# DEPENDENCE OF THE L- TO H-MODE POWER THRESHOLD ON TOROIDAL ROTATION AND THE LINK TO EDGE TURBULENCE DYNAMICS

**G. R. McKee**
*University of Wisconsin-Madison*

**D.J. Schlossberg, M.W. Shafer**
*University of Wisconsin-Madison*

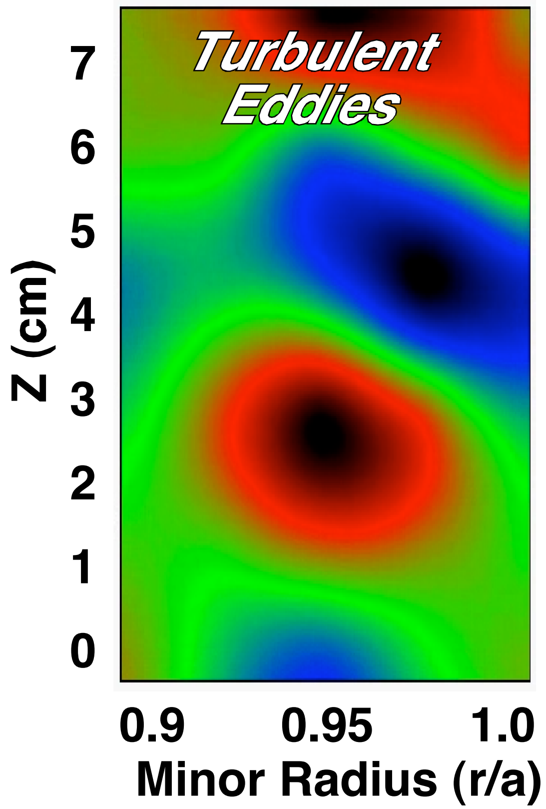
**K.H. Burrell, P. Gohil, R.J. Groebner**
*General Atomics*

**L. Schmitz, G. Wang, T.L. Rhodes**
*University of California - Los Angeles*

**J.A. Boedo, R.A. Moyer, D.L. Rudakov**
*University of California - San Diego*

**M.A. Makowski, M. Umansky, X. Xu**
*Lawrence Livermore National Laboratory*

**W.M. Solomon**
*Princeton Plasma Physics Laboratory*



22ND INTERNATIONAL ATOMIC ENERGY AGENCY FUSION ENERGY CONFERENCE

GENEVA, SWITZERLAND
OCTOBER 18, 2008

# DEPENDENCE OF EDGE TURBULENCE DYNAMICS AND THE L-H POWER THRESHOLD ON TOROIDAL ROTATION

- **Power flux required to trigger an L-H transition increases rapidly with injected torque and toroidal rotation**

- **Edge turbulence characteristics change dramatically and consistently with toroidal rotation**

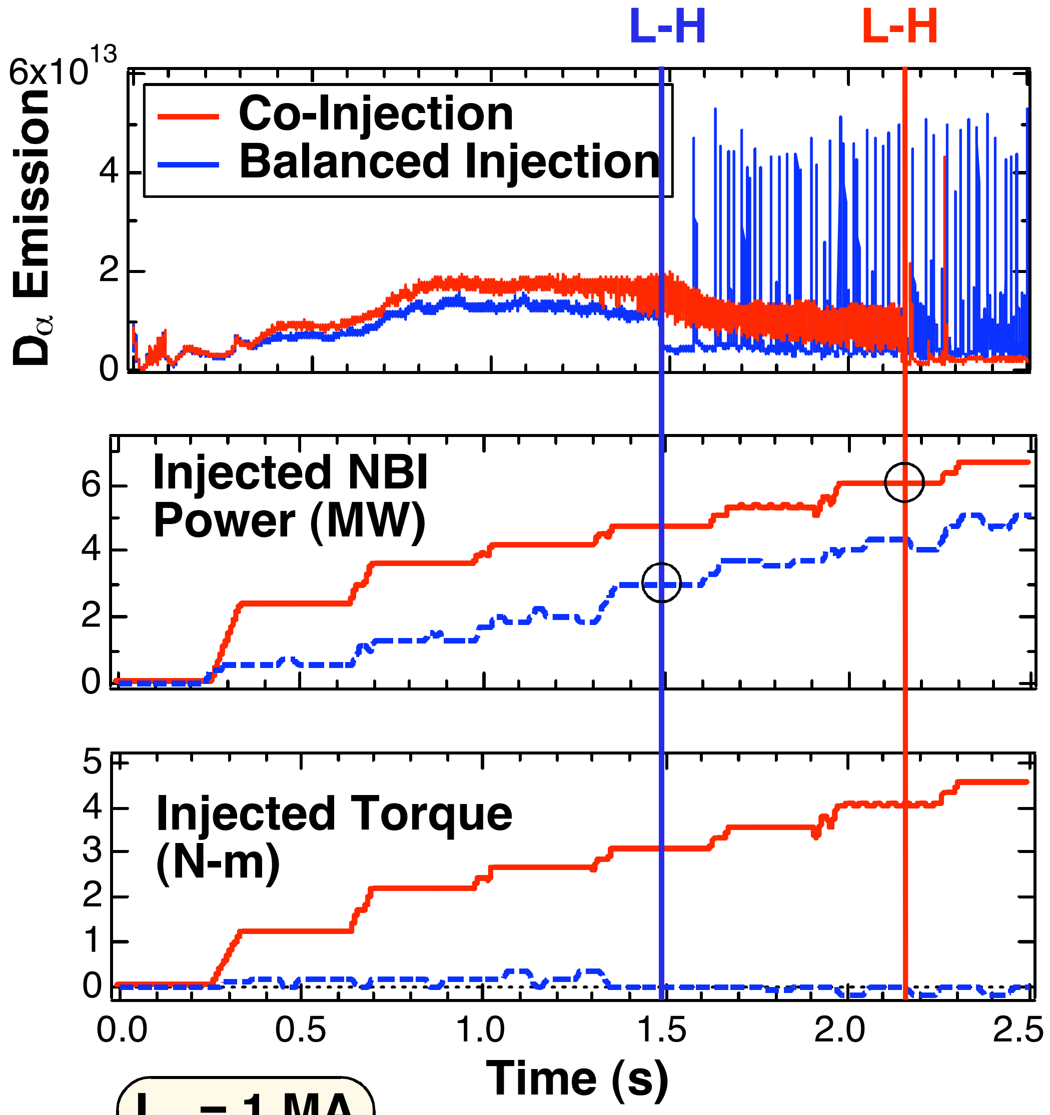
- **Radial electric field shear increases more rapidly at low rotation**

- **Connection between toroidal rotation and ion ∇B drift dependence**

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

# CO-ROTATING DISCHARGE REQUIRES TWICE THE INJECTED POWER OF BALANCED INJECTION DISCHARGE TO UNDERGO L-H TRANSITION

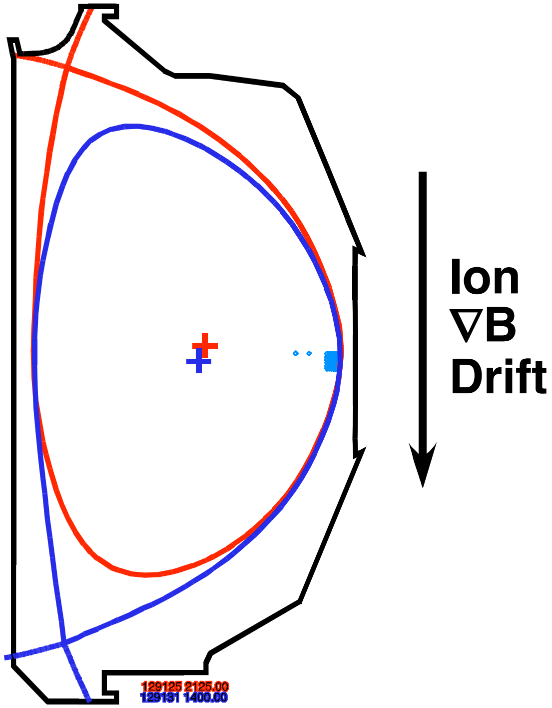
- **Upper-Single-Null plasmas: ion ∇B drift away from X-point**
  - *Higher L-H power threshold than with ion ∇B drift towards X-point*
- **Beam power ramped gradually**
- **Co and counter NBI sources control torque and power**
- **Fluctuating $D_\alpha$ phase determined to be L-mode**
- **$P_{LH}$,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

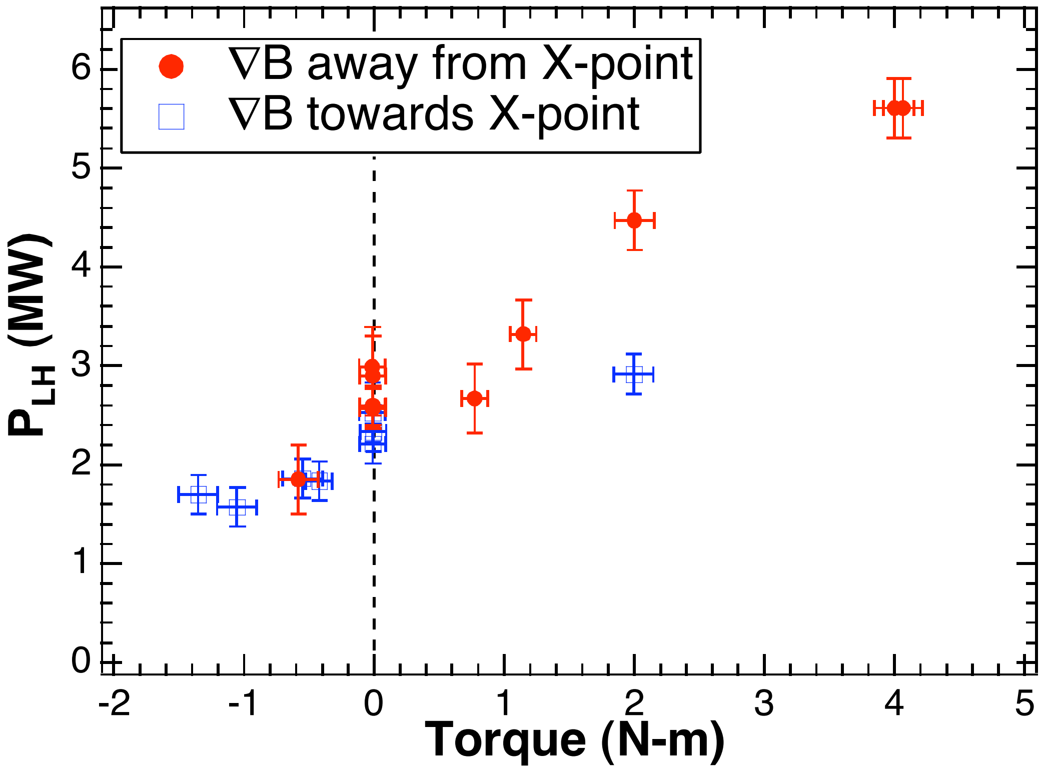


**$I_p$ = 1 MA**

**$B_T$ = -2 T**

# $P_{LH}$ INCREASES SIGNIFICANTLY WITH INCREASING NEUTRAL BEAM 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 and ∇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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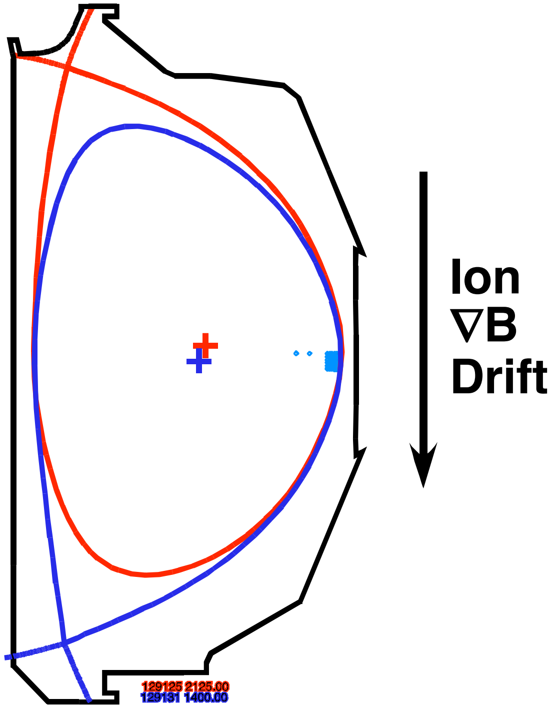
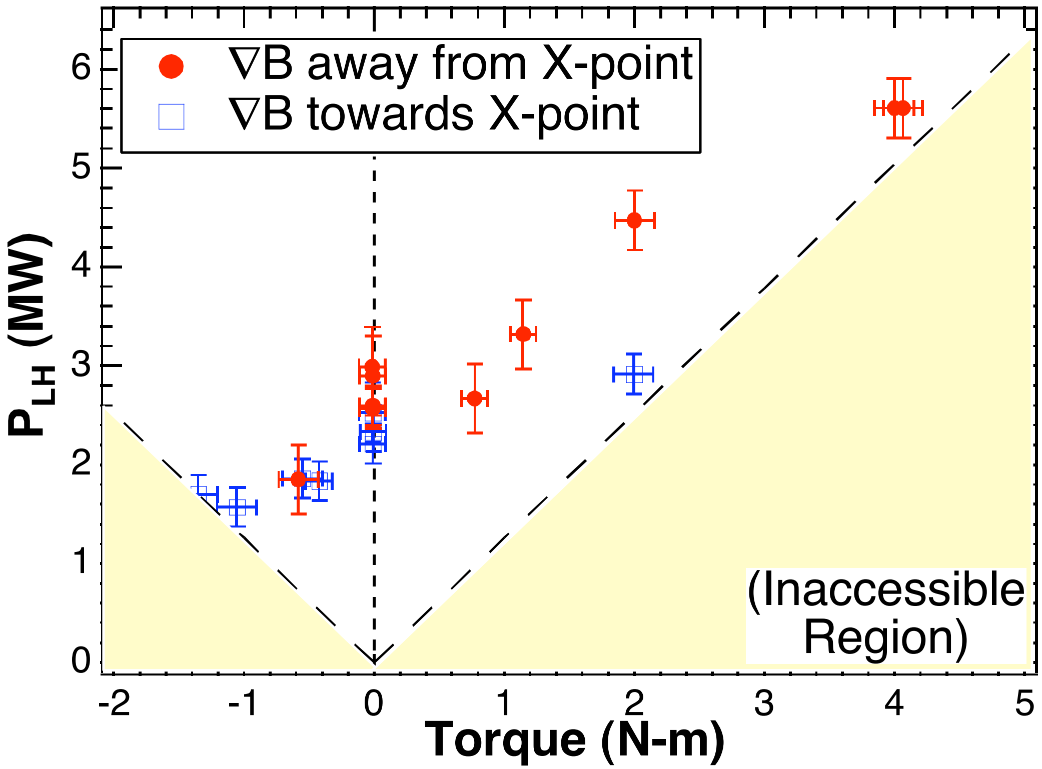
# $P_{LH}$ INCREASES SIGNIFICANTLY WITH INCREASING NEUTRAL BEAM TORQUE





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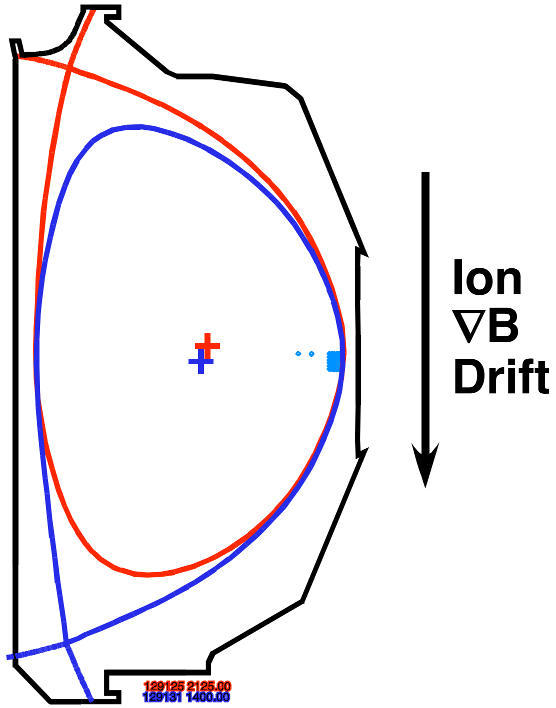
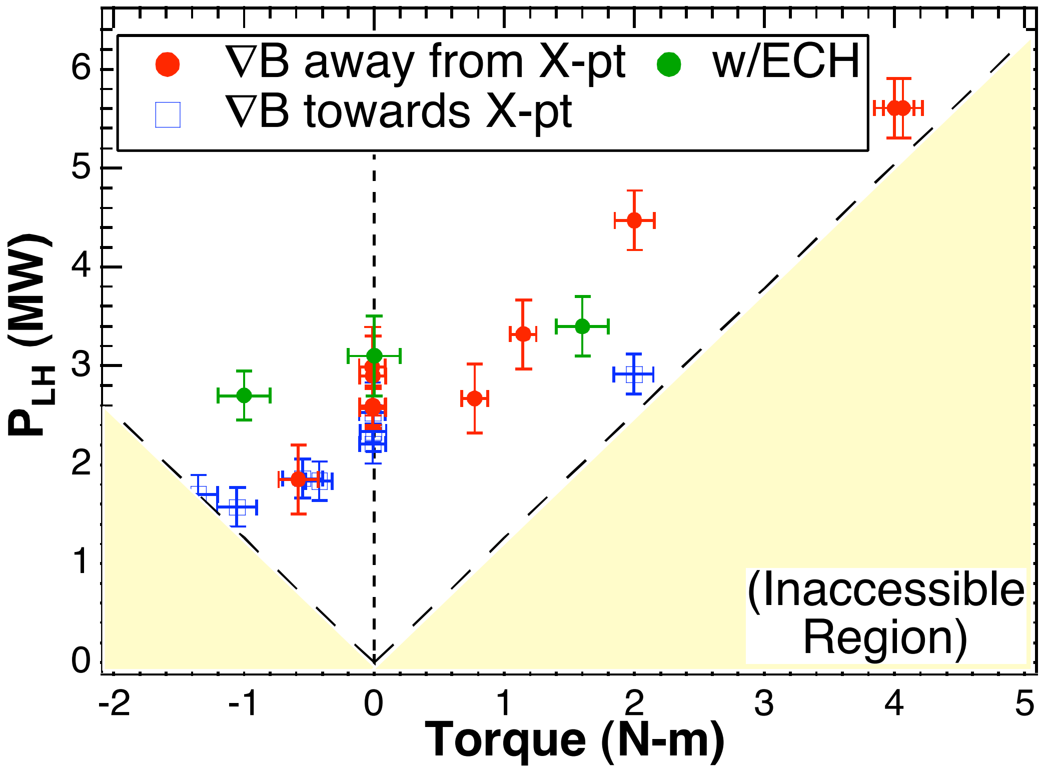
# $P_{LH}$ Increases Significantly with Increasing Neutral Beam Torque





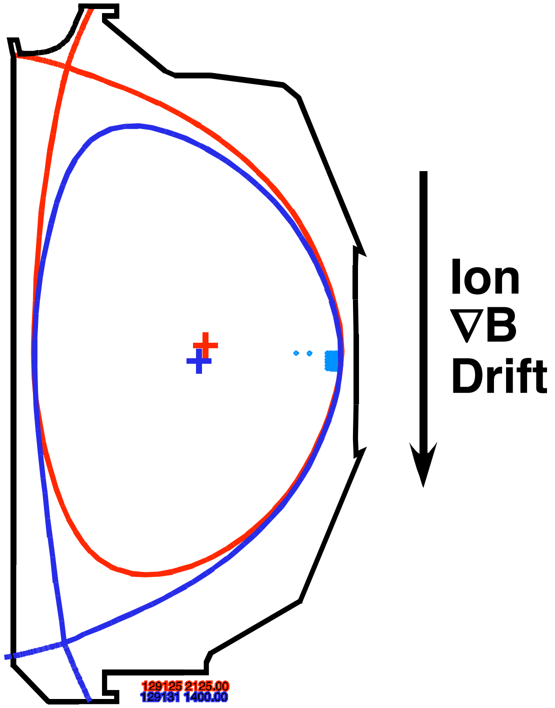
▬ Lower Single Null: ∇B towards X-Point

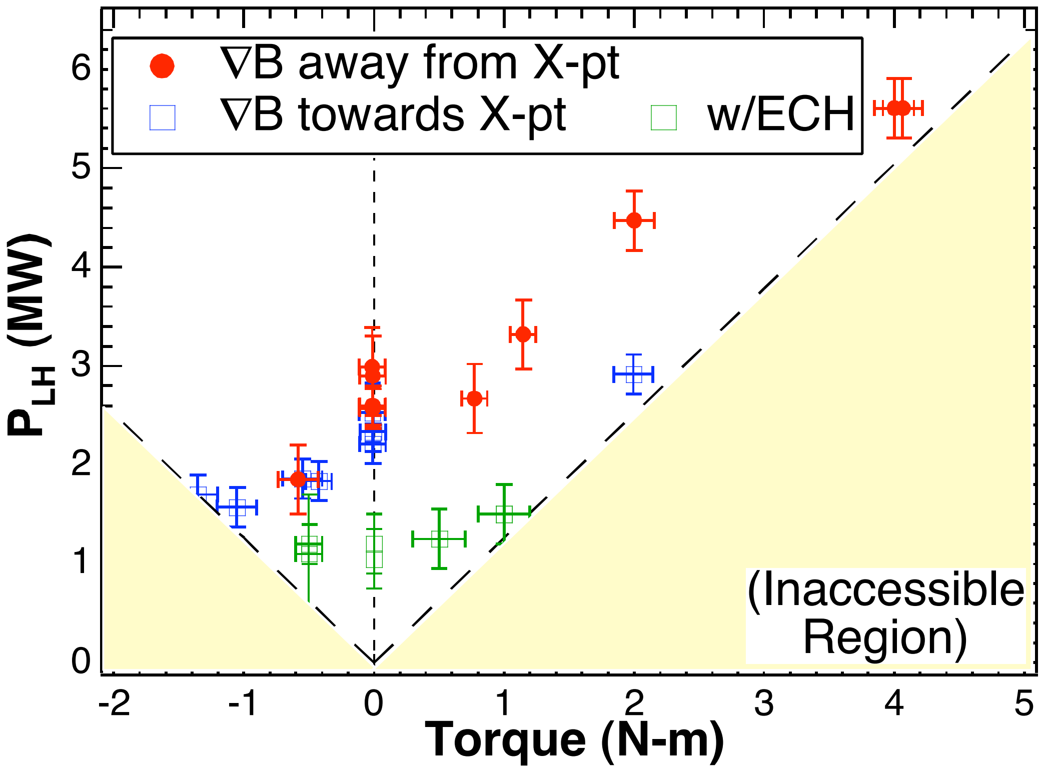
▬ Upper Single Null: ∇B away from X-Point

- **ECH used in conjunction with NBI to examine importance of neutral beam ion orbit effects**
- **Density is 25% higher in ECH shots for operational reasons**
- **Similar trend with torque is observed:**

***No significant beam-orbit effect***

# $P_{LH}$ INCREASES SIGNIFICANTLY WITH INCREASING NEUTRAL BEAM TORQUE





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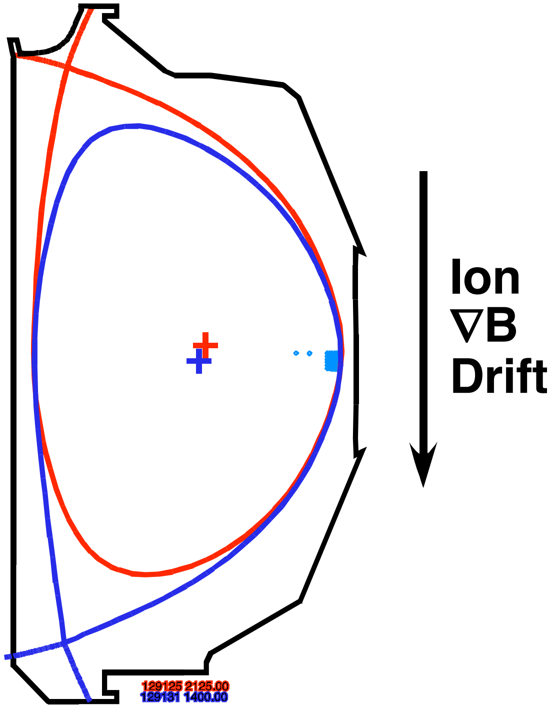
# ROTATIONAL DEPENDENCE MAY EXPLAIN SIGNIFICANT UNCERTAINTY IN $P_{LH}$ SCALING RELATION



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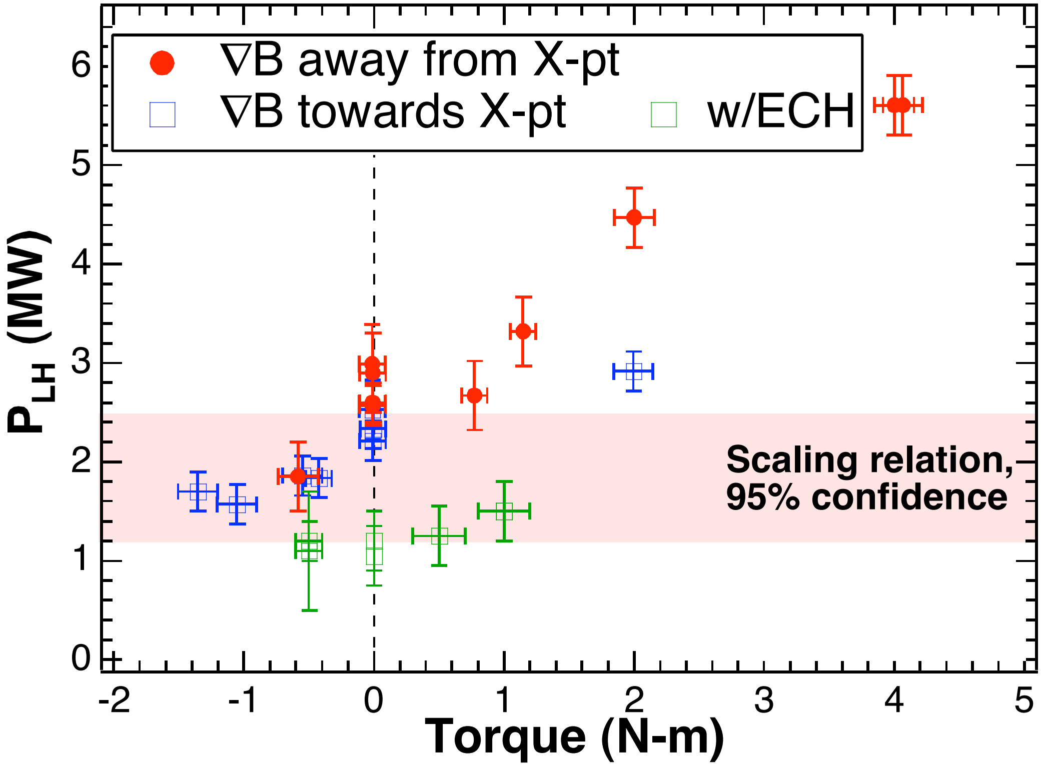
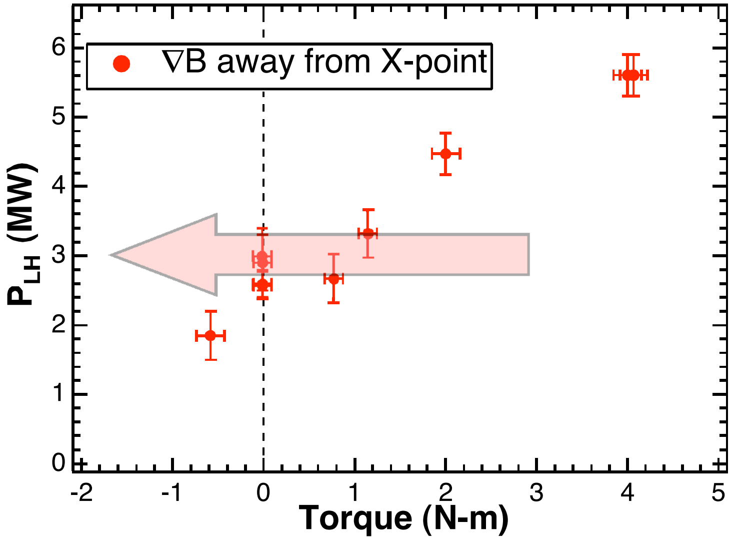


- **L-H Threshold scaling relation (red band)**

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

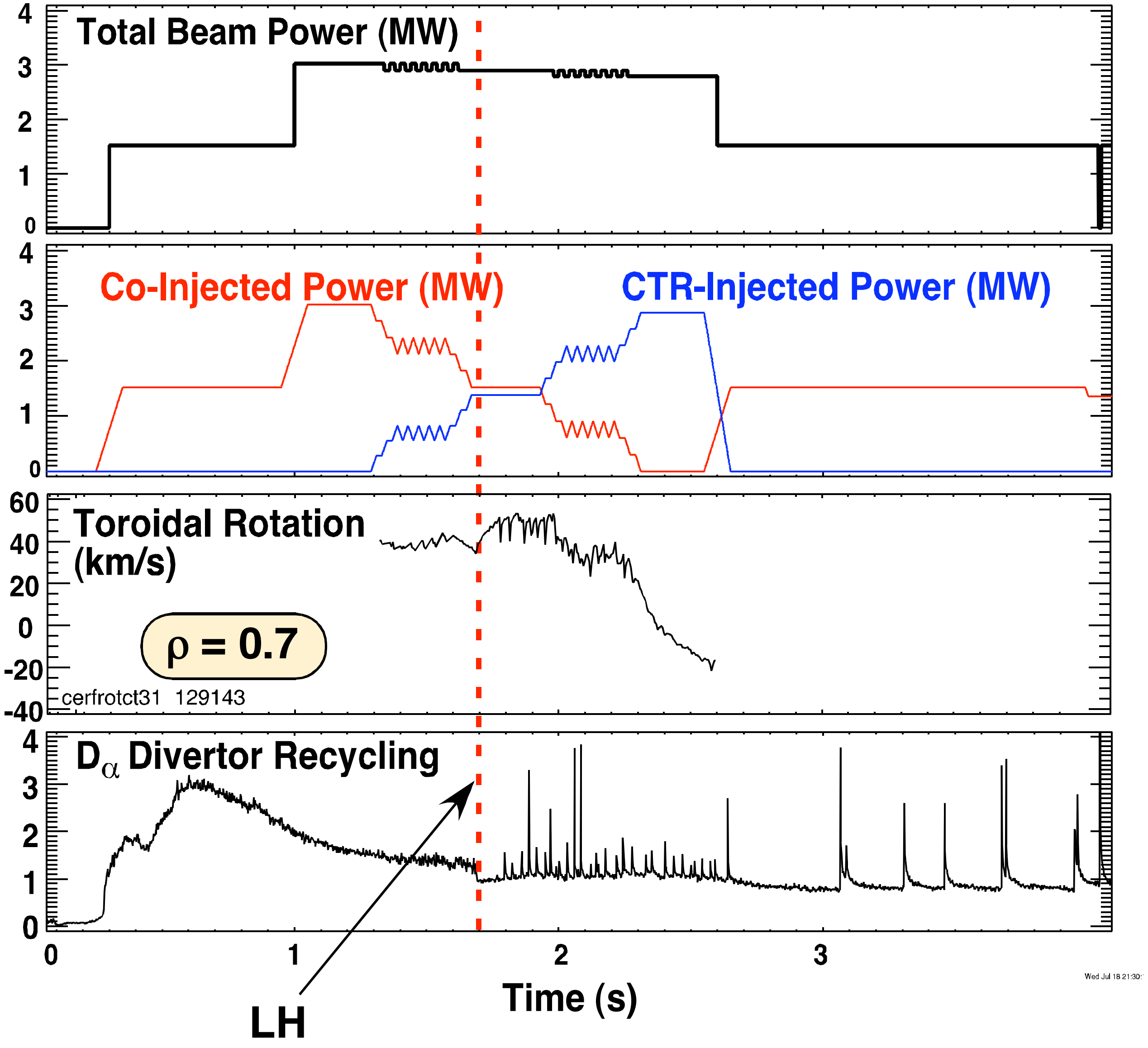
- **$P_{LH}$ values in range of scaling relation, but large variation suggests a "hidden variable," such as rotation**

# LH TRANSITION INDUCED VIA TORQUE-SCAN AT CONSTANT POWER

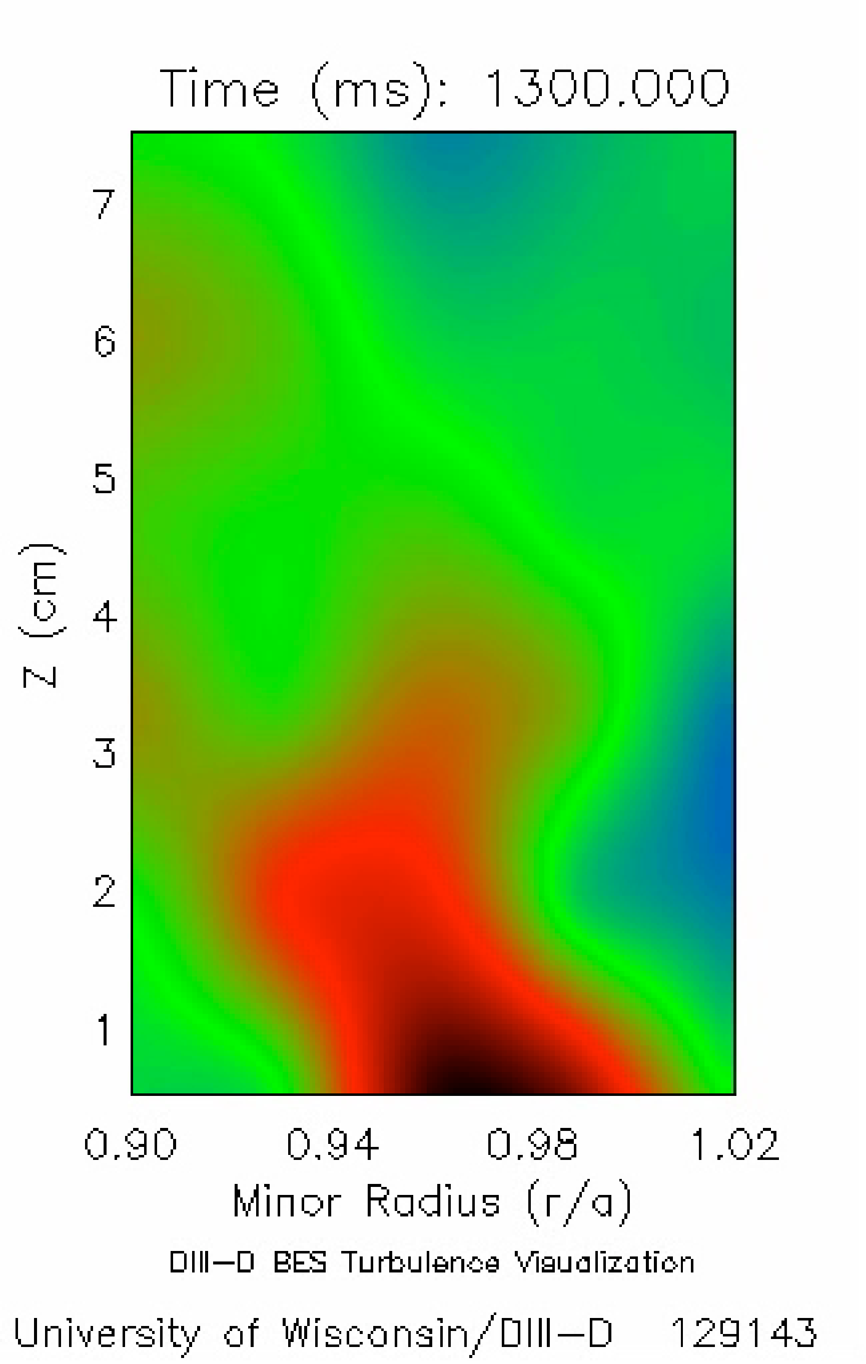


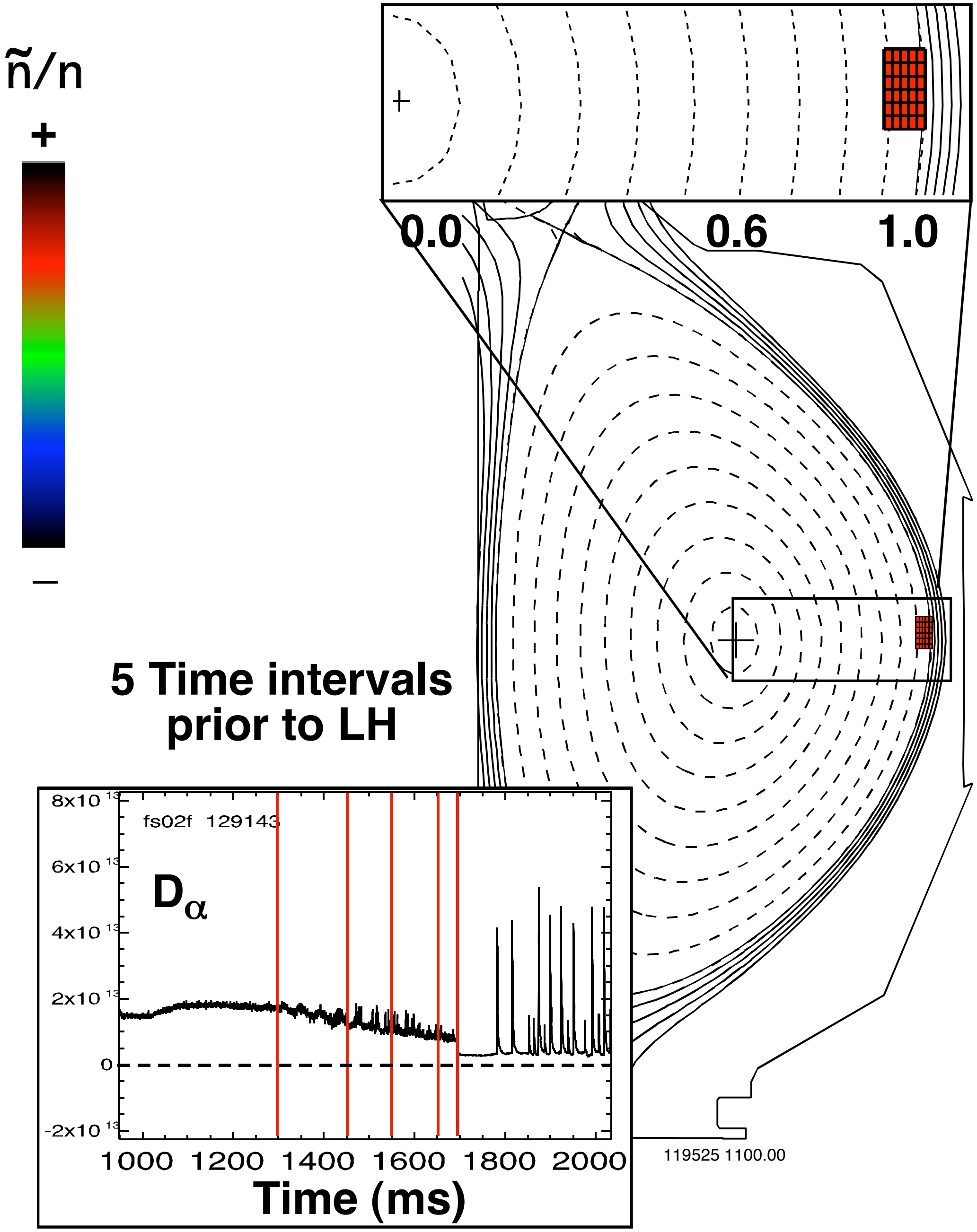
- $P_{LH}$ = 3 MW
- Consistent with previous measurements
- Slowly evolving turbulence characteristics

**∇B away from X-point**



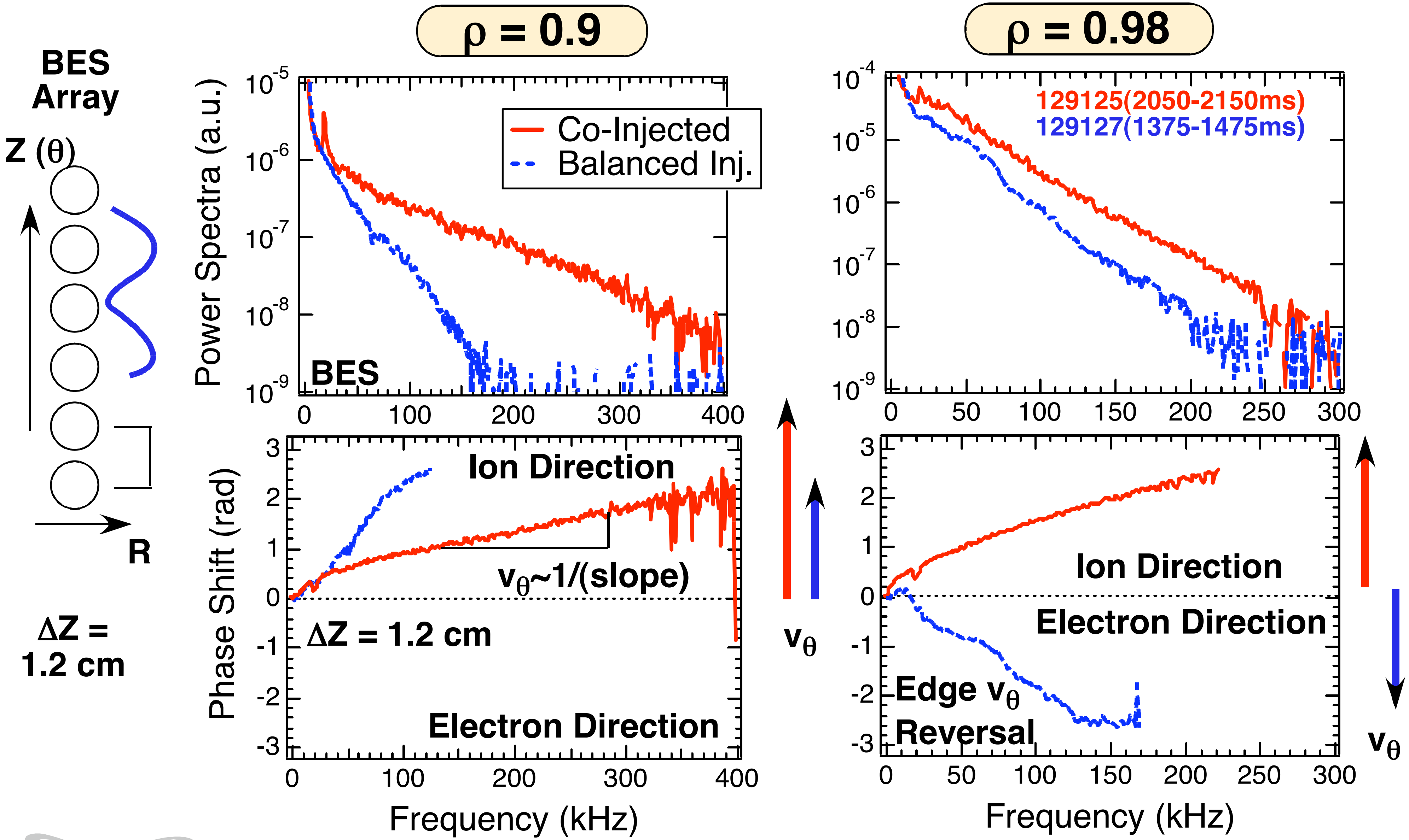
# VISUALIZATIONS OF EDGE TURBULENCE DEMONSTRATE SIGNIFICANT VARIATION IN FLOW PATTERNS AND MODE STRUCTURE WITH ROTATION





**5 Time intervals prior to LH**

# SIGNIFICANT DIFFERENCE IN EDGE TURBULENCE & FLOWS BETWEEN CO-INJECTION & BALANCED INJECTION ($\nabla$B *AWAY FROM* X-POINT)



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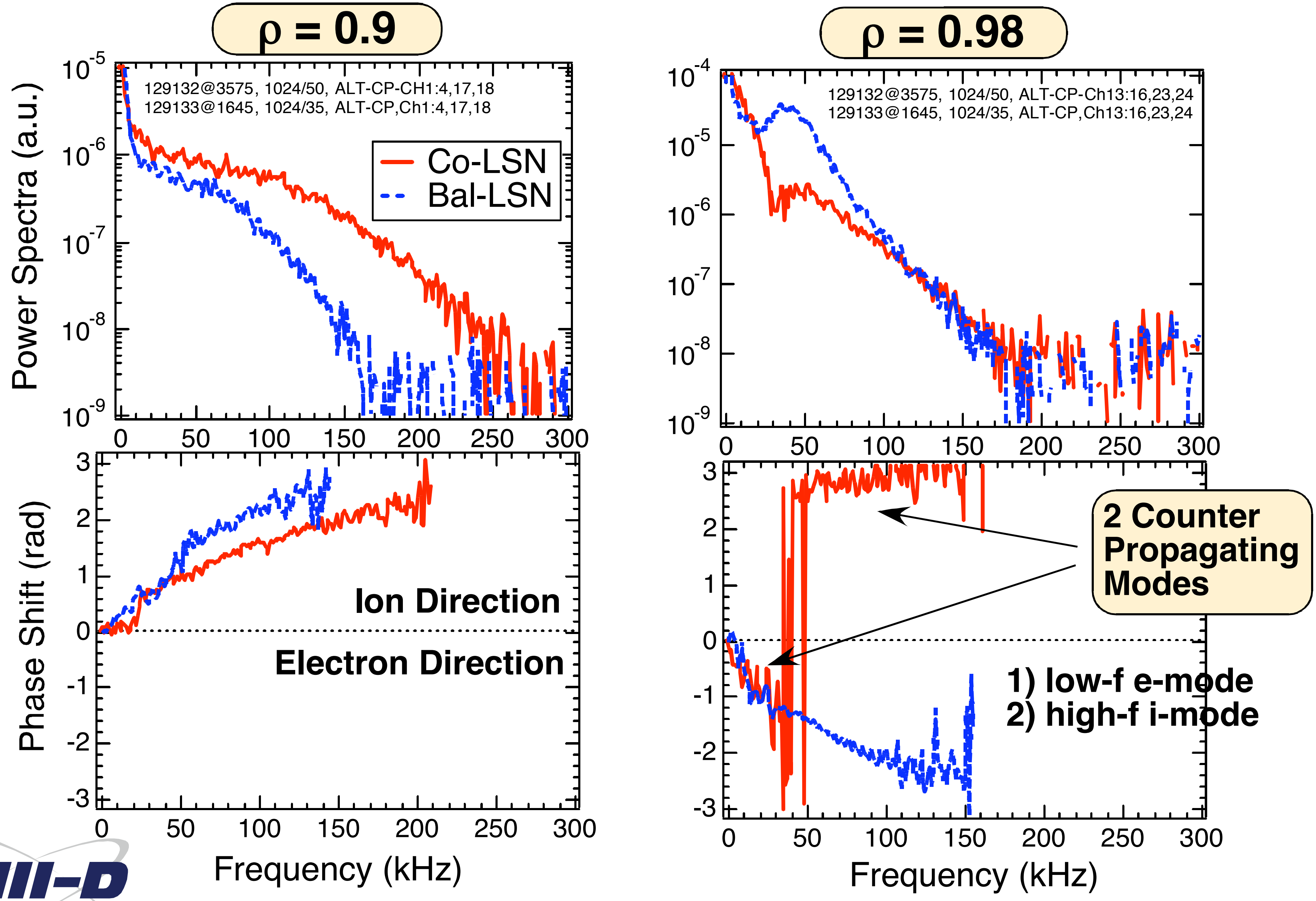
# Plasmas with Ion $\nabla$B *Towards* X-Point Exhibit Similar Flows as well as Multiple Turbulence Modes



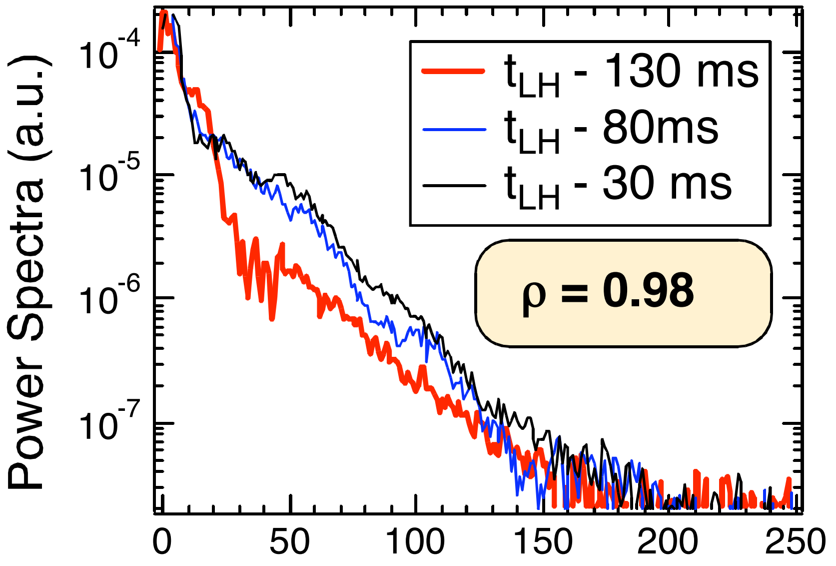
2 Counter Propagating Modes

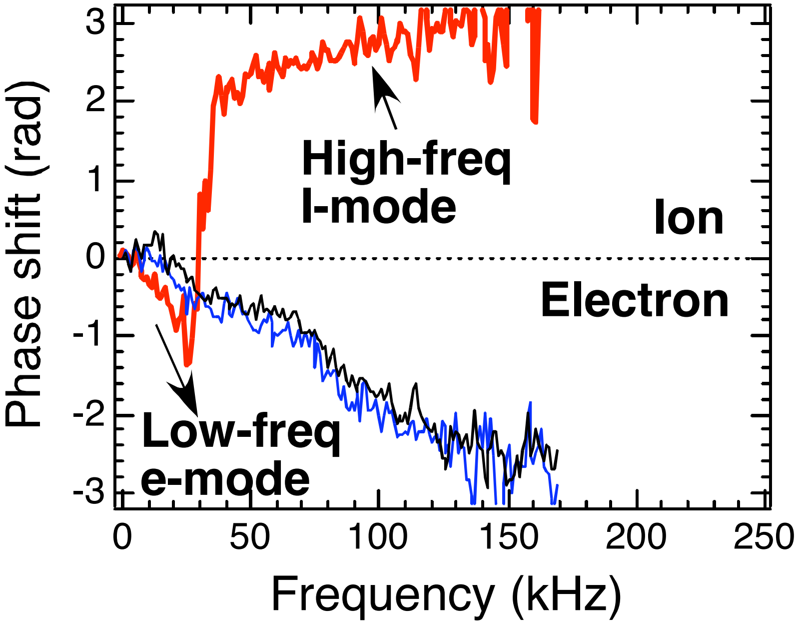
# MULTI-MODE STRUCTURE OBSERVED IN BALANCED-INJECTION PLASMAS WITH ∇B AWAY FROM X-POINT

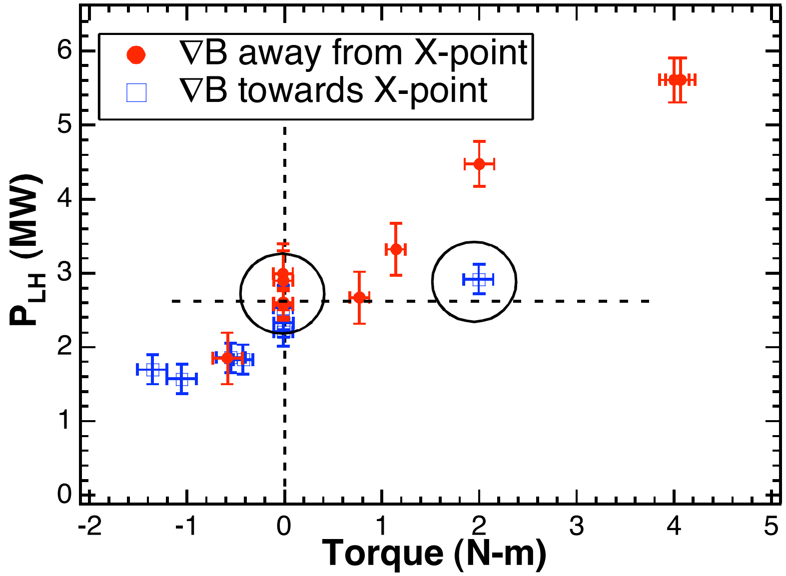
- **Dual-mode structure observed in both balanced injection discharges with ∇B away from X-point,**

  *AND*

  **Co-injected discharge with ∇B towards the X-point**
- **Two conditions have similar $P_{LH}$**
- **Correlation with dual-mode structure and lower LH power threshold**



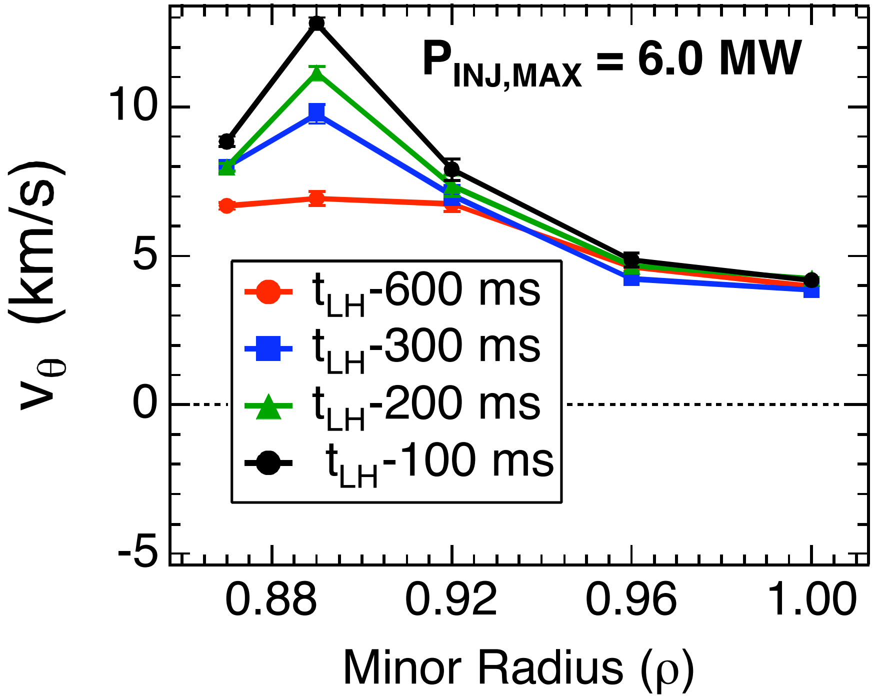




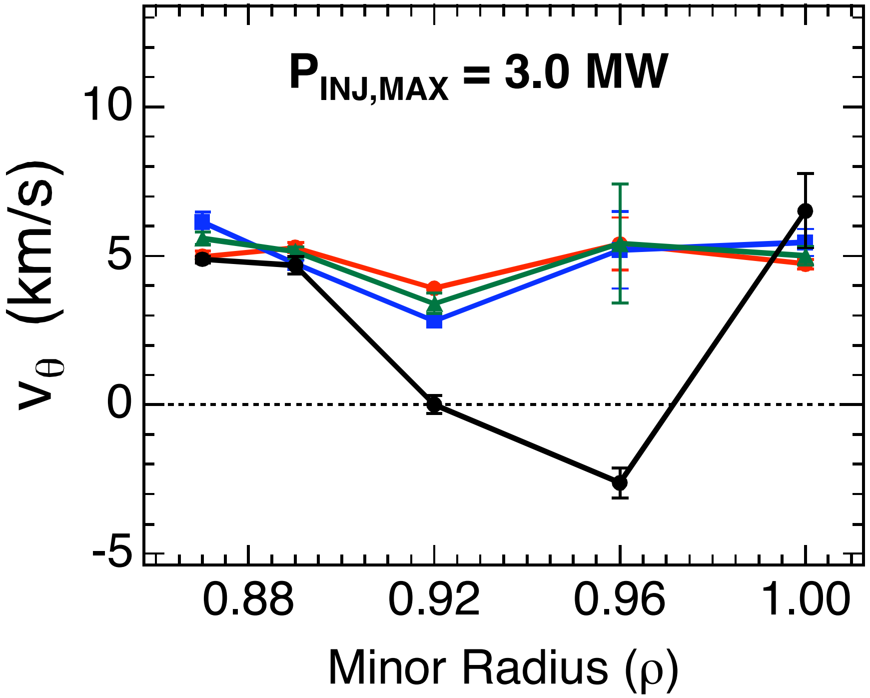
International Atomic Energy Agency Fusion Energy Conference, Geneva, Switzerland - G. McKee- October, 2008

# RADIALLY-SHEARED POLOIDAL TURBULENCE FLOWS EVOLVE DIFFERENTLY FOR CO- AND BALANCED-INJECTION PLASMAS

**Co-Current Injection**
**∇B away from X-point**



**Balanced Injection**
**∇B away from X-point**



- **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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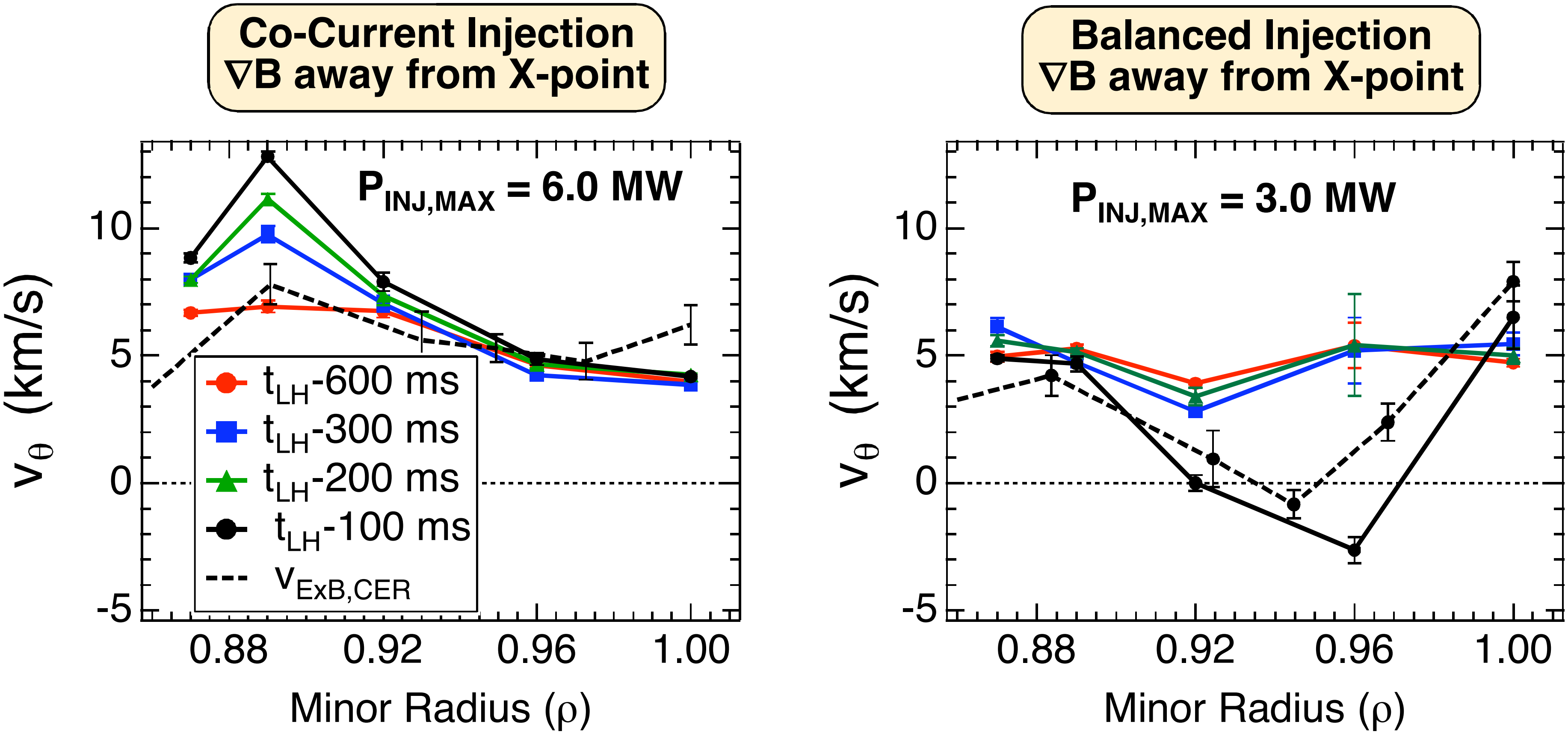

- Turbulence poloidal velocity obtained via cross-correlation analysis
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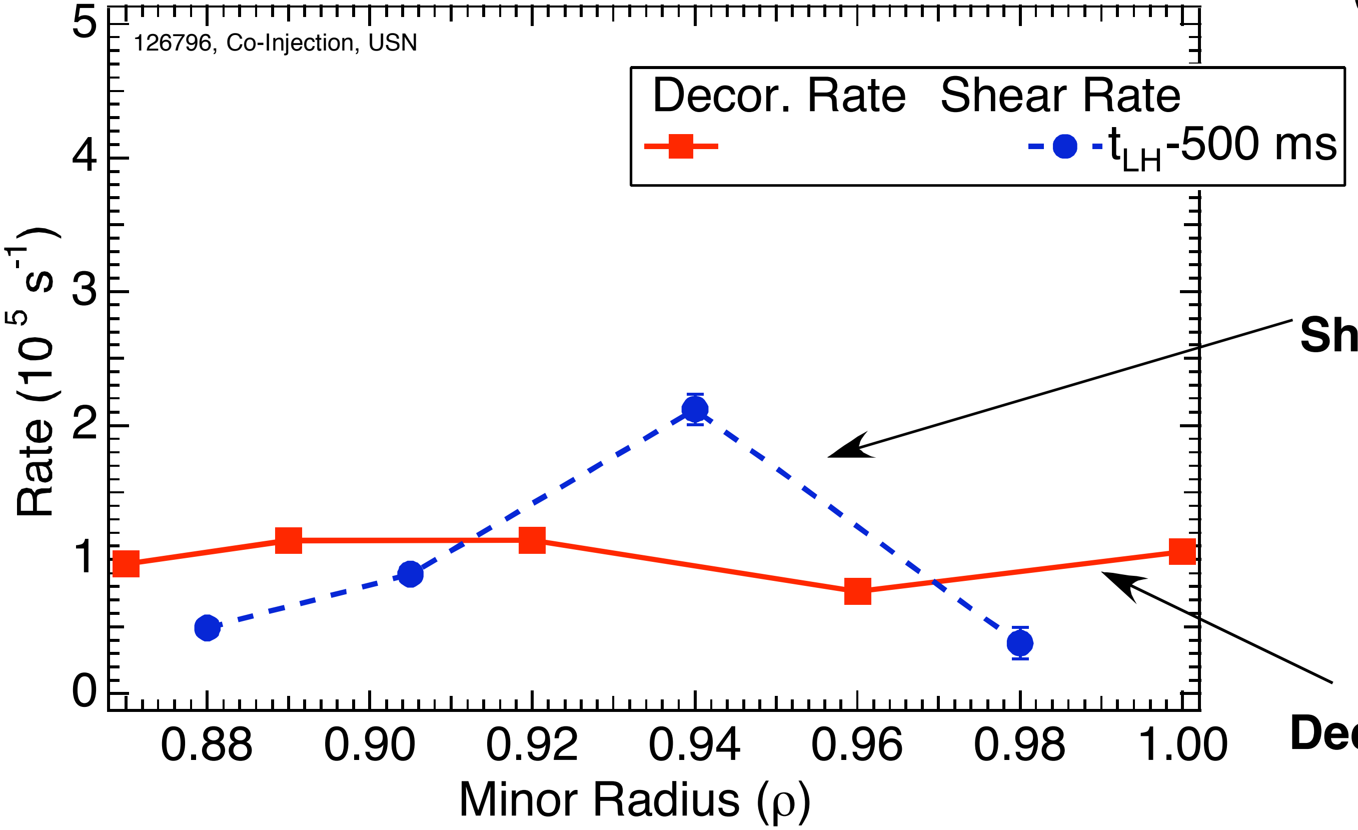
# LH Transition Occurs as Shearing Rates Increase and Exceed Turbulence Decorrelation Rates

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

**Co-Injection, ∇B away from X-point**

**$\omega_S \sim (\tau_C)^{-1}$**



**Velocity Shearing Rate:**

**$\omega_s = dv_\theta/dr$**

**Turbulence Decorrelation Rate**

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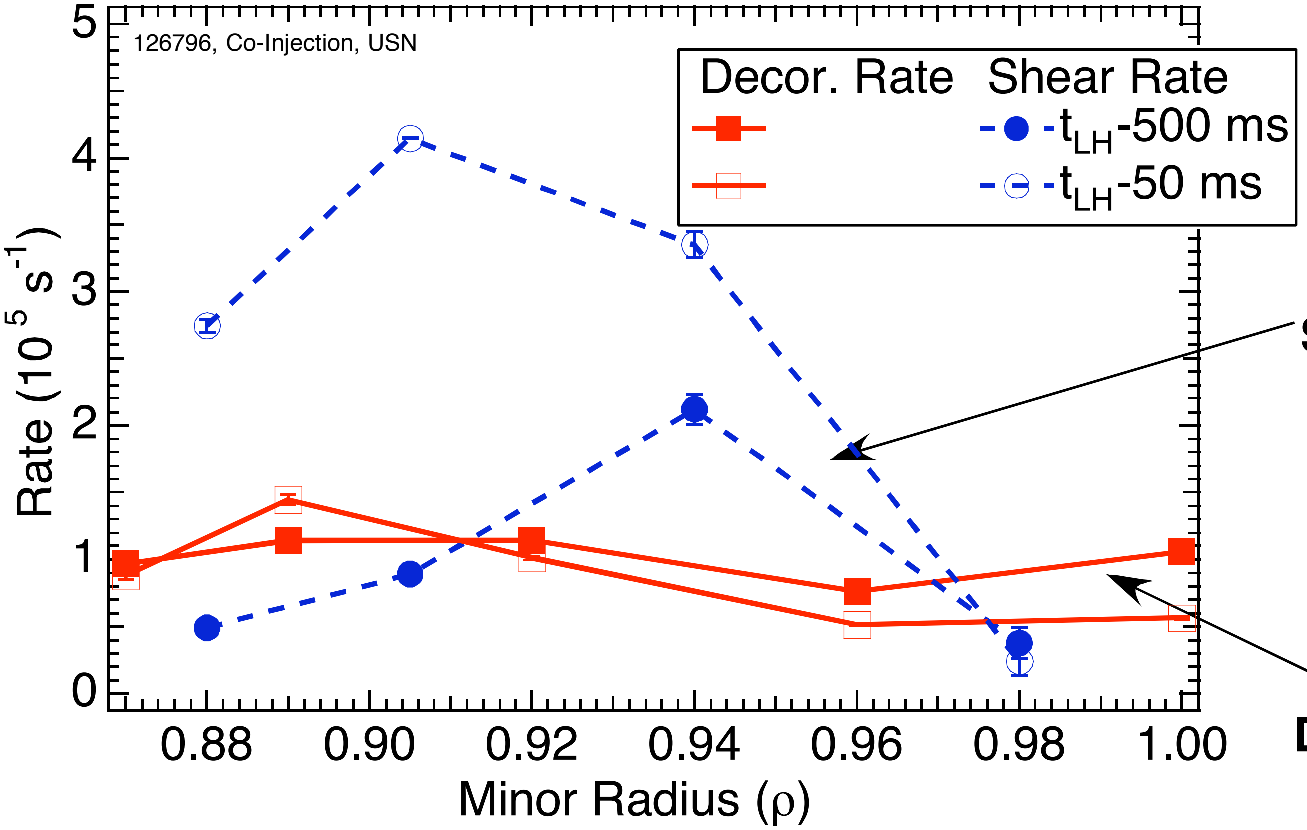

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*D. Schlossberg et al., submitted to PRL (2007)*

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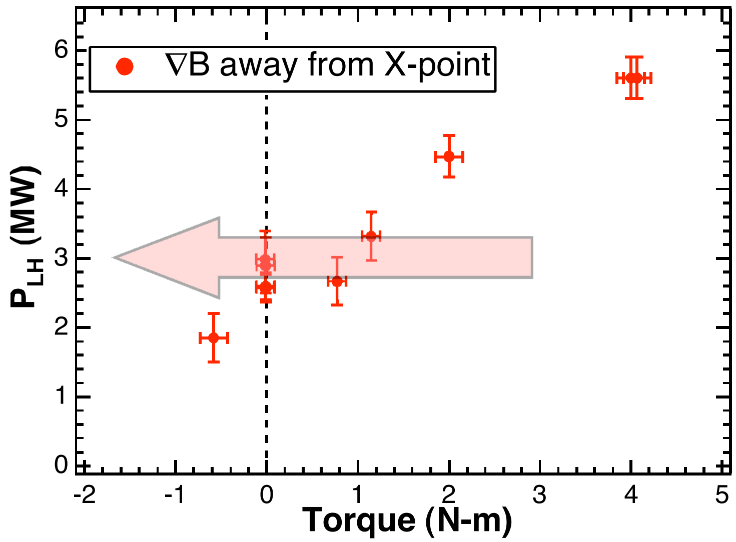
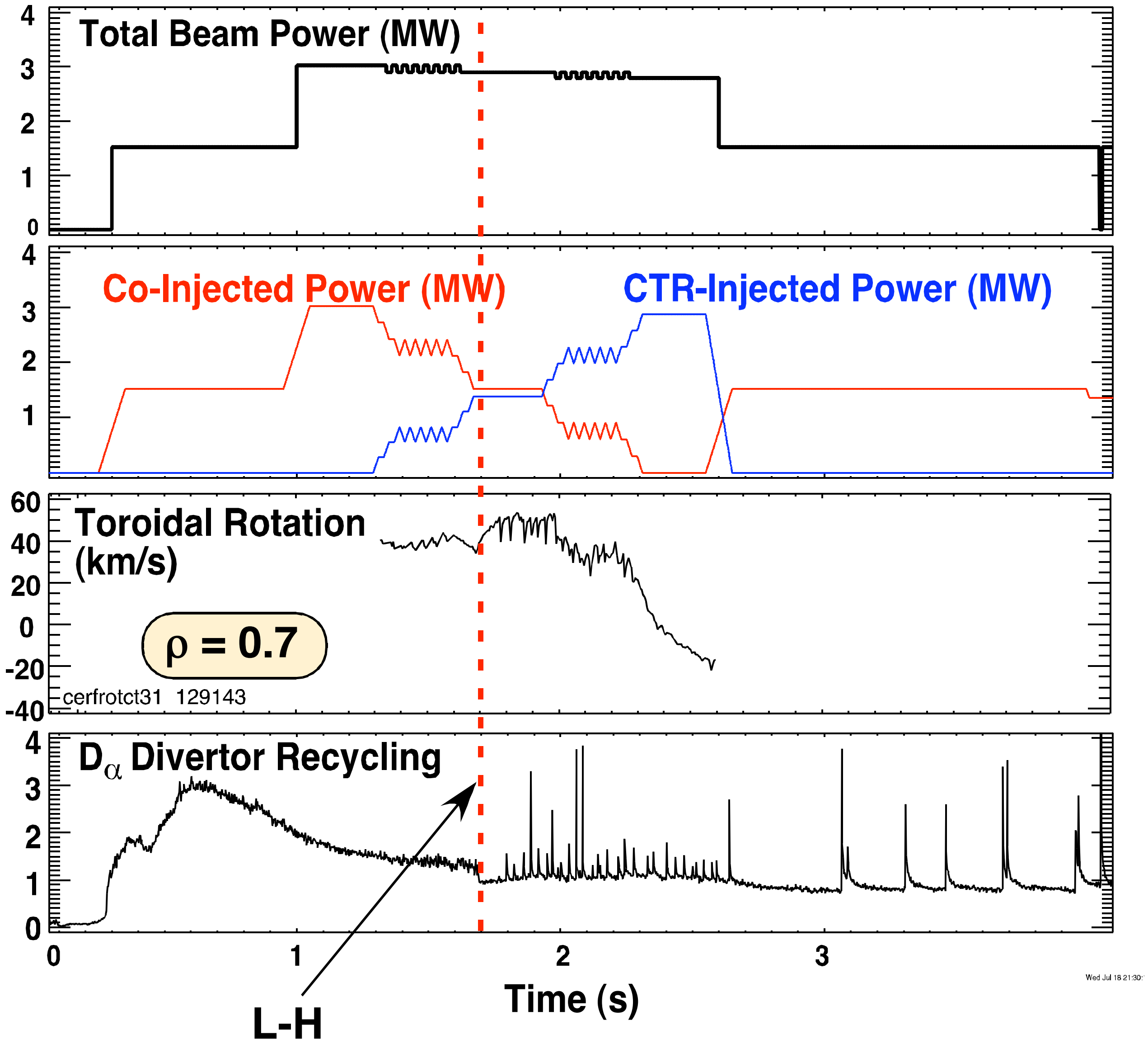


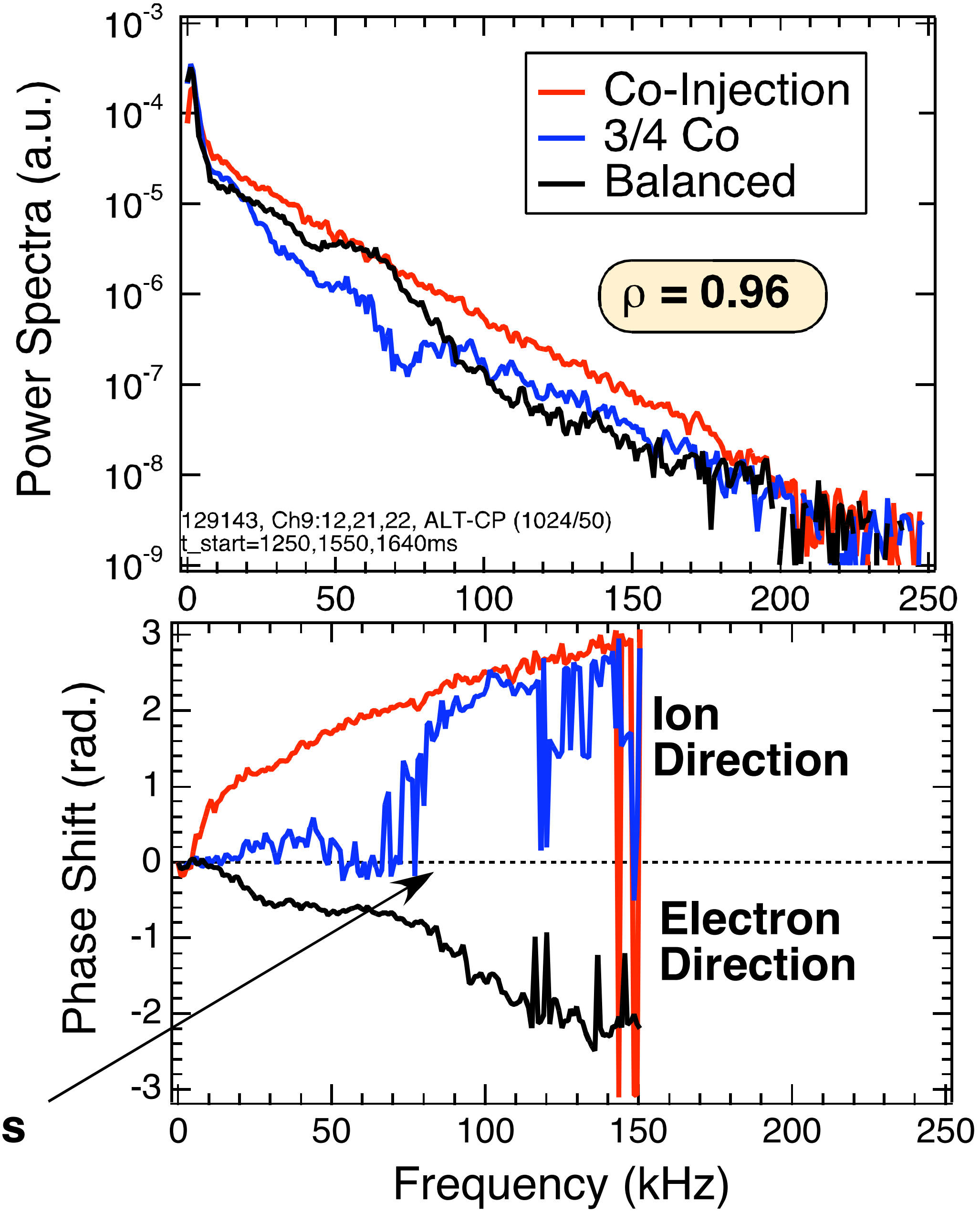
**∇B away from X-point**



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

# EDGE TURBULENCE POLOIDAL FLOW REVERSES DURING CONSTANT-POWER TORQUE SCAN

- **Reversed $v_\theta$ during balanced injection, shortly before LH-transition**
- **Shear increases as rotation varied from co- to balanced**



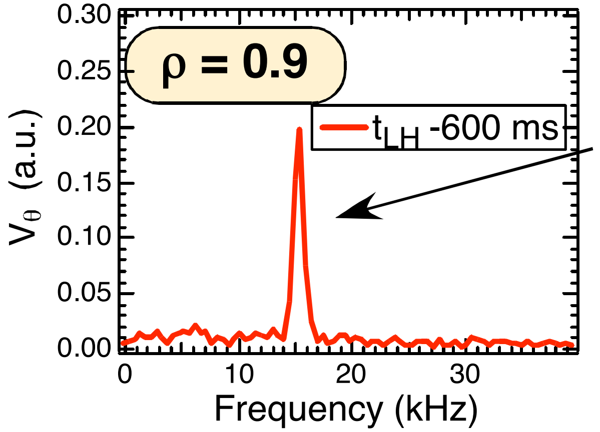
**Break in phase reflects dual modes**

# 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 $\mu$s 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=15 kHz $\approx c_s/2\pi R$*

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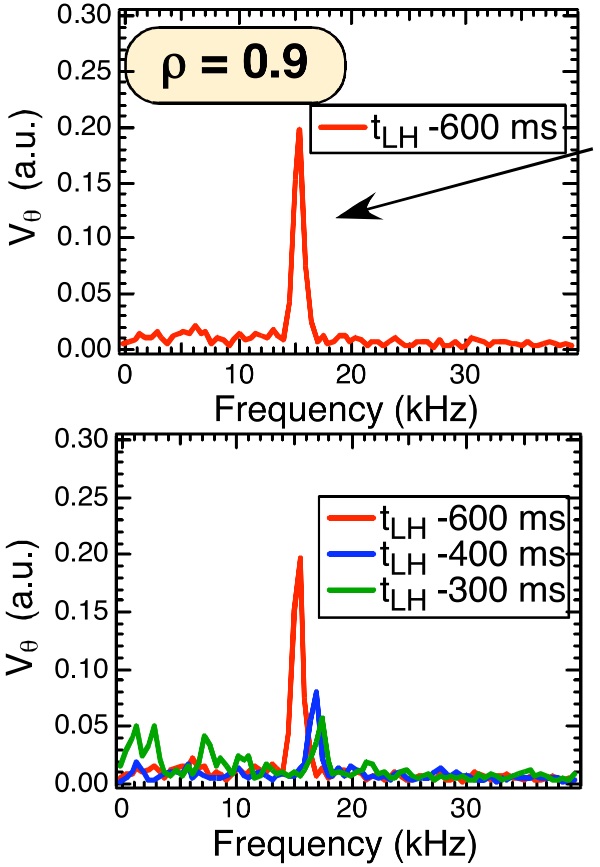

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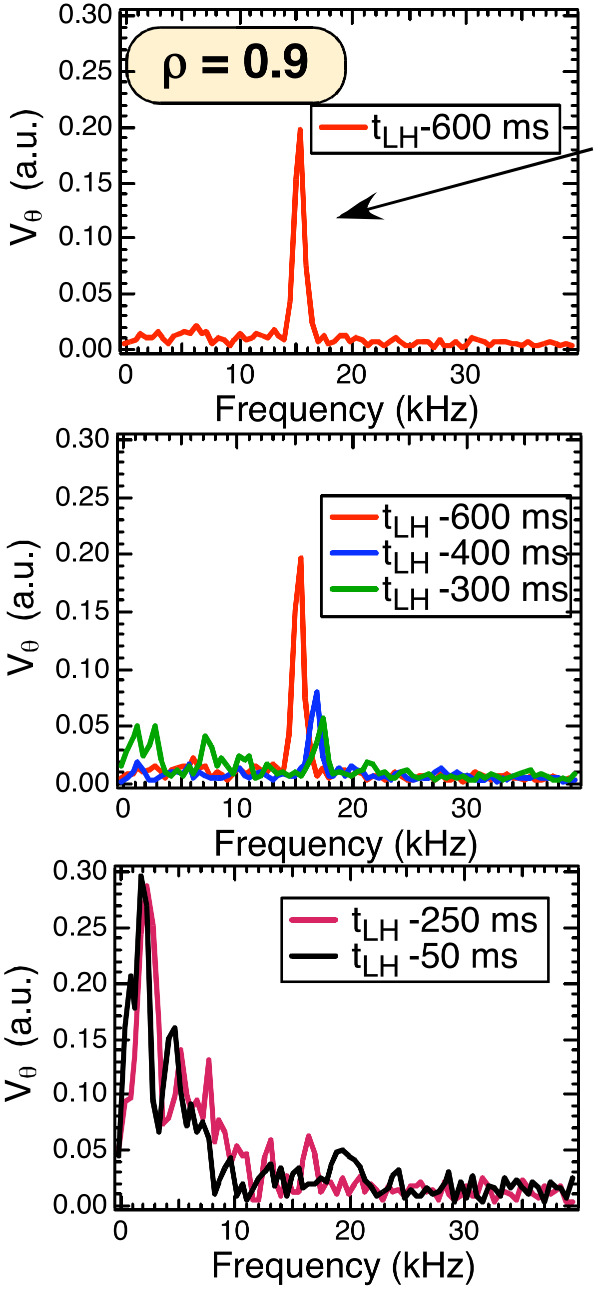
- **GAM dominates ZF spectrum at high rotation**
  - *gradually decays in amplitude and disappears as plasma slows*
- **Zero-Mean-Frequency Zonal Flow arises and dominates spectra**
  - *ZMF-ZF power significantly higher than GAM power*
  - *Lower frequency shears more effectively (Hahm-1999)*
  - *More likely to trigger transition?*

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



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**GAM decays with time**

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

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# CONCLUSIONS

- **Power flux required to trigger an L-Mode to H-mode transition increases with applied torque and toroidal rotation**
  - *Affects plasmas with ion ∇B drift towards and away-from X-point*
  - *ECH+NBI exhibit similar trend as NBI-only (not a beam ion effect)*
- **Edge turbulence characteristics change dramatically and consistently with toroidal rotation:**
  - *Radially sheared poloidal turbulence flows*
  - *Shear exceeds turbulence decorrelation rates prior to transition (all cases)*
  - *Zonal flow behavior strongly dependent on rotation: candidate trigger mechanism*
- **Connection between toroidal rotation and ion ∇B drift dependence**
- **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**
  - *Presently $P_{LH}$ scaling does not consider rotation*

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

## Radial Electric Field:

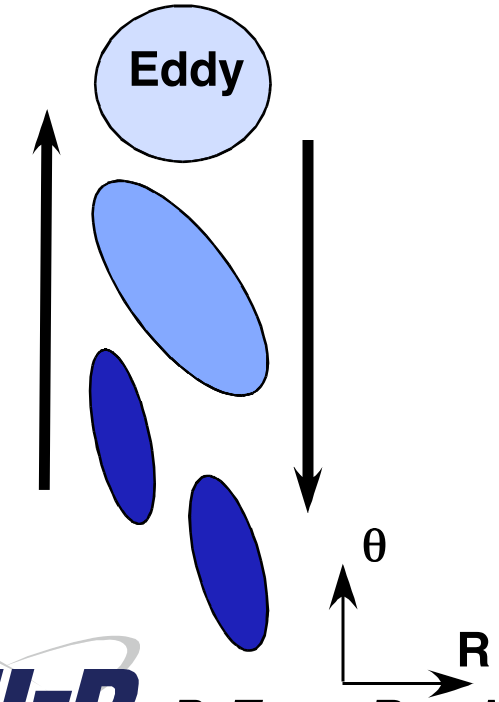
$$E_r = \frac{\nabla P_I}{Z_I e n_I} + v_{\phi,i} B_\theta - v_{\theta,i} B_\phi$$

**Pressure Gradient**

**Rotation**

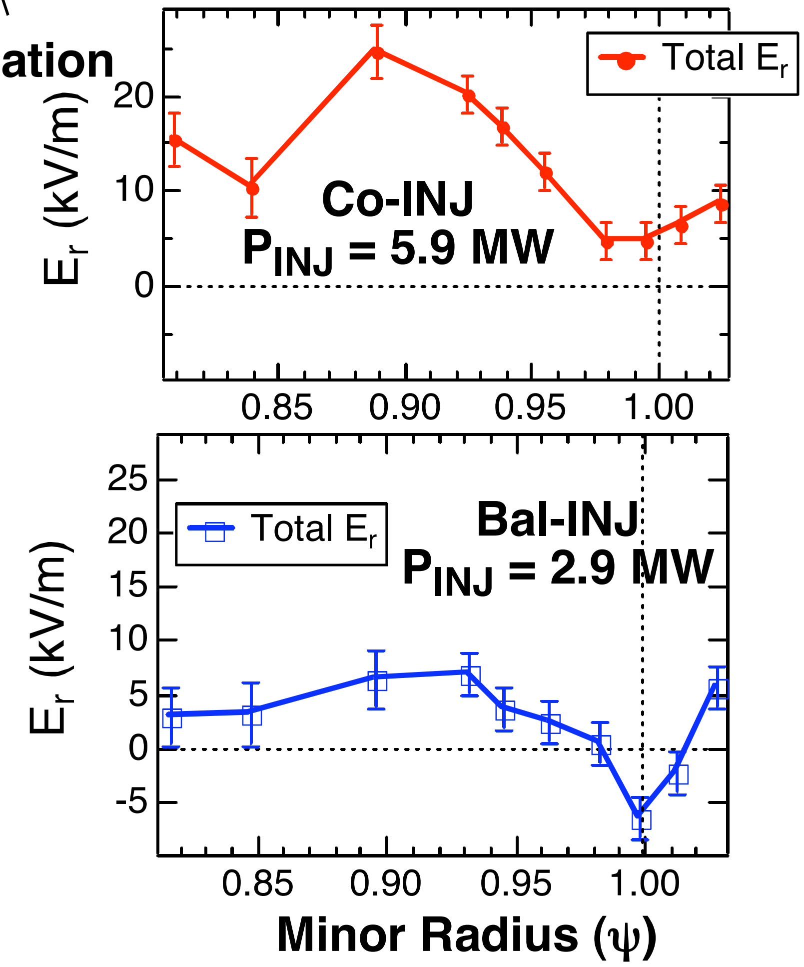
- **Consider model of ExB shear suppression of turbulence**
- **$\nabla$P term dominates Er and Er’ near the plasma edge in balanced-INJ discharges**

**$\nabla$B away from X-point**



*P. Terry, Rev. Mod. Phys. (2000)*

***$E_r$* prior to LH Transition**



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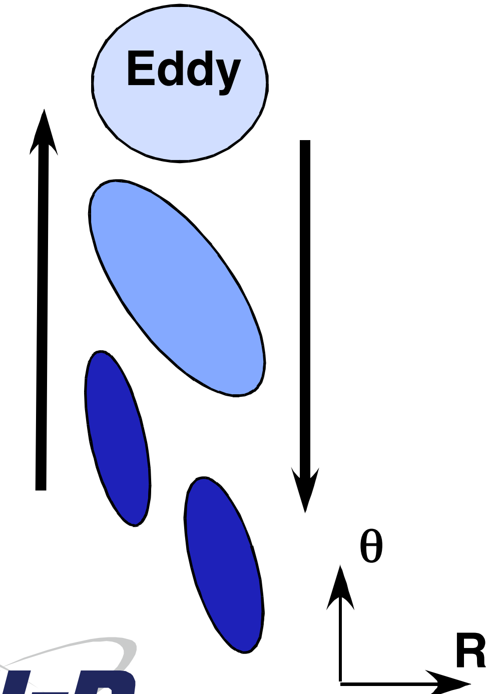
$$E_r = \frac{\nabla P_I}{Z_I e n_I} + v_{\phi,i}B_\theta - v_{\theta,i}B_\phi$$

**Pressure Gradient**

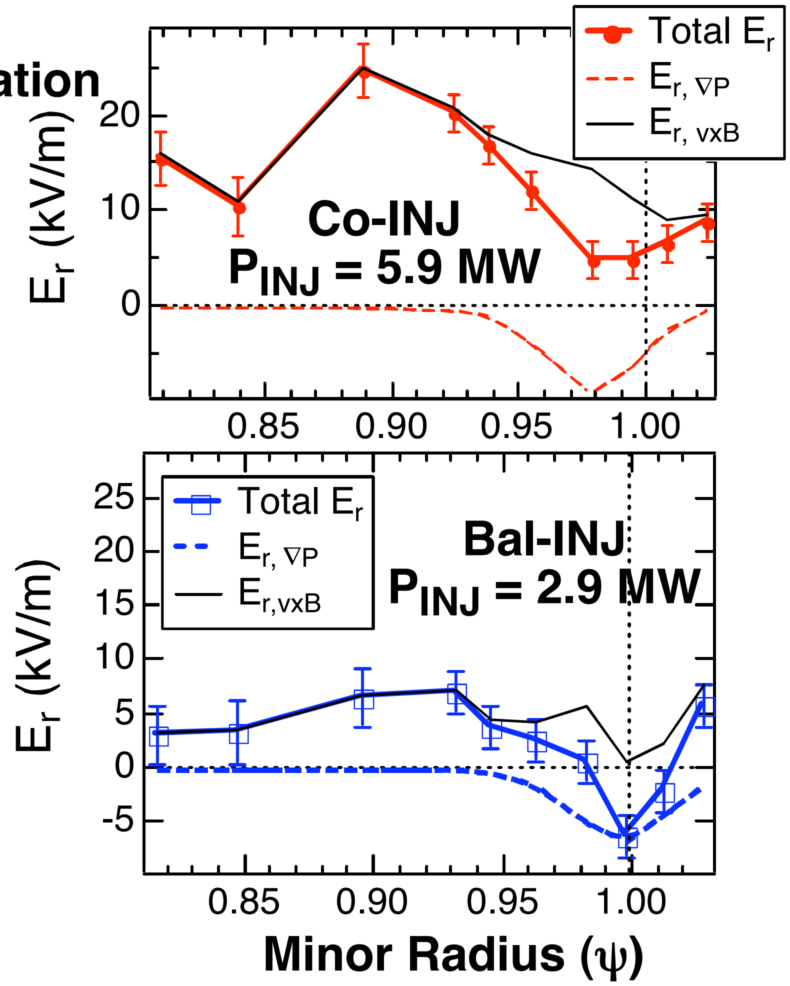
**Rotation**

**∇B away from X-point**



*P. Terry, Rev. Mod. Phys. (2000)*

***Er* prior to LH Transition**



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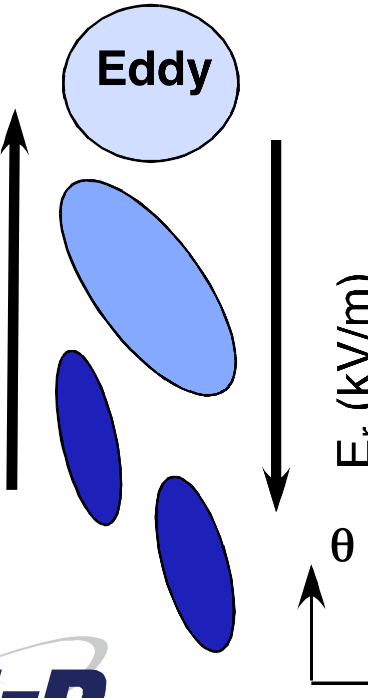
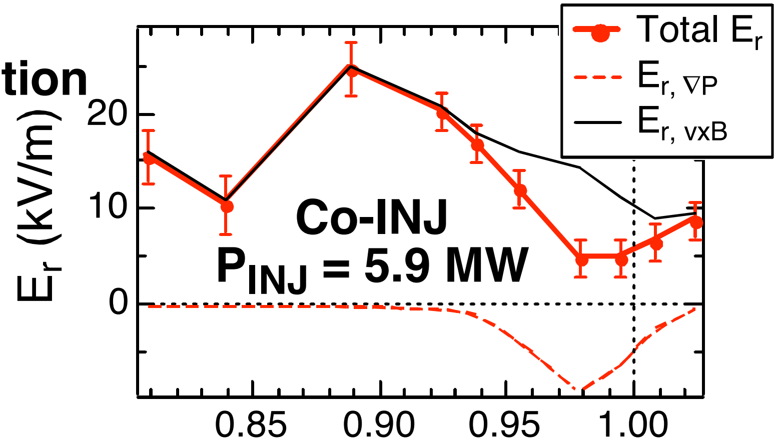
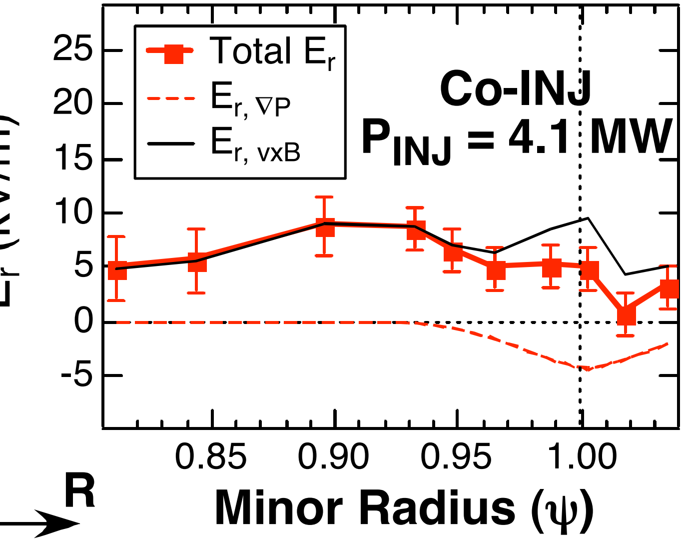


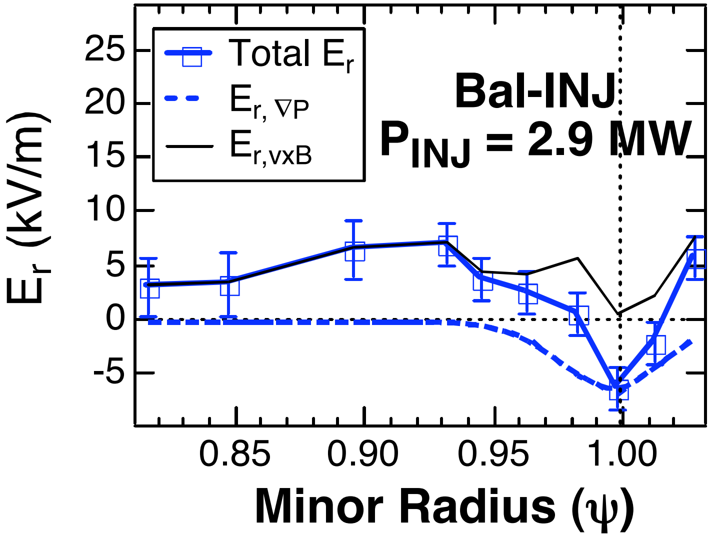
P. Terry, Rev. Mod. Phys. (2000)

**∇B away from X-point**

***$E_r$* prior to LH Transition**

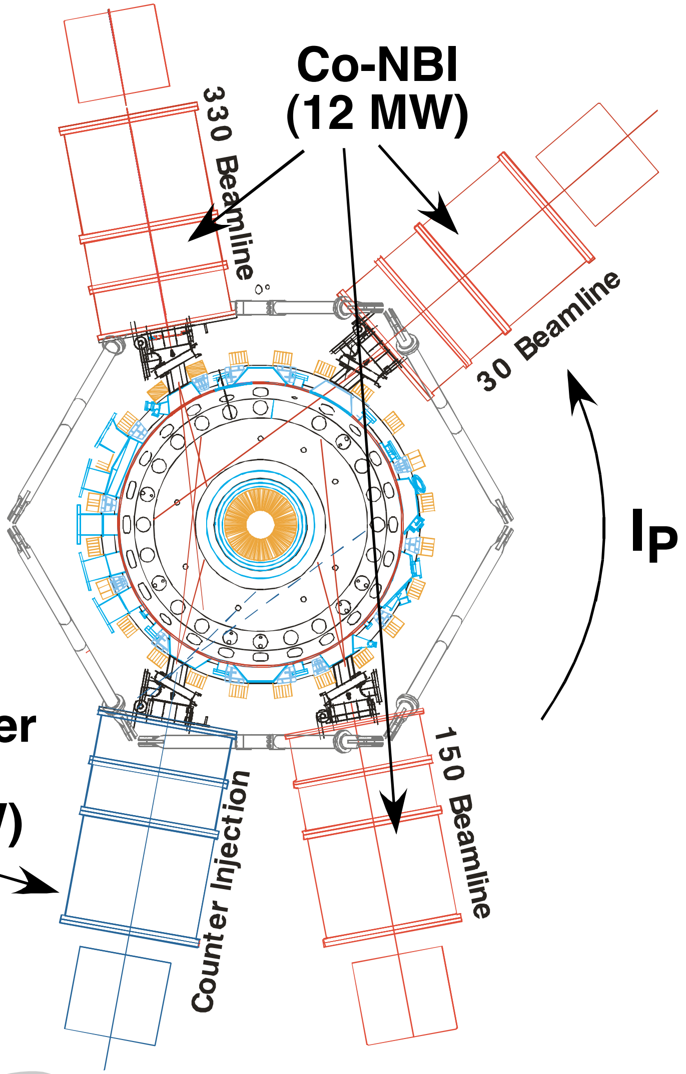






# CO-CURRENT AND COUNTER-CURRENT NBI INJECTION AND ARRAY OF FLUCTUATION DIAGNOSTICS FACILITATE DETAILED EXAMINATION

**Plan View of the DIII-D Tokamak**

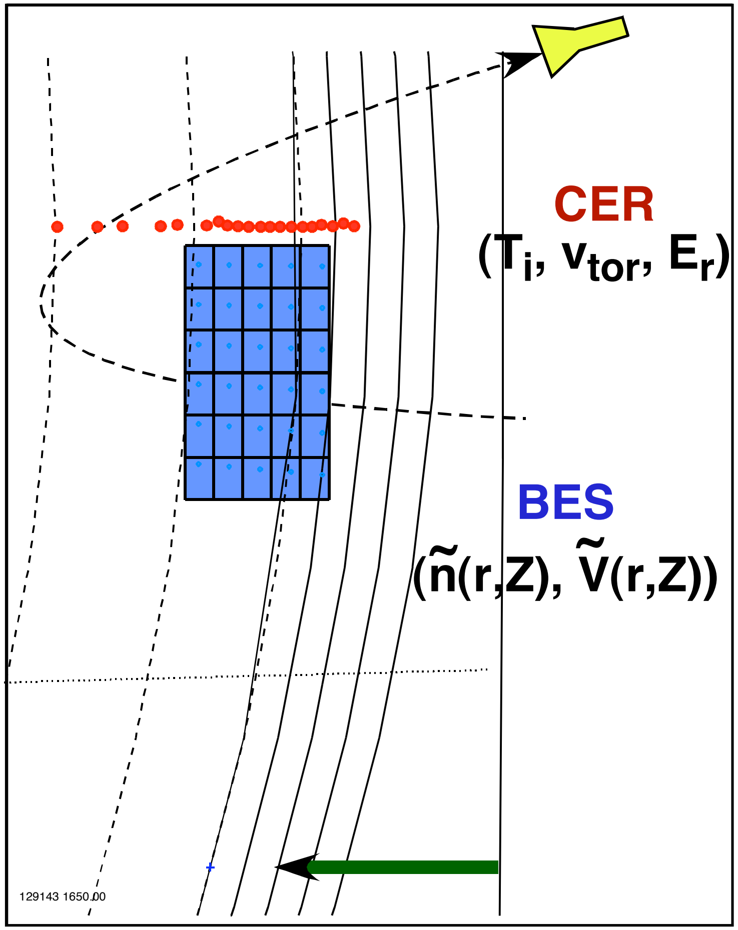


**Co-NBI (12 MW)**

**$I_P$**

**Counter NBI (5 MW)**

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

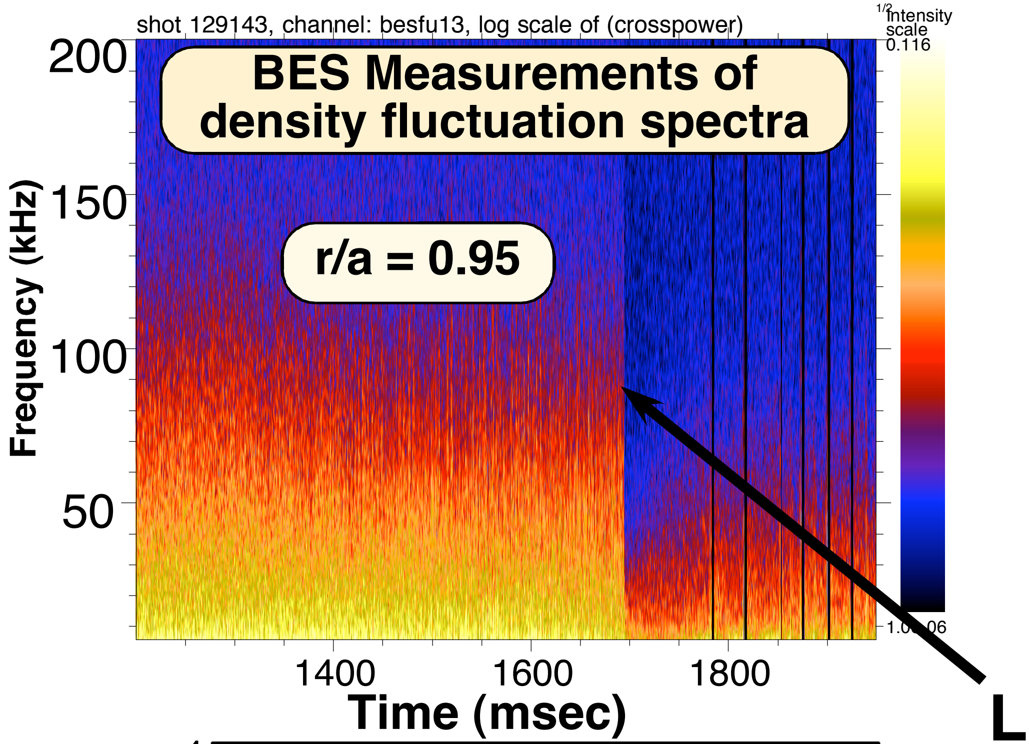


**CER**
**$(T_i, v_{tor}, E_r)$**

**BES**
**$(\tilde{n}(r,Z), \tilde{V}(r,Z))$**

**Reciprocating Langmuir Probe**
**$(M, \phi, n)$**

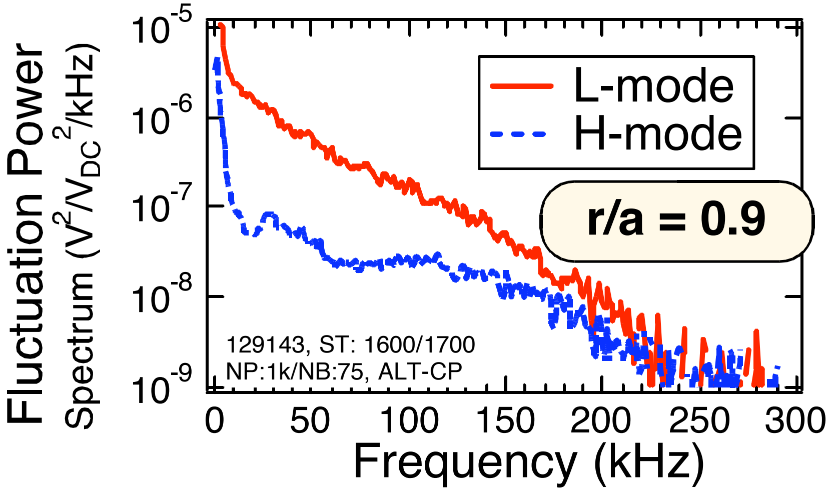
# RAPID FLUCTUATION SUPPRESSION OBSERVED IN EDGE AT LH TRANSITION



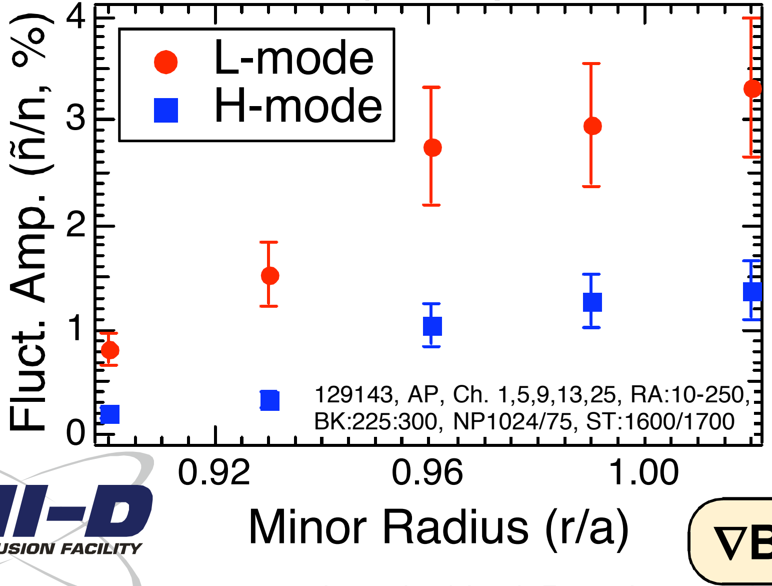
**BES Measurements of density fluctuation spectra**

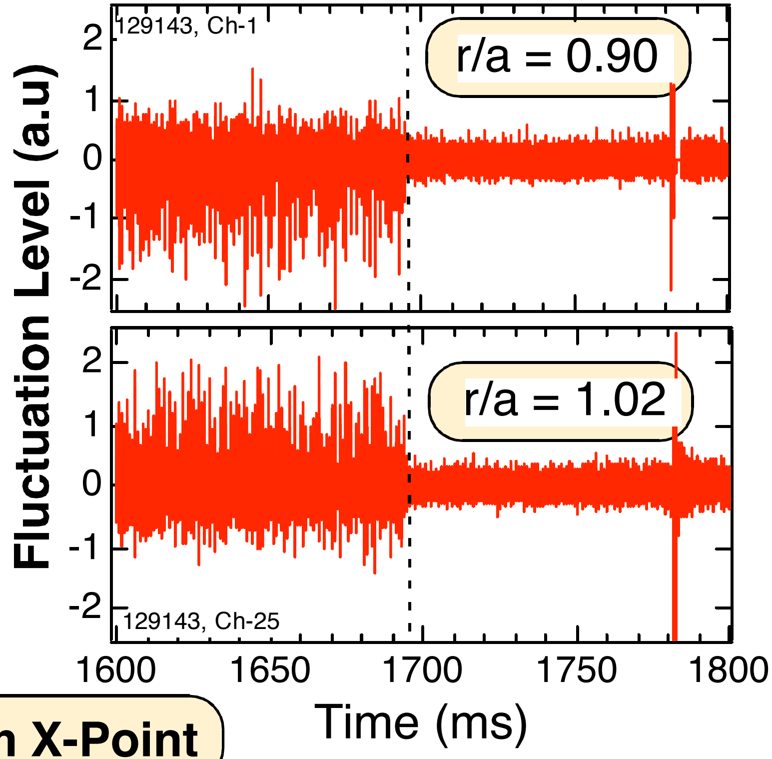
**r/a = 0.95**

**L-H**



**r/a = 0.9**



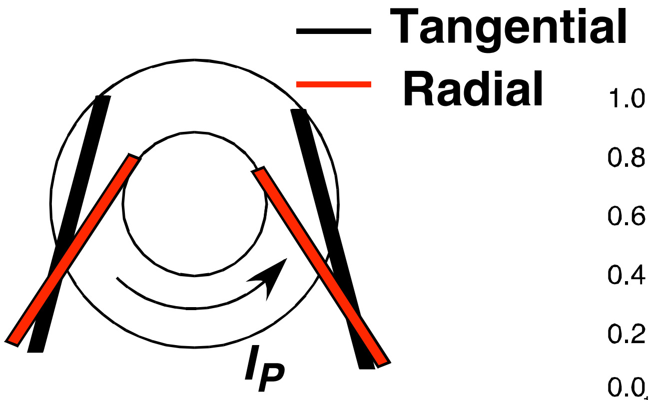


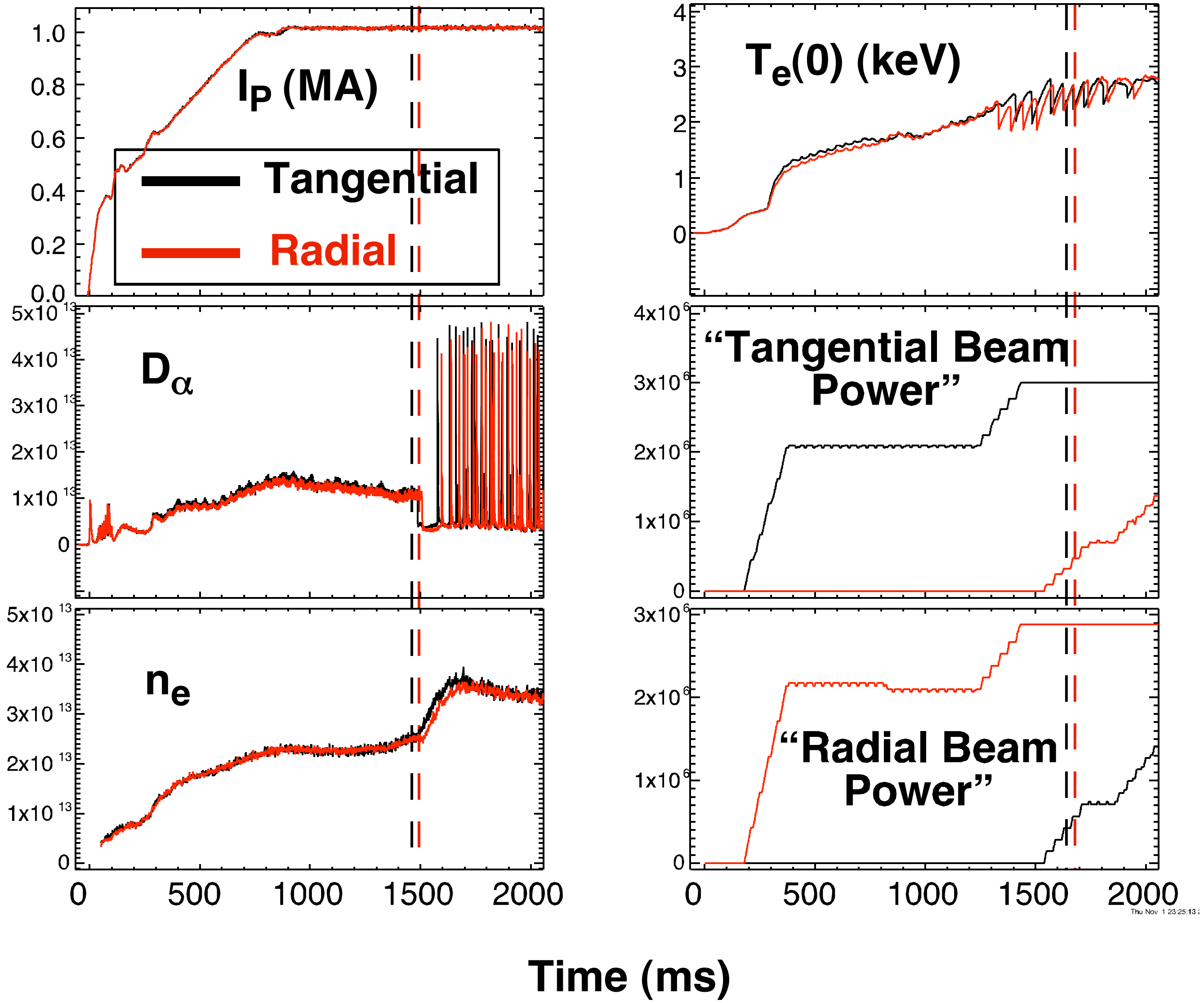
r/a = 0.90

r/a = 1.02

**∇B away from X-Point**

# 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

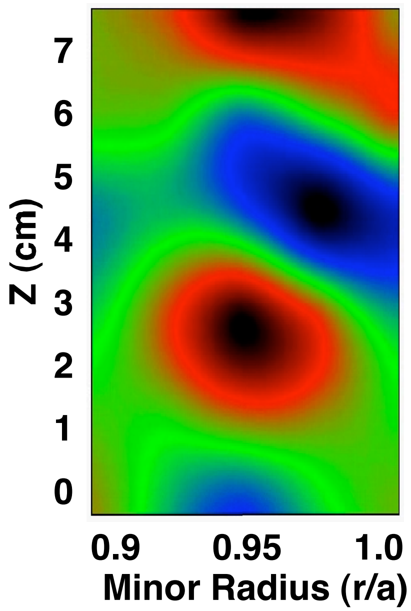
2) More radial beams

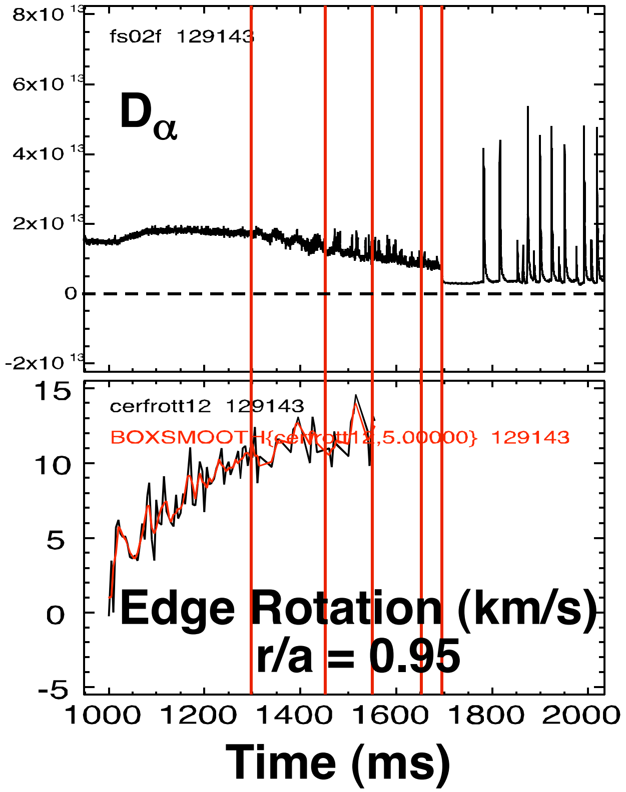
- Beam ion confinement changes significantly between conditions

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

# VISUALIZATIONS OF EDGE TURBULENCE DEMONSTRATE SIGNIFICANT EVOLUTION IN FLOW PATTERNS AND MODE STRUCTURE

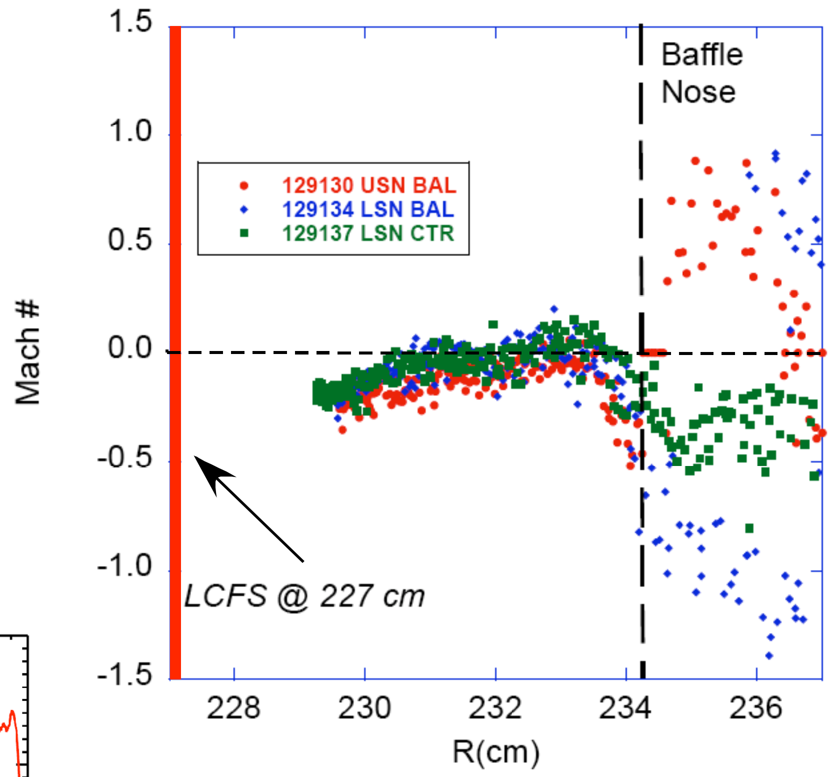
- **200 μs segments at 5 intervals**





**Mach Probe shows little change in SOL toroidal flow**

Mach # Profile Reciprocating Probe



**Doppler Reflectometer shows localized *increase* in $v_\theta$ during torque scan**