Observation of Poloidal Asymmetry in Impurity-Ion Emission Due to ∇B Drifts

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Poloidally asymmetric impurity-ion emission has been observed in high-density discharges of the Alcator Tokamak. The sense of the asymmetry reverses when the direction of the toroidal field is reversed, and all observed dependences of the strength of the asymmetry upon proton density and safety factor are consistent with the explanation that the gradient and curvature drifts of the highly collisional impurity ions cause the asymmetry. Thus the asymmetry implies that the drift is a major impurity transport process at high densities.

Basic to all tokamak and stellarator plasma-confinement systems are helical magnetic field lines which reduce to a diffusion process (neoclassical diffusion) the particle drifts due to the gradient and curvature inherent in the confining field (hereafter, ∇B drifts). This Letter reports the first experimental evidence that, in Alcator[1] plasmas, the ∇B-drift distance of the highly collisional *impurity* ions (O VI, O V, and N V) near the plasma edge is sufficiently large at line-average electron densities $>5\times10^{13}$ cm^{-3} that a large number of impurity ions strike the torus wall or limiter before making a full poloidal excursion and thus break the poloidal symmetry. Since this effect is not specific to Alcator discharges, but generally significant for highly collisional ions, a simple formalism which estimates the magnitude of the effect as a function of basic plasma parameters is presented. The observations make it clear that the ∇B drift must now be included explicitly as a major impurity transport process in tokamaks, and previous poloidally symmetric models of impurity penetration and transport must be reviewed.

Up-down scans of resonance emission from impurity ions were performed with a 0.4-m normal-incidence monochromator. The field of view at the plasma was 1 cm (vertical) by 3 cm (horizontal), and the line of sight was scanned on a shot-to-shot basis by tilting the system about a fixed point in the beam line. The measured quantity was volume emission rate integrated along a chord of the plasma cross section. This quantity is proportional to the number of impurity ions (in a particular ionization state) along the line of sight since the excitation rate should be poloidally symmetric.

Figure 1 shows two vertical scans of the O VI, 1032-Å emission. One is the emission profile when the line-average electron density was 4.0 $\times10^{13}$ cm^{-3} (during a low-density emission plateau); the other shows emission after the density was raised to 3.6×10^{14} cm^{-3} (during a high-density emission plateau).[2]

The marked emission asymmetry at high density may be understood qualitatively by calculating the vertical ∇B-drift distance of an O V ion which is diffusing along a field line in the top or bottom quarter of the torus. This distance is

$$d_{\nabla B}{}^{\mathrm{O\,V}} = v_{\nabla B}\tau_{Rq} = \left[\frac{3cT_i(r)}{2Z_iRB_t|e|}\right]\left[\frac{q^2R^2Am_p\nu_{\parallel}}{T_i(r)}\right], \quad (1)$$

where τ_{Rq} is the time needed for the ion to move through a poloidal angle of 1 rad; $v_{\nabla B}$ is the drift

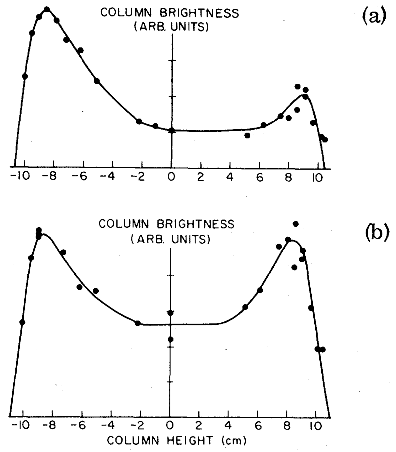

FIG. 1. Two emission profiles in O VI 1032-Å light. "Column height" refers to height of the line of sight above or below the torus midplane. For this toroidal field direction the ion ∇B drift is up. (a) Asymmetric high-density profile for discharge conditions $\bar{n}_e = 3.6\times10^{14}$ cm^{-3}, $B_T = 60$ kG, $q(a) = 2.9$. (b) Symmetric low-density profile with $\bar{n}_e = 4.0\times10^{13}$ cm^{-3}, $B_T = 60$ kG, $q(a) = 3.9$.

velocity; $q(r) = rB_t/RB_p$ is the safety factor; R is the major radius; T_i is the temperature of the OV ions; B_t is the toroidal field in Gauss; (Am_p) is the impurity ion mass, and $\nu_{\parallel}$ is the parallel ion-impurity collision frequency. With applicable Alcator parameters where $Z_{\text{eff}} \cong 1$ $d_{\nabla B}{}^{\text{O V}}$ is 4.0 cm at high density and 0.5 cm at low density. Thus at higher densities, an OV ion with a large *outward* ∇B-drift component will not penetrate and be ionized to OVI unless inward transport processes compensate the 4-cm drift. However, the OV ions located in that portion of the torus where the ∇B drift has an inward component will quite probably penetrate to higher-temperature regions and be ionized, thereby enhancing the asymmetry in the OVI emission. Using the same arguments, but comparing the penetration of OIV ions, an asymmetric poloidal distribution of OV ions would also be expected at high densities. This has also been observed. For the cases shown in Fig. 1, the drift direction is up, and thus the sense of the asymmetry (more OVI below the midplane) is in agreement with the model.

It is possible that OVI ions seen in the depleted region [at $r \approx 8$ cm in Fig. 1(b)] penetrated to this radius while closer to the torus midplane and then diffused poloidally along field lines to this region. At the highest densities, outward drifting OVII ions may to some extent compensate the depleted OVI ion concentrations since the OVII ∇B drift is about 1 cm in a recombination time.

Because the other impurity transport processes are not well known (impurity concentrations are no longer constant over magnetic flux surfaces)[3] and because these processes may have diffusion or drift velocities comparable to ∇B-drift velocities, impurity transport has not been quantitatively modeled. However, the magnitude of the asymmetry has been observed for different drift distances—calculated by Eq. (1) and varied by changing ion density, n_b, and the safety factor, q. The results are shown in Fig. 2.

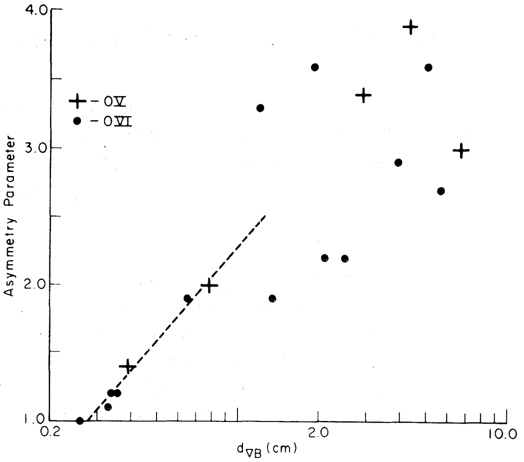

FIG. 2. Variation of asymmetry with ∇B-drift distance. "Asymmetry parameter" is defined as the ratio of the larger to the smaller peak in the column brightness profiles (see for example Fig. 1). Here, the asymmetry parameter is plotted vs the drift distance defined in Eq. (1). Estimates of uncertainties in the quantities used to calculate $d_{\nabla B}$ indicate that the value is accurate to about ± 50% [the main contribution coming from uncertainties in $T_i(r)$]. Uncertainties in the asymmetry parameter are less than ± 10%.

Generally, Fig. 2 shows that the asymmetry increases with increasing ∇B-drift distance. In the region of small drift distance ($d \lesssim 1$ cm the asymmetry parameters for the seven data points increase monotonically, with little scatter, as the ∇B-drift distance increases. For these points this distance has been varied both by changing $n_b(r)$ (from 6.0×10^{12} to 4.6×10^{13} cm^{-3}) and by changing q (from 2.4 to 4.6). Since the variation of the asymmetry in this region appears to depend only on the ∇B-drift distance, rather than on a specific n_b or q, we conclude that the dependences upon these quantities, expressed by Eq. (1), are approximately valid. For drift distances $\gtrsim 1$ cm, there is a large scatter in the data. A detailed examination of data shows that the scatter is not systematically related to high or low values of n_b or q used in the calculation of $d_{\nabla B}$.

The direction of the ion ∇B drift is given by $\vec{B} \times \nabla |\vec{B}|$ and will reverse when $\vec{B} \to -\vec{B}$. Thus the most convincing evidence that the poloidal asymmetry of impurity ion density is due to the ∇B drift is the change in the sense of that asymmetry upon reversal of the toroidal field. The observed OVI emission profiles for both field directions are shown in Fig. 3.

The reversal of the asymmetry with field reversal eliminates a number of other possible explanations. That the effect is instrumental is no longer tenable. Also eliminated is the possibility that the asymmetry is related to the pulsed gas, which is used in Alcator to attain high densities. The deuterium gas is pulsed into the developed discharge through one of two values, which are located at the top and bottom of the torus. It has been suggested that pulsed gas penetration should affect impurity transport,[4] so that an impurity asymmetry might be the result of an asymmetry in the gas penetration. However, for both pro-

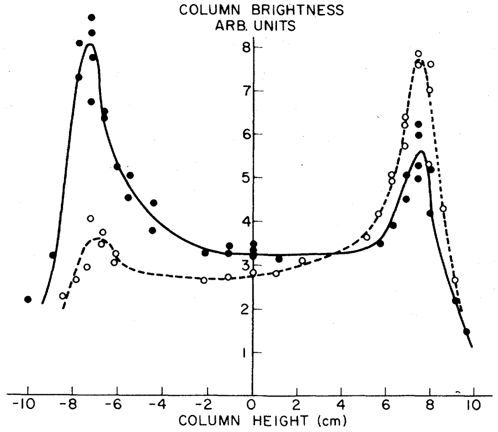

FIG. 3. O VI 1032-Å emission profiles for each toroidal field direction. The solid line indicates the emission profile with the field direction for which the ion drift is upward; the dashed line shows emission with the field and drift directions reversed. In each case, the deuterium plasma conditions were $\bar{n}_e = 2.5 \times 10^{14}$ cm^{-3}, $B_T = 50$ kG, $q(a) = 4.8$.

files shown in Fig. 3 the gas was pulsed from the top value.

It may also be argued that the asymmetry is caused by a vertically uncentered plasma. Furthermore, it might be the case that this positioning would reverse when the field direction is reversed. This explanation is made extremely unlikely since the center of the temperature profile was found not to move (experimental error ± 0.5 cm) upon field reversal.[5]

Since impurity transport is significantly affected by ∇B drifts, we ask to what extent will the drift affect working gas ion transport in Alcator? The ∇B-drift distances for a deuteron at an O VI radius may be calculated using Eq. (1); $d_{\nabla B}{}^{\mathrm{O\,II}} = 0.04$ and 0.5 cm at low and high densities. This implies that there is no effect at low densities, and that a large effect at high densities is unlikely. This was borne out experimentally when evidence for enchanced gas penetration was sought by pulsing gas from the same value with the toroidal field in each direction. No difference in either the rate of density increase or the final density achieved was observed.

The significance of ∇B-drift transport in other present-day tokamaks may be estimated by calculating the ∇B-drift distance using Eq. (1), and by scaling that distance by the minor radius of the device. For typical TFR,[6] PLT,[7] and Pulsator[8] discharges, estimates of $d_{\nabla B}{}^{\mathrm{O\,V}}/a$ yield 0.03, 0.015, and 0.16 respectively. If, by comparison to Alcator, values of $d_{\nabla B}{}^{\mathrm{O\,V}}/a > 0.06$ are required for a significant asymmetry, the effect should be observable on Pulsator. No consideration was given to impurity-impurity collisions in the derivation of these values, and while such collisions should increase $d_{\nabla B}{}^{\mathrm{O\,V}}$, care must be taken in interpreting the results. Since the proton deficiency may be as high as 50% on these devices, a rearrangement of impurity densities along field lines may have macroscopic effects on the plasma which could drastically change any equilibrium distributions.

As mentioned previously, observation of a poloidal asymmetry in impurity densities implies that assumptions usually made in the derivations of impurity diffusion models are not valid for these discharges. It is no longer true that densities and pressures are functions only of radius to lowest order in the inverse aspect ratio. Thus the problem of impurity transport is not reducible to one dimension as in Ref. 3, and a strictly two-dimensional treatment is required. Intuitively one would expect the effects of ∇B transport to be of least importance for impurity emission measurements made in the torus midplane; this should, however, be explored in a more detailed and quantitative manner.

The presence of the asymmetry places an upper limit on the poloidal rotation speed of the plasma periphery, since any rotation effectively decreases τ_{Rq}. This upper limit is approximated by estimating the drift time through an ionization shell (about 5 msec), and assuming that symmetry would be retained if the plasma were making a full rotation faster than this. Thus $v_\theta \lesssim 2\pi r/(5 \times 10^{-3}) \approx 10^4$ cm/sec. This is comparable to the electron diamagnetic-drift velocity, $V_d = cT_e/\{eB_T[(d/dr)\ln n(r)]\} \approx 10^4$, also considered to be a reasonable upper limit to v_θ. Comparison may also be made with theoretical predictions for the rotational velocity based on considerations of electron viscosity effects,[9] which give $v_\theta \gtrsim 10^3$ cm/sec.

Because both the low-density symmetric and the high-density asymmetric Alcator discharges are very clean,[2] we do not attribute the low impurity concentrations in Alcator to the ∇B-drift transport. Nevertheless, the presence of the effect suggests a possibility for even better impurity control in ultrahigh-density discharges. In Alcator the Mo density is typically about 10 times that of Fe, implying that most of the heavy-metal impurities in the discharge evolve from the limiter. Instead of using a limiter around the entire minor circumference, it should be possible to use a limiter on only one-half of this circumference—in that part of the torus where the ion ∇B-drift direction is outward. Then most atoms removed from the limiter (by charge-exchange neutrals, runaway electrons, bulk plasma contact, etc.) should drift out, making no significant penetration. Bulk plasma interaction with the wall in the other half of the torus would remain negligible, since field lines near the wall there would still intersect the limiter at some point. Alternatively, even with a complete limiter, the plasma might be positioned above or below the midplane of the vacuum vessel by the programming of the external horizontal field coils. In this way, bulk plasma contact with the limiter in the appropriate portion of the torus would be minimized.

In conclusion, this Letter reports the first direct observation of the effects of ∇B-drift transport of impurity ions in tokamak geometries. The very general nature of the effect has been discussed. Finally, we stress its most important consequence—that in regimes of very high collisionality, impurity transport in tokamaks can no longer be considered one dimensional, but must be given a full two-dimensional treatment.

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[1] E. Apgar *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, West Germany, 1976* (International Atomic Energy Agency, Vienna, 1977), Vol. 1, p. 247.

[2] J. L. Terry *et al.*, U. S. Energy Research and Development Administration Report COO-2711-3 (1977).

[3] P. H. Rutherford, Phys. Fluid 17, 1782 (1974).

[4] K. H. Burrell, Phys. Fluid 19, 401 (1976).

[5] J. E. Rice and H. I. Helava, private communication.

[6] TFR group, EURATOM—Commissariat à l'Energie Atomique Report No. EUR-CEA-FL-783, 1975 (unpublished).

[7] N. Bretz *et al.*, Princeton Plasma Physics Laboratory Report No. PPPL-1356, 1977 (unpublished).

[8] O. Klüber *et al.*, Nucl. Fusion 15, 1194 (1975).

[9] A. A. Ware, Bull. Am. Phys. Soc. 21, 9, 4D-3 (1976).

Simulation of Large Magnetic Islands: A Possible Mechanism for a Major Tokamak Disruption

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It is known that an internal tokamak disruption leads to a current profile which is flattened inside the surface when the safety factor equals unity. It is shown that such a profile can lead to $m = 2$ magnetic islands which grow to fill a substantial part of the tokamak cross section in a time consistent with the observation of a major disruption.

The involvement of the tearing mode in the major tokamak disruption has been suspected for some time.[1] We have developed a numerical method for examining the full nonlinear behavior of tearing modes of a single helicity.[2] The essential approximation in this analysis is the use of the tokamak ordering $B_z \gg B_\theta$ to expand the magnetohydrodynamic fluid equations to lowest order in the inverse aspect ratio. In this approximation modes of different helicities are uncoupled and the full nonlinear development of an initial perturbation consisting of a single helicity can be described in two dimensions.

Derivation of the reduced set of magnetohydrodynamic fluid equations is carried out in Ref. 2. Eliminating the unknown pressure by operating on the equation of motion with $\hat{z}\cdot\nabla\times$, and keeping only lowest order in inverse aspect ratio, but including finite conductivity in Ohm's law, we find a closed set of equations. The resulting two-di-