Scaling of edge turbulence properties and implications for the SOL width

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LODESTAR NSTX-U

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Background – theory

- Theory-based scaling of the SOL heat flux width by turbulence
  - J. W. Connor, et al., Nucl. Fusion **39**, 169 (1999)
  - F. D. Halpern, et al., Nucl. Fusion **53**, 122001 (2013)
  - J. R. Myra et al., Phys. Plasmas **22**, 042516 (2015)

$$\frac{q_\perp}{\lambda_q} = \frac{q_\parallel}{L_\parallel} \sim \frac{g\, p c_s}{qR}$$

$q_\parallel \equiv g\, p c_s$
g = parallel energy transmission factor

$$\lambda_q \approx \frac{qR}{g}\frac{q_\perp}{p c_s} = \frac{qR}{g}\frac{\langle \delta v_x\, \delta p \rangle}{c_s\, p}$$

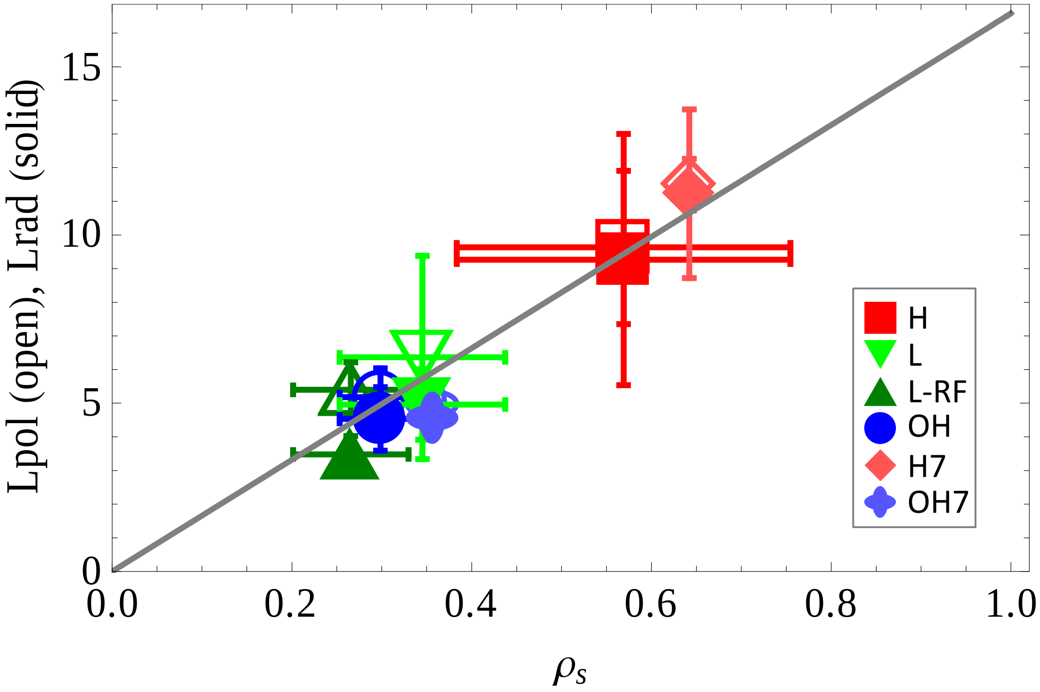
- Obtain scalings for $\lambda_q(R, \rho_s, q, \ldots)$ once we know turbulence properties
  - $\delta v_x / c_s$, $\delta p/p$ which depend on:
    - type of instability ← drift-resistive? curvature? flow? quasi-local? nonlocal?
    - wavenumber or scale size $k\rho_s$, $k\lambda_p$
    - saturation mechanism ← wave-breaking? profile modification? sheared flows?
    - type of transport
- PoP 2015 analysis ⇒ $\lambda_q \propto R^\mu$ with $1/3 < \mu < 1$
- Challenge and expand this approach with experimental data & computation

Background – NSTX edge turbulence database

- Comprehensive edge database for NSTX using gas puff imaging (GPI)
  - S. J. Zweben, et al., Nucl Fusion **55**, 093035 (2015)
  - 140 NSTX discharges,
    - 93 H mode
    - 9 (neutral beam heated) L mode
    - 5 (high harmonic fast wave heated) L-RF mode
    - 33 OH mode
- High quality subset "blob" database
  - S. J. Zweben, Plasma Phys. Control. Fusion **58**, 044007 (2016)
  - 7 similar H modes and 7 similar OH modes
- This talk: databases examined and interpreted based on theoretical estimates relevant to SOL width scaling
  - complementary to pure theory-based work
  - obtain information on near-separatrix turbulence:
    - time and spatial scales; saturation levels, type of instability
  - inferences for scaling

Length scale of edge turbulence consistent with drift waves

- Turbulence scale lengths from GPI correlation analysis in the edge (Zweben 2015)
- $L_{pol} \sim L_{rad} \sim 17\ \rho_s \Rightarrow\ k_\perp \rho_s \sim 0.13$
- Consistent with drift waves or drift-resistive modes
- Note scaling between different operational modes
- Data at –2 cm (just inside separatrix) here and in following
- Error bars ⇒ std. dev. (not uncertainty of the means)

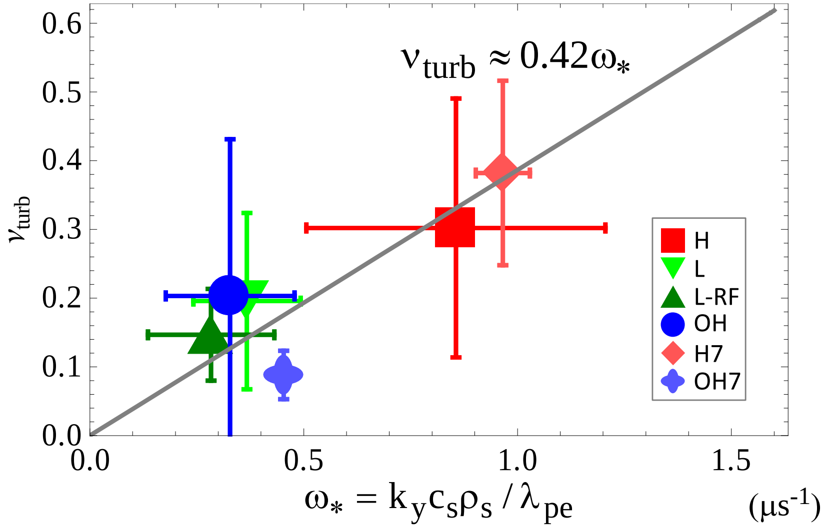


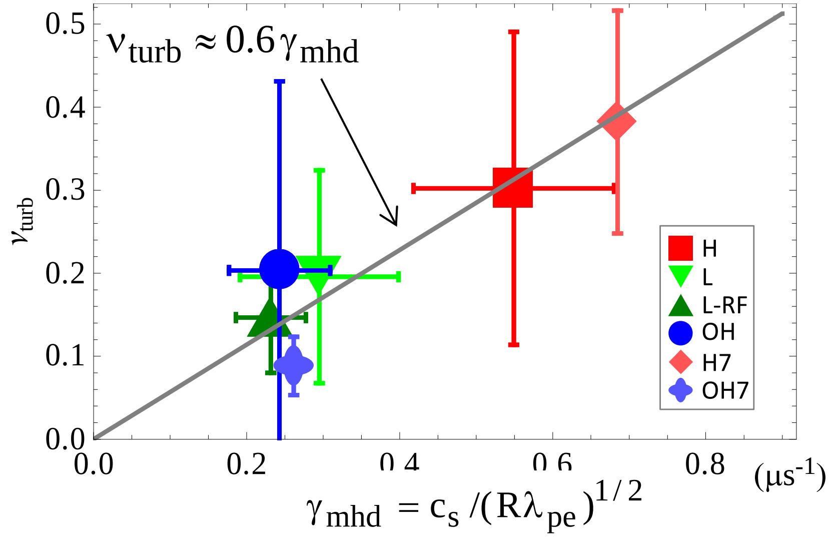
Time scale of turbulence consistent with drift-interchange

- Auto-correlation time dominated by convection (of moving structures and spatial size). Need a measure of time scale in the local plasma frame.
- Define ν_{turb} from continuity equation assuming E×B convection

$$\nu_{turb}\delta p = \delta v_x p / \lambda_p$$

- Use ν_{turb} as a proxy for ω in the plasma frame
- Estimate δp/p ~ δI/I (GPI intensity)
- Scaling is consistent with both drift waves and curvature-driven interchange

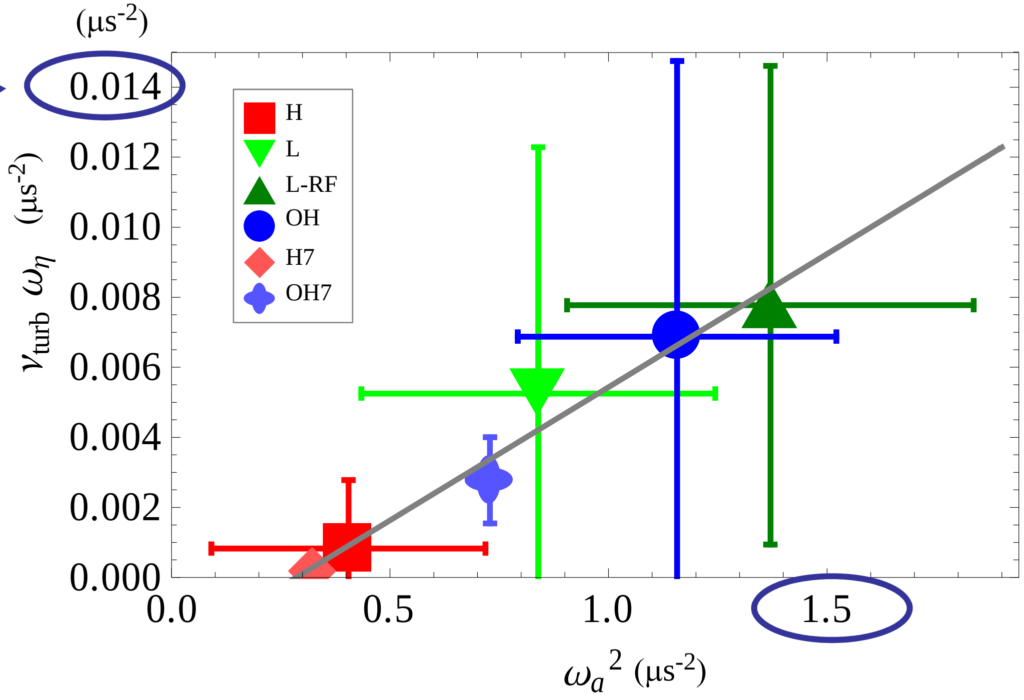




X-pt enhanced resistive ballooning is likely in OH & L modes

- In the resistive ballooning equation, resistivity overcomes EM line bending when $\omega\omega_\eta > \omega_a^2$
  - where the magnetic diffusion rate is given by $\omega_\eta = k_\perp^2 \delta_e^2 \nu_{ei}, \quad \delta_e = c / \omega_{pe}$
  - the Alfven frequency is $\omega_a = v_a / R$

- Resistivity is weak at the outer midplane
- Linear correlation consistent with significant enhancement of ω_η, in X-pt region by magnetic shear
  - need $k_\perp$ enhanced by ~ 14 ✓
  - resistive X-point physics likely in OH and L modes:
    - Xu PoP 2000
    - Myra PoP 2000

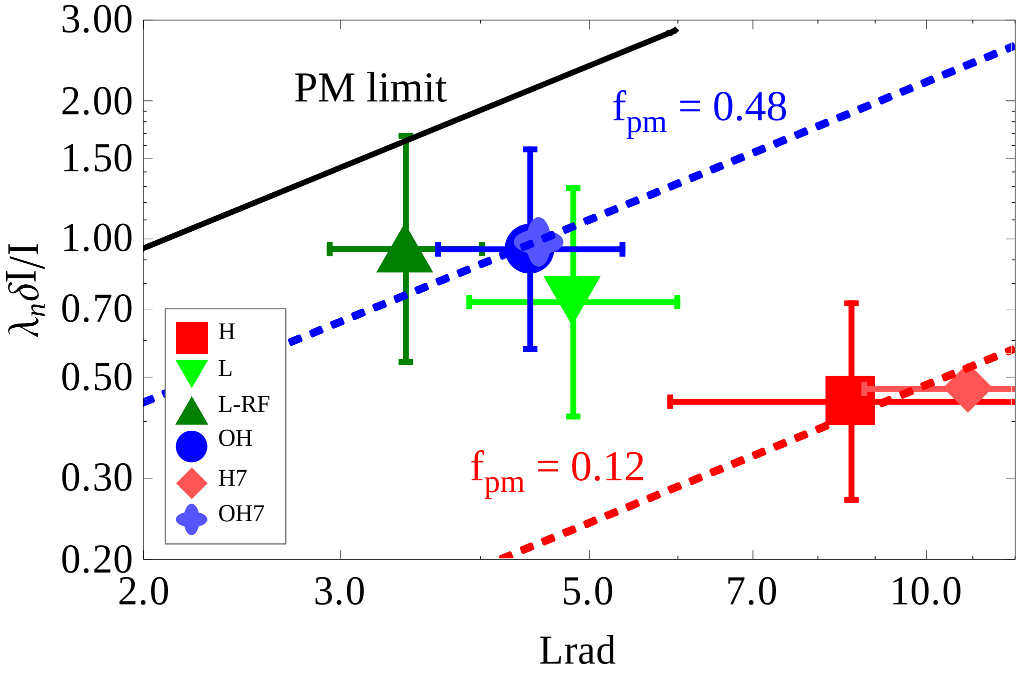


Saturation level is near (OH, L) or well below (H) PM limit

- Profile modification (PM) limit: $\frac{\delta n}{n} = \frac{f_{pm}}{k_x \lambda_n}$
  - compares fluctuation and equilibrium gradients

f_{pm} = scaling factor

- Estimate $k_x \sim 2.1/L_{rad}$
- OH and L modes near PM limit (less so if $\lambda_n \rightarrow \lambda_p$)
- H mode far below
  - sheared flow turbulence suppression?



See also (Zweben NF 2015)

Scaling implications for the SOL width

- Eliminating δv_x using ν_{turb} and expressing in terms of f_{pm}

$$\lambda_q = \frac{qR}{g}\frac{\langle \delta v_x \, \delta p \rangle}{c_s \, p} \qquad \rightarrow \qquad \lambda_q \approx \frac{qR}{g}\frac{f_{pm}^2 \nu_{turb}}{k_x^2 \lambda_p c_s}$$

- Invoking the drift-interchange character

$$\boxed{\nu_{turb} = C_{dw}\omega_*} = \frac{C_{dw} k_y c_s \rho_s}{\lambda_p} \qquad \text{and} \qquad \boxed{\nu_{turb} = C_{mhd}\gamma_{mhd}} = \frac{C_{mhd} c_s}{(R\lambda_p)^{1/2}}$$

- Equating the two expressions $\dfrac{\lambda_p}{R} = \dfrac{C_{dw}^2 C_{k\rho}^2}{C_{mhd}^2}$ where $C_{k\rho} \equiv k_y \rho_s$

- For H-modes there is another plausible constraint:
  - expect the E×B shearing rate induced by ion diamagnetic drifts to compete with the interchange drive

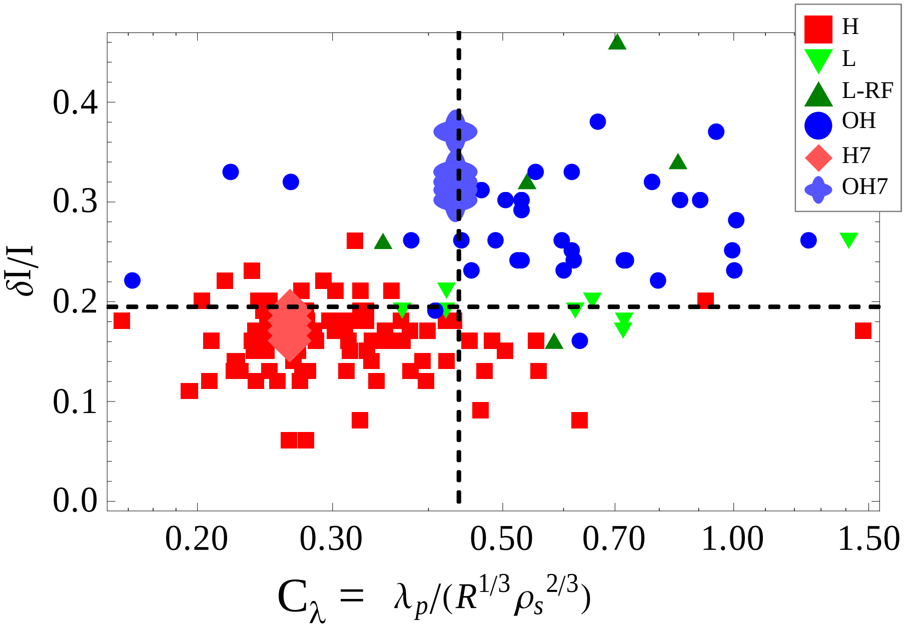
$$\gamma_{mhd} \le V'_{di} \qquad \Rightarrow \qquad \frac{c_s}{(R\lambda_p)^{1/2}} \le \frac{c_s \rho_s}{\lambda_p^2} \qquad \Rightarrow \qquad \boxed{\lambda_p \le R^{1/3}\rho_s^{2/3}}$$

Scaling implications for H-modes

- Define C_λ by $\boxed{\lambda_p = C_\lambda R^{1/3} \rho_s^{2/3}}$
  - for NSTX H-modes $C_\lambda \sim 0.3$
- Combining with previous results

$$\frac{\lambda_p}{R} = \frac{C_{dw}^2 C_{k\rho}^2}{C_{mhd}^2}, \qquad \frac{\rho_s}{R} = \frac{C_{dw}^3 C_{k\rho}^3}{C_{mhd}^3 C_\lambda^{3/2}}$$

drift-interchange   sheared flow



- and finally

$$\lambda_q = \frac{qR}{g}\left(\frac{f_{pm}^2 C_{dw}^3 C_{k\rho}}{C_{mhd}^2 C_\lambda^3}\right) \approx \frac{qR}{g}\left(\frac{f_{pm}^2}{51\, C_\lambda^3}\right) \Rightarrow$$

normalized perp heat flux: expressed entirely in terms of 5 measured dimensionless quantities

- 0.2 to 0.8 cm using previous C_{mhd}, C_{dw} …
- comparable to IR measurements
- explicit $\lambda_q \propto qR \propto \varepsilon^2 RB/I_p$
  - difficult to separate out mechanisms

Numerical simulation

- The five dimensionless ratios that determine the turbulent perpendicular heat flux in the preceding analysis are:

$$\left.\begin{aligned} C_{dw} &= \nu_{turb} / \omega_* \\ C_{mhd} &= \nu_{turb} / \gamma_{mhd} \\ C_{k\rho} &= k_y \rho_s \end{aligned}\right\} \quad \text{drift interchange}$$

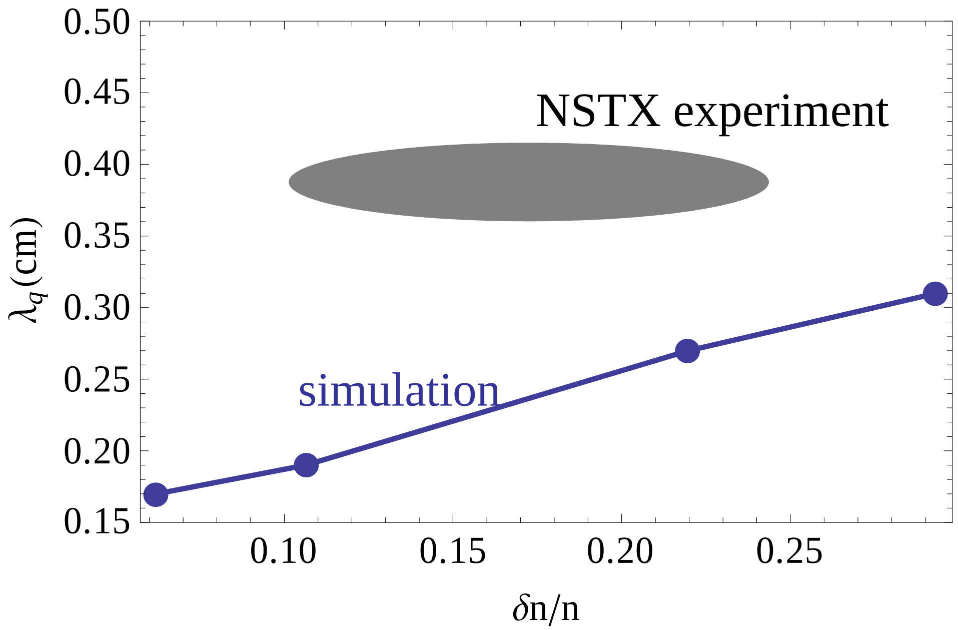
$$C_\lambda = \lambda_p R^{-1/3} \rho_s^{-2/3} \qquad \text{sheared flow H-mode}$$

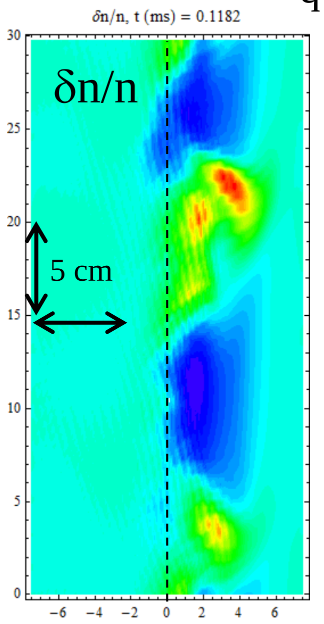
$$f_{pm} = (k_x \lambda_n)(\delta n / n) \qquad \text{saturation level}$$

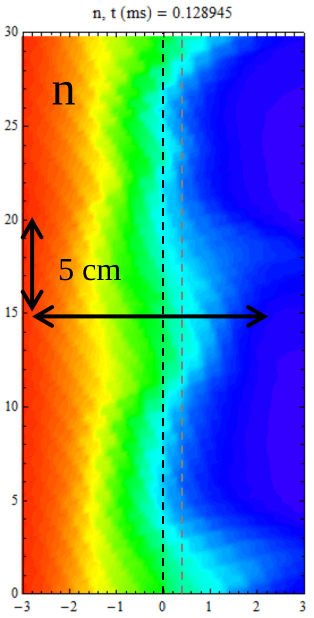
  - Measured inside the separatrix (turbulence generation) but drive transport into the SOL
- Assess role of drift-interchange physics, sheared flows and resulting saturation levels.
  - compare with experiment; test theoretical scalings
- SOLT code (reduced 2D fluid turbulence model for edge/SOL)
- XGC1 5D kinetic simulations [S. Ku, R.M. Churchill, C.S. Chang, J.R. Myra, S.E. Parker]

SOLT code simulation

- Simulate NSTX H-mode #127975 (I_p = 1MA, P_{NBI} = 6 MW, B_t = 0.4 T)
  - prepared for 2016 theory milestone: thanks to Maingi, Ahn, Gray, Canal
- Interpretive SOLT simulations: varied sources, R_{sep}, diffusion to match
  - measured n_e, T_e profiles, P_{sol} , $(\delta n/n)_{sep}$
- Vary turbulent dissipation ⇒ $(\delta n/n)_{sep}$ to test effect on λ_q







- Turbulence is neither dominant or negligible at I_p = 1 MA
  - leaves room for NC drift to explain dominant $1/I_p$ scaling
  - leaves room for turbulence at larger I_p or larger R

Conclusions

- Scalings of edge turbulence in NSTX emerge among operational modes
  - $k_y \rho_s \sim 0.13$; $\omega \sim 0.4\, \omega_* \sim 0.6\, \gamma_{mhd}$
  - consistent with drift-interchange modes
- 5 dimensionless numbers characterize the turbulent perpendicular heat flux for drift-interchange modes
  - evaluated from the NSTX database and theoretical considerations
- Quantitative estimates and simulations for the turbulent contribution to λ_q suggest that it is not negligible, at least for discharges with high plasma current.
  - λ_q based on this physics has an explicit positive scaling with R