IMPURITY BEHAVIOR IN PBX L- and H-MODE PLASMAS

K. Ida*, R.J. Fonck, S. Sesnic, R.A. Hulse, B. LeBlanc, and S. F. Paul

Princeton University, Plasma Physics Laboratory

Princeton, New Jersey 08543

PPPL--2538

DE88 15864

ABSTRACT

Intrinsic impurity behavior and transport properties in neutral-beam-heated L- and H-mode PBX tokamak plasmas were studied with a variety of impurity diagnostics. Central impurity accumulation was most often observed in H-mode discharges and sometimes resulted in a thermal collapse due to high central metallic radiation ($\sim 1.5 \text{ W/cm}^3$). The accumulation was evident from peaked Z_{eff} and radiated power profiles and further substantiated from specific VUV and X-ray spectroscopy measurements. It is shown that impurity accumulation was neither unique nor inevitable in H-mode discharges, and it could be suppressed by sufficient gas puffing. Central accumulation was also seen in L-mode plasmas even with co-injected neutral beams. This usually occurred at high beam power and relatively low density. While there was no significant difference in the degree of accumulation between L- and H-mode discharges, the Z_{eff} profile itself was more peaked in the H-mode due to flatter electron density profiles in H-mode plasmas than in L-mode plasmas. The degree of accumulation increased as $Z_{\text{eff}}(0)$ itself increased and is qualitatively explained by neoclassical convection and diffusion driven by impurity-impurity collisions in addition to the usual impurity-plasma ion contributions in the central plasma region of interest.

*Present Address: Institute of Plasma Physics, Nagoya University,
Nagoya, Japan

MASTER

1. Introduction:

Impurity control and energy confinement are topics of central importance to the achievement of high temperature plasmas in tokamak fusion research. In general, radiation losses due to impurities have been minimized in neutral-beam-heated discharges to the point where transport processes limit the maximum stored energy. Recently, however, the issue of impurity control has received renewed attention in neutral-beam-heated discharges displaying the improved confinement characteristics of H-mode discharges, as discovered in ASDEX¹⁻³ and reproduced in PDX^{4,5} and Doublet-III.^{6,7} In particular, these discharges often display substantial metallic impurity concentrations, sometimes to the point where central metallic impurity accumulation results in radiative losses becoming the dominant energy loss mechanism. This has been most evident in the "burst-free" H-mode plasmas in ASDEX.^{3,8} The preliminary interpretation of these results has been that the impurity accumulation is the result of the improved particle confinement times in H-mode plasmas compared to the low confinement (L-mode) regime. It is not clear, however, that this catastrophic metallic accumulation is inevitable in H-mode plasmas, or that it is purely an H-mode phenomenon. In addition, the production of H-mode discharges in the new generation of larger diverted experiments like DIII-D⁹ and JET¹⁰ gives added relevance to further discussion of impurity behavior in both the H- and L-mode regimes of operation.

Other phenomena have also been shown to have strong effects on impurity behavior. For example, MHD behavior, mainly in the form of sawtooth oscillations, have been studied in ohmically heated plasmas for their influence on impurity behavior.^{7,11-13} In neutral-beam-heated plasmas, the influence of the direction of the induced plasma rotation on impurity transport has been the subject of intensive study, especially in the ISX-B^{14,15} and PLT¹⁶

experiments. In ISX-B, co-injection was indicated to inhibit impurity accumulation while counter-injection clearly was correlated with strong accumulation and subsequent disruption. On the other hand, controlled impurity injection experiments in PLT found no noticeable differences in the impurity radial distributions which could be attributed to the beam direction, although impurity influx rates from the edge changed. Likewise, there is evidence from TFTR that strong co-rotation may reduce the penetration of high-Z impurities into the plasma center.¹⁷ While detailed discussions of these results are still ongoing in order to reconcile these apparent discrepancies,¹⁸⁻²⁰ it may be that other non-negligible factors beyond plasma rotation are also having a significant influence on the impurity transport.

In this paper, we describe observations of impurity accumulation in PBX discharges with neutral beam injection. By accumulation, we mean here that the impurity concentration, relative to the background electron density, was strongly peaked on the discharge axis. Thus, a discharge exhibited impurity accumulation when the Z_{eff} profile was peaked on axis. While an H-mode plasma is presented in detail as a typical case, both L- and H-mode plasmas, with and without substantial accumulation of impurities on the discharge axis, are discussed. The dominant criterion for the degree of central accumulation in PBX, regardless of L- or H-mode discharges, appeared to be the clearliness of the plasma itself, with more intense peaking of impurities in the center occurring in plasmas with higher Z_{eff} . This suggests that, in PBX at least, the reduction of impurities in H-mode plasmas primarily involved the usual concerns of controlling and reducing the influx of impurities from the plasma edge.

The next section of this paper describes the apparatus used for the measurements discussed herein, along with relevant characteristics of the PBX

experiment itself. The following two sections discuss detailed observations of impurity accumulation as a function of impurity species for both a plasma with strong accumulation and accompanying thermal collapse of the discharge, and a plasma with much of the accumulation reduced by the use of gas puffing to control the plasma cleanliness. The fifth section describes a global comparison of the degree of impurity accumulation in several L- and H-mode plasmas in PBX. The use of a multi-species impurity transport model to both analyze the data and provide a quantitative characterization of the impurity peaking as the ratio of a model convective influx speed to a model diffusion coefficient is described, along with a connection to simple neoclassical impurity transport theory in the last section.

2. Experimental Apparatus and Techniques:

The Princeton Beta Experiment (PBX) is a large tokamak ($R_{p1} = 1.43 - 1.53$ m, $a = 0.30 - 0.37$ m, $\langle B_t \rangle = 0.7 - 1.4$ T) which was designed to study the effects of strong poloidal cross section shaping on high beta ($\langle \beta \rangle \geq 4-5\%$) plasma stability.²¹ The shaping of interest was achieved by strongly indenting the plasma on the inboard side of the major radius, resulting in the characteristic kidney-bean-shaped poloidal cross section, as shown in Fig. 1 for two characteristic operating conditions. Plasmas exhibiting H-mode transition characteristics were usually achieved when the plasma was limited by a free separatrix inside the nearby conducting passive stabilizers, as shown in Fig. 1(b). The routine attainment of H-mode discharges in separatrix-limited plasmas, accompanied by strong impurity accumulation and consequent thermal collapse, led to the present study. Metallic impurity influxes from the plasma periphery (especially nickel) were higher by factors of 2 to 3 in H-mode plasmas compared to L-mode cases, presumably because the

"diverted" plasmas outside the separatrix impacted substantially on the nickel-coated passive stabilizers, which were protected only locally at 4 to 7 toroidal locations by 2 cm high carbon rail bumper limiters. However, this increased metallic influx alone does not appear to be the cause of the central impurity accumulation, and both L- and H-mode discharges could evolve into either an impurity accumulated or non-accumulated case.

The time evolutions of various signals for an H-mode discharge with strong impurity accumulation are shown in Fig. 2. At some time during the neutral beam heating phase, a transition to an H-mode plasma spontaneously occurs and was indicated by the characteristic sharp drop in the midplane H_α/D_α signal, accompanied by a rapid rise in the electron density even while the gas fuelling rate was held constant or decreased. This rise in the particle confinement time was the most persistent indicator of an L- to H-mode transition having taken place and, as done in PDX studies,^{5,6} we use the existence of this event as an operational definition of whether the plasma was in the H- or L-mode phase. As observed in PDX, the transition to the H-mode was often triggered by a sawtooth crash propagating from the plasma core. The issue of improved energy confinement accompanying this rise in τ_p is considerably more involved and will be reported in detail in a later paper. We do note here that the improvement in τ_E in H-mode plasmas over that in L-mode plasmas (i.e., those not exhibiting the characteristic H_α drop and sharp rise in $\bar{n}_e$) was often marginal, being of the order of 10% or less depending on several operational parameters, such as the divertor configuration and the value of the toroidal field.

The focus of the present paper is on the strong impurity accumulation which plagued both H-mode and, sometimes, L-mode studies in PBX. The presence of a rapid rise in the overall impurity content is suggested in Fig. 2 by the

rise in both the central chord observations of the visible bremsstrahlung signal (which is proportional to $Z_{\text{eff}} n_e^2 T_e^{-1/2}$) and the central chordal signal from the soft X-ray array ($-n_e^2 T_e^\gamma$, $\gamma = 2$ to 5). Both signals rose more rapidly than n_e^2 , indicating a sharp rise in impurity content and, as will be shown below, a strong central accumulation of impurities.

To obtain a global view of impurity behavior under relatively non-reproducible high-beta discharge conditions requires a diverse set of diagnostics with multichannel capability, and PBX was well equipped in this regard. For example, Fig. 3 shows the toroidal location and viewing sightlines of the major diagnostics used in this study, along with the location and orientation of the heating neutral beams (44 keV H⁰ or D⁰, 1-1.5 MW each). The beam injection angle for the NW and East beams was nearly perpendicular with a beam tangency radius of $R_T = 35$ cm while the South and SW beams injected more tangentially with $R_T = 130$ cm. All beams injected in the co-plasma current direction.

A 16-channel visible bremsstrahlung detector array provided a profile of Z_{eff} as a function of major radius by viewing the plasma tangentially in the torus midplane to take advantage of the toroidal plasma symmetry in that field of view, regardless of the plasma poloidal cross section shape.¹³ The SPRED multichannel VUV spectrometer^{22,23} has two interchangeable diffraction gratings which provide coverage over the 95-320 Å and 100-1100 Å spectral regions with a spectral resolution of 0.4 and 2.0 Å, respectively. The normal integration time per spectrum readout was set at 20 msec. This spectrometer was calibrated for absolute intensity measurements via the branching ratio method²⁴ using a 0.6 m visible spectrometer located next to the SPRED spectrometer. The SPRED system was used to monitor impurity influx via CIV, OVI, and NIXI line radiations originating in the plasma periphery. Line radiation

from higher charge states like NiXXII or NiXVIII, coupled with measured electron density and temperature profiles, provided central metallic impurity concentrations. Since the central electron temperature was high enough to ionize carbon and oxygen fully, charge exchange recombination spectroscopy²⁵ using SPRED and mainly the East neutral beam was used to measure the central carbon-to-oxygen ratio at $R = 141$ cm. Depending on the plasma parameters, the charge-exchange-induced signal from the South beam was three to five times smaller than that due to the East beam. Typically, the $\Delta n = 1$ transitions at $102 \text{ \AA}$ (OVIII, $n = 3-2$) and $182 \text{ \AA}$ (CVI, $n = 3-2$) were used. Metallic impurity densities were also measured with a 5-spatial-channel X-ray pulse height analyzer (PHA)²⁶ which viewed the plasma vertically and provided both $n_Z(h,t)$ and $T_e(h,t)$ with a 20 msec time resolution. Finally, impurity information was also obtained with a 19-channel bolometer array which viewed the plasma vertically in a poloidal plane to provide a total radiated power profile from inversion of the chordally integrated signals using the plasma cross-sectional shape from an MHD equilibrium code.

Background plasma characteristics were also relatively well described by several diagnostics. The electron density and temperature profiles were provided by a multichannel Thomson scattering system (TVTS) which measured across the midplane as did the visible bremsstrahlung array, thus avoiding uncertainties due to plasma shape and/or asymmetric profiles. MHD activity and impurity behavior was monitored by a 28-channel soft X-ray diode array (SXR) which viewed the plasma vertically on a poloidal cross section. Finally, a 1-m air-filled spectrometer was quartz-optics-coupled to a scanning mirror which provided a shot-to-shot spatial scan of the NW beamline, allowing measurements of the ion temperature and toroidal rotation velocity profiles via charge exchange recombination spectroscopy observation of the OVIII 2976 $\text{\AA}$

($n = 8-7$) line.²⁷ These measurements also provided a spatial profile of O^{8+} across the plasma midplane.

We place a strong emphasis here on the quantitative analysis and correlation of the measurements from these separate diagnostic systems in our attempts to verify unambiguously the experimental picture of the impurity distributions. Without such quantitative analyses, little progress is possible in attempts to compare different conditions in a given experiment or, even more importantly, different conditions among different tokamak experiments. The PPPL multispecies impurity transport code MIST²⁸ is used to analyze quantitatively the observations from the SPRED and PHA diagnostics. In particular, it solves the simultaneous coupled continuity equations for all charge states of a given impurity species, including the effects of all relevant atomic processes and diffusive and convective radial transport. For simplicity in the calculations, cylindrical symmetry was assumed, which is a reasonable approximation for the central flux surfaces (cf. Fig. 1).

This code is employed as an analytical tool for the reduction of data in several ways. First, it is used with a simple diffusive/convective flux model to provide metallic impurity densities from the VUV line emissions measured with the SPRED spectrometer. It also is used to provide estimates of the total radiated power as a function of radius by calculating and summing all contributions from all impurity species of interest, using measurements from the PHA, SPRED, and visible continuum diagnostics. Finally, the modelling code is combined with measurements of the relative impurity densities to provide model Z_{eff} and P_{rad} profiles to compare to the direct measurements of these quantities, and thus provide a measurement of a convective peaking parameter c_v , which can in turn be used to characterize the degree of impurity accumulation in the discharge. This final application is discussed in more detail later in this paper.

3. Data Analysis and Observations of Central Impurity Accumulation:

The evidence for a strong accumulation of impurities in PBX plasmas under certain conditions is compelling due to the simultaneous measurements from several diagnostics. In this section, we present detailed observations of an H-mode plasma with strong accumulation in order to demonstrate an overall picture of impurity behavior in these discharges. In the course of this discussion, we also describe the quantitative analysis techniques used for the interpretation of the impurity-related data.

An immediate, albeit a bit indirect, indication of central accumulation came from examination of the time-evolving vacuum ultraviolet (VUV) spectrum from the SPRED diagnostic. For example, Fig. 4(a) shows the VUV spectrum before the H-mode transition and strong accumulation, while Fig. 4(b) shows it well into the accumulated phase. In the early time phase, the spectrum is dominated by oxygen and carbon emissions except for the NiXVII and XVIII resonance lines. Several prominent hydrogenic oxygen and carbon transitions, excited via charge exchange recombination, are evident when the East beam was turned on. At late times during the beam injection period, the spectrum became more dominated by metallic emissions from nickel, iron, and titanium, as shown in Fig. 4(b). The very presence of the highest charge states (e.g., NiXXII with an ionization potential at 1.9 keV, and FeXXIII likewise at 1.9 keV) indicates long central confinement of these ions because the central electron temperature was 1 keV or so, and long confinement (> 100 msec) is necessary to allow enough time to ionize up to these highly charged states.

The time evolution of several prominent VUV spectral lines are shown in Fig. 5 to further indicate qualitative evidence of increasing central impurity densities. The CIV (312 Å) and OVI (173 Å) emissions, originating from the edge plasma, indicated little change in the oxygen and carbon influx during

the beam phase, except for the presence of a slight transient drop in these emissions at the onset of the H-mode, presumably due to an increase in the edge temperature and some steepening of the edge gradients. The charge-exchange-excited lines of OVIII (102 Å) and CVI (182 Å) both rose somewhat, oxygen steadily while the carbon signal tended to plateau in time. Since the plasma density was continuously increasing after the H-mode transition, and the central beam neutral density was thus decreasing, the central carbon and oxygen densities were also increasing during the H-mode phase at later times.

Unlike the low-Z impurities, the influx of the metallic species (c.f., the Ni XIII and XIV emissions in Fig. 5) jumped up by a factor of 2 to 3 after the transition to the H-mode, possibly reflecting a higher edge temperature near the metallic passive plates. As one observes charge states arising from ever deeper into the plasma, the increase in metallic density became quite large, as indicated by the progressively larger increase in intensity as the charge state goes up. This holds until one gets to near-terminal states, such as NiXXII to XXV, which initially showed a very large rise in intensity but then decayed back down. This decay is due to recombination to lower charge states as the central electron temperature collapsed due to increasing central radiated power.

A further indication of precipitous central impurity accumulation is seen in the radial profiles of the visible continuum radiation, as shown in Fig. 6. Figure 6(a) shows the integrated chordal signals of the tangentially viewing array, while the local emissivity as a function of major radius is obtained by a cylindrical Abel inversion of this data and is shown in Fig. 6(b). Since this emission profile increased much more rapidly than the square of the plasma density (the bremsstrahlung emission is roughly proportional to $Z_{\text{eff}} n_e^2 T_e^{-1/2}$) and became very centrally peaked, a strongly peaked $Z_{\text{eff}}(R)$ is indicated. The impurity accumulation was usually delayed after

the H-mode transition by ~ 100 msec, about twice the estimated cross-field transport time scale. In this particular case, the profile in Fig. 6 became progressively more peaked until the discharge was terminated by a major disruption.

Quantitatively, the Z_{eff} profile is obtained from the measured local emissivity of the visible bremsstrahlung by the expression²⁹

$$\frac{\partial \epsilon}{\partial \lambda} = \frac{Z_{\text{eff}} n_e^2}{T_e} \bar{g}_{\text{ff}} \quad , \quad (1)$$

where $\bar{g}_{\text{ff}}$ denotes the energy-averaged free-free gaunt factor given by Ref. 30. A full radial profile of $Z_{\text{eff}}(R)$ is provided for each case where a Thomson scattering profile of $n_e(R)$ and $T_e(R)$ is available. The central metallic densities were measured in two ways. First, the X-ray PHA diagnostic provided direct estimates of the central electron temperature and metal densities, with only minor assumptions on the charge state distribution of the ions in the plasma center. Second, the chordally integrated VUV line emissions measured with the SPRED spectrometer were compared with the solutions from the MIST code to derive a central ion density for a given species. As mentioned earlier, this code calculates solutions of the coupled continuity equations for each charge state. The continuity equation for a given charge state q in cylindrical geometry is given by

$$\frac{\partial n_q}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} r \Gamma_q = -(I_q + R_q) n_q - R_{q+1} n_{q+1} + I_{q-1} n_{q-1} + S_q \frac{n_q}{\tau_j} \quad , \quad (2)$$

where I_q and R_q are the total ionization and recombination rates, respectively, for the charge state q with density n_q . The S_q term denotes a volume source for the deposition of neutral impurities as $q = +1$ ions (i.e.,

$S_{q \neq 1} = 0$) at the plasma edge, while the $r_{||}$ term denotes a loss term for plasma flow along the field lines for values of r outside the plasma scrape-off radius. Since the atomic rates depend on n_e and T_e , these calculations also require the measured Thomson scattering plasma profiles as input. With an appropriate model for the radial flux term r_q , the densities of each charge state q are calculated and, using the general expressions for electron impact excitation rates of line emissions provided by Mewe,³¹ an intensity of a given spectral line is calculated. Comparison of the calculated to the measured absolute intensity then provides a measure of the metallic impurity density. Due to the relative paucity of data for a given ion species, only the most elementary model for the radial flux is justified. Hence, we take

$$r_q = -D \frac{\partial}{\partial r} n_q + v(r) n_q, \quad (3a)$$

$$v(r) = -c_v \frac{2Dr}{a}. \quad (3b)$$

Here, we assume a common constant diffusion coefficient for all species and charge states, and allow a simple spatial variation in the convective flow speed to provide for central accumulation of the ions. The multiplicative factor c_v is referred to as the impurity peaking factor since, in steady state, the solution for total density of a given species is given by a Gaussian distribution raised to the c_v power:

$$\sum_q n_q(r) \propto \exp(-c_v r^2/a^2) \quad (4)$$

in the source- and sink-free central plasma. As we have shown in an earlier paper,³² and, as will be evident later herein, the value of c_v increased as the nuclear charge Z of the impurity species increased. That is, the heavier impurities had more strongly peaked profiles than lighter species.

For simply estimating the central metallic densities and the corresponding influx rate from the VUV observations, we take a steady-state solution of the transport equations and get an estimate of the appropriate c_v value for nickel by varying c_v to give the proper ratio of the NiXVII, XVIII, XXII, and XXV spectral lines. The resulting value of c_v is used for all metallic impurities.

The ratio of fully ionized oxygen density to that of carbon is derived from the measured intensity ratio of the OVIII (102 Å, $n = 3-2$) and CVI (182 Å, $n = 3-2$) charge-exchange-excited lines. A calculation of the density of the East beam via standard beam attenuation codes along the spectrometer line of sight is coupled with these measurements and estimates of the excitation rates for charge exchange recombination to derive this central oxygen-to-carbon ratio.

Once the local metallic impurity densities, the central value of Z_{eff} , and the carbon-to-oxygen ratio were all determined as described above, a picture of the total impurity inventory was constructed by obtaining the absolute carbon and oxygen densities by requiring that the sum of all plasma ion and impurity ion contribution to Z_{eff} add up to the measured Z_{eff} value. The results of one such case are shown in Fig. 7(a), where the value of $Z_{eff}(0,t)$ is plotted as a function of time along with the measured distribution of Z_{eff} among the various ion species present. Plasma profiles from Thomson scattering measurements were available for 4 distinct times throughout the pictured interval, and interpolated profiles were used between these times. As indicated, the central Z_{eff} measured by the PHA system shows good agreement with that derived from the visible bremsstrahlung diagnostic.

The central Z_{eff} decreased slightly after the H-mode transition due to the rapid increase in n_e . Gradually, however, the increase in impurity densities overcame the plasma ion density rise and the value of $Z_{eff}(0)$

started to increase. As mentioned earlier, the metallic ions showed a more severe accumulation than the low-Z impurities. The metallic contribution to $Z_{\text{eff}}(0)$ increased by a factor of 20, while oxygen and carbon increased by factors of five and two, respectively. Nevertheless, oxygen and carbon dominated the Z_{eff} value even at late times, and the Z_{eff} profile gives a reasonable estimate of the spatial distribution of the low-Z impurities.

A more detailed picture of the rapid increase in the metallic ion concentrations is shown in Fig. 7(b). Results from both the PHA diagnostic and the VUV (SPRED) measurements, coupled with the MIST code analysis, agree very well with one another. Nickel and iron are the major metallic impurities with concentrations of ~ 0.2 to 0.3%, and chromium and titanium are evident in the strongly accumulated phase of the discharge. Detailed examination of the radial profiles of metallic impurities, obtained with the PHA for a few of the cases studied here, showed that both an increase of the impurity influx and a strong accumulation in the plasma center are necessary to account for the observed metallic ion densities.³³

Of possibly more interest than the impurity densities is the central radiated power losses due to these high impurity densities. Using the results of the MIST code, we calculated the central radiation power density for all impurity ions. The result is shown in Fig. 8(a), along with a value of $P_{\text{rad}}(0,t)$ obtained by a bolometer array. Again, the agreement between all diagnostics is good. With P_{rad} reaching values of 1 W/cm^3 or more, the central plasma temperatures started to collapse (c.f. Fig. 8(b)) since the radiated power losses were comparable to the local input power density. The drop in $T_e(0)$ was greater than the rise in $n_e(0)$ during the later phase of the discharge, and the discharge often terminated in a major disruption. This general picture of impurity behavior, as depicted in Figs. 3 through 8, was characteristic of plasmas with strong central impurity accumulation.

4. Suppression of Impurity Accumulation via Gas Puffing:

Central impurity accumulation can be suppressed by certain types of MHD activity, especially sawtooth oscillations. In the presence of sawteeth, a peaked impurity density profile is redistributed to be roughly flat at the time of the internal disruption,^{12,32} and it then may recover to a peaked profile due to strong inward convective flows before the next sawtooth drop. This sawtooth-induced transport effect is especially non-negligible when the $q = 1$ inversion radius, r_{inv} , is large and/or the sawtooth period t_{st} is short, since the sawtooth flattening effects give an effective diffusion coefficient $D_{st} \sim (0.7 r_{inv})^2 / t_{st}$.³⁴ This effective diffusion coefficient can often be comparable to estimated transport coefficients in the plasma core. Details of sawtooth effects on impurities in PBX have been reported earlier in Refs. 13 and 32.

In this section of the paper, we briefly describe the effect of gas puffing on central impurity accumulation in PBX. Since results from the ASDEX experiment indicated that strong impurity accumulation was an unavoidable consequence of the "burst-free" H-mode (or vice versa), we carried out a series of observations to determine if it is possible to produce H-mode plasmas without catastrophic impurity accumulation. While the electron density increased in a roughly linear fashion in time after the H-mode transition and was relatively unaffected by changing gas fuelling rates (over the range of 0 to ~ 30 torr-liter/sec), the impurity behavior was strongly influenced by changing fuelling rates. Similar results have recently been reported from the DITE experiment.³⁵

As an example of the effects of different gas puffs, Fig. 9 shows the time evolution of the inverted visible continuum profiles and the central Z_{eff}

value for one discharge whose gas flow was cut off to zero at the onset of neutral beam injection at $t = 400$ msec, and another in which a constant gas fuelling rate of ~ 8 torr-liter/sec was sustained throughout the discharge. The corresponding H_α emissions are shown in Fig. 10, with the time of constant gas feed shown for each case. Both discharges compared here had $I_p \sim 350$ kA, $P_{inj} = 2.5$ MW ($t_{NBI} = 400 - 700$ msec), and $R_{pl} = 147$ cm, the only differences being in the gas feed waveform and the consequent impurity behavior.

As seen in Fig. 9(a), the discharge with truncated gas feed showed a significantly peaked visible bremsstrahlung profile, and the central Z_{eff} value reached up to ~ 8 at the end of the beam heating phase. Central impurity increases were significantly suppressed in the case with constant gas puff, as seen in Fig. 9(b). Here, the central Z_{eff} reached at most 4 by late times in the discharge.

Of course, with such high values of $Z_{eff}(0)$, and the fact that metallic impurities accounted for only $1/4$ to $1/2$ of the total $Z_{eff}(0)$, significant dilution of the proton density occurred in the plasma core. As indicated in Fig. 11, the central electron density in each gas puff case increased almost linearly in time after the H-mode transition, but the proton density, estimated from the measured $Z_{eff}(0)$ and central impurity densities, showed a substantial decrease and finally dropped to less than 40% of the electron density. In the case with constant gas puff, however, the reduced impurity content led to the proton density remaining at least 70% of the electron density. The similarity of the $n_e(0)$ curves in Fig. 11 give the distinct impression that the primary effect of the H-mode transition in PBX was an increase in the particle confinement time for the electrons. The plasma and impurity ions simply adjust to achieve quasi-neutrality. Indeed, while an increase in τ_p was a constant feature of the H-mode in PBX, the energy

confinement times and the ion behavior were more sensitive to the exact tailoring of the discharge.

We also indicate in Fig. 11 the rapid rise in central nickel density in the no-gas puff case compared to the constant gas feed case. The metallic concentrations differed by a factor of ~ 3 , and often lead to a decrease in the electron temperature for the case with little gas feed. Interestingly, the observed difference in the central impurity content cannot be explained solely by changes in impurity influxes at the plasma edge. To see this qualitatively, Fig. 12 shows the time evolution of emissions from several charge states of interest for these two discharges. While there were some differences in the nickel influx rates as suggested by the NiXI line emission, it does not appear adequate to account for the drastic difference in the central NiXXII density. Likewise, as indicated by the central electron temperature values shown in Fig. 11, the difference in the higher charge state densities does not derive from plasma parameter differences, but indicates that the impurities experienced a longer central confinement time in the low gas feed case. Further evidence for long impurity confinement can be seen in the fact that the medium ionized states, NiXVII and XVIII, showed an ionization burnout peak in their time evolutions for the no-gas feed case, while they just barely reached a plateau value before the end of the beam injection phase of the discharge in the constant gas feed case.

In a like manner, the line radiation from the low charge states of C(CIV 312 Å) and O (OVI 173 Å) showed perhaps some decrease in the C influx with little change in the O influx when gas puffing was sustained throughout the duration of the discharge. However, the charge-exchange excited emissions from CVI and OVIII indicated a drop in the central density by $\sim 30\%$ for C and $\sim 50\%$ for O. This large difference in central impurity buildup, brought on by

a relatively small change in gas feed rate, indicated the presence of a strongly nonlinear mechanism which led to central impurity accumulation.

5. Comparison of Impurity Accumulation in L- and H-mode Discharges:

From neoclassical theory, one may expect that impurities experience strong inward convection when dilution of the proton density is large and impurity-impurity driven terms in the transport cannot be ignored.^{34,35} If such effects were coming into play, the impurity accumulation in PBX may depend more on the absolute impurity amount and mix inside the plasma rather than whether one were in the H- or L-mode confinement regime. Of course, both confinement and influx can influence the net impurity level in the discharge, but it is worthwhile to compare H- and L-mode plasmas with equivalent impurity levels to explore underlying connections between them.

To that end, we examine here four distinct types of discharges produced in PBX: L- or H-mode with low or high Z_{eff} levels. The time evolutions of the central Z_{eff} value for these four cases are shown in Fig. 13. They were derived from the visible bremsstrahlung measurements, the central $T_e(0,t)$ from the X-ray PHA, and the line-integrated density assuming a constant density profile modelled on the single-time point Thomson scattering profile. Full electron temperature and density profiles were obtained at the times marked TVTS in Fig. 13, and are shown in Fig. 14. As seen in this figure, the electron temperature profile was relatively flat in the inner 10 cm for the high $Z_{eff}(0)$ cases (a) and (c). The H-mode density profiles tended to be flatter in the plasma core than the L-mode cases, and the H-mode plasmas (a) and (b) showed a 50% higher electron density due to the improved particle confinement in H-mode plasmas.

Direct evidence for central impurity peaking for the cases with high $Z_{\text{eff}}(0)$ is seen in Fig. 15 where the Z_{eff} radial profiles, obtained from the visible bremsstrahlung and Thomson scattering measurements, are shown for the four cases. As seen in Fig. 15(a), the Z_{eff} profile was flat at early times of beam injection ($t_{\text{NBI}} = 400 - 700 \text{ msec}$) before the H-mode transition ($t_{\text{trans}} = 510 \text{ msec}$) while it became quite peaked late in the discharge. However, the Z_{eff} profile showed no central peak in the case where the central value of Z_{eff} was suppressed by gas puffing, as seen in Fig. 15(b). As shown in Figs. 15(c) and (d), very similar results were obtained for L-mode plasmas, indicating that the impurity accumulation was not an H-mode specific phenomenon.

Since the contribution of metallic impurities to the value of Z_{eff} was usually small, the Z_{eff} profiles in Fig. 15 mostly represent the low-Z impurity spatial distributions. On the other hand, the radiated power losses from the hot plasma core were due mostly to incompletely ionized metallic impurities, and the central radiated power profiles give a good indication of the metal impurity profiles. Figures 16(a) through (d) show the radiated power profiles for the four cases of interest. The radiated power was measured directly by a bolometer array, and has also been calculated from the PHA - measured metal densities coupled with radiative cooling curves derived in coronal equilibrium. The two measurements agree well, and show the same results as the Z_{eff} profiles: H- and L-mode plasmas were obtained with and without strong central accumulation. In the peaked cases, the radiation profiles were more peaked by a factor of 5 or so above the Z_{eff} profile. The radiative energy losses themselves were most severe in the accumulated H-mode case, Fig. 16(a), due to both the higher electron density and higher impurity levels.

Later measurements of radiated power with both tangentially and poloidally scanning bolometer arrays indicated substantial poloidal asymmetry in radiation outside the separatrix near the divertor region.³⁶ Thus, the hollow profiles in Figs. 16(b) and 16(d) can only be considered to be approximately representative of the central radiation levels. However, asymmetries in edge radiation had little influence on the measurement of central radiation for the cases of strong central accumulation.

In order to compare the degree of impurity accumulation in these different discharge conditions, we used the MIST code, with the flux terms defined by Eqs.(3), to obtain a quantitative measure of the degree of impurity accumulation. As noted earlier, the peaking factor c_v in Eq. (3b) indicates the power to which a Gaussian profile is raised to model the impurity profile under steady-state conditions [c.f., Eq.(4)]. The solid and dashed lines in Fig. 15 indicate the calculated Z_{eff} profile obtained from MIST for each case of interest using a common c_v factor, which we denote here as $c_v(Z_{eff})$, for all ion species. However, our earlier report on central impurity accumulation in PBX clearly showed that there is a strong dependence of the values of c_v needed to describe simultaneous measurements of both the low-Z and high-Z ion densities on the ion charge number Z .³² The c_v value for metals, $c_v(\text{metals})$, was calculated from radiated power profiles and direct metallic ion distributions and found to be roughly 10 to 40 in an accumulated discharge. The solid lines in Figs. 16(a) and (c) indicate the radiated power profiles calculated by MIST for the indicated values of c_v for metallic impurities. On the other hand, direct measurements of O^{8+} and fits to the Z_{eff} radial profile showed the low-Z peaking factor $c_v(\text{low-Z})$ to be 3 to 5, which are closer to the fitted values of $c_v(Z_{eff})$ in Fig. 15. Since metallic impurities do contribute somewhat to Z_{eff} , the value of $c_v(Z_{eff})$ is always between the

values for the low- and high-Z impurities: $c_v(\text{low-Z}) < c_v(Z_{\text{eff}}) < c_v(\text{metals})$. The value of $c_v(Z_{\text{eff}})$ does, however, provide a reasonable average quantity to describe the degree of impurity peaking in a given discharge. We see from Fig. 15 that there was no apparent difference between H- and L-mode plasmas with respect to this average peaking parameter.

For the purpose of comparing a large number of discharges for trends in impurity accumulation, it is convenient to define an effective impurity density³⁷

$$n_Z^{\text{eff}}(r) \equiv [Z_{\text{eff}}(r)-1] n_e(r) \approx \sum_Z Z^2 n_Z(r), \quad (5)$$

which is roughly proportional to the impurity density profile in the case of a single dominant impurity species. We then model the profile of n_Z^{eff} by getting the best fit to

$$n_Z^{\text{eff}}(r) \propto \exp(-c_Z r^2/a^2), \quad (6)$$

in analogy to Eq. (4). This fitting parameter c_Z equals c_v in the limit that the plasma has one fully ionized impurity species and $n_p/n_e \approx 1$. That this value of c_Z gives a good approximation to the value of c_v , estimated by detailed impurity transport analysis, is shown in Fig. 17 for a sample discharge with significant accumulation. Figure 17(a) shows the measured values of $n_Z^{\text{eff}}(R)$ along with the least-squares fitted Gaussian corresponding to a value of $c_Z = 4.8$. The actual Z_{eff} profile and model profiles obtained with MIST for nearby values of c_v are shown in Fig. 17(b). The agreement between c_Z and c_v from the detailed impurity modelling is quite reasonable.

In general, we find that the n_z^{eff} profile is reasonably well fitted by a Gaussian profile as in Eq. (6). This is due in part to the fact that these measurements are, by their nature, relatively coarse and we are just modelling the most accessible features of the profile. Any reasonably smooth function with an arbitrary peaking parameter would do.

When the Z_{eff} profile was flat, the total impurity density profile was roughly as peaked or broad as the electron density profile. It is of interest later to define the normalized peaking parameter

$$c_N \equiv c_z / c_{ne} \quad (7)$$

as a measure of the central peaking of the Z_{eff} profile itself. Here, c_{ne} is the peaking parameter obtained by fitting the measured electron density profile to a Gaussian [$n_e(r) \propto \exp(-c_{ne} r^2 / a^2)$]. For a plasma with a flat Z_{eff} profile, $c_N = 1$.

For a relatively large number of discharges of both L- and H-type, we find that the impurity peaking factor c_z correlated strongly with the value of $Z_{\text{eff}}(0)$. This is shown in Fig. 18(a), where we plot the fitted c_z as a function of $Z_{\text{eff}}(0)$ for a collection of discharges for which Thomson scattering plasma profiles were available. The wide range of data was obtained by examining discharges which were produced with a variety of total injected neutral beam power and gas feed rates. In general, discharges with more impurity content and impurity accumulation were obtained by increasing P_{inj} and/or decreasing the gas feed rate during neutral injection.

While no obvious difference between L- and H-mode plasmas existed in the degree of impurity profile peaking, a clear distinction between the two types of discharge was found in the normalized peaking parameter c_N , which is a

measure of how centrally peaked the Z_{eff} profile itself is. To see this, we plot the value of c_N as a function of $Z_{\text{eff}}(0)$ in Fig. 18(b) for the same data as in Fig. 18(a). Here, the H-mode plasmas are seen to have had a consistently higher value of c_N than L-mode discharges. This difference arises from the fact that the H-mode plasmas in general had broader electron density profiles than those obtained in L-mode cases. This led to broader Z_{eff} profiles in L-mode plasmas although the impurity spatial distribution itself appears to be unrelated to whether the discharge was in an L- or H-mode condition.

6. Discussion:

Since the total impurity profiles themselves, as parameterized by c_Z , seem to have been uncorrelated to the shape of electron density profile, it appears that the impurity transport processes, at least in this impurity accumulated regime, were relatively independent of the background plasma profile. Earlier observations indicated that impurity transport in the plasma core for a strongly accumulated H-mode plasma in PBX was consistent with elementary neoclassical estimates.³² Indeed, impurity-impurity-driven neoclassical fluxes are also reasonable candidates to explain the origin of an impurity-density-dependent inward convection which gives rise to the observed increase of c_Z with $Z_{\text{eff}}(0)$.^{38,39} It is thus worth discussing these fluxes here to put the present results in context.

For simplicity, we consider the diffusive and convective transport coefficients as given in the Pfirsch-Schlüter collisional regime³⁸:

$$D_B = C_0 q^2 \left[C_1(\alpha) n_H + \sum_B \left(\frac{m_B}{m_H} \right)^{1/2} Z_B^2 C_1(\beta) n_B \right], \quad (8)$$

$$\begin{aligned} v_B = C_0 q^2 & \left\{ C_1(\alpha) \frac{\partial n_H}{\partial r} + \left[C_1(\alpha) - \left(\frac{1}{Z_I} \right) C_1(\alpha) - C_2(\alpha) \right] \frac{n_H}{T} \frac{\partial T}{\partial r} \right. \\ & + \sum_B \left(\frac{m_B}{m_H} \right)^{1/2} Z_B \left\{ C_1(\beta) \frac{\partial n_B}{\partial r} + \left[C_1(\beta) - \left(\frac{Z_B}{Z_I} \right) C_1(\beta) \right. \right. \\ & \left. \left. - C_2(\beta) \right] \frac{n_B}{T} \frac{\partial T}{\partial r} \right\} \left. \right\} Z_I, \end{aligned} \quad (9)$$

where the subscript H refers to the plasma ions, I refers to the impurity species of interest, and B refers to all other background impurity species in the plasma. The parameters $C_1(\alpha)$ and $C_2(\alpha)$ are given in Ref. 38 for different plasma conditions, and we use for the present plasma conditions:

$$C_0 = \frac{s(2\pi m_H)^{1/2} e^2 q^2 \ln \Lambda}{3 (kT)^{1/2} B_T^2 (4\pi \epsilon_0)^2} \quad (a)$$

$$C_1(\alpha) = 0.48 + \frac{0.31}{0.59 + \alpha}, \quad (b)$$

$$C_2(\alpha) = 0.31 + \frac{0.41}{0.59 + \alpha}, \quad (c) \quad (10)$$

$$\alpha \equiv \left(\frac{n_I}{n_H} \right) Z_I^2 + \left(\frac{n_B}{n_H} \right) Z_B^2, \quad (d)$$

and

$$s \equiv \frac{n_I Z_I^2}{n_B Z_B^2}. \quad (e)$$

Examination of these neoclassical fluxes leads to a possible nonlinear mechanism for the observations from PBX. Since the background plasma ion density profile was nearly flat or even slightly hollow due to ion dilution in discharges with significant impurity accumulation, the impurity convective velocity driven by the plasma ions was directed outward in the plasma core. However, the convection driven by the other impurities (besides the species of interest) was inward due to the gradients of impurity density. As the plasma impurity content increased, this inward convection driven by impurity-impurity interaction dominated and strong accumulation occurred. As the impurities accumulated, the inward convection became increasingly enhanced, leading to a positive feedback mechanism for the accumulation. The initial stage of the accumulative process, before strong central accumulation occurs, may have been driven by inward convection due to impurity-plasma ion interaction before the plasma ions were strongly diluted or, of course, to other effects such as rotation-driven effects or improved particle confinement.

That these neoclassical fluxes may give rise to the relationship between c_z and $Z_{eff}(0)$ observed in PBX data [Fig. 18(a)] is supported by Fig. 19, where we plot the calculated c as a function of $Z_{eff}(0)$ for carbon, oxygen, and nickel impurities in PBX using the fluxes in Eqs. (8)-(10). The results of these calculations are shown as solid lines in the figure, while the range of the PBX data in Fig. 18(a) is indicated by the area enclosed by the dashed lines. The solid curves represent the value of c_v calculated at a radius of 10 cm using model background impurity profiles and relative densities which are fixed to agree with our typical measured values: $c_v(\text{low-Z}) = 4$, $c_v(\text{metals}) = 20$, $n_{Ni} : n_{Fe} : n_O : n_C = 2:1:30:30$. Since the background impurity profiles are not varied as $Z_{eff}(0)$ is increased, the neoclassical value of c_v tends to saturate for each species of interest, whereas in reality one would

expect all impurities to change their spatial distributions as impurity accumulation intensifies. This nonlinear feedback is not included in the simple calculations used to produce the curves in Fig. 19, but its inclusion would result in the curves rising more steeply at high $Z_{eff}(0)$ than seen in Fig. 19 since each species would peak more on axis. Nonetheless, it is interesting to note that the observed c_z values are consistent with these estimated c_v curves, and the tendency of the PBX data to have a steeper slope than the calculated curves at high $Z_{eff}(0)$ is readily explained by a breakdown in the unrealistic assumption of constant background impurity profiles as $Z_{eff}(0)$ increases. While these results suggest the general conclusion that the dependence of c_z on $Z_{eff}(0)$ is tentatively explained by neoclassical impurity-impurity-driven fluxes, much more careful modeling which takes into account the proper collisionality regimes for all radii, coupling between the background impurity species and the species of interest, noncircular plasma cross sections, and other effects such as plasma rotation, is obviously needed to arrive at more conclusive comparisons with theory.

In recent years, the discussion of impurity behavior in neutral-beam-heated plasmas has centered on the effects of plasma rotation. It is therefore worthwhile to address briefly this issue for the PBX data presented here. Experimentally, we found no obvious correlation between impurity accumulation and the central plasma rotation velocity for rotation speeds ranging from 0.5 to 2.2×10^5 m/sec and c_z ranging from roughly two to four (all for co-injection). It is not clear from theoretical estimates, however, that a strong rotation effect should have been observable in these data in any case. For example, we consider neoclassical fluxes driven by rotation in a plasma without significant background impurity densities, as described in Refs. 19 and 40. The net toroidal rotation speed, u , for an impurity species

is a sum of the parallel impurity flow, $v_{||}$, caused by frictional coupling with the rotating plasma plus the toroidal flow v_{ϕ} induced by the radial electric field present in the discharge. Depending on the balance between these two flows, the convection driven by them can be inward or outward. Even if these effects result in a net outward convective flux, it is usually smaller than the outward convective flow caused by the direct momentum transfer from the neutral beams to the ions and impurities over most of the plasma in our co-injection cases. This direct momentum-driven term is estimated for our case to have been on the order of $3 \times 10^2(r/a)\text{cm/sec}$ in the outward direction for $n_e(0) = 7 \times 10^{13}\text{cm}^{-3}$, $Z_{\text{eff}}(0) \sim 5$, $T_i(0) = 2.1\text{ keV}$, $v_{\phi}(0) = 2 \times 10^7\text{ cm/sec}$, and $n_2(0)/n_e(0) = 2 \times 10^{-3}$ for Ni^{20+} , while the inward convective speed for Ni^{20+} driven by impurity-impurity collisions was roughly $6 \times 10^2(r/a)\text{ cm/s}$ for the same parameters. Thus, we may expect any rotation-driven outward flux was masked by the strongly inward flux from impurity-impurity interactions.

While the details of neoclassical fluxes relevant to each particular case in PBX can be pursued, it seems far more important here to note the general feature that anomalous transport, either diffusive or convective, appears to have been negligible in most of these PBX plasmas. This is especially striking since a relatively large anomalous diffusion coefficient of $D_A \sim 10^4\text{cm}^2/\text{sec}$ was routinely observed in the discharges in PDX, the original incarnation of the PBX device. Identifying the conditions under which the anomalous transport is negligible with respect to neoclassical fluxes seems to be the paramount issue of impurity confinement physics in tokamaks, and may provide a means of reconciling apparently contradictory results from different machines.

Unfortunately, no feature of the plasma itself or the way in which PBX was operated stands out as a clear candidate for the cause of the reduction of

anomalous transport from the levels observed in PDX. One speculation is that the neoclassical terms dominated in these strongly shaped PBX discharges because the $q = 1$ surface usually was in the range of $r/a = 1/3$ to $1/2$, thus providing a relatively large plasma volume inside the $q = 1$ surface. Results from Alcator-C with pellet injection also indicate that anomalous transport is relatively negligible in the central plasma core.⁴¹ Besides the large $q = 1$ radius, the electron density profiles in PBX tended to be flatter than they were in PDX, even for L-mode discharges, which may have given rise to reduced anomalous transport in the core region if the anomalous transport is related to electron or proton density gradients. The lack of a clear distinction between L- and H-mode plasmas in Fig. 18 suggests, however, that this factor may not have been relevant here. Other possible differences between PBX and PDX were the electrical grounding of the limiter surfaces or the relative amounts of particle fuelling due to outboard side gas puffing versus either internal fuelling via neutral beam injection or fuelling via strong recycling on the inboard side of the plasma. Whatever the level of anomalous transport, neoclassical effects should be more evident as Z_{eff} increases since the impurity collisional terms increase in importance, unless, of course, the anomalous terms increase with increasing impurity concentration. Overall, it is clear that we do not have, from our limited data base, a clearly identified mechanism for the reduction of anomalous transport, and future experiments on the modified PBX-M device will concentrate on efforts to pursue this crucial issue.

It is of interest to compare the present data to that available from other tokamak experiments. To that end, we have taken results available from other tokamaks, fitted the data as described for PBX, and plotted the derived c_z values as a function of $Z_{eff}(0)$. Figure 20 shows the results of this

analysis for both ohmic- and neutral-beam-heated discharges. Ohmically heated discharges in Alcator-C had flat Z_{eff} profiles ($c_2 \sim 1$) for a clean ($Z_{eff} = 1.5$) plasma,⁴² while high density ohmic discharges in JIPPT-II showed impurity accumulation ($c_2 = 5-6$) for relatively dirty plasmas ($Z_{eff}(0) = 3.3$).²⁹ The S- and O-type ohmic discharges in D-III showed flat or slightly hollow nickel profiles ($c_v \sim 0$) for $Z_{eff}(0) = 2.7$ (S-type) and a very peaked nickel profile ($c_v \sim 10$) for $Z_{eff}(0) = 4.6$ before onset of the $n/m = 1/1$ oscillations (O-type).⁷ Similar results were observed on PBX¹³, where sawtooth-free ohmic discharges had $c_2 = 11$ for $Z_{eff}(0) = 3$ and the value of c_2 dropped to ~ 3 for $Z_{eff}(0) = 2$ in the presence of sawtooth oscillations. We also show previously unpublished results from the PBX predecessor device, PDX. Results from ohmically heated studies in ISX-B also fit into the general scheme here. The impurity accumulation observed in deuterium, but not hydrogen, plasmas in ISX-B may possibly be explained by impurity-driven fluxes since the impurity content of deuterium plasmas was usually higher than hydrogen plasmas.⁴³ In a like manner, the long confinement times of injected silicon into a relatively dirty ($Z_{eff} \sim 3.7$) ohmic plasma in ISX-B was explained by convection driven by collisions with the background oxygen.⁴⁴

The amount of quantitative impurity data from neutral-beam-heated tokamak plasmas is more sparse than for ohmic plasmas. The measurements that do exist have tended to concentrate on the influence of beam-induced plasma rotation on impurity transport. For example, the molybdenum injection experiment in co- and counter-injected plasmas in PLT¹⁶ indicated little difference in impurity transport itself between the two cases and both discharges were relatively clean. Estimates of the peaking factor c_v for Mo in these PLT discharges with $Z_{eff} = 2-3$ are plotted in Fig. 20. If the background plasma were dirtier, then the greater impurity influx observed in the counter-injected case may

cause Z_{eff} to rise sufficiently so that strong impurity accumulation results. In addition to possible rotation effects, this mechanism may cause impurity accumulation to occur more readily in counter-injected discharges than in co-injected cases, as was clearly observed in ISX-B.¹⁴ The impurity distributions in H-mode plasmas in the PDX and D-III experiments were also modelled and the results are plotted in Fig. 20. The PDX results come from unpublished measurements of the Z_{eff} profile in co- and counter-injected H-mode plasmas, while the D-III results are from modelling the nickel radial profiles inferred from X-ray measurements.⁷

The paucity of quantitative measurements from a variety of devices make it hazardous to come to a general conclusion from Fig. 20 at this time. The present results do, however, point out the absolute necessity of more systematic quantitative impurity measurements on tokamak experiments if significant progress is to be made in understanding the underlying physical mechanisms involved in impurity transport and confinement.

7. Summary:

In an analysis of impurity accumulation in PBX discharges, we have emphasized here the apparent role of the plasma cleanliness and its relation to the degree of central impurity peaking. These results, along with our earlier discussion of impurity accumulation inside the $q = 1$ surface, indicate that impurities behave in a manner that is in semi-quantitative agreement with neoclassical theory for impurity transport in a plasma with substantial impurity concentrations. These results are qualitatively similar to indications from other experiments, and they all emphasize the non-negligible effects of impurity-impurity terms in discussions of impurity transport in neutral-beam-heated tokamaks. For example, we see strong impurity

accumulation in plasmas with substantial toroidal rotation in the co-direction, indicating that rotation-induced transport is not the dominant agent here. We also wish to emphasize the importance of detailed measurements of all major impurity species in a plasma, both high-Z and low-Z, when considering comparison of theory and experimental results. Such comparisons are often necessarily incomplete because of the lack of information of the various impurity species and profiles.

It is clear, of course, that substantially more work is needed for a careful comparison of these PBX results to neoclassical theory. While we have discussed several isolated influences, a more complete analysis should consider different collisionality and impurity density regimes, rotation effects, details of time variations, estimates of anomalous transport, a noncircular plasma cross section, and effects of MHD activity in a self-consistent way to compare rigorously these results to neoclassical theory. We note, however, that further efforts to quantify the magnitude and radial profile of anomalous transport fluxes are just as important as a detailed comparison to neoclassical theory in the effort to gain a complete picture of impurity transport processes.

Most importantly for its implications on energy confinement, the present results indicate that the impurity-impurity collisional effects produce strong accumulation in both L- and H-mode plasmas, with no obvious difference between the two classes of discharges. This encourages us to study the processes by which one can reduce the impurity influx into H-mode plasmas since, in PBX at least, it did not appear that catastrophic impurity accumulation was an inevitable consequence of operation in the H-regime.

Acknowledgments

The authors wish to acknowledge the support of K. Bol and M. Okabayashi throughout this work and the help of the PBX physics and technical staffs in these experiments. Useful discussions with G. Jahns, M. Murakami, M. Shimada, and S. Suckewer are also gratefully acknowledged. This work was supported by U.S. Department of Energy Contract No. DE-AC02-76-CH03073.

References

- ¹F. Wagner et al., Phys. Rev. Lett. 49, 1408 (1982).
- ²F. Wagner et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 9th Int. Conf. Baltimore, 1982) (IAEA, Vienna, 1983) Vol. 1., p. 43.
- ³M. Keilhacker et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 10th Int. Conf. London, 1984) (IAEA, Vienna, 1985) Vol. 1.
- ⁴R.J. Fonck et al., Proc. 4th Inter. Symp. on Heating in Toroidal Plasmas, Rome, 1984, Ed. by H. Knoepfel and E. Sindoni (ENEA, Rome, 1984) Vol. 1, p. 37.
- ⁵S.M. Kaye et al., J. Nucl. Mater. 121, 115 (1984).
- ⁶M. Nagami et al., Nucl. Fusion 24, 183 (1984).
- ⁷M. Shimada et al., J. Nucl. Mater. 128/129, 340 (1984).
- ⁸E. R. Muller, G. Janeschitz, P. Smeulders, and G. Fussmann, Nucl. Fusion 27, 1817 (1987).
- ⁹K. Burrell et al. Phys. Rev. Lett. 59, 1432 (1987).
- ¹⁰A. Tanga et al., Nucl. Fusion 27, 1877 (1987).
- ¹¹G.L. Jahns et al., Nucl. Fusion 22, 1049 (1982).
- ¹²F.H. Seguin, R. Petrasso, and E.S. Marmor, Phys. Rev. Lett. 51, 455 (1983).
- ¹³K. Ida, R.J. Fonck, S. Sesnic, and B. LeBlanc, Plasma Phys. and Controlled Fusion 28, 879 (1986).
- ¹⁴R.C. Isler et al., Phys. Rev. Lett. 47, 649 (1981).
- ¹⁵R.C. Isler et al., Nucl. Fusion 23, 1017 (1983).
- ¹⁶S. Suckewer et al., Nucl. Fusion 24, 815 (1984).
- ¹⁷B. C. Stratton et al., J. Nucl. Mater. 145/147, 587 (1987).
- ¹⁸R.S. Isler, W.L. Rowan, and W.L. Hodge, Phys. Rev. Lett. 55, 2413 (1985).
- ¹⁹W.M. Stacey and D.J. Sigmar, Nucl. Fusion 19, 1665 (1979).

- ²⁰K. L. Wong and C. Z. Cheng, Phys. Rev. Lett. 59, 2643 (1987).
- ²¹M. Okabayashi et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 10th Int. Conf. London, 1984) (IAEA, Vienna, 1985) Vol. I, 229.
- ²²R.J. Fonck, A.T. Ramsey, and R.V. Yelle, Appl. Opt. 21, 2115 (1982).
- ²³B.C. Stratton, R.J. Fonck, K. Ida, K.P. Jaehnig, and A.T. Ramsey, Rev. Sci. Instrum. 57, 2043 (1986).
- ²⁴E. Hinnov and F.W. Hoffman, J. Opt. Soc. Am. 53, 1259 (1963).
- ²⁵R.J. Fonck, Rev. Sci. Instrum. 56, 885 (1985).
- ²⁶E.H. Silver et al., Rev. Sci. Instrum. 53, 1198 (1982).
- ²⁷K.P. Jaehnig, R.J. Fonck, K. Ida, and E.T. Powell, Rev. Sci. Instrum. 56, 865 (1985).
- ²⁸R.A. Hulse, Nucl. Technol. Fusion 3, 259 (1983).
- ²⁹K. Kadota, M. Otsuka, and J. Fijita, Nucl. Fusion 20, 209 (1980).
- ³⁰T. Kato and H. Narum, Nagoya University Institute of Plasma Physics Report IPPJ-AM-6 (1978).
- ³¹R. Mewe, Astron. Astrophys. 59, 275 (1977).
- ³²K. Ida, R.J. Fonck, S. Sesnic, R.A. Hulse, and B. LeBlanc, Phys. Rev. Lett. 58, 116 (1987).
- ³³S. S. Sesnic et al., J. Nucl. Mater. 145/147, 580 (1987).
- ³⁴B.B. Kadomtsev, Sov. J. Plasma Phys. 5, 389 (1975).
- ³⁵N. C. Hawkes et al., Proc. 14th European Conf. on Controlled Fusion and Plasma Physics, Ed. F. Engelmann and J. L. Alvarez Rivos IID Part I (1987) 101.
- ³⁶S.F. Paul, R.J. Fonck, and G.L. Schmidt, J. Nucl. Mater. 145/147, 626 (1987).
- ³⁷R.J. Fonck et al. J. Nucl. Mater. 128/129, 330 (1984).

- ³⁸P.H. Rutherford et al., Princeton Plasma Physics Laboratory Report PPPL-1297 (1976).
- ³⁹K.H. Burrell and S.K. Wong, Phys. Fluids 24, 284 (1981).
- ⁴⁰K. H. Burnell, T. Ohkawa, and S. K. Wong, Phys. Rev. Lett. 47, 511 (1981).
- ⁴¹R. D. Petrasso et al., Phys. Rev. Lett. 57, 707 (1986).
- ⁴²M.E. Foord, E.S. Marmor, and J.L. Terry, Rev. Sci. Instrum. 53, 1407 (1982).
- ⁴³M. Murakami, private communications.
- ⁴⁴K.H. Burrell et al., Nucl. Fusion 21, 1009 (1981).

FIGURE CAPTIONS

- Fig. 1. Typical poloidal cross-sectional plasma shape in PBX (a) L-mode and (b) H-mode discharges.
- Fig. 2. Time evolution of the plasma (I_p) and indentation (I_{IF}) currents, line-integrated electron density, visible bremsstrahlung (VB) emission, soft X-ray (SX) emission, and H_{α} emissions, with H-mode transition at $t = 505$ ms.
- Fig. 3. Schematic diagram of diagnostics for impurity transport study on PBX, including the tangentially viewing visible bremsstrahlung spectroscopy array, the multichannel vacuum ultraviolet spectrometer (SPRED) and a 0.6 m spectrometer for the branching ratio calibration, the soft X-ray (SXR) diode array, Thomson scattering (TVTS), pulse height analyzer (PHA), bolometer array, and 1.0 m spectrometer for charge-exchange recombination (CXR) spectroscopy.
- Fig. 4. Vacuum ultraviolet (VUV) spectrum at $t = 480$ ms (a) (pre- H-mode transition) and at $t = 640$ ms (b) (post-transition). Note that the scale of the intensity in plot(a) is a factor of five times higher than in plot(b).
- Fig. 5. Time evolution of the individual impurity lines in VUV spectrum, with integration time of 20 ms for the H-mode discharge. Neutral injection occurs from 400-700 msec, as in Fig. 2.

Fig. 6. Time evolution of the visible bremsstrahlung line-integrated intensity (a) and the Abel-inverted emissivity profile (b) for an H-mode discharge.

Fig. 7. (a) Time evolution of the central Z_{eff} measured by the visible bremsstrahlung (VB) and the soft X-ray pulse height analyzer (PHA). The dashed lines show the contribution of individual impurities of $Z_{\text{eff}}(0)$ estimated from VUV spectroscopic measurements.

(b) Time evolution of the central metallic impurity concentration measured by PHA (lines with open circles) and VUV spectrometer (SPRED) (indicated symbols) coupled with calculations from the impurity transport code MIST.

Fig. 8. (a) Time evolution of the central radiated power density as measured by bolometer array (solid line) and PHA with radiated power calculations from the MIST code. The dashed line shows the estimated contribution of oxygen and carbon to the total radiation.

(b) Time evolution of the electron temperature from PHA measurements and the ion temperature from charge-exchange recombination spectroscopy.

Fig. 9. Time evolution of the visible bremsstrahlung profiles and the central Z_{eff} for discharges with no gas puff during NBI (a) and with moderate gas puff after 400 ms (b).

Fig. 10. Time evolution of the midplane H_α emissions for the H-mode plasmas with (a) gas puff (indicated by the shaded region) turned off at 400 ms and (b) gas puff extending through the neutral injection time ($\Delta t = 400-700$ ms). The L- to H-mode transition occurs at $t = 445$ ms (a) and $t = 455$ ms (b).

Fig. 11. Time evolution of the central electron density, proton density estimated from $Z_{eff}(0)$, electron temperature, and nickel concentration (measured from PHA measurements) without gas puff (a) and with moderate gas puff (b) after 400 ms.

Fig. 12. Time evolution of individual impurity lines for the discharges in Fig. 9 through Fig. 11. The intensity scales for the two cases [(a): no gas puff; (b): moderate gas puff] are the same.

Fig. 13. Time evolution of the central Z_{eff} for the discharges with (a) H-mode impurity accumulation case; (b) H-mode impurity non-accumulation case; (c) L-mode impurity accumulation case. (d) L-mode impurity non-accumulation case. The times of the Thomson scattering laser firing are also shown for each case and marked by TVTS.

Fig. 14. Electron temperature and density profiles measured by TVTS for the discharges in 13(a-d).

Fig. 15. Z_{eff} profile at the time of TVTS firing for the four discharges in 13(a) - (d). Solid and dashed lines show the calculated profile with the MIST transport code for the indicated c_v values.

Fig. 16. Radiation profiles measured by bolometer and estimated from PHA measurements coupled with coronal equilibrium radiative loss estimates for the discharges in Fig. 13(a-d). The closed circles and triangles stand for the radiation in H-mode and open circles and triangles stand for that in L-mode. The solid lines in (a) and (c) show the MIST results for $c_v = 10, 20$, and 40 .

Fig. 17. Effective impurity density $n_z^{\text{eff}} [(Z_{\text{eff}}-1)n_e]$ and Z_{eff} profile for the L-mode impurity accumulative discharge in Figs. 14(c), 15(c) and 16(c). $t = 640$ ms. The solid lines are the results of a simple Gaussian (power to c_z) fitting to the n_z^{eff} profile. The dashed lines are MIST calculations for $c_v = 4, 5$, and the best-fit value from the MIST code was $c_v = 4.7$.

Fig. 18. Impurity profile peaking parameter c_z and normalized peaking parameter c_N vs. central $Z_{\text{eff}}(0)$ for L-mode (open circles) and H-mode (closed circles) discharges. The plots include data from discharges with two perpendicular (21), one perpendicular and one tangential (111), and 3 beams (211) and 4 beams (212) cases.

Fig. 19. Peaking parameter C_z calculated from neoclassical transport. the range of PBX data is indicated by the dashed boundary. The solid lines are model calculations from neoclassical fluxes including contribution from both the base plasma ions and impurity terms with the ratio of the central impurity concentrations to be Ni:Fe:O:C = 2:1:30:30 for nickel, iron, oxygen, and carbon.

Fig. 20. Peaking parameter c_z (open and circles) and c_v (shaded area) for data from various tokamak experiments as a function of the central Z_{eff} .

Figure 1

Figure 2

#85X1813

Figure 3

Figure 4

#85X1825

Figure 5

Figure 6

Figure 7

#88X0571

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 13

Fig. 19

Figure 20

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Plasma Research Lab., Australian Nat. Univ., AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. M. Heindler, Institut für Theoretische Physik, AUSTRIA
 M. Goossens, Astronomisch Instituut, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Commission-European, Dg-XII Fusion Prog, BELGIUM
 Prof. R. Boucique, Laboratorium voor Natuurkunde, BELGIUM
 Dr. P.H. Sakanaka, Instituto Fisica, BRAZIL
 Instituto De Pesquisas Espaciais-INPE, BRAZIL
 Documents Office, Atomic Energy of Canada Limited, CANADA
 Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
 Dr. H.M. Skarsgard, University of Saskatchewan, CANADA
 Dr. H. Barnard, University of British Columbia, CANADA
 Prof. J. Teichmann, Univ. of Montreal, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. C.R. James, Univ. of Alberta, CANADA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 The Librarian, Rutherford Appleton Laboratory, ENGLAND
 Mrs. S.A. Hutchinson, JET Library, ENGLAND
 C. Mouttet, Lab. de Physique des Milieux Ionisés, FRANCE
 J. Radet, CEN/CADARACHE - Bat 506, FRANCE
 Univ. of Ioannina, Library of Physics Dept. GREECE
 Dr. Tom Muai, Academy Bibliographic Ser., HONG KONG
 Preprint Library, Hungarian Academy of Sciences, HUNGARY
 Dr. B. Dasgupta, Saha Inst of Nucl. Phys., INDIA
 Dr. P. Kaw, Institute for Plasma Research, INDIA
 Dr. Philip Rosenau, Israel Inst. Tech, ISRAEL
 Librarian, Int'l Ctr Theo Phys, ITALY
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Miss Clelia De Palo, Assoc EURATOM-ENEA, ITALY
 Biblioteca, Instituto di Fisica del Plasma, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Prof. I. Kawakami, Atomic Energy Res. Institute, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Direc. Dept. Large Tokamak Res. JAERI, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. S. Tanaka, Kyoto University, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Nobuyuki Inoue, University of Tokyo, JAPAN
 S. Mori, JAERI, JAPAN
 Librarian, Korea Advanced Energy Res. Institute, KOREA
 Prof. D.I. Choi, Adv. Inst Sci & Tech, KOREA
 Prof. B.S. Lilley, University of Waikato, NEW ZEALAND
 Institute of Plasma Physics, PEOPLE'S REPUBLIC OF CHINA
 Librarian, Institute of Phys., PEOPLE'S REPUBLIC OF CHINA
 Library, Tsing Hua University, PEOPLE'S REPUBLIC OF CHINA
 Z. Li, Southwest Inst. Physics, PEOPLE'S REPUBLIC OF CHINA
 Prof. J.A.C. Cabral, Inst Superior Tecnico, PORTUGAL
 Dr. Octavian Petrus, AL I CUZA University, ROMANIA
 Dr. Johan de Villiers, Fusion Studies, AEC, SO AFRICA
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 C.I.E.M.A.F., Fusion Div. Library, SPAIN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Centre Phys des Plasmas, Ecole Polytech Fed, SWITZERLAND
 Bibliotheek, Fom-Inst voor Plasma-Fysica, THE NETHERLANDS
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electrophysical Apparatus, USSR
 Dr. V.T. Tolok, Inst. Phys. Tech. USSR
 Dr. L.M. Kovrizhnykh, Institute Gen. Physics, USSR
 Nuclear Res. Establishment, Julich Ltd., W. GERMANY
 Bibliothek, Inst. für Plasmaforschung, W. GERMANY
 Dr. K. Schindler, Ruhr Universität Bochum, W. GERMANY
 ASDEX Reading Rm, IPP/Max-Planck-Institut für
 Plasmaphysik, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Prof. R.K. Jansev, Inst Phys, YUGOSLAVIA

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.