

# Molybdenum sources and transport in the Alcator C-Mod tokamak

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## Abstract

Atomic molybdenum influxes in the Alcator C-Mod tokamak have been monitored using visible spectroscopy. Measured source rates from the outer divertor, the largest source location, are compared to rates calculated from a standard physical sputtering model utilizing divertor Langmuir probe data. Comparison of the sputtering model with the measured molybdenum source rate shows good agreement during the Ohmic phase of the discharges examined. During the rf phase, the sputtering model consistently underestimates the molybdenum source rate. Analysis of a number of discharges shows no strong dependence of the divertor source on the plasma density for both L-modes and H-modes. The same source rates can be used to follow the screening of Mo from the core plasma. The penetration factor,  $PF \equiv N_{\text{core}} / \Phi$ , i.e. the ratio of the total number of Mo ions in the plasma core to the particle source rate, is higher for limited than diverted portions of discharges. The PF for Mo is found to be lower than another non-recycling impurity, nitrogen, during L-mode diverted plasmas.

## 1. Introduction

The choice of first wall materials, especially for the divertor, is of crucial importance for the design of fusion devices. Apart from having a number of favorable thermodynamic and mechanical properties, the plasma facing materials should be optimized to minimize erosion from sputtering and evaporation. Two classes of materials are used in present-day tokamaks. Low-Z divertor materials, such as beryllium and carbon, have the advantage of being fully stripped of electrons in the core, thus minimizing radiation losses. The majority of tokamaks use these materials in an attempt to minimize such power losses. On the other hand, the use of a high-Z material, such as molybdenum or tungsten, leads to a reduction of the source generation owing to their low sputtering yields compared to low-Z materials. However, the transport of such high Z impurities from the plasma interaction surface into the main plasma

needs to be minimized, since only low concentrations of these highly efficient radiators can be tolerated in the core.

All of the plasma interaction surfaces Alcator C-Mod consist of molybdenum tiles. The experiment is operated at high magnetic fields (5-8 T) and densities ( $\overline{n_e} \leq 1. \times 10^{21} m^{-3}$ ). It is therefore a unique environment for the study of the plasma interaction with molybdenum and its subsequent transport to the main plasma.

Spectroscopic determination of impurity influx from tokamak surfaces has been widely used to determine C influx [1,2]. The study of high-Z materials with this method is somewhat limited [3,4]. Source rate calculations have also been routinely made, especially in tokamaks with low-Z plasma interaction surfaces [5,6]. However, calculations involving high-Z plasma interaction surfaces have become more frequent the last few years [7-9].

In this work we investigate spectroscopically the generation of molybdenum influxes at tile surfaces and characterize their screening from the core plasma. In particular, the molybdenum sources from the outer divertor are compared to rates calculated from a standard physical sputtering model and subsequent redeposition utilizing divertor Langmuir probe data.

## 2. Experiment and technique

Alcator C-Mod is a high-field, high density tokamak, normally operating with a closed single-null divertor located at the bottom of the machine [10]. Typical plasma parameters for the results presented here, which are from the 1995-1996 experimental campaign, were  $I_p = 0.8-1.1$  MA,  $\overline{n_e} = 0.8-4.0 \times 10^{20} m^{-3}$ ,  $B_T = 5.3$  T,  $P_{RF} \leq 2.5$  MW and an elongation of 1.6.

For the identification of the various molybdenum sources in Alcator C-Mod a multiple-spatial-input, absolutely calibrated, visible spectrometer was used [11]. This system can continuously monitor emissions from up to 14 source locations with a spectral resolution of 0.15-0.25 nm and a time resolution of 45 ms. The spectroscopic determination of the molybdenum source rate was made possible by monitoring the MoI line at 386.4 nm. This line is a member of a MoI triplet ( $\lambda = 379.2, 386.4, 390.2$  nm). Quartz windows and fibers were used to minimize the transmission losses. The inner and outer divertor as well as inner wall surfaces were systematically monitored during these experiments. The  $n_e$  and  $T_e$  profiles along the outer divertor target, necessary for the modeling of the molybdenum sources, were measured with an array of Langmuir probes in the tiles [12].

For the screening studies, the core impurity content of molybdenum was measured using a multilayer mirror based, XUV polychromator [13]. This system had a fixed radial chord through the center of the plasma and was configured to simultaneously measure specific emission regions of the molybdenum spectrum in the 3.0 to 4.0 nm, 6.0 to 8.5 nm and 11.0 to 14.0 nm wavelength regions. These emissions are emanating from the core of the plasma.

The array of viewing chords used to monitor the radiation from the outer target are shown in Fig. 1, together with the location of the Langmuir probes used in the modeling. The neutral molybdenum particle influx,  $\Gamma$ , can be derived from the measured intensity  $I$  of the MoI line using the relation  $\Gamma = 4\pi I (S/XB)$ , where  $(S/XB)$  is the number of molybdenum ionizations per emitted photon.  $S$  is the ionization rate,  $X$  is the excitation rate,  $B$  the branching ratio. For a description of this technique see Field [2] and Fussmann [3]. Appropriate  $S/XB$  data for the line of interest as a function of the plasma electron temperature and density are obtained from the ADAS database [14]. The local electron temperature and density were obtained from the Langmuir probes.

### 3. Source model

The influx of sputtered molybdenum at the divertor surface can also be computed at each probe location based on a sputtering model utilizing the measured ion saturation current density  $J_s$ , the inclination angle,  $\theta$ , of the field lines with respect to the divertor target surface from magnetic field reconstruction, and the local plasma characteristics ( $T_e$ ,  $n_e$ ). The important elements of the erosion/ redeposition model used in this study are based on a study by Naujoks et al. [9]. With boron being the main low- $Z$  impurity following boronization of the Alcator C-Mod vessel, the molybdenum influx is calculated from

$$\Gamma = \frac{(J_s / e)}{1 + bZ_B} \sin\theta \frac{(Y_D + bY_B)}{(1 - rY_{Mo})}. \quad (1)$$

$Z_B$  is the charge of the boron ions,  $Y_D$ ,  $Y_B$  and  $Y_{Mo}$  are the molybdenum sputtering yields due to deuterium, boron and molybdenum ions, respectively.  $\beta$  is the ratio of boron to deuterium ion flux which is not independently measured but inferred from the comparison with the spectroscopic results.  $r$  is the fraction of the promptly redeposited molybdenum ions,

i.e. the fraction of the ions redeposited within the first gyration. The calculation of  $r$  is based on the description given elsewhere [9,15]. The result, without including the sheath potential, is (see Eq. 2 of Ref. [9]):

$$r = \frac{1}{2} \left[ 1 + \text{sig}(1-p) \left( 1 + \frac{4p^2}{(1-p^2)^2} \right)^{-1/2} \right] \quad (2)$$

where  $p$  is the ratio of the ionization length  $\lambda_{\text{ion}}$  to the gyroradius  $\rho$ :

$$p = \lambda_{\text{ion}} / \rho \propto B_T / (m_{\text{Mo}} S n_e). \quad (3)$$

$B_T$  denotes the local magnetic field,  $m_{\text{Mo}}$  the molybdenum mass and  $S$  the temperature dependent molybdenum ionization rate obtained from the ADAS database [16] and the Langmuir probe data. The smaller the value of  $p$  the bigger the probability of prompt redeposition  $r$  which, for the conditions occurring in the Alcator C-Mod divertor, can reach values close to unity.

Several important assumptions have been made that are essential to this model. For the calculation of the molybdenum influx the boron ions are assumed to be helium-like (i.e.  $Z_B = +3$ ). This choice is supported from previous experiments [17]. Only promptly redeposited Mo ions are considered to contribute to Mo self-sputtering. This means that all ions that are not promptly redeposited enter the plasma. These ions are assumed to disperse uniformly in the scrape-off layer and thus represent a small contribution at the outer strike point. An average charge  $Z_{\text{Mo}} = +1.5$  is used for the promptly redeposited Mo ions. This is based on the fact that at high electron densities, such as is the case for Alcator C-Mod, particles can be ionized multiple times before completing their first orbit [9]. Although these additional ionizations will reduce the probability of prompt redeposition, some of the ions will make it back to the target. This assumption is further supported by a calculation for tungsten, in which an average charge of 2 is obtained for the redeposited ions [18].

The energy of the deuterons and boron ions can be approximated by

$$E = 2 T_i + 3 Z_i T_e \approx (2 + 3 Z_i) T_e. \quad (4)$$

However, the sputtering yields used here for deuterons and boron ions are convolutions of the single energy yield curve with a Maxwellian energy distribution shifted by the energy gained from the sheath potential,  $3 Z_i T_e$ . In the current model, molybdenum is assumed, for simplicity, to be ionized just outside the sheath, gaining the full energy of  $3 Z_{\text{Mo}} T_e$  on returning to the surface. The original energy of the sputtered atoms, which is a few eV, is neglected.

The calculation of yields is based on the widely used sputtering formula by Bohdansky [19,20] for normal incidence. Since two of the parameters, the yield factor and the threshold energy, needed for the calculation of boron sputtering of molybdenum were not available, a fit of the boron yield from available molybdenum sputtering data on H, D, T,  $^4\text{He}$  and C [20] was used.

With the magnetic field lines at oblique angles to the divertor surface, the appropriate yields for an angle of incidence  $\alpha = 65^\circ$  ( $\alpha = 90^\circ - \theta$ ) should be used [21]. However, for light ions, such as deuterons and borons, incident on heavy targets, the sputtering yield for the energies of interest at  $\alpha = 65^\circ$  is close to the yield at normal incidence [22], so no yield enhancements have been used. Sputtering models have shown that different set of parameters characterize heavy ion sputtering of heavy targets. It has been shown that promptly redeposited tungsten ions tend to impact at near normal angles of incidence ( $\alpha \approx 18^\circ$ ) [18]. Since no data were available regarding the dependence on the angle of incidence of the Mo self-sputtering yield, the corresponding yield enhancement for tungsten self-sputtering as a function of the ion energy [23] was applied to the Mo self-sputtering.

#### 4. Results

The fractional abundance of boron,  $\beta$ , is determined by comparing the sputtering model source rate with that inferred from spectroscopy. There are 7 probes located on the vertical face of the outer divertor and 6 chordal views of this same surface (Fig. 1). The total Mo source rate,  $\Phi$ , is obtained by integrating the Mo influxes over the divertor surface for both the model and the experiment. A comparison of the two results for a number of discharges leads us to select  $\beta \sim 1.9\%$  as the optimum match for the ohmic phase of plasmas. Such a comparison is shown in Fig. 2. Good temporal agreement can be seen during the ohmic part of the shot. On the other hand, during the rf phase, the sputtering model predicts values 2-3 times lower for the molybdenum source. These trends for both the ohmic and rf phases of the discharge have been found to be very common for our plasmas and are also observed in individual probe and chord comparisons.

The results of such cases as Fig. 2 can also be integrated over an entire discharge. In Fig. 3 we show a comparison between model and measurement for 49 discharges from the

1995-1996 period. These discharges have widely varying conditions but among them are included those with the highest Mo measured source rates. The boron ion flux was kept to 1.9% for all shots presented other than those in the shaded region. For a fraction of the discharges shown we were required to use a higher boron flux of 4.8% in order to achieve quantitative agreement of the sputtering model with measured Mo influx during the ohmic part of those discharges (all from the same run day). The agreement between the two ohmic curves [Fig. 3(a)] is fairly good. On the other hand, the two rf curves [Fig. 3(b)] exhibit the pattern initially mentioned in reference to Fig. 2. The Langmuir probe based calculations consistently underestimate the molybdenum emissions by up to a factor 4.

The boronization of the Alcator C-Mod vessel has been shown to significantly reduce the concentration of Mo in the plasma core. In terms of the Mo sources it has been observed that at the beginning of a run day that immediately followed boronization of the chamber, the Mo emissions from all locations observed were practically zero and gradually started to recover to their original levels as the day progressed. The speed of recovery back to ‘normal’ Mo levels depends, of course, on the boronizing conditions and the type of plasma discharges. This effect is partly revealed in Fig. 3(a) where it is shown that the spectroscopically measured sources were lower than the calculated ones during the beginning of the first run day after a boronization of the vessel.

The model underestimation of the Mo source rate during the ICRF heated discharge phase is consistent across all the discharges studied. In an effort to understand the cause we have looked for a dependence of the discrepancy with various plasma parameters. In Fig. 4 we show the dependence of the enhancement of the model source rate needed to match that measured through spectroscopy. No clear dependence on the rf power level is found. However, this comparison seems to imply the existence of a power threshold around 1.15 MW. Above this power, an enhancement by a factor of  $\sim 2$  is needed, on average, for the two results to match.

During the 1995-1996 experimental campaign the total molybdenum net erosion at various locations inside the C-Mod vessel, including the outer divertor, was measured with the use of appropriately modified molybdenum tiles [24]. These net erosion measurements have been compared with a campaign-integrated net erosion prediction, based on the model assumptions discussed above and probe measurements. Only tiles from the outer divertor

showed significant amounts of net erosion. Net erosion is calculated by multiplying the gross erosion, Eq. (1), by the fraction of the atoms that did not promptly redeposit  $(1 - r)$  [9]. As shown by Wampler [24] the measured and calculated net erosions differ, depending on the location, at most by a factor of about 3. In this calculation, an enhancement of the calculated erosion by a factor of 2 during rf heating was included, based on the data of Fig. 4.

The investigation of the various molybdenum sources in Alcator showed that the outer divertor is the largest contributor, at least during plasma current flattop conditions. Analysis of a number of discharges showed that the MoI emissions peak is close to the divertor strike point. No dependence of the outer divertor source rates on  $\overline{n_e}$  has been found for either L-mode and H-mode conditions. In H-modes the Mo source rate is typically  $\sim 4\times$  larger than during L-modes. In addition, the plasma Mo content is somewhat independent of the divertor source levels, implying that the majority of Mo ions in the core did not originate from there.

Other sources of sputtered molybdenum have been identified as well. One of them is the inner wall which is, in many cases, a significant source during the initial limited phase of each discharge. High current ramp-up rates,  $\geq 5$  MA/s, are correlated with increased Mo concentrations in the plasma core during this phase but there has not been a consistent identification of the inner wall as being the source of the Mo. In general, however, a linear dependence of the molybdenum content in the core on the inner wall source rate is observed at the beginning of discharges. MoI radiation from the ICRF antenna protection limiters has also been occasionally detected, especially during rf heating, but there has not been a consistent correlation between core Mo and the MoI derived source rate from these locations. No Mo emissions have been measured emanating from the ICRF Antennas themselves. The inner divertor is always much colder than the outer divertor under typical C-Mod experimental conditions, and hence is not a source of significant molybdenum emissions.

The same source rates can be used to follow the screening of Mo from the core plasma. An empirical penetration factor for Mo, which behaves as a non-recycling impurity, can be defined as the ratio of the total number of Mo ions in the plasma core, which is obtained from the XUV spectrometer, to the particle source rate:  $PF_{\text{Mo}} \equiv N_{\text{core}}/\Phi$ . Figure 5 shows the Mo PF for L-mode and H-mode diverted discharges as well as for limited discharges (during current ramp-up) as a function of the line averaged density. The factors for the L-mode diverted portions of discharges are, in general, much lower than those for limited portions but there is a

small overlap of the experimental data in terms of the electron density. The PF for diverted discharges is actually an upper limit, since there can be other Mo source rates around the chamber that we do not observe. The L-mode divertor penetration factors are typically at least  $10\times$  lower than characteristic L-mode impurity particle confinement times,  $\tau_p \sim 20$  ms [25], implying extremely good divertor screening [26]. In the shaded region of Fig. 5 the penetration factor obtained with another non-recycling impurity, nitrogen, is given [27]. Molybdenum PF for diverted L-mode discharges are, on average, lower than the corresponding values for nitrogen.

## 5. Discussion

The discrepancy between the measured and modeled Mo source rate results during the rf discharge phase is a source of concern. We have considered several mechanisms which could explain this enhancement. One assumption that is called into question is that of toroidal symmetry. The probe and MoI spectroscopic measurements are made at two separate toroidal locations. It is possible that the level of toroidal asymmetry (unknown) changes upon transition to the rf phase of a discharge. However, we have no evidence that would support such a possibility.

Another possible explanation of the discrepancy between model and Mo source measurements is that the energy of sputtering ions is somehow enhanced during the rf phase of the discharge. This could occur due to either the emergence of a non-thermal electron population or an increase in  $T_i/T_e$ . The former increases the sheath potential even in the presence of very small ( $\sim 1\%$ ) non thermal populations [28]. The latter directly affects the energy of the ion and is, perhaps, more likely to be the cause of the discrepancy. While this requires further investigation, it is important to note that energetic ion particle tails of up to 4 keV, during rf heating, have been observed in the plasma edge of Alcator C-Mod [29].

Variations of the boron levels within a shot may also be partly responsible for the increased source rates during ICRF heated phases of discharges. In our study we have completely ignored this factor and assumed that the boron levels stay constant during the shot.

An important assumption in our model is the inclusion of only the promptly redeposited Mo ions in the self-sputtering of Mo. Although the probability of redeposition frequently reaches values close to one for the conditions occurring in our plasmas, the value used for  $Y_{Mo}$  should be considered a lower estimate of the self-sputtering yield, since highly



charged Mo ions escaping from the core can reach substantial energies as they get accelerated through the sheath and pre-sheath (by friction with the background plasma). On the other hand, if some of the promptly redeposited ions are ionized inside the sheath that would lead to a reduction of the calculated yield. These assumptions have a direct impact on the level of boron needed in the modeling to explain the measured results.

The level of boron needed to match measurement and model is significant. If such levels were actually occurring in the core plasma the contribution to  $Z_{\text{eff}}$  would have been  $\sim 0.4$ . This is at the upper range of possibility for C-Mod ohmic plasmas where  $Z_{\text{eff}}$  is typically  $\leq 1.3$ . However, the concentration of boron in the divertor is probably higher than in the core.

## **6. Conclusions**

Measured Mo source levels for the outer divertor in Alcator C-Mod are in good agreement, during the ohmic heating phase of plasmas, with the modeled levels assuming, typically, a combination of deuterium and  $\sim 2\%$  of helium-like boron ion fluxes and including the promptly redeposited Mo ions. An enhancement of the modeled source rates up to a factor of 4 is needed for the ICRF heated phase of discharges.

The Mo core content is somewhat independent of the outer divertor source rate but it increases linearly with inner wall source rate during the limited phase of plasma discharges. No clear correlation between the divertor source rate and the core plasma density has been observed, for either L-modes and H-modes. The divertor source rates are generally higher ( $\sim 4\times$ ) during H-modes.

The divertor is effective in screening most of the molybdenum that is generated there. The divertor Mo penetration factors are typically  $10\times$  smaller than L-mode particle confinement time of Mo ions. L-mode penetration factors of Mo are, on average, lower than that of nitrogen.

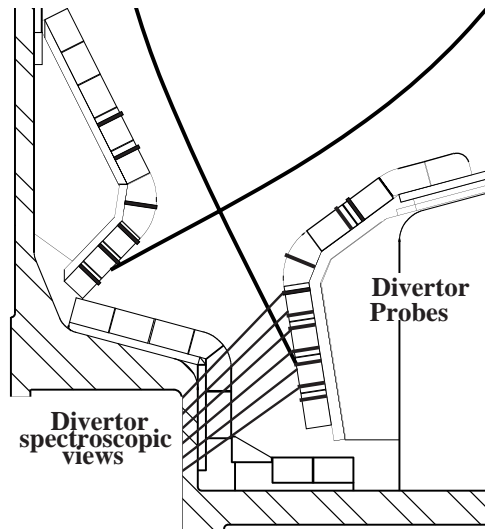
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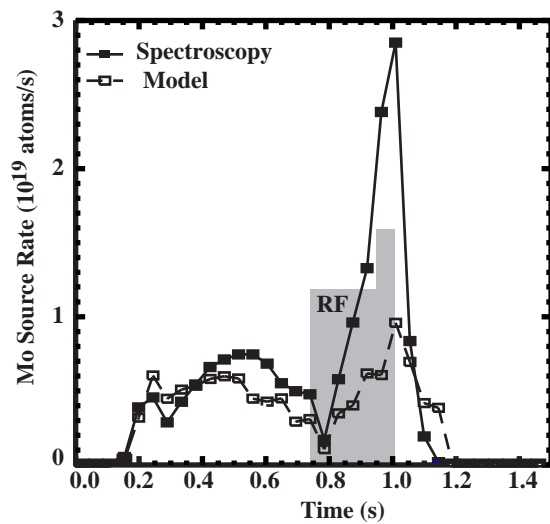
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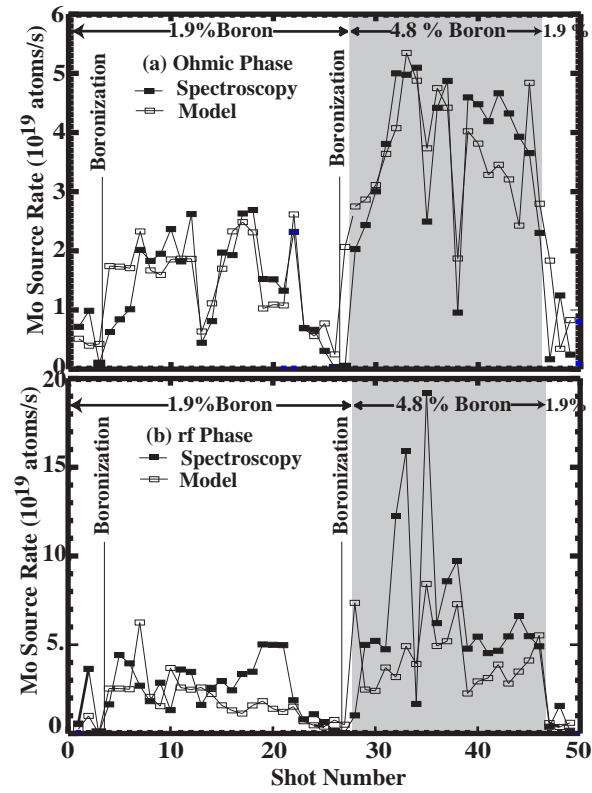
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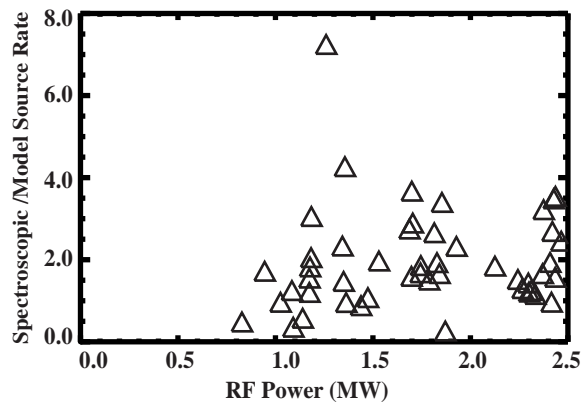
**Fig. 1.** Poloidal cross section of the divertor region. The divertor spectroscopic views use local electron temperature and density obtained with the Langmuir probes.



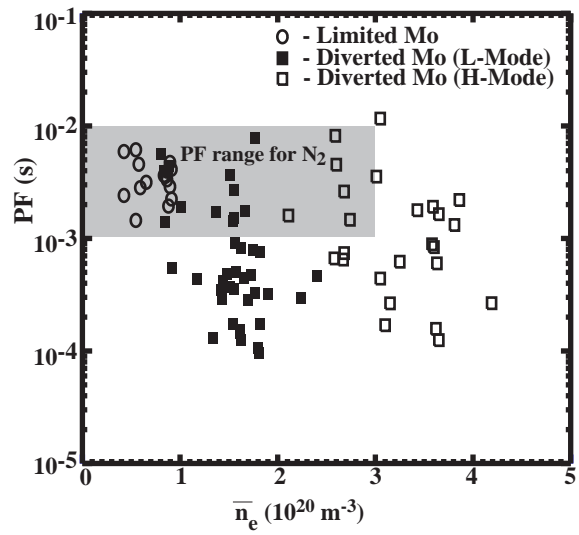
**Fig. 2.** Comparison of the calculated outer divertor source rate from spectroscopic data and the sputtering model. The rf power, which is also shown, is increased from 1.2 to 1.6 MW at 0.95 s.



**Fig. 3.** Mo source rates from spectroscopy and model for a number of shots. (a) Averages during the ohmic phase of each shot. (b) Averages during the rf phase. 1.9% boron was assumed except at the shaded region where it was increased to 4.8%. Boronizations of the vessel are marked.



**Fig. 4.** Ratio of the spectroscopically measured Mo source rates to the calculated vs. rf input power. Above an rf power threshold of 1.15 MW, an average enhancement of the modeled source rates by a factor of 2 is needed for the two results to match.



**Fig. 5.** Mo penetration factors for limited and diverted portions of discharges. Typical penetration factors for nitrogen are denoted by the shaded region.