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The Energy Spectrum of Neutrals Formed in an Ion Accelerator

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1. Introduction

The detrimental effect of low energy neutrals on the efficiency of ion pumping in the thermal barriers of a tandem mirror reactor is generally acknowledged. It has led to restrictions on the allowable fraction of molecular ions which can be used to form the pump beams. Ion sources of almost pure atomic beams are needed because molecular ions, which are neutralized after having been accelerated to full energy, tend to split into atomic components of fractional energy. For this reason positive ion sources delivering as much as 90% atomic beams are now under development, and negative ion sources, which are inherently atomic, are being considered for pump beams. However little attention has been paid to the low energy neutrals formed in the accelerator by interaction between the ion beam and the background gas. This may not be an overwhelming source of low energy neutrals, but it is not an insignificant one either.

This subject was originally investigated in some detail by O. A. Anderson[1] in 1978 with regard to the TFTR/MFTF ion sources, accel-decel grids for low energy beams and the JET-surface-conversion source of negative ions. In the present work a set of equations is derived for a

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simple accelerator, by which the energy spectrum of neutrals formed in a single accel gap can be estimated for negative as well as positive ions. For this purpose the approximate gas efficiency of the source must be known, along with the ion beam composition, energy and current density. In addition, some estimate is needed of the temperature of the gas flowing out of the ion source, and of the pressure of the background gas beyond the accelerator.

The procedure followed here consists of first determining the fractions of the extracted ion current which are lost to the beam at successive increments of beam energy and then converting them into fractions of the extracted ion current which correspond to the current of neutrals equivalent to the lost ions. The result is presented in a bar chart, showing the fraction of neutrals that are formed over discrete ranges of energy.

This, however, does not represent the energy distribution of the neutrals that enter the reactor. The low energy neutral components are markedly reduced with respect to the full energy beam by their greater angular divergence, by scattering in the gas neutralizer (or gas stripping cell), and by re-ionization along the beam path.

2. Ion Loss in a Beam Drift Region

A significant loss of ion current can result from charge exchange between positive ions in a beam and the background gas. If I_i represents the atomic, di-atomic, or tri-atomic component of a positive ion for which i = 1, 2, or 3, respectively,

$$\frac{dI_i}{d\pi} = -\sigma_i(V)I_i \qquad [1]$$

where $\sigma_i(V)$ is the charge exchange cross section of the ions (of appropriate species i, and energy V, see Fig. 1), and π the thickness of the background gas.

With a uniform gas density n along the ion path z,

$$d\pi = ndz, \qquad [2]$$

whereby the fraction of ions of species i that do not experience charge exchange is:

$$F_i = \eta_i \exp\left[-n \int_0^{z_0} \sigma_i(V)dz\right] . \qquad [3]$$

In the above, η_i is the fraction of the total ion beam which consists of species i.

3. <u>Ion Loss in an Accel Gap</u>

Because the space charge of the ion beam peturbs the potential across the accel gap, and because the charge exchange cross-section is a function of the potential, it is convenient to change the variable in Eq. (3) from z to V. The relationship needed to make this substitution can be obtained from Poisson's equation for a planar geometry, which is assumed to be applicable in this case.

$$\frac{\partial^2 V}{\partial z^2} = \frac{1}{\epsilon_0} \sum_{i=1}^{3} \left[J_i \left(\frac{M_i}{2eV}\right)^{1/2}\right] \qquad [4]$$

in which ε_0 is the permitivity of vacuum, J_i the current density of the ith ion species and M_i the corresponding ion mass.

If the total current density is J_T, the current density of the ith ion species is:

$$J_i = \eta_i \, J_T, \tag{5}$$

while the mass of the ith ion species is:

$$M_i = i \, M_1 \, . \tag{6}$$

Thus for the accel gap shown in Fig. 2,

$$\frac{\partial^2 V}{\partial z^2} = (J_T/\varepsilon_0) \left(\frac{M_1}{2e}\right)^{1/2} V^{-1/2} \sum_{i=1}^{3} \left[\eta_i \, i^{1/2}\right]. \tag{7}$$

or

$$\frac{\partial^2 V}{\partial z^2} = (4/9) \, (J_T/q) \, V^{-1/2} \sum_{i=1}^{3} \left[\eta_i \, i^{1/2}\right] \tag{8}$$

in which q, the perveance of an atomic ion beam is:

$$q = (4/9) \, \varepsilon_0 \, (2e/M_1)^{1/2} \, , \tag{9}$$

($q = 3.85 \times 10^{-8}$ $Av^{-3/2}$ for an atomic deuterium beam).

Equation (8) can be solved to give the desired relationship assuming $dV/dz = 0$ at $z = 0$, where $V = 0$. Thus

$$dz = \left(\frac{3}{4}\right) \frac{(q/J_T)^{1/2}}{\left(\sum_{i=1}^{3} [n_i i^{1/2}]\right)^{1/2}} V^{-1/4}\, dV. \qquad [10]$$

Introducing this into Eq. (3) results in the fraction of ions which arrive on the far side of the accel gap, i.e.

$$F_i = n_i \,\mathrm{Exp}\left[-\left(\frac{3}{4}\right) n \frac{(q/J_T)^{1/2}}{\left(\sum_{i=1}^{3} [n_i i^{1/2}]\right)^{1/2}} \int_0^{V_0} \sigma_i(V) V^{-1/4} dV \right], \qquad [11]$$

in contrast to the fraction of ions which are lost,

$$L_i = (n_i - F_i) \qquad [12]$$

4. <u>Ion Loss Over a Specific Range of Energy</u>

If the full beam energy V_0 is divided into N_0 bands of energy ΔV, then:

$$V_0 = N_0 \, \Delta V, \qquad [13]$$

and the energy at the center of the Nth band is

$$V_N = (N - 0.5)\, \Delta V \,. \qquad [14]$$

The integral in Eq. (11) can now be approximated by the sum of the contributions of all of the energy bands, i.e.

$$\int_0^{V_0} \sigma_i(V) V^{-1/4} dV = \sum_{N=1}^{N_0} \left[\sigma_i(V_N)\ V_N^{-1/4}\ \Delta V \right] \qquad [15]$$

or

$$\int_0^{V_0} \sigma_i(V) V^{-1/4} dV = (\Delta V)^{3/4} \sum_{N=1}^{N_0} \left[\sigma_i(V_N)\ (N - 0.5)^{-1/4} \right]. \qquad [16]$$

(See Fig. 3 for values of the integral[2] for positive and negative deuterium ions.)

Because the contribution over any one energy band is small, Eq. (12) can be rewritten to describe the ion loss in the Nth band.

$$L_i(N) = \eta_i\ (3/4)\ n \frac{(q/J_T)^{1/2} (\Delta V)^{3/4} [\sigma_i(V_N)(N-0.5)^{-1/4}]}{\left(\sum_{i=1}^{3} [\eta_i\ i^{1/2}]\ ^{1/2} \right)}, \qquad [17]$$

while the range of energy over which this loss takes place is

$$R_N = N\ \Delta V \begin{cases} +0 \\ -\Delta V \end{cases} \qquad [18]$$

5. <u>Gas Density in the Accel Gap</u>

The pressure P_A between the grids of an accelerator, consisting of a single gap like that shown in Fig. 2, equals the sum of the pressure drop across the accel grid plus the pressure P_0 beyond the grid, i.e.

$$P_A = (P_A - P_0) + P_0 . \qquad [19]$$

Neglecting any high temperature gas which may be streaming out of the ion source, the conductance of the grid is such that, the flow of gas through the grid is

$$Q_P = (P_A - P_0)\ (v/4)\ A_G T_G \times 10^{-3}\ \ (TLS^{-1}) \qquad [20]$$

in which the grid area is A_G (cm^2), its transparency is T_G(%) and the average velocity of the molecular gas of temperature TK and mass M_2, is

$$v = \left(\frac{8kT}{\pi M_2}\right) (cms^{-1})\ . \qquad [21]$$

The gas flow Q_P can also be evaluatec from the gas efficiency of the ion source and the ion current density drawn from it.

The flow of neutral molecular gas (i = 2) equivalent to an ion beam of current density J_T (consisting of fractions η_i of species i) is:

$$Q_B = 0.5\ J_T A_G T_G\ (RT/e) \sum_{i=1}^{3} [\eta_i i]\ (TLS^{-1})\ , \qquad [22]$$

in which R is the gas constant, T the gas temperature and e the charge on the ions. [For T = 500 K, (0.5 kT/e) = 0.17 TL per molecule].

Operating at a gas efficiency ζ_G, the ion source requires a gas input of

$$Q_{IN} = Q_B/\zeta_G\ , \qquad [23]$$

whereby the difference, between the gas input and the gas flow equivalent to the ion beam Q_B, is the gas flowing down the beamline, i.e.

$$Q_P = (Q_{IN} - Q_B) = Q_B(1/\zeta_G - 1) \quad . \qquad [24]$$

The pressure in the accel region can be found from Eq. (19), using Eqs. (20), (22) and (24).

$$P_A = \left[(2 \times 10^3)(J_T/v)(RT/e)(1/\zeta_G - 1) \sum_{i=1}^{3} [n_i i] + P_0\right] , \qquad [25]$$

from which the gas density, at a gas temperature TK, is found

$$n = 10^{19} (P_A/T) \text{ (molecules cm}^{-3}) \quad . \qquad [26]$$

6. Neutrals Formed in a Specific Energy Band

Combining Eqs. (17), (25) and (26) results in the ion loss in the Nth energy band of a positive ion beam per Eq. (18).

$$L_i(N) = A[BJ_T^{1/2} + CJ_T^{-1/2}]\, n_i[\sigma_i(V_N)(N-0.5)^{-1/4}] \qquad [27]$$

where:

$$A = \frac{7.5 \times 10^{18}}{T} \frac{q^{1/2}(\Delta V)^{3/4}}{\left(\sum_{i=1}^{3} [n_i i^{1/2}]\right)^{1/2}} \qquad [28]$$

$$B = (2 \times 10^3)\,(RT/e)/v\,(1/\zeta_G - 1) \sum_{i=1}^{3} [n_i i] \quad [29]$$

$$C = P_0 \quad [30]$$

Molecular ions are lost to the ion beam by becoming neutral, and upon being neutralized, break up into atomic components of fractional energy. Thus if an ion current $L_i(N)$, per Eq. (27), is lost in the Nth energy band, the corresponding neutral current

$$L_i^0(N) = iL_i(N), \quad [31]$$

will be found in the energy band that encompasses (N/i). This is because the neutrals now fall in an energy range of:

$$R_N = N\,\Delta V/i \begin{cases} +0 \\ -\Delta V/i \end{cases} . \quad [32]$$

As an example consider the energy distribution of the equivalent neutral currents obtained from a positive ion beam. It is arbitrarily decided that for this analysis the beam energy will be divided into N_0 = 8 ranges. As shown in Table 1, the atomic component of the beam, for which i = 1 in Eq. [27], contributes to each of the eight ranges.

The diatomic ions for which i = 2, split into two atomic components upon neutralization. This doubles their current and halves their energy range per Eq. (31) and (32). Thus the neutrals formed from ions in the first and second energy band (N = 1 and 2) contribute to the neutral current in the first energy band as shown in Table 1, while neutrals formed from ions in the third and fourth energy band contribute to the neutral current in the second energy band, etc.

Similarly tri-atomic ions, for which $i = 3$, split into three atomic components upon neutralization, which triples their current and cuts their energy range down by one-third. According to Table 1, the first three ranges, $N = 1$, 2 and 3, contribute neutral current to the first range of neutral energy; the second three ranges, $N = 4$, 5 and 6, contribute neutral current to the second range of neutral energy; while the remaining two ranges of ions, $N = 7$ and 8, contribute to the third neutral range.

The current in each of the energy bands is then determined by summing the contributions of all the species to the particular energy range in question.

The ion loss, and the equivalent neutral current which results from a negative ion beam in a simple planar accelerator, can also be evaluated from Eq. (27). For this case J_T represents the negative ion beam current density. Because negative ions have no molecular components, Eq. (28), (29) and (30) also apply, but for i, and $\eta_i = 1$.

Table 1 Current Distribution Over Eight Energy Bands

Energy	Atomic	*Diatomic*	Triatomic
N	$L_1^0(N)$	$L_2^0(N)$	$L_3^0(N)$
1	$L_1(1)$	$2[L_2(1) + L_2(2)]$	$3[L_3(1) + L_3(2) + L_3(3)]$
2	$L_1(2)$	$2[L_2(3) + L_2(4)]$	$3[L_3(4) + L_3(5) + L_3(6)]$
3	$L_1(3)$	$2[L_2(5) + L_2(6)]$	$3[L_3(7) + L_3(8)]$
4	$L_1(4)$	$2[L_2(2) + L_2(8)]$	
5	$L_1(5)$		
6	$L_1(6)$		
7	$L_1(7)$		
8	$L_1(8)$		

7. Specific Examples

For the particular case of a 40 KeV positive deuterium ion beam of J_T = .25 Acm^2 with a composition of η_1, η_2 and η_3 equal to 90%, 5% and 5% respectively, and an ion source operating at a gas efficiency of ζ_G = 30%, it is assumed that the gas temperature T = 500 K and the pressure P_0 is 1.5 X 10^{-3} Torr (to accommodate a neutralizer cell of reasonable length). The beam energy is divided into eight bands of 5000 V each so that the ions lost from the ith ion specie in the Nth energy band per Eq. (27) is:

$$L_i(N) = (9.82 \times 10^{12})\ \eta_i\ [\sigma_i(V_N)\ (N - 0.5)^{-1/4}]$$

V_N is taken from Eq. (14), and $\sigma_i(V_N)$ from the appropriate cross-sections in Fig. 1.

The result is shown in Fig. 4. The neutral fraction is not particularly sensitive to the molecular composition, but it is very much a function of ζ_G, J_T and P_0.

A similar analysis is presented for a 40 keV negative deuterium ion beam of J_T = .1 A cm^{-2}, using an ion source with a gas efficiency of 20%. The gas temperature is 500 K and the pressure P_0 is 5 X 10^{-5} Torr corresponding to the minimum background pressure which could provide space charge neutralization for the ion beam.[3] These results are shown in Fig. 5.

8. Conclusion

This work presents an estimate of the energy distribution of the neutrals formed in the ion beam accelerator. See Fig. 4 and 5. However it does not determine the fraction of those neutrals which leave the neutral beam injector and go on into the reactor. To do that, more details of the beam line performance are reeded.

It is necessary to know the magnitude of the aberrations introduced into the beam optics by the grids; if these aberrations swamp out the energy by which the molecules are disassociated, that is if the neutral atoms formed from disassociated molecules are uniformly distributed thoroughout the beam divergent angle; if there is a plasma generated in the gas neutralizer; if it affects the beam divergence; if it is dense enough to ionize an appreciable fraction of the low energy neutrals, etc.

Irrespective of these questions however, this work gives some clues as to what might be done to reduce the fraction of low energy neutrals formed in the accelerator. It can be seen from Eq. (30), that if the beam line pressure P_0 is excessive, "C" will be the dominant factor in Eq. (27). Under these conditions it is best to operate at a high ion beam current density. This entails a shorter accelerator gap per Child's Law, resulting in a smaller ion loss with a corresponding lower component of neutrals.

Should the factor"B" in Eq. (27) be dominant, as it is in a negative ion beam line, the tendency is to reduce the current density J_T. This undesirable circumstance is usually the result of a relatively poor gas efficiency ζ_G (in Eq. (29)). When this happens it may be desirable to modify the accelerator design. Better overall performance might be obtained with a low-voltage pre-accelerator stage (incurring a relatively high ion loss) and a well pumped drift region followed by a final high voltage acceleration stage at low pressure.

Obviously there is no way to generalize these circumstances. Each beamline design must be analysed in detail.

References

1. O. A. Anderson, "Parasitic Components from Charge Transfer in Neutral Beams for Fusion," Lawrence Livermore National Laboratory, UCID 17581 (February 1, 1978).

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

3. M. D. Grabovich, et al., "Effect of D.C. Compensation of a Dense Beam of Negative Ions," JETP Letters, 29, 489 (1980).

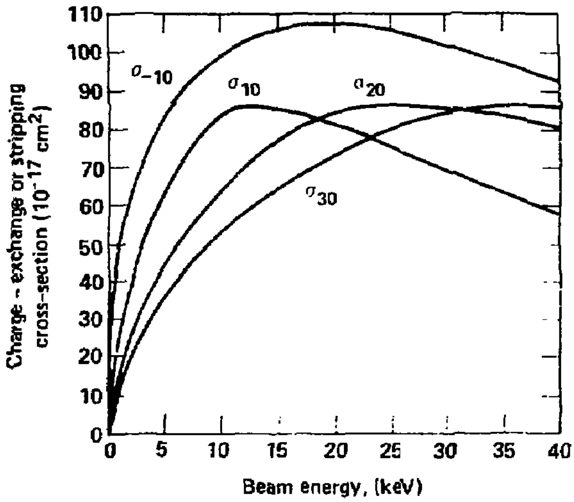

Figure 1

Charge-Exchange and Stripping Cross-Sections

for Positive and Negative Deuterion Ions

in Deuterium Gas.

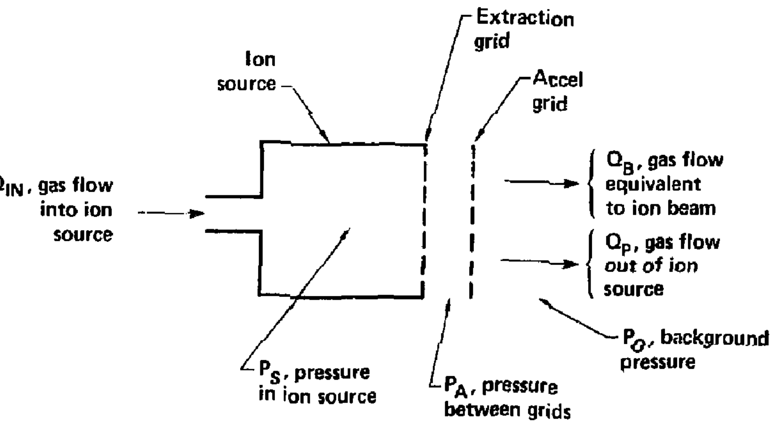

Figure 2

Ion Source and Accelerator

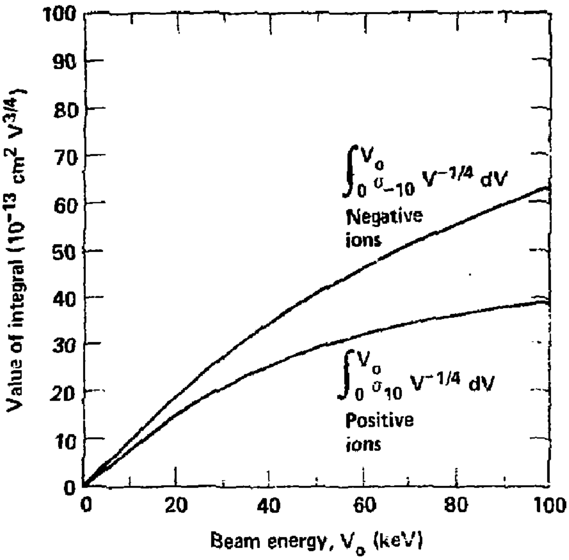

Figure 3

The Integral $\int \sigma_i(V) V^{-1/4} dV$

for Positive and Negative Deuterium Ions

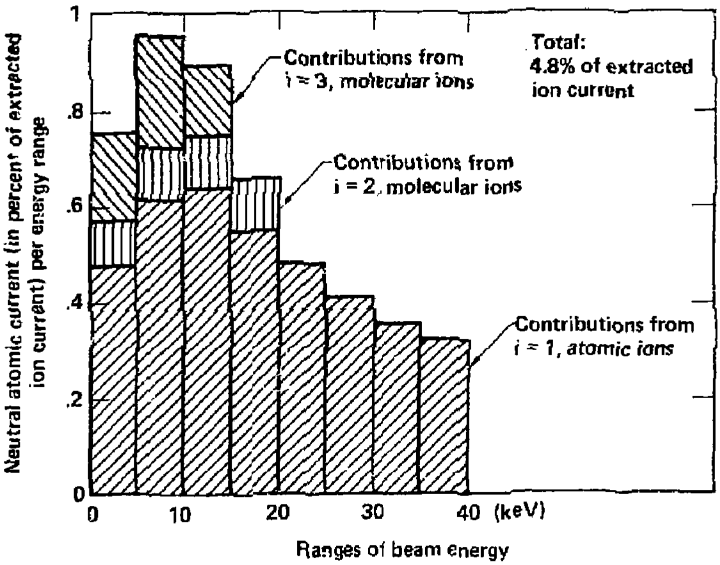

Figure 4

Atomic Neutrals of various energy ranges formed by charge exchange in the accel gap of a positive ion beam; η_1 = .90, $\eta_2 \approx 0.05$, η_3 = .05, $J_T = 0.25\ A\ cm^{-2}$, ζ_G = 30%.

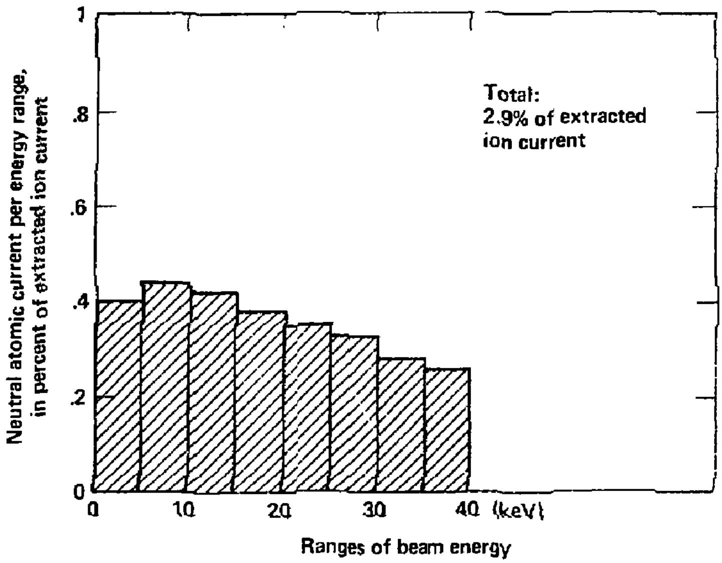

Figure 5

Atomic neutrals of various energy ranges formed by stripping in the accel gap of a negative ion beam; J_T = 0.1 A cm^{-2}, ζ_G = 20%.