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3/10/86
PPPL-2313

PPPL-2313

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DR-1589-X

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By

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FEBRUARY 1986

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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CED-3073.

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OBSERVATION OF NEOCLASSICAL-LIKE IMPURITY
TRANSPORT IN THE $q \lesssim 1$ REGION OF THE PBX TOKAMAK

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ABSTRACT

Charge-dependent convective impurity transport is observed in the central core of PBX H-mode discharges by measuring radial profiles for both low- and high-Z intrinsic impurities in the presence of strong sawtooth activity. Transport coefficients are derived by simulating the data with a diffusive/convective transport model which includes an internal disruption model. The time evolving Z_{eff} profile and central metallic densities are fitted during the quiescent phase between internal disruptions to yield a diffusion coefficient of $D = 1 \times 10^3 \text{ cm}^2/\text{s}$ for all species and an inward convective speed of $v = 2.2 \times 10^2 (r/a) \text{ cm/s}$ for oxygen and carbon and $v = 1.1 \times 10^3 (r/a) \text{ cm/s}$ for metals. These transport coefficients are in quantitative agreement with simple cylindrical neoclassical estimates for the region within $q \lesssim 1$.

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Central impurity accumulation is a potentially serious problem for toroidal magnetically confined plasmas since both high radiation losses from metallic impurities and significant dilution of the proton density from low-Z impurities can occur. Impurity accumulation in ohmically heated plasmas was observed in several devices,¹⁻⁵ while neutral-beam-heated H-mode plasmas in D-III⁶ and ASDEX⁷ have shown strong metallic accumulation, as have counter-injection cases in ISX-B.⁸ Most of these observations concentrated on the behavior of high-Z (metallic) impurities, but a detailed study of the impurity behavior usually was not possible due to a lack of sufficient information concerning the low-Z impurities such as carbon and oxygen and detailed knowledge of the background plasmas. Since neoclassical theory predicts a Z-dependence in the impurity transport and since impurity-impurity collisions can strongly affect this transport,⁹ a reasonable evaluation of impurity accumulation observations requires simultaneous measurements of all the dominant impurity species, as done just recently for pellet injection experiments in the Alcator-C device.¹⁰

In this letter, we describe observations of neoclassical-like impurity accumulation in neutral-beam-heated PBX plasmas. While impurity accumulation in PBX is observed in ohmic discharges with no sawteeth and in relatively dirty beam-heated discharges (both L- and H- mode), it is most easily studied in H-mode discharges because of improved particle confinement and relatively long sawtooth periods ($t_{st} \geq 40$ ms) which are comparable to particle transport time scales. A steady-state analysis of radial profiles of low- and high- Z impurity species reveals a definite difference in the degree of accumulation for impurities of different charge. In addition, the time-evolving impurity distributions in the presence of large periodic internal disruptions (i.e., sawtooth oscillations) are used to derive central values of the diffusion and

convection velocity coefficients for impurities in the central plasma.

The discharges discussed here had plasma major radius of $R_{pl} = 148$ cm, toroidal magnetic field of $B_t = 1$ T, plasma current of $I_p = 300 - 330$ kA, safety factor of $q_{\psi} \sim 5$, line-averaged electron density of $\bar{n}_e = 5.4$ to $6.2 \times 10^{13} \text{ cm}^{-3}$, and injected beam power of $P_{inj} = 2.4\text{--}3.2$ MW (perpendicular and co-tangential injection). The plasma cross-sectional shape is noncircular, being shaped like a kidney bean with a midplane half-width of $a = 36$ cm.¹¹ The vertical elongation was $\kappa = 1.4$ and the plasma was bounded by a free separatrix, giving rise to a local expanded boundary divertor region and allowing operation with H-mode plasmas. Discharges with a varying sawtooth period have been observed, allowing studies of both relatively steady-state and time-evolving impurity profiles.

A variety of diagnostics was used to measure simultaneously both low- and high-Z impurity behavior. A 16-channel tangentially viewing visible bremsstrahlung detector array provided a $Z_{eff}(R,t)$ profile across the plasma midplane.⁵ Radial electron temperature and density profiles are provided by Thomson scattering in the same midplane. Radial profiles of ion temperature, toroidal rotation velocity, and the relative density of O^{3+} were derived from charge-exchange recombination spectroscopy measurements.¹² The central oxygen-to-carbon ratio was measured by charge-exchange recombination spectroscopy of the $n = 3 + 2$ lines of C^{5+} and O^{7+} obtained with a multichannel vacuum ultraviolet (VUV) spectrometer¹³ viewing across a heating neutral beam. Metallic impurity densities are derived from line-integrated VUV intensity measurements and K_{α} line measurements with a 5-channel vertically viewing X-ray pulse height analyzer (PHA) array.¹⁴ Finally, a 19-channel bolometer array views the plasma vertically for central radiation power measurements. Both the PHA and bolometer data were inverted to radial

profiles using the shapes of the magnetic flux contours calculated by an MHD equilibrium code.

An example of central impurity accumulation, in the presence of sawtooth oscillations, is shown in Fig. 1(a), which plots the chordally integrated visible bremsstrahlung intensities for an H-mode plasma with $P_{inj} = 2.4$ MW. The central Z_{eff} profile, derived from the data in Fig. 1(a) coupled with model density and temperature profiles obtained from fitted Thomson scattering profiles, shows a periodic modulation whose drops coincide with the sawteeth seen with soft X-ray diodes. The average impurity density is redistributed to be roughly flat immediately after the internal disruption, but then recovers to a peaked distribution due to strong inward convection before the next sawtooth drop.

With an increase in beam power to 3.2 MW, the sawtooth period becomes very long (~ 100 msec).¹⁵ Detailed radial profiles of plasma parameters and impurity distributions are shown in Fig. 2 at a time near the end of this period. It is clear from Fig. 2(b) that the high-Z impurities have a much more peaked profile than the low-Z (i.e., O^{8+}). The dominant metallic impurities are Ni [$n_{Ni}(0)/n_e(0) = 0.002$] and Fe (0.001), and these contribute a value of $\lesssim 1$ to $Z_{eff}(0)$. The remaining Z_{eff} is due to the low-Z impurities ($n_C \sim n_O$) and hence the Z_{eff} profile in Fig. 2(c) resembles the O^{8+} profile in Fig. 2(b), emphasizing that the Z_{eff} profile is determined mainly by the low-Z impurity radial distributions. Since oxygen and carbon are almost fully ionized in the plasma core, the peaked radiated power profile is determined mainly by the peaked metallic impurities, and the level of radiation is enough to cause the flattening of the electron temperature profile for $r \lesssim 10$ cm.

The smooth curves shown with the data in Fig. 2 (b), (c), and (d) represent corresponding solutions of the coupled one-dimensional radial

continuity equations for all charge states of a given impurity ion species, as calculated from the MIST impurity transport code,¹⁶ which includes all relevant atomic processes in addition to radial transport. For these simulations, cylindrical symmetry is assumed and the radial flux for a given ion species of charge $+q$, Γ_q , is modeled by a simple diffusive/convective model with differing coefficients for low- and high-Z impurities:

$$\Gamma_q = -D_i \frac{\partial}{\partial r} n_q + c_i \frac{2rD_i}{a^2} n_q, \quad (1)$$

where n_q is the density of charge state $+q$, a is the plasma minor radius, and the subscript $i = l$ or h stands for low- and high-Z impurities, respectively. The diffusion coefficients, D_i , and the convective term peaking factors, c_i , are all taken to be independent of radius.

The calculated profiles corresponding to the several measured parameters are shown in Fig. 2 for several values of c_i . While the results in Fig. 2(b) are obtained by considering individual impurity species, the calculated $Z_{\text{eff}}(r)$ and radiated power profiles in Figs. 2(c) and (d) are obtained by including all major impurities using the measured absolute densities of metallic ions and the measured O^{8+} to C^{6+} ratio while normalizing to the central value of $Z_{\text{eff}}(0)$. The Z_{eff} and radiated power profiles for three pairs of c_l, c_h values are shown with the data in Figs. 2(c) and (d). Only the $c_l = 4, c_h = 20$ case is consistent with both of these measurements, as well as with the specific ion measurements in Fig. 2(b).

Since the above steady-state profile analysis gives only the ratio of the convective to diffusive fluxes, as represented by the peaking factor c_i , the time-evolving data with sawteeth (Fig. 1) are used to derive absolute transport coefficients for the core region. Figure 3(a) shows the detailed

time evolution of $Z_{\text{eff}}(0)$ from visible bremsstrahlung using fixed density and T_e profiles (obtained by fitting to Thomson scattering at one time) along with $\bar{n}_e(t)$ and $T_e(t)$, and of the central metallic densities from PHA measurements. The Z_{eff} data with vertical error bars represent points obtained with the measured $n_e(r)$, $T_e(r)$ profiles from Thomson scattering. The corresponding Z_{eff} profiles are seen in Fig. 3(b).

The solid and dashed curves in Fig. 3 are time-dependent solutions from the transport code which include a redistribution of all impurities to a flat profile within a mixing radius given by $r_{\text{mix}} = 1.4 r_{\text{inv}}$ (where r_{inv} is the $q = 1$ inversion radius) at each internal disruption.¹⁷ The peaking parameters $c_1 = 4$ and $c_h = 20$ are taken from the long-sawtooth case discussed above, and the impurity edge influxes are adjusted to match the average increases of $Z_{\text{eff}}(0,t)$, $n_{\text{Ni}}(0,t)$, and $n_{\text{Fe}}(0,t)$ to the measurements. Under these conditions, the sawtooth-induced central impurity time evolutions provide a fairly precise discrimination for deriving values of D , the core impurity diffusion coefficient. Reasonable fits for both the $Z_{\text{eff}}(0)$ and metallic data are given by $D = 1 \times 10^3 \text{ cm}^2/\text{s}$, $v_1 = 2.2 \times 10^2 (r/a) \text{ cm/s}$, and $v_h = 1.1 \times 10^3 (r/a) \text{ cm/s}$, and are represented by the solid lines in Fig. 3a.

Given that the observed difference between the low-Z and high-Z impurity transport behavior and the low transport coefficients is similar to those expected by neoclassical theory, it is of interest to compare these results to theory. A full time-evolving solution to the coupled continuity equations using neoclassical fluxes is beyond the scope of this letter, but as a preliminary attempt, we show in Fig. 4 the model transport coefficients derived here (dashed lines) and steady-state transport coefficients obtained from neoclassical fluxes⁹ using the measured plasma and impurity profiles (solid lines). It is assumed that the plasma is cylindrically symmetric and

that all impurities are in the Pfirsch-Schlüter collisionality regime. Contributions from all impurity species plus the plasma ions are included, with $n_{Ni}(0)/n_e(0) = 0.001$, $n_{Fe}(0)/n_e(0) = 0.0005$, and $n_O(0)/n_e(0) = n_C(0)/n_e(0) = 0.03$. The strong accumulation (i.e., inward convection) is driven exclusively by the impurity contributions since both the proton density gradient and temperature gradient terms are directed outward (the proton distribution is hollow due to the peaked Z_{eff} profile). In this interpretation, the strong impurity accumulation in relatively dirty plasmas arises from a nonlinear dynamic process wherein higher impurity levels lead to ever stronger central accumulation as impurity-impurity collisions increase. This suggests that strong accumulation may be avoided operationally by reducing the impurity influxes and lowering the overall impurity levels.

While the calculated neoclassical coefficients are not precise due to our assumptions of cylindrical symmetry, steady-state conditions, and purely Pfirsch-Schlüter collisionality, plus our neglect of toroidal plasma rotation ($v_\phi(0) \sim 2 \times 10^7$ cm/s), the agreement between the model transport coefficients and the estimated neoclassical values is surprisingly good within the $q = 1$ radius ($r_{inv} = 14$ cm). Of course, some anomalous inward pinch may be necessary to drive the time-evolving system after the sawtooth crash if the sawtooth does in fact flatten all gradients in the plasma core. Barring any surprises from more detailed modeling of this data, we conclude that the observed impurity transport in the plasma core does manifest the effects of neoclassical fluxes. The uncertainty in the data does not, of course, rule out the possibility of additional small anomalous transport in the core, but these terms would have to be on the order of neoclassical fluxes.

The authors wish to thank E. Powell, G. Schmidt, M. Shimada, and G. Jahns for help and useful conversations. We also thank K. Bol, M. Okabayashi, and the PBX group for support and encouragement in this effort.

This work was supported by the U.S. DOE Contract No. DE-AC02-76-CH03073.

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FIGURE CAPTIONS

Fig. 1. (a) Chordally integrated visible continuum profiles along the plasma midplane. (b) Z_{eff} profiles obtained from data in (a) using model electron density and temperature profiles.

Fig. 2. Impurity and plasma parameter profiles for a sawtooth-free case with strong impurity accumulation: (a) plasma electron density and temperature profiles; (b) relative density profiles of O^{8+} and several metallic species along with calculated profiles for various impurity peaking parameters c_l and c_h ; radial profile of Z_{eff} (c) and radiated power (d). In (b), (c), and (d), the individual points represent data values while the smooth curves (broken and solid) correspond to impurity transport model calculations.

Fig. 3. (a) Time evolution of $Z_{\text{eff}}(0,t)$ and central metallic densities in the presence of strong sawteeth, compared with results of the transport code for various values of the diffusion coefficient. (b) Measured and calculated Z_{eff} profiles at three times with respect to the sawtooth phase. The corresponding central values are indicated in (a). For both cases, $c_l = 4$, $c_h = 20$, and $r_{\text{mix}} = 20$ cm are used.

Fig. 4. Comparison of measured and estimated neoclassical transport coefficients as a function of radius. The solid lines are the neoclassical estimates while reasonable fits to the data correspond to $D = 1000 \text{ cm}^2/\text{s}$ with $c_l = 4$ and $c_h = 20$, which are indicated by the dashed lines in the figure.

Fig. 1

Fig. 2

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Fig. 3

Fig. 4

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