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TANDEM NEGATIVE ION SOURCE

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ANALYSIS AND INTERPRETATION OF A HIGH DENSITY
TANDEM NEGATIVE ION SOURCE*

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INTRODUCTION

In the last few years the development of tandem-discharge hydrogen-negative-ion-source systems has proceeded along both experimental and theoretical lines. To some extent these developments have proceeded independently, either the available theoretical model was inadequate to account for a specific geometrical configuration, or the experimental data was not sufficient to provide adequate input parameters for calculation. In the tandem system described here the electron temperature, electron density, and other relevant parameters have been obtained for a high-density system whose electron densities range up to $3 - 5 \times 10^{12}$ electrons cm^{-3} . The model calculation for the atomic processes has been extended to include both electron density and electron temperature spatial variations through the second chamber. These spatial variations are essential for an adequate interpretation of tandem systems where steep density gradients may occur beyond the magnetic filter region. In this paper we shall combine the experimental density data with the new spatially dependent atomic model for the purpose of attempting a correlation of the observed and calculated current densities.

EXPERIMENTAL

The experiment was performed on the Test Stand 1 (TS-1) facility (Fig. 1) at the Lawrence Berkeley Laboratory. For this experiment, we limited TS-1 to accelerate one beam, from a $1 \times 2.5 \text{ cm}^2$ rectangular slot, with an energy of 6 kV. The beam was detected electrically by saturated +ion collection and calorimetrically by water-flow calorimetry, 60 cm downstream, on a beam dump. The electrical signal was calibrated against the current inferred from the steady-state calorimetry whenever the pressure or accelerator voltage was changed.

The H^- plasma chamber consisted of a standard "cusp SmCo magnetic bucket" ($22 \times 22 \times 22 \text{ cm}$). Four rods (separated by 6.4 cm) of water-cooled magnets (SmCo, $4.7 \times 4.7 \text{ mm}$), were inserted in the plasma chamber at three axial locations: 2.5 cm., 6.9 cm., and 11.3 cm. upstream from the beam-forming electrode. (Fig. 2) The magnet rods separated the plasma chamber in two regions: 1) a hot electron region where the filaments were located and 2) a cold electron region which was terminated by the beam-forming electrode. Visualization of these two chambers is aided by visualizing the B-field lines. The relative electron density for the exit chamber was controlled by the

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"strength" of the magnetic filter and by the voltage of the beam-forming electrode. For this experiment, we chose source parameters which maximized the H⁻ delivery to the beam dump, i.e. optically overdense and on the verge of beam-clipping by the exit electrode.

The parameters for the data used in the fitting are listed in Table 1. Density and temperature information is reported elsewhere at this conference.

FILTER PLANE SERIES

SOURCE PARAMETERS:		FILTER LOCATION		
		2.9cm	6.9cm	11.3cm
Arc	0-200 A			
	100 V			
Gas Pressure	10 mTorr			
Rect. Aperture	1 x 2.54cm			
J ⁺ current (mA/cm ²)		313	370	(460)
Filter frame	@anode			
45mCo filter rods	@anode			
Ext. Magn. (GmCo)	none			
B _{G1}	-0			
V _{G1} (Bias adj. for max. H ⁻ @200A)		+2.5	+4.0	+4.0
V _{accel}	6.0kV			
B _{G2}	T(N)			
V _{G2} Bias (volts)	0			
I _{G2} (mA)		260	500	730
I _{dump} (sec.) (mA)		31	17.5	12.5±1%
I _{H⁻} (0x1.8) (mA)		17.2	8.7	6.9
I _{H⁻} (Area=2.54cm ²) (mA/cm ²)		8.8	3.8	2.7

THEORETICAL DISCUSSION

The array of atomic and molecular processes that determine the vibrational population distribution and the negative ion concentration in a tandem discharge has been discussed in previous works.^{2,3,4} A principal parameter that remains uncertain is the atomic concentration. Some estimates for the atomic concentrations in high-power hydrogen discharges designed for the optimum extraction of protons have been made by Chan et al.,⁵ and by Vella.⁶ In a positive ion source discharge the species mix favors high proton ratios provided the discharge contains a high concentration of atoms.⁵ In hydrogen discharges intended for negative ion extraction however, a high atomic concentration is deleterious, causing negative ion destruction via the associative detachment process

To gain a perspective of the relative atomic concentrations we calculate the ratio of atomic to molecular density for two limiting

cases that are expected to represent lower and upper limits, respectively. We obtain a lower limit assuming the source of atoms is limited to molecular collisional dissociation, process (1) in Table II, and dissociation of H_2 molecules impinging on the hot filament, process (7). The energetic atoms ($E \approx 2.5\text{eV}$) that result from collisional dissociation and the lower energy thermally dissociated products are assumed to be completely absorbed upon striking the chamber walls ($\gamma = 1$). For an upper limit we have taken into account the sum of processes listed in the Table. The relative atomic contributions from these different processes are shown on the right. The recombination of positive ions on the chamber walls, process (2), is seen to be an important source of atoms. The rates for these processes are summarized by Chan et al., who performed a similar calculation. The mean atomic energy for this upper limit case is taken to be 0.35eV , derived from spectroscopic data⁷. Inspection of Fig. 4 shows a possible range of values for these two limiting values that runs from one percent to thirty percent at electron densities near $3 \times 10^{12}\text{cm}^{-3}$.

TABLE II

Relative contributions to the atomic concentration at $n=3.3 \times 10^{12}$ electrons cm^{-3} .

	<u>Process</u>	<u>Contribution</u>
1.	$e + H_2 \rightarrow H + H + e$	36%
2.	$\begin{matrix} H_2^+ \\ H_2^+ \\ H_3^+ \end{matrix} + \text{WALL} \rightarrow H + \dots$	28%
3.	$H_2^+ + H_2 \rightarrow H + H_3^+$	8.8%
4.	$e + H_2 \rightarrow e + H_2^* \rightarrow H + H + e$	6.8%
5.	$e + H_3^+ \rightarrow \begin{matrix} H + H_2 \\ H + H + H \end{matrix}$	6.3%
6.	$e + H_2^+ \rightarrow H + H$	5.2%
7.	$H_2 + \text{Filament} \rightarrow H + H$	5.1%
8.	$e + H_2^+ \rightarrow H + H^+$	2.9%
9.	$e + H_3^+ \rightarrow 2H + H^+ + e$	<1%

The model calculation for the negative ion concentration and current density to be described here is based upon the schematic shown in Fig. 5. In the first chamber the electron and gas densities do not vary with position along the chamber. The first chamber is defined as that region to the left of the magnetic filter where fast electrons ($E > 25\text{eV}$) are present. The density of fast electrons is calculated using the model for the electron energy distribution described in Ref. 2. The second chamber is defined as that region where no fast electrons are present.

In the second chamber the electron densities, electron temperatures, vibrationally-excited-molecule densities, and negative ion densities are known to vary with axial position from the region of the magnetic filter up to the extraction plane. To account for these spatial variations in the model we have divided the second

chamber into four zones, with the representative electron density and electron temperature variations shown in the lower portion of the figure.

With the experimental data described above the necessary input parameters for the calculation are available but with the exception of the atomic concentration. Here we treat the atomic concentration as a free parameter that is adjusted until the calculated current density agrees with the extracted current density. This fit is attempted at a filter-extraction plane separation of $z = 2.5$ cm. For a first-chamber electron density of 3.3×10^{16} electrons cm^{-3} , the extracted current density is observed to be 6.8 mA cm^{-2} . In the earlier analysis of the high-density positive-ion-source discharge Chan et. al., arrived at an H_2 gas temperature of approximately 1500°K . In the multipole system under investigation here, the required discharge current per unit gas pressure to achieve the same electron density is lower, and we might expect the gas temperature also to be lower.

On Fig. 4 is shown the atomic ratio necessary to reproduce the observed 6.8 mA cm^{-2} , and calculated for two gas temperatures, 900°K and 1500°K . The atomic ratios are close to, but less than, the projected upper limit values.

It is found experimentally that the extracted current density of 6.8 mA cm^{-2} is a maximum as a function of gas pressure about a pressure of 10 mtorr for fixed discharge current. We have varied the gas pressure by a factor of two in the calculation so as to examine the pressure dependence. Increasing the gas density will decrease proportionately the number of high energy electrons, and shift the ratio of atomic to molecular densities along a line parallel to the upper-limit line shown in Fig. 4. The results of these gas density variations at a temperature of 1500°K are shown in Fig. 6. The calculations confirm the current density maximum near 10 mtorr.

Having found the atomic ratio parameter at the $z = 2.5$ cm filter position we use this value as a basis for predicting the extracted current densities at the $z = 7$ and $z = 11.2$ cm filter positions, respectively. In moving the filter to $z = 7$ or 11.2 cm the volume of the first chamber is reduced and the electron density is increased. Moving to the $z = 7$ cm position causes the volume to be reduced by a factor of 1.3 but the electron density is observed to increase by about a factor 1.2. At the $z = 11.2$ position the volume is approximately halved compared to the original $z = 2.5$ position, and the electron density increase here is extrapolated upward by a factor of 1.5. These density increases cause the atomic/molecular ratio to increase toward larger values, along the two temperature lines shown in Fig. 4. These calculated values projected from the $z = 2.5$ position data are shown in Fig. 7 and compared with the observed extracted current densities. The model calculation provides for a reasonably good comparison with the experimental values.

These model results are clarified by examining the negative ion density variations along the tandem system. The negative ion density variations for the three filter positions, $z = 2.5, 7$, and 11.2 cm, respectively, are shown in Fig. 8. For these calculations we have taken the negative ion energy to be equal to 0.3eV , a value suggested by the dissociative attachment calculations of Wadnhra. The calculated negative ion densities are multiplied by the negative ion velocity appropriate to 0.3 eV to provide the ordinate current density scale shown in the figure.

Inspection of the figure shows a constant negative ion density in the first chamber, then rising and falling in the first zone of the second chamber. The rise in this first zone is due to the removal of the effect of H collisional destruction caused by the energetic electrons; the subsequent fall is due to attenuation of the vibrationally excited molecules as they move out of chamber one into chamber two. In zone two the negative ion concentration rises sharply due to the more optimum electron temperature for dissociative attachment and the reduction of collisional detachment. The densities rise to a maximum and begins to fall because of the increased attenuation of the excited molecules moving through the second chamber. The attenuation of the negative ions at the larger distances, toward $z = 7$ and 11.2 cm, is due principally to the associative detachment, process (1).

The thermal electron density, n , the fast electron density, $n(f)$, the atomic density, N_1 , and the molecular density, N_2 , used in these calculations are summarized in Table III. The values for the various rate processes are those given in Refs. 2,3,4. For the ion-ion collision process

we have used the recent values of Fussen and Kubach⁽⁹⁾.

TABLE III

Density values used for the solutions of Figs. 7 and 8

	$z = 2.5 \text{ cm}$	$z = 7. \text{ cm}$	$z = 11.2 \text{ cm}$
$n(\text{cm}^{-3})$	3.3×10^{12}	4.0×10^{12}	5.0×10^{12}
$n(f) \quad (900^\circ\text{K})$	1.4×10^{11}	1.7×10^{11}	2.1×10^{11}
(1500°K)	2.2×10^{11}	2.7×10^{11}	3.4×10^{11}
$N_1 \quad (900^\circ\text{K}) +$	2.7×10^{13}	3.6×10^{13}	4.7×10^{13}
(1500°K)	2.7×10^{13}	3.6×10^{13}	5.0×10^{13}
$N_2 \quad (900^\circ\text{K}) +$	1.3×10^{14}	1.3×10^{14}	1.3×10^{14}
(1500°K)	0.8×10^{14}	0.8×10^{14}	0.8×10^{14}

CONCLUSIONS

A spatially-dependent model calculation for the negative ion density in a high-density tandem-negative-ion generator has been applied to a specific ion source apparatus. The calculated extracted current densities agree qualitatively and quantitatively with the observed current densities. The atomic concentrations inferred in the system are within a factor of two of the upper limits for the atomic concentrations expected for a high-density hydrogen discharge.

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Figure 1. SCHEMATIC OF TS-1

Figure 2. DETAILS OF FILTER AND EXTRACTION REGION

B: FIELD LINES, MAGNITUDE

FIGURE 3

Figure 4.

Figure 5.

Figure 6

Figure 7

Figure 8