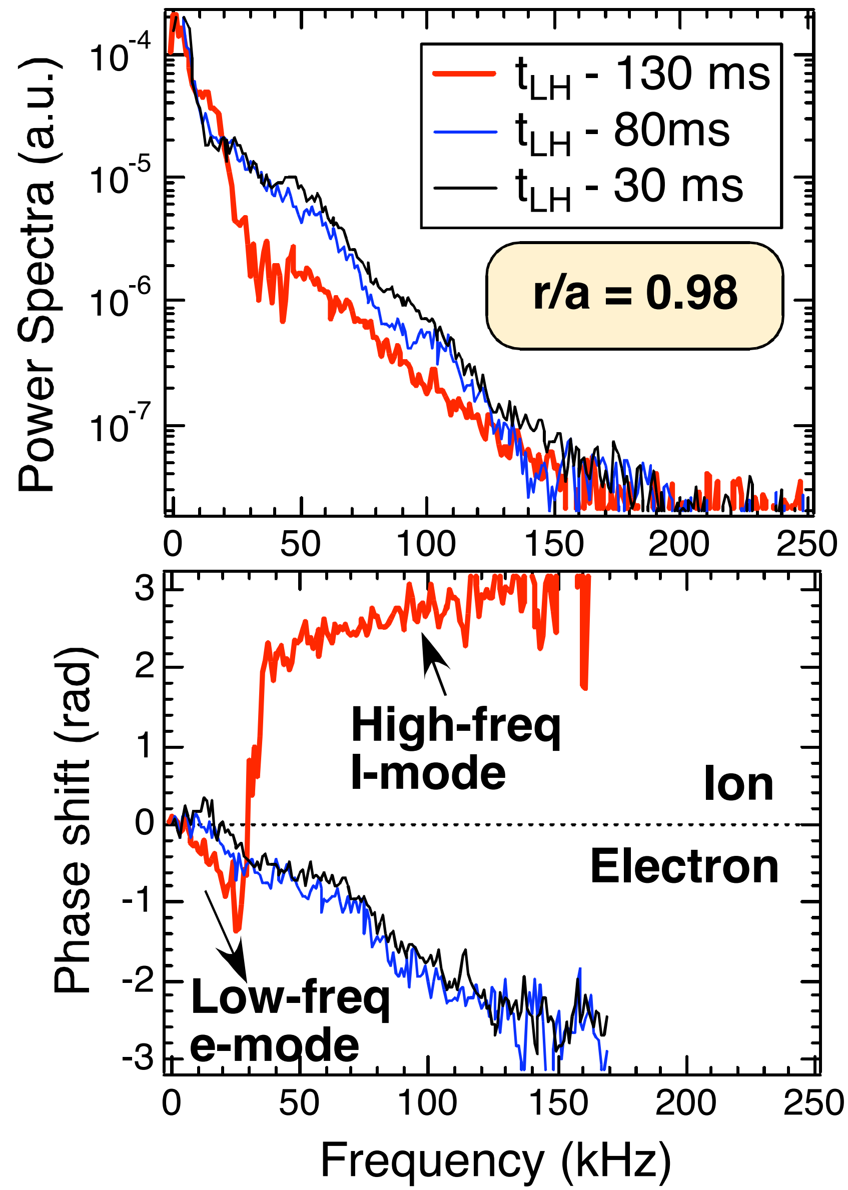
American Physical Society - Division of Plasma Physics, Orlando, Florida - G. McKee- November 16, 2007

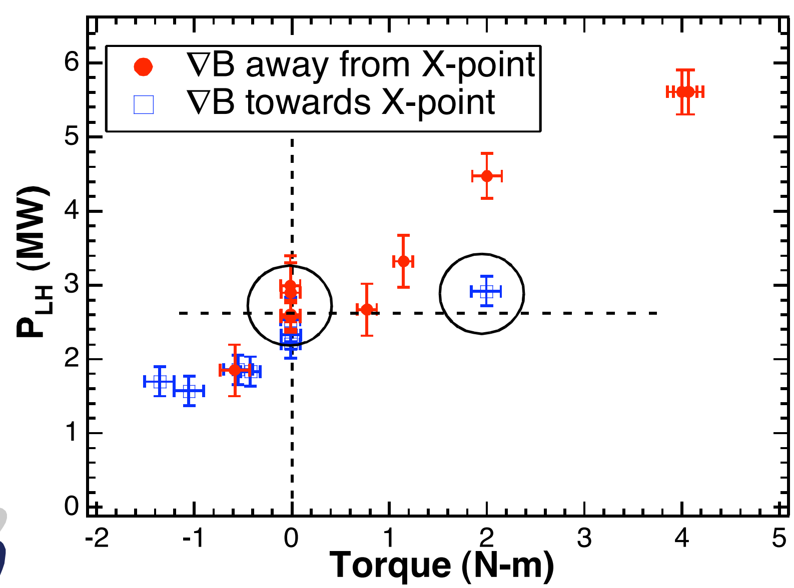
Multi-Mode Structure Observed in Balanced-Injection Plasmas with ∇B away from X-point

- Dual-mode structure observed in both balanced injection discharges with ∇B away from X-point,

  AND

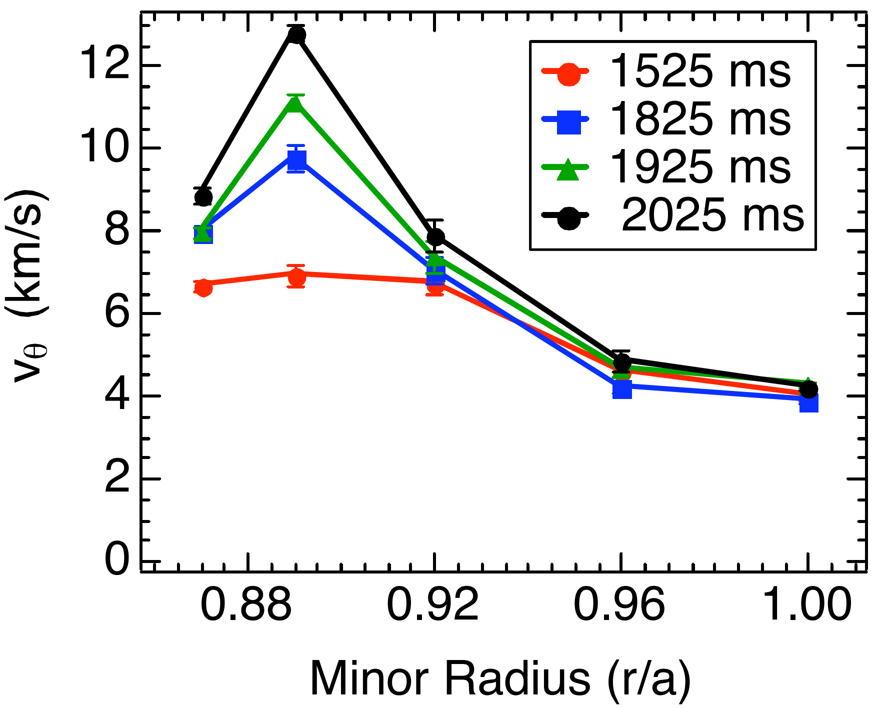
  Co-injected discharge with ∇B towards the X-point
- Two conditions have similar P_{LH}
- Correlation with increased turbulence flow shear suggests causal relation



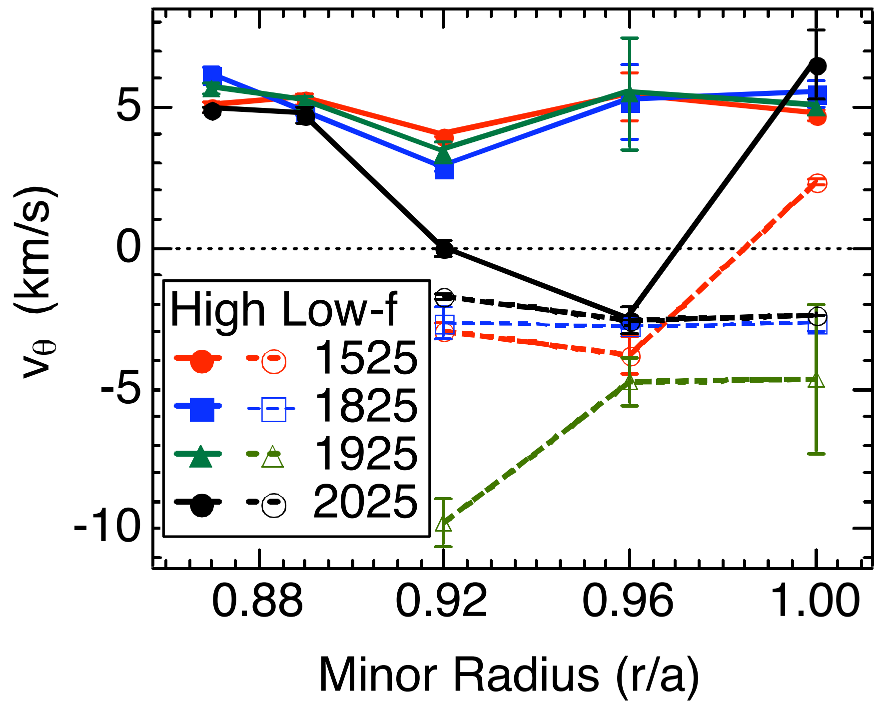


Radially-Sheared Poloidal Turbulence Flows Evolve Differently For Co- and Balanced-Injection Plasmas

Co-Current Injection
USN Plasma



Balanced Injection
USN Plasma



- **Turbulence poloidal velocity obtained via cross-correlation analysis**
- **Gradual evolution and increasing shear in Co-injection discharge**
- **Sudden "reversal" of poloidal flow in balanced prior to LH**

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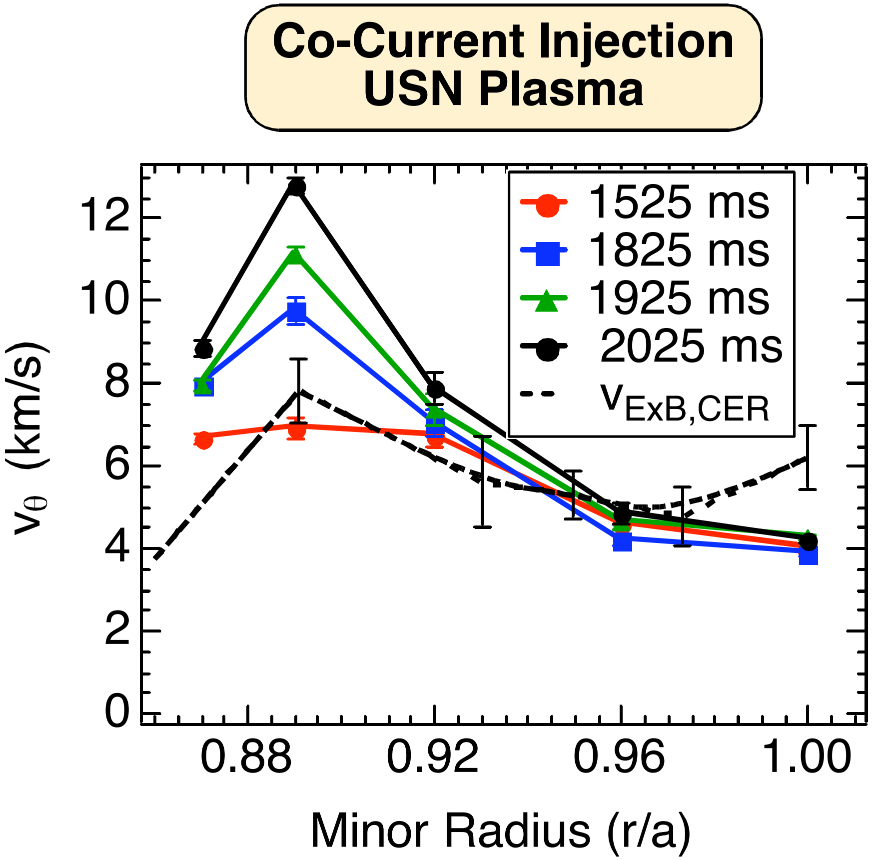
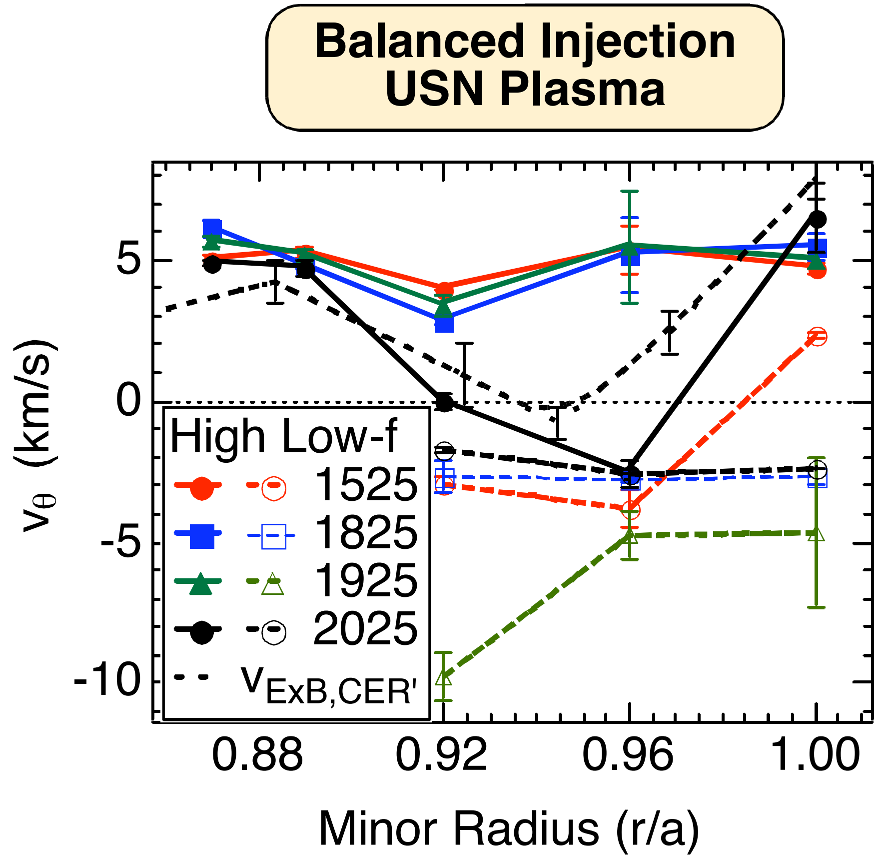
Radially-Sheared Poloidal Turbulence Flows Evolve Differently For Co- and Balanced-Injection Plasmas





- **Turbulence poloidal velocity obtained via cross-correlation analysis**
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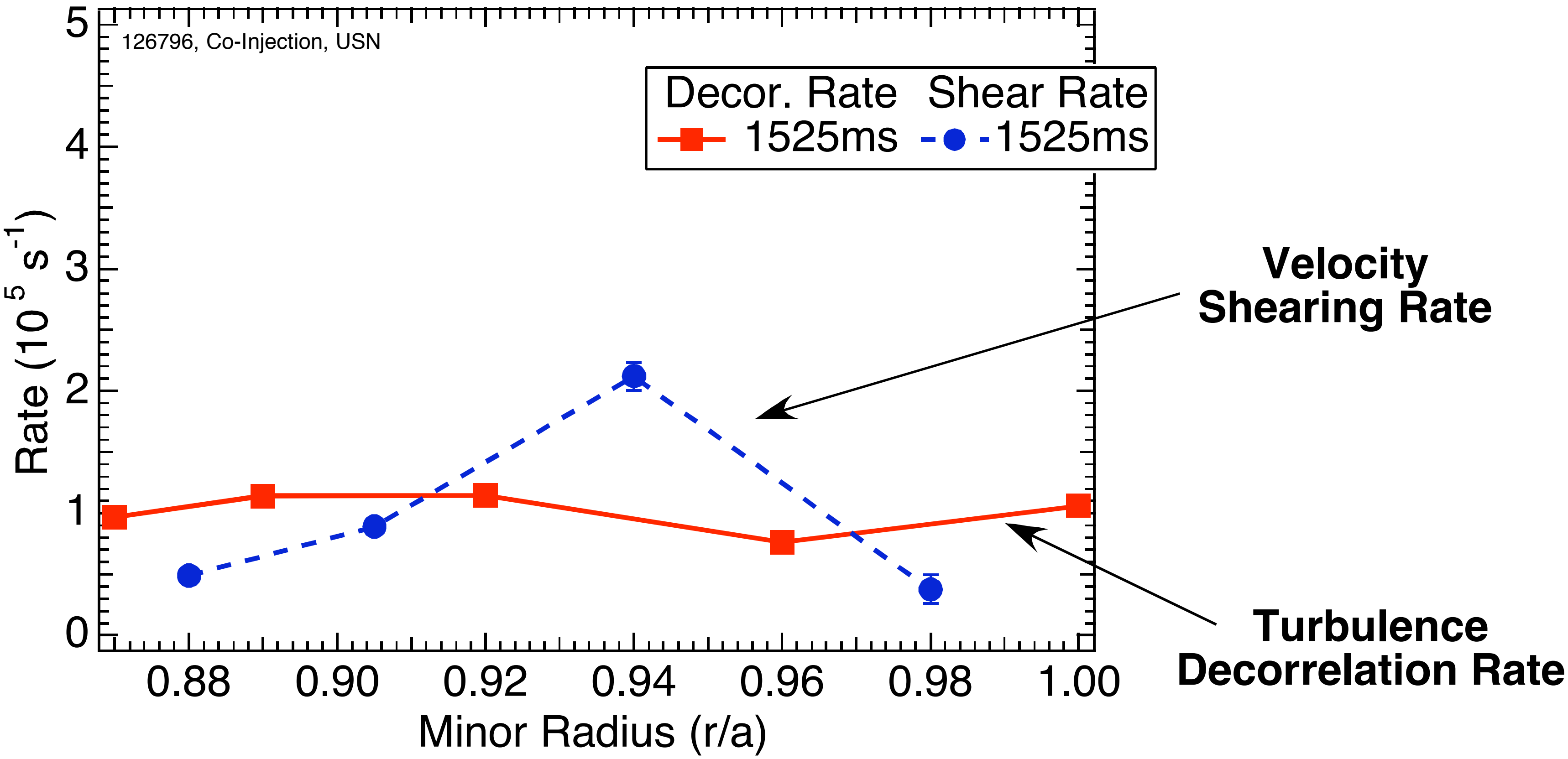
LH Transition Occurs as Shearing Rates Increase and Exceed Turbulence Decorrelation Rates

- **BES data allow for independent measurement of poloidal velocity, velocity shear, and turbulence decorrelation rates**

Co-Injection, ∇B away from X-point



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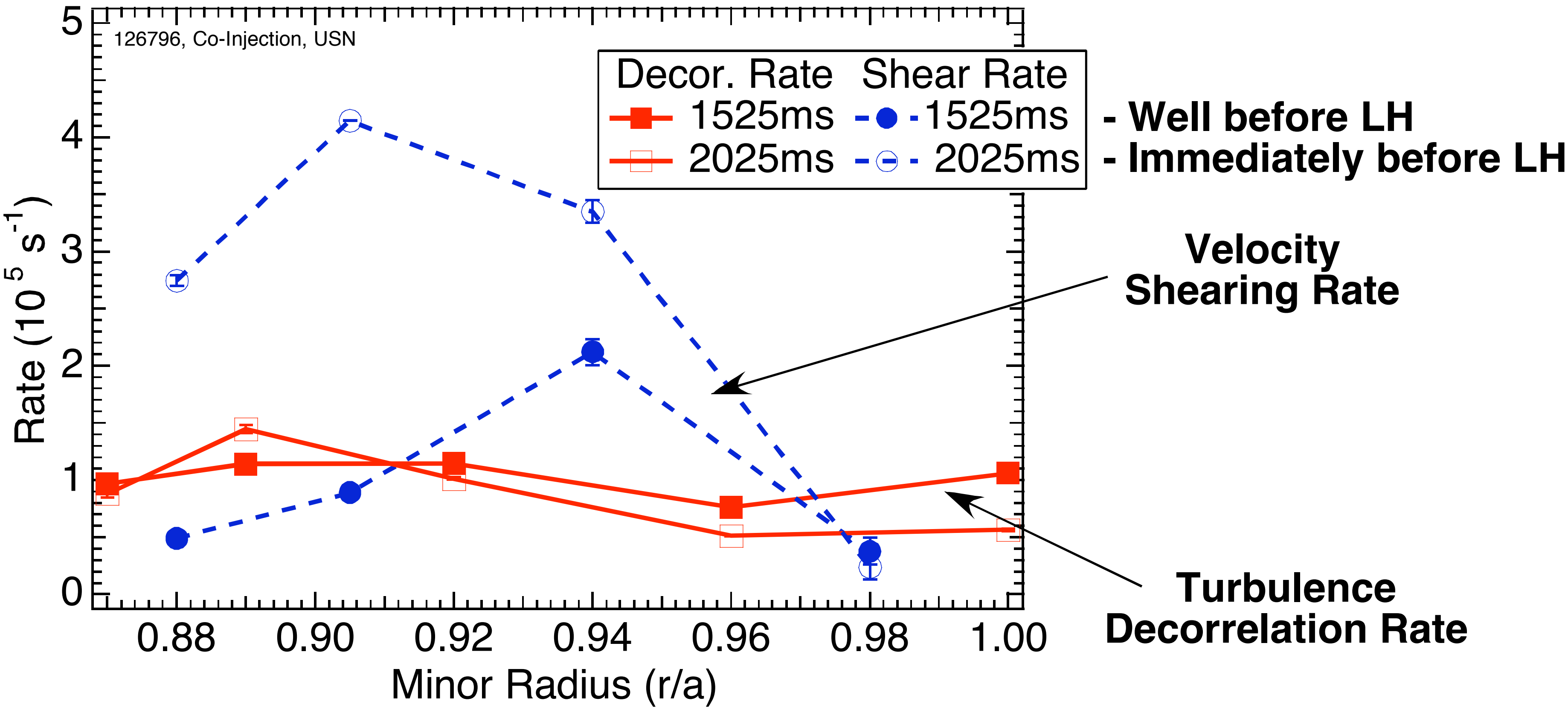

D. Schlossberg et al., submitted to PRL (2007)

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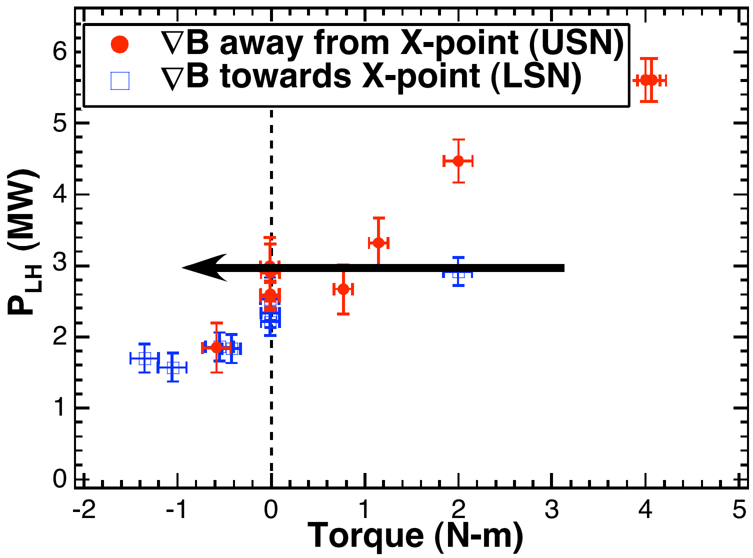
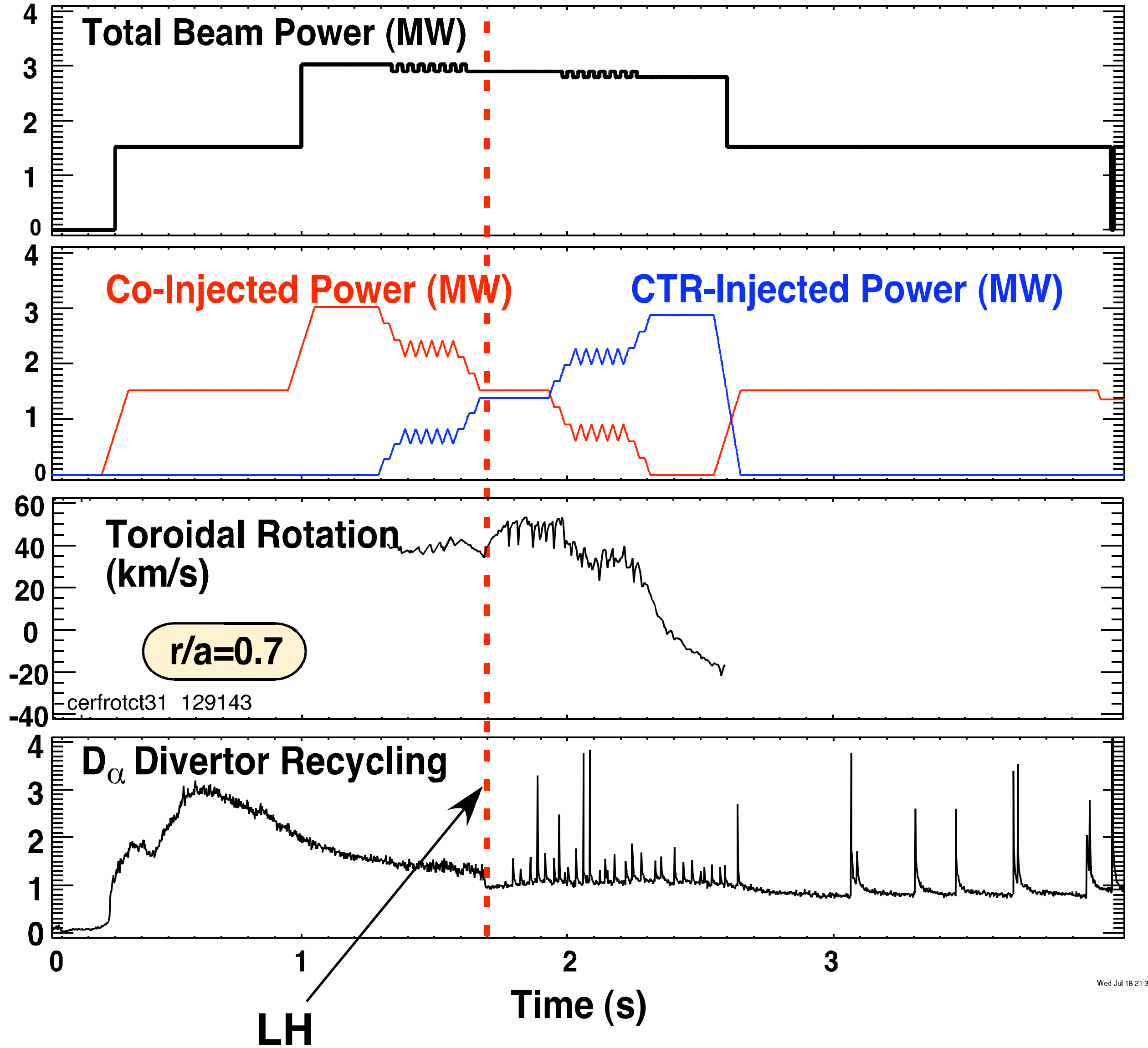
LH Transition Induced Via Torque-Scan at Constant Power

∇B away from X-point





- P_{LH} = 3 MW
- Consistent with previous measurements
- Slowly evolving turbulence characteristics

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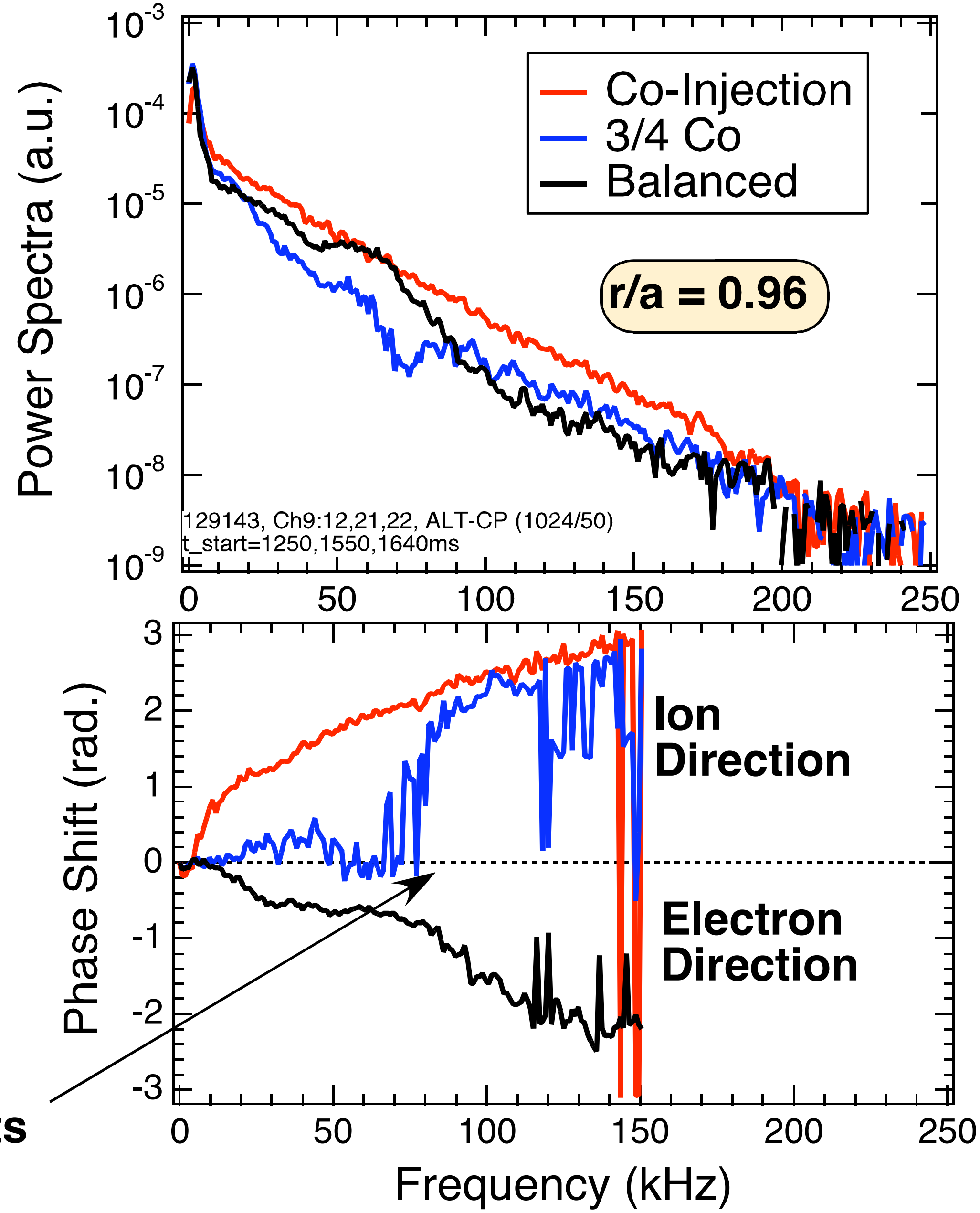
Edge Turbulence Poloidal Flow Reverses During Constant-Power Torque Scan

- Reversed v_θ during balanced injection, shortly before LH-transition
- Shear increases as rotation varied from co- to balanced



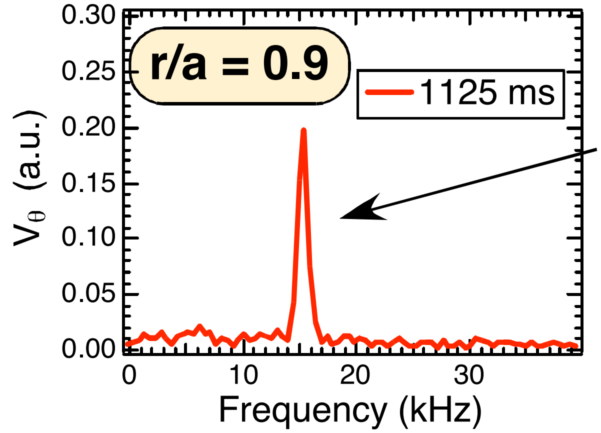
Break in phase reflects dual modes

Poloidal Velocity Spectrum Evolves From GAM-Dominated to Low-Frequency Zonal Flow as Plasma Rotation Slows

- **Time-Delay-Estimation (TDE) methods applied to poloidally-separated BES measurements to determine $v_\theta(t)$ (t = 20 μs resolution, 25 kHz)**

- **GAM oscillation identified in $v_\theta(t)$ spectra (E_r oscillation => $v_\theta(t)$)**

- **GAM dominates ZF spectrum at high rotation**
  - *gradually decays in amplitude and disappears as plasma slows*



Geodesic Acoustic Mode:

- *coherent*
- *m=0, n=0*
- *finite k_r*
- *$f \approx c_s/2\pi R$*

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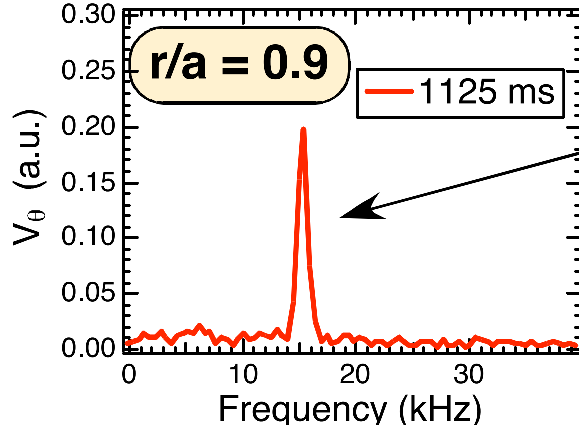

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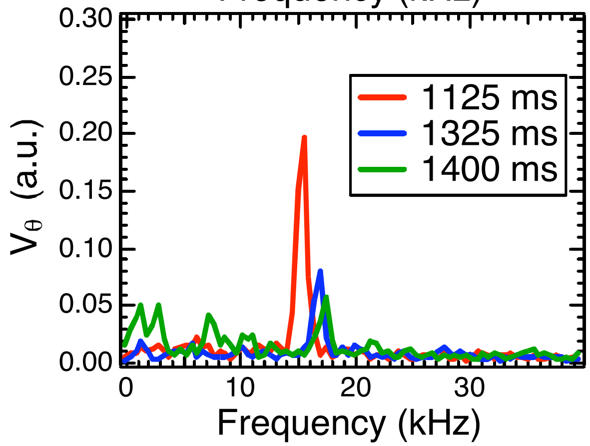

GAM decays with time

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Poloidal Velocity Spectrum Evolves From GAM-Dominated to Low-Frequency Zonal Flow as Plasma Rotation Slows

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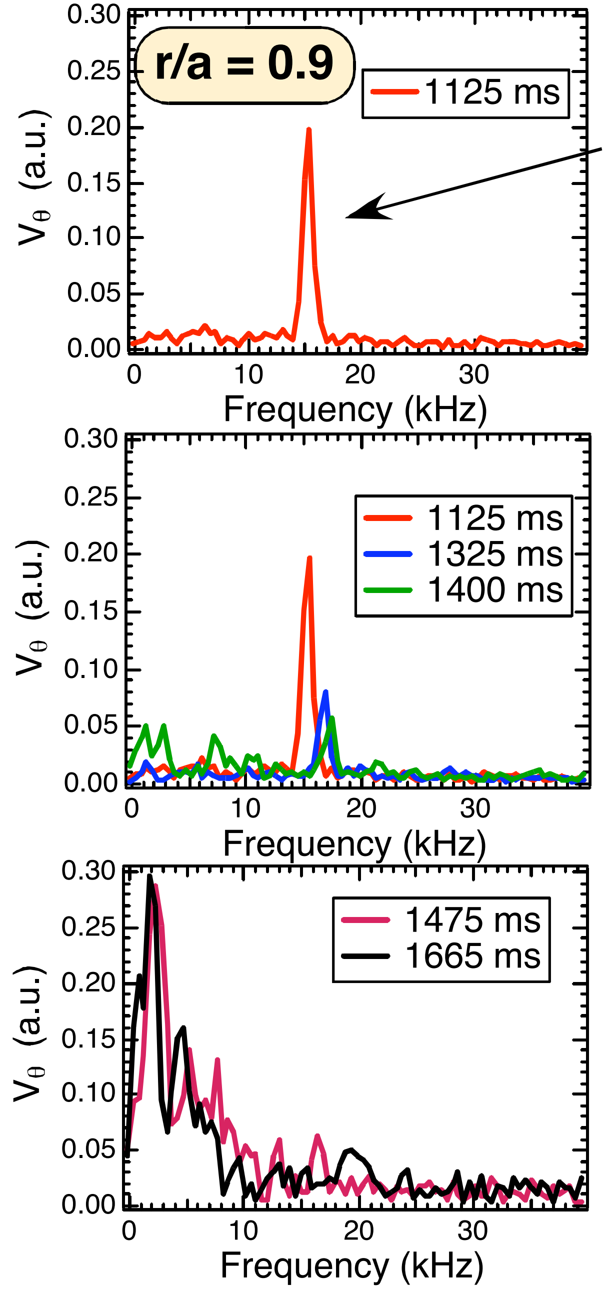
- **GAM oscillation identified in $v_\theta(t)$ spectra (E_r oscillation => $v_\theta(t)$)**
- **GAM dominates ZF spectrum at high rotation**
  - *gradually decays in amplitude and disappears as plasma slows*
- **Zero-Mean-Frequency Zonal Flow arises and dominates spectra**
  - *ZMF-ZF power significantly higher than GAM power*
  - *More likely to trigger transition*
- **Correlation between rotation and zonal flow behavior**

E.J. Kim, P.H. Diamond, PRL (2003)



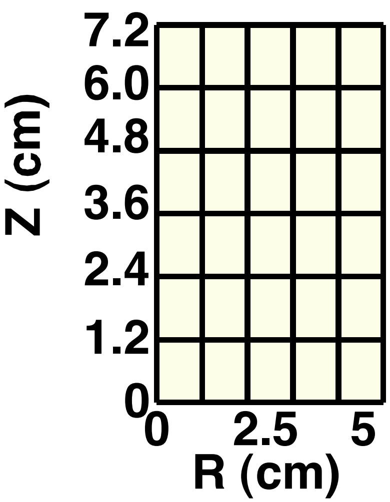
Geodesic Acoustic Mode:

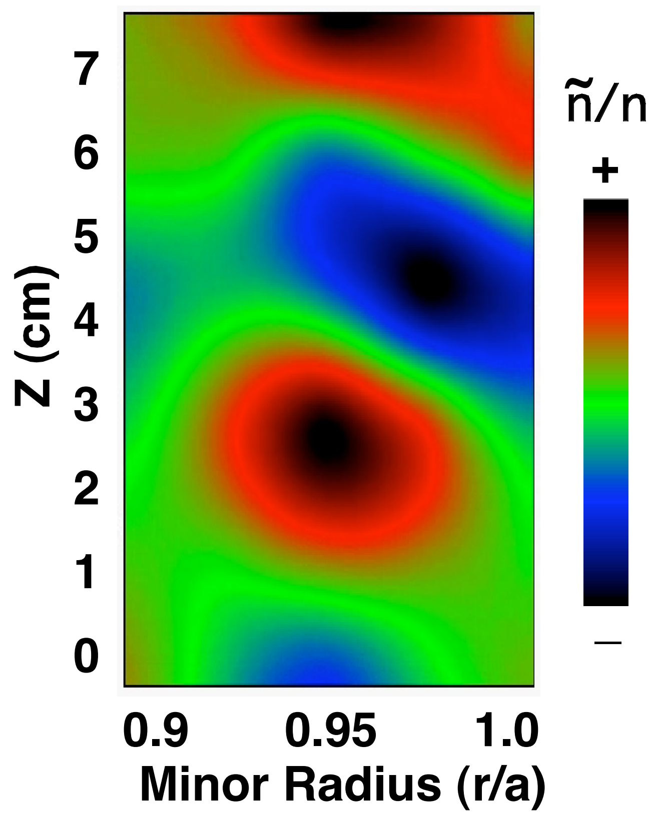
- *coherent*
- *m=0, n=0*
- *finite k_r*
- *$f \approx c_s/2\pi R$*

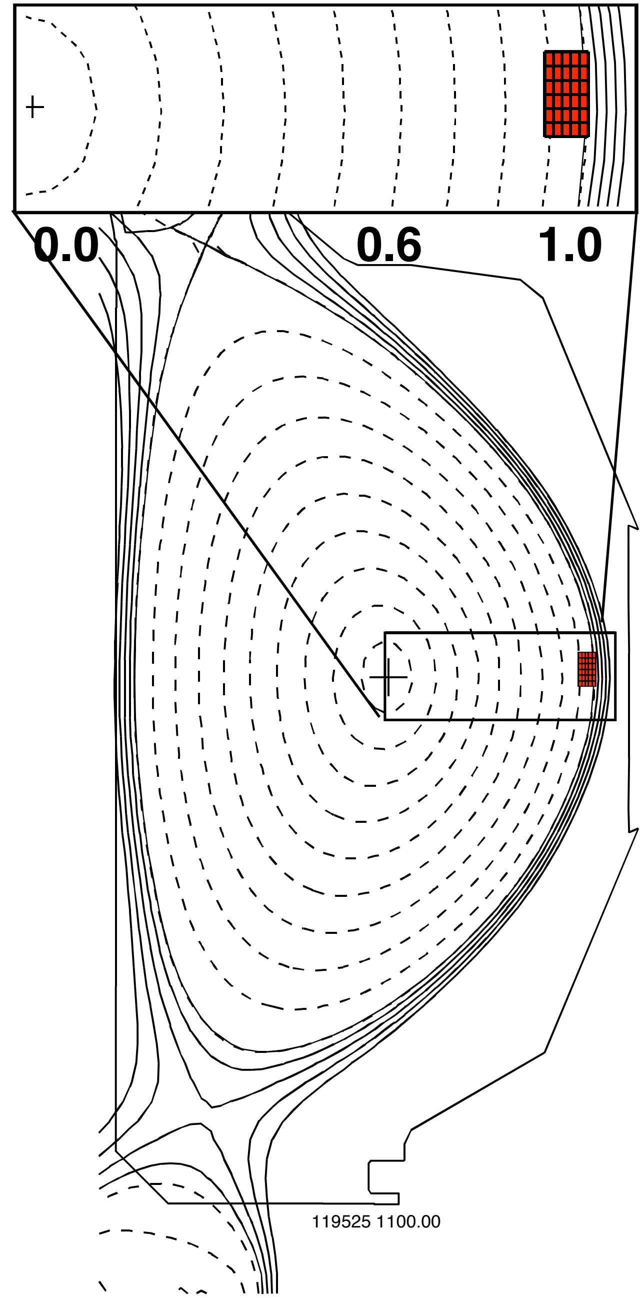
GAM decays with time

ZMF-ZF signature arises at low-frequency prior to LH

Visualizations of Edge Turbulence Demonstrate Significant Variation in Flow Patterns and Mode Structure







- 1 MHz sampling over 5x6 grid
- Frequency-filtered per spectrum
- 2D spline interpolation
- 10^5 time dilation (10 μs = 1 sec)

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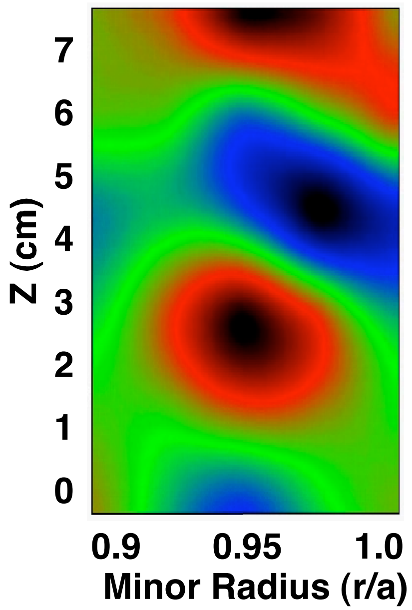
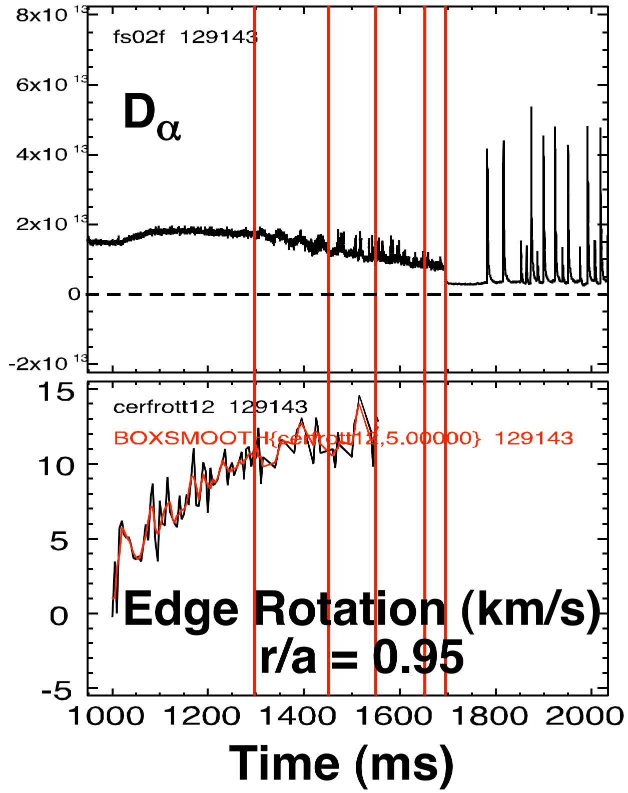
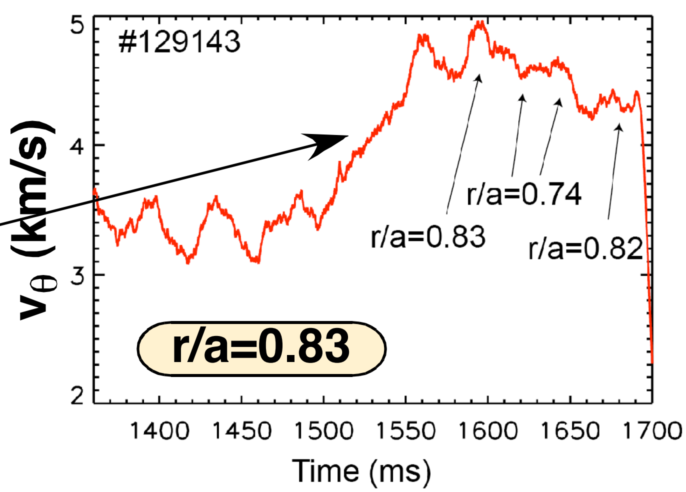
Visualizations of Edge Turbulence Demonstrate Significant Evolution in Flow Patterns and Mode Structure

- **200 μs segments at 5 intervals**

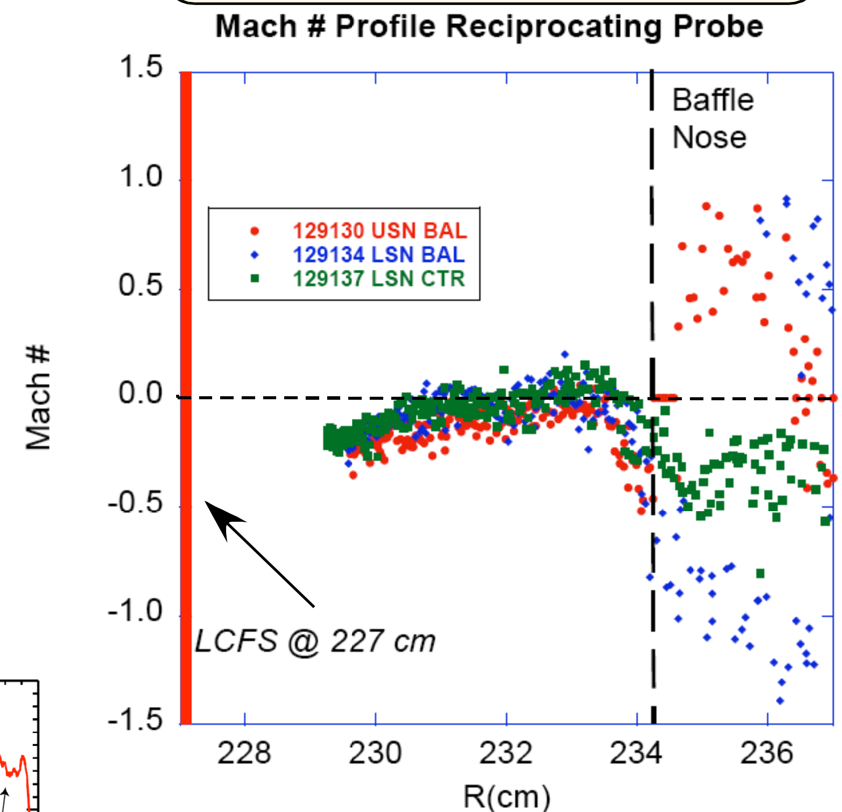




Doppler Reflectometer shows localized *increase* in v_θ during torque scan



Mach Probe shows little change in SOL toroidal flow



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Conclusions

- **Power flux required to trigger an L-Mode to H-mode transition is found to vary with applied torque and toroidal rotation**
  - *P_{LH} reduced with balanced and counter-current NBI injection, relative to co-current NBI injection*
  - *Affects plasmas with ion ∇B drift towards (LSN) and away-from (USN) dominant X-point*
    - *More pronounced for USN plasmas*

- **Edge turbulence characteristics change dramatically with toroidal rotation**
  - *Radially sheared poloidal flows strongly influenced by rotation*
  - *Shear exceeds turbulence decorrelation rates prior to transition*
  - *Turbulence mode structure depends on magnetic configuration and toroidal rotation*
  - *Zonal flow behavior strongly dependent on rotation: possible trigger mechanism*

- **Mechanism appears to depend on radial electric field, turbulence, flows, and zonal flow dynamics in edge region of plasma**

- **Beneficial implications for accessing H-mode in slowly rotating plasmas (e.g., ITER)**
  - *Presently P_{LH} scaling does not consider rotation*

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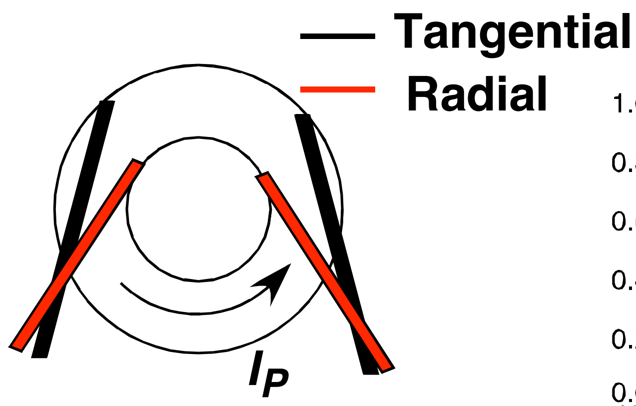
Beam Ion Prompt Losses Appear Not to Have a Significant Impact on LH Transition Power Threshold



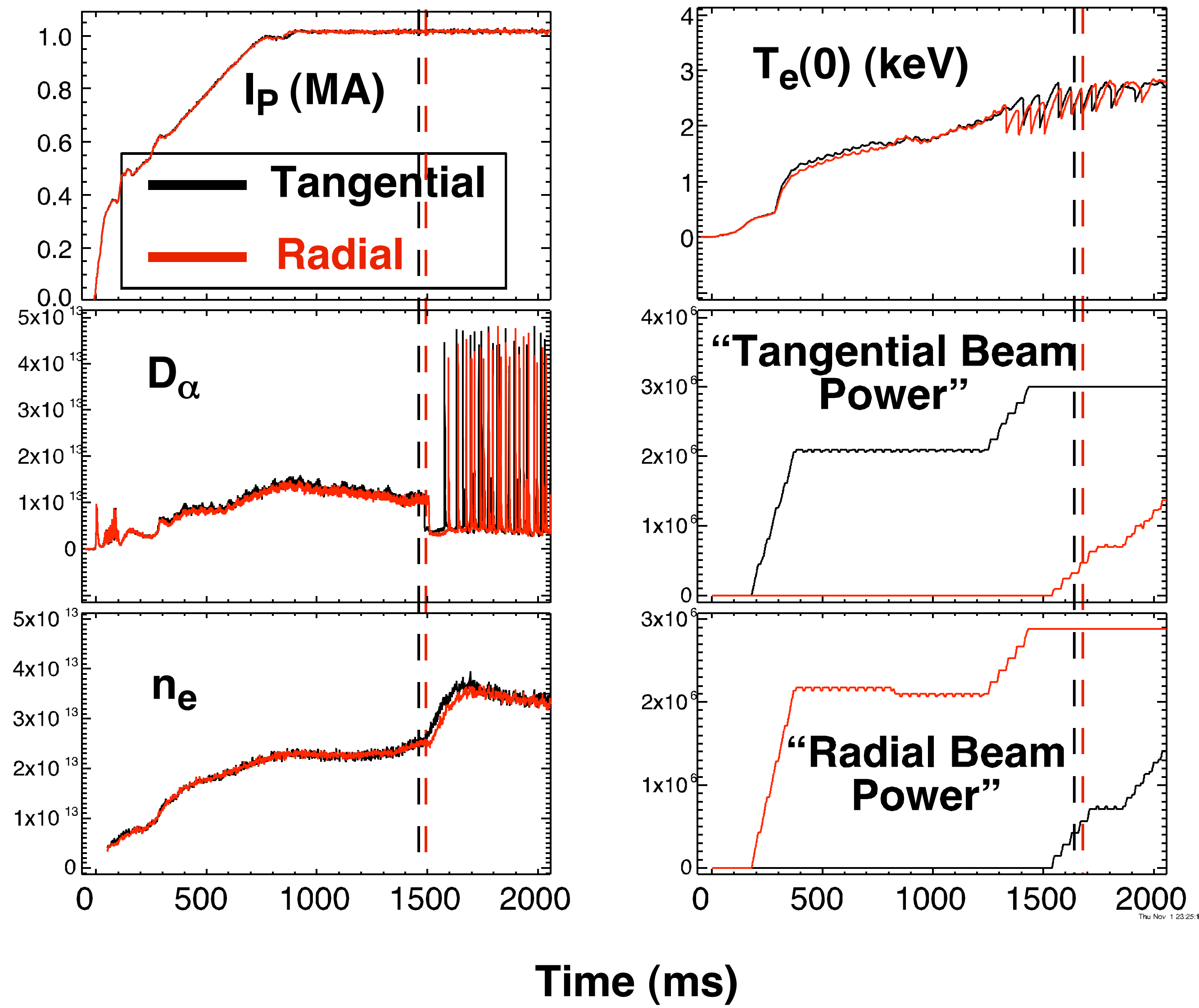
- Similar discharges: (USN - Net Balanced NB Injection)

1) More tangential beams

2) More radial beams

- Beam ion confinement changes significantly between conditions

- LH power nearly identical: ($P_{INJ} \approx 2.9$ MW)



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Implications of These Results for P_{LH} Scaling Relationships

- **LH Power Threshold is a critical issue for ITER and Reactors, H-mode achieves:**
  - *Higher confinement ($\tau_{E,H\text{-}mode} \sim 2\text{-}3^* \tau_{E,L\text{-}mode}$)*
  - *High β (2-3* L-mode)*
- **H-mode access readily achieved in most modern experiments**
  - *H-mode access in ITER may be challenging especially for Hydrogen plasmas*
- **Current scaling relations do not consider plasma rotation:**

$$P_{LH} = 0.042 n_{20}^{0.73} B_T^{0.74} S^{0.98} \ \text{(MW)}$$

*ITER Physics Design Basis, Nuclear Fusion **47** (6), 2007*
Chapter 2: Plasma Confinement and Transport:
*E. Doyle et al., Nucl. Fusion **47**, S18 (2007)*

  - *Dependent on density (n), toroidal field (B_T) and surface area (S)*
  - *Database employ primarily co-rotating discharges (??)*
- **Rotational dependence significant**
  - *Parametric dependence inclusion should be considered*
  - *Need to isolate critical parameters (V_{TOR}, M)*
  - *Determine beam ion loss effects*

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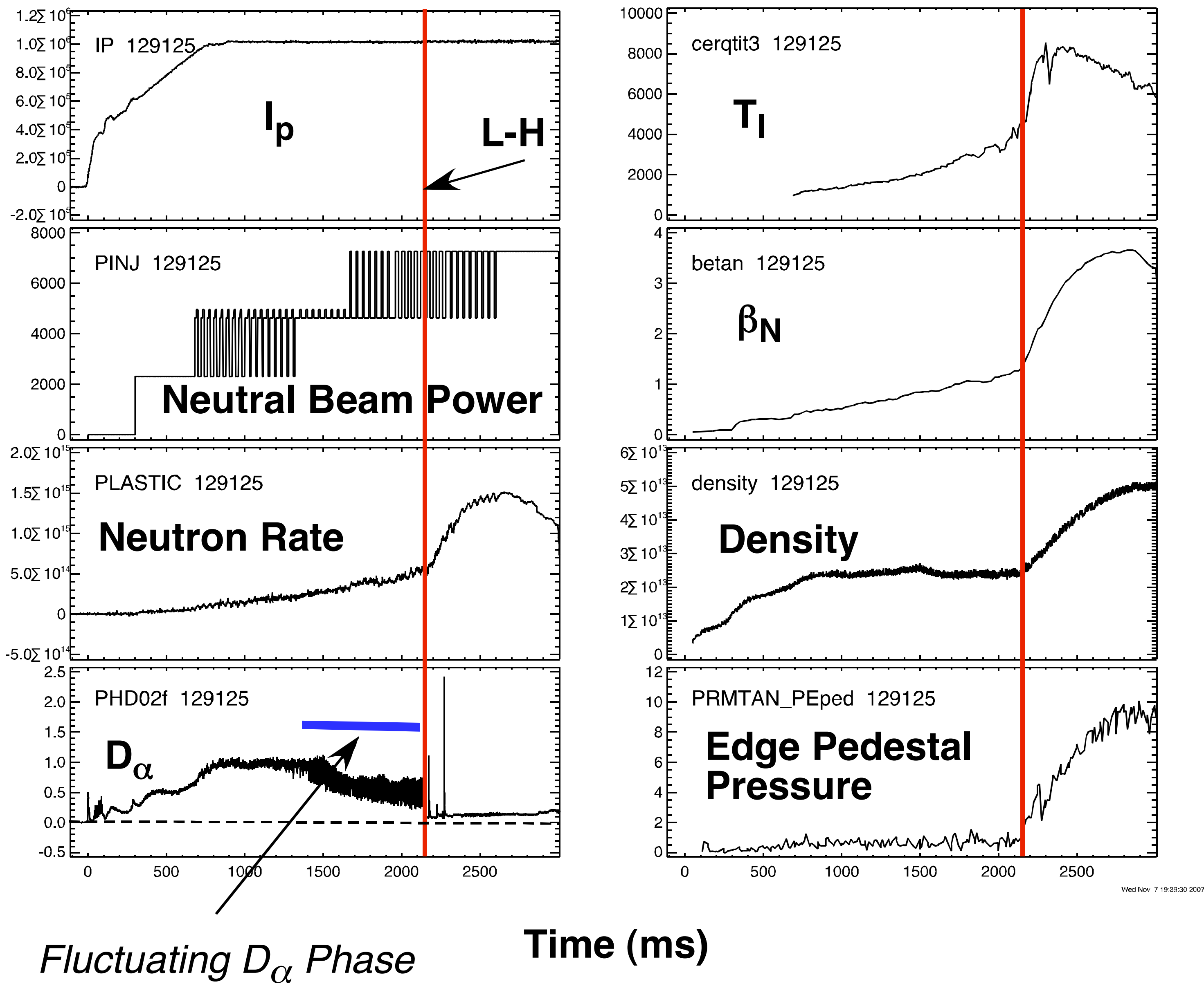
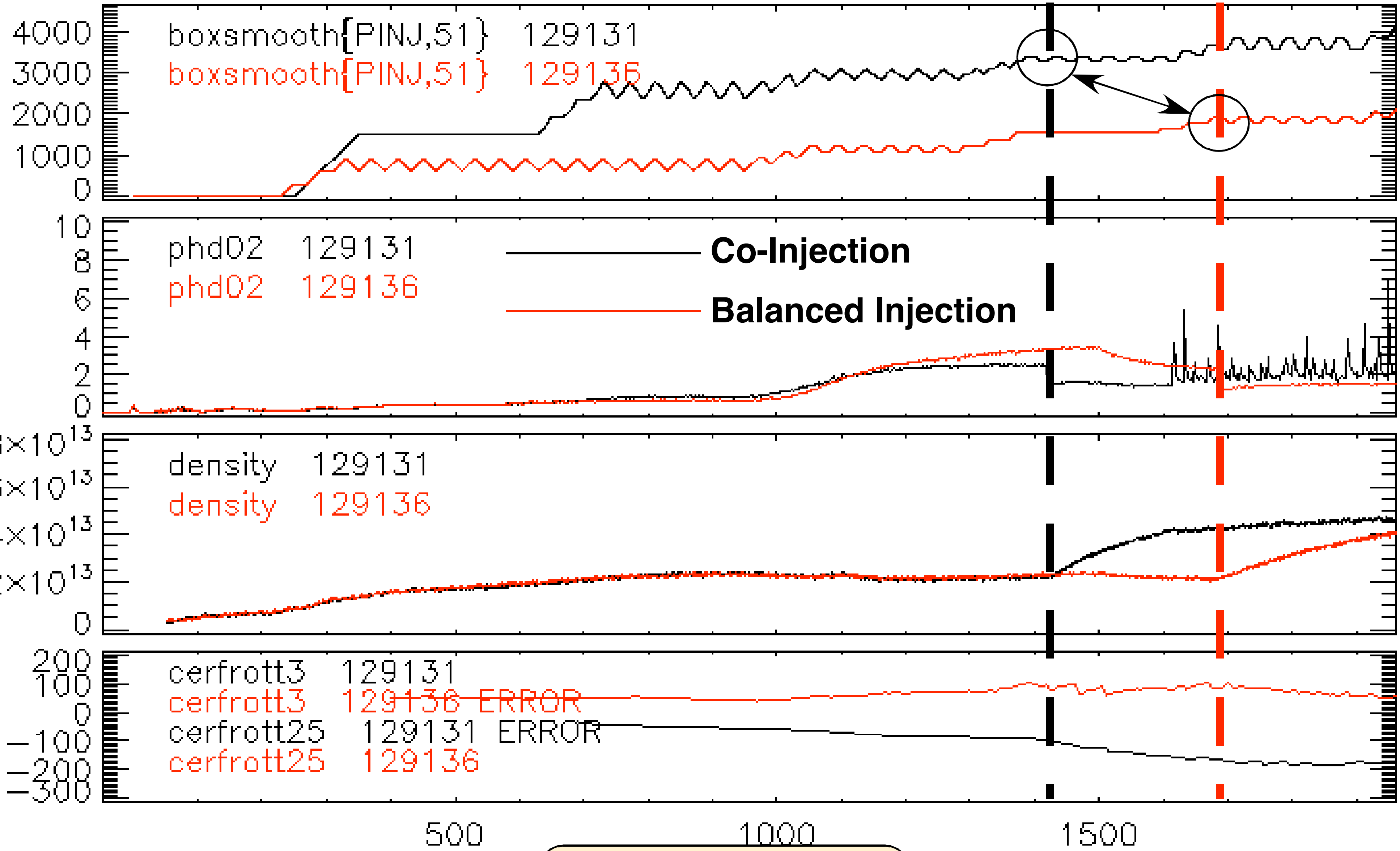
FLUCTUATING D_α PHASE EXHIBITS L-MODE BEHAVIOR UNTIL L-H TRANSITION



DIII-D NATIONAL FUSION FACILITY

Co-Rotating LSN Discharge Requires Nearly Twice the Power of Balanced Injection Discharge to Trigger LH Transition



$P_{inj}(CO) = 3.3$ MW
$P_{inj}(CTR) = 1.8$ MW

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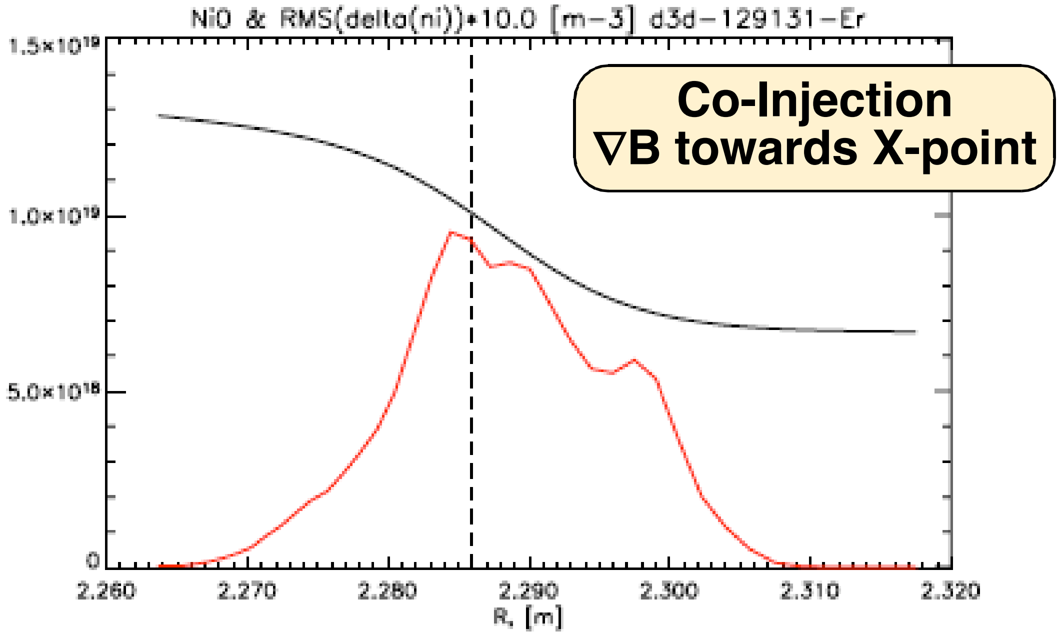
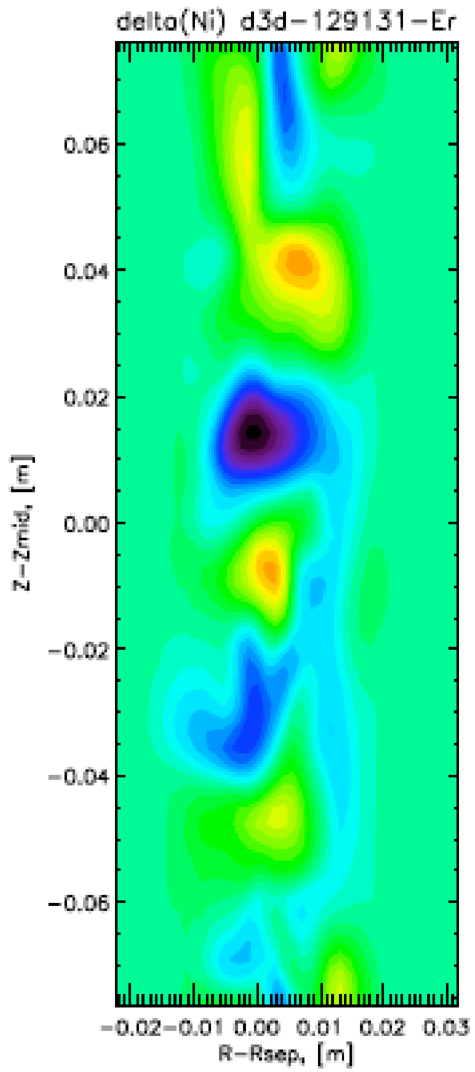
PRELIMINARY BOUT SIMULATIONS OF EDGE/SOL REGION

- Modified Braginskii fluid equations simulate resistive ballooning and drift turbulence and their interaction
- Density turbulence peaks at separatrix
- Eddy structures are ~1-2 cm, similar to BES observations
- Future simulations will compare co-injeciton and balanced in USN/LSN geometries





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