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THE MAGNETRON DISCHARGE AS A SOURCE OF H^- IONS

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Abstract: The energy distribution of fast hydrogen atoms formed by neutralization of positive ions and subsequent backscattering at the magnetron cathode is derived from the contours of Balmer lines emitted in the direction parallel to the electric field. The effects of inelastic collisions in the discharge on the distribution function thus obtained are considered.

The effective yield of H^- per backscattered H atom, $\bar{\alpha}$, is estimated from the calculated coefficients of secondary emission[8)] and from the energy distribution of atoms backscattered at the cathode; $\bar{\alpha}$ is found to be ~ 0.5 for a cesiated molybdenum surface.

It is shown that the attenuation of the flux of fast H^- ions generated at the magnetron cathode is mainly due to slowing down of H^- by charge exchange and destruction of slow H^- by charge transfer and collisional detachment in the positive column.

The thermal regime of magnetron cathodes and the rate of desorption of chemisorbed cesium are considered and a scaling law is derived which relates thermal load, discharge pulse duration and increase of cathode surface temperature.

1. Introduction

Injection of intense high-energy beams of hydrogen atoms is a very promising method for plasma heating in large fusion devices. At energies of $\gtrsim$ 100 keV, a neutral beam formed by acceleration and neutralization of negative ions has a higher efficiency than a comparable system based on positive ions, especially if direct extraction sources of negative hydrogen ions are used. Recently, magnetron sources

of negative hydrogen ions have been developed[1,2], yielding pulsed-ion currents of up to 1 A, with pulse lengths between 1 and 10 ms. The magnetron discharge appears to be at present the most efficient source of negative ions, though encouraging results have also been recently obtained with a Penning source[1,3]. There is strong evidence that the locus of H^- ion formation in a magnetron source is at the cathode surface[4], the contribution of electron attachment in plasma itself being negligible.

The mechanism of H^- formation at a metal surface exposed to proton bombardment has been discussed by several authors[5-7]. According to Kishinevsky, the yield of H^- ions per proton incident upon a metal surface should approach unity, provided the work function is sufficiently low, and the kinetic energy of ions back-scattered at the surface exceeds a few tens of eV[7,8].

Both conditions are met in a magnetron discharge. The work function of the cathode may be reduced to rather low values by addition of cesium and, as shown in the present paper, the kinetic energies of H-atoms back-scattered at the cathode are comparatively high.

Scaling-up of existing magnetron sources encounters severe problems in cathode temperature control; there is a tendency of glow-to-arc transition due to intense heating of the electrode surface. A scaling law is proposed, which gives the relation between the maximum admissible thermal load at the cathode, pulse duration and surface temperature increase.

It is also the purpose od this paper to examine the density and energy distribution of particles in a magnetron discharge, to estimate the attenuation of the beam of H^- ions emitted from the cathode surface and to assess the yield of negative ions emitted from a cesiated molybdenum cathode.

2. *Apparatus*

The discharge chamber of the magnetron has a ribbon-shaped race track geometry with mutually perpendicular electric and magnetic fields (Fig. 1). Except in the expansion chamber, the distance between the cathode and the anode was between 0.5 and 1 mm, and the total active cathode area was approximately 13.5 cm^2. The interelectrode gap in the expansion chamber was 3 mm. The source was run in pure hydrogen (H-discharge) or, alternatively, in hydrogen with addition of small amount of cesium vapour (H-Cs discharge). Gas was admitted into the source by an electromagnetically driven pulsed valve. The operation of the valve was synchronized with triggering of the magnetron discharge.

Cesium vapour was generated in the cavity within the cathode by chemical reaction of Cs_2CrO_4 with titanium powder, and admitted into the discharge through channels drilled in the cathode body made from molybdenum.

An artificial line supplied the source with square-wave pulses of approximately 60 Amps amplitude, and 10 ms duration, at a repetition frequency of 0.1 Hz. The voltage drop in the discharge was 580 Volts in pure hydrogen and 225 Volts in a hydrogen-cesium mixture, the difference of discharge voltages being due to the lowering of the work function by chemisorbed cesium.

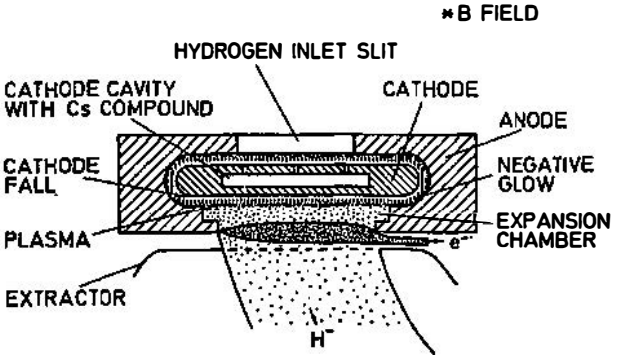

Fig. 1. Illustration of negative ion magnetron.

The spectral emission of the discharge was resolved by means of a Spex 1704 grating monochromator, at a resolving power of ~ 60.000. The intensity of spectral lines was measured by means of a sensitive photomultiplier. In order to investigate the profiles of Balmer lines, pulses from the photomultiplier were fed, upon integration, to the Y axis of an XY plotter. The wavelength of the monochromator was continuously swept at a very slow and uniform rate, the velocity of grating rotation being controlled by special circuitry. The displacement on the X axis of the plotter (corresponding to wavelength scan) was synchronized with discharge pulses.

3. *Energy distribution and density of H atoms*

Light emitted from the discharge in the direction parallel to the electric field was observed through the extraction slit in the anode. Particular attention was paid to the analysis of Balmer line contours.

In pure hydrogen discharge Balmer H_α to H_δ were found considerably broadened and asymmetric; upon subtraction of the dashed part of the H_β profile (Fig. 2a) the line still differs from Voigt profiles. Incidentally, the Balmer lines emitted from the discharge containing some cesium have a shape which is fairly close to the dispersion profile (Fig. 2b). However, this is mainly due to the actual energy distribution in which states of higher kinetic energies are relatively more populated than in a Maxwellian distribution; beside thermalized atoms fast H atoms are present in the discharge. They are formed by:

(i) — neutralization of protons, of energies $\lesssim eV_c$, at the cathode and back-scattering upon multiple collisions within the metal lattice. Since the interelectrode distance is smaller than the mean free path, these fast atoms moving to and fro between the electrodes lose their energy mainly by collisions with walls; their energy distribution upon back-scattering at surface is far from being Maxwellian and the angular distribution is, of course, highly anistropic;

(ii) — charge exchange involving fast H^- ions and protons (the latter only in the cathode fall), the fate of the fast H atoms thus formed is analogous as above; and

(iii) — neutralization of H^- ions (accelerated in the cathode fall) at the anode and back-scattering. Since a large fraction of H^- undergoes charge exchange prior to attaining the anode, this process is of less importance than (ii).

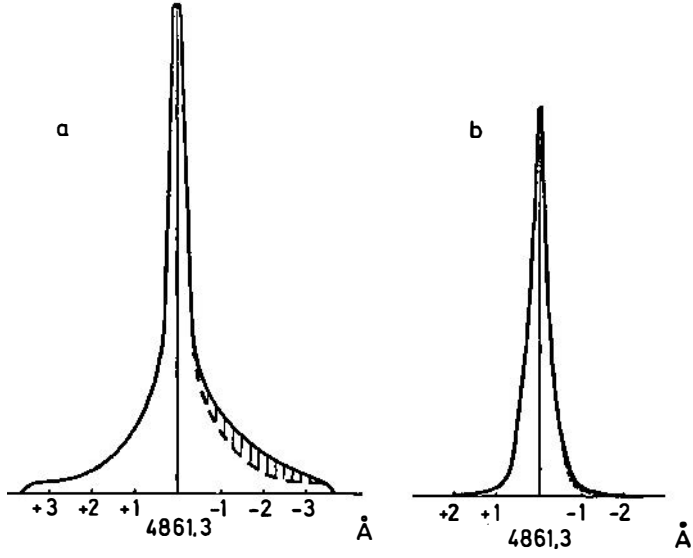

Fig. 2. Line contours of Balmer $H\beta$ emitted $X_{\parallel}$ from magnetron discharge in: a) hydrogen, b) hydrogen + cesium.

The asymmetry of the lines in Fig. 2 may be readily interpreted as due to the presence of a beam of fast H atoms moving in the direction of the anode. The beam is composed of first, third and higher generations of atoms formed by process (i) and of second, fourth and higher generations of atoms formed by processes (ii) and (iii). The compound profiles shown in Fig. 2 may thus be thought of as composed of Voigt profiles which are overlapped in both wings by Doppler-shifted bands originating from groups of fast H atoms. The contribution of bands in the $+\Delta\nu$ wings of the lines is much more pronounced. At the actual resolving

power of the spectral instrument the effect of fourth and higher generations of back scattered or reflected atoms is not detectable.

Excitation of H atoms into quantum states $n \geq 2$ by interactions with metal surfaces is negligible in the actual range of kinetic energies[9] and one may assume that excitation of Balmer lines is due to electron impacts only. For that case an approximate energy distribution may be obtained by applying the $k\,\Delta\,\nu$-transform[10] to the Doppler-shifted (shaded) areas of the line contours in Fig. 2. The results thus obtained are shown in Fig. 3. As seen, the upper energy limits of the distribution functions are by a factor of ~ 3 lower than the corresponding mean kinetic energies of protons impinging upon the cathode and the maxima are attained at $\sim 1/6$ eV_c. The shapes of the energy distributions resemble those of H^- ions emitted from metal surfaces under proton bombardment[6] but the effect of the approximation done by using the $k\,\Delta\,\nu$-transform is also clearly visible. The hump on the distribution function at ~ 12 eV may be attributed to the third generation of atoms produced by process (i) and the second generation of atoms from processes (ii) and (iii). On the other hand, the second generation from process (i) and the first generation of atoms from processes (ii) and (iii) lead to the emission of unresolved bands (overlapping the basic profile) centered at 4863 and 4863.8 Å; the $k\,\Delta\nu$-transform, therefore, underestimates the amplitudes at ~ 55 and ~ 120 eV and hence the slight inflections at these energies[11].

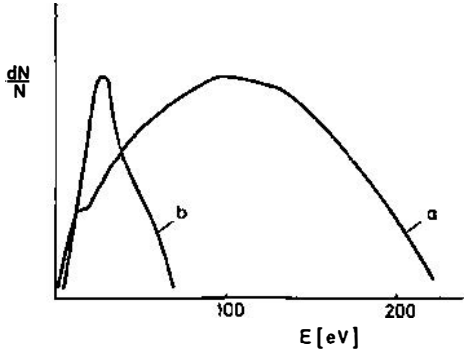

Fig. 3. Energy distribution of H atoms back scattered at cathode surface as derived from Balmer H_β line contours:

a) H-discharge, b) H-Cs discharge.

Analogous considerations are expected to apply also in the case of H-Cs discharges. The absence of any pronounced effect may be attributed to the smaller width (and insufficient amplitude) of Balmer lines, with respect to the actual dispersion of the monochromator. A closer analysis of the subject is in progress and will be considered elsewhere.

At the actual current densities and pressures the degree of dissociation of hydrogen is rather large and atomic hydrogen prevails. The quasi-isotropic part

of the kinetic pressure in the cesium mode is ~ 0.17 torr (Ref.[11]) and continuity requirements as well as other estimates lead to the conclusion that the density of H-atoms is approximately $10^{15}/\text{cm}^3$. The accuracy of this estimate is expected to be within a factor of 1.5. According to the kinetic pressure and the density the mean energy of quasithermal particles would be $\cong 0.13$ eV.

According to the tabulated values of $S(\alpha)/\alpha$ (Ref.[12]) and at the actual dispersion of the spectral instrument statistical Stark broadening of the Balmer H_δ should be noticeable in the cesium mode discharge at electron densities of $\gtrsim 2 \cdot 10^{13}/\text{cm}^3$. Since the widths of the Balmer H_δ and H_β contours did not perceptibly differ, this value is considered to be the upper limit to the plasma density.

4. *Efficiency of H^- formation at the cathode*

The yield of H^- per fast H-atom leaving the metal surface under proton bombardment depends on work function and on the normal component of the velocities with which H-atoms emerge from the lattice. Recently, Kishinevsky has calculated the yield of H^- ions, α, for the range of kinetic energies and work functions characteristic of the cesium mode discharge[8]. Using these results and plausible assumptions on the work function, the efficiency of H^- formation is assessed for the present experimental conditions.

At an optimum cesium coverage Θ_m, established at T_m 680—730 K (Ref.[13]) the discharge voltage is about 100 V or less and the cathode work function presumably ~ 1.6 eV. Because of the moderate thermal load in the present experiment the temperature of the cathode was $< T_m$, and consequently the work function slightly higher than $e\varphi_m$. We shall assume a comparatively high value of 1.7 eV for $e\varphi$.

With this value of work function, α varies from a few percent at kinetic energies ~ 2 eV up to 60% at $\varepsilon \cong 70$ eV (Ref.[8]). The mean value of α for the energy distribution in cesium mode discharge, is found to be $\cong 0.46$. This is by a factor of 4 to 5 larger than recently assumed by Green[14]. One may argue that the discharge parameters in the Novosibirsk experiment largely differed from the present conditions, the discharge voltage in Dimov's experiment being by a factor of 2.2 lower and the current density ~ 20 times larger. However, using an analogous distribution function for protons impinging upon the cathode with $\varepsilon \cong 100$ eV and the same value of $e\varphi$ (although it was probably close to $e\varphi_m$), one obtains, according to the $\alpha/v_\perp$ plot of Ref.[8] a mean $\alpha \geq 0.35$. Of course, the present values of $\bar{\alpha}$ heavily rely on Kishinevsky's estimates and one cannot completely rule out that some additional mechanism, like the polar dissociation of adsorbed CsH molecules with subsequent desorption of H^-, be also effective in yielding H^- ions*).

*) J. R. Hiskes, private communication.

The effect of the external magnetic field, which tends to decrease the neutralization probability of H^- at surface[15], was neglected. On the other hand, as discussed in the previous section and section 7, the distribution function obtained by the $k\Delta\nu$-transform possibly overestimates the population density at lower kinetic energies and vice versa and this also contributes to an underestimate of α. A slightly higher value of $\overline{\alpha}$ ($\cong 0.5$) might be thus more realistic.

5. *The attenuation of the beam of H^- ions in the dicharge*

As established by Belchenko et al.[16] the current of H^- ions extracted from a magnetron source is proportional to the discharge current up to comparatively high current densitites and also proportional to the area of the extraction aperture, S. The flux of H^- ions at the anode, J^-, may be expressed by

$$J^- = A \cdot \overline{\alpha} \cdot J^+, \tag{1}$$

where A accounts for the attenuation of the beam of H^- ions in the discharge; J^+ is the density of positive ions at cathode and $\overline{\alpha} \cong 0.5$.

Good vacuum was established in the main chamber of the BNL source and it is therefore realistic to assume that the attenuation of the beam of H^- between the anode and the collector was negligible. One may thus write $J^- = i^-/S$, where i^- is the current of H^-, measured at the collector. With $J^- = 0.6$ A/cm^2 and $J_t = 20$ A/cm^2 (Ref.[2]) and taking that $J^+ = 0.6\, J_t$ A is found to be $\cong 0.10$.

Alternatively, one may estimate the attenuation factor by considering the individual processes bringing about the destruction of H^- ions in the discharge. This is of interest for a better understanding of the influence of various discharge parameters on the efficiency of the source.

The most prominent among the destruction processes are[17]:

— collisional detachment involving electrons and hydrogen atoms

$$H^- + e \rightarrow H + 2e, \tag{a}$$

$$H^- + H \rightarrow 2H + e, \quad \text{and} \tag{b}$$

— charge transfer according to

$$H^- + H^+ \rightarrow H + H. \tag{c}$$

Charge exchange, though indirectly, largely contributes to the destruction of H^- by increasing the containment time of ions in the discharge. Slow negative

ions formed by charge exchange drift across the magnetic field in direction of the electric field of strength X, with a velocity $v_d(X)$; the drift velocity is given by[18,19]

$$v_d(X) = v_d(O)\left[1 + 0.13\left(\frac{eX}{2kTN_H Q_{ce}}\right)^2\right]^{-1/4} \frac{1}{1+\omega_c^2 \cdot \tau^2}, \tag{2}$$

where $v_d(O)$, the drift velocity for low electric field strengths, reads[18,20]

$$v_d(O) = \frac{0.341}{(MkT)^{1/2}} \frac{eX}{N_H Q_{ce}}. \tag{3}$$

Here Q_{ce} denotes the cross section for charge exchange involving slow H^- ions and H-atoms; ω_c is the cyclotron frequency; τ is the ionic mean free time; other signs have their usual meaning.

A comparison immediately shows that the velocity of H^- ions accerelated in the cathode fall exceeds the drift velocity $v_d(X)$ by ~ 2 orders of magnitude; the chance that slow H^-ions be destroyed in the discharge is thus much larger than that of fast H^-.

One may consider the destruction of fast and slow H^- separately and to express the atenuation coefficient A as the product of factors A_1 and A_2 which relate to the two groups of negative ions

$$A = A_1 \cdot A_2. \tag{4}$$

It is convenient at this point to introduce also the following simplifications: to assume the densities of hydrogen atoms and positive ions to be uniform throughout the positive column and the negative glow, to consider only the interactions of thermalized electrons with H^-, i. e. to neglect fast electrons generated in the cathode fall (the density of fast electrons and the thickness of the positive space charge zone being comparatively small).

Denoting the cross sections for charge transfer involving fast H^- ions by Q_{ct} and the cross sections for processes (a) and (b) by Q_c and Q_H, respectively, the attenuation of fast H^- is given by

$$A_1 = \exp\left[-(Q_c N_c v_e/v_t + Q_H N_H + Q_t \cdot N_t)\, d\right]. \tag{5}$$

Here d is the interelectrode distance in the expansion chamber, v_e is the mean velocity of electrons and v_t is the mean velocity of H^- upon acceleration in the cathode space charge zone.

The factor of attenuation for slow H^- ions reads

$$A_2 = \exp\left[-fQ'_{ce} N_H \cdot d\right], \tag{6}$$

where Q'_{ce} denotes the cross section for charge exchange involving fast H^- ions and slow H atoms; f accounts for the destruction of slow H^- ions formed by charge exchange and is expressed by

$$f = 1 - \exp\left[-t(\nu_1 + \nu_2)\right]. \tag{7}$$

The mean containment time, t, of slow H^- in the discharge is

$$t = \frac{d}{2} \cdot \frac{1}{v_d(X)}, \tag{8}$$

and ν_1 and ν_2 are the collision frequencies for processes (a) and (c), respectively. They are given by

$$\nu_1 = Q_e N_e v_e, \tag{9}$$

$$\nu_2 = Q'_t N_t v_+, \tag{10}$$

where Q'_t is the cross section for charge transfer involving slow H^- ions; the velocity of positive ions, v_+, is probably close to kT.

Most of the data needed for evaluation of Equs. (2)—(10) are known. The relevant cross sections have been reviewed by Prelec and Sluyters[17]. The density N_H and the mean energy of H-atoms were estimated in Section 3. Only X and v_e are ill known and for the plasma density only the upper limiting value could be estimated.

Setting $A = 0.10$ and using plausible values for $X(\sim 5$ V/cm) and $v_e(\sim \sim 10^8$ cm s^{-1}) the set of Equs. (2)—(10) yields for N_e a value of $\sim 8 \cdot 10^{12}$/cm^3. Because of the assumptions made the uncertainty concerning N_e is still considerable, probably not less than 50%, but this suffces for a discussion of Equs. 2—10. Even if N_e attained a value of $2 \cdot 10^{13}$/cm^3 and N_H were as low as $\sim 10^{14}$/cm^3 A_1 would still exceed A_2.

One might argue that an increase of current density, at constant gas supply, would reduce N_H because of enhanced ionization and heating. However, a check of the continuity condition for the cathode zone immediately shows that the density of hydrogen atoms, say at $J_t \sim 50$ to 100 A/cm^2, cannot decrease significantly below $\sim 10^{15}$/cm^3 without causing instability of the discharge. This is in agreement with the observation of Belchenko et al[4] that the gas supply must be more abundant at higher current densities.

At densities of 10^{15}/cm^3 charge exchange combined with processes (a) and (c) is of prime importance, for the attenuation factor A_2 is as low as 0.22—0.26. It is thus Equ. (6), combined with Equs. (1) and (4), the most relevant for an estimate of the maximum attainable value of J^- and the agreement of Green's calculation[14] with Dimov's experimental results appears to be rather fortuitous and due to an underestimate of α and d.

According to Equs. (5) to (8) a decrease of the interelectrode distance would reduce the loss of H^- ions. But if diminishing d the need for separating electrons from H^- in the extraction gap imposes an increase of the magnetic field strength. Although an increase of B improves the ionization efficiency for increasing ω_c it also extends the containment time — Equ. (2) — and thus the chance for destruction of H^-. This clearly shows that in order to optimize J^- at a given value of d and J_t careful adjustment of the magnetic field strength and of the supply of cold molecular gas is required.

6. *The thermal regime of cesiated cathodes*

One of the essential conditions for the efficiency of the source is that the work function of the magnetron cathode be sufficiently low, both for negative ion and for secondary electron emission. On the other hand it is desirable that the rate of cathode sputtering be low.

The lowest work functions of cesiated refractory metals vary between 1.4 -1.65 eV and the minima of $e\varphi$ are attained at cesium coverages of $\Theta_m \cong 0.5$ (Ref.[8]) to $\Theta_m \cong 0.55$ (Ref.[21]). Θ depends on surface temperature (since T determines the rate of desorption of cesium atoms) and on the number of cesium atoms incident upon unit cathode area per unit time. In order to maintain a slow diffusion rate of cesium out of the source it is desirable to use as little cesium as possible; it is thus advantageous to use materials having comparatively small Θ_m.

Most satisfactory results in several respects have been obtained with cesiated molybdenum cathodes[16]. So far there has been no information on the density of cesium in the discharge nor on the flux of cesium upon the cathode. However, it has been found experimentally that highest H^- current densities are attained at average cathode surface temperatures of 680 to 730 K (Ref.[13]).

The magnetron source operates intermittently with relatively long intervals between pulses. A fast temperature rise at surface during pulse is followed by a slow temperature decrease toward equilibrium. The temperature of the cathode surface thus oscillates between a value attained at the end of the cooling period, T_{min}, and T_{max} reached at the end of the discharge pulse.

In order to assess the effects of cathode temperature variation, let us now estimate the rate of cesium desorption. According to the Polanyi—Wigner equation

$$\frac{dN_s}{dt} = N_m \Theta \cdot \frac{kT_s}{h} \cdot \exp\left[-\Delta E_s/kT_s\right], \tag{11}$$

where N_m is the number of Cs atoms in a completely filled monolayer, T_s is the surface temperature and ΔE_s is the binding energy of Cs atoms at a metal surface with a cesium coverage Θ_{Cs}.

The evaluation of Equ. (11) shows that surface coverage of Cs may only very little change during a single discharge pulse since ΔE_s in case of molybdenum is presumably 2—3 eV. For the same reason the change of Θ is small even during cooling periods, which last 10^2—10^3 times langer.

Sputtering of chemisorbed cesium by 100—250 eV protons is not expected to play a major role because of the comparatively strong binding forces experienced by Cs atoms at a Mo-surface and the large difference of masses. Unless Cs-coverage is affected by formation of CsH which is probably much looser bound at surface than atomic cesium, it is the balance between the diffusion rate of cesium from the interior of the cathode and desorption which determine Θ_{Cs}. The persistency of cesium in the source, the quasi—permanent lowering of work function by traces of this element do not support efficient desorption mechanism via CsH--formation. All this strongly suggests that a surface coverage $\overline{\Theta}_{Cs}$, corresponding to the mean cathode temperature $\overline{T}$ and to the rate of cesium supply, is only slowly established and that subsequent variations of $\overline{\Theta}_{Cs}$ during a single cycle are small.

$\overline{T}$ depends on the energy transferred to the cathode and on the heat lost by conduction, per unit time. By balancing heat losses by an adequate heat load, q, $\overline{T}$ may be adjusted to the optimum value regardless of constructional details of the source.

The temperature rise of the cathode during a single pulse can be estimated[13] by using the expression for temperature distribution in a semi-infinite body as a result of a constant heat flux input to the surface. This model will be valid as long as the heat penetration depth into the cathode body during the pulse is small compared to the dimensions of the active part of the cathode. If this is the case, then the heat conduction losses during the discharge pulse can be neglected.

This problem of unsteady heat conduction has been solved analytically[22], and the temperature distribution $t(x, \tau)$ as function of the depth x and time τ is given by

$$T(x, \tau) = \frac{q_0}{k}\sqrt{\frac{4a\tau}{\pi}}\left(e^{-\frac{x^2}{4a\tau}} - x\sqrt{\frac{\pi}{4a\tau}}\,\operatorname{erfc}\frac{x}{\sqrt{4a\tau}}\right) + T(\tau = 0). \qquad (12)$$

In this expression q_0 is the heat flux in W/m^2, k is thermal conductivity in W/mK, and a the thermal diffusivity in m^2/s. On the surface $x = 0$, so that the expression in parenthesis gives the temperature at a depth x relative to the temperature on the surface. The surface temperature increase is

$$T(0, \tau) = \frac{q_0}{k}\sqrt{\frac{4a\tau}{\pi}}. \qquad (13)$$

If required that for a given magnetron source the temperature increase during single pulse be the same for different discharge conditions it follows that

$$q_0\sqrt{\tau} = \text{const.} \qquad (14)$$

Equ. (14) can be considered to be a scaling law for magnetron sources. The law will be valid as long as the conditions mentioned earlier are fulfilled, which will be true for pulses up to ~ 100 ms duration in a standard magnetron. Substituting for k and α the corresponding values for molybdenum and taking into account that the energy transferred to the cathode is approx. $0.6 J_i V_d$ (Ref.[11]) we get the expression

$$0.6 J_i V_d \sqrt{\tau} = 1.5 \cdot 10^4 \Delta T \ \mathrm{Ws^{1/2} m^{-2} K^{-1}},$$

which allows to evaluate Equ. (14) for various discharge conditions. In order to operate the source in the range of the optimum work function, i. e. at discharge voltages of 100—200 V and at the present current density and repetition frequency the discharge pulses should last — according to the characteristics of the BNL source[2] and Equ. (14) — longer than 100 ms. Although these pulse lengths approx. correspond to the present goal a magnetron yielding 10 Amps of H^- at cathode current densities of 5 A/cm² would be comparatively large in size and uneconomic, particularly because of excessive gas consumption. In order to increase the flux of negative ions to a satisfactory level, the cathode current density should be larger by a factor of ~ 3.

Estimates based on Equ (11) indicate that provided ΔE_s is ≥ 2.75 eV and this seems to be a realistic assumption, the variation of $\bar{\Theta}_{Cs}$ during a single pulse would not be excessive, even if ΔT attains ~ 300 K. In that case H^- current densities of 0.5 A/cm² could be easily attained, provided efficient cooling of the cathode body is ensured.

This and other possible improvements[11] seem to offer the chance to obtain powerful beams of H^- at rather long pulse durations. It is essential at present to obtain information on the energy of adsorption of Cs on molybdenum surfaces and on the dependence of ΔE_s on Θ_{Cs}.

7. *Discussion*

The discharge voltage, V_d, was comparatively high in both discharge modes and thus characteristic of the glow regime. Consequently, the voltage drop in the cathode fall, V_c, differed probably little from V_d.

In the absence of energy losses in the space charge zone, the maximum energy gained by positive ions would be close to eV_d. The comparatively low upper limit of the energy distributions (Fig. 3) therefore deserves special attention. Let us first consider charge exchange which often may considerably affect the velocity of ions.

According to the expression for space charge limited current density[23] the thickness of the cathode fall, d_c was $\sim 3 \cdot 10^{-3}$ cm. Estimates based on Thomson's formula [24] lead to a value of d_c which is by one order of magnitude larger and in

agreement with observation at low current densities[25]. Assuming that the density of neutral particles capable of entering in symmetric charge exchange collisions was $10^{15}/cm^3$ and taking cautiously for d_c the value of $3 \cdot 10^{-2}$ cm still more than 50% of ions would have escaped charge exchange during passage across the cathode fall.

This conclusion is supported by the energy distribution of H^- ions extracted from the discharge. As observed by Dimov and coworkers[4], the velocity distribution of the extracted H^- beam has two marked peaks, one due to H^- ions accelerated in the cathode fall and the other originating from H^- undergoing charge exchange in the discharge and in the extraction gap[4]. The energy threshold of the group of fast H^- ions is lower than eV_c by $\sim 20\%$ and this may be attributed only to the effect of charge exchange in the cathode fall. The tails of the energy distributions of H^- ions presented in Fig. 2a of Ref.[4] extend up to $\sim 2\, eV_c$, and this is in agreement with the expectation that a fraction of protons (~ 0.1) undergoes only binary collisions at surface and is reflected upon neutralization with energies close to eV_c[6].

The low value of the upper energy limit of the energy distributions in Fig. 3 could be easily explained if the current of positive ions flowing to the cathode were composed only of H_3^+ ions. In that case dissociation of molecular ions at surface with equipartition of energy among fragments[6] would give an upper energy limit of $1/3\, e_c$. However, this explanation does not apply since, as discussed below, H_3^+ ions probably represented only a minor component of the positive ion current flowing to the cathode.

Ionization in an anomalous glow discharge is most intense in the cathode fall and the negative glow and yields at small interelectrode distances a large fraction of positive ions formed in the discharge. Assuming that electron impact ionization in the cathode zone had generated only H_2^+ ions and taking a cross section of $\sim$ $\sim 10^{-14}\,cm^2$ for the reaction

$$H_2^+ + H_2 \equiv H_3^+ + H$$

only a smaller fraction of the H_2^+ current would have interacted with hydrogen molecules because of $d_c \leq 3 \cdot 10^{-2}$cm and the moderate particle densities ($\sim$ $\sim 10^{15}/cm^3$).

These and other arguments lead to the conclusion that although charge exchange and beam composition do effect the energy distribution, they were not the main factor to give rise to the observed substantial reduction of the upper energy limit of reflected H atoms. Let us therefore, consider the range of validity of the assumptions on which the $k\Delta\nu$ — transform is founded.

In Section 3 it was implicitely assumed that the intensity distribution within the contours of the investigated spectral lines was solely a function of the chance that atoms of a given kinetic energy be excited during passage through the exci-

tation zone. This chance being proportional to the interval of time during which atoms stay in the excitation zone, the energy distribution was derived by multiplication of intensities in the Doppler shifted area with the »reduced« velocities corresponding to the wavelength shifts.

However, it may be expected on general grounds[26] that:

((i)) — excitation transfer,

((ii)) — excitation to higher levels by electron and heavy particle impact,

((iii)) — quenching by superelastic collisions and,

((iv)) — elastic collisions, do affect the shape of the distribution function of fast excited H atoms. Thus, the distribution functions derived from Balmer line contours are reliable only in the range of kinetic energies in which the sum of collision frequencies for the above processes is much smaller than the corresponding transition probability for radiative decay.

Unfortunately, a quantitative estimate of the effects of most of the above listed processes is not yet possible and one is limited to comparisons with relevant experimental results. A parallel with the results of Levine and Berry and McCaughan et al.[6] is encouraging at lower and intermediate energies. The main difference between the present results and the energy distributions of fast H atoms generated at the cathode of an anomalous glow discharge in argon as matrix[9] appears to be also at the high energy tail. It is remarkable in this context that in the case of hydrogen mode discharge the upper energy limits of the distribution functions derived from Balmer H_β, H_γ and H_δ are not equal; there is a decrease of the upper energy limit with increasing series number.

Excitation transfer cross sections falloff as v^{-1} while quenching depends apparently little on the relative velocity of impact, v;[26] consequently, one may exclude both processes as responsible for the depletion of excited H atom population at kinetic energies of $\sim 1/3\ eV_c$. Depopulation of excited states of H atoms (at these kinetic energies) by collisions with electrons is probably not negligible under the actual experimental conditions, but seems to be largely counterbalanced by electron impact excitation of H atoms in lower quantum states; otherwise the effect would also appear at low and intermediate energies. The apparent upper limit at $\sim 1/3\ eV_c$, curve a Fig. 3, may thus be attributed to the depletion of excited fast H atom population by heavy particle impacts, presumably by processes of the type (ii). Experiments in glow discharges with argon as matrix[9] indicate that H atoms in the quantum state $n = 3$, up to kinetic energies of ~ 100 eV, are little affected by interactions with argon atoms — in agreement with the expectation based on Massey's criterion[27]. The suitability of Balmer H_α as a probing line may also be expected because of the larger transition probability as compared with other lines of that series.

The amplitude of the Doppler shifted band in the $+\Delta\nu$ wing of Balmer lines was small in cesium — mode discharge, and the actual detection system did not allow to attain satisfactory accuracies in the asymmetric part of the line wing. Nevertheless, there is fair agreement between the energy distributions derived from Balmer H_α and H_β line contours in spite of the effect of noise.

The weak intensity of the Doppler shifted (asymmetric) band in the $+\Delta\nu$ wing may be attributed to the fact that a substantial fraction of protons neutralized at the cathode is backscattered as H^- and hence a corresponding decrease of the flux of fast neutral H atoms. Besides, the ratio of positive ion to electron current at the cathode was probably smaller than in hydrogen mode discharge because of the higher efficiency of cesiated surfaces.

The low value of the upper limit of curve b in Fig. 3 cannot be atributed to processes ((i)) to ((iv)), since at these energies neither the behaviour of curve a in Fig. 3 nor that of the distribution functions derived from Balmer H_α in argon matrix[9] indicate perceptible depopulation of excited states. It is inferred that the effect is mainly due to copious H^- formation at the cathode, the yield of fast backscattered neutrals becoming smaller than that of negative ions considerably below $1/3\ eV_c$. The features of Balmer lines in cesium mode discharge, as well as the considerable attenuation of the flux of H^- in the positive column, as estimated in Section 5, are consistent with the rather large value of $\bar{\alpha}$ derived in Section 4.

The stability of the discharge was not considered in the preceding sections. The discharge was run in glow regime but there was a marked tendency for glow-to-arc transition even at the comparatively moderate current density of ~ 5 A/cm^2 and surface temperatures of 550—600 K.

The instability of the glow discharge is attributed either to the patchiness of the cathode surface and enhanced local electron emission[28] or to accidental local increase of metal vapour density giving rise to intensified ionization and sputtering[29]. In both cases the net result is a local growth of current density with contraction of the positive space charge zone and temperature increase at a small spot of the cathode surface.

According to the Richardson equation containing the Schottky term, field intensified thermoionic emission attains substantial values at the actual low work function ($e\Phi \cong 1.7$ eV) and estimated field strengths of $1.5-2\cdot 10^5$ V/cm, provided a surface temperature of ~ 1000 K is reached. The noisiness of the magnetron discharge and the negative characteristics of fluctuations are indicative of the formation of transient microspots with a tendency to switch over into an arc regime.

Up to a certain current density, a local increase of surface temperature might have a self-healing effect, since the density of chemisorbed cesium may be reduced by lateral diffusion of Cs atoms towar dareas of lower temperature and particle density. However, the chance that some instability evolves, due to a local rise of electron emissivity or vapour density or field strength, will increase with lengthening of

discharge pulse duration. One should therefore keep $\overline{T}$ close to the ambient temperature by forced cooling, and Θ_{Cs} should be maintained sensibly smaller than Θ_m. It is expected that this will allow to operate the source at fairly long pulse durations, still maintaining comparatively high current densities. Moreover, the economy of cesium will be considerably improved.

A brief comment concerns the set of equations in Section 5. Although essentially correct, they are a rather rough presentation of the processes involved. Particularly, the averaging character of Equ. (8) may introduce a considerable error. With the necessary experimental information at disposal, a more sopshisticated treatment may become desirable. However, it is expected that in spite of some limitations, the description of the phenomena in the magnetron source offered by the present approach will be a useful tool for optimization of discharge parameters for long pulse durations and future geometries. Spectroscopic diagnostics at higher resolution and with improved sensitivity is in progress.

References

1) Yu. I. Belchenko, G. I. Dimov, V. G. Dudnikov and A. A. Ivanov, DAN SSSR **213** (1973) 1283; Yu. I. Belchenko, G. I. Dimov and V. G. Dudnikov, Nuclear Fusion **14** (1974) 113;
2) K. Prelec and Th. Sluyters, Proc. 2nd Symp. Ion Sources and Formation of Ion Beams, Berkeley VIII-6 (1974);
3) V. G. Dudnikov, preprint Inst. of Nucl. Phys., Novosibirsk (1975);
4) Yu. I. Belchenko, G. I. Dimov and V. G. Dudnikov, Izvestiya ANSSSR, ser. fiz. **37** (1973) 2573;
5) R. A. Smith, Proc. Roy. Soc. (London) **A 168** (1938) 19, F. L. Arnot and C. Beckett, ibidem. **A 168** (1938) 103;
6) L. P. Levine and H. W. Berry, Phys. Rev. **118** (1960) 158, D. P. Smith, Surface Sci, **25** (1971) 171, D. V. McCaughan, R. H. Sloane and J. Geddes, Preprint;
7) R. K. Janev, Surface Sci. **45** (1974) 609, M. E. Kishinevsky, Ž. T. F. **45** (1975) 1281;
8) M. E. Kishinevsky, Preprint Inst. of Nucl. Phys., Novosibirsk, I Ya F 76—18, (1976);
9) Z. W. Šternberg, IRB Report 0315 (1969), M. Kajzer and Z. W. Šternberg, Proc. IVth Yug. SPIG, Hercegnovi (1968) p. 11;
10) Z. W. Šternberg and M. Kajzer, Proc. 8th Int. Conf. PIG, Vienna (1967) p. 441;
11) Z. W. Šternberg, BNL Report, 1976;
12) H. R. Griem, Plasma Spectroscopy, McGraw-Hill Inc., N. Y. 1964;
13) K. Prelec, BNL H^- Technical Note No. 11, 1975;
14) T. S. Green, Nucl. Instr. and Meth. **125** (1975) 345;
15) R. K. Janev, Surface Sci. **47** (1975) 583;
16) Yu. I. Belchenko, G. I. Dimov and V. G. Dudnikov, Ž. T. F. **45** (1975) 68;
17) K. Prelec and Th. Sluyters, Rev. Sci. Instrum. **44** (1973) 1451;
18) E. W. McDaniel, Collision Phenomena in Ionized Gases, (J. Wiley, N. Y., 1964);
19) E. W. McDaniel and E. A. Mason, The Mobility and diffusion of Ions in Gases (J. Wiley, N. Y., 1973);
20) B. M. Smirnov, UFN, **92** (1967) 75;
21) J. B. Taylor and I. Langmuir, Phys. Rev. **44** (1933) 423;
22) F. M. Camia, M. Véron, Traité de Thermocinétique Impulsionelle (Dunod, Paris, 1967);
23) I. Langmuir, Phys. Rev. **33** (1929) 954, W. L. Granovski, Der elektrische Strom im Gas, Vol. I (Akademie Verlag, Berlin (1955);

24) J. J. Thomson and G. P. Thomson, Conduction of Electricity through Gases (Cambridge University Press) (1933);
25) A. Z. Güntherschulze, Z. Phys. **24** (1924) 140;
26) H. S. W. Massey in H. S. W. Massey, E. H. S. Burhop and H. B. Gilbody, Electronic and Ionic Impact Phenomena, Vol. III (Clarendon Press, Oxford) (1971);
27) H. S. W. Massey, Rept. Progr. Phys. **12** (1949) 248;
28) C. G. Suits, Phys. Rev. **53** (1938) 609; H. J. Höfert, Ann. der Physik (5) **35** (1939) 547;
29) H. Plesse, Ann. der Physik **22** (1935) 473.

MAGNETRONSKI IZBOJ KAO IZVOR H^- IONA

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Sadržaj

Raspodjela energije brzih atoma vodika, nastalih neutralizacijom pozitivnih iona i refleksijom na katodi magnetrona, određena je na osnovu profila Balmerovih linija emitiranih u smjeru paralelnom sa električnim poljem. Razmatra se utjecaj neelastičnih sudara u izboju na tako dobivene funkcije raspodjele.

Efektivni iscrpak H^- iona po reflektiranom H atomu, α, procijenjen je na osnovu izračunatih koeficijenata sekundarne emisije i raspodjele energije atoma reflektiranih na katodi; nađeno je da za molibdensku katodu prekrivenu kemisorbiranim cezijem α iznosi ~ 0.5.

Dokazuje se da do atenuacije toka brzih H^- iona, formiranih na magnetronskoj katodi, dolazi uglavnom zbog usporavanja H^- iona u izboju usljed izmjene naboja te razaranjem sporih H^- iona putem ionske rekombinacije i otcjepljenja elektrona neelastičnim sudarima.

Razmatra se termički režim magnetronskog izvora i brzina desorpcije cezija sa površine Mo-katode te izvodi teorem sličnosti, koji povezuje termičko opterećenje katode, trajanje izbojnog impulsa i porast temperature površine katode.