

A SOURCE OF He^{++} IONS FOR A VAN DE GRAAFF ACCELERATOR *

J. L. Weil

University of Kentucky and Rice University
and

I. J. Taylor **
Rice University
Houston, Texas

Summary. An ion source for the production of well-collimated beams of doubly charged helium ions has been constructed, tested, and put into operation. It consists of an einzel lens to maintain a well-focussed beam and a crossed field analyzer that permits only one component of the beam to leave the source assembly. Beam currents of 1 to 2 microamperes of analyzed $(\text{He}^4)^{++}$ or $(\text{He}^3)^{++}$ ions are obtainable from the source assembly for acceleration in a Van de Graaff generator. Up to 0.25 microamperes of $(\text{He}^4)^{++}$ beam has been obtained at the entrance to the beam tubes after acceleration in a Van de Graaff generator and after momentum analysis, but this figure is subject to improvement. The source can also be used with H^+ , D^+ , and He^+ ions. By applying an RF voltage to the deflector plates, it has been found possible to pulse the singly ionized beams. A pulsed beam of $1/2 \mu\text{a}$ of $(\text{He}^3)^+$ ions with a pulse width of 7 ns has been obtained. The design and installation of the source is described.

Introduction

A source of doubly charged helium ions makes possible the acceleration of ion beams in electrostatic accelerators through the equivalent of twice the terminal potential i. e. a 6 MV generator can produce 12 MeV helium ion beams. In general many more (approximately 99:1) singly than doubly charged helium ions are produced by a gas discharge. To prevent loading of the accelerating tube, it is desirable to make a separation of the two charge states so that only the weaker doubly charged component enters the accelerating tube. Such a separation then makes it possible to use the very high output sources that have been developed in recent years and thus to maximize the absolute output of He^{++} ions, with no fear of overloading the accelerator.

* Supported in part by the U.S. Atomic Energy Commission.

** Present address: Physics Dept., Columbia University, New York, N. Y.

An ion source system has been constructed at Rice University for general use which is also capable of providing workable beams of doubly ionized helium from the 5.5 MeV Van de Graaff accelerator. Using an analyzer to select the beam of the required charge state from the source, it is possible to run the ion source with helium at high beam output levels and to extract the approximately 1-2% of doubly ionized beam component for acceleration without incurring problems of tube loading. The design considerations, performance and installation are discussed below.

Other means of producing He^{++} beams have been devised in other laboratories^{1, 2} and are compared to the present method in a more extensive paper that will appear in Nuclear Instruments and Methods³. This paper also gives more of the details of the design and construction of the present source than could be included in this short communication.

Design Considerations

As there are ion sources already available which will produce several hundred microamps of helium ions of which 1-2% are doubly-charged helium, the main issue lies in the design of the analyzer to select the desired beam and inject it into the accelerator. For correct injection into the accelerator focussing system after passing through the analyzer, the diverging beam from the ion source needs some measure of pre-focussing and is also required to be accurately on axis.

An in-line system where, at selection, the beam is focussed on axis, meets these requirements very well. Such a system can be constructed using crossed electric and magnetic fields for beam analysis. With a magnetic field produced by permanent magnets and the electric deflecting field as the variable parameter there is economy in the necessary power requirements as compared to methods using a variable magnetic field for momentum analysis. Also, beam pulsing features are readily incorporated into this type of design.

To retain the existing focussing system of the accelerator and essentially leave the ion optics unaltered, the beam from the source

requires prefocussing through the analyzer into an aperture located in place of the previous ion source exit canal. If a single gap lens of the type used in the accelerator is also used for this pre-focussing, then the required electric field of the deflectors for the transmission of a selected beam of ions of charge number Z and mass number N is given by,

$$E = 1.38 \times 10^{-2} B \sqrt{V} \sqrt{Z/N} \text{ volts/cm}$$

where V is the sum of focussing plus probe voltages, and B is the magnetic field intensity (oersteds). For an intended magnetic field of 1000 oersteds and 30 KV focussing voltage, the necessary deflecting field to analyze doubly charged helium is 1.69×10^3 volts/cm, which is readily attainable.

The performance criterion of the analyzer lies in the lateral separation of the various beam components at the entrance aperture of the accelerating tube. This relative displacement for ions of charge number Z_1 , Z_2 and mass numbers N_1 , N_2 is given by

$$d = 6.92 \times 10^{-3} \frac{B}{\sqrt{V}} \left(\frac{\ell^2}{2} + \ell h \right) \left(\sqrt{\frac{Z_2}{N_2}} - \sqrt{\frac{Z_1}{N_1}} \right) \text{ cm}$$

where ℓ and h are the flight path of the ion in the magnetic field and the flight path from the analyzer to the exit aperture respectively. Assuming each of the flight paths to be 8 cm and with a focussing voltage of 30 KV, a probe voltage of 5 KV and a magnetic field of 1000 oersteds, the lateral separation between the singly charged helium beam and the analyzed doubly charged helium beam is 7.3 mm.

Although for an entrance aperture to the machine of 3 mm diameter this separation is sufficient for complete resolution of a well focussed beam spot, bench tests indicated that the focussing of the beam spot at some 25 cm below the ion source (the available distance in the accelerator terminal to contain the analyzer plus a lens system) was quite insufficient with such a simple single-gap lens to attain fully adequate resolution. For operation of the ion source at 5 KV probe voltage this type of focussing system requires quite high focus voltages and, since the beam component separation depends on $V^{-1/2}$, is basically not compatible with the requirements of the analyzer.

A more suitable type of pre-focussing system employs an einzel lens between the ion source and analyzer. With this arrangement ions can enter the analyzer with velocities determined only by the probe voltage and hence the resolving power of the analyzer is increased. This feature is most valuable in view of the space limitations of the installation as it permits the

use of smaller flight paths while still retaining adequate beam separation. Thus the flight paths ℓ and h can be reduced to 5 cm and the separation between singly charged helium and the analyzed doubly-charged beam becomes 7.6 mm, comparable with the previous value. The electric field for this separation is reduced to 0.69×10^3 volts/cm as compared to 1.69×10^3 volts/cm previously. With the smaller flight paths the focussing properties can be improved by using an einzel lens which is symmetrical (unit magnification) to produce a desired small beam spot of the order of the 1.8 mm source canal diameter. The final design lay in making a proper compromise to obtain optimum transmission through the lens and approximately unit magnification, consistent with the required flight paths for adequate resolution and with the limitation on the size of the whole system.

The analyzer itself was essentially the same, except for modifications mentioned below, as that used in a system designed at Los Alamos by Dr. J. L. McKibben⁴. The einzel lens dimensions were calculated using conventional optical thick lens formulae and the necessary conversions to ion optics given by Spangenberg⁵. The final form of the lens was not quite symmetric, being longer on the analyzer end, but the aberrations thus caused are negligible. It operates in the accelerating mode with the first and third elements grounded and a negative potential on the center element of 6-8 times the ion source probe voltage. This operation requires a higher lens voltage, and thus a larger power supply, than the decelerating mode, but has the advantage of a larger effective aperture. One goal in the design of the whole lens and analyzer system was that there should be the maximum possible pumping speed between the ion bottle and the accelerating tube to avoid ionization of gas in the lens regions. An assembly drawing of the lens and analyzer system is shown in fig. 1. In order to show more of the details, the drawing consists of two half sections taken at right angles to each other. Only the sliding viewer below the analyzer is not shown.

Accurate alignment of the various cylindrical sections was obtained by the use of concentric location of all machined parts. The magnetic field was produced by using banks of Indox V ceramic permanent magnet wafers[†] to obtain a field of 1000 oersteds across a gap of 3.5 cms. The magnet pole tips were machined from Armco iron and the magnet assembly was housed in a cylinder of mild steel which acted as the flux return yoke. The ceramic magnets were placed as close to the gap as possible to produce the maximum field.

[†] Cat. #F-5601, Indiana Steel Products, Valparaiso, Indiana.

Tests on the focussing properties of the analyzer led to the insertion of upper and lower field shims for the magnetic field. The lower lens element of the einzel lens system was made from Armco iron and designed to serve as the upper field shim, shielding the focussing regions of the einzel lens from the fringing fields of the magnet. Similarly a field shim was inserted in the lower magnet plate to prevent defocussing of the beam in the region below the analyzer. With this arrangement field measurements with a commercial gaussmeter[‡] indicated a central uniform field of 900 ± 10 oersteds, with fringing fields in the lens region of less than 10 oersteds and below the analyzer of less than 20 oersteds.

Photographs of the analyzer and the lens housing are shown in fig. 2.

The focussing properties of the system could be visually checked on a viewing screen, coated with MgO , which could be moved by external control into a preset position between the analyzer and the exit aperture (fig. 2a). A tightly focussed central beam spot of the order of the ion source canal dimensions could be obtained on the scintillation screen though there were visible indications of the presence of astigmatic defects arising from the planar focussing action introduced by the magnetic field. With the magnets removed, the focussing of the beam spot by the einzel lens was essentially free from any visible non-axial defects.

Ion Source

The R. F. ion source was of the type developed by Moak et al.⁶ and supplied commercially by ORTEC[†]. The oscillator and power supplies were constructed to ORTEC specification apart from a few minor details, and the solenoidal magnetic field used to bunch the R. F. discharge was obtained from a coil of 4000 turns of No. 22 copper wire operated at currents up to 2 amps and producing maximum axial fields of approximately 850 oersteds. Power supplies for the einzel lens (40 KV) and the electrostatic deflectors (5 KV) were compact epoxy-sealed units obtained commercially^{‡‡}.

Performance figures for the source on bench test indicated that steady beams of up to $400 \mu\text{a}$ of helium ions could be obtained at 5 KV probe voltage. A typical plot of the beams resolved by the analyzer, using He^4 in the source, is shown in fig. 3. The resolved doubly-charged

beam is approximately 2% of the primary beam current. By judicious control of gas flow and optimisation of the oscillator coupling and source parameters, up to $2.5 \mu\text{a}$ of analyzed $(\text{He}^4)^{++}$ could be obtained. As no hydrogen was used in the bench test apparatus, the resolved $(\text{He}^4)^{++}$ beam is expected to contain relatively small amounts of $(\text{H}_2)^+$ beam. Although this was not separately investigated, it is supported by the fact that there is no evidence for any significant amount of H^+ component in the spectrum of analyzed beams, (fig. 3).

The typical operation of the system in the accelerator closely followed that on the test bench. Beams of $2 \mu\text{a}$ of doubly-charged component were readily obtained at the entrance to the 90° analyzing magnet, indicating almost 100% transmission through the accelerator focussing system. Magnetic analysis indicated that the $(\text{He}^4)^{++}$ beam contained a molecular hydrogen $(\text{H}_2)^+$ contaminant which was observed as a separate beam spot on quartz viewers along the beam tubes. Initially of approximately the same intensity as the $(\text{He}^4)^{++}$ beam, the $(\text{H}_2)^+$ component weakened steadily after several hours of running and is attributed to outgassing of hydrogen in the ion source and the gas-feed system. Beam current measurements with $(\text{He}^3)^{++}$, mentioned later, do not include such molecular components and are more indicative of the analyzer performance.

Installation

The new ion source assembly was positioned in place of the existing H. V. E. C.[†] RF ion source. The terminal wiring was altered to accommodate the extra power supplies and to include the facility of powering the terminal from an external alternator. With this system the ion source could be tested without running the machine drive motors and alternator.

The scintillation screen was moved into position above the exit aperture and viewed through an observation window to establish that the beam was leaving the analyzer on axis, was being focussed correctly, and was being swept across the exit aperture by the electrostatic deflectors.

The focussing properties of the accelerator were somewhat changed by the installation of the new source system. In an attempt to obtain a focussed spot of He^{++} at the entrance slits above the analyzing magnet without excessive (greater than 40 KV) tube focus voltage, the graded resistors at the top of the accelerator were replaced by ones with higher values. It was still not possible to obtain a focus for He^{++} above the

‡ Rawson Electric Instrument Co.,
Cambridge, Massachusetts.

† Oak Ridge Technical Enterprises Co.,
Oak Ridge, Tennessee.

‡‡ Series S. units. Del Electronics Co.,
Mount Vernon, New York.

† High Voltage Engineering Corp.,
Burlington, Massachusetts.

magnet and, in fact, an approximately parallel beam appeared to be emerging from the accelerator. As this beam did not focus onto the stabilizing slits of the analyzing magnet, much beam was lost in passing through the slits.

Beams of $0.25 \mu\text{a}$ of $(\text{He}^4)^{++}$ at 8 MeV have been obtained at a point just after the stabilizing slits. This significant decrease from the beam of $2 \mu\text{a}$ above the magnet is due to the poor focusing properties of the He^{++} beam, and also, in part, to the apparent need for relatively large slit currents to stabilize the accelerator satisfactorily. After passage through defining apertures and electrostatic lenses along the beam tubes, a $(\text{He}^4)^{++}$ beam of $0.1 \mu\text{a}$ has been obtained on a $2 \text{ mm} \times 2 \text{ mm}$ target spot at a distance of 5 meters from the analyzing magnet.

Preliminary experiments with He^3 at 8 MeV and 9.4 MeV have been performed. A $(\text{He}^3)^{++}$ beam of $1.5 \mu\text{a}$ at 8 MeV was obtained above the analyzing magnet. Magnetic analysis showed that this beam was free from any significant amount of singly-charged beam or any other contaminants. However, in analogy to the $(\text{He}^4)^{++}$ beam, only $0.1 \mu\text{a}$ could be put on a $2 \text{ mm} \times 2 \text{ mm}$ target spot 4 meters from the magnet.

Although changing the values of the topmost resistors in the accelerator helped in achieving good focus conditions above the analyzing magnet for hydrogen and deuterium beams, without requiring higher focus voltages, it had relatively little effect on the focussing of the doubly-charged helium beam.

The ion source has been in operation for several months with hydrogen, deuterium, helium-3 and helium-4 gases. It is found that the $(\text{He})^{++}$ beam intensity is very sensitive to the pressure of helium gas in the ion source, and also that trace amounts of hydrogen or deuterium seriously affect the output of the doubly-ionized beam. A period of "running-in" is therefore needed when helium beams are to be used. Also, to obtain adequate shut-off, it is considered necessary to have extra solenoid valves in the hydrogen and deuterium lines.

These performance figures are preliminary and are certainly subject to considerable improvement. The amount of beam entering the beam tubes should be significantly increased by relocating the stabilization slits, increasing the sensitivity of the stabilizer system and by an improved alignment of the lens systems in the beam tubes after the analyzing magnet. An enlargement of the aperture below the terminal analyzer (at present $1/8''$) would probably increase the output of $(\text{He})^{++}$ beam while still not passing excessive amounts of $(\text{He})^+$. The accelerator could then be stabilized on the larger $(\text{He})^+$ beam at the mass-2 port and so allow all of the $(\text{He})^{++}$ component to be analyzed

through the mass-1 port of the analyzing magnet. By this method the previously mentioned problems of $(\text{He})^{++}$ loss through the stabilization slits would be avoided. This method has been used successfully at Duke University⁷. Also, the ion source which has been used in this system (ORTEC type 320) is intended mainly for proton beam production and, as such, is not specifically designed to yield high amounts of helium ions. With a more suitable type of ion bottle, permitting the use of higher powered R.F. oscillators and higher probe voltages, the beam output from the source with helium could doubtless also be increased by a factor of two. One should thus reasonably expect doubly ionized beams of more than $1 \mu\text{a}$ on target with this system.

Very recently, the desirable feature of pulsing the beam has been added to the ion source system⁸. A 2.5 Mc crystal controlled oscillator with a 25 T driver stage is used to apply a 1500 volt peak-to-peak RF signal to the deflection plates. All singly charged beams can be pulsed with this arrangement and still give useable quantities of beam. An experiment is now being carried out using a pulsed $(\text{He}^3)^+$ beam of $1/2 \mu\text{a}$ and pulse widths of 5-7 ns. This corresponds to a DC beam of only $28 \mu\text{a}$ and hence larger pulsed beams could undoubtedly be obtained.

Advantages of this system are listed below:

- 1) Low cost ($\sim \$3000$) compared to commercial systems ($\sim \$20,000$).
- 2) Accelerated He^{++} ion beams ($\geq 1.5 \mu\text{a}$) as large or larger than those obtained elsewhere.
- 3) Low power requirements in the terminal. The present system is performing satisfactorily in a terminal with a 1.5 KW alternator.
- 4) Small size. This system fits inside the short terminal spinning supplied with early models of the HVEC type CN 5.5 MeV Van de Graaff.
- 5) Possibility of terminal pulsing and bunching.
- 6) Acceptable focussing of all other beams over full energy range of the accelerator.
- 7) Freedom from breakage of stripping foils or misalignment of gas stripper used in other systems.

References

- 1) S. Hinds and R. Middleton, Proc. Phys. Soc. (London) 75 (1960) 745
- 2) J. W. Bittner, Rev. Sci. Instr. 25 (1954) 1058
- 3) I. J. Taylor and J. L. Weil, Nucl. Inst. and Meth. (to be published, 1965)
- 4) J. L. McKibben, private communication
- 5) Karl R. Spangenberg, Vacuum Tubes (McGraw-Hill Book Co., Inc., New York, 1948) p. 328
- 6) C. D. Moak, H. Reese, Jr., and W. M. Good, Nucleonics 9, No. 3 (1951) 18
- 7) D. R. Tilley, private communication
- 8) D. Bernard, Rice Univ., private communication



Fig. 2.
Photographs of parts of the analyzer and lens:
a) bottom of crossed field analyzer showing viewer,
b) top of analyzer, c) analyzer with center lens element installed and lens housing.

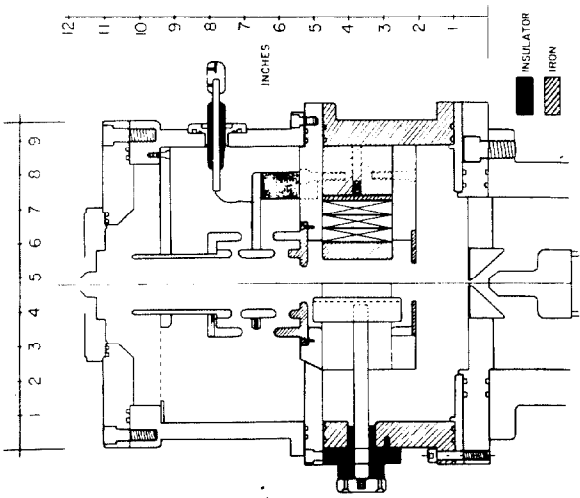


Fig. 1.
An assembly drawing of einzel lens and analyzer, consisting of two half sections at 90° to each other.

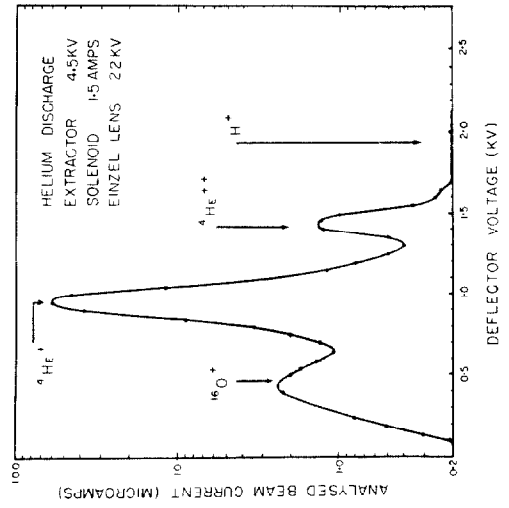


Fig. 3.
The spectrum of analyzed beams, using helium-4 in the ion bottle.