Roles of a Plasma Grid in a Negative Hydrogen Ion Source

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Abstract. The plasma grid is electrically biased with respect to other parts of source chamber wall in both volume sources and sources seeded with alkali metals. The roles of the plasma grid in these two kinds of sources will be described. The main functions of the plasma grid in volume sources are: optimizing the extracted negative ion current, reducing the co-extracted electron current, controlling the axial plasma potential profile, recycling the hydrogen atoms to molecules, concentrating the negative ions near its surface and, when biased positive, depleting the electron population near its surface. These functions are maintained in the sources seeded with alkali metals. However an additional function appears in the Cs seeded sources, namely direct emission of negative ions under positive ion and neutral hydrogen bombardment.

INTRODUCTION

The plasma grid is one of the major components of the negative ion source. It is present in both volume sources and in sources seeded with an alkali metal. The contemporary negative ion source is a magnetic multipole or bucket plasma source. The first bucket plasma source, invented by Limpaecher and McKenzie[1], was a chamber surrounded by confining magnets, aimed to demonstrate the possibility of producing a dense, quiescent plasma at low neutral atom density. Ehlers and Leung[2] at LBL (Berkeley, US) and Holmes[3] at Culham Laboratoty (Abingdon, UK) replaced one of the end walls by an electrode, called plasma grid or plasma electrode (PE), which contains the extraction openings and is insulated from the chamber walls. Thus they converted the magnetic multipole plasma source into an ion source.

Figure 1 presents schematically the hot cathode ion source geometry. The magnetic multipole ion source is usually a chamber (cylindrical or rectangular) surrounded externally by columns or rows of permanent magnets, arranged to enhance the plasma confinement. One end of the chamber is enclosed by the PE and the extraction system. A plasma is generated in the source by primary electrons emitted from tungsten filaments located in the field-free region. A magnetic filter installed at the center of the chamber divides the source volume into a source (S) and an extraction (E) regions. This ion source configuration is designated as a tandem source. A weak magnetic field parallel to the PE is usually present due to the penetration of the filter magnetic field and the electron suppression magnetic field.

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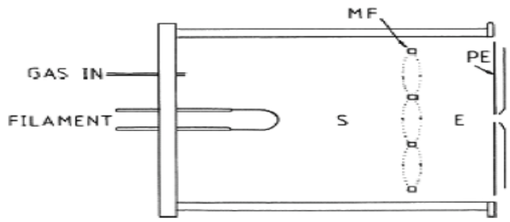

Figure 1. Schematic representation of a tandem source. S represents the source plasma region, MF is the magnetic filter, PE is the plasma electrode (Reprinted with permission from Bacal, Hatayama and Peters, IEEE TPS, **33**, N° 6, 1845 (2005))

ROLES OF THE PE IN PURE HYDROGEN VOLUME SOURCES

The PE Bias Controls the Current Collected by the PE

The PE acts as a large Langmuir probe. When the bias applied to the PE is positive with respect to the plasma potential the PE collects an electron current, and when this bias is negative with repect to the plasma potential it collects a positive ion current. Therefore a positive bias applied to the PE with respect to the plasma potential allows to reduce the electron density in the extraction region and the co-extracted electron current. An example of PE current-voltage characteristic is shown on Fig. 2 (from Holmes[3]).

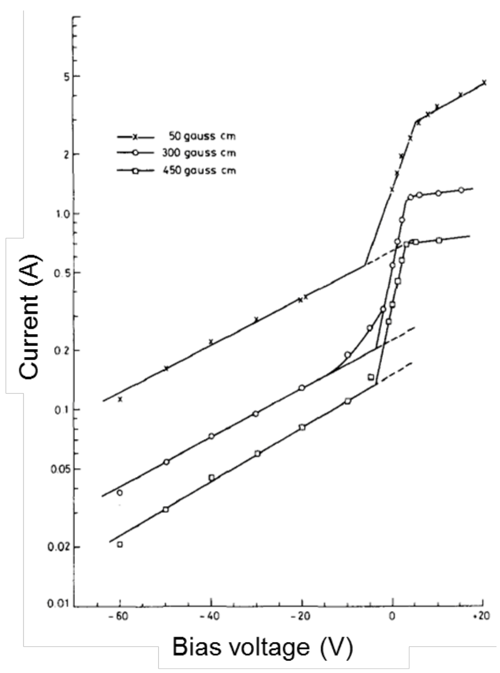

FIGURE 2. The plasma electrode current-voltage characteristic. The saturation ion current at deep negative plasma electrode bias is subtracted from the electron current at more positive bias voltage. (Reprinted with permission from A.J.T. Holmes, Rev. Sci. Instrum. **53,** 1517 (1982), Ref. 3).

The PE Bias Controls the Extracted Currents

Leung *et al*[4] found that in the presence of the magnetic filter a positive PE bias with respect to the wall considerably enhances the extracted negative ion current and reduces the co-extracted electron current (Fig. 3). These are two very important roles of the PE.

Leung *et al*[4] also reported that the variation of the extracted negative ion current (I^-) against the PE bias with respect to the wall potential (denoted V_b) depends on the strength of the magnetic filter field: a weak magnetic filter produced a monotonic increase of the extracted negative ion current, followed by saturation, while a stronger magnetic filter field led to a rapid increase of I^- followed by a rapid decrease, after having attained a maximum at V_b = +2.5 V (Fig. 3). The co-extracted electron current (I_e) monotonically decreases with increasing V_b, leading to the increase of the ratio I^-/I_e at the optimum V_b.

Measurements of the H^- ion density by photodetachment and of the electron density by Langmuir probes in a tandem multipole (Camembert II) at Ecole Polytechnique (Palaiseau, France) showed[5] that a small positive, with respect to the wall potential, bias of the PE produced a significant increase in the H^- ion density and a reduction of the electron density in the extraction region of the source. Figure 4 shows the relative negative ion density n^-/n_e in the extraction region as a function of V_b. Note that n^-/n_e increases with V_b and reaches a maximum of 13%. These results explain the variation of the extracted currents, observed earlier at LBL shown in Fig. 3.

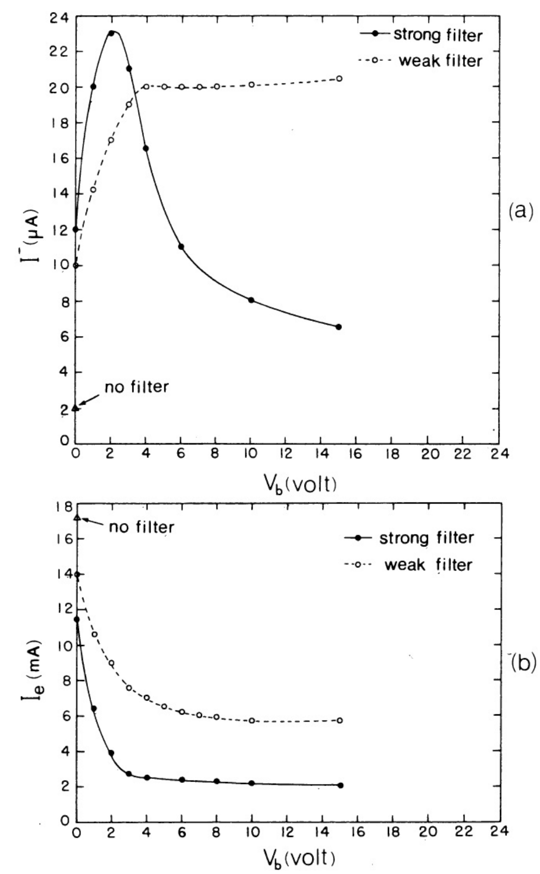

FIGURE 3. The dependence on the plasma electrode bias of (a) the extracted H^- current, and (b) the co-extracted electron current (Reprinted with permission from K.N. Leung, K.W. Ehlers and M. Bacal, Rev. Sci. Instrum., **54**, N°1, 56 (1983), Ref. 4).

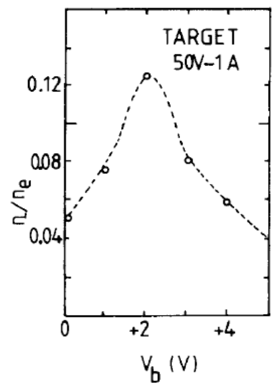

FIGURE 4. H^- relative density n^-/n_e in the extraction (target) region of the tandem source. (Reprinted with permission from K.N. Leung and M. Bacal, Rev. Sci. Instrum. **55** (3) 338 (1984), Ref. 5).

The observation at LBL and Ecole Polytechnique that the positive PE bias with respect to the wall potential optimizes the extracted negative ion current and reduces the co-extracted electron current was confirmed by several research groups. It can be noted that in the large sources at Culham and IPP Garching the positive PE bias reduced the electron current, but no enhancement of the negative ion current was obtained.[6,7]

The PE Bias Controls the Potental Drop across the Magnetic Filter

The axial plasma potential (V_p) profile in the source Camembert II, equipped with a rod mgnetic filter, has been measured using a movable Langmuir probe[5] and is shown in Figure 5. The profile at $V_b = 0$ indicates that the plasma potential in the source region is 0.7 V more positive than in the extraction region and 2.7 V more positive than the wall. An H^- ion in the source region has to climb up the potential hill of 0.7 V to reach the extraction region. Consequently, H^- ions formed in the source (driver) region S will be trapped electrostatically and they cannot escape either to the wall or to the extraction region E. Figure 5 shows also that when the PE is biased by 2.5 V more positive with respect to the wall, only V_p in the extraction region E increases and the plasma potential gradient across the two regions is substantially reduced. Some of the H^- ions in the source region can now traverse across the filter magnetic field into the extraction region, increasing the local H^- ion concentration. Thus the PE bias controls the potential drop across the magnetic filter and consequently the flow of H^- ions formed in the source region into the extraction region.

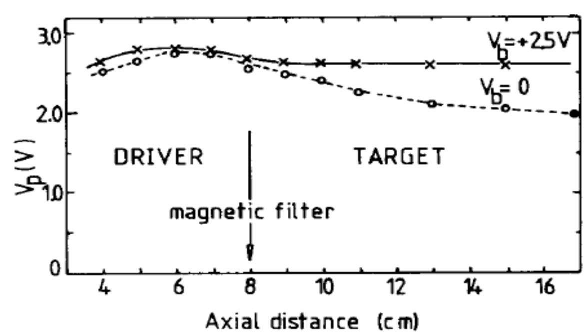

FIGURE 5. The axial plasma potential profile in the tandem ion source Camembert II with two different plasma electrode bias voltages. (Reprinted with permission from Leung and Bacal, Rev. Sci. Instrum. **55** (3) 338 (2004), Ref. 5).

The PE Surface Recycles Atoms to Vibrationally Excited Molecules

The source (driver) region of the tandem magnetic multicusp source is very efficient in dissociating molecules and the resulting atoms destroy the H^- ion by associative detachment and quench vibrationally excited molecules by vibration-translation (V-t) transfer. A suitable choice of the PE material helps reducing the impact of these reactions by recycling the atomic hydrogen into highly vibrationally excited molecular hydrogen, due to the recombinative desorption phenomenon. The experiments of Hall *et al* [8] have shown that recombinative desorption of hydrogen atoms on both tantalum and tungsten leads to vibrationally excited molecules in levels up to v"=9 (Fig. 6). However the vibrationally excited molecule populations with v">3 are ten times higher for tantalum than for tungsten. The experiments at Ecole Polytechnique[9,10] showed that the deposition of a fresh tantalum film on the PE and walls of a source with tantalum filaments significantly enhances the H^- density and the extracted H^- ion current compared to the same source with tungsten filaments (see Fig. 7). Deposition of caesium on the PE and walls when seeding caesium into the source also enhances the extracted negative ion current, as also shown on Figure 7. The extracted electron current is also affected by the deposited material on the PE and wall: the tantalum or caesium covered PE and wall lead to a lower extracted electron current than the tungsten covered PE and wall (see Fig. 7). [9]

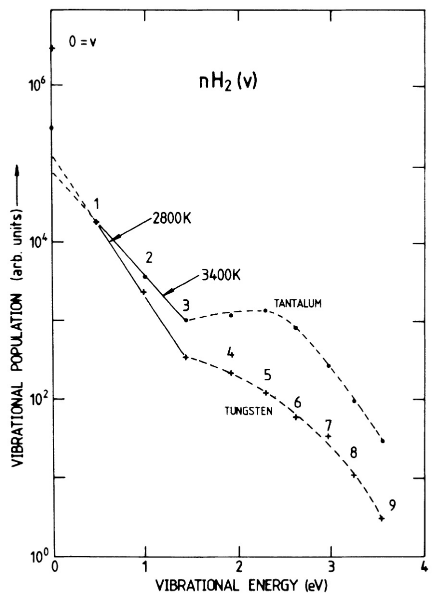

FIGURE 6. Vibrational populations against vibrational energy on a semi-logarithmic scale for tungsten and tantalum filaments (Reprinted with permission from R.I. Hall, I. Cadez, M. Landau, F. Pichon and C. Schermann, Phys. Rev. Lett., **60** (4) 337 (1988) Ref. 8)

A Positive Bias of the PE Depletes the Electron Population

Figure 8 presents a typical example of the variation of the current collected by the PE as a function of the PE bias with respect to the wall, along with the associated variation of the extracted electron and negative ion currents.[11] This experiment was effected in the source Camembert III in which the plasma was produced by seven dipolar sources operated by microwaves (2.45 GHz). The first important result in Fig. 8 is that the extracted H^- ion current shows a clear peak against the change of the PE bias. Moreover this peak is reached for a value of the PE bias close to the plasma potential. The second important result is that the extracted electron current is significantly reduced by applying the PE bias positive with respect to the wall. The drop of the electron current corresponds to the reduction of the electron density by the positive bias with respect to the wall of the PE as can be seen on Fig. 9. In a collisionless situation the electrons from the bulk plasma are unable to cross the transverse magnetic field in front of the PE. Therefore negative ions from the bulk plasma replace the depleted electrons in the magnetized region near the PE to maintain plasma neutrality. Indeed the H^- ion density near the PE increases as positive PE bias with respect to the wall is applied and peaks when V_b is slightly higher than V_p.

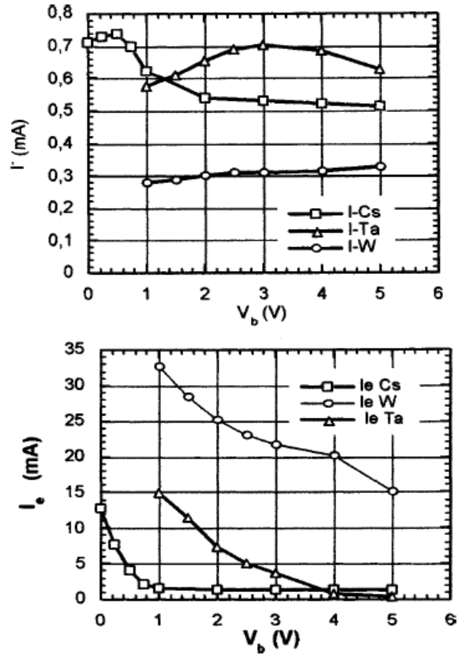

FIGURE 7. Dependence of extracted H^- ion and electron currents on plasma electrode bias with plasma electrode and walls covered with tantalum, tungsten or caesium films (Reprinted with permission from M. Bacal, A.A. Ivanov Jr, M. Glass-Maujean, Y. Matsumoto, M. Nishiura, M. Sasao and M. Wada, Rev. Sci. Instrum.,**75** (5) 1699 (2004), Ref. 9).

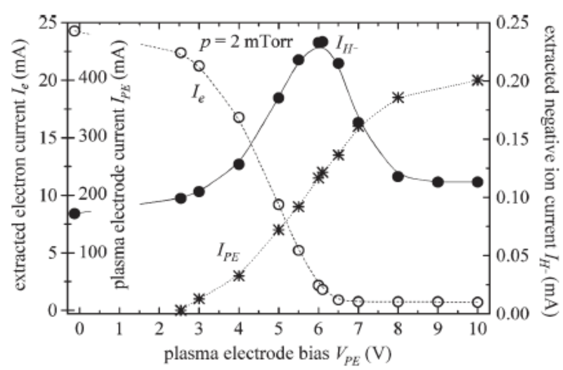

Figure 8. Typical evolution of the extracted electron and negative ion currents and the current collected by the PE. (Reprinted with permission from P. Svarnas, J. Breton, M. Bacal and R. Faulkner, IEEE TPS **35**, N° 4, 1156 (2007), Ref. 11)

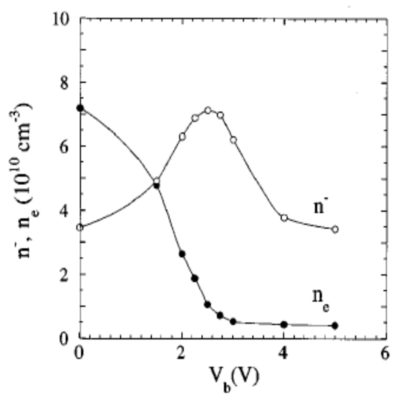

Figure 9. Variation with plasma electrode bias with respect to the wall V_b of the negative ion density n^- and electron density n_e at 8 mm from the PE, in a weak, transverse magnetic field (Reprinted with permission from F. El Balghiti-Sube, F.G. Baksht and M. Bacal, Rev. Sci. Instrum., **67** (6) 2221 (1996), Ref.12)

A Positive Bias of the PE Concentrates H^- Ions Near its Surface Generating an Ion-Ion Plasma

The photodetachment diagnostic was applied to the extraction region of the source Camembert III where a weak transverse magnetic field was present near the PE. Figure 9 shows the measured variation with V_b of the electron density n_e and negative ion density n^- at 8 mm from the plasma electrode in a 50 V, 50 A discharge at 3 mTorr.[12] A very high ratio $n^-/n_e = 12$ occurs in these conditions at $V_b = 2.5$ V. A plasma with such high n^-/n_e ratio contains a very low electron fraction and the negative ion density is only slightly lower than the positive ion density, namely $n^- = (12/13)n^+$. Therefore such a plasma is designated as "ion-ion plasma".

Experimental and theoretical studies on the H^- ion transport near the PE in the extraction region of the H^- sources[13-16] have revealed the existence of enhanced transport of H^- ions toward the extractor correlated to the plasma grid bias. This is the physical reason for the enhancement of the negative-ion fraction in the extracted beam when the PE is biased positive. The effect of the weak transverse magnetic field on negative ion transport in negative ion extraction was further studied by two-dimensional electrostatic particle simulation.[16,17]

A collar structure assembled in front of the extraction hole[18] modifies the electrostatic potential geometry of the plasma grid. The bias potential to the collar located in the filter magnetic field affects the local H^- transport in the region and should affect the extractable amount of H^- ion current.

ROLES OF THE PE IN H^- SOURCES SEEDED WITH CAESIUM

In some ion sources, like the Kamaboko source in JAERI, surface production on the plasma grid is the dominant mechanism for negative-ion production.[19] The surface production is enhanced when the work function of the PE surface is lowered. Therefore it is essential to use the PE with the lowest work function surface. Tests for choosing the PE material were effected in the filament-free Kamaboko source, utilizing a microwave (2.45 GHz) discharge. Tests based on measuring the photoelectric current showed that Cs covered Ni, Au and Ag were the best candidates for the plasma grid material.

Seeding Cs into the ion source modifies the characteristics of H^- ion current and electron current extraction on PE bias, because of the contribution from direct H^- production by positive ion impact on the PE surface, which generates an additional mechanism determining the characteristic effects of V_b as it is biased negative with respect to plasma potential (V_p = 1eV).[20, 21] This can be seen on the results from Camembert III in Fig. 10.

In IPP Garching optimum performance was obtained in the well caesiated source BATMAN when the PE bias voltage was near the floating potential.[7]

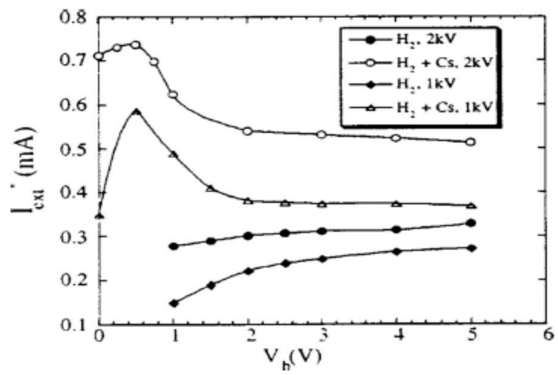

Figure 10. Variation of the extracted H^- ion current with the PE bias voltage at two values of the extraction voltage, in pure hydrogen and caesium seeded operation. The hydrogen pressure was 0.4 Pa. (Reprinted with permission from M. Bacal, F. El Balghiti-Sube, L.I. Elizarov and A.Y.Tontegode, Rev. Sci. Instrum. **69** (2) 932 (1998), Ref. 20)

ROLES of the PE in Li^- and Na^- ION SOURCES OPERATING in ALKALI METAL VAPOR

Negative ions of lithium (Li^-) are formed by dissociative attachment to vibrationally and rotationally excited Li_2 molecules, a process similar to the production of H^- ions in hydrogen volume sources. Since Walther *et al* [22] have demonstrated that a small multicusp source can generate Li^- ion current, Li^- extraction characteristics including V_b dependence have been investigated for source application to plasma diagnostic[23,24,25]. This source can also be used to produce sodium negative ions by simply introducing Na instead of Li into the ion source but with a larger magnitude of the filter magnetic field.[24] In both Li^- and Na^- sources a dependence of extracted negative ion current upon V_b similar to the H^- ion sources is observed, namely the extracted negative ion current variation vs V_b presents a maximum and the electron density exhibits a decrease for increasing V_b beyond the maximum of I^-. The smooth drop of the co-extracted electron current with increasing V_b is observed in the Li^- source. As shown in Figure 11, the electron temperature in the extraction region of a Li^- volume source does not become high enough for the electron impact detachment of Li^- to dominate the ion-ion mutual neutralization indicating that the change of the negative ion transport by applying a PE bias played the essential role in the negative ion extraction.

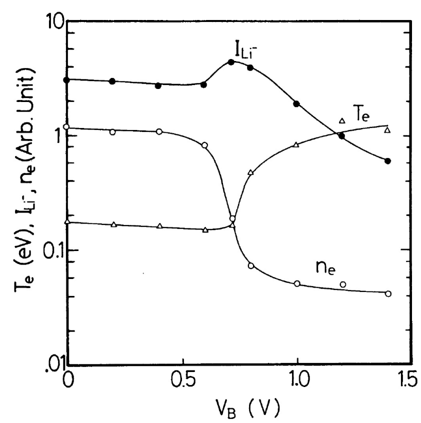

Figure 11. Variation with PE bias of the Li^- extracted current, electron density and electron temperature in a Li^- ion source. (Reprinted with permission from M. Wada, H. Tsuda, M. Sasao, Rev. Sci. Instrum. **63** (4) 2729 (1992), Ref. 23)

CONCLUSION

In small volume sources of H^- with a strong magnetic filter a maximum in the variation of I^- with V_b and a very rapid decrease of the co-extracted electron current are observed. Such a maximum of I^- is also observed in sources of Li^- and Na^-. A smooth drop of the co-extracted electron current with increasing V_b is observed in most of these sources.

The H^-, Li^- and Na^- are formed by volume plasma processes in the respective sources. Therefore the PE bias causes change in plasma parameters in the extraction region, and thus causes improvements in negative ion extraction, only when it is positive with respect to plasma potential. In caesium seeded H^- sources the negative ions are formed also by direct H^- production due to positive ion and atom impact on the PE surface. For these ion sources the PE bias negative with respect to the plasma potential also enlarges the extracted negative ion current[21]. Proper positive PE bias realizes enhanced transport toward the PE of H^- ions formed by a volume process in the bulk plasma, and maximizes the ratio of H^- ion current to electron current.

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