Core Turbulence Structures and $\rho^*$ Scaling in H-Mode Plasmas on DIII-D

George R. McKee,
R. J. Fonck, D. Gupta, M. Shafer, D. Schlossberg

University of Wisconsin-Madison

J. Candy, C.C. Petty, M.R. Wade, R.E. Waltz

General Atomics

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INTRODUCTION AND OVERVIEW

- Core turbulence in H-mode discharges are investigated via the significantly upgraded Beam Emission Spectroscopy (BES) at DIII-D

- Turbulence characteristics are examined during $\rho^*$ scan of Hybrid Scenario (H-mode) discharges, a stationary plasma at high beta with good confinement
  - $\rho^*$ scan performed to examine non-dimensional scaling of turbulence characteristics
  - Broadband fluctuation levels measured and compared ($\tilde{n}/n < 1\%$)
  - Radial and poloidal correlation lengths
  - Decorrelation times
  - Flow shear of turbulence ($v_{EB} \text{ vs. } v_{\theta,BES}$)

- Tilted turbulent eddy structure observed in H-mode, and not in L-mode
  - Finite time-lag observed in radial cross-correlations
  - 2D spatiotemporal correlation functions examined
  - Visualization of core L-mode and H-mode turbulence
**ABSTRACT**

The characteristics of long-wavelength density fluctuations $k_{\perp}\rho_i$ are examined in the core region ($0.5 < r/a < 0.9$) of H-mode discharges and compared to turbulence in L-mode discharges. Measurements are obtained with the upgraded 16-channel (4-radial x 4-poloidal), high-sensitivity beam emission spectroscopy system at DIII-D. The $\rho^*$ scaling of turbulence structures in hybrid scenario H-mode plasmas demonstrates that the radial correlation lengths scale closely with the local ion gyroradius, as predicted theoretically and observed in L-mode plasmas. Eddy spatial structures, in contrast, differ dramatically between L and H-mode plasmas, with H-mode turbulence exhibiting a highly tilted structure in the radial-poloidal plane, as measured via 2D spatiotemporal correlations. Whether this difference results from flow-shear, radial propagation, or inherent turbulence dynamics will be investigated via comparison to measured flow shear.
Collisionally-excited, Doppler-shifted neutral beam fluorescence

\[ D^0 + e, i \rightarrow \left(D^0\right)^* \rightarrow D^0 + \gamma (n = 3 \rightarrow 2, \lambda_o = 656.1 \text{ nm}) \]

BES Viewing Geometry on DIII-D

Remoteely Located Spectrometers

Photodiodes
Cryo-cooled, Ultra-low-noise pre-amplifiers,
DAQ: 1 MHz, 14-bit

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**BES System Significantly Upgraded to Enhance Sensitivity for Core Turbulence and Nonlinear Studies**

**Upgrades:**
- Increased Optical Fiber Light Collection Area
- Advanced Filters to Exploit Thermal CX emission
- Improved High-Efficiency, High Throughput Optics
- Larger Area Photodiode
- Higher Resolution, Deep Memory Digitizers

**Result:**

5-10x Increase in Signal ➔ 10-30x Increase in Signal-to-Noise Power

4x4 Previous array

Areal Coverage: 19%

4x4 Upgraded array

Areal coverage: 79%

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Upgraded, high sensitivity BES system measures turbulence in high confinement/low-turbulence plasma conditions

- 4x4 Channel Grid (Radial/Poloidal) 3.5 x 4.5 cm
- Located on outboard midplane
- Radially Scanned shot-to-shot
HYBRID SCENARIO DISCHARGES ACHIEVE HIGH PERFORMANCE WITH STATIONARY CONDITIONS

• “Hybrid” scenario discharges seek to achieve high beta and good energy confinement at moderate q: overall performance between conventional ELM’ing and Advanced Tokamak:
  - Stationary performance on $\tau_f$ time-scale (55 $\tau_E$, 9 $\tau_f$)
  - Pressure near n=1 no-wall beta limit
  - Good energy confinement (20-50% above conventional scaling)
  - ExB shear mitigates transport according to GLF23
  - Small 3/2 NTM inhibits sawteeth, help sustain performance
  - Wide operational range: $2.8 < q_{95} < 4.7$; $0.35 < n_G < 0.7$
  - Projects to $Q_{fus} = 10 - 40$ operation in ITER
  - Hybrid Scenario discharges achieved on DIII-D, JET, JT-60U, ASDEX-U

• Nearly stationary plasma conditions for many $\tau_E$ (several seconds)
  - Permits long-time ensemble - averaging of fluctuation data to improved signal-to-noise

• $\rho^*$ scan performed to examine turbulence and transport scaling
  - 1.6 * change in $\rho_I$
  - Other relevant dimensionless parameters held nearly constant
$\rho^*$ Scan of Hybrid Discharges Performed to Examine Turbulence and Transport Scaling

$\rho^* = \rho_f/a$

Fixed Dimensionless Parameters:

$\beta = nT/(B^2/2\mu_0)$

$v^* = v_{ii}/\omega_b$

$T_e/T_i$

$M = V_{rot}/V_{th,i}$

$q_{95}$
Profiles for $\rho^*$ Scan of Hybrid Discharges

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Profiles of Dimensionless Quantities Reasonably Well Matched

![Graphs showing the profiles of dimensionless quantities.](image)
GLF23 simulations demonstrate role of shear stabilization of turbulence to maintaining high confinement.
Normalized Density Fluctuation Levels < 1%; Exhibits Little Dependence on $\rho^*$

- Fluctuation amplitudes much lower than L-mode (~one order of magnitude)
  - Typical amplitude $n/\bar{n} < 1$
  - Spectra Doppler shifted (greater shift at low-$\rho^*$ due to higher power and torque to match the Mach number)
- Low turbulence amplitude qualitatively consistent with high confinement:
  $H_{89p} = 2.1$, $H_{98y2} = 1.3$
- *Not* consistent with gyroBohm predictions ($\tilde{n}/n \sim \rho^*$): why is this?

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RADIAL CORRELATION LENGTHS OF TURBULENCE SCALE WITH $\rho_I$

- Correlation functions broaden in core relative to edge, as expected with increasing temperature
  - 4-point measurement with 4x4 array allows for improved accuracy

- Correlation length increases with temperature and $\rho_I$, $\rho^*$, consistent with previous measurements performed in L-mode

(McKee et al., IAEA-2000, Nuc. Fus. 2001)
**Decorrelation Time and Poloidal Correlation Length of Turbulence**

- Gyrokinetic equations predict $\tau_c \sim a/c_s$ with $\rho^*$ scan
- Poloidal correlation lengths exhibit little dependence on $\rho^*$

![Decoration Time of Turbulence](chart1.png)

- Poloidal Correlation Length of Turbulence

- Low turbulence amplitude and limited spatial extent of measurements leads to significant noise in derived parameters
**FINITE RADIAL TIME-DELAY APPARENT IN HYBRID SCENARIO PLASMAS**

- Correlation functions indicate wavenumber spectra has finite $k_r$, radially outside L-mode plasmas typically exhibit $k_r \approx 0$ (except at very edge)

![Time-Lag Cross-Correlation Functions for increasing $\Delta R$](image)

- Characteristic of Hybrid scenario discharges (and H-modes in general)
- Consistent feature across 4 radial arrays and mid-radii, $0.6 < r/a < 0.9$
- Finite $k_r$ condition ceases near inside of pedestal region, $r/a > 0.9$

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FINITE RADIAL TIME DELAY OBSERVED ACROSS 2D MEASUREMENT ARRAY

\[ V = \frac{\Delta X}{\tau_d} \] - Simple relation no longer correct; requires geometric correction

Typical L-mode wavevector

"Apparent" H-mode wavevector

Time-delay of peak Correlation Across 4x4 array (Ref @ corner)

\[ \Delta R = 3.5 \text{ cm} \]
\[ \Delta R = 2.3 \text{ cm} \]
\[ \Delta R = 1.2 \text{ cm} \]
\[ \Delta R = 0.0 \text{ cm} \]

\[ \Delta Z = \Delta R \]

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WHAT MIGHT CAUSE FINITE RADIAL TIME-LAG?

- Strongly tilted eddies in the radial-poloidal plane propagating passed fixed detectors

\[ \Delta R \]

- Radial propagation of eddies

\[ \mathbf{v} = \mathbf{v}_r + \mathbf{v}_\theta \]

Use 2D Spatiotemporal Cross-correlation to examine propagation dynamics (direct visualization challenging at low fluctuation amplitudes).
“EXPANDED” 2D SPATIOTEMPORAL CORRELATION FUNCTION OBTAINED FROM ENSEMBLE-AVERAGED 2D DATA

- Cross correlation evaluated across 2D array from 4 corner reference channels
- Temporal spline (10*)
- 2D spatial spline (10*)
2D Spatial Correlation Function ($\Delta \tau = 0$) in (Hybrid) H-mode Discharge

H-mode (Hybrid)

L-mode

Radial Direction (cm)

Poloidal Direction (cm)

50-60 degree tilt

little or no tilt

see time-resolved correlation function $\rho(\Delta r, \Delta \theta, \Delta \tau)$

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TILTED EDDY EXPLAINS OBSERVED RADIAL TIME-DELAY

• Consider simple elongated, tilted structure advecting purely poloidally through fixed detection locations

\[ \Delta \tau_R = \frac{\Delta R \tan(\phi)}{v_\theta} \]

= 3.0 cm * tan(50°)/22 km/s

= 1.6 µs (tilting effect)

= 2.0 µs (measured)

• Measured time-delay and that inferred from poloidal velocity and structure compare well

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MEASURED POLOIDAL TURBULENCE VELOCITY COMPARES WELL TO MEASURED EXB VELOCITY

Comparison of ExB velocity from CER and measured turbulence velocity from BES

- $v_{\text{BES}}$ obtained from time-lag cross correlation measurements from BES: represents advection of turbulent eddy structures
- $v_{\text{ExB}}$ obtained from CER measurements of ion distribution and radial force balance
- Turbulence expected to advect at near ExB velocity assuming $v_{i}^{*}$ is small (as is the case)
- Velocity shear can be obtained from CER measurements or directly from BES measurements

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Velocity shear appears too small to explain eddy tilt

Simple Eddy Shear Model

\[ \Delta L_\theta \sim \frac{dv_\theta}{dr} \times L_{c,r} \times \tau_c \]

with

- \( \frac{dv_\theta}{dr} \) - measured shearing rate
- \( L_{c,r} \) - radial correlation length
- \( \tau_c \) - decorrelation time (eddy lifetime)

\[ \Delta L_\theta \sim (7 \times 10^4 \text{ s}^{-1})(3 \text{ cm})(5 \mu\text{s}) \sim 1.0 \text{ cm} \]

(or about 20 degree tilt)

Significantly less than observed tilt:

\[ \Delta L_\theta \sim 4 \text{ cm}, (50 \text{ degree tilt}) \]

Simple shear appears *too small* to explain eddy tilt:

More fundamental differences in L-mode vs H-mode turbulence likely needed to explain difference

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One discharge “accidentally” had an H-L back transition, allowing direct comparison of turbulence characteristics at mid-radius.

Indicates that turbulence parameters change dramatically in core, in addition to edge region.

Poloidal Flow Shear in L-mode generally too small to incur tilt based on model shown previously.
PROFILES RELAX SIGNIFICANTLY AT H-L BACK-TRANSITION

• Both magnitude and gradients of density and electron temperature vary:
  - Higher gradients in L-mode phase
  - Higher magnitude in H-mode phase
• Can be expected to lead to large changes in turbulence

![Graphs showing density and electron temperature profiles in H-mode and L-mode phases.](image)
SUMMARY

- **ρ* Scaling of Turbulence Characteristics in H-mode:**
  1) *Radial Correlation Length Scales with local ion gyroradius*: $L_r \sim 5*\rho_I$
  2) *Amplitude does not exhibit gyro-Bohm scaling*: $\tilde{n}/n \sim \text{constant}$
  3) *Decorrelation time scales as* $\tau \sim a/c_s$ (gyro-Bohm like)
  4) *Poloidal turbulence velocity (BES) matches measured ExB (CER)*

- **Tilted Turbulent Eddy Structure in H-mode**
  - *Small amplitude fluctuations* ($n/n = 0.1-0.5\%$)
  - *Eddies sharply tilted in radial-poloidal plane in H-mode plasmas*
    - L-mode eddies are elliptical, do not exhibit tilt
    - Poloidal flow shear appears insufficient to explain tilt
  - *2D spatiotemporal cross-correlation suggests no radial propagation*
  - *Finite radial wavenumber observed from* $0.5 < r/a < 0.9$
    *contrasts with L-mode plasmas* ($k_r = 0$)