Turbulence spreading dynamics approaching the density limit

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6th Asia-Pacific Conference on Plasma Physics, 9 - 14 Oct, 2022, Remote e-conference

Outline

1. Motivation: role of turbulence in density limit

2. Turbulence spreading dynamics $\rightarrow$ density limit

- Density fluctuation events
- Turbulence internal energy evolution
- Connection with $\boldsymbol{E} \times \boldsymbol{B}$ flow shear
- Beyond the diffusion process

3. Summary and future plan

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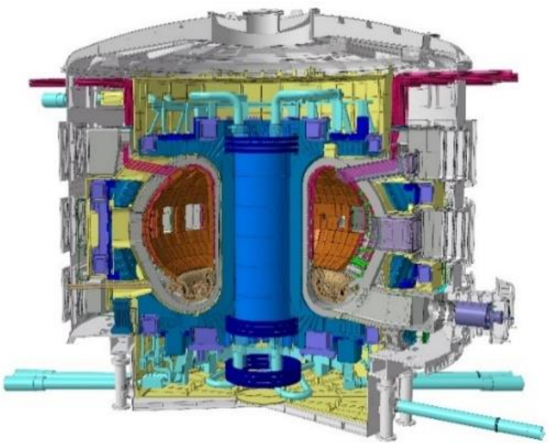
Motivation: role of turbulence in density limit

- **High plasma density: important for efficient and economic fusion power output**
- **High density operation: favorable for fusion reactors**
  (baseline scenario for ITER and DEMO)

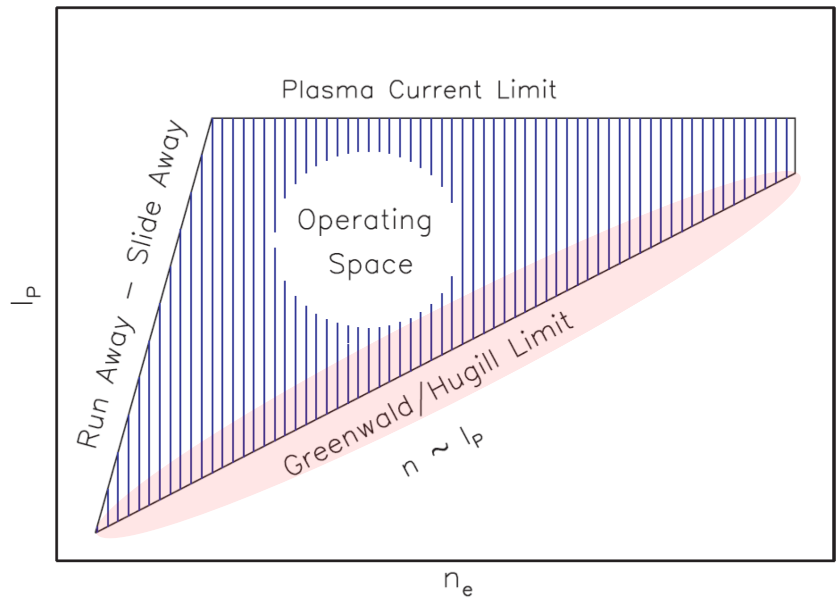
$$P_{fusion} \propto \langle \sigma v \rangle \, n^2$$

fusion power — **reaction coefficient** — **plasma density**



Motivation: role of turbulence in density limit

- **Density limit: constraints on the maximum attainable operational density for current-generation tokamaks**
- **Greenwald empirical scaling:** $\bar{n}_{max} \sim n_G[10^{20} m^{-3}] = I_p[MA]/\pi a^2[m^2]$

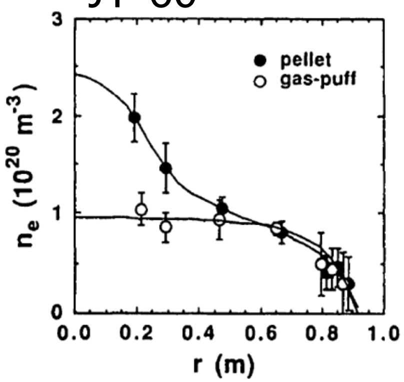


✓ *M. Greenwald et al 2002 Plasma Phys. Control. Fusion 44 R27*

Motivation: role of turbulence in density limit

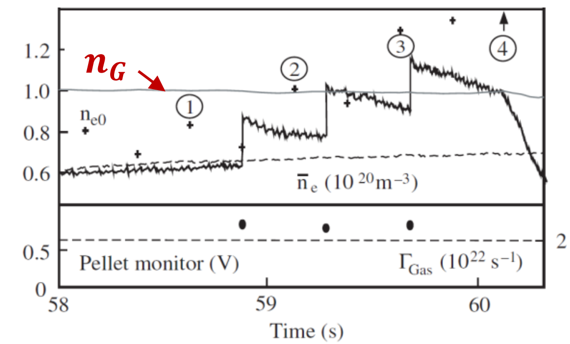
- **Discharges with pellet fueling: n_G is exceeded with peaked density**
- **What physical process underpin density limit?**

JT-60



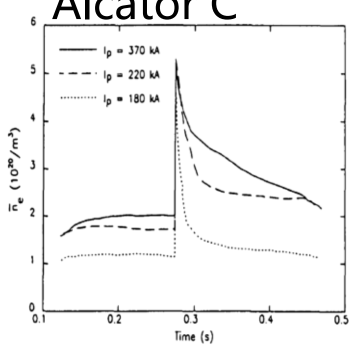
density limit with pellet exceeds that with gas-puff

JET



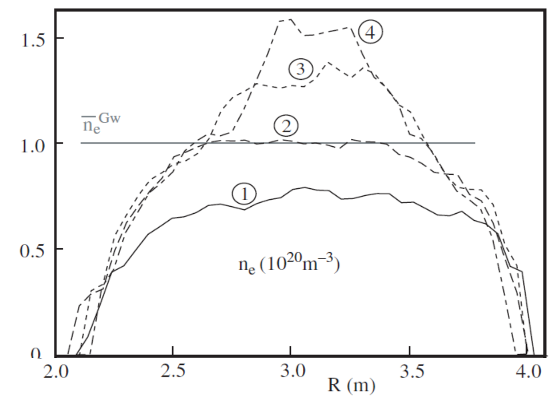
Alcator C

$\bar{n}_e$



time (s)

density relaxation after pellet, without density limit disruption



✓ *M. Greenwald et al 1988 Nucl. Fusion 28 2199*
✓ *Y. Kamada et al 1991 Nucl. Fusion 31 1827*
✓ *P .T. Lang et al 2002 Plasma Phys. Control. Fusion 44 1919–1928*

Motivation: role of turbulence in density limit

- **A widely quoted picture of high density disruption**

general agreement

High density

↓

Edge cooling

↓

Current shrinking

↓

MHD instability

↓

Disruption

secondary outcomes

→ **Mechanisms:**

particle transport,

impurity radiation,

ionization losses,

charge exchange,

…

✓ *K. Borrass et al 1991 Nucl. Fusion 31 1035-1051*

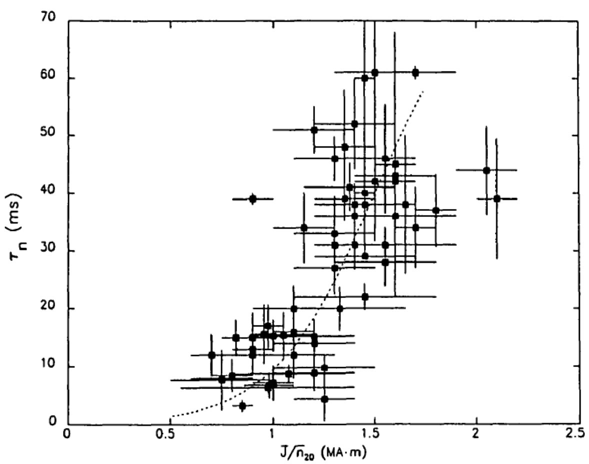
✓ *M. Greenwald et al 2014 Phys. Plasma 21 110501*

Motivation: role of turbulence in density limit

- **Density limit associated with increased particle transport and particle confinement degradation in discharges with low impurity content**

Alcator C

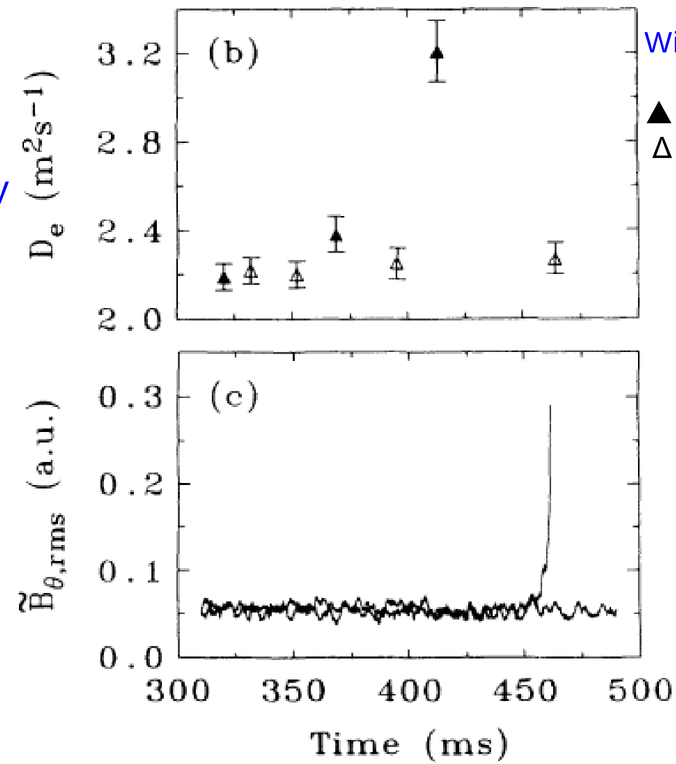
density relaxation time after pellet



$n_G/\bar{n}_e$

TEXT

particle diffusivity



With close $\bar{n}$

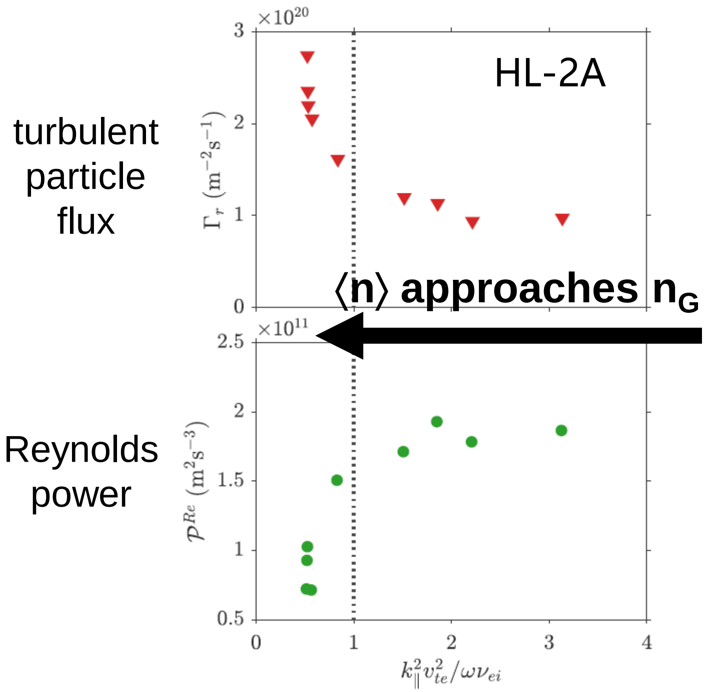
▲ disrupting

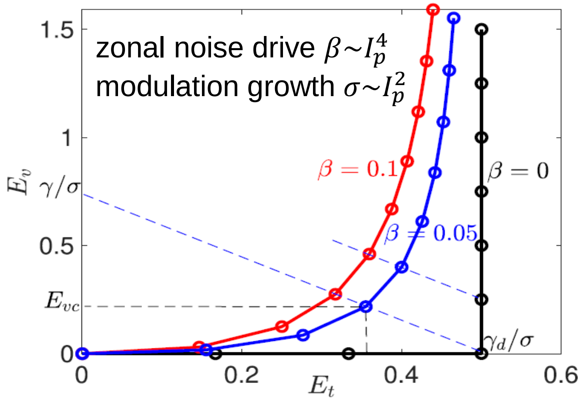
Δ non-disrupting

- ✓ *M. Greenwald et al 1988 Nucl. Fusion 28 2199*
- ✓ *D. L. Brower et al 1991 Phys. Rev. Lett 67 200*

Motivation: role of turbulence in density limit

- **Edge $E \times B$ flow shear layer collapse → enhanced turbulent particle flux near density limit**
- The limiting edge density for shear layer collapse: scales with I_p due to the neoclassical screening of zonal flow





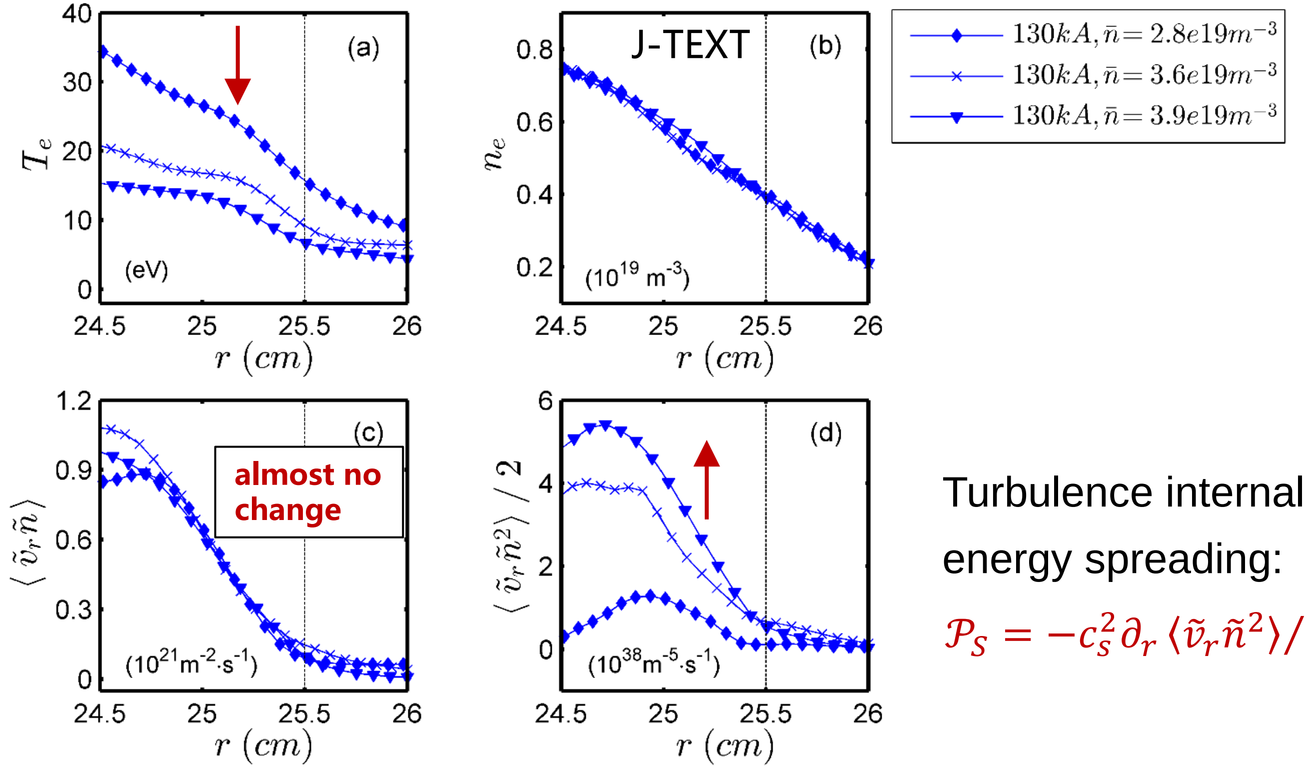
Zonal flow energy E_v vs turbulence energy E_t

$$n < \frac{\rho_s}{\rho_\theta}\left(\frac{S}{c_s}\right)^{\frac{1}{3}}(crit') \sim I_p$$

✓ R. Hong et al 2018 Nucl. Fusion 58 016041
✓ R. J. Hajjar et al 2018 Phys. Plasma 25 062306
✓ R. Singh and P.H. Diamond 2021 Nucl. Fusion 61 076009

Motivation: role of turbulence in density limit

- **Recent experiments: turbulence intensity flux $\langle\tilde{v}_r\tilde{n}^2\rangle/2$ shows different dynamics from particle flux $\langle\tilde{v}_r\tilde{n}\rangle$ as $\bar{n} \rightarrow n_G$**
- **Turbulence spreading: a better indicator associated with edge cooling**



Turbulence internal energy spreading:

$$\mathcal{P}_S = -c_s^2 \partial_r \langle\tilde{v}_r\tilde{n}^2\rangle/2\,\langle n\rangle^2$$

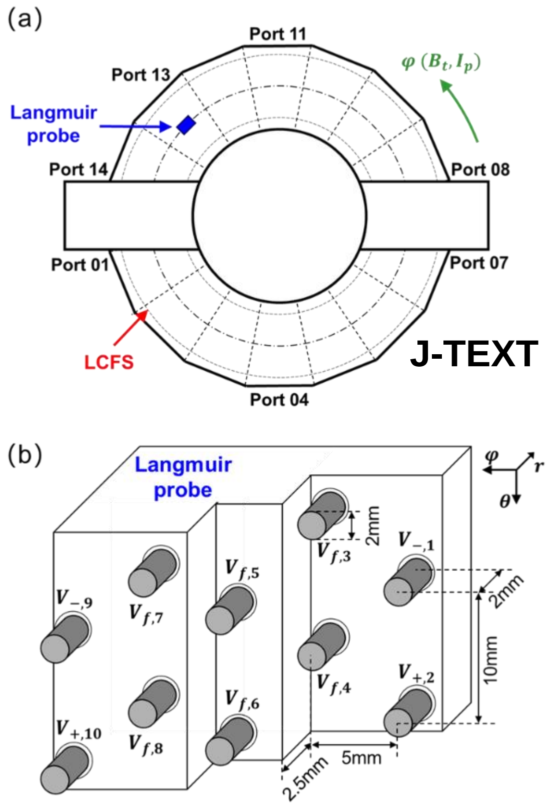
LCFS at $r = 25.5$ cm

✓ *T. Long et al 2021 Nucl. Fusion 61 126066*

Motivation: role of turbulence in density limit

- **In this talk: studies of turbulence spreading dynamics approaching the density limit**

- **Experimental set up**
  - Ohmic hydrogen discharges, limiter
  - $B_t \sim 1.6/1.9/2.2\text{T}$, $I_p \sim 130/150/185\text{kA}$, $q(a) \sim 3.8$
  - $\bar{n}_e = 2.8 - 4.9 \times 10^{19}\text{m}^{-3}$
  - $\bar{n}_{max}$ (before disruption) $\sim 0.7 n_G$
  - Langmuir probe: T_e, ϕ_p, n_e, $E \times B$ velocity, turbulent particle flux, turbulence spreading
  - Fluctuations $2 - 100$ kHz



✓ *T. Long et al 2022 (to be submitted)*

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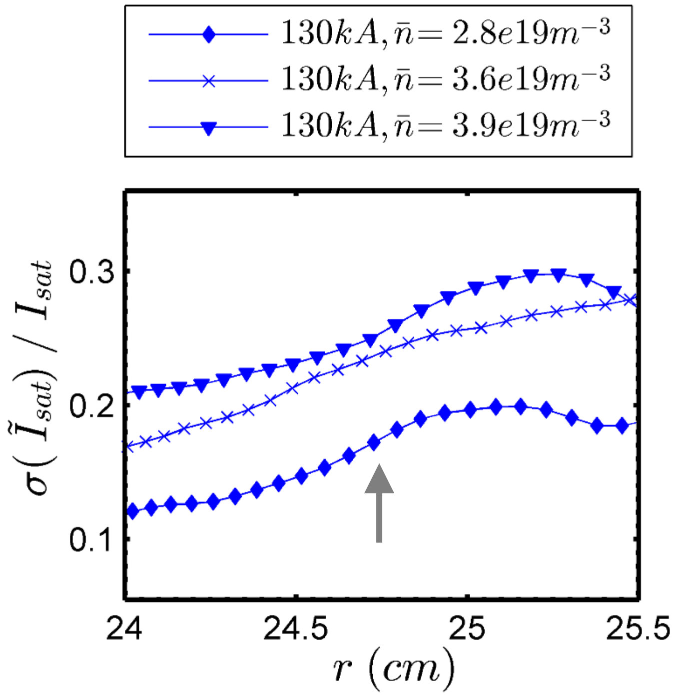
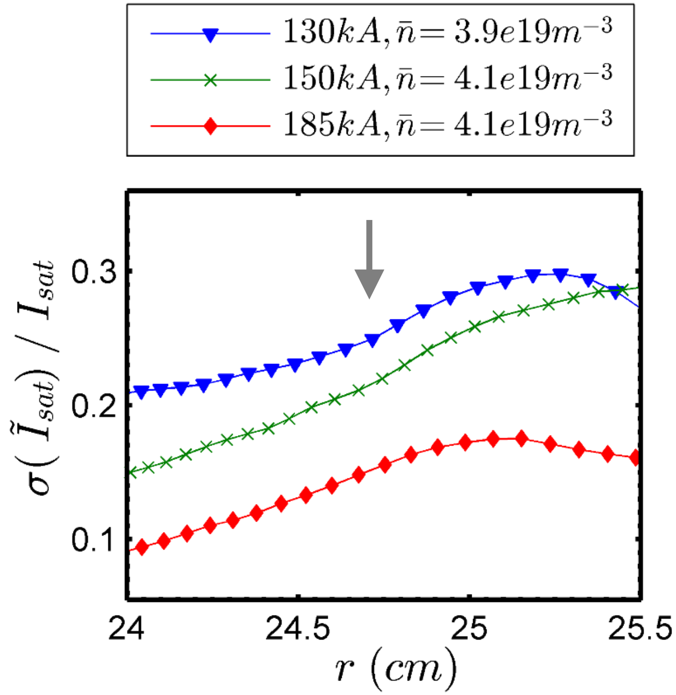
Density fluctuation events

- **Normalized fluctuation amplitude** $\frac{\sigma(\tilde{I}_{sat})}{I_{sat}} \sim \frac{\sigma(\tilde{n})}{n}$

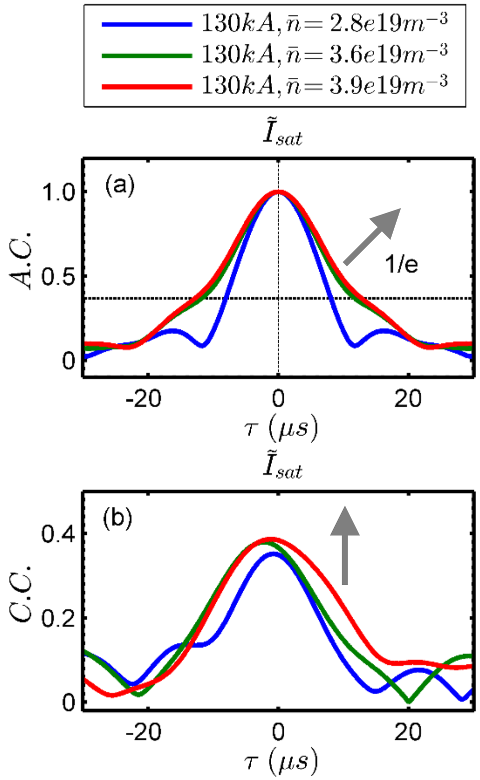


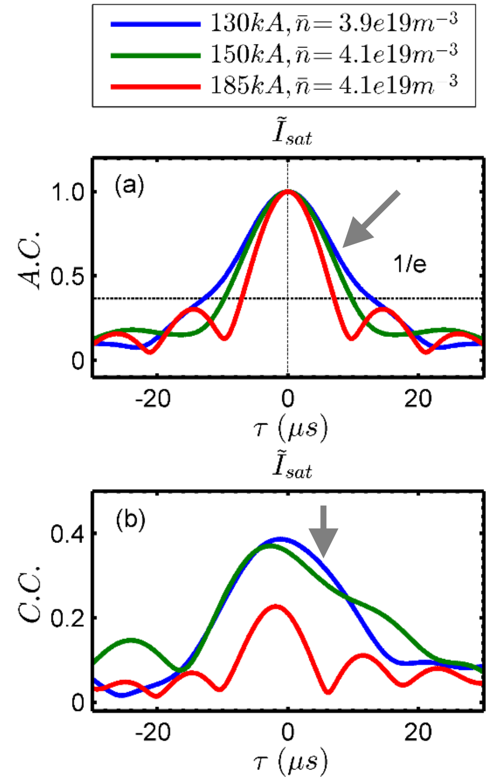


- **For the same I_p: fluctuation amplitude increases as $\bar{n}$ increases**
- **For the close $\bar{n}$: fluctuation amplitude decreases as I_p increases**

Density fluctuation events

- **Auto-correlation and cross-correlation**

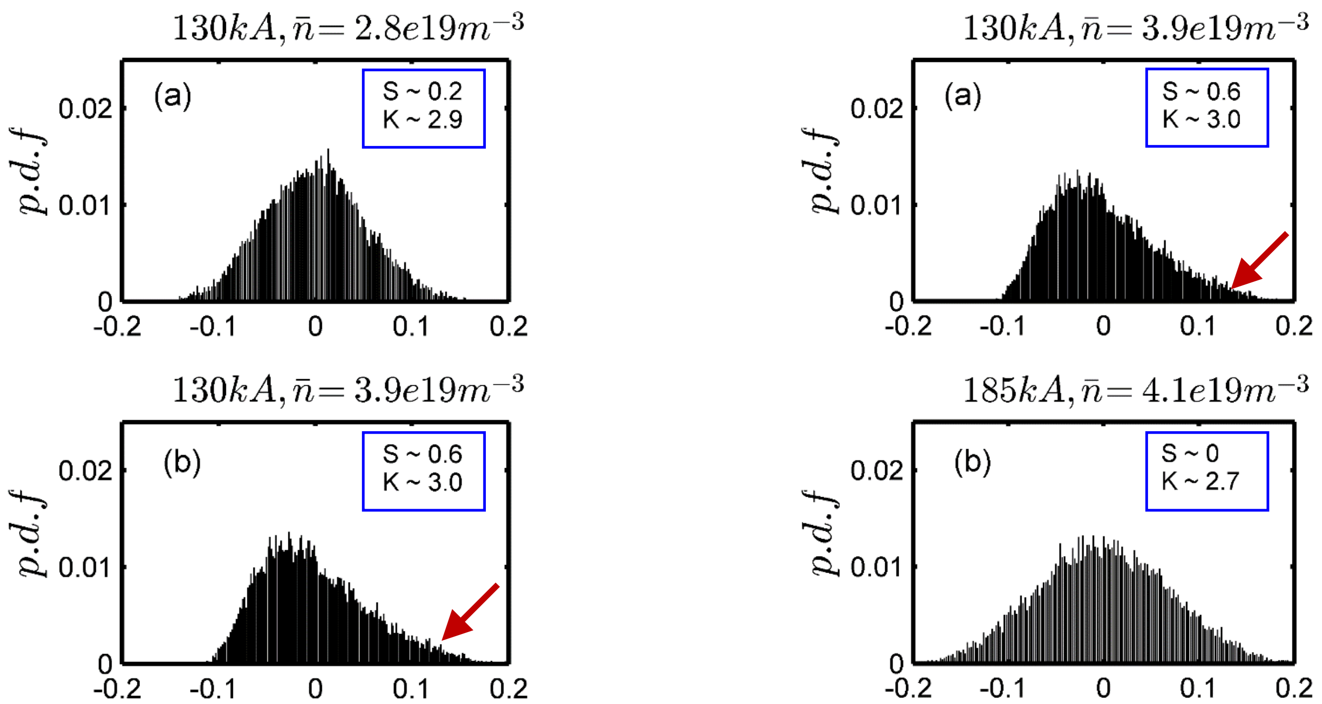




- **For the same I_p: correlation increases as $\bar{n}$ increases**
- **For the close $\bar{n}$: correlation decreases as I_p increases**

Density fluctuation events

- **PDF characteristics**



- **For the same I_p: skewness increases as $\bar{n}$ increases**
- **For the close $\bar{n}$: skewness decreases as I_p increases**

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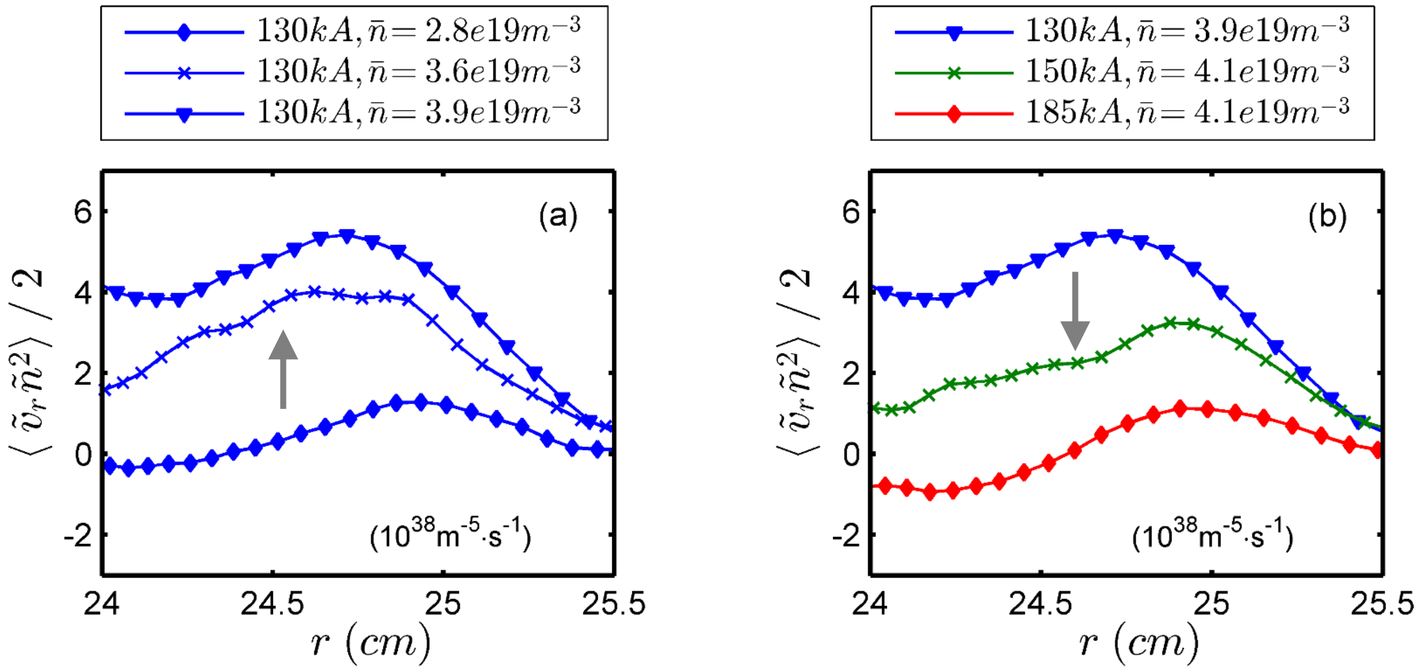
Turbulence internal energy evolution

- **Turbulence intensity flux $\langle\tilde{v}_r\tilde{n}^2\rangle/2$**



- **For the same I_p: intensity flux increases as $\bar{n}$ increases**
- **For the close $\bar{n}$: intensity flux decreases as I_p increases**

Turbulence internal energy evolution

$$\partial_t \frac{c_s^2 \langle \tilde{n}^2 \rangle}{2\langle n \rangle^2} = \mathcal{P}_I + \mathcal{P}_S$$

Spreading power:

$$\mathcal{P}_S = -c_s^2 \partial_r \langle \tilde{v}_r \tilde{n}^2 \rangle / 2\langle n \rangle^2$$

divergence of turbulence internal energy flux due to spreading

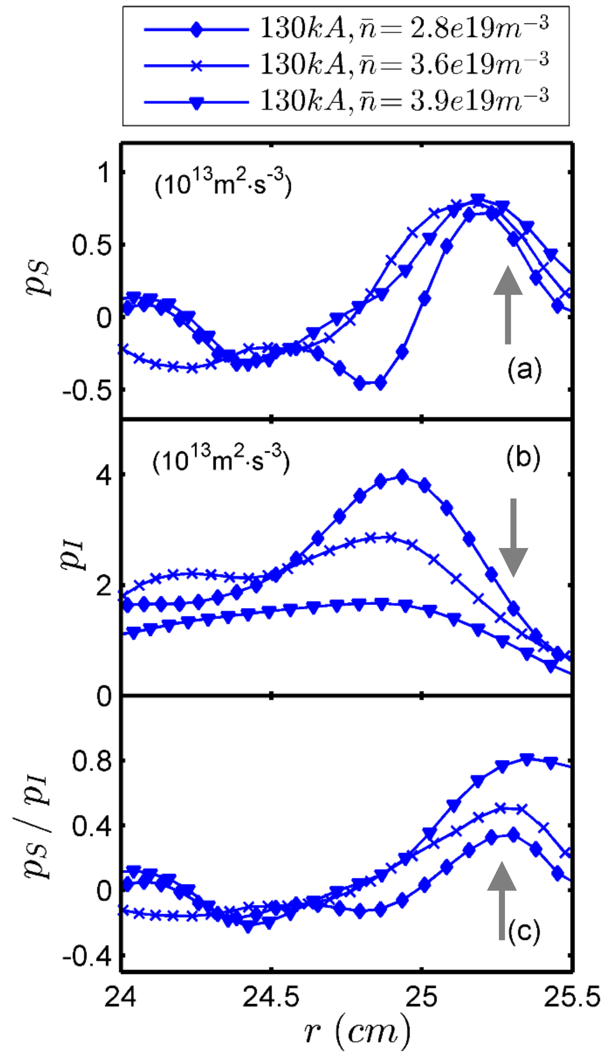
Production power:

$$\mathcal{P}_I = \frac{-c_s^2 \langle \tilde{v}_r \tilde{n} \rangle \partial_r \langle n \rangle}{\langle n \rangle^2}$$

internal energy transfer from source $\nabla\langle n \rangle$ to turbulence

Dimensionless ratio: $\mathcal{P}_S / \mathcal{P}_I$

turbulence power increment due to spreading relative to local production



- **For same I_p: spreading relative to production increases as $\bar{n}$ increases**

Turbulence internal energy evolution

$$\partial_t \frac{c_s^2 \langle \tilde{n}^2 \rangle}{2\langle n \rangle^2} = \mathcal{P}_I + \mathcal{P}_S$$

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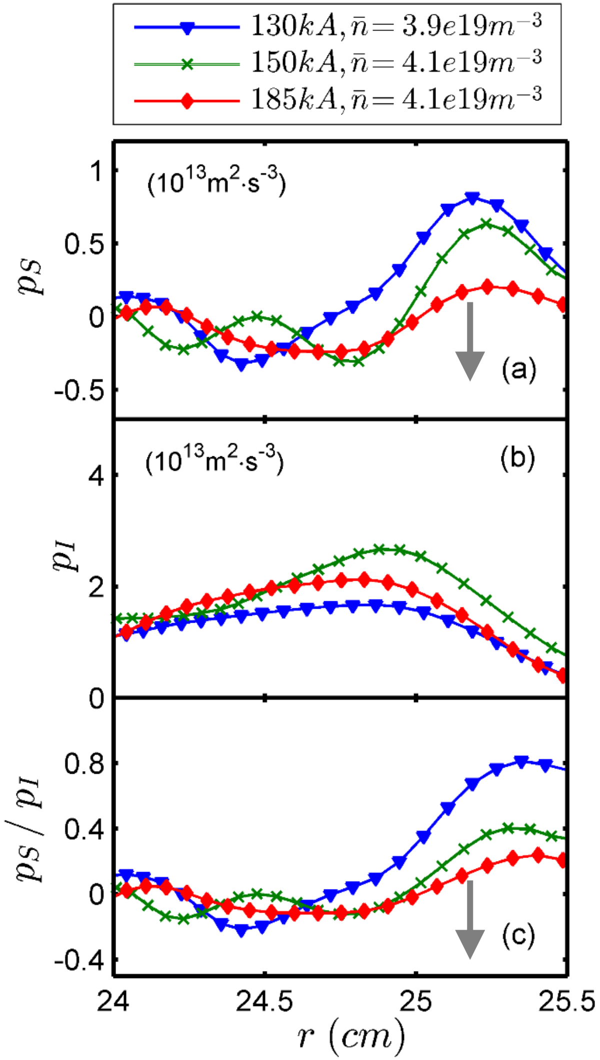
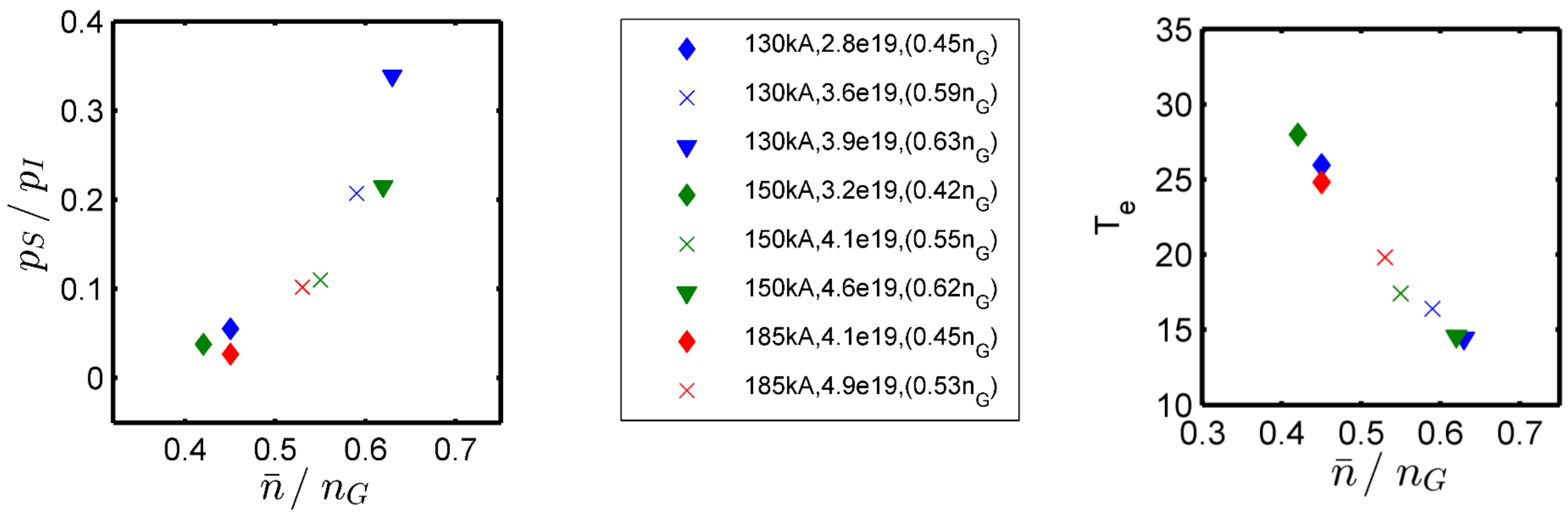


➢ **For close $\bar{n}$: spreading relative to production decreases as I_p increases**

Turbulence internal energy evolution

- **Density fluctuation events and turbulence spreading ratio:**
  - ✓ **enhance as $\bar{n}$ increases**
  - ✓ **weaken as I_p increases**

→ $\frac{\bar{n}}{n_G}$ i.e. $\frac{\bar{n}\,\pi a^2}{I_p}$



➢ **Increasing turbulence spreading leads to the edge cooling**

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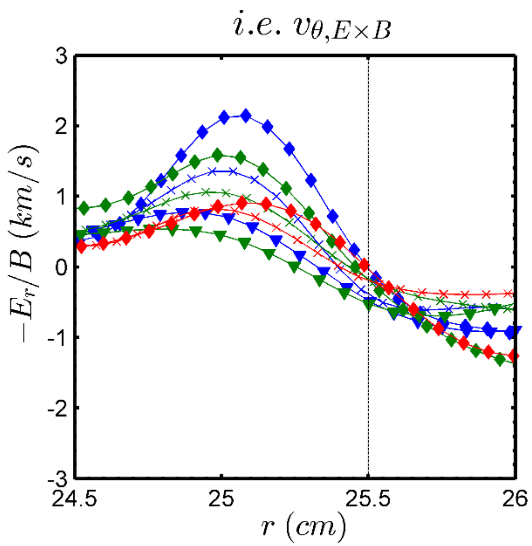
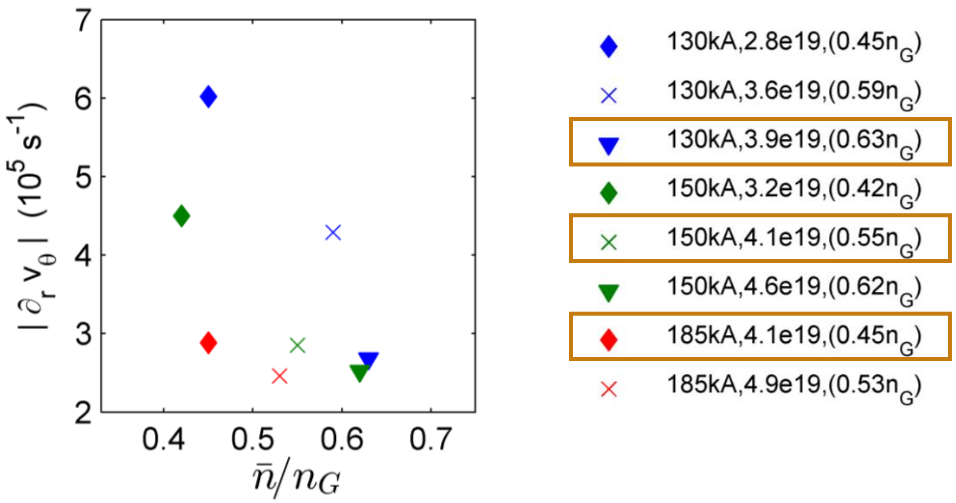
Connection with $\boldsymbol{E} \times \boldsymbol{B}$ flow shear

- **$\boldsymbol{E} \times \boldsymbol{B}$ poloidal flow at plasma edge**
  - For the same I_p: flow shearing rate decreases as $\bar{n}$ increases
  - For the close $\bar{n}$: flow shearing rate doesn't change as I_p increases





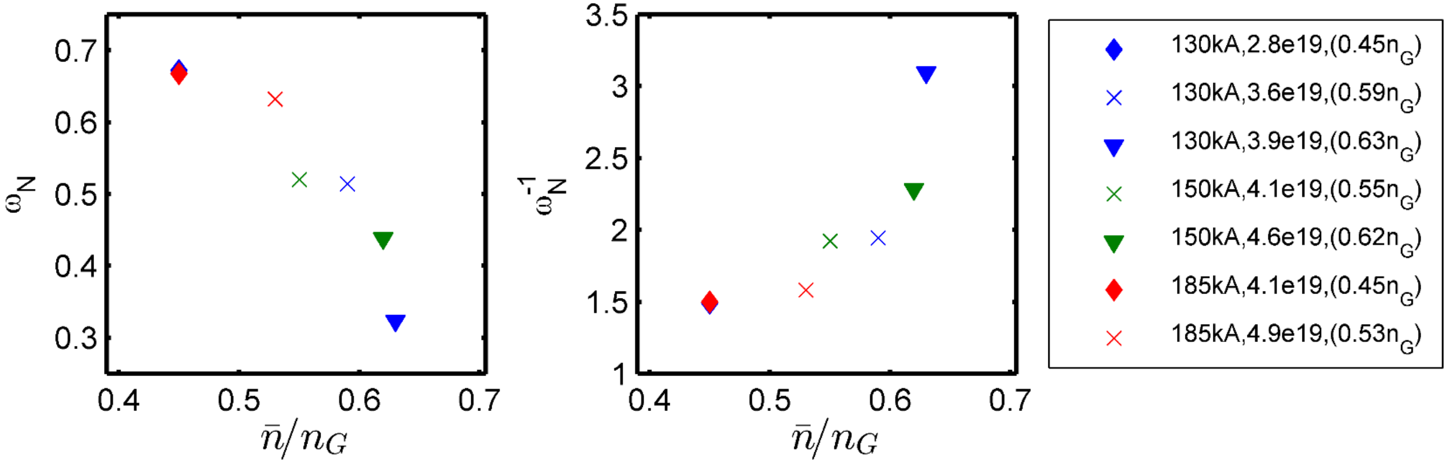
- **Flow shear itself is not responsible for increased turbulence spreading as $\bar{n}/n_G$ increases**

Connection with $\boldsymbol{E \times B}$ flow shear

- **Turbulence suppression criterion:** poloidal flow shear is lager than random diffusive scattering rate of the ambient turbulence (BDT model)
  - Normalized $E \times B$ flow shearing rate

$$\omega_N = \left|\frac{\partial v_\theta}{\partial r}\right| \frac{1}{4D_t} k_\theta l_{cr}^3 > 1$$

$$(D_t \cong \langle \tilde{v}_r^2 \rangle \tau_{ac})$$

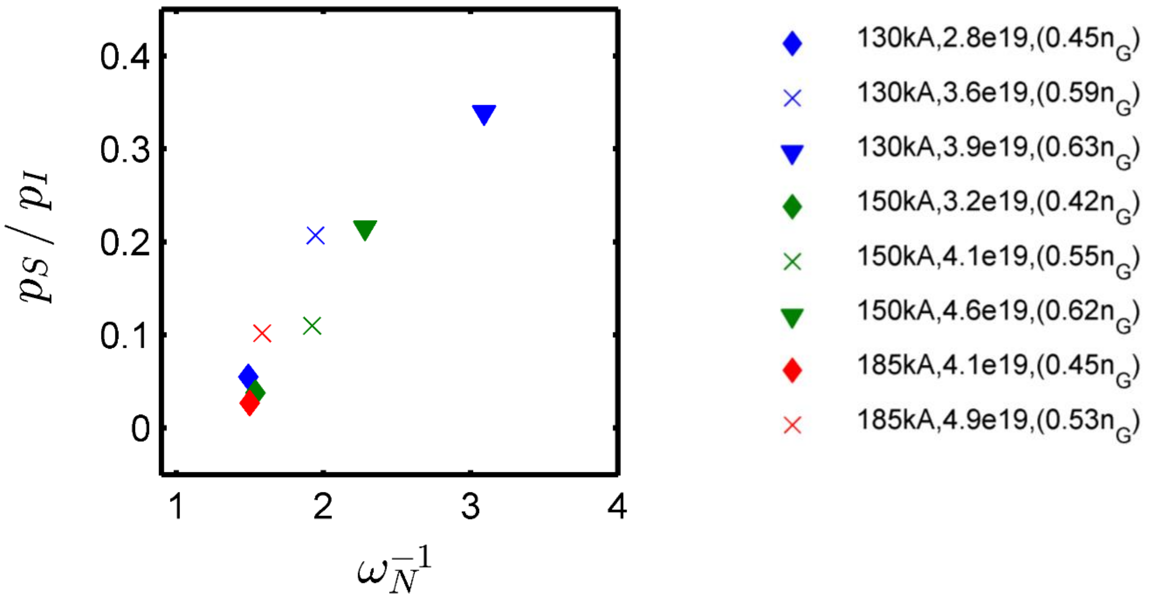


- **ω_N^{-1} is consistent with Greenwald scaling parameter $\bar{n}/n_G$**

✓ *H. Biglari, P. H. Diamond, and P. W. Terry 1990 Physics of Fluids B 2,1*

Connection with $\boldsymbol{E} \times \boldsymbol{B}$ flow shear

- **Turbulence enhancement parameter ω_N^{-1}**



➢ **Turbulence spreading strength increases as ω_N^{-1} increases**

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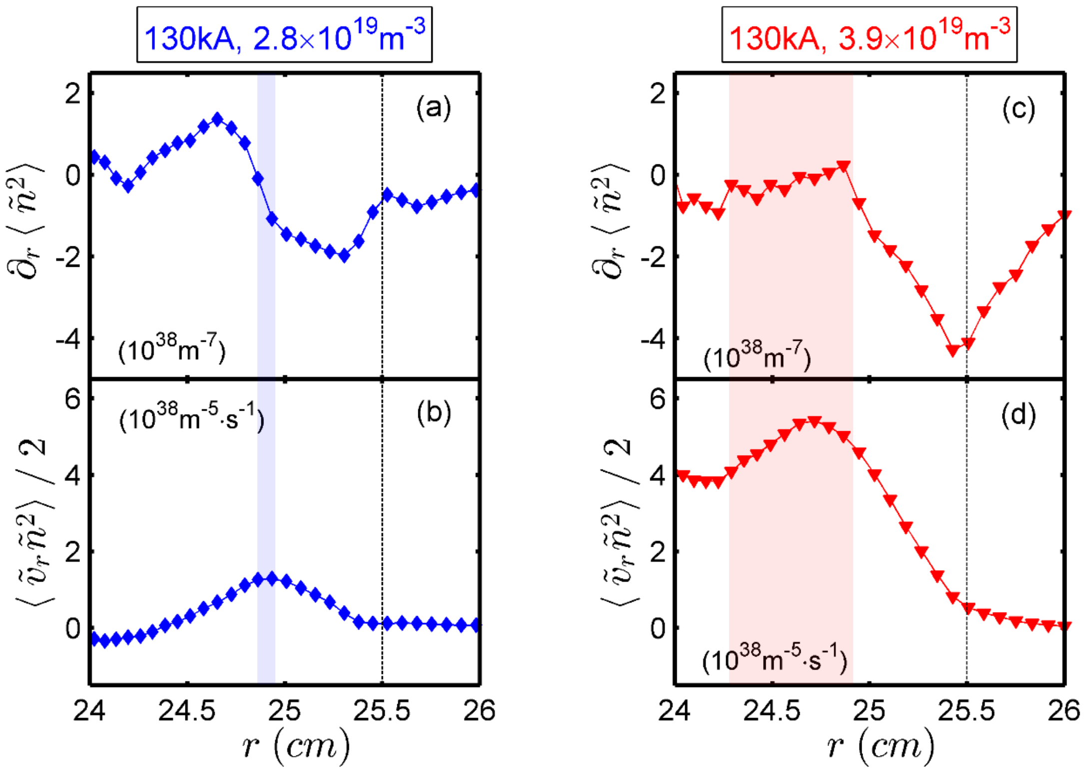
Beyond the diffusion process

- A region in plasma edge, turbulence intensity flux $\langle \tilde{v}_r \tilde{n}^2 \rangle / 2$ is large, but turbulence intensity gradient $\partial_r \langle \tilde{n}^2 \rangle$ is near zero



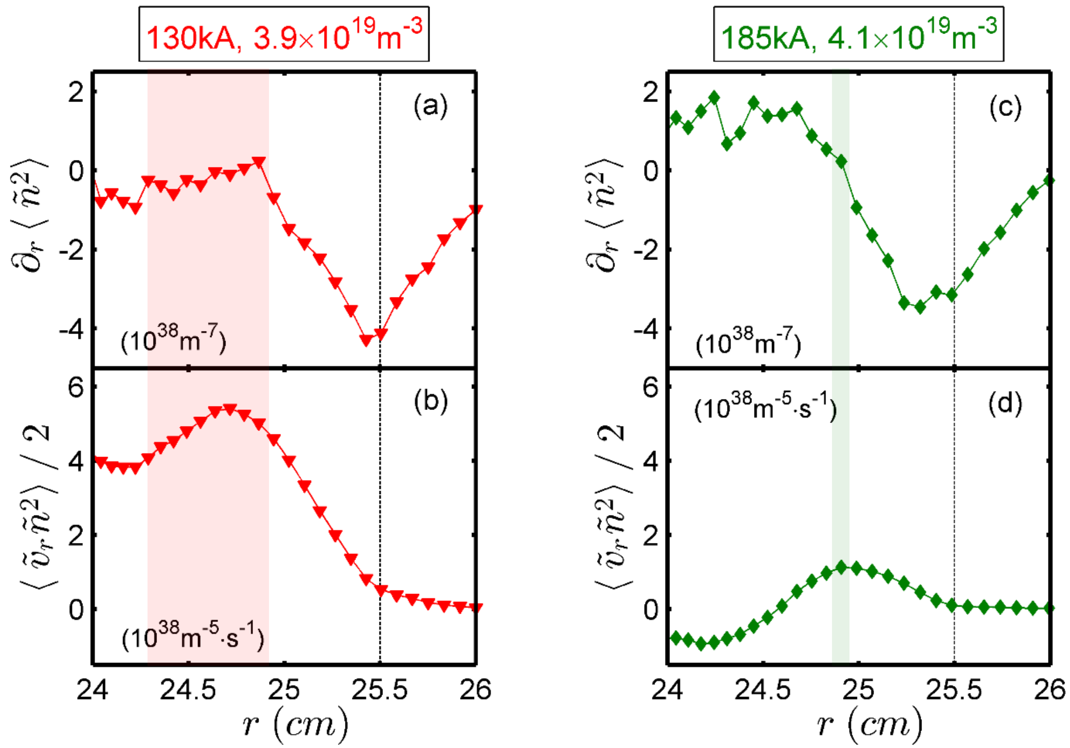
For same I_p

- Lower density, width of region is $< 1\ mm$ ($\rho_i \sim 0.35\ mm$)
- Higher density, width of region is $\sim 5\ mm$ ($l_{cr} \sim 4.3\ mm$)
- Notice: spreading diffusivity

$$\chi_I = -\frac{\langle \tilde{v}_r \tilde{n}^2 \rangle}{\partial_r \langle \tilde{n}^2 \rangle}$$

Beyond the diffusion process

- A region in plasma edge, turbulence intensity flux $\langle \tilde{v}_r \tilde{n}^2 \rangle / 2$ is large, but turbulence intensity gradient $\partial_r \langle \tilde{n}^2 \rangle$ is near zero



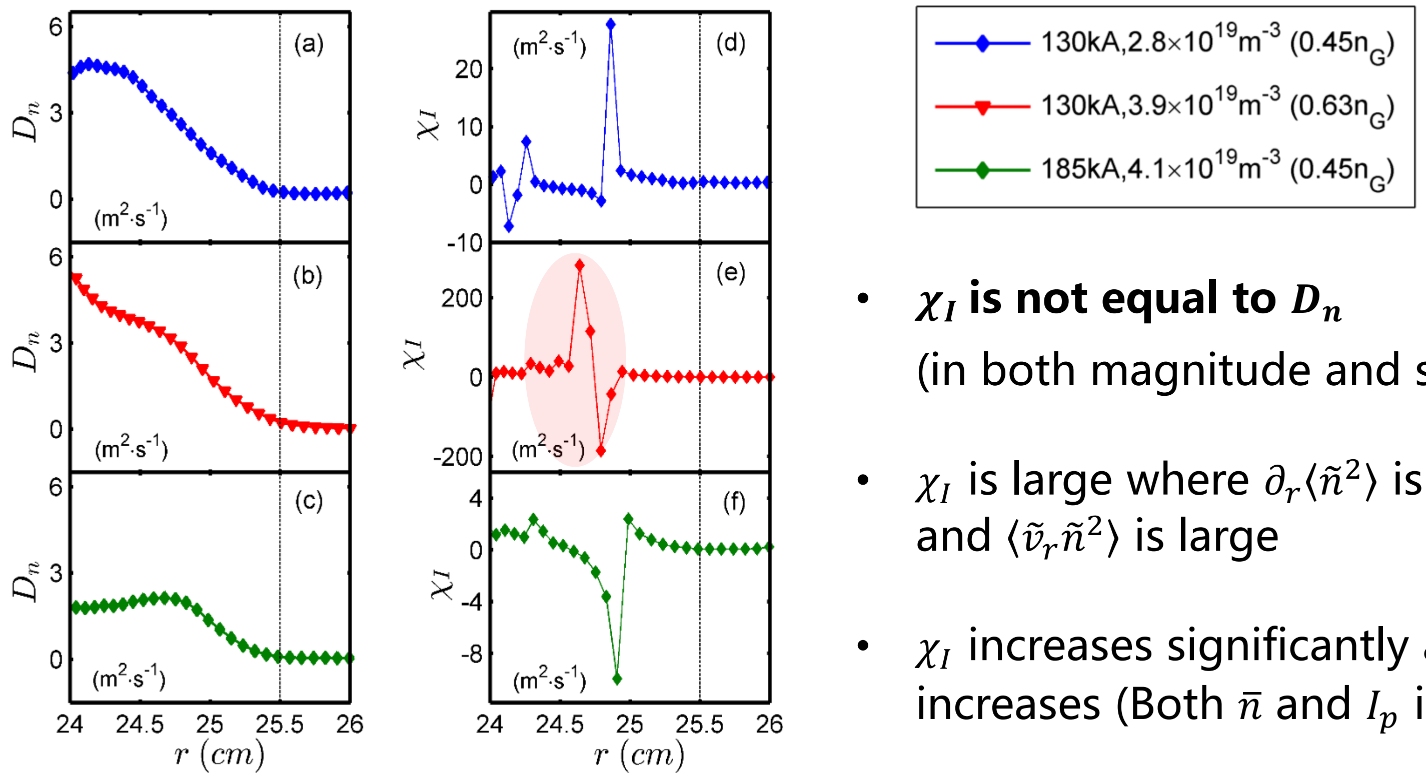
For close $\bar{n}_e$

- Lower current,
  width of region is $\sim 5\ mm$
  $(l_{cr} \sim 4.3\ mm)$
- Higher current,
  width of region is $< 1\ mm$
  $(\rho_i \sim 0.25\ mm)$
- Notice: spreading diffusivity

$$\chi_I = -\frac{\langle \tilde{v}_r \tilde{n}^2 \rangle}{\partial_r \langle \tilde{n}^2 \rangle}$$

Beyond the diffusion process

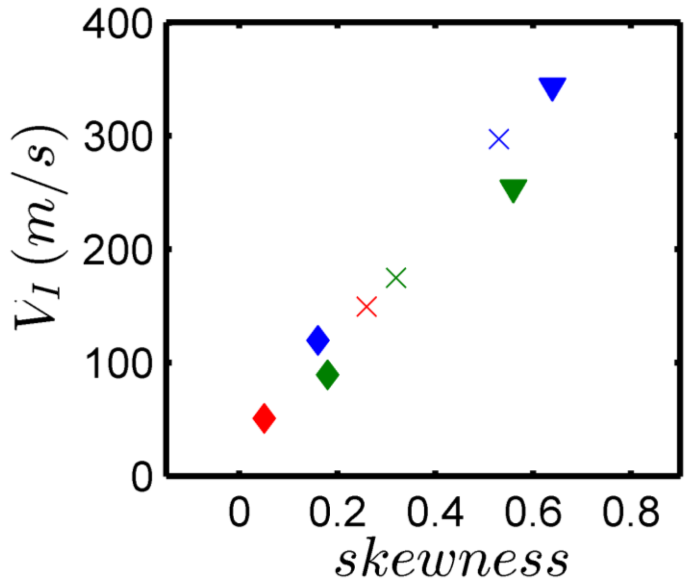
- Difference between particle diffusivity and energy spreading diffusivity
  - Diffusivity of turbulent particle flux $\langle \tilde{n}\tilde{v}_r \rangle = -D_n \partial_r \langle n \rangle$
  - Diffusivity of turbulence spreading $\langle \tilde{v}_r \tilde{n}^2 \rangle = -\chi_I \partial_r \langle \tilde{n}^2 \rangle$



- **χ_I is not equal to D_n**
  (in both magnitude and sign)
- χ_I is large where $\partial_r \langle \tilde{n}^2 \rangle$ is near zero and $\langle \tilde{v}_r \tilde{n}^2 \rangle$ is large
- χ_I increases significantly as $\bar{n}/n_G$ increases (Both $\bar{n}$ and I_p involved)

Beyond the diffusion process

- **"Mean jet velocity" of turbulence spreading** $V_I = \frac{\langle \tilde{v}_r \tilde{n}^2 \rangle}{\langle \tilde{n}^2 \rangle}$



- **Show linear correlation with skewness of density fluctuation**

  (blob relevant…..)

  - ✓ *A. A. Townsend 1948 Momentum and energy diffusion in the turbulent wake of a cylinder*

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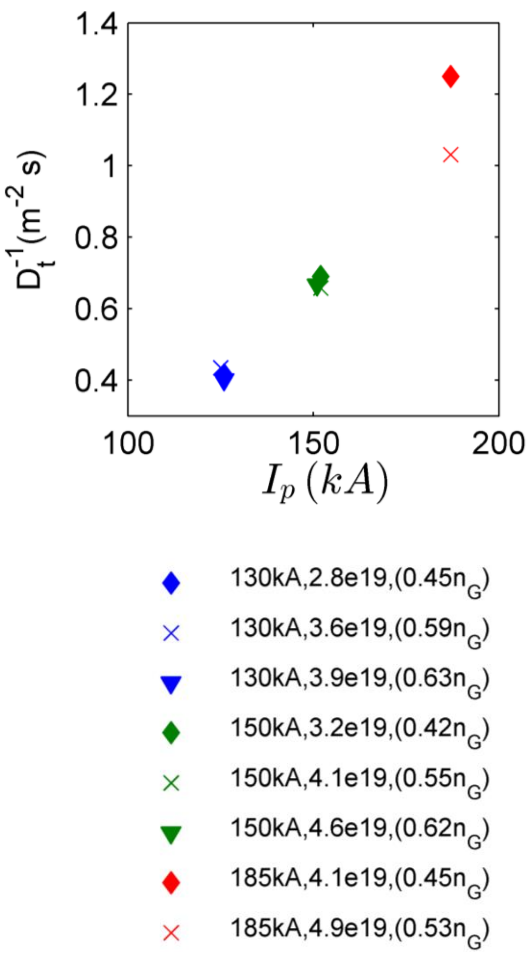
Summary and future plan

- **Summary**
  - **Density fluctuation events and turbulence spreading strength enhance as $\bar{n}$ increases while weaken as I_p increases**
  - **Increasing turbulence spreading coincides with the edge cooling approaching the density limit**
  - **Turbulence enhancement parameter ω_N^{-1}, which takes both $E \times B$ flow shear and turbulence random diffusive scattering into account, is consistent with Greenwald scaling $\bar{n}/n_G$**

Summary and future plan

- **Future plan**
  - **Physical understanding of the plasma current dependency of turbulence spreading and particle transport.**
  - **Non-diffusive process of turbulence spreading and its relations to blobs/holes.**
  - **The correlation between turbulence spreading dynamics and power dependence of density limit.**



Thank you!

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