Efficiencies of Gas Neutralizers for Multi-MeV
Beams of Light Negative Ions

PPPL--1857

DE82 005726

L. R. Grisham and D. E. Post
Princeton University Plasma Physics Laboratory
Princeton, N. J. 08544

and

B. M. Johnson, K. W. Jones, J. Barette, T. H. Kruse,*
I. Tserruya,** and Wang Da-Hai***
Brookhaven National Laboratory
Upton, N. Y. 11973

ABSTRACT

We report measurements of the neutral and charged particle fractions produced by running beams of Li^- , C^- , O^- , and Si^- at energies up to 7 MeV through gas cells of N_2 , Ar, or CO_2 . We discuss the implications of these measurements for the design of neutralizers to produce high energy light atom beams for heating or current drive in tokamaks.

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- * Rutgers University, New Brunswick, N. J.
- ** Weizmann Institute, Israel
- *** IAE, Peking

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I. Introduction

Fusion reactors will almost certainly require some method of auxiliary heating to reach thermonuclear ignition temperatures, and, if steady - state operation is necessary, then they will also require a non-inductive technique for current drive. At the present time, the injection of high energy beams of atoms is the best understood method of heating a plasma. Its efficiency has been demonstrated on a number of tokamaks¹ using neutral hydrogen beams formed from positive ions neutralized by charge exchange in a gas neutralizer.² However, the rapid decline of the equilibrium neutral fraction as the energy increases renders positive-ion-based neutral deuterium beams uneconomical at energies in excess of 150-200 keV. D^- based neutral beams offer the possibility of better efficiency at the higher energies which will be required for sufficient penetration in reactor grade plasmas, but much work remains before they are developed to an adequate point.²

Recently, two alternative methods for heating or current drive have been proposed. The first of these, injection of beams of light positive ions (such as Ne^+) at 1-2 MeV per amu,^{3,4} requires no neutralizer, but faces significant uncertainties in the transport of the positive ions across the spatially-varying magnetic fields outside the plasma. The other recently proposed method, injection of multi-MeV beams of light atoms such as $O^+ 5-8$ formed from negative ions, circumvents the cross-field transport problems but requires a method of neutralizing beams of light

negative ions at energies of 1-2 MeV/amu (such beams have also been proposed for the end plugs of tandem mirrors⁹). The simplest neutralizer would be one incorporating a gas to strip off the extra electron. Since the neutralizer would be located many meters away from the ion source, the neutralizer gas need not be the same as that in the source and could be chosen for its pumping properties.

In Refs. 5-9, four negative ions (Li^- , C^- , O^- , and Si^-) have been considered as candidates for heating, current drive, or mirror plugging. However, data on the neutralization efficiency achievable with gas cells is available only for Li^- ^{10,11} at energies in the MeV range. Information on the gas neutralization efficiencies of the negative ions heavier than Li^- is essential to determine whether light atom beam systems are feasible with gas stripper cells, or whether some other type of neutralizer will be required. In this paper we report measurements of neutral and charged particle fractions in beams formed from negative ions of lithium, carbon, oxygen, and silicon which have passed through neutralizer cells of N_2 , Ar, or CO_2 .

II. Experimental Arrangement

Figure 1 shows the beamline arrangement used to make the measurements. The negative ions were accelerated by the MP-6 tandem at Brookhaven National Laboratory, which was able to hold a maximum potential of 7 MV operating in the negative mode. In the beamline electrostatic plates ahead of the gas cell deflected the negative ions through 2° to purify the beam of other charge

states which might have been formed during transport to the gas cell. Electrostatic plates after the gas cell separated the resultant charge states onto a position sensitive detector, yielding a clean spectrum of peaks.

III. Results

The charge state composition of the beam emerging from the gas cell was measured as a function of cell thickness for each incident negative ion with various target gases. The target gases, N_2 , Ar, and CO_2 , could all be easily pumped by cryocondensation if they were used in a neutral beam heating system. The gas cell thickness was monitored with a capacitance manometer on the gas feed line. The cell thickness measurements are not absolute, but for our purposes (determining the maximum neutral fraction) it is adequate to plot the neutral yield against the relative thickness.

Figures 2-14 give representative samples of the charge state data. With the more massive projectiles, the maximum neutral fraction achievable is considerably less than for Li^- , apparently in part because of the significance of multiple-electron-loss collisions. That such collisions are important with the more complex projectiles (C^- , O^- , Si^-) is indicated by the large fraction of positive ions (which have lost at least two electrons) which is present even for low cell thicknesses where the probability of multiple collisions is small. Table I gives the maximum neutral fraction obtained for each combination of energy, negative ion beam, and neutralizer gas used. The maximum neutral fraction,

$F_{\max}^{\circ}$, which could be obtained with a given beam was not strongly dependent upon the type of gas used. Further, for the cases for which a comparison could be made (Li and C), $F_{\max}^{\circ}$ was not declining with energy between 4 and 7 MeV, but in fact appeared to have been rising slightly. The lithium results are consistent with the previous available measurements at the only two points where they can be compared. Reference 11 found a $F_{\max}^{\circ}$ of ~ 0.43 for 2 MeV Li^{-} in N_2 , while we measure 0.42. Reference 10 found a $F_{\max}^{\circ}$ of 0.49 at 6 MeV for Li^{-} in N_2 , while we observe 0.46 at 7 MeV. Reference 10 did not observe any Li^{+++} , while we found $F^{3+} \sim .01$ at $F_{\max}^{\circ}$; if the .01 is subtracted from the ref. 10 value of $F_{\max}^{\circ}$, it brings it even closer to our measurements.

IV. Discussion

Present plans⁷ for light atom heating beams based upon negative ions with $Z \geq 3$ call for the accelerator to be a RF linac. This would most probably be a RF Quadrupole accelerator of the type being developed at LASL.¹² The gross system efficiency of such an accelerator is estimated to be in the range of 35-38%.¹³ With this accelerator efficiency, a gas neutralizer for Li^{-} might be marginally acceptable at 7 MeV, giving a total efficiency of 15-17%. The operating energies for neutral beam systems using the ions more massive than Li^{-} would be higher than 7 MeV, but even if we assumed that the maximum neutral fractions would not decrease significantly in going to 1-2 MeV/amu, the total power efficiencies resulting from gas neutralization of C^{-} , O^{-} , and Si^{-} appear to be too low for current drive applications, and they are rather low

for tokamak ignition purposes unless the accelerator efficiency can be increased. Ref. 10 found that $F_{\max}^{\circ}$ was somewhat higher for 6 MeV Li^{-} using H_2 instead of N_2 (.56 versus .49). We did not have adequate pumping to try H_2 , but it seems unlikely that its use would increase $F_{\max}^{\circ}$ for the heavier ions (C^{-} , O^{-} , Si^{-}) sufficiently to significantly change the feasibility. At 7 MeV, $F_{\max}^{\circ}$ is considerably lower for carbon than for lithium, while the $F_{\max}^{\circ}$ for oxygen and silicon are similar to each other and are appreciably lower than the $F_{\max}^{\circ}$ for carbon. It appears probable, then, that still more massive negative ions would yield maximum neutral fractions which were no higher than about 19-23% and which might be lower.

Thus, a non-gaseous neutralizer — probably a photodetachment neutralizer — will be required to achieve a high efficiency light atom beam system using a RF quadrupole accelerator. Gas neutralizers might be used, especially for Li^{-} , if the relatively low power efficiencies which result can be tolerated, or if a more efficient accelerator system can be devised.

Acknowledgment

This Work was Supported by U.S.D.O.E. Contract DE-AC02-76-CH03073.

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FIGURE CAPTIONS

- (1) Diagram of experimental arrangement.
- (2) Charge state fractions resulting from 2 MeV Li^- passing through N_2 .
- (3) Charge state fractions resulting from 4 MeV Li^- passing through CO_2 .
- (4) Charge state fractions resulting from 7 MeV Li^- passing through CO_2 .
- (5) Charge state fractions resulting from 4 MeV C^- passing through Ar.
- (6) Charge state fractions resulting from 7 MeV C^- passing through N_2 .
- (7) Charge state fractions resulting from 7 MeV C^- passing through Ar.
- (8) Charge state fractions resulting from 7 MeV C^- passing through CO_2 .
- (9) Charge state fractions resulting from 7 MeV O^- passing through N_2 .
- (10) Charge state fractions resulting from 7 MeV O^- passing through Ar.
- (11) Charge state fractions resulting from 7 MeV O^- passing through CO_2 .
- (12) Charge state fractions resulting from 7 MeV Si^- passing through N_2 .
- (13) Charge state fractions resulting from 7 MeV Si^- passing through Ar.
- (14) Charge state fractions resulting from 7 MeV Si^- passing through CO_2 .

TABLE I

PROJECTILE	ENERGY (MeV)	GAS	$F_{\max}^{\circ}$
${}^7\text{Li}^-$	2	N_2	.42
${}^7\text{Li}^-$	4	N_2	.40
${}^7\text{Li}^-$	4	CO_2	.40
${}^7\text{Li}^-$	7	N_2	.45
${}^7\text{Li}^-$	7	CO_2	.42
${}^{12}\text{C}^-$	4	N_2	.25
${}^{12}\text{C}^-$	4	CO_2	.24
${}^{12}\text{C}^-$	4	Ar	.26
${}^{12}\text{C}^-$	7	N_2	.28
${}^{12}\text{C}^-$	7	CO_2	.26
${}^{12}\text{C}^-$	7	Ar	.27
${}^{16}\text{O}^-$	7	N_2	.21
${}^{16}\text{O}^-$	7	CO_2	.19
${}^{16}\text{O}^-$	7	Ar	.21
${}^{28}\text{Si}^-$	7	N_2	.22
${}^{28}\text{Si}^-$	7	CO_2	.21
${}^{28}\text{Si}^-$	7	Ar	.23

Fig. 1

FIG. 2

81X1127

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

FIG. 13

FIG. 14