Spontaneous and externally driven shear flow evolution near the density limit

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Outline

- Motivation
- Spontaneous shear flow near density limit
- Externally driven shear flow near density limit
- Summary and future plan

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Motivation

- **High density operation: favorable for fusion reactors (baseline scenario for ITER)**

$$\underbrace{P_{fusion}}_{\text{fusion power}} \propto \underbrace{\langle \sigma v \rangle}_{\text{reaction coefficient}} \underbrace{n}_{\text{plasma density}}{}^{2}$$

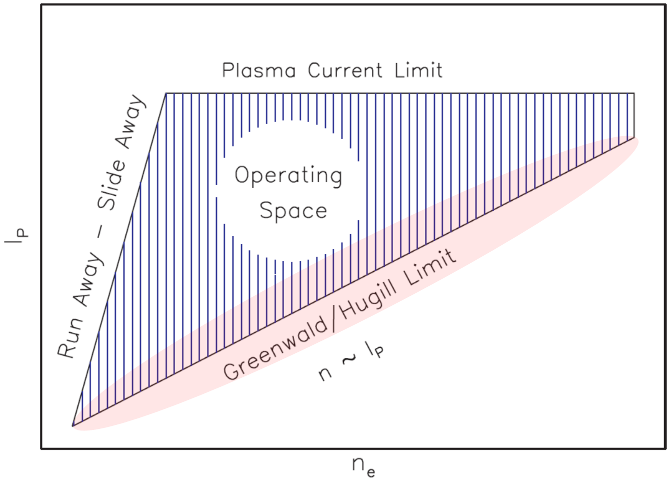
fusion power

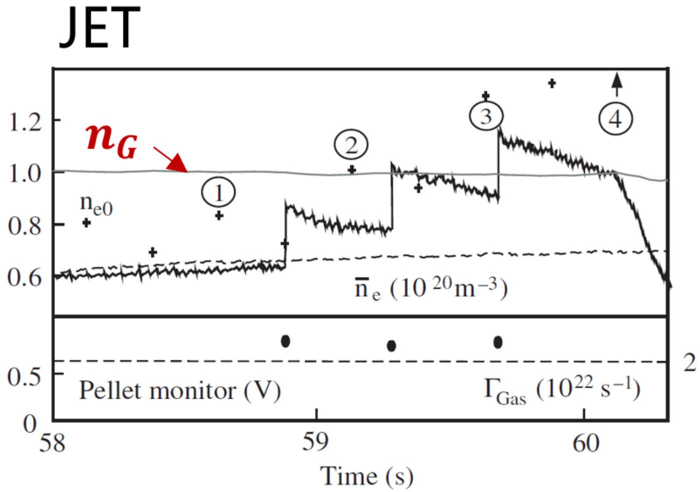
reaction coefficient

plasma density

Motivation

- **Density limit**: constraints on maximum attainable density
- **Greenwald empirical scaling:** $\bar{n}_{max} \sim n_G[10^{20}m^{-3}] = I_p[MA]/\pi a^2[m^2]$
- **Discharges with pellet fueling:** n_G **is exceeded with peaked density**



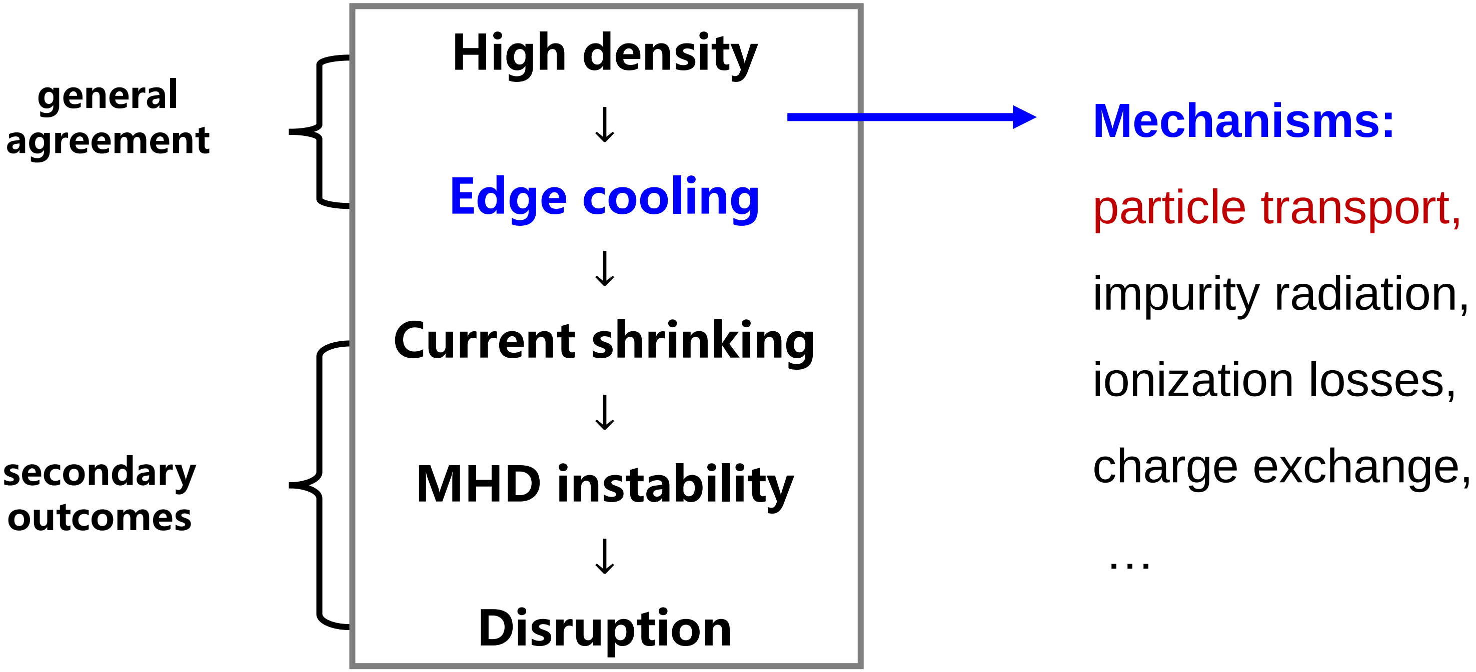


➢ **What physical processes underpin density limit?**

✓ *M. Greenwald et al 2002 Plasma Phys. Control. Fusion 44 R27*
✓ *P .T. Lang et al 2002 Plasma Phys. Control. Fusion 44 1919–1928*

Motivation

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



general agreement

secondary outcomes

High density

↓

Edge cooling

↓

Current shrinking

↓

MHD instability

↓

Disruption

→ **Mechanisms:**

particle transport,

impurity radiation,

ionization losses,

charge exchange,

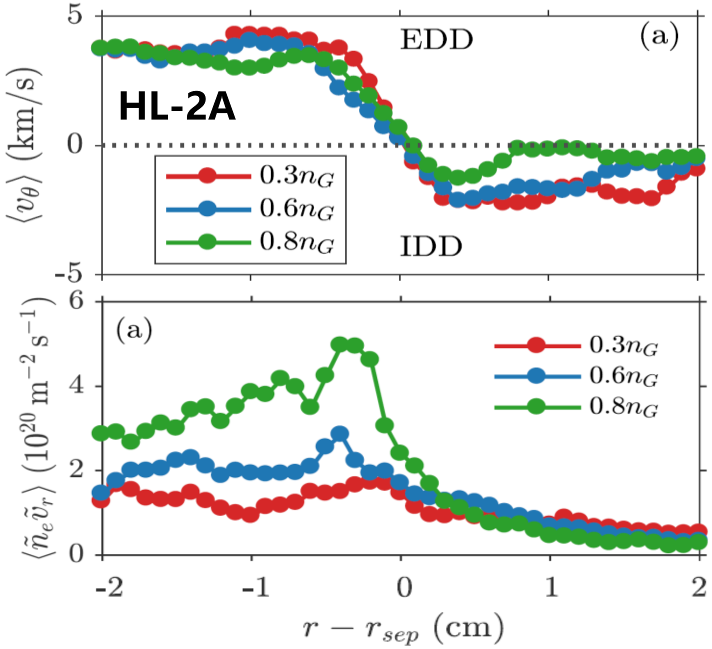
…

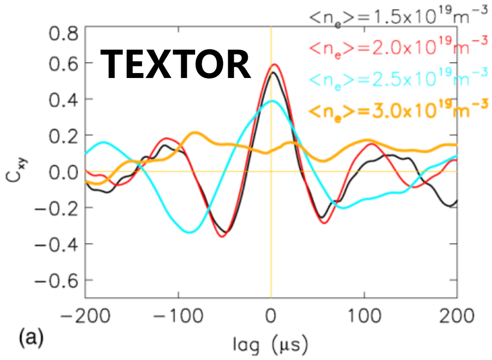
➢ **What triggers enhanced particle transport near density limit?**

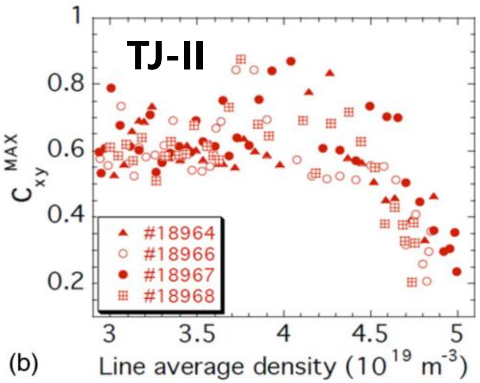
✓ *K. Borrass et al 1991 Nucl. Fusion 31 1035-1051* ✓ *M. Greenwald et al 2014 Phys. Plasma 21 110501*

Motivation

- **Turbulent transport can be suppressed by shear flow**
- **Edge shear layer collapse → enhanced particle flux near density limit**







- ✓ *R. Hong et al 2018 Nucl. Fusion 58 016041*
- ✓ *R. Singh and P.H. Diamond 2021 Nucl. Fusion 61 076009*
- ✓ *Y. Xu et al 2011 Nucl. Fusion 51 063020*
- ✓ *R. J. Hajjar et al 2018 Phys. Plasma 25 062306*

Motivation

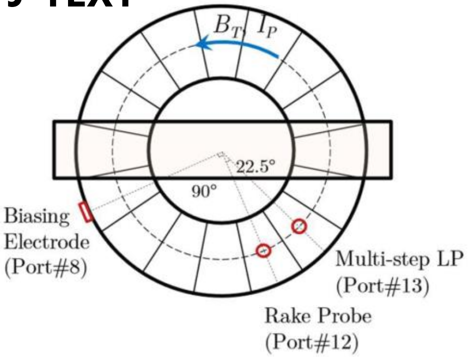
In this report:

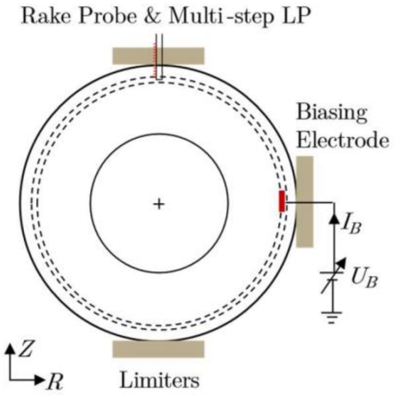
1. **Physics of spontaneous shear flow and turbulent transport near density limit.**
   (turbulence energy evolution)

2. **Externally driven shear flow to control transport and realize higher density?**
   (biased electrode-driven shear flow)

- ✓ *T. Long et al 2021 Nucl. Fusion 61 126066*
- ✓ *R. Ke et al 2022 Nucl. Fusion (accepted)*

J-TEXT





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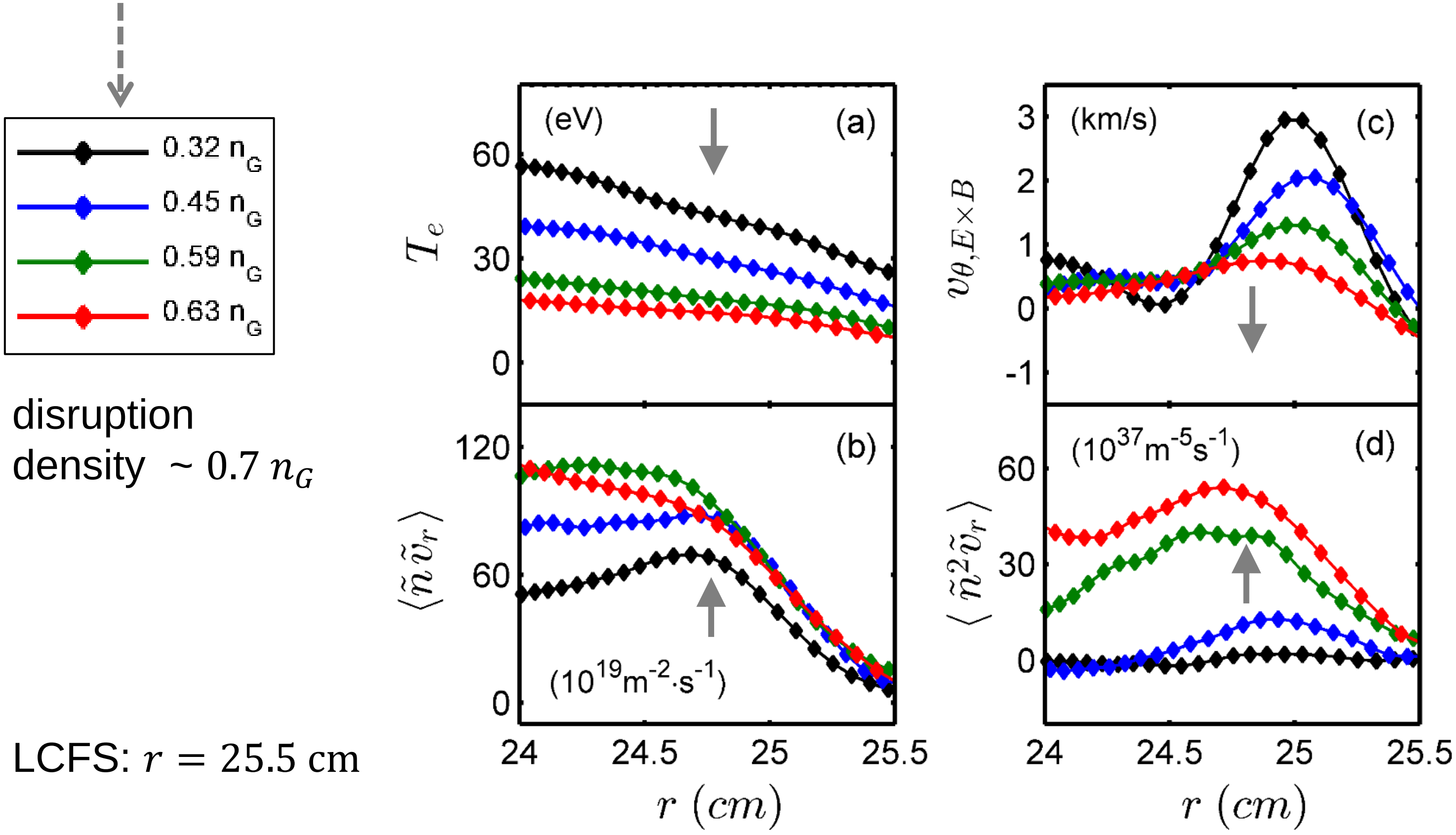
Spontaneous shear flow near density limit

- **As $\bar{n}$ →Greenwald density (n_G), edge $E \times B$ flow & shearing decrease**



disruption
density ~ $0.7\, n_G$

LCFS: $r = 25.5$ cm

Shear layer collapse → enhanced particle transport & turbulence intensity flux → edge cooling

Spontaneous shear flow near density limit

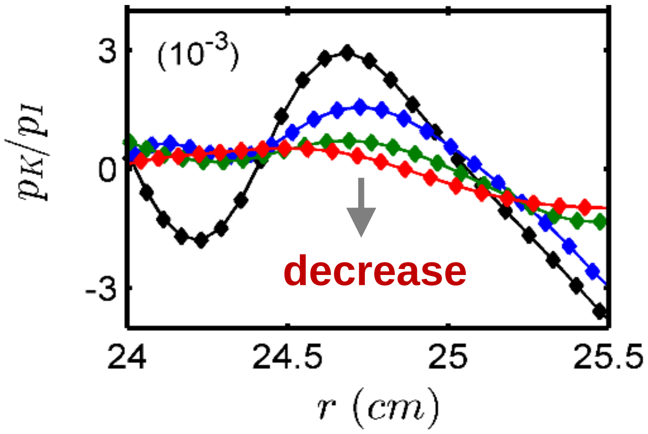
- **Turbulence kinetic and internal energy evolution**

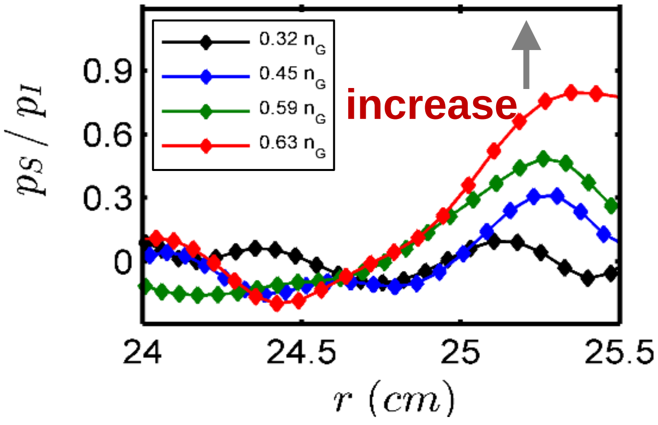
- **efficiency of kinetic energy transfer from turbulence to shear flow**

$$\frac{\textbf{Reynolds power } \mathcal{P}_K}{\textbf{Production power } \mathcal{P}_I} = \frac{\langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle v_\theta \rangle}{-c_s^2 \langle \tilde{v}_r \tilde{n} \rangle \partial_r \langle n \rangle / \langle n \rangle^2}$$

- **internal energy increment due to spreading relative to local production**

$$\frac{\textbf{Spreading power } \mathcal{P}_s}{\textbf{Production power } \mathcal{P}_I} = \frac{-c_s^2 \partial_r \langle \tilde{v}_r \tilde{n}^2 \rangle / 2 \langle n \rangle^2}{-c_s^2 \langle \tilde{v}_r \tilde{n} \rangle \partial_r \langle n \rangle / \langle n \rangle^2}$$





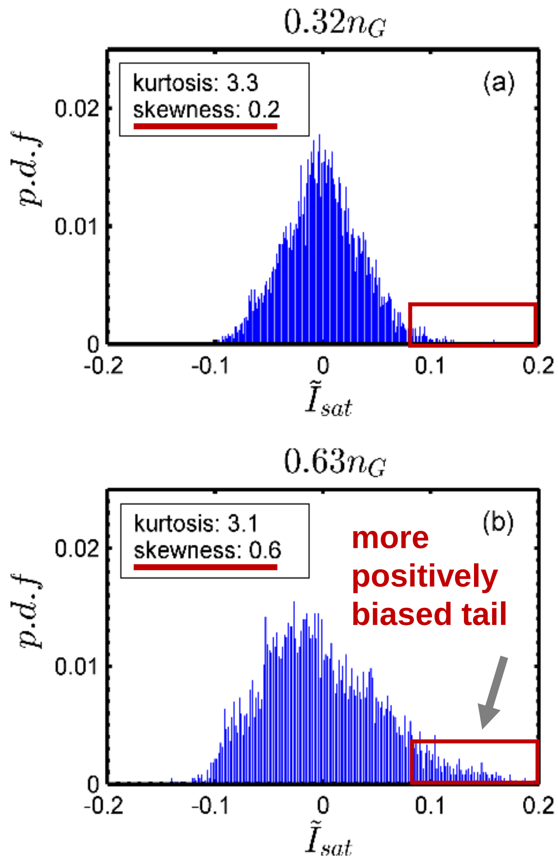
$$(\mathcal{P}_K/\mathcal{P}_I)_{peak} * (\mathcal{P}_S/\mathcal{P}_I)_{peak} \sim \textbf{const}\ (\sim 0.4 \pm 0.1\ \times 10^{-3})$$

Energy is diverted from shear flow drive to outward spreading

→ **shear layer collapses, turbulent particle transport enhances**

Spontaneous shear flow near density limit

- **PDF of $\tilde{I}_{sat}$: skewness increases**



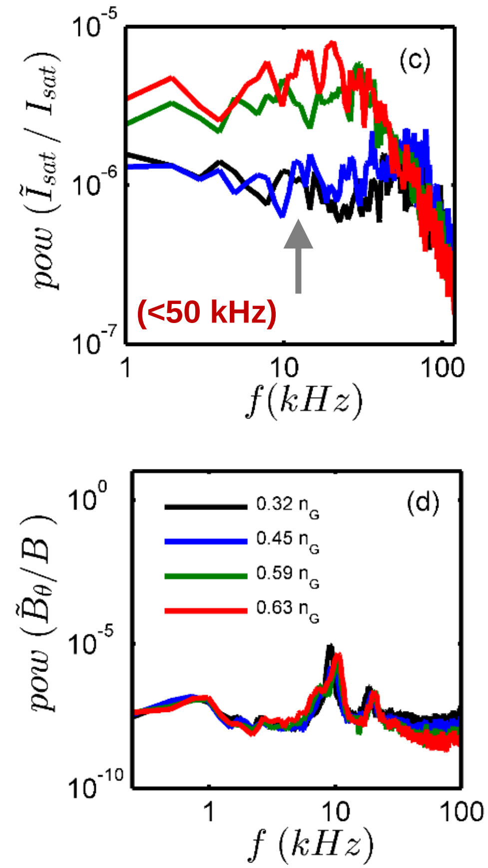
density fluctuation
~
ion saturation current fluctuation

$$\frac{\tilde{I}_{sat}}{I_{sat}} \sim \frac{\tilde{n}_e}{n_e}$$

relation to blob, (ongoing study)

- **$\tilde{n} > 0$ fluctuations is predominant in enhanced transport events**

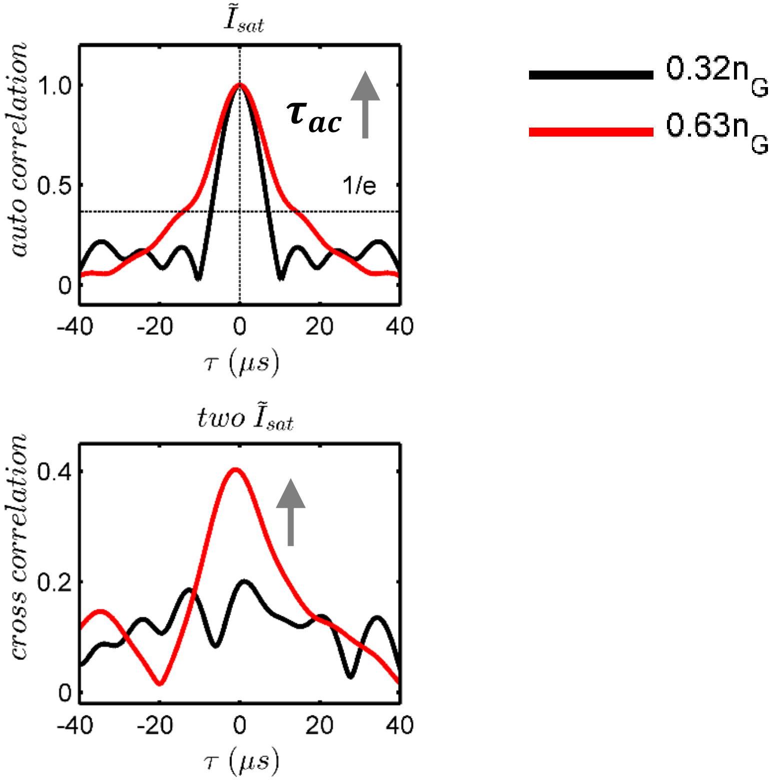
- **power spectra: $\tilde{I}_{sat}/I_{sat}$ increase**

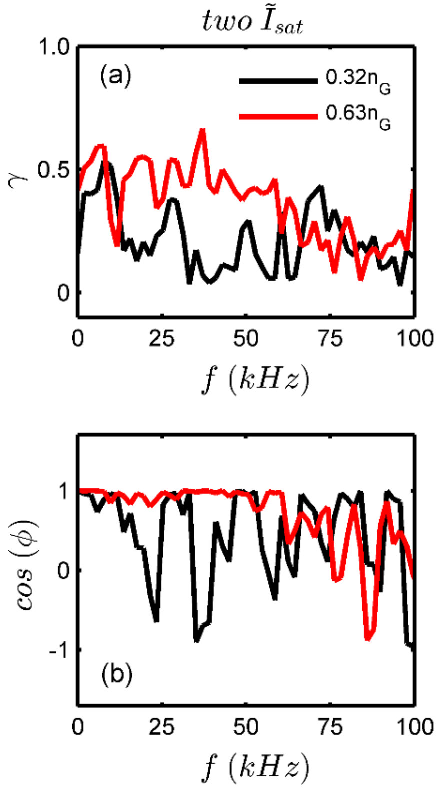


- **No obvious change in low-frequency MHD activity → electrostatic fluctuation**

Spontaneous shear flow near density limit

- **Auto and cross correlation function of $\tilde{I}_{sat}$**
- **Coherence and cross phase between radially separated $\tilde{I}_{sat}$**

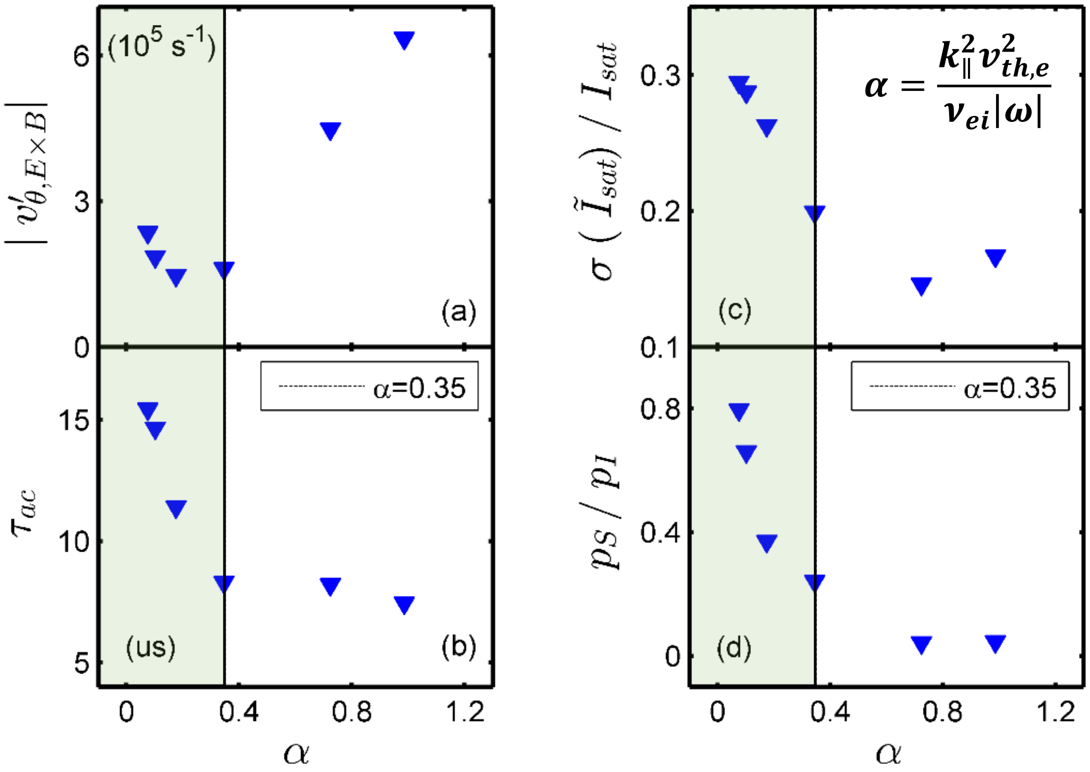




Increases of auto-correlation time and radial correlation in $\tilde{I}_{sat}$ coincide with enhanced particle transport events

Spontaneous shear flow near density limit

- **As $n \rightarrow n_G$, electron adiabaticity α decreases from $\alpha \sim 1 \rightarrow \alpha \ll 1$**



Electron response:

adiabatic

→

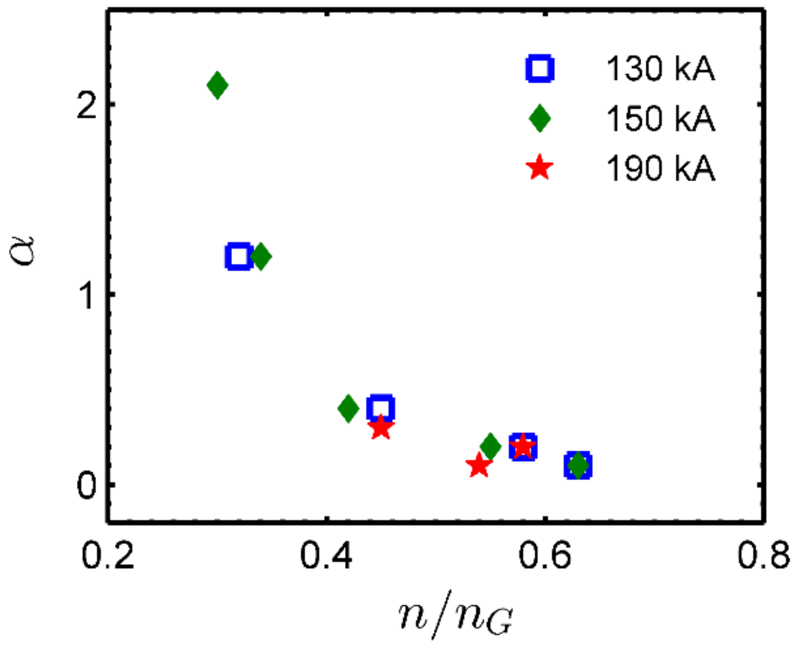
hydro-dynamic

Weaken coupling between $\tilde{n}$ and $\tilde{\phi}$

α emerges as a critical parameter (threshold < 0.35) to signal onset of edge shear layer collapse & enhanced particle transport events

Spontaneous shear flow near density limit

- **Transition from adiabatic ($\alpha > 1$) to hydrodynamic regime ($\alpha \ll 1$) is a common characteristic**



Higher operational density available in discharges with higher I_p is coincident with evolution of adiabaticity

Outline

Motivation

Spontaneous shear flow near density limit

Externally driven shear flow near density limit

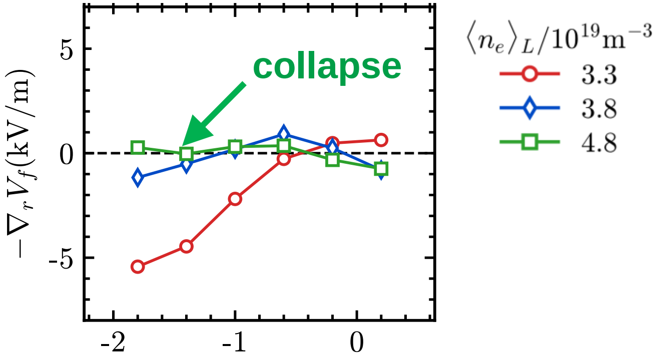
Summary and future plan

Externally driven shear flow near density limit

- **Biased electrode to sustain edge shear flow in high density**

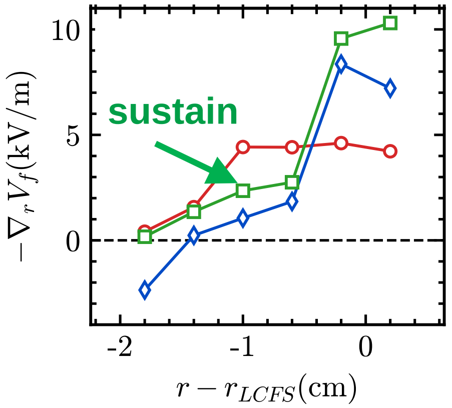
without bias

$\sim E_r$



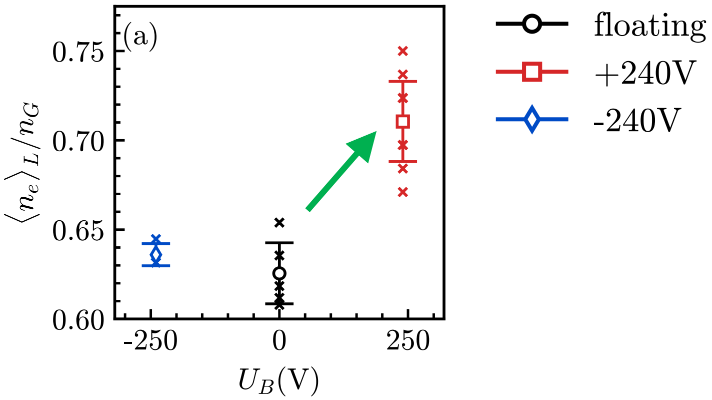
with + 240V bias

$\sim E_r$



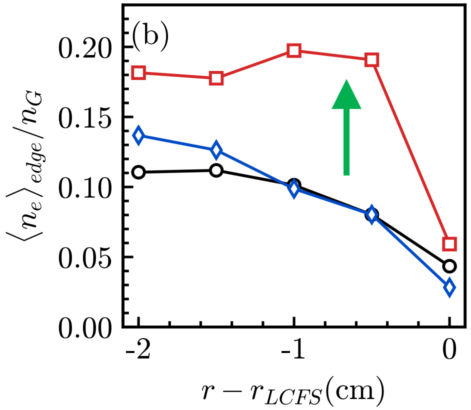
line-averaged density:

increase ~10%



edge density:

double



Maintenance of edge shear layer → increase in density

(line-averaged density along with edge density)

Externally driven shear flow near density limit

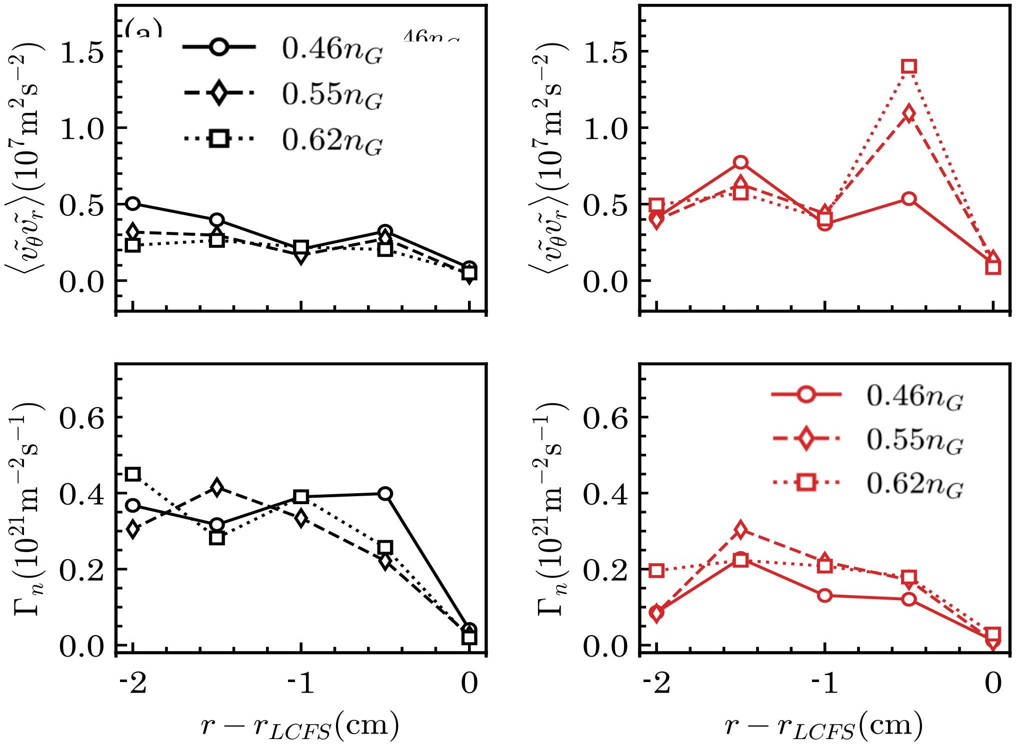
- **With electrode biasing, Reynolds stress increases, while turbulent particle flux decreases**

without bias

with + 240V bias

Reynolds stress

particle flux

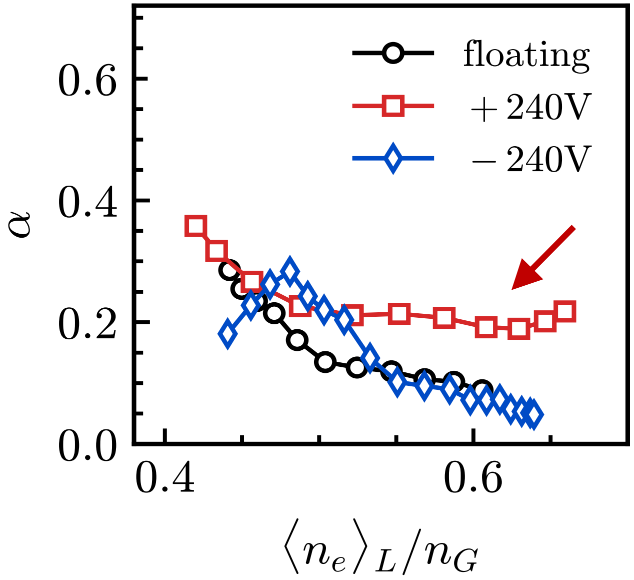


Enhanced Reynolds stress → maintenance of edge shear layer

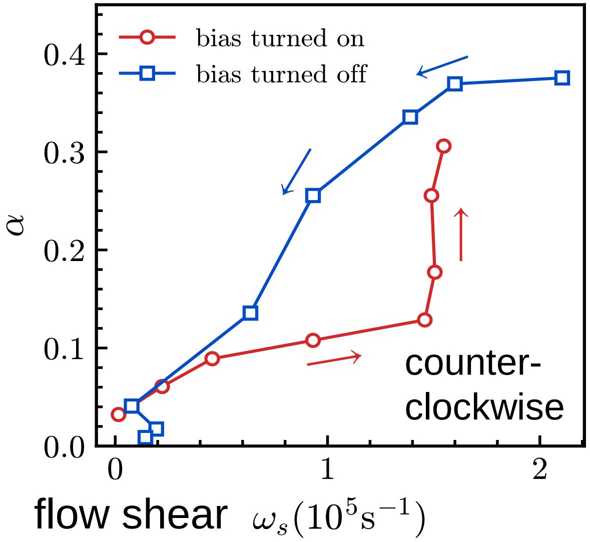
Reduced particle flux → increase of edge density

Externally driven shear flow near density limit

- Sufficient shear flow driven by positive bias → prevent decrease of electron adiabaticity α → higher n



- Hysteresis loop of $\omega_s - \alpha$ phase space: increase in edge flow shear leads increase in adiabaticity



Indication of causality:

changes in adiabaticity follow changes in edge shear flow

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Summary and future plan

- **Summary**
  - **Edge shear layer collapse as $n \rightarrow n_G$, resulting in enhanced turbulent particle flux.**
  - **Turbulence spreading increases while Reynolds power decreases as $n \rightarrow n_G$. (fluctuation power is channeled to spreading instead of turbulent drive of shear flow)**
  - **Adiabaticity emerges as a critical parameter to signal onset of enhanced particle transport events (quasi-coherence & positive skewness).**
  - **Externally driven shear flow by electrode biasing: sustain edge plasma states to decrease transport and realize higher density.**

Summary and future plan

- **Future plan**
  - ➢ $\alpha \sim T^2/n \rightarrow$ **The correlation between the dynamics of edge shear layer as well as particle transport events and the possible power dependence of density limit**
  - ➢ **The current dependency of internal and kinetic energetics and that of particle diffusion and density fluctuations near density limit**
  - ➢ **Beyond density limit: extended experimental study of turbulence spreading: its effect on SOL width broadening, pedestal height and width, …**

Thank you!

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Acknowledgments

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Back up

- **Kinetic energy evolution**

$$\partial_t \frac{\langle v_\theta \rangle^2}{2} = -\partial_r \langle \tilde{v}_r \tilde{v}_\theta \langle v_\theta \rangle \rangle + \langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle v_\theta \rangle$$

$$\partial_t \frac{\langle \tilde{v}_\theta^2 \rangle}{2} = \underbrace{-\langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle v_\theta \rangle}_{\mathcal{P}_K} - \partial_r \langle \tilde{v}_r \tilde{v}_\theta^2 \rangle$$

relative fraction of turbulence power transferred to the zonal flow

$$\boxed{\frac{\mathcal{P}_K}{\mathcal{P}_I} = \frac{\langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle v_\theta \rangle}{-c_s^2 \langle \tilde{v}_r \tilde{n} \rangle \partial_r \langle n \rangle / \langle n \rangle^2}}$$

- **Internal energy evolution**

$$\frac{c_s^2}{\langle n \rangle^2} \partial_t \frac{\langle n \rangle^2}{2} = -\frac{c_s^2 \partial_r (\langle \tilde{v}_r \tilde{n} \rangle \langle n \rangle)}{\langle n \rangle^2} + \frac{c_s^2 \langle \tilde{v}_r \tilde{n} \rangle \partial_r \langle n \rangle}{\langle n \rangle^2}$$

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

turbulence power increment due to spreading relative to local production

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

Kinetic and internal energy evolution

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

Reynolds power:

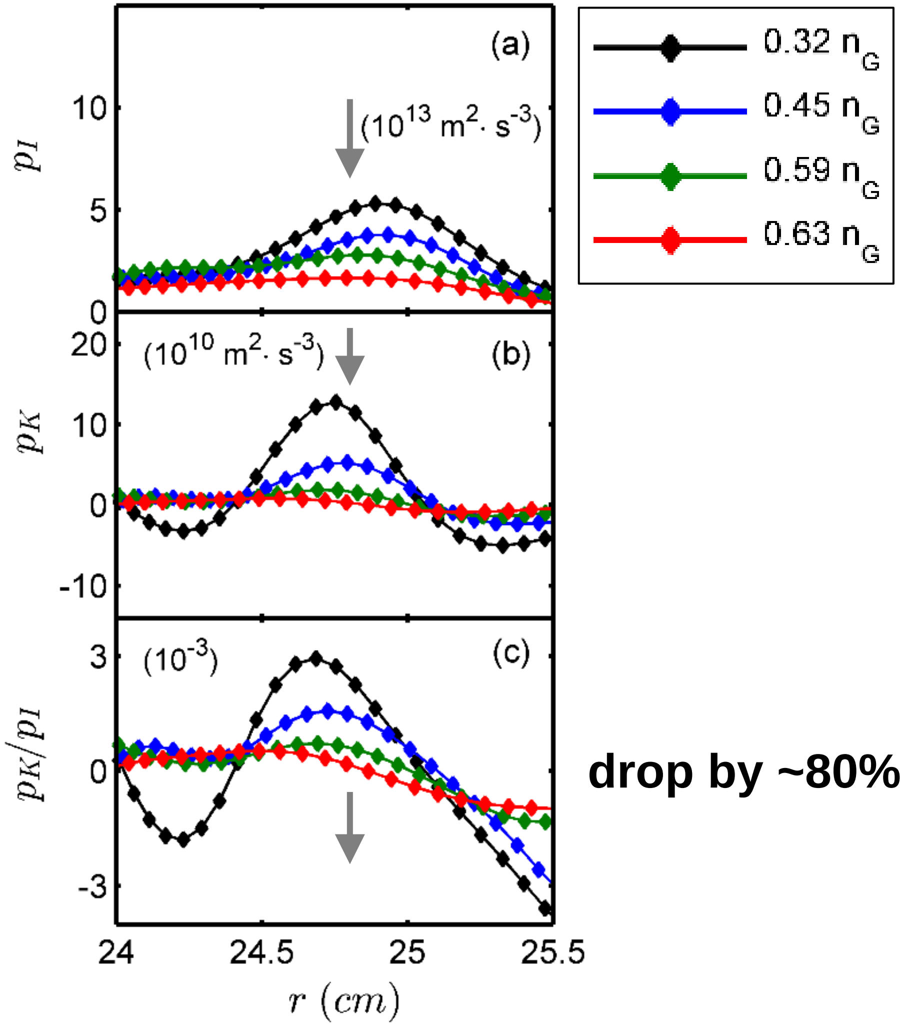
$$\mathcal{P}_K = \langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle v_\theta \rangle$$

kinetic energy transfer from turbulence to zonal flow

Dimensionless ratio:

$$\mathcal{P}_K / \mathcal{P}_I$$

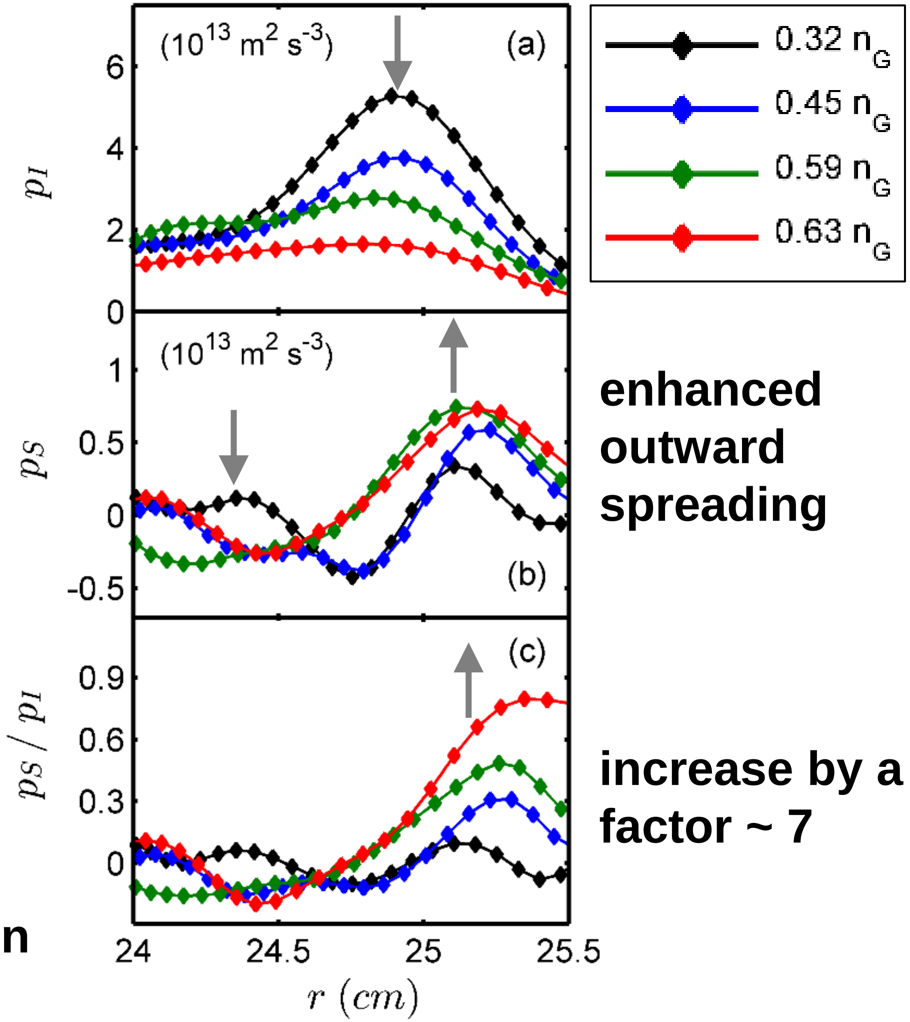
relative fraction of turbulence power transferred to the zonal flow



drop by ~80%

As $\bar{n} \to n_G$, relative reduction in the efficiency of energy transfer from edge turbulence to $E \times B$ flow → shear layer collapse

Kinetic and internal energy evolution



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 ∇⟨n⟩ to turbulence

Spreading power:

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

divergence of turbulence internal energy flux due to spreading

Dimensionless ratio:

$$\mathcal{P}_S/\mathcal{P}_I$$

turbulence power increment due to spreading relative to local production

enhanced outward spreading

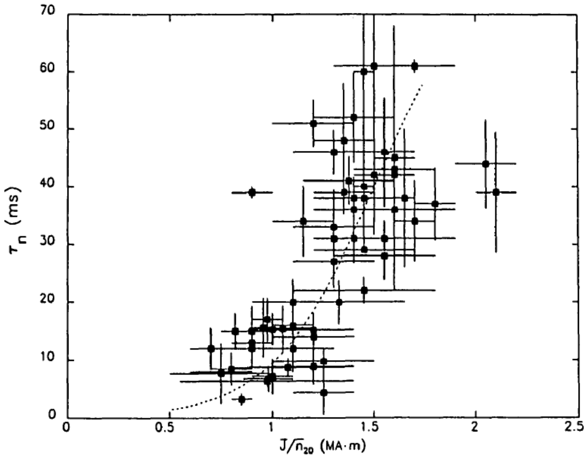
increase by a factor ~ 7

As $\bar{n} \rightarrow n_G$, fraction of turbulence internal energy spreading relative to production increases dramatically

Back up

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

Alcator C

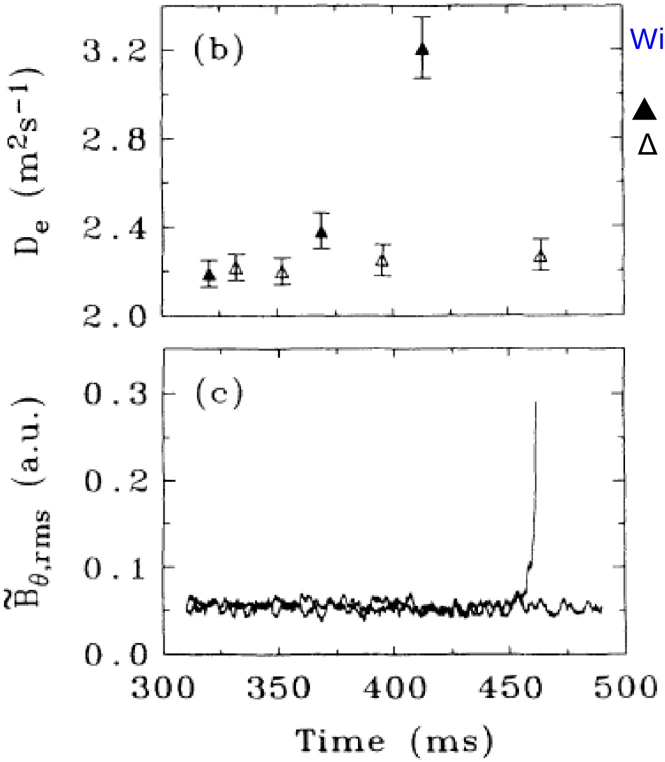


density relaxation time after pellet

$n_G/\bar{n}_e$

TEXT

particle diffusivity



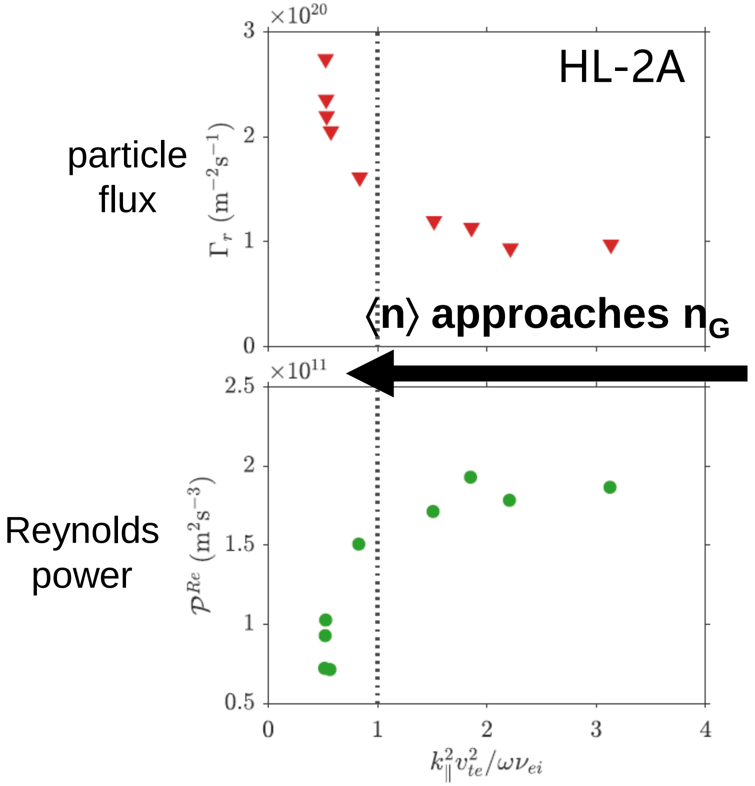
With close $\bar{n}$

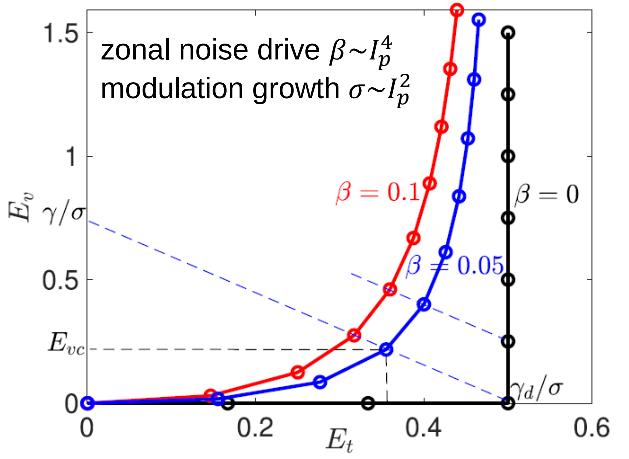
▲ disrupting
Δ non-disrupting

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

Back up

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





Zonal flow energy E_v vs turbulence energy E_t

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

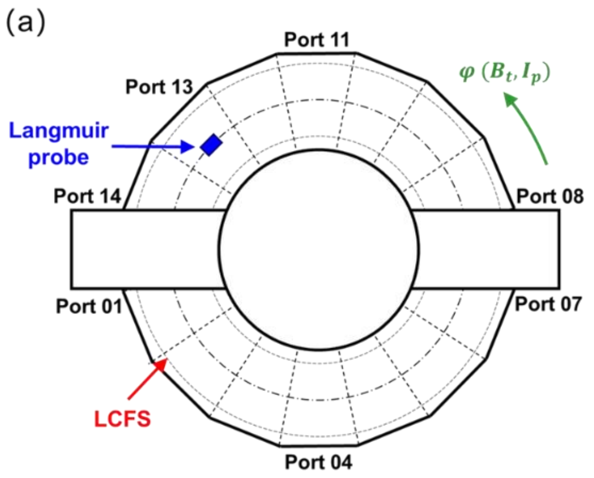
- ✓ *R. Hong et al 2018 Nucl. Fusion 58 016041*
- ✓ *R. J. Hajjar et al 2018 Phys. Plasma 25 062306*

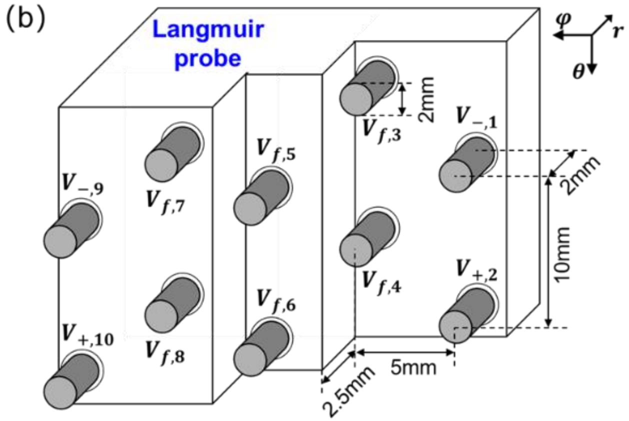
- ✓ *R. Singh and P.H. Diamond 2021 Nucl. Fusion 61 076009*

Back up

- **In this talk: experimental studies of edge shear layer and particle transport events approaching the density limit of J-TEXT tokamak**

- **Experimental set up**
  - ➢ Ohmic hydrogen discharges
  - ➢ Limiter, $R = 1.05\text{m}, a = 0.255\text{m}$
  - ➢ $B_t = 1.6 - 2.2\text{T}, I_p = 130 - 190\text{kA}$
  - ➢ $\bar{n}_e = 2.0 - 5.3 \times 10^{19}\text{m}^{-3}$
  - ➢ Langmuir probe: $T_e, \phi_p, n_\text{e}, E \times B$ velocity, turbulent particle flux, turbulence intensity flux and Reynolds stress can be measured.
  - ➢ Fluctuations $2 - 100$ kHz

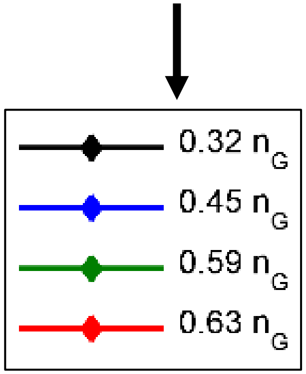




- ✓ *T. Long et al 2021 Nucl. Fusion 61 126066*
- ✓ *R. Ke et al 2022 Nucl. Fusion (accepted)*

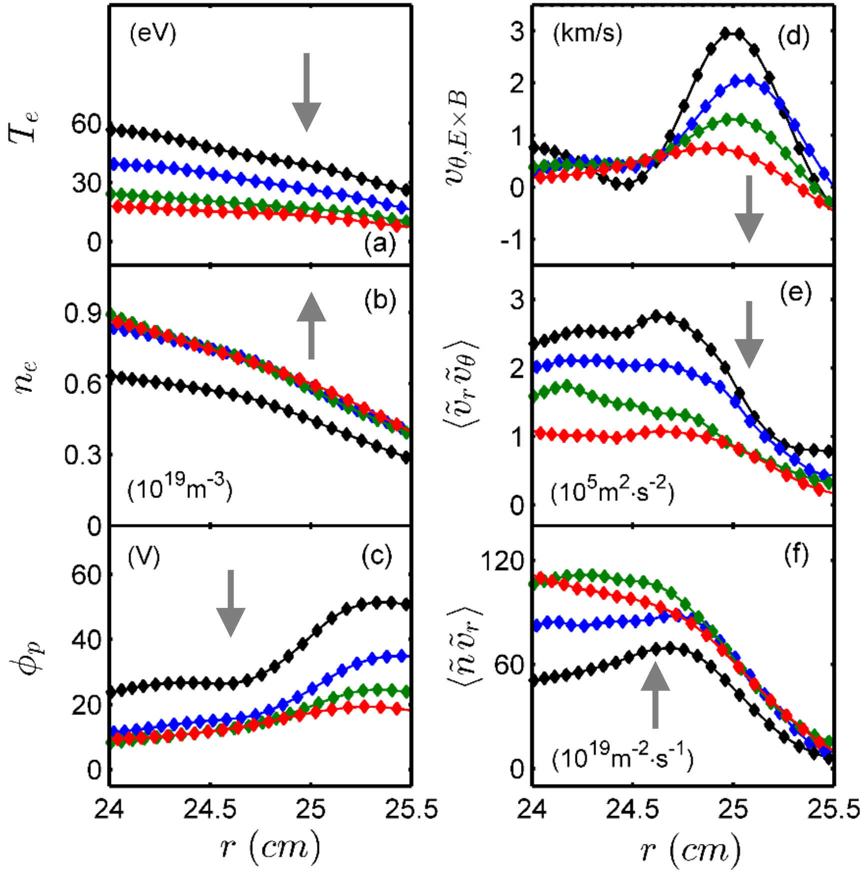
Back up

- As $\bar{n}$ →Greenwald density (n_G), edge $E \times B$ flow & shearing decrease



disruption density ~ $0.7\,n_G$

LCFS: $r = 25.5$ cm



edge shear layer
$E \times B$ flow

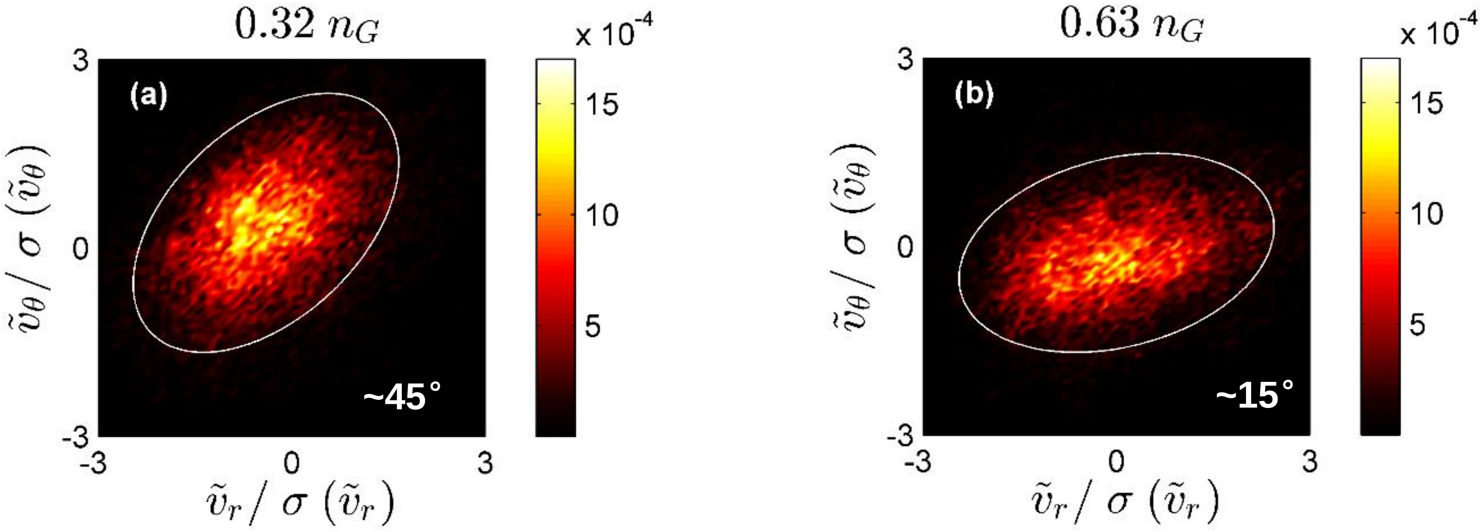
Reynolds stress

particle flux

Shear layer collapse → enhanced particle transport → edge cooling

Back up

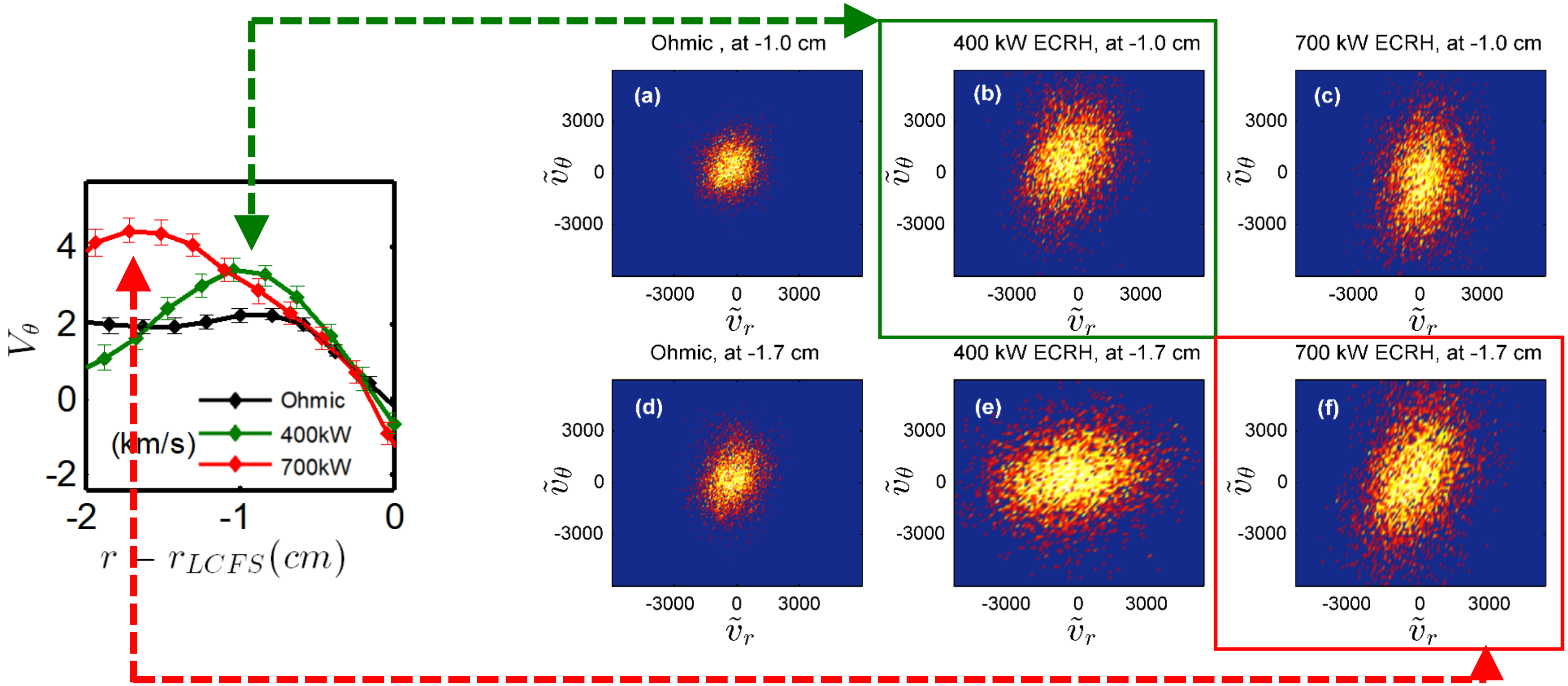
- **Joint PDF (normalized $\tilde{v}_r - \tilde{v}_\theta$) for $0.32\, n_G$ tilts more to 1st and 3rd quadrants than for $0.63\, n_G$**
- **Decreasing symmetry breaking in turbulence spectra: consistent with reduced Reynolds stress**



Decreased turbulent drive for edge $E \times B$ flow as $\bar{n} \rightarrow n_G$

Turbulent generation of edge poloidal flow

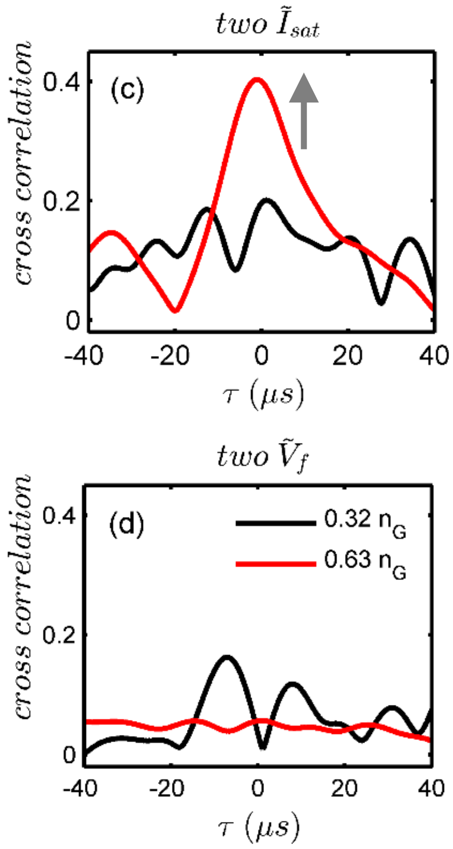
- **Result (not density limit study though) on HL-2A tokamak**
- **In turn, increasing symmetry breaking coincides with increased shear flow as ECRH power increases.**



✓ *T. Long et al 2019 Nucl. Fusion 59 106010*

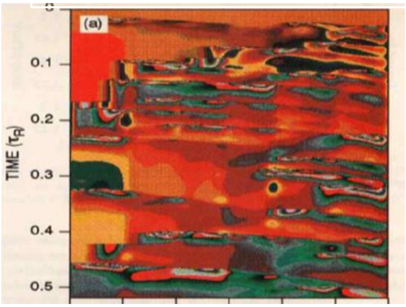
Particle transport events

- **Extended correlation in density but not in potential fluctuations**



pressure contour

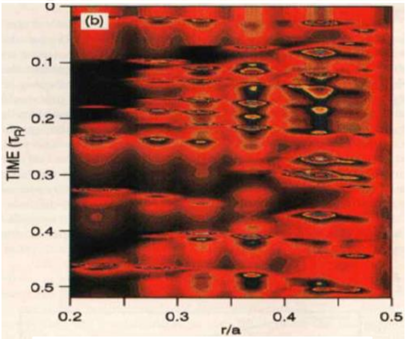
time



much wider spatial range

potential fluctuations contour

time



radial position

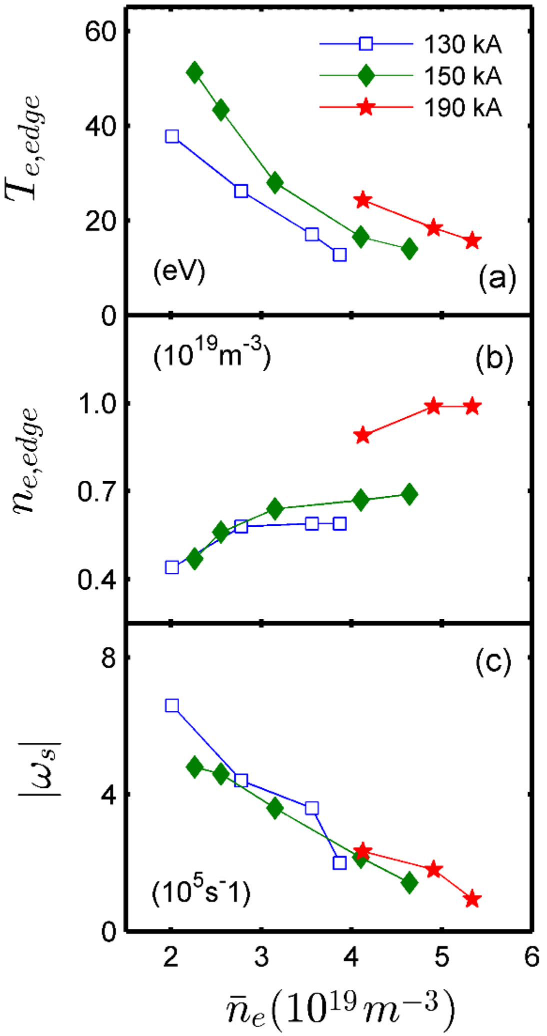
✓ *B. A. Carreras et al 1996 Phys. Plasma 3 2903*

“Small avalanches” in density fluctuations on a scale of the edge shear layer

Their onset coincides with shear layer collapse as $\bar{n} \to n_G$

Back up

- **As $n \rightarrow n_G$ for different I_p**



$$D_n = -\langle \tilde{n}\tilde{v}_r \rangle / \nabla n$$