Enhanced Production of Negative Ions in Low-Pressure Hydrogen and Deuterium Discharges

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A new approach to enhance the production of negative ions in low-pressure hydrogen and deuterium discharges is described. The procedure, which requires on-off modulation of the discharge current, is applied to a conventional magnetic multicusp or "bucket" volume negative-ion source. The extracted D^- current from a 15-A discharge at a filling pressure of 2.4 mTorr is increased from 0.5 to 2.0 mA/cm^2 by discharge-current modulation at 10 kHz and 23% duty cycle. The D^- beam current is not significantly modulated ($<5\%$). The extracted electron current density and average discharge current are reduced by over a factor of 4. The work is relevant to production of D^- beams for neutral-beam injectors.

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Substantial fractional densities (n_-/n_e) of negative ions exist in low-pressure hydrogen and deuterium gas discharges [1,2]. The formation of such high densities of negative ions is believed to be due to dissociative attachment (DA). Theoretical studies by Wadehra and Bardsley [3] in H_2 show a very strong dependence of the dissociative-attachment cross section on the initial vibrational level of the H_2 molecule. Their paper predicts that H_2 molecules in the high vibrational levels ($v > 5$), where v is the vibration quantum number, will have an attachment cross section which is 5 orders of magnitude greater, near threshold, than H_2 molecules in the vibrational ground state. The threshold energy is also reduced from 3.75 eV for $v=0$ to less than 1 eV for $v>5$. Experimental verification of the large dissociative-attachment cross section and low threshold energies for vibrationally excited H_2 and D_2 was obtained by Allan and Wong [4] using electron-beam studies.

An intensive research and development effort is being made worldwide [5] to exploit volume production, by dissociative attachment, of H^- and D^- as a source for neutral-beam injection systems. While the research effort has been very successful, the volume negative-ion source still has poor gas and power efficiencies compared to H^+ and D^+ ion sources. This is a major concern to the designers of high-energy D^--based neutral-beam injectors which will be required for the next generation of tokamaks.

In order to be effective the H^- (D^-) volume source requires a high fraction of the gas in the source to be in vibrational levels $v \geq 5$. Several mechanisms exist to populate the $v \geq 5$ levels of the hydrogen molecule [6,7]. Vibrational excitation occurs in collisions with low-energy electrons through the H_2^- resonance, but the low gas pressure needed in ion sources does not favor this process. Auger neutralization of molecular hydrogen ions, and atomic recombination of atoms, on the walls of the ion source may contribute to the $H_2(v \geq 5)$ population, and a very effective source [6,7] is by radiative decay from singlet electronic states excited by collisions of the ground-state molecule with energetic electrons. In low-pressure volume negative-ion sources, energetic electrons ($\epsilon > 20$ eV) are required to ionize, excite, and dissociate the gas and thus populate the $v \geq 5$ levels; however, a major limiting factor is that these energetic electrons are very efficient at destroying negative ions via electron detachment (ED).

The universal approach [5–7] to the development of a volume negative-hydrogen-ion source has been the tandem source which contains a region (excitation region) with a hot dense plasma characterized by a non-Maxwellian electron-energy distribution function (EEDF) with a relatively high density of energetic electrons. This is achieved by using a hot-cathode magnetic multicusp plasma generator as the excitation region. The source contains a second region (extraction region) into which the plasma produced in the excitation region diffuses. The two regions are separated by a transverse magnetic field (filter field) which cools the diffusing electrons. Molecules which have been vibrationally excited in the excitation region diffuse freely into the extraction region where the H^- ions are formed. In the tandem source, it is essential for proper operation that the electron temperature in the extraction region does not exceed ~ 1 eV, both to maximize DA, but even more important, to minimize ED.

In this Letter a radically new approach to the production of H^- (D^-) rich plasma at low pressure is proposed. The procedure is similar to the tandem concept, using the energetic electrons to vibrationally excite a high fraction of the H_2 (D_2) molecules, but maintaining a cool EEDF to optimize DA and minimize ED. However, the fast electrons are removed in time rather than spatially, and the technique is called a temporal filter [8]. The results described here introduce two new concepts, density pumping and EEDF control. A full treatment of the atomic and molecular physics of the modulated discharge is currently under way but is outside the scope of the present Letter; however, the underlying principles are illustrated below. The arguments apply equally well to both H_2 and D_2.

It has been proposed [9] that in the absence of a discharge, the population in the high-lying vibrational states $H_2(v \geq 5)$ may survive, on average, at least a few wall collisions, and there is experimental evidence that they may survive many wall collisions [10]. In the postdischarge period, the $H_2(v \geq 5)$ relaxation time for wall collisions, for the present source, from simple geometrical considerations is $\tau_v = (1.6 \times 10^3)(b/\sqrt{T})$ μs, where b is the average number of wall bounces survived by $H_2(v \geq 5)$ and T is the translational gas temperature, typically 500 K. As a result the $H_2(v \geq 5)$ will have a long decay time in the absence of a discharge ($\gg 100$ μs). On the other hand, collisions with energetic electrons will greatly increase the $H_2(v \geq 5)$ relaxation rate in a high-power discharge at low pressure [6]. The situation can be expressed as follows:

$$dn_v = \begin{cases} [P - L_{vd}]\,dt, & I = I_p, \\ -L_{v0}\,dt, & I = 0, \end{cases}$$

where n_v is the $H_2(v \geq 5)$ density, P is the n_v production term, I is the instantaneous discharge current, I_p is the current during the discharge, and L_{vd} and L_{v0} are the loss terms during the discharge and in the absence of the discharge, respectively. It is possible to pump the $H_2(v \geq 5)$ density, in a manner similar to charge pumping of a capacitor, by pulsing the discharge current at a frequency f_p and duty cycle D, provided the following conditions hold:

$$f_p \tau_v > 1\,, \tag{1}$$

where τ_v is the n_v relaxation time in the postdischarge period (i.e., $\tau_v = n_v/L_{v0}$),

$$L_{vd} > L_{v0}\,, \tag{2}$$

$$t_d/t_0 > L_{v0}/L_{vd}\,, \tag{3}$$

where t_d is the discharge pulse length and t_0 is the length of the postdischarge period. This "density pumping" will result in the $H_2(v \geq 5)$ population attaining a value in the pulsed discharge similar to that in the continuous discharge. However, the time-averaged discharge current I_d will be reduced, $I_d = I_p D$, where D is the duty cycle ($D = t_d f_p$) and I_p is the current during the on period of the discharge. The three conditions ensure that gains made during the discharge period are not lost during the postdischarge period, otherwise pumping of the density will not occur; they also ensure that the density is not modulated to any significant extent. Pumping will occur for the H^- density, as the experimental results below show, but the situation is made more complex, in this case, as the main production of H^- occurs in the postdischarge period, and destruction during the active discharge.

Next, let us consider the effect of the modulation of the discharge on the DA and ED reaction rates. If $f_p \tau_\epsilon < 1$, where τ_ϵ is the characteristic decay time for the electron energy, the EEDF will be modulated. The reaction rate coefficients for processes such as DA and ED are calculated using the time-averaged EEDF and can be optimized by varying the duty cycle D. For example, if the EEDF during the discharge can be represented by an average electron temperature, kT_{ed}, and during the postdischarge by a much colder average temperature, kT_{e0}, then the effective or time-averaged EEDF is controlled between kT_{e0} and kT_{ed} by varying the parameter D. It should be noted that the EEDF's are not normally Maxwellian and the time-averaged, or effective, EEDF will not be Maxwellian.

The density pumping and EEDF control are demonstrated by the following experiment. A schematic of the apparatus is shown in Fig. 1. The plasma is produced in a standard hot-cathode multicusp plasma generator (20 cm in diameter by 30 cm long), to which is attached a two-grid, 2-kV accelerator; the device is similar to that described by Leung, Ehlers, and Bacal [11]. The plasma is operated in a pulsed mode with an on time of 2.66 ms and off time of 8.8 ms; this facilitates the measurement of time-dependent data. Negative ions are extracted through a 3.5-mm aperture on the plasma electrode which is at a bias $V_b = +50$ V. Only a small area of the plasma electrode (3 cm^2) is exposed to the plasma to prevent excessive depletion of the plasma. The first grid is biased at $V_{grid} = +280$ V. Electron current extracted from the plasma is suppressed at the first grid using a standard magnetic electron-suppression system. The final grid of the accelerator is biased at 2 kV. A Faraday cup attached to a fast digital scope records the extracted H^- (D^-) ion signal which is proportional to the negative-ion

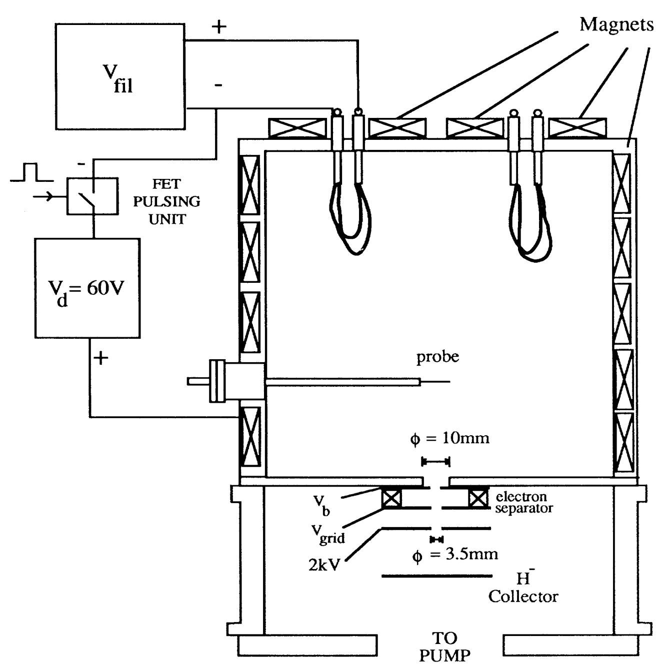

FIG. 1. Schematic diagram of the negative-ion source.

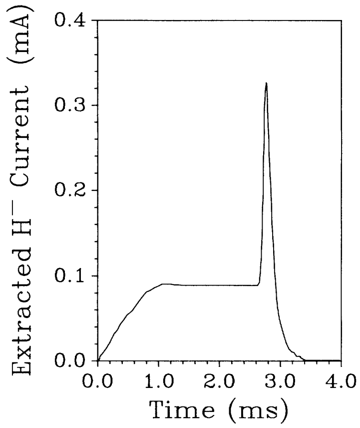

FIG. 2. The extracted negative-ion current from a pulsed hydrogen discharge. The gas pressure is 2.4 mTorr. The discharge pulse length is 2.7 ms and the repetition rate is 87 Hz. The discharge current $I_p = 15$ A.

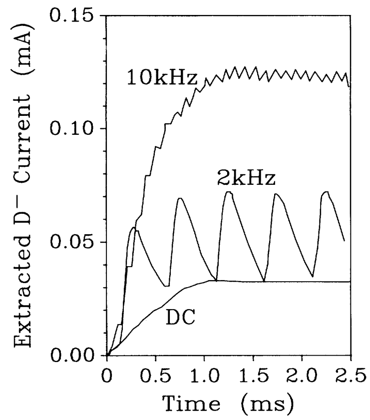

FIG. 3. The extracted negative-ion current from an unmodulated (dc) and modulated (2 and 10 kHz) deuterium discharge. The discharge current $I_p = 10$ A, pressure is 2.0 mTorr, and modulation duty cycle is 40%.

flux J_- at the plasma electrode.

The electron flux in the source is measured using a small Langmuir probe located near the central axis of the source and 3 cm from the plasma electrode. The electron flux J_e at the plasma electrode is also measured but is less than that in the center of the source because of the stray magnetic fields from the electron separator in the accelerator. The discharge current is modulated [12] by switching the discharge voltage applied to the filaments from -60 V to ground with a variable frequency f_p and a variable (on-off) duty cycle D.

The time variation of the extracted H^- current from a 15-A discharge is shown in Fig. 2. The zero on the time axis corresponds to the switching on of the discharge. The extracted H^- current reaches a steady-state value at a time of 1 ms. The slow rise in the H^- signal is consistent with a long lifetime (> 200 μs) for the $H_2(v \geq 5)$ density; the vibrational distribution evolves slowly in the early discharge and this is reflected in the slow increase in H^- production.

At a time of 2.66 ms the discharge is switched off. As the fast electrons are lost and the bulk electrons cool, the extracted current increases reflecting the enhanced production of H^- by DA and the lower losses than during the discharge. The enhanced production is only sustained for a short period and a peak in extracted H^- current is reached 90 μs after the discharge is switched off. The time dependence confirms that the $H_2(v \geq 5)$ appear to survive at least 90 μs into the postdischarge period. For times greater than 200 μs the H^- current decays exponentially with a decay rate $\tau_- = 110$ μs.

Figure 3 shows the current extracted from a D_2 discharge. The results are similar to H_2 but the extracted currents are typically a factor of 1.4 less. In the case of a continuous current (dc), shown in Fig. 3, the D^- current rises slowly, reaching a steady-state value of 0.033 mA at 1.1 ms after switch on. The behavior at switch off, although not shown, is very similar to that described for H_2; the peak in D^- is reached 110 μs after switch off and the D^- decay rate late in the postdischarge period is $\tau_- = 120$ μs. Also shown in Fig. 3 is the D^- current from a discharge modulated at 2 and 10 kHz. The duty cycle $D = 40\%$ and the average discharge current is 4 A.

In the 2-kHz case, the discharge current is 10 A from 0 to 0.2 ms. The D^- current follows the dc curve until the discharge current goes to zero at 0.2 ms; then the extracted current increases rapidly in the postdischarge, reaching a peak value of 0.056 mA at 0.32 ms. The extracted current is decaying when the discharge is switched on at 0.5 ms and continues to decay less rapidly while the discharge is on. During the subsequent three postdischarge periods the D^- current rises to 0.07, 0.073, and 0.073 mA but decays towards the dc value during the subsequent discharge periods. Note that the time between switch off and the peak in the D^- current is 120 μs.

In the 10-kHz case, the on period is 40 μs and the off period is 60 μs which is less than the D^- decay rate, so that the negative-ion density should not be strongly modulated. The extracted current rises to 0.123 mA, which is a factor of 4 greater than the dc case, in a time of 1.2 ms. The D^- current is not significantly modulated, with the modulation depth less than 5%.

The slow rise in the D^- signal in the dc case has been explained above in terms of the slow evolution of the vibrational distribution and $D_2(v \geq 5)$ population. It is noted that a similar slow rise in the average D^- current is observed in both the 2- and 10-kHz cases, indicating that the vibrational population is continuing to build up, even in the 2-kHz case, and, if our assumptions are correct, is evidence for the long relaxation time for $D_2(v \geq 5)$. Furthermore, the effect is not observed at frequencies below 1 kHz, indicating a failure to pump the vibrational density.

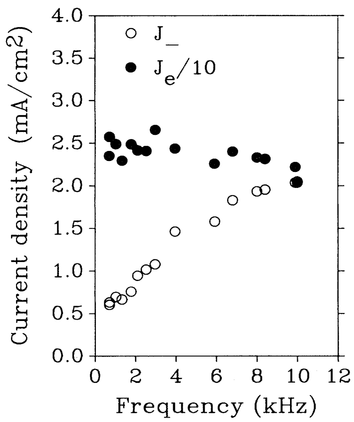

FIG. 4. The time-averaged negative-ion and electron current densities extracted from an on-off modulated discharge as a function of modulation frequency. The extraction aperture is 3.5 mm diam and the duty cycle is 50%. The current during the discharge I_p is 15 A at 1 kHz, but falls gradually to 13 A at 10 kHz. The discharge voltage is 60 V and the deuterium gas pressure is 2.4 mTorr.

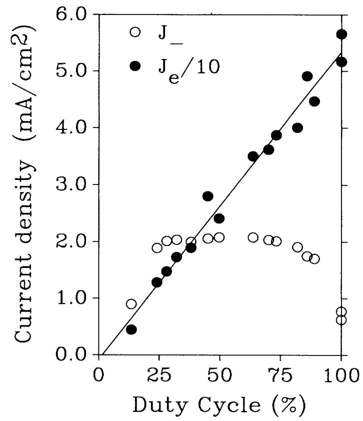

FIG. 5. The time-averaged negative-ion and electron current densities extracted from an on-off modulated deuterium discharge as a function of the on-off duty cycle D. The modulation frequency $f_p = 10$ kHz and $I_p = 15$ A. Other parameters are as in Fig. 4.

It is important to note that while the modulation increases the average extracted D^- current it also reduces the electron flux, which is a major consideration for negative-ion sources. Figure 4 shows the time-averaged extracted D^- flux, J_-, and the time-averaged electron flux at the plasma electrode, J_e, as a function of modulation frequency f_p with a fixed duty cycle of 50%. The results show a dramatic enhancement of J_- with increasing f_p, due to density pumping of n_- and n_v, with the J_-/J_e ratio being increased by a factor of 4.

Varying the duty cycle D will produce a further improvement in J_-/J_e as the EEDF is optimized. Figure 5 shows J_e and J_- as a function of D, for a fixed frequency $f_p = 10$ kHz. As D is reduced J_e decreases linearly and remains proportional to the average discharge current I_d, where $I_d = DI_p$, as discussed above. On the other hand, decreasing D increases J_- as the optimum value of EEDF is achieved; at very small values of D, J_- begins to fall as the conditions for pumping, outlined above, fail. With $D = 0.24$ and $f_p = 10$ kHz, the ratio $J_-/J_e = 0.15$, compared to a value of 0.013 in a continuous discharge.

In conclusion, a pulse-modulation technique has been proposed which provides the ideal conditions for H^- and D^- formation in a standard multicusp volume ion source. The new source is more efficient, at low gas pressure, than filtered multicusp ion sources [5–7,11]. Using this technique a continuous unmodulated D^- current of 2 mA/cm^2 has been extracted from a 2.4-mTorr discharge operating with a time-averaged discharge current of 3.5 A. The new technique may prove important in accelerator applications, such as neutral-beam injectors for the heating of fusion plasmas where low source gas pressures and high negative-ion to electron current ratios are required.

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[1] E. Nicolopoulou, M. Bacal, and H. J. Doucet, J. Phys. (Paris) **38**, 1399 (1977).

[2] M. Bacal and G. W. Hamilton, Phys. Rev. Lett. **42**, 1538 (1979).

[3] J. M. Wadehra and J. N. Bardsley, Phys. Rev. Lett. **41**, 1795 (1978).

[4] M. Allan and S. F. Wong, Phys. Rev. Lett. **41**, 1791 (1978).

[5] See, for example, *Proceedings of the Fourth International Symposium on the Production and Neutralization of Negative Ions and Beams—1986,* edited by J. G. Alessi, AIP Conference Proceedings No. 158 (American Institute of Physics, New York, 1987).

[6] M. Bacal and D. A. Skinner, Comments At. Mol. Phys. **23**, 283 (1990).

[7] J. R. Hiskes, Comments At. Mol. Phys. **19**, 59 (1987).

[8] M. B. Hopkins, M. Bacal, and W. G. Graham, J. Appl. Phys. (to be published).

[9] J. R. Hiskes, A. M. Karo, M. Bacal, A. M. Bruneteau, and W. G. Graham, J. Appl. Phys. **53**, 3469 (1982).

[10] R. I. Hall, I. Čadež, M. Landau, F. Pichou, and C. Schermann, Phys. Rev. Lett. **60**, 337 (1988).

[11] K. N. Leung, K. W. Ehlers, and M. Bacal, Rev. Sci. Instrum. **54**, 56 (1983).

[12] M. B. Hopkins and W. G. Graham, J. Appl. Phys. **69**, 3461 (1991).