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Impurity Behavior During Neutral Beam Injection and Gas Puffing into ORMAK

R. C. Isler
E. C. Crume
H. C. Howe

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FUSION ENERGY DIVISION

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AND GAS PUFFING INTO ORMAK

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ABSTRACT

Variations of the intensities of spectral lines are utilized to determine the extent to which the impurity concentrations of ORMAK-produced plasmas are altered by neutral beam injection and, in some cases, by the simultaneous introduction of a puff of hydrogen. Concurrent variations of oxygen emissions resulting from alterations in the profiles of electron temperatures and concentrations are taken into account through solving the coupled continuity equations of the several ionic species of this element. Ad hoc transport velocities are utilized and a complete recycling model is assumed.

I. INTRODUCTION

Unless the concentrations of impurity ions are minimized in tokamaks, serious obstacles may arise for the development of these devices into efficient fusion reactors. Of particular interest at the present time are questions concerning the influence exerted on impurities by supplementary heating and by fueling. In this paper we describe and analyze observations of impurity radiation for several experiments on ORMAK in which neutral beam injection was used to heat the plasma. Almost all of these observations concerned coinjection; i.e., the neutral beam current was in the same direction as the plasma current. Only a few results are available for the counter-injection experiments. During the investigations hydrogen gas was puffed into the plasma in some cases to maintain a constant electron density or in other cases to achieve the highest possible density during injection.

As a prelude to discussing these experiments we briefly outline the typical impurity composition and the spectral characteristics of ORMAK-produced plasmas. Figure 1 illustrates a densitometer trace of a photographed spectrum in the region from 20-170 $\text{\AA}$. Most of the prominent spectral lines can be identified with ions of oxygen and iron. The most intense lines are the first resonance transitions of O VII and O VIII, but the response of the ruled grating used to obtain this spectrum decreases rapidly at the low wavelength end of the range so that these lines appear disproportionately weak. A more detailed spectrum of this region has been obtained using a holographic grating which is more efficient than the ruled grating below 40 $\text{\AA}$, and a densitometer trace is shown in Fig. 2. Several lines from O VII and O VIII

can be identified, and lines of Fe XVII-XX are clearly visible.

Most of the power radiated in the wavelength region shown in Fig. 1 appears in pseudocontinua between about $25 \text{ \AA}$ and $70 \text{ \AA}$ (the second and third orders of these pseudocontinua account for the strong features above $70 \text{ \AA}$). Although the three prominent features had been observed almost from the beginning of the operation of ORMAK [1], they have only recently been identified with unresolved $4f \rightarrow 4d$ and $4d \rightarrow 4p$ transitions of highly ionized tungsten [2,3] (perhaps with some contribution from gold). The narrow band between 25 and $40 \text{ \AA}$ can also be assigned to single-electron transitions ($n=5 \rightarrow n=4$) of tungsten. It appears disproportionately weak in Fig. 1 due to the aforementioned decrease of the grating sensitivity, but may, in fact, account for as much as 25% of the power radiated in the tungsten pseudocontinuum. It is uncertain whether the tungsten enters the plasma directly from the limiter or from the walls where a thin layer of this metal has been deposited during the operation of the machine.

Although spectral lines from elements other than oxygen, iron, and tungsten are observed in ORMAK-produced plasmas, these three species are respectively the dominant light, medium, and heavy impurities. The largest contribution to $\langle Z_{\text{eff}} \rangle$, which has values between 3 and 8, is from oxygen; tungsten and iron contributions to $\langle Z_{\text{eff}} \rangle$ are calculated to be less than 0.5 from estimates that these impurities exist respectively in concentrations of the order of $10^{10}/\text{cm}^3$ and $10^9/\text{cm}^3$. Oxygen and tungsten together usually account for about 90% of the radiated power. Although the iron lines are prominent in the spectrum they only account for approximately 5% of the radiated losses.

Under a wide variety of operating conditions it has been determined that 60% of the input power is lost as radiation to the walls [4]. Whether the

dominant radiative losses are due to oxygen or to tungsten depends upon the mode of discharge cleaning employed prior to beginning normal tokamak discharges. If hydrogen is used as the only working gas during discharge cleaning, the radiation from the tungsten comprises as much as 75% of the total radiated power. However, if oxygen is employed as a discharge-cleaning gas, even though a change to hydrogen discharge cleaning is always made one hour before firing normal tokamak discharges, the oxygen content remains high enough that oxygen lines account for 50-60% of the radiative losses, whereas the tungsten accounts for 30-40%.

II. INTERPRETATION OF SPECTRAL DATA

In principle, the interpretation of impurity behavior from intensities of spectral lines is accomplished most easily if several chords can be scanned and the results inverted to provide radial profiles of the emission rates per unit volume,

$$I_v^{j,k}(r) = \sum_i n_z^i(r) n_e(r) R^{i,j} [T_e(r)] B^{j,k} \quad (1)$$

This formula is valid for coronal conditions where radiative deactivation of the excited state of a spectral line is much more probable than collisional deactivation. Here, n_z^i is the concentration of the z^{th} times ionized atom in the state i , $R^{i,j}$ is the rate coefficient for excitation by electron collisions from the state i to the excited state j , $B^{j,k}$ is the branching ratio of the transition to state k , and n_e is the electron concentration. The only states which are sufficiently populated to be included in the summation of Eq. (1) are the ground state and the metastable states of the ions. Because excitation is most probable between states of the same multiplicity, it is often sufficient to consider only a single term. Independent measurements of $n_e(r)$ and $T_e(r)$ then permit a determination of n_z^i if $I_v(r)$ is known. However, in many experiments, including all those which we report here, spatial scans are not possible and all interpretations are made from signals integrated along the line of sight of the observations. Such measurements are commonly expressed as

$$I_s^{j,k} \text{ (photons/cm}^2\text{-sec-sterad)} = \frac{1}{4\pi} \int_{-a}^a I_v^{j,k}(r) dr \quad (2)$$

where a is the minor radius of the plasma. Absolute ion densities can only be extracted from I_s by using models which specify their relative spatial distributions. Such analyses do not necessarily produce less reliable results

from low stages of ionization than do those which utilize I_V directly because ionization stages of carbon, nitrogen, and oxygen with more than two electrons are usually localized within 3 cm of the limiter where the accuracy of measurements of T_e and n_e is poor. In addition, profiles obtained from Abel inversions have limited accuracy unless the position and the internal parameters of the plasma are highly reproducible for all shots. For many purposes the integrated line intensities coupled with a plasma model for electrons and impurities can provide sufficient accuracy to interpret spectroscopic results.

A static coronal equilibrium model is not generally applicable to the analysis of line-integrated data because impurities may move through strong temperature gradients (or circulate completely out of the plasma) in times which are shorter than characteristic electron-ion recombination times. Thus, it is necessary to relate the experimental measurements to solutions of the coupled rate equations for the ions which include transport as well as ionization and recombination. These equations can be written as

$$\begin{aligned}
 \frac{dn_0}{dt} &= -S_0 n_0 n_e + \alpha_1 n_1 n_e - \frac{1}{r} \frac{d(rn_0 v_0)}{dr} \\
 \frac{dn_1}{dt} &= S_0 n_0 n_e - S_1 n_1 n_e - \alpha_1 n_1 n_e + \alpha_2 n_2 n_e - \frac{1}{r} \frac{d(rn_1 v_1)}{dr} \\
 \frac{dn_{z'}}{dt} &= S_{z'-1} n_{z'-1} n_e - \alpha_{z'} n_{z'} n_e - \frac{1}{r} \frac{d(rn_{z'} v_{z'})}{dr}
 \end{aligned} \tag{3}$$

The concentration of an ion in a given charge state is denoted by $n_{z'}$ and z' is the charge of a fully stripped ion. S and α are ionization and

recombination coefficients. The transport terms are written simply as the radial gradients of the fluxes, $n_z v_z$, for each ion species.

In general the transport velocity, v_z , is a function of r and an additional set of equations is necessary in order to determine the n 's and v 's. If the ion diffusion can be described by neoclassical theory then $v_z(r)$ depends upon the gradients of concentrations and temperatures of all ions present at the position r and the solution of a large number of coupled equations is required to obtain the ion concentrations. Such a procedure is obviously quite complex and has only recently been accomplished.

A simplified approach that has sometimes been used to obtain the v 's for substitution in Eqs. (3) when considering the diffusion of a minor impurity, utilizes the measured proton (electron) distributions and incorporates the assumption that the major impurities, such as oxygen, are distributed according to coronal-equilibrium calculations [5]. Even though coronal equilibrium does not generally exist this approach often provides a reasonable first-order solution for spectral lines emitted from the plasma.

Our present goal has been to obtain semiquantitative interpretations of the changes in the impurity content of the plasma from variations in spectral line radiation during neutral beam injection and gas puffing. Because the impurity content of the plasmas is relatively large and the distributions are not known, attempts at calculating neoclassical transport velocities for use in Eqs. (3) appear unwarranted. Instead, we calculate steady-state numerical solutions for oxygen by specifying inward radial velocities for neutral particles from the wall and inward ion velocities consistent with neoclassical transport theory for v_1 at the

edge of the plasma. The particles are then assumed to diffuse inward, to turn around at some point near the center of the plasma, and to completely recycle back to the edge. By keeping the magnitudes of rnv equal at all points for both the influx and efflux, and by specifying the distribution of the total oxygen content, the v 's are determined at all radii in the plasma. Distributions of oxygen which are independent of r or which are proportional to n_e have been investigated. Most of the calculations have employed ionization coefficients equal to one-half the values obtained by Lotz [6], for O I-O VI and equal to the full values specified by him for O VII and OV III. Recombination rates as tabulated by Mattioli [7] are used.

Analytic expressions for the electron temperatures and concentrations are assumed for the computations,

$$T_e = T_{e1} \left[1 - \left(\frac{r^2}{a^2} \right)^m \right]^n + T_{e2} \quad (4)$$

$$n_e = n_{e1} \left[1 - \left(\frac{r^2}{a^2} \right) \right] + n_{e2}. \quad (5)$$

T_{e2} and n_{e2} are the values of the electron temperature and density at the limiter radius, a ; $T_{e1} + T_{e2}$ and $n_{e1} + n_{e2}$ are the values at $r=0$. The quantities m and n are the integers chosen to allow us to investigate the effects of various temperature profiles on the relative intensities of the oxygen lines. The curves in Fig. 3 are typical of the functions which have been employed.

Before discussing the numerical results it is useful to point out some of the conclusions which can be drawn from Eqs. (3) in highly oversimplified cases. If the recombination rates are much smaller than the ionization rates, a situation which generally holds for light impurities in

the plasmas considered here, we obtain a solution for the first of Eqs. (3),

$$n_0(r) = \frac{an_0(a)}{r} \exp\left[\int_r^a \frac{S_0 n_e}{v_0} dr'\right]. \quad (6)$$

The velocity v_0 is negative for inward diffusion from the walls. If it is assumed that the neutral atoms are ionized in a narrow shell over which S_0 , R_0 , and n_e are approximately constant near $r = d$, then substitution into Eqs. (1) and (2) yields

$$I_s^0 = \frac{1}{2\pi} \frac{a}{d} n_0(a) v_0 \frac{R_0(d)}{S_0(d)} B. \quad (7)$$

The intensity in this model depends only upon the wall flux and the ratio of excitation and ionization coefficients. It is independent of n_e . It is not difficult to see that if the distribution of impurities is such that at some radius in the plasma only a single species exists, it will ionize as it diffuses inward so that an exponential decay similar to that expressed in Eq. (6) is expected. If the surface integrated inward flux remains constant then $r_z n_z v_z = an_0 v_0$ and the intensity of every spectral line depends only on the influx from the wall and the ratio of the appropriate rate coefficients. This model has sometimes lead investigators to the incorrect conclusion that increases of the electron concentration from gas puffing should not affect the intensities of the low ionization stages and that any variations of signal are reflections only of the impurity flux. But the ratio R/S can be a strong function of temperature for the intense $\Delta n=0$ transitions of many light ions. The energy required for excitation of these lines may be much lower than the ionization potential of the species so that slight changes of its location

within the electron temperature profile result in small variations of R , but in large changes of S . For a fixed temperature profile, increases in the electron concentration cause ionization of impurities to proceed faster as they move inward so that a given stage of ionization appears closer to the limiter where the value of S is decreased. Hence, the line intensity may rise even if the impurity concentration is unchanged. Moreover, there is usually an overlap in the distributions of the various ionization stages so that Eq. 7 is a poor approximation.

The only ions which might be expected to exist as a sole species of light atoms at any point in the plasma are the helium-like ions. The lithium-like ions have relatively low ionization potentials compared to the two-electron atoms; hence, at some radius in the plasma most of the lithium-like species are "burned out" at a temperature which is too low to produce significant ionization of the helium-like ions. Thus it is expected a-priori that lines radiated from O VII should be least sensitive to the electron concentration.

Although Eqs. (3) have been solved for a wide variety of profiles, neutral-particle velocities, ion velocities, rate coefficients, etc., it is not useful to present all of these results. Instead, we limit ourselves to a discussion of those parameters which appear to be most important for analyzing the experimental results discussed here; viz, the effects of changing electron concentrations and temperature profiles.

We compare the intensities of several lines for a fixed temperature profile and two different electron concentrations. The original concentrations are taken as $n_e(0) = 3 \times 10^{13}/\text{cm}^3$ and $n_e(a) = 3 \times 10^{12}/\text{cm}^3$; these values are then

doubled, and the relative line intensities are computed as shown in Table I. As expected, changes in the line intensities may occur from operations which add electrons to the plasma even though the flux of a particular impurity species remains constant. However, these changes are not linear with n_e . It can be noted from Table I that the resonance line of O VII does, indeed, exhibit the smallest dependence on n_e of any of the lines listed, although the dependence of the $\Delta n=1$ transition of O VI at $150\text{ }\overset{\text{O}}{\text{\AA}}$ is approximately the same.

Of even greater significance than the electron density in affecting the intensity of lines from low ionization stages is the temperature profile near the edges of the plasma. The results of changing the temperature profiles while holding all other parameters constant are illustrated in Figs. 4 and 5 for two values of the ion transport velocity at the edge of the plasma, 10^2 and 10^3 cm/s. The intensities for (m,n) parameters of (1,2) and (1,4) are compared to those calculated for parameters of (1,1). The higher the value of n, the smaller are the temperatures and the gradients toward the edge of the plasma. It is seen that the intensities of the lower stages of oxygen are very strongly dependent upon the temperature profiles on the outside, and any alteration of these profiles by injection or gas puffing can cause significant changes of radiated intensities even though the total oxygen flux and density are not altered. Such changes tend to be more pronounced at low transport velocities. The lines from the higher ionization stages, O VII and O VIII, are much less influenced by profile changes than are the lines from the lower stages.

III. COINJECTION EXPERIMENTS

A. Plasma Conditions: 70 kA, 15 kG, discharge cleaned with oxygen

The first experiments which we discuss are those in which neutral beams with 350 kW total power are injected into plasmas in which the ohmic heating current is maintained at 70 kA. The beam current is in the same direction as the ohmic heating current. Two cases have been studied. In the first, the oxygen discharge-cleaning technique was employed before the experiment was performed, and in the second, only hydrogen discharge cleaning was used.

Figure 6 illustrates the behavior of several spectral lines when oxygen discharge cleaning precedes the tokamak operation. The dashed lines are indicative of the radiation in absence of injection. The solid lines show the temporal evolution when the beam pulse nominally spans the period between 40 and 85 ms after the traces start. (Breakdown of the plasma occurs at 4 ms after the traces start.) Signals from the beam pulse, from O VI, and from the microwave interferometer which measures the average electron density are shown in Figure 7. The atypical behavior of the Balmer- α line of O VIII in these experiments has been discussed elsewhere as showing directly the charge exchange between H^0 and O^{8+} [8].

It is seen that immediately upon the beginning of injection there is a sharp change in the slope of the trace from the O VI line; this line is most likely produced within 3 cm of the limiter. The intensities of the other lines which are produced toward the interior of the plasma increase more slowly than does the O VI line. We infer from the results of Sect. II that the increased radiation of the oxygen lines in this particular experiment shows that the impurity concentration of the plasma has increased due to the

neutral beam injection. Temperature profile changes would affect radiation from the low stages of ionization much more than the radiation from the higher stages, but the experimental data indicate that the signals from both O VI and O VIII increase by approximately a factor of three over the noninjection levels. Also, the rise of the electron density during injection cannot account for all of the increased intensity. The value of $\bar{n}_e$ increases by a factor of 1.4 from a time just prior to injection to a time at which the line radiation is maximum. The increases of the oxygen line intensities are larger than this factor, even though there is generally less than a linear dependence upon n_e (Table I). Once the contribution of the increased electron concentration has been taken into account, it is estimated that the spectral line intensities from O VI and O VIII are indicative of increases of a factor of two in the oxygen concentration due to neutral beam injection. Because the absolute levels of the oxygen concentration in ORMAK-produced plasmas are large, $0.06-0.08 n_e$, when oxygen discharge cleaning is used to condition the vacuum vessel, a doubling of the oxygen concentration during injection implies that most of the increment of the electron concentrations results from an influx of impurities rather than hydrogen.

The signals from tungsten and iron indicate that there is also an influx of metals during injection. In particular, the intensity of the tungsten lines around $50 \text{ \AA}$ are not strongly dependent upon the temperature over a wide range of variation, and the dielectronic recombination rates should be large enough so that the distribution of ionization stages is not strongly affected by transport but is close to a coronal equilibrium distribution. As a result, the intensity of this band should depend directly

on the product of the electron and the tungsten concentrations. Once the increase of the electron concentration has been accounted for, the intensity in the pseudocontinuum also implies an increase of a factor of two in the tungsten concentration during injection.

After the neutral beam injection stops the oxygen and tungsten concentrations decay back toward the levels they would have without injection. The characteristic time to drop halfway to this level is of the order of 10 ms, which is also the typical time for the fast trapped ions from the beam to thermalize. However, the concentration of iron does not appear to decrease so rapidly after injection ceases. If it is assumed that the O VII and the tungsten radiation emanate from a region which lies at about half of the minor radius, say 12 cm, then the rates of rise and decay of the radiation indicate that both the oxygen and tungsten are transported in the plasma at velocities of at least 5×10^2 cm/sec.

B. Plasma Conditions: 70 kA, 15 kG, discharge cleaned with hydrogen

The experiment described in the preceding section (III A) was repeated for a set of tokamak discharges prior to which the vacuum vessel was prepared by discharge cleaning exclusively with hydrogen rather than oxygen. All of the controlled parameters — current, toroidal field, neutral-beam power and timing — were kept at the same values for the two investigations. However, one significant difference between the two investigations was the necessity to introduce a puff of hydrogen at 20 msec after breakdown in order to keep the electron concentration from decaying too rapidly in the experiments performed after discharge cleaning with hydrogen. The gas was continuously bled into the discharge until

60 msec; the neutral beam injection was initiated at 40 msec and terminated at 80 msec. A large increase of the electron temperature was observed during injection [9]. Figures 8 and 9 illustrate the evolution of the electron concentration and temperature during these shots.

Signals from lines of oxygen, tungsten, and iron are shown in Figure 10. The concentration of oxygen is reduced by a factor of three as a result of switching from oxygen to hydrogen in the discharge-cleaning process, with the consequence that the background, presumably due to radiation from tungsten, constitutes a significant fraction of the signal in the neighborhood of the resonance lines of O VII and O VIII. In Figure 10 the background radiation at $20.1 \text{ \AA}$ is shown from comparison with the intensity at $18.97 \text{ \AA}$, and the actual signal from the oxygen line is the difference of the two traces.

The rapid changes of electron concentrations and temperatures and the influence of the gas puff all contribute to uncertainties of interpreting the effect of injection upon the impurities. Until 20 msec after breakdown, when the gas feed is begun, the intensities of the lines from oxygen evolve in the usual manner; i.e., an onset in the radiation from O VI starting at 3 msec followed by rapid peaking and a "burnthrough" phase as the electron temperature rises. The resonance line of O VIII appears at 10 msec. The gas puff, which is introduced at 20 msec when the central electron temperature is 300 eV, exerts a markedly different influence upon the two oxygen lines. It is seen in Figure 10 that the intensity of the O VIII line decreases until it is not distinguishable above the background whereas the "burnthrough" phase of the O VI line is arrested and its intensity rises. Signals from the intermediate

ionization stages of tungsten and iron which, like O VIII, are produced toward the interior of the plasma rather than in the periphery also decrease as a result of bleeding hydrogen into the discharge.

It is not possible to interpret with confidence the spectroscopic data from the early part of the discharge, primarily because of the uncertainty of the central electron temperature. The best fits to the data obtained from a Thomson-scattered laser beam indicate that this temperature is near 300 eV at both 22 and 35 msec, but the uncertainty is $\pm 25\%$. If $T_e(0)$ is actually as low as 225 eV before the puff is introduced, then subsequent changes could exert a strong influence on the intensity of the O VIII line (and perhaps upon the tungsten lines). Thus cooling of even some tens of electron volts could result in almost complete extinction of the O VIII radiation and account for the observed behavior. The Fe XVI line would not be affected as strongly; and, as pointed out in Sec. II, cooling at the outer edge of the plasma could actually produce the observed increased radiation from the lower ionization stages of oxygen.

The following alternative explanation for the early time behavior of the spectral line radiation must also be considered. Figure 8 indicates that $n_e(0)$ remains the same or decreases somewhat between 25 and 35 msec although the average electron concentration, $\bar{n}_e$, is rising. This result implies that the electron concentration near the edge is increasing in this period. Both the rising electron concentration at the edge and any coincident cooling should enhance the radiation from the low ionization stages of oxygen. If the central electron temperature is truly at 300 eV all through this period the O VIII radiation should exhibit very little, if any, "burnthrough"

peaking so we could infer from the observed decrease that the gas puff is effective in reducing the influx of oxygen, but that the similar expected loss of signal from the peripheral ions is more than compensated for by changes of T_e and n_e which occur near the edge of the plasma. Although this reasoning may appear somewhat tenuous for explaining the results of Figure 10, we show that a similar analysis explains the gas-puffing data to be discussed in Sec. III D, hence we also tend to favor it here. In addition, since it appears that the tungsten and iron concentrations are reduced by the gas puff, it seems reasonable to conclude that the inflow of oxygen is reduced too.

When the injectors are turned on the signals from the O VIII line and from the tungsten lines increase strongly, but the radiation from the O VI line shows no distinctive change due to the injection, and, in fact, the intensity begins decreasing at 50 msec, 25 msec before the injectors are turned off. Again, it is difficult to assess any changes in behavior of impurity transport during the period of injection because the temperature and concentration of the electrons are changing rapidly and the hydrogen gas puff is still exerting a strong influence on the impurities.

The most reliable interpretation of the effect of injection upon the impurity content of the plasma can be extracted from the spectroscopic data by examining the differences in the line radiation at 75 ms and at 90 ms after break down, i.e., just before the injectors are turned off and 15 msec later. The intensities of the O VII, O VIII, and the tungsten lines at 50 Å all decrease by at least a factor of two in this period. However, $n_e(0)$ and $\bar{n}_e$ decline by only 15% and the central temperatures decay only from 800 eV to 700 eV. The small changes of electron

temperature and concentrations should result in the O VII and O VIII radiation remaining almost unchanged after injection if the impurity content were constant. Thus we conclude that the oxygen influx and concentration must decrease by a factor of two as a result of terminating neutral beam injection. The behavior of the O VI line is consistent with this interpretation. Similarly, the tungsten lines, which appear to be only weakly dependent upon T_e in the 700-800 eV range, should reflect the product of the tungsten and the electron concentrations so we can infer that the level of tungsten decreases by a factor of two after the beam is turned off.

C. Plasma Conditions: 175 kA, 26 kG, discharge cleaned with hydrogen

Spectroscopic data from a high current, 175 kA, ORMAK-produced plasma is illustrated in Figure 11. The dashed lines are representative of an experiment without neutral beam injection or gas puffing; the solid lines typify data from an experiment performed five days later in which 350 kW of coinjected neutral beam power was used to provide auxiliary heating. The curves for the O VIII traces result from subtracting the background at $20.1 \text{ \AA}$ from the signal at $18.97 \text{ \AA}$. All other traces are direct reproductions of oscillograms. Line-averaged concentrations of electrons in the experiments were $2.1 \times 10^{13}/\text{cm}^3$ at 40 and 60 ms during injection and $1.6 \times 10^{13}/\text{cm}^3$ without injection. Central electron temperatures were 1000 eV in both cases.

Although the radiation from both oxygen lines is more intense in the injection experiments than in the noninjection experiments, part of the increase can be ascribed to the higher electron concentration. As a result, the small variation observed in the O VI line cannot necessarily

be construed to indicate higher impurity concentrations due to the injection. However, in view of the relatively larger increase of O VIII radiation a 10-20% change of the oxygen concentration could be inferred. After the current begins to decrease at 60 ms, the beam appears to sustain the impurity concentration at a slightly higher level than would otherwise exist.

The radiation from the metals does not increase due to injection. Indeed, the signal from Fe XVI becomes lower by a factor of two. This change is typical of the radiation from iron which is quite variable even between experiments in which plasma current and toroidal field strength have quite similar values. The tungsten radiation is almost identical between the two experiments, although it too appears to be sustained by the injection after the current begins to decrease.

The results of this experiment indicate that the neutral beam influences the impurity concentration only slightly at the higher discharge currents and larger magnetic fields.

D. Plasma Conditions: 175 kA, 26 kG, high-density gas puff, discharge cleaned with hydrogen

In an attempt to achieve maximum electron concentrations during neutral beam injection, hydrogen was puffed into the plasma between 30 and 55 ms while the injectors were operating. Profiles of the electron temperatures and concentrations are shown in Figures 12 and 13 for times immediately before, during, and immediately after the gas puff. As expected the electron concentration increases at all locations within the plasma due to the added hydrogen. The temperature profile appears to remain about the same at the intermediate radii, but increases at the center so that the slightly "hollow" profile becomes peaked. It is, however, most significant for the interpretation of the

spectroscopic data to notice that the temperature gradients at outer radii appear to decrease as a result of the gas puff.

The evolution of the radiation from several spectral lines is shown in Figures 14 and 15. Similar to the experiment discussed in the previous section, the low ionization stages of oxygen exhibit little or no change when the injectors are turned on. Although the O VII, O VIII, and the Fe XVI line intensities increase beginning at or near the time of injection, the same features are also present in the noninjection experiments and seem not to result from the action of the beams.

The addition of the gas puff produces rather dramatic changes in the signals, however. Several lines from the low stages of ionization rapidly increase until the puff is turned off and then begin to relax back into a steady state in which the emission is much greater than it was before the gas puff. For lines which demonstrate this behavior it is obvious that the lower the ionization stage, the larger the relative rise in amplitude, in contrast to the results from gas puff experiments on the PULSATOR device [10]. Therefore, we do not conclude that recombination, which would proceed successively from the higher to the lower stages of ionization, plays a significant role here.

Results similar to those for the $1032 \text{ \AA}$ line of O VI, for example, are often interpreted as indicating an influx of impurities by invoking expressions such as Eq. (7). However, if changes of radiation are construed as being due only to changes of the impurity influx, then all the lines of a given ionization stage should behave in exactly the same manner. But it is clear

from Fig. 14 that although the $1032 \text{ \AA}^{\text{O}}$ line of O VI rises by a factor of four during the gas puff that the O VI line at $150 \text{ \AA}^{\text{O}}$ appears to remain almost constant so that factors other than impurity concentrations must be considered.

Again in contrast to the strong lines of the low ionization stages, the resonance transitions of O VII and O VIII appear to decrease due to the addition of hydrogen. In order to reconcile these observations with the idea that the low ionization stages indicate an increased influx of oxygen it would be necessary to conclude that such an influx did not reach the interior of the plasma, but recirculated only within the periphery. Such conclusions appear unwarranted for explaining the present data. We believe that the spectroscopic results are more readily understood by considering the calculations presented in Sec. II and the variations of T_e and n_e shown in Figures 12 and 13. Although the measured profiles for T_e and n_e are less reliable in the outer regions of the plasma than they are in the interior, there is a clear indication that the gas puff reduces the magnitude of the temperature gradient near the limiter. In view of the results illustrated by Figures 4 and 5 we should expect that the evolution of the temperature profile alone would generate progressively larger changes of radiation from progressively lower stages of ionization. In addition, the observation that the intensity of the $1032 \text{ \AA}^{\text{O}}$ of O VI increases much more than the intensity of the $150 \text{ \AA}^{\text{O}}$ line is consistent with the calculations.

The narrowing of the temperature profile and the rise of the electron concentration should result in higher intensities from all the lines of oxygen after the addition of the gas puff if the oxygen distribution is unchanged. The fact that the signals from the O XII and O VIII lines actually decrease is indicative of a smaller concentration of oxygen after the gas puff despite the

fact that the peripheral ions emit more strongly. The change of temperature is relatively minor at radii less than 13 cm where the O VII and O VIII radiation is most intense so that variations of the lines are controlled more strongly by variations of the electron and ion concentrations than by other factors. Between 30 and 60 ms the profile of the electron concentration increases almost uniformly by a factor of 2.5, so we estimate from Table I that the oxygen concentration has fallen by a factor of 0.3 to 0.4. This conclusion is supported by analysis which shows that $\langle Z_{\text{eff}} \rangle$ as measured from the resistivity changes from 6.3 to 2.5 in this period. Such an analysis implies that the oxygen concentration is 0.7 of its initial value after taking the dilution into account. In view of the experimental uncertainties and the ad hoc nature of the theoretical calculations, better agreement cannot be expected between the two results.

The emission of $50 \text{ \AA}$ indicates that the tungsten concentration is also significantly lowered by the introduction of the gas puff, perhaps by as much as a factor of 7 or 8. Similar conclusions can be drawn for iron, but with the realization that radiation from this element is often highly variable as a function of the type of discharge and of time into the discharge so that some caution must be exercised in relating its behavior to the influence of the gas puff.

IV. COUNTERINJECTION EXPERIMENTS

The scope of spectroscopic data available from counterinjection experiments is quite limited, but it indicates that the influx of metallic ions is much more severe than the corresponding coinjection cases. Figures 16 and 17 show results from a 170 kA, 26 kG experiment for which discharge cleaning in oxygen preceded tokamak operation. The power supplied by the neutral beams was 120 kW for each direction of injection. At 45 ms into the discharge, the intensity of the O VI line is 20% larger due to the coinjected beam alone than it is with no injection, but almost 50% larger due to the counterinjected beam alone. However, it appears slightly lower than in the coinjection experiment when co- and counterinjection are employed at the same time!

Radiation from iron is increased strongly because of the counterinjection; it is almost a factor of three larger at 45 ms into the discharge than it is for the coinjection case. Again, it appears that the simultaneous operation of the two injectors produces less intensity than does counterinjection alone.

Although a limited amount of spectroscopic data is available it is consistent with our discussions of Sec. III to infer that the changes of intensity due to injection are mainly dependent upon altered influxes rather than upon profile changes. This interpretation is also consistent with the electron temperature profiles obtained for four different experiments as shown in Figure 18. Whereas coinjection raises T_e slightly, counterinjection results in a lowered central temperature and a slightly "hollow" center in the profile. This inverted profile has been observed in several experiments and is now known to be caused by large radiative losses due to tungsten in the plasma. Thus it is obvious to infer that counterinjection undoubtedly results in a large influx

of tungsten as well as of iron. The profile obtained when both injectors are operated also confirms the conclusion from the spectroscopic data that simultaneous co- and counterinjection leads to smaller impurity influxes than does counterinjection alone.

V. SUMMARY

We have attempted to assess the behavior of impurities in ORMAK during neutral beam injection and gas puffing by analyzing line-integrated spectroscopic data. In order to do so, the steady state continuity equations for oxygen ions have been solved numerically to determine radiated intensities as a function of various plasma parameters such as electron temperatures and concentrations. The results show that changes in these parameters due to injection or gas puffing may influence the radiation from some lines enough that changes in concentrations or influxes are of secondary importance in determining the intensities. It is, therefore, desirable to observe lines of light ions from as many ionization stages as possible in order to evaluate the extent to which various operations on the plasma influence the impurity behavior.

In general, we have found that for coinjection at low toroidal fields, 15 kG, and low ohmic heating currents, 70 kA, neutral beam heating increases the impurity content by factors of two to three. At 26 kG and 175 kA, the increase is only 10-20%. It must be noted that the 350 kW of injection power is a much larger fraction of the total input power at low currents, however. In the experiments we have analyzed, the ohmic heating provides 140 kW (oxygen discharge cleaned) and 110 kW (hydrogen discharge cleaned) at 70 kA and approximately 600 kW at 175 kA. It is quite possible that greater neutral beam power densities at the larger currents may lead to higher impurity influxes. Investigations of this possibility will be tested soon on the ISX-B device at Oak Ridge.

Although only limited data is available concerning counterinjection, we conclude that this operation causes a much higher influx of impurities

than does coinjection. In particular the concentration of metals in the plasma may increase by factors of two or three rather than by 20%. Simultaneous operation of both co- and counterinjectors results in a smaller influx of impurities than does counterinjection alone.

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Table I. Calculated increase of multiplet emission rates, I'/I , if $n_e(0)$ and $n_e(a)$ are changed from $3.0 \times 10^{13}/\text{cm}^3$ and $0.3 \times 10^{13}/\text{cm}^3$ to $6.0 \times 10^{13}/\text{cm}^3$ and $0.6 \times 10^{13}/\text{cm}^3$. Other plasma parameters are the following: $T_e(0) = 1000$ eV, $T_e(a) = 10$ eV, $(m,n) = (1,2)$, $v_i(a) = 10^2$ cm/sec, $v_0 = 55$ cm/sec, $n(\text{oxygen}) = 1.9 \times 10^{11}/\text{cm}^3$

Species	Mean Wavelength (Å)	I'/I
O II	833.8	1.65
O III	834.5	2.03
O IV	789.4	1.94
O V	629.7	1.73
O VI	1033.8	1.72
O VI	150.1	1.41
O VII	217.6	1.39
O VIII	19.0	1.55

FIGURE CAPTIONS

1. Typical ORMAK-produced spectrum between $20 \text{ \AA}^{\circ}$ and $170 \text{ \AA}^{\circ}$.
2. Detailed ORMAK-produced spectrum below $22 \text{ \AA}^{\circ}$.
3. Analytic temperature profiles employed for theoretical computations.
4. Relative emission rates for oxygen lines as a function of electron temperature profiles. Velocity of neutral oxygen is $55 \times 10^3 \text{ cm/sec}$; inward velocity of ions at wall, $v_i(a)$, is 10^2 cm/sec .
5. Relative emission rates for oxygen lines as a function of electron temperature profiles. Velocity of neutral oxygen is $55 \times 10^3 \text{ cm/sec}$; inward velocity of ions at wall, $v_i(a)$, is 10^3 cm/sec .
6. Temporal dependence of impurity lines during injection of 35 kW of neutral-beam power into a 70 kA plasma (solid lines). Oxygen discharge cleaning was employed. Traces begin 4 ms before breakdown. Dashed lines are typical of noninjection shots.
7. Relative behavior of line-averaged electron density, $\bar{n}_e$, O VI radiation, and the beam pulse monitor for the experiment described in Sec. III A.
8. Central and line-averaged electron concentrations for the experiment described in Sec. III B.
9. Central and volume-averaged temperatures for the experiment described in Sec. III B.
10. Radiation from impurities during injection of 350 kW of neutral beam power into a 70 kA plasma. Discharge cleaning was solely in hydrogen. Traces begin 4 ms before breakdown.
11. Comparison of line intensities with (solid lines) and without (dashed lines) 350 kW of neutral beam injection into a 175 kA discharge. Traces begin 4 ms before breakdown.

12. Electron temperature profiles when neutral-beam injection is accompanied by a hydrogen gas puff between 30 and 55 ms.
13. Electron concentration profiles when neutral-beam injection is accompanied by a hydrogen gas puff between 30 and 55 ms.
14. Spectral emissions from low ionization stages of oxygen during 350 kW neutral-beam injection into a 175 kA plasma when accompanied by a hydrogen gas puff. The lower trace in the $150.1 \text{ \AA}$ data is nearby background; actual line intensity is the difference of the two signals. Traces begin 4 ms before breakdown.
15. Spectral emissions from O VII, O VIII, tungsten, and iron during 350 kW neutral beam injection into a 175 kA plasma when accompanied by a hydrogen gas puff. The lower traces in the O VII and O VIII data is nearby background. Traces begin 4 ms before breakdown.
16. Dependence of O VI ($1032 \text{ \AA}$) radiation on various combinations of co- and counterinjection.
17. Dependence of Fe XVI ($361 \text{ \AA}$) radiation on various combinations of co- and counterinjection.
18. Electron temperature and concentration at 45 msec into discharge for various combinations of co- and counterinjection.

Fig. 1.

Fig. 2.

ORNL / DWG / FED - 77706

Fig. 3.

ORNL/DWG/FED-78109

Fig. 4.

ORNL/DWG/FED-78108

Fig. 5.

ORNL/DWG/FED-77547

Fig. 6.

ORNL/DWG/FED-78107

Fig. 7.

ORNL/DWG/FED 78-137

Fig. 8.

Fig. 9.

ORNL/DWG/FED-77544R

Fig. 10.

Fig. 11.

Fig. 12.

Fig. 13.

ORNL/DWG/FED-77545R

Fig. 14.

ORNL/DWG/FED-77546R

Fig. 15.

ORNL/DWG/FED 78-155R

Fig. 16.

ORNL/DWG/FED-78-154

Fig. 17.

ORNL-DWG 77-7403

 $I=170$ kA, $B_T=26$ kG, H^0 INTO H^+

Fig. 18.

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