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SCALING LAWS FOR HIGH CURRENT H- MAGNETRON ION SOURCES

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ABSTRACT

High current negative hydrogen beams (∿ 1 amp) have recently been produced by direct extraction from magnetron (or planotron) ion sources. However these sources are limited to short pulse durations by the high power densities at which they operate. In this paper, consideration is given to the scaling laws for these sources in order to examine the possibility of operation at lower power densities for longer periods. The laws derived are based on (a) the calculation of the effect of the magnetic field on the motion of ions in the source and of electrons in the extraction gap, (b) calculation of the rate of negative ion production by positive ion flux to the cathode and attenuation of negative ions traversing the source by ions and electrons in the source plasma.

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(1). INTRODUCTION

The production of intense beams of negative hydrogen ions ($\sim$ 1 amp) by direct extraction from magnetron (or planotron) ion sources has recently been reported by Belchenko et al$^{(1)}$ and by Prelec and Sluyters$^{(2)}$. In a discussion of the performance of these sources, Belchenko et al$^{(3)}$ propose that the negative ions arise dominantly from the positive ion bombardment of the cathode surface which is coated with caesium. These ions, after acceleration across the cathode sheath, may reach the extraction region directly or may undergo charge exchange with atomic hydrogen to produce slower moving negative ions which may be extracted.

These sources, shown schematically in figure 1, are characterised by two features, a short cathode to anode spacing and a high power level, both of which lead to difficulties in operation. The high power level, in particular, limits the pulse duration of the source to a few milliseconds. In order to alleviate these problems, and work at lower extracted current densities, it is necessary to consider the scaling laws for these sources.

In this note we consider three effects which are of importance:-

(a) the need for a high magnetic field intensity in the extraction region to prevent extraction of the electrons as well as the negative ions.

(b) the limit to the distance from cathode to the extraction region set by the requirement that this distance be greater than the larmor radius of the negative ions emitted by the cathode.

(c) the limit to the density of positive ions and electrons in the source set by attenuation of the flux of the negative ions due to the charge transfer reactions

$$H^- + H^+ \rightarrow H + H$$

$$H^- + H_2^+ \rightarrow H + H_2$$

and

$$H^- + e \rightarrow H + 2e \quad .$$

(2). DERIVATION OF SCALING LAWS

One may derive relationships between the parameters of the source from consideration of these three effects as follows:

(a) The electrons and negative ions are extracted from a plasma boundary by the applied electric potential. One should calculate the motion of the electrons in the magnetic field and in an electric field whose spatial distribution must be consistent with Poisson's equation. In principle the calculation may be carried out in plane geometry to derive a modified Child-Langmuir equation in a manner similar to that used by Forrester(4) to calculate positive ion motion in a sheath in a magnetic field. However, one should perform a two-dimensional calculation in order to allow for the drain of the electrons and for derivation of the beam optics properties of the system. In the absence of a complete calculation one can make an estimate of the limits from the requirement that the turning point of the electrons which is specified by the potential ϕ and the distance x from the plasma boundary should be such that $\phi < V$ the applied extraction voltage, and $x < d$ the extraction gap. At the turning point

$$\frac{eB}{mc}\, x = \left(\frac{2e\phi}{m}\right)^{\frac{1}{2}} \quad .$$

Thus a necessary but not sufficient condition, is that

$$\frac{eB}{mc} > \frac{1}{d}\left(\frac{2eV}{m}\right)^{\frac{1}{2}} \quad . \qquad (1)$$

If the electrons are well inhibited from moving across the extraction gap, then the conditions for forming a low divergence ion beam depend on the space charge forces in the negative ion flux only and are equivalent to those derived for positive ion beams (Coupland et al[5]) viz:

$$J_- \doteq 1.2 \times 10^{-8} \frac{V^{3/2}}{d^2} \text{ A cm}^{-2} \tag{2}$$

where J_- is the current density of the negative ion beam (V is in volts, d in cm). Coupling equations 1 and 2, one obtains the result

$$B > \frac{3.10^4 . J_-^{\frac{1}{2}}}{V^{\frac{1}{4}}} \text{ gauss .} \tag{3}$$

(b) If one requires that the H^- ions emitted from the cathode, accelerated through the potential drop at the cathode (U volts), should reach the plasma boundary at a distance a_1, without being deflected by more than 90° in the magnetic field B, then it follows that

$$a_1 < \frac{1.4 \times 10^2 \; U^{\frac{1}{2}}}{B} \text{ cm .} \tag{4}$$

A similar relation may be derived for slow negative ions of energy ε created in the source by charge exchange of the energetic, primary, negative ions,

$$a_1 < \frac{1.4 \times 10^2 \; \varepsilon^{\frac{1}{2}}}{B} \text{ cm .} \tag{4a}$$

The latter relation will be more restrictive than that in equation 4. Eliminating B from equations 3 and 4a, one derives the result

$$a_1 < 0.5 \times 10^{-2} \; \varepsilon^{\frac{1}{2}} \, . \, V^{\frac{1}{4}} \, J_-^{-\frac{1}{2}} \text{ cm .} \tag{5}$$

(c) The attenuation of the flux of primary negative ions in traversing the discharge arises from transfer reactions listed above. Consider first attenuation by the positive ions. In a high density plasma the H^+

component may dominate over the H_2^+ component (Gabovich[6]) and the cross-section from the reaction of H^- with H^+ is greater than that for reaction with H_2^+, being 1-2 x 10^{-14} cm^2 in the energy range 10-100 eV (Sluyters[7]).

The attenuation factor is $\exp\{-n_+ \sigma_t a_2\}$, where n_+ is the density of the positive ions, σ_t the cross-section for the charge transfer, and a_2 the width of the dense plasma. The current density of positive ions to the cathode in the planotron geometry, J_+ is proportional to n_+ and may be written as $\frac{e\, n_+ v_+}{2}$, where v_+ is the average velocity of the ions accelerated in the plasma potential gradient being of order $\frac{1}{4}\left(\frac{k\, T_e}{m_i}\right)^{\frac{1}{2}}$. The model for production of the negative ions at the surface of the cathode proposed by Belchenko et al(3), predicts that the flux of H^- from the cathode is proportional to the positive ion current to the cathode. Thus one may estimate the current of negative ions reaching the plasma boundary to be

$$J_- = \alpha\, J_+ \exp\left(-\frac{2J_+ \sigma_t a_2}{e\, v_+}\right) \tag{6}$$

(α = ratio of H^- ions emitted to incidence of H^+ ions).

Similarly one may estimate the attenuation due to the electrons. The attenuation factor is $\exp\left\{-\frac{n_e \sigma_e v_e a_2}{v_-}\right\}$ where n_e is the electron density, σ_e the cross section for electron detachment due to electron impact, v_e the electron velocity and v_- the velocity of the negative ions. Since the electron density equals the positive ion density one can write this attenuation factor as $\exp\left[-\frac{2\, J_+ a_2}{v_+} \cdot \frac{\sigma_e v_e}{v_-}\right]$. Thus equation 6 may be modified to include attenuation by electrons, and written in the form

$$J_- = \alpha\, J_+ \exp\left[-\frac{2\, J_+ a_2}{v_+}\, \sigma_{eff}\right] \tag{6a}$$

where σ_{eff} equals $\sigma_t + \frac{\sigma_e v_e}{v_-}$. Typically σ_t has a value between 1 and 2×10^{-14} cm^2, and $\sigma_e v_e$ is of order 3×10^{-7} cm^3 sec^{-1} for electrons of energies 10-100 eV falling rapidly at lower energies$^{(7)}$. Thus for negative ions accelerated through 100 eV at the cathode $\frac{\sigma_e v_e}{v_-}$ may be comparable with σ_t i.e. $\sigma_{eff} \simeq 2\sigma_t$.

(3). COMPARISON WITH DATA FOR THE BELCHENKO SOURCE

Equations 1, 2, 5 and 6 relate the physical dimensions of the source, and the operating conditions (through J_+) and magnetic field strength to the current density of negative ions which are to be extracted at a given voltage. One may compare the data given by Belchenko et al$^{(3)}$ with these equations.

When operated with a caesiated cathode, values in the extracted beam of J_- equal to 3.7 amps cm^{-2} are obtained at an extraction voltage of 30 kV across an extraction gap of about 2 mm. The magnetic field strength in the source is varied from 1 to 2 kilogauss. The distance from cathode to plasma boundary at the extraction region (a_1) is in the range 1.5 to 3.5 mm and the thickness of the dense plasma is quoted as 0.5 mm.

From equation 2, one can estimate the extraction gap distance required for these operating parameters to be 1.3 mm. This compares with the value used of 2 mm. The magnetic field required to stop electrons crossing the 2 mm gap is 2.9 kilogauss according to equation 1. The operating magnetic fields used are lower than this value by factors of 2-3, indicating that the model used to derive equation 3 is an oversimplification.

Estimates of the value of the cathode-anode spacing, a_1, can be made from equations 4, 4a and 5. Taking typical values of the parameters which enter in these equations, viz U equal to 50 volts,

ε equal to 1 eV, B equal to 1.5 kilogauss and J_- equal to 3.7 amps cm^{-2}, one derives the following estimates:-

from equation 4, 7 mm

from equation 4a, $\sim$ 1 mm

from equation 5, 3.4 mm .

These values compare with operating values of 1.5 - 3.5 mm . It is difficult, at this time, to make a detailed comparison of the predicted and operating values, except to note that equation 4a gives a lower value of a_1 than does equation 4, and appears to be more in line with the operating value. Consequently we propose to use this equation coupled to equation 3 to derive the scaling law for a_1 in terms of the independent variables V and J_- (as in equation 5), taking ε to be 1 eV.

$$a_1 = 0.5 \times 10^{-2} V^{\frac{1}{4}} J_-^{-\frac{1}{2}} \text{ cm} . \tag{7}$$

The variation of J_- with J_+ for a fixed value of a_2 is given by equation 6a which predicts that J_- reaches a maximum value equal to $\frac{\alpha v_+ e}{2\sigma_{eff} a_2} \exp(-1)$. For α equal to 0.1 (in a caesiated surface), v_+ equal to 2.5×10^5 cm sec^{-1} ($T_e \simeq 1$ eV), σ_{eff} equal to 4.0×10^{-14} cm^2 and a_2 equal to 0.5 mm, one obtains an estimated maximum value for J_- equal to 3.4 amps cm^{-2}. This value is closer to the value obtained experimentally than one would expect from the approximations made.

This estimate of the attenuation of the H^- flux, neglects the contribution due to collisional detachment

$$H^- + H_2 \rightarrow H + H_2 + e$$

which Belchenko et al$^{(3)}$ consider to be important at high gas flow rates. This approximation is justified in the present treatment since attenuation by positive ion and electron collisions are inherent in a source depending on wall bombardment by the positive ions, whilst gas attenuation is only important if the type of source being used requires a high operating gas density.

(4). APPLICATION TO SOURCE DESIGN

Thus for sources which can be operated with sufficiently low neutral gas density equations 6 and 7 may be considered as the important scaling relations. To exploit them in designing operating ranges for sources, it is necessary to assume that there is a simple relationship between a_1 and a_2: for simplicity we take them to be equal. One may then plot a curve for the variation of J_- with a_1 for a given extraction voltage V , as shown in figure 2 for V equal to 30 kV. Only the region to the left hand side of the curve is available as an operating region. Further one may plot the variation of J_- with a_1 for various values of J_+ also as shown in figure 2 If the cathode potential is U , then the incident power density on the cathode P_c is $J_+ U$ (typically $U \sim 100$ volts and $P_c \sim 100\ J_+$).

These curves therefore indicate the relation between extractable H^- current density, the power density on the cathode and the range of values of cathode anode spacing which can be used. It is clear that the work of Belchenko et al$^{(3)}$ whilst achieving high current densities has necessitated high power fluxes to the cathode and low cathode anode spacings. The power level can be relaxed if lower H^- current densities are acceptable, eg ($\sim$ 100 watts/cm^2 at 100 mA/cm^2) but the range of anode cathode spacings is limited.

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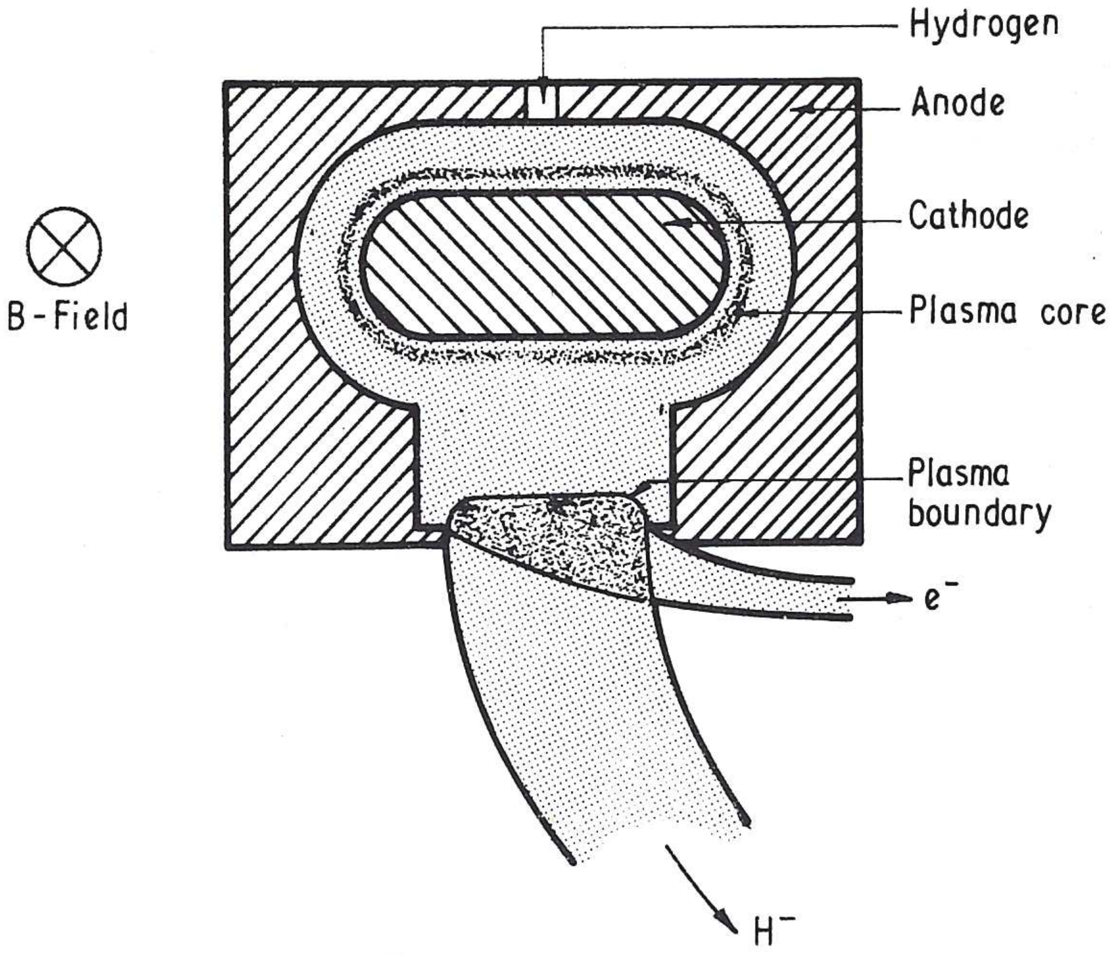

Fig.1 Illustration of negative ion magnetron (after Prelec and Sluyters(2)).

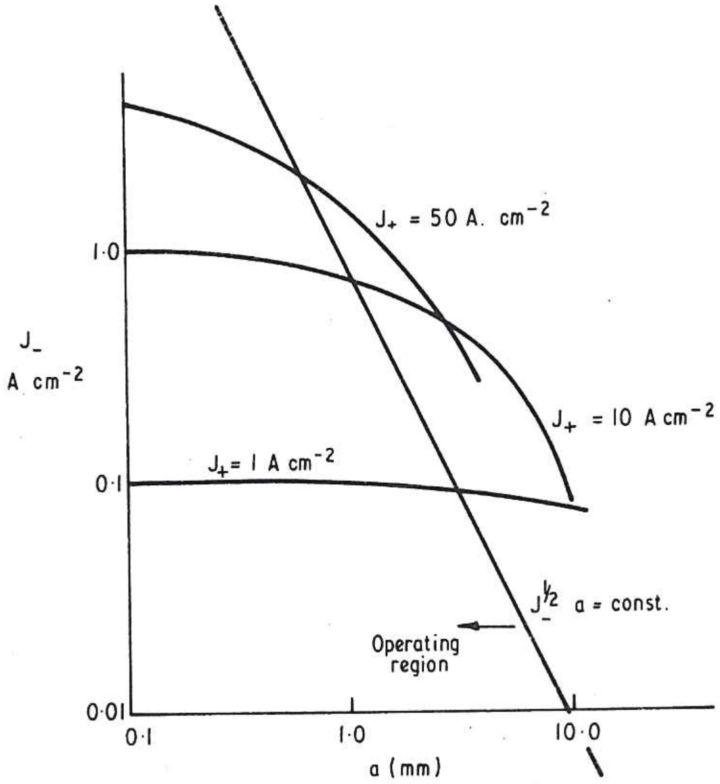

Fig.2 Variation of current density of H^- ions with source parameters (assuming 10% conversion of H^+ to H^- at the cathode).