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Pressure Limits of Negative Ion Sources Based Upon Gas Efficiency and Extracted Ion-Current Density

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Pressure Limits of Negative Ion Sources Based Upon Gas Efficiency and Extracted Ion Current Density*

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ABSTRACT

The nature of the electrical discharge has an obvious impact upon the gas efficiency of an ion source and on the current density which can be drawn from it. However external factors, such as the conductance of the grids and the background pressure along the beamline, also have an effect. Simple approximations based upon these factors show that there is a lower limit to the pressure of an ion source, which can deliver an ion beam of given current density at a specific gas efficiency. Estimates of ion stripping losses in a double gridded structure show that for all practical purposes, there is an upper limit as well.

I. Ion Source Pressure

The operating pressure of an ion source can be considered to be equal to the sum of the partial pressures of the electrons, ions and neutrals in the discharge, i.e.:

$$P_S = n_e kT_e + n_+ kT_+ + n_0 kT_0, \quad [1]$$

+ On assignment from Westinghouse Electric Corporation.

in which n_e, n_+, n_0 are the respective particle densities and T_e, T_+, T_0 their corresponding temperatures.

The temperature of the ions however, is of the same order of magnitude as that of the neutrals, while the density of the electrons and positive ions are about equal. Hence:

$$P_S/P_N = [1 + \xi_i(T_e/T_0)] \qquad [2]$$

in which the ionization fraction is

$$\xi_i = \left(\frac{n_+}{n_+ + n_0}\right). \qquad [3]$$

In most sources the ionization fraction is usually small, perhaps 1 or 2%, therefore:

$$n_+ \ll n_0 , \qquad [4]$$

whereby the partial pressure of the ion component is also small and that of the neutrals is:

$$P_N = n_0 k T_0 . \qquad [5]$$

Because the electron temperature may be a hundred times greater than that of the neutrals, the ion source pressure P_S is expected to be several times larger than that of the partial pressure of neutrals P_N (per Eq. 2).

The pressure in an ion source equals the sum of the pressure drops across the various grids mounted in front of it, plus the pressure of the region beyond the grids. Referring to Fig. 1, the pressure in a double gridded source is

$$P_S = (P_S - P_A) + (P_A - P_0) + P_0 \text{ (Torr)}, \qquad [6]$$

in which P_A is the pressure between the extraction and accel grids, and P_0 the background pressure further down the beamline.

Neglecting any high temperature gas that may be streaming out of the source, the conductance of the accel grid to the flow of relatively low temperature neutral gas is such that:

$$Q_P = (P_A - P_0)\ (v_G/4)\ A_G T_G \times 10^{-3}\ (\text{TLS}^{-1}), \qquad [7]$$

where Q_P is the gas flow through the grids, A_G the grid area (cm^2) and T_G the grid transparency. The average velocity of the gas molecule is

$$v_G = \left(\frac{8kT}{\pi M_2}\right)^{1/2} \ (\text{cm s}^{-1}) \qquad [8]$$

in which T is the gas temperature, and M_2 the mass of the molecule.

When extracting negative ions from an ion source it is necessary to hold back the electrons in the electrical discharge to prevent them from being accelerated along with the negative ions. This is usually accomplished by introducing a transverse magnetic field near the extraction grid. Meanwhile the electric field E, which accelerates the negative ions also confines the positive ions to the discharge. Thus the pressure drop in the vicinity of the extration grid must include a magnetic pressure term to confine the partial pressure of electrons to the ion source chamber as well as an electric pressure term for the positive ions. As an approximation then:

$$(P_S - P_A) = \left(\frac{Q_P \times 10^3}{(v_G/4)\, A_G T_G} + \frac{B^2}{2\mu} + \frac{\varepsilon_0 E^2}{2} \right) (\text{Torr}) . \qquad [9]$$

In the above, the gas flow, gas velocity, grid area and grid transparency are assumed to be the same as that in Eq. (7). It is evident that the ion source pressure must be greater than the sum of the external pressure drops, neglecting the magnetic and electric pressure terms.

Therefore the pressure in the ion source must be such that

$$P_S \geq P_N = \left[\frac{2Q_p \times 10^3}{(v_G/4)\, A_G T_0} + P_0 \right] , \qquad [10]$$

in which P_N is defined as above.

Q_p, the gas flowing through the grids (and ultimately out into the beamline beyond the ion source) is equal to the difference between the flow of gas into the source Q_{IN} and the equivalent flow of gas Q_B from which the ion beam is formed. Thus:

$$Q_P = (Q_{IN} - Q_B) . \qquad [11]$$

By defining the gas efficiency as,

$$\zeta_G = Q_B/Q_{IN}, \qquad [12]$$

the gas flow out of the ion source is found to be:

$$Q_P = Q_B(1/\zeta_G - 1) \ . \qquad [13]$$

For a negative ion beam, (which is purely atomic) the equivalent flow of molecular gas is

$$Q_B = .5\ J_-\ A_G T_G\ (RT/e)\ (TLS^{-1}) \qquad [14]$$

in which J_- is the negative ion current density (A cm^{-2}), R the gas constant, T the gas temperature, and e the charge per ion. [For T = 500 K, 0.5 RT/e = 0.17 Torr-liter - molecule^{-1}.]

Introducing Eq. (13) and (14) into Eq. (10), assuming a deuterium gas temperature of 500 K and a background pressure of 5 X 10^{-5} Torr (to provide space charge neutralization to the negative ion beam), the source pressure is

$$P_S \simeq P_N = (5.4 \times 10^{-3})\ [J_-(1/\zeta_G - 1) + (9.2 \times 10^{-3})]\ (\text{Torr}), \qquad [15]$$

Calculated values of P_N are shown in Fig. 2 for various gas efficiencies, as a function of J_-. One data point corresponds to the negative ion source developed at the Lawrence Berkeley Laboratory[2] (LBL) which operates at a source pressure P_S of about 10^{-3} Torr, with a gas efficiency of 20%, delivering a beam of 8 mA cm^{-2}. The other data point refers to the Brookhaven National Laboratory[3] (BNL) source which operates at about 10^{-1} Torr, with a gas efficiency of 6%, delivering a beam of 0.5 A cm^{-2}. The ratio of P_S/P_N for the LBL source is 4.5, while that of the BNL source is 2.4; both reasonable values for the approximations used in this analysis.

II. Ion Loss in the Accelerator

A high ion source pressure results in a correspondingly high background gas pressure P_A in the region between the grids. This causes a high fraction of the negative ions to be stripped before they have acquired the full beam energy.

The magnitude of this effect can be appreciated by considering the fraction F_- of a negative ion beam which is not stripped as it accelerates a distance z_0 from grid to grid in an over-simplified extraction geometry similar to that in Fig. 1.

$$F_- = \left[\mathrm{Exp} \quad -n_A \int_0^{z_0} \sigma(V) dz \right]. \qquad [16]$$

In the above $\sigma(V)$ is the stripping cross-section (a function of the ion energy) and n_A the background gas density between the grids. The pressure in this region is:

$$P_A = (P_A - P_0) + P_0 , \qquad [17]$$

which from Eqs. (13) and (14) [using the same conditions that went into Eq. (15)] is found to be:

$$P_A = (2.7 \times 10^{-3}) \, [J_-(1/\zeta_G - 1) + (1.8 \times 10^{-2})] \, . \qquad [18]$$

With the gas at 500 K, its density (cm^{-3}) is

$$n_A = (5.4 \times 10^{13})\ [J^-(1/\zeta_G - 1) + (1.8 \times 10^{-2})] \qquad [19]$$

As the extracted current density must satisfy Child's Law;

$$J_- = q\ \frac{V^{3/2}}{z^2}\ , \qquad [20]$$

in which q is the perveance of an atomic deuterium beam [3.85×10^{-8} ($AV^{-3/2}$)], V the beam potential, and z the beam path through the accelerator. From this relationship,

$$dz = (3/4)\ (q/J_-)^{1/2}\ V^{-1/4}\ dV, \qquad [21]$$

whereby Eq. (16) becomes

$$F_- = \text{Exp}\left\{-(7.9 \times 10^9\ [(J_-)^{1/2}\ (1/\zeta_G - 1) + (J_-)^{-1/2}\ (1.8 \times 10^{-2})] \int_0^{V_0} \sigma(V)\ V^{-1/4}\ dV\right\} \qquad [22]$$

Values of the integral using cross-section data from Ref. 1, are shown in Fig. 3.

For a 100 keV beam, the integral equals 60×10^{-13} ($cm^2\ V^{3/4}$). Thus the fraction of extracted ions which do not get stripped, [per Eq. (22)], is

$$F_- = \mathrm{Exp}\left\{ -(4.7 \times 10^{-2}) \left[(J_-)^{1/2} (1/\zeta_G - 1) + (J_-)^{-1/2} (1.8 \times 10^{-2}) \right] \right\} . \qquad [23]$$

This expression is shown in Fig. 4.

III. Conclusion

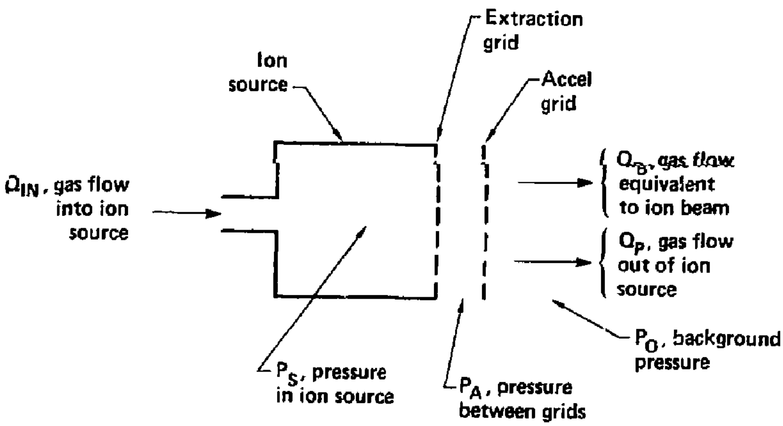
One of the virtues of neutral beams formed from negative ions is the supposed absence of neutrals of partial beam energy. Nevertheless Fig. 4 shows that unless the extracted ion current density is very low or the ion source gas efficiency very high, a significant component of neutrals with less than full beam energy can be formed. Of course only a small percentage of the low energy neutrals will pass through the exit aperture at the far end of the beamline, but this is not the point. The ion source pressure must be high enough to support a reasonable beam current density, but not so high as to cause excessive ion loss in the accel gap.

Reference

1 K. H. Berkner, R. V. Pyle, J. W. Stearns, "Intense Mix-Energy Hydrogen Beams for CTR Injection," Nuclear Fusion 15 (1975) p. 249.

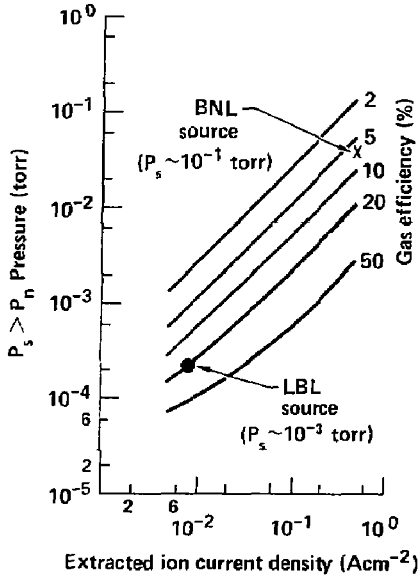
2 K. N. Leung, K. W. Ehlers, "LBL Self-Extraction Negative Ion Source," Lawrence Berkeley laboratory Report LBL-13261, Aug. 1981, Submitted to the Review of Scientific Instruments.

3 J. Alessi, Th. Sluyters, "Regular and Asymmetric Negative Ion Magnetron Sources with Grooved Cathodes," Second Intern. Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven National Laboratory, Upton, NY, Oct. 6-10, 1980, p. 153.



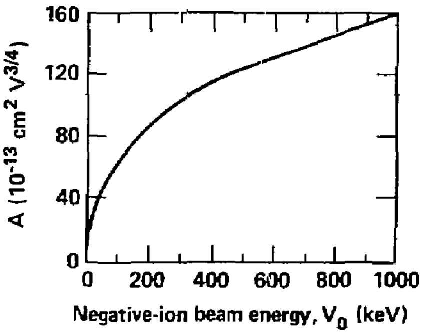
Ion Source Schematic

Figure 1



The pressure P_N as a function of extracted ion current density, for different gas efficiencies.

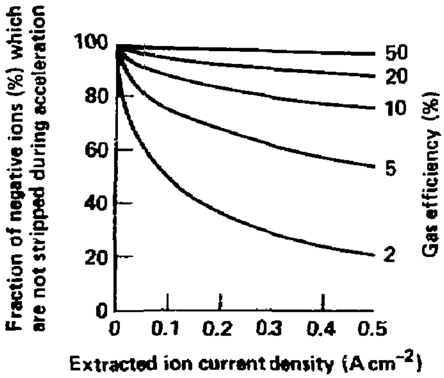
Figure 2



Values of the integral

$$A = \int_0^{V_0} \sigma(V)\, V^{-1/4}\, dV$$

Figure 3



The fraction of extracted 100 keV ions which do not get stripped during acceleration.

Figure 4