Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Submitted to Nuclear Fusion

OPTIMIZED SYSTEM FOR D^- PRODUCTION FROM CHARGE
EXCHANGE IN ALKALI METALS

E.B. Hooper, Jr., P. Poulsen, and O.A. Anderson

August 1980

RECEIVED
LAWRENCE
BERKELEY LABORATORY

MAR 5 1981

LIBRARY AND
DOCUMENTS SECTION

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 6782.*

LBL-10917
c.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Optimized System for D⁻ Production from
Charge Exchange in Alkali Metals*

E. B. Hooper, Jr.**
P. Poulsen**
O. A. Anderson**

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

August, 1980

*This work was supported by the Fusion Energy Division of the Department of Energy under contract no. W-7405-ENG-48.

**Permanent address: Lawrence Livermore National Laboratory, Livermore, CA, 94550.

OPTIMIZED SYSTEM FOR D⁻ PRODUCTION FROM
CHARGE EXCHANGE IN ALKALAI METALS*

E. B. Hooper, Jr.**
P. Poulsen**
O. A. Anderson**

Lawrence Berkeley Laboratory, University of California
Berkeley, CA 94720

ABSTRACT

Negative ion production for neutral (deuteron) beam injectors is considered for a general system utilizing charge exchange production in alkali metals. Experimental results provide parameters and show good correlation with calculations using known atomic cross sections, so that beam behavior can be predicted. It is found that coupling into the high voltage accelerator poses significant constraints on optimization of the system, e.g., to determine its minimum size. A typical design for 200 keV final energy provides D⁻ at 1.5 keV from charge exchange in rubidium, with an average current density of 23 mA/cm² and a total current of 20 A.

*This work was supported by the Fusion Energy Division of the U. S. Department of Energy under contract no. W-7405-ENG-48.

**Permanent address: Lawrence Livermore National Laboratory, Livermore, CA 94550

1. INTRODUCTION

The generation of efficient, very high energy, neutral beams of the hydrogen and its isotopes is generally believed to require the use of negative ions [1,2]. Positive ions are difficult to neutralize: For deuterons at 200 keV, for example, the efficiency of neutralization by charge-exchange in deuterium is 20%, and it decreases rapidly as the energy increases. The efficiency of stripping an electron from the negative deuterium ion is about 60% at 200 keV, however, and even greater stripping efficiencies might be obtained in plasmas [3] or in intense photon (light) fields [4]. Given this information, it is straightforward to show that neutral beams based upon negative ions are potentially a highly efficient means of obtaining plasma heating in thermonuclear experiments and reactors if injection energies in excess of 200 keV are required [1,5,6].

A general beamline based on negative ions consists of a source of negative ions, an accelerator, a stripper to convert the negatives to neutral atoms, and a means for handling the residual beam ions either by dumping them on cooled surfaces or (preferably) by recovering their energy. The status of this work is reviewed in Ref. 7; see also Ref. 8.

Many different sources of negative ions have been proposed and studied [9]. The approaches tested include charge-exchange in alkali metals, production on surfaces, production in the volume of a plasma, and others.

In this paper negative ion (D^-) beam production by charge exchange is considered for use as a neutral beam. The parameters of the negative ion system are varied to yield designs with minimum sizes at fixed total D^- current. In these designs the energy cost per D^- ion is small enough that it is not a major consideration. The analysis draws on experiments in which

H^- and D^- are formed in cesium [10-12] and in sodium [13-17]. In all these experiments a positive ion beam is extracted from a source and passed through an alkali metal jet. Post-acceleration, when done, follows propagation through a drift space which minimizes the flow of gas and electrons into the accelerator.

The results of these experiments demonstrate that one can predict the negative ion beam parameters with considerable confidence from atomic measurements. Quantities such as beam current and current density, angular divergence, gas flow, etc., can be calculated to within about 20%. Given this capability we consider a general D^- production system as a function of geometry, energy and charge exchange medium. Optimization is done to determine a "best" system for neutral beam production. This design is intended to demonstrate what can be done and to serve as a guide for future work in charge exchange sources of H^- and D^- .

The final design depends, of course, on the initial assumptions as to the system design. There are two approaches to negative ion generation using charge exchange which differ enough from the present model that our conclusions do not hold. Geller et al. [18,19] have constructed a system in which the positive ion source and entire beamline is placed in a magnetic field. This permits the source to operate at a very high gas efficiency, and greatly reduces problems associated with angular divergence and stripping of the negative ion before acceleration. On the other hand, the magnetic field may cause problems of plasma and electron control, beam stability, and voltage holding near the accelerator which are absent from the unmagnetized system and thus not considered here.

Even more different is the proposal by Becker et al. [20,21] to use positively charged hydrogen clusters which are accelerated to high energy,

broken up, and converted to negative ions in cesium. The resulting H^- or D^- ions are then accelerated to the final energy. The present results are clearly not pertinent to their system.

2. DESIGN PHILOSOPHY

There are several issues which need to be considered to establish a basic design. These include: the possible use of molecular ions in the initial (positive) ion beam, the type and geometry of the high voltage accelerator, and the means of handling gas. These basic issues have a large effect on the general design and thus are considered first.

ATOMIC VS MOLECULAR IONS

The positive ion source is operated with some fraction of its current in molecular ions. Because the perveance of an accelerator scales as $(m_i)^{-1/2}$, with m_i the ion mass, whereas the ratio of the accelerator voltage to the energy per nucleus is proportional to m_i , the available current of nuclei for the positive ion source can be increased by $(m_i)^{1/2}$. This potentially results in an increase in the current density of negative ions.

To utilize this current density, however, the molecular ions must be dissociated before conversion to negative ions. This can be done either in deuterium or in the charge exchange vapor. In both cases a line density of about 10^{16} cm^{-2} is required [2,22] for complete dissociation. The deuterium line density could be provided by a "neutralizer" tube downstream from the source, but there are two penalties: (a) The gas density in the source grid region is high, causing a significant level of secondary processes during the

positive ion acceleration process (ionization, charge exchange, secondary electrons) [23]. (b) The neutralizer tube will be quite long; extrapolating from the source used in the authors' work [15-17], about 80 cm would be required. This in turn lengthens the system considerably. These penalties are significant and indicate that breakup of a large fraction of molecular ions in deuterium would be difficult to implement, especially in a steady state system.

Alternatively, the charge exchange medium can be used to dissociate the molecules. This is the approach taken by Semashko et al. [13,14] in sodium. However, the D^- current produced from atomic deuterium reaches its full value at a line density in the range of 10^{15} cm^{-2} to $2 \times 10^{15} \text{ cm}^{-2}$, so that breakup implies 5 to 10 times more vapor flow than necessary for production of D^- . This is an undesirable situation as excess vapor causes more scatter in the D^- beam, more background plasma which can flow to the high voltage accelerator, larger losses of material from the charge exchange region, and a larger inventory of material.

In addition to the practical problems associated with breaking up the molecular ions, there is no present accelerator design capable of yielding good optics for the range of energies (factor of 3) associated with ions resulting from an initial $D^+/D_2^+/D_3^+$ beam. The problem is similar to that of chromatic aberrations [24] in lenses and presumably could be solved by the use of complicated accelerator structures.

The conclusions for the present study are that the complications associated with the use of molecular ions are unwarranted and that it is best to design for a single energy system. Present deuterium sources [25] yield more than 75% D^+ in the initial beam, and one of the efforts in the neutral beam research and development based on positive ions is to increase this

fraction. Any contributions to the D^- current from molecular ions are useful but will not be included in the present analysis.

THE ACCELERATOR GEOMETRY

Historically, the accelerators used in neutral beam systems have used electrostatic potentials. It is assumed that the accelerator used in this design is electrostatic in nature, although it is worth noting that there have been recent proposals to use a multiaperture RF linear accelerator [26]. If this can be successfully developed it will influence the system design.

The accelerator entrance aperture affects the source geometry because the negative ion current must be mapped into it with high efficiency. Traditional accelerator apertures have been either circular holes or long narrow slots (or an array of holes or slots) because for them the calculation of the beam optics for these geometries is a two dimensional problem and thus relatively amenable to analysis. For the negative ion accelerator one would like to work with a single large aperture in order to avoid losses due to incomplete grid transparency (typically 50%). In principle, a slot can be scaled to arbitrarily large currents by increasing its length; the optics of the resulting beam is unaffected. A circle, on the other hand, cannot be increased to arbitrary large radius. The potential field does not penetrate the beam and the grid optics will deteriorate at large currents. A narrow slot is thus the more desirable geometry.

The entrance geometry of an accelerator whose aperture is a long slot is approximately matched by the beam pattern of LBL ion sources [25]. The divergences of the output particles create an elliptical current density profile near and beyond the source focus if the grids are designed to focus

the beam. However, analysis of an accelerator which accepts an elliptical profile is inherently three dimensional in nature and thus extremely difficult. The accelerator is thus placed as near the source as possible and the beam focused in only one direction (the narrow width) to provide a long, slot-like beam. The beamlets from the wide ends of the source can be aimed inward to maximize the amount of beam with constant current density along the slot length.

GAS HANDLING

The gas streaming from the positive ion source must be pumped rapidly to minimize secondary effects within the source grid region, stripping of the negative ions once they are formed in the alkali metal vapor, and generation of downstream plasma. The charge exchange vapor assists in this situation by acting as a barrier to gas flow from the source region to the accelerator region [14,27]. Thus most of the gas can be handled by a cryopump placed upstream of the charge exchange jet. Gas which leaks through the jet and gas generated on surfaces downstream from the jet can be handled by additional cryopumping.

The vapor jet can also assist in pumping, acting essentially as a diffusion pump [14]. At the high line densities of vapor required for breaking up molecules this might provide all the pumping. At the lower densities assumed here cryopumping is needed in addition to pumping provided by the jet.

3. CHARACTERISTICS OF THE COMPONENTS

THE POSITIVE ION SOURCE

As discussed above, the analysis assumes a source of the basic LBL design [25]. These sources provide an atomic ion fraction greater than 75% at a gas efficiency (nuclei in beam/gas nuclei used) of 35%, and an energy cost per ion of 0.9 keV.

The grid design will be assumed to be the accel-decel variety using a set of water cooled grids [16]. The optics of such an accelerator [28] is limited by the thermal energy of the ions in the direction parallel to the slots in the source accelerator. Across the slots it is limited by the combination of thermal energy and beam compression during the acceleration process. Measured and calculated values for low energy beams are shown in Fig. 1.

The more critical angle for the slot high voltage accelerator is the divergence $\theta_{\parallel}$ along the slots. This can be described by an ion temperature of 1 to 1.5 eV [28]; thus, $\theta_{\parallel} \sim 2/\sqrt{E_b}$ degrees, with the beam energy, E_b , in keV.

Although not as important for our conceptual design, $\theta_{\perp}$, the divergence across the slit, should be minimized so as to minimize divergence at the ends of the system. In order to obtain a current density of 0.3 A/cm^2 at the source plasma, the probable maximum which can be provided on a long pulse or dc basis, an accel-decel system is required. The indicated point at 1 keV is that of the accel-decel system used in the cesium charge exchange system [11,12]. The point at 10 keV is the water cooled design described in Ref. 16. The point at 2 keV is an untested design for a non-cooled system with a ratio of accel voltage to final voltage of 10. Given the untried nature of the designs, the best that can be expected with confidence is $\theta_{\perp} = 7/\sqrt{E_b} \text{ (keV)}$ degrees.

THE CHARGE EXCHANGE VAPOR

The largest conversion factors for H^- and D^- production are in the vapors of the alkali metals. In the range <10 keV the largest values of F_-^∞ are in cesium, rubidium, and sodium as shown in Fig. 2, adapted from Refs. 29 and 30.

In addition to the equilibrium value of F_-^∞ , we are interested in the line density required to produce the negative ions. Simple rate equations show that equilibrium is approached exponentially with a rate $(\sigma_{0-} + \sigma_{-0})n_1$; thus the e-fold line density is given by $(\sigma_{0-} + \sigma_{-0})^{-1}$. Measured results are shown in Fig. 3. In a practical system one wants several e-folds; three will yield 95% of the maximum. Thus $1 \times 10^{15} \text{ cm}^{-2}$ to $1.5 \times 10^{15} \text{ cm}^{-2}$ is adequate to generate the D^- .

The final information required is the angular scattering during the charge exchange process. Measurements made by Cisneros et al. [33] and by Agafonov et al. [34] are analyzed in Ref. [16]. The data fits a common scaling law with a scattering angle θ_s given by

$$\theta_s = k R^2/R_{Na}^2 (n_1)^{0.7}/E \quad (1)$$

with $k = 0.15 \pm 0.02^\circ\text{-keV}-(10^{15} \text{ cm}^{-2})^{-0.7}$ and R the atomic radius. From cross section data it follows that $R^2/R_{Na}^2 = 1.76$ for rubidium and $R^2/R_{Na}^2 = 2.04$ for cesium.

CHARGE EXCHANGE CELL

There are three primary candidates for the charge exchange jet, all using supersonic flow: The exterior nozzle of Poulsen et al. [36] used in the authors' sodium experiment [15-17], the Laval nozzle of Semashko et al. [13,14] and the slit nozzle of Bacal et al. [37]. The most critical problem in these systems is the control of the alkali metal, so as to minimize losses to the rest of the beamline. Good confinement has been demonstrated in the first two systems. The nozzle of Semashko et al. operates in steady flow; the authors argue that sodium has a significant advantage over other materials because its vapor pressure at its melting point is lower [14] (Na: 1×10^{-7} Torr, Rb: 1×10^{-6} Torr, and Cs: 2×10^{-6} Torr). However, Condit [38] has pointed out that the binary and ternary alloys of the alkali metals have very low melting points [39]. The extreme example is an alloy consisting of 10% Na, 47.5% K, and 42.5% Cs (Mole percents) with a melting point of -73°C . At that temperature the vapor pressures are negligible, and even in less extreme alloys vapor pressures of 10^{-9} Torr and below are common. Development is required of systems which would utilize these materials for liquid flow and extract the desired component for a vapor jet, but it is clear that dc operation at low vapor pressures is possible for all the candidate materials.

THE ACCELERATOR

As noted above, the geometry of the negative ion source is constrained by the entrance aperture requirements of the accelerator. For a slot type accelerator the electrode configuration is determined by the "perveance per

square," $P_s = j W_a^2 / V^{3/2}$, with j the average current density and W_a the width of the entrance slot. Good optics have been obtained up to $p_s^{\max} = 1.6 \times 10^{-8} \text{ A} - V^{-3/2} = 5.1 \times 10^{-4} \text{ A} - (\text{kV})^{-3/2}$, for deuterium in an accel-decel system at 10 keV [16]. For this design, the temperature of the ions injected into the accelerator causes only corrections to the divergence.

If the beam at the entrance has a peak current density J_0 and half-width to the $1/e$ point of W_b , one finds that

$$j = \left(J_- / W_a \right) \operatorname{erf} \left(W_a / 2W_b \right) \quad (2)$$

Here $J_- = \sqrt{\pi} W_b J_0 F_-^\infty$ is the current per unit length; in terms of the current density at the source, $J_- = F_-^\infty j_s W_s$. If, as assumed, the source is focused in the narrow direction, $W_b = L_f \theta_\parallel$, with L_f the distance from source to accelerator. (Angular scattering considerations may change this slightly.)

The current accepted into the accelerator is thus

$$J_a = j W_a F_-^\infty = J_- \operatorname{erf} \left(W_a / 2W_b \right) \quad (3)$$

with W_a given by

$$W_a \operatorname{erf} \left(\frac{W_a}{2W_b} \right) \lesssim p_s^{\max} V^{3/2} / J_- \quad (4)$$

Note that there are other constraints: the accelerator slot length must be at least 10 times its width in order that end effects will be small [28]. In addition, the electric field in the accelerator must be less than 100 kV/cm to prevent breakdown [25].

4. SELECTION OF BEAM ENERGY AND CHARGE EXCHANGE MEDIUM

This completes the information needed to determine the optimum beam energy and (thus) the charge exchange medium and system parameters. As a first step, compare the predicted current density with measured results. For focusing in both planes at a distance L_f (or far from the source), the peak current density of negative ions is predicted to be

$$j_- = F_-^\infty \frac{j_s A_a}{\pi} \left[\left(\frac{180}{\pi L_f} \right)^2 \left(\frac{1}{\theta_{\parallel} \theta_{\perp}} \right) \right] \quad (5)$$

For comparison with previous experiments $\theta_{\parallel} = 2.1 E_b^{-1/2}$ is chosen. The resulting current density is plotted in Fig. 4. Results from cesium [11,12] and sodium [15-17] are plotted at their acceleration voltage; as these experimental beams are mixtures of full, half, and third energy particles the agreement is concluded to be good.

With focusing in both dimensions, sodium has a clear advantage in obtainable current density. This, coupled with designs using sufficient sodium to permit the use of molecular ions (thereby increasing the current density at the source above what could otherwise be achieved) has made sodium a contender for a system [13,14].

A different conclusion emerges for the "one dimensional" (slot) design considered here. In this case focusing is done in only one direction, and

$$j_0 = F_-^\infty j_s W_s \frac{180}{\pi} \theta_{\parallel} L_f \quad (6)$$

The result is plotted in Fig. 5. Angular scattering effects will be considered later. Note that in this limit the current density is almost independent of energy, so that the system optimum can be expected at lower energy.

Using the above conditions, the total current accepted in the accelerator is found to be:

$$I^- = F_-^\infty (j_s W_s l_a) \operatorname{erf} \left(\frac{45}{\pi} \frac{W_a}{L_f} E_b^{1/2} \right) \quad (7)$$

with l_a the accelerator length. Because of the angular divergence of the initial beam, the source is longer than the accelerator slot. The current density at the accelerator can be made uniform in the dimensions along the slot by choosing

$$l_s = l_a + 2\alpha L_f \theta_l \quad (8a)$$

$$= l_a + 2\alpha L_f \left(7\pi/180 E_b^{1/2} \right) . \quad (8b)$$

The source is curved near its ends to focus those beamlets inward. Preliminary calculations indicate that $\alpha = 0.5$ is possible.

There are two constraints on the accelerator length. The condition on perveance, Eq. (3), can be written as

$$\frac{l_a}{W_a} \geq \frac{1}{p_s^{\max}} \frac{I^-}{V^{3/2}} \quad (9)$$

with $p_s^{\max} = 5.1 \times 10^{-4} A \text{-(kV)}^{-3/2}$. The condition to neglect end effects is

$$\frac{l_a}{W_a} \geq 10 . \quad (10)$$

Condition (6) constrains the system first if

$$I^- > I_0^- = 10 p_s^{\max} V^{3/2} \quad (11)$$

In the numerical examples considered below $V = 200$ keV is chosen; consequently the perveance will be constraining for $I^- > 14.4$ A.

In the limit of high source energy the initial beam is well focused. There is no need to make the argument of the error function in Eq. (1) greater than 1.5, at which point the function is 0.97. Thus, in the limit of large E_b , we set

$$W_\alpha = \pi L_f / 30 E_b^{1/2} \quad (12)$$

The energy above which this is valid is found by combining Eqs. (7) and (9)-(12), yielding

$$\frac{F_-^\infty}{E_b^{1/2}} = \frac{3 I^-}{0.97 \pi j_s W_s L_f} \quad I^- \leq I_0 \quad (13a)$$

$$\frac{F_-^\infty}{E_b^{1/2}} = \frac{30 p_s^{\max} V^{3/2}}{0.97 \pi j_s W_s L_f} \quad I^- \leq I_0 \quad (13b)$$

In the following several numerical examples are considered. All have $V = 200$ keV, $j_s = 0.15$ A/cm², $5 \text{ cm} \leq W_s \leq 10 \text{ cm}$, and $L_f = 250$ cm. Three values of I^- will be considered: 5 A, 10 A, and 20 A. Thus, one finds from Fig. 2 that the high energy approximation is valid for:

$$\begin{array}{ll} E_b \geq 12 \text{ keV} & I^- = 5 \text{ A} \\ E_b \geq 8.5 \text{ keV} & I^- = 10 \text{ A} \\ E_b \geq 6.2 \text{ keV} & I^- = 14.4 \text{ A} \end{array}$$

At lower beam energies the appropriate limiting condition from Eqs. (9) or (10) must be included. There are essentially two options: (a) Reduce $j_s W_s$,

thus reducing the current density into the accelerator and compensating by lengthening the source and accelerator. To the extent that it can be done by reducing W_s this will lead to a minimum area of the source. (b) Reduce W_a while keeping the current density as high as possible but reducing the current accepted into the accelerator per unit length. This will lead to a design of minimum length.

Both of these extreme options are considered. One could, of course, design a system between these limits. Results are shown in Figs. 6 to 8.

a. $I^- = 5$ A. At all energies the system is constrained by the condition $l_s/W_s \geq 10$. the results are surprisingly independent of energy. The design for minimum l_s has a weak minimum from 6 to 8 keV (sodium operation) whereas that for minimum area has a weak minimum at 2 keV (rubidium operation). The minima are quite shallow, however, and considerations such as ease of handling the particular charge exchange vapor could be dominant.

b. $I^- = 10$ A. Here the system is limited by available current at energies 8.8 keV and by $l_s/W_s \geq 10$ at lower energies. The design for minimum l_s has a weak minimum at about 2.5 keV (rubidium), but the results are almost independent of energy. The design for minimum area, on the other hand, has a pronounced minimum at 1.5 to 2 keV (rubidium).

c. $I^- = 20$ A. The system is limited by available current above 6.2 keV and by the accelerator perveance at lower energies. The minimum length design has a definite minimum at 1.5 to 2 keV (rubidium) and that for minimum area optimizes at 1 to 1.5 keV (cesium or rubidium).

It is necessary to estimate the effect of angular scattering on these results. The lowest energy of interest is 1 keV, at which cesium has the largest conversion efficiency. From Eq. (1) $\theta_s = 0.31(n1)^{0.7}$. The line density required is about $1 \times 10^{15} \text{ cm}^{-2}$ (Fig. 3), so $\theta_s \sim 0.31^\circ$. The source

divergence at 1 keV is 2^0 ; as the scattering is a diffusion process and as the scattering center (jet) is midway between source and the accelerator, the final beam width is increased by about $1 + (0.5 \times 0.31/2)^2 1/2 = 1.003$. Thus even at this energy the angular scattering is not a serious problem.

The designs are far from voltage holding limits. The fields in the accelerator are comparable to those in a Child-Langmuir design, which has an average field $29 J^{1/2} V^{1/4}$. At 0.02 A/cm^2 and 200 kV, the field is only 15 kV/cm.

The beam parameters for a 20 A, D^- beam are summarized in the two cases in Table I. It is clear that the beam angular divergence is large enough that considerable D^- current is missing the accelerator in both cases. To take more advantage of the high production at low energies there are four options:

- a. Decrease L_f , minimizing angular divergence. However, as the acceleration is perveance limited at the design energy this will not significantly reduce the accelerator length.
- b. Learn how to relax the constraints on a single slot system.
- c. Use a multiaperture system for the accelerator. The utilization of available current at low energies is low enough that competitive multiaperture sources may be possible.
- d. Operate at higher ($>200 \text{ keV}$) final energies.

These options will not be explored further here, but should be considered in future development efforts.

5. CONCLUSIONS

We have presented an analysis of a negative ion system based upon charge exchange production of D^- in alkali metals and extrapolating from results in

experimental beamlines. Those results demonstrate that system performance can be predicted.

Subject to the assumptions used in the present designs, we conclude that systems producing 5 to 20 A of D^- at 200 keV are feasible although large. The energy cost per ion is less than 23 keV (Table I). As this is much less than the final 200 keV energy is is not a major limiting factor.

Detailed layout of such a system was not considered here - problems of pump configuration, power supplies, voltage holding, stored energy, etc. offer real constraints on a final design, but lie outside the scope of the present considerations.

It is concluded that unless some of the constraints used in the analysis are relaxed, the optimum system will operate with an initial beam energy of 1.5 to 2 keV and use rubidium as the charge exchange medium. A list of options which might permit better utilization of the large negative ion production in cesium was presented. These should be considered in future work.

6. ACKNOWLEDGEMENTS

We wish to thank R. V. Pyle and the staff of the LBL-MFE group for its hospitality during the period that this work was done. We also wish to thank Joel Fink for reading and commenting on the manuscript.

This work was supported by the Fusion Energy Division of the Department of Energy under contract no. W-7405-ENG-48.

REFERENCES

- [1] RIVIERE, A., Neutral Injection Heating of Toroidal Reactors, Culham Report CLM-R112 (1971), Appendix 3.
- [2] BERKNER, K. H., PYLE, R. V., STEARNS, J. W., Nucl. Fusion 15, (1975) 249.
- [3] DIMOV, G. I., ROSYLAKOV, G. V., Nucl Fusion 15, (1975) 551.
- [4] FINK, J. H., FRANK, A. M., LLL Report UCID-16844 (1975).
- [5] HOOPER, E. B., Jr., Proc. 3rd Symp. Plasma Heating in Toroidal Devices, SINDONI, E., ed (Editorial, Bologna, 1976), p. 278.
- [6] FINK, J. F., Proc. Symp. and Neut. of Negative Hydrogen Ions and Beams, PRELEC, K. Ed. (Brookhaven, 1977), p. 290.
- [7] HOOPER, E. B., JR., IEEE Trans. Nucl. Sci. NS-26 (1979) 1287.
- [8] See Proc. Symp. Prod. and Neut. Negative Hydrogen Ions and Beams, PRELEC, K., ed. (Brookhaven 1977).
- [9] HOOPER, E. B. JR., LLL Report UCID-18067 (1979).
- [10] OSHER, J. E., GORDON, F. J., HAMILTON, G. W., Proc. 2nd Intl. Ion Source Conf., Vienna, 1972.
- [11] POULSEN, P., ANDERSON, O. A., HOOPER, E. B. JR., ORZECOWSKI, T. J., TURNBULL, R. J., Proc. 7th Symp. Eng. Prob. Fusion Research, (1977) 1408.
- [12] HOOPER, E. B. JR., ANDERSON, O. A., ORZECOWSKI, T. J., POULSEN, P. Ref. 8, p. 163.
- [13] SEMASHKO, N. N., KUSNETSOV, V. V., KRYLOV, A. I., Ref. 8, p. 170.
- [14] SEMASHKO, N. N., KUZNETSOV, V. V., KRYLOV, A. I., Proc. 8th Symp. Eng. Prob. Fusion Research, (1979).
- [15] POULSEN, P. HOOPER, E. B. JR., Proc. 8th Symp. Eng. Prob. Fusion Research (1979).

- [16] HOOPER, E. B. JR., POULSEN, P., PINCOSY, P. A., ANDERSON, O. A., DUFFY, T. J., "High Current D^- Production by Charge-Exchange in Na: Neutral Beam Applications" LBL-10454 (1980).
- [17] HOOPER, E. B., POULSEN, P., PINCOSY, P. A., in preparation.
- [18] GELLER, R., JACQUOT, C., SERNET, P. Proc. Symp. Prod. and Neut. Negative Hydrogen Ions and Beams, K. Prelec, ed. (Brookhaven, 1977). p. 173.
- [19] GELLER, R., JACQUOT, B., JACQUOT, C., SERNET, P., TSHEROS, J., to be published.
- [20] BECKER, E. B., FALTER, H. D., HAGNEA, O. F., HENKES, R. KLINGELHOFFER, R., MOSER, H., OBERT, W., POTH, I., Proc. Symp. Prod. and Neut. Negative Hydrogen Ions and Beams, K. Prelec, ed. (Brookhaven, 1977), p. 322.
- [21] BECKER, E. B., FALTER, H. D., HAGEMA, O. F., HENKES, R., KLINGELHOFFER, R., MOSER, H., OBERT, W., POTH, I., Nucl. Fusion 17, 617 (1979).
- [22] SCHLACHTER, A. S., private communication.
- [23] ANDERSON, O. A., Lawrence Livermore Lab. Report UCID-17581 (1978).
- [24] BORN, M., WOLF, E., Principles of Optics (Pergamon, N.Y. 1970).
- [25] BERKNER, K. H., BURRELL, C. F., COOPER, W. S., EHLERS, K. W., LIETZKE, A. F., OWREN, H. M., PATERSON, J. A., PYLE, R. V., STEARNS, J. W., IEEE 8th Symp. Eng. Prob. Fusion Research, 1979.
- [26] MASCHKE, A. W., Brookhaven Report BNL-51029 (1979).
- [27] ANDERSON, O. A., Lawrence Livermore Laboratory Rept. UCID-16914 (1975).
- [28] COOPER, W. S., HALBACH, K., MAGYARY, S. B., Proc. 2nd Symp. Ion Sources and Formation of Ion Beams, (Lawrence Berkeley Lab, LBL-3399, 1974); p. II-1.

- [29] SCHLACHTER, A. S., K. STALDER, K. R., STEARNS, J. W., Proc. 10th Intl. Conf. Phys. Elec. and Atomic Coll., Paris, 1977, p. 870.
- [30] SCHLACHTER, A. S., STALDER, K. R., STEARNS, J. W., submitted to Phys. Rev. A.
- [31] ANDERSON, C. J., HOWALD, A. M., ANDERSON, L. W., Nucl. Instr. Meth. 165, 583 (1979).
- [32] SCHLACHTER, A. S., STALDER, K. R., STEARNS, J. W., in preparation.
- [33] HOOPER, E. B. JR., WILLMANN, P. A., SCHLACHTER, A. S., Lawrence Livermore Report UCID-17726 (1978).
- [34] CISNEROS, C., ALVAREZ, J. BARNETT, C. F., RAY, J. A., Phys. Rev. A14, 76 (1979).
- [35] AGAFONOV, Yu. A., D'YACHKOV. B. A., PAVLII, M. A., J. Tech. Phys., to be published.
- [36] POULSEN, P. RATEKIN, G. H., DUFFY, T. J., Bull. Am. Phys. Soc. 23, 846 (1978).
- [37] BACAL, M., private communication.
- [38] CONDIT, R., private communication.
- [39] HANSEN, M., ANDERKO, K., Constitution of Binary Alloys (McGraw-Hill, N. Y., 1958).

Table I. 20 A, D⁻ Source for Injection into 200 kV Accelerator

	<u>MINIMUM LENGTH DESIGN</u>		<u>MINIMUM AREA DESIGN</u>	
	<u>+ D SOURCE</u>	<u>- D BEAM</u>	<u>+ D SOURCE</u>	<u>- D SOURCE</u>
Accelerator Dimensions	10 cm × 134 cm (1340 cm ²)	7.9 cm × 110 cm (870 cm ²)	5 cm × 190 cm (950 cm ²)	11.6 cm × 160 cm (1860 cm ²)
Beam Energy	1.5 keV	1.5 keV	1.5 keV	1.5 keV
Current	200 A	20 A	143 A	20 A
Average Current Density	150 mA/cm ²	23 mA/cm ²	150 mA/cm ²	11 mA/cm ²
Peak Current Density	300 mA/cm ²	26 mA/cm ²	300 mA/cm ²	14 mA/cm ²
F ₋ [∞] (Rubidium)	-	21.5%	-	21.5%
Net Conversion Efficiency	-	10%	-	14%
Energy Cost/Ion	0.9 keV	22.5 keV	0.9 keV	15.6 keV
Gas Efficiency	35%	3.5%	35%	4.9%

FIGURE CAPTIONS

- FIG. 1. Angular divergence for slot-type accelerators; $\theta_{\parallel}$ = along slots; $\theta_{\perp}$ = across slots. The angles shown are half-widths to $1/e$ of the angular profile.
- FIG. 2. Deuterium Equilibrium Fraction (F_{-}^{∞}) in alkali metal vapors. (From Refs. 29 and 30). The materials yielding the maximum values in the energy range 0.3 to 12 keV are shown.
- FIG. 3. E-folding length for negative ion production, $(\sigma_{o-} + \sigma_{-o})^{-1}$. Sodium data from Anderson et al. [31], cesium data from Schlachter et al. [21], and Hooper, et al. [29]. The latter cross sections have been multiplied by 1.8 to bring them into agreement with Schlachter et al. [21]
- FIG. 4. Current density for focusing in two dimensions.
- FIG. 5. Current density for focusing in one dimension.
- FIG. 6. Minimum source length and area designs for $I^{-} = 5$ A.
- FIG. 7. Minimum source length and area designs for $I^{-} = 10$ A.
- FIG. 8. Minimum source length and area designs for $I^{-} = 20$ A.

XBL 806-1027

Fig. 1

Fig. 2

XBL 805-1008

XBL 805-1006

Fig. 3

XBL 805-1007

Fig. 4

-27-

XBL 809-11769

Fig. 5

XBL 805-1005

Fig. 6

XBL 805-1003

Fig. 7

XBL 805-1004

Fig. 8

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720