Fig. 4; for $\omega \lesssim \Omega_p$ we see that there is not even qualitative agreement with the standard mean-field (Vlasov) result, particularly in the behavior of $\epsilon'(q, \omega)$ at low frequencies.

Our results indicate that a simulation of the microscopic behavior of a hydrogen plasma is feasible and yields quantitatively meaningful results; the latter indicate that the OCP is only moderately successful in modeling the real plasma. In future work we plan to extend the calculations in three main directions: (i) the computation of transport coefficients, including thermal conductivity; (ii) the incorporation of external magnetic and high-frequency electromagnetic fields; and (iii) the study of nonequilibrium (two-temperature) plasmas.

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Experimental Observation of the Impurity-Flow–Reversal Effect in a Tokamak Plasma

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The inward trasport of a neon test impurity injected into the plasma in the Impurity Study Experiment (ISX) tokamak has been significantly reduced by poloidally asymmetric injection of hydrogen gas into the discharge. The result is consistent with the impurity-flow–reversal effect as predicted by neoclassical transport theory.

The inward transport of impurity ions in tokamak plasmas, which is predicted by neoclassical theory and which was clearly seen in the ATC (adiabatic toroidal compressor) tokamak,[1] poses a major problem. Impurities, especially high-Z impurities, can be quite deleterious to energy confinement in fusion-reactor plasmas. Accordingly, it is of interest to study impurity transport with a view towards methods of impurity control.

Ohkawa[2] has shown that within the Pfirsch-Schlüter framework a poloidally asymmetric source of protons can reduce or reverse the inward transport of impurities, thus providing a method of impurity control. Subsequent calculations[3-5] have generalized this result to include the effect of heat sources, lower collisionality, and general flux-surface geometry. The impurity-flow–reversal experiment was designed to test this neoclassical theory, especially the predictions concerning the asymmetric source terms.

In experiments performed on the Impurity Study Experiment (ISX) tokamak,[6] we have found a substantial alteration of the transport of an injected neon impurity when poloidally localized injection of hydrogen gas is used to produce the asymmetric sources. The observed changes are qualitatively consistent with expectations based on simple theoretical models. More quantitative comparisons will be reported later. If these preliminary indications are confirmed by subsequent experiments, this technique could be the basis for a simple, compact impurity-control technique for tokamak plasmas.

The essence of the flow-reversal effect is the use of poloidally localized sources to alter the parallel proton flows.[2-5] This modifies the proton-impurity friction, thus reducing or, perhaps, reversing the inward impurity transport. Theoretical calculations have shown that in the presence of asymmetric sources the radial flux of an impurity Γ_I of charge Z_I is given by[3]

$$\Gamma_I=\frac{2q^2n_i}{Z_I|eB_\varphi|\omega_{ci}\tau_{iI}}\left[\Delta_1\left(\frac{1}{n_i}\frac{\partial p_i}{\partial r}-\frac{1}{n_IZ_I}\frac{\partial p_I}{\partial r}\right)-\tfrac{5}{2}\Delta_2\frac{\partial T_i}{\partial r}-\tfrac{1}{2}eB_\varphi R\left(\Delta_1\frac{a_{i1}}{n_i}-\Delta_2\frac{a_{T1}}{p_i}\right)\right], \qquad (1)$$

where the subscript i (I) denotes protons (impurities), q is the safety factor, τ_{iI} is the proton-impurity collision time, ω_{ci} is the proton cyclotron frequency, B_φ is the toroidal field, R is the major radius, r is the minor radius, and e is the magnitude of the electron charge. The quantities Δ_1 and Δ_2 are numerical factors of order unity which depend on the precise collision model used.[5]

Equation (1) indicates that radial transport is driven by gradients in the density n and temperature T ($p=nT$), but that the $\sin\theta$ Fourier components of the proton source a_{i1} and the heat source a_{T1} can also affect the flux. Neutral-transport calculations have been done to estimate the H_2-injection rate required to make the source terms comparable to the other terms in Eq. (1). For model profiles similar to those in the ISX, the requirement is of the order of 10^{21} particles/sec, a rate close to the natural particle loss rate from the ISX plasma. However, since gas is used as the source, the source terms are large only in the outer 1–2 cm of the plasma. Thus, the flow-reversal effect can alter impurity transport only in the plasma edge.

The poloidal asymmetry of the sources due to H_2 injection into the bottom of the plasma was somewhat enhanced by depositing a layer of titanium getter over the top half of the vacuum chamber every few shots, thus reducing hydrogen recycling there. (In addition, the titanium reduced the effective Z in the plasma from values around 2 to a value close to 1.) Because of the ninefold symmetry of the ISX vacuum chamber, nine getter sources and nine feedback-controlled gas injectors[7] were used.

The effect of the source terms has been investigated by observing the spectral lines produced by short bursts of neon and aluminum that are introduced into the plasma after the H_2 injection has been established. The 1-msec neon pulse was produced by a fast gas valve located on the top of the vacuum chamber. The 200-μsec aluminum burst was injected from the side of the chamber; it was generated by a $\frac{1}{2}$-J, 20-nsec laser pulse focused onto an aluminum-coated glass slide. (This latter technique is similar to one used on the ATC tokamak.[8])

According to Eq. (1), reversing the sign of B_φ reverses the sign of the contribution that the source terms make to Γ_I. If similar plasmas can be obtained with both clockwise (CW) and counterclockwise (CCW) polarities of the toroidal field, this dependence on B_φ can be used to separate the effect of the source terms from that of other plasma parameters.

In Figs. 1 and 2, we summarize a series of measurements that were made on CW and CCW discharges to verify that the plasmas were the same. (To minimize problems with error fields, the plasma current was reversed whenever the toroidal field was.) While there are some differences during the breakdown phase prior to 20 msec, the plasmas are very similar during the main discharge phase where the H_2 injection takes place and where the neon and aluminum transport is investigated. Both the gross discharge parameters in Fig. 1 (voltage, current, and line-aver-

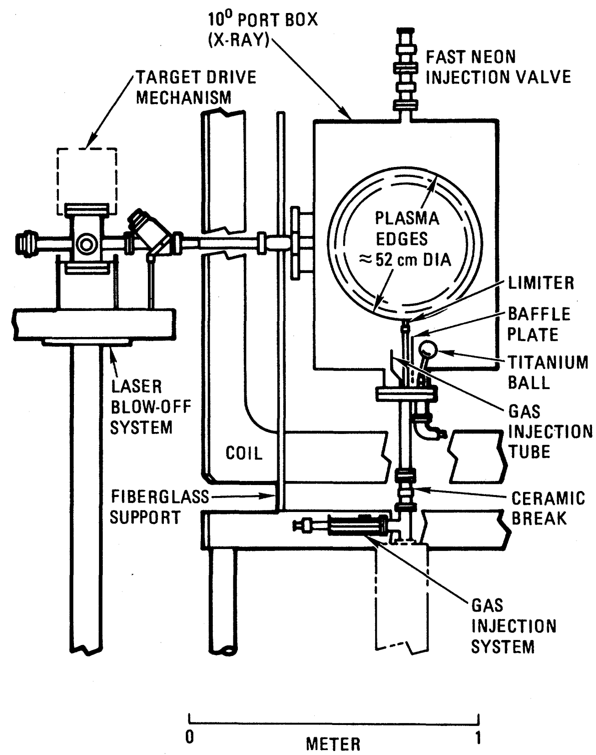

FIG. 1. Comparison of plasma parameters for the toroidal magnetic field clockwise (CW) and counterwise (CCW): (a) plasma density, (b) H_α line intensity, (c) plasma current and one-turn voltage. The toroidal field was 1.5 T. Noise on the voltage trace is caused by the feedback system controlling the plasma current.

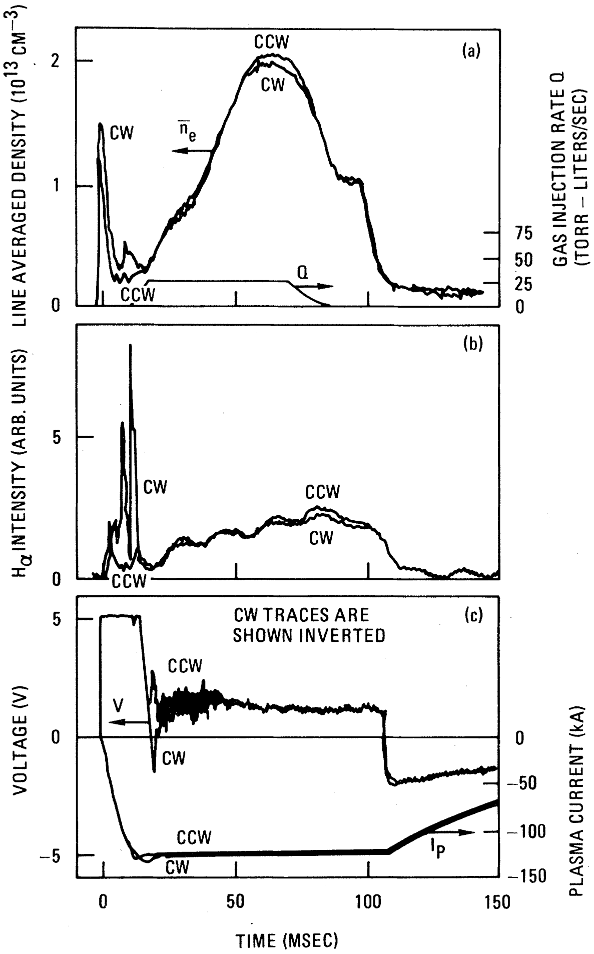

FIG. 2. Plasma electron temperature profile (a) and density profile (b) for CW and CCW toroidal magnetic field. These profiles are taken at 40 msec in the discharges used for Fig. 1.

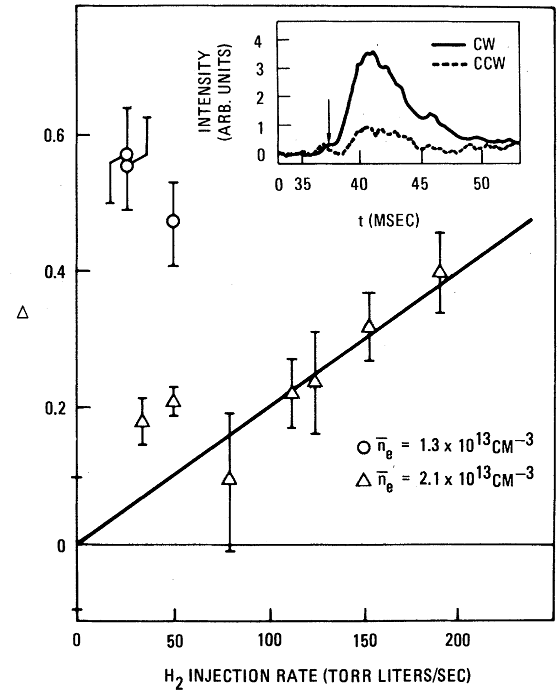

FIG. 3. Normalized difference in neon spectral line intensity as a function of gas-injection rate for two different values of line-averaged density. To give an idea of shot-to-shot reproducibility, the mean and standard deviation of each set of data are given. The inset shows the time behavior of the Ne VIII (770-Å) line intensity for both polarities of the magnetic field. For this, the H_2-injection rate is 27.5 Torr l/sec and line-averaged density is 1.3×10^{13} cm^{-3}.

aged density) and the edge processes producing the H_α radiation are quite similar for both polarities of the toroidal field. In addition, the time behavior of the charge-exchange neutral flux is almost identical, indicating a great similarity in proton parameters. Finally, the radial profiles in Fig. 2 agree to within the error in the data. The spectrometer and the radiometer do find some dissimilarities. For example, the radiometer signal for CW plasmas is always greater than or equal to that for CCW plasmas. We will discuss the spectroscopic dissimilarities presently.

The theory predicts that, with gas injection from the bottom, the spectral intensity S of NeVIII should be smaller for a CCW toroidal field; hence, the ratio $\Delta=(S_{CW}-S_{CCW})/(S_{CW}+S_{CCW})$ should be positive. All data in Fig. 3 show $\Delta \geq 0$.

For the gas-injection rates used here, calculations have shown that, if the background plasma *does not change*, Δ should vary linearly with the gas-injection rate. A linear relationship is manifested in the $\bar{n}_e = 2.1\times10^{13}$ cm^{-3} points in Fig. 3. (The four $\bar{n}_e = 1.3\times10^{13}$ cm^{-3} data points demonstrate an increase of Δ with increasing gas-injection rate; however, since the three values of Δ near 0.5 are the same within the experimental scatter, one may not say more.)

The slope of the line relating Δ and the gas-injection rate depends on the density and temperature profiles in the plasma [see Eq. (1)]. In general, in actual discharges, these profiles also depend on gas-injection rate. As the gas-injection rate decreases, the expected changes in the profiles are in the proper direction to account for the fact that the points lie somewhat above the line, as is seen in Fig. 3 at low injection rates for the $\bar{n}_e = 2.1\times10^{13}$ cm^{-3} data. To check if these changes are sufficiently large to account for the observations requires more detailed calculation.

By varying the trigger time for the neon pulse, we could study the change of the neon transport with plasma density at constant gas-injection rate. As the density rose, Δ decreased (see Fig. 3). This is consistent with Eq. (1), since the sources appear there normalized by the local density and since decreasing neutral penetration causes the source terms themselves to decrease as density rises. As part of this sequence, neon was injected into the plasma before the H_2-gas injection was established. A value of $\Delta = 0.01 \pm 0.10$ was found, which is consistent with the theoretical prediction, $\Delta = 0$.

These results make it unlikely that one could explain our results with a model based on the poloidal asymmetry of impurity density as seen in the Alcator tokamak.[9] First, that asymmetry increases as density increases[9]; our Δ values decrease. Second, that effect is sensitive to gas-injection rate only through changes in the background plasma; our data for $\Delta = 0.01$ and $\Delta = 0.55$ in Fig. 3 have comparable values not only of $\bar{n}_e$ but also of edge electron density and temperature. However, since these edge values are somewhat uncertain and since the quantitative effects of poloidal asymmetry on impurity radial transport have yet to be worked out, we cannot entirely eliminate the possibility that the present effect and that observed in the Alcator tokamak[9] are connected.

Aluminum was injected simultaneously with neon for several sets of discharges. In spite of an appreciable difference in the neon signal for the CW and CCW discharges in each set, no consistent variation in the aluminum signals was seen. Any systematic changes were smaller than the 30% shot-to-shot variation in the amplitude of the spectroscopic signal. This may be because of the superior ability of the fast aluminum atoms to penetrate the edge of the plasma where the flow-reversal layer exists. The aluminum-injection system[1,8] produces atoms with 1–6-eV energy, while the neon is at room temperature. In addition, the relatively-high-density, neutral-aluminum stream, which is deposited in a 10-cm^2 region of the plasma, may be able, through self-shielding, to penetrate the flow-reversal layer. This process should not be significant for the neon, since roughly the same number of neon atoms as aluminum are deposited over a 26-cm^2 region.

We also studied the effect of H_2 injection on the naturally occurring impurities. One might support that, just as with neon, more intense impurity radiation should be seen from the CW discharges. However, the opposite is true for ArVIII, TiXI, and TiXII, while no clear-cut changes were seen in the OIII, OIV, OVI, and NIV lines. Since all these lines initially appear well before the H_2 injection is established, it may be that their initial populations differ too greatly in the CW and CCW discharges for the subsequent effect of the H_2 injection on their flow to be seen.

In conclusion, we have produced a significant change in the transport of neon ions in the plasma. This change is connected with the H_2 injection since it does not exist without the gas injection and since it varies as the injection rate changes. The sign of the change and its qualitative behavior are consistent with the results of neoclassical theory. Since theory predicts that the flow-reversal effect will increase with B_φ and R [see Eq. (1)], this effect should be more significant in the larger, higher-field machines of the future.

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