Impurity fluxes and concentrations in the ISX-B beryllium limiter experiment

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ABSTRACT. An experiment to test beryllium as a limiter material has been performed in the ISX-B tokamak. One facet of the studies centred on characterizing impurity influxes and concentrations. The radiation from both low-Z (Be, C, N, O) and intermediate-Z (Ti, Cr) contaminants was measured at the limiter surface and at a wall location 90° away from the limiter to assess the relative contributions of metallic impurities from the two different sources. The effect of limiter melting, with concomitant reduction of both low-Z and intermediate-Z elements, was also documented. The analysis, including atomic rate coefficients, for interpreting spectral radiation in terms of production rates is discussed in detail.

1. INTRODUCTION

Beryllium has often been proposed as a material for the first wall and for limiters in fusion devices because of several potentially favourable properties, among them a partial solution to the problem of impurity contamination. Since it is a very low-Z material (Z = 4), the radiative cooling rates [1] are much less than the rates from metallic elements that have been used heretofore in these machines, e.g. iron, nickel, molybdenum. As progress is made toward high-temperature, long-pulse operation, plasma contamination problems may well become severe. Neither of the currently operating large tokamaks, JET and TFTR, incorporates provisions for a divertor to reduce primary production rates of metallic elements by remote radiative cooling [2–4]. It is possible to produce an internal-separatrix and open-divertor configuration in the JET vacuum vessel similar to D III [4], but only at the expense of current capability and plasma volume which might prove to be a crucial loss when trying to achieve breakeven conditions. Thus, attention is being paid to the possible use of beryllium inside the vacuum chambers of fusion devices. A beryllium limiter was first tested with promising results in the Unitor tokamak [5]. Most notably, discharges operated for a longer time than when using other materials, and the frequency of disruptions was reduced below previous rates. Also, based on the observation of a Cr I line at the edge of the plasmas, ablated beryllium appeared to have covered the walls after several shots, thereby shielding the stainless steel from sputtering and reducing the concentrations of intermediate-Z elements. The transition occurred without major damage to the limiter. In view of the potential benefits of employing beryllium in a large machine, a well diagnosed and documented test using a limiter of this material was
initiated in the ISX-B tokamak [6, 7]. This paper incorporates only the details of the spectral studies; a broad overview of all the results will be presented elsewhere [8].

Several aspects of impurity generation and plasma contamination have been addressed in the ISX-B experiments. First, the primary influxes (production rates) of dominant metallic elements (Be, Cr, Ti) are measured from the limiter face and from the wall at one mid-plane location to assess the relative importance of contamination from the two sources. Quantifying this distinction is motivated by results from JET [9], TEXTOR [10] and ASDEX [11, 12], where impurities from the wall materials are observed at the limiter surface. Clearly, it is not useful to contemplate the reduction of intermediate-\(Z\) contaminants solely by changing the limiter to beryllium if impurities generated from the wall quickly cover the limiter face and are subsequently introduced into plasmas from that location. Second, the transition from sputtering to evaporation as the major impurity release mechanism from the limiter has been documented under heat loads up to 2500 W \(\cdot\) cm\(^{-2}\), in order to gain some insight into material cooling problems in larger machines with much smaller heat loads but greater pulse lengths. A third major point examined at some length is the reduction of low-\(Z\) impurities together with the inhibition of sputtered intermediate-\(Z\) elements once beryllium has covered the walls. The principal results of these studies are presented here; a minor aspect, the comparison of co- and counter-injection discharges, has already been published [13]. Since no in-depth treatment of the analysis of influxes from neutral and singly ionized

**FIG.1. Location of spectrometers, beamlines and beryllium limiter on ISX-B.**
response of the grazing-incidence spectrometer was obtained by CXE techniques [16], and the normal-incidence instrument was cross-calibrated against it by comparing signals from simultaneously recorded spectral lines. The uncertainty in the responses is estimated to be 15% for the limiter-viewing spectrometer and 30% for the other three instruments.

Figure 2 illustrates the orientation of the limiter, which was constructed of 12 closely fitting Be tiles and was installed as a horizontal rail [7]. A diagonal view of a single tile is depicted in the inset of Fig. 2; every other one of these is slotted to relieve surface stresses. Most of the heat load is deposited in the vicinity of the ridge along the centre of the tiles.

2. OHMICALLY HEATED DISCHARGES

Although most impurity studies were performed with neutral beams, the earliest investigations utilized OH plasmas. Determining whether impurities other than beryllium were emitted from the limiter surface constituted one of the major goals during this early phase of the experiment. It was possible to evaluate how rapidly metals such as chromium and titanium migrated to the limiter by examining photographic spectra from the first few plasma shots. Titanium had been used regularly for gettering, but the last experiment before installing the beryllium limiter also tested the efficiency of chromium for this purpose [17].

A segment of the photographic spectrum from the first 12 discharges, taken with the limiter-viewing spectrometer, is shown in Fig.3. Radiation from neutral and singly charged species having low ionization potentials is usually representative of local influxes (Section 3). As expected, lines from beryllium are readily observed, but somewhat surprisingly, lines of Cr I also appear strongly in the vicinity of the limiter. Titanium is identifiable in Fig.3, although most of the strong lines occurring between 3350 and 3400 Å are obscured by blends. The strongest feature in the spectrum at 3360.4 Å is not identified nor are certain other emissions above 3800 Å which have the appearance of narrow molecular bands. To substantiate the viewpoint that lines of the intermediate-Z elements in the photographic spectrum truly represent impurities released from the limiter, we shall show in Section 3 that the emission rates per cm² of their low-ionization stages are much greater at the limiter than at the walls. The same is not true for oxygen and nitrogen, and it is not possible to assign a definite fraction of the radiation from the low

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FIG. 3. Spectrum recorded with limiter-viewing spectrometer during first 12 OH discharges following installation of beryllium limiter. Chromium lines emitted by atoms sputtered from limiter face are clearly in evidence. Hg lines are from lamp used for wavelength calibration.

FIG. 4. Spectrum recorded with limiter-viewing spectrometer after 400 OH discharges using beryllium limiter.
stages to locally released ions. (The neutral stages of the low-Z impurities are not observed in the photographic spectra.) Whether the metal deposition results primarily during the discharge cleaning phase or whether it occurs during the first few OH shots is not known, but absolute flux measurements indicate that the chromium released from the walls during one discharge is sufficient to provide a monolayer film over the entire limiter surface. A spectrum of the same wavelength region taken after 400 OH discharges is shown in Fig. 4. The unidentified features have essentially disappeared. Ti II lines are brighter and are easily distinguished. The Cr I intensities have not changed drastically compared to the Be signals, but it is expected, of course, that an equilibrium is eventually reached between release and deposition of all impurities at any given location.

The time behaviour of radiation from the low stages of beryllium, chromium, and titanium viewed at the limiter during the OH discharges is shown in Figs 5 and 6. (Column emission rates are stated in gigarayleighs; 1 GR = 10^{15} photons · cm^{-2} · s^{-1}.) These are presented primarily for later comparison with the emissions from beam-heated discharges. The 2349 Å line of Be I is the resonance transition; the 3321 Å line terminates on the 3P metastable state. Measurements of the primary influx must account for populations of both the ground and metastable states. The Be III lines arise from the 2P → 2S transitions, which are monitored regularly, but are not employed for quantitative estimates of concentrations. The resonance lines of Be III (100 Å) and Be IV (75 Å) are used to calculate the fluxes of the He-like and H-like stages. It is noteworthy that temporal variations of

FIG. 5. Time behaviour of beryllium lines from limiter-viewing position during OH discharges.

FIG. 6. Time behaviour of titanium and chromium lines from the limiter-viewing position during OH discharges.
all the signals are similar, an indication that chromium and titanium originate from the same source and via the same process as beryllium. The release mechanism is presumed to be sputtering, as deduced from previous ISX-B experiments where the influxes of iron were shown to be three times larger for deuterium than for hydrogen plasmas [18].

3. INFLUXES OF METALS

To ascertain whether the wall or limiters serve as the primary sources of impurities, neutral and singly ionized species are monitored with both visible spectrometers. Even so, it must be emphasized that these production rates do not by themselves indicate the determining factors for impurity concentrations. The scrape-off layer exerts a controlling influence on the fraction of impurities that survive to enter the main plasma, but no spatially resolved measurements are available to define impurity transport processes in this region.

Before presenting the results of the flux measurements, we discuss in detail (Section 3.1) the atomic physics necessary to interpret the spectroscopic data. This is done in order to point out the complications and uncertainties that must be considered in measurements of primary fluxes of all elements, although the emphasis is mainly placed on understanding the beryllium results since this material has not been used or studied extensively in tokamaks. Rate coefficients for beryllium are discussed in the Appendix. Following the presentation of this background material, its applications to the pre-melting experiment (Section 3.2) and to the melting and post-fluence sequences (Section 3.3) are treated separately.

3.1. Atomic physics considerations

The simplest approximation for the flux of ions in a particular level is usually taken as [19–21]

$$\Gamma = \frac{1}{2B} \frac{S(T_e)}{R(T_e)}$$

where $I$ is the columnar intensity of a spectral line in photons $\cdot$ cm$^{-2}$ $\cdot$ s$^{-1}$, $R(T_e)$ and $S(T_e)$ are, respectively, the excitation and ionization rate coefficients of interest, $B$ is the branching ratio, and $\Gamma$ is the flux. The derivation of Eq.(1) requires that the atomic rate coefficients be approximately constant in the range of temperatures over which the ions radiate and that recombination be negligible. This requirement is generally fulfilled for very low stages having ionization potentials ($I_p$) less than or equal to $T_e$ at the edge, since they ionize rapidly enough to remain well localized radially. The ionization potentials of the ground states of Be I, Cr I, and Ti II are, respectively, 9.3, 6.8, and 13.6 eV.

When evaluating the production rates of atoms for which both the ground state and the metastable state populations must be taken into account, it is necessary to monitor lines that terminate on each of these. It is preferable that direct excitation from the lower levels be much greater than cascade contributions in order to simplify the evaluation of $R(T_e)$. Excitation rates requiring electron spin changes are much smaller than rates for optically allowed channels [22, 23], so a given spectral line is almost always indicative of the population of only a single long-lived state.

An additional requirement for Eq.(1) to hold is that ionization must be the dominant mechanism determining the population of the lower level of the transition observed. If metastable states are populated significantly, the total flux is given by the sum of terms as expressed by Eq.(1) only if the ionization rates from each level are much faster than the collisional coupling rates between them. In the event the coupling rates are comparable to the ionization rates, $S(T_e)$ is replaced by a much more complicated expression that includes collisional transfer between the long-lived states and which requires a knowledge of their initial populations. In the limit that the collisional coupling between these states is much larger than the ionization rates, average values for $S(T_e)$ must be used in Eq.(1). For example, in a two-level system such as Be I,

$$S_T = \frac{n_g S_g + n_m S_m}{n_g + n_m}$$

$$\Gamma_T = \Gamma_g + \Gamma_m$$

where the subscripts $g$ and $m$ refer to the ground and metastable states, and the ratio of the state populations, $\rho = n_m/n_g$, is given by the ratio of the degeneracies when the Boltzmann factor is near unity. The total flux, $\Gamma_T$, is then given by

$$\Gamma_T = S_T \left[ \frac{I_g}{R_g} + \frac{I_m}{R_m} \right]$$
FIG. 7. Ratios of ionization coefficients ($S$) to excitation coefficients ($R$). The Be I curves refer to the resonance line (2349 Å) from the ground state ($g$) and the 2651 Å line from the metastable state ($m$).

The actual chord-averaged ratio $\rho$ for Be I is determined experimentally from the relationship

$$\rho = \frac{R_{g}I_{m}}{R_{m}I_{g}}$$

which is between 0.5 and 2.5 for all the experiments described here instead of the value of 9 expected for collisional equilibrium. Theoretical calculations for the ground-to-metastable collisional coupling in Be I are not available to provide guidance for the importance of this interaction compared to ionization. Because of the uncertainty of the best approximation to use for the total flux, we have adopted Eq.(3) with the experimentally measured values of $\rho$. The ratios $S_{g}/R_{g}$ and $S_{m}/R_{m}$, assuming equal populations of ground and metastable states, are plotted in Fig.7 for two Be I lines to show their temperature dependence. Actually, the two ionization rate coefficients do not differ significantly, and $S_{g}$ is not very sensitive to the weighting of the two populations. Using the sum of two independent terms of the form of Eq.(1) for the two levels makes no more than a 5% difference in the calculated fluxes. Ratios for the resonance lines of Be II and Be III, for which almost all of the population resides in the ground states, are also indicated in Fig.7. The Be II ($I_{p} = 18.2$ eV) curve tends to follow those of Be I above 15 eV, but falls off much faster below this temperature. This fact indicates that, for a given production rate, the Be II resonance line is relatively more intense from ions existing in a low-temperature region. The ratio for Be III ($I_{p} = 153.9$ eV) varies much more widely over the range from 5–50 eV than the ratios for the lower stages, but modelling calculations indicate that this ion does not radiate strongly in regions where $T_{e}$ is below 25 eV.

Figure 8 shows the time history of three Be I lines observed at the limiter position during a sequence of discharges in which 850 kW of neutral-beam injection is initiated at 100 ms. Both the 2651 Å ($2p^2 \rightarrow 2s2p$) and the 3321 Å ($2s3s \rightarrow 2s2p$) transitions terminate on the metastable level. The emission rates are comparable although the detailed discussions of the theoretical rate coefficients for direct excitation found in the Appendix indicate that the 2651 Å line should be the brighter by more than a factor of five. However, it is quite possible that a major contribution to the 3321 Å line may come through cascades from the $2p3p$ configuration. Therefore, the 2651 Å transition is used in all cases to compute the metastable level population, although the 3321 Å line is employed to compare limiter and wall fluxes since the window transmission of the wall-viewing spectrometer is not characterized well at the shorter wavelengths. The ratio of the excitation coefficients of the 2349 Å and the 2651 Å lines varies by only 6% between 10–50 eV.

FIG. 8. Time behaviour of three Be I lines before limiter melting. Neutral-beam injection power is 850 kW.
so it is not a large source of uncertainty in determining $\rho$ from Eq. (3). Indications are that 50–70\% of the Be I population resides in the metastable state. The fraction is not constant throughout a discharge; it often appears to increase as evidenced by the traces in Fig. 8.

The data analysis requires some knowledge of the electron temperatures and densities at the site of the radiating ions. In addition to requiring a correct value for $S/R$, it is also necessary to be sure that insignificant numbers of ions leave the field of view around the limiter before they are ionized. Although particles may be sputtered most intensely near the contact point between the limiter and the plasma, non-negligible contributions to the flux may come from parts of the surface where temperatures and densities are lower. Moreover, since neutral particles are sputtered in all directions, many of the Be* ions are born at temperatures below the temperature at the limiter tip.

Several pieces of information are available concerning the edge. The temperature at the magnetic boundary is typically 30–50 eV as determined by Thomson scattering for 850 kW of beam power, but approximately 3 cm behind the limiter tip it has been measured with a vertical Langmuir probe to be as low as 5 eV. The rapid drop indicates a scrape-off length of only 1.8 cm for $T_e$. Thermocouple measurements of the individual tiles have shown that the characteristic decay length for power deposition is 0.75–1.5 cm. These two pieces of evidence corroborate the existence of a narrow effective scrape-off layer at the limiter location. If the effective scrape-off layer is only a few centimetres wide, sputtered particles can be excited over a wide range of low temperatures, and the calculations of Be I fluxes from the $S/R$ values given in Fig. 7 become correspondingly uncertain. Evaluation of the Be II emission is affected to an even greater extent.

Provided the characteristic path length for ionization is short enough, the signal detected by the spectrometer system accounts for all the radiation from atoms released at the limiter. For free-streaming particles, this distance is simply the mean free path, $\delta$, given by

$$\delta = \frac{v_{ion}}{S\rho_e}$$

(5)

where $v_{ion}$ is the thermal velocity. For diffusive flow the velocity is smaller, and the resulting ionization length is shorter so Eq. (5) represents an upper limit. Table I lists the values of $\delta$ for $n_e = 10^{13}$ cm$^{-3}$ and $v_{ion}$ corresponding to a 5 eV sputtered particle. The limiter itself is 10 cm wide, and the spectrometer field of view at the centre extends about 2.5 cm away from either edge. Thus, only negligibly small fractions of the photons emitted by Cr I and Ti II are expected to go undetected at all electron temperatures above 5 eV. The same holds true for Be I at electron temperatures above 10 eV. In the case where evaporation is the dominant production mechanism, and particles are released at thermal energies, the mean free path is a factor of ten shorter. Table I also indicates that Be III can be transported as much as several hundred centimetres toroidally. The detailed distribution depends sensitively on the edge conditions and on the relative rates of the slow perpendicular and rapid parallel transport; it is likely, however, that these ions travel well around the machine before being ionized (the circumference is 591 cm) so that they may have an almost axisymmetric distribution even when parallel diffusion, rather than free-streaming, is dominant. Be II constitutes an intermediate case where significant numbers of these ions should leave the field of view undetected, especially if the electron temperatures are below 15 eV, but should not spread uniformly over flux surfaces before being converted to Be III. The spreading of Be II can be even more extensive, of course, if it thermalizes to a temperature higher than the 5 eV we have assumed for the sputtered energy; however, the equilibration times in the plasma edge are comparable to the ionization times. We have emphasized these points concerning the mean free
paths in order to establish a basis for putting all the spectroscopic data into perspective, and we return to them in Section 4 after considering the production rates of the impurities observed in this experiment.

3.2. The pre-melting sequence

Radiation from hydrogen and low ionization stages of several impurities is shown in Figs 9 to 11, for a well characterized pre-melting sequence using 850 kW of neutral-beam injection. In all cases the signals from the limiter-viewing spectrometer and the wall-viewing spectrometer are depicted, respectively, by solid and dashed lines. The two signals do not refer to exactly the same phenomena. Data from the wall-viewing instrument are interpreted in the usual sense, that is, as a column emission rate from a small cross-section of two peripheral layers. Toroidal and poloidal uniformity is assumed, but there is no experimental verification of
TABLE II. INTEGRATED INFLUXES FROM THE WALL AND LIMITER. THE ELECTRON TEMPERATURE IS ASSUMED TO BE 30 eV

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Ion</th>
<th>$\Gamma'_W (s^{-1})$</th>
<th>$\Gamma'_L (s^{-1})$</th>
<th>$\Gamma'_W / \Gamma'_L$</th>
<th>Figure</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before melting</td>
<td>Be I</td>
<td>$1.6 \times 10^{17}$</td>
<td>$1.1 \times 10^{18}$</td>
<td>0.14</td>
<td>9</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>Cr I ($\alpha$)</td>
<td>$1.2 \times 10^{19}$</td>
<td>$1.7 \times 10^{18}$</td>
<td>6.9</td>
<td>10</td>
<td>280</td>
</tr>
<tr>
<td>115 kA</td>
<td>Ti II ($\alpha$)</td>
<td>$4.7 \times 10^{18}$</td>
<td>$4.7 \times 10^{17}$</td>
<td>10.0</td>
<td>10</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>Ti II ($\alpha$)</td>
<td>$2.0 \times 10^{18}$</td>
<td>$1.6 \times 10^{17}$</td>
<td>10.0</td>
<td>10</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>D I</td>
<td>$5.0 \times 10^{21}$</td>
<td>$1.5 \times 10^{21}$</td>
<td>3.3</td>
<td>11</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>O II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melting sequence</td>
<td>Be I</td>
<td>$2.9 \times 10^{18}$</td>
<td>$1.2 \times 10^{19}$</td>
<td>0.25</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>150 kA</td>
<td>Cr I</td>
<td>$1.1 \times 10^{19}$</td>
<td>$3.6 \times 10^{17}$</td>
<td>32.0</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>After fluence test</td>
<td>Be I</td>
<td>$5.0 \times 10^{18}$</td>
<td>$1.3 \times 10^{20}$</td>
<td>0.04</td>
<td>340</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cr I</td>
<td>$7.5 \times 10^{18}$</td>
<td>$3.2 \times 10^{17}$</td>
<td>24.0</td>
<td>340</td>
<td></td>
</tr>
<tr>
<td>115 kA</td>
<td>Be I</td>
<td>$4.5 \times 10^{18}$</td>
<td>$1.39 \times 10^{19}$</td>
<td>0.3</td>
<td>14</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>Cr I</td>
<td>$5.5 \times 10^{18}$</td>
<td>$8.3 \times 10^{17}$</td>
<td>6.6</td>
<td>15</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>Be I</td>
<td>$3.3 \times 10^{18}$</td>
<td>$7.2 \times 10^{19}$</td>
<td>0.05</td>
<td>14</td>
<td>290</td>
</tr>
<tr>
<td></td>
<td>Cr I</td>
<td>$3.9 \times 10^{18}$</td>
<td>$4.6 \times 10^{17}$</td>
<td>8.4</td>
<td>15</td>
<td>290</td>
</tr>
</tbody>
</table>

This supposition. In fact, spatially resolved measurements of the distributions of emission from low ionization stages in tokamaks usually do show poloidal asymmetries [24], and the likelihood of such occurrences must be kept in mind when considering our estimates of influxes from the machine walls. Measurements of low ionization stages of metals from the limiter spectrometer are an average of a very non-uniform source over the field of view. Signals from relatively high ionization stages, that are more or less uniformly spread over flux surfaces (e.g. Be II), are also presented as if the radiation were originating from a flat field of view at the limiter. To put these measurements in the same terms as the data from the wall-viewing spectrometer, the radiating arc length in the field of view must be taken into account. The correction requires multiplying the data from the limiter view by 0.65; the uncertainty in this correction is ± 20%.

The integrated emission from each source is estimated by multiplying the displayed data by the effective surface areas, 422 cm$^2$ for the limiter and 4.5 $\times$ 10$^4$ cm$^2$ for the wall (one-half the plasma surface area). Integrated influxes, $\Gamma'_L$ and $\Gamma'_W$, and their ratios calculated under the assumption that the edge temperature is 30 eV are shown in Table II. If the effective temperature where the atoms are excited is as low as 10 eV, the estimates of the production should be a factor of two lower, as indicated by the S/R ratios in Fig. 7. Even though the limiter is a strong local source of beryllium, about 12% of the primary production inferred from Be I radiation appears to occur at the wall during this sequence.

Comparison of the Be I emission in Fig. 9 with the data of Fig. 5 indicates that neutral-beam injection initially raises the beryllium influx by a factor of three over the rate caused by Ohmic heating alone. After 200 ms the emission declines concurrently with the growth of oscillations in the signal. The relationships between the radiation from atoms and various beryllium ions are examined in Section 4, but it should be noted here that while the Be III history is similar to that of Be I, radiation from Be II increases rather than falls after 200 ms. This dichotomy is indicative that the sputtering rates, plasma parameters, and edge transport mechanisms may all be changing simultaneously in such a way that it is difficult to construct a consistent explanation of the data. Nevertheless, it is safe to conclude from the Be I emission that the sputtering rates at the limiter decrease after 200 ms,
presumably because of a falling edge temperature. The same phenomenon is observed in the CrI and TiII lines.

Figure 10 illustrates signals from chromium and titanium, the two dominant metallic impurities other than beryllium itself. Low stages of iron are not observable in the visible region, and although the strong VUV lines from Fe XV and Fe XVI could always be detected, their intensities became progressively weaker during the course of these experiments. The influxes of CrI and TiII are not so well defined as that of beryllium because the populations of the several metastable levels are not well known. In principle, a detailed-balance calculation involving excitations from all the long-lived levels is required for an accurate evaluation of spectral data. This task is very formidable and far beyond the scope of our present capabilities. We have determined the fluxes for the intermediate-Z elements in the same manner as for the beryllium, by assuming that the upper levels of a given multiplet are populated solely by electron excitation from its lower levels. Moreover, it has not been possible to perform quantitative measurements of the populations of all the metastable levels even by this method; they must be estimated from a limited amount of data. The influxes of chromium and titanium atoms in specific states are listed in Table II. Transitions of CrI terminating on long-lived states other than a7S are observed in the photographic spectra, but with much lower intensities. When only population uncertainties are considered, we estimate that the total chromium influx is a factor of two to five greater than listed in Table II for the ground state alone. Results from JET indicate that this correction is probably closer to a factor of two than to a factor of five. Similarly, the titanium production rate would be construed as somewhat higher than the sum of the listed TiII results, although two states have been evaluated for this ion. If the effective electron temperature in the scrape-off layer is indeed as low as 10 eV, the tabulated intermediate-Z influxes from the walls may be overestimated by a factor of three to five.

By contrast with the beryllium, the assumption of toroidal and poloidal uniformity implies that greater amounts of chromium, titanium, oxygen, and hydrogen are introduced into plasmas, or at least into the scrape-off layer, from the walls than from the limiter. The total production of metal atoms at the walls is more than an order of magnitude greater than the production of beryllium atoms at the limiter. When it is considered that most of the ions from the wall may be scraped off, this result is not inconsistent with previous conclusions that roughly equal contributions come from the two sources in OH plasmas [18].

Approximately 10^21 recycled atoms per second are necessary to maintain the plasma density, and this rate is comparable to the measured deuterium fluxes at the limiter. The ratio of the BeI and deuterium fluxes shows an average sputtering yield of 7 X 10^{-4} Be atoms per D^+ ion incident on the limiter. We believe that the limiter surface is probably oxidized for the pre-melting sequence since collection samples for Be around the machine show it mostly in the form of BeO, except during studies with heavy melting when the oxygen content is low [25]. The yield curves for BeO from Ref.[26] imply an effective bombardment energy of 40 eV or an electron temperature near 13 eV if the sputtering is caused by acceleration through a typical sheath potential equal to 3kT_e(\text{ag}). Recent unpublished results [27] indicate that the sputtering rates for pure beryllium are greater than for BeO.

The absolute influxes of oxygen cannot be determined from the visible OII radiation (Fig.11) since the excitation rates are not known. Discrepancies between intensities recorded by the two spectrometers are not so large as for the metallic elements, indicating that low stages of oxygen radiate more uniformly around the torus. At late times in the discharges, the columnar radiation differs by a factor of only 1.7 for OII at the two viewing locations. This observation is not to be construed as showing that limiter recycling is negligible in maintaining the oxygen density within the main plasma because the mechanics of transport in the scrape-off layer and at the edge of the main plasma are not well understood. The increase of the peripheral oxygen signals starting at 100 ms is not the result of neutral injection per se, but comes about by also raising the fuelling rate at this time. The edge density is increased so that a particular ion is produced at a lower temperature. At the same time, more oxygen may be introduced by formation and detachment of molecules at the walls.

3.3. Melting and post-fluence sequences

Following the initial documentation of beam-heated discharges, the operating current was raised from 115 to 155 kA in order to test the limiter under power loads that could induce more than minimal damage. The limiter surface temperature rose to the melting point during the course of these discharges, and the impurity inventory in the tokamak was altered significantly. Figures 12 and 13 compare data from
the low- and high-current discharges. The increase of Be I radiation immediately following injection is 10 times greater than previously observed. More strikingly, after 200 ms (100 ms after injection begins) the radiation of all beryllium lines rises by an additional factor of 10, as illustrated for the Be IV resonance line in Fig. 12. This increase is undoubtedly caused by a rapid rise in vapour pressure as the limiter heats.

Melting deposits enough beryllium on the walls that the content of light ions is reduced. Comparisons of the fully stripped low-Z ions in the plasma centre, measured by charge-exchange spectroscopy, are illustrated in Fig. 13 for the low- and high-current cases. Oxygen and carbon are lowered by a factor of three to four; N\(^{7+}\) was not observed during the melting sequence because of an interference with a beryllium line, but N IV in the periphery evidenced reductions comparable to O VI and C III. The ratio of the early burnout peak of the O VI lines also corroborates changes of a factor of four in the oxygen content, although the signals differ by a factor of eight toward the end of the shots. The gas puffing at 100 ms was not so strong for the melting sequence as for the pre-melting sequence, and the peripheral ions were not influenced so much by fuelling. Some indications also exist from pump limiter experiments that reduction of the reservoirs of low-Z impurities in the scrape-off layer reduces the peripheral ion radiation more than anticipated from changes of central densities. Titanium and oxygen lines in the vicinity of the limiter could not be measured reliably because of the large amount of scattered light from nearby beryllium lines; the Cr I lines were removed far enough in wavelength that they could still be detected.

Just as in experiments utilizing titanium or chromium evaporation, it is difficult to tell whether light-ion reduction comes about primarily by gettering or by coverage of the sources. The decrease of the nitrogen content indicates that gettering takes place for this impurity because it apparently comes from a very small leak in the vacuum vessel and is continually drawn into the system between discharges. Also, gettering must occur for oxygen since clean beryllium surfaces are known to oxidize readily. Therefore,
with the realization that burial may not be negligible, we frequently use the term gettering to characterize the reduction of the gaseous impurities by beryllium films in the same general sense as it is used for other evaporated metallic films.

The fluxes determined for two times during the melting sequence are also presented in Table II. At 150 ms, before the rapid change in the beryllium production rate, sputtering is probably the dominant release mechanism; at 340 ms, evaporation most likely controls the influx. It is seen that the beryllium rates are an order of magnitude greater from both sources during the sputtering phase of the 155 kA sequence than during the pre-melting sequence. The rate for chromium has been lowered by a factor of five, however. It is believed that the increase of sputtered
TABLE III. INTENSITIES OF METALLIC LINES (GR) FOR SEVERAL LIMITER MATERIALS AND GETTING CONDITIONS

<table>
<thead>
<tr>
<th>Limiter</th>
<th>Getter</th>
<th>Ti XI</th>
<th>Ti XII</th>
<th>Cr XV</th>
<th>Fe XV</th>
<th>Fe XVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiC</td>
<td>none</td>
<td>7.0</td>
<td>6.0</td>
<td>1.5</td>
<td>4.3</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiC</td>
<td>none</td>
<td>2.5</td>
<td>1.2</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiC</td>
<td>Cr</td>
<td>3.2</td>
<td>4.0</td>
<td>12.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be</td>
<td>none</td>
<td>2.4</td>
<td>1.4</td>
<td>0.35</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be</td>
<td>Be</td>
<td>0.70</td>
<td>1.0</td>
<td>0.70</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be</td>
<td>Be</td>
<td>0.10</td>
<td>0.35</td>
<td>0.27</td>
<td>0.70</td>
<td>0.20</td>
</tr>
</tbody>
</table>

beryllium from the limiter results from higher edge temperatures, because of diminished radiative power, as well as from irregular melt spots and bubbles protruding into relatively hot regions of the plasmas. The sputtering yield is indicative of 120 eV bombardment energies or temperatures that are three times greater than for the pre-melting sequence. The change in the wall source of beryllium is undoubtedly caused by the more extensive coverage of the wall following the initial melting, although the chromium production rate from the wall has not been reduced significantly. At 340 ms the rate of beryllium production at the limiter is two orders of magnitude greater than in the pre-melting case, but the chromium influx is not affected by the change in surface temperature.

After the studies at 155 kA, an extensive fluence test of 2500 shots at \( I_p = 115 \) kA was undertaken. Following this test, a 115 kA plasma was again characterized. The lowered current did not reduce the beryllium production in the sputtering phase of the discharge from the rate observed at 155 kA, and at most, a reduction by a factor of two was realized during the evaporation phase. Local hot spots on the protrusions existing at the limiter face were detected by an infrared camera. These were probably the origin of the evaporated atoms since the bulk temperature increase of the tiles during a discharge indicated that the energy deposited was insufficient to melt the surface uniformly. Radiation from the low stages of the metals is shown in Figs 14 and 15. It is seen that the time dependence of the beryllium ion radiation at the limiter is very similar to the evolution in the high-current case shown in Fig.12. Be I and Be II lines viewed at the wall show only minor indications of evaporation taking place. The Cr I influx from the limiter has increased above the influx during the melting sequence but is still only one-half the pre-melting rate.

Since Be-gettering reduces the low-Z impurity density in the plasma core, it is of interest to determine if the intermediate-Z elements are also diminished, because of deposited beryllium shielding the structural wall from sputtering as implied by the Unitor experiment [5]. It is somewhat difficult to compare data from the first IXS-B beryllium limiter experiments to previous observations in this machine. Earlier, a baseline study had been performed using a horizontal TiC bar limiter, which was later replaced with TiC-coated pump limiters [28]. The latter became partially covered with evaporated chromium from the prior gettering experiment. Therefore, the densities of these two metals are expected to be reduced simply by changing the limiter material to beryllium. However, some trends during the course of the beryllium limiter test itself can be discerned from the VUV lines of chromium, titanium, and iron. Intensities from several experiments are listed in Table III together with the limiter and getter materials. A reduction of titanium by a factor of two to three could be inferred following the installation of the beryllium limiter. Differing plasma conditions may, of course, influence the intensities for comparable impurity densities, and changes by factors of two or three are not necessarily indicative of trends. The final measurements following the fluence test do indicate, however, that reduction by an additional factor of four to ten has occurred. The overall change from the time of the chromium gettering experiment shows an unmistakable drop in the titanium content. Similar conclusions appear to hold for iron, although complete sets of data for all the experiments are not available for either Fe XV or Fe XVI. The chromium in the plasma does not show a clear change over the course of the beryllium tests, although the fluxes from Table II would indicate that the production rate has fallen to one-half or one-third of the initial value.

It is appropriate here to summarize briefly the understanding of sources and influxes of metallic impurities that have been obtained from these experiments:

1. Before significant damage occurred (115 kA discharges), the total beryllium flux from the limiter was \( \approx 10^{18} \) s\(^{-1}\) with sputtering presumed to be the
major production mechanism. Following the occurrence of severe limiter damage (155 kA discharges), the flux during the first 100 ms after injection, when sputtering dominated, was about $10^{19} \text{s}^{-1}$, roughly a factor of 10 above the previous levels, and it could not be reduced by returning to low-current operation. During phases of discharges when melting took place, the rate rose as high as $10^{20} \text{s}^{-1}$ and was still increasing when the discharges terminated.

2. The first set of 12 OH discharges showed that intermediate-Z elements from internal structures of the machine had been deposited on the limiter face. This is not surprising in view of the fact that the integrated wall fluxes of Cr and Ti were of the order of $10^{19} \text{s}^{-1}$. Assuming a shot lasts 330 ms and taking account of the 240 cm$^2$ area of the limiter leads to the conclusion that the average deposition from one discharge could amount to $10^{16} \text{particles \cdot cm}^{-2}$, or about one monolayer, if most of the wall flux is scraped off by the limiter.

3. Local influxes $\text{cm}^{-2}$ of Cr and Ti were greater from the limiter surface than from the walls, but the integrated fluxes were implied to be 6–30 times greater from the walls if toroidal and poloidal symmetry was assumed. The fraction of particles from the walls that passes through the scrape-off layer and into the main plasma is not known.

4. Once the beryllium melted and covered much of the vessel wall, low-Z impurities in the core of the plasmas were reduced by a factor of three through gettering. Titanium and iron concentrations were significantly lower by the end of the fluence test, the chromium density was not clearly reduced.

4. BERYLLIUM ION RADIATION

Up to this point the analysis of beryllium radiation to determine influxes has centred on the neutral species. We now try to correlate the intensities from all the ionization stages. Radiation from the ions should present a consistent picture with the radiation from the neutral particles if all of our assumptions are reasonably correct. That is, approximately the same influx of beryllium should be deduced from any one species. We examine this aspect of the experiment by comparing measured intensities to intensities computed from a transport code that assumes that the ions move inward from a plasma boundary where the neutrals are created so that successive ionization stages have their maximum concentrations at increasingly higher temperatures [29]. The possibility that singly charged ions may be born at lower temperatures than the neutral atoms does not fit this model, of course, and is perhaps responsible for some of the inconsistencies that will be pointed out. Approximate theoretical results for the relative intensities can be inferred from Fig.7 without numerical transport simulation by realizing that Be I and Be II should radiate close to their points of origin, and Be III is most likely to radiate where $T_e \approx I_p/3$, 51 eV. Calculations have been done for temperature profiles represented by a parabolic or a parabolic squared function ($T_e(0) = 850 \text{eV}$) superimposed on pedestals of 5 eV and 30 eV. The results are listed in Table IV. If all the Be I is assumed to be in the ground state, the ratio of the 3131 Å line of Be II to the 2349 Å line of Be I should be in the range from 2.3–5.3. It is implicit in this comparison that the Be II remains localized in the field of view at the limiter. Similarly, the ratio of the relative intensity of the Be III resonance line to the Be I line spans the range from 0.45–0.88. If significant fractions of the ions are lost by radial diffusion back to the limiter this ratio is lower. Since the Be III is essentially distributed axisymmetrically, the comparison with lower, more localized stages is accomplished by multiplying its intensity by 100, the ratio of the effective plasma surface area to the area viewed at the limiter.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Limit</th>
<th>100X</th>
<th>Wall</th>
<th>100X</th>
<th>Be II</th>
<th>Figure</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be II</td>
<td>Be I</td>
<td>112</td>
<td>Be I</td>
<td>112</td>
<td>2.3–5.3</td>
<td>14</td>
<td>150</td>
</tr>
<tr>
<td>Theoretical 2.3–5.3</td>
<td>0.45–0.88</td>
<td>14</td>
<td>290</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After fluence test</td>
<td>4.9</td>
<td>0.33</td>
<td>112</td>
<td>14</td>
<td>150</td>
<td>14</td>
<td>150</td>
</tr>
<tr>
<td>Melting sequence</td>
<td>5.7</td>
<td>0.42</td>
<td>259</td>
<td>14</td>
<td>150</td>
<td>14</td>
<td>290</td>
</tr>
<tr>
<td>Before melting</td>
<td>3.9</td>
<td>0.80</td>
<td>259</td>
<td>14</td>
<td>150</td>
<td>14</td>
<td>290</td>
</tr>
<tr>
<td>3.1</td>
<td>0.29</td>
<td>259</td>
<td>14</td>
<td>150</td>
<td>14</td>
<td>14</td>
<td>150</td>
</tr>
<tr>
<td>18.6</td>
<td>2.5</td>
<td>510</td>
<td>9</td>
<td>200</td>
<td>9</td>
<td>280</td>
<td>150</td>
</tr>
<tr>
<td>45</td>
<td>2.1</td>
<td>1300</td>
<td>9</td>
<td>200</td>
<td>9</td>
<td>280</td>
<td>150</td>
</tr>
</tbody>
</table>

NUCLEAR FUSION, Vol.25, No.11 (1985)
The data recorded from the melting sequence and from the sequence following the fluence test indicate that the experimental values referred to the limiter position are close to those expected from the calculations, both at 150 ms when the release mechanism is presumed to be sputtering and at 290 ms when evaporation appears to dominate. This result shows that only a small fraction of the Be II is lost from the limiter field of view. However, the comparison at the wall location shows that the Be II flux is 50-100 times as bright as anticipated if it were all formed from neutral atoms uniformly released from the walls. Two problems arise in trying to explain this observation. First, the mean free path for ionization at our typical limiter tip conditions is, at most, 20 cm (assuming that the ions are thermalized) so that the fraction of Be II appearing at the wall-viewing position 150 cm away would be of the order of $10^{-4}$ even if it all remained concentrated within the acceptance cone of the wall-viewing spectrometer. Instead, it is only a factor of 15 lower at 150 ms (Fig. 14). Secondly, if some transport anomaly is invoked which would explain rapid spreading along flux surfaces having the characteristic electron temperature of 30 eV at the limiter tip, then the emission that would have otherwise appeared in the limiter region would be greater by about a factor of 8, i.e. eight times greater than expected from the Be I flux. Such a circumstance does not seem plausible in view of the agreement between the theory and experiment at the limiter location. One possible resolution of this dichotomy is that the Be II observed by the wall-viewing spectrometer does not originate by release at the limiter, but actually results from a non-uniform wall source such that significantly greater numbers of ions migrate through the scrape-off layer than are expected from the local Be I signals. Another possibility is that some fraction of the Be II in the region of the limiter is born at relatively low temperatures, either from neutral particles emitted so they do not directly enter the main plasma or by sputtering a few centimetres behind the tip where the temperatures are 10 eV or lower and the electron density is less than $10^{13}$ cm$^{-3}$. In this case, most of the neutrals could still be detected, but some fraction of the ions could move well around the torus in the low-temperature scrape-off layer. Because of uncertainties in $T_e$, $n_e$, and transport in the scrape-off layer, it is not possible to determine whether the emission is consistent with only a small fraction of the Be II moving away from the immediate vicinity of the limiter. It can be discerned from Fig. 7 that the ratio of excitation to ionization increases very rapidly below 10 eV, and without detailed spatially resolved measurements there is no way of ascertaining the actual density of ions in the low-temperature region.

The agreement of the calculated and measured relative intensities around the limiter region gives us confidence that we are interpreting the influxes correctly despite the uncertainties connected with understanding the Be II emission, and that most of the primary flux appears within the plasma, at least at the radii where the He- and H-like stages radiate. This argument is supported by noting that the Be II radiation at the wall location tends to follow the signal from the limiter up to 200 ms when evaporation becomes noticeable (Fig. 14), but afterwards, there is only a slight indication of the rapid change of influx which occurs at the limiter surface. Since evaporated atoms have very low energies and are released predominantly at the limiter tip where $T_e$ is several tens of eV, singly charged ions have little chance of being transported very far. Thus, the favourable comparison of relative emissions in the vicinity of the limiter, both during the sputtering phase and the melting phase of a discharge, argues that the fluxes for the melting and the post-fluence sequences presented in Table II are accurate despite uncertainties concerning temperature contours over the limiter surface. It is still possible, however, that the wall source of the beryllium is not accounted for correctly because of non-uniformities of the deposition.

Reconciling the radiation from atoms and ions during the pre-melting sequence is more difficult than for the other two. Figures 9 to 11 indicate that oscillations after about 200 ms are seen in the hydrogen emission as well as in radiation from Cr I, Ti II, Be I, and Be III. These oscillations are accompanied by a drop in the average signal levels that indicates a lowered production rate with the exception of the Be II emission which continues to climb throughout the discharge. Moreover, the Be II signal at the end of the discharge is about eight times brighter than expected from comparison with the Be I lines in the vicinity of the limiter and is about 1300 times brighter at the wall-viewing position (Table IV). Significantly, the time behaviour at the two observation positions is identical, indicating a common source for the Be II ions.

The relative intensity of Be III to Be I is also greater than expected from the theoretical range, although the signal-to-noise ratio at this early stage of the experiment, when beryllium densities are small, is poor. Comparison of the 3721Å radiation from different sequences suggests that the experimental ratio, as shown in Table III, may be too large by a factor of two.
Taking this uncertainty into account still implies ratios somewhat greater than expected, particularly in view of the results from the other sequences.

We cannot construct a self-consistent picture of the beryllium behaviour during the pre-melting sequence, but we also note that the oxygen radiation at the edge is not easily interpreted, particularly at late times in the discharges. Figure 16 shows vacuum ultraviolet lines from O II, O IV, and O VI for this sequence. It is obvious that the time histories of O II and O IV emissions are not exactly the same as the histories of the visible lines detected by the wall-viewing spectrometer (Fig. 11). The vacuum ultraviolet lines are more strongly indicative of a phenomenon that has been observed frequently in ISX-B: a rapid rise in intensity at late times, accompanied by the onset of high-amplitude oscillations. Both phenomena become less apparent for progressively higher ionization stages. Similar features are observed in ASDEX preceding high-density disruptions [30], where they are associated with poloidal asymmetries reminiscent of marfes [31]. Small indications of this edge instability are seen in both the 3386 Å and 718 Å lines of O IV, but are not present in the 1032 Å radiation from O VI. Curiously, it does not appear in the visible line of O II at either viewing location, despite its being so obvious in the vacuum ultraviolet line. Nor do hydrogen lines in either the visible or vacuum ultraviolet region reflect this phenomenon. Although the rapid increase of radiation is suggestive of marfes, other characteristics do not fit the observations from Alcator. The difference in the O II lines seems to indicate that it is not toroidally symmetric, it is not confined to the inner wall because it can be seen by the limiter-viewing spectrometer, and there is no change in the hydrogen radiation. Moreover, it is worth noting that this instability prevents impurity accumulation in balanced injection discharges, whereas the occurrence of marfes on Alcator does not alter the transport and confinement of interior ions.

As a final comment concerning ion radiation, we compare the total radiated power as measured with a wide-angle bolometer to the power deduced from the spectroscopic results. The bolometer, which does not view the limiter, indicates 330 kW radiated power at 290 ms during the pre-melting sequence. From the spectral line emissions we infer that 345 kW are lost from oxygen, carbon, nitrogen, and deuterium. Less than 5 kW are radiated each by the intermediate-Z elements and the same limit is placed on losses from beryllium. The analysis of the spectroscopic results is estimated to be uncertain by 35%, so the agreement between the two methods of obtaining $P_{\text{rad}}$ is very satisfactory. During the evaporation phase of the melting sequence the two measurements do not agree so closely. At this time the bolometer shows that 150 kW radiated but only about 70% of this can be accounted for from the spectroscopy, approximately 60 kW from beryllium and 45 kW from the other low-Z impurities and deuterium. Despite the intense levels of radiation from Be I and Be II in the vicinity of the limiter, the power lost from these ions constitutes only 3—4 kW; the dominant losses come from Be III and Be IV.

5. IMPURITY DENSITIES

The final point of interest concerning beryllium as a limiter material is its density in the plasmas produced under various conditions. It burns out very near the edge and the bulk of its concentration resides in the fully ionized species. We could not measure these ions...
TABLE V. COMPARISONS OF MEASURED SIGNALS WITH EMISSION RATES CALCULATED ASSUMING UNIFORM IMPURITY PROFILES. ALL SPECTRAL LINE INTENSITIES ARE EXPRESSED IN GIGARAYLEIGHS

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Measured (n(0)(cm^-3))</th>
<th>Emission Rate (Calculated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(254 Å)</td>
<td>(170 Å)</td>
</tr>
<tr>
<td>Calc.</td>
<td>7.5 x 10^9</td>
<td>0.69</td>
</tr>
<tr>
<td>Meas.</td>
<td>0.85</td>
<td>1.5</td>
</tr>
<tr>
<td>Oxygen (non-melting limiter)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>n(0)(cm^-3)</td>
<td>O VI (1032 Å)</td>
</tr>
<tr>
<td>Calc.</td>
<td>6.5 x 10^11</td>
<td>113</td>
</tr>
<tr>
<td>Meas.</td>
<td>6.4 x 10^11</td>
<td>450</td>
</tr>
<tr>
<td>Oxygen (melting limiter)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>n(0)(cm^-3)</td>
<td>O VI (1032 Å)</td>
</tr>
<tr>
<td>Calc.</td>
<td>1.6 x 10^11</td>
<td>28</td>
</tr>
<tr>
<td>Meas.</td>
<td>1.6 x 10^11</td>
<td>30</td>
</tr>
</tbody>
</table>

Comparisons of calculated and experimental results relating to determinations of densities are shown in Table V. Measured central chord emission rates of titanium lines from the pre-melting sequence are matched to calculated intensities for a uniform distribution of 7.5 x 10^9 ions \cdot cm^-3 using measured radial profiles of T_e and n_e. The agreement is quite satisfactory in view of the uncertainties associated with this type of analysis. For oxygen, the central densities are known from the CXE measurements, and the intensities of the O VI resonance doublet (2p \rightarrow 2s) are simulated for comparison with experiment. Results for two sequences are listed in Table V, where the total oxygen profiles have also been taken to be independent of minor radius. With beryllium gettering, both the RECYCL code [21, 29] (which uses convective transport only) and the ASDEX code [9, 32] (where we have employed only diffusive terms with D = 4800 cm \cdot s^-1 to be consistent with measured impurity confinement times [33]) indicate that the profile is well represented by a uniform distribution. In the case without beryllium gettering, the comparison implies that the actual profile is peaked toward the edge of the plasma. However, the incongruities of trying to construct a self-consistent model for the low-Z impurity radiation for the pre-melting sequence have already been emphasized, and we believe that the preponderance of data implies that it is best to take the total beryllium profile as uniform. By making this assumption, central densities of 1 \times 10^{11}, 5 \times 10^{11}, and 4 \times 10^{12} cm^-3 are obtained, respectively, for the pre-melting case at 280 ms, and for the melting case at 150 ms when sputtering dominates and at 340 ms when evaporation dominates. The minimum density is 0.12% n_e, and the maximum is 6.6% n_e.

6. CONCLUSIONS

The use of beryllium as a limiter seems to be very satisfactory insofar as impurity problems are concerned provided thermal damage is minimized. The influxes and densities of this material appear to be no worse than those of intermediate-Z elements so long as melting is avoided, and the surface remains relatively smooth. With melting, the maximum concentration in the plasmas studied rose to 6—7% n_e, and the proton defect owing to beryllium was 28%. Most probably though, higher concentrations would have been realized if the discharges had lasted longer, since the beryllium influx was usually increasing at the end of shots in which melting occurred. Also, once the limiter had been damaged by high heat loads at 155 kA, it was not possible to return to low influx operation simply by reducing the current back to 115 kA. Melting continued to occur locally where the roughened surface protruded.

Before deposition of significant amounts of beryllium on the walls, the intermediate-Z metals produced at this source became deposited on the limiter and subsequently entered the plasmas. This deposition occurred either during discharge cleaning or during the first 12 OH shots. Therefore, simply using beryllium as a limiter is no guarantee that the densities of these heavier elements can be kept to a sufficiently low level in a fusion device. Concentrations of titanium and iron within plasmas declined by a factor of five or more because of beryllium plating out on the...
machine walls, but reduction of chromium was not so evident. It is possible that release and migration occurs more readily for chromium than for other metals since it was observed so distinctly at the limiter face after only 12 OH discharges.

Beryllium getters as efficiently as titanium or chromium, and, following the melting sequence, the low-Z impurities in the cores of the plasmas were reduced by a factor of three.

Appendix

ATOMIC RATE COEFFICIENTS

Since little spectral analysis has been performed on beryllium in fusion plasmas, it is worthwhile to outline the rate coefficients used in the present work. Detailed theoretical studies have been carried out for several excitation and ionization rates, and they are compared to commonly used general formulas. For Be I it is necessary to recognize that the $^{3}P$ metastable state, as well as the $^{1}S$ ground state, may be significantly populated. Therefore, excitation cross-sections for at least two lines are required so that the fractional density in each of these long-lived states may be determined. The three Be I transitions that were monitored during the course of the Be limiter experiment were 2349 Å ($2s2p\,^{1}P_{0}\rightarrow2s\,^{1}S$), 2651 Å ($2p^{2}\,^{3}P\rightarrow2s2p\,^{3}P_{0}$), and 3321 Å ($2s3s\,^{3}S\rightarrow2s2p\,^{3}P_{0}$). The 2349 Å line is excited only from the ground state, and the 2651 Å line is predominantly excited from the metastable state since the double-electron excitation, $2s^{2}\rightarrow2p^{2}$, has a very low probability. The 3321 Å line is also excited directly from the metastable state, but the possibility that it has a strong cascade contribution from the $2s3p\,^{3}P$ levels cannot be discounted.

Detailed calculations of excitation rates are available for the 2349 Å line of Be I [34], the 3131 Å doublet of Be II [35], and the 100.25 Å line of Be III [36]. The Be I and Be II calculations are shown as dashed lines in Figs 17 and 18. In the absence of specific calculations for a given transition, it is customary to use some generalized approximation which is proportional to the optical oscillator strength [37] for allowed transitions. We have employed the form given by Mewe [38] which uses a specific set of constants to calculate the averaged Gaunt factor, $\langle \tilde{g} \rangle$. The results of such calculations are shown as solid lines in Figs 17 and 18. Comparison with the more sophisticated investigations shows the semi-empirical rate to be too great for the 2349 Å line by a factor of two. It is felt, however, that the fractional populations of the Be I levels are best determined by using the ratio of the two semi-empirical coefficients since they are based on the same model. Absolute fluxes are then determined by applying the results of Ganas and Green [34] to the measured emission from the resonance transition. It should also be noted in Fig.17 that excitation of the 3321 Å line from the metastable state is theoretically an order of magnitude less than the rate of the 2651 Å line because of the large difference in oscillator strengths. The measured emission rates of the two lines are comparable, however, and this fact has led us to conclude that the $2s3s$ configuration may be populated to a large extent from the $2s3p\,^{3}P_{0}$ level which has no other branch for its decay. Since no
adequate theoretical calculations for this excitation exist, the 3321 Å line has not been used for quantitative analysis but only as a monitor for some relative comparisons between limiter and wall emissions.

Rate coefficients employed for the Be III and Be IV resonance lines are those from the \( g \) approximation. The direct collisional excitation coefficient of Pradhan, Norcross, and Hummer [36] for Be III is lower by a factor of two. However, some contribution to excitation of the \( 2^1P \) state comes about by collisions from the metastable levels. Therefore, it is believed that the semi-empirical formula represents a reasonable choice for the present accuracy of plasma analysis, in view of the fact that we have not specifically added any contributions from processes other than direct excitation from the ground state.

The ionization rate coefficients calculated from the Lotz [39, 40] formula are expressed as

\[
S = 3.0 \times 10^{-6} \sum_{m} \frac{\omega_{m}}{I_{p,m}\sqrt{kT}} E_1 (I_{p,m}/kT) \tag{A1}
\]

where \( \omega_{m} \) is the number of electrons in the \( m \)-th shell. The result for Be II is estimated to be no more than 10\% different from the DWBA calculations of Younger [41]. Again, it is necessary to account for the fact that a significant population of Be I exists in the metastable level, and three ionization processes must be considered, \( 2s^2 \rightarrow 2s + e, 2s2p \rightarrow 2s + e, \) and \( 2s2p \rightarrow 2p + e \). The last of these also gives rise to resonance emission of Be II, but the rate is much below the direct excitation from the \( 2s \) configuration of this ion. Inner-shell ionization is negligible at the temperatures where Be I and Be II are found in the present experiments. The solid lines in Figs 19 and 20 are calculated from Eq.(A1). The dashed lines in these two figures are the recommended fits from Bell et al. [42]. The two formulations show little discrepancy for Be II, but differ by about 25\% for Be I (g). The recommended rates of Bell et al. have been used for analysing the present data.

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