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Conceptual Design of a 200 keV, 1 MW
Negative-Ion-Based Neutral Beam Line*

LBL-13404

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Abstract

We present a design for a 200 keV, 1 Megawatt negative-ion-based beam line which is intended to serve as a proof-of-principle demonstration for the LBL surface-conversion negative ion source. The design is straightforward and conservative, and uses existing technology for all major components. An alternate beam line design is also presented, to demonstrate the advantages of reduced size and gas load and increased neutral beam power accruing from the introduction of a laser photo-detachment neutralizer. This design is less conservative, but requires only reasonable extrapolations from existing technology.

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1. Introduction

The program at the Lawrence Berkeley Laboratory (LBL) to develop multiampere long-pulse negative ion sources has as its long term goal their use on multi-megawatt neutral beam lines. It is therefore appropriate that, concurrent with the development of a negative ion source design, a serious study be made of its suitability for use in a realistic neutral beam line.

For this study, we chose to consider a beam line capable of quasi-DC operation (i.e., pulse lengths in excess of 30 sec with a high duty factor), which could deliver a 1 MW, 200 keV beam of neutral deuterium atoms. This choice is not entirely arbitrary; at one time such a requirement was considered for neutral injection on MFTF, and more recently, was suggested as a guideline by the Office of Fusion Energy (U.S. Department of Energy) in a September 1981 review of its negative-ion-based neutral beam program.

In summary, our goal in this study was to design a beam line which would serve as a proof-of-principle demonstration for the LBL negative ion source concept. Such a demonstration would not only have to show that the source could be scaled to 10 A, but that a practical beam line could be constructed based on it.

These considerations led to the following guidelines for our beam line design:

1. Practical System Characteristics

Included under this heading were beam line size and a beam emittance which would result in a beam of acceptable size and divergence at the target. Other important factors included gas load and pumping, and the related questions of beam losses during acceleration,

as well as the design of suitable systems for beam neutralization and ion removal.

2. Use of the Simplest Existing Technology

While in the long run, this criterion might not result in the optimal design, we felt that a beam line design that needed no technological breakthroughs would provide the most effective proof of principle. We made a partial exception to this rule in the case of the neutralizer system, where the advantage of a laser photo-detachment system (LPDS) appeared to be sufficient to warrant its inclusion as an alternate scheme.

3. Worst-Case Assumptions

In a number of cases, conceptual design parameters were dependent on currently unverified system performance (e.g. divergence of the beam emerging from the 200 keV accelerator). In such cases plausible worst-case values were assumed. On occasion, this resulted in apparent internal inconsistencies. For example, in estimating the size neutralizer that would accomodate the beam, the worst case would correspond to the largest plausible beam divergence expected; on the other hand, for purposes of calculating power density on the beam dumps, the pessimistic assumption would correspond to the smallest divergence. (Needless to say, one could not realize both of these worst cases simultaneously in practice).

The main purpose of this report is to describe the design of a beam line complying with the above requirements. As we have noted, we also consider the effect on such a design of including a technological innovation, a neutralizer using an LPDS.

2. Beam Line Overview

The basic beam line design is shown in Fig. 1. The source is a scaled up version of the LBL surface-conversion source designed by Ehlers and Leung,⁽¹⁾ of which a 1 A version recently has been built and has operated successfully.⁽²⁾ The increased current required for the 1 MW beam line is achieved by going to an array of three converters and increasing their length. As discussed below, the converters are separated so that the beam starts out as three individual beamlets. The source is mounted so that the long dimension of the converters is vertical.

The accelerator is a conventional electrostatic Pierce-gun type with a single slot for each beamlet. The design is conservative, the voltage gradients nowhere exceeding 25 kV/cm. Figure 2 shows the equipotentials and the ion trajectories through the accelerator as calculated by the accelerator design code WOLF. This accelerator is a modified version of an earlier design, a detailed description of which is given in Ref. 3. The present version incorporates structural modifications which give full suppression of backstreaming ions from the downstream plasma.

The neutralizer is a gas stripper (the alternate beam line design mentioned earlier, using an LPDS neutralizer, is discussed separately below), and is divided into three channels, one for each beamlet. Pumping of the neutralizer, as well as the source, is done using cryo-panels. Charged particles remaining in the beam after it traverses the neutralizer are removed using a transmission type bending magnet. Like the neutralizer, it is divided into three channels.

The length of the beam duct beyond the ion-removal system has been chosen to be 4 m. This figure is typical of existing beam lines and as such, provides a realistic requirement for beam optics. A list of the principal beam line characteristics is presented in Table I in the column labeled "Gas Neutralizer."

3. Beam Optics

The factors (other than lens aberrations) governing beam divergences for a negative ion source differ from those for positive ion sources. Parallel to the accelerator rails, the transverse motion of the negative ions at the entrance to the accelerator is not limited to thermal velocities but can, for the most pessimistic case, reflect a sizable fraction of the converter voltage, depending on how the incident positive ions backscatter from the converter. Experiments to date have shown transverse velocities considerably less than this figure--the associated energies are typically on the order of 6-7 eV.* For the case of motion perpendicular to the rails, similar considerations apply, but in this case a collimator at the source exit restricts the divergence of particles entering the accelerator. Such a collimator in fact provides a hard-edge cutoff to the entering particles so that, in principle, trajectory calculations yield the actual angular limits of the accelerated beam, rather than averaged quantities such as the 1/e divergence.

The divergences shown in Table I, which were the ones used for determining neutralizer conductances, source spacing, etc., are larger than we actually calculate them to be by a factor of 3 for the divergence

*Based on analysis of data supplied by K. N. Leung.

parallel to the slots and by a factor of 2 for the divergence perpendicular to the slots; discrepancies of this magnitude have been observed in positive ion systems, and, in the absence of measurements, we make the assumption that similar discrepancies will occur here, in order that our system evaluation be based on conservative estimates of performance.

From the standpoint of both the neutralizer and the ion-removal magnet (see Sections 4a and 5), it is desirable that the beamlets remain separated while traversing these elements. If the beamlets are placed as close together as the converter dimensions will allow (8 cm separation), the divergence causes the beamlets to overlap within 2 m of the end of the accelerator. Hence it is necessary to separate the converters.

To minimize the overall horizontal size of the beam, the beamlets are directed at angles of 2.6° relative to one another so that they fully overlap at the end of the beam duct. To minimize the vertical beam size, the accelerator rails, as well as the converter, are curved to focus the beam vertically.

4. Vacuum Considerations; Beam Neutralization

a. Gas Neutralizer

Analysis of the beam line pressure distribution has been done with the aid of two-dimensional Monte-Carlo calculations. For the source gas flow, calculations were normalized to give the correct (room-temperature-equivalent) operating pressure in the source. For the gas neutralizer, normalization was done in such a way as to give the correct integral line density of particles in the neutralizer.

Because of the cryopanel and collimator configuration between the accelerator and the neutralizer, gas introduced in the source made an almost negligible contribution to the pressure in the neutralizer, and vice-versa. Hence, in the discussion below, we consider the source and neutralizer gas flows separately, although the quantitative results presented were actually obtained from calculations in which the two flows were considered simultaneously.

For the source-accelerator geometry shown in Fig. 1, the calculated gas flow for the 10 A source is ~ 8.5 Torr-l/sec, which yields a gas efficiency of roughly 12 percent, in good agreement with the experimental results quoted in Ref. 2. Based on the calculated pressure distribution and known stripping cross sections for H^- as a function of energy, we have calculated the beam losses in the accelerator. The particle loss as a function of energy is shown in Fig. 3; integrating the area under the curve, one finds the total beam loss due to stripping to be about 6 percent.

As mentioned earlier, our choice for a neutralizer in our "basic" beam line design was a deuterium gas stripper. Despite the drawback of its added gas load, it was deemed preferable to the only alternative "existing technology" scheme of a metal vapor jet. Compared with such a device, a gas stripper achieves comparable neutralization efficiency (~ 60 percent) with much simpler operation and without the risk of heavy-element contamination.

For a deuterium gas neutralizer a maximum neutralization efficiency of about 60 percent is obtainable with a neutralizer thickness⁽⁴⁾ of $3-4.5 \times 10^{15}$ molecules/cm². To minimize the gas flow, the neutralizer should be designed for minimum conductance. One way to achieve this

is by using a separate neutralizer for each beamlet: Since the conductance of a thin duct (width $\ll$ height) varies inversely as the square of its width, a neutralizer with three separate channels has one third the conductance of a single neutralizer of three times the width. Lengthening the neutralizer also reduces the conductance, although the widening of a longer duct, necessitated by the beam divergence, imposes the law of diminishing returns somewhere around 2 m overall length. A further reduction of a factor of two in gas flow can be effected by cooling the neutralizer gas to LN_2 temperature; however, since we do not know at present whether power deposited by stray beam would constitute an intolerably large heat load for the LN_2 system, we have based our calculations on a room temperature neutralizer.

To limit the gas flow at the source end of the neutralizer, we intend to use a 5 x 90 cm collimator (water cooled and armored) at that point to further reduce the conductance. For the initial design, we have chosen to inject the gas at the neutralizer midpoint. Because of the tight baffling between neutralizer and source, it may be possible to reduce the total gas load by moving the injection point forward, without appreciably increasing the stripping losses in the accelerator.

The calculated pressure distribution for the full system of source, accelerator and gas neutralizer is shown in Fig. 4. The gas is assumed to be at room temperature throughout. The gas flow out of all three channels of the neutralizer is less than 15 Torr-l/sec at the source end and less than 25 Torr-l/sec at the magnet end.

For a beam line volume of roughly 50 m³, this means that after approximately four hours of continuous operation, the amount of deuterium trapped on the cryopanel will reach the maximum deuterium inventory

allowed on the basis of preventing an explosive deuterium-air mixture from occurring in the event of an up-to-air accident.⁽⁵⁾ It should be emphasized that this is a pessimistic limit for the cryopanel recycling interval. Should a LN_2 -cooled neutralizer prove workable, the above figure could be nearly doubled. Should the beam divergence prove to be closer to the calculated value than we have assumed, the neutralizer ducts can be made narrower, possibly also doubling the above figure. Should both the above possibilities be realizable, the recycling interval could be extended beyond 12 hours.

Even if the pessimistic figure cannot be improved on, the beam line is a viable one. Experience with the prototype TFTR beam line has shown that complete recycling of the cryopanel can be done in less than 45 minutes, which we feel is tolerable once every four hours. In addition, a cryopanel that can be isolated and recycled in situ has been developed at the Lawrence Livermore National Laboratory. Initial experiments⁽⁶⁾ indicate that the full recycling time for one of these panels is less than ten minutes; hence one could continuously recycle the panels in sequence while still maintaining over 95 percent of the pumping capacity at all times.

b. Laser Photo-Detachment Neutralizer

Since one of our self-imposed design requirements was use of existing technology, we felt it inappropriate to incorporate an LPDS neutralizer in our primary design; the components of such a system would represent extrapolations, albeit reasonable ones, from existing devices, and there have been essentially no studies of the practical problems associated with the operation of an LPDS. Nonetheless, the advantages

which appear possible with such a system appear sufficiently attractive that we felt it would be a valuable exercise to consider how its incorporation would modify the beam line design.

The basic advantages of an LPDS neutralizer are that it produces no gas load, it introduces flexibility in the beam line design by permitting a configuration in which the ion source is grounded and the neutralizer is at high voltage, and has the potential for neutralization efficiencies on the order of 99 percent.⁽⁷⁾ A word of explanation on the last point is in order. One of the main advantages to this high efficiency is that it eliminates or greatly simplifies the ion-removal system, thereby significantly reducing both the length, and more importantly, the cross-sectional area of the beam line. While there also appears to be an increase in beam line power efficiency in going from 60 percent to essentially 100 percent neutralization, this can be misleading. As may be seen from Ref. 7, going from 90 percent to 99 percent efficiency in a LPDS requires doubling the laser power. When one examines the numbers, this is almost never warranted exclusively on the basis of power efficiency, but can be justified in terms of the price one is willing to pay for additional space available in the area surrounding the confinement device.

The power required for an LPDS is directly proportional to the mirror height,⁽⁷⁾ which in turn must equal or exceed the neutral beam height; since the beam height grows with distance from the source, it is desirable to keep the neutralizer as short as possible, consistent with the power capability of existing lasers and mirrors. For a 200 keV D-beam, a 1.5 m long neutralizer 12 cm high would have a neutralizing efficiency of 99 percent, with an optical power density within the

neutralizer of roughly 30 kW/cm^2 (such specifications appear to represent a reasonable extrapolation of demonstrated laser and mirror technology).⁽⁸⁾

A conceptual design for a 1 MW negative-ion neutral beam line employing a LPDS neutralizer is shown in Fig. 5. The laser itself is not shown, since it may not be necessary for the device to be attached directly to the beam line. As pointed out by McGeoch, the iodine chemical laser appears to be the one best suited for use in an LPDS⁽⁹⁾; the cavity for an iodine laser meeting the power and wavelength requirements for this system would have dimensions⁽⁸⁾ of roughly $.15 \times .15 \times 2.5 \text{ m}$. Comparison with Fig. 1, which is drawn to the same scale, clearly indicates the reduction in beam line size attainable through use of the LPDS. A detailed quantitative comparison of properties for the LPDS and gas neutralizer beam lines is presented in Table I. Note that since the LPDS beam line shown has the same size ion source as the conventional one, the increased efficiency of the laser neutralizer now enables the beam line to deliver 2 MW of neutral power, rather than 1.2 MW.

5. Ion Removal System

With the gas neutralizer, 41 percent of the accelerated beam emerging from the neutralizer ($\sim 0.8 \text{ MW}$) consists of positive and negative ions which must be deflected and deposited on ion dumps. Fortunately, the power density is low enough to allow a very conventional design, as shown in Figure 1. The bending magnet has a separate channel for each beamlet in order to simplify computation of trajectories.

For each channel, the entrance and exit apertures are parallel to each other and normal to the centerline of the incoming beamlet. Thus, the optics in the direction transverse to the beam deflection plane is easy to calculate, and we find the maximum power density at the D⁻ dump (taking 23 percent of the beam power in D⁻) to be approximately

$$P_{\text{dump}} = \frac{0.23 W_{\text{beamlet}}}{2\theta |M_{12}| L_{\text{bend}}}$$

where $W_{\text{beamlet}} = 720$ kW, θ is the (hard-edge) beam half-angle (.011 rad), and M_{12} is the appropriate magnet matrix element (estimated to be about 780 cm in the present case), and the factor L_{bend} is the length of the beam footprint on the ion dump.

The optics in the bend plane, including the effect of the focussed source, can be computed by trigonometry. Crossover points occur at 88 cm and 150 cm for the upper and lower beam edges respectively, as measured from the magnet exit along the beam centerline. Thus, with the dump placed and tilted as shown, the beamlet extends only 35 cm along the dump, neglecting thermal broadening. To get the worst case, we assume an angular half-width of 0.33° parallel to the rails, and find that the maximum power density is unaffected; thus $L_{\text{bend}} = 35$ cm.

Under the above condition, we calculate the power density on the dump to be 0.28 kW/cm², which is quite low. The actual power density will be smaller if the beam divergences are as high as the maximum values in Table I. (However, note that M_{12} was only calculated to lowest order and could be in error by ± 50 percent.) In the figure, the ion dumps appear to determine the vertical size of the beam line, but as

the calculation shows, they could actually be made much more compact if the space were needed for other purposes.

6. Possible Improvements

There are a number of areas in which it may be possible to improve on the basic design shown in Fig. 1. These range from areas in which, due to lack of time, the existing design was not fully optimized, (e.g. the overall mechanical design) to those where optimal design depends on a detailed knowledge of as-yet-unmeasured subsystem performance (e.g., beam divergence, full-scale ion source operating characteristics), to those which depend on the development of new technologies or techniques (e.g., laser photo-detachment). One possible improvement which might effect a qualitative change in the design is that of beam current density; here a factor of three increase would not only result in a single beam channel, but might therefore also permit the replacement of the ion-removal magnet by an electrostatic deflector.

The various areas in which possible improvements are foreseen and the various aspects of system performance they affect are shown in Table II. Note that the various system characteristics are not entirely independent; for example, reduced gas flow may make possible improved operability and/or power efficiency. Moreover in some instances the improvements must be traded off; for example, the reduced conductance made possible by using an LN_2 -cooled neutralizer could be used to reduce either the beam line length or the gas flow. An "X" in the table indicates a definite resulting improvement in that aspect of system performance; a "?" indicates that further study is required to determine whether system performance can be improved by the given development.

7. Conclusion

We have demonstrated that, even under the most pessimistic assumptions, a realistic 1 MW 200 keV neutral beam line can be constructed using a negative ion source of the Ehlers-Leung design. The beam line design uses existing technology, is conservative, and has low risk. Indeed, it is so straightforward that detailed design and construction could be started immediately. Moreover, because of the modular nature of the source, both source and beam line can be "expanded" to achieve higher total power, assuming the resulting range of beam angles to be acceptable to the associated fusion device. A substantial reduction in overall beam size (and gas loading, as well), along with a substantial increase in beam power, is made possible if one can replace the gas neutralizer with a laser photo-detachment system.

8. Acknowledgments

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9. See discussion following presented paper in Ref. 7.

Figure Captions

- Fig. 1. Proposed 1 MW, 200 keV negative-ion beam line using 10 A scaled version of LBL surface-conversion negative ion source and a gas stripper.
- Fig. 2. Ion trajectories and potential distribution for 200 keV accelerator.
- Fig. 3. Particle loss during acceleration, as a function of energy.
- Fig. 4. Calculated pressure distribution in accelerator and neutralizer.
- Fig. 5. Proposed 200 keV beam line using LPDS neutralizer. The scale is the same as that in Fig. 1.

Table 1. Comparison of LPDS Beam Line and Beam Line with Gas Neutralizer

	Gas Neutralizer	LPDS Neutralizer
I. Beam		
Beamlet Cross-Section at Accelerator Exit	2.6 x 87 cm *	2.6 x 85 cm *
Orientation (Long Dimension)	Vertical	Horizontal
Angle Between Beamlets	2.6°	2.1°
Divergences		
Angular Half-Width Perpendicular to Slot†		
Calculated	0.7°	Same
Anticipated Worst Case	1.3°	Same
1/e Angular Half-Width Parallel to Slot		
Due to Beam Alone	1° Max	Same
Including Effect of Electrode Curvature	2.8**	3.8**
Beam Footprint at End of Beam Duct *	45 x 50 cm	31 x 35 cm
Current Per Beamlet (D ₂ Operation)	3.6 A	Same
Energy	200 keV	Same
Pulse Length	DC	Same
II. Source		
Number of Converters	3	Same
Converter Dimensions	13 x 100 cm	Same
Spacing of Converters (Center to Center)	46 cm	26 cm
Converter Voltage	200 V	Same
Gas Efficiency (Calculated)	>12 %	Same
Gas Flow (Calculated)	8.5 Torr-L/sec	
III. Neutralizer		
Effective Neutralizer Thickness	$3.2 \times 10^{15} \text{ cm}^{-2}$	N/A
Total Length of Neutralizer	2.0 m	1.5 m
Cross Section	14 x 90 cm	N/A
Entrance Collimator Width	5 cm	N/A
Gas Flow Out Front of Neutralizer (D ₂)	15 Torr-L/sec	0
Gas Flow Out Rear of Neutralizer (D ₂)	25 Torr-L/sec	0
Neutralizer Efficiency	59%	99%
Fraction of Beam Converted to D ⁺	18%	0%
Fraction of Beam Remaining as D ⁻	23%	1%
IV. Other		
Overall Internal Dimensions,		
Excluding Beam Duct (L x W x H)	5.6 x 2.0 x 4.4 m	3 x 2 x 2 m
Distance From End of Accelerator		
To End of Duct	9.6 m	6.5 m
Cryopanel Area	50 m ²	19 m ²
Allowed Interval Between Cyclings of Cryopanel		
(Without on-Line Recycling Capability)	3.8 Hrs.	5.7 Hrs.
Estimated On-Line Recycling Time	<10 Min	Same
V. Anticipated System Performance		
Current From Source	10.8 A	Same
Beam Loss During Acceleration	6%	Same
Reionization Loss	1%	<1%
Neutral Power to Plasma	1.2 MW	2.0 MW

* Differences due to altered focal length of accelerator in "parallel" direction as a result of change in length of beam line

† Hard-edge limit produced by collimator in source

** Hard-edge limit in "transverse" direction; (1/e)² full-width "parallel"

TABLE II. Effect of Various Improvements on System Performance

	<u>Reduced Beam Line Size</u>	<u>Reduced Gas Flow</u>	<u>Improved Operability</u>	<u>Improved Power Efficiency</u>
Increased Current Density	X	X		X*
Source Housing Design			X	?
Optimize Gas Neutralizer Geometry		X		
LN ₂ -Cooled Neutralizer	X	X		
Laser Photo Detachment System	X	X		
Improved Beam Divergence	X	X		
Ion Removal System	X			
Cryopanel Orientation				
Near Source			X	?
Optimized Mechanical				
Design	X	?		

* Applies primarily to LPDS system; a considerably smaller improvement (as a result of reduced stripping in the accelerator) may also result, and this benefit would accrue to both beam lines.

XBL 8110-11953

Fig. 1

5 cm

XBL 821-68

Fig. 2

XBL 821-67

Fig. 3

XBL 821-66

Fig. 4

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Fig. 5

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