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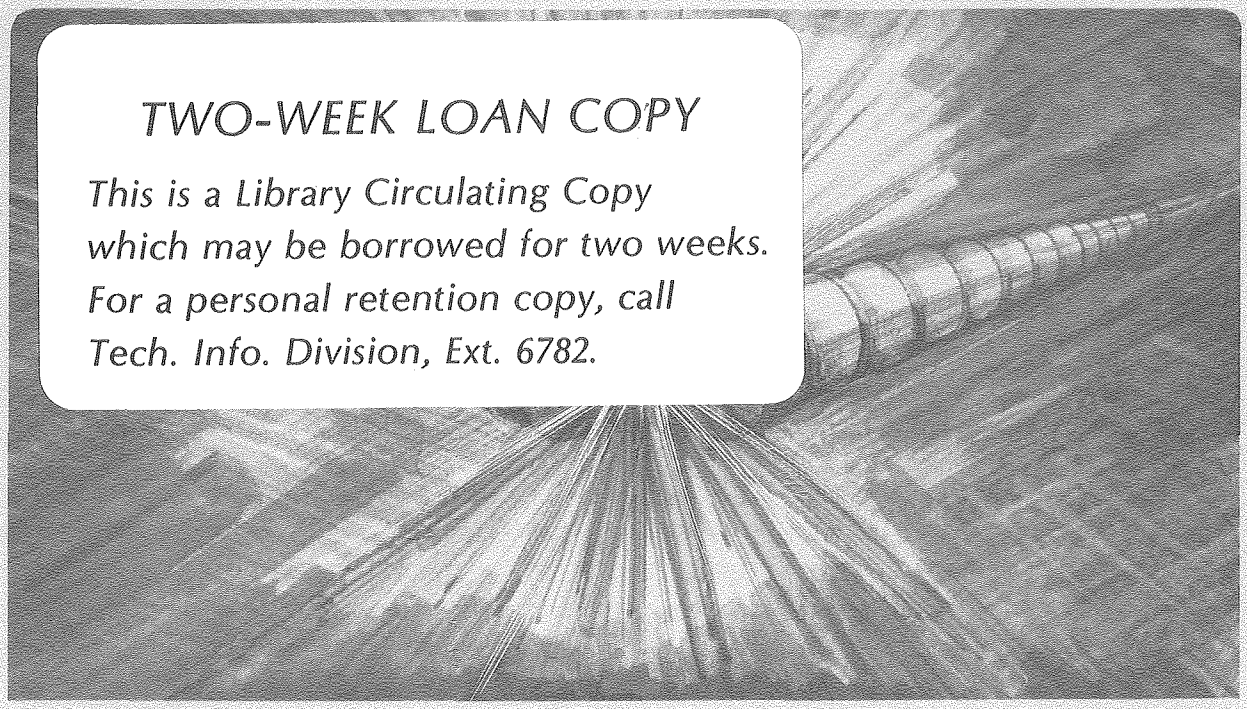

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High Current Source of He^- Ions

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Abstract

A negative helium ion beam of 70 mA at 10.5kV has been produced by charge exchange in sodium. The production is studied as a function of sodium line density, beam energy and background helium gas density. The characteristics of this high current He^- source are analyzed to determine the design requirements for He^- beam generation in the range of tens to hundreds of milliamperes.

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I. Introduction

A high energy, ^3He beam has been proposed as an alpha particle diagnostic for the TFTR tokamak.[1] The required beam could be obtained by accelerating 25 mA of negative helium ions to greater than 1 MeV and stripping the electron.[1,2] The currents involved, however, are much greater than the present state-of-the-art.

Existing sources[3-6] of He^- are designed for injection into accelerators, an application for which microamperes are sufficent, and utilize charge exchange in alkali metal vapors. The use envisioned here requires an increase in the current production by three orders of magnitude from these values. A short pulse (100 μs) of 10 mA of He^- was produced by Dimov and Roslyakov[7] using charge-exchange in sodium, but long pulses (~ 1 second) will be required for the proposed use. A recent study of a surface-plasma source has produced a d.c., 30 mA beam of He^-;[8] the present work produced 70 mA of $^4He^-$ (10 ms pulse) utilizing the charge exchange technique used in accelerator sources.

The experiment was conducted using a large, sodium charge exchange system developed for the production of D^-.[9,10] The purpose was to study the characteristics of a large area, high current source, to determine whether there are any serious difficulties which would hinder the development of the desired beam, and to provide information for the design of a beam for the diagnostic system. As will be seen from the results, there are no serious problems which prevent the scaling of a charge exchange system to the desired currents. Design information will be discussed below.

II. Production Mechanism

Donnally and Thoeming[11] were the first to demonstrate that the negative helium ion could be produced by a two step process:[12]

$$He^+ + X \rightarrow He(1s2s)^3S_1$$

$$He(1s2s)^3S_1 + X \rightarrow He^-(1s2s2p)^4P_{5/2}$$

where X is a target atom; in their experiment cesium was used. The process proceeds via the metastable 3s state rather than the ground state because the electron configuration in the metastable atom matches that of the inner electrons in the negative ions. Since that time a detailed study of the processes in cesium was made by Schlachter et al.[13] and of those in rubidium by Girnius and Anderson.[14] Other measurements of conversion efficiencies in alkali metals include potassium,[15,16] sodium,[16, 7] and lithium.[16] Additional measurements[17] show that charge exchange in several gases other than helium have the characteristics of the two step process. Charge exchange collisions with helium predominately lead to the ground state for the fast atom; the production thus has no maximum as a function of helium line density[17] and a small rate for production of He^-.

For the alkali vapors with largest values for maximum production (1.4-2%), the process peaks at energies ranging from 6 keV for cesium[13] to between 10 and 12 keV for sodium.[7,16] At these energies cross sections of re-ionization to form He^+ and thus generate new

metastable atoms are small, so that at large vapor densities quenching of the metastables[13] causes the density of He^- to drop to a low level. The resulting maximum in He^- occurs at alkali line densities between $5 \times 10^{14} cm^{-2}$ and $1 \times 10^{15} cm^{-2}$.

III. Apparatus

The experiment was performed using the test stand shown in Fig. 1. This apparatus was developed for the production of D^- for use in neutral beam development.[9,10] The positive ion beam was generated by an LBL 7 cm x 35 cm source of the type developed[18] for the 2XIIB mirror fusion experiment. For the present experiment the neutralizer was removed from the source to permit the helium to expand into the volume of the source tank (2200ℓ), thereby minimizing charge exchange destruction of He^+ by the helium gas. The source was pulsed (10 ms) and the gas pressure kept low by expansion into this volume. A beam defining aperture (8 cm x 36 cm) was placed between the source tank and the charge exchange cell to minimize gas flow into the cell. The aperture also minimized bombardment of surfaces downstream of the vapor jet by beam particles, thus minimizing gas creation which would result in stripping and loss of He^- ions. For the same reason, a similar aperture (10 cm x 40 cm) was placed between the beam dump and diagnostic tanks to minimize backflow of gas from the beam dump.

In order to match the impedance of the source arc to the arc power supply, the source was operated at a large helium flow, typically 40 Tℓ/S. This is not a fundamental limitation as operation at gas flows 4 times less can be achieved, but did cause charge exchange losses of

He^+, thus limiting the positive ion current available in the present experiment.

The minimum beam divergence at 10.5 kV was obtained at an acceleration power supply drain of 23 A. The beam angular distribution is bi-Gaussian, typically diverging by 0.8^o in the direction along the acceleration slots and 2.8^o across the slots. The current at minimum divergence scaled as $V^{3/2}$ as expected for electrostatic accelerators. The beam is focused in both planes at 300 cm from the source.

Calorimetric measurements at the far end of the test stand (c.f. Fig. 1) accounted for 65% of the acceleration power. Approximately half of the missing power is attributed to charge exchange, ionization, and secondary electrons in the accelerator grids. The remainder of the discrepancy is unaccounted for; a similar discrepancy occurs for deuterium beams[10] and may indicate an error in calibration.

Sodium was used as the charge exchange medium, and was supplied by a highly directional jet.[19] The sodium was pulsed (0.5s) and collected on a cold surface below the beam. Sodium could be recycled by periodically heating the surface and draining the material into an oven.

IV. Results

The positive current density was measured by a travelling Faraday cup, and the negative current by a travelling momentum analyzer using permanent magnets; both are indicated on Fig. 1. An example of the current densities at the beam center are shown in Fig. 2.

There are several possible sources of negative ions other than He^-: H^- and O^- from water vapor in the source, D^- from deuterium trapped during previous operation, etc. Positive identification of the negative current as He^- was achieved by three measurements:

(1) The collector (Faraday cup) in the magnetic analyzer is of a size and location to measure the sum of current densities of H^-, D^-, and He^-. The measured negative ion current thus did not include any higher mass impurities. To verify that the current was He^- the analyzer was rotated relative to the beam, thereby moving the point at which the negative ions strike the collector. The negative signal dropped to zero at the angle predicted for He^- rather than that predicted and measured for D^- (or H^-).[10]

(2) To further verify that H^- and D^- were not contributing to the current, spectroscopy was used to search for Doppler shifted Balmer-beta line radiation from fast atoms in the beam. To enhance the Doppler shifted line radiation, the helium pressure was increased to 10^{-4} torr by leaking helium into the vacuum chamber. No Doppler shifted Balmer-beta line emission from hydrogen or deuterium was observable under these conditions. To calibrate the sensitivity of these measurements the Doppler shifted line emission from an accelerated deuterium beam was measured under the same conditions. These measurements placed an upper limit of 0.5% on the hydrogen and deuterium impurity. The conversion efficiency for deuterium in this apparatus and at 10.5 kV acceleration voltage is 8.5%,[9,10] and that for hydrogen much less because of its higher velocity. At the detector the total equivalent beam current density is 165 mA/cm^2, so the maximum possible H^- and D^- current density at 10.5 keV is 0.07 mA/cm^2. A maximum negative current density of 0.5 mA/cm^2 was measured so that any impurity is less than 14% of the current.

(3) Any source of impurity would be expected to be independent of helium gas flow or to increase with it if introduced with the helium. Increased gas flow also decreases the positive ion fraction in the beam, and thus the resulting He^- current. The measured negative current density decreased with the gas flow proportionally to the measured positive (He^+) current density in agreement with the known production mechanism and contrary to expectations for impurities.

It was concluded, therefore, that the measured negative ion current was He^-.

It is shown below that the slow decay of current during a beam pulse (Fig. 2) is due to charge exchange losses of He^+ on He^0. Except for this slow variation the beam and its environment had reached steady state. The ratio of He^- to He^+ was independent of time. It was also verified that background processes other than the gas flow had reached equilibrium. For example, a Langmuir probe near the sodium jet was monitored; the plasma density reached its equilibrium value in about 400 μs.

The spatial profile of the total beam was measured by the calorimeter and profiles for the ions by the Faraday cup and the momentum analyzer. These results are compared in Fig. 3. Broadening of the beam due to scattering in the sodium is negligible.

The negative current density is plotted in Fig. 4 as a function of the sodium line density. A malfunction in the sodium jet prevented the sodium density from being increased beyond the value shown. The line density of sodium required for the maximum is in agreement with measurements in low current experiments.[16]

The maximum production efficiency of He^- obtained in this experiment is plotted as a function of energy in Fig. 5, where it is compared with the results of D'yachkov and Zinenko[16] and of Dimov and Roslyakov.[7] The results of 8.5 and 10.5 keV were obtained at sodium line densities believed to be close to optimum. Optimum density was not reached at 7 and 12.5 keV. Note that our efficiencies are obtained from the ratio of He^- current density (j_-) to the He^+ current density (j_+), not the total ($He^+ + He^0$) current density. The results are in fair agreement with the previous measurements, indicating that there are no mechanisms limiting production in a large system. The energy dependence is different, however, and similar to results for other alkali metals.[13-16] The results of the D^- experiment in this apparatus[9,10] were in good agreement with atomic measurements, so that the cause for this discrepancy is unclear.

The total He^- current obtained in this experiment was obtained by integrating the beam profile. The maximum obtained was at 10.5 keV: a peak current density of 0.52 mA/cm^2 and a total current of 70 mA.

V. Implications for High Current Production of He^-.

As noted above, the He^+ current, and thus the He^- current, were limited by charge exchange losses of helium positive ions in the gas in the beam line. The line density of gas in the beam has two components:

(1) Because of the gas flow through the source, the pressure in the source tank increases linearly in time, thus causing the helium line density along the beam to increase linearly in time.

(2) There is gas in the acceleration grids and in an expansion plume downstream from the source. The resulting line density of gas will be proportional to the source flow rate, but, until the tank pressure becomes high enough for collisions to be important, it will be independent of time.

The fractional loss of He^+ will be $\exp(-\sigma \int ndl)$ with σ the neutralization charge exchange cross section in helium ($5.8 \times 10^{-16} cm^2$) at 10 keV,[20] and $\int ndl$ the line integrated density of helium along the beam up to the sodium jet.

The magnitude of the volume loss mechanism (1) above, can be measured from the decay of the positive ion signal with time (Fig. 1). The result is plotted in Fig. (6a) which includes data from single shots and from shots delayed with respect to the gas turn-on by various times. From this decay rate we find that the effective pathlength of He^+ in the background He^0 is 83 cm, in excellent agreement with the measured distance (100 cm) from the source to the aperture between the source tank and the charge exchange cell.

The contribution of the plume, (2) above, is found by measuring the dependence of the He^+ current density on the source gas flow, Fig. 6b. From this measurement we obtain $\int ndl = 3.7 \times 10^{13} F\ cm^{-2}$ at 7.5 ms after the gas pulse, with F the flow rate in Tℓ/s. From the time measurement we find $\int ndl = 1.0 \times 10^{13} cm^{-2}$ at 7.5 ms for the volume effect. The line density in the plume is thus $2.7 \times 10^{13} F\ cm^{-2}$, almost three times that of the background gas.

The positive ion current density in the absence of charge exchange losses can be found from the F = 0 intercept of Fig. 6b. We find $130 \pm 15\ mA/cm^2$, with the error estimated from the data scatter in

figure. This is 76 ± 9% of the current density calculated from the 23A acceleration power supply drain and is in agreement with the calorimeter measurements.

In the design of future systems it is desirable to maximize the production efficiency of a source relative to actual acceleration power supply drain and source dimensions It is obviously necessary to provide sufficient pumping (either active or by expansion into a volume) to handle the gas load for the required pulse length. The pumping is required both between the source and the charge exchange cell to minimize neutralization of He^+ and after the cell to minimize stripping of He^-. In addition the effect of the plume from the source must be minimized both by operating at high gas efficiency and by design of the geometry near the source grids to minimize gas impedance to the pumps.

It should be noted for future work that the He^+ beam showed evidence of an instability at about 70 kHz. The scatter in current observed in Fig. 6a is a consequence of this instability. It was presumedly the result of a beam-plasma instability arising when the ionization rate of the background gas becomes low enough to make space-charge neutralization marginal.[21] Consistent with this hypothesis, there was no evidence of instability when the sodium line density was greater than $3 \times 10^{14} cm^{-2}$. Ionization and charge exchange in the sodium presumedly produces sufficient plasma to provide space-charge neutralization.

The optimum energy for He^- operation is not clear from these measurements. If the results of D'yachkov and Zinenko[15] are folded into a system design, including source perveance, optimum operation is

at energies in excess of 12 keV. The present results suggest that a lower energy will be best. Further work is desirable to clarify this issue.

For design purposes note that the present ion source has excellent optics as desired for coupling to an accelerator. It is not cooled during the beam pulse and thus not capable of long pulse operation. A design exists, however, for a source with water cooled grids which should permit long pulses[10].

The sodium jet used in this experiment has been shown[10] to have good confinement of sodium despite the large (20 cm x 50 cm) exit aperture. During the present experiment the jet was operated for 0.5 s; pulses of 5 s have been demonstrated.

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Figure Captions

Fig. 1 Charge exchange test stand. Diagnostics are indicated by the numbers: (1) Nude ion gages for fast gas pressure measurements; (2) Large calorimeter to measure the total beam power and power distribution; (3) Large bending magnet to separate ion and neutral particles; (4) Moveable Faraday cup to measure net current density; (5) Moveable momentum analyzer to measure the current density of low mass negative ions; (6) Langmuir probe to measure plasma properties in the beam; (7) Langmuir probe to measure plasma properties in the cx cell; and (8) Hot-wire probe to measure sodium density in the charge exchange (cx) jet.

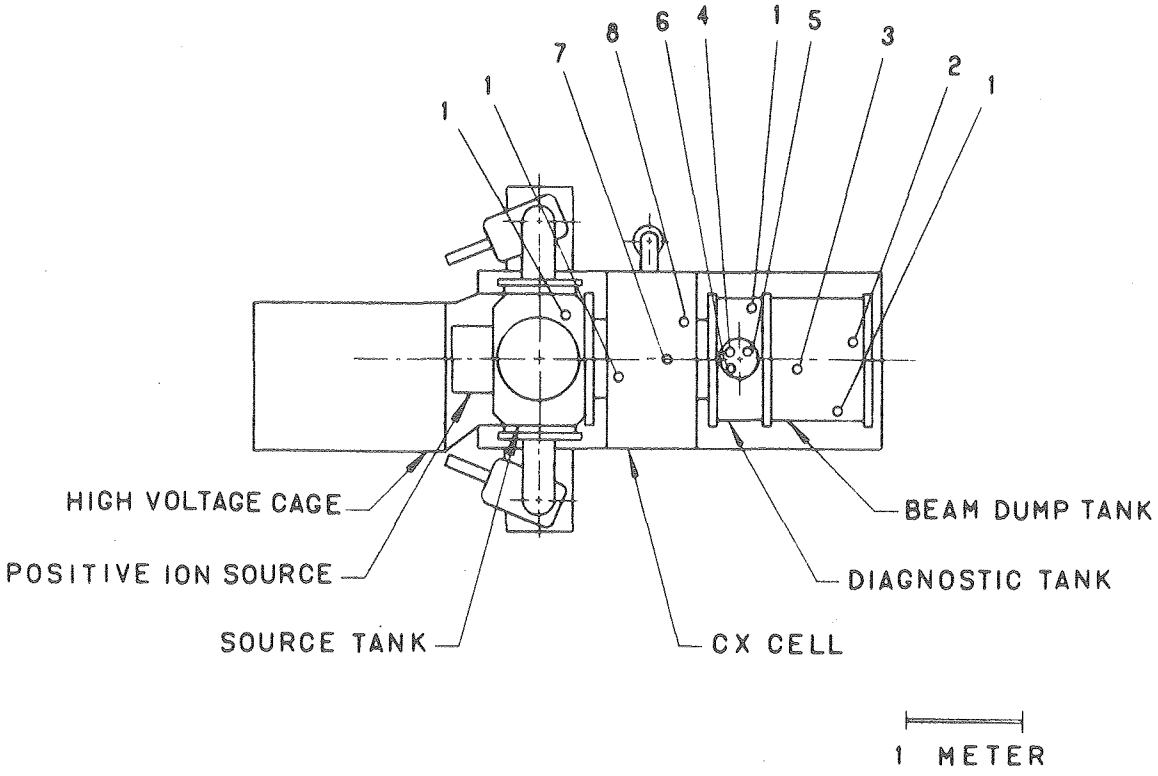
Fig. 2 (a) Positive ion current density and (b) negative ion current density versus time. The upper trace in (b) is the signal with sodium jet off. The pulse was initiated 7.5 ms after the source gas was turned on. The ripple originated in the source arc power supply. The decrease in time is due to neutralization of positive ions near the source.

Fig. 3 Beam profiles at 10.5 kV, across the narrow source dimension. The neutral profile is determined by the calorimeter and equals that calculated for an 0.81^{o} Gaussian divergence at the source. The negative ion profile was measured at a sodium line density of $5 \times 10^{14} cm^{-2}$.

Fig. 4 He^{-} production efficiency (j_{-}/j_{+}) at 10.5 kV. The sodium line density calibration[10] is accurate to $\pm$ 20%. Gas flow rate 40Tℓ/s except for the point labeled x (80 Tℓ/s).

Fig. 5 He^- production efficiency versus energy for optimum sodium density. The results are compared with references (7) and (16). The arrows indicate lower limits for cases in which it was not clear that the optimum density was achieved. The tip of the arrow indicates the uncertainty in the measured value.

Fig. 6 (a) He^+ current density at beam center as a function of time after source gas turn-on. (b) He^+ current density at beam center as a function of source gas flow rate.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1
7
8
6
4
1
5
3
2
1
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POSITIVE ION SOURCE
SOURCE TANK
CX CELL
BEAM DUMP TANK
DIAGNOSTIC TANK
1 METER
XBL 803-8831

Fig. 1

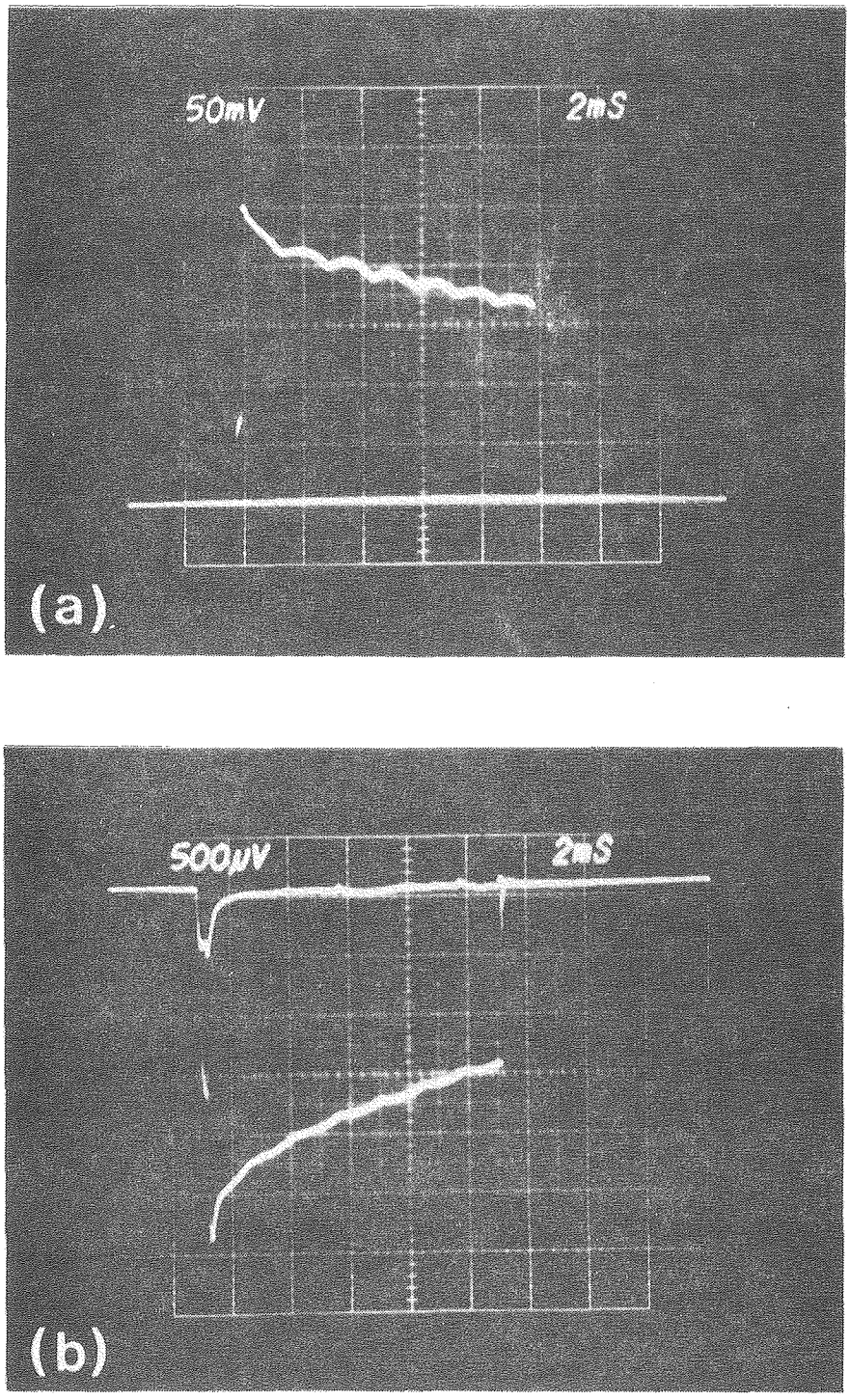

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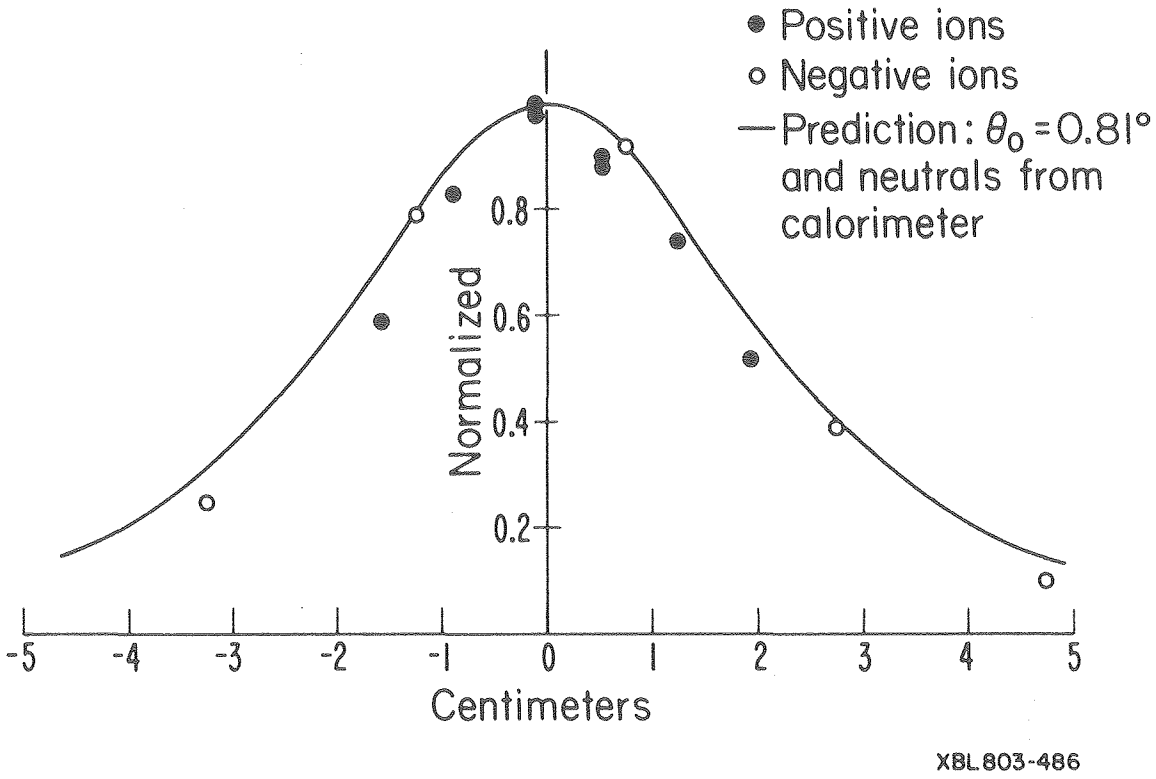
Fig. 2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Negative ions
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0.2
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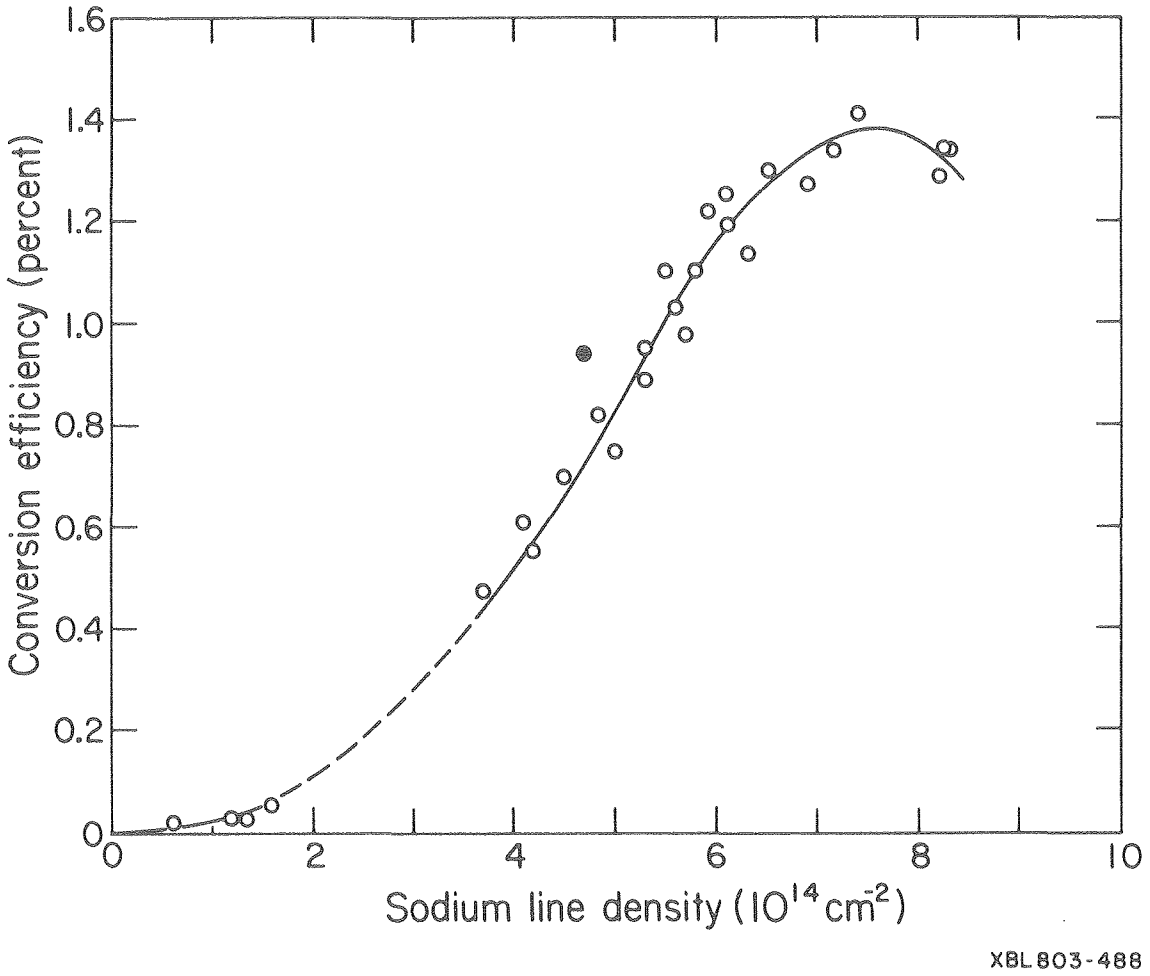
-3
-2
-1
0
1
2
3
4
5
Centimeters
XBL803-486

Fig. 3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0.6
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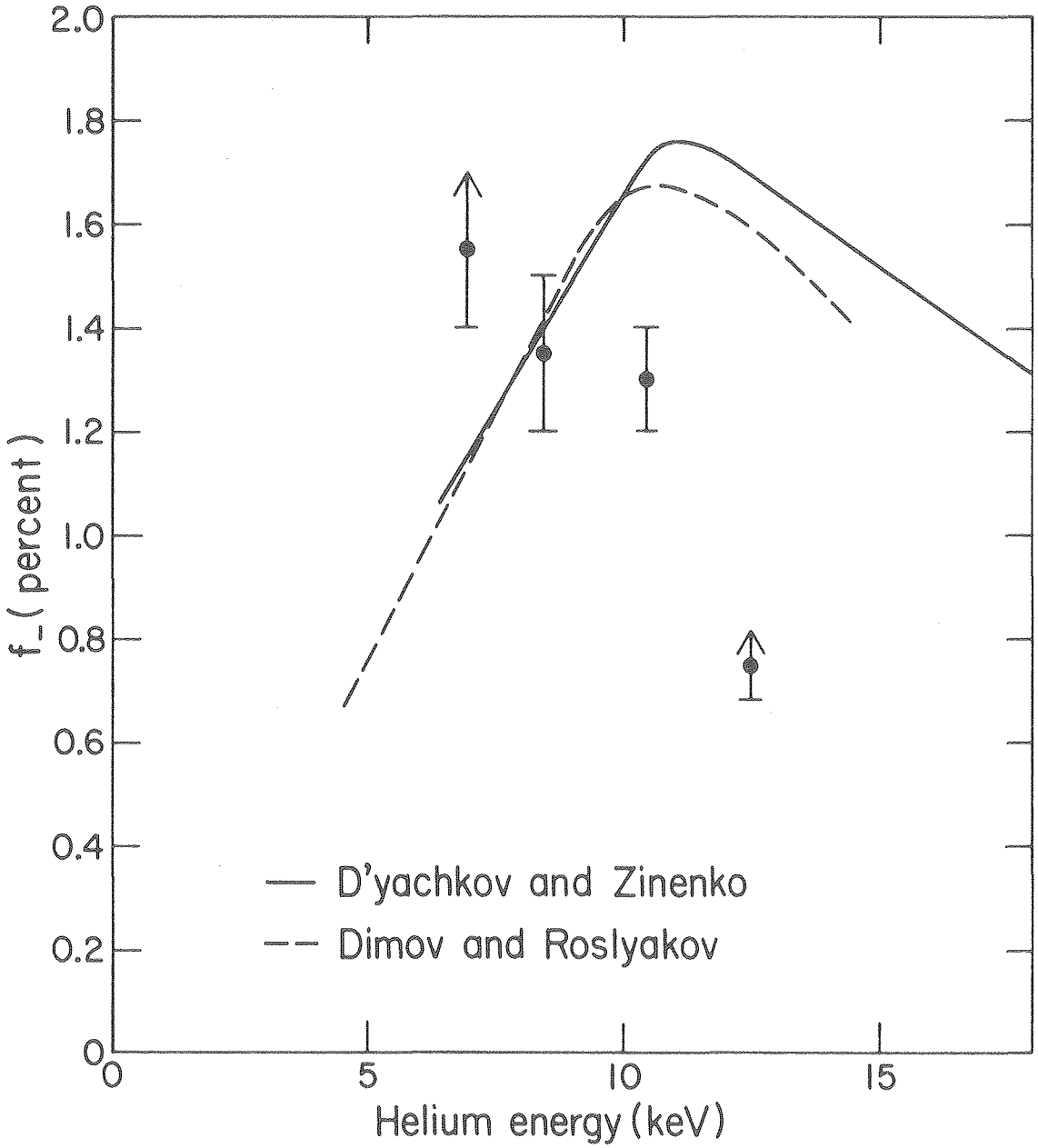
10
Sodium line density (10^{14} cm^{-2})
XBL803-488

Fig. 4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10
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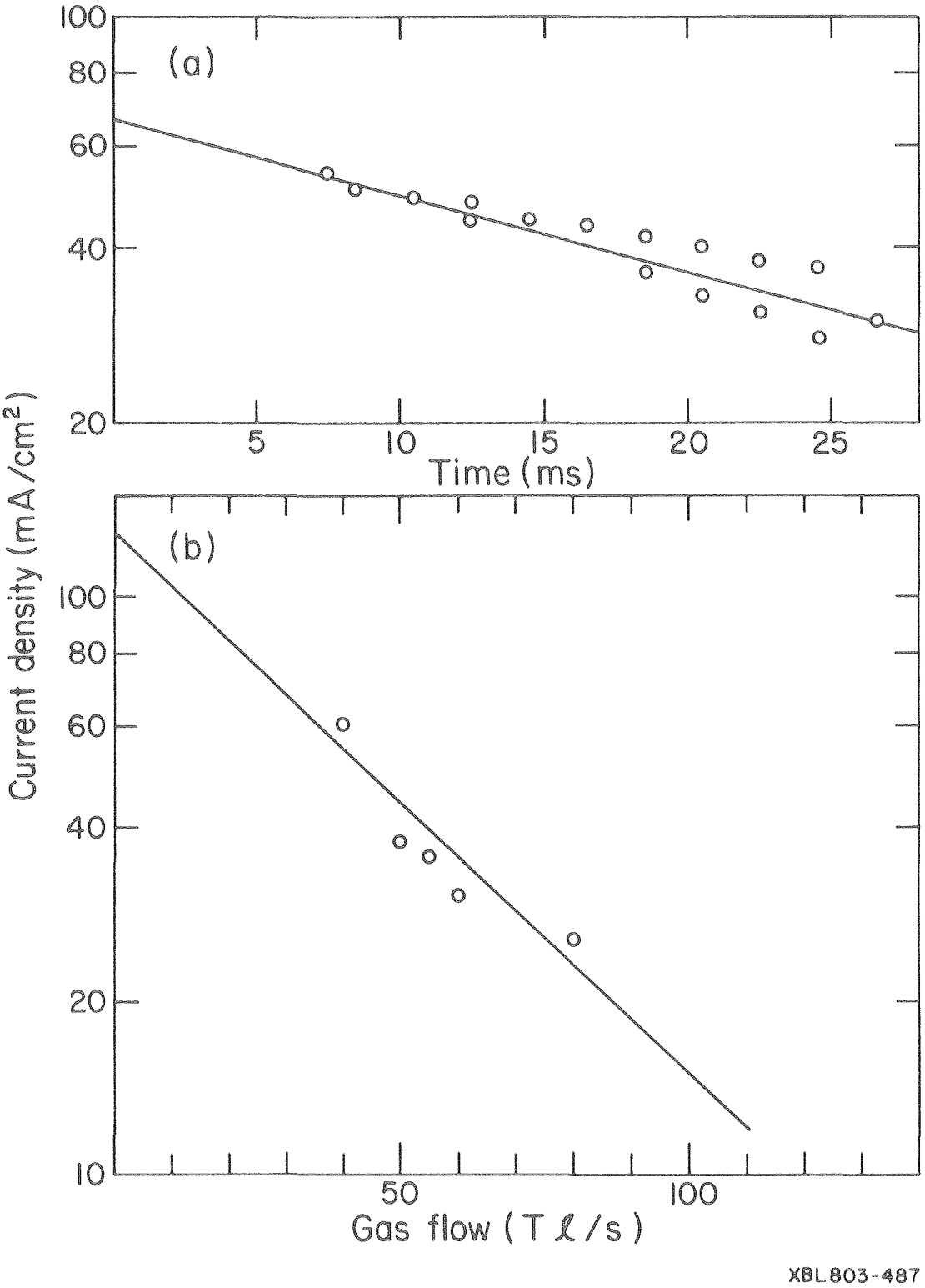
Helium energy (keV)
D'yachkov and Zinenko
Dimov and Roslyakov
XBL 803-489

Fig. 5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5
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15
20
25
Time (ms)
(b)
100
80
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40
20
10
50
100
Gas flow (T ℓ/s)
Current density (mA/cm²)
XBL803-487

Fig. 6