Effect of cesium and xenon seeding in negative hydrogen ion sources

M. Bacal, A.M. Bruneteau, C. Deniset, L.I. Elizarov[a], F. Sube, A.Y. Tontegode[b] and J. H. Whealton [c]
Laboratoire de Physique des Milieux Ionisés, U.M.R. 7648 du C.N.R.S., Ecole Polytechnique, 91128 Palaiseau.

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It is well known that cesium seeding in volume hydrogen negative ion sources leads to a large reduction of the extracted electron curent and in some cases to the enhancement of the negative ion curent. The cooling of the electrons due to the addition of this heavy impurity was proposed as a possible cause of the mentioned observations. In order to verify this assumption, we seeded the hydrogen plasma with xenon, which has an atomic weight almost equal to that of cesium. The plasma properties were studied in the extraction region of the negative ion source Camembert III using a cylindrical electrostatic probe while the negative ion relative density was studied using laser photodetachment. It is shown that the xenon mixing does not enhance the negative ion density and leads to the increase of the electron density, while the cesium seeding reduces the electron density.

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I. INTRODUCTION

Cesium seeding in volume hydrogen negative ion sources leads to a large reduction of the extracted electron curent and in some cases to the enhancement of the negative ion curent. The cooling of the electrons due to the seeding of cesium atoms has been proposed[1] as a possible cause for the mentioned observations. It was thought[2] that an increase of the plasma density for a given discharge power would occur and it was also supposed that this will lead to increased negative ion density.

Leung *et al*[3, 4] and Walther *et al*[2] reported an enhancement of the extracted H^- ion current when xenon was seeded into the hydrogen plasma. The reason for mixing xenon with hydrogen in Ref. 2 was to compare xenon mixing to cesium addition for the same ion source and filter geometry. These species have comparable atomic weight (131.30 for xenon, 132.90 for cesium), large ionization cross sections and low thresholds for ionization relative to H_2. It is mentioned in Ref. 4 that the increase of the negative ion current when mixing xenon was observed only when the source was operated below the optimum hydrogen pressure, and therefore with lower H^- output. However when the source was operated near optimum hydrogen pressure, adding xenon to the source did not improve the H^- output current. The electron/H^- current ratio was reduced at optimum plasma electrode bias.

We mixed xenon into the plasma of the negative ion source Camembert III in order to clarify the differences between its effect and that of seeding cesium. Both additives should lead to reduced electron temperature, but the cesium coating on wall surfaces could modify the electron density due to its effect on the wall surface work function. The advantage of measuring the negative ion density in the center of Camembert III is that negative ions formed by surface processes on the walls will not survive to moving to the source center in high density plasma.

Since we found that the negative ion density in xenon seeded plasma is not significantly different from that in hydrogen plasma, we can conclude that the increase of this density due to cesium seeding has to be attributed to other properties of cesium, but not to its large mass. The electron temperatures measured in cesium and xenon-seeded plasmas are very close and the observed difference in negative ion density cannot be related to the reduced electron temperature.

The important difference we observed between xenon and cesium seeding is the behaviour of the electron density: the strong reduction of this density due to cesium seeding, and the increase of this density due to xenon mixing. A related parameter which behaves differently in these two plasmas, is the plasma potential, which strongly decreases in cesium seeded plasmas.

It can be inferred from the observations that the effect of cesium seeding on the electron density, *i.e.* the decrease of the latter, is related to a surface effect, while the increase of the negative ion density, observed in the center of the extraction region of Camembert III is a volume effect at a hydrogen pressure above 1 mTorr. The particularity of cesium compared to xenon which may explain the enhanced volume H^- ion production due to cesium seeding is the presence of molecules CsH and of cesium induced Rydberg H_3* states.[5]

II. EXPERIMENTAL SETUP

The large hybrid multicusp negative ion source Camembert III has been described earlier[6, 7]. In this source the magnetic filter is represented by the multicusp magnetic field. It separates the driver region, located on the source border, from the extraction region, located in the center of the source. The hydrogen and xenon pressures were measured with a Baratron gauge. The typical xenon partial pressure used was $3x10^{-4}$ Torr; at lower pressure no significant changes could be observed.

In a separate experiment[8] cesium was introduced into Camembert III from an oven in which a sealed glass container was loaded. The glass container broke when the oven attained a temperature of about 200°C. After this initial introduction of cesium vapor, the cesium oven could be heated again, to obtain higher cesium pressure. We had no trouble with the electrostatic probes or with operating the filaments and the discharge. We determined the cesium partial pressure with a surface ionization gauge, which was installed on the flange opposite to the plasma electrode. The maximum cesium pressure studied was 1.1×10^{-5} Torr.

The plasma characteristics were measured in the center of Camembert III, *i.e.* in the center of its extraction region.. The negative ion relative density, n_-/n_e, was measured by photodetachment [9]; the Nd-YAG laser beam diameter was 6 mm. A cylindrical probe, 0.5 mm in diameter and coaxial with the laser beam, was biased positive at 50 V. In all the experiments the discharge parameters were 50 V, 50 A. The electron density and temperature were measured using the same cylindrical electrostatic probe which was used for the measurement by photodetachment of the negative ion relative density n_-/n_e. The principal results for pure hydrogen will be reported for comparison.

III. RESULTS

A. Effect of xenon.

Table I summarizes the plasma parameters at the center of the extraction region. Note that the addition of 0.3 mTorr of xenon to the initial 3 mTorr of hydrogen leads to the increase of the electron density by a factor 1.7 and to the reduction of the electron temperature by a factor 0.7, compared to the pure hydrogen case.

The change in plasma potential V_p is not significant. The relative negative ion density n_-/n_e, measured by photodetachment, goes down by a factor of 2, but this is mainly due to the increase of the electron density, while the drop in negative ion density is by only 15%.

A simple theoretical estimate[10] of the electron density in presence of the 10% xenon additive was done, assuming that only the primary electrons (50 eV) participate in the ionization of both hydrogen and xenon. This estimate leads to an increase of the electron density by a factor of four, which is more than the observed one (only a factor 1.7). This estimate takes into account the five times larger cross section of xenon ionization compared to that of hydrogen and the eight times lower wall loss time of xenon ions, which is related to the mass ratio of Xe^+ and H_2^+ ions.

The effect of cesium seeding, which we reported earlier in Ref. 8, is also shown in Table I for the same conditions of pure hydrogen plasma. Adding a very low partial pressure of cesium ($5.5x10^{-6}$ Torr) which was found to be the optimum pressure[8] for minimum electron density, electron temperature and plasma potential, leads to the reduction of the electron density by more than a factor 2.2, and to a reduction of the electron temperature by a factor 1.9. The relative negative ion density, measured by photodetachment, goes up by a factor of 2.6, but this is mainly due to the decrease of the electron density, while the increase in negative ion density is by only a factor 1.15. An important change is that of the plasma potential, which went down from 3.2 V to 1.35 V.

It is not possible to estimate the effect of adding cesium on the electron density, in the same way as we did above for xenon mixing. Due to the low threshold potential for ionization of cesium, the low energy plasma electrons will participate in the ionization process.

In conclusion the striking difference between xenon and cesium seeding into hydrogen plasma is the fact that the electron density goes up in the case of xenon, as expected, while it goes down considerably in the case of cesium seeding.

B. Effect of cesium.

Figure 1 shows the observed variation of the electron density versus the cesium partial pressure, namely that the minimum electron density is attained at a partial pressure of cesium of 5.5×10^{-6} Torr, for all the hydrogen pressures shown on this graph (1 to 3 mTorr). The plot shown in Ref. 8 indicates that this is true in a wider range of hydrogen pressure (1 to 6 mTorr).

Figure 2 shows the observed variation of the negative ion density with cesium partial pressure. For hydrogen pressures of 2 and 3 mTorr, the negative ion density goes up very slowly in the studied range of cesium partial pressure and there is no indication of saturation. Only at the lowest hydrogen pressure, 1 mTorr, the negative ion density is maximum at $5.5.\times10^{-6}$ Torr.

Figure 3 shows the variation of the plasma potential with the partial cesium pressure. It can be noted that the plasma potential is minimum when the cesium pressure is $5.5.x10^{-6}$ Torr.

The plasma potential, *i.e.* the self-bias of the plasma with respect to the plasma electrode (the electrode facing the plasma and separating it from the extractor) and in general to the source walls, has a considerable role in decreasing the electron density in the plasma extraction region and presumably the extracted electron current. In the presence of cesium coverage of the walls the plasma potential can change from that which it would be without cesium, as shown on Fig. 3. Assuming the absence of charged particle emission from the wall (which strictly speaking is not correct), the charge flow is balanced by slowing down the source plasma electrons electrostatically until they match the much slower positive ions, flowing to the wall. As an example for H^+ ions and a Boltzmann equilibrium electron distribution, the plasma potential V_p is 3.6 kT_e/e. The presence of a cesium coating with its lower work function, allows new emission processes from the wall to occur: the conversion to negative ions of positive ions and atoms intercepted by the wall and the electron emission due to the absorption of ultraviolet radiation. Finally from neutral cesium evaporated from the wall or introduced by other means a positive ion can be formed which will return to the wall. These processes lead to an increase of the positive particle flow to the wall, and to a decrease of the net negative particle flow to this wall, the result of both being the decrease of the plasma potential. A strong decrease of V_p, along with a strong reduction of the electron temperature, have been found experimentally at the center of the extraction chamber, when an optimum amount of cesium was added to the hydrogen plasma (see Fig. 3).

Returning to Figures 1 and 2, note that the low cesium pressure of 5.5×10^{-6} Torr reduces the electron density to its minimum value, while much higher cesium pressure is necessary to enhance the negative ion density. This explains why in some experiments, like that of Michaut, Guerrini and Riz [11], the introduction of a small amount of cesium reduced considerably the extracted electron current, but did not enhance significantly the extracted negative ion current.

Ogasawara *et al* [12] noted that at the pressure of 5.5×10^{-6} Torr the cesium coverage θ on a tungsten surface would be 0.5, which corresponds to the minimum work function and thus to maximum surface production of negative ions. For cesium pressure higher than 5.5×10^{-6} Torr, θ will be less than 0.5; the work function will become larger and the surface production will go down. The cesium pressure of 5.5×10^{-6} Torr corresponds to a cesium density of 1.8×10^{11} cm^{-3}. Ogasawara *et al* conclude that at the mentioned density the surface work function is minimum and surface production is maximum, while at higher cesium density the work function becomes larger and the surface production goes down.

Thus it follows from our experiment that the minimum plasma potential, electron density and electron temperature occur when the surface work function is minimum. As already mentioned, maximum surface production of H^- ions occurs at minimum work function. However, Fig. 2 indicates a monotonous enhancement of the negative ion density in the studied range of cesium partial pressure, for all the hydrogen pressures, except the lowest one, which indicates that the negative ions observed at the center of the extraction chamber of Camembert III are not due to surface production. At the lowest hydrogen pressure (1 mTorr) the plasma density is low, therefore surface produced negative ions can travel to the center of the extraction region, before being destroyed by mutual neutralization.

Relative to the reduction of the electron density with cesium partial pressure, we propose the following interpretation : for small Debye length, the electron density adjusts to the difference of the positive and negative ion densities, in order to maintain the plasma neutrality.

In the presence of cesium, the electron density can go down due to the increased loss of electrons to the wall, without the positive ion density decreasing, if the surface produced negative ions act as replacements in the plasma. This effect reminds the effect of biasing positive the plasma electrode in pure hydrogen ion sources, where the electrons lost to this electrode are replaced by negative ions from the plasma.[13]

We will show now that the electron current loss per unit wall surface (j_W) goes up when cesium is added, since this current strongly depends on eV_p/kTe:

$$j_W = (1/4)\,(1-\sigma)\; e\, n_e\, (8kTe/\pi m_e)^{1/2} \exp(-eV_p/kT_e) \qquad (1)$$

Here σ is the secondary electron-electron emission coefficient of the surface. It was shown in Ref. 8 and in Fig. 3 that both kT_e and eV_p are minimum for a cesium pressure of 5.5×10^{-6} Torr. The analysis of these data shows that the ratio eV_p/kT_e is also minimum at this cesium pressure, with the consequence that j_W is maximum. Thus the electron loss to the wall is maximum at the cesium pressure of 5.5×10^{-6} Torr.

On the other hand additional positive ion destruction will occur, due to positive ion-negative ion recombination (mutual neutralization), which will reduce the total plasma density.

It can be concluded, that the reduction of the electron density is a surface effect, related to the lower work function on the cesiated wall.

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[a] Permanent address: Russian Research Center « Kurchatov Institute », Moscow, Russia.

[b] Permanent address: A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russia.

[c] Oak Ridge National Laboratory, Oak Ridge, TN 37831-8088, USA

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FIGURE CAPTIONS

Figure 1. Variation of the electron density measured in the center of the extraction chamber, versus the cesium partial pressure, for three values of the hydrogen pressure . 50 V, 50 A discharge. Plasma electrode bias $V_b = 0$.

Figure 2. Variation of the negative ion density measured in the center of the extraction chamber, versus the cesium partial pressure, for three values of the hydrogen pressure. 50 V, 50 A discharge. $V_b = 0$

Figure 3. Variation of the plasma potential versus cesium partial pressure, for three values of the hydrogen pressure. 50 V, 50 A discharge. $V_b = 0$

Table I. Plasma characteristics of pure hydrogen, xenon-seeded and cesium-seeded hydrogen plasma, for a discharge of 50 V, 50 A, 3 mTorr (H_2). The xenon partial pressure in the xenon-seeded hydrogen plasma is 0.3 mTorr (10% of the H_2 pressure). The cesium partial pressure in the cesium seeded hydrogen plasma is 5.5×10^{-6} Torr (0.18 % of the H_2 pressure).

Gas	kT_e	V_p	n_e	n_- / n_e	n_-
	eV	V	cm^{-3}		cm^{-3}
H_2	0.79	3.2	1.3×10^{11}	0.073	9.5×10^{9}
H_2 + Xe	0.55	3.2	2.3×10^{11}	0.035	8.1×10^{9}
H_2 + Cs	0.42	1.35	6.0×10^{10}	0.19	1.1×10^{10}

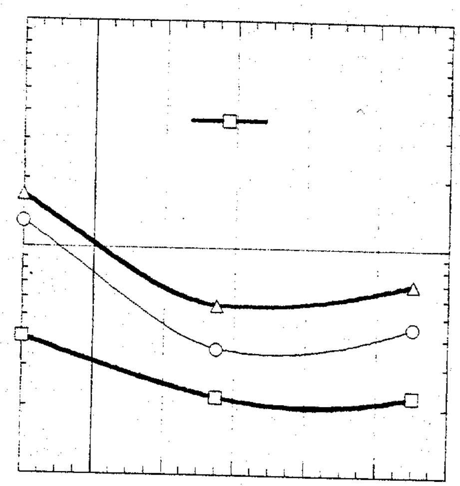

Fig. 1

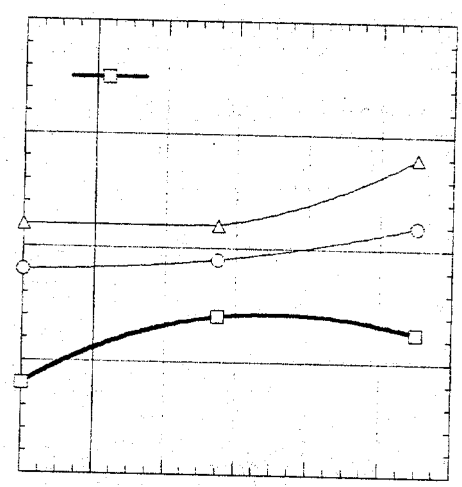

Figure 2