ETG Scale Turbulence and Transport in the DIII–D Tokamak

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New results since FEC 2004

- Observed correlation of increased high $k$ ($\sim 35 \text{ cm}^{-1}$, $k_{\perp} \rho_i = 4-10$) turbulence with increased electron heat transport.
  - Consistent with high $k$ turbulence driving at least part of electron heat transport.
- Determined that high $k$ ($\sim 35 \text{ cm}^{-1}$) is not a short $\lambda$, remnant or tail of low $k$ ($\sim 1 \text{ cm}^{-1}$) ITG/TEM type modes
- Differing effect of electric field shear on low and high $k$ observed:
  - Low $k$ fluctuation behavior consistent with reduction due to $E_r$ shear
  - High $k$ apparently not affected by $E_r$ shear
- Relative levels of high and low $k$ fluctuation levels comparable to non-linear turbulence simulation (GYRO) results
Recent theoretical work indicates high $k$ turbulence may contribute to anomalous electron heat transport

- Source of electron thermal transport often not well understood.
  - Ion temperature gradient (ITG) ($k_{\perp} \rho_i \sim 0-1$),
  - Trapped electron drive (TEM) ($k_{\perp} \rho_i \sim 0-2$)
  - Electron temperature gradient (ETG) ($k_{\perp} \rho_i > 2$)
- High frequency, high $k$ modes predicted to drive varying levels of electron heat transport.
  - Predictions range from small to significant depending upon model and plasma.
  - Motivates experimental measurements
    - DIII-D, NSTX, FT-2, Tore-Supra
Ultimate goal: test and validate turbulence simulations via experimental comparison.

- Compare turbulence behavior over large k range.

BES, FIR, PCI, reflectometry, magnetics, high k backscatter.

- Broad k range:
  - \( \sim 0-40 \ \text{cm}^{-1}, k_{\perp} \rho_i \sim 0-10 \)

Important to measure broad k range due to potential interaction of various k ranges + allows closer comparison to theory.
Can cover large range of k's depending upon geometry and probe frequency used.

Approach: Collective Thomson scattering is well-suited to study long-to-short wavelength turbulence.

Momentum matching gives
\[ k_i + k_w = k_s \]

Energy conservation gives
\[ \omega_i + \omega_w = \omega_s \] i.e scattered radiation Doppler shifted.

Bragg Law:
For \(k_i \sim k_s\), can show that
\[ k_w = 2k_i \sin(\theta/2) \]
Where \(\theta\) is scattering angle

FIR scattering is dominantly \(k_\theta\)
High k backscattering is dominantly \(k_r\)
Simultaneous data from low to high k using FIR and mm-wave scattering diagnostics

- **Low-k FIR**
  - Poloidal k: $k_\theta = 0-2$ cm$^{-1}$, $k_{\rho_s} = 0-0.3$
  - Chord average
- **Intermediate-k FIR**
  - Poloidal k: $k_\theta = 8-15$ cm$^{-1}$, $k_{\rho_s} = 2-5$
  - Spatial localization, ±15 cm at 15 cm$^{-1}$
- **High-k mm-wave backscatter**
  - Radial k: $k_\theta = 35-40$ cm$^{-1}$, $k_{\rho_s} = 4-10$
  - Chord from r/a=1 to r/a=0.4
High k system measures $k_r$ along a chord

- $k$ is dominated by radial $k_r$ with small poloidal $k_\theta$ component
  - e.g., $k_r \approx 34.95 \text{ cm}^{-1}$ and $k_\theta \approx 1.2 \text{ cm}^{-1}$ for $k=35 \text{ cm}^{-1}$.
- Wavenumber resolution $\Delta k \approx \pm 0.2 \text{ cm}^{-1}$.
- Frequency is well above cutoff
  - Refraction small, $<1^\circ$
- Refractive index reduces probed $k$ 35-40 cm$^{-1}$ for plasmas discussed here.
Electron Cyclotron Heating (ECH) of plasma primarily modified Te and turbulence behavior

- Used ECH (~2.5 MW) to locally heat plasma
  - \( I_p = 800 \text{kA}, B_T = 2 \text{T}, n_e = 1.7 \times 10^{13} \text{ cm}^{-3} \)
- \( T_e \) increased, small decrease in \( n_e \), no effect on \( T_i \)
- Monitor fluctuation levels, gradients, etc. and compare to theory.

Times used in analysis:
- ECH, 3100 ms
- Ohmic, 1975 ms
$T_e$ increased with ECH, $n_e$ decreased, modifying potential instability drives

- Effect of ECH is observed most strongly on $T_e$. 

ECH heating at $r/a \sim 0.6$
Electron heat flux increased substantially with ECH

- Fluxes determined using power balance and ONETWO transport code.
- Ion heat flux not strongly modified.

ECH heating at r/a~0.6
Differing response to ECH indicates that high $k$ (35 cm$^{-1}$, $k_{\perp} \rho_i = 4-10$) is not a remnant or tail of low $k$ ($\sim$1 cm$^{-1}$)

- **High $k$ fluctuation level increases while low $k$ $\sim$constant.**
  - Low $k$ reflectometry also shows no increase with ECH
  - Important as this relates to origin of high $k$
- **Note narrowing of low $k$ frequency spectrum**
  - Consistent with a change in the Doppler shift.
Increase in high k turbulence correlates with increased electron heat flux

- Lack of change in ion heat flux consistent with lack of change in low k turbulence
- Increased electron heat flux due solely to increased high k fluctuations not measured, can be estimated to be as much as 30% over base flux using \[ \tilde{q}_e = n\langle \tilde{T}_e \tilde{E}_\theta \rangle/B \propto nk_\theta T_e^2 (\tilde{n}/n)^2 / B \]
  - Flux due to high k higher if include measured increase in \( T_e \)
  - Need more direct experimental tests plus non-linear simulations.
Critical gradient analysis indicates plasma is unstable to electron temperature gradient driven modes (ETG)

- Experimental $T_e$ scale length exceeds predicted critical scale length for electron temperature gradient driven modes (ETG) over large region
- Critical scale length from Jenko, et al. PoP2001

ECH heating at $r/a \sim 0.6$
Linear gyrokinetic calculations (GKS code) show increases in both low and high k growth rates with ECH.

- Expect increases in both low and high k in outer plasma regions - however, experimentally low k \( k \) is constant.

- **GKS**: linear gyrokinetic code calculates growth rates and frequencies for toroidal drift waves.

  - Calculations are for \( k_\theta \), high k is principally \( k_r \).

  \[
  k = 1 \text{ cm}^{-1}
  \]

  \[
  k = 35 \text{ cm}^{-1}
  \]
Radial $E_r$ decreases with ECH however resulting $E_r$ shear is increased.

- Resulting decrease in $V_{ExB}$ is consistent with observed decrease in frequency width of low $k$ fluctuations.
- $ExB$ shearing rate is found to be a significant fraction of calculated low $k$ growth rates.
  - Potential explanation for GKS prediction of increased low $k$ during ECH while experiment shows constant level
  - Note that high $k$ apparently unaffected by shear.

ECH heating at $r/a\sim0.6$
Recent GYRO simulations find ETG scale turbulence isotropic in $k_r$-$k_\theta$

- Non-linear turbulence GYRO simulations addressing realistic coupling ITG/TEM/ETG simulations (From R. Waltz, et al., General Atomics)
- GYRO simulation conditions are close to but not same as experimental plasma studied here and only one radial position.
  - Experiment covers range in both $r/a$ and in plasma parameters
  - Need more simulation results to compare with!
GYRO simulation parameters are close to experiment

- **GYRO simulation parameters (so-called “GA standard conditions”)**
  - \( \hat{s} = 1, q = 2, r/a = 0.5, R/a = 3, a/L_T = 3, a/L_n = 1, T_e/T_i = 1 \)
- **“Cyclone conditions” are similar:**
  - \( \hat{s} = 0.8, q = 1.4, r/a = 0.54, R/a = 3, a/L_T = 2.3, a/L_n = 0.73, T_e/T_i = 1 \)
- **In simulation only one radial position documented, r/a~0.5**
Broadband turbulence response to short NBI blips somewhat different from ECH response

- Perturbed Ohmic plasma with short NBI blips ($P_{inj} \approx 2.5 \text{ MW}$)
  - $I_p = 800 \text{kA}$, $B_t = 2 \text{T}$, $n_e = 1.7 \times 10^{13} \text{ cm}^{-3}$
- $T_e$, $T_i$ increased but no significant change in $n_e$
- Fluctuation levels increase with NBI over broad range in $k$
  - As opposed to only the high $k$ increasing with ECH
  - Example shown is high $k$, $35 \text{ cm}^{-1}$.
  - Next compare theoretical and experimental response of different wavenumbers
GKS predicts plasma unstable over broad range in k: 1-35 cm\(^{-1}\), \(k_\perp \rho_i \approx 0-10\)

- Good counterpoint to ECH data.
- Range of instabilities corresponds to ITG, TEM, ETG type instabilities.
- Note that with exception of high \(k\) the growth rates do not change strongly with the NBI
Quantitative comparison of high k and low k fluctuation levels reveals large difference in magnitude

- Fluctuation magnitude increases and broadens with NBI
- Ohmic fluctuation levels $\tilde{n}/n$:
  - Low k: $\tilde{n}/n \sim 8 \times 10^{-3}$
    - $\rho=0.7$, $k_\perp \rho_i \sim 0.2-0.4$, BES
  - High k: $\tilde{n}/n \sim 3 \times 10^{-6}$
    - $\rho=0.4-1.0$, $k_\perp \rho_i=4-10$ high k
  - $\tilde{n}/n$ increases $\sim 25\%$ with NBI
Ratio of high to low k fluctuation levels compare reasonably well with non-linear GYRO simulation

- Simulation:
  - \((\bar{n}/n)_{\text{high k}}/(\bar{n}/n)_{\text{low k}} \approx 10^{-3}\)

- Ratio compares reasonably well with experimental ratio
  - \((\bar{n}/n)_{\text{high k}}/(\bar{n}/n)_{\text{low k}} \approx 0.4 \times 10^{-3}\)

- Simulation shown is at \(r/a=0.5\) and for conditions which are close to but not same as experimental plasma.
Summary

- DIII-D has a comprehensive set of turbulence diagnostics spanning a wide range in k: ITG, TEM, ETG relevant
- Observed correlation of increased high k (~35 cm\(^{-1}\), \(k_{\parallel\rho_i}=4-10\)) turbulence with increased electron heat transport.
  - Consistent with high k turbulence driving at least part of electron heat transport.
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