On the energy transfer between flows and turbulence in the plasma boundary of fusion devices

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The mechanisms underlying the generation of plasma flows play a crucial role in understanding transport in magnetically confined plasmas. It is accepted the important role of momentum fluxes (perpendicular and parallel) in the suppression of turbulence and in the access to improved confinement regimes in fusion plasmas.

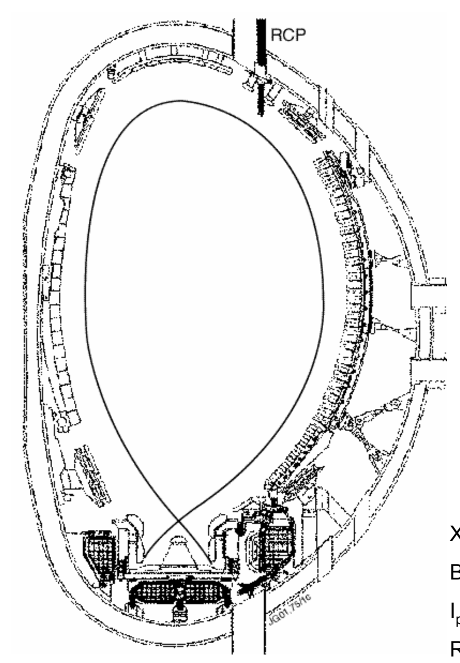
PDFs of fluctuations and turbulent transport have shown evidence of multiple radial scale lengths in the plasma boundary region. Radial effective velocities and turbulence radial coherence are modified in the presence of sheared poloidal flows. These findings show a link between the structure of SOL profiles, sheared flows and turbulence statistical properties.

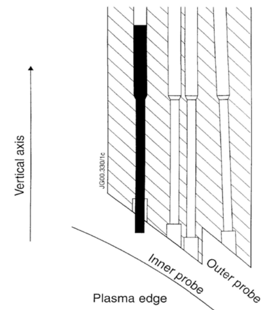
In the plasma boundary region of JET tokamak the energy transfer (per unit mass and unit time) from DC flows to turbulence is directly related with the momentum flux and the radial gradient in the flow. The energy transfer can be either positive or negative (implying a damping of DC plasma flows due to turbulence or acceleration via turbulence). These results show the dual role of turbulence as a damping (eddy viscosity) and driving of flows in fusion plasmas.

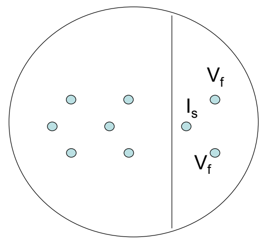
The Reynolds stress terms can also provide a mechanism for parallel momentum redistribution. The first experimental evidence of significant radial gradients in the cross-correlation between parallel and radial fluctuating velocities near the LCFS in JET tokamak and in the plasma boundary region of the TJ-II stellarator is reported.

EXPERIMENTAL SET-UP

The JET plasma boundary region was studied using a fast reciprocating Langmuir probe system.







Arrays of Langmuir probes allow the simultaneous investigation of the radial structure of fluctuations and electrostatic driven turbulent transport.

$\Delta r = \Delta\theta \sim 5$ mm

X-point plasma configurations

B_T = 1 - 2.5 T

I_p = 1 – 2.2 MA (ohmic), P_{NBI} = 5 MW) (L-mode) .

Radial ExB turbulent induced fluxes, , neglecting the influence of T_e.

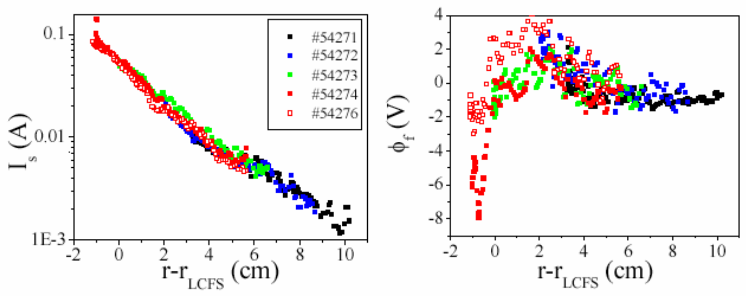
Effective radial velocity (v_r) defined as the normalized Γ_{ExB} / I_s

EVIDENCE OF MULTIPLE SCALES IN EDGE TRANSPORT

A velocity shear layer exists near the location of the Last Closed Flux surface (LCFS) in the JET tokamak.

The poloidal phase velocity of fluctuations (vphase) increases in the electron drift direction up to 2000 m/s, in the proximity of the separatrix

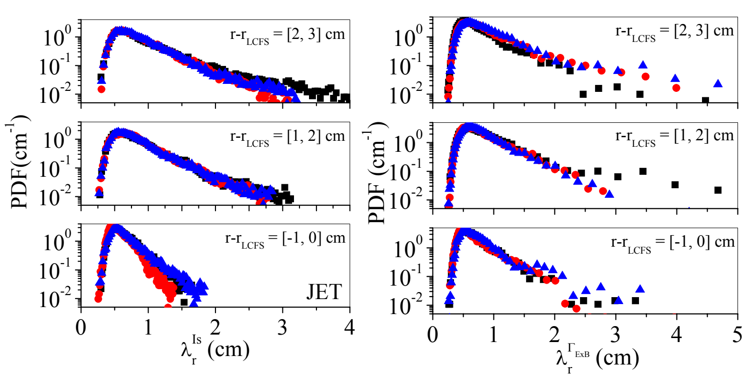
Radial gradient in vphase is ~10^5 s^{-1}, comparable to the inverse of the correlation time of fluctuations (t ≈10 ms) [8].



Radial profiles of ion saturation current and floating potential in the JET boundary region (ohmic plasmas) in reproducible discharges. The reproducibility in the measured radial profiles is very good.

Observations in TJ-II stellarator show that the development of the velocity shear layer at the LCFS requires a minimum plasma density above which the poloidal phase velocity reverses => <u>both in tokamaks and stellarators, spontaneous sheared poloidal flows and fluctuations remains near marginal stability.</u>

Statistical properties of the radial coherence computed from the cross correlation of ΓExB signals and floating potential signals.

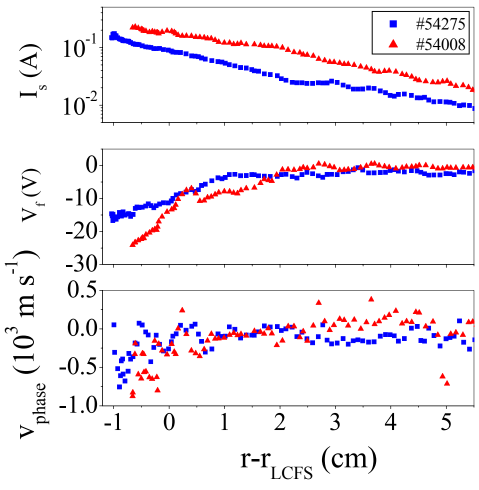


•Correlation length (λ_c) computed assuming exponential decay between two probes radially separated.

•**Multiple radial scale lengths in the JET plasma boundary region,** both in ohmic and L-mode plasmas.

•**Tails in radial-PDFs are modified in the presence of sheared poloidal flows.**

DYNAMICAL COUPLING BETWEEN FLUCTUATIONS IN GRADIENTS AND RADIAL VELOCITIES: INFLUENCE ON SOL PROFILES

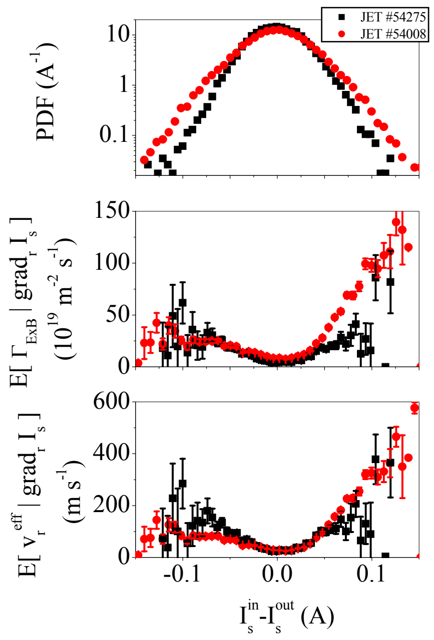


Influence of heating power has been investigated comparing ohmic plasmas (B = 2 T / Ip = 2 MA) and L-mode plasmas (B = 2 T / Ip = 2 MA, PNBI = 5 MW).

•Ion saturation current increases in L-mode as compared with ohmic plasmas.

•At the inner probe position ($r-r_{LCFS}$ ≈ -1 cm) the poloidal phase velocity increases up to 500 m/s, both in ohmic and L-mode plasmas.

The location of the velocity shear layer has been used as reference.



As heating power and density increases:

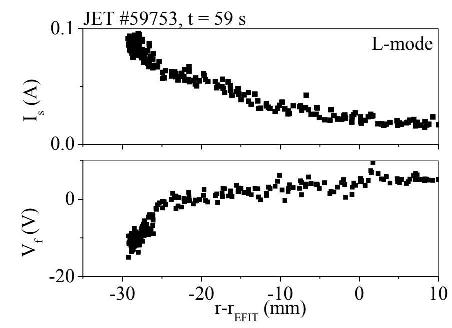
• the PDF of the ion saturation current becomes broader due to the increase of large amplitude events;

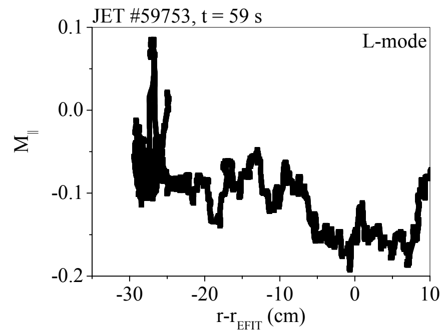
•the relation between fluctuations in gradients and transport becomes much steeper and the **effective radial velocity of transport events also increases up to 600 m/s for** .

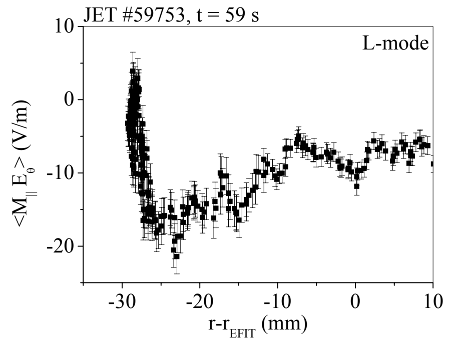
•**Radial velocity increases linearly with the size of transport events** (consistent with investigation of the radial propagation of ELMs events which also suggest an increase in the radial velocity of ELM events with their amplitude [1]).

ON THE CROSS-CORRELATION BETWEEN PARALLEL AND RADIAL FLUCTUATING VELOCITIES

The contribution of the Reynolds stress term, $d < \tilde{v}_r \tilde{M}_{||} > / dr$ (v_r fluctuating (ExB) radial velocity and $M_{||}$ the fluctuating parallel Mach number), provides the mechanism to convert the turbulent scales (high frequency fluctuations) into a mean parallel flow.







Radial profiles of ion saturation current, floating potential, Mach number and cross-correlation between parallel and radial fluctuating velocities in JET L-mode plasmas near the LCFS.

In the plasma region where the floating potential becomes more negative (closed to the region where the perpendicular velocity shear is developed)

⇒ <u>significant radial gradients (in the order of 10^3 – 10^4 s^{-1}) in the cross-correlation between parallel and radial fluctuating velocities.</u>

Experiments in TJ-II stellarator have also shown radial variations in the cross correlations between parallel and radial velocity fluctuations (comparable to JET) near the LCFS.

<u>These gradients are due to the radial variations in the level of poloidal electric filed fluctuations and in the cross-phase coherence.</u>

Damping of the plasma rotation due to charge-exchange can be expressed as, $\nu_{cx} M_{||}$, (being ν_{cx} the collision frequency for the charge-exchange reaction).

Assuming for JET neutral density near the LCFS, n_n ≈ 10^{16} m^{-3} (the upper limit value obtained from EDGE2D) it follows that $\nu_{cx} = n_n < \sigma v >_{cx} \approx 10^3 s^{-1}$

Experimental results show that the <u>contribution of</u> $d < \tilde{v}_r \tilde{M}_{||} > / dr$ <u>is larger than charge-exchange loss mechanisms in the parallel momentum balance equation at the plasma boundary region.</u>

However, a quantitative estimate of the role of turbulence would need to consider all mechanisms (driving / damping) contributing to the parallel momentum.

ENERGY TRANSFER BETWEEN FLOWS AND TURBULENCE

•Electrostatic radial-poloidal component of Reynolds stress $< \tilde{v}_\theta \tilde{v}_r >$ is computed from electric field estimates, taking into account the ExB drift fluctuating velocities ($\tilde{v}_\theta = \tilde{E}_r \times B / B^2 ; \tilde{v}_r = \tilde{E}_\theta \times B / B^2$).

•The mean perpendicular velocity of fluctuations can be estimated by the two points correlation technique [10] at two radial positions using probes poloidally separated.

⇒ The radial component of perpendicular velocity gradient can be estimated.

Turbulence production term (P) [2,3]

$$P = -< \tilde{v}_r \tilde{v}_\theta > \frac{\partial v_\theta}{\partial r}$$

•P gives a measure of the amount of energy (per unit mass and unit time) that is transferred between mean flow and fluctuations.

The averaged quantities, cross-correlations and perpendicular mean velocities are calculated using 2500 signal points (5 ms)

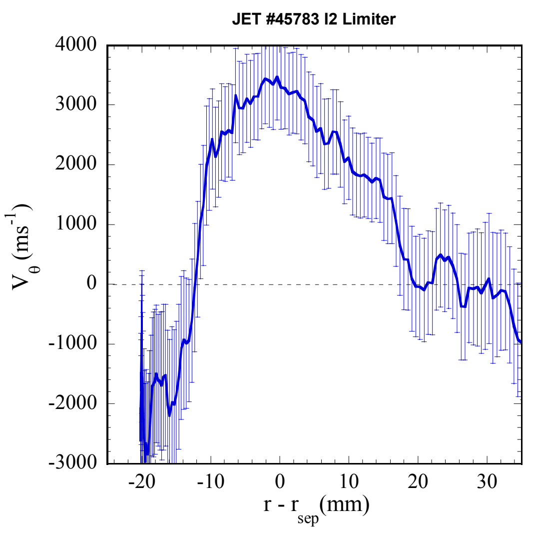
⇒ The probe, and also the measured signals, can be considered stationary

Limiter configuration

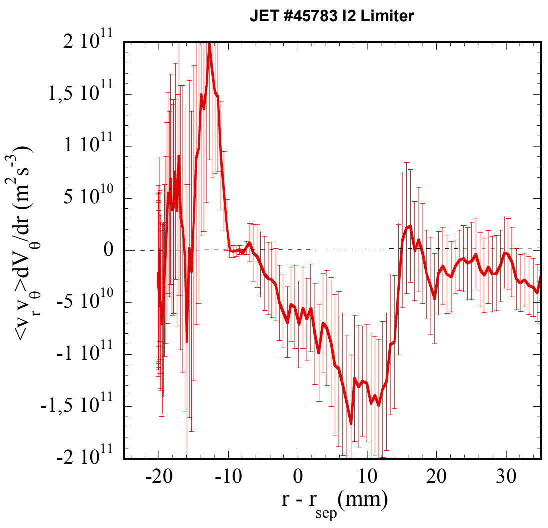
•Ohmic heating

•Magnetic field B=2.4 T

•The angle between "radial" and poloidal components of electric field close to 90º.



Poloidal velocity of fluctuations measured in JET plasma discharge 45783 under limiter configuration, ohmic heating



Turbulence production term measured in JET plasma discharge 45783 under limiter configuration, ohmic heating

•Error bars take into account the statistical errors in cross-correlation calculation (Reynolds stress) and also the error in mean velocity estimates.

•Given the signs taken in calculations, positive sign in P means energy going from the mean flow to the fluctuations, and negative the opposite situation.

•<u>**Two different signs are found in P**</u>

⇒ Turbulence acts as **<u>an energy sink</u>** for the mean flow (viscosity) at the velocity shear location

⇒ Turbulence acts as **<u>an energy source</u>** (pumping) in the scrape-off layer (SOL) side.

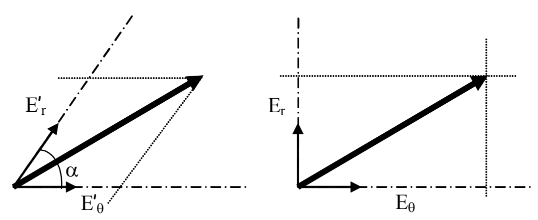
Divertor configuration

•Ohmic heating

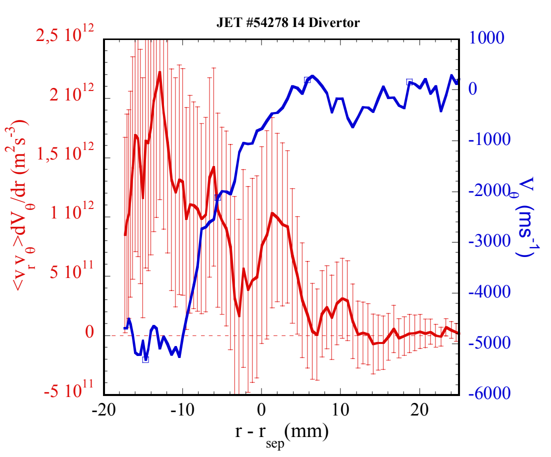
•Magnetic field B=2.4 T

•The angle between estimates of "radial" ($[\phi_J - \phi_A]/ \Delta r$) and poloidal ($[\phi_A - \phi_B]/ \Delta\theta$, $[\phi_J - \phi_H]/ \Delta\theta$) components of electric field is close to 60º.

⇒ <u>A correction can be applied</u> in order to obtain an estimate of E_r (and consequently) in an orthogonal frame of reference.



$$E_r = -\frac{\cos\alpha}{\sin\alpha} E_\theta' + \frac{1}{\sin\alpha} E_r'$$



•Production term is positive near the region with strong sheared flows

•No evidence of negative production region is seen in this case.

Production term and poloidal velocity of fluctuations measured in JET plasma discharge 54278 under divertor configuration taking into account the axis correction

The energy approach. A qualitatively different point of view.

•No hypothesis is made about flux surface averaging, like it was implicit in previous works computing the radial-poloidal component of Reynolds Stress [4-7].

•Averaged quantities are time-averaged and flux surface averaging is not supposed.

•Present measurements can be considered as local estimates. Care should be taken to extrapolate from these local measurements to the whole plasma

Two different regions in the radial profile have been observed.

•In the plasma region with strong gradients in the perpendicular velocity P > 0

⇒ Fluctuations are generated by the mean flow shear thus acting as a viscous term for the mean flow.

•In the SOL side of the velocity shear layer P < 0

⇒ In this region fluctuations contribute to pump the mean flow. No pumping region (P negative) has been observed in divertor configurations.

How relevant is the contribution of turbulence to DC plasma momentum (kinetic energy)?

•Shot #45783 (limiter) as reference.

- The **turbulent viscosity** (ν_T) in the flow shear region is

$$\nu_T = \frac{< v_\theta v_r >}{\partial v_\theta / \partial r} = \frac{(3.6 \pm 0.2)\times 10^5}{(4.3 \pm 2)\times 10^5} \approx (0.8 \pm 0.4)\ m^2/s$$

⇒ <u>ν_T is comparable to the particle diffusivity</u> (D ≈ 1 m²/s), in consistency with previous measurements [8, 9].

⇒ As far as the authors know this is <u>the **first direct measurement of turbulent viscosity in fusion plasmas**</u>,

- At the region were the production term is negative (flow pumping) (see figure)

$$P = -< v_\theta v_r > \frac{\partial v_\theta}{\partial r} \approx (-1.2 \pm 0.5)\times 10^{11}\ W/kg$$

⇒ The turbulence production term is close to the power per unit mass necessary to pump the flow up to the velocity value experimentally measured.

$$\frac{E}{\tau_t} = \frac{\frac{1}{2} v_\theta^2}{\tau_t} = \frac{(1.25 \pm 0.8)\times 10^6\ m^2/s^2}{(2.25 \pm 0.7)\times 10^{-5}\ s} \approx (5 \pm 4.6)\times 10^{10}\ W/kg$$

⇒ This result suggests that <u>the magnitude of **mean flow generated by turbulence is relevant for plasma rotation.**</u>

CONCLUSIONS

•Multiple radial scale lengths in the JET plasma boundary region were observed.

•The dynamical interplay between fluctuations in gradients and radial velocities is strongly modified in different plasma confinement regimes. Strong increase in the radial velocity of large transport events in L-mode plasmas.

⇒ Present findings show the importance of the statistical characterization of the radial scales of transport and fluctuations to improve our understanding of the physics underlying transport processes in fusion plasmas.

•The investigation of the interaction between flows and fluctuations become one of the important open issues in the plasma edge dynamics and an active research programme in progress in tokamaks and stellarators.

⇒ Experiments carried out in the plasma boundary of JET tokamak and TJ-II stellarator have shown the existence of significant gradients in the cross-correlation between parallel and perpendicular flows as well as a dynamical coupling between edge (ELM-like) instabilities and parallel flows. In the TJ-II stellarator, the level of edge fluctuations is linked with the evolution of parallel flows.

•The energy transfer from mean flows to turbulence (P), directly related with the momentum flux (e.g.) and the radial gradient in the flow, can be both positive (energy transfer from DC flows to turbulence) and negative (turbulence driven flows) in the proximity of sheared flows in ohmic plasmas. So far, no evidence of pumping region (P negative) has been observed in divertor configurations.

•The direct computation of the turbulent viscosity gives values comparable to the anomalous particle diffusivities (in the order of 1 m²/s).

•The estimated energy transferred from turbulence to the mean flow in the pumping region (P negative) in limiter configuration measurements is close to the power per unit mass needed to pump the flow up to the experimentally measured values in a turbulent characteristic time (tens of microseconds)

⇒ These results show, for the first time, the dual role of turbulence as a damping (eddy viscosity) and driving of flows in fusion plasmas emphasizing the important role of turbulence to understand perpendicular dynamics in the plasma boundary region of fusion plasmas.

References

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