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ABSTRACT

Detailed measurements in two dimensions by probes and Thomson scattering reveal unexpected local electric potential and electron pressure (p_e) maxima near the divertor X-point in L-mode plasmas in the DIII-D tokamak [J.L. Luxon and L.G. Davis, Fusion Technol. **8**, 441 (1985)]. The potential drives $\mathbf{E} \times \mathbf{B}$ circulation about the X-point, thereby exchanging plasma between closed and open magnetic surfaces at rates that can be comparable to the total cross-separatrix transport. The potential is consistent with the classical parallel Ohm's law. A simple model is proposed to explain the pressure and potential hills in low power, nearly detached plasmas. Recent two-dimensional edge transport modeling with plasma drifts also shows X-point pressure and potential hills but by a different mechanism. These experimental and theoretical results demonstrate that low power tokamak plasmas can be far from poloidal uniformity in a boundary layer just inside the separatrix. Additional data, though preliminary and incomplete, suggest that $\mathbf{E} \times \mathbf{B}$ circulation across the separatrix might be a common feature of low confinement behavior.

I. INTRODUCTION

Many tokamaks divert escaping plasma along magnetic lines to target surfaces somewhat removed from the main plasma. The magnetic separatrix, indicated in Fig. 1, separates the interior region of plasma, confined on closed toroidal magnetic surfaces, from the open line scrape-off layer (SOL), where plasma flows almost parallel to the magnetic field $\mathbf{B}$ to the targets, where it deposits its energy and recombines. The X-point, a null point of the poloidal magnetic field, defines the separatrix in conventionally diverted tokamaks. The region between the strike points, with magnetic lines that do not encircle the confined plasma, is called the private region. It is beneath the X-point in Fig. 1. The region roughly from the X-point to the targets is usually called “the divertor.”

The X-point is the apex of four quadrant regions: the private region, the outer and inner SOLs (at larger and smaller radii, respectively, than the X-point) and closed confinement surfaces. The X-point region is complex, because the four plasma quadrants, each with distinct temperature, density and electric potential, meet there. Theoretical analysis predicts the formation of a viscous boundary layer across the separatrix to accommodate the disparate regions.¹ Numerical solutions of the edge plasma by the UEDGE^{2,3} computer model, with electric potentials and magnetic gradient drifts self consistently included,^{4–6} indeed exhibit a boundary layer of electric field normal to and just inside the separatrix. The same numerical solutions also discovered the existence and importance of a large $\mathbf{E} \times \mathbf{B}$ plasma drift in the private region. Recent measurements of the electric potential⁷ in the divertor of the DIII-D tokamak⁸ quantitatively confirmed the private $\mathbf{E} \times \mathbf{B}$ plasma convection in agreement with the prediction.⁴ However, those measurements did not explore the X-point region.

FIG. 1. Single-null diverted plasma geometry shown inside the DIII-D vacuum vessel outline with the disposition of probe, Thomson scattering and ion temperature diagnostics. The 98% and 99% normalized flux surfaces are drawn inside the separatrix and the 101% and 102% surfaces outside.

Although tokamak divertor plasmas have been intensively studied, the X-point region has not been adequately evaluated. Furthermore, the roles of $\mathbf{E} \times \mathbf{B}$ and $\nabla p \times \nabla B$ drifts in this region have received little attention. The DIII-D tokamak offers divertor diagnostics with good X-point coverage that enable experimental investigations of these and other topics.

In this paper we review recent measurements taken in two dimensions around the X-point.⁹ The measurements reveal the unexpected presence of a positive electric potential and electron pressure (p_e) maxima near the X-point. We show new preliminary data that suggests that the p_e maxima, and by inference the $\mathbf{E} \times \mathbf{B}$ convection, appear in L-mode and Type-3 ELMy¹⁰ H-mode¹¹ discharges, but not in ELM-free H-mode. We present a UEDGE numerical solution that exhibits X-point peaking, and we propose a mechanism for the generation of these maxima. To our knowledge, these results have not been predicted. We show that transport across the separatrix by $\mathbf{E} \times \mathbf{B}$ convection can be large, in some cases. Furthermore, the combined experimental data and numerical simulation results, though preliminary, suggest that poloidal nonuniformity and $\mathbf{E} \times \mathbf{B}$ plasma exchange across the separatrix might be a common, perhaps ubiquitous feature of low-confinement edge behavior.

II. EXPERIMENTAL ARRANGEMENT

The experiments were performed in the DIII-D tokamak,⁸ operated with an applied toroidal magnetic field $B_T = 2.1$ T at radius $R = 1.7$ m and a plasma current of 1.0 MA. Both directions of B_T were employed. The line average electron density of the plasmas presented in this paper, for which we have the most complete data, was $2.5 \times 10^{19} \text{ m}^{-3}$. The plasma was heated by 0.3 MW of neutral beam and 0.6 MW of Ohmic power and was in L-mode. The divertor plasma was attached to the target at the outer strike point, but with $T_e \sim 5$ eV at the target in these low power plasmas, it was on the verge of detachment. The divertor plasma was cold and detached from the inner target, which is typical in DIII-D under these conditions.

Electric potential was measured by a pair of fast-stroking ($\sim 1/4$ s) Langmuir probes, one moving vertically through the divertor region¹² and the other horizontally through the upstream SOL just below the torus equatorial plane.¹³ The probe locations are indicated in Fig. 1. Langmuir probe tips on the arrays measured electron temperature T_e and the floating potential Φ_f . The actual plasma potential, Φ , was calculated from Φ_f and T_e by conventional probe theory. The divertor array also measured the Mach number M of plasma flow parallel to $\mathbf{B}$. Two Thomson scattering systems provided the primary measurements of T_e and electron density n_e . The divertor Thomson scattering system¹⁴ provided measurements at eight vertically separated locations, as shown in Fig. 1 and Fig. 2, along the same radius as the divertor probe. The upstream Thomson scattering system¹⁵ measured at many closely spaced points (≈ 13 mm separation) vertically across the edge and SOL near the top of the plasma, as indicated in Fig. 1. Probe and Thomson scattering T_e measurements agreed well. Plasma ion temperature T_i was measured near the equator by charge exchange recombination spectroscopy (CER).¹⁶ The CER diagnostic also measures impurity ion mean velocity. No suitable T_i diagnostic covers the X-point in DIII-D.

In order to measure all around the X-point region, the X-point was stepped horizontally past the fixed divertor diagnostics, between the extremes shown in Fig. 2, by changing the external divertor magnetic field. The core plasma remained constant. The magnetic surfaces were calculated

FIG. 2. Maximum range of divertor geometry used to measure outside and inside the X-point radius. The dots are the eight divertor Thomson scattering measurement points. The X-point height, lower than customary, permits Thomson scattering measurements above the X-point.

by the equilibrium fitting code EFIT.¹⁷ In this paper we label the magnetic surfaces by their normalized poloidal magnetic flux ψ_n . $\psi_n = 0$ is the magnetic axis; $\psi_n = 1$ is the separatrix, $\psi_n > 1$ is in the SOL with ψ_n increasing outward from the separatrix; and $\psi_n < 1$ is either closed confinement or open private surfaces with ψ_n decreasing away from the separatrix. The X-point is a saddle point about $\psi_n = 1$.

Figure 3 shows profiles of the upstream ion and electron temperature, near the separatrix as a function of ψ_n . Note that $T_i > T_e$ just inside and outside the equatorial separatrix, a well-known effect where the energy transport time out of the edge layer becomes less than the electron-ion energy equilibration time.

FIG.3. Upstream ion and electron temperature profiles near the separatrix as a function of ψ_n . Ellipses span the standard deviation of three to five T_i measurements. Squares indicate measured T_e values. The T_e time sequential data were smoothed somewhat, prior to plotting, for clarity.

III. EXPERIMENTAL RESULTS

Figure 4 shows divertor and upstream plasma potential plotted as a function of ψ_n , enabling comparison of X-point and upstream quantities that lie on the same magnetic surfaces. Despite large fluctuations at $\lesssim 100$ Hz, which are characteristic of both Φ and T_e near the separatrix,¹⁸ the potential in all four quadrants near the X-point is positive (~ 100 V) and is much larger than the upstream potential (~ 20 V). These data are from discharges with B_T directed into the page in Fig. 1 (“reversed” B_T , ion ∇B drift away from the X-point), for which we have the most complete data. With oppositely directed B_T (“standard” B_T , ion ∇B drift toward the X-point), the potentials were similarly distributed but the divertor and upstream potentials were more positive than the reversed B_T case by ~ 25 V and ~ 50 V, respectively. A potential in the outer SOL near the X-point more positive than upstream was reported in an earlier DIII-D L-mode discharge,¹⁸ but the rest of the X-point region was not explored. The large potential hill on closed magnetic surfaces, where neoclassical plasma theory predicts only a weak poloidal potential nonuniformity, $e\Delta\Phi \ll kT_e$, is particularly remarkable. In the SOL, the non-monotonic poloidal potential variation, from target to potential peak in the X-region, to a modest value upstream, is also noteworthy, because it is commonly thought that Φ should increase monotonically with T_e .

FIG. 4. Potential Φ plotted as a function of ψ_n . Target is at $\Phi = 0$. (a) Data from a probe stroke through the private region, the X-point and into the confinement surfaces. (b) Data from one inner SOL and two outer SOL strokes, combined to make a radial scan at near the X-point height. Upstream data combine two strokes.

Figure 5 shows n_e , T_e and $p_e = n_e T_e$ from Thomson scattering as functions of ψ_n from the same reversed B_T shot as Fig. 4. The “X-region” data cover inner SOL, outer SOL, and closed surfaces. The plotted data are from the diagnostic view points located above or just below the X-point position. Electron pressure near the X-point is ~ 2 times greater than at the upstream separatrix. Therefore, there is a local p_e maximum near the X-point. The relative excess p_e is highest on closed surfaces and least on inner SOL surfaces, at least within the field of view of the diagnostic and for this class of discharge. A p_e hill is observed in L-mode with both B_T directions. It is also observed in the few Ohmically heated plasmas for which we have data, for example, Ref. [19]. The X-point nonuniformity extends inward for about 0.5%–1% of poloidal flux from the separatrix. In contrast, in ELMing (Type 1 ELMs¹⁰) H-mode discharges with sufficiently low X-point where we have obtained data, p_e appears to be constant on the closed surfaces, as nearly as we can resolve, in accordance with conventional expectations.

The p_e hill is associated mainly with a density maximum near the X-point relative to upstream. However, as seen in Fig. 5, T_e inside the separatrix is also somewhat higher near the X-point (~ 55 eV) than upstream (~ 40 eV) and contributes somewhat to the p_e hill. The higher X-point T_e is less prominent or absent with standard B_T direction. We have been unable to find a theoretical basis for a higher X-point T_e of the magnitude shown. We verified the validity of the Thomson scattering operation and data. Channel-to-channel Thomson scattering errors are ruled out by comparison of data as the divertor and upstream geometries change and bring the same region of plasma into the view of successive channels. Systematic errors between up- and downstream are ruled out, because (a) the divertor and upstream T_e values merge together at about 1% of poloidal flux in from the separatrix, and (b) the divertor T_e jumps across the X-point separatrix, as usual. The Langmuir probes also indicate that T_e is greater at the X-point than upstream. The expanded flux near the X-point makes the EFIT calculation of the flux value of a diagnostic point very insensitive to the precise location of the X-point. Upstream, however, $\Delta\psi_n$ of 0.5% corresponds to only 2 mm radially at the outer midplane, which is much less than the commonly stated EFIT midplane accuracy of about ± 5 mm. Therefore, we must rely on other indicators of EFIT accuracy. Since electron thermal transport changes drastically between closed and open magnetic surfaces, the change of slope of T_e vs. ψ_n in Fig 3 is one possible separatrix marker. According to this criterion, the EFIT surfaces used to construct the figures are very accurate. In Ref. [19] we adjusted the upstream flux surfaces so that up- and downstream T_e profiles matched as well as possible on closed surfaces. Here and in Ref. [9], we have chosen to present the data as calculated and leave the T_e issue unresolved. Because the T_e and n_e gradients are weak at the L-mode edge, the existence of the local X-point potential and p_e hill is insensitive to the higher X-point T_e , though the magnitude of the hills is affected by it.

FIG. 5. Electron p_e , n_e , and T_e , measured by Thomson scattering, as a function of ψ_n . Data from upstream and the X-region are distinguished by their plot symbols. Private flux and cold plasma near the target are excluded. The left plot includes data from above the X-point and the inner SOL. The right plot includes data from above the X-point and the outer SOL. Data above the X-point are common to both plots.

The evolution of the X-point p_e hill was studied as the neutral beam (NB) heating power was increased to effect a transition from L- to H-mode. The L-mode plasma had an average NB heating power of 0.55 MW (25% duty pulse modulation). See Fig. 6. The power was increased to 2.2 MW for 50 ms and then modulated at 50% duty to give 1.1 MW average to sustain the H-mode. This yielded a brief period of L-mode at the higher power, followed by transition to a low power H-mode with Type 3 ELMs¹⁰ and then to ELM-free H-mode. The Thomson scattering lasers were timed to pulse within a 1.4 ms interval, to compare the upstream and divertor plasmas at nearly the same time,

but the lasers are each limited to a 20 Hz rate. The NB timing was varied relative to the laser firing times, in order to collect data at representative times through the L-H transition process. The X-point was stationary and was at the divertor Thomson diagnostic radius. Data were obtained from seven L- to H- sequences in this preliminary experiment. Despite the small data set, the results plotted in Fig. 6 show that p_e is higher at the X-point than upstream during L-mode and H-mode with Type 3 ELMs. However, the low power ELM-free H-mode appears to have no significant p_e difference between the two locations. An upstream separatrix location error is of more consequence in H-mode plasmas, because the H-mode edge gradients are larger, and here the H-mode EFIT magnetic surfaces upstream were shifted to bring their $T_e(\psi_n)$ profiles in agreement with those at the X-point. Since the electric potential is linked to p_e by the parallel Ohm's law (see below), the pressure differences imply the corresponding presence or absence of an X-point potential hill during the different plasma modes.

FIG. 6. Evolution of X-point p_e hill through low power L-to-H-mode transition. Top box is time history of the applied neutral beam power. Middle box is H_α light at the outer divertor, indicative of plasma recycling rate. Three plasma modes are indicated. Bottom box is measured p_e at the X-point (closed symbols) and upstream (open symbols). The p_e points come from seven separate L-to-H-transition sequences. They are placed at the correct time relative to the transition events.

IV. X-POINT CIRCULATION

The cross- $\mathbf{B}$ potential gradient drives plasma electrons and ions on equipotentials around the X-point, as sketched qualitatively in Fig. 7, at the electric drift velocity, $\mathbf{v}_E = \mathbf{E} \times \mathbf{B} / B^2 \approx -\nabla \Phi \times \mathbf{B}_T / B_T^2$. Here we use the tokamak approximation, $\mathbf{B} \approx \mathbf{B}_T$. This circulation convects particles, energy and momentum across the separatrix. The $\mathbf{E} \times \mathbf{B}$ exchange time, defined as the time for a fluid element traveling at $\mathbf{v}_E$ to go from an entry to an exit point on an equipotential surface, is

$$\tau_x = |B dA / d\Phi| \quad . \quad (1)$$

Here dA is the area in the RZ plane enclosed between equipotential surfaces Φ and $\Phi + d\Phi$ in the volume of interest. The area A to calculate the exchange time is not accurately known in the experiments, because the full extent of the potential structure cannot be measured with the available diagnostics. For the potential hill region above the X-point, roughly the area bounded by the separatrix, the $\psi_n = 0.99$ surface and extending part way upstream, $A \sim 0.01 \text{ m}^2$. Approximating $dA/d\Phi$ by $A/|\Phi_2 - \Phi_1|$ with $|\Phi_2 - \Phi_1| = 65 \text{ V}$, yields $\tau_x \sim 0.3 \text{ ms}$. This is much shorter than the ion-neutral charge exchange time, $(n_0 \langle \sigma_{cx} v_i \rangle)^{-1}$, which is $\gtrsim 3 \text{ ms}$ for $n_0 \lesssim 1 \times 10^{10} \text{ m}^{-3}$, measured in the X-region of similar discharges in the same experimental series.²⁰ Therefore, X-region charge exchange, which has been advanced as significant mechanism to remove plasma angular momentum,^{21,22} is about an order of magnitude less important in these discharges than the X-point $\mathbf{E} \times \mathbf{B}$ circulation.

The number of particles per second $\dot{N}$ convected by $\mathbf{v}_E$ through any axisymmetric surface bounded by potentials Φ_1 and Φ_2 (Fig. 8) is given by^{7,9}

$$\dot{N} \approx (2\pi / R_0 B_0) \langle n R^2 \rangle (\Phi_1 - \Phi_2) \quad , \quad (2)$$

where $\langle \dots \rangle$ indicates a flux surface average, and $R_0 B_0 = (1.7 \text{ m})(2.1 \text{ T}) = 3.57 \text{ T m}$ in these experiments. Using values for the X-point separatrix region, $\langle n R^2 \rangle \approx (1.1 \times 10^{19} \text{ m}^{-3}) (1.6 \text{ m})^2$ and $\Delta\Phi = 65 \text{ V}$, yields $\dot{N} \approx 3 \times 10^{21} \text{ s}^{-1}$. This is more than half of the total cross-separatrix transport rate $\sim 5 \times 10^{21} \text{ s}^{-1}$. Since particles are convected in and out at about the same rate, the net rate is substantially less, but mixing between SOL and confined plasma is assured. Plasma energy and angular momentum convected from closed to open magnetic surfaces are not readily replaced by the corresponding inward

convection. The energy (enthalpy) per second Q convected by the circulation is calculated by substituting $5p/2$ for n in Eq. (2). Taking $p \approx 200$ Pa near the X-point yields $Q \approx 0.14$ MW, which is about 20% of the 0.7 MW total power crossing the separatrix. Similarly, the toroidal angular momentum per second $\dot{L}$ convected across the separatrix is calculated by substituting $m_i n_i \Omega R^2$ for n in Eq. (2), where Ω is the plasma toroidal angular frequency. From CER measurements, $\Omega \approx 3500$ s⁻¹. Then $\dot{L} \approx 0.14$ N·m, which is comparable with ≈ 0.165 N·m injected by the neutral beam.

Clearly, the X-point circulation plays a significant and previously unappreciated role in transport across the separatrix.

FIG. 7. Qualitative illustration of $\mathbf{E} \times \mathbf{B}$ circulation around the X-point driven by the positive potential hill.

FIG. 8. Integration path used to calculate $\mathbf{E} \times \mathbf{B}$ convection across an axisymmetric ribbon surface.

V. POTENTIAL HILL FORMATION

We propose a simple model to explain the formation of the observed X-point potential hill as a consequence of the variation of the ion pressure p_i along a magnetic flux tube. We use the conventional approximation that the total pressure, $p = p_e + p_i$, is nearly constant on a closed magnetic surface and upstream of the X-point in the SOL during high recycle operation. Uniform p is consistent with the fact that plasma flow velocities, measured by CER upstream and by the Mach probe just above the X-point, yield low Mach numbers, $\lesssim 0.1$. Then, the high measured p_e at the X-point implies a complementary low p_i there. Data from Figs. 3 and 5, just inside the upstream separatrix, show $n_e \approx n_i \approx 0.75 \times 10^{19} \text{ m}^{-3}$, $T_e \approx 40 \text{ eV}$, $p_e \approx 30 \times 10^{19} \text{ eV/m}^3$, $T_i \approx 125 \text{ eV}$, $p_i \approx 95 \times 10^{19} \text{ eV/m}^3$. Similarly, near the X-point separatrix we have $n_e \approx n_i \approx 1.6 \times 10^{19} \text{ m}^{-3}$, $T_e \approx 55 \text{ eV}$, $p_e \approx 90 \times 10^{19} \text{ eV/m}^3$. T_i is not measured near the X-point in DIII-D, but by invoking uniformity of the total pressure we calculate that the X-point $p_i \approx 35 \times 10^{19} \text{ eV/m}^3$, and then X-point $T_i \approx 22 \text{ eV}$. Such a low local T_i is plausible, because ion heating is weak and cooling is strong near the X-point. Heating by the classical ion parallel thermal conduction power from the equator to the X-point in the layer between the separatrix and $\psi_n = 0.995$ is calculated to be $\approx 0.08 \text{ MW}$ for these plasmas. The electron-ion collisional energy exchange rate is $\sim 0.01 \text{ MW}$ and is negligible, as is ion cooling to neutrals. However, convection of cool ions inward and hot ions outward across the separatrix by the X-point circulation removes $\sim 0.07 \text{ MW}$ by the calculation in Section IV, if the hotter ions are convected out at about half their upstream pressure.

The parallel electric field equilibrates the p_i and p_e gradients along a magnetic flux tube. According to the parallel component of the electron momentum equation,²³

$$\begin{aligned} e\nabla_{\parallel}\Phi &= -eE_{\parallel} = \nabla_{\parallel}p_e/n_e + 0.71\nabla_{\parallel}kT_e = kT_e\nabla_{\parallel}\ln n_e + 1.71\nabla_{\parallel}kT_e \\ &= \nabla_{\parallel}(p - p_i)/n_e + 0.71\nabla_{\parallel}kT_e \end{aligned} \quad (3)$$

The plasma resistance term, which is small in the present context, is omitted from Eq. (3). Thus, if T_e and total p are nearly constant on a magnetic surface, then the potential is high where p_i is low and n_e is large, as at the X-point. Estimating $\Delta\Phi$ from Eq. (3) with the measured p_e , n_e , and T_e yields an X-point potential about 63 volt higher than the upstream. Of this, 38 V comes from the density logarithm gradient and the remainder from the questionable T_e gradient. Thus, the calculated potential is in rough agreement with the potential data in Fig. 4.

The above considerations suggest a model of the potential and p_e X-point hills in which T_i is clamped to a lower value at the X-point by the $\mathbf{E} \times \mathbf{B}$ circulation. The low T_i reduces p_i , making p_e larger at the X-point than upstream, which then generates the local potential hill that sustains the circulation. Thus, the state is self-sustaining. The X-point density hill arises from redistribution of the plasma particles to satisfy the parallel equilibrium and does not necessarily depend on *e.g.*, an X-point gas source.

The X-point ion heating estimates presented above omitted one important term, the energy convected by the ion vertical drift velocity due to nonuniform $\mathbf{B}$, $v_{iB} \approx 2kT_i/eRB_T$. This is about 70 m/s near the separatrix in these experiments. The convected power into the X-point volume spanning ΔR in radius is

$$P_{iB} = (2\pi R \Delta R) (5p_i/2) v_{iB} \quad . \quad (4)$$

Its divergence yields X-point ion heating or cooling, depending on whether v_{iB} is toward or away from the X-point. For our L-mode plasmas, $T_i \approx 125$ eV, $n \approx 0.9 \times 10^{19} \text{ m}^{-3}$ and $p_i \approx 177$ Pa on the 0.99 flux surface. Also, let $\Delta R \approx 0.3$ m. Then $P_{iB} \approx 0.09$ MW. Since this is comparable with the other major ion heating and cooling processes already calculated, the B_T -direction-dependent P_{iB} ought to strongly influence the X-point ion temperature, especially when v_{iB} is away from the X-point P_{iB} . However, we do not infer much T_i dependence on B_T direction from the data and the assumption of poloidally uniform total pressure. Perhaps the X-point hills are produced by a mechanism more like the one described in Section VI than in this section.

VI. TWO-DIMENSIONAL MODELING

The two-dimensional UEDGE transport code^{2,3} was used to model a low power single-null-diverted DIII-D discharge with the self-consistent inclusion of the $\mathbf{E} \times \mathbf{B}$ and ∇B drifts.⁴⁻⁶ Recent numerical improvements to the code yielded solutions with greater divertor cooling by impurity radiation and neutral collisions than in Refs. 4 through 6. Only one plasma has been studied so far with the improved code. The UEDGE case has the ion ∇B drift toward the X-point and a divertor geometry with about twice the X-point height above the target and twice the divertor leg length than the experiments. This UEDGE inner divertor plasma is detached from its target, as in the experiment. Preliminary results are reported and discussed here.

The UEDGE solution has a notable electron pressure peak near the X-point on both closed and open magnetic surfaces near the separatrix, as shown in Fig. 9. T_e is nearly constant at about 45 eV on the separatrix, so the p_e hill corresponds to increased density. The X-point potential is about 25 V greater than at the outer equatorial separatrix. T_i is about 50 eV near the X-point and 95 eV upstream, again on the separatrix. The ion temperature and density poloidal variations roughly cancel, so that the ion pressure difference between the X and upstream regions is small. The total pressure is larger near the X-point than near the outer equator.

The most notable difference between the UEDGE solution and the experimental data is that the

FIG. 9. Electron pressure p_e as calculated by UEDGE on a closed magnetic surface just inside the separatrix (solid line) and on a SOL surface just outside it (dashed line). The poloidal coordinate is the computational cell number. In the SOL it begins at the inner divertor target and runs clockwise (in Fig. 1) around to the outer target. On a closed surface it runs clockwise from the X-point. Computational cells are shorter poloidally near the X-point and especially toward the targets in order to resolve the larger gradients occurring in those regions.

UEDGE SOL potential remains on the order of 80 V everywhere upward of a few poloidal cells below the X-point, whereas the experimental potential falls to ~25 V upstream. The difference might arise because the UEDGE outer divertor plasma has higher temperatures than the experimental, ~15 eV vs. ~5 eV, which in turn might be due to the different UEDGE divertor geometry. Because the UEDGE poloidal potential gradient is not as large as the experiment, the UEDGE $\mathbf{E} \times \mathbf{B}$ velocity is lower than discussed earlier. UEDGE achieves its p_e hill by a different mechanism than the X-point ion cooling proposed in the preceding section. In UEDGE the ∇B drift increases n_e near the X-point, which drives the usual Pfirsch–Schlüter parallel return flow. The parallel ion viscosity is sufficient to restrict the parallel flow, thereby causing the X-point density to increase. The result is the X-point p_e hill. The magnitude of the UEDGE parallel viscosity was clamped by a flux limiting factor⁶ that was varied between 0.15 and 0.5 with little global effect.

The UEDGE model develops a “peak and valley” or doublet feature between the outer midplane and the X-point. This feature is very apparent in Fig. 9, and it is manifest in p_i and potential as well. It arises from the same parallel viscous impedance mechanism, triggered here by increased B_p due to a nearby poloidal field coil. It still remains to determine whether the UEDGE results are real or artifactual. DIII-D presently has no diagnostics able to observe such a phenomenon if it were present.

Although UEDGE investigation of tokamak edge drift phenomena is preliminary, it does suggest that the few experimental discharges from DIII-D studied so far, which operated near detachment of the outer divertor plasma, might be special. On the other hand, UEDGE results also show that, contrary to common belief, pressure and potential are not poloidally uniform, at least in low power discharges. Furthermore, local pressure and potential nonuniformities might be readily generated by inadvertent perturbations. We conjecture that $\mathbf{E} \times \mathbf{B}$ circulation might be a common feature of low confinement modes, and that the absence of a reproducible condition for transition to high confinement in tokamak experiments might be due to circulation cells triggered by small uncontrolled perturbations.

VII. SUMMARY

An electron pressure hill was discovered at the single-null divertor X-point in low power plasmas. A particular L-mode plasma was studied in some detail, and an X-point potential hill was also discovered, for both directions of ∇B drift. The potential hill drives $\mathbf{E} \times \mathbf{B}$ circulation about the X-point, thereby exchanging plasma between closed and open magnetic surfaces at rates that can be comparable to the total cross-separatrix transport. The potential is consistent with the classical parallel Ohm's law. A simple model is proposed to explain the pressure and potential hills in low power, nearly detached plasmas. Recent two-dimensional UEDGE transport modeling with plasma drifts also shows X-point pressure and potential hills but by a different mechanism. The experimental and theoretical results, though preliminary and incomplete, argue strongly that low power tokamak plasmas can be far from poloidally uniform just inside the separatrix. We conjecture that the corresponding $\mathbf{E} \times \mathbf{B}$ plasma exchange across the separatrix is a common, perhaps ubiquitous, feature of low confinement behavior.

REFERENCES

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- ¹F.L. Hinton and Y.-B. Kim, Nucl. Fusion **34**, 899 (1994).
- ²T.D. Rognlien, J.L. Milovich, M.E. Rensink, and G.D. Porter, J. Nucl. Mater. **196–198**, 347 (1992).
- ³G.R. Smith, P.N. Brown, R.B. Campbell, D.A. Knoll, P.R. McHugh, M.E. Rensink, T.D. Rognlien, J. Nucl. Mater. **220–222**, 1024 (1995).
- ⁴T.D. Rognlien, G.D. Porter, and D.D. Ryutov, J. Nucl. Mater. **266–269**, 654 (1999).
- ⁵T.D. Rognlien, D.D. Ryutov, N. Mattor and G.D. Porter, Phys. Plasmas **6**, 1851 (1999).
- ⁶T.D. Rognlien, D.D. Ryutov, and N. Mattor, Czechoslovak J. Phys. **48**, Suppl. S2, 201 (1998).
- ⁷J.A. Boedo, M.J. Schaffer, R. Maingi, and C.J. Lasnier, Phys. Plasmas **7**, 1075 (2000).
- ⁸J.L. Luxon and L.G. Davis, Fusion Technol. **8**, 441 (1985).
- ⁹M.J. Schaffer, J.A. Boedo, R.A. Moyer, T.N. Carlstrom, and J.G. Watkins, “Large E×B Convection near the divertor X-point,” accepted for publication in J. Nucl. Mater.
- ¹⁰H. Zohm, Plasma Phys. Contr. Fusion **38**, 105 (1996).
- ¹¹F. Wagner, G. Becker, K. Behringer, et al., Phys. Rev. Lett. **49**, 1408 (1982).
- ¹²J.G. Watkins, J.G. Hunter, B. Tafoya, et al., Rev. Sci. Instrum. **68**, 373 (1997).
- ¹³J.G. Watkins, J. Salmonson, R.A. Moyer, et al., Rev. Sci. Instrum. **63**, 4728 (1992).
- ¹⁴T.N. Carlstrom, C.-L. Hsieh, R.E. Stockdale, et al., Rev. Sci. Instrum. **68**, 1195 (1997).
- ¹⁵T.N. Carlstrom, G.L. Campbell, J.C. DeBOO, et al., Rev. Sci. Instrum. **63**, 4901 (1992).
- ¹⁶P. Gohil, K.H. Burrell, R.J. Groebner, et al., Proc. of 14th Symp. on Fusion Engineering, San Diego, California, 1992, Vol. 2 (IEEE, New York, 1993) p. 1199.
- ¹⁷L.L. Lao, H.E. St John, R.D. Stambaugh, et al., Nucl. Fusion **25**, 1161 (1985).
- ¹⁸R.A. Moyer, R. Lehmer, J.A. Boedo, et al., J. Nucl. Mater. **266–269**, 1145 (1999).

- ¹⁹M.J. Schaffer, J.A. Boedo, and R.A. Moyer, J. Nucl. Mater. **266–269**, 264 (1999).
- ²⁰R.J. Colchin, R. Maingi, M.E. Fenstermacher, et al., Nucl. Fusion **40**, 175 (2000).
- ²¹M.A. Mahdavi, et al., J. Nucl. Mater. **176–177** 32 (1990).
- ²²B.A. Carreras, P.H. Diamond, and G. Vetoulis, Phys. Plasmas **3**, 4106 (1996).
- ²³S.I. Braginskii, in *Reviews of Plasma Physics*, edited by M.A. Leontovich (Consultants Bureau, New York, 1965) Vol. I, p. 205.

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