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ABSTRACT
Higher than expected electron temperatures (T_e) are often measured by divertor Langmuir probes (LP) in high recycling and detached regimes in JET and other tokamaks. As a possible mechanism to explain this discrepancy, we investigate the effect of penetration of fast, almost collisionless electrons connecting the hot upstream scrape-off layer (SOL) region to the divertor targets in JET. We simulate the electron velocity distribution function (EVDF) near the divertor targets using a simple 1D kinetic model using parallel SOL profiles from EDGE2D-EIRENE simulations. The resulting EVDF is used to construct synthetic LP IV characteristics and evaluation of T_e is performed in the same way as for experimental data. Results indicate that the process does not explain the anomalously high T_e values registered by the target probes if the EDGE2D-EIRENE simulated parallel profiles are a good representation of reality.

1. INTRODUCTION
Volume recombination processes in tokamak divertor plasmas become significant or even dominant in detached regimes. The electron temperature (Te) in the vicinity of divertor targets is expected to be comparable or lower than 1eV. This expectation is confirmed by spectroscopic [1, 2] and Thomson scattering [3] measurements. In contrast, divertor Langmuir probes (LP) in such cases often indicate Te several times higher [4-6]. Since high parallel Te gradients are a characteristic feature of these scrape-off layer (SOL) plasmas, several authors have proposed the penetration of hot, almost collisionless, upstream electrons down to the divertor as the possible mechanism to explain the observed overestimation of Te by divertor LPs [6-8].

As a result of the filtering effect of the sheath, the evaluation of T_e from measured LP current–voltage (IV) characteristics is particularly sensitive to the presence of fast electrons. A detailed numerical assessment of this effect was performed for TCV diverted discharges [6], but the results were inconclusive. In this work, we adapt the numerical approach in [6], using a more appropriate expression for the electron mean-free-path (mfp), and apply the procedure to JET plasmas, comparing our numerical results with experimental data from JET divertor LPs. We also benchmark results of our simulations against those of the much more sophisticated particle-in-cell (PIC) codes BIT1 parallel [9], and QPIC [10].

2. MODEL DESCRIPTION
The numerical model conceptually developed according to the approach in [6] computes the electron velocity distribution functions (EVDF) near the divertor targets. The geometry of the model is 1D both in space and velocity (coordinate x is in the parallel direction along open magnetic field lines in SOL). We assume fixed T_e and n_e parallel profiles obtained from EDGE2D-EIRENE simulations (since this information is not available experimentally), and Maxwellian EVDFs at all locations except in the direct vicinity of the divertor targets, i.e. at the end points of the magnetic field line (sheath edge). Electron-ion and inelastic collisions are not included in the model.

We evaluate the probability $\Delta p(x) = \Delta x/\lambda(x)$ that an electron with a certain energy E traversing a distance Δx undergoes an e-e collisional process with mfp $\lambda(x)$. In order to evaluate $\lambda(x)$, we adopt the approach in [11] in which a single test particle travels through a uniform, field-free plasma in thermal equilibrium. In this approximation, the Fokker-Planck equation is considerably simplified and various collisional parameters are obtained by computing particular moments of this equation. We investigated the effect of a number of various collisional processes (friction, deflection, energy exchange, etc.) leading to qualitatively very similar results. The results presented within this paper were obtained using the mfp for energy exchange described by the collision frequency:

$$\nu^E = \frac{2e^4 n_e \ln(\Lambda)\,\Psi\,(\mathrm{x})}{\pi\varepsilon_0^2 m_e^2 V^3} \tag{1}$$

where

$$\Psi\,(\mathrm{x}) = \frac{2}{\sqrt{}\,x^2}\int_0^x \xi^2 \exp(-\xi^2)d\xi \qquad x = \sqrt{\frac{m_e V^2}{2kT_e}}\ , \tag{2}$$

with V, e, and m_e are electron velocity, charge, and mass and ln(Λ) is the Coulomb logarithm. Then, the mfp is straightforwardly evaluated as $\lambda = V/v^E$. Further, we define a function p(x,E) signifying the total number of collisional processes (in a statistical sense) an electron with particular energy E undergoes when traveling from the location x upstream down to the divertor target (x=0). Specifically,

$$p(x,E) = \int_0^x \frac{dx'}{\lambda(E(x'), n_e(x'), T_e(x'))}\ . \tag{3}$$

Finally, the new EVDF, *f(v)* at the divertor target is evaluated as the weighted average of all Maxwellian EVDFs along the magnetic field line given by:

$$f(v) = \frac{\int_0^L S(x) f(v, n_e(x), T_e(x))\,dx}{\int_0^L S(x)\,dx}\ , \tag{4}$$

where the weight function S(x) is defined as:

$$S\,(x) = e^{-p(x)}\ . \tag{5}$$

Knowing the EVDF, one can evaluate the synthetic IV characteristic of a single LP as:

$$j\,(V) = j_i - j_e\,(V) \ = en_e c_s - e\int_w^\infty vf\,(v)\,dv \tag{6}$$

where

$$w = \sqrt{2eV/m_e} \ . \tag{7}$$

The resulting IV characteristics are fitted by a 4 or 3 parameter (A = 0) fit function to determine T_e:

$$j_{prb}\,(V_{prb}) = j_{sat}\left(1 - e^{\frac{V_{prb}-V_{fl}}{T_e}}\right) + A(V_{prb}-V_{fl}) \ \ . \tag{8}$$

The 4-parameter fit is usually introduced in order to account for sheath expansion effects which are often seen experimentally as a linear increase of ion saturation current density jsat for negative voltages [12].

3. RESULTS

3.1 COMPARISON WITH PIC MODELS

The results of this EVDF model have been compared to those obtained from two PIC based codes: BIT1 parallel, a quasi 2D, massively parallel PIC/MC code [9], and QPIC, a quasineutral PIC code [10]. In the case of BIT1, the EVDF results have been benchmarked against simulation of JET Pulse No: 74830, using T_e and n_e parallel profiles deduced from BIT1 (see Fig.1) as input to the EVDF model. Both EVDFs are very similar and both indicate significant enhancement of the population of energetic electrons compared to the thermal Maxwellian distribution. Divertor LPs in plasmas with such skewed distributions would measure $T_e \sim 30$eV, in contrast to the $T_e \sim 8$eV, deduced from the bulk of the EVDF.

The QPIC code [10] has been adapted for the purposes of the present problem. Specifically, plasma sources are now also situated at the targets. Initial results from this version of QPIC (see Fig. 2) indicate that the divertor target EVDF can indeed be significantly modified by a hot upstream electron population.

3.2 COMPARISON WITH EXPERIMENTAL LP MEASUREMENTS

Simulations and comparison with experimental LP data have been performed for two series of experiments represented by JET Pulse No's: 81469-90 (a detailed description may be found in [13]) and JPN82342, both executed in the JET ITER-like wall configuration. Due to the high degree of symmetry of ne and Te parallel profiles obtained from EDGE2D-EIRENE, the results for both divertor targets are very similar and we present only those for the outer target.

Both discharge series were performed as density ramp-up and density step experiments, beginning from attached (JET Pulse No's: 81469–90) or high recycling (JET Pulse No: 82342) regimes and reaching detachment in the later phase of the discharge. Both synthetic and experimental divertor LP IV characteristics were processed using the 4-parameter fitting technique (eq.8). Figures 3 and 4 summarize the results obtained for these two separate JET density ramp cases. At all values of upstream separatrix density, the T_e deduced from the EVDF model is in good agreement with the EDGE2D-EIRENE target temperatures. In the case of JET Pulse No's 81469-90, the measured divertor LP T_e correspond well to the EDGE2D-EIRENE simulated values for attached plasmas, but deviate strongly at high densities when the divertor plasma passes through high recycling and into detachment. This is a clear demonstration of the principal concern of this paper – to identify a possible mechanism for the overestimation in a detached regime when it is known that the local target T_e must be at the 1eV level or below for recombination to occur.

Clearly, the good correspondence between the EVDF and EDGE2D-EIRENE models at all densities demonstrates that strong parallel T_e gradients cannot be responsible for the discrepancy provided the EDGE2D-EIRENE parallel profiles can be assumed to be correct (see Section 4 below for more discussion on this). In the case of JET Pulse No: 82342 (Fig.4), where the EVDF simulation again lies very close to the EDGE2D-EIRENE result, significantly higher Te is measured by divertor LPs compared to the fluid code prediction across the whole density range.

Figure 5 illustrates the importance of the selection of the fit function for evaluation of T_e either from experimental or synthetic LP IV characteristics. Here, an example single LP IV characteristic is synthetized from a bi-Maxwellian EVDF with bulk temperature of 5eV and a 0.2% population of hot 50eV electrons. The 4 parameter fit leads to significantly better results, yielding T_e = 6.5eV, while the result is strongly affected by a small hot electron population if a 'standard' 3 parameter fit is applied, giving T_e = 12.8eV in this particular case. In case of 4 parameter fit, the improved result is due to the similar impact on the IV characteristic shape of both a hot electron fraction and the sheath expansion effect.

4. DISCUSSION

According to the results of this study, the penetration of hot upstream electrons down to the divertor target is not the explanation for the anomalously high target electron temperatures measured at the JET divertor targets in high recycling or detached regimes. For attached regimes, the parallel T_e profiles are flat and so the effect of electron collisions described by the EVDF model cannot, by definition, play any role. In detached regimes, high parallel Te gradients exist, but the cold, high density cloud in the divertor effectively screens the hot electrons and prevents them from reaching the divertor target. This is confirmed by EVDF simulations using a series of artificial parallel ne profiles with variable divertor density.

Even when a small fast electron population is present, application of a 4 parameter fit to extract T_e from IV characteristics effectively suppresses the effect and the measured LP Te should again be expected to correspond to the local temperature. In contrast, as shown for example in Fig.3, experimental T_e values measured by single divertor target LPs significantly exceed EDGE2D-EIRENE predictions in high recycling and detached regimes. It is important to recognize, however, that the EVDF model is extremely sensitive to the details of the input ne and T_e profiles. As shown in Fig.1, when profiles from BIT1 are used for the high recycling JET case (JET Pulse No: 74380), the EVDF simulation clearly produces a strong hot tail in the distribution function which in turn yields a significantly higher fitted T_e, driven more by hot upstream electrons than by the local bulk.

CONCLUSIONS

A simple model of upstream SOL electron transport down to a divertor target has been developed in order to assess whether this process is capable of explaining the experimentally observed overestimation of T_e measured by divertor target single LPs in high recycling and detached regimes. The application of this model to JET, using EDGE2D-EIRENE simulations of density ramp discharges to provide the required parallel profiles of n_e and T_e (which are not measured) demonstrates that the process does not explain the anomalously high T_e values registered by the target probes if the simulated parallel profiles are a good representation of reality. By applying 3 and 4 parameter fits to synthetic LP IV characteristics generated with the collisional mean-free-path model, the importance of using a 4-parameter fitting technique emerges in view of the tendency of this fitting method to reduce the effect of an enhanced hot electron tail on the resulting T_e.

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REFERENCES

[1]. Lumma D, Terry J.L, and Lipschultz B, Physics of Plasmas **4** (1997) 2555.
[2]. Lipschultz B, Terry J.L, Boswell C et al, Journal of Nuclear Materials **266-269** (1999) 370.
[3]. Boedo J A, Porter G.D, Schaffer M.J et al, Physics of Plasmas **5** (1998) 4305.
[4]. Fussman G, Ditte U, Eckstein W et al, Journal of Nuclear Materials. **128-129** (1984) 350.
[5]. Watkins J.G, Stangeby P, Boedo J.A et al, Journal of Nuclear Materials **290-293** (2001) 778.
[6]. Horacek J, Pitts R.A, Stangeby P.C et al, Journal of Nuclear Materials **313-316** (2003) 931.
[7]. Wesson J.A, Plasma Physics and Controlled Fusion **37** (1995) 1459.
[8]. Stangeby P.C, Plasma Physics and Controlled Fusion **37** (1995) 1031.
[9]. Tskhakaya D, Jachmich S, Eich Th et al, Journal of Nuclear Materials **415** (2011) S860.
[10]. Gunn J.P, Fuchs V, Physics of Plasmas **14** (2007) 032501.
[11]. Boyd T.J.M, Sanderson J.J, The Physics of Plasmas, Cambridge University Press, 2003.
[12]. Gunn J.P, Boucher C, Stansfield B.L et al, Review of Scientific Instruments **66** (1995) 154.
[13]. Groth M, Brezinsek S, Belo P et al., Nuclear Fusion **53** (2013) 093016.

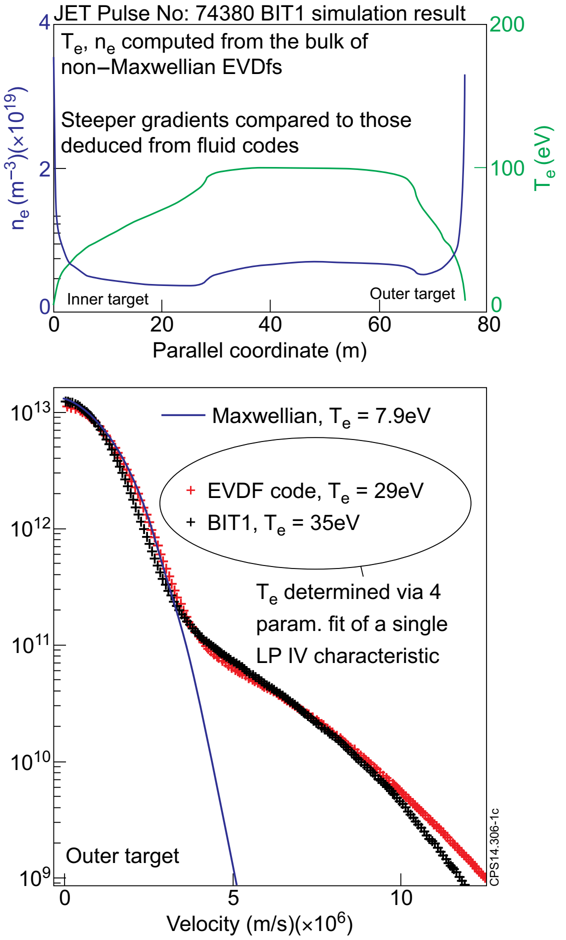

Figure 1: Upper: T_e and n_e parallel profiles resulting from BIT1 parallel simulation of JET Pulse No: 74380 used as an input for EVDF code. Lower: comparison of resulting divertor target EVDFs as computed by BIT1 (black) and EVDF (red) codes. Maxwellian EVDF is plotted for the reference (blue).

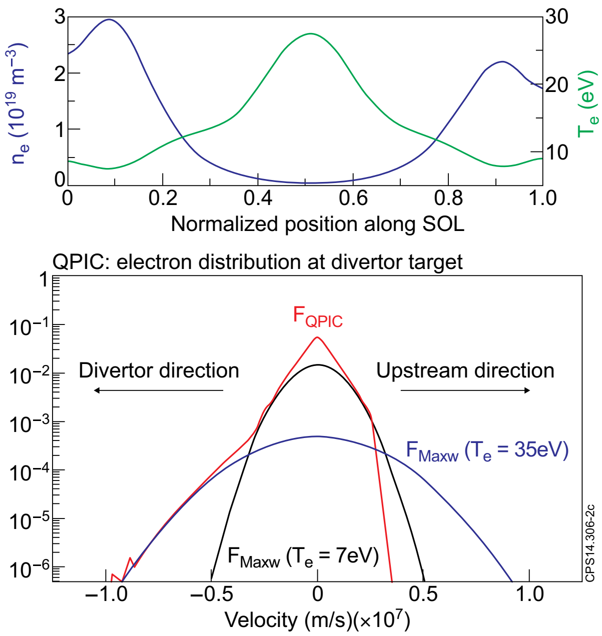

Figure 2: QPIC equilibrium results after 4 ion transit times. Top panel - electron density and temperature parallel profiles. Bottom panel – electron velocity distribution function at divertor target.

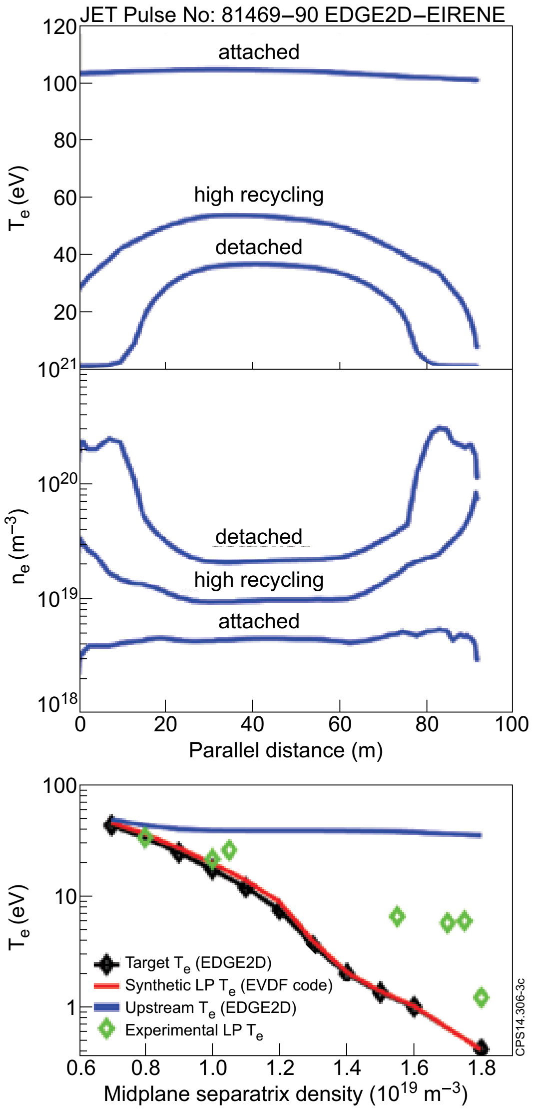

Figure 3: Upper: T_e and n_e parallel profiles on the SOL flux surface radially 5mm from separatrix (mapped to the outer mid-plane) resulting from EDGE2D-EIRENE simulation of JET Pulse No: 81469–90 used as an input for EVDF code. Lower: EVDF code prediction of divertor LP measurement of T_e (red) compared to the EDGE2D- EIRENE estimate: divertor (black), upstream (blue) and to the divertor LP experimental data (green).

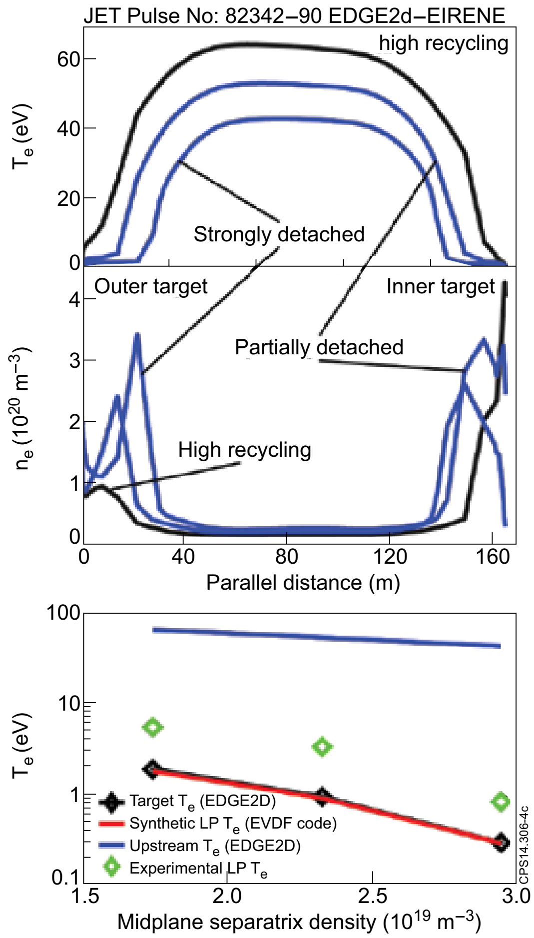

Figure 4: Upper: T_e and n_e parallel profiles resulting from EDGE2D-EIRENE simulation of JET Pulse No: 82342 used as an input for EVDF code. Lower: EVDF code prediction of divertor LP measurement of T_e (red) compared to the EDGE2D- EIRENE estimate: divertor (black), upstream (blue) and to the divertor LP experimental data (green).

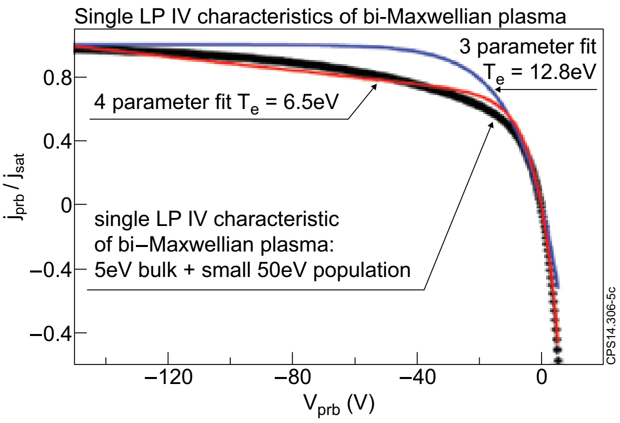

Figure 5: Single LP IV characteristic for bi-Maxwellian plasma composed from 5V bulk and 0.2% fraction of 50eV tail (black) fitted by 3 (blue) and 4 (red) parameter fitting function.