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OBSERVATION OF IMPURITY ACCUMULATION AND
CONCURRENT IMPURITY INFLUX IN PBX

By

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OBSERVATION OF IMPURITY ACCUMULATION AND CONCURRENT
IMPURITY INFLUX IN PBX

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ABSTRACT

Impurity studies in L- and H-mode discharges in PBX have shown that both types of discharges can evolve into either an impurity accumulative or nonaccumulative case. In a typical accumulative discharge, Zeff peaks in the center to values of about 5. The central metallic densities can be high, $n_{\text{met}}/n_e \approx 0.01$, resulting in central radiated power densities in excess of 1 W/cm^3 , consistent with bolometric estimates. The radial profiles of metals obtained independently from the line radiation in the soft X-ray and the VUV regions are very peaked. Concurrent with the peaking, an increase in the impurity influx coming from the edge of the plasma is observed. At the beginning of the accumulation phase the inward particle flux for titanium has values of 6×10^{10} and 10×10^{10} particles/cm²s at minor radii of 6 and 17 cm. At the end of the accumulation phase, this particle flux is strongly increased to values of 3×10^{12} and 1×10^{12} particles/cm²s. This increased flux is mainly due to influx from the edge of the plasma and to a lesser extent due to increased convective transport. Using the measured particle flux, an estimate of the diffusion coefficient D and the convective velocity v is obtained.

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MASTER

I. Introduction

Impurity studies in a tokamak plasma continue to be an integral component of general tokamak investigations for several reasons. For example, radiation losses can impair the confinement and stability of plasmas, and the hydrogen concentration can be diluted by significant impurity densities, resulting in a lower fusion rate. A considerable amount of effort has been expended in studying various facets of tokamak impurity behavior, as described in the excellent review on impurities in tokamaks by R.C. Isler [1]. In this paper we are concerned with one small part of the more general impurity problem: with the flux, accumulation, and transport of metallic impurities in neutral-beam-heated plasmas. The general feature of impurity accumulation in ohmically heated plasmas, including the facts that accumulation can be prevented by high gas puff rates, only medium-Z impurities appear to accumulate strongly, and sawtooth oscillations can mitigate effects of accumulation by redistribution of the centrally peaked impurities, were all reported in the seminal work on high density plasmas in the Pulsator tokamak - [2]. Most recently, in ASDEX burst-free H-mode discharges a strong accumulation of iron in the center of the plasma was observed [3]. At the same time, impurity accumulation, sawtooth-driven redistribution and transport coefficient measurements have received considerable attention in ohmic- and neutral-beam-heated PBX discharges [4 - 6], while accumulation and subsequent sawtooth redistribution have been studied in the Alcator-C experiment during silicon injection [7] and pellet fuelling experiments [8]. Even when the steady-state phase of large tokamak discharges does not show strong accumulation, the discharge is usually observed to display accumulation and strong MHD activity early in the discharge, leading to a giant sawtooth crash with pumpout of the peaked impurities at the onset of regular sawteeth

[4,9]. This wide variety of effects and often conflicting results from different experiments point to the continuing importance of the study of impurity transport in tokamaks.

As reported in detail elsewhere [5, 6], PBX discharges often display strong accumulation of impurities in the discharge center. In this paper, we discuss evidence for an increased impurity influx leading to the accumulation phase, and show that a novel analysis of radially resolved soft X-ray spectra support the earlier conclusions of low transport coefficients in the discharge center [5]. Section II of this paper describes the experimental conditions and the diagnostics utilized in these studies. In the third part, we discuss the medium-Z impurity influx and accumulation in neutral-beam-heated H-mode discharges in PBX, while Sec. IV presents an analysis of impurity transport in an accumulating discharge.

II. Description of Experiment and Diagnostics

The Princeton Beta Experiment (PBX) is a neutral-beam-heated tokamak experiment devoted primarily to investigations of high beta plasmas. To facilitate the achievement of high β , the discharge cross section has a kidney bean shape, which is produced by an additional current-carrying "pusher" coil located on the inside midplane of the vacuum chamber [10]. To improve the axisymmetric stability of the discharge, the plasma is surrounded by nickel-plated aluminum plates, which results in nickel being the predominant metallic impurity in the plasma. Depending on the position of the X-point of the separatrix, the beam-heated discharge had characteristics of either an L-mode (X-point outside the conducting wall) or an H-mode (X-point inside the conducting wall) plasma. The minor and major radii varied between 30 to 37 cm and 143 to 153 cm, respectively. The indentation varied between 0 and 0.2 and

elongation from 1 to 1.8. The toroidal magnetic field was relatively low (0.8 to 2.0 T), and the plasma current had values between 250 and 600 kA. Although the primary objective of PBX was the study of the high β regime, an effort was made to understand impurity transport, since impurity fluxes and content very often impaired the sustainment of high β investigations.

PBX was also well suited for impurity transport studies because it had a comprehensive set of diagnostics appropriate for impurity investigation. A multichannel visible bremsstrahlung detector array provided time-resolved Z_{eff} profiles. SPRED, a multichannel VUV spectrometer, yielded absolute intensities of various impurity lines simultaneously, covering the wavelength region between 95 Å to 1100 Å with two different diffraction gratings. It was used to measure the impurity influx (lower charge states) and impurity densities (higher charge states) with a time resolution of 20 ms. Two multichannel bolometer arrays provided radiation profiles [11]. Five spatial channels of soft X-ray pulse-height analyzers (PHA), two of which were also scannable in minor radius, were used to obtain profiles of the electron temperature $T_e(r,t)$, $Z_{eff}(r,t)$, and the metallic impurity densities, $n_Z(r,t)$, with a variable time resolution which was usually set at 25 ms in these investigations. Vertical and horizontal multichannel soft X-ray diode arrays, normally used for MHD studies, provided additional measures of the impurity influx and accumulation. Detailed observation of impurity behavior in PBX from these and other diagnostics are reported elsewhere [5, 6] and we concentrate here mainly on information obtained by additional analysis of the data from the soft X-ray diagnostics.

III. Impurity Influx, Accumulation, and Consequent Thermal Collapse

The discharges considered here had a plasma current of 300 kA, an indentation of ≈ 0.1 , central elongation of ≈ 1.33 , and a working gas of either H or D heated with D⁰ neutral beams with $P_{inj} \approx 2 - 5$ MW. Depending on the positioning of the X-point, these discharges accessed either L-mode or H-mode confinement operating regimes [10] and both types of impurity behavior - accumulation or no accumulation - occurred in both L-mode and H-mode discharges [6]. The emphasis in this paper is on the H-mode accumulation case, because the transport can be most readily analyzed in this case. Such discharges were characterized by a thermal collapse of the central plasma, preceded by strong medium-Z impurity influx and accumulation. Some of the plasma parameters for an H-mode discharge with accumulation are shown in Fig. 1. Note that although the density is steadily rising, the central value of the total $Z_{eff}(0)$ and the metal contribution to $Z_{eff}(0)$, $Z_{eff,met}(0)$, is also rising. During this entire time, the density profiles obtained from Thomson scattering are flat over most of the discharge. The metallic contribution to Z_{eff} begins to increase at approximately 560 ms, about 50 to 60 ms after the onset of the H-mode; at first it is negligible ($Z_{eff,met} \approx 0.2$), but it then rather quickly reaches the final value of over 2.6. The very last point in $Z_{eff,met}$ and Z_{eff} necessarily contains a large uncertainty due to the low kT_e values, and the actual values are most probably smaller than indicated. Simultaneous with the increase in $Z_{eff,met}(0)$ and the increase in density, we observe a steep decrease in electron temperature which drops from 1.2 keV to 0.55 keV and is more than expected from the density increase. We ascribe this drop in temperature to the accumulation of the metals in the center of the discharge and the resulting radiation collapse in the center. Very similar nonaccumulating discharges, with a similar increase

in density, do not show this decrease in electron temperature. The indication that this is a thermal collapse due to excessive impurity radiation comes from direct bolometric measurements [11] and estimates of the time-evolving central radiation density derived from the PHA measurements of all major metallic impurities (Ni, Fe, Cr, and Ti) coupled with coronal equilibrium cooling rates [12]. Both measurements indicate central radiation losses of $1 - 5 \text{ W/cm}^3$, which is comparable to or larger than the local electron heating power. Radiation losses due to central low-Z impurities, derived from PHA soft X-ray continuum measurements, are much smaller and increase more slowly in time, confirming that the accumulation of low-Z impurities is less severe [5].

That the impurity accumulation phase in the discharge is preceded by the impurity influx from the outside is clearly seen in Fig. 2, where the soft X-ray diode enhancement factor ξ is plotted against an expanded time scale and for a range of the diode tangency heights z ($z = \epsilon r$, ϵ is the elongation). These data shown were obtained from the vertically scanning soft X-ray diode array. The enhancement factor ξ is defined as a ratio of the diode signal to the signal of the same diode if the plasma was purely hydrogen:

$$\xi(z, t) = \frac{U_D(z, t)}{\int dl \int dE \cdot \epsilon_H(E, 1) \cdot F(E) \cdot R(E)} \quad (1)$$

Here $U_D(z, t)$ is the measured diode signal. It represents the continuum and the line radiation (mostly L-lines) from metallic impurities. The part of ξ which comes from the continuum radiation is equivalent to the usual PHA enhancement factor ξ [13]. ϵ_H is the hydrogen bremsstrahlung emissivity, $F(E)$ is the transmission function of the filter in front of the diode, $R(E)$ is the response function of the diode including the diode/plasma geometry, E is the photon energy, and $\int dl$ is the line of sight integral. The arrows in Fig. 2

show the times of the onset of the increase in signal due to the increasing influx. It takes about 20 ms for the impurities from $z = 30$ cm to reach the center of the discharge and indicates a surge in the medium-Z impurity influx before the onset of accumulation. A similar increase in influx is seen in the SPRED VUV lines for lower ionization states of metallic impurities [6], but without spatial resolution.

Very soon after the increased influx has propagated from the outer diodes toward the central diodes, one observes an almost simultaneous increase of radiation over the whole profile, followed by a peaking of the profile. This is seen quite clearly in Fig. 3, where the diode enhancement factor ξ is plotted against the radial position (or height) for various times. The central enhancement factor increases by a factor of 50, whereas at $z = 30$ ξ increases only by a factor of 4, indicating a very strong central peaking of metallic impurities. The ξ profiles are considerably broader than the spatially resolved n_{Ti} profile measurements from the PHA (shown in Fig. 4) because they are strongly weighted by a lower energy continuum radiation, which has broader profiles than the titanium K_{α} - line radiation at the relatively high energy of 4.5 keV or n_{Ti} itself. In addition, the profiles are broadened by strong metallic L-line radiation, which radiate at rather low energy and therefore have a radiation peak in a shell somewhat off the center of the discharge. The titanium central density increases during the influx and accumulation phase by a factor of 100 but the increase at $z = 30$ cm is much smaller (only a factor of 10). The n_{Ti} profiles of Fig. 4 are obtained from the PHA measurements, but a similar peaking and enhancement of the central medium-Z impurity density is seen by SPRED and the bolometer radiation profiles. The bolometer radiation profiles and their absolute intensity in the plasma core agree quantitatively very well with the metallic impurity

profiles (titanium, chrome, iron, and nickel) obtained from the soft X-ray PHA and VUV measurements [5, 11]. Note also, that the n_{Ti} profiles of Fig. 4 additionally support the claim that most of the n_{Ti} increase is due to influx from the edge of the plasma. By comparing n_{Ti} profiles at 0.51 s and 0.69 s, one can easily show that most of the titanium increase inside the minor radius of 22.5 cm can only come via the influx from the edge ($r \geq a$) and not via influx from the region between 22.5 cm and $a \approx 32$ cm by profile rearrangement alone. Otherwise, we would have to postulate an unrealistic, very high density titanium shell between 22.5 cm and the edge of the plasma to account for the observed increase in the core region.

Almost an identical H-mode discharge, having the same electron density, beam power, and plasma current, can occur without any accumulation by careful tailoring of the gas feed and other discharge parameters. In that case there is no significant medium-Z influx, and the metallic impurity density and the ξ factor stay at the level of $t = 0.56$ s of Fig. 4. The only difference between these two discharges is that the Z_{eff} at the onset of neutral beam injection is somewhat higher in the accumulation case. This dependence of the accumulation on Z_{eff} and its control by gas puffing is fully described in other papers [5 - 6]. There it has been shown that the impurity coefficient is proportional to the Z_{eff} value at the center of the discharge and that a small increase in gas puffing can prevent the central accumulation by lowering the impurity influx and $Z_{eff}(0)$.

IV. Impurity Transport Analysis Utilizing PHA Data

If the spatial and temporal variation of the density of a particular impurity ion species is known in detail, it is then straightforward to find the temporal and spatial behavior of the particle flux for the case of

toroidal and poloidal symmetry. We have already shown measurements of such densities utilizing soft X-ray PHA for the four most common, medium-Z PBX plasma impurities: titanium, chrome, iron, and nickel. In this section we show how to obtain the impurity flux from the PHA density measurements and, having the flux and assuming that in the most general case it contains a diffusive and a convective term, how to get the diffusion and convection coefficients.

We start with a continuity equation for a single impurity in the source-free plasma core

$$\partial n / \partial t + \nabla \cdot \Gamma = 0, \quad (2)$$

where $n = \sum_q n_q$ is the impurity density and $\Gamma = \sum_q \Gamma_q$ is the impurity flux, n_q is the ion density of charge state q , and Γ_q is the flux of ions of charge state q .

If Γ is assumed to be constant on nested circular cross-sectional toroidal surfaces of minor radius r , the volume integration of Eq. 2 over the nested toroidal volume with minor radius r yields the particle flux

$$\Gamma(r, t) = -1/r \partial / \partial t \left(\int n(r, t) r dr \right). \quad (3)$$

When the impurity density $n(r, t)$ is measured, we can obtain the impurity particle flux Γ by utilizing Eq. (3). This flux can be either diffusive or convective, and in the most general case we assume that it contains both terms:

$$\Gamma(r, t) = -D(r, t) \nabla n(r, t) + v(r, t) n(r, t), \quad (4)$$

where D and v represent an unknown diffusion coefficient and convective velocity, respectively, which for simplicity we assume to be independent of charge state q . Thus, measurements of $n(r,t)$, $\nabla n(r,t)$, and $\Gamma(r,t)$ as a function of radius (or time) allow evaluation of the local values of D and v as a function of time (or radius). That is, the simultaneous equations

$$\Gamma_1 = -D \nabla n_1 + v n_1$$

$$\Gamma_2 = -D \nabla n_2 + v n_2, \quad (5)$$

where 1 and 2 denote n , ∇n and Γ values at either r_1 and r_2 with $t = \text{constant}$ or t_1 and t_2 with $r = \text{constant}$ can be used to solve for the diffusion coefficient and convection speed. The explicit solutions for D and v from the two linear equations given above are:

$$D(r,t) = \frac{\frac{\Gamma_1}{n_1} - \frac{\Gamma_2}{n_2}}{\frac{\nabla n_2}{n_2} - \frac{\nabla n_1}{n_1}} \quad (6)$$

$$v(r,t) = \frac{\frac{\Gamma_1}{n_1} \frac{\nabla n_2}{n_2} - \frac{\Gamma_2}{n_2} \frac{\nabla n_1}{n_1}}{\frac{\nabla n_2}{n_2} - \frac{\nabla n_1}{n_1}}. \quad (7)$$

Comparison of the values of D and v obtained by fixing either r or t allows an evaluation of the sensitivity of the results to the spatial and temporal resolutions and uncertainties of the measurements. The advantage of this method is obvious: averaging over two measurement points provides local measurements of both D and v . Of course, substantial uncertainty can arise in

the results due to measurement errors in the density gradient ∇n . The resulting uncertainty in D and v is even higher than the relative error in ∇n since the denominator in Eqs. (6) and (7) are usually a fraction of the magnitude of the individual $\nabla n/n$ terms. An additional drawback to the use of this method for these particular data is that it can be applied only at electron temperatures high enough to observe K_{α} -line radiation. In spite of such uncertainties, this analysis approach nonetheless allows semiquantitative transport coefficients to be derived from relatively straightforward measurements. Diffusion coefficient and convective velocity profiles obtained with this method are average values, averaged over a few charged states which are dominant at the particular radial position. One can, therefore, interpret these values as the local coefficients for the local average charge state.

The application of this method is demonstrated for the case of the titanium H-mode accumulation by using the data in Fig. 4. To get the particle flux the data of Fig. 4 were smoothed both in time and radius. The radial dependence is represented by a smooth Gaussian profile: through two measured points at a fixed time to allow evaluation of Γ and ∇n . Because we have only three measured points in r , we use two Gaussians and fit the first from $r = 0$ to $r = 11.3$ cm and the second from $r = 11.3$ cm to $r = 22.6$ cm. This fitting results with a break point at 11.3 cm, where the density gradient is discontinuous in the model profiles. The particle flux obtained by this fitting of the titanium density data in Fig. 4 is shown in Fig. 5. The rate of increase of the titanium flux is higher near the center of the discharge, but starts to show some saturation effect late in time. Further out in the discharge, this flux increase is slower and the last point even shows a decrease in inward flux, which is an indication that the influx is slowed but that the central accumulation still persists. The two curves for 11.3 cm are

obtained from the two different Gaussians valid for the point at $r = 11.3$ cm. The difference between these two curves is the indication of the error introduced by the modelled discontinuity at 11.3 cm.

Using the titanium flux results of Fig. 5 and Eqs. (6) and (7), the values for D and v can be obtained for three radial positions ($r = 6, 11$, and 17 cm) and as a function of time. Because n_{Ti} is measured at only three radial positions in this first experiment, the errors in $n_{Ti}(r)$ are large and the knowledge of the local values of the density gradients is even poorer, resulting in very large uncertainties in D and v . Moreover, there are other, but probably weaker sources for errors in $n_{Ti}(r,t)$ evaluation: Abel inversion, poorly known elongation in the central part of the plasma, and possible poloidal asymmetries. Nevertheless, the trends in the radial and the temporal behavior of D and v can be established. The values of D near the center ($r = 6$ cm) is rather low, of the order of $500 \text{ cm}^2/\text{s}$, and around $2000 \text{ cm}^2/\text{s}$ further out at $r = 17$ cm. The inward convective velocity is also a function of radius; near the center its value lies between -100 and -200 cm/s and around -800 cm/s outside at $r = 17$ cm. The convective velocity seems to increase faster than linearly with radius. To investigate the sensitivity of these results to model assumptions we have used several other fitting procedures, (e.g. single Gaussian), and have found that the resulting values of D and v are indeed somewhat different but again the diffusion coefficient is of the order of $1,000 \text{ cm}^2/\text{s}$, while the convective velocity scales faster than linearly with radius and has values of a hundred to several thousands cm^2/s , depending again on the radial position. These values are in a very good agreement with Ida's values [5] obtained earlier for the same discharges and utilizing spectroscopic VUV measurements and a time-dependent one-dimensional transport code (MIST) [14]. In most cases the value of the global impurity

diffusion coefficient in a tokamak discharge has been found to be substantially higher - about $10,000 \text{ cm}^2/\text{s}$ - and only in a few accumulating cases does one find lower values [1, 2, 5, 7]. For these accumulating H-mode discharges in PBX Ida et al. [5] have shown that these coefficients are not inconsistent with simple neoclassical values [5, 6], and these results indicate that the main driving term for the inward convection is the impurity-impurity collisions.

This leads to an interesting speculation that other cases of impurity accumulation, such as discharges with counter neutral beam injection, may be due more to the increased impurity influx driven by counter injection [15], which in turn induces accumulation, than to rotation effects themselves. In any case, the present studies on PBX emphasize the need for simultaneous detailed evaluation of all impurity species in a given discharge to even begin to determine relevant dynamic processes, even in the case where nonclassical transport appears to be negligible.

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Figure Captions

Fig. 1. Accumulation and thermal collapse: Time development of the electron temperature, kT_e , at three vertical positions ($z = 0, 15$, and 30 cm), central electron density, n_{e0} , central Z_{eff} and $Z_{eff,met}$ (contribution of metallic impurities to Z_{eff}). Shaded area indicates staggered firing of three neutral beams.

Fig. 2. Particle influx: Time evolution of the Si-diode enhancement factor at different vertical tangency heights z . The enhancement starts to rise outside ($z = 30$ cm) and propagates inward (arrows) in about 20 ms. The enhancement factor ξ represents the degree of impurity contamination of the plasma. For pure hydrogen plasma $\xi = 1$. The dashed lines separate the vertical scales for different diode tangency heights z . S.T. denotes a sawtooth.

Fig. 3. Accumulation: Time evolution of the Si-diode enhancement profile. Peaking starts slightly before 0.59 s.

Fig. 4. Titanium accumulation: Time development of the titanium density profile as measured by the soft X-ray PHA. Double values at 0.51 and 0.54 s indicate the uncertainty of n_{Ti} measurement at early times. Measurements were made at $z = 0, 15$, and 30 cm (corresponding to $r = 0, 11.3$, and 22.6 cm with plasma edge at $a = 32$ cm). z is the vertical and r the horizontal coordinate of the bean shaped plasma. PHA measurement of n_{Ti} beyond $r = 22.5$ cm is not possible because the electron temperature is too low to excite the titanium K_α lines.

Fig. 5. Time evolution of the titanium particle flux for three radial positions. Two gaussians are used to describe titanium density profiles up to and beyond $r = 11.3$ cm resulting in a double value at 11.3 cm. Each curve is labelled by the radial zone used in the model. 1 indicates $r = 0$ to 11.3 cm and 2 indicates $r = 11.3$ to 22.6 cm.

Fig. 1

Fig. 2

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Fig. 3

Fig. 4

Fig. 5

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