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Neutral-Beam Injectors for 1990 and 2005

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April 1, 1981

Lawrence
Livermore
National
Laboratory

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J. H. Fink*

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ERRATA

Please note the following corrections in your copy of UCRL-53112:

Page 10

The illustrations, but not the captions, for Figures 4 and 5 should be reversed.

Page A6

The illustration as shown for Figure A5 should be removed and replaced with the graph shown in the corrected Figure 5 on Page 10.

W. C. Shissler, Editor
Technical Information Department

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Neutral-Beam Injectors for 1990 and 2005

ABSTRACT

Anticipated developments in neutral-beam technology are described. Particular attention is given to gas efficiency, power efficiency, beam optics, and injector size. It is concluded that negative-ion sources can be made to operate with gas efficiencies in excess of 10%, while negative-ion neutral-beam injectors, using D_2 gas stripping cells, will operate at power efficiencies of roughly 50% in ten years. Twenty-five years from now, negative-ion neutral-beam injectors, using photodetachment, will operate at efficiencies approaching 70%.

1.0 INTRODUCTION

Ongoing studies of new reactor concepts require continuous reevaluation of future neutral-beam performance. Just as reactor designs for 1990 anticipate progress in fusion research during the next decade, neutral-beam injectors should reflect advances in their technology. Similarly, reactor designs for 2005 should be based upon what neutral-beam performance will be at that time. To make these studies creditable, the prospect of future advances in all related fields must be considered.

Obviously it is impossible to schedule or even predict inventions. Extrapolation of past progress will provide the criteria needed to predict the technological progress that can be anticipated for the future. In this paper, two criteria are used. I assume that any currently funded project will have been successfully concluded by 1990. By the year 2005, all the beam projects that I can conceive of, will have been completed.

Accordingly, I expect that by 1990 negative-ion beamlines will have been demonstrated and positive-ion sources, delivering 90% atomic ions, will be "state-of-the-art". By then, direct conversion of energy by unneutralized ions should be standard practice.

Twenty-five years from now injectors need not be bound by today's technological limits. However, they must be founded on sound principles of physics. They will probably be composed of units that are unfamiliar to us today. In fact, to be acceptable in an advanced reactor study, an injector should be based on a plausible, if not tenuous concept. No one knows what will be accomplished in the next quarter century, and today's designers of future systems must be free to "conceptualize".

An overly conservative attitude toward future components can be harmful. Acceptable reactor concepts might be rejected for want of appropriate engineering development. With this in mind I assume that neutral beamlines, formed of negative ions and stripped by photodetachment, will be available by the year 2005.

Four neutral beamline characteristics are discussed:

- (1) gas efficiency,
- (2) operation efficiency,
- (3) beam optics, and
- (4) neutral-beam injector design.

2.0 GAS EFFICIENCY

In this section we discuss gas efficiency, its significance, and how it can be improved by source designers.

As defined, gas efficiency corresponds to that fraction of deuterium atoms that enter an ion source as room temperature gas to leave it as part of the extracted-ion beam. It is an important parameter because it establishes the pumping load along the neutral beamline.

Knowing I_E , the extracted-ion beam current, and η_1 , η_2 , and η_3 its molecular composition (corresponding to the fractions of D_1 , D_2 , and D_3 in the beam), we can compute Q_B , the (300 K) D_2 gas flow equivalent to the ion beam from Eq. (1):

$$Q_B = 0.1(\eta_1 + 2 \eta_2 + 3 \eta_3) I_E \quad . \quad (1)$$

where Q_B is in Torr liter. $\cdot$ s $^{-1}$.

The D_2 gas flow into the source Q_{in} , operating at gas efficiency ξ_G , is calculated from Eq. (2):

$$Q_{in} = Q_B / \xi_G \quad . \quad (2)$$

where Q_{in} is in Torr liter. $\cdot$ s $^{-1}$.

The difference between Eqs. (1) and (2) represents the quantity of gas Q_p that flows out of the source, to be pumped away along the beamline, i.e.:

$$Q_p = Q_B F_p \quad , \quad (3)$$

where Q_p is in Torr liter s^{-1} . The pumping factor F_p is calculated in Eq. (4):

$$F_p = 1/\xi_G - 1 \quad (4)$$

Values of the pumping factor are shown as a function of gas efficiency in Fig. 1. At a gas efficiency of 30%, the pumping factor is 2.3. However, at a gas efficiency of 10%, the pumping factor is 9 (3.8 times greater), and at a gas efficiency of 3%, the pumping factor is 32.3 (almost 14 times larger than that at the gas efficiency of 30%). Thus, the advantages of an ion source with a high gas efficiency result from the reduction of the quantity of gas that needs to be pumped away.

By means of crude approximations we can determine some factors of source design that are critical to good gas efficiency. Consider a positive-ion source delivering a beam of predominantly D_2^+ ions at a current density of J_E through an aperture of area A_s . The atom flow rate Γ_B in the beam is

FIG. 1. Pumping factor as a function of gas efficiency.

$$\Gamma_B = 2 J_E A_s / e \quad , \quad (5)$$

where Γ_B is measured in $\text{atoms} \cdot \text{s}^{-1}$.

With a D_2^+ ion density n_i and an electron temperature T_e in the source plasma, the extracted ion-current density J_E is:

$$J_E = 0.4 n_i e (kT_e / M)^{1/2} \quad , \quad (6)$$

where J_E is measured in $\text{atoms} \cdot \text{cm}^{-2}$.

Through the same aperture, the flow of gas Γ_G conveys neutral deuterium atoms at a rate corresponding to:

$$\Gamma_G = 0.5 n_0 (kT_0 / M)^{1/2} A_s \quad , \quad (7)$$

where Γ_G is measured in $\text{atoms} \cdot \text{s}^{-1}$, n_0 is the neutral D_2 gas density, and T_0 is the neutral D_2 temperature in the source plasma.

Because the flow of atoms into the source equals the flow of atoms out of it, the gas efficiency ξ_G in percent, as previously defined, is:

$$\xi_G = \Gamma_B / (\Gamma_B + \Gamma_G) \quad . \quad (8)$$

whereby

$$\xi_G = 1 + 0.6 (T_0 / T_e)^{1/2} (n_0 / n_i)^{-1} \quad . \quad (9)$$

But the fraction of ionization in the source plasma is $\xi_i = n_i / (n_i + n_0)$, therefore:

$$\xi_G = 1 - 0.6 (T_0 / T_e)^{1/2} (1 - \xi_i)^{-1} \quad . \quad (10)$$

Provided the temperatures do not change too much, gas efficiency of a source can be improved by increasing the fraction of ionization of the source plasma.

The gas efficiency of a negative ion source can be analyzed in a similar manner. Because negative ions are predominantly atomic, the atom flow Γ_B in a negative-ion beam in $\text{atoms} \cdot \text{s}^{-1}$ is

$$\Gamma_B = J_E A_s / e \quad . \quad (11)$$

From Eqs. (7) and (8), the gas efficiency G is

$$\xi_G = [1 + (n_0 e v_0 / 2 J_E)]^{-1} . \quad (12)$$

In a direct extraction source of negative ions, using a plane electrode to form negative ions, see Fig. 2(a), positive ions from the discharge region are accelerated across the plasma sheath to bombard the cesium-coated negative-ion-forming electrode, Ref. (1).

As the ions approach the electrode, they become neutralized. Some fraction of the neutrals backscatter, impact with the negative-ion-forming electrode, to become negative by means of tunneling electrons departing from the low work-function, cesium-coated surface. The plasma sheath now accelerates the newly formed negative ions toward the anode.

Because sources, built as shown in Fig. 2(a), have been found to operate at gas efficiencies of roughly 1%, we find from Eq. (12) that

$$(n_0 e v_0 / 2 J_E) \sim 99 . \quad (13)$$

More advanced sources use curved negative-ion-forming electrodes as shown in Fig. 2(b). The curvature serves to focus the backscattered negative ions into the anode aperture. Assuming the discharge plasma to be the same as it

FIG. 2. Direct extraction sources with (a) plane electrode and (b) curved electrode.

was in Fig. 2(a), the negative-ion current in the aperture will increase by a factor γ equal to the ratio of the curved area of the negative-ion-forming electrode to the area of the anode aperture.

The gas efficiency of the new source is roughly

$$\xi_G = \left(1 + \frac{1}{\gamma} \cdot \frac{n_0 e v_0}{2 J_E} \right)^{-1} . \quad (14)$$

For $\gamma = 3$, $\xi_G = 3\%$, $\gamma = 10$, and $\xi_G = 9\%$. This assumes that the ion temperatures, the ratio of positive ions to neutrals, and the production efficiency with which the negative ions are formed from positives are the same as before.

Although this is a crude approximation, it does show that with today's technology, an ion-source designer has some control over the ion-source gas efficiency. For a more detailed discussion, see Ref. (2).

3.0 OPERATING EFFICIENCY

In this section, the performance of 1990 positive-ion injectors, with or without direct conversion, are compared with negative-ion injectors of two different designs. Negative-ion systems with photodetachment are considered for the year 2005.

Considerable attention is given to the Lawrence Berkeley Laboratory (Ref. 3) and the Brookhaven National Laboratory (Ref. 4) negative-ion beamlines. Information on the Oakridge National Laboratory negative-ion beamline is included as Appendix A to this report. These are leading contenders for DOE funding and it is likely that the 1990 designs and possibly those of the year 2005 will be based on the most promising system of the three.

Both laboratories have chosen sources using negative ions formed from positive ions that are backscattered off curved, cesium-coated metal surfaces. LBL has negative-ion-forming electrodes inserted into a discharge that is sustained by tungsten-filament cathodes and confined by cusped magnetic fields at the anode walls. BNL employs an asymmetric magnetron with a grooved cathode to generate negative ions. Although the mechanism that forms the negative ions is the same in both sources, the nature of the discharges and the concepts of ion transport, acceleration, and removal of unwanted electrons from the D^- beam are very different. LBL takes advantage

of this cusp magnetic field and plans to adjust the plasma potential to retard the flow of low-energy electrons from the source. The high-energy negative ions pass through openings in the discharge wall, crossing the cusped field, to enter the high-voltage accelerator.

At BNL, negative ions are accelerated away from the source by a low-voltage extractor and subsequently transferred to the high-voltage accelerator by a sector magnet. The extractor is designed to minimize the electron current flowing with the negative-ion beam. Nevertheless, some electrons intercept the extractor grids while the remainder are separated from the ion beam by the sector magnet prior to high-voltage acceleration.

Beyond the high-voltage accelerator, both the LBL and BNL beamlines are the same. They both include stripping cells (Ref. 5) and electrostatic deflectors with beam dumps to remove ions remaining with the neutral beam. See Figs. 3 and 8.

3.1 LBL BEAMLINE EFFICIENCY

To evaluate the efficiency of a neutral-beam injector, it is necessary to determine the input power required to sustain the desired neutral-beam output. Figure 3 shows a schematic diagram of a neutral-beam injector based

FIG. 3. Schematic diagram of a neutral-beam injector based on a LBL negative-ion accelerator.

on the LBL negative-ion source and accelerator. Both the filament and arc-voltage power supplies are needed to operate the ion source, along with a high-voltage power supply for the accelerator stage. Additional power is needed for magnets, pumps, and various other services, but this is of minor significance when the overall injector efficiency is considered. However, the power required for a plasma stripper or photodetachment cavity might be significant. The power requirement of the ion-deflection circuit is small and the power to operate a gas cell is negligible.

The power output P_0 (i.e., $I_0 V_0$) of a neutral-beam injector, which delivers I_0 amperes of neutrals at an energy of V_0 volts, requires an input power consisting primarily of P_S watts for the ion source and P_A watts for the high-voltage accelerator. The injector efficiency ξ in percent is then:

$$\xi_{\text{LBI}} = P_0 / (P_S + P_A) \quad . \quad (15)$$

Ion-source performance is often described in terms of the ratio of power consumed by the source to the extracted ion current. Accordingly, the performance rating $\overline{PR}$ in $\text{kW}\cdot\text{A}^{-1}$ is as follows:

$$\overline{PR} = (P_{\text{FIL}} + P_{\text{ARC}}/I_E) \quad , \quad (16)$$

where P_{FIL} is the input power to heat the filaments and P_{ARC} is the input power to operate the arc in watts and I_E is the ion current delivered by the source in amperes.

Assuming the efficiencies of the filament and arc voltage power supplies to be approximately the same and represented by the value ξ_S , the power required to operate the source is

$$P_S = I_E (PR/\xi_S) \quad . \quad (17)$$

The power needed to operate the accelerator, assuming a power supply efficiency of ξ_A is

$$P_A = I_E (V_0/\xi_A) \quad . \quad (18)$$

By substituting Eqs. (17) and (18) into Eq. (15), the injector efficiency can be found using Eq. (19):

$$\xi_{\text{LBL}} = \frac{I_0 / I_E}{\frac{PR}{\xi_S V_0} + \frac{1}{\xi_A}} \quad (19)$$

The ratio I_0/I_E represents the overall efficiency of converting negative ions into neutrals. In the LBL beamline this can be approximated by the product of three factors. The first, F_A , is the fraction of negative ions that are not stripped of electrons (by collision with background gas molecules) in the acceleration stage; the second, η_N , is the neutralization efficiency of the gas stripping cell; and the third, F_L , is the fraction of neutrals that escape ionizing collisions as they travel from the stripping cell into the reactor. This is shown by

$$I_0/I_E = F_A \eta_N F_L \quad (20)$$

and

$$\xi_{\text{LBL}} = \frac{(F_A \eta_N F_L)}{\frac{PR}{\xi_S V_0} + \frac{1}{\xi_A}} \quad (21)$$

The stripping efficiency η_N in Eq. (21) is found for D^- in Fig. 4. As a function of beam energy, it is equal to the optimum value η_0 .

Figure 5 shows a schematic of the LBL negative-ion source and accelerator. As a result of collisions in the accelerator stage, some fraction of the negative ions become stripped of their electrons at energies less than the desired value V_0 . Most of these low-energy neutrals become reionized before they make a useful contribution to the reactor plasma. Hence, they constitute a loss to the primary beam.

The fraction of extracted ions entering the acceleration stage that exit at full energy is

$$F_A = \left(1 - n_A \int \sigma_{-10} dZ \right), \quad (22)$$

FIG. 4. Optimum neutralization efficiency in D₂ as a function of ion energy for D⁺, D₂, D₃, and D⁻ beams (Ref. 6).

FIG. 5. Schematic of the LBL negative-ion source and accelerator.

in which n_A is the background gas density, σ_{-10} the stripping cross section in D₂ gas (a function of the beam energy as shown in Fig. 6), and Z the ion path through the acceleration stage.

The background density, mentioned above, is estimated by assuming the gas temperature is 300 K and the gas pressure is at some average value P_A . Then the background gas density in cm⁻³ is

$$n_A = (3.3 \times 10^{16}) P_A \quad (23)$$

FIG. 6. Deuterium charge-exchange cross sections (Refs. 5, 6).

Since the extracted ion current density J_A can be approximated by Child's law for a planar geometry, we find

$$J_A = (q V^{3/2})/Z^2, \quad (24)$$

where J_A is in $A\ cm^{-2}$, $q = 3.85 \times 10^{-8}\ A\ V^{-3/2}$ (the perveance of a D^+ beam), and V is the potential at a distance Z along the ion path.

Taking the derivative of Eq. (24) and introducing the result, along with the substitution of Eq. (23) into (22), results in:

$$F_A = \left[1 - (4.9 \times 10^{12}) p_A J_A^{-1/2} A_{-10} \frac{V_0}{0} \right], \quad (25)$$

where

$$A_{-10} \left| \frac{V_0}{0} \right| = \int_0^{V_0} (\sigma_{-10} V^{-1/4}) dV, \quad (26)$$

and the values of A_{-10} , obtained by graphical integration, are shown in Fig. 7.

Finally, the fraction of the neutral beam F_L that does not ionize by collisions with the background gas and therefore enters the reactor is

FIG. 7. Values of the integral $A_{-10} = \int (\sigma_{-10} v^{-1/4}) dv$ for negative deuterium ions.

$$F_L = \left[1 - (3.3 \times 10^{16}) p_L \sigma_{01} Z \right], \quad (27)$$

where p_L is the average pressure, σ_{01} the ionization cross section (given in Fig. 5), Z represents the corresponding neutral-beam path length, and 300 K is the assumed background gas temperature in the region between the neutralizer and the reactor.

Calculated values of the LBL injector performance are shown in Table 1 as a function of beam energy. The source is rated at 2.5 kW/A, with a power supply efficiency that is only 90% due to the large I^2R losses encountered in the high-current, low-voltage circuits. The high-voltage power supply is assumed to operate at 95% efficiency. No allowance is made for the large voltage drop and poor efficiency of today's switching tubes. It is expected that future power supplies will be unregulated, have low voltage drops, and solid-state switches.

The low operating pressure of the source, about 10^{-3} Torr, limits the maximum extracted current density to 0.02 A cm^{-2} .

In the region between the stripping cell and the reactor, assuming an average pressure p_L of 10^{-5} , an ionization cross section σ_{01} at its maximum value of $1.4 \times 10^{-16} \text{ cm}^2$, and a path length Z of 1000 cm, the loss of neutrals is about 5%, whereby F_L is 95%.

FIG. 6. Deuterium charge-exchange cross sections (Refs. 5, 6).

Since the extracted ion current density J_A can be approximated by Child's law for a planar geometry, we find

$$J_A = (q v^{3/2})/Z^2, \quad (24)$$

where J_A is in $A\ cm^{-2}$, $q = 3.85 \times 10^{-8}\ A\ v^{-3/2}$ (the perveance of a D^- beam), and V is the potential at a distance Z along the ion path.

Taking the derivative of Eq. (24) and introducing the result, along with the substitution of Eq. (23) into (22), results in:

$$F_A = \left[1 - (4.9 \times 10^{12}) p_A J_A^{-1/2} A_{-10} \begin{vmatrix} v_0 \\ 0 \end{vmatrix} \right], \quad (25)$$

where

$$A_{-10} \begin{vmatrix} v_0 \\ 0 \end{vmatrix} = \int_0^{v_0} (\sigma_{-10} v^{-1/4}) dv, \quad (26)$$

and the values of A_{-10} , obtained by graphical integration, are shown in Fig. 7.

Finally, the fraction of the neutral beam F_L that does not ionize by collisions with the background gas and therefore enters the reactor is

FIG. 7. Values of the integral $A_{-10} = \int (\sigma_{-10} v^{-1/4}) dv$ for negative deuterium ions.

$$F_L = \left[1 - (3.3 \times 10^{16}) p_L \sigma_{01} Z \right], \quad (27)$$

where p_L is the average pressure, σ_{01} the ionization cross section (given in Fig. 5), Z represents the corresponding neutral-beam path length, and 300 K is the assumed background gas temperature in the region between the neutralizer and the reactor.

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TABLE 1

	V ₀ , units								kV	Reference
	50	75	100	150	200	300	400			
PA, Torr.										
J _A , A cm ⁻²										Fig. 4
A-10, 10 ⁻¹³ cm ² v ³ /4										Assumption
F _A , %										Fig. 6
										Eq. 25
η _N , %										Fig. 7
F _L , %										Assumption
ξ _{LBL} , %										Eq. 21

Additional assumptions:

$$\frac{PR}{A} = 2.5 \text{ kW/A}$$

$$\xi_{es} = 90\%$$

$$\xi_A = 95\%$$

$$T_{GAS} = 300 \text{ K}$$

3.2 BNL BEAMLINE EFFICIENCY

Figure 8 shows a schematic diagram of the BNL neutral-beam injector. The equation, for its efficiency, similar to Eq. (15) for LBL, is

$$\xi_{\text{BNL}} = P_0 / (P_S + P_E + P_A) \quad (28)$$

In Eq. (28), the power input to the source P_S is the same as shown in Eq. (17). However, in contrast to Eq. (16), the performance rating of the BNL ion source, which has no filament, is

$$\overline{\text{PR}} = P_{\text{arc}} / \xi_S \quad (29)$$

FIG. 8. Schematic diagram of a neutral-beam injector based on a BNL negative-ion source and accelerator.

In Eq. (28), P_E represents the power spent to operate the ion extractor at a potential V_E . With the power supply operating at an efficiency ξ_E , this term is

$$P_E = (I_E + I_e) V_E / \xi_E, \quad (30)$$

where I_e is the current of electrons accelerated along with the current of negative ions I_E .

Let α be the fraction of the extracted negative-ions current equal to the electron current. Equation (30) can then be written as:

$$P_E = (1 + \alpha) I_E V_E / \xi_E. \quad (31)$$

When the ions arrive at the high-voltage accelerator stage, the electrons are gone from the beam, having been removed during transit through the sector magnet. Thus, the power spent at the high-voltage accelerator stage, P_A in Eq. (28), is used to accelerate only negative ions from their extracted energy V_E up to their final energy V_0 . Because the extracted current of negative ions has been reduced by a factor F_E (due to electron stripping in the low-voltage accelerator stage) and by a factor F_T (resulting from stripping during transit through the sector magnet), the power needed for acceleration becomes:

$$P_A = I_E F_E F_T (V_0 - V_E) / \xi_A. \quad (32)$$

Taking account of all the factors along the beamline that cause a reduction in beam current, the overall conversion efficiency of negative ions into neutrals in the BNL injector, in contrast to the LBL beamline, Eq. (20) is

$$I_0/I_E = F_E F_T F_A \eta_N F_L. \quad (33)$$

Substituting Eqs. (17), (31), (32), and (33) into (28), results in the following expression for the efficiency of the BNL neutral-beam injector:

$$\xi_{BNL} = \frac{F_E F_T F_A \eta_N F_L}{\frac{PR}{\xi_E V_0} + (1 + \alpha) \frac{V_E}{\xi_E V_0} + \frac{F_E F_T}{\xi_A} \left(1 - \frac{V_E}{V_0}\right)}. \quad (34)$$

A schematic of the BNL negative-ion source, extractor stage, sector magnet, and accelerator stage is shown in Fig. 9. Following the same reasoning which led to the derivation of Eq. 25 for the LBL beamline, it can be shown that the fraction of the extracted negative-ion current, which survives passage through the low-voltage accelerator stage, is:

$$F_E = \left[1 - (4.9 \times 10^{12}) p_E J_E^{-1/2} A_{-10} \left| \frac{V_E}{0} \right| \right], \quad (35)$$

where the values of A_{-10} are taken from Fig. 6.

The ion loss due to electron stripping as the beam passes through the sector magnet is:

$$\delta_L = n_T \sigma_{-10} Z_T, \quad (36)$$

where n_T is the average background gas density, σ_{-10} is the stripping cross section appropriate to the beam energy as shown in Fig. 5, and Z_T is the beam-path length through the sector magnet. Consequently, the factor

FIG. 9. Schematic of the BNL source, extractor, sector magnet, and accelerator stage.

representing the fraction of ions that did not suffer charge exchange in the sector magnet is:

$$F_T = \left[1 - (3.3 \times 10^{16}) p_T \sigma_{-10} Z_T \right], \quad (37)$$

in which the background gas at 300 K is assumed to be at an average pressure p_T in Torr.

The factor F_A in Eq. (34) is similar to the one in Eq. (25), except for the A_{-10} term. In the BNL high-voltage accelerator stage the ions enter at the potential V_E and exit at V_0 , while in the LBL unit the ions enter at zero potential. Therefore,

$$F_A = \left[1 - (4.9 \times 10^{12}) p_A j_A^{-1/2} A_{-10} \left| \frac{V_0}{V_E} \right| \right], \quad (38)$$

in which $A_{-10} \left| \frac{V_0}{V_E} \right|$ can be evaluated from Fig. 6, by taking the

difference between $A_{-10} \left| \frac{V_0}{0} \right|$ and $A_{-10} \left| \frac{V_E}{0} \right|$.

The stripping efficiency η_N in Eq. (34) is a function of beam energy. It corresponds to the optimum neutralization η_0 of D^- as shown in Fig. 5. Meanwhile, the fraction of neutrals F_L that enter the reactor is the same as in Eq. (27).

Neutral-beam injector efficiencies based on the BNL negative-ion beamline are tabulated as a function of energy (Table 2). The source performance rating is 7.5 kW/A with a power supply of 90% efficiency. The low-voltage power supply (at 10 kV) and the high-voltage power supply efficiencies were both assumed to be 95%.

Experiments have shown that $0.5 \text{ A}\cdot\text{cm}^{-2}$ of negative ions can be extracted from the BNL source with an additional component of electron current that is about one half that value. As the negative ions travel through the sector magnet, the beam is allowed to expand, while the background gas density is reduced. It is estimated that the high-voltage grid transparency will be about 7%. Thus, the initial extracted current density at $0.5 \text{ A}\cdot\text{cm}^{-2}$ drops off to about $0.040 \text{ A}\cdot\text{cm}^{-2}$ at the high-voltage accelerator stage.

The factor F_L is taken to be 95% for the same reasons as before.

TABLE 2

V ₀ , units		50	75	100	150	200	300	400	Reference
P _E , Torr. J _E , A cm ⁻² A ₀ ⁻¹ , ₀ ^E , 10 ¹³ cm ³ /4 F _E , %		5 × 10 ⁻³						5 × 10 ⁻³	Fig. 9 Assumption
		0.5						0.5	
		20						20	Fig. 6
		93						93	Eq. 35
P _T , Torr. O-10, cm ² Z _T , cm F _T , %		10 ⁻¹⁵						7 × 10 ⁻⁴	Fig. 9 Fig. 5 Assumption Eq. 37
								10 ⁻¹⁵	
								10	
								10	
								77	
P _A , Torr. J _A , A cm ⁻² A ₀ ⁻¹ , ₀ ^E , 10 ¹³ cm ³ /4 F _A , %		10 ⁻⁴						10 ⁻⁴	Fig. 9 Assumption
		0.040						0.040	
		25	32	40	60	70	80	95	Fig. 6
		99	99	99	98	98	98	98	Eq. 38
V _N , % F _L , %		77	67	63	61	60	60	60	Fig. 7 Assumption
		95						95	
ξ _{BNL} , %		48	46	46	47	48	50	51	Eq. 34

Additional assumptions:

$\overline{PR} = 7.5 \text{ kW/A}$
 $\xi_S = 90\%$
 $\xi_E = A = 95\%$
 $\alpha = 0.5$
 $V_E = 10 \text{ kV}$
 $T_{GAS} = 300 \text{ K}$

3.3 POSITIVE-ION BEAMLINE EFFICIENCY

The efficiency of a neutral-beam injector formed from a positive-ion beamline can be readily evaluated. Referring to Fig. 10, we find that

$$\xi_{POS} = P_0 / (P_S + P_A) \quad , \quad (39)$$

in which the power input to the source P_S corresponds to Eq. (17) and the power required for the arc is expressed in Eq. (18).

The first deflecting magnet, as shown in Fig. 10, separates the fraction of the extracted positive-ion beam which is atomic η_1 from its unwanted diatomic and triatomic components η_2 and η_3 . Of the atomic component originating in the source, only some fraction F_T passes through the region before the first deflecting magnet without having become prematurely neutralized by charge exchange with the background gas. A full-energy atomic ion is lost to the beam if it is neutralized before it has reached its final trajectory along which it should travel, as a neutral, to the reactor.

FIG. 10. Schematic diagram of a neutral-beam injector based on a LBL positive-ion source and accelerator.

In contrast to Eq. (20), the overall conversion efficiency, from extracted positive ions to neutrals, is:

$$I_0/I_E = F_A \eta_1 F_T \eta_N F_L . \quad (40)$$

The factor F_T in Eq. (40) is similar to that for negative ions in Eq. (37) and the factor F_L is shown in Eq. (27).

Substituting Eqs. (17), (18) and (40) into Eq. (39), the injector efficiency is:

$$\xi_{POS} = \frac{F_A \eta_1 F_T \eta_N F_L}{\frac{PR}{\xi_S v_0} + \frac{11}{\xi_A}} . \quad (41)$$

The fraction of positive ions extracted from the source that do not become neutralized at partial energies by charge-exchange in the high-voltage stage is:

$$F_A = (1 - n_A \int \sigma_{10} dz) , \quad (42)$$

where the background gas density n_A is as calculated in Eq. (23).

The charge-exchange cross section σ_{10} is a function of beam energy, as shown in Fig. 5, while the derivative of the beam path from Eq. (24), is:

$$dz = \frac{3}{4} (q_+/J_A)^{1/2} v^{-1/4} dv . \quad (43)$$

The perveance of the positive-ion beam, with fractional molecular components of η_1 atomic, η_2 diatomic, and η_3 triatomic ions, is

$$q_+ + (3.85 \times 10^{-8})(\eta_1 + \sqrt{2} \eta_2 + \sqrt{3} \eta_3)^{-1} A v^{-3/2} . \quad (44)$$

Then

$$F_A = \left[1 - (4.9 \times 10^{12})(\eta_1 + \sqrt{2} \eta_2 + \sqrt{3} \eta_3) P_A J^{-1/2} A_{10} \left| \begin{smallmatrix} v_0 \\ 0 \end{smallmatrix} \right. \right] \quad (45)$$

in which:

$$A_{10} \Big|_0^v = \int_0^v (\sigma_{10} v^{-1/4}) dv \quad (46)$$

Values of A_{10} are plotted as a function of the positive-ion beam energy (see Fig. 11). The factor F_T , Eq. (40), is similar to that for negative ions. However, the cross section for positive ions is different: Eqs. (47) and (37).

$$F_T = \left[1 - (3.3 \times 10^{16}) p_T \sigma_{10} Z_T \right] \quad (47)$$

The background gas in Eq. (47) is assumed to be 300 K and the pressure p_T in Torr. The ion path length Z_T is taken from the output side of the high-voltage accelerator stage to a point just beyond the first deflecting magnet where the ions proceed to travel in a straight line into the reactor.

Because the optimum neutralization efficiency for positive ions η_0 , as shown in Fig. 7, are calculated for cells of infinite thickness, we use cells of finite length to obtain a neutralization efficiency η_N that is 95% of η_0 .

The neutralization efficiency of positive ions in a gas cell drops off so rapidly with increased beam energy, that the power efficiency of the high-energy neutral-beam injector, based on positive-ion beams, is very poor. As a result, recovery of the energy of the unneutralized portion of the beam offers an attractive way to improve the injector performance, Ref. (7). When used with the appropriate direct-conversion circuits, energy recovery can greatly reduce the size of the power supply needed for the high-voltage accelerator stage. This results in a sizable reduction in the capital cost of

FIG. 11. Values of the integral $A_{10} = \int (\sigma_{10} v^{-1/4}) dv$ for positive deuterium ions.

the injector, but it does not provide more amperes of neutrals per unit area of source.

Therefore, it is important to reconsider the positive-ion beamline, as shown in Fig. 10, on the assumption that the deflecting electrodes and the ion dump located beyond the neutralizer cell might be replaced by a direct conversion unit with an efficiency of η_R . Under these circumstances, the power needed to operate the high-voltage power supply is reduced by the amount of the recovered power, i.e.:

$$P_A = \left[1 - F_A \eta_1 F_T (1 - \eta_N) \eta_R \right] I_E V_0 / \xi_A, \quad (48)$$

and the neutral injector based on a positive-ion beamline with direct conversion has an efficiency of

$$\xi_{\text{CONV}} = \frac{F_A \eta_1 F_T \eta_N F_L}{\frac{P_R}{\xi_s V_0} + \frac{1}{\xi_A} - \frac{F_A \eta_1 F_T (1 - \eta_N) \eta_R}{\xi_A}}. \quad (49)$$

The results of this analysis of a neutral-beam injector based on a positive-ion beamline is shown in Table 3. The ion source, using filament and arc voltage power supplies of 90% efficiency, is assumed to operate with a performance rating of 2.5 Kw/A. The high-voltage power supply efficiency is 95%. The positive ions, composed of 90% η_1 atomic ions, 7% η_2 diatomic ions, and 3% η_3 triatomic ions, are extracted at a current density of 0.25 A cm⁻². The average pressure in the high-voltage accelerator region is taken to be 2×10^{-2} Torr.

In transit through the deflecting magnet the beam travels about 100 cm before arriving at its final trajectory. The average background pressure in this region is roughly 3×10^{-4} Torr.

As stated earlier, the neutralization efficiency is about 95% of optimum, while 95% of the neutrals leaving the neutralizer are not ionized by impact with the background gas as they travel to the reactor.

Direct conversion, meanwhile, is assumed to make 70% of the energy, carried by atomic ions leaving the neutralizer, available to the high-voltage power supply.

It should be noted, in passing, that the energy recovered in a negative-ion beamline is important in a large injector by virtue of the

TABLE 3

V_0 , units	kV						Reference
	50	75	100	150	200		
P_A , Torr. $\cdot$ 2	2×10^{-2}						Assumption
J_A , A cm^{-2}	$0.25 \xrightarrow{\hspace{1cm}} 0.25$						
$A_{10} I_0$, $10^{-13} \text{ cm}^2 V^{3/4}$	3.0	3.5	3.8	4.2	4.4		Fig. 11
F_A , %	94	93	92	91	91		Eq. 45
P_T , Torr.	3×10^{-4}						Fig. 8
σ_{10} , 10^{-17} cm^2	47	27	17	6	2.5		
Z_T , cm	100	$\xrightarrow{\hspace{1cm}} 100$					
F_T , %	53	73	83	94			
$\eta_N = 0.95 \eta_0$, %	74	62	48	29	21		Fig. 7
F_L , %	95	$\xrightarrow{\hspace{1cm}} 95$					
ξ_{POS} , %	28	33	29	15			Eq. 41
ξ_R , %	75	$\xrightarrow{\hspace{1cm}} 75$					Assumption
CONV	33	45	47	42	35		Eq. 49

Additional assumptions:

$$P_R = 2.5 \text{ kW/A}$$

$$\xi_S = 90 \%$$

$$\xi_A = 95 \%$$

$$\eta_1 = 90 \%$$

$$\eta_2 = 7 \%$$

$$\eta_3 = 3 \%$$

$$T_{\text{GAS}} = 300 \text{ K}$$

additional power it makes available. However, it will not have the same impact on the power efficiency and capital cost to be found in a high-energy positive-ion beamline. This is because the efficiency of the negative-ion beamline is inherently better and the power available for conversion is less. Consequently, power conversion will not make a significant reduction in the size of the high-voltage power supply in a negative-ion beamline.

The unneutralized output of an optimized negative-ion stripping cell can consist of a large fraction of positive ions. While energy recovery from the unstripped negative ions can be used directly to reduce the size of the high-voltage power supply, the output of the positive-ion power conversion unit is of the wrong polarity. It requires additional power conditioning equipment to change the polarity and make it available along the beamline. Schemes have been proposed to alter the design of the stripper to make the unneutralized output either all positive or all negative. These approaches solve the specific problems of voltage holding and power conditioning, but at the expense of stripping efficiency; the neutral current output per source is also reduced. As a result, the advantages of power conversion in a negative-ion beamline are of less significance and are more difficult to evaluate than those in a corresponding positive-ion beamline. Because of the complexity of power conversion in negative-ion beamlines, we will not pursue it any further at this time.

3.4 NEUTRAL-BEAM EFFICIENCY WITH PHOTODETACHMENT

If neutral beams formed from negative ions are sufficiently developed for use in demonstration reactors by 1990, they will also be available for operational reactors in the year 2005. Furthermore, it is not unreasonable to assume that the technology of beam formation and packaging, along with the art of ion acceleration, will have progressed to where beam current densities of 100 mA cm^{-2} can be reliably brought to energies of 400 keV or more.

In this paper, it was found that neutral-beam injectors, using negative ions and gas stripping cells, could be designed to operate at 50% efficiency over a wide range of energies. In other words, taking the reciprocal of the efficiency, an input of two watts is required for every output watt.

Should the efficiency of the stripping cell be changed from the value associated with a gas stripper η_N to a value obtainable with photodetachment η_p , the power required by the beamline would change by the ratio η_N/η_p .

This is because less beam is required to form the same neutral current with a stripping cell of greater efficiency.

To determine the power efficiency of a beamline using photodetachment, we must consider the power P_p required to operate the photodetaching cell. By definition, the reciprocal of the efficiency is the sum of the power input divided by the power output.

Hence,

$$\left[1/\xi_p = (\eta_N/\eta_p) (1/\xi) + P_p/P_0 \right], \quad (50)$$

where P_0 is the neutral beam power, ξ_p is the efficiency of the photodetachment beamline, and the efficiency ξ of the beamline with a gas stripping cell is 50%.

The power required for a photodetachment cell, similar to the one shown schematically in Fig. 12, has been analyzed in Ref (8), i.e.:

$$P_p/P_0 = (6.5 \times 10^3) \left(\frac{1-R}{\xi_L} \right) \left(\frac{v_0^{-1/2}}{J_S} \right) \frac{1}{\eta_p} \log_e \left(\frac{1}{1-\eta_p} \right). \quad (51)$$

FIG. 12. Laser activated photodetachment cell.

Using an appropriate laser with an efficiency ξ_L of 1.0% and mirrors of reflectivity R of 99.9%, a photodetachment cell can be made to operate with a stripping efficiency η_p of 95%. With negative-ion beams of current density $J_- = 0.1 \text{ A}\cdot\text{cm}^{-2}$ and a mirror separation S of 200 cm, the efficiency of an injector using photodetachment is found from Eqs. (50) and (51) to be

$$1/\xi_p = \left(2.11 \eta_N + 99.4 v_0^{-1/2} \right), \quad (52)$$

where η_N is the stripping efficiency of the gas cell used with a negative-ion beam of energy v_0 .

The length of the stripping cell L_s is determined as follows:

$$L_s = (5.9 \times 10^3) \frac{v_0^{1/2}}{\phi} \log_e \left(\frac{1}{1 - \eta_p} \right) \quad (53)$$

in which, the incident energy density ϕ of the light beam in the photocell is assumed to be $60 \text{ kW}\cdot\text{cm}^{-2}$.

Calculated values taken from Eqs. (52) and (53) are presented in Table 4.

A mirror width T of 3 cm and a stripping cell 200-cm wide, with a negative-ion beam of current density $0.1 \text{ A}\cdot\text{cm}^{-2}$ results in a negative-ion beam of 30 A. (See Fig. 13.) More current could be accommodated by increasing the mirror width. However, it is unlikely that any negative-ion beam would pass through a stripping cell narrower than 3 cm. Some other factor must be changed in order to use lower currents in this type of beamline.

It can be seen from Eqs. (52) and (53), that for beams of the same energy, stripping efficiency, and power requirements for photodetachment (i.e., power efficiency), the value $(1/R)/(\xi_L J_- S)$ must be the same. i.e., 4×10^{-3} . Therefore,

$$J_- S = 200 (1 - R/\xi_L) . \quad (54)$$

Then, for a grid system of transparency T_G ,

$$I_- = J_- S T_G . \quad (55)$$

Thus, with a grid transparency T_G of 50% and a mirror width T of 3 cm,

TABLE 4

V_0 , units	kV						Reference	
	50	75	100	150	200	300	400	
J_- , A cm $^{-2}$	0.1						0.1	Assumption
η_p , %	95						95	Assumption
η_N , %	77	67	63	61	60	60	60	Fig. 7
L_S , cm	66	81	93	114	132	162	187	Eq. 53
ξ_p , %	48	56	61	65	67	69	70	Eq. 52

FIG. 13. Schematic diagram of a neutral-beam injector based on a negative-ion source using photodetachment.

$$I_- = 300 (1 - R/\xi_L) \quad , \quad (56)$$

and a 30 ampere D^- beam can be accommodated by a laser of 1% efficiency operating with a cavity whose mirror reflectivity is 99.9%.

The required mirror reflectivity is high, but not beyond reason. The critical problem is not how to achieve such high reflectivity, but how to maintain it. Obviously, the mirrors will have to be cleaned often.

The neutral-beam output is

$$I_0 = I_- \eta_p F_L \quad , \quad (57)$$

in which both the stripping efficiency η_p and the transport efficiency from the stripper to the reactor F_L are 95%.

3.5 OPERATING EFFICIENCIES OF THE VARIOUS BEAMLINES

The efficiencies of the beamlines, discussed previously, are shown as functions of beam energy in Fig. 14. Figures illustrating the various

FIG. 14. Operating beam-line efficiencies.

beamlines and associated tables of data are indicated next to each curve. There is no figure showing the LBL positive-ion beamline without a separating magnet, but it would look something like Fig. 3. Because there is no magnet, there is negligible beam loss. Therefore, the data showing beamline efficiency with and without direct conversion is taken from Table 3, as amended for $F_T = 1$.

4.0 BEAM OPTICS

4.1 DISCUSSION

Fundamentally, beam optics is the study of the component of beam particle motion that is normal to the beam direction. This transverse component of ion velocity is initiated by the thermal energy in the ion source plasma. As the ions are extracted from the source and accelerated to their ultimate beam energy, slight curvatures in potential lines (between grids) introduce weak transverse fields that greatly enhance the normal component to the ion velocity. Scattering of the beam by the background gas also adds to this, but it is unlikely to be a major factor under the conditions encountered in a neutral beamline. Stray magnetic fields can disturb ion-beam trajectories too, but it is assumed that the beamline is adequately shielded.

A more serious source of transverse ion motion results from the diffuse plasma, generated by ionizing collisions between the high-energy beam and the background gas. Ideally, this plasma prevents space charge blow-up of the beam by providing background electrons for positive-ion beams, or background positive ions for negative-ion beams. The ions or electrons neutralize the beam space charge. However, should the plasma be subject to oscillation, the local space charge neutralization can be perturbed, causing the transverse velocity of the beam ions to fluctuate. Furthermore, should the plasma assume a positive potential, because its electron energy is coupled to the beam energy, a positive-ion beam will tend to diverge, while a negative-ion beam will converge. As a consequence, optics of large neutral beams is complex and may not appear to conform with the relationships associated with elementary electron optics.

The observed transverse energy of beams is usually several times greater than that which can be accounted for by ion temperature. The divergence of neutral beams, originating as positive ions, has been reported to be independent of the beam energy. This is in contrast to theory, that indicates the beam divergence should be inversely proportional to the square root of the beam energy. The discrepancy is presumed to result from the interaction between the unneutralized ions and the background plasma in the neutralizer cell.

Unfortunately, we do not fully understand the observed positive-ion phenomena, and at the present time there is no corresponding data for negative

ions. Nevertheless, some improvement in neutral-beam optics is anticipated during the next decade, if only because it is important and considerable effort will be spent on it. Cost factors, related to structure size, create a need for better packaging and, as discussed in a later section of this paper, this too is a function of beam divergence. Good reactor designs require compact neutral beams that can pass through relatively small apertures at comparatively high current densities.

In order to proceed, it is necessary to define critical beam angles. (See Fig. 15.) In an ideal, axial-symmetric optical system each point on a virtual source emits a pencil of rays whose axis intercepts the focal plane at the focal point. Each ray, at some angle α to its own axis, will intercept the focal plane in a common circle of radius R centered about the focal point. With a focal point F , from the source to the focal plane, the radius is

$$R = \alpha F_0 \quad . \quad (58)$$

Observations of the neutral-beam current in the focal plane, in a nonsymmetric system created by slit-extractor apertures, show distributions parallel and perpendicular to the long dimension of the slit that are nearly Gaussian. To simplify the analysis, we assume current density distributions that are Gaussian in all directions to the focal plane. (See Fig. 15.) We also assume that the locus of points, with equal current densities in the focal plane, to be an ellipse.

If X is the direction parallel to the slits and Y perpendicular to them, let X_e represent the minor radius and Y_e the major radius of an ellipse in the focal plane, which corresponds to a current density that is $1/e$ times the peak current density at the focal point.

FIG. 15. Beam optics.

The equation of the ellipse is:

$$(X/X_e)^2 + (Y/Y_e)^2 = 1 \quad (59)$$

and the equation of the current density in the focal plane at any of the X,Y coordinates is:

$$J_{(X,Y)} = \hat{J}_0 \exp \left[-(X/X_e)^2 - (Y/Y_e)^2 \right] . \quad (60)$$

From any point on a source the emission angle, which is parallel to the slits and encompasses the minor radius X_e in the focal plane, is:

$$\alpha_e = X_e/F , \quad (61)$$

where F is the focal length.

The corresponding angle perpendicular to the slits is:

$$\beta_e = Y_e/F . \quad (62)$$

Using slit grids, these angles have been observed to be 0.5° and 1.5° , respectively, for positive-ion-based neutral beams at approximately 20 keV.

At any other beam energy V_0 , the angles should theoretically be:

$$\alpha_e = (0.5) \left(\frac{20 \times 10^3}{V_0} \right)^{1/2} \quad (63)$$

and

$$\beta_e = (1.5) \left(\frac{20 \times 10^3}{V_0} \right) , \quad (64)$$

where α_e and β_e are in degrees.

The discrepancy between theoretical and observed angles in positive-ion beams introduces questions as to the performance to be expected from negative-ion beams. Much work remains to be done in this field. However, initial observations indicate that negative-ion beams have beam angles of

approximately the same magnitude as positive-ion beams. We assume that within ten years techniques will be found that will provide beam angles closer to the theoretical limit.

The two-dimensional Gaussian distribution of current density in the focal plane is such that the total beam current equals its peak amplitude $\hat{J}_0$ multiplied by the area enclosed by the ellipse that corresponds to the $(1/e)$ $\hat{J}_0$ current density. This relationship is derived as follows:

Consider the total beam current in the focal plane to be

$$I_0 = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} J \, dX dY \quad (65)$$

From Eq. (60),

$$I_0 = 4\hat{J}_0 \int_0^{\infty} \int_0^{\infty} \left[\exp(-X/X_e)^2 \exp(-Y/Y_e)^2 \right] dX dY \quad (66)$$

where I_0 , in amperes, is equal to

$$\hat{J}_0 \pi X_e Y_e \quad (67)$$

or with Eqs. (61) and (62)

$$\hat{J}_0 = I_0 / \pi F^2 \alpha_e \beta_e \quad (68)$$

where $\hat{J}_0$ is measured in $A \cdot cm^{-2}$.

Introducing α_e and β_e from Eqs. (63) and (64), after converting the angles to radians, results in the following:

$$\hat{J}_0 = (14.4) (I_0 V_0) / F^2 \quad (69)$$

where $\hat{J}_0$ is measured in $A \cdot cm^{-2}$.

The peak current density $\hat{J}_0$ corresponds to the maximum possible value. In reality, the optics of a large operating system will probably not be perfect and the beam divergence will only tend to vary inversely with the square root of the beam energy. Furthermore, the beam will not have a truly Gaussian

distribution. As a consequence, it is unlikely that a current density one-third of that given in Eq. (69) will ever be achieved.

If we wished to place an aperture in the vicinity of the focal plane, it would be necessary to limit the maximum power density it would intercept to some value W_A W cm^{-2} . With a beam energy V_0 , this corresponds to a current density $J_A = W_A/V_0$. We find from Eq. (60) that in the focal plane an ellipse of minor and major radii X_A and Y_A corresponds to the locus of current density J_A in A cm^{-2} . Therefore, in the plane parallel to the grid slits,

$$J_A = J_0 \exp(-X_A/X_e)^2 \quad (70)$$

and, in the plane perpendicular to the slits,

$$J_A = J_0 \exp(-Y_A/Y_e)^2 \quad (71)$$

As a result, the ellipse has minor and major radii of

$$X_A = X_e \left[\ln(J_0/J_A) \right]^{1/2} \quad (72)$$

and

$$Y_A = Y_e \left[\ln(J_0/J_A) \right]^{1/2} \quad (73)$$

where X_A and Y_A are measured in cm.

In practice, an aperture should be about three times larger, to allow for the oversimplifications of this analysis and for the possible misalignment.

4.2 LIMITS TO THE SIZE OF ION SOURCES

The overall dimension of ion sources used in large neutral beams are limited:

- (a) by the precision with which a very large component can be housed and built,
- (b) by the mechanical problems of replacing a failed unit by remote handling,
- (c) by the reliability of a large unit vis-a-vis a small one, and

(d) by the maximum tolerable stored energy in each unit.

In the event of a spurious discharge, the energy available to the fault must be limited to prevent the creation of a damaging arc. Fast switches open the circuit and isolate the ion source from the power supply, shunts are closed to short out the grids, while arc snubbers and suppressors dissipate the energy stored in the cables and other miscellaneous equipment permanently wired to the source.

However, the energy stored in the source assembly itself is still available to the discharge. It is this energy that limits the size of the grids and also the size of the ion sources. This is discussed in Section 5.

The narrow dimension of a grid (i.e., the grid width W_G) is limited by factors related to grid dissipation. To prevent overheating and excessive expansion, the individual grid rods, between the emitting slits, must be cooled. This requires a significant grid-rod width and creates a restriction on the allowable grid transparency and the average extracted-ion current density.

As it is not our intent to analyze the grid design here, we will use the data for the various ion sources as shown in Table 5. Note that the product of the extracted-ion current density, the ion-source anode transparency, and anode width equals the product of the accelerated-ion current density, grid transparency and grid width, shown in the table. The negative-ion source for the year 2005 has a minimum grid width that is related to the ion beam divergence and the 3-cm width of the mirror in the photodetachment cell. (See Fig. 12.) If the width were reduced, there would be a reduction in the fraction of the beam exposed to the laser, causing the stripping efficiency to suffer. The maximum grid width for the year 2005 source is established by the grid thermal limit.

A simple estimate of the envelope of a beam emitted by an ion source can be calculated from the information shown in Fig. 16. It is assumed that the emitting surface forms a part of a sphere whose center coincides with the focal point of the beam. If W_G is the width of the grid and F the focal length, the extreme angle at which the particles arrive at the focal point is

$$\gamma_X = W_G/2F \quad . \quad (74)$$

TABLE 5

	Extracted ion current density $J_E, (A \cdot cm^{-2})$	Anode transparency $T_A, (\%)$	Anode width $W_A, (cm)$	Accelerated ion current density $J_A, (A \cdot cm^{-2})$	Grid transparency $T_G, (\%)$	Grid width $W_G, (cm)$
LBL positive-ion source	0.250	40	12	0.250	40	12
LBL negative-ion source	0.010	25	25	0.008	62	25
BNL negative-ion source	0.500	7	8	0.040	60	12
2005 narrow negative-ion source	0.500	10	3	0.100	50	3*
2005 wide negative-ion source	0.50	10	12	0.100	50	12**

* - Minimum width

** - Maximum width

FIG. 16. Approximate envelope of beam emitted from a spherical emitting surface.

At the edge of the grid those particles, which are emitted along a path that is normal to the grid, intercept each other at the focal point. Let the extreme path be at an angle $\mathcal{A}$ to the grid normal, such that $\mathcal{A}$ is 2.5 times the $1/e$ value α_e that encompasses the grid radius X_e as described in Eq. (59). Thus, the current density along that path can be shown to be less than 2% of the current density along the normal.

The angle of that path with respect to the beam axis is

$$\theta_X = (\mathcal{A} - \gamma_X) \quad (75)$$

But

$$\mathcal{A} = 2.5 \alpha_e \quad (76)$$

hence

$$\theta_X = (2.5 \beta_e - W_G/2F) \quad . \quad (77)$$

From the geometry, the beam diameter parallel to the grid slits at any point Z along the beam path is

$$W_Z = (W_G + 2 \theta_X Z) \quad . \quad (78)$$

In the plane perpendicular to the grid slits, the grid length is H_G and the corresponding diameter along the beam is

$$H_Z = (H_G + 2 \theta_Y Z) \quad , \quad (79)$$

where

$$\theta_Y = (2.5 \beta_e + H_G/2F) \quad . \quad (80)$$

5.0 NEUTRAL-BEAM INJECTOR LAYOUT

This section investigates the design of an array of many ion sources in a large neutral-beam injector, the factors that control the spacing between adjacent sources, and the factors that limit the size of the sources.

It should be recognized that a conservative design philosophy has been assumed throughout this analysis.

It may not be necessary to house each source in a grounded enclosure. Previous studies have considered the prospect of mounting many sources in a common enclosure and relying on the arc suppression circuits to prevent breakdown between adjacent components. This approach results in a more compact ensemble, but its reliability has not been demonstrated. If it cannot be done effectively, neutral-beam injectors must be assembled as described here.

In many respects it would be easier, and thereby cheaper, to mount the sources at ground potential. It certainly would make the connections for power and services less complicated by eliminating the need for isolation transformers. However, when several parallel beamlines are contemplated, the spacing between adjacent beams should be a minimum. To accomplish this, the ion sources must be at a high potential, while the other components, downstream along the beamline are at ground.

5.1 SEPARATION BETWEEN ADJACENT ION SOURCES

The minimum achievable separation between adjacent ion sources is determined by either beamline geometry, high-voltage standoff, or the conductance needed for pumping between beamlines.

With respect to the geometric factors, consideration must be given to the beam angles α_e and β_e as shown in Fig. 15. In the plane parallel to the grid slits the beamline geometry is as shown in Fig. 17. It can be seen that the separation between the edges of adjacent emitting surfaces, in the plane parallel to the grid slits, must be

$$S_W = (5X_e L_W) / (F - L_W) \quad , \quad (81)$$

FIG. 17. The separation, S_W , between adjacent edges of ion-emitting surfaces as a function of the clearance length, L_W , between adjacent beam lines.

where S_W is in cm, F is the focal length, L_W is the clearance between adjacent beams, and X_e and α_e are defined in Eq. (61). In the plane perpendicular to the slits, the corresponding relationship is

$$S_H = (5 Y_e L_H) / (F - L_H) , \quad (82)$$

where S_H is in cm and Y_e is defined in Eq. (62).

To estimate the values of S_W and S_H , we assume that 2 meters is needed along a beamline for the stripping cell (or neutralizer) and another 2 meters is needed for the ion beam dump. If the stripping cells are stacked so that beams can begin to merge in the region of the ion beam dumps, then $L_H \geq 2$ meters and $L_W \geq 4$ meters. Value of S_H and S_W are shown as functions of the beam energy in Fig. 18. The focal length F was assumed to be 10 meters, while X_e and Y_e were evaluated from the angles α_e and β_e by means of Eqs. (63) and (64). Curves for constant α_e and β_e are also included in the figure.

Removal of the unneutralized ions from the beamline by a magnetic field is undesirable. With the ions deflected above and below the beamline, depending on their charge, in a direction perpendicular to the grid slits, space must be allotted for beam dumps in the direction of the largest deflection angle, β_e . Thus, it is found that magnetic-ion separation produces a beamline configuration that is not as compact as one obtained by electrostatic deflection.

Figure 18 shows a curve representing the separation necessary between the edges of adjacent grids to withstand high voltage. It is assumed that the source are separated by a grounded, double-sided, continuously-operating cryopump that is mounted in the 20-cm-thick wall. (See Fig. 19.) The edge of each source, extending 4 cm beyond the edge of the grids, is separated from the cryopanel shields by a distance proportional to the beam energy V_0 . That is the distance inversely proportional to the maximum tolerable electric field strength E_F . The corresponding spacing S_E (in cm) between the extreme edges of the grid surfaces on adjacent sources, as established by electrical considerations, is

$$S_E = (28 + 2V/E_F) . \quad (83)$$

FIG. 18. Separation between edges of grid surfaces on two adjacent ion sources.

This relationship is applicable between adjacent sources in directions both parallel and perpendicular to the grid slits.

The field strength, $E_f = 20 \text{ kV cm}^{-1}$, was selected as a conservative value that would make it relatively easy to design electrode shapes over which field emission and breakdown is unlikely to occur. It is expected that intermediate electrostatic shields will be used to limit the voltage drop between adjacent electrodes to no more than 150 kV. Since breakdowns are most likely to occur over insulator surfaces, the field over these surfaces is reduced to $10 \text{ kV} \cdot \text{cm}^{-1}$. This is accomplished by increasing the spacing between the electrostatic shields at the rear of the source.

At this high voltage and low field strength, consideration must be given to the prospect of low-pressure breakdown. The Paschen curve for breakdown in hydrogen, shown in Fig. 20, indicates that there will be little problem with planar electrodes operating at 150 kV and a pressure-spacing product pd of 0.15 Torr-cm. In this application,

$$pd = pV/E_f \leq 0.15 \quad . \quad (84)$$

FIG. 19. 400-keV D^- source housing.

When $E_F = 10^4 \text{ V}\cdot\text{cm}^{-1}$ and $V = 150 \text{ kV}$, the pressure p would have to exceed 10^{-2} Torr for the background gas to present a problem. This is unlikely.

Figure 18 shows the grid separation to be dominated by considerations of high-voltage standoff, for beam energies of 80 kV or more.

Another factor of importance to the beamline design relates to the length of the cryopanel needed on both sides of the beamline to remove the gas flowing out of the source.

The gas flow equivalent to the extracted-ion beam is given in Eq. (1), while the quantity of gas to be pumped away is given in Eqs. (3) and (4). With these expressions, the gas flow, in $\text{Torr}\cdot\text{liter}\cdot\text{s}^{-1}$, to be pumped per amperes of extracted-ion current is readily found from Eq. (85),

FIG. 20. Left side of hydrogen Paschen curve for planar geometry.

$$(Q_p/I_e) = (0.1) (\eta_1 + 2 \eta_2 + 3 \eta_3) (1/\epsilon_G - 1) . \quad (85)$$

If T_A is the transparency of the anode of the source and J_E the extracted-ion current density, the neutral gas flowing out of each source is

$$Q_p = (0.1) (\eta_1 + 2 \eta_2 + 3 \eta_3) (1/\epsilon_G - 1) T_A J_E H_G W_G, \quad (86)$$

where H_G and W_G are the source height and width.

Assuming that the gas flowing from the source is pumped away from continuously-operating cryopanel at a speed of about $4 \text{ liter} \cdot \text{s}^{-1}$ per cm^2 of pump area, the quantity of gas pumped in $\text{Torr} \cdot \text{liter} \cdot \text{s}^{-1}$ is equal to

$$8 H_G L_p P_A , \quad (87)$$

where H_G is the source height, P_A the ambient pressure, and L_p is the length of the two panels; one on each side of the beamline. In the above, it is assumed that the cryopanel height equals the height of the ions source.

Equating (86) with (87), we find the required apnel length to be:

$$L_p = \frac{0.1 (\eta_1 + 2 \eta_2 + 3 \eta_3) (1/\epsilon_G - 1) T_A J_E W_G}{8 P_A} . \quad (88)$$

Typical values for the above expression are given in Table 6.

There are several restrictions on the size of the ion source grids. Perhaps the most critical results from the maximum allowable energy that can be stored by the capacitance between each source and ground. As shown in Fig. 19, the capacitance can be considered as having two parallel components. One consists of the planar configuration of grids that accelerate the ions away from the source and the other consists of the electrostatic shields.

The grids are rectangular, H_G long by W_G wide, spaced one behind the other. Hence, the capacitance of the grid to ground results from the series combination of the individual grid-to-grid capacitances.

The capacitance C_G of the ensemble is

$$C_G = \frac{1}{\sum \frac{1}{C_i}} . \quad (89)$$

TABLE 6

	Ion specie			Gas efficiency ξ_G , (%)	Anode transparency T_A , (%)	Extracted ion current density J_E , (A·cm ⁻²)	Slit width W_G , (cm)	Average pressure p_A , (Torr)	Cryopanel length L_p , (cm)
	n_1	n_2	n_3						
LBL positive-ion source	90	7	3	30	40	0.250	12	3×10^{-4}	127
LBL negative-ion source	100	0	0	3	25	0.020	25	3×10^{-4}	168
BNL negative-ion source	100	0	0	9	7	0.500	8	7×10^{-4}	51
2005 narrow negative-ion source	100	0	0	15	10	0.500	3*	5×10^{-4}	21
2005 wide negative-ion source	100	0	0	15	10	0.500	12**	5×10^{-4}	85

* - Minimum width

** - Maximum width

The capacitance between any two grids is

$$C_i = \epsilon_0 (A_G/d_i) , \quad (90)$$

where ϵ_0 , the permittivity of vacuum, is $(8.85 \times 10^{-14} \text{ farads} \cdot \text{cm}^{-1})$, A_G is the grid surface area, and d_i is the grid-to-grid separation.

Substituting Eq. (90) into Eq. (89), we can calculate the capacitance of the ensemble C_G from

$$C_G = \frac{\epsilon_0 A_G}{\sum_i d_i} \quad (91)$$

where

$$A_G = (H_G W_G) , \quad (92)$$

and the total distance from the source to the furthest grid is

$$Z_0 = \sum_i d_i . \quad (93)$$

If an ion current of density J_A is accelerated to a beam energy V_0 , the distance Z_0 is found from Child's law to be

$$Z_0 = (q/J_A)^{1/2} V_0^{3/4} , \quad (94)$$

where the perveance q was determined from Eq. (44). The total capacitance C_G in farads of the grids-to-ground is then:

$$C_G = \epsilon_0 H_G W_G (J_A/q)^{1/2} V_0^{-3/4} . \quad (95)$$

The contribution of the electrostatic shields to the capacitance can be roughly considered to be that of 3/4 of a cylindrical capacitor whose length is H_G , inner radius R_S , and outer radius is $(R_S + V_0/E_F)$. V_0/E_F is the interelectrode spacing at an average electric field of $E_F \text{ V cm}^{-1}$. Accordingly, the capacitance C_S of the shields in farads is

$$C_S = (3\pi/2) \epsilon_0 H_G \log_e \left[1 + (V_0/R_S E_F) \right] . \quad (96)$$

where the inner radius R_S is equal to

$$R_S = \frac{1}{2} \left[W_G^2 + 225 \right]^{1/2} . \quad (97)$$

If the maximum allowable stored energy is, E_S in joules, then it must be that

$$E_S = \frac{1}{2} C_T V_0^2 , \quad (98)$$

where the total capacitance C_T in farads is the sum of the two parallel components:

$$C_T = C_G + C_S . \quad (99)$$

From Eqs. (85), (95), and (98), the stored energy E_S in joules is

$$E_S = 1/2 \epsilon_0 H_G \left\{ W_G (J_A/q)^{1/2} V_0^{5/4} + \frac{3\pi}{2} V_0^2 \log_e \left[1 + V_0 / (R_S E_F) \right] \right\} . \quad (100)$$

Values of the stored energy E_S are shown in Fig. 21 as a function of beam energy for the five beamlines described in Table 5. In all of these examples the source length H_G was assumed to be 2 meters. The results indicate that the energy stored in grids and electrostatic shields can become a problem as the beam energy is increased. To overcome this it may be necessary to redesign the electrostatic shields or reduce the source length H_G .

A good injector design will deliver a maximum current per unit area of the mounted ion source array. (See Fig. 22.) If I_0 represents the neutral-beam current obtained from a single source, this quantity is

$$\bar{J}_0 = \frac{I_0}{(W_G + S_E) (H_G + S_E)} . \quad (101)$$

FIG. 21. Energy stored in grids and electrostatic shields of five different ion sources two-meters long.

FIG. 22. Array of ion sources in their grounded enclosures.

To evaluate the above for the beamlines under consideration, let $H_G = 200$ cm and the values for J_A , T_G , and W_G correspond to those given in Table 5. Then,

$$I_E = J_A T_G H_G W_G, \quad (102)$$

and the ratio I_0/I_E is determined from Eq. (20) for the LBL D^- beamline, from Eq. (33) for the BNL D^- beamline, and from Eq. (40) for the LBL D^+ beamline.

For the 2005 D^- photodetachment beamlines, I_- is calculated in Eq. (55) and I_0 in Eq. (57). S_E is calculated in Eq. (83).

Values of $\bar{J}_0$ are plotted in Fig. 23. Consideration of this curve and of Eq. (101) leads to the conclusion that the maximum J_0 results from a source with a high extracted current density J_E , good transparency T_G , a

FIG. 23. Neutral current per unit area of source array.

favorable conversion efficiency from negative ions to neutrals I_0/I_E , a maximum tolerable grid height H , and a reasonable grid width W_G .

6.0 CONCLUSIONS

Four neutral-beam characteristics are analyzed in this report:

- (1) gas efficiency of ion sources,
- (2) operating efficiency,
- (3) beam optics and limitations on the size of ion sources, and
- (4) neutral-beam injector design.

The prospect of improving the gas efficiency of ion sources is particularly important to negative-ion beamline development. Whereas positive-ion sources operate in excess of 35% efficiency, just three years ago a gas efficiency of 3% was considered good for a negative-ion source (Ref. 9). Progress in ion-source technology offers promise of gas efficiencies for negative-ion sources that will approach and possibly exceed 10%.

The second characteristic analyzed was beamline operating efficiency (Fig. 14). The study of positive-ion beamlines showed a great loss of

efficiency resulting from the introduction of a deflecting magnet to remove the unwanted molecular species of ions, even taking advantage of energy recovery.

The performance of neutral-beam injectors, constructed in accordance with Brookhaven National Laboratory and Lawrence Berkeley Laboratory negative-ion concepts, was within 5% of each other. Hence, neither concept can be said to be better than the other. Although experimental data is needed to provide actual data, it is evident that negative-ion beamlines, using D_2 gas stripping cells, can be made to operate with roughly 50% efficiency.

An additional study was made of a negative-ion beamline using photodetachment. At the higher beam energies, the resulting neutral-beam injector had an efficiency approaching 70%.

The third characteristic considered was beamline optics. In particular, it was noted that positive-ion beamlines do not perform in accordance with classical theory. The transverse angles α_e and β_e (as defined in Fig. 15) do not vary inversely with the square root of the beam energy. Because this phenomena is not fully understood, it was assumed that the angles are constant for both positive- and negative-ion beamlines. However, it is expected that subsequent research will result in significant improvement.

Finally, an attempt was made to estimate the size of a large neutral-beam injector using different beamline concepts. To do this the average neutral current that can be obtained from an array of ion sources mounted at the head of the beamline was evaluated. It was found that the size of individual sources was limited by heat dissipation and stored energy restrictions. Meanwhile, the minimum allowable spacing between sources was established by a need for high-voltage reliability from source to source (Fig. 23).

Positive-ion beamlines were found to require smaller injectors than negative-ion beamlines using gas stripping cells. However, negative-ion beamlines that are stripped by photodetachment are the most favorable of all.

While it is impossible to predict the future, it is clear that significant improvements in neutral-ion beamline performance can be anticipated.

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APPENDIX A

OAK RIDGE NATIONAL LABORATORY NEGATIVE-ION NEUTRAL BEAMLINE

A1.0 INTRODUCTION

This appendix provides information on the negative-ion neutral beamline using the Oakridge National Laboratory Calutron as a source of D^- ions [Ref. (A1)]. With suitable development, this source can be competitive with the neutral-beam injectors at the Lawrence Berkeley Laboratory and Brookhaven National Laboratory.

A2.0 DISCUSSION

Neglecting the power needed to operate pumps, magnets, and other services, the efficiency of a neutral-beam injector is roughly:

$$\xi_{OR} = P_0 / (P_S + P_A) \quad , \quad (A1)$$

in which P_0 is the output power of the neutral beam, P_S is the power needed to operate the source, and P_A the power needed for the ion accelerator.

If V_0 and I_0 represent the neutral beam energy and equivalent current, while I_E is the current of the ions extracted from the ion source, Eq. (A1) can be written in the following form.

$$\xi_{OR} = \frac{I_0/I_E}{\frac{P_S}{\xi_E J_E V_0} + \frac{1}{\xi_A}} \quad , \quad (A2)$$

where $P_0 = I_0 V_0$, $P_A \approx I_E V_0$, ξ_E is the efficiency of the ion source power supplies and ξ_A is the efficiency of the accelerator power supply.

Ion sources are often evaluated by a performance rating PR which is the ratio of the power required by the source per ampere of extracted ion current, thus:

$$\overline{PR} = (P_S/I_E) \quad , \quad (A3)$$

whereby

$$\xi_{OR} = \frac{I_0/I_E}{\frac{\overline{PR}}{\xi_E V_0} + \frac{1}{\xi_A}} \quad . \quad (A4)$$

With reference to Fig. A1(a) and (b), the Calutron [Ref. (A2)] requires a filament and arc power supply. Because both circuits require high currents at relatively low voltages, it is assumed that the I^2R losses limit the associate power supply efficiencies to $\xi_E = 90\%$. The accelerator power supply being unregulated has an efficiency of $\xi_A = 95\%$. The performance rating of the Calutron is $\overline{PR}$ assumed to be 9 kW of arc and filament power per ampere of D^- .

As shown in Fig. A2, the extracted beam suffers four significant losses. They can be expressed in terms of survival fractions, i.e., F_E (at extraction and just prior to acceleration), F_A (during acceleration), η_0 (in the

FIG. A1. Schematic diagram of the ORNL D^- Calutron.

FIG. A2. Schematic diagram of a neutral-beam injector based on the ORNL D⁻ Calutron.

negative-ion stripper), and finally F_L (in the transport from the stripper into the reactor). Thus, the neutral-beam current is

$$I_0 = F_E F_A \eta_N F_L I_E \quad (A5)$$

The fraction of negative ions, extracted from the source, which arrive at the accelerator is

$$F_E = (1 - n_E \sigma_{-10} L_E) \quad (A6)$$

in which n_E is the neutral gas density in that region, σ_{-10} is the stripping cross section at low energies [Refs (A3) and (A4)], approximately $10^{-15} \text{ cm}^2/\text{D}_2$ per Fig. A3, and L_E is the path length (roughly 2 cm).

If it is assumed that the background gas temperature is 300 K and the pressure is p_A , the background neutral-gas density is

$$n_E = (3.3 \times 10^{16}) p_A \quad (A7)$$

where n_E is in cm^{-3} .

FIG. A3. Deuterium charge-exchange cross sections. [See Refs. (2) and (3).]

Thus, the survival factor prior to acceleration in a region of 5×10^{-4} Torr is roughly $F_E = 97\%$.

In the acceleration region the ion survival factor is

$$F_A = 1 - n_E \int \sigma_{-10} dz, \quad (A8)$$

where z is the ion path length through the accelerator grids and σ_{-10} is the stripping cross section, a function of beam energy as per Fig. A3.

The grids accelerate the ions in accordance with Child's Law. Hence, the accelerated ion current density is

$$J_A = q (V_0^{3/2} / z^2), \quad (A9)$$

in which the perveance for deuterium is

$$q = (3.85 \times 10^{-8}) A V^{-3/2}.$$

Taking the derivative of Eq. (A9), results in an expression for dz that is a function of the beam energy. Accordingly,

$$F_A = 1 - 3/2 n_E q^{1/2} J_A^{-1/2} \int_0^{V_0} (\sigma_{-10} v^{-1/4}) dv. \quad (A10)$$

Values of the integral

$$A_{-10} \Big|_0^{v_0} = \int_0^{v_0} (\sigma_{-10} v^{-1/4}) dv \quad (A11)$$

were found graphically, using σ_{-10} from Fig. A3. These results are shown in Fig. A4.

From Eq. (A7), n_E is found as a function of the average pressure p_E . Introducing this into Eq. (A10), we then obtain:

$$F_A = \left[1 - (4.9 \times 10^{12}) p_E J_A^{-1/2} A_{-10} \Big|_0^{v_0} \right] . \quad (A12)$$

In the stripping cell, made from a gas-type neutralizer [Ref. (A3)], the stripping efficiency η_0 is as shown in Fig. A5. The fraction of the neutral beam, which does not ionize by collisions with the background gas, similar to Eq. (A6), is

$$F_L = [1 - (3.3 \times 10^{16}) p_L \sigma_{01} Z] . \quad (A13)$$

It is assumed that the conditions for beam transport can be designed such that $F_L = 95\%$. No special allowance is made for beam blockage in the duct, taking the beam from the injector into the reactor. This is because we are considering a continuously operated system with no time to build up a gas

FIG. A4. Values of the integral $A_{-10} \Big|_0^{v_0} = \int_0^{v_0} (\sigma_{-10} v^{-1/4}) dv$ for negative ions.

FIG. A5. Optimum neutralization efficiency in D_2 as a function of ion energy for D^+ , D_2^+ , D_3^+ and D^- beams.

layer on the walls. The rate of wall outgassing must equal the equivalent rate at which the ions arrive at the walls. This need not be excessive and a suitable duct can readily be designed for the beam current densities considered here.

Going back to Eq. (A4), the efficiency of the ORNL D^- Calutron is found to be

$$\xi_{OR} = \frac{\frac{F_E F_A \eta_0 F_L}{PR}}{\frac{F_E V_0}{\xi_A} + \frac{1}{\xi_A}} \quad (A14)$$

Values of ξ_{OR} , and the critical assumptions are listed in Table A1. They are plotted in Fig. (A6) as a function of the beam energy along with estimates of the performance of LBL and BNL negative-ion beamlines. (See Subsections 3.1 and 3.2.)

TABLE A1. Efficiency of neutral-beam injector based on ORNL D⁻ Calutron source.

V ₀ , units	kV								Reference
	50	75	100	150	200	300	400		
P _E , Torr	5 × 10 ⁻⁴								Assumption
F _E , %	97								Eqs. A6, A7
J _A , A cm ⁻²	0.15								Assumption
A-10, 10 ⁻¹³ cm ² v ^{3/4}	45	52	60	80	90	100	115		Fig. A4
F _A , %	97	97	96	95	94	94	93		Eq. A12
F _L , %	95								Assumption
n ₀ , %	77	67	63	61	60	60	60		Fig. A5
ε _{OR} , %	55	51	48	48	48	48	48		Eq. A14

Additional assumptions:

$L_E = 2$ cm
 $P_R = 9$ kW/A
 $\epsilon_S = 90\%$
 $\epsilon_A = 95\%$
 $T_{GAS} = 300$ K

4.0 CONCLUSIONS

It should be recognized that these estimates of efficiency are good for +5% at best. The results of the analysis do not indicate that any of the source concepts considered here, as devised by ORNL, BNL, or LBL, are better than any other. Only experimental data can prove that. On the other hand, it is evident that negative-ion beamlines, using gas strippers, can achieve efficiencies of roughly 50%.

FIG. A6. Operating efficiencies of neutral beamlines made from ion sources under development at the Brookhaven National Laboratory (BNL), the Oakridge National Laboratory (ORNL), and the Lawrence Berkeley Laboratory (LBL).

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