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ABSTRACT.

The structure of the naturally occurring velocity shear layer and the dynamical coupling between gradients and transport have been investigated in the JET plasma boundary region. The naturally occurring velocity shear layer organizes itself to reach a condition in which the radial gradient in the poloidal phase velocity of fluctuations is comparable to the inverse of the correlation time of fluctuations ($1/\tau$). This result suggests that ExB sheared flows organized themselves to be close to marginal stability (i.e. $\omega_{\text{ExB}} \approx 1/\tau$). Experimental results show that there is a strong coupling between the Probability Density Function (PDF) of gradients and ExB turbulent transport. The size of turbulent events increases when the plasma deviates from the average gradient. The resulting radial velocity of fluctuations is of the order of 20 m/s for transport events implying a small deviation from the most probable gradient. This effective radial velocity is consistent with a diffusive modeling of the plasma boundary in JET. On the contrary, the effective radial velocity increases up to 500 m/s for transport events in which the local gradient increases significantly above the most probable gradient. These results suggest a link between the size of transport events and the nature of transport (diffusive versus non-diffusive) in the plasma boundary region.

1. INTRODUCTION

Broadband electrostatic and magnetic fluctuations have been observed in the boundary region of magnetically confined devices. The electrostatic fluctuations produce a fluctuating radial velocity given by $\tilde{v}_r = \tilde{E}_q/B_\theta$, \tilde{E}_θ being the fluctuating poloidal electric field and B is the toroidal magnetic field and the resulting electrostatic fluctuation driven radial particle flux is given by $\Gamma_{\text{ExB}}(t) = \tilde{n}(t) \tilde{E}_\theta(t) / B$. Ignoring poloidal and toroidal asymmetries the total electrostatic fluctuation driven particle fluxes have been measured in the plasma boundary region of tokamaks, stellarators and reversed fields pinches. It has been experimentally shown that in some cases the fluctuating flux can account for an important part of the total particle flux in the edge region [1,2]. However, it should be noted that in some cases fluctuation fluxes appear too high to be consistent with global particle balance [3]. Poloidal asymmetries, large scale convective cells or the possible role of temperature fluctuations may account for these apparent inconsistencies. At present, this disagreement still remains as an open question [4]. It has been recently suggested the importance of the statistical description of transport processes, based on probability density functions, as an alternative approach to the study of transport based on the commutation of effective transport coefficients [5]. This approach would be useful to clarify the underlying physics of turbulent driven transport in fusion plasmas.

On the other hand, one of the important achievements of the fusion research community in the last years has been development of techniques to control plasma turbulence based on the ExB shear stabilization mechanism [6,7,8]. Several mechanisms have been proposed as responsible for the generation of shear flow. Understanding the physics of sheared flows is a crucial issue to explain the transition to improved confinement regimes and the generation of transport barriers in fusion plasmas. This paper reports results on the characterization of the statistical properties of turbulence

and the physics of ExB sheared flows in the JET plasma boundary region. The paper has been organized as follows. Experimental evidence of sheared flows and fluctuations near marginal stability in the edge region of JET tokamak is presented in section 2. The investigation of the coupling between fluctuations in gradients and the effective radial velocity of transport and transport is discussed in section 3. Finally conclusions are presented in section 4.

2. EXPERIMENTAL SET-UP AND ANALYSIS TOOLS

Plasma profiles and turbulence have been investigated in the JET plasma boundary region using a fast reciprocating Langmuir probe system located on the top of the device. The experimental set-up allows the simultaneous investigation of the radial structure of fluctuations and electrostatic driven turbulent transport. Plasma fluctuations are investigated using standard signal processing techniques and 500kHz digitisers. Plasmas studied in this paper were produced in X-point plasma configurations with toroidal magnetic fields $B = 1-2.5$ T, $I_p = 1-2$ MA, $P_{NBI} = 0-5$ MW (Ohmic and L-mode plasmas).

The mean velocity of fluctuations perpendicular to B_T has been computed as $v_{\text{phase}} = S S(k, \omega) / (k/\omega) S S(k, \omega)$, from the wave number and frequency spectra $S(k, \omega)$, computed from the two points correlation technique [9] using floating probes separated 0.5 cm in the poloidal direction in the JET plasma boundary region.

Turbulent particle transport and fluctuations have been calculated, neglecting the influence of electron temperature fluctuations, from the correlation between poloidal electric fields and density fluctuations as $\Gamma_{\text{ExB}}(t) = \tilde{n}(t) \tilde{E}_\theta(t) / B$ at the inner probe position. The poloidal electric field has been estimated from floating potential signals measured by poloidally separated probes, $E_\theta = \Delta\Phi_r / \Delta\theta$ with $\Delta\theta \approx 0.5$ cm. Fluctuations in the radial component of ion saturation current gradients have been computed as $\tilde{\nabla} I_s(t) = [\tilde{I}_s^{\text{inner}}(t) - \tilde{I}_s^{\text{outer}}(t)]$ with $\langle \Delta \tilde{I}_s \rangle = 0$ where $\tilde{I}_s^{\text{inner}}$ and $\tilde{I}_s^{\text{outer}}$ are the ion saturation current fluctuations simultaneously measured at two different plasma locations radially separated 0.5cm.

An effective radial velocity has been defined as the normalized ExB turbulent particle transport to the local density: $v_{\text{eff}} = \tilde{\nabla} I_s E_\theta / \tilde{I}_s B_T$ where I_s is the ion saturation current of the inner probe. As this coefficient is not affected by uncertainties in the effective probe area, it provides a convenient way to compare experimental results with edge code simulations.

3. THE NATURALLY OCCURRING VELOCITY SHEAR LAYER AND L-H TRANSITION PHYSICS

3.1. THE VELOCITY SHEAR LAYER

A velocity shear layer has been observed near the location of the LCFS (as determined from magnetic measurements-EFIT). In divertor plasmas, the poloidal phase velocity of fluctuations (v_{phase}) increases in the electron drift direction up to 2000m/s, in the proximity of the separatrix. This change can be explained in terms of ExB drifts. The resulting radial gradient in v_{phase} is in the range of 10^5 s^{-1} , which turns out to be comparable to the inverse of the correlation time of fluctuations,

in the range of 5 -10ms. This result is verified in ohmic plasmas with $I = 1\text{MA} / B = 1\text{T}$, in which the power threshold for the L-H transition is about 1 MW. It should be noted that the present results are consistent with previous observations in tokamaks [10], stellarators [11] and reversed field pinches [12] which have shown that the shearing rate of the naturally occurring velocity shear layer is closed to the inverse time of fluctuations in different devices. Whereas this property is consistent with turbulent driven fluctuating radial electric field [13], it is difficult to understand in which way other mechanisms, like those based on ion orbit losses mechanisms, can allow sheared flows and fluctuations to reach marginal stability.

3.2. FLOWS NEAR MARGINAL STABILITY AND L-H TRANSITION PHYSICS

Previous results are consistent with the paradigm of turbulent transport self-regulated via fluctuations. In this section we discuss the impact of these findings in the properties of turbulent transport and in the power threshold for the transition to H-mode regimes.

Once turbulence driven sheared electric fields (e.g. Reynolds stress, anomalous stringer spin-up) reach the critical value to modify fluctuations a negative feedback mechanism will be established which will keep the plasma near the condition ω_{ExB} critical. However, this negative feedback mechanisms might not allow the transition to the improved confinement regime unless a ExB shear positive feedback mechanism is triggered by the Reynolds stress. This positive feedback mechanism might be provided by the ∇P_i contribution to the ExB shear flow. In the framework of the interpretation, the following condition should be verified to reach the L-H transition

$$\omega_{\text{ExB}}^{\text{critical}} \approx \frac{1}{Z_i e} \frac{d}{dr} \left(\frac{1}{n_i B} \nabla P_i \right)$$

Considering that the ion heat flux can be related to the pressure gradient through an effective diffusivity (χ_i)

$$Q_i \approx -\chi_i \frac{\partial P_i}{\partial r}$$

and neglecting dB/dr and $\partial^2 P_i / \partial r^2$, it follows

$$\omega_{\text{ExB}}^{\text{critical}} \approx \frac{1}{Z_i B n_i^2} \frac{dn_i}{dr} \nabla P_i \approx \frac{L_n^{-1}}{Z_i e B \chi_i} \frac{Q_i}{\chi_i}$$

Thus the transition to the improved confinement regime will be characterized by a critical heat flux,

$$Q_i \approx Z_i^e \omega_{\text{ExB}}^{\text{critical}} L_n \chi_i B n \quad (1)$$

Using typical JET edge plasma parameters for the L-H transition, $\omega_{\text{ExB}}^{\text{critical}} \approx 10^5 \text{ s}^{-2}$, $B n_{\text{L-H}} \approx 10^{20} \text{ m}^{-3} \text{ T}$, $\chi_i \approx 1\text{-}10 \text{ m}^2/\text{s}$, $L_n^{-1} \approx 10^{-2} \text{ m}$, it follows that $Q_i \approx (0.01\text{-}0.1) \text{ MW m}^{-2}$. This value is close to the L-H power threshold values reported in JET [14]. Expression (1) shows that the critical heat flux depends on the plasma density and magnetic field, which resembles the parametric dependences of the

power threshold reported in tokamak plasmas [15] [$P_{th} \propto n^\alpha B^\beta$ ($\alpha \approx \beta$) ≈ 1]. Expression (1) also shows that the critical heat flux depends on transport (e.g. χ_i) and Z_i (the ion charge). The dependence with the ion charge (Z_i) would be consistent with the increase of the power threshold in He plasmas as compared with D plasmas [$P_{th\ LH}(\text{He}_4)/P_{th\ LH}(\text{D}) \approx 1.5$]. Finally, it should be noted that, in the framework of the proposed synergy between fluctuation driven flows (e.g. Reynolds stress) and pressure gradients, the characteristic time for the L-H transition would be determined by the time scale of the energy transfer between different turbulent scales (i.e. the turbulence correlation time).

4. DYNAMICAL INTERPLAY BETWEEN FLUCTUATIONS IN GRADIENTS AND EXB TRANSPORT

Turbulent transport and effective radial velocities of turbulent events have been characterized in terms of Probability Distribution Function. The joint probability P_{ij} of the two variables X and Y , meaning the probability that at a given instant X and Y occur simultaneously, is given by

$$P_{ij} = P(X_i, Y_j) = \frac{N_{ij}}{N}$$

where N_{ij} the number of events that occur in the interval (X_i, X_i+DX) and (Y_j, Y_j+DY) and N the time series dimension. DX and DY are the bin dimension of X and Y time series, respectively, where the indices stands for i -th (or j -th) bin average value.

The expected value of X at a given value of Y_j is defined as

$$E[X | Y_j] = \frac{\sum_i P_{ij} X_i \nabla X_i}{\sum_i P_{ij}}$$

and represents the average value of the probability distribution of X at a given value of Y .

Figure 3 shows the Probability Density Function (PDF) for fluctuations in gradients, and the expected value of the ExB flux for a given density gradient ($E[\Gamma_{ExB} | \nabla_r I_S]$) in L-mode plasmas. The results show that most of the time the plasma is at its average gradient and the size of transport events has minimum amplitude ($\Gamma_{ExB} / \langle \Gamma_{ExB} \rangle < 0.5$). Large amplitude transport events ($\Gamma_{ExB} / \langle \Gamma_{ExB} \rangle \approx 3 - 8$) take place when the plasma displaces from the most probable gradient average value. The expected value of ExB turbulent transport events increases strongly as the gradient increases above its most probable value (i.e. $\nabla I_S / \sigma > 0$).

The present experimental results show that the bursty and strongly non-gaussian behaviour of turbulent transport is strongly coupled with fluctuations in gradients. As the density gradient increases above the most probable gradient the ExB turbulent driven transport increases and the system perform a relaxation which tends to drive the plasma back to the marginal stable situation which minimized the size of transport events. The increase in the size of transport events as gradient increases is consistent with the self-regulation of turbulent transport and gradients near marginal stability in the plasma boundary region. However, the non-monotonic dynamical relation between ExB transport (Γ_{ExB}) and gradients (∇I_S) may be also partially due to the direct link between Γ_{ExB} and ∇I_S through density fluctuations.

Figure 4 shows the expected value of the effective radial velocity of fluctuations for a given density gradient ($E[v_{\text{eff}} | \nabla_r I_s]$). The radial velocity is close to 20m/s for small deviations from the averaged gradient but increases up to 500 m/s for large transport events implying a strong deviation from the most probable radial gradient.

It is interesting to compare the present experimental results with predictions from a diffusive modeling of the plasma boundary in JET [16]. Figure 5 shows the results from simulations with B2-Eirene for JET ohmic conditions. This simplified model assumes that particle transport can be characterized by a diffusion coefficient $D_{\text{perp}} = 0.1\text{m}^2/\text{s}$ with a density decay length of about 1 cm and neglecting the influence of drifts. The resulting typical effective radial velocity is of the order of 10m/s. This radial velocity turns out to be rather close to the experimental values for the radial velocity of transport events implying a small deviations from the most probable gradient; however, it is very far away from the several 100m/s of the large transport events.

5. CONCLUSIONS

The structure of the naturally occurring velocity shear layer and the dynamical coupling between gradients and transport have been investigated in the JET plasma boundary region and the following conclusions have been reached:

- a) The naturally occurring velocity shear layer organizes itself to reach a condition in which the radial gradient in the poloidal phase velocity of fluctuations is comparable to the inverse of the correlation time of fluctuations ($1/\tau$). This result suggests that there is no continuous increase of the ExB flow when approaching the critical power threshold for the transition to improved confinement regimes and that ExB sheared flows organized themselves to be close to marginal stability (i.e. $\omega_{\text{ExB}} \approx 1/\tau$). A synergy between fluctuation driven flows (e.g. Reynolds stress) and pressure gradient driven flows is suggested to trigger the L-H transition.
- b) The investigation of the dynamical interplay between fluctuations in gradients and turbulent transport has shown that their PDFs are strongly coupled. The bursty behaviour of turbulent transport is linked with a departure from the most probable radial gradient. Transport event, related with small departures from the most probable local gradient, propagates radially with an effective velocity of about 20 m/s, with is consistent with simplified simulations of diffusive transport in the SOL region. On the contrary, large transport events, related with significant departures from the most probable gradient, propagates radially with an effective velocity up to 500 m/s. These results strongly suggest a link between the size of transport events and the nature of transport (diffusive versus non-diffusive) in the plasma boundary region.

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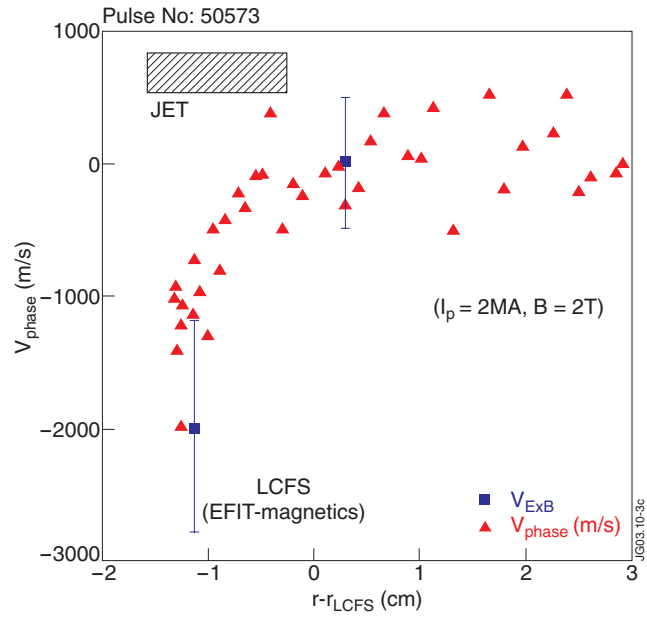


Figure 1: Phase velocity of fluctuations and ExB drift

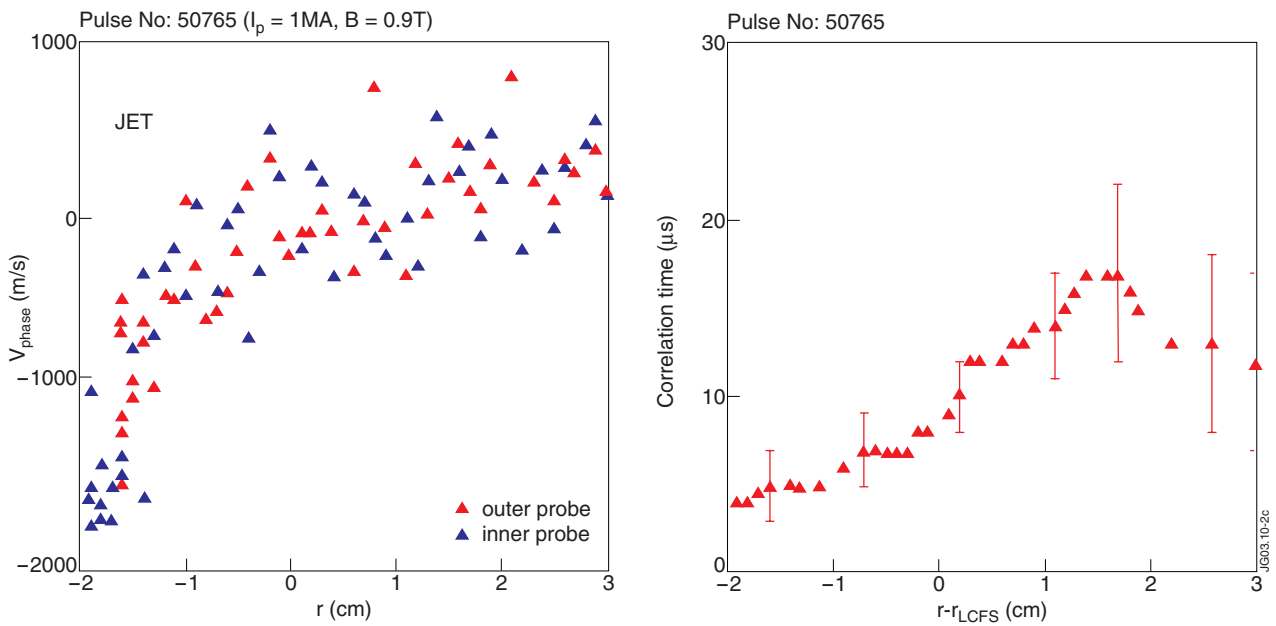


Figure 2: Phase velocity of fluctuations and auto-correlation times.

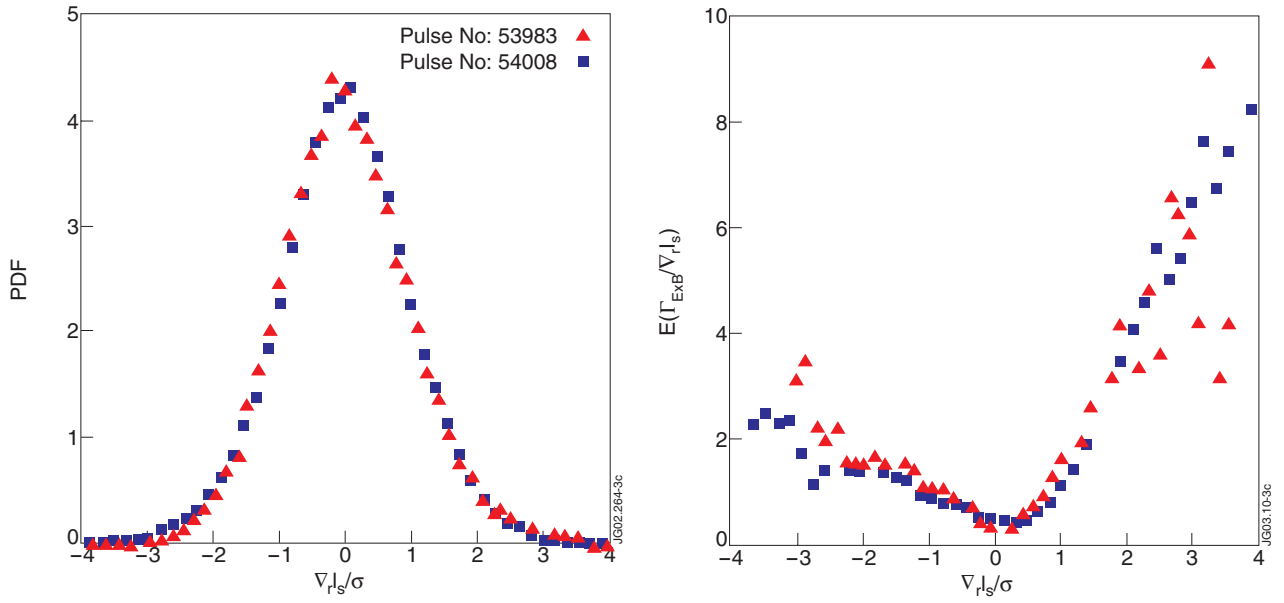


Figure 3: PDF fluctuations in radial gradients and amplitude for the expected value of the ExB turbulent versus $\nabla_r I_s / \sigma$.

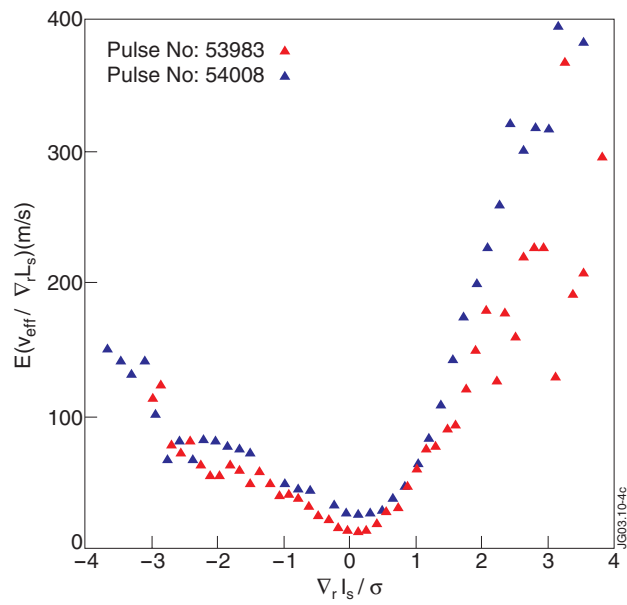


Figure 4: Expected value of the radial effective velocity versus $\nabla_r I_s / \sigma$.

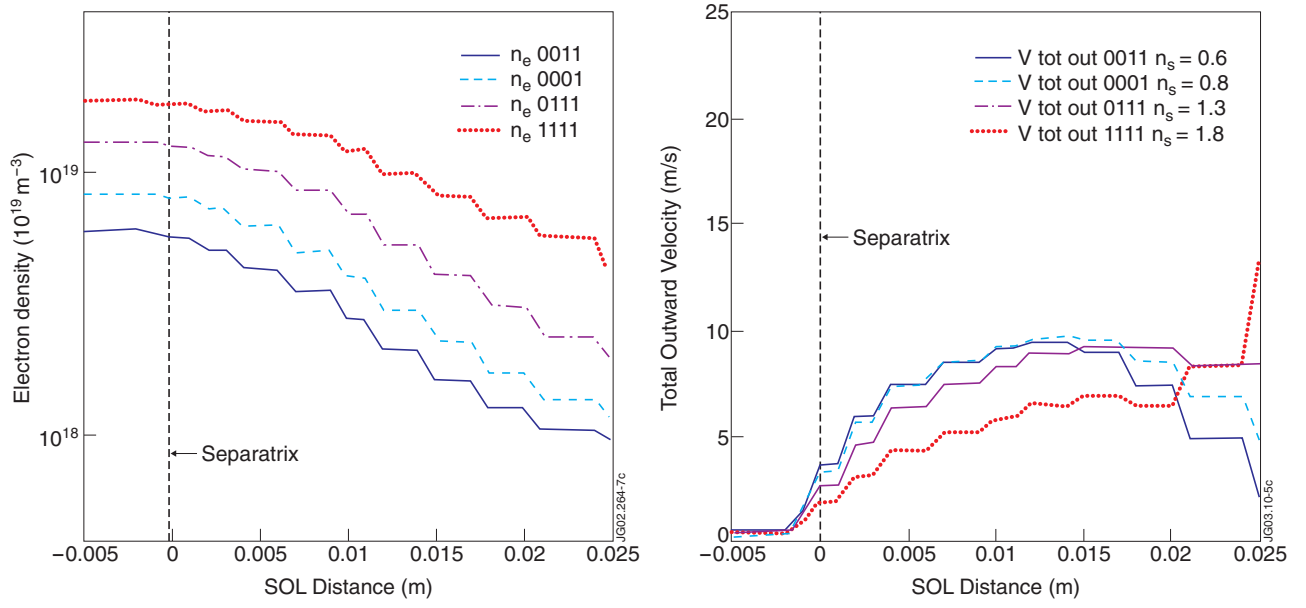


Figure 5: Density and effective radial velocities from simulations with B2-Eirene for JET ohmic conditions.