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Authors

Ehlers, K.W.

Leung, K.N.

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EFFECTS OF CESIUM IN THE PLASMA OF THE SURFACE
CONVERSION H⁻ SOURCE

K. W. Ehlers, K. N. Leung
Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

ABSTRACT

The usual method for replacing the partial monolayer of cesium which is removed by sputtering from the surface of the converter electrode of a surface production negative ion source, is to allow cesium atoms to condense or adsorb onto this surface. While this method is easily employed for short pulsed source operation, it becomes increasingly difficult in the dc case because of the high probability of ionization of the cesium atoms as they pass through the discharge. In this paper, we attempt to analyse the severity of this problem in which cesium arrives at the converter surface as an energetic ion rather than as a thermal atom.

INTRODUCTION

Perhaps the most difficult problem encountered by those working with surface production sources which must produce continuous, multi-ampere beams of H⁻ and D⁻ ions, is that of maintaining a uniform, low work-function coating of cesium on large converter surfaces. For pulsed source operation, this problem is minimized as cesium atoms can be allowed to adsorb onto the converter surface during the time the discharge is off. The optimum coverage¹ of approximately 0.67 monolayers can be obtained by supplying ample cesium vapor and then allowing the converter electrode to heat up to the temperature where only a partial monolayer will exist. When the discharge is struck, this optimum coverage will be eroded away at a rate depending on the energy and the number of ions which strike the surface. In this manner one obtains the very short pulses of very high ion current density that are characteristic of the Magnetron and Planotron.² In the case of dc operation, this ability to coat the converter with cesium atoms essentially disappears as the cesium must travel through the plasma and in doing so, it becomes ionized.

Fig. 1 is the cross-section for the ionization of cesium by electron impact.³ Because of the low ionization potential of cesium atoms (3.89 eV), the cross-section remains large for even very low electron energies. Thus a very large portion of the electrons contained in a plasma are capable of ionizing cesium atoms as they enter the plasma from either a wall or from a cesium feed system located outside the plasma. Because of the effectiveness of the bulk of the plasma electrons to ionize, plus the large mass of the cesium atoms ($A = 133$), we can expect the ionization mean free path to be quite short.

Fig. 1. Cross-Section for Ionization of Cesium by Electron Impact

If we assume that the temperature of the cesium neutrals is about 500°K ($T_0 = \sim .04$ eV), and that the average effective electron energy is 6 eV ($\sigma = 5 \times 10^{-16}$ cm²), we then find:

$$\lambda_{\text{mfp}} = \frac{1}{\sigma \times n_e} \times \sqrt{\frac{m_e}{M_{\text{cs}}} \times \frac{T_0}{T_e}}$$

$$= \frac{3.6 \times 10^{11}}{n_e}$$

Thus at plasma densities of 5×10^{11} /cm³, which is about our minimum plasma density of interest, the mean free path for ionization of cesium is ~ 1.0 cm. As the density is increased, the path length becomes progressively shorter, and for a given geometry, there will be a limiting plasma density at which insufficient neutral cesium will reach the converter. When this density limit is exceeded, then more cesium will be sputtered from the converter than can be resupplied, and it is our present conviction that it is this situation that limits the output of surface sources that must operate dc.

Fig. 2 shows the output signals from a spectrometer that was tuned to monitor several Cs I (neutral) and Cs II (Cs⁺) lines while viewing a hydrogen discharge with cesium added. While maintaining a constant arc voltage, the arc current was increased from 10 to 40 A, and as shown in Fig. 2-A, the cesium ion lines increased greatly with the increase in plasma density. The relative intensity of the 4555.28 Å cesium neutral line and the 4603.76 Å cesium ion line are plotted in Fig. 2-B. Because the intensity of the cesium ion line is not linear with arc current, we suspect that the

Fig. 2. Cesium Light from a Discharge vs. Arc Current

average effective electron energy also increased as the arc current was raised.

Thus it becomes apparent that we should expect a sizable difference in H⁻ output from short pulse and dc operated systems. We know the converter can be coated by cesium atoms, but what happens to this loading when the vast majority of the cesium strikes the converter in the form of energetic ions. We have found it very difficult to answer this question as much of the basic physics data has never been taken. But it does seem important to use our experience and that data we can find to make a best guess as to the magnitude of the problem and of the important parameters involved.

Specifically, we wish to know just what happens when a Cs⁺ ion hits a surface, preferably molybdenum, with an energy of about 100 to 300 eV.

When a positive ion strikes a solid surface, it may give rise to a variety of phenomena:

1. Atoms can be sputtered from the surface.
2. The ion can be neutralized at the surface and then reflect as a neutral atom.
3. The ion can reflect as a positive ion with some loss in energy.
4. The ion may be neutralized and adsorbed on the surface.
5. The ion may penetrate the surface and be adsorbed.
6. The positive ion can release secondary electrons from the surface.
7. The positive ion may capture two electrons and leave the surface as a negative ion.

SPUTTERING

The fractional monolayer coverage of cesium on tungsten vs. temperature was rather extensively studied by Taylor and Langmuir⁴ who found that a minimum work-function coverage of cesium could be maintained if tungsten was heated to about 550°K, and that all adsorbed cesium could be removed in the form of positive ions, if the temperature was increased to ~1200°K. Although this method of cesium control is important for pulsed sources, it is not pertinent to dc sources, where the converter electrode is well cooled and the problem is one of providing enough cesium rather than too much.

For dc sources, the principal mechanism by which cesium is removed from the converter surface is the sputtering away of the cesium layer by the cesium ions present in the discharge. Experimental data for determining this sputtering ratio is not available, but as this ratio is important for this consideration, an attempt has been made to determine its approximate magnitude.

Fig. 3. Sputtering Yields for H^+ , D^+ , Xe^+ , and Cs^+ (calculated) on Molybdenum.

Fig. 3 shows the experimentally obtained sputtering ratio of xenon, with a mass similar to that of cesium, on molybdenum.⁵ This ratio should represent a lower limit to the ratio we wish to know. Needless to say, if the xenon, or cesium ions, can sputter the moly substrate, which has a high binding energy of 6.83 eV, they certainly will have removed adsorbed cesium which has a much reduced heat of sublimation. Also shown in Fig. 3 is the sputtering ratio of hydrogen and deuterium on molybdenum. The sputtering effects from these two light ions can be ignored as they are two to three orders of magnitude lower than that of a cesium mass ion. Bay⁶ predicts that at 150 eV, sputtering of moly by hydrogen should be null as this energy is about his predicted sputtering threshold.

Theoretical sputtering ratios and thresholds are related to the heat of sublimation or the heat of desorption of the target surface. Thus the sputtering of

cesium from the surface should be expected to be greater than that of moly as the heat of desorption is less. In addition, the heat of desorption increases as the cesium coverage decreases, hence the

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Fig. 4. Heat of Desorption for Cesium on the $\square$ 100 and $\bigcirc$ 110 Faces of Tungsten versus Coverage.

approaches 1 in our energy range of interest, and very likely doubles as the ion energy increases from 150 to 300 eV.

We have repeatedly observed that as the plasma density is increased, which results in less cesium neutrals and more cesium ions reaching the converter surface, the converter bias must be reduced in order to reduce the sputtering ratio. In our test stand with plasma densities of $\sim 10^{12}/\text{cm}^2$, we find the optimum converter potential is often 100 volts, where as we would rather operate with a higher bias as the H^- output would likely be increased.

REFLECTION

One normally concludes that when 150 to 300 eV ions strike a surface at normal incidence, they would neutralize, impart much of their energy to the surface, and then rebound from the surface as lower energy neutrals. However, this is not true when the ionization potential of the impacting ion is very low. Arifov⁹ has investigated the processes which occur when alkali ions strike a sur-

sputtering ratio should not stay constant. Fig. 4 shows this sizable increase in the heat of desorption as the cesium coverage on a tungsten substrate decreases.⁷ This indicates a thick cesium layer is more easily sputtered away than a partial monolayer. The minimum work function for the 100 face of tungsten requires about 2.5×10^{14} cesium atoms per cm^2 , and the 110 face requires about $3.2 \times 10^{14}/\text{cm}^2$.

Using the Garching TRIM code for sputtering, Eckstein⁸ has calculated the sputtering ratio of Cs^+ on thick cesium, and these results are also plotted in Fig. 3. Because of unknown factors, these yields can have an error as large as a factor of two. In addition the code shows a factor of two reduction in the sputtering rate when the heat of desorption is changed from .75 eV to 1.75 eV.

Thus our data is limited as to the actual sputtering rate of the partial coverage of cesium by cesium ions, however the indications are that it

face, and he finds that a remarkably high fraction of impacting Cs^+ ions scatter from the surface as low energy positive ions.

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Fig. 5. Ratio of Scattered Secondary Ions vs. Energy for Similar Mass Impacting Ions. $\circ$ = Cesium $\bullet$ = Barium

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Fig. 6. Energy Spectrum of Secondary Cs^+ Ions, for 300 eV Primary Cs^+ Ions on Molybdenum

Fig. 5 is a plot of Arifov's data which shows that when 150eV Cs^+ ions (ionization potential = 3.89 eV) impact at normal incidence on molybdenum, about 63% reflect as Cs^+ . For the case of barium, which has a mass similar to cesium but a slightly higher ionization potential (5.81 eV), less than 10% scatter from the surface as positive ions. Thus one can see that for gases like hydrogen and deuterium which have a considerably higher ionization potential, essentially no scattered ions would result, and only low energy neutrals would leave the surface.

Fortunately, Arifov was also able to measure the energy spectra of the reflected positive ions and these results are shown in Fig. 6. Essen-

tially all the reflected ions are contained in the spectrum shown which ranges from near zero to less than 10 eV, and with a maximum at ~ 3.5 eV. This is a most fortunate effect for surface conversion sources. The sheath immediately adjacent to the converter surface which provides the cesium ion impact energy, will be effective in returning these low energy cesium ions back to the

converter surface. Their next encounter with the surface will now be at such a reduced energy that they should now neutralize and stick to the surface as neutral atoms. Therefore, with a converter potential of 150 volts, we should expect nearly 60% of the incoming energetic cesium ions to be retained on the converter surface. In turn, it is interesting to note that one retains nearly 20% more of the incoming cesium ions by operating the converter bias at -150 rather than -300V. Both this effect as well as the reduced sputtering ratio favor reduced converter potentials.

ADSORPTION AND ABSORPTION

If Arifov's data is correct, and at 150 eV we are able to retain 60% of the impacting cesium ions, the remaining 40% must either be absorbed on the converter surface, penetrate the surface and be adsorbed, or scatter from the surface as a low energy neutral. Arifov⁹ did an interesting experiment, the results of which are shown in Fig. 7. By heating a molybdenum target after it had been bombarded for some time with Cs^+ ions, he was able to detect a group of thermally produced ions which had been absorbed by the target and which required time to diffuse to the surface and become ionized. The first weak indication of cesium ions having penetrated the target was observed at ~ 200 eV. These currents were very weak, and thus we can conclude that only a few percent of the cesium ions in our energy range of interest are retained by penetration or absorption.

Although it is not conclusive, the same experiment seems to indicate that not too many of the cesium ions remained on the surface when the target was initially heated. It is much more probable that the large majority of the remaining 40% are neutralized and then leave the surface as neutral cesium atoms with energies similar to that shown in Fig. 6.

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Fig. 7 Dependence of Cesium Ion Penetration of Molybdenum on Ion Energy

From this data, though admittedly incomplete, we have constructed the following model for the effects of cesium in the discharge: Approximately 60% of the cesium ions which strike the molybdenum converter electrode scatter as very low energy cesium ions. Because of their reduced energy, they are prevented from leaving the converter by the cathode sheath and are ultimately retained on the converter surface as neutral cesium atoms. The majority of the remaining 40% of impacting ions, leave the surface as low energy neutrals and they re-enter the plasma. If the sputtering ratio exceeds 0.6, additional cesium neutrals must arrive at the converter to maintain the desired cesium coverage. As the plasma density is increased, fewer cesium neutrals can penetrate the plasma and the converter surface becomes under-cesiated. If more cesium neutrals reach the converter than are required, one can easily maintain the desired coverage by increasing the converter potential which increases the cesium sputtering rate. If we are generally undercesiated as our test results indicate, it is probable that the sputtering ratio does exceed 0.6 even at the reduced converter potential at which we operate. An indication of this is shown in the photographed waveform shown in Fig. 8. H⁻ ions were being extracted from the LBL surface production test source by a pulsed (3 sec.) 15 kV power supply. The lower flat trace is the three second pulse of the acceleration potential as read across a voltage divider. The self-extraction source was running dc, but prior to the high voltage pulse, the converter potential had been turned off. This allowed the converter to float electrically, and its floating potential was just 30 volts below anode potential. At this potential, cesium ions which strike the converter do very little sputtering of the cesium coverage, hence the cesium coverage increases. Just prior to the application of

Fig. 8. Extracted H⁻ output vs. time (See text)

the acceleration potential, the converter bias was raised to -150 volts, and one can see (on the top trace) that the H^- output is considerably higher at the beginning of the pulse. With time, the cesium coverage sputters away and the H^- output drops back to its original dc operating level.

SECONDARY ELECTRON PRODUCTION

By changing Faraday bias potentials, Arifov⁹ was able to determine the secondary electron ratio for Cs^+ ions striking tantalum that contained an adsorbed film of cesium atoms. In order to change the film coverage, he determined the secondary electron ratio vs. the temperature of the tantalum target and this data is shown in Fig. 9.

Fig. 9. Secondary Electron Ratio for 300 eV Cs^+ on Tantalum vs. Temperature

The secondary electron production ranges from 30 to 35% as the target is heated up to about 900°K. Above this temperature the secondary production drops as the cesium film is driven from the heated surface. At a temperature of about 1350°K, and for ion energies up to 1 keV, the secondary electron ratio drops to less than 1%. Thus the presence of the adsorbed film on the target is the source of the ion-electron emission.

This data would indicate that ~ 30% of the converter power supply drain is due to secondary electrons, which then enter the plasma with energy equal to the bias potential. The magnitude of photon produced secondary electrons from the converter surface is not known, but they would add to the drain of the power supply as well.

CONCLUSION

We have attempted to determine the approximate magnitude of the effects which can occur at the surface of a converter, when cesium is added to a hydrogen discharge. Due to the lack of experimental data, one can only make his best guess based on that data which does presently exist. Our best guesses may change with the addition of time, experience, and experimentally obtained physics data.

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