On the origin of anomalous transport in the tokamak SOL

J. Horacek,[a,b] O. E. Garcia,[c] R. A. Pitts,[a] A. H. Nielsen,[c] W. Fundamenski,[d] J. P. Graves,[a] V. Naulin,[c] J. Juul Rasmussen[c]

[a] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association Euratom–Confédération Suisse, CH-1015 Lausanne, Switzerland*

[b] *Association EURATOM–Institute of Plasma Physics, Prague, Czech Republic*

[c] *Association EURATOM–Risø National Laboratory, OPL-128 Risø, DK-4000 Roskilde, Denmark*

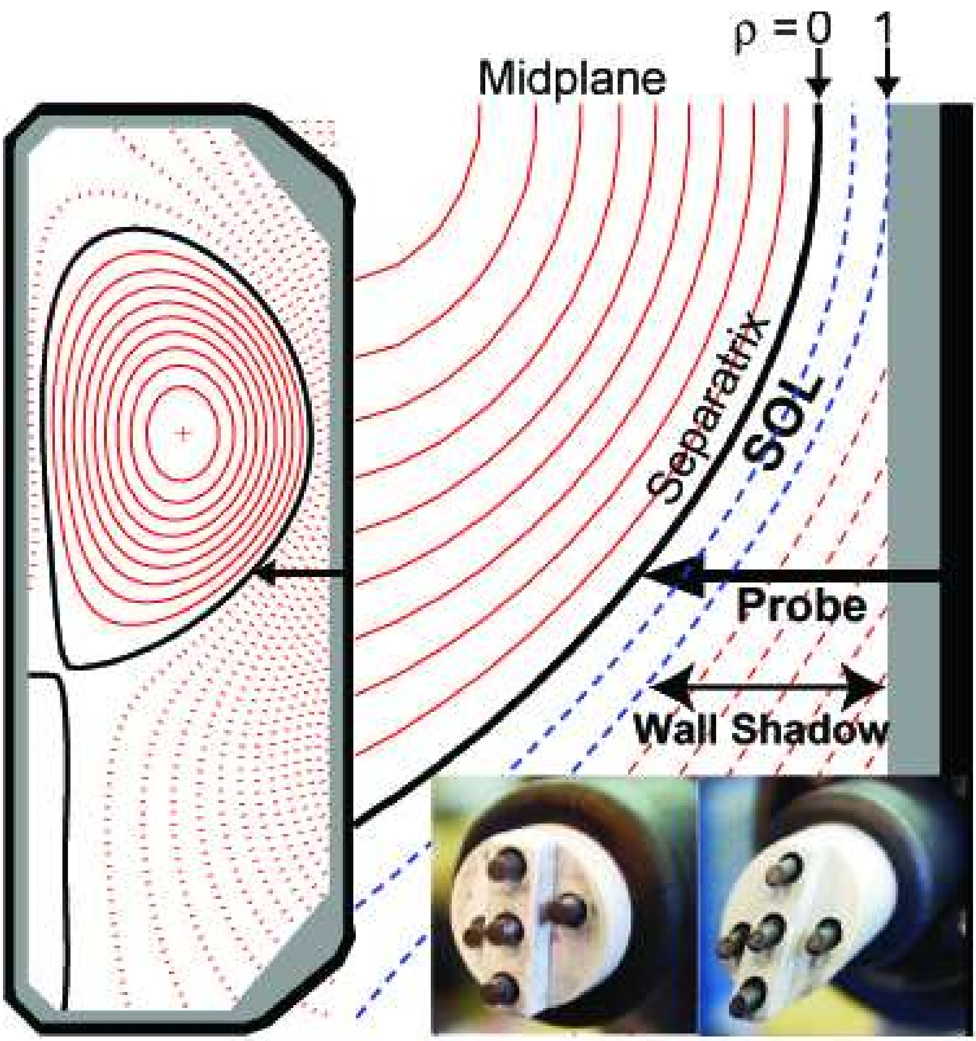
[d] *EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*

TCV Experiments

Ohmically heated, $340\,\text{kA}$ plasma current pulses

Single lower null magnetic divertor geometry

Two probe reciprocations in each discharge



TCV Density Scan Experiments

Pulse #	Reciprocation	$\overline{n}_e$ $[10^{19}\,\mathrm{m}^{-3}]$	Symbol
24530	2	11	▲ (red)
26092	1 & 2	8.4	▲ (green)
26060	1 & 2	6.5	◆ (black)
26084	1 & 2	4.8	▼ (blue)
24530	1	4.4	▼ (magenta)
ESEL			—●— (grey)

Pulse number 24530 is a density ramp experiment

- First reciprocation at low density
- Second reciprocation at high density

ESEL Turbulence Simulations

Two-dimensional domain at the outer midplane

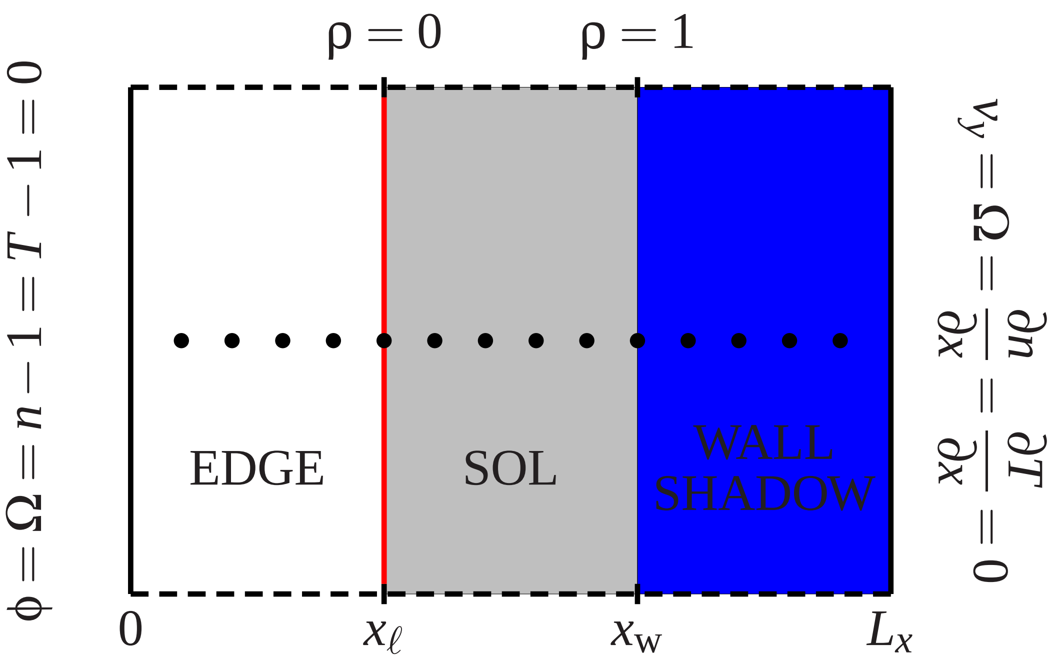
Vorticity, electron density and temperature evolution

Collective motions driven by the non-uniform $\mathbf{B}$ field

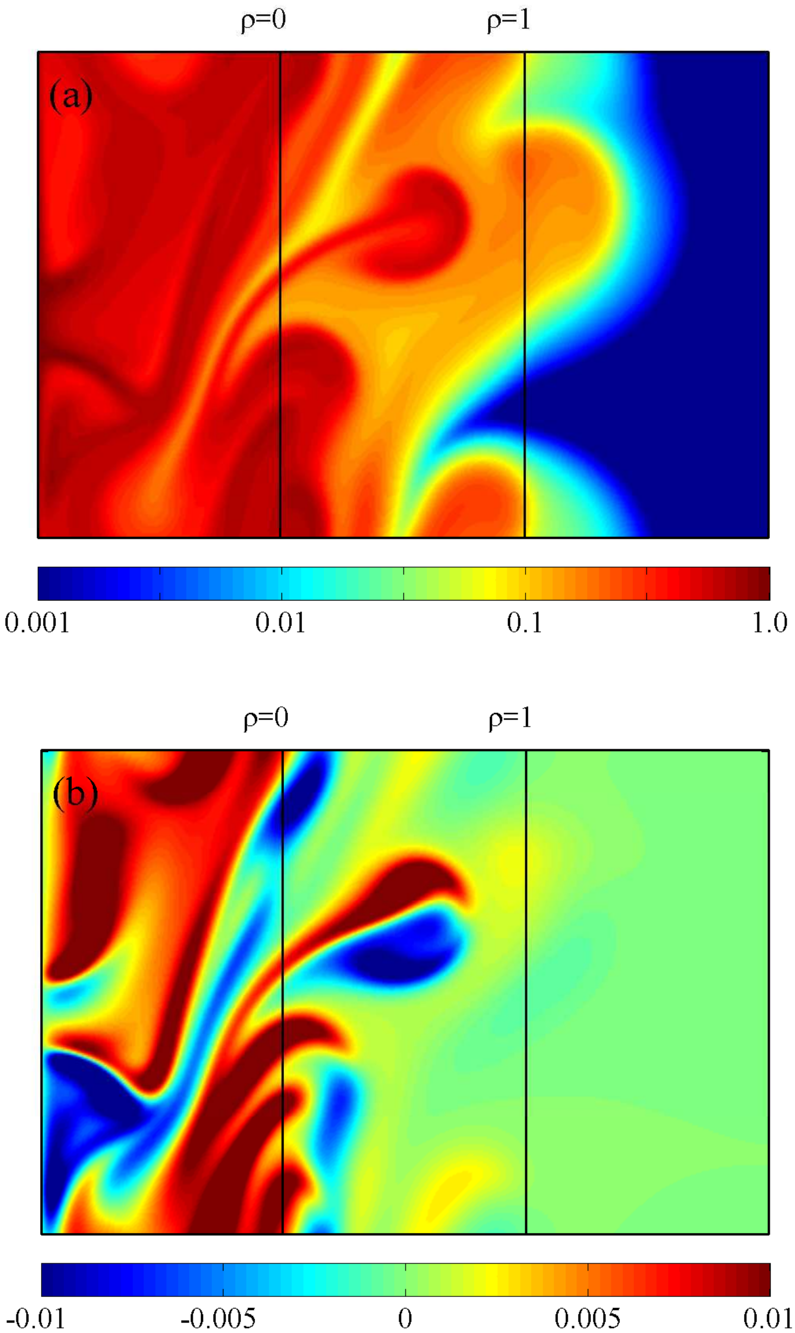
Linear SOL damping terms due to parallel transport

Model parameters set by a high density TCV case

Long time series recorded by an array of probes

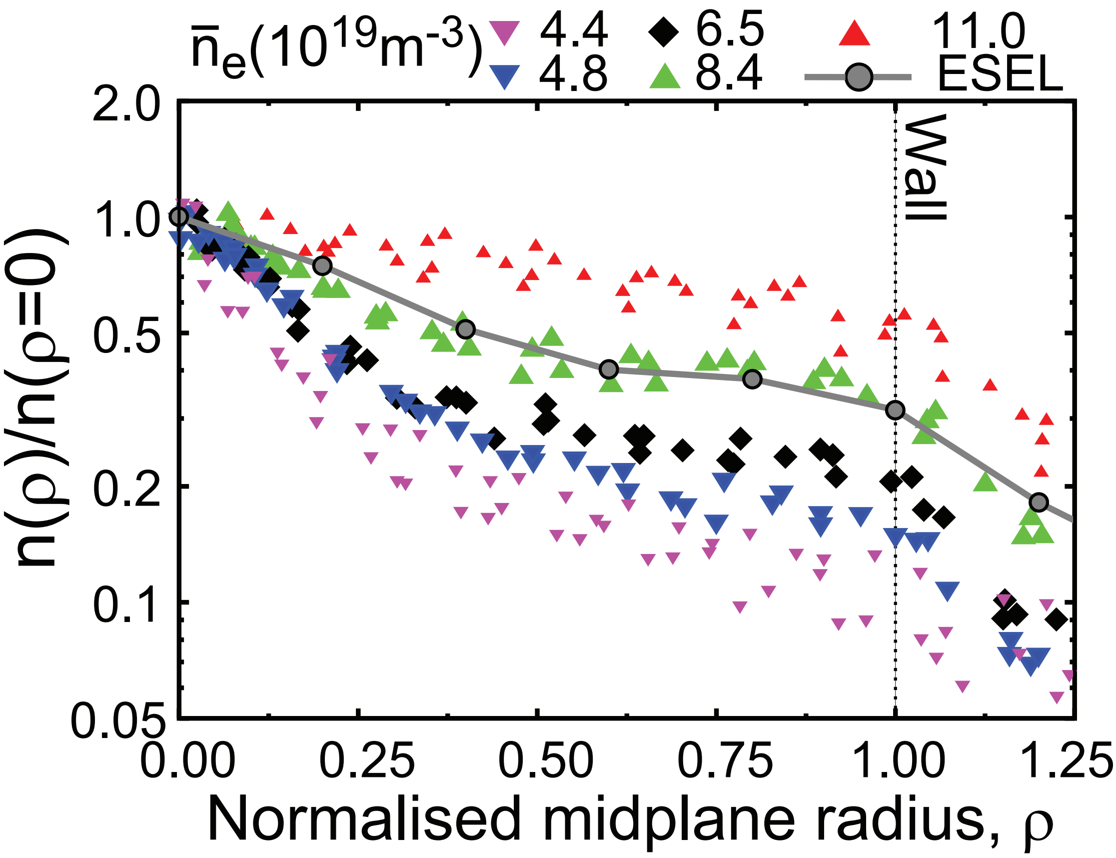


Density (a) and Vorticity (b) Structures



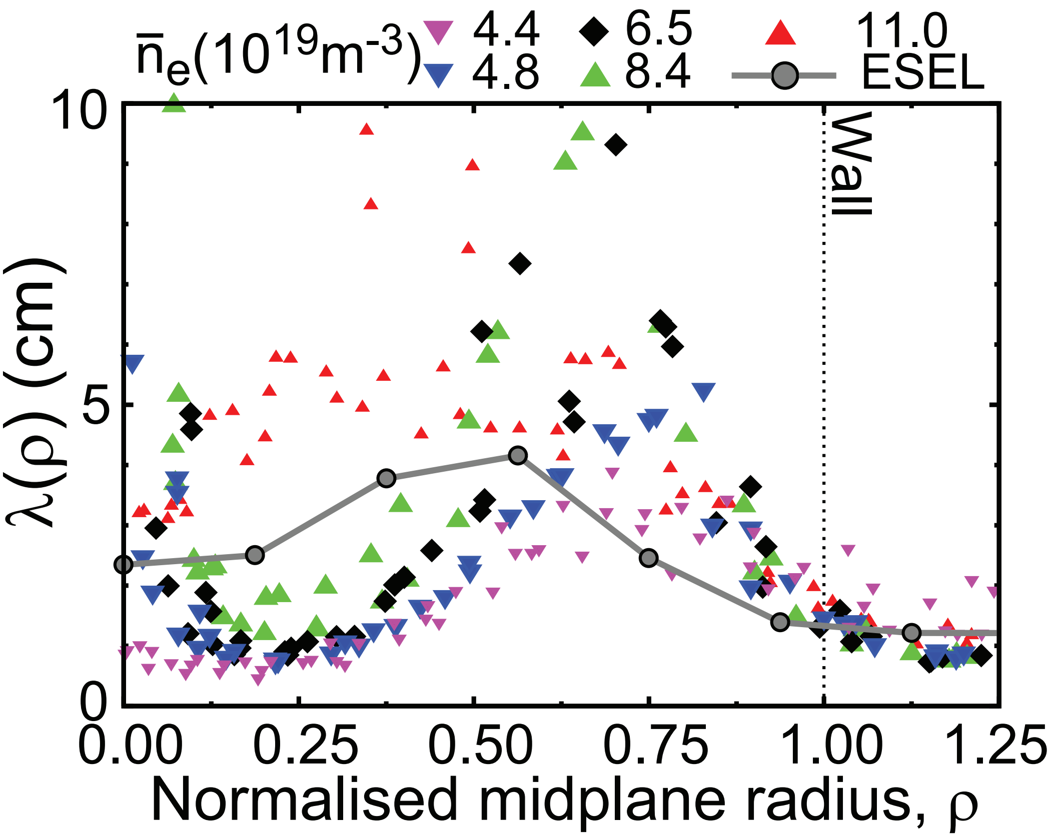
Animations: `ftp.risoe.dk/pub/plf/erga/esel`

Time-Averaged Density Profiles



- Steep in the vicinity of the separatrix for low $\overline{n}_e$
- Broad in the outer half of the SOL for all $\overline{n}_e$
- Broader in radial extent and scale length with $\overline{n}_e$
- Well matched with high density ESEL simulation

Exponential Density Scale Lengths

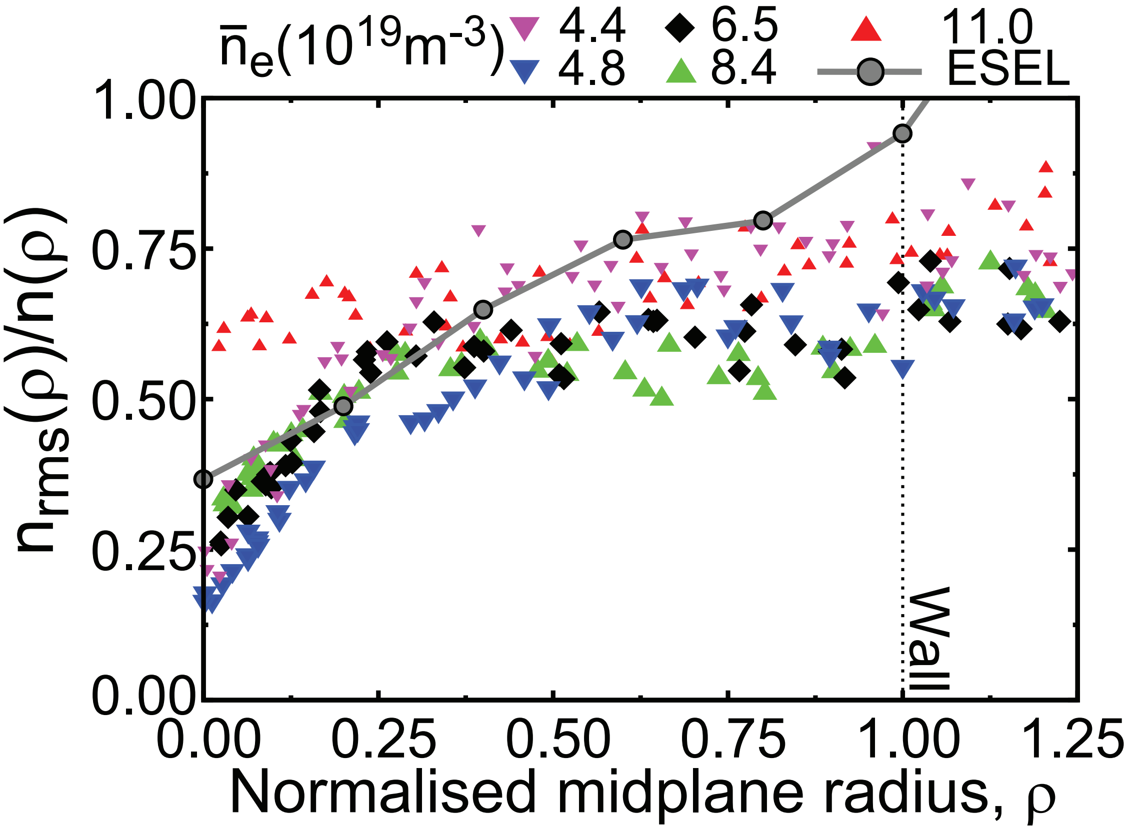


- Exponential density profile scale length defined by

$$\lambda_n = -\frac{n}{\partial n/\partial r} = -\frac{1}{\partial \ln n/\partial r}$$

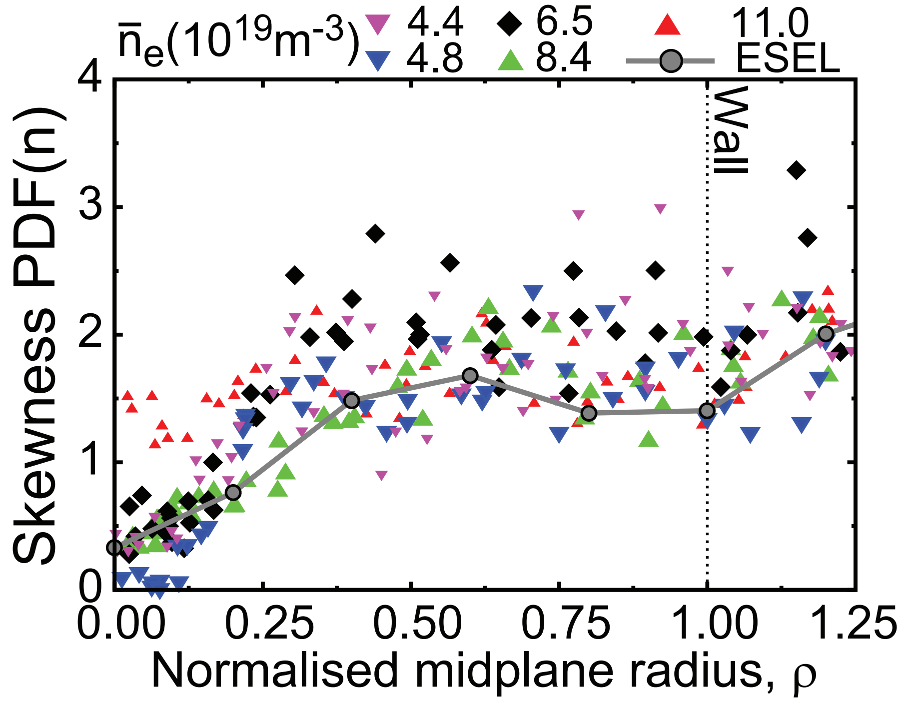
- Steep profile in near SOL for low $\overline{n}_e$
- Broad throughout SOL for high $\overline{n}_e$

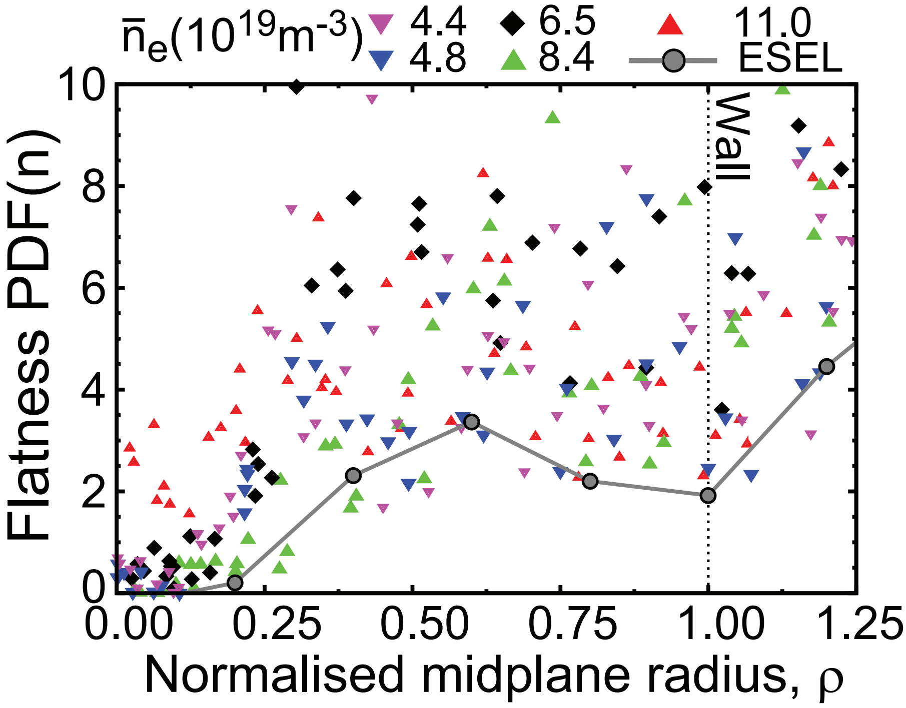
Relative Density Fluctuation Level



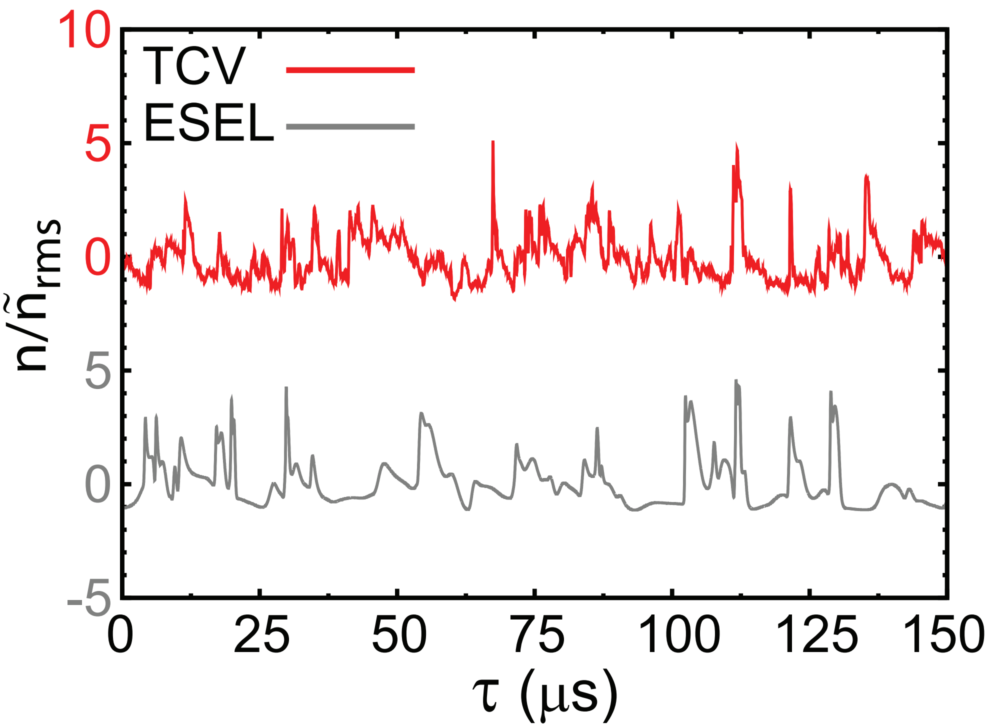
- Relative fluctuation level of order unity
- Similar values in region with broad profiles
- Well matched by ESEL turbulence simulation
- True also for skewness and flatness moments

Particle Density Skewness and Flatness



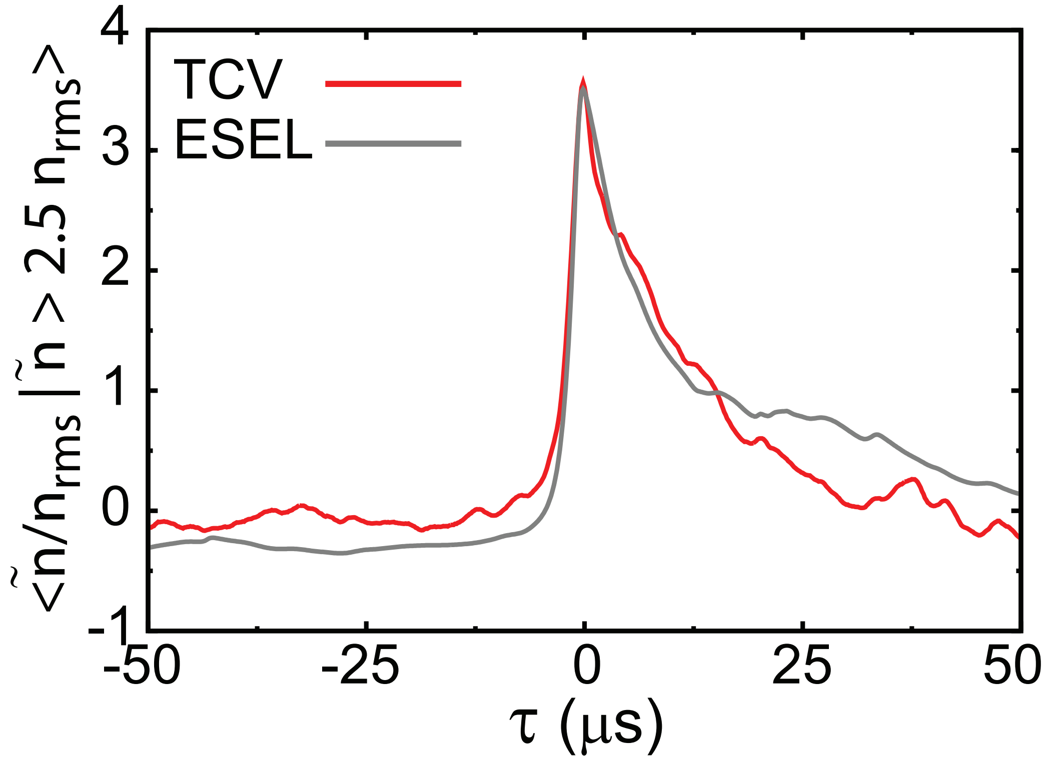


Raw Times Series at Wall Radius



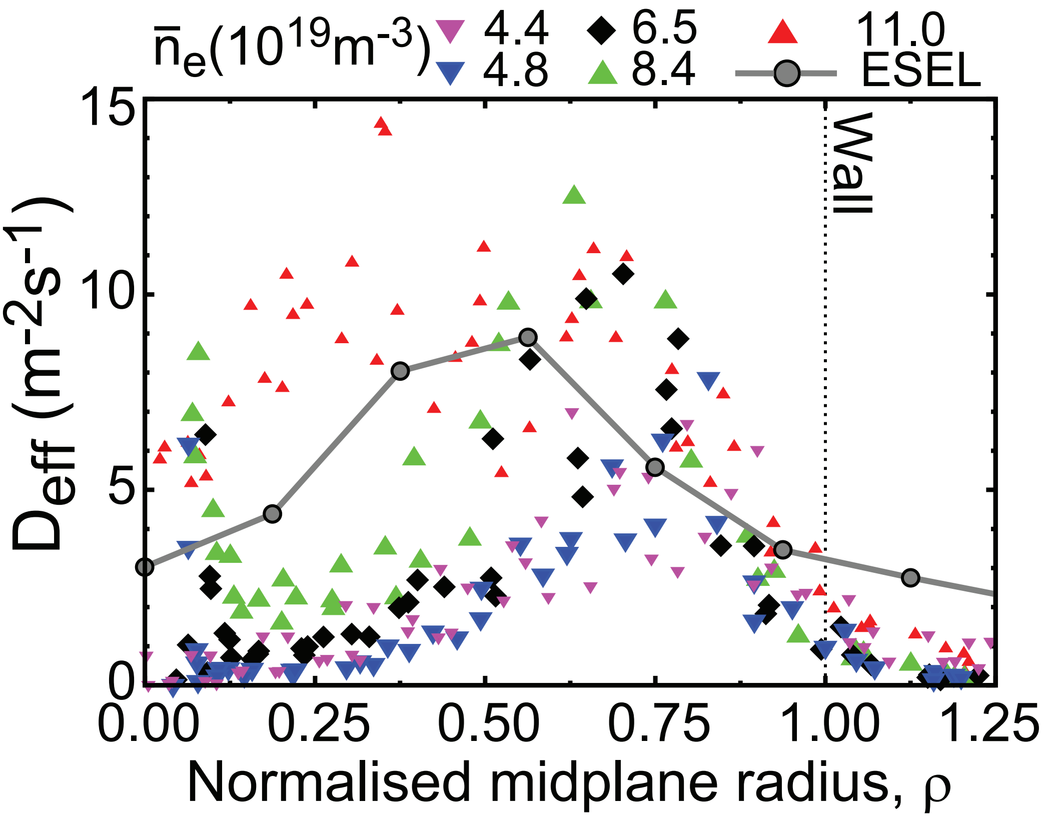
- Abundance of large amplitude positive bursts
- Apparent time-asymmetry for the large events
- Well matched by ESEL turbulence simulation

Conditional Average at Wall Radius



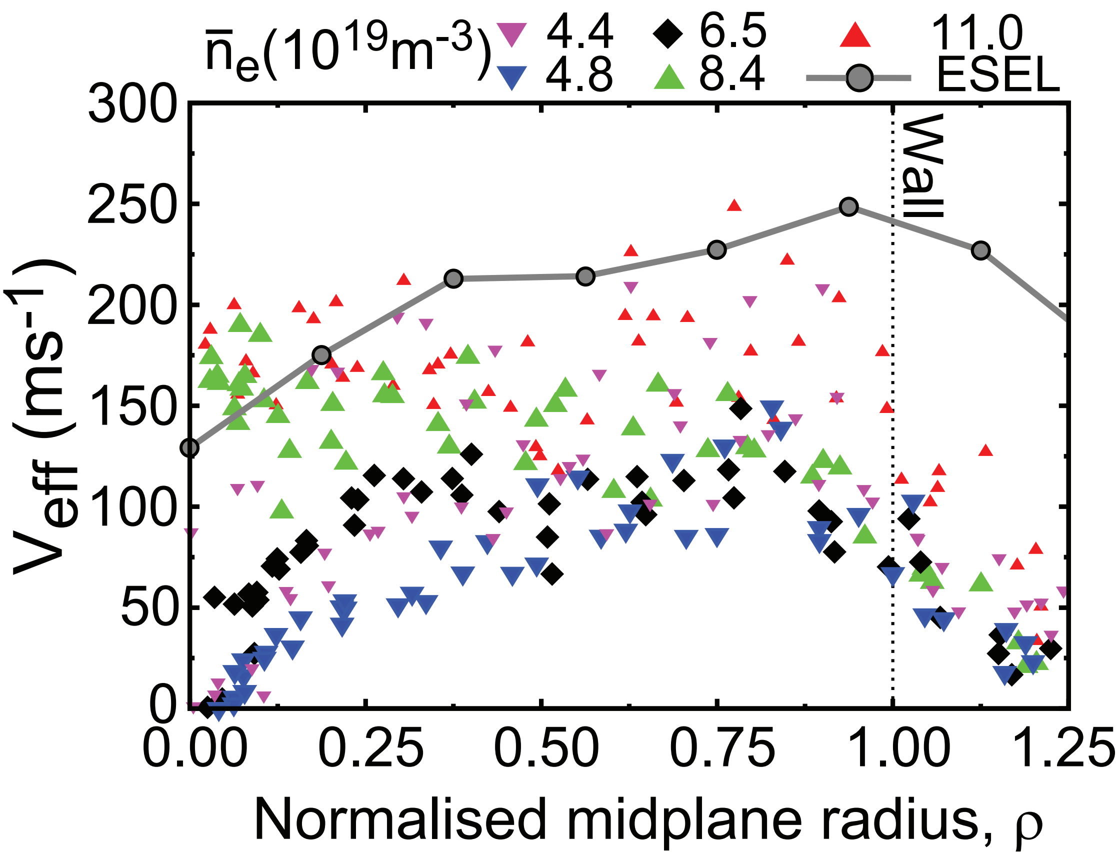
- Time series dominated by large-amplitude bursts
- Asymmetry with steep front and trailing wake
- Due to radial motion of blobs in the simulations
- Well matched by ESEL turbulence simulation

Effective Diffusion Coefficient



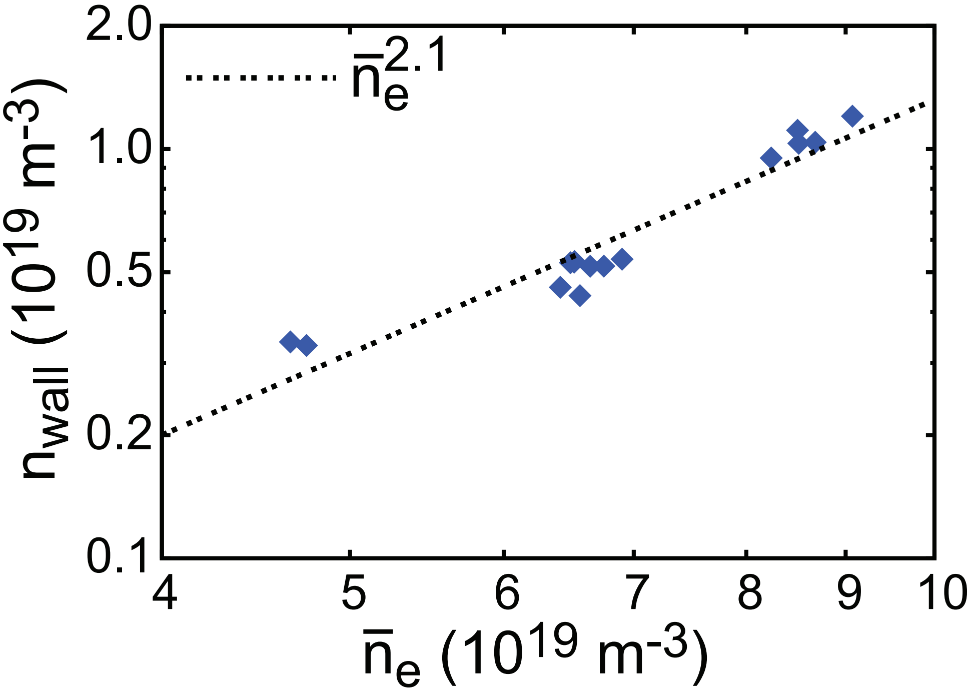
- D_{eff} defined by $\lambda_n \Gamma / n$
- Strong radial variation of D_{eff} for all $\overline{n}_{\text{e}}$
- D_{eff} differs in both magnitude and shape
- High density cases well matched by ESEL

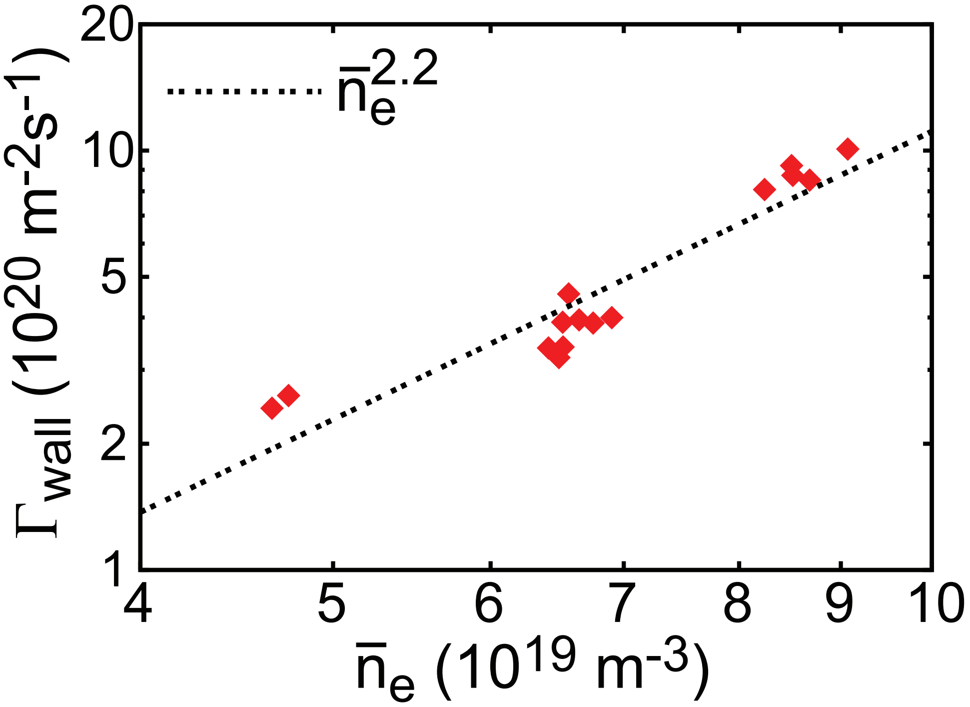
Effective Convection Velocity



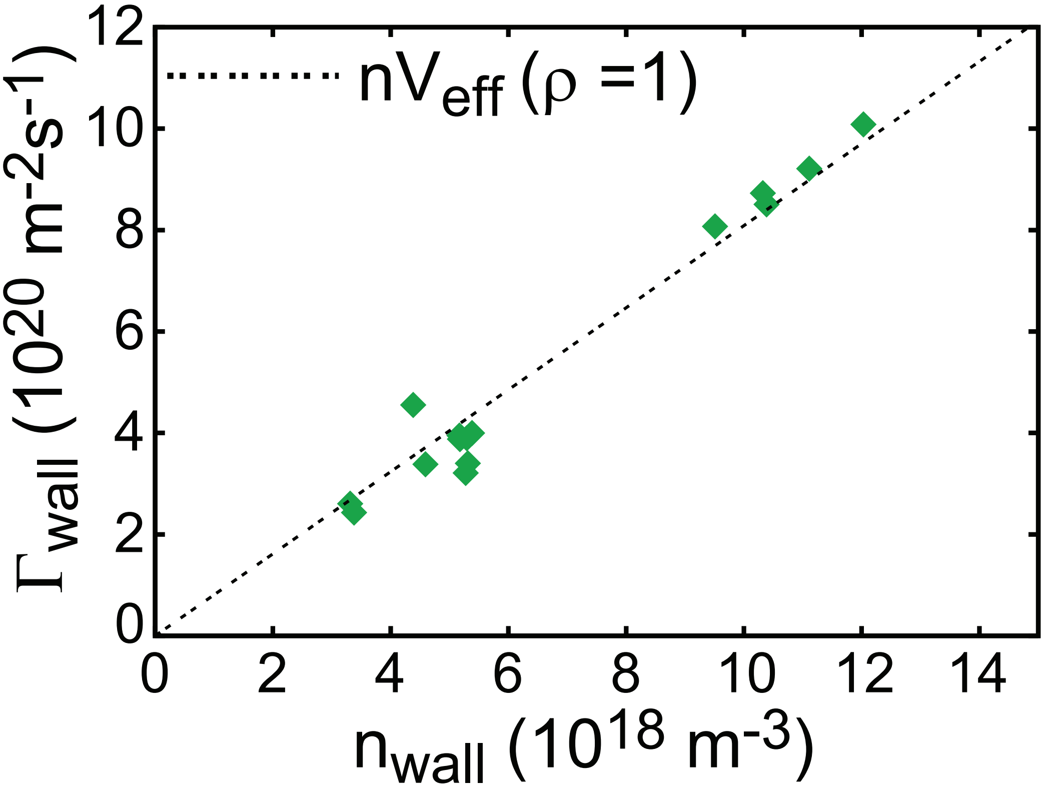
- $V_{\rm eff}$ defined by Γ/n
- Strong radial variation for low density cases
- $V_{\rm eff}$ roughly constant for high density cases
- Same value of $V_{\rm eff}$ in region with broad profiles

Particle and Flux Density Scaling



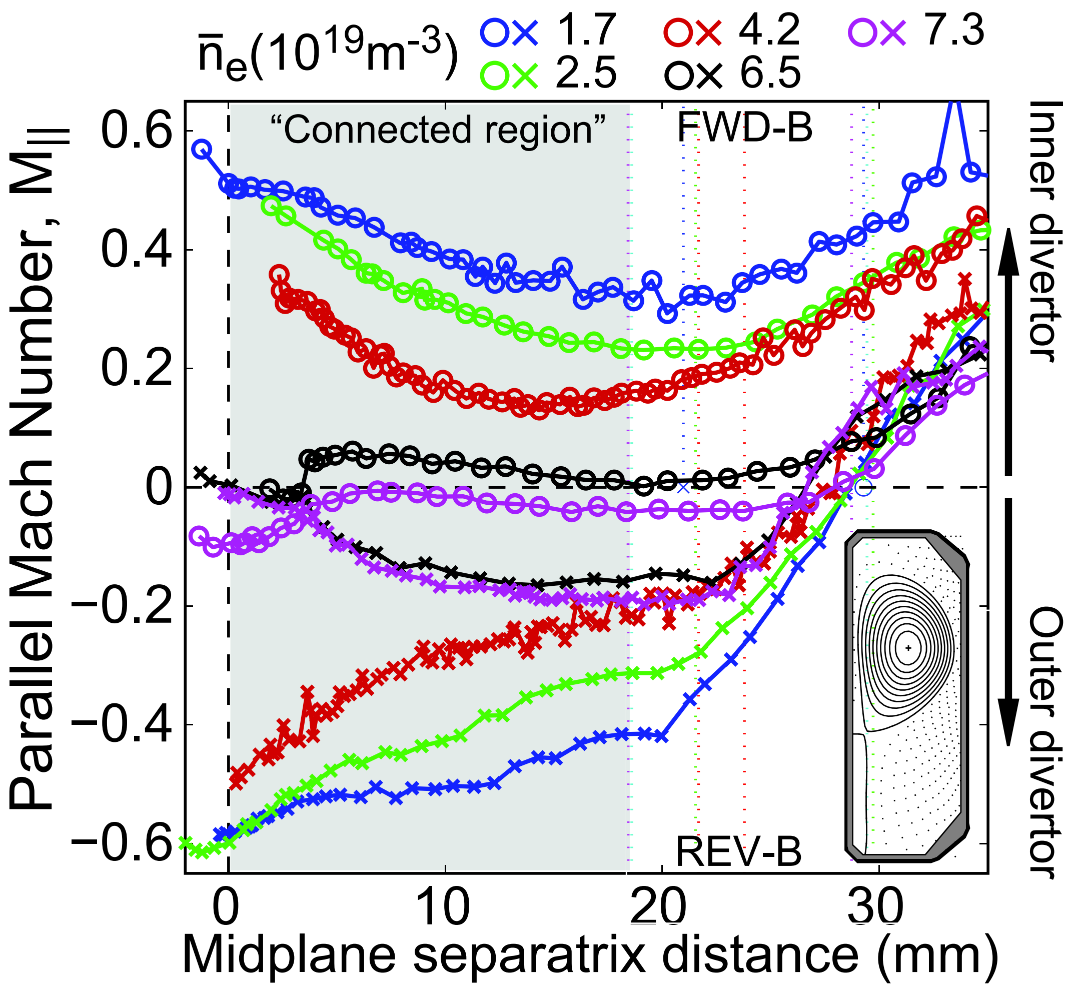


Local Flux vs Density Scaling



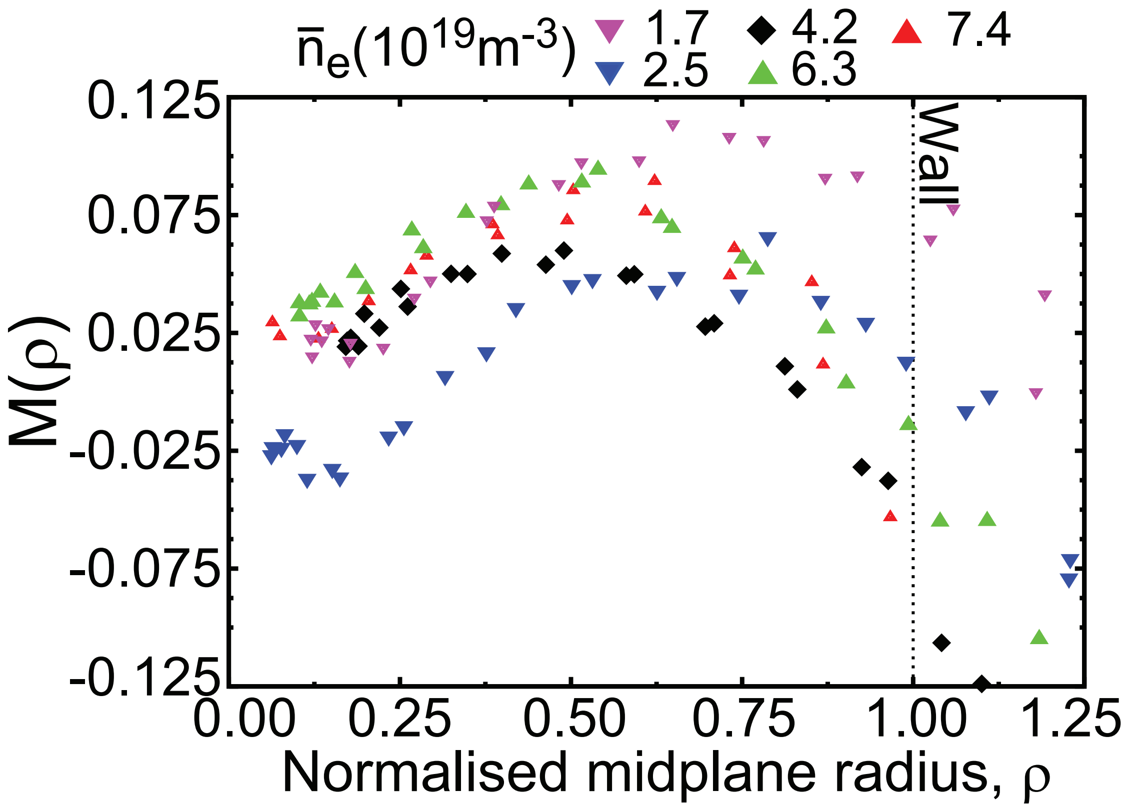
- Particle density at wall radius scales as $\overline{n}_{\text{e}}^{2.1}$
- Turbulent flux at wall radius scales as $\overline{n}_{\text{e}}^{2.2}$
- Their relation at wall radius is $\Gamma = V_{\text{eff}}\, n$
- Convective velocity $V_{\text{eff}}(\rho = 1) \approx 75\,\text{m}\,\text{s}^{-1}$.

Measured Parallel Flow Profiles



- Flow experiments performed at $I_{\rm p} = 260\,$kA
- Parallel flow component measured by Mach probe
- Matched FWD/REV $\mathbf{B}$-field pulses for each $\overline{n}_{\rm e}$

Transport Driven Parallel Flows



- Mean value of FWD/REV yields 'offset' component
- Magnitude of offset in central SOL is $0.025 - 0.125$
- Flow is directed towards the outer divertor
- Consistent with flow driven by ballooning of turbulent transport at the outer midplane

Estimate From Pressure Fluctuations

Normalized parallel flow due to turbulent pressure fluctuations can be estimated with the following ansatz:

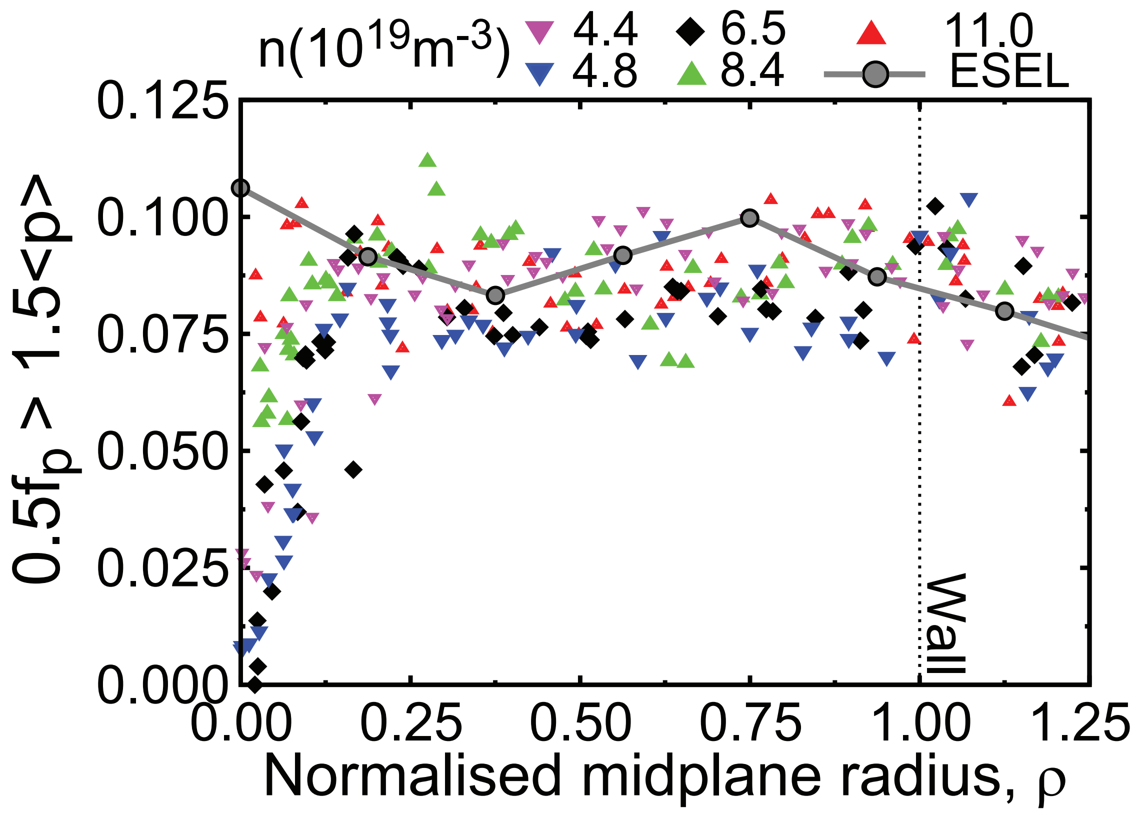
$$0.5 f_p = 0.5 \frac{t_{p>\alpha\langle p\rangle}}{\triangle t}$$

where we have defined

- 0.5 as the normalized transient flow amplitude
- $\langle p\rangle$ is the local time-averaged pressure
- $\triangle t$ is the total length of the time series
- $t_{p>\alpha\langle p\rangle}$ is the fraction of time that the pressure exceeds the local value by a factor α

Ansatz assumes that localized high pressure plasma filaments transiently set up parallel SOL flows.

Estimated Parallel Flow Profiles



- Amplitude agrees with measurements at low I_p
- Predicts transport driven parallel flow with amplitude in agreement with field independent offset at $I_\mathrm{p} = 260\,\mathrm{kA}$
- Roughly constant as function of radius and $\overline{n}_\mathrm{e}$
- Reasonably well matched by the ESEL simulation

Conclusions

The behaviour of time-averaged plasma profiles in the TCV SOL show a behavior with increasing line averaged density similar to that seen in other tokamaks: the profiles become broader in both scale length and radial extent.

Moreover, the fluctuation statistics in the region of broad plasma profiles remain the same. This a further manifestation the universal statistical properties seen in TCV probe time series.

At the wall radius the local plasma transport is well described in terms of an effective convective velocity.

Estimates of transport-driven parallel SOL flows due to transient over-pressure in filament structures at outer midplane is in agreement with the Mach probe measured field independent flow offset.

ESEL interchange turbulence simulations are in quantitative agreement with most of the experimental measurements, demonstrating that intermittent plasma transport can be ascribed to radial motion of plasma blobs.

References

TCV Experiments

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ESEL Simulations

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Also see PSI 2006 proceedings to appear in JNM

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