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ABSTRACT
Measurements of the plasma conditions at the high field and low field side target plates in JET ITER-like wall ohmic and low confinement mode plasmas show minor differences in divertor plasma configurations with horizontally and vertically inclined targets at the low field side. Both the reduction of the electron temperature in the vicinity of the strike points and the rollover of the ion current to the plates follow the same functional dependence on the density at the low field side midplane. Configurations with vertically inclined target plates, however, produce twice as high sub-divertor pressures for the same upstream density. Simulations with the EDGE2D-EIRENE code package predict significantly lower plasma temperatures at the low field side target in vertical target configurations. Including cross-field drifts and imposing a pumping by-pass leak at the low-field side plate can still not recover the experimental observations.

I. INTRODUCTION
The spatial distribution of deuterium neutrals (i.e., deuterium atoms and molecules) in the divertor chamber of tokamaks and their dynamics play a key role in achieving detached divertor conditions. Partial detachment of the divertor plasma at the strike zones is the mode of operation required in ITER to limit the heat fluxes to the divertor target plates below $10MW/m^2$ and to minimise erosion [1]. This is, in particular, important in tokamaks with tungsten plasma-facing components as tungsten sputtering is significantly reduced at plasma temperatures below 10eV [2]. In tokamaks neutrals arise predominately from recycling of plasma ions at plasma-facing components. These neutrals re-ionise and charge-exchange with plasma ions, thereby dispersing heat and momentum. A fraction of neutrals leaks into the main chamber leading to both fuelling of the core plasma and power losses due to charge exchange with plasma ions. The divertor geometry, target inclination and plasma configuration are key parameters in confining neutrals within the divertor chamber. In particular, vertical target (VT) configurations in closed divertors have shown to better confine neutrals than horizontal configurations as recycling neutrals are preferentially released in the direction of the separatrix and private flux-region (PFR) [3,4,5]. Higher neutral densities in the divertor chamber also promote better pumping of deuterium, thus fuel density control, and helium ash removal. While there is a clear effect of the divertor neutral density distribution on divertor plasma configuration, its impact on the plasma conditions is more ambiguous. Measurements of the electron temperature, T_e, in Alcator C-mod showed a five-fold reduction of T_e at the low-field side (LFS) target plate in detached conditions when the LFS strike point is place on a vertically inclined surfaces compared to a horizontal (flat) surface [3]. Initial experiments in JET with the 1994-95 MkI pumped divertor showed a similar effect, in particular when the divertor strike zone was located on the lower end of the vertical target plate [5]. However, gas recirculation within the divertor structure produced a complicated ionisation pattern that masked some of the geometry effects.

In this contribution the effect of the divertor plasma configuration on the plasma conditions at the divertor target plates and the neutral pressure in the sub-divertor is re-visited in extensively characterized ohmic and neutral-beam heated, low-confinement (L-mode) discharges in the JET

ITER-like wall configuration [6],[7]. The JET ITER-like wall (ILW) comprises beryllium plasma-facing component in the main chamber, and tungsten in the divertor [8]. Key scrape-off layer (SOL) parameters, such as profiles of the ion currents, j_{sat}, to, and T_e along the high-field side (HFS) and LFS plates, and the sub-divertor pressure, $p_{sub-div}$, near the divertor cryogenic pump were measured for two different divertor plasma configurations (Fig.1): a configuration with the LFS strike point placed in the centre of the load-bearing horizontal tile (V5) and a configuration with the LFS strike point on the lower part of the JET vertical divertor structure on the LFS (VT). In both configurations the HFS strike point was on the HFS vertical target plate. The magnetic shapes in the main chamber were almost identical, including large gaps to the HFS and LFS wall (9.5 cm and 5.1 cm, respectively). To minimise the impact of plasma interaction with the top of the vacuum vessel, low triangularity configurations (of δ_u of approximately 0.2) were chosen (separatrix-top real space, 22 cm). The experiments were carried out at JET-typical pairs of plasma currents (I_P) and toroidal fields (B_T) were: (2.0MA, 2.0T) and (2.5MA, 2.5 T) for the ohmic and L-mode plasma, respectively. These currents and fields resulted in an edge safety factor, q_{95}, of 3.4. The ion $\mathbf{B}\mathrm{x}\nabla B$ drift direction was into the divertor. The discharges were fuelled with deuterium gas from the top of the vacuum vessel, and from injection modules at the HFS and LFS of the divertor base plates (Fig.1). In both V5 and VT configurations the injection from the HFS divertor module was into the PFR, while the injection from the LFS module was either into the common SOL (V5) or into the PFR (VT). In both cases the selected injection modules are sufficiently close to the pumping plena in the lower corners of the divertor for some D_2 to reach the sub-divertor directly without processing through the divertor plasma. The divertor cryo pump located within the sub-divertor structure at the LFS (Fig. 1) was held at liquid nitrogen temperature to pump deuterium gas in this region. Both continuous fuelling to the density limit, and fuelling steps to establish constant plasma conditions for several seconds were performed. During the continuous fuelling scan, the strike point locations were held constant, while 2-3 cm strike point sweeps over the divertor Langmuir probes were executed to obtain the spatial profiles of j_{sat}, T_e and the electron density, n_e, along the target plates. A baratron was used to measure the pressure at the end of an approximately 3 m long tube below the cryo pump [9]. In addition to these key diagnostics, the plasma conditions upstream and the radiation profiles across the SOL were comprehensively characterised using the full suite of JET diagnostics. A comprehensive description of these plasmas and measurements is given in [7]. The neutral Monte-Carlo code EIRENE [10] was used to predict the neutral dynamics of deuterium in the SOL in the V5 and VT configurations. The code solves the kinetic Boltzmann equations for atomic and molecular hydrogen species in plasmas (electrons, hydrogen ions, and impurity ions). EIRENE is iteratively provided by the edge fluid code EDGE2D [11],[12], which solves the Bragiinski fluid equations in the parallel-**B** direction and assumes a diffusive-convective model in the radial direction. The radial transport coefficients for particles (here, diffusion only) and energy were determined by matching the measured radial profiles of n_e and T_e at the LFS midplane (see figure 9 of [7]). For deuterium-only cases, cross-field drifts due to $\mathbf{E}\mathrm{x}\mathbf{B}$ and $\mathbf{B}\mathrm{x}\nabla B$ [13] were included in the simulations. The (coupled) EDGE2D-EIRENE calculations were carried out on a non-orthogonal grid including the SOL and the pedestal region. The EIRENE grid utilises the EDGE2D grid, but also extends to the actual main chamber and PFR walls; for the halo plasma region vacuum was assumed. To fully account for hydrogen ion-neutral and ion-molecular interaction at high divertor densities (> 10^{20} m^{-3}) the currently most complete EIRENE model [14] was used. Deuterium fuelling was achieved by injection from the outermost grid boundary in the PRF in EDGE2D, and pumping by imposing albedos (of value 0.94) at two primary surfaces in the divertor corners on the EIRENE grid (Fig.1). Following deuterium into the sub-divertor was not yet included, and thus the current to the pump surfaces used as a proxy to assess the impact of deuterium removal on the plasma solution. Pumping of neutrals at other surfaces was not imposed. Deuterons were fully recycled at the divertor targets and the outermost EDGE2D grid cells. Beryllium and tungsten were included in the simulations. Carbon was presently omitted due to limitations with the EDGE2D; however, the carbon content was measured at the level of 0.05%, or below, [15] justifying such simplification. Further details on the impurity model can be found in [7] and therein.

The primary outputs of the EDGE2D-EIRENE simulations used throughout this paper are the radiated power in the SOL and pedestal regions ($P_{rad,SOL+ped}$), the profiles j_{sat} and T_e at the target plates, the neutral currents to the pumping surfaces (I_{pump}), and the leakage neutral currents from the divertor into the main chamber (I_{leak}). These parameters will be compared to the experimental equivalents where available.

2. MEASUREMENTS OF PLASMA AND NEUTRAL CONDITIONS IN THE DIVERTOR

In ohmic and neutral beam-heated plasmas held at approximately constant heating power (Fig.2a), the radiated power integrated over the SOL and pedestal regions increased nearly linearly with increasing electron density at the core plasma edge (Fig.2b). Here, the line-averaged electron density across the outer edge at the LFS of the core plasma, $<n_e>_{l,edge}$ is used as the independent parameter. Within the data set shown for the neutral beam-heated plasmas, $P_{rad,SOL+ped}$ tripled from going to low-recycling to fully detached plasmas in the V5 configuration. When integrated over the SOL and pedestal region, there is no difference in $P_{rad,SOL+ped}$ between the V5 and VT configurations. (At the writing of this report there no data available for fully detached plasmas in the VT configuration.) The same trend and increase in $P_{rad,SOL+ped}$, and its independence on divertor plasma configuration was observed in ohmic plasmas [6].

The peak T_e in the immediate vicinity of the separatrix at the LFS plate, $T_{e,LFS,pk}$, monotonically decreased from about 30 to 40eV at the lowest $<n_e>_{l,edge}$ to 20eV at mid-range $<n_e>_{l,edge}$, and decreased steeply from 20eV to less then 10eV as $<n_e>_{l,edge}$ was raised further (Fig. 2c). At the highest $<n_e>_{l,edge}$ in the V5 configuration $T_{e,LFS,pk}$ was measured (with the probes) at 4 eV. High-n Balmer line analysis would suggest temperatures below 1eV [16]. At the HFS plate $T_{e,pk}$ was observed at or below 10eV over the entire $<n_e>_{l,edge}$ range investigated, indicating significantly cooler plasma conditions within the HFS divertor plasma. This observation is consistent with many similar studies in other tokamaks in configurations with the ion $\mathbf{B}\times\nabla B$ drift direction into the divertor (Ref. [17]

and therein).

The peak T_e (and j_{sat}) were determined from the Langmuir probe profiles at the targets within a radial distance of ±2 cm from the separatrix, and chosen to avoid misstating T_e and j_{sat} at the separatrix due to the uncertainty of separatrix location. (Due to the brevity of this paper, the target profiles are not shown here.) The profile shapes T_e and j_{sat} were almost identical between the V5 and the VT configuration, including the spatial position of the peaks in these parameters. For nearly identical $\langle n_e \rangle_{l,edge}$ values, the magnitudes of T_e and j_{sat} at the LFS plate are the same within 50% for the V5 and VT configurations. Similar qualitative and quantitative observations were made for the profiles of T_e and j_{sat} at the HFS plate. Here, the peak in j_{sat} was measured twice as high in the VT than in the V5 configuration for low and mid-range $\langle n_e \rangle_{l,edge}$ (see also Fig.2f).

Rollover of the ion saturation current occurred at almost identical $\langle n_e \rangle_{l,edge}$ in the V5 and VT configurations (Fig.2f). Furthermore, the rollover occurred at the same $\langle n_e \rangle_{l,edge}$ at the HFS and LFS plates. Here, the profiles of j_{sat} very spatially integrated across the HFS and LFS plates to give the total current. Generally, $I_{div,LFS}$ was 1.5 to 2 times higher than $I_{div,LFS}$. In both configurations I_{div} decreased by up to an order of magnitude (data for V5 only) for $\langle n_e \rangle_{l,edge}$ approaching the density limit. These observations in neutral beam-heated plasmas are consistent with those in ohmic plasmas [6].

The neutral pressure in the sub-divertor, $p_{sub\text{-}div}$, was a factor of 2 higher in the VT than in the V5 configuration (Fig.2e), consistent with previous observations of increased neutral divertor pressures in vertical versus horizontal configurations [5]. Correspondingly, to achieve the same $\langle n_e \rangle_{l,edge}$ in the VT configuration, approximately twice as much D_2 fuelling was required than in the V5 configuration (Fig.2d). In ohmic plasmas approximately 2-3 times higher fuelling rates were required in the VT configuration [6]. Whether this increase in $p_{sub\text{-}div}$, and thus higher pumping rates, in the VT configuration is due to direct pathway of neutrals from the gas injection system to the sub-divertor pumping plena could not be addressed within these studies. Previous studies of injecting methane into the LFS strike zone in a V5 configuration in JET with the carbon wall, however, indicated that about 33% of the methane injected from the same gas module was pumped out of the vacuum directly without entering the plasma [18]. Hence, it is conceivable that a significant fraction of the injected deuterium is indeed pumped directly, and thus could explain the observed difference in required fuelling and $p_{sub\text{-}div}$.

3. EDGE2D-EIRENE SIMULATIONS OF THE PLASMA CONDITIONS AND NEUTRAL DYNAMICS IN V5 AND VT CONFIGURATIONS

Raising the fuelling and thus the separatrix density at the LFS midplane ($n_{e,sep,LFS\text{-}mp}$), while keeping the power across the core boundary constant (2.2MW), EDGE2D-EIRENE simulations show qualitatively the same response of $P_{rad,SOL+ped}$, I_{div}, and $T_{e,plate,pk}$ as observed in the experiments (Fig. 3). The rollover of I_{div} is predicted to occur at about 10% lower $n_{e,sep,LFS\text{-}mp}$ in the VT configuration, and takes place at the HFS and LFS plate at same $n_{e,sep,LFS\text{-}mp}$ (Fig.3f). Assuming a 1-to-2 linear relationship between $n_{e,sep,LFS\text{-}mp}$ and $\langle n_e \rangle_{l,edge}$, as proposed previously by the authors [19], the rollover density of $I_{div,LFS}$ is predicted at the same density as observed in the experiment. At densities beyond the rollover, the predicted $I_{div,LFS}$ decreases by a factor of 2 in the V5 configuration, while by 40% only in the VT configuration. Stable solutions could not be obtained for $n_{e,sep,LFS\text{-}mp}$ beyond those shown in Fig.3. It is important to note that the rollover of $I_{div,LFS}$ is predicted to occur when $T_{e,LFS,pk}$ is as low as 2eV, or lower.

The total radiated power in SOL and pedestal regions is predicted up to 30% higher in the VT than in the V5 configuration (Fig.3a): this is mainly due to stronger deuterium radiation in the divertor legs. Concomitantly, the predicted values for T_e at the HFS and LFS plates at the separatrix are significantly lower in the VT than in the V5 configuration (Fig.3b). For mid-range densities, i.e., $n_{e,sep,LFS\text{-}mp}$ in the range of 0.8 to $1.4\text{x}10^{19}$ m^{-3}, $T_{e,sep}$ is predicted to be a factor of 10 lower in the VT than in the V5 configuration. For vertical targets, the predicted T_e profiles typically peak in the common SOL away from the separatrix (Fig.3c). Therefore, the predicted $T_{e,plate,sep}$ better represent the measured $T_{e,plate,pk}$ than the predicted $T_{e,plate,pk}$. In general, the simulations reproduce what is conceptually considered for vertically inclined target configurations: reflection and release of deuterium atoms and molecules in the direction of the separatrix, leading to cooling of the plasma close to the separatrix and lower T_e.

Including cross-field drifts in the simulations significantly reduces T_e at the HFS plate for a given $n_{e,sep,LFS\text{-}mp}$ (Fig.4b and 4c). Or, in other words, plasma conditions of T_e of < 2eV are obtained at significantly lower $n_{e,sep,LFS\text{-}mp}$. The largest difference in $T_{e,HFS,}$ is observed for the V5 configuration, in which T_e < 2 eV conditions across the entire plate are obtained at $n_{e,sep,LFS\text{-}mp}$ half required for a no-drift case. These observations are consistent with previous investigations using EDGE2D-EIRENE [13] as well as other fluid codes, such as SOLPS [20] and UEDGE [21]. Concomitantly, the rollover of $I_{div,HFS}$ is predicted to occur at 15% lower $n_{e,sep,LFS\text{-}mp}$ (Fig.4f), coinciding with $T_{e,HFS,pk}$ reaching 2eV (Fig.4c). However, the LFS plasma is less affected by the inclusion of drifts, and therefore, drifts not explain why the T_e profiles at the LFS plates are almost identical in the experiments, and not in the simulations. The radiation in the SOL slightly increases when including cross-field drifts due to increase radiation in the HFS divertor (Fig.4a). Colder HFS divertor conditions also lead to an increase in deuterium removal at the divertor corners (Fig.4d).

EDGE2D-EIRENE calculations of the neutral currents, including both deuterium atoms and molecules, indicate that the pump in the LFS divertor corner removes about 80% of the total injected deuterium in the V5 configuration (Fig.3e). In contrast, about 70% of the total injected deuterium is removed at the HFS corner in the VT configuration. The calculations are based on assuming equal albedos on both pumping surfaces. Considering the pathways for neutrals to reach the cryo pump and their associated conductances in the sub-divertor, the LFS pump ought to be more efficient (have a higher albedo) than the HFS pump. The simulations signify that even in vertical configurations, in which neutrals have to penetrate through the divertor plasma and PFR to reach the pump, this transport mechanism is sufficiently efficient to compete with the more ballistic reflection of particles into the LFS corner in a horizontal configuration. The total amount of deuterium pumping is equal in the two configurations (Fig.3d), and approximately a factor of 3 lower than what was observed experimentally. Hence, either the actual cryo pumping is higher in the experiment than assumed here, or other (divertor and main chamber) surfaces remove significant amount of deuterium, or deuterium gas is directly pumped from the gas injection module without entering the plasma. To address the former issue, in the V5 configuration the pumping albedo of both pump surfaces was lowered from 0.94 to 0.5 to reach the experimental throughput, with little effect on the divertor plasma. In other studies [14], [22], albedos of down to 0.84 at the main wall were assumed to reproduce the experimental deuterium throughput. Little is know about the direct pumping of the gas by the cryo pump.

To investigate the impact of by-pass leaks in the JET divertor structure on the plasma conditions at the LFS plate, an artificial pump surface in front of a gap between the two toroidal rows forming the vertical target at the LFS (Fig.1). Conceptually, such pumping ought to lead to increase in T_e provided the neutral density in front of the pump is sufficiently high. Lowering the albedo of the by-pass leak surface from 1.0 (no pumping) to 0.1 (90% pumping), however, shows that the predicted neutral density at the location of the pump surface is too small to impact the overall recycling at the LFS plate to reduce T_e. These studies were carried out for the VT configuration at $n_{e,sep,LFS\text{-}mp} = 1.0\times10^{19}$ m^{-3}, which showed the largest difference between V5 and VT in the simulations. By imposing an albedo of 0.1 at the gap, the removed deuterium current reached 30% of the current going to both the HFS and LFS divertor pumps. Yet, $T_{e,LFS,sep}$ is predicted to remain at 3 eV.

Finally, EDGE2D-EIRENE predicts that the neutral leakage from the divertor into the main chamber is dominated via the HFS divertor in both the V5 and VT configurations. With increasing $n_{e,sep,LFS\text{-}mp}$, and thus divertor degree of detachment, the leakage current at the HFS is predicted to increase from 1×10^{22} D/s to 4×10^{22} D/s. The magnitude of these currents is about 10-20% of the total ion currents to the plates, and of the same order as the pump currents. The LFS divertor is predicted to remain more opaque to neutrals, producing neutral leakage currents of the order 1×10^{22} D/s, and to become more transparent (about 2x) when the LFS divertor is fully detached. Hence, these EDGE2D-EIRENE simulations would suggest that JET is a neutral-tight divertor. Inclusion of cross-field drifts makes the HFS divertor more transparent to neutrals, as expected. For $n_{e,sep,LFS\text{-}mp}$ in the mid-density range, the HFS leakage current doubles to triples. Neutral leakage from the LFS divertor is less affected by the inclusion of drifts.

SUMMARY

Similar plasma conditions and, in particular, almost an identical functional dependence on upstream density were measured in JET ohmic and neutral beam-heated L-mode plasmas in configurations with the LFS strike point on the LFS horizontal (V5) and on the LFS vertical (VT) divertor target plates. The HFS strike point was on the HFS vertical plate in both configurations. These data would suggest a very small impact of target plate inclination on ion current to and plasma temperature at the LFS divertor plate. The sub-divertor pressure, however, was observed being systematically higher in the VT configuration, by factors of 2 to 5, in turn, requiring higher D_2 fuelling rates to obtain the same core and SOL profiles at the LFS midplane. EDGE2D-EIRENE simulations of these plasmas also show the ion currents to the divertor plates to rollover into partial detachment at the same upstream density. However, lower plasma temperatures at the separatrix on the LFS plate are predicted. Inclusion of cross-field drifts leads to a reduction of the plasma temperature at the HFS, but have little effect on the conditions on the LFS plate. Introducing an additional pump surface at the tile gap on the LFS vertical target plate to mimic a by-pass leak, and assuming neutral albedos of this surface as low as 0.1, does not raise the plasma temperature at the separatrix on the LFS plate.

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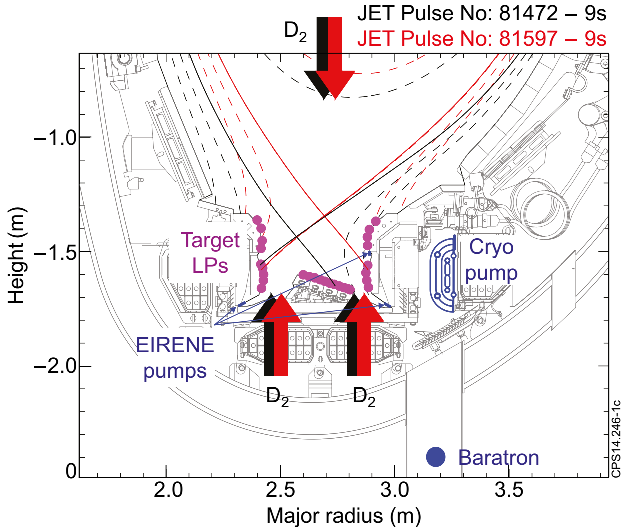

Figure 1: JET divertor and sub-divertor structure, and the V5-horizontal (V5, black, JET Pulse No: 81472) and vertical (VT, red, JET Pulse No: 81597) divertor plasma configurations. The main features of the sub-divertor, the gas injection locations, and the primary divertor diagnostics are highlighted.

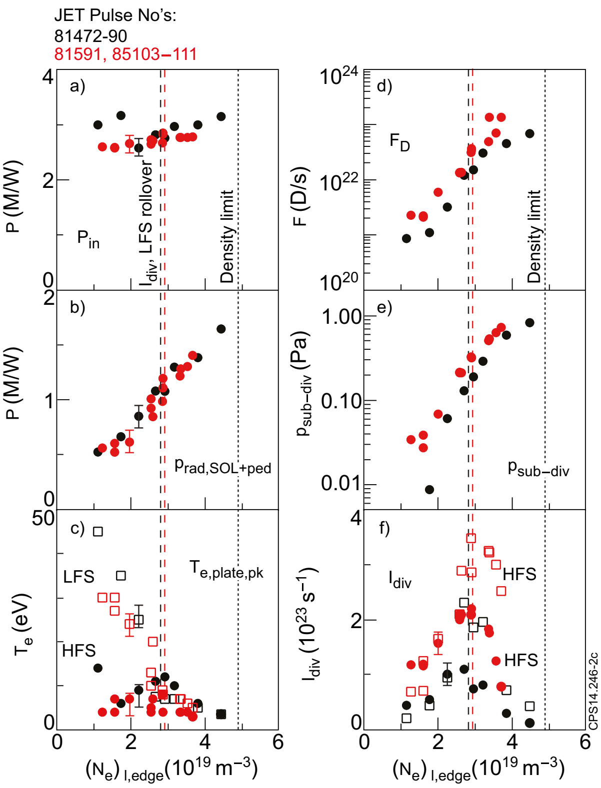

Figure 2: Measured (a) total input power (P_{in}), (b) total radiated power in the SOL and pedestal region ($P_{rad,SOL+ped}$), (c) peak T_e in the near-separatrix region at the HFS (solid circles) and LFS (open squares), (d) total atomic deuterium input, (e) baratron sub-divertor pressure, and (f) total ion current to the HFS (closed circles) and LFS (open squares) plates as function of line-averaged density at the core edge. Black symbols refer to the V5 configuration, red symbols to the VT configuration.

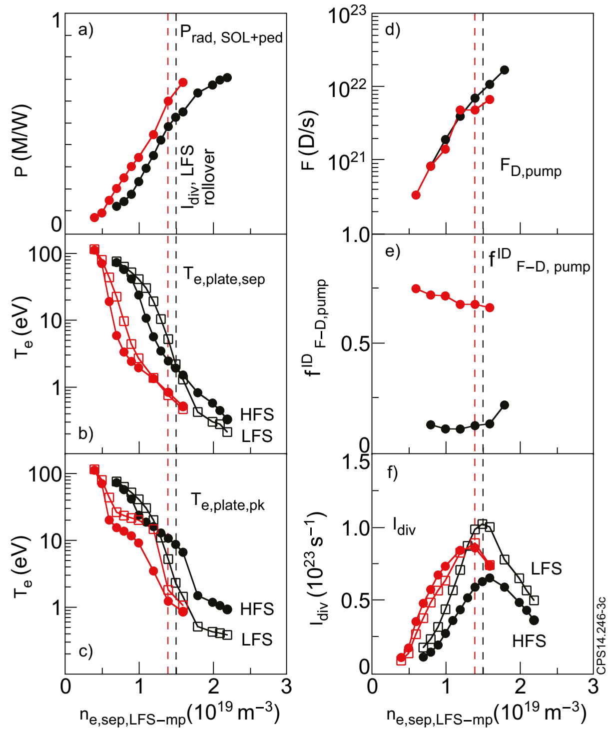

Figure 3: EDGE2D-EIRENE predicted (a) total $P_{rad,SOL+ped}$, (b) T_e at the separatrix of HFS (closed circles) and LFS (open squares) plates, (c) peak T_e along the HFS (closed symbols) and LFS (open squares) plates, (d) total pumped atomic and molecular deuterium currents, (e) fraction of the total pump deuterium currents to the HFS pump surface, and (f) total ion current to the HFS (closed symbols) and LFS (open squares) plates as a function of separatrix density at the LFS midplane. Colour and symbol code as in Fig.2.

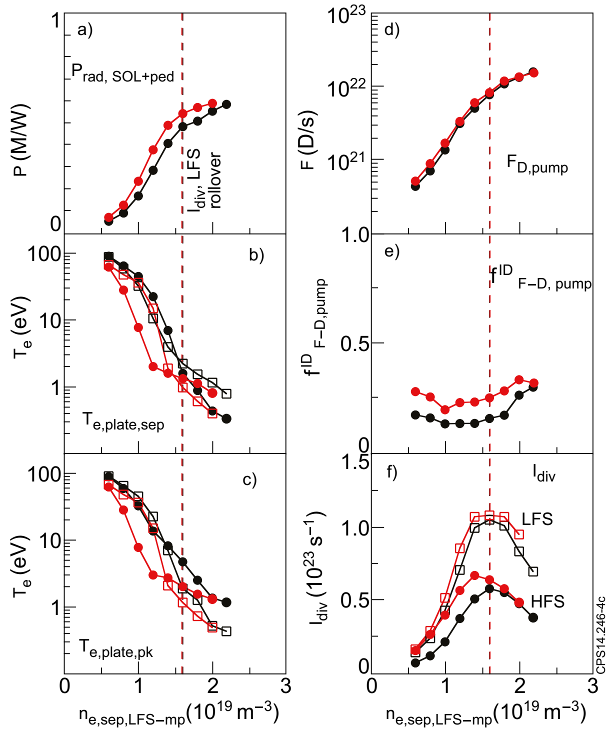

Figure 4: EDGE2D-EIRENE predictions of same parameters as in Fig.3 for pure-deuterium plasma without (black) and with (red) cross-field drifts.