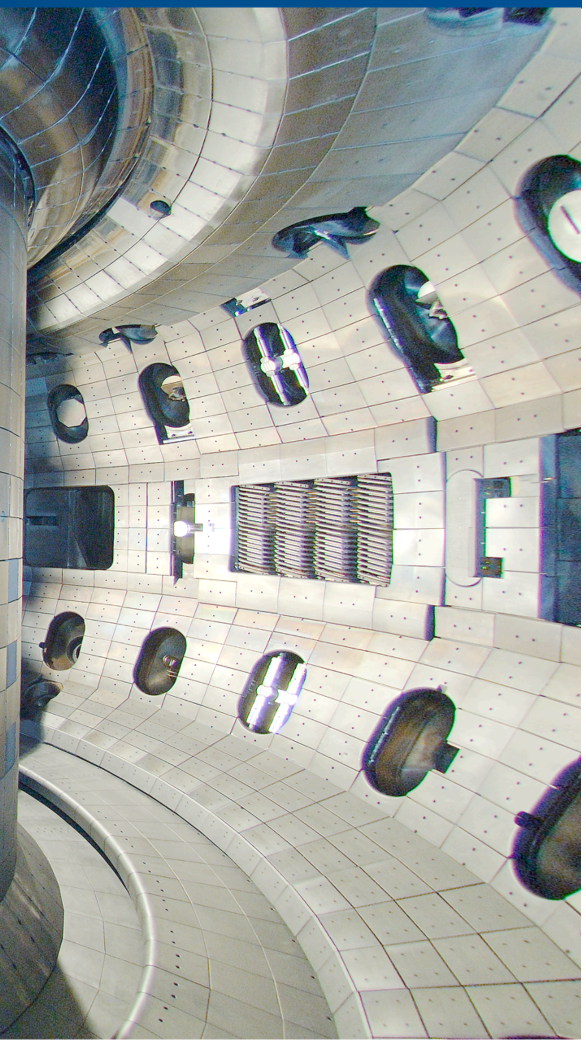
Turbulence Flow Dynamics and Mode Structure Impacts on the L-H Transition



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Presented at the
28th IAEA Fusion Energy Conference (FEC 2020)

10-15 May, 2021

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Overview of Results

- **L-H transition power threshold has dependences on multiple hidden parameters**
  - Safety factor, Grad-B drift, and Resonant magnetic perturbation (RMP)
- **Unifying observations of multimode turbulence structure in plasmas with lower P_{LH}**
  - Associated with larger Reynolds stress and mode velocity shear
  - Individual mode velocity does not match E×B velocity from CER measurements
- **Reynolds stress drive continuously increases as plasma moves from unfavorable towards favorable configuration**
  - No changes in plasma profiles
  - Increase of Reynolds and turbulence velocity approaching the transition
- **Application of RMPs reduces Reynolds stress and diminishes shear suppression of turbulence**
  - Increases turbulence decorrelation rate
  - Reduces velocity shear
  - Reduces transient Reynolds stress drive at time of L-H transition

Understanding L-H Power Threshold Dependence on Multiple Parameters is Critical for ITER to Access H-mode

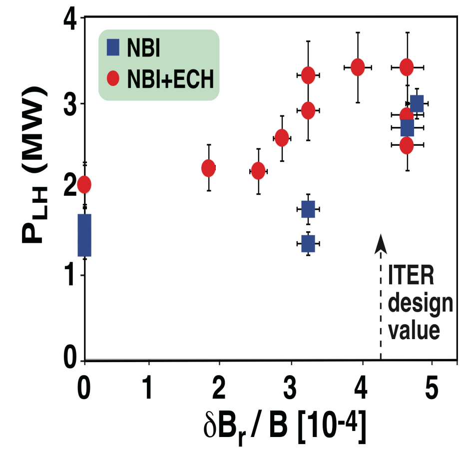
- **Empirical L-H transition power threshold (P_{LH}) scaling developed from multi-machine database:**

  $$P_{LH} = 0.049 \times B_t^{0.8} \times n_e^{0.72} \times S^{0.94}\ [1]$$

- **Experiments demonstrate significant departures from scaling law, undermining confidence in predicted P_{LH} in ITER**
  - Low density branch, Safety factor, Isotope, Rotation, ion ∇B direction, RMP

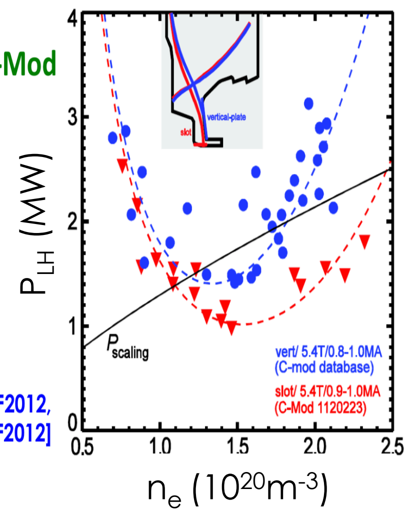
- **Understanding physics behind the L-H transition trigger and power threshold scaling is necessary for developing a predictive model for ITER**

DIII-D



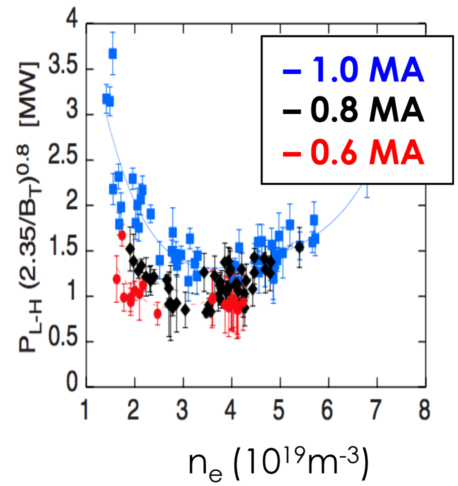
[Gohil, NF, 2011]

C-Mod



[Y Ma, NF2012, PPCF2012]

AUG

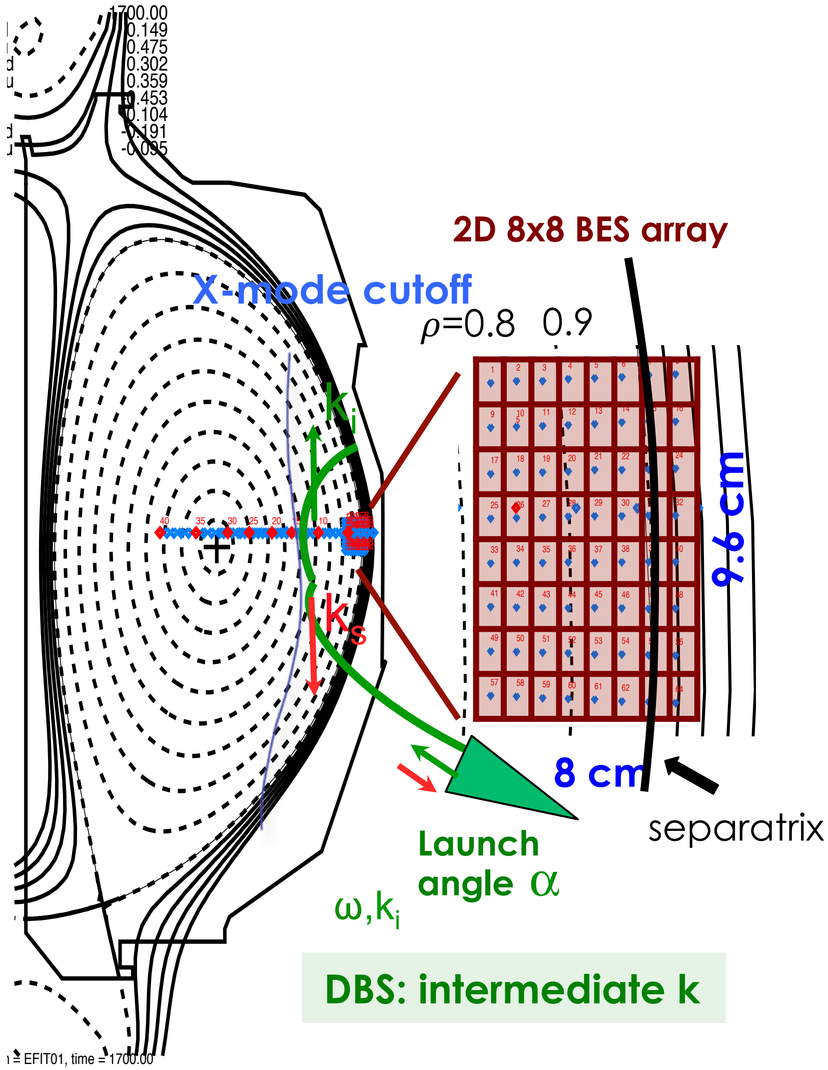


[Ryter, NF, 2013]

[1] Y. Martin, J. Phys. Conf. 2008

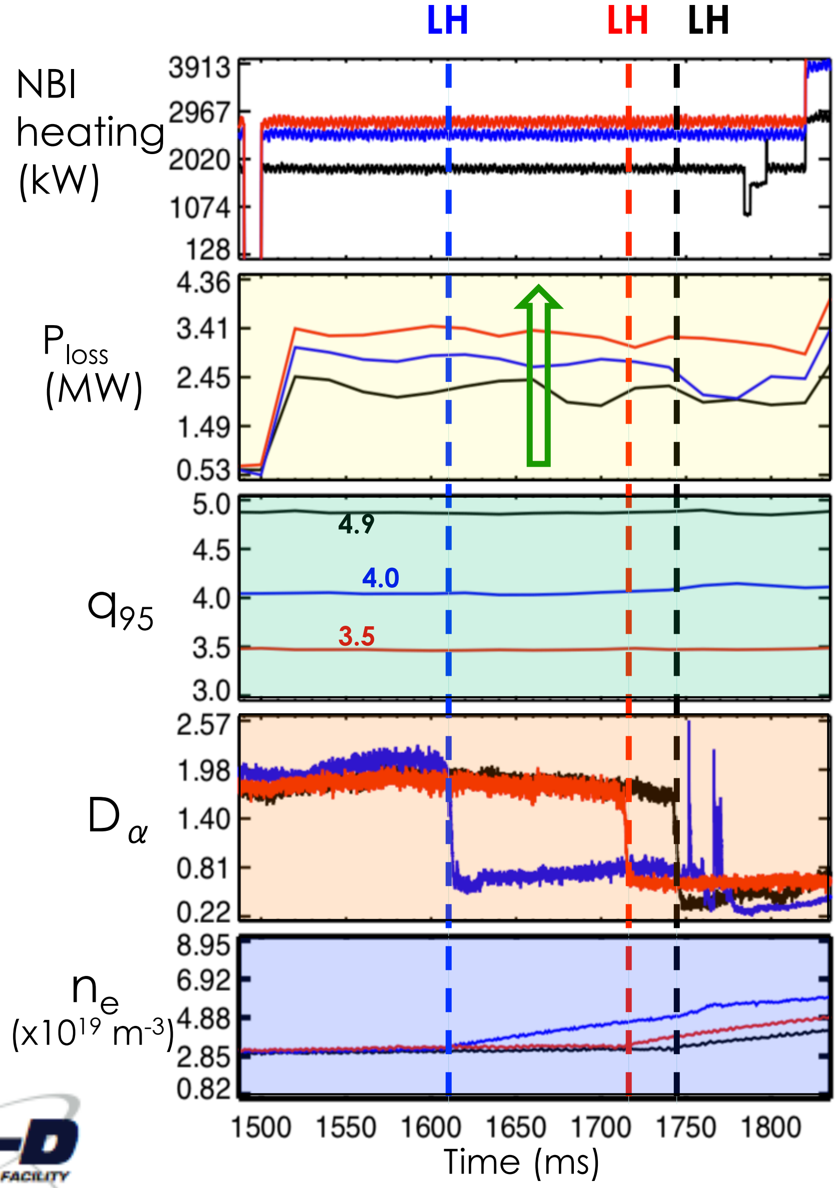
A Set of L-H Transition Experiments Performed at DIII-D with Varying Density, Safety Factor, ion ∇B Drift Direction and Application of RMP

- **ITER similar shape (ISS) with pure NBI heating**
- **Low torque via balance co-counter current neutral beam injection**
- **Multiple parameters are varied:**
  - Density
  - Safety factor
  - Ion ∇B drift direction
  - RMP application
- **Comprehensive edge plasma diagnostics providing detailed turbulence and flow dynamics measurements**



q_{95} dependence of L-H power threshold

Plasma Current Scanned in ITER Similar Shape Plasmas with Balanced NBI Heating



P_{loss}= NBI input + Ohmic heating – dW/dt – Radiated power

B_t=2T

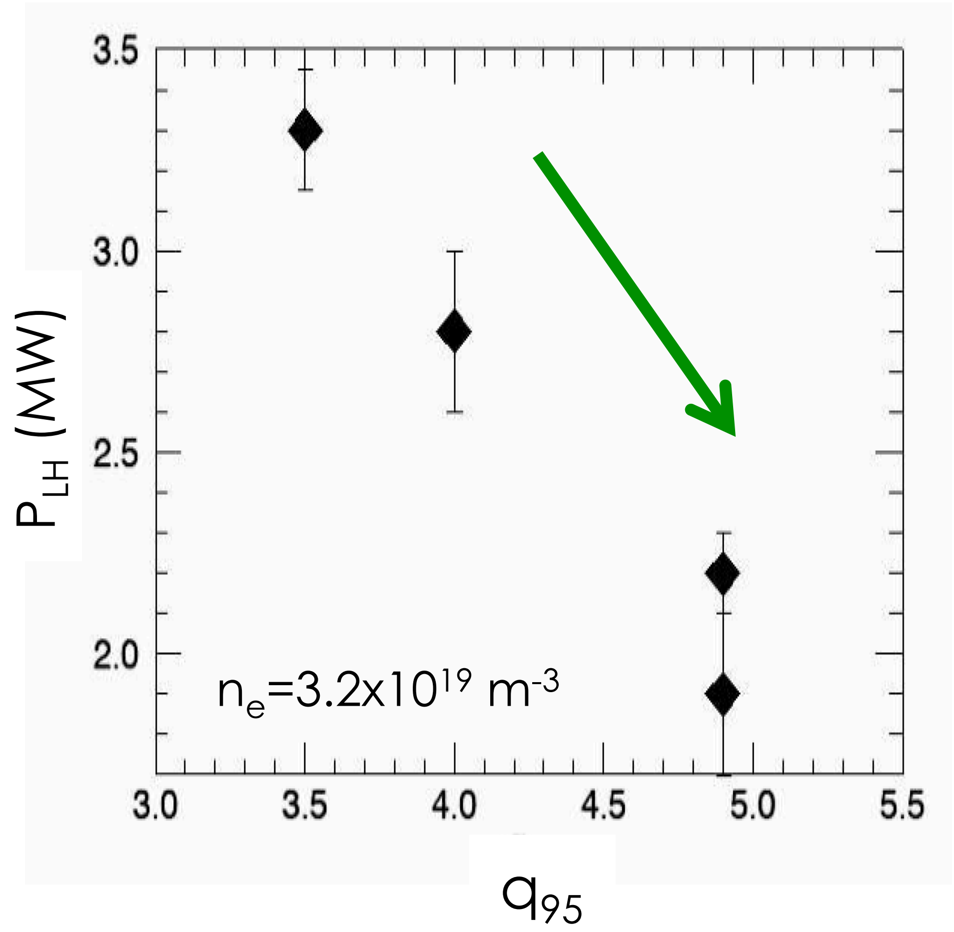
P_{LH} increases with lower q_{95}

q_{95}=4.9,4.0,3.5

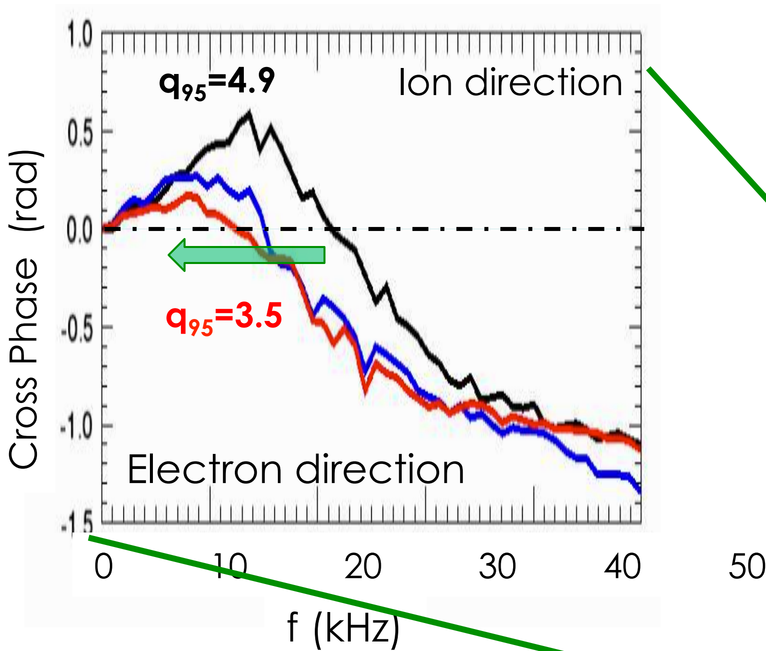
n_e=3.2e19 m^{-3} fixed while scan I_p (q_{95})

L-H Transition Power Threshold Reduces with Increasing q_{95} near Density Minimum

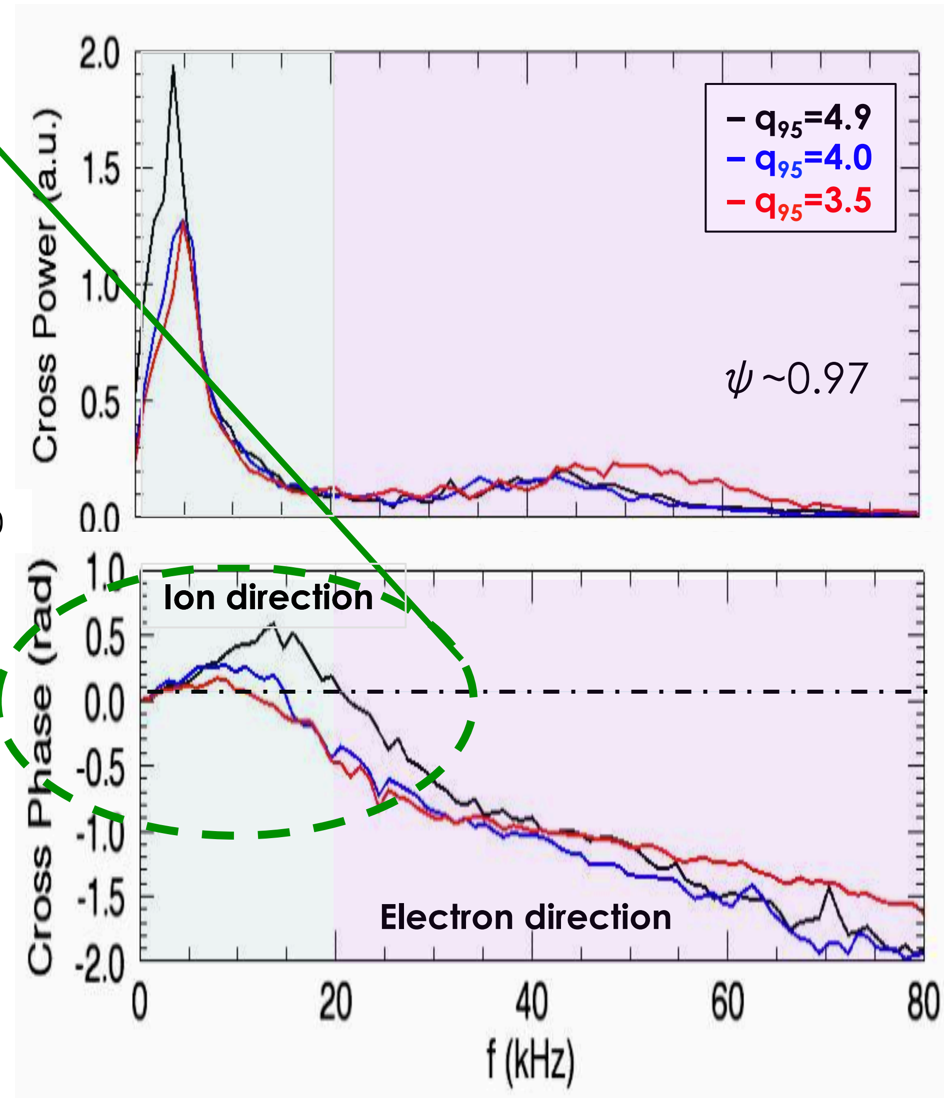
- **ISS with balance beam injection**
- **Vary I_p with constant B_t and n_e**
- **At power threshold density minimal, P_{LH} reduces with higher q_{95}**
- **At lower density little dependence of P_{LH} on q_{95}**



Dual Turbulence Modes Observed at Higher q_{95} (Lower Power Threshold) inside the Separatrix



Poloidal Cross Power



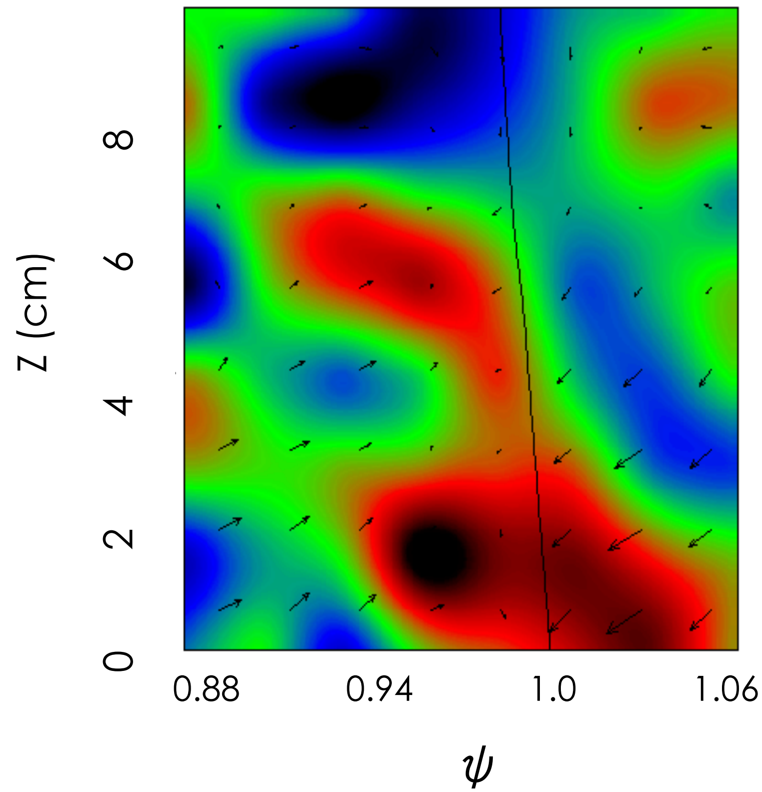
- **< 20 kHz propagates in ion diamagnetic direction (IDD)**
- **> 20 kHz propagate in electron diamagnetic direction (EDD)**

Turbulent Velocity Fluctuation Measured from Image-based Velocimetry

- **Vector-matching frame by frame to infer short time scale velocity fluctuation**
  - Orthogonal Dynamic Programming [1]

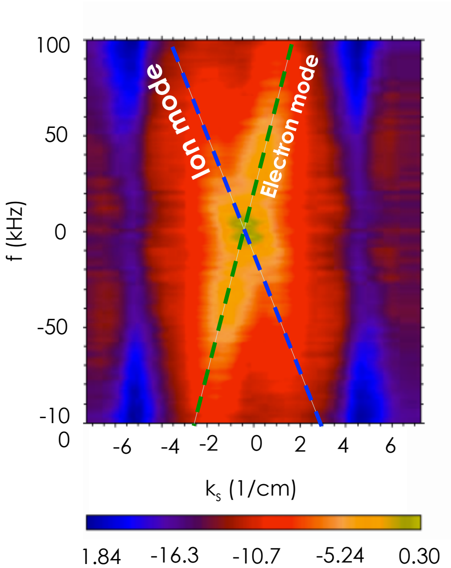
- **With measured $\tilde{V}_r$ and $\tilde{V}_\theta$**
  - Infer instantaneous Reynolds stress (~100μs) $<\tilde{V}_r\tilde{V}_\theta>$

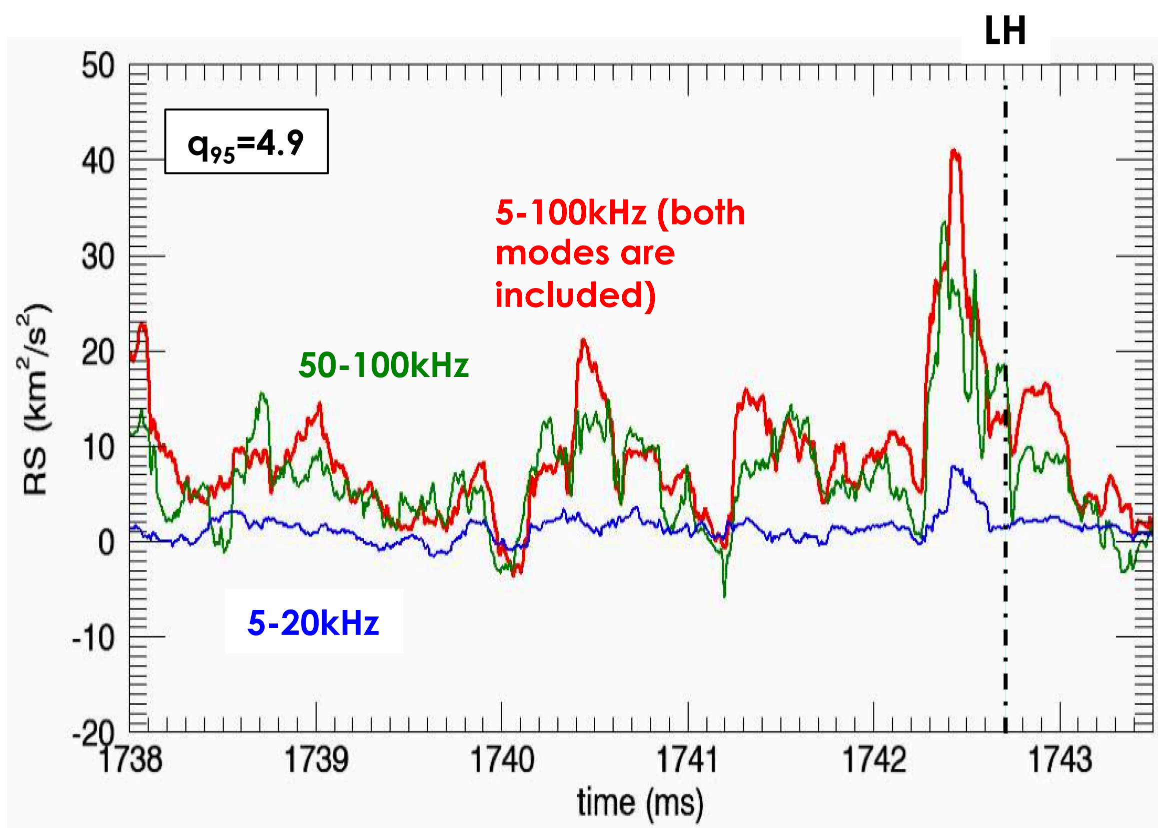
BES Density Fluctuation 2D Image



[1] G. McKee, et al., RSI, 75, 3490, 2004

Larger Reynolds Stress near the Transition when Both Modes are Included





- **Qualitatively consistent with observation of lower power threshold when dual mode is present**

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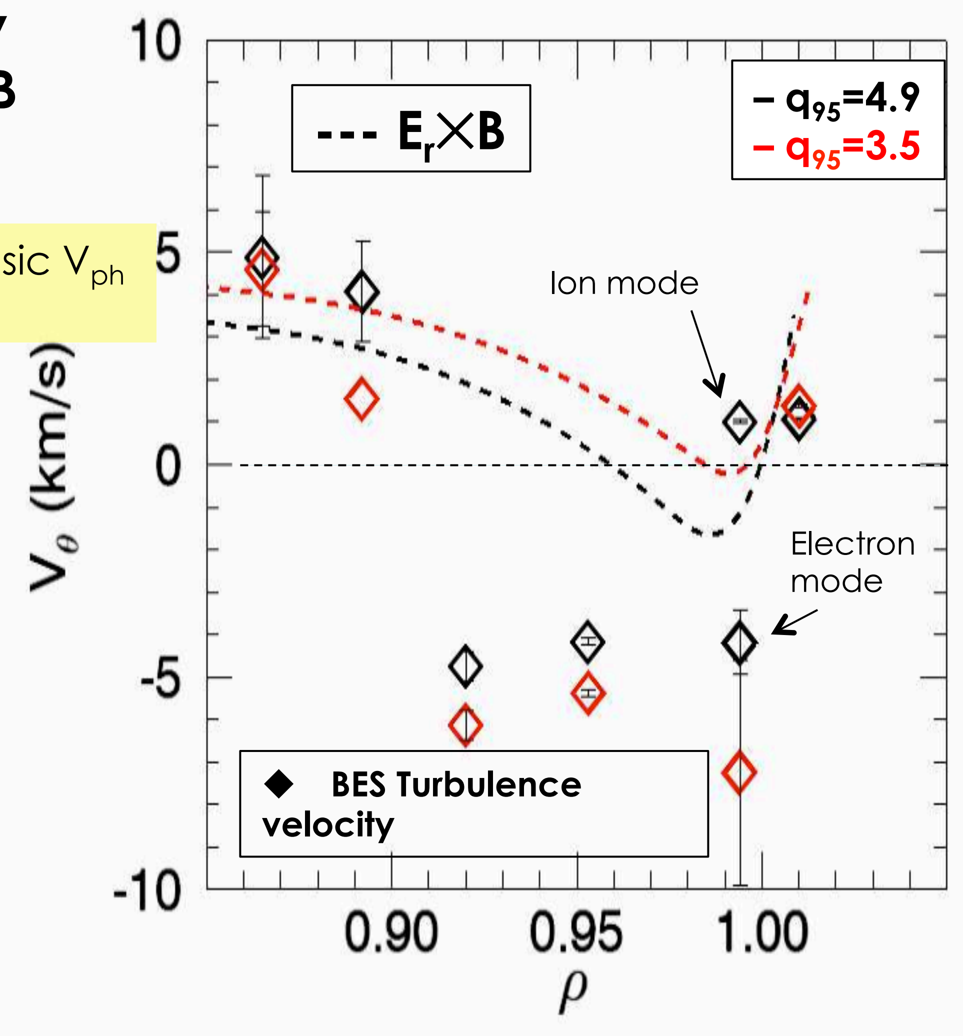
Poloidal Velocity of Dual Bands Do Not Individually Match E×B Velocity

- **Measured turbulence velocity is a sum of the equilibrium E×B and mode intrinsic velocity**

$V_{\theta,turbulence}$= Equilibrium V_{EXB}+ drift wave intrinsic V_{ph}
V_{ph}~$V_{d,e}$

- **Mode intrinsic velocity is different with the equilibrium E×B velocity**

- **Intrinsic diamagnetic drift wave phase velocity shear becomes important to turbulence stabilization [1]**



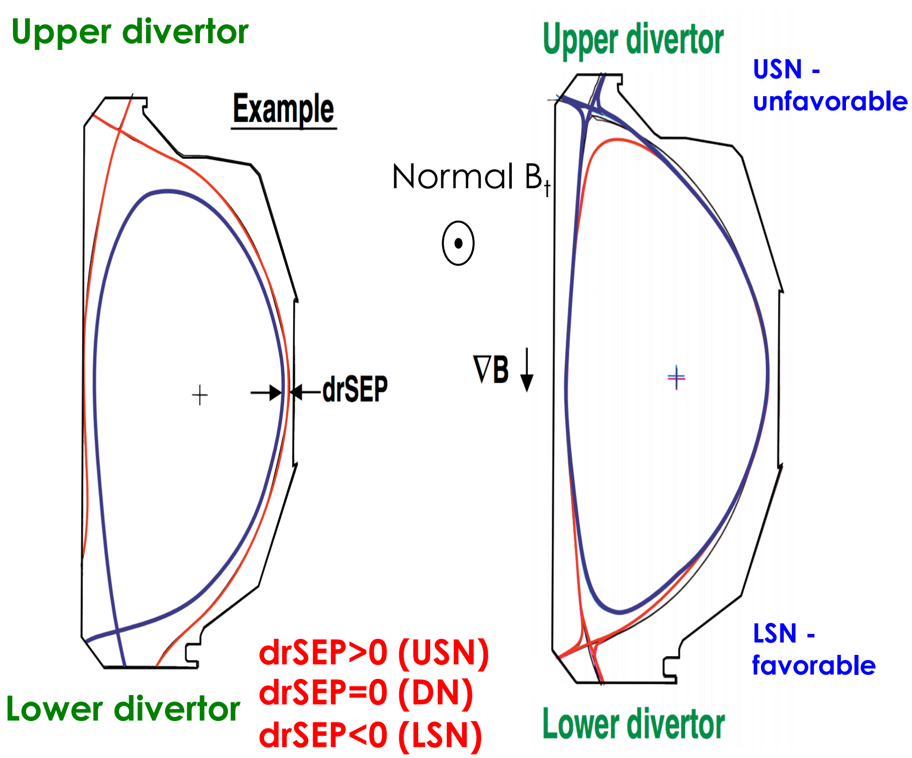
[1] R. Waltz, et al., PoP, 2011

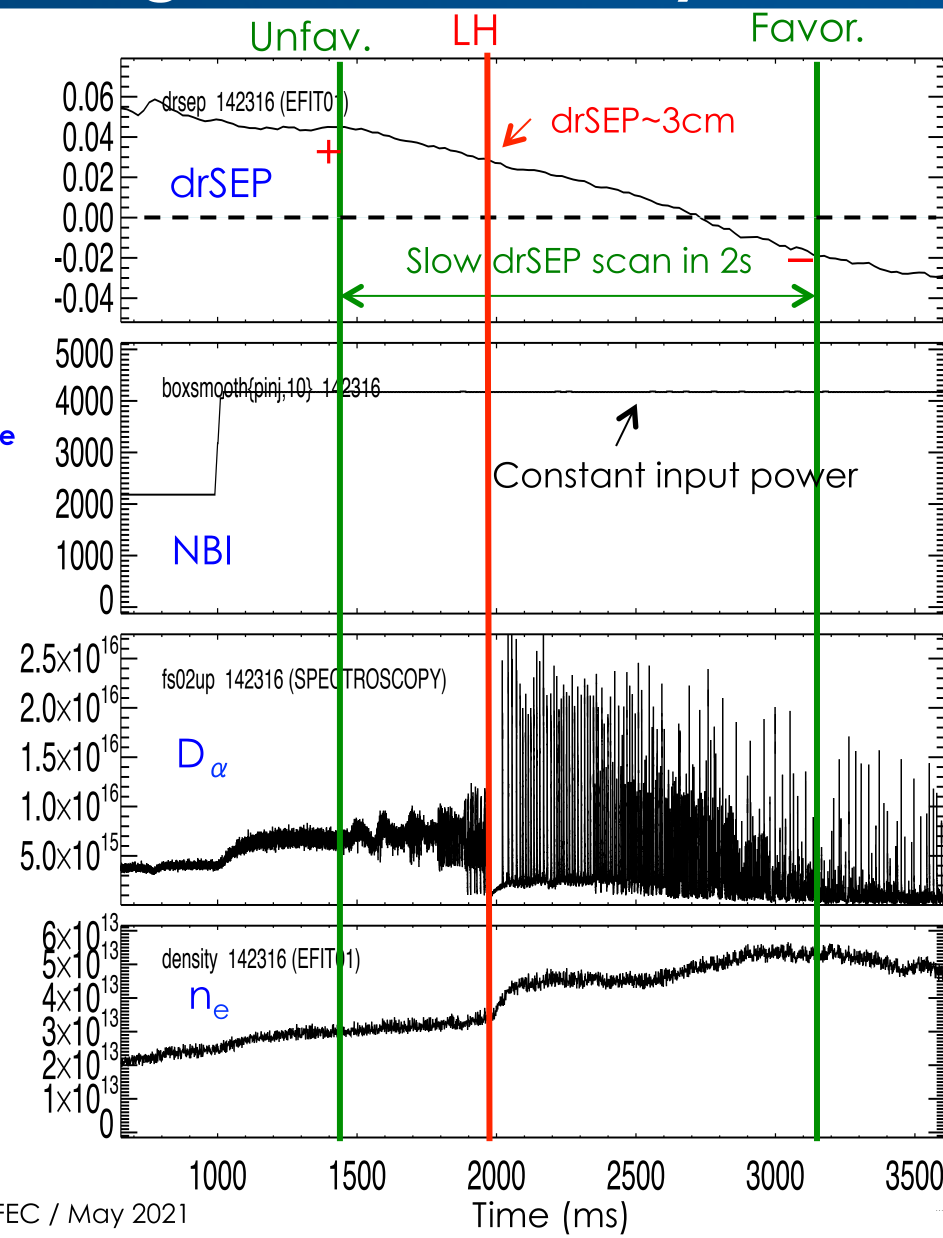
V_d~2 km/s

Ion ∇B drift direction impacts on the L-H power threshold

Dedicated Experiment Investigating L-H Transition at Favorable v.s. Unfavorable Magnetic Geometry

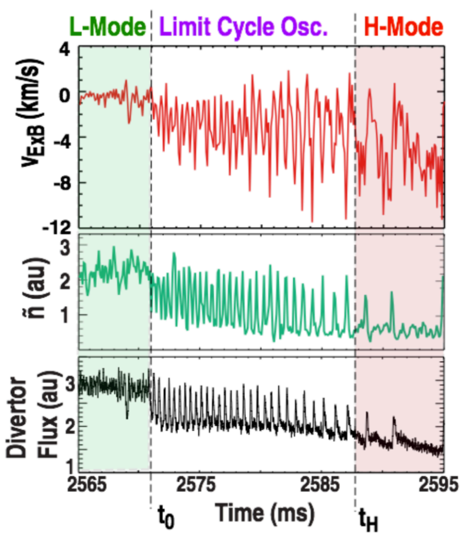
- **Slow drSEP scan from unfavorable to favorable geometry**
  - Input power in between the two P_{LH}



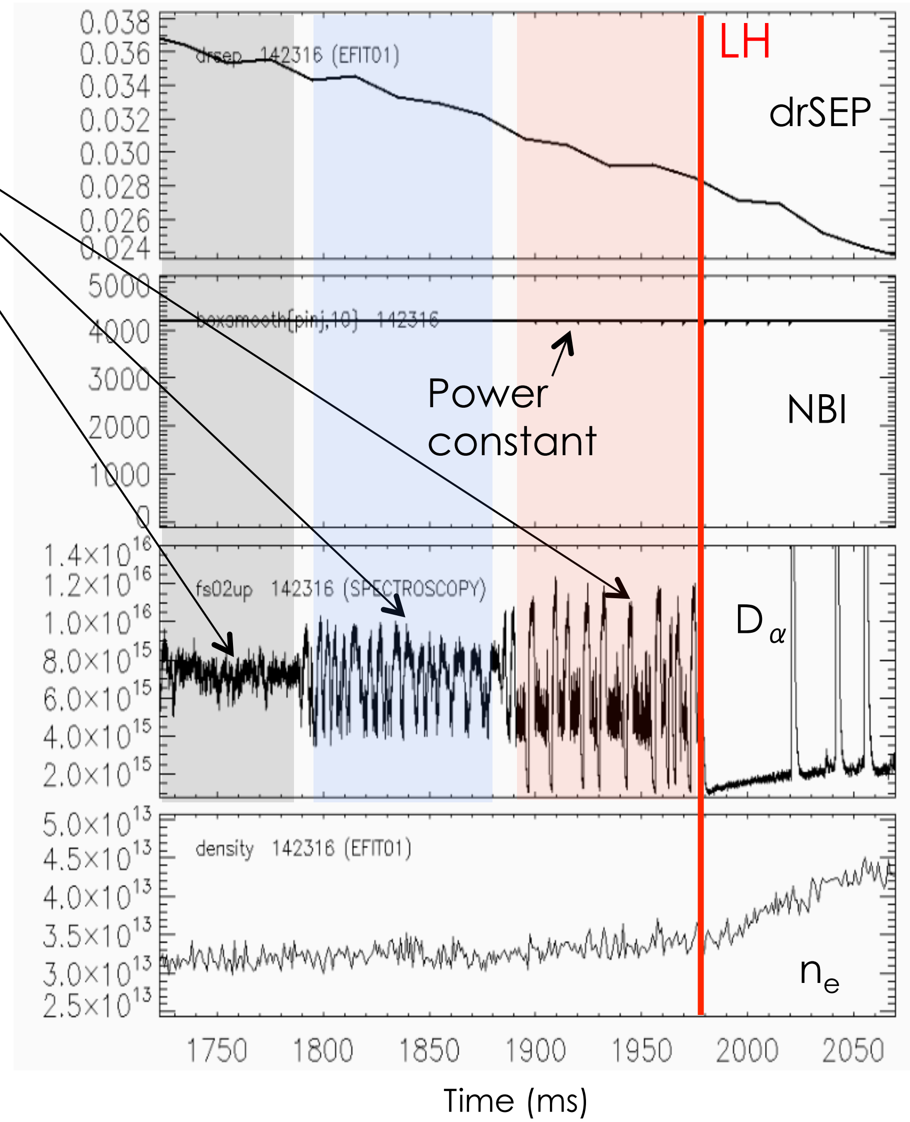


Three Phases of Turbulence Flow Dynamics Observed approaching the L-H Transition as drSEP is Reduced

- **Three-phase flow dynamics approaching the transition**
- **Constant power, density, toroidal field, plasma current**
- **Qualitatively looks like LCO but with lower frequency**



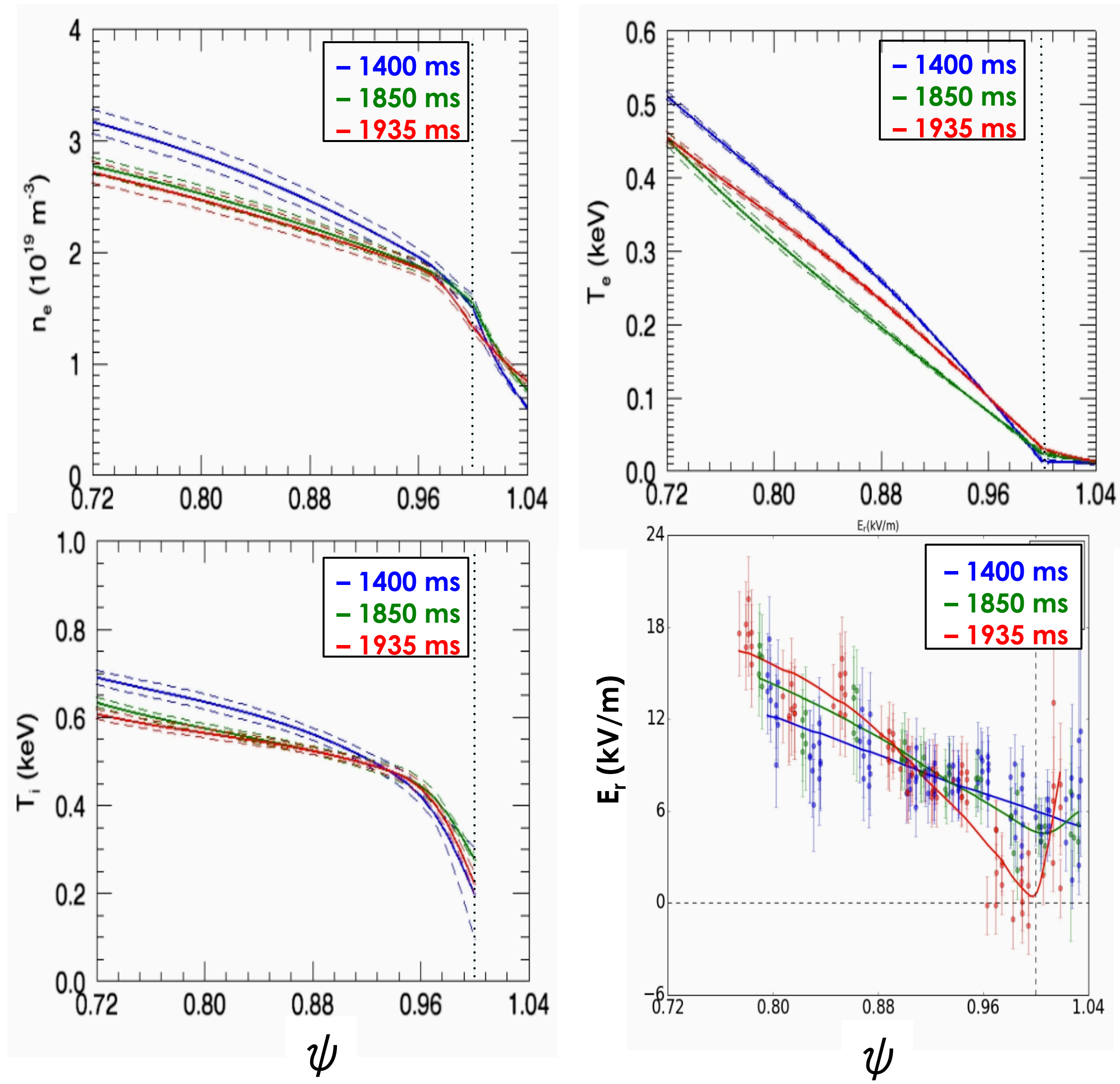
Schmitz, et al., PRL, 2012



Temperature and Density Profiles are nearly the Same as Ion ∇B Drift Changes from Unfav. Towards Favor. Direction

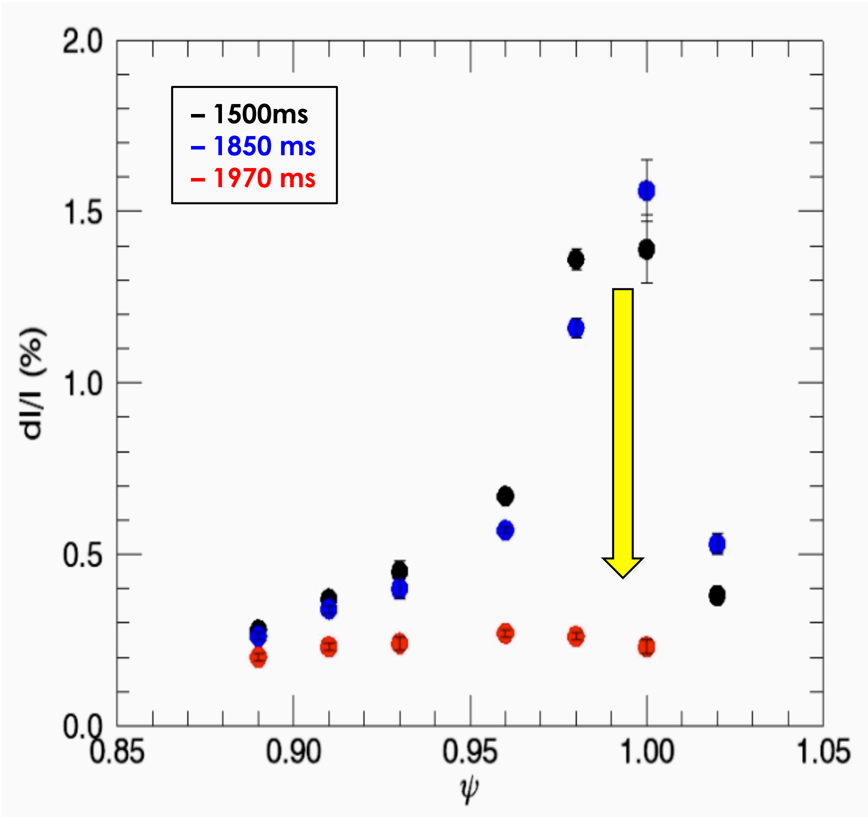
- **Plasma n_e, T_e, and T_i profiles do not change approaching the L-H transition**

- **Equilibrium radial electric field (CER) increases approaching the L-H transition**

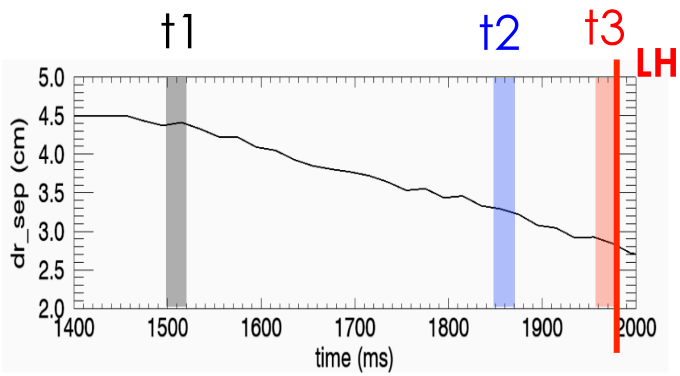


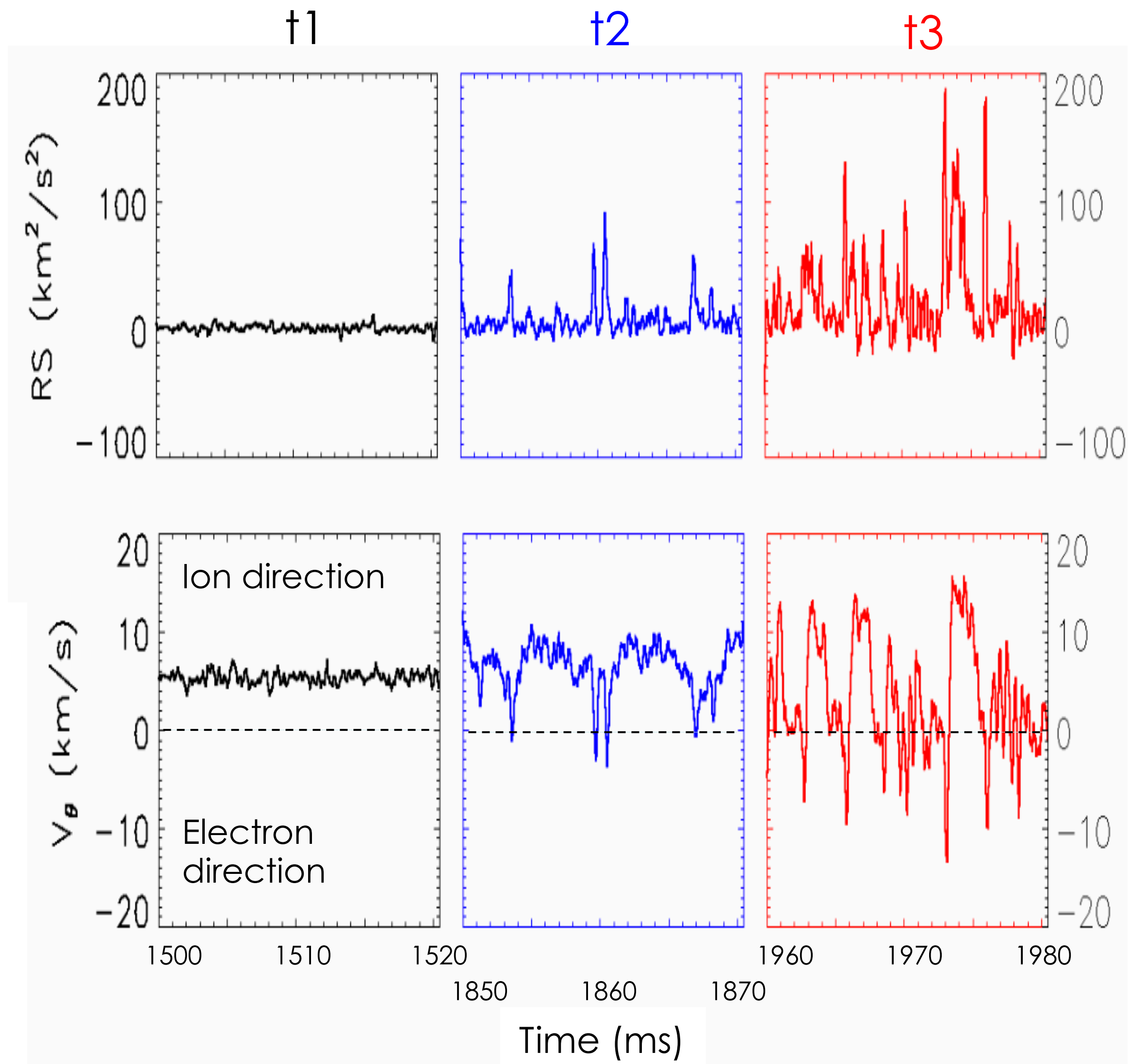
Turbulence Amplitude Reduces as Ion ∇B Drift Changes from Unfavorable towards Favorable at Constant Input Power

- **Stronger turbulence suppression approaching the transition**
- **Reduction in turbulence is not from changes in gradient drive**
  - Constant input power
  - Profiles at mid-plane nearly no changes
- **Maybe related to changes in flow dynamics**



Stronger Turbulence Flow Dynamics Observed during the Changes in Ion ∇B Drift Direction approaching the L-H Transition





- **Turbulence Reynolds stress largely increases approaching the transition**
- **Turbulence poloidal velocity field increases and rapidly changes between IDD and EDD**

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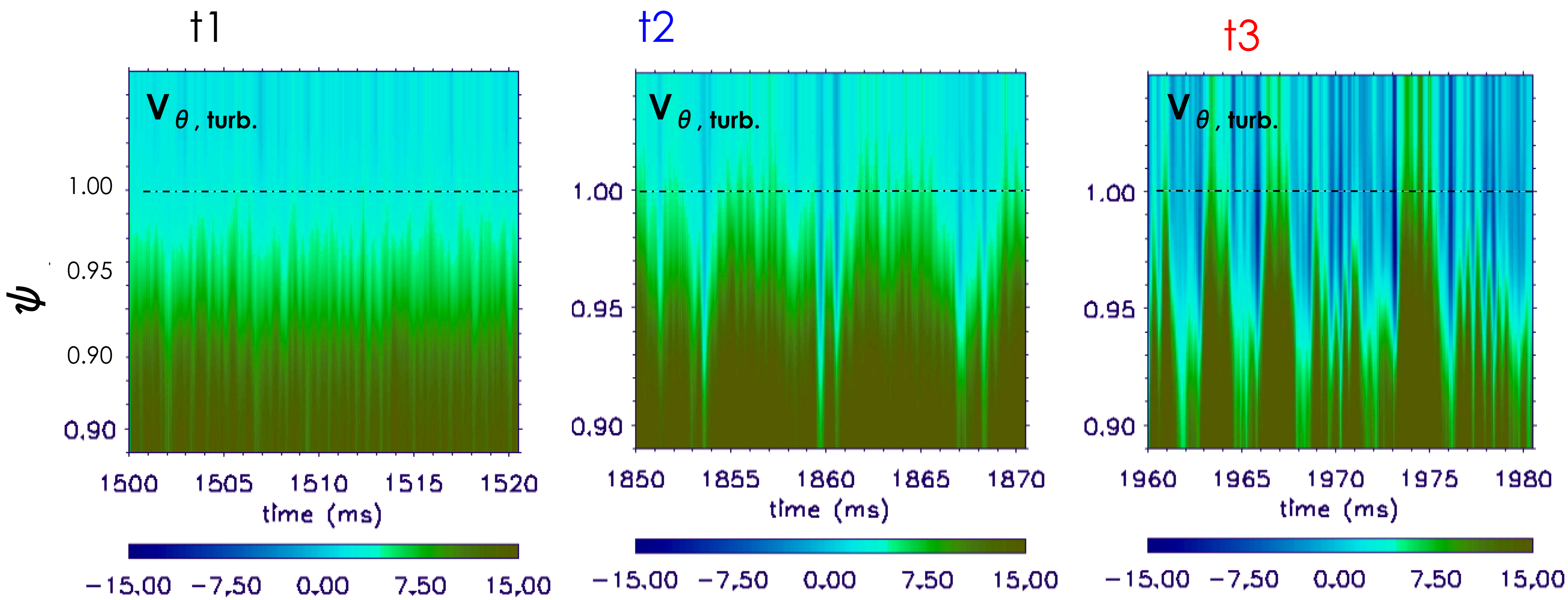
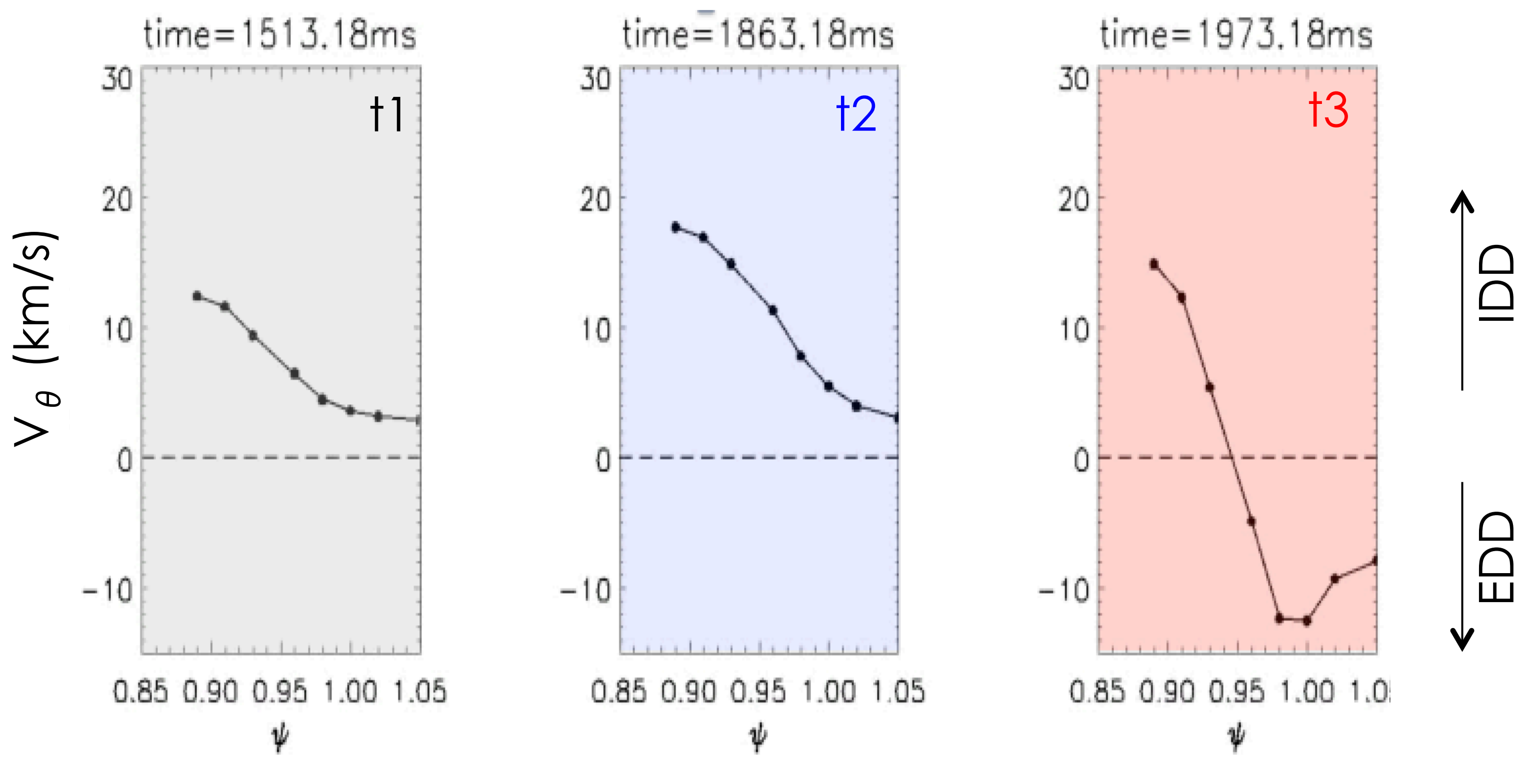
Changes in Flow Dynamics is mainly in Plasma Edge Region



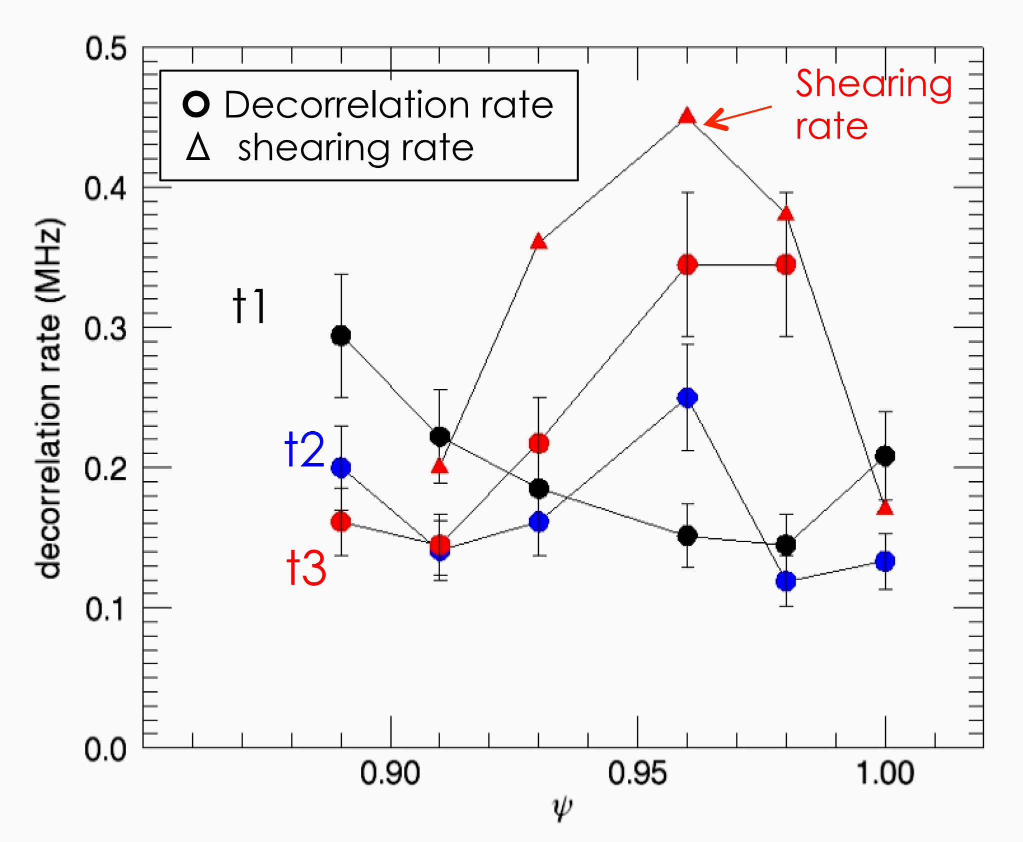
- At ψ~0.95-1.0, $V_{\theta\text{, turb.}}$ propagates in IDD direction
- Starts to see $V_{\theta\text{, turb.}}$ changes to EDD direction a few times
- $V_{\theta\text{, turb.}}$ periodically changes direction between IDD and EDD

Stronger Flow Shear at the Edge Occurs approaching to the Transition



Turbulence Decorrelation Rate Increases as Ion ∇B Drift Moves in the direction from Unfav. to Favor. Configuration

- **Increasing flow shear approaching the transition exceeding the decorrelation rate**

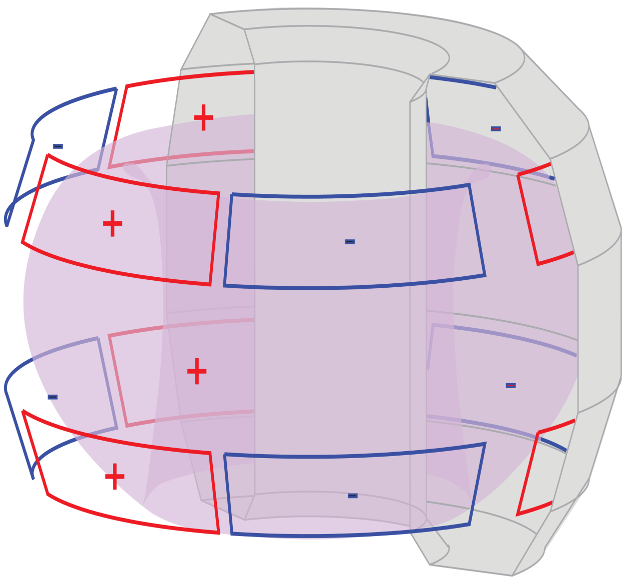


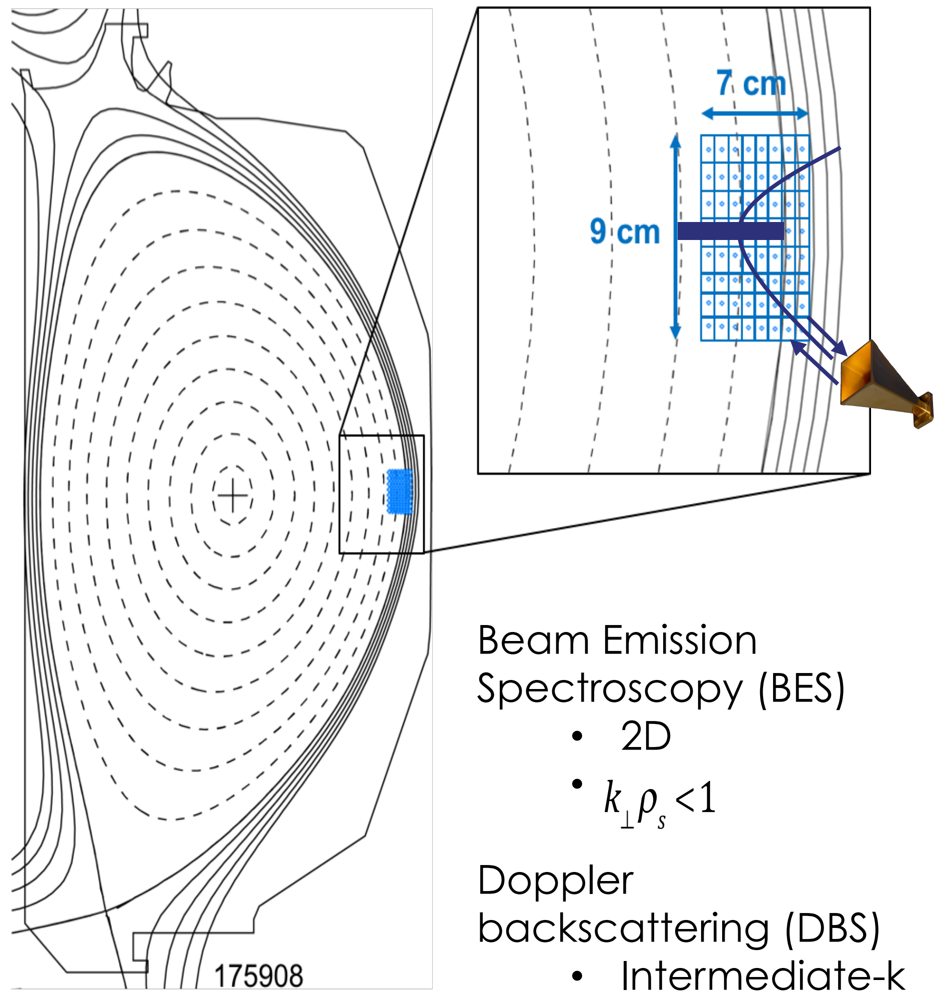
RMPs impacts on the L-H power threshold

Fluctuations and Flows Measured Across L-H Transitions in ITER-Similar Shape, Low-Rotation Plasmas with Applied n=3 RMPs

- **Balanced NBI**
- **q_{95}=3.6 (ELM suppression conditions)**

RMPs from internal coils





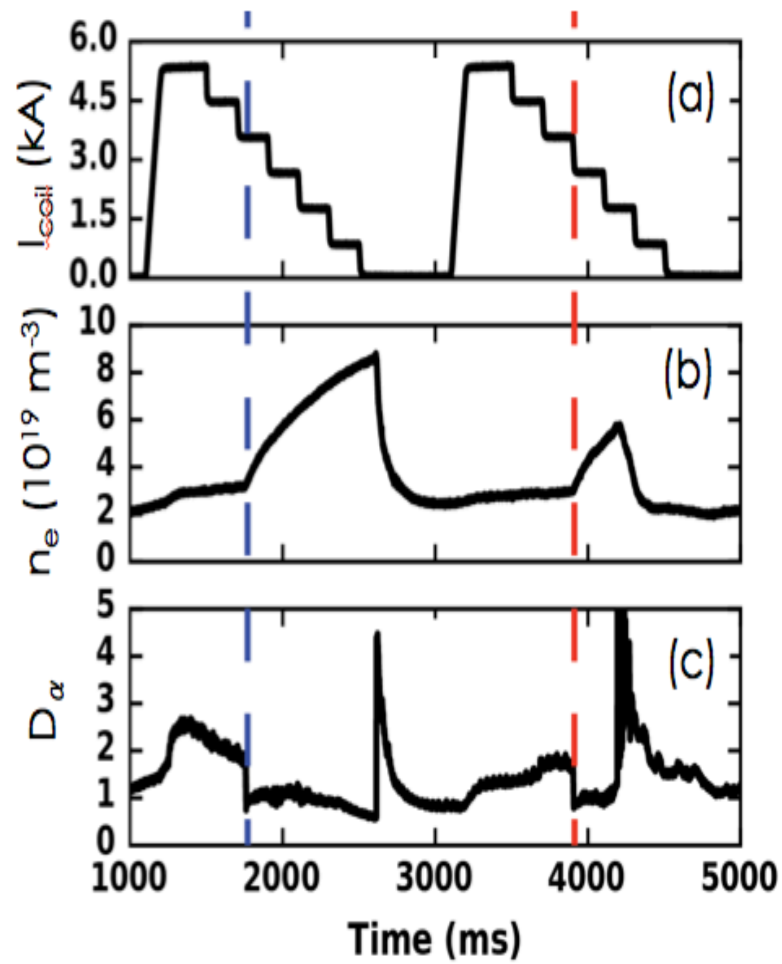
Beam Emission Spectroscopy (BES)
- 2D
- $k_{\perp}\rho_s < 1$

Doppler backscattering (DBS)
- Intermediate-k

$$k_{\perp}\rho_s = 0.5 - 2$$

L-H Transitions Occurred as RMP Amplitude was Reduced from Maximum to a Lower Value at Constant Input Power

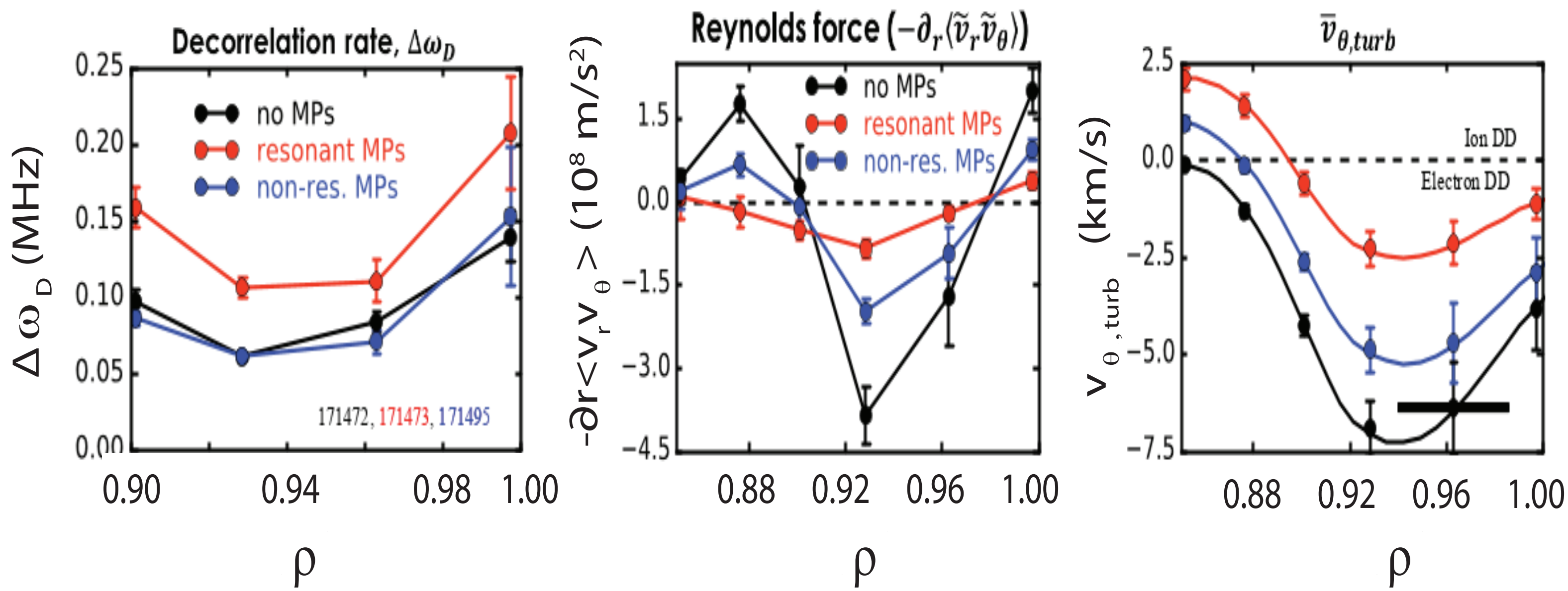
- **Plasma was initially in L-mode with maximum RMP amplitude**
- **$\delta B_r/B_r$=4.4×10^{-4} with I-coil current of 5.4kA**
- **Two transitions at different ECH level**



D.M. Kriete, et al., PoP, 2020

RMPs Alter Turbulence Properties and Reduce Flow Shear Leading up to the L-H Transition

- **RMPs raise turbulence decorrelation rates**
- **RMPs reduce Reynolds stress drive for poloidal flow over edge region**
- **Reduction of Reynolds stress consistent with the reduced flow shear**



D.M. Kriete, et al., PoP, 2020

Summary

- **Experimental observations of P_{LH} dependence on multiple parameters:**
  - q_{95}: lower P_{LH} at higher q_{95}
  - Ion ∇B drift direction: Reynolds stress drive and flow shear significantly increased as the ion ∇B drift changes direction from unfavorable to favorable
  - RMP application: raises the turbulence decorrelation rates and reduces Reynolds stress drive for flow and flow shear, which increases P_{LH}

- **The unifying observations demonstrate the significance of turbulence and turbulence driven flow in lowering the L-H transition power threshold**