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Increasing the space charge limit and other effects of cesium seeding in hydrogen negative ion sources

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The role of cesium seeding in increasing the negative ion current in volume sources is described. By a reduction in the local plasma potential the current of extracted electrons is vastly reduced. As a result, cesium increases the fraction of the transverse space charge limit available to the ions by as much as a factor of three. In addition, cesium can increase the total space charge limit by injection of Cs^+ into the presheath—a newly recognized phenomenon consistent with experimental measurements and determined from application of a Double-Vlasov model for negative ion extraction.

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I. INTRODUCTION

Intense negative ion beams of hydrogen and deuterium are of current interest in high-energy physics, nuclear physics and fusion technology.

Two major breakthroughs in the generation of negative ion beams occurred in the 70's: cesiating surfaces in hydrogen discharges (at Budker INP in Novosibirsk) [1] and thus producing negative ion beams by a surface charge exchange process, and discovering that negative hydrogen ions are generated in the low pressure plasma volume by dissociative electron attachment to vibrationally excited H_2 molecules [2] designated as volume production of H^-. However neither of these techniques can provide the beams which are required for the mentioned applications.

Progress has been recently achieved [3] by seeding cesium in the pure hydrogen sources, *i.e.*, two-chamber (tandem) sources which have been developed to make use of the volume production of H^-. However as a result of cesium seeding into the large ion sources developed for neutral beam injection only a modest enhancement of the

H^- ion beam current but a dramatic reduction of the co-extracted electron current were observed [4].

Several reasons for the enhanced negative ion current have been discussed [5,6]: (a) enhancing the production of hydrogen negative ions by dissociative attachment, for example due to electron cooling or to hydrogen molecule vibrational excitation by excited cesium energy transfer and H_3^+ + Cs charge transfer [5]; (b) conversion of hydrogen atoms and positive ions into negative ions on cesiated, low work function wall surfaces [6]. The enhancement of the negative ion density in the center of a large plasma chamber due to cesium seeding has been proved by direct measurements by photodetachment [7]. This showed that the explanation (b) is not expected to be sufficient, since negative ions formed at the walls are significantly depleted on their way to the center of the chamber. On the other hand direct probe measurements [7] showed that the electron density is reduced in the source extraction region by the cesium seeding. None of the proposed explanations accounts for this unexpected feature: the addition of cesium does not enhance the plasma density, as assumed first [3], but reduces it, as shown in [7]. This observation is supported by the extraction experiments [4] where a strong reduction of the extracted electron current was observed. A noticeable reduction of the electron temperature in the source extraction region due to cesium seeding was also observed [7].

The first purpose of this paper is to show that the reason for the reduced electron density due to cesium seeding is related to the reduction of the plasma potential, as the result of the increased emission by the wall surface of negatively charged particles, balancing the positive ion flow from the plasma to the wall.

The second purpose of this paper is to show that the observed change in the extracted negative ion current can be the result of the increased share of negative ions in the total space-charge limited current budget due to the above discussed reduced electron density and temperature.

The third purpose of this paper is to show, both by explicit calculation and by inference from measurements, that the total transverse space-charge limited (TSCL) current can be increased absolutely by the addition of positive space charge near the extraction sheath—a condition readily achieved in the presence of cesium, and with some planning can be achieved without cesium.

II. EFFECT OF CESIUM SEEDING ON THE PLASMA POTENTIAL

The plasma potential, i.e., the self-bias of the plasma with respect to the plasma electrode has a considerable role in decreasing the extracted electron current and the electron density in the plasma extraction region. The decrease of the extracted electron current with an increase in the plasma electrode positive bias observed in most sources substantiates this argument. In the presence of cesium coverage of the surfaces, the plasma potential can change from that which it would be without cesium. Assuming the absence of charged particle emission from the wall (which is generally not correct), the charge flow is balanced by retarding the source plasma electrons (which have a much higher mobility) 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 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 also eventually return to the wall. These processes lead either to an increase in the positive particle flow to the wall, and to a decrease of the negative particle flow, the result of either being the decrease of the plasma potential. A strong decrease of the plasma potential along with a strong reduction of the electron temperature, have been found experimentally when an optimum amount of cesium was added to the hydrogen plasma [7].

Actually, for small Debye length, the electron density adjusts to the difference of the positive and negative ion densities, in order to maintain plasma neutrality. The increase of the negative ion density in the plasma volume can reduce the share of the electron density in the total plasma density. On the other hand, additional positive ion destruction will occur, due to positive ion-negative recombination, which will reduce the total plasma density.

III. TRANSVERSE SPACE-CHARGE LIMITS

In volume sources the addition of cesium can cause an increase in the negative ion current by a factor of three [see Fig. 1(*b*)] and a decrease in extracted electrons by a factor of as much as 100 [see Fig. 1(*a*)]. One reason for the increase in negative ion current extracted is thought to be that cesium converts positive ions to negative ions at a suitably coated surface. However, since the source typically operates at the space-charge limit, addition of more negative ions by surface production does not account for the increase in negative ion beam current. However, the associated decrease in electrons extracted may increase the partition of the space-charge limit occupied by the negative ions. If for example, the electrons extracted were 100 times the ion current, not unusual for a negative ion source operating without cesium, then the electrons could be taking up as much as two-thirds of the space-charge limit.

An example of this space charge limit for negative ion extraction is illustrated in [8], where experimental data of negative ion beam current shows a marked dependence on acceleration potential. Any attempts to increase the current beyond the transverse space charge limit by increasing the negative ion current density extracted from the source plasma will only result in less beam current since more interception on the electrodes will occur.

IV. DOUBLE-VLASOV MODEL

For volume negative ion sources it is necessary to consider the plasma positive ions in a kinetic description because they are far from equilibrium, executing, in the collisionless limit, at most two passes through the region. It is still appropriate to consider the electrons in the presheath to be a Boltzmann distribution since they are collision dominated and generally have to traverse a magnetic field in the pre-extraction region. The model consists of appropriate kinetic equations for the positive ions, negative ions and electrons.

All of these equations for the motion of the charged species are coupled to a Poisson Equation where the charge density of the above species is considered along with an equilibrium Boltzmann density for the presheath electrons. This model is described in more detail in [9,10]. The model has enough features in it so that implications of space charge imbalance in the pre extraction sheath can be accounted for.

V. INCREASING THE TRANSVERSE SPACE-CHARGE LIMIT (TSCL)

Now that it has been shown that cesium allows the negative ions to occupy virtually the entire transverse space-charge limit, it remains to examine if and how the space-charge limit itself can be increased. The transverse space-charge limit is thought to depend only on the geometry of the electrodes, the potentials applied, and the beam current density. Actually, the transverse space-charge limit depends explicitly on the shape of the extraction sheath, which is itself determined by the above-mentioned parameters but can in addition be further manipulated by artificial means. For example, the deliberate introduction of small amounts of additional positive charge into the preextraction-sheath region would have the effect of changing the curvature of the sheath effecting a higher space-charge limit at least in overdense situations. This can alternatively be considered as simply adding a converging lens to the ion optical system. An analogous sheath effect has been predicted for positive ions by deliberately oversupplying the presheath with electrons [11]. For negative ion extraction, ionized sputtered cesium is just such a source of positive ions because positive ions hitting the plasma electrode can sputter off neutral cesium, which quickly gets ionized by electrons and H^+ after passing through the sheath between the source plasma and the plasma electrode. Any other mechanism of getting neutral cesium into the discharge will have the effect. These Cs^+ ions are heavy and slow and so are quite effective in depositing positive space charge into the presheath. Cs^+ has been observed to be a dominant species of positive ions [12]. The Cs^+ space charge in the region just before extraction serves to increase the transverse space-charge limit, by causing the extraction sheath to be more concave [10]. There is experimental indication of the existence of this increase in space-charge limit that we will describe presently.

Let us consider data taken at Ecole Polytechnique [7] where the bias of the extraction electrode is varied. Fig. 1 shows the dependence of extracted electrons [Fig. 1(*a*)] and negative ions [Fig. 1(*b*)] on this bias, V_b, both with and without cesium. It is obvious from the Fig. 1(*b*) that I_T^- is not in fact constant, but still the system was operating at the TSCL {as indicated by the observation [Fig. 1(*b*)] that the ion current depends on the extraction fields}. The variation of the TSCL is plotted explicitly in Fig. 2 (assuming that the ratio of the average electron space charge deposited over a trajectory to the negative ion current is 96). For small values of bias, V_b, on the plasma electrode, the TSCL is increased by as much as 60 percent for the case where cesium is used. As V_b is raised the plasma potential (still presumed positive with respect to the plasma electrode) gets closer to the plasma electrode potential. The reduced sheath hill, besides causing the absorption of more electrons into the plasma electrode, forecloses their extraction. Also the positive H^+ ions intercepting the plasma electrode do so with less velocity reducing the amount of sputtered cesium. Which in turn reduces the positive space-charge build-up due to Cs^+ and thus reduces the enhanced TSCL to the normal value without cesium.

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FIGURE CAPTIONS

Fig. 1. Variation of the extracted (*a*) electron current and (*b*) negative ion current with the plasma electrode bias for two extraction voltages in pure hydrogen and cesium seeded hydrogen plasma (the partial pressure of cesium was 1.1×10^{-5} Torr) [7]. The negative ion current is a function of extraction potential indicating that the system was operating at the transverse space charge limit (TSCL). The peaks in the negative ion current at low V_b are interpreted as increases in the TSCL itself. This is the best way to explain how the negative ion current increased when the situation was already at the TSCL and the electrons are accounted for.

Fig. 2. The Transverse space charge limit has been calculated from the data [7] in Fig. 1 for the case with cesium and 1 kV accelerating voltage compared with the case with no cesium assuming that the ratio of the average electron space charge deposited over a trajectory to the negative ion current is 96. From this, it can be seen that the TSCL doesn't remain a constant but rather increases for certain values of the electrode bias.

STUDY OF THE EXTRACTED CURRENTS

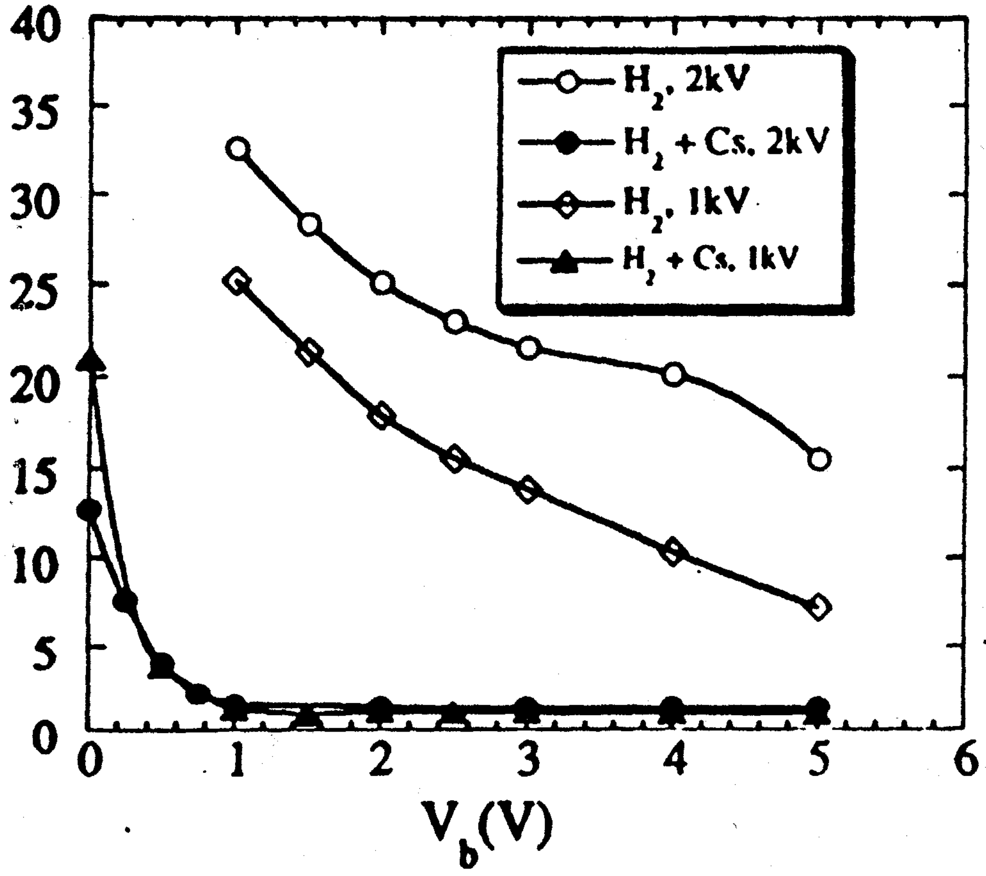

Fig. 1a

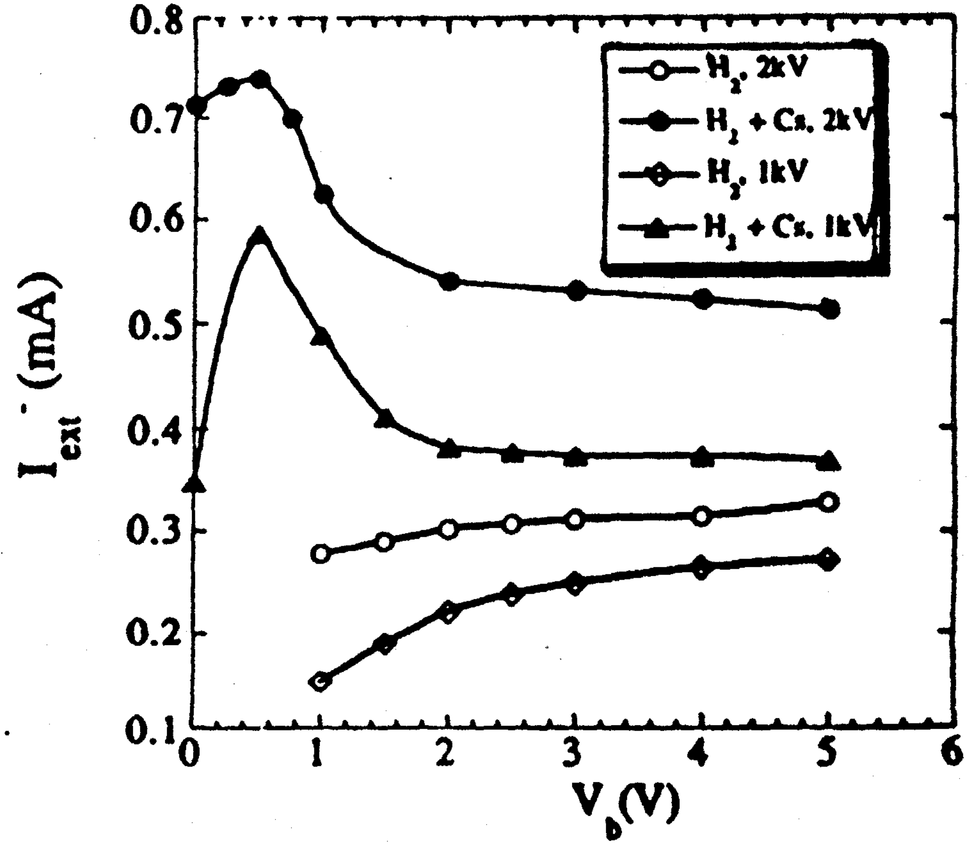

Fig. 1b

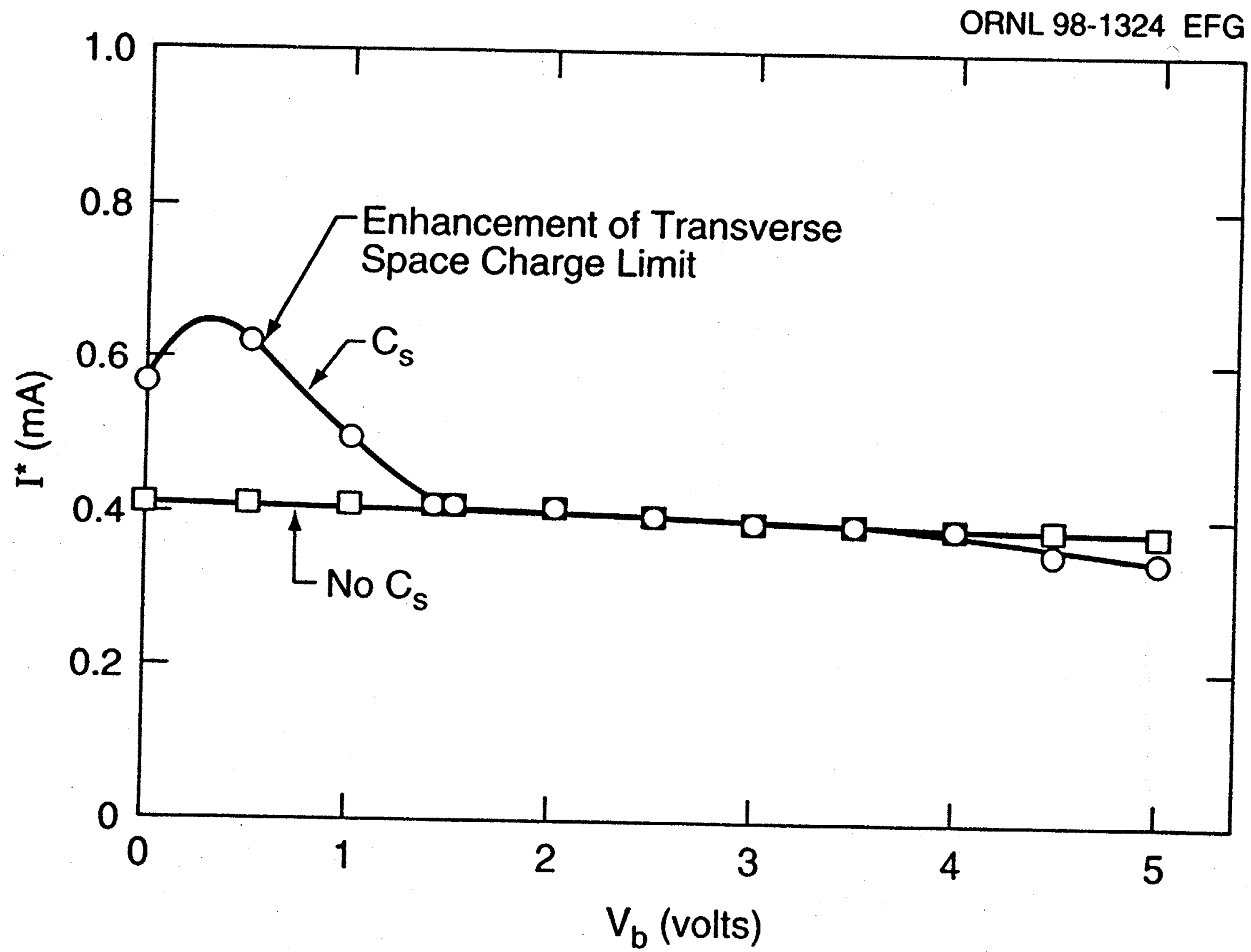
ORNL 98-1324 EFG
1.0
0.8
0.6
0.4
0.2
0
I* (mA)
Enhancement of Transverse
Space Charge Limit
Cs
No Cs
0
1
2
3
4
5
Vb (volts)

Fig. 2