Turbulence Behavior and Transport Response
Approaching Burning Plasma Relevant Parameters

by
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with
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Burning plasma parameters strongly impact turbulence, resulting transport and the energy confinement time, $\tau_E$.

- Burning plasmas will be dominated by $\alpha$-driven electron heating and have low injected torque:
  1. Low average toroidal rotation and $\text{ExB}$ shear
  2. Equilibrated temperatures: $T_e \approx T_i$

- $\text{ExB}$ shear impacts low and high-$k$ turbulence
- Turbulence and transport increase as $T_e/T_i \rightarrow 1$
- Experimentally characterize turbulence; test & validate transport models in high performance burning-plasma regimes
  - How instabilities (ITG, TEM, ETG) affected
  - Impact on thermal, particle, momentum transport

Build Confidence in Predicting Confinement in ITER and future Burning Plasmas
1. Effects of Toroidal Rotation

2. Effects of Equilibrated Temperatures

3. Conclusions
1. Effects of Toroidal Rotation

2. Effects of Equilibrated Temperatures

3. Conclusions
Confinement Increases with Core Toroidal Rotation in High-$\beta_N$ Advanced-Inductive H-Mode Plasmas

- Long-pulse, high-pressure plasmas: $\beta_N \approx 2.7$, 2-3 sec steady phase
  - Density, temperature, rotation held constant via feedback control
- Highest $ExB$ shear difference near mid-radii ($0.5 < \rho < 0.7$)

**Toroidal Rotation (Mach #,$_{max} \approx 0.4$)**

**ExB Shearing Rate Profiles**

**Rotation** $\tau_E$(ms)

<table>
<thead>
<tr>
<th>Rotation</th>
<th>$\tau_E$(ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>105</td>
</tr>
<tr>
<td>High</td>
<td>148</td>
</tr>
</tbody>
</table>

**Fluctuation Diagnostics:**
- Beam Emission Spectroscopy: low-k (2D)
- Doppler Back-Scattering: intermediate-k
- Phase Contrast Imaging: low to high-k
Temperature and Density Profiles Well-Matched as Toroidal Rotation is Varied

- Feedback control utilized to obtain similar profiles
  - Core $T_i$ well-matched; modest reduction in mid-radii
  - Increased power required at low rotation
- $T_e$ profile exhibits effects of 3/2 mode
  - Sustains $q_{\text{min}}>1$, prevents sawteeth in Advanced-Inductive plasmas
- Density profiles well matched
  - Modest changes in particle transport
TGLF Profiles Compare Reasonably Well With Some Notable Deviations

- **TGLF calculates profiles:**
  - Heat and particle sources
  - Gradients drive experimentally measured fluxes
  - Boundary Conditions ($\rho=0.8$)

- **$T_i$ well-matched in core**
  - Underestimated at high rotation

- **$T_e$ overestimated**
  - Doesn’t include 3/2-mode

- **Density profile overestimated**
  - Coupling of temperature and density profiles
  - Large electron-ion thermal exchange at $T_i \gg T_e$
Low-k Turbulence Amplitude Reduced in Core at High Toroidal Rotation yet Remains Similar Radially Outwards

\[ \gamma_{\text{NET}} \approx \gamma_{\text{LIN}} - 0.3 \gamma_{\text{ExB}} \]

Density Spectra (\(d^2I/I^2/\text{kHz}\))

\(\rho = 0.5\)

\(\rho = 0.75\)

\(\gamma_{\text{lin}} (\text{kHz}) \rho_{\text{tor}} = 0.5\)

\(\gamma_{\text{lin}} (c_s/a) \rho_{\text{tor}} = 0.75\)
• Low-k turbulence amplitude similar outside $\rho=0.5$
  - $\text{ExB}$ shearing rates differ
• Turbulence amplitude similar despite difference in shearing rates in $0.55 < \rho < 0.75$
Turbulence Adjusts to Increasing ExB Shearing Rates by Faster Decorrelation and Reduced $k_{\theta}$

- Tilted eddy structure observed in both high and low rotation plasmas
  - $\text{ExB}$ shearing rates similar locally, though toroidal rotation differs
  - Finite $k_r$: contrasts with L-mode turbulence, which exhibits little/no tilting
Intermediate & Higher-Wavenumber Fluctuations Suppressed at Higher Toroidal Rotation: Challenges Expectations

- **DBS & PCI show significantly lower high-k turbulence with increasing toroidal rotation**
- **GYRO calculates higher linear growth rates**
- **Exceed ExB shear rates**

**GYRO $\gamma_{LIN} \text{ Calculations}**

\[ \gamma_{lin} \left( \frac{c_s}{a} \right) \rho_{tor} = 0.75 \]

**DBS Spectra**

- $k_{\perp} \rho_s = 2.5-3.5$, $\rho = 0.7$

**PCI Spectra, 4.0–4.5 s, ELMs discarded**

- $k_R = 2-15 \text{ cm}^{-1}$, $\rho > 0.4$

**GYRO Graph**

- High Rot.
- TEM/ETG
- ITG
- Low Rot.
- low rot. $\gamma_{ExB}$
- high rot. $\gamma_{ExB}$

**P(\bar{n})_{Low Rot} = 3*P(\bar{n})_{High Rot}**
• Consistent with turbulence changes at low rotation
  – Low-k turbulence increase near $\rho=0.5$
    – Low-k decorrelation changes at larger radii with little amplitude change
  – High-k turbulence increases
1. Effects of Toroidal Rotation

2. Effects as $T_e \rightarrow T_i$

3. Conclusions
Te Self-Similarly Increased with ECH + Fast Wave to Maintain Nearly Constant Gradient Scale Length

- Advanced Inductive Plasmas:
  - $\beta_N \approx 2.5$, ITER Shape, $q_{95} = 5.8$
- Core $T_i$ well matched
  - Mid-radii $T_i$ exhibits reduction at higher $T_e/T_i$
- $\sim 25\%$ increase in $T_e$
  - Fixed gradient scale lengths
- Density reduced with $T_e/T_i$
  - Density “pump-out”
  - Gas-puffing partially compensates
  - Reduced toroidal rotation with out compensation via NBI

<table>
<thead>
<tr>
<th>$T_e/T_i$</th>
<th>$\tau_E$ (ms)</th>
</tr>
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<tbody>
<tr>
<td>Low</td>
<td>115</td>
</tr>
<tr>
<td>High</td>
<td>75</td>
</tr>
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</table>

TGLF Calculated Profiles Reproduce Trends with Changing $T_e/T_i$

- $T_i$ well matched in core, slightly overestimates in mid-radii at higher $T_e/T_i$
- Accurately reproduces increased $T_e$ profile with core-localized ECH source
- Captures reduction in density at increased $T_e/T_i$
- All trends in same direction as experiment
Low-k Density Turbulence and Ion Thermal Diffusivity
Increase Across Profile as $T_e/T_i \Rightarrow 1$

- Spectrally uniform increase in fluctuation amplitude
  - Intermediate-k exhibits increase in amplitude with bursty features
- Ion, electron, momentum and particle diffusivity increase across profile
  - Explains 35% reduction in $\tau_E$
GYRO Indicates $T_e/T_i$ Increases Trapped Electron Mode Growth Rates More Than Ion Temperature Gradient Mode

• Can explain increased particle transport at higher $T_e/T_i$
  – Frequency changes to electron diamagnetic direction at higher $T_e/T_i$
  – Growth rates increase more strongly at intermediate $k_\theta \rho_s$

\[ \gamma_{\text{lin}} = 0.65 \]

\[ \omega_r = 0.65 \]

D. Ernst, this session
Low-k Electron Temperature Fluctuations Increase with $T_e/T_i$

- **CECE (Correlated Electron Cyclotron Emission)** measured localized $T_e$ fluctuations
  - Spatially localized, low-k
- **Consistent with increase in low-k density fluctuations**
  - GYRO: increased linear growth rates for low-k electron mode
  - May reflect increase in Trapped Electron Mode (TEM) turbulence
- **Consistent with increased electron thermal and particle transport with $T_e/T_i$**

![Electron temperature fluctuations at $\rho \sim 0.67$]

- $\bar{T}_e/T_e \sim 1.3 \pm 0.2\%$ (50-300 kHz)
- $\bar{T}_e/T_e \sim 1.1 \pm 0.2\%$ (50-300 kHz)

Noise level $\sim 0.7\%$

G. Wang, UCLA
Calculated Quasilinear Density Fluctuation Spectra Compare Well with Measured Turbulence Spectra

- TGLF spectra reflect turbulence that drives heat fluxes
  - Consistent with local density and temperature gradients and $\mathbf{E}\times\mathbf{B}$ shear
  - Peak of spectra very similar

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**BES Spectra**

<table>
<thead>
<tr>
<th>Density Spectra ($V^2/V_{DC}^2$kHz)</th>
<th>$k_\parallel\rho_s=0.13$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (kHz)</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td>0.0</td>
<td>1.0</td>
</tr>
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<tr>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>6.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

**TGLF Quasilinear Spectra**

| TGLF syn. BES $|\delta n/n|^2$ $\rho_{tor} = 0.65$ |
|---------------------------------------------|
| $142011$ $4500$ $ms$                        |
| $142019$ $4500$ $ms$                        |

- High $T_e/T_i$ $|\delta n/n|^2$
- Low $T_e/T_i$ $|\delta n/n|^2$
Turbulence and Transport are Altered in Fundamental Ways Approaching Burning Plasma Parameters

• Toroidal rotation and ExB shear alters high and low-k $\tilde{n}$:
  – Low-k turbulence: Decorrelation rates change to match $\text{ExB}$ shearing rates, eddy structure shifted, while amplitude is not significantly affected over outer-core ($\rho=0.6-0.8$); large suppression at $\rho=0.5$
  – High-k turbulence: decreases amplitude at higher rotation

• Increasing $T_e/T_i \Rightarrow 1$ increases low-k density and temperature fluctuations
  – Consistent with GYRO growth rates, TGLF quasilinear fluctuation spectra
  – Transport increases in channels

• TGLF and GYRO capture profile and turbulence trends

• Future nonlinear simulations will quantitatively compare with fluctuation spectra and seek to identify modest discrepancies
Confinement Increases with Core Toroidal Rotation in High-$\beta_N$ Advanced-Inductive H-Mode Plasmas

Beam Emission Spectroscopy: low-k (2D)
Doppler Back-Scattering: intermediate-k
Phase Contrast Imaging: low to high-k
Confinement Reduced with Increased $T_e/T_i$

- **ECH/RF increases $T_e/T_i$**
  - 3.3 MW ECH/0.8 MW RF
  - 25% increase in $T_e$

- **Advanced-Ind. Plasmas**
  - $I_p = 1.06$ MA
  - $B_T = 1.9$ T
  - $q_{95}=5.9$
  - ITER Shape (ISS)
  - Steady for 2.5 s

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Higher $T_e/T_i$ (ECH)

Lower $T_e/T_i$ (No ECH)

Time-Window of Interest
Spatial Correlation Structure Demonstrates Velocity Shear Effects on Turbulent Eddy Structure

- Poloidal correlation function in low rotation plasma exhibits shorter wavelength
  - Consistent with frequency/wavenumber spectra
  - Amplitude is similar: structure varies with rotation

![Diagram showing correlation functions and spectral analysis](image-url)
Low-k Turbulence Suppression Localized to Mid-Core Zone

- Low-k turbulence amplitude similar outside $\rho=0.5$
  - $\text{ExB}$ shearing rates differ
- $\text{ExB}$ and turbulence velocities agree very well
  - BES: Time-lag cross-correlation
  - CER: $E_r$ via Force Balance
  - Deviation at outer radii may reflect strong diamagnetic flows

![Graph of Low-k Fluctuation Amplitude (BES)]

#### Density Fluctuation Profile ($n/n$, %)

<table>
<thead>
<tr>
<th>Minor Radius ($\rho$)</th>
<th>Poloidal Velocity (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
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</table>

#### Minor Radius ($\rho$)

- BES - High Rotation
- CER - High Rotation
- BES - Low Rotation
- CER - Low Rotation

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Establishing the Connection between Local Turbulence Behavior, Transport and $\tau_E$ in Burning Plasma Conditions

• Systematically evaluated dependence of turbulence, transport, growth rates, profiles, $\tau_E$ approaching burning plasma parameters:
  – Lower injected torque: lower toroidal rotation, averaged ExB shear
  – Increasing $T_e/T_i$ towards unity

• Fluctuations consistent with and explain transport modification:
  – Increased ExB shearing at higher toroidal rotation $\Rightarrow$ reduced turbulence, transport, higher $\tau_E$
    • Consistent with low-k linear growth rates
    • Reduced high-k fluctuations, yet higher calculated growth rates
  – Increase fluctuation amplitude as $T_e \Rightarrow T_i$
    • Particle, momentum and thermal transport increased

• Testing TGLF and GYRO in BP-relevant high-performance scenarios
  – TGLF modeling reasonably reproduces observed profiles
    • Identified notable discrepancies (density profiles, mid-radii temperatures)
  – Developing the scientific basis for predicting transport in burning plasma conditions
Turbulent Eddy Structure Tilted by Velocity Shear

- Tilted eddy structure observed in both high and low rotation plasmas
  - $\textbf{ExB}$ shearing rates similar locally, though toroidal rotation differs
- Contrasts with L-mode turbulence, which exhibits little tilting

**Correlation Functions**

<table>
<thead>
<tr>
<th>Radial (cm)</th>
<th>Poloidal (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>-2</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

**Low Rotation**

Low Rot (155584), $\rho=0.8$, $\tau=0.0$ \(\mu\text{sec}\)

**High Rotation**

High Rot (155576), $\rho=0.8$, $\tau=0.0$ \(\mu\text{sec}\)

2D BES Array Measures Spatiotemporal Correlation Function
Turbulence Adjusts to Increasing ExB Shearing Rates by Faster Decorrelation and Reduced $k_\theta$

- Turbulence reorganizes to new shearing rates, but *isn’t suppressed*
  - Consistent with frequency/wavenumber spectra changes
  - Similar $\tilde{n}/n$ amplitude with rotation over $0.6<\rho<0.8$ region
  - Little change in radial correlation length

### Comparison of Turbulence Decorrelation time, ExB time poloidal wavenumber ($\rho=0.6$)

<table>
<thead>
<tr>
<th>$\Omega$</th>
<th>$\tau_C$ ($\mu$s)</th>
<th>$\tau_{ExB}$ ($\mu$s)</th>
<th>$k_{\theta,pk}$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>2.5</td>
<td>3.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Low</td>
<td>5</td>
<td>7</td>
<td>0.5</td>
</tr>
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