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NEGATIVE IONS AS A SOURCE OF LOW ENERGY NEUTRAL BEAMS+

Joel H. Fink*
Brookhaven National Laboratory
Upton, New York 11973

Abstract

Little consideration has been given to the impact of recent developments in negative ion source technology on the design of low energy neutral beam injectors. However, negative ion sources of improved operating efficiency, higher gas efficiency, and smaller beam divergence will lead to neutral deuterium injectors, operating at less than 100 keV, with better operating efficiencies and more compact layouts than can be obtained from positive ion systems.

I. Introduction

In the past it was generally acknowledged that all neutral beam injectors, operating at energies below 150 keV, would be made from positive ions. This was because positive ion beams were available that worked well at lower beam energies. At higher energies, however, their neutralization efficiencies are so poor that even with direct recovery of the energy in the unneutralized fraction of the beam they could not be made into useful beam lines.

Thus the impetus for negative ion development was to provide high energy neutral beams. Electrons can be stripped from negative ions to form neutrals at high efficiencies that are relatively independent of beam energy.

As negative ion technology improves, it becomes more attractive as a basis of low energy injector design. So much so, that if low energy beams are needed in future operating reactors, say 25 years from now, they will most likely be formed from negative ions, stripped by photodetachment.

Positive ions are preferred in today's injectors because there is no immediate need for high energy beams and large negative ion systems have yet to be demonstrated. In addition, they form beam lines which have several important advantages over our earlier concepts of negative ion performance. To be specific, it is believed that positive ion systems have:

a) Ion sources which operate more efficiently.

b) Lower ion losses.

c) Ion sources with higher gas efficiencies.

d) Good operating efficiencies at beam energies below 150 keV, particularly when used with direct energy recovery.

e) Beams of smaller divergence.

f) A larger output of neutrals from an injector of given size.

In the following, I discuss the six items listed above and show the impact of recent negative ion development upon them.

II. Ion Source Efficiency

A measure of ion source efficiency is the power required by the source per ampere of extracted ion current. Evaluated in units of input watts per output amperes, it represents a critical factor in the overall operating efficiency of a low energy neutral beam injector. Divided by the beam energy, it presents the fraction of the power in the accelerated beam which is equal to the power needed to operate the ion source. At very high beam energies, it is not very significant.

Large positive ion sources operate at about 2.5 kW per ampere. Used in a 75 keV beam line, the power going into the ion source is roughly 3.3% of the power in the accelerated ion beam. If such a source were used in conjection with a cesium vapor cell to form negative ions, approximately 20% of the positives would be converted to negative ions and the combination of positive ion source with Cs cell would operate as a negative ion source with an efficiency of 12.5 kW per ampere of negative ions. The power required to operate this source would be about 16.5% of the power in a 75 keV negative ion beam derived from it. At 200 keV, the source would require only 6.3% of the power in the ion beam.

Three years ago, at the previous Brookhaven conference on negative ions, data was presented on the performance of several different types of negative ion sources under investigation at that time.[1] These included a hollow discharge duoplasmatron, as well as several Penning and magnetron sources. The source performance ranged from 18 to 263 kW per ampere, corresponding to 24 to 350% of the energy in a 75 keV beam.

Today, negative ion sources have been reported[2] to work at 5 kW/A, with better performance anticipated in the future. In a 75 keV beam, 5 kW/A represents 6.7% of the beam energy. Whereas three years ago, low energy neutral beams based upon negative ions were out of the question, they now present a viable alternative.

*On assignment from Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

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III. Ion Losses

During the initial stages of beam formation, some ions become neutralized prematurely, either by charge exchange of positive ions with the background gas, or by electron stripping of negative ions upon impact with the background gas. In either case this constitutes a loss of ions to the beam, provided the newly formed neutrals have not achieved their ultimate energy or assumed their final trajectories.

The loss of negative ions will always be greater than the loss of positive ions to beams of the same energy passing through a background gas of the same density. But as can be seen by the ratio of the two cross-sections, σ_{-10}/σ_{10}, shown as a function of beam energy in Fig. 1, the comparative loss of negative to positive ions is not as serious at low energies as it is at high.

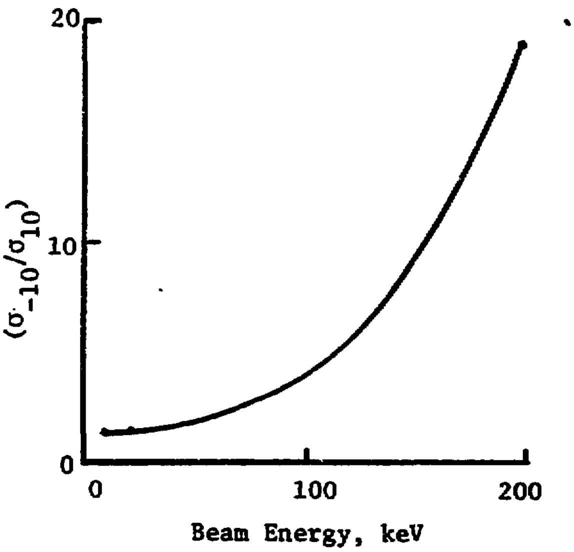

Fig. 1: Ratio of negative ion stripping cross-section, σ_{-10} to the positive ion charge-exchange cross-section, σ_{10}.

To minimize the loss, it is conceivable that the background gas density could be reduced, but only so far. Positive ion beams depend upon electrons, generated by impact ionization of the background gas to provide space-charge neutralization and prevent space-charge blow up. Similarly negative ion beams depend upon positive ions, generated by impact ionization, to provide space-charge neutralization. Because electrons are so much more mobile than ions, the background gas density required to space-charge neutralize a positive ion beam is almost an order of magnitude greater than that required for a negative ion beam. As a consequence, negative ion beams with energies up to 160 keV (where $(\sigma_{-10}/\sigma_{10})$ becomes equal to 10) could theoretically be made to operate with less losses than positive ions - provided the background density can be suitably controlled. Indeed, pumping in the vicinity of the ion sources is critical for satisfactory negative ion beam line performance. This is discussed in the next section on gas efficiency.

Positive ion sources, as used in today's neutral beam injectors, operate at a disadvantage with respect to ion losses. Because the neutral gas flowing out of the source is used to feed the neutralizer cell, the background gas density is considerably higher in the vicinity of the accel grids than is desirable or need be. Redesign of the gas neutralizer cell could make a significant improvement.

In the following section a positive ion beam line is considered in which a deflection magnet is used to separate the D_2^+ and D_3^+ ion components from the desired D^+ ion beam. The neutralization of full energy D^+ ions in the vicinity of the magnet, before they achieved their final trajectory, constitutes a serious loss to the operating efficiency, particularly at low beam energies where σ_{10} is large. Obviously, this is not a good practice. To provide a comparison, another beam line is considered which uses no deflection magnet. The improvement is impressive.

IV. Gas Efficiency

Gas efficiency is another ion source parameter which has improved significantly over the past three years. At the 1977 conference, direct extraction sources were discussed[1] that operated at 1-2% gas efficiency. Recently a magnetron source was described[3] which works at over 6%, while in Russia efficiencies of 10-20% have been reported.[4]

As used in this discussion, gas efficiency is defined as the ratio of ion flow out of the source, in atoms per second, to the flow of room temperature gas into the source, in the same units. It is an important factor in neutral beam injector design because it establishes the quantity of gas which must be pumped away from the vicinity of the source. This can be evaluated from the flow of room temperature gas, Q_B equivalent to that going into the extracted ion beam. The total flow of gas into a source of efficiency, ϵ_G is:

$$Q_{IN} = Q_B/\epsilon_G, \qquad (1)$$

while the gas which must be pumped away is:

$$Q_P = Q_{IN} - Q_B \qquad (2)$$

and

$$Q_P = (1/\epsilon_G - 1)\, Q_B \qquad (3)$$

The gas flow equivalent to a positive ion beam of predominantly atomic D^+ ions extracted at a current density, J_E^+, through a grid of area, A_G and transparency T_G^+ is:

$$Q_B^+ = .1\, J_E^+ T_G^+ A_G \quad T\ell s^{-1} \qquad (4)$$

while the gas flow equivalent to a negative ion beam of atomic D^- ions is:

$$Q_B^- = .1\ J_E^-\ T_G^-\ A_G \qquad T\ell s^{-1} \qquad (5)$$

Thus the quantity of gas (evaluated at room temperature) per unit area which must be pumped away from a positive ion source becomes:

$$Q_p^+/A_G = .1\ (1/\zeta_G^+ - 1)\ J_E^+\ T_G^+ \quad T\ell s^- CM^{-2} \qquad (6)$$

and the corresponding value for a negative ion source is

$$Q_p^-/A_G = .1\ (1/\zeta_G^- - 1)\ J_E^-\ T_G^- \quad T\ell s^{-1} CM^{-2} \qquad (7)$$

According to the above, a positive ion source, operating at a gas efficiency of 30%, delivering D^+ ions at a current density of $.25ACM^{-2}$, via grids of 40% transparency requires pumps which can remove $.023\ T\ell s^{-1}$ of gas per CM^2 of emitting area. A negative ion source, meanwhile operating at a 10% gas efficiency, delivering D^- ions at a current density of $.5ACM^{-2}$ with extraction grids of 10 transparency entails $.045\ T\ell s^{-1}$ of gas per CM^2 of source. Thus the pumping load of today's negative ion sources is about twice that of positive ion sources.

A key problem in the vicinity of the ion sources is to remove the gas in such a way that minimizes the ion losses. For the highest pumping speed over the shortest length along the beam line, higher background pressures are required. For the lowest ion losses, a short beam path through lower pressures is preferred. When consideration is given to the way the gas streams out of the ion sources, it is no surprise that after the ion source, the extraction region is the most difficult section of a neutral beam line to design. In the following analysis of a negative ion beam line, it is assumed that over 20% of the extracted ions become lost to the beam in this region.

V. Injector Operating Efficiency

By definition, the operating efficiency of a neutral beam injector is the ratio of the neutral beam power output to the total power input. This is equal to the reciprocal of the sum of the power needed to operate each beam line component per watt of neutral beam output. Thus:

$$\eta = \left[\sum_i (p_i/p_o) \right]^{-1} \qquad (8)$$

In the following, to simplify the analysis, the power required for pumping, refrigeration, and other services are neglected. Hence:

$$\sum_i (P_i/P_o) = P_s/P_o + P_A/P_o + P_p/P_o + (-P_R/P_o) \qquad (9)$$

where P_s/P_o is the power need per output neutral watt of the ion source; P_A/P_o the power need of the ion extractor and accelerator, P_p/P_o the power need of the photo detachment cell and P_R/P_o is the power recovery obtained by direct conversion of the energy in the unneutralized fraction of the high energy beam.

Three injectors are considered. The first, as shown in Fig. 2 uses an ion source that delivers an ion current density, $J_E = .25\ A/cm^2$ to an accel grid of transparency, $T_G + .4$. The atomic component of the ion beam is $\eta_1 = 90\%$.

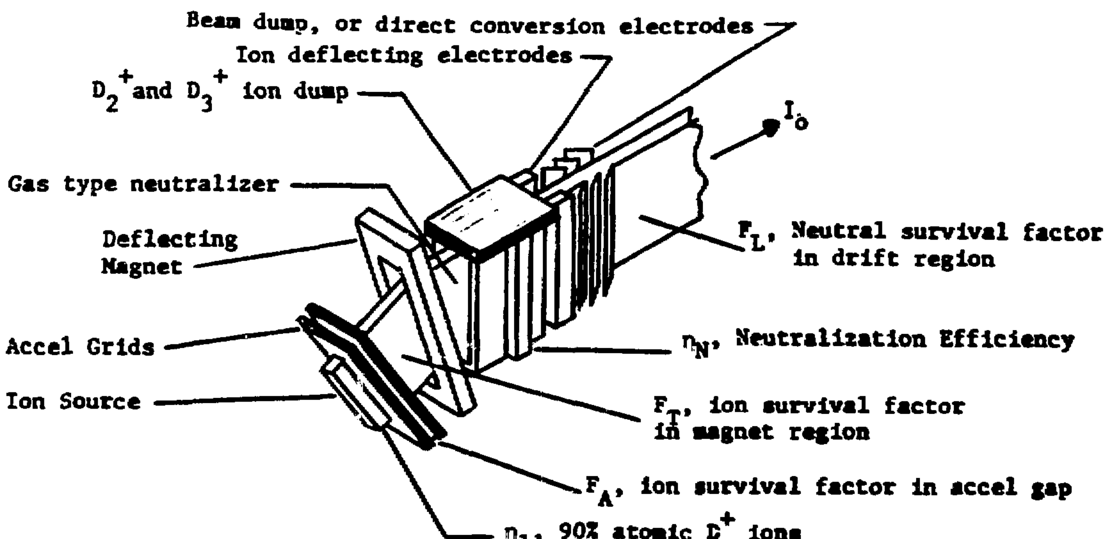

Fig. 2: Neutral beam line based upon positive ions with a deflecting magnet to remove the D_2^+ and D_3^+ molecular ions.

The D_2^+ and D_3^+ components are subsequently removed by a deflecting magnet, which permits a pure D^+ beam to enter the neutralized cell. After neutralization, those ions that remain with the beam are removed by electrostatic deflection, to be collected on a water-cooled beam dump or on biased electrodes for direct energy conversion.

The fraction of extracted ions which make it through the accel grids without suffering charge exchange is:

$$F_A = \left[1 - \int n_A \, \sigma_{10} \, dZ\right] , \tag{10}$$

While the fraction of atomic ions that remain with the beam after passage through the deflecting magnet is:

$$F_T = \left[1 \quad n_T \, \sigma_{10} \, Z_T\right] \tag{11}$$

and, the fraction of high energy neutrals which are not ionized while in transit from the neutralizer cell to the reactor is:

$$F_L = \left[1 - \sigma_{01} \int n_L \, dZ \right. . \tag{12}$$

These factors are given in Table 1 as evalurated in Reference 5.

TABLE 1

Positive Ion Source with Deflecting Magnet Removing Molecular Ions, Fig. 2

V_0	50 kV	75 kV	100 kV	150 kV	200 kV	Reference
η_1	.90	.90	.90	.90	.90	Assumption
F_A	.94	.93	.92	.91	.91	Ref. 6
F_T	.53	.73	.83	.94	.98	Ref. 6
η_N	.74	.62	.48	.29	.21	Ref. 6
F_L	.95	.95	.95	.95	.95	Ref. 6
η_R	0	0	0	0	0	Assumption
ζ without recovery	.30	.34	.30	.20	.15	Eq. 18
η_R	.75	.75	.75	.75	.75	Assumption
ζ without recovery	.33	.41	.41	.34	.29	Eq. 18

Assumptions:
K_s = 2.5 kW/A: ion source efficiency
ζ_s = 90%, ion source power supply efficiency
ζ_A = 95%, accel power supply efficiency

Using an ion source whose efficiency is K_s = 2.5 kW per ampere, and an ion source power supply with an efficiency, ζ_s = 90%, the power need of the source is:

$$P_s/P_o = \frac{K_s}{\zeta_s V_o} \quad \left(I_E/I_0\right) \tag{13}$$

in which the ratio of extracted ion current to output neutral current is:

$$I_E/I_0 = \left(\eta_1 \, F_A \, F_T \, \eta_N \, F_L\right)^{-1} , \tag{14}$$

and the neutralization efficiency, η_N equals 95% of the maximum value, i.e.:

$$\eta_N = .95 \quad \left(\frac{\sigma_{10}}{\sigma_{10} + \sigma_{01}}\right) \tag{15}$$

In the above, σ_{10} and σ_{01} are the neutralizing and ionizing cross-sections of D^+ in D_2 at the beam energy, V_0.

With an accel power supply efficiency, ζ_A = 95%, the power need of acceleration is:

$$P_A/P_0 = \frac{1}{\zeta_A} \quad (I_E/I_0) \tag{16}$$

With a direct conversion efficiency of η_R = 75%, the energy recovery term is:

$$P_R/P_0 = \eta_R \left(\frac{1 - \eta_N}{\eta_N}\right) . \tag{17}$$

Combining Equations 13 thru 17, the injector efficiency is found to be:

$$\zeta = \frac{\eta_1 \, F_A \, F_T \, \eta_N \, F_L}{K_s/(\zeta_s V_o) + \left[1 - (1-\eta_N) \, \eta_R \, \eta_1 \, F_A \, F_T\right]/\zeta_A} \tag{18}$$

Values of the various factors are listed as functions of beam energy in Table I.

The second injector shown in Fig. 3 uses the same positive ion source with no deflecting magnet. Thus, $F_T = 1$. Other than that, the efficiency is as given in Equation 18.

$$\zeta = \frac{\eta_1 F_A \eta_N F_L}{K_s/(\zeta_s V_o) + \left[1-(1-\eta_N)\, \eta_R\, \eta_1 F_A\right] /\zeta_A} \qquad (19)$$

These values are listed in Table 2.

The third beam line per Fig. 4 uses negative ions, stripped in a photo detachment cell, to form the neutral beam. The negative ions are extracted from the source at some voltage, V_E, to be separated from whatever electrons that may have also been drawn out of the source, and to be transported to the high voltage grid system by sector magnets. After acceleration, the negative ion beam is stripped of electrons in the photo detachment cell. Subsequently, those ions remaining with the neutral beam are electrostatically deflected out of the beam, to be collected on water-cooled beam dumps.

The fraction of the negative ions that are not stripped during extraction is:

$$F_E = \left[1 - \int \eta_E\, \sigma_{-10}\, dZ\right], \qquad (20)$$

while the fraction that survives transport through the sector magnets is:

$$F_T = \left[1 - \eta_T\, \sigma_{-10} Z_T\right], \qquad (21)$$

and the surviving fraction that get past the accelerator is:

$$F_A = \left[1 - \int \eta_A\, \sigma_{-10}\, d\right]. \qquad (22)$$

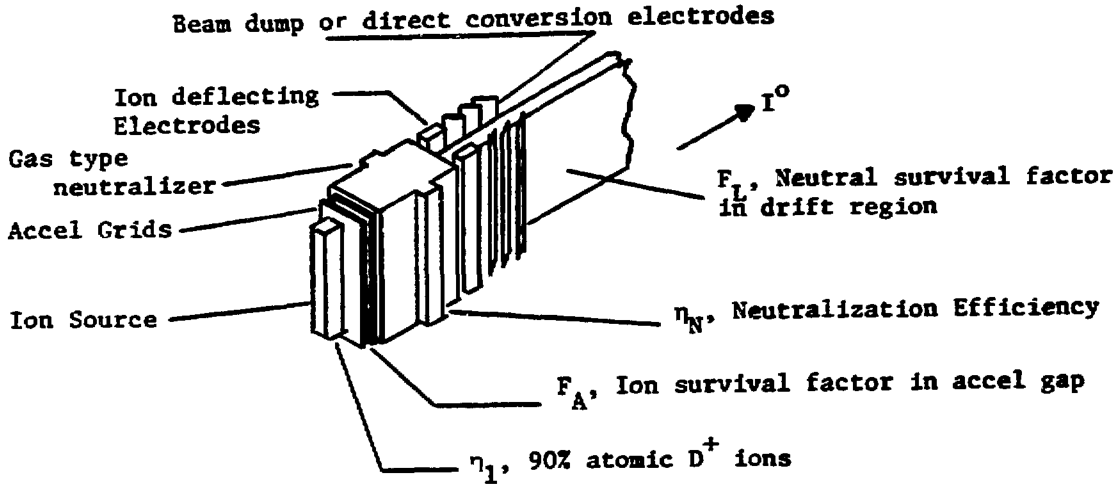

Fig. 3: Neutral beam line based upon positive ions.

TABLE 2

Positive Ion Source, Fig. 3

V_0	50 kV	75 kV	100 kV	150 kV	200 kV	Reference
η_1	.90	.90	.90	.90	.90	Assumption
F_A	.96	.93	.92	.91	.91	Ref. 6
η_N	.74	.62	.48	.29	.21	Ref. 6
F_L	.95	.95	.95	.95	.95	Ref. 6
η_R	0	0	0	0	0	Assumption
ζ without recovery	.56	.47	.36	.21	.16	Eq. 19
η_R	.75	.75	.75	.75	.75	Assumption
ζ without recovery	.68	.62	.53	.38	.30	Eq. 19

Assumptions:
- K_s = 2.5 MW/A ion source efficiency
- ζ_s = 90%, ion source power supply efficiency
- ζ_A = 95%, accel power supply efficiency

Finally, the fraction of neutrals that make it to the reactor is F_L, as in Equation 12.

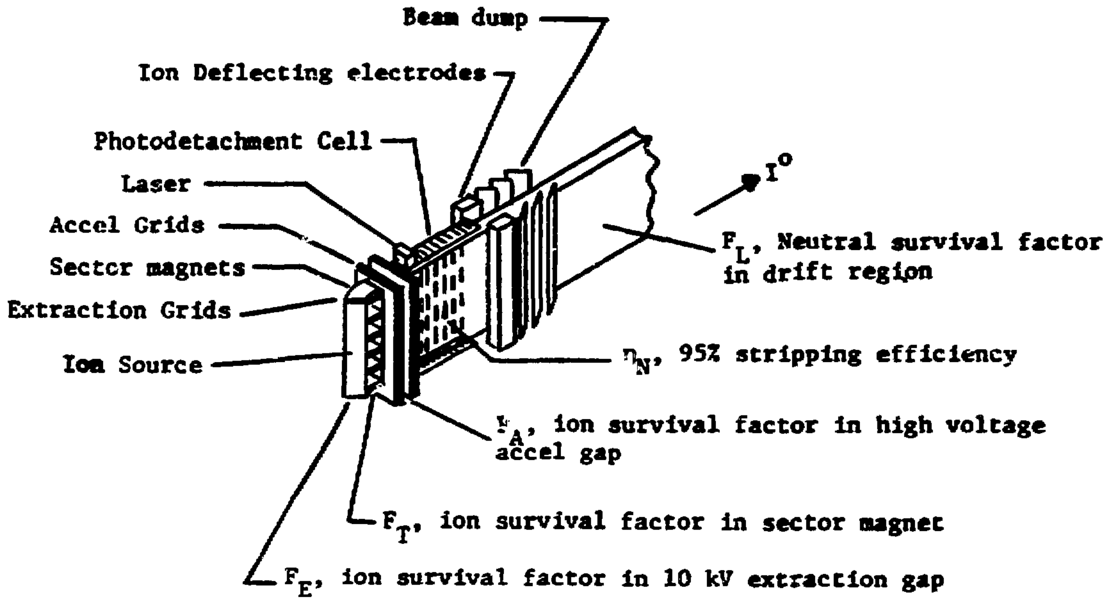

Fig. 4: Neutral beam line based upon negative ions, stripped by photo detachment.

TABLE 3

Negative Ion Source with Photo Detachment, Fig. 4

V_0	50 kV	75 kV	100 kV	150 kV	200 kV	Reference
F_E	.93	.93	.93	.93	.93	Ref. 6
F_T	.77	.77	.77	.77	.77	Ref. 6
F_A	.99	.99	.99	.98	.98	Ref. 6
η_N	.95	.95	.95	.95	.95	Assumption
F_L	.95	.95	.95	.95	.95	Ref. 5
P_p/P_0	.49	.40	.35	.28	.24	Eq. 25
η	.48	.54	.58	.62	.65	Eq. 26

Assumptions:
- K_s = 5 kW/A: ion source efficiency
- η_s = 90%. ion source power supply efficiency
- η_A, η_E = 95%. extractor and accel power supply efficiency
- V_E = 10 kV. extraction voltage
- α = .5. ratio extracted electron to negative ion current.

The power need of the source is as shown in Equation 13. For the negative ion source let K_S = 5 KW/A and:

$$I_E/I_0 = \left(F_E\, F_T\, F_A\, \eta_N\, F_L\right)^{-1} \tag{23}$$

Using photo detachment let the stripping efficiency, η_N = 95%.

The power need of extraction and acceleration is:

$$P_A/P_0 = \frac{1}{\eta_A V_0}\left[V_E(1+\alpha) + (V_0 - V_E)\, F_E F_T\right] . \tag{24}$$

in which the efficiency of the extraction power supply is taken to be the same as that of the high voltage power supply, i.e. η_A = .95.

In the above the current of electrons that is extracted along with the negative ions is equal to a fraction, α of the extracted ion current, I_E. In the following α is taken to be .5.

Finally, the power need of the photo detachment cell[6,7] is:

$$P_p/P_0 = \frac{6.5 \times 10^3 (1-R)}{J_A\, T_G S\, V_0^{\frac{1}{2}}\, \eta_N\, F_L}\, \lambda_n \left[\frac{1}{1-\eta_N}\right] \tag{25}$$

In the above, the laser which excites the photo detachment cell is assumed to work at an efficiency, η_L = 1.5%, the mirrors along the edges of the cell have a reflectivity, R = 99.9%, and the separation between mirrors is S = 250 cm. The negative ion current density entering the cell is J_A = 0.1 A/cm², through a grid of transparency, T_G = 50%.

The injector efficiency is:

$$\eta = \frac{F_E\, F_T\, F_A\, \eta_N\, F_L}{\text{[illegible]}} \tag{26}$$

The results are shown in Table 3 and plotted in Fig. 5.

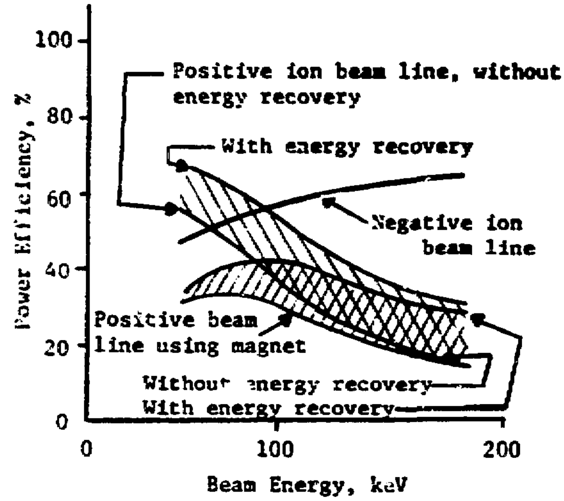

Fig. 5: Beamline power efficiencies.

VI. Beam Divergence

The ions originate from a slotted grid structure, which is curved to form a focus at point 0 in the focal plane, as shown in Fig. 6.

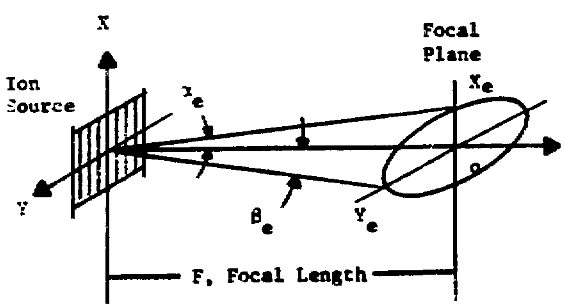

Fig. 6: Beam optics.

In the focal plane the beam is assumed to have a gaussian current distribution over all radii. Thus, if X_e is the radius in the focal plane, parallel to the grid slots, that corresponds to a beam current density which is 1/e times the peak axial value at point 0, and Y_e is the corresponding radius, normal to the grid slots, the focus of points at which the current density is 1/e times the peak value is:

$$(X/X_e)^2 + (Y/Y_e)^2 = 1, \qquad (27)$$

and the beam current density throughout the focal plane is:

$$J = \hat{J}_0 \exp \left| \left(X/X_e\right)^2 + \left(Y/Y_e\right)^2 \right| \qquad (28)$$

The peak current density, $\hat{J}_0$ is found by integrating the above over the entire focal plane, thus:

$$\hat{J}_0 = \frac{I_0}{\pi F^2 \alpha_e \beta_e} \quad \text{A cm}^{-2} \qquad (29)$$

in which F is the focal length, and the beam angles are

$$\alpha_e = X_e/F \qquad (30)$$

$$\beta_e = Y_e/F \qquad (31)$$

Data from the analysis of neutral beams formed from positive ions extracted via slotted grids show the beam angles to be relatively constant over an energy range from 20 to 120 keV. α_e and β_e are approximately .5° and 1.5°, respectively.

Theoretically, these angles should be a function of the ion temperature in the source, and they should vary inversely with the square root of the beam energy. That the angles do not behave this way, is indicative of some other factor, (such as the grid design or the interaction of the beam with the background plasma in the neutralizer) taking a dominant role in control of the beam divergence. Unfortunately, we do not know what causes the descrepancy, and we have no comparative data for negative ion beam lines.

Early measurements of the emittances of negative ion beams indicated that they were considerably larger than those of positive ion beams. More recent measurements however, indicate that they are not much more than two times larger.[3] Obviously, considerable work must be done in this field, not only to improve the emittance of negative ion beams, but to understand the process and to improve the positive ion beam angles, as well.

There is no basic reason why the emittance of a neutral beam formed from negative ions should be worse than one originating as a positive ion beam, in fact negative ions might form more favorable neutral beams, because the beam-plasma interaction in a photodetachment cell should be considerably less than that in a gas neutralizer.

VII. Beam Packaging

A well-designed neutral beam injector will provide a maximum neutral current from the smallest possible assembly. To form a compact, high current unit, the component beam lines must be mounted closely together. But the packaging is limited by the need to keep each beam line electrically isolated from its neighbors. In the event of a beam line failure, the voltage in each beamline may have to be turned off and allowance made to permit the remaining beam lines to continue operation.

Geometric considerations make it desirable to operate the ion sources at high voltage. This makes the water and electrical connections more complicated as they must be designed for remote operation. However it eliminates the extra space needed between beamlines to insulate the adjacent neutralizer cells, which are at high voltage, if the ion sources are at ground.

In this study, the ion sources are assumed to be at high voltage, mounted in grounded enclosures as shown in Fig. 7, with the neutralizer at ground.

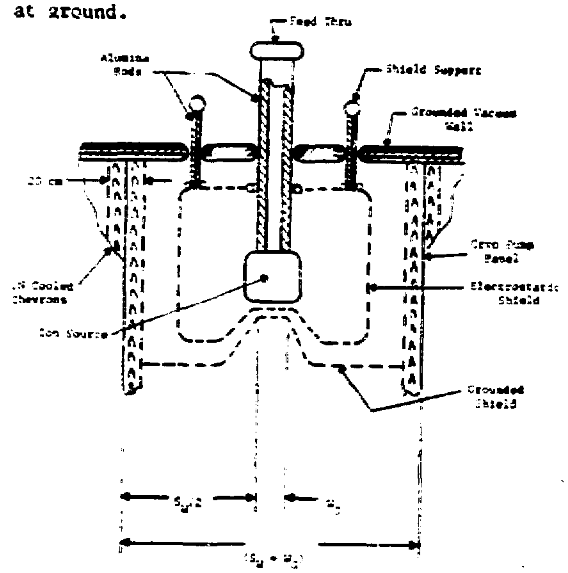

Fig. 7: Ion source housing.

A configuration of stacked ion sources is shown in Fig. 3. W_G and H_G represent the active width and height of each grid, while S_W and S_H are the corresponding grid to grid spacings. From the figure it can be seen that the neutral current output per unit area of stacked ion sources is:

$$j^o_{A\Gamma} = \frac{J_E T_G W_G H_G (I_0/I_E)}{(W_G + S_W)(H_G + S_H)} \qquad (32)$$

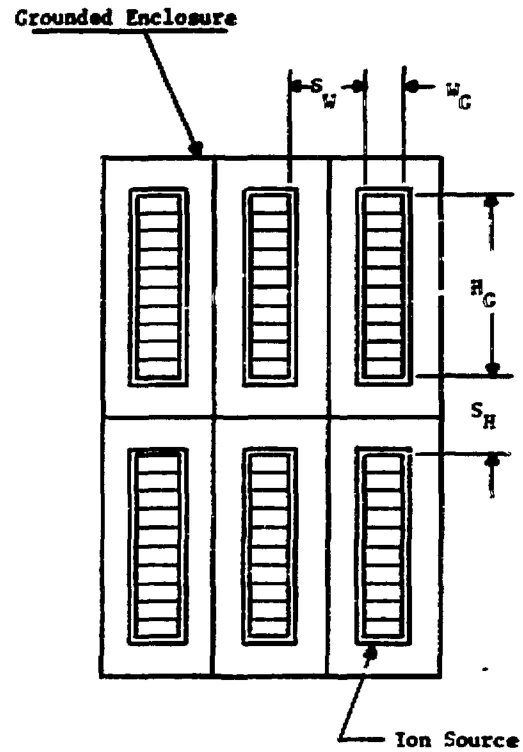

Fig. 8: Stacked ion sources.

Obviously, the most advantageous packaging results from the ion source with the largest emitting area. But the ion source dimensions are restricted by practical considerations. With a slotted grid, the grid width is limited by the ability of each grid rail to remove heat. Consistent with positive ion source design, it is assumed that the grid width, W_G is 12 cm.

The maximum tolerable source length, assuming the grids are built up out of smaller sections, depends upon what can be handled remotely, provided the energy stored in the high voltage electrodes is not excessive. I assume that a source 250 cm in length will be acceptable.

Calculated estimates[5] of the energy stored in the shield and grid structure of sources delivering current densities equal to .25 and .1 A cm^{-2} are plotted in Fig. 9. They appear to be acceptable.

The spacing between sources is determined either by consideration of pumping, high voltage insulation or beam line geometry. The gas load is assumed to be taken care of by placing cryopumps along the grounded walls of the source enclosure. With 4 cm on each side of the grid to the edge of the ion source, 20 cm for the double sided cryopanel shown in Fig. 7, the minimum allowable grid to grid spacing, as determined by voltage insulation is:

$$S_E = (2S + 2\ Vo/E_F) \qquad (33)$$

in which the average field between electrodes, E_F = 20 kV/cm.

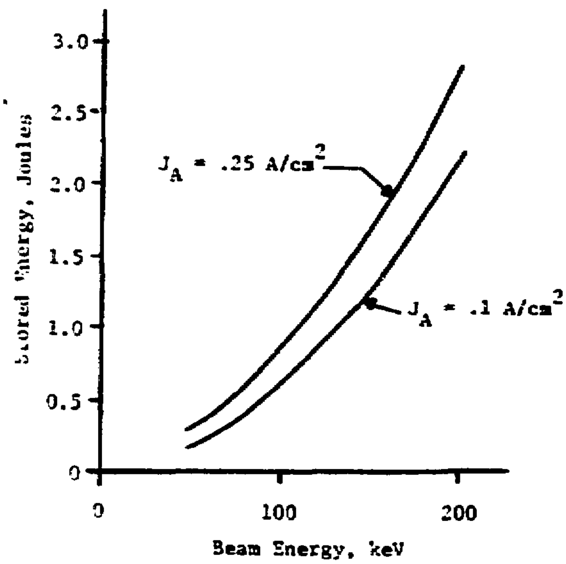

Fig. 9: Estimates of energy stored between grids and shields.

The geometric constraints of spacing are shown in Fig. 10. With a focal length, F and a clearance length, L_W between beam lines, the spacing between sources in a direction parallel to the grid slots is:

$$S_W = \left(\frac{5FL_W}{F-L_W}\right) \alpha_e \quad . \qquad (34)$$

while the spacing in the direction perpendicular to the slots is:

$$S_H = \left(\frac{5FL_H}{F-L_H}\right) \beta_e \quad . \qquad (35)$$

Values of spacings, S_E, S_W, and S_H are shown plotted in Fig. 11 for F = 1000 cm, L_W = 400 cm and L_H = 200 cm; for α_e and β_e equal to .5 and 1.5° over the full range of energy, and for the theoretical case where they vary inversely with the square root of the beam energy. It is evident that the separation between grids must satisfy S_E per Equation 33 in all cases.

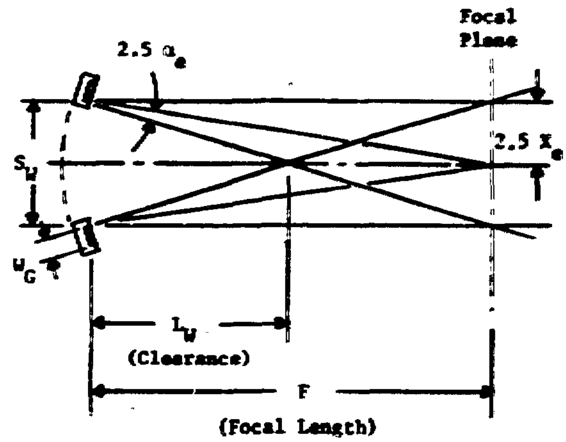

Fig. 10: Beam line geometry.

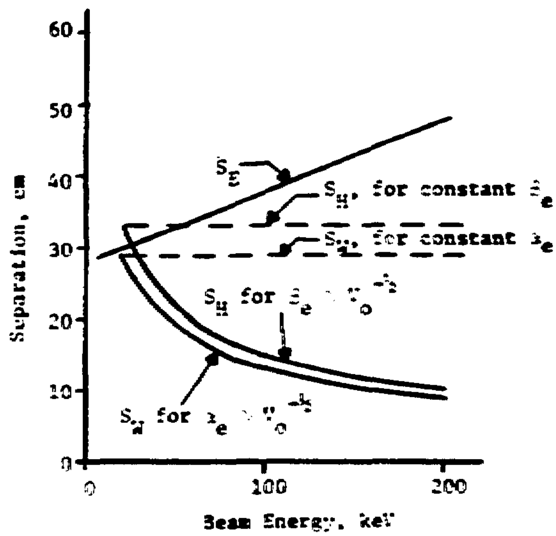

Fig. 11: Separation between grids.

Values of the neutral current output unit area of stacked ion sources are shown in Fig. 12. For the positive ion sources, J_A = .25 A/cm² and T_G = .4, while for the negative ion source, J_A = .1 A/cm² and T_G = .5. The ratio I_0/I_B was taken from Equations 14 and 23.

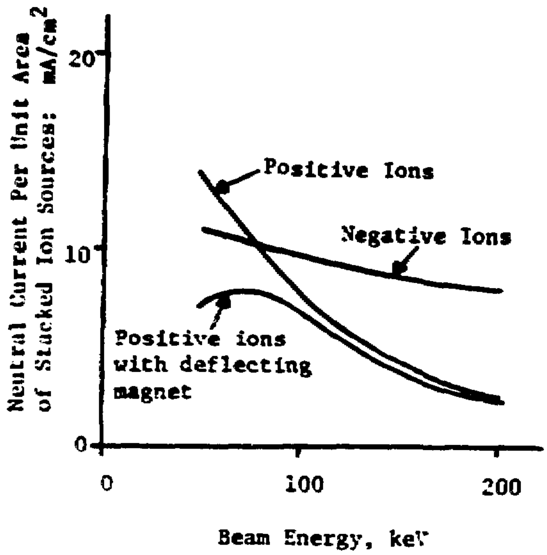

Fig. 12: Neutral current per unit area of stacked ion sources

VIII. Conclusion

The direct extraction sources of negative ions[8] have started a trend of development that will lead to neutral beam injectors of higher efficiency and smaller size than was previously envisioned. In regards to the six advantages that positive ions had over low energy negative systems, it now appears that:

a) The efficiency of negative ion sources has improved to the point where they can be effectively used in low energy beam lines.

b) With good pumping designs, negative ion losses need not be worse than the positive ion losses in today's systems.

c) Negative ion sources can now be designed with gas efficiencies that are as much as one-third to one half that of positive ions.

d) Taking advantage of the anticipated development of photo detachment, negative ion systems will have better operating efficiencies than those of positive ions - over a broad range of beam energies.

e. Neutral beams formed from negative ions will have divergences that at least will be of the same order of magnetude of those obtained from positive ions.

f. The output of neutrals from an injector based upon negative ions will be competative with one of equal size based upon positive ions over a broad range of beam energies.

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