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Citation: [Review of Scientific Instruments](#) **85**, 02B103 (2014); doi: 10.1063/1.4825387

View online: <http://dx.doi.org/10.1063/1.4825387>

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Extracted H⁻ ion current enhancement due to caesium seeding at different plasma grid bias^{a)}

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(Presented 10 September 2013; received 4 September 2013; accepted 26 September 2013; published online 29 October 2013)

This paper discusses the possibility that there is an enhancement of volume production due to gettering of atomic hydrogen by the caesium deposited on the walls, which reduces the negative ion destruction by associative and non-associative detachment. Such an enhancement would take place for all plasma grid bias voltages. Furthermore at plasma grid bias voltages higher than the plasma potential there is flow of the negative ions from the bulk plasma. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4825387>]

I. INTRODUCTION

The heating neutral beam (HNB) for the International Thermonuclear Experimental Reactor (ITER) requires a D⁻ beam of 40 A at an energy of 1 MeV, and the diagnostic neutral beam (DNB) requires a 60 A H⁻ beam at 100 keV.¹ The equivalent current densities at the extraction plane are 30 mA cm⁻² for the HNB, and 35 mA cm⁻² for the DNB. Low source pressure operation (0.3 Pa) is another requirement of the ITER design. Conventional volume plasma sources of hydrogen and deuterium negative ions can produce only modest current densities of ~5–20 mA cm⁻² with reasonably large extraction apertures, and it is intended that the difference in performance be achieved by injection of caesium into the ion source. Historically the addition of caesium into the ion source has produced enhancement factors in the extracted current in the region of ~2–8 and has the additional advantages of reducing the co-extracted electron current and the operating pressure of the ion source.

In the vast majority of the literature on the subject, the enhancement in extracted ion current due to the addition of caesium into the ion source is described as being due to direct production of negative ions on caesiated surfaces by ion and atom impact. However, this is only true when the plasma grid is biased negative with respect to the plasma potential since the negative ions can cross back through the sheath. McAdams and Surrey² considered a simple model of the surface production of negative ions on the caesiated plasma grid as the bias of this grid varies relative to the plasma potential.

The goal of the present work is to review the causes of the extracted current enhancement at different values of the plasma grid bias (V_b). In Sec. II a model for the dependence of the extracted current of surface-produced H⁻ ions on plasma grid bias will be presented. In Sec. III the observed variation of the extracted H⁻ current versus V_b in pure hydrogen

and caesiated source operation regimes will be reported. In Sec. IV the possible explanations of the extracted H⁻ ion current enhancement due to caesium seeding will be discussed. Section V will summarize the conclusions.

II. THEORETICAL MODEL

The formation of a negative ion requires a minimum energy equal to the threshold energy, $E_{thr} = \phi - E_A$, where ϕ is the work function of the surface and E_A is the electron affinity (0.75 eV). The energy of the negative ion is given by $E_{neg} = (R_E/R_N)E_{in} - E_{thr}$, where E_{in} is the energy of the incoming particle (ion or neutral), R_E is the energy reflection coefficient, and R_N is the particle reflection coefficient (see Ref. 3). For neutral incoming particles, the potential difference between the plasma and the plasma grid bias potential only affects the negative ion transport into the plasma. If the plasma grid bias potential, V_b , is negative with respect to the plasma potential, V_p , all negative ions can leave the surface and cross the sheath into the plasma. (This ignores the effect of virtual cathode formation⁴ which will modify the energetics of negative ion transport across the sheath in a straightforward manner.) As the bias potential becomes positive with respect to the plasma potential there is a potential barrier for the negative ions to overcome, and the fraction able to return to the plasma diminishes as this voltage increases, eventually reaching zero at

$$E_{in} \left(\frac{R_E}{R_N} \right) - E_{thr} \leq e(V_b - V_p). \quad (1)$$

Since the atomic temperature is likely to be less than 1 eV, at $V_b - V_p$ of more than a couple of volts very few negative ions can leave the surface. This remains true even if the atoms were not thermal but had most of the 2.25 eV Franck–Condon energy from their formation by hydrogen molecule dissociation. In this case higher yields and negative ions with higher initial energy would be obtained (compared to a thermal distribution of atoms). Such negative ions would be able to overcome a barrier of $0.7 \times 2.25 - 0.75$ eV = 0.825 eV ($R_E/R_N = 0.7$ is considered in this estimate, which is the value found for

^{a)}Contributed paper, published as part of the Proceedings of the 15th International Conference on Ion Sources, Chiba, Japan, September 2013.

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$E_{in} = 45$ eV using equations proposed in Ref. 3 for calculating R_E and R_N).

If the incoming particle is a positive ion, E_{in} is modified by the potential difference between the plasma and the grid bias potential. If $V_b < V_p$, the positive ions are accelerated towards the surface, arriving with greater energy than at the sheath. This increases both the yield and energy of the resulting negative ions, so that transport into the plasma is increased. As the bias voltage is increased towards the plasma potential, the energy of the positive ions is reduced and so the probability of formation of a negative ion, and thus the yield of negative ions is reduced. At some bias potential sufficiently positive with respect to plasma potential, no negative ions will leave the surface, a condition given by the equation,

$$e(V_b - V_p) \geq [E_{ion}(R_E/R_N) - E_{thr}] / [1 + (R_E/R_N)], \quad (2)$$

and this will be a function of the work function, ϕ , the ion energy in the plasma, E_{ion} , directed normal to the surface and the plasma potential. Again, this ignores the formation of a virtual cathode. Substitution of typical values for a well caesiated source $\phi = 2.14$ eV, $V_p = 19$ V, shows that for $E_{ion} \leq 8$ eV negative ion transport across the sheath will be suppressed for $V_b > 21.5$ V. Since an enhancement has been observed up to $V_b = 25$ V, this implies an additional mechanism is associated with caesium.

This simple model does not take into account the transport of particles across the sheath and the possibility of formation of a virtual cathode as discussed by McAdams *et al.*⁴ At the expected levels of negative ion production due to atoms, a virtual cathode is formed in front of the plasma grid. This represents a potential barrier to negative ions leaving the plasma electrode. As the potential difference between the plasma and the plasma grid is decreased, the virtual cathode depth increases and the current density of negative ions across the sheath reduces significantly since the sheath cannot support the negative ion space charge. If the potential on the plasma grid was higher than that of the plasma then only if the initial energy of the negative ions was greater than the potential difference plus that of the virtual cathode could any negative ions be transported across the sheath.

III. OBSERVED VARIATION OF THE EXTRACTED H^- ION CURRENT VERSUS V_b

A. Pure hydrogen operation

The typical variation of extracted negative ion and electron currents versus V_b in pure hydrogen was reported by Svarnas *et al.*⁵ for the microwave driven operation of Camembert III, from Ecole Polytechnique. The maximum negative ion extraction occurs for V_b slightly higher than the local plasma potential, V_p . The typical difference $V_b - V_p$ for maximum extraction is less than 1 eV. The decrease of the extracted H^- ion current when V_b is increased beyond the maximum is due to the fact that the volume produced negative ions are accelerated toward the plasma grid and their density near the plasma grid goes down. In reality a maximum extracted current is observed at plasma potential and H^- ions are also extracted at $V_b < V_p$ (see, e.g., Refs. 6 and 7).

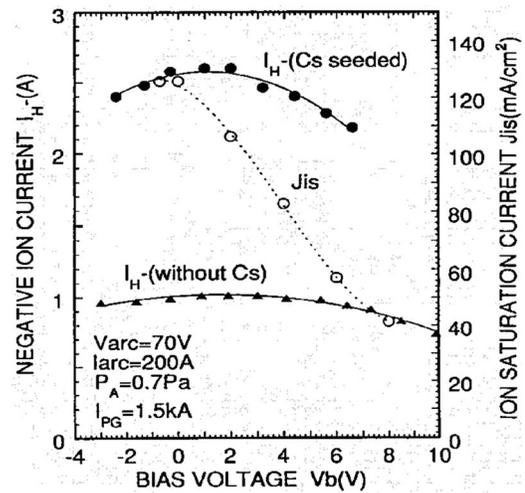


FIG. 1. Extracted H^- ion current from JAERI 10 Amp source, in caesiated and pure hydrogen operation regimes.

B. Caesiated operation

Results relative to caesiated operation were compared with operation in pure hydrogen for filamented sources from the Japan Atomic Energy Research Institute (JAERI)^{6,7} (Figure 1), designated JAERI 10 Amp source, and Ecole Polytechnique⁸ (designated Camembert III, Figure 2). Obviously in Camembert III, as in JAERI 10 Amp source, the negative ion current in caesiated operation is enhanced compared to the current found in pure hydrogen operation. This enhancement is in both sources by a factor 2.5 at plasma potential. In the case of caesiated operation of Camembert III (Figure 2) the decrease of the extracted H^- current when the bias voltage increases above the plasma potential is by a factor two only. These data indicate a clear threshold of the surface component, i.e., a sudden decrease in the extracted H^- ion current near 0.5 V.

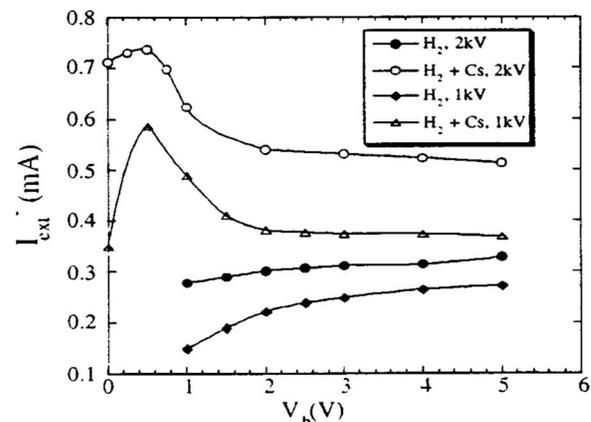


FIG. 2. Variation of the extracted H^- ion current with the plasma electrode bias voltage at two values of the extraction voltage, in pure hydrogen and caesium seeded operation. The hydrogen pressure was 0.4 Pa. Reprinted with permission from M. Bacal, F. El Balghiti-Sube, L. I. Elizarov, and A. Y. Tontogode, Rev. Sci. Instrum. 69, 932 (1998). Copyright 1998 American Institute of Physics.

IV. POSSIBLE EXPLANATIONS OF THE H^- CURRENT ENHANCEMENT DUE TO CAESIUM SEEDING

We estimated that under typical operation conditions ($N_e = 10^{17} \text{ m}^{-3}$, $T_e = 1 \text{ eV}$, $N(H^0) = 10^{19} \text{ m}^{-3}$, $T(H^0) = 1 \text{ eV}$, $T(H^-) = 1 \text{ eV}$), the H^- ion loss due to collisions with atomic hydrogen (i.e., the H^- ion destruction by associative and non-associative detachment) is significantly higher (by a factor 20) than the loss due to electron impact. Therefore, we suggest that the gettering of atomic hydrogen by caesium is a possible cause of H^- ion current enhancement due to caesium in the whole bias range. This suggestion is supported by experiments in which gettering by caesium or tantalum produced an increase of the negative hydrogen ion density and extracted current.⁹

At bias voltage below plasma potential, the existence of extracted current at negative with respect to V_p bias voltage ($V_b < V_p$) is usually ascribed to the direct production of H^- ions by positive ions and atoms incident to the low work function caesiated surface. Gettering of atomic hydrogen by caesium has two opposite effects:

1. it enhances the H^- ion current since it reduces H^- ion destruction, but
2. it reduces the H^- ion current by reducing the direct production by atoms.

Since the observation is that the extracted H^- ion current is enhanced by caesium seeding, we conclude that the first effect is dominant.

At bias voltage above plasma potential, $V_b > V_p$, volume produced H^- ions are the only component of the extracted current in pure hydrogen. Volume H^- ions continue being produced in the caesiated operation, however the observed current is enhanced compared to its level in pure hydrogen. In this bias voltage range, direct production (by positive ions and atoms) is not active, presumably because the negative ions cannot leave the surface. We propose the following two explanations for this current enhancement:

- gettering of atomic hydrogen by caesium, and
- negative ion current enhancement due to negative ion flow from the bulk plasma.

This is supported by experiments in the National Institute for Fusion Science (NIFS).¹⁰ These experiments proved that the negative ions forming the H^- ion current measured at $V_b > V_p$ originate from the plasma beyond the extraction region, but do not originate from the plasma grid surface. In the bulk plasma the H^- ions are formed by volume and surface processes mediated by caesium, in addition to the usual volume production. The surface processes mediated by caesium generate H^- ions on the walls limiting the bulk plasma following positive ion and atom conversion on these caesiated

surfaces. The volume processes mediated by caesium we refer to are gettering of atomic hydrogen by caesium and charge exchange between negative ions and atoms.

V. DISCUSSION AND CONCLUSION

The effect of gettering is to reduce the H^- destruction by associative and non-associative detachment due to reduction of the atomic hydrogen density. The latter has been studied recently by Friedl and Fantz.¹¹ They found that the density of atomic hydrogen is reduced by a factor two by caesium seeding in a plasma produced at a hydrogen pressure of 10 Pa. The change in atomic hydrogen density could be much larger when the hydrogen pressure is as low as 0.3–0.5 Pa as in the ion source operation, because the same number of absorbed hydrogen atoms represents a higher fraction of their initial density at the lower pressure of 0.3–0.5 Pa than at 10 Pa.

An important conclusion of this work is explaining the enhancement due to caesium seeding of extracted H^- current in the plasma grid bias range above the plasma potential by gettering of atomic hydrogen by caesium and negative ion flow from the bulk plasma. This enhancement was unexplained until now.

ACKNOWLEDGMENTS

CCNB is acknowledged for facilitating the exchanges on this topic and UPMC for kind encouragement. This work was part-funded by the RCUK Energy Programme [under Grant No. EP/I501045] and the European Communities under the contract of Association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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