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Alcator C-Mod Divertor**

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Particle drift effects on the Alcator C-Mod divertor

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Abstract. The sign of the toroidal magnetic field has a major effect on the divertor in Alcator C-Mod, determining whether the higher recycling is on the inboard or outboard side and leading to inboard/outboard temperature and density differences up to a factor of ten. A recently published paper [1] reported in detail on these observations, which are an indication of the importance of plasma particle drifts for understanding and modelling the divertor. The conference presentation covered these published results and also some additional results, documented here, in which the plasma flows associated with the field-direction-dependent asymmetries are measured using a Mach probe and a localized impurity puffing plume analysis technique.

1. Introduction

Most single-null tokamak divertor experiments show imbalances between the inboard and outboard legs of the divertor in heat flux, density, temperature and plasma radiation that depend on the direction of the toroidal field (see refs [1,2] and references therein). These imbalances are almost certainly an indication that particle cross-field drifts are leading-order effects and must be included in any realistic model of the divertor. Alcator C-Mod shows particularly large imbalances and its extensive divertor diagnostics have been able to document these rather clearly. In the present paper we summarize briefly the previously published divertor asymmetry results from Alcator C-Mod in this introduction, and then present some more recent observations that help to extend our knowledge of these effects.

All the results reported here are from a plasma configuration with a lower single-null divertor. For a right-handed cylindrical coordinate system (r, ϕ, z) with the z -axis vertically upward, the normal field direction, with the direction of $\mathbf{B} \wedge \nabla B$ towards the divertor, is that the toroidal component of the magnetic field, B_ϕ is *negative*. These plasmas are compared with others having *abnormal* field direction, i.e. B_ϕ *positive*. The equilibria are (with some exceptions to be noted) essentially the same in shape. The direction of the plasma current is always the same as the toroidal field, so that the sign of the helicity of the field lines is maintained. However, the direction of the plasma current is expected to have no effect on the in-out asymmetries.

Striking changes are observed in the total visible radiation, between normal and abnormal field direction plasmas. The normal situation has strong recycling light enveloping the inboard divertor, and much less at the outboard. This situation reverses for the abnormal field. Wide-angle videos show significant visible radiation in the abnormal field case only along lines of sight that can view into the closed outer divertor region. Tomographic reconstructions specifically of D_α light confirm that the hydrogen emission is predominantly near the outer strike-point on the vertical section of the divertor plate in the abnormal field case, whereas the highest emission extends along the inner divertor for the normal field.

Bolometric tomography of the radiative losses in the divertor show the same trends, the dominant radiation moving from inboard to outboard when the field is changed from normal to abnormal. The main difference between the bolometry and the D_α profiles is that the bolometric profiles tend to be predominantly in the vicinity of the x-point, either to the inboard or outboard sides, whereas the D_α is more spread towards the divertor plates themselves. More recent bolometer measurements confirm that the radiation asymmetries persist in H-mode plasmas but with the radiation somewhat lower with respect to the x-point. Neither reduction in the neutral gas leakage of the divertor nor boronization of the walls appear to have a strong effect on the asymmetry.

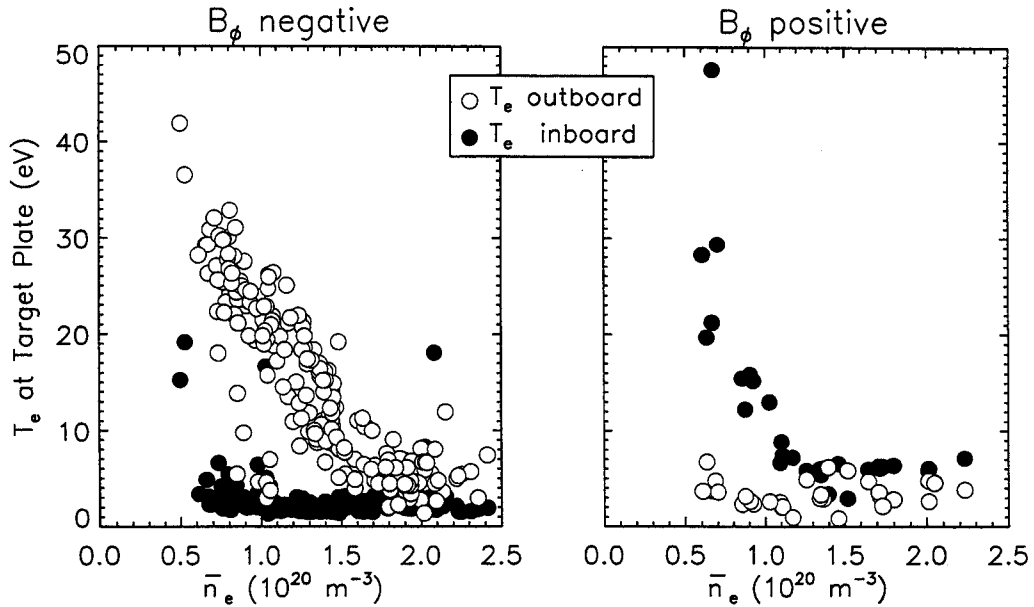


Figure 1. Divertor plate temperatures on the inboard and outboard sides for normal (negative) and abnormal (positive) field direction, as a function of line-average core density.

Embedded Langmuir probes in the inboard and outboard divertor plates enable a quantitative evaluation to be made of the density, electron temperature, electron pressure, and power flux at the plate. Profiles of these quantities have been compared,

referred to flux surface distance from the separatrix at the outer mid-plane (ρ). It is found that the imbalances are quite a strong function of core plasma density, \bar{n}_e . At low densities, $\bar{n}_e \lesssim 10^{20} \text{ m}^{-3}$, large imbalances, in plate density and temperature are observed, increasing as the density is lowered and reaching a factor of about 10 at the lowest densities systematically studied ($\bar{n}_e \sim 0.7 \times 10^{20} \text{ m}^{-3}$). As the density is raised, however, the imbalances decrease, till, above about $1.7 \times 10^{20} \text{ m}^{-3}$ they are small. By this density, the temperature at both plates is low, $\sim 5 \text{ eV}$ or below, and there is significant pressure drop between the upstream position, measured by reciprocating probe, and both plates; this is divertor detachment. These trends are illustrated in Fig 1, which shows that the cold, high-recycling side, remains at a temperature of $\lesssim 5 \text{ eV}$ over the whole density range, while the hot, low-recycling side (outboard or inboard, depending on the field direction) cools from over 30 eV (at $\rho \sim 4.5 \text{ mm}$) as the density is increased. This data also shows that the higher temperature side is hotter when it is at the outboard (B_ϕ negative) than when it is at the inboard (B_ϕ positive). This is interpreted as a geometric effect of toroidicity that has also been seen on other tokamaks. In Alcator C-Mod, the drift effects, which depend on field direction, far outweigh the geometric effect. Figure 2 shows the drift and flow patterns that are thought to be key for understanding these results.

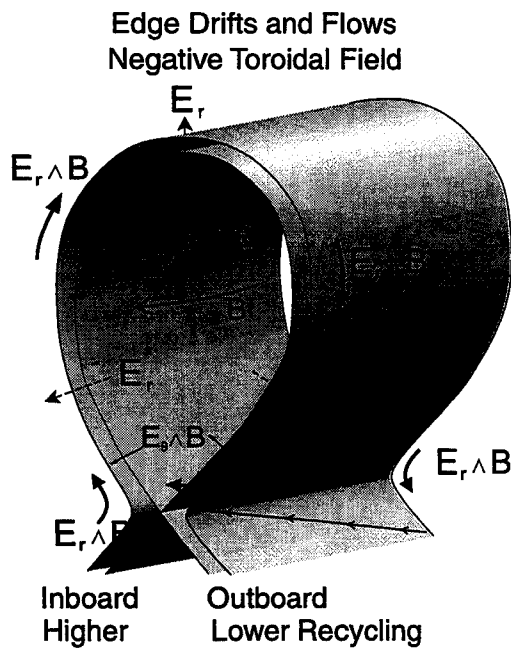


Figure 2. Schematic of the fields, drifts and flows in the SOL for the normal field direction.

At the lower densities, where there is no detachment on either plate, but the imbalances are large, it is found that the ratio of densities and temperatures inboard to outboard in the two field-directions is consistent with there being an imbalance of *power flow* to the plates (greater power on the hotter side), but not with there being an imbalance of *pressure*. This is a key finding. It argues against the mechanism of divertor imbalance being primarily a phenomenon affecting the momentum-balance

equation. Instead it argues for a mechanism that acts through the energy-balance equation. The convected energy associated with the poloidal $\mathbf{E} \wedge \mathbf{B}$ drift was suggested [1] as a possible underlying mechanism consistent with these observations.

In the final steady state, radiative losses are largely responsible for the imbalance of power to the plates. A power accounting shows that the imbalance in the measured radiation is sufficient to account for the observed plate power imbalance. If anything, the total of radiated and plate power is slightly larger on the higher recycling, colder side, but then, because this radiative side is colder, it also preferentially receives somewhat greater parallel heat conducted from the main chamber.

2. Parallel scrape-off-layer flow

The reciprocating Langmuir probe is able to scan the entire scrape-off-layer (SOL) profile at a poloidal position about half way between the midplane and the outer divertor plate; see figure 3. It has a head divided into four elements. From the ratio of the ion saturation current to the two elements that face in either direction along the magnetic field, the parallel flow of the ions can be deduced. This Mach-probe operation shows that the parallel flows are strongly affected by the field direction.

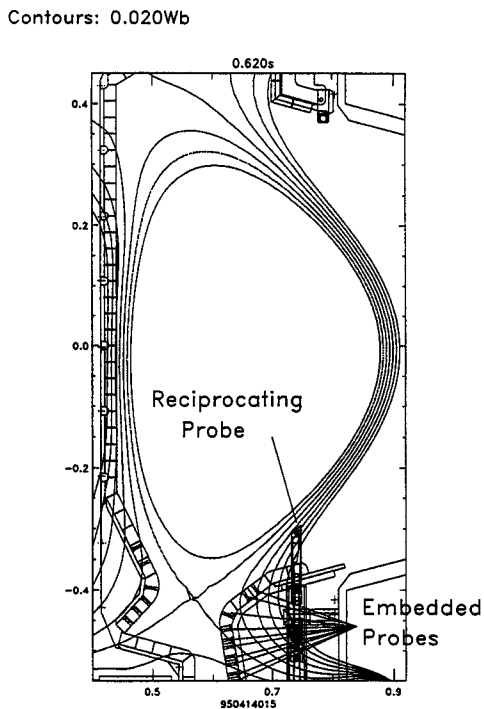


Figure 3. Locations of the Langmuir probe measurements. This atypical equilibrium is close to being double-null, which explains an unusual observation described in the text.

Profiles of the parallel flow are shown in figure 4 for a low density case and a high density case, comparing normal and abnormal field directions. Since the position of the probe is between the midplane and the outer divertor, outflow of plasma would be expected to give rise to a flow towards the outer divertor. What we observe can be interpreted as the sum of this outflow plus a “flow imbalance”: a flow component whose direction depends on field direction. As with the other SOL asymmetries, the

flow imbalance is strongest at the lowest densities. It is also strongest on flux surfaces closest to the separatrix, and in fact the normal field direction plasmas have substantial flow reversal, with Mach numbers up to almost 0.2, at low density. This tendency is indicated schematically in figure 2 by the two bold arrows along the magnetic field direction. The reversed flow (away from the divertor) does not extend to the outer regions of the SOL, where the flow at the probe is always towards the divertor.

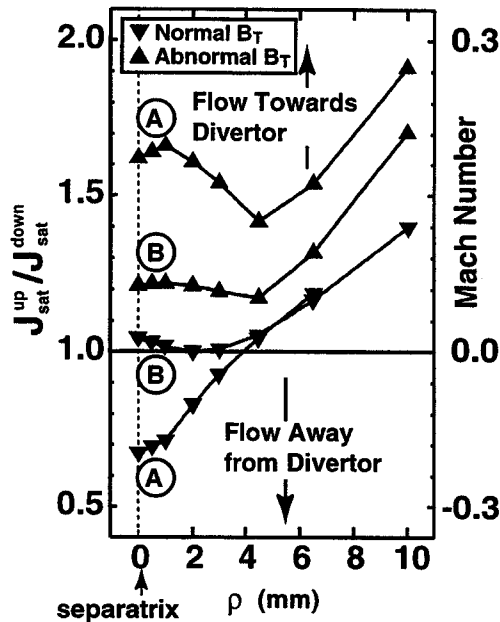


Figure 4. Radial profiles of the Mach-probe measurements for core density (A) $0.7 \times 10^{20} \text{ m}^{-3}$ and (B) $1.9 \times 10^{20} \text{ m}^{-3}$ with the toroidal field in the normal and abnormal directions.

Another method of detecting parallel flow has also been developed [3,4] on Alcator C-Mod. It utilizes a highly localized puff of an impurity species such as nitrogen or carbon and imaging of the impurity ‘plume’ that results as the impurity is ionized and accelerated by the background plasma. Analysis has focussed on plumes injected at the inboard mid-plane, and viewed horizontally from the outboard. An example of the resulting image is shown in figure 5. Most plumes show significant asymmetry corresponding to flow of the plasma past the puffing location. The degree of asymmetry has been used to deduce the parallel flow velocity using a fluid model of the plasma and impurity. The parallel Mach numbers deduced vary between about 0.1 and 0.5, but lie more typically in the range 0.2 to 0.4. So far, the number of shots to which this detailed analysis has been applied is limited to 17 and so statistics are poor for deducing general results. The technique is not non-perturbing with the present setup because an appreciable quantity of impurity has to be injected in order to obtain measurable signals.

The direction of parallel flow observed with the plumes is, with one apparent exception, always towards the nearest strike-point. The exception was observed on a detached-divertor plasma with abnormal field direction. However, it was found, in retrospect, that the equilibrium in question had a second separatrix, corresponding

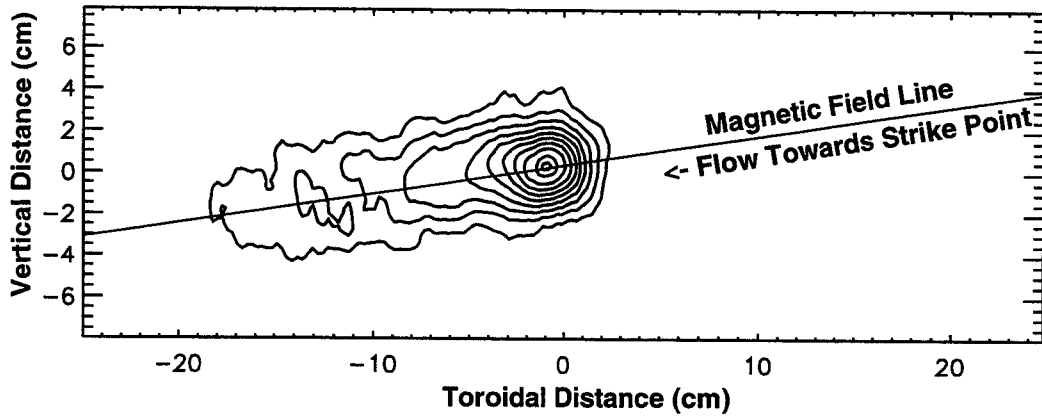


Figure 5. Video frame of NII emission from a plume converted to contours of intensity. Parallel flow of the background plasma causes an asymmetry along the field towards the inner divertor.

to the upper x-point, so close to the first that the plume was actually puffed outside the second separatrix. This non-typical equilibrium is shown in figure 3. We do not regard this as a true exception to the general rule that parallel flow is towards the divertor at the inboard wall.

The SOL radial position of the plume measurements depends on the ionization rate of the injected impurities. Calculations indicate that the lines from singly charged states used for most of the quantitative diagnosis are localized within a few mm of the wall, typically quite far out ($\rho \sim 1.5$ cm) in the SOL. However, independent confirmation of this fact is still lacking. There being no parallel flow-reversal on this flux surface at the inboard is consistent with the Mach probe observations at the outboard, since the flow reversal observed at the outboard occurs only close to the separatrix.

We also observed, though with very poor statistics in view of the small number of shots, that the parallel flow toward the inboard divertor is greater on average in the normal field direction case than in the abnormal case. This observation is also consistent with the Mach probe measurement at the outboard. The parallel Mach number at any position can be considered to consist of two components: $M = M_i + M_d$ one of which (M_i) is independent of field direction, and the other (M_d) positive or negative depending on the sign of the field. Both the Mach probe and the plume observations indicate that the magnitude of M_d is of order 0.05 (or larger at lower densities), and its direction is from outboard to inboard for plasmas with normal field direction.

3. Perpendicular Flow

It should be recalled that the parallel flow velocity is not the only flow component in the poloidal direction. The perpendicular $\mathbf{E} \wedge \mathbf{B}$ particle drift has poloidal

component of comparable magnitude. It is expected to arise from the radial temperature gradient and the corresponding sheath potential, since the divertor plate is an equipotential surface. The radial electric field is positive (outward in minor radius) when the temperature decreases moving outward in the SOL, and the resulting poloidal drift is illustrated in figure 2. It is in such a direction as to oppose the poloidal component of M_d . In other words, the net poloidal particle flow dependence on field direction is less than that of either the parallel or perpendicular components separately because they (at least partially) cancel.

This cross-field flow is much more difficult to detect experimentally than the parallel flow. In the first place it is smaller in absolute magnitude. To give the same poloidal flow, the perpendicular velocity required is smaller than the parallel by approximately the field angle (~ 0.2). Secondly, although there have been experiments which attempted to deduce cross-field flows from segmented Langmuir probe measurements [5], these experiments are technically very difficult and there exists no established magnetized probe theory that enables one to interpret the perpendicular flow measurements with confidence. Thirdly, spectroscopic measurements based on Doppler shifts face extreme challenges in obtaining adequate spatial resolution, as well as in detecting the flow in the first place.

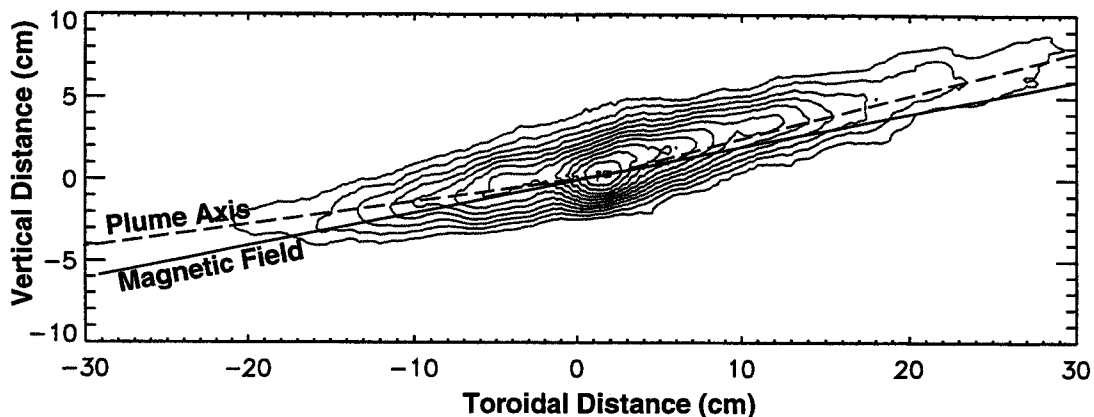


Figure 6. Example of a CIII plume showing perpendicular flow. Gas is injected at the midplane and viewed radially inward.

We find on Alcator C-Mod that the plume measurements provide evidence of perpendicular flows in addition to the parallel. The approach is illustrated by figure 6. This figure shows a case with particularly low parallel velocity (symmetric along the field). What is clear, even by eye, is that the plume is poloidally asymmetric. It has a 'boomerang' shape arising from the superposition of an upward perpendicular drift upon the parallel diffusion. (Theoretically, the shape should be more of a 'gullwing' but this is hardly detectable in the plot). The fluid analysis of the plumes has been fitted to obtain estimates of the perpendicular drift velocity of the impurities. This analysis

is plainly subject to substantial uncertainty, and currently there is no independent confirmation of its results. Nevertheless the results are suggestive. We find that the average perpendicular drift for analysed normal-field-direction plumes with lower x-point plasmas is 230 m/s with standard error of 60 m/s, while the average of the few abnormal field shots is 5 m/s (measured in the vertically upward direction). The fact that the normal field direction has more upward drift than the abnormal is in agreement with the expectations based on radial electric field; (although the drift would be expected to be negative in the abnormal case, which it isn't.) Quantitatively, we may express the velocity in terms of an equivalent radial electric field which would be needed to give rise to this velocity when crossed with the 8T toroidal field at the plume. It is $E_r \approx 2000 \text{ Vm}^{-1}$ for 230 m/s. This is comparable to the order of magnitude of radial electric field deduced from the scanning-probe measurements and expected from the sheath potential. Since the sound speed is approximately 3×10^4 m/s, the perpendicular Mach number is less than 0.01.

4. Mechanisms and Interpretation

Phenomenologically, what occurs on Alcator C-Mod is that the SOL essentially always has at least one high-recycling end. The temperature at that end is low, roughly 3 eV, and that end is always at the inboard for normal field direction operation and the outboard for abnormal field. This situation appears to be a saturated nonlinear state, in the sense that it is not a small perturbation from a symmetrical SOL. Instead it seems likely that there is a feedback mechanism that tends to enhance any asymmetry that occurs, leading to a final state in which this destabilizing mechanism is balanced by other effects, possibly associated with reaching the temperature at which ionization rate drops precipitously and divertor detachment approaches.

At least two destabilizing mechanisms exist. The radiative condensation process responsible for marfes and active in divertor detachment [6] has been suggested [7] as a possible cause of asymmetries. It is undoubtedly at work, as the measured bolometric imbalances indicate, though it is not sufficient to explain the results. A second process that may also be important is the parallel thermoelectric current [8]. This electric current is caused by asymmetric sheath potentials and flows from the hotter to the colder plate. The electron current, flowing from colder to hotter, carries significant energy flux, and so this is also a destabilizing mechanism.

Although both of these mechanisms may be important in the final state, neither on their own can explain the universal direction of the asymmetry. One could arbitrarily invoke an imbalance in the impurity radiation (for example through impurity concentration) to explain the direction, but that leaves open the question of how the initial impurity asymmetry arose. To explain the impurity asymmetry, presumably through drifts, then becomes the key problem. For the parallel SOL currents there is a naturally-occurring bias of a few volts, towards the observed asymmetry direction, which arises from the toroidal electric field. Although this may

be significant, we do not see the asymmetry reverse when the toroidal electric field reverses at the end of the plasma current flat-top. Therefore it does not seem to explain our observations unless there is sufficient hysteresis to lock in the initial asymmetry direction.

Cross-field particle drifts depend on field direction and so may more readily explain the direction of asymmetry. The order of magnitude of the curvature and grad-B drifts is much smaller than that of the diamagnetic and electric field drifts, by roughly the ratio of the SOL thickness to the major radius. The relative magnitude of the electric field and diamagnetic drifts, compared with parallel flows is [1,9] approximately equal to the ratio of the poloidal ion gyro-radius to the SOL thickness. In Alcator C-Mod, the poloidal ion gyro radius is approximately 1 mm (at 10 eV), in comparison with a SOL width of a few mm, at the midplane. Therefore these drifts are indeed significant. The diamagnetic drifts carry electrons and ions in opposite directions, and so a difference between ion and electron temperature gradient has been postulated [10] to provide power asymmetry.

The radial and poloidal electric fields in the SOL give rise to $\mathbf{E} \wedge \mathbf{B}$ drifts of comparable magnitude to the diamagnetic drifts but in the same direction for electrons and ions. Asymmetries in divertor *pressure* are predicted from the momentum equation to arise from the poloidal drift [9]. However, our results indicate little pressure difference at the plates, prior to detachment. Moreover, the predicted density is higher (in a uniform temperature model) at the outer plate for normal field direction, so the theoretical effect is in the opposite direction to what is observed. The convection of energy due to the $\mathbf{E} \wedge \mathbf{B}$ drift, on the contrary, is towards the hotter side, so its polarity is in accordance with experiments. On the basis of this and other circumstantial evidence, the $\mathbf{E} \wedge \mathbf{B}$ drift appears to be a strong contender to explain the results [1]. Radial drifts may also be important, and a fuller two dimensional understanding of the problem is needed.

5. Conclusion

Ongoing experiments on Alcator C-Mod confirm and amplify our previously reported results and those from other tokamaks. The inboard to outboard divertor asymmetries are a zeroth-order effect, and the experimental results cannot be comprehensively modelled in any but the very highest density regimes by physics that is insensitive to the toroidal field polarity. Experimental measurements show clearly that a parallel SOL flow component exists that is dependent on toroidal field direction. There is also direct evidence of poloidal transverse drifts in the direction anticipated on the basis of the plasma potential gradient. The precise mechanism causing the fully-developed asymmetries is not yet certain but it is clear that the dominant effects are in the energy balance not the pressure balance.

Acknowledgments

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