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UCRL-90951, Rev. 1
PREPRINT

607-841218-3-Rev. 1

Hydrogen Vibrational Population Distributions and Negative Ion Generation in Tandem High-Density Hydrogen Discharges

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UCRL--90951-Rev. 1

DE85 006764

This paper was prepared for presentation at the 31st National Symposium of the American Vacuum Society, MGM Grand, Reno, Dec. 4-7, 1984. A condensed version of this paper will be published in the Journal of Vacuum Science and Technology A, 1985.

December 3, 1984

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HYDROGEN VIBRATIONAL POPULATION DISTRIBUTIONS AND NEGATIVE ION CONCENTRATIONS IN TANDEM HIGH-DENSITY HYDROGEN DISCHARGES*

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Abstract

The tandem high-density hydrogen negative-ion-source system is optimized to identify the largest possible ion concentrations and extracted ion currents. The optimization includes varying the length of the second chamber, varying neutral gas and electron densities, and varying the ratio of atomic to molecular density. Vibrational excitation occurs via high-energy electron excitation (E-V process) and H_2^+ surface neutralization (s-V process). These processes are considered separately and acting in parallel. The solutions are presented in terms of a dimensional scale factor, R . For a system scale length $R = 1$ cm, optimum extracted current densities are in the range 50 to 100 mA cm⁻². A single-chamber s-V system with the high-energy electron component suppressed can provide larger ion concentrations than a tandem E-V, s-V system.

I. Introduction

The development of a computational model for the description of negative ion concentrations in high-density hydrogen discharges is extended here to include the combined effects of both electron excitation and molecular ion surface neutralization. These calculations are applied to the multiple-chamber tandem system discussed previously,¹ but now with particular emphasis on the variation of the negative ion density along the second chamber (the negative ion formation chamber). The effects of vibrational population enhancement

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

that result from the Auger neutralization of molecular ions impinging on the chamber walls are taken into account and compared with the electron excitation process. Our emphasis continues to be to identify the maximum possible currents that can be extracted within a useful range of system parameters.

Our central hypothesis calls for the formation of negative ions by dissociative attachment: low energy electrons in collision with vibrationally excited molecules leading to spontaneous dissociation into atoms and ions.¹ A principal source of vibrational excitation is energetic electron excitation, the E-V process.^{2,3} We have noted earlier⁴ that at least for low gas pressures the surface neutralization of H_2^+ ions can compete favorably with the E-V process and thus provide an additional source of vibrational excitation. In this paper we shall compare three distinct parameter regimes associated with a two-chamber tandem configuration. In the first system only E-V processes are operative in the first chamber as the source vibrational excitation. In the second, both energetic electron excitation and H_2^+ -surface excitation (the s-V process) are operating in parallel. In our third example we consider a system for which the first chamber is devoid of high energy electrons and only the s-V process is operative.

The parameter range to be explored is appropriate to high-power ion-source discharges: the hydrogen gas density ranges from 10^{13} to 10^{15} molecules cm^{-3} , the electron density ranges from 10^{12} to 10^{14} electrons cm^{-3} , and the system scale length, R , is presumed to range from 0.1 to 10 cm. The data are presented in terms of the density-dimensional scaling parameters, nR electrons cm^{-2} and N_2R molecules cm^{-2} discussed in Ref. 1, that allow for a large amount of data to be presented compactly.

In the first chamber the fast electron density, for which the electron energy is greater than $E > 30$ eV, is assumed to be fixed at ten per cent of the total electron density. For electron energies ranging from 30 eV up to 500 eV the σv values range within $\pm 20\%$ of $\sigma v(v'' = 0) = 3.8 \times 10^{-9}$, the value we shall use here. The remaining $\sigma v(v'' > 0)$ values differ from the above by a constant factor independent of energy.² The main body of electrons in the first chamber are distributed according to a Maxwellian distribution and with an electron temperature of $kT = 5$ eV. The electrons in the second chamber have only a thermal component $kT = 1$ eV, whose temperature is chosen to enhance the dissociative attachment process. The electron temperature differential is maintained by a magnetic filter separating the two chambers.⁵

With this choice of parameters the negative ion concentration in the second chamber is optimized by selecting a range of values for nR and N_2R . The ratio of electron to gas density is normally restricted to a maximum of ten percent. A few exceptions illustrate the parametric dependence.

If s-V processes alone are operative and no high energy electrons are present a single-chamber system will also provide for an optimum system. In the succeeding sections we shall follow our earlier format¹ and discuss the vibrational distributions and their parametric dependences first, followed by a discussion of the optimized two-chamber and single-chamber negative ion systems. Some other recent work on negative ion concentrations in high-density hydrogen discharges has been discussed by Fukumasa and Saeki.⁶ A condensed version of this report will be published.⁷

II. System Geometry

The scale length, R , by itself is not sufficient to determine the wall relaxation rates. For a specific calculation we need recourse to a particular

geometry. We consider a tandem system with cylindrical chambers of radius R , with the axial length of the first cell is taken equal to $2 R$. In the first cell vibrational excitation to levels v'' occurs by collisional excitation of the energetic electrons (E-V process) with the residual gas molecules, according to

The intermediate electronic states, H_2^* , of principal importance are the $B'^1\Sigma_u$ and $C'^1\Pi_u$ states.² When the s-V process is operative, vibrational excitation occurs on the surface of the first chamber,

The vibrational excited molecules flow unimpeded through the magnetic filter separating the two chambers and into the second chamber where negative ions are formed by dissociative attachment⁸

The $H_2(v'')$ are not regenerated in the second chamber. The H^- ions once formed are subsequently attenuated in their passage through the second chamber by the action of ion-ion neutralization collisions⁹

and associative detachment collisions^{10,11}

In consequence, the negative ion concentration in the second chamber will pass through a maximum for some value of the axial position, Z/R , and the optimum

negative ion extraction is obtained by positioning the extraction grid at this point.

III. Vibrational Population Distributions

The vibrational population distributions generated in the first chamber are calculated using the model described in Ref. 1. In this paper we have extended the distribution to the lower portion of the spectrum. The values used here for the wall collision parameter, $b(v'')$, range continuously from $b = 2.5$ at $v'' = 1$ to $b = 1.0$ at $v'' = 13, 14$.

In Ref. 1 we had expressed the ratio of atomic to molecular concentrations through the intermediary of the atomic wall recombination coefficient, γ . It now seems more likely that the system diagnostics will reveal the atomic concentration directly rather than the recombination coefficient. We have carried out this parametric study using specific values for the atomic to molecular ratio, $N_1/N_2 = 0.1$ and 1. The relationship of this ratio to γ can be obtained by referring to Fig. 1 of Ref. 1.

The sources of vibrational excitation include the E-V process and the H_2^+ -surface neutralization. For H_2^+ ions impinging on the surface with kinetic energies in the range 4 to 10 eV our calculations show approximately a third or more reflect as H_2 molecules. Of these reflected molecules we find that the vibrational spectrum is populated uniformly across the entire spectrum. The fraction of incident H_2^+ ions converted to molecules in a particular level v'' is taken to be $f = .022$. The flux of H_2^+ incident on the chamber walls is equal to $0.6 N(2+) \sqrt{\frac{kT}{M}}$. It follows that the total flux per unit volume of $H_2(v'')$ entering the chamber is equal to

$$1.8 N(2+) \sqrt{\frac{kT}{M}} \frac{f}{R} \quad (6)$$

One purpose of this survey is to identify the optimum extracted negative ion currents. Accordingly, we shall take the molecular ion density, $N(2+)$, equal to the total electron density. In high-power discharges the H_2^+ concentration will range from fifteen to forty per cent of the total electron density with typical values near twenty-five percent.^{12,13} In RF heated discharges H_2^+ concentrations can be substantially larger.¹⁴ For H_2^+ concentrations less than the electron density the negative ion concentrations can be interpolated from the solutions presented below.

In this paper we include the effect of e-V collisions¹ and extend the calculation of the vibrational distributions down to the $v''=1$ level. The rate equation for the density of molecules in a particular level v'' become

$$\begin{aligned} \frac{dN_2(v'')}{dt} = & n(f)N_2r_1 + nN_2r_2 + N(2+)s_3/R \\ & + N_2(v''+1)N_2r_4 + N_2(v''+2)N_2r_5 + \dots + N_2(14)N_2r_n \\ & + N_2(v''-1)N_2r_m + \dots + N_2(1)N_2r_p \\ & - N_2(v'') [N_2s_1 + N_1s_2 + n(f)s_3 + ns_4 + s_5/R] \end{aligned}$$

The rates r_i , s_i are discussed in Refs. 1,4. The first three terms are the source terms due to the E-V, e-V, and s-V processes, respectively. The last term, s_5 , is the wall collision term.

In equilibrium, $dN_2(v'')/dt = 0$, and the above set of equations reduces to a set of fourteen coupled but linear inhomogeneous equations for the $N_2(v'')$. These equations can be expressed in matrix form

$$AN = -K$$

with solution $N = -A^{-1}K$. The N is a column matrix whose elements are the $N_2(v'')$. The K is a column matrix whose elements are the source terms shown above on the first line on the right-hand side of the equation.

The matrix N or its elements scale like $1/R$ as the densities $n(f)$, n , N_2 , and N_1 are scaled as $1/R$. This scaling is obtained in the following way: If the electron and neutral densities are scaled inversely with R , e.g., $N_2 \rightarrow N_2^0 R_0/R$, each element of A scales as R_0/R and each element of A^{-1} as R/R_0 . The elements of K however, scale as $(R_0/R)^2$. Factoring R_0/R , we have

$$N = - \frac{R_0}{R} A^{-1} K ,$$

and the scaling law is obtained. The scaled densities, nR , N_2R , N_1R and $N_2(v'')R$, are independent of R and provide the set of independent variables.

In Figs. 2 and 3 are plotted the equilibrium vibrational population distributions, being the ratio of the equilibrium concentration of $N_2(v'')$ to the concentration of unexcited background gas molecules, N_2 , versus vibrational level, v'' . Three sets of data are presented here: the solid circles refer to excitation via the E-V process only; the open circles refer to excitation by the combined effects of both E-V and s-V processes and assuming the entire concentration of positive ions in the first chamber is composed of H_2^+ ions; and, the crosses refer to a condition of excitation by s-V processes only together with an absence of high-energy electrons in the first chamber.

Referring first to Fig. 2, in all cases the atomic density, N_1 , is taken equal to the molecular density, N_2 ; the total electron densities are set equal in the two chambers, with the fast electron density in the first chamber equal to one-tenth the total electron density. In curves A the scaled neutral and electron densities are 10^{14} molecules cm^{-2} , and 10^{12} electrons cm^{-2} , respectively. In curves C the neutral densities are a factor 10 higher than for case A, 10^{15} molecules cm^{-2} . The curve A for s-V excitation only lies just a few per cent lower than the E-V curve and is not shown in the figure. In all cases the C distributions are substantially lower than the A distributions due

to the enhanced de-excitation caused by the atom-molecule collisions. These are principally the atom-de-excitation (A-DX) collisions discussed in Ref. 1.

In the distributions B the scaled neutral densities are 10^{14} molecules cm^{-2} , as in case A, but the electron densities are increased to $nR = 10^{13}$ electrons cm^{-2} . In distributions D, the neutral densities are 10^{15} molecules cm^{-2} as in case C but with electron densities increased to 10^{13} electrons cm^{-2} .

In case B but for s-V excitations only the attenuation of the $\text{H}_2(v'')$ into the volume is becoming marginally important at the upper end of the spectrum. This will cause deviations from the spatial uniformity of the densities as implied in this paper. Note that the attenuation of the s-V excitations is reduced by the high recoil velocity of the s-V generated $\text{H}_2(v'')$ as they leave the surface and penetrate the discharge. Comparing distributions B and D, the effects of the enhanced atomic de-excitation are also evident at these higher electron densities. Comparing distributions A with B or C with D illustrates the vibrational enhancement resulting from the larger high-energy electron densities.

In Fig. 3 the same conditions apply as in Fig. 2 excepting that in all cases the atomic density is now only one-tenth the molecular density. In this figure the s-V distribution for case A is not shown but lies a few per cent below the open-circle distribution; the s-V distribution for case D is not shown but lies a few per cent below the E-V distribution. Comparing cases A and C, the distributions are now of more similar magnitude because of the reduced role of the atom-de-excitation processes. For those distributions for which the s-V process alone is operative, the transition from case B to case C is especially pronounced. The higher ion (electron) density and lower molecular density of case B cause the excitation process to be enhanced and the de-excitation processes to be reduced in comparison with the processes of case D.

IV. Generation of Negative Ions Through the Second Chamber

The variation of negative ion density in the axial direction along the second chamber is given by

$$N(-) = \sum_{v''} n_c N_2^0(v'') \left\{ n(b - a + h) - [N_2 d + N_1(e + f - g) + w] \right\}^{-1} \left\{ \exp[-an + N_2 d + N_1(e + f) + w] \left(\frac{Z}{R}\right)^R - \exp[-n(b + h) + N_1 g] \left(\frac{Z}{R}\right)^R \right\}. \quad (7)$$

The collision terms $a, \dots, h$ are defined in Ref. 1. The factor $N_2^0(v'')$ is the concentration of vibrationally excited molecules, v'' , at the entrance to the second chamber and is taken from Figs. 2 or 3. Included in Eq. (7) are the effects of wall relaxation operating in the second chamber, given by the term w , where

$$w = \frac{3}{4} \frac{1}{b(v'')} \frac{1}{R}. \quad (8)$$

A. E-V Excitations

The scaled negative ion density along the second chamber for E-V excitation processes only is shown in Fig. 4 plotted as a function of Z/R .

For the calculations summarized in this figure, we have taken the atomic density to be one-tenth the molecular density; the solid lines refer to scaled molecular densities of 10^{15} molecules cm^{-2} , and for the dashed curves 10^{14} molecules cm^{-2} . The successive curves 1-4 refer to successively larger scaled electron densities in the two chambers, 10^{12} , 5×10^{12} , 10^{13} , and 2×10^{13} electrons cm^{-2} , respectively. For all curves the negative ion density first increases as negative ions are formed in the leading part of the second chamber, then reaches a maximum and falls in the latter portion of the chamber as the formation process comes into competition with ion-ion and associative detachment loss processes, reactions (4) and (5).

For successively larger electron densities, the maxima increase but are shifted to smaller and smaller values for Z/R . The optimum extraction currents would occur if the second cell length were chosen equal to the maximum at $(Z/R)_m$.

Calculations show that the maxima continue to increase and shift toward smaller Z/R as the electron density increases. There is a minimum practical value for Z/R however, due to the finite structure of magnetic filter system. While a choice for the minimum value of the second cell length, $(Z/R)_2$, is necessarily subjective, useful values much less than 1 to 1.5 are difficult to achieve. A comparison of curves 3, 4 shows no advantage in increasing the electron density above 10^{13} electrons cm^{-2} for $(Z/R)_2$ values near unity.

The extracted negative ion current density is proportional to the product of the negative ion density and axial velocity at the point $(Z/R)_2$. We shall assume as before¹ that the electric potentials in the second chamber are arranged so as to allow all negative ions to be gathered and carried off in the axial direction. The negative ion energy appropriate to a high-power discharge remains an uncertain quantity, but is expected to be some few tenths of an eV. For purposes of discussion, we shall adopt a value of 0.3 eV. We define a scaled current density given by

$$j(-) R = N(-) R v(-) \quad . \quad (9)$$

On the ordinate in Fig. 4 and in following figures we have indicated with an arrow the scaled negative ion density for which the scaled current density would equal 50 mA cm^{-1} . For a system with scale length $R = 1 \text{ cm}$ this corresponds to 50 mA cm^{-2} , and for $R = 10 \text{ cm}$, 5 mA cm^{-2} .

In Fig. 5 are shown data similar to the conditions of Fig. 4 excepting that the atom density is now taken equal to the molecular density. The enhanced attenuation due to the associative detachment is evident. For this

case the lower molecular density, 10^{14} molecules cm^{-2} , is more attractive than the higher molecular density, 10^{15} molecules cm^{-2} . Here again the optimum scaled electron density is near 10^{13} electrons cm^{-2} for $(Z/R)_2$ near unity. Note that the useful maximum of the negative ion density and hence the optimum extracted current density is reduced here by about a factor of eight compared with the lower atomic density condition of Fig. 4.

Since the low atom density solutions of Fig. 4 with $N_1 = 1/10 N_2$ and $N_2 = 10^{15}$ mol. cm^{-2} clearly represent the more optimum condition, we expand these solutions further in Fig. 6 but now using a linear scale. The solutions labeled 1-4 correspond to a fixed electron density of 10^{13} electrons cm^{-2} maintained in the second chamber while the total density in the first chamber assumes values 1, 2, 4, and 10×10^{13} electrons cm^{-2} . The maximum of the negative ion density increases but approaches an asymptotic value of 10^{12} ions cm^{-2} . This asymptote is a consequence of the asymptotic value for the vibrational excitation generated in the first chamber. At the high electron densities the fast-electron excitation of the vibrational levels comes into equilibrium with the fast-electron destruction of these levels. Choosing $(Z/R)_2$ near unity, this factor of ten increase of electron density in the first chamber increase the negative ion concentration in the second chamber by about a factor of two.

The dashed curves a, b correspond to equal electron densities, 10^{13} , in the two chambers but the gas pressure lowered to 0.8×10^{15} and raised to 2.0×10^{15} molecules cm^{-2} , respectively. The factor of two increase in pressure increases the ion concentration about a third.

The long-dashed curves, α , β , γ , correspond to lowering the electron density in the second chamber to 5×10^{12} cm^{-2} , but successively increasing the electron density in the first chamber to values 0.5 , 2.0 , and 4.0×10^{13} cm^{-2} , respectively. The lower electron density in the second chamber broadens the

distribution in Z/R but the increased density in the first chamber offers little advantage for optimizing the negative ion concentration.

Choosing values of $(Z/R)_2$ near unity the open extraction end of the second chamber intercepts such a large solid angle as viewed from the first chamber that the wall relaxation term, w , included in Eq. 7 may overestimate the vibrational relaxation. We have examined this point for several optimum solutions of Fig. 4 by setting $w = 0$. The new solutions with $w = 0$ are increased 25 percent and shifted outward in Z/R by about 40 percent for the high molecular density solutions. For the lower molecular densities, 10^{14} molecules cm^{-2} , the solution is increased a third and expanded in Z/R by about 40 percent.

B. E-V and s-V Excitations

In Figs. 7 and 8 are shown the density variations as a function of Z/R taking into account the E-V and s-V excitations occurring simultaneously in the first chamber. In Fig. 7 the atomic density is taken to be one-tenth the molecular density, and the successive curves 1-4 correspond to electron densities of 10^{12} , 5×10^{12} , 10^{13} , and 2×10^{13} electrons cm^{-2} , respectively. Notice that there is relatively little difference in the solutions at the two different gas densities, in contrast to the solutions of Fig. 4. In particular, the inclusion of the s-V process here causes the negative ion density to increase by about a factor of five or six at 10^{14} molecules cm^{-2} compared with the solutions of Fig. 4. At 10^{15} molecules cm^{-2} the increase is rather small. As before, for values $(Z/R)_2$ near unity, the optimum electron density is near 10^{13} electrons cm^{-2} .

Figure 8 is a similar set of solutions excepting here the atomic and molecular concentrations are taken to be equal. The higher molecular density, 10^{15} molecules cm^{-2} , now causes severe attenuation due to associative detachment. The optimum electron density remains near 10^{13} electrons cm^{-2} .

C. s-V Excitations

If the high-energy electrons are suppressed in the first chamber so that E-V processes are not operative, the s-V excitations will remain as the sole source of vibrational excitation. The solutions for this case are shown in Figs. 9 and 10. In Fig. 9 the atom density is one-tenth the molecular density. For the 10^{14} molecules cm^{-2} case (dashed curves) the successive solutions, 1-4 correspond to electron densities in each chamber of 10^{12} , 5×10^{12} , 10^{13} , and 2×10^{13} electrons cm^{-2} , respectively. Again the optimum density is near 10^{13} electrons cm^{-2} for $(Z/R)_2$ near unity. At the higher molecular density, 10^{15} molecules cm^{-2} , we include an additional solution, 5, corresponding to 4×10^{13} electrons cm^{-2} . For the higher molecular density the negative ion concentration at the same electron density is always less than the low gas density case.

In Fig. 10 the solutions correspond to the case for equal atomic and molecular densities. The curves are labelled as in Fig. 9. Here the lower gas density is clearly preferred.

It is interesting to compare these s-V solutions with the E-V solutions of Figs. 4 and 5. Comparing first Fig. 4 with Fig. 9, note that for low molecular densities the optimum negative ion density is nearly an order of magnitude larger for s-V than for E-V. At the higher molecular density, 10^{15} molecules cm^{-2} , the s-V process yields a result about 40 per cent larger. Comparing Fig. 5 with Fig. 10 at the low molecular density the optimum negative ion concentration is approximately an order of magnitude larger for s-V than E-V. For molecular densities of 10^{15} , the negative ion concentrations are comparable for s-V and E-V. In summary, the s-V process when compared with the E-V process allows for larger negative ion concentrations and operation at lower gas densities.

The s-V process operating alone together with the suppression of high-energy electrons in the first chamber provides for negative ion concentrations comparable to or in excess of those possible using the combined E-V and s-V processes. Inspection of Figs. 7 and 9 where $N_1 = 1/10 N_2$ shows comparable negative ion concentrations excepting that for the s-V solutions of Fig. 9 these comparable densities are achieved at the lower gas pressures. Comparing Figs. 8 and 10 for which $N_1 = N_2$ the optimum ion concentration occurs for the s-V process of Fig. 10. The lack of high-energy electrons in this latter case reduces the attenuation of the $H_2(v'')$ molecules in the first chamber and provides an overall enhancement of the ion concentration that exceeds the E-V contribution.

The above discussion is directed toward a two-chamber system; however if we limit the discussion to s-V vibrational excitation only we can consider a single-chamber system in which both s-V excitation and dissociative attachment are operative. Although an alternate chamber may be required to prepare the H_2^+ ions, from an operational point of view one is dealing with a single chamber system if both excitation and negative ion formation are occurring within the same volume.

Because vibrational excitation is being continuously regenerated rather than attenuated along the chamber one might expect a larger concentration of negative ions could be achieved in the single-chamber system. To examine this point we shall compare the optimum negative ion concentration found in Figs. 9 and 10 for the low molecular density case, 10^{14} molecules cm^{-2} , and $nR = 10^{13}$ electrons cm^{-2} , with the single-chamber concentration.

The local negative ion concentration is given by the ratio of the formation process to the ion-ion and associative detachment destruction processes

$$N(-) = \frac{n \sum_{v''} N_2(v'') \overline{\sigma(DA, v'')v}}{n \sigma v(i-i) + N_1 \sigma v(AD)} \quad (10)$$

Here $\sigma v(i-i)$ is now taken appropriate to H^- , H_2^+ collisions with value $2 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$. For $N_1 = 1/10 N_2$ the single chamber concentration given by Eq. 10 shows a 75 per cent increase over the corresponding solution in Fig. 9 evaluated at $Z/R = 1$. For $N_1 = N_2$ the single-chamber concentration is double that of the solution in Fig. 10.

Both with respect to the comparison with E-V processes in the two-chamber system and with the enhanced operation in the single-chamber mode, the s-V process together with the absence of high-energy electrons offers the prospect for both the optimum negative ion concentration and operation at the lower gas pressures.

V. Conclusions

The largest negative ion concentrations and extracted currents in a tandem system will be achieved by varying the length of the second chamber. In general the largest concentrations will occur for smaller axial lengths, expressed in the ratio of axial length to radius, Z/R . For values of Z/R near unity, the optimum scaled negative ion extraction current densities are in the range $50\text{-}100 \text{ mA cm}^{-1}$.

The s-V process, acting in addition to E-V, adds significantly to the total vibrational excitation and will allow for optimum negative ion concentrations at lower gas pressures. For a discharge whose positive ion component is almost entirely H_2^+ ions and provided the high-energy electron component is suppressed, the s-V process in a tandem system can provide larger

negative ion concentrations either as compared to the E-V process alone or as compared to a combination of E-V and s-V processes.

A single-chamber system operating with s-V vibrational excitation and dissociative attachment can lead to higher negative ion concentrations and negative ion extracted current densities than are available in a tandem system.

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Figure Captions

1. Schematic of the Tandem Negative Ion Source
2. Vibrational population distribution versus vibrational level. Closed circles: E-V process only. Open circles: E-V and s-V processes both operative. Crosses: s-V process only. The atom density is taken equal to the molecular density for all solutions.
 Curves A: $N_2R = 10^{14}$ molecules cm^{-2} , $nR = 10^{12}$ electrons cm^{-2} .
 Curves B: $N_2R = 10^{14}$ molecules cm^{-2} , $nR = 10^{13}$ electrons cm^{-2} .
 Curves C: $N_2R = 10^{15}$ molecules cm^{-2} , $nR = 10^{12}$ electrons cm^{-2} .
 Curves D: $N_2R = 10^{15}$ molecules cm^{-2} , $nR = 10^{13}$ electrons cm^{-2} .
3. Vibrational population distribution versus vibrational level. The atom density is taken equal to one-tenth the molecular density. Captions as in Fig. 2.
4. The scaled negative ion density, $N(-)R$, in the second chamber versus the scaled axial distance, Z/R . Atom density one-tenth molecular density. Solid curves: molecular density $= 10^{15} \text{ cm}^{-2}$. Dashed curves: molecular density $= 10^{14} \text{ molecules cm}^{-2}$. Curves 1-4 correspond to electron densities 10^{12} , 5×10^{12} , 10^{13} , and 2×10^{13} electrons cm^{-2} , respectively.
5. Negative ion density versus axial distance in second chamber. Atom density equal to molecular density. Captions as in Fig. 4.
6. Negative ion density versus axial distance in second chamber. Atom density equal to one-tenth molecular density. Solutions 1-4: molecular density equals $10^{15} \text{ molecules cm}^{-2}$, electron density in second chamber equals 10^{13} electrons cm^{-2} , electron density in the first chamber 1, 2, 4, and 10×10^{13} electrons cm^{-2} , respectively. Dashed solutions a, b: electron density equals 10^{13} electrons cm^{-2} in both chambers, molecular density equals 0.8 and $2.0 \times 10^{15} \text{ molecules cm}^{-2}$, respectively. Long-dashed curves α , β , γ : molecular density $10^{15} \text{ molecules cm}^{-2}$, electron density

in second chamber equals 0.5×10^{13} electrons cm^{-2} , electron density in the first chamber 0.5, 2.0, and 4.0×10^{13} electrons cm^{-2} , respectively. Note linear scale.

7. Negative ion density versus axial length. E-V and s-V processes both operative. Atom density one-tenth molecular density. Captions as in Fig. 4.
8. Negative ion density versus axial length. E-V and s-V processes both operative. Atom density equal to molecular density. Captions as in Fig. 4.
9. Negative ion density versus axial length. s-V process operative only. Atom density one-tenth molecular density. Captions as in Fig. 4. Solution 5 corresponds to electron density of 4×10^{13} molecules cm^{-2} .
10. Negative ion density versus axial length. s-V process only. Atom density equal to molecular density. Captions as in Fig. 9.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10