Operation and Maintenance of an Accelerator for Neutral Bombardment Level-Crossing Spectroscopy

James Vincent Morford
Western Michigan University

Follow this and additional works at: https://scholarworks.wmich.edu/masters_theses
Part of the Physical Sciences and Mathematics Commons

Recommended Citation
https://scholarworks.wmich.edu/masters_theses/2674

This Masters Thesis-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Master's Theses by an authorized administrator of ScholarWorks at WMU. For more information, please contact maira.bundza@wmich.edu.
OPERATION AND MAINTENANCE OF AN ACCELERATOR FOR NEUTRAL BOMBARDMENT LEVEL-CROSSING SPECTROSCOPY

by

James Vincent Morford

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment
of the
Degree of Master of Arts

Western Michigan University
Kalamazoo, Michigan
April 1974
OPERATION AND MAINTENANCE OF AN ACCELERATOR FOR NEUTRAL
BOMBARDMENT LEVEL-CROSSING SPECTROSCOPY

James Vincent Morford, M.A.
Western Michigan University, 1974

The accelerator is equipped with a charge exchange canal so that a well collimated energetic neutral hydrogen beam is produced. This beam will be used to produce excited states of atoms which will be studied by level-crossing spectroscopy. Both theoretical and-experimental predictions of the beam composition and focus are presented.
ACKNOWLEDGEMENTS

I would like to thank Professor R. D. Kaul for his guidance and patience throughout this project. In addition, my thanks go to Professors Michitoshi Soga and John Herman for their assistance.

I would also like to thank my wife, Susan, for her assistance in preparation of this thesis as well as her encouragement and patient understanding.

James Vincent Morford
INFORMATION TO USERS

This material was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.

2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.

3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in "sectioning" the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again — beginning below the first row and continuing on until complete.

4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from "photographs" if essential to the understanding of the dissertation. Silver prints of "photographs" may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.

5. PLEASE NOTE: Some pages may have indistinct print. Filmed as received.

Xerox University Microfilms
300 North Zeeb Road
Ann Arbor, Michigan 48106

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
MASTERS THESIS

MORFORD, James Vincent

OPERATION AND MAINTENANCE OF AN ACCELERATOR FOR NEUTRAL BOMBARDMENT LEVEL-CROSSING SPECTROSCOPY.

Western Michigan University, M.A., 1974
Physics, atomic

University Microfilms, A XEROX Company, Ann Arbor, Michigan

THIS DISSERTATION HAS BEEN MICROFILMED EXACTLY AS RECEIVED.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>INTRODUCTION .......................................</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>CONSTRUCTION OF THE ACCELERATOR .....................</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>A. Vacuum System ..................................</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>B. High Voltage Terminal ..........................</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>C. High Voltage Power Supply ......................</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>D. Lens..................................</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>E. Charge Exchange Chamber ........................</td>
<td>24</td>
</tr>
<tr>
<td>III</td>
<td>RADIO FREQUENCY ION SOURCE..........................</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>A. Theory.........................................</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>B. Installation ...................................</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>C. Tuning.................................</td>
<td>32</td>
</tr>
<tr>
<td>IV</td>
<td>MEASUREMENTS........................................</td>
<td>38</td>
</tr>
<tr>
<td>V</td>
<td>RADIATION...........................................</td>
<td>46</td>
</tr>
<tr>
<td>VI</td>
<td>NORMAL OPERATION....................................</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>A. Start Up.......................................</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>B. Shut Down......................................</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>C. Radio Frequency Ion Source ......................</td>
<td>53</td>
</tr>
<tr>
<td>VII</td>
<td>COMPOSITION OF OUTPUT BEAM ...........................</td>
<td>54</td>
</tr>
<tr>
<td>VIII</td>
<td>OUTPUT BEAM SCATTERING..............................</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>APPENDIX I........................................</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>APPENDIX II.......................................</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>BIBLIOGRAPHY.......................................</td>
<td>97</td>
</tr>
</tbody>
</table>
### INDEX TO FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Front View of Accelerator</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Vacuum Manifold</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Vacuum Manifold and Pumping System</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Rear View of Accelerator</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>Safety Enclosure</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>Lens and Radio Frequency Ion Source</td>
<td>22</td>
</tr>
<tr>
<td>7</td>
<td>Radio Frequency Ion Source</td>
<td>31</td>
</tr>
<tr>
<td>8</td>
<td>Beam Current Measurement</td>
<td>42</td>
</tr>
<tr>
<td>9</td>
<td>Beam Fraction Versus PL and G at 20 KeV</td>
<td>58</td>
</tr>
<tr>
<td>10</td>
<td>Beam Fraction Versus PL and G at 35 KeV</td>
<td>60</td>
</tr>
<tr>
<td>11</td>
<td>Beam Fraction Versus PL and G at 50 KeV</td>
<td>62</td>
</tr>
<tr>
<td>12</td>
<td>Number of Particles Produced per Incident $H_2^+$ Ion Versus PL and G</td>
<td>68</td>
</tr>
<tr>
<td>13</td>
<td>Number of Particles Produced per Incident $H_2^+$ Ion Versus PL and G</td>
<td>70</td>
</tr>
<tr>
<td>14</td>
<td>Number of Particles Produced per Incident $H_2^+$ Ion Versus PL and G</td>
<td>72</td>
</tr>
<tr>
<td>15</td>
<td>Diffusion Pump Electrical Interlock System</td>
<td>87</td>
</tr>
<tr>
<td>16</td>
<td>Radio Frequency Oscillator</td>
<td>89</td>
</tr>
<tr>
<td>17</td>
<td>Radio Frequency Oscillator Power Supply</td>
<td>91</td>
</tr>
<tr>
<td>18</td>
<td>Magnet Coil Power Supply</td>
<td>93</td>
</tr>
<tr>
<td>19</td>
<td>Probe Power Supply</td>
<td>95</td>
</tr>
</tbody>
</table>
# INDEX TO TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>39</td>
</tr>
<tr>
<td>II</td>
<td>40</td>
</tr>
<tr>
<td>III</td>
<td>44</td>
</tr>
<tr>
<td>IV</td>
<td>64</td>
</tr>
<tr>
<td>V</td>
<td>74</td>
</tr>
</tbody>
</table>

1. Data from Tuning Procedure for Source Using Aluminum Tip
2. Data from Tuning Procedure for Source Using Nickel Tip
3. Beam Current Measurement
4. Cross Section Values Used for Calculation of Output Beam Composition for $H^+$ Incident on $H_2$
5. Cross Section Values Used for Calculation of Output Beam Composition for $H_2^+$ Incident on $H_2$
I. INTRODUCTION

A 50 KeV accelerator was constructed to produce excited states of atoms by ion and neutral particle bombardment excitation. The excited states will be studied by the level-crossing spectroscopy technique.

The level-crossing technique requires that two fine or hyperfine levels be tuned through degeneracy (crossed) by the application of a magnetic field. A prerequisite of this technique is that both levels must be coherently excited. The most common method of excitation is accomplished by resonant absorption of light. However, there are many non-resonant states one may wish to study that cannot be excited by resonant absorption of light.

Another method of coherent excitation is by electron bombardment. Here the electron beam must define a direction that is not parallel to the magnetic field. In order to define a beam direction, the radius of curvature of the electron beam in the magnetic field must be large as compared to the length of the observation region. A typical length for the observation region is approximately 0.5 cm. The minimum radius of curvature of the electron beam in the magnetic field should be roughly five times the length of the observation region or, in this example, 2.5 cm. With a 100 eV electron beam the magnetic field required to produce this radius of curvature is 13.5 gauss. Note that level-crossings at higher magnetic fields would be difficult to observe. At low magnetic fields one is limited in the number of states which may be effectively studied. Since low
magnetic fields and high electron velocities will produce a larger radius of curvature, one could increase the magnetic field and proportionately increase the electron velocity to maintain the same radius of curvature. However, the excitation cross sections for higher electron velocities (>100 eV) are very small. Second, the polarization of the emitted radiation from the excited state generally decreases as the electron energy goes far above the threshold for excitation. Polarization of the emitted radiation implies coherent excitation which is a requirement for observation of level-crossings. Therefore, by the nature of this technique, electron energies are limited to 10 eV to 100 eV for proper excitation. It then follows that at high magnetic fields (>100 gauss) the radius of curvature for electrons in a magnetic field is so small that observation of the level-crossing becomes almost impossible.

Ion bombardment allows level-crossings to be observed at higher magnetic fields. It is found that proper excitation (large cross sections and polarization) occurs when the velocity of the bombarding ions are in the same range as bombarding electron velocities. At constant velocity the radius of curvature scales as m/B (mass/magnetic field strength) for a charged particle in a magnetic field. Using the same criterion as was used in the electron case, one could almost expect a two thousand fold increase in the maximum allowable magnetic field used to observe level-crossings.

As a comparison, a 20 KeV H⁺ proton beam, which is at the same velocity as a 10 eV electron beam, will produce a 2.5 cm radius of curvature with a magnetic field strength of approximately eight
kilogauss. However, the situation for use of ion bombardment is not as simple as described above. When electron bombardment is employed, the cathode source is situated directly in the magnetic field used to produce the level-crossings. In the case of ion bombardment the ions are produced externally to the magnetic field. The ions are then accelerated and focused into the center of the electromagnet gap. Thus, in the example above, the 20 KeV ion beam would never reach the center of even a small electromagnet with 10 cm diameter pole faces at a field of eight kilogauss. The magnetic field must be reduced to allow the ions to reach the observation region at the center of the electromagnet. Therefore one must introduce the additional criterion that the radius of curvature of the ion beam in the magnetic field should be five times the electromagnet pole face radius. This criterion gives a maximum allowable magnetic field of approximately 800 gauss for a small electromagnet. Level-crossings at arbitrarily high magnetic fields cannot be observed. However, the maximum allowable magnetic field is extended considerably beyond that which occurs for electron bombardment excitation.

The use of heavier ions would extend the maximum magnetic field to even higher values, but the magnetic field limitation would still exist. If neutral-atom bombardment is considered, no magnetic field limitation arises.

A neutral particle beam comparable in velocity to that of electron beam velocities should be used. The excitation cross sections of a non-resonant state by neutral atoms is comparable to the excitation cross sections for electrons. Thus a neutral beam
would provide coherent excitation of a wide variety of atomic states and allow observation of level-crossings at arbitrarily high magnetic fields.

For this reason, the accelerator is designed so as to produce a neutral hydrogen (H°) beam at a maximum energy of 50 KeV. Neutral H° atoms can be used because of their simplicity of production; there is no advantage in using heavy neutrals. The particle source consists of an ORTEC 320 radio frequency ion source, focused with an ORTEC 3301 variable focus gap lens. The ion source, with a hydrogen gas supply, produces an H⁺ or H₂⁺ beam. A charge exchange canal after the gap lens is located in the beam path to produce a neutral H° beam. The following paragraphs describe the construction and operation of the accelerator as well as the characteristics of the output beam.
II. CONSTRUCTION OF THE ACCELERATOR

A. Vacuum System

The accelerator vacuum manifold consists of three brass chambers. For reference, the chambers are numbered 1, 2, and 3 from left to right when facing the accelerator. The center chamber, number 2, is sectionalized from each side chamber by 1 cm diameter apertures. This chamber contains the charge exchange canal (see Figures 1, 2, and 3). The gas feed to the canal is controlled by a micrometer valve (Vactronic VV-50) which is mounted on the chamber flange cover. Chamber number 1 contains the high vacuum valve which is used to isolate this section from chambers number 2 and number 3. Mounted below each vacuum chamber is a water cooled oil diffusion pump.

The mechanical vacuum fore pumps (A) and (B) are capable of pumping 15 and 35 cubic feet per minute respectively. Each pump is supplied with a vented exhaust valve to minimize condensation of vapors in the pumps.

Differential pumping is necessary due to the heavy gas load of the charge exchange canal upon the vacuum system. A National Research Corporation (VHS-6) 2400 liter per second oil diffusion pump is mounted directly below the charge exchange canal chamber. A high pump speed is required because of the high gas efflux (0.1 to 1.0 cm$^3$ per sec at standard temperature and pressure) from the charge exchange canal. Mounted below chambers number 1 and number 3 are identical TM Vacuum Corporation (TM4) 680 liter per second (with baffle installed) oil diffusion pumps. Diffusion pump number 1
Figure 1
Front View of Accelerator
The experiment chamber is in place between the pole faces of the electromagnet.
Figure 2
Vacuum Manifold
This figure shows the location for the high vacuum valve (left chamber number 1), micrometer valve (center chamber number 2), glass viewing port (right chamber number 3), as well as the thermocouple and ion gauge control units. Thermocouple TC2 is located directly behind the micrometer valve.
Figure 3
Vacuum Manifold and Pumping System
removes gas which enters into vacuum chamber number 1 from the charge exchange chamber number 2 as well as from the experiment chamber. Diffusion pump number 3 removes gas escaping from chamber number 2 and gas from the ion source. In reference to Figure 1, diffusion pump number 1 is backed alone by the 15 cubic feet per minute fore pump (A). This enables one to close the high vacuum valve and shut down chamber number 1, allowing the experimental section of the accelerator to reach atmospheric pressure. Therefore, chamber number 2, number 3, and the ion source may remain at high vacuum. The 35 cubic feet per minute fore pump (B) backs diffusion pumps number 2 and number 3. Likewise, this section of the accelerator may be shut down as above while the experimental section and chamber number 1 remain at high vacuum.

Power is applied to each diffusion pump heating element by closing their respective circuit breakers. However, in series with each circuit breaker is a normally open relay. The relay closes only when the respective mechanical fore pump is turned on and the cooling water pressure is at least 15 pounds per square inch. (See Appendix II, Figure 15.) This electrical interlock trys to prevent the diffusion pumps from being operated with insufficient cooling water and/or inoperative pumps. Thus, if the water pressure should decrease or if a mechanical pump shuts off, power will be removed from the respective diffusion pump. Mounted on the panel above the fore pump starting switches are three green pilot light indicators, one for each diffusion pump. The indicators will illuminate only when the heating element of each diffusion pump is actually
energized. In addition, each diffusion pump is supplied with a thermal interlock by the manufacturer. This thermal switch, which is in the base of each diffusion pump, monitors the boiler temperature and will open the heater circuit if the temperature should rise above a predetermined level.

Hand operated valves mounted on the back frame of the accelerator control the cooling water supply to each of the diffusion pumps (see Figure 4). A single water supply line and return line are brought overhead to the accelerator. Rubber hose is used for the lines since its greater insulating factor prevents condensation.

Dow Corning DC-704 silicone pump fluid is used in each diffusion pump. This oil is used due to its stability at high temperature and pressure. If a leak should occur in the vacuum system which allows the accelerator to reach atmospheric pressure, the oil will not break down and become useless as is the case with some pumping fluids.

Two types of gauges are available to measure the pressure at various locations throughout the accelerator vacuum system. One thermocouple tube is located in the fore line of each mechanical pump to monitor the pressure between the intake of the mechanical pump and the outlet of the diffusion pump (TC1, TC3). Another thermocouple tube (TC2) is connected directly to monitor the pressure at the center of the charge exchange canal. A Veeco TC-7 thermocouple gauge control unit is used to select any one of the three gauge tubes via a front panel selector switch. A calibrated scale from 1 to 1000 microns pressure is read directly to monitor the
Figure 4
Rear View of Accelerator
This figure shows the location of the ion gauge tube (chamber number 1), thermocouple gauge tube TC1, diffusion pump cooling water hand valves, and fore pump (A) air bleed-in valve.
pressure at any switch setting. Bayard-Alpert ionization gauge tubes are mounted on the back side of each vacuum chamber above the diffusion pumps. A Veeco RG-83 ionization gauge control with a modified Veeco RG gauge tube selector switch (P/N 0307-844) selects any one of the three ion gauge tubes. The ion gauge control unit indicates the vacuum system pressure in eight ranges from $1 \times 10^{-2}$ torr to $1 \times 10^{-9}$ torr full scale.

A quick actuating vacuum valve isolates chamber number 1 with its corresponding diffusion and mechanical pump from chambers number 2 and number 3. A bleed-in valve on each mechanical pump may be used to bring the vacuum system to atmospheric pressure after shut down of the accelerator. Normally, the bleed-in valve on the small mechanical pump (A) is used to bring the system to atmospheric pressure because of its easy accessibility. This valve also has a provision for a hose connection to a Veeco leak test instrument.

B. High Voltage Terminal

The high voltage terminal is an aluminum enclosure which contains the radio frequency ion source and auxiliary operating equipment. The terminal itself rests on a Plexiglas pedestal which serves as an insulating support. All edges and corners of the high voltage terminal have a minimum radius of 5 cm to prevent corona discharge when the terminal is operating at voltages as high as 50 kilovolts (kV). The terminal is constructed so as to provide a completely smooth exterior surface free from any sharp points which would produce corona. Easy access to the radio frequency ion source and
auxiliary equipment is accomplished by lifting off the top dome of the terminal, additional access being provided by removable side panels. Each side panel is held in place by four quick-open fasteners. There are also several small openings in the top and side panels. These openings are necessary to allow visual monitoring and control operation of the ion source and enable cooling air to be drawn inside. The edges of these openings are appropriately rounded to prevent corona.

The auxiliary equipment used to operate and monitor the radio frequency ion source is supported on shelves and panels within the terminal. However, the high voltage terminal does not provide structural support for the ion source. The ion source and magnet coil are supported by the lens.

The terminal is located within a screened safety enclosure (see Figure 5). The purpose of this safety enclosure is two-fold. First, the enclosure prevents operating personnel from coming into contact with the high voltage terminal when it is energized. Second, the enclosure acts as a smooth-flat electrical ground plane to prevent corona discharge from sharp pointed objects at ground potential in the vicinity of the terminal. If the screen were not present, corona might originate from sharp ground points (negative with respect to the high voltage terminal) and spray back to the high voltage terminal. Two examples of such sharp ground points might be the manifold flanges and the accelerator support frame.

An aluminum panel is mounted in a section of the safety enclosure screen. This panel provides bearing support for Lexan
Figure 5
Safety Enclosure
This figure shows the high voltage terminal, terminal control panel and high voltage isolation transformer. For clarity in the photograph the safety screen above the control panel has been removed.
control rods attached to switches and variacs inside of the terminal. Thus, all control functions of the ion source can be operated external to the safety enclosure thru the use of the Lexan control rods.

C. High Voltage Power Supply

An oil immersed high voltage direct current power supply (Universal Voltronics BPO 50-5.5, 1.5% ripple RMS @ 5.5 ma) is located in a far corner of the safety enclosure. The high voltage direct current output of the supply can be varied from 0 to 50 kV by adjusting the input voltage to the supply using a control variac. The high voltage control variac as well as a kilovoltmeter and milliammeter are mounted on the front panel of the accelerator above the fore pump starter switches. The kilovoltmeter (0 - 50 kV) and milliammeter (0 - 10 mA) monitor the output of the power supply. A five ampere breaker in the input line to the high voltage supply provides overload protection.

The input circuit of the high voltage direct current power supply is energized by a key operated switch and is electrically interlocked to the door of the safety enclosure. If the door of the enclosure should accidently be opened while the high voltage supply is energized, the input circuit of the supply is shut off. In addition, the high voltage direct current is grounded by the fall of a shorting contact in the power supply. As a secondary precaution before entering the safety enclosure, a metal shorting rod grounded to the enclosure is inserted through the terminal control panel into
an opening in the high voltage terminal. This will ground any charge
collected on the terminal and electrically short out the filter
capacitors in the high voltage supply in the case the shorting
contact should fail to fall.

The positive polarity high voltage lead from the power supply
is not connected directly to the high voltage terminal. Rather, the
lead is connected to one side of the secondary of a 50 kV, one kilo­
volt-ampere isolation transformer. The isolation transformer is
required to supply 120 volts, 60 hertz power for operation of the
auxiliary equipment in the high voltage terminal. To supply this
power, two cables (insulating value greater than 50 kV) run from the
secondary of the isolation transformer to the high voltage terminal.
One of the cables common to the high voltage supply lead is connected
directly to the frame of the high voltage terminal. The other cable
connection is insulated from the terminal frame. The input power
for the auxiliary equipment inside the terminal is supplied by the
voltage between the two power cables brought to the high voltage
terminal. (See Figure 6.) Therefore, the terminal is at a positive
high voltage direct current potential above ground and energized
internally to supply ac power to the auxiliary equipment for
operation of the radio frequency ion source.

D. Lens

The ORTEC 3301 variable focus gap lens is supplied 0 to 20 kV
direct current by an encapsulated power supply (Universal Voltronics
BPE-22-15, 0.5% ripple RMS) within the high voltage terminal. A high
Figure 6
Lens and Radio Frequency Ion Source
This figure shows the interconnection of the high voltage supply, lens supply, and the isolation transformer.
voltage lead is brought out from inside the terminal. This external lead is the negative lead from the lens power supply and is connected to the intermediate focusing electrode. The positive lead of the supply is common to the high voltage terminal (see Figure 6). The voltage input to the lens power supply is controlled by a variac within the high voltage terminal. Control of this variac in turn is accomplished by turning a Lexan rod from the terminal control panel. The lens power supply controls the strength of the electric focusing field in the accelerating gap present in the lens.

The ORTEC 3301 lens is of a special design to prevent the magnet coil, which is used when operating the ion source, from having any focusing effects on the ion beam. Two of the electrodes contained in the lens are constructed of magnetic stainless steel. These shield the interior of the lens and eliminate any interference between the magnetic field and the electric focusing field.

E. Charge Exchange Chamber

The center brass chamber (number 2) contains the charge exchange canal. (See Figure 2.) The canal consists of a stainless steel tube 20 cm in length by 1.3 cm inside diameter. The canal is supported at the center from the chamber flange cover by a 1.3 cm inside diameter stainless steel tube. This tube also serves as the gas feed line to the canal from the micrometer valve. A separate line from the center of the canal to a thermocouple gauge tube (TC2) is necessary to monitor the pressure at the center of the canal.
III. RADIO FREQUENCY ION SOURCE

A. Theory

A hydrogen discharge is supported in a Pyrex bottle by an externally applied radio frequency field at approximately 80 megahertz. The radio frequency field dissociates and ionizes the hydrogen gas in the Pyrex bottle producing atomic hydrogen and free protons. A clean Pyrex bottle is used since it is a poor catalyst for recombination of atomic hydrogen into molecular hydrogen. Most metals are considered a good catalyst in this respect and must be far removed from the discharge region. Any metal components in this region would drastically reduce the percentage of protons in the output beam because of recombination. Therefore, external radio frequency excitation provides a unique method of sustaining a gas discharge within the Pyrex bottle without the need of internal metal electrodes which would increase the recombination rate.

A self-excited oscillator of 100 watts output power is closely coupled to the Pyrex bottle by two metal bands. The radio frequency loading changes with varying discharge parameters. Probe voltage, magnet current, gas flow rate, and radio frequency coupling affect the amount of power delivered to the gas discharge. A self-excited oscillator will shift frequency to maintain proper radio frequency loading into the discharge as the operating parameters of the gas discharge vary.

In order to obtain a usable proton beam from the source, the protons must be extracted from the discharge region. The extraction
system consists of an aluminum anode (probe), and a cathode consisting of a cylindrical aluminum tip. A 0.0625 inch diameter canal in the aluminum tip provides an exit path for protons into the ORTEC focusing lens. The canal tip is constructed of aluminum because of the low sputtering rate of aluminum as compared to other metals. Another advantage of aluminum is its slightly smaller surface recombination rate for protons. The canal tip is recessed from the discharge region by a sapphire insulating sleeve.

According to Moak et al., a virtual lens is formed over the canal tip by the plasma as the extraction voltage (probe voltage) is applied. This lens will focus a large percentage of protons into the exit canal. An axial magnetic field along the canal increases output by reducing space-charge spreading in the canal. Another advantage of the magnetic field is that radio frequency power requirements are reduced. This is due to the action of the stray magnetic field in the discharge region which limits the electron paths, thereby increasing the ionization probability per unit electron.

The ion source not only produces an $H^+$ beam but an $H_2^+$ beam as well by exchanging the aluminum canal tip for a pure nickel tip. The nickel canal tip changes the recombination ratio in the gas discharge to favor an $H_2^+$ output beam.

After many hours of operation, aluminum or nickel from the canal tip will be sputtered on the walls of the Pyrex discharge bottle, increasing the recombination rate along the walls. In effect, this will considerably reduce the percentage of the protons or, in
the case of the nickel tip, hydrogen molecular ions in the output beam. When this point is reached, the ion source should be removed and disassembled. The Pyrex bottle is cleaned with hydrofluoric acid to remove the sputtered metal deposits. (See Appendix I).

Appendix II contains circuit diagrams of the radio frequency oscillator, oscillator power supply, probe supply, magnet coil supply, and the diffusion pump electrical interlock system.

B. Installation

The radio frequency ion source and magnet coil are mounted directly on the lens and are enclosed by the high voltage terminal. The lens, in turn, is mounted on the end flange of the vacuum chamber number 3. Shelves mounted directly below the ion source within the high voltage terminal support the auxiliary equipment used in the operation of the source.

Lexan control rods from the terminal control panel pass through a side panel of the high voltage terminal. These rods actuate controls necessary for operation of the source. Monitoring of the ion source circuit parameters is accomplished by three recessed instrument panel meters mounted on the side of the high voltage terminal. It is necessary in some instances to visually monitor the ion source gas discharge characteristics (color, intensity, and location) during operation of the source. For this purpose a small side opening near the top of the terminal allows one to view the Pyrex discharge bottle. Then, by careful adjustment of the source parameters—gas flow, probe voltage, magnet current, and oscillator...
coupling—one can obtain optimum performance of the source during actual operation.

With the accelerator in operation, low energy x-rays are produced in the vicinity of the ion source base and lens. A metal shield which includes a window of lead x-ray glass surrounds the source. This effectively stops the radiation and still allows one to view the radio frequency discharge through the opening in the terminal.

Hydrogen is admitted to the Pyrex discharge bottle through the base of the ion source. The gas supply must be free from contaminants. Heavier ions will increase the sputtering rate, reducing source life and proton output.

A palladium leak is used to control the hydrogen gas flow. The metal palladium presents an unusual property in that when heated it will allow only hydrogen to pass through it. The rate of the gas flow through the palladium increases as the temperature of the palladium is increased. Thus, the palladium leak not only provides a simple method of controlling small flow rates of hydrogen but also purifies the gas as well.

The palladium leak assembly is mounted within the high voltage terminal near the ion source. A palladium tube (3.3 mm outside diameter) is sealed at one end, forming a small thimble about 5 cm in length. The palladium thimble is inserted into a glass insulating sleeve. A heating element of nichrome wire is wound around the glass sleeve. This assembly is sealed into a small metal canister. A copper line from the open end of the thimble feeds hydrogen gas from inside the thimble to the base of the ion source. The canister is
pressurized with 20 pounds per square inch of hydrogen via a feed line from a small lecture bottle (two cubic feet) and regulator valve. Thus, the thimble is surrounded by a hydrogen atmosphere. The nichrome heating element is heated by current from a small filament transformer which is controlled by a variac within the high voltage terminal. The nichrome heating element in turn raises the temperature of the palladium thimble. This allows hydrogen in the canister to pass into the thimble and into the copper line feeding the ion source.

If, for any reason, the gas lecture bottle is changed or the palladium leak is cleaned and reassembled, the line feeding the leak should be pumped down with a portable vacuum pump. Access to the gas supply line and valve is accomplished by removing the side panel opposite the controls on the high voltage terminal. Be sure the gas supply valve to the leak is closed. Attach the rubber hose and stopper to the intake of the pump. Start the pump and open the pump out valve. This will pump down the palladium leak and its corresponding feed line from the gas supply valve. Momentarily open the gas supply valve to dilute the air present in the system with hydrogen and immediately reclose the valve. This will decrease the pump down time and limit the amount of residual air left in the system. Evacuate for approximately five minutes. Then close the pump out valve. Disconnect the hose from the pump and shut off the pump. Now the gas supply valve may be opened to refill the palladium leak canister. Usual pressure in the line feeding the leak is 20 pounds per square inch as adjusted by the regulator valve.
The ion source and auxiliary equipment are cooled by two blowers mounted within the high voltage terminal. One blower near the base of the high voltage terminal brings in cool air and provides some air circulation within the terminal. The other blower, mounted in line with the ion source, maintains the ion source discharge bottle, magnet coil, and the radio frequency oscillator tubes at a reasonably cool temperature. (See Figure 7). ORTEC recommends using a special heat sensing paint (Tempilac-400 F) to monitor the operating temperature of the oscillator tubes.

C. Tuning

A simple procedure must be followed for initial start up of a new or reconditioned ion source. The procedure is necessary to set operating parameters as no two ion sources will operate under the exact same conditions. The Pyrex discharge bottle must be outgassed in this process and the vinyl seals checked for leaks.

Once the ion source is mounted, the radio frequency bands are placed on the bottle. The aluminum heat radiator cap must be removed to slide the bands onto the discharge bottle. Slide one of the copper bands along the bottle until the front edge is even with the magnet coil. Be careful not to bend the band or scratch the bottle. The second band should be placed midway between the first band and the top seal of the source. The bands are held by clip leads which are attached to the radio frequency oscillator tank coil. The clips are symmetrically attached to the coil approximately one-quarter turn either side of the center tap as a starting position. Replace the
Figure 7
Radio Frequency Ion Source
This figure shows the location of the radio frequency ion source, radio frequency oscillator, air cooling blower, palladium leak assembly, and the metal shield, with the x-ray glass window.
heat radiator cap.

Start the vacuum system (Chapter II) and allow it to pump down the ion source for several hours. When a relatively good vacuum is attained (\(< 10^{-5}\) torr as measured by the ion gauge selector switch at position number 3), switch on the radio frequency oscillator. (A thermal relay delays application of the plate voltage to the oscillator tubes for one minute after the initial turn on. This allows enough time for the oscillator tube filaments to reach the correct operating temperature.) After the power supply warm up period, the radio frequency field should start a discharge in the Pyrex bottle. This gas discharge is due to outgassing of air from the walls of the Pyrex bottle. This discharge will be light white-blue in color.

The discharge due to the outgassing should gradually become weaker over a period of 25 to 30 minutes and disappear. A very weak discharge may fill the bottle or remain near the sapphire insulating sleeve. This may be due to cold leak of hydrogen through the palladium and should not be considered an air leak. Usually the discharge will go out completely. However, this will be dependent upon the length of time the accelerator has been under a good vacuum. This process may take anywhere from 15 minutes to 12 hours. If a very bright discharge remains after several hours, search for a leak or a source of contamination.

When the source is pumped down and blackened out (no visible discharge), switch on the palladium leak. Since the leak requires
1 to 3 minutes to arrive at operating temperature, advance the control knob slowly. Bring up the control in increments until a weak discharge begins. At first, the color of the discharge will probably be light pink. Continue to advance the control until the discharge begins to flicker. The discharge intensity will go back and forth from a weak discharge to a relatively bright discharge. Increase the gas feed until the discharge remains in the brighter mode with no tendency to flicker. When this point is reached, allow the source and the palladium leak to outgas for 15 minutes. There should be a noticeable color improvement during this period. The discharge should shift to a reddish-purple color.

If the performance is not as described, stop the procedure and find out why the source is not operating correctly. The blackout and flicker point should be observed. If neither is observable, the most probable cause is an air leak.

A milliammeter can be inserted between the high voltage terminal and ground. This measures the return current as the ion beam is sprayed into the lens and accelerator manifold. The coax lead between the high voltage direct current power supply and the isolation transformer is disconnected from the high voltage supply and inserted into the coax recepticle mounted on the meter box. This will effectively short the high voltage terminal to ground through the milliammeter. The intermediate focusing electrode of the lens should be grounded. This is accomplished by removing the high voltage lead to the focusing electrode and connecting a lead from the focusing electrode to ground.
Now the ion source must be tuned for optimum performance. However, a word of caution should be inserted regarding operation of the source. When starting the source, always turn on the probe voltage last. When shutting down the source, turn off the probe voltage first. This will prevent the sapphire sleeve from fracturing due to electrical and thermal stress.

After the source has operated above the flicker point for 15 minutes, switch on the probe voltage. Slowly raise the voltage to 1 kV. The probe current should not exceed 2 mA. Hold the probe voltage at 1 kV for five minutes. Switch on the magnet and adjust the current for maximum output as indicated on the 1 mA return current meter. Increase the probe voltage in 1 kV increments every 15 minutes until 5 kV is reached. Correspondingly, adjust the magnet coil current for maximum output each time the probe voltage is increased. In some instances, several maxima may be noticed at a given probe voltage as indicated by the return current meter while the magnet current is adjusted. Stable operation of the ion source occurs at the maxima associated with lowest magnet current and probe current. If the source begins to flicker, stabilize the discharge by increasing the gas flow. Also, note any color change which would denote a leak. The discharge should be an intense reddish-purple color centered at the sapphire insulating sleeve. Relatively little, if any, discharge should be seen near the anode probe cap when 5 kV is reached. The probe current should be greater than 7 mA but should not exceed 15 mA. Probe currents less than 7 mA would indicate inadequate radio frequency coupling.
With the source operating at 5 kV probe potential, adjust the magnet current for maximum output. Note the output meter reading. Decrease the probe voltage to 0 kV and switch off. Turn off the radio frequency oscillator plate supply with the switch on the oscillator power supply chassis in the high voltage terminal. Increase the radio frequency coupling by symmetrically moving the clip leads away from the center tap of the oscillator tank coil. Then switch on the oscillator plate supply and probe voltage. Increase the probe voltage to 5 kV and adjust the magnet current for maximum output. Repeat this procedure until the return current reading is maximized.

The above procedure will not always affect the return current so as to produce a noticeable increase in the current readings. If, after several adjustments, the return current has not increased, check the probe current at 5 kV. Excessive radio frequency coupling may increase the probe current to such an extent that a continuous discharge may develop between the cathode tip and the anode probe at a 5 kV probe potential. An indication of this condition would be excessive probe currents above 15 mA which peg the probe current meter. If the increased radio frequency coupling does not affect the return current, return the clip leads to the original starting position. This will decrease the temperature of the Pyrex bottle, and prevent the discharge from overheating and possibly melting it. If probe currents are above 15 mA be sure to reduce the radio frequency coupling.
Increased gas flow rates will also increase the probe current readings but could reduce the source output current. Insufficient gas flow rates will produce the same effect. Adjust the gas feed for maximum output as indicated on the return current meter. Maximum output occurs at gas flow rates just above the flicker point. However, avoid setting the gas rate too close to the flicker point as erratic operation and output will result. Record all meter readings and dial settings for future reference.

In operation of the ion source it is best to experiment and try different probe voltages, magnet currents, and gas flow rates to determine the best operating parameters. These parameters will not always remain constant but may vary from one start up to another if the accelerator is shut down and opened to the atmosphere. In some instances, when the radio frequency oscillator is turned on the discharge will not immediately ignite after the oscillator warm up period. The reason for this is not completely understood. A high frequency source such as a Tesla coil may be used to start the discharge in extreme cases. Different positionings of the radio frequency coupling bands may help as well.

When the high voltage (acceleration potential) is energized, beam currents produced will not always be at maximum values if the ion source is set at the values obtained from the tuning procedure for maximum return current. The effect of the high voltage and lens will detune the source from maximum output. Therefore, final settings for magnet current, probe voltage, and gas flow rates should be found under actual operating conditions with the acceleration potential and lens in use. A Faraday cup inserted in the beam path will act as a tuning indicator for obtaining maximum beam currents.
IV. MEASUREMENTS

Typical data from the tuning procedure is given in Table I. Measurements of the return current with the high voltage shut off are shown in this table. Maximum $H^+$ output for the ORTEC 320 ion source is approximately 1 mA when using an aluminum tip and a Pyrex bottle. The return current readings are dependent upon probe voltage, magnet current, and gas flow as well as the radio frequency coupling to the discharge bottle.

Operating parameters found when first tuning the source may change slightly once the accelerator is opened to the atmosphere. This effect is probably due to contamination of the ion source by atmospheric gasses. After the vacuum system is pumped down and the source is again operated for several hours, readings may return to their original values. However, this will not occur in every case.

Return beam currents for sources using aluminum and nickel canal tips are shown in Tables I and II respectively. Return current for the $H_2^+$ source was low as compared to the $H^+$ source. In tuning the $H_2^+$ source, it was found that increasing the radio frequency coupling did not increase the return current. Increasing the radio frequency coupling raised the probe current to a point at which a continuous discharge developed between the canal tip and probe at higher probe voltages. When this discharge occurred the return current would drop to zero. Increasing the gas flow to excessive rates would have the same effect. The discharge would be very difficult to start in some instances. The color of the $H_2^+$
## Table I

Data from Tuning Procedure for Source Using Aluminum Tip

<table>
<thead>
<tr>
<th>Probe Voltage (kV)</th>
<th>Probe Current (mA)</th>
<th>Magnet Current (A)</th>
<th>Return Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.25</td>
<td>0.1</td>
<td>0.09</td>
</tr>
<tr>
<td>2</td>
<td>4.9</td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>10.0</td>
<td>1.08</td>
<td>0.40</td>
</tr>
<tr>
<td>4</td>
<td>12.0</td>
<td>1.35</td>
<td>0.60</td>
</tr>
<tr>
<td>5</td>
<td>13.0</td>
<td>1.50</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Table II

Data from Tuning Procedure for Source Using Nickel Tip

<table>
<thead>
<tr>
<th>Probe Voltage (kV)</th>
<th>Probe Current (mA)</th>
<th>Magnet Current (A)</th>
<th>Return Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>0.08</td>
</tr>
<tr>
<td>2</td>
<td>3.8</td>
<td>0.3</td>
<td>0.10</td>
</tr>
<tr>
<td>3</td>
<td>6.0</td>
<td>0.5</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>5.0</td>
<td>0.65</td>
<td>0.28</td>
</tr>
<tr>
<td>5</td>
<td>5.4</td>
<td>0.6</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
source discharge is lighter pink as compared to the reddish-purple of the $\text{H}^+$ source. Behavior of the $\text{H}^+$ source was more stable and higher return currents were noted as compared to the $\text{H}_2^+$ source.

Beam current is measured by allowing the accelerated beam to strike a Faraday cup. The beam collecting device is insulated from ground (accelerator manifold). The device is then grounded through a microammeter to measure beam current (see Figure 8).

Typical data for $\text{H}^+$ with various probe and accelerating voltages is given in Table III. In each case the magnet current, gas flow, and lens focusing is adjusted for maximum beam current as indicated on the microammeter. It should be noted here that the lens voltage adjustment is very critical. A small adjustment will make the difference between a focused beam or none at all. Adjustment of the magnet current or probe voltage will require readjustment of the lens focusing voltage. This is due to a change in the focusing of the ion source beam at the canal tip within the ion source. Adjustment of the high voltage (acceleration potential) will also require readjustment of the lens. This action is expected due to the construction of the lens. The effective focal length is determined by the ratio of the accelerating potential to the intermediate focusing electrode potential. A change in either of these potentials will change the plane of focus.

Actual beam focus is observed by allowing the accelerated beam to impinge on a quartz plate. Quartz has the property of fluorescing upon impact where struck by an energetic particle beam. A quartz plate sealed in a metal ring is placed in the beam path. The metal
Figure 8
Beam Current Measurement
Upper portion of the figure shows Faraday cup used in measuring beam current. Lower portion of the figure shows quartz window used to observe the beam focus.
## Table III

Beam Current Measurement

<table>
<thead>
<tr>
<th>High Voltage (kV)</th>
<th>Probe Voltage (kV)</th>
<th>Probe Current (mA)</th>
<th>Magnet Current (A)</th>
<th>Beam Current* (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.65</td>
<td>6.6</td>
<td>0.82</td>
<td>15.0</td>
</tr>
<tr>
<td>20</td>
<td>3.20</td>
<td>10.8</td>
<td>1.65</td>
<td>25.0</td>
</tr>
<tr>
<td>30</td>
<td>1.60</td>
<td>5.8</td>
<td>0.85</td>
<td>35.0</td>
</tr>
<tr>
<td>40</td>
<td>4.10</td>
<td>7.0</td>
<td>0.95</td>
<td>100.0</td>
</tr>
<tr>
<td>50</td>
<td>4.20</td>
<td>10.1</td>
<td>1.65</td>
<td>140.0</td>
</tr>
</tbody>
</table>

*Note: Beam current in this case was measured as the return current to the metal ring that mounts the quartz window. This return current neutralized the ion beam impinging on the quartz window. The quartz window is used rather than the Faraday cup due to difficulty of mounting the Faraday cup because of the close proximity of the magnet pole faces. At 40 kV and 50 kV a red spot 2 to 3 mm in diameter would form due to heating of the quartz by ion bombardment.
ring is then grounded through a microammeter so as to provide relative beam current indication. It is difficult to observe the focusing of the beam because of a broad, over-all fluorescence which covers most of the quartz plate. This fluorescence is due to unfocused ions caused by scattering near the lens. At high accelerating potentials a red spot may form indicating a highly collimated and intense beam. The red spot diameter is approximately 2 to 3 mm.

With the level-crossing bombardment chamber in place at the experimental section of the accelerator, beam currents were measured by the collector cup at the observation region of the chamber. The ion beam had to pass through a 3 mm diameter aperture to enter the observation region of the chamber. Beam current measured by the collector cup would average between 25 and 75 microamperes, depending upon the value of the acceleration potential. This should be contrasted to a total beam current, coming down the accelerator tube of 200 microamperes and above on this occasion.
V. RADIATION

During operation, x-rays are produced by backstreaming electrons falling through the accelerating potential and hitting the ion source base. X-rays produced at the ion source base escaping between the source base and the magnet coil could lead to a dangerous radiation hazard outside the safety enclosure. For this reason, a one-quarter inch thick steel shield surrounding two sides of the ion source is used to protect the operator from the radiation produces. A window of lead x-ray glass in this shield limits the radiation and still allows one to observe the radio frequency discharge.

The amount of radiation increases rapidly above 20 kV as the high voltage is increased to 50 kV. Also, the radiation level increases if the accelerated beam is not properly focused. Without the metal shield present, the radiation level approaches 250 milliroentgen per hour at 50 kV measured at a point in front of the terminal control panel. With the shield present, the radiation is always reduced to a negligible level of 0.02 milliroentgen per hour or less. Federal and state requirements limit the total amount of radiation exposure to 100 milliroentgen per week.

A Victoreen 808B radiation monitor is mounted on the safety enclosure to continually monitor the radiation level. The detector is placed at the point at which the greatest intensity was measured at the terminal control panel. If the radiation rises above a predetermined level, an alarm will be sounded. Radiation film badges are worn by operating personnel as an extra precaution.
No ionizing radiation is emitted from the experiment chamber. This is because the acceleration of ions striking a target is much smaller than electrons striking a similar target at the same energy. As an example, a 50 KeV proton beam striking an aperture plate at the experiment chamber will produce no ionizing radiation. However a backstreaming 50 KeV electron striking the lens will produce considerable radiation which would require shielding to protect the operating personnel.
VI. NORMAL OPERATION

A. Start Up

The following is a suggested procedure which should be followed when starting the accelerator. This would alleviate any possible chance of error and resulting damage to the equipment.

Be sure both bleed-in valves on the fore pump lines are closed. The high vacuum valve separating chambers number 1 and number 2 should be open to equalize pressure throughout the vacuum system (valve control knob is rotated full clockwise position to detent). Check breaker panel to see that both fore pump breakers are in the on position. The fore pumps are started by closing their respective starter switches on the front panel of the accelerator. A gurgling noise, characteristic of mechanical vacuum pumps while operating at high pressure, should disappear after a minute. If not, check the vacuum system for possible leaks.

Next, apply power to the thermocouple gauge control unit. The ionization gauge control unit may also be turned on to temperature stabilize, but do not depress the filament switch. The pressure in the vacuum system is not low enough for correct operation of the ionization gauge. Observe the thermocouple gauge meter with the selector switch in position number 1 or number 3. When the vacuum system reaches 20 microns pressure, open the three diffusion pump cooling water valves. Apply power to each diffusion pump heating element by use of the circuit breakers on the breaker panel. Three
green pilot light indicators should light, one for each energized diffusion pump. The indicators contain 145 volt bulbs which decrease the possibility of rapid burn out. Thus, if an indicator does not illuminate, trouble may exist in the cooling water lines or a fore pump is not energized.

Carefully monitor fore pump (A) using the thermocouple gauge unit in position number 1. Watch for a sudden pressure increase in the vacuum system. This phenomena is due to a rapid outgassing of the pump fluid in the TM4 diffusion pump. If the pressure increases, shut off the power to both TM4 diffusion pumps number 1 and number 3 and wait for the pressure to decrease. Then re-energize both diffusion pumps and repeat this procedure until the fore pumps maintain a fore pressure of 50 microns or less.

The mechanical construction of the TM4 diffusion pump is such that the heating element is actually immersed in the oil. Only a thin film of pump oil is drawn into the capillary type heating element and raised to vaporizing temperature. The pumps require only three minutes to go from a cold start to full pumping capacity. Thus, the oil is heated and outgassed at such a high rate that the fore pumps cannot initially maintain a low fore pressure. This situation is quite evident if the vacuum system is exposed to atmospheric pressure for a period of a day or more.

Due to the large thermal capacity of the VHS6 diffusion pump, no problem should arise with rapid outgassing of the fluid. The heating element is bolted to the bottom of the pump boiler and it is externally mounted. The thermal time lag in heating the oil is thus
quite long and allows the fore pump to maintain a low pressure during start up. If the fore pressure should reach 100 microns, the diffusion pumps may stall and allow oil to backstream into the vacuum system. Therefore, one must be sure that the fore pressure does not rise above 50 to 100 microns.

After the diffusion pumps have been on for 20 minutes, place the range switch on the ionization gauge unit in the log position and depress the filament switch. One of the three gauge tubes should light depending on the position of the RG gauge tube selector. If the gauge tube filament lights but is suddenly extinguished, the system pressure is not low enough. Wait a few more minutes and repeat. The log scale indicates the general pressure range of the system. The other positions of the range selector switch provide linear pressure measurements. (The scale on the selector switch must be multiplied by the meter reading in order to obtain the pressure reading. For instance, a meter reading of 2 when the selector switch is set on $10^{-6}$ corresponds to a pressure of $2 \times 10^{-6}$ torr.) For correct measurement at low pressures, the gauge tube should be outgassed. This is accomplished by pressing the outgassing button. Outgas the gauge for approximately one minute and be sure to depress the button again to discontinue the process.

After several hours of pumping, the vacuum should reach between $0.5 \times 10^{-6}$ torr and $2 \times 10^{-6}$ torr with all external gas sources closed. A longer period of pump down time may be necessary if the vacuum system was open to atmospheric pressure for an extended length of time. The same would apply if the ion source is rebuilt or changed.
in any way. Outgassing of the radio frequency discharge bottle and associated hardware will increase the pressure and limit the maximum obtainable vacuum.

B. Shut Down

As noted before, chamber number 1 may be shut down without affecting chambers number 2 and 3. The experimental section of the accelerator can be worked on while the ion source and chambers number 2 and 3 remain under a high vacuum. This feature allows less down time than would be required by bringing the entire accelerator to atmospheric pressure.

When shutting down only chamber number 1, the ionization gauge tube number 1 should not be used. Thus, the RG gauge tube should be in position number 2 or number 3. Close the high vacuum valve (knob arm fully counter clockwise to detent) and shut off power to diffusion pump number 1. After 10 to 15 minutes check near the base of the diffusion pump to see if it is cool to the touch. If so, shut off the cooling water valve and allow the pump to reach room temperature. When the pump has reached room temperature, shut off the fore pump (A) and open the foreline air bleed-in valve. If immediate access to this chamber is required, bleed-in of dry air or other gas will prevent condensation of water vapor on the inner walls of the diffusion pump.

When restarting this section of the accelerator, the fore line bleed-in valve should first be closed. Restart fore pump (A) and allow the pressure to reach at least 20 microns as indicated by
the thermocouple gauge unit at position number 1 before starting diffusion pump number 1. However, be careful not to switch the ion gauge tube selector to position number 1. The vacuum in this chamber is not yet low enough for proper operation of the gauge tube. Start the cooling water to diffusion pump number 1 and energize the pump heater by turning on its circuit breaker. Observe the thermocouple gauge for any sudden pressure increase. If the pressure rises above 50 microns, temporarily shut off the diffusion pump heater until the pressure drops below 50 microns, then re-energize the diffusion pump. Repeat this procedure until the pressure remains below 50 microns. After 5 minutes switch the ion gauge tube selector to position number 1 and monitor the pressure. Then open the high vacuum valve between chambers number 1 and 2 when the vacuum is sufficiently low ($10^{-4}$ torr).

Final shutdown proceeds in the same sequence. First, turn off the thermocouple and ionization gauge control units. Switch off power to each diffusion pump but be sure to leave the cooling water on. Periodically check near the base of each diffusion pump to feel if the pump boiler is cool to the touch. As each pump becomes cool, turn off its respective cooling water valve. The TM4 pumps will cool down in about 15 minutes, while the VHS-6 will require about 1½ hours. Discontinue the flow of cooling water to each pump and allow the pumps to reach room temperature. This will prevent condensation from forming on the diffusion pump's inner walls when the vacuum system is opened to atmospheric pressure. When all three diffusion pumps have reached room temperature, shut off fore pumps (A) and (B).
Slowly open the fore pump (A) fore line air bleed-in valve.

C. Radio Frequency Ion Source

After the initial start up of a new radio frequency ion source (Chapter III), a routine procedure is followed.

First, close the isolation transformer breaker. This should start the air cooling blowers present inside the high voltage terminal. Turn on the radio frequency oscillator and palladium leak. Rotate the leak control to the desired setting. The radio frequency oscillator requires one minute to warm up, while the palladium leak needs one to three minutes to reach correct temperature. Turn the magnet on and adjust the current to the required value. Finally, turn on the probe voltage and adjust to the required value. Always turn on the probe voltage last as this will prevent damage to the sapphire insulating sleeve within the ion source. When shutting down turn down the probe voltage first; then shut off the magnet, palladium leak, and radio frequency oscillator respectively.
COMPOSITION OF OUTPUT BEAM

Theoretical calculations are shown here to predict the fraction of a fast hydrogen beam that exists in the neutral state \( \text{H}^0 \) after passing through hydrogen gas. Production of \( \text{H}^0 \) from the charge exchange of \( \text{H}^+ \) and from the dissociation of \( \text{H}_2^+ \) are considered.

The experimental situation is shown in Figure 3. The beam produced at the ion source is moving in a vacuum toward the charge exchange canal into which hydrogen gas \( \text{H}_2 \) may be introduced. The beam passes through the canal, emerges into high vacuum, and then into the experiment chamber. If the input beam to the charge exchange canal is of a known composition, the charge composition of the beam emerging from the charge exchange canal can be calculated. The charge composition of the emerging beam is calculated as a function of the canal gas pressure.

These calculations determine the optimum pressure at which to operate the charge exchange canal. One tries to obtain a large production of \( \text{H}^0 \) while minimizing two undesirable effects. The first of these undesirable effects is beam divergence caused by scattering in the charge exchange canal. This would prevent one from obtaining a finely focused beam. The second effect is that too much pressure in the charge exchange canal would cause too large a gas load on the vacuum system.
As indicated by Allison\textsuperscript{2,3}, the charge exchange process for H\textsuperscript{+} (> 20 KeV) incident on hydrogen gas involves two reactions

\[ \text{H}^+ + e \rightarrow \text{H}^0 \]  
(\sigma_o) \quad (1)

\[ \text{H}^0 \rightarrow \text{H}^+ + e \]  
(\sigma_i) \quad (2)

where \( \sigma_o \) is the electron capture cross section and \( \sigma_i \) is the electron loss cross section. Note the hydrogen target molecule is omitted from both sides of the reaction equations. The equations refer only to the energetic reaction products.

At energies below 20 KeV, H\textsuperscript{-} may be produced in small quantities (<2% of the total beam composition) as a possible third component. However, above 20 KeV, H\textsuperscript{+} and H\textsuperscript{0} are considered as the only prevalent reaction products and production of H\textsuperscript{-} is negligible.\textsuperscript{3}

For a two component system consisting of H\textsuperscript{+} and H\textsuperscript{0} two differential equations may be written to predict the production of H\textsuperscript{+} and H\textsuperscript{0} in the beam emerging from the charge exchange canal. They are:

\[ \frac{dF_0}{dN} = F_i \sigma_o - F_o \sigma_i \]  \quad (3)

\[ \frac{dF_i}{dN} = F_o \sigma_o - F_i \sigma_i \]  \quad (4)

with the requirement \( F_0 + F_i = 1 \) where \( F_0 \) and \( F_i \) are the fractions of H\textsuperscript{0} and H\textsuperscript{+} respectively in the emergent beam. \( N \) is the number of hydrogen molecules per square centimeter traversed by the H\textsuperscript{+} incident beam in the charge exchange canal.
Multiplying both sides of equation (4) by -1 one obtains

$$\frac{dF}{d\eta} = -\frac{dF}{d\eta} = F_0 \sigma_{00} - F_0 \sigma_{01}.$$  \hspace{1cm} (5)

The solution of equation (5) for the fraction of $H^0$ and $H^+$ are respectively

$$F_0 = F_{0\infty} - F_{0\infty} \exp \left[-\eta (\sigma_{00} + \sigma_{01})^2 \right]$$  \hspace{1cm} (6)

$$F_1 = F_{\infty} + F_{\infty} \exp \left[-\eta (\sigma_{00} + \sigma_{01})^2 \right]$$  \hspace{1cm} (7)

where

$$F_{0\infty} = \sigma_{00} / (\sigma_{00} + \sigma_{01})$$  \hspace{1cm} (8)

and

$$F_{\infty} = \sigma_{01} / (\sigma_{00} + \sigma_{01}).$$  \hspace{1cm} (9)

The constants of integration, $F_{0\infty}$ and $F_{\infty}$, are plateau values otherwise known as equilibrium fractions which $F_0$ and $F_1$ will reach as the pressure is raised in the charge exchange canal. The relationship between the pressure and $\gamma$ in the charge exchange canal is

$$\gamma = \frac{A}{RT} \left( PL \right)$$  \hspace{1cm} (10)

where $A$ is Avogadro's constant, $R$ is the gas constant ($6.24 \times 10^7$ micron-cm$^3$ per mole-°K, $P$ is the average pressure in microns in the canal, $T$ is the absolute temperature, $L$ is the length of the canal in centimeters. (The cross sections ($\sigma_{00}$, $\sigma_{01}$) given by Allison are in units of cm$^2$ per atom. However, to be consistent with the data given by McClure for reaction cross sections of $H^+_2$ incident on...
$H_2$, which are in units of cm$^2$ per molecule, Allison's cross section values will be multiplied by two to change to units of cm$^2$ per molecule so calculations will be consistent throughout.) At 20°C equation (10) becomes

$$\gamma = 3.30 \times 10^{-13} (PL).$$  (11)

Equation (11) is substituted into equations (6) and (7). $F_0$ and $F_1$ are plotted against increasing values of PL at 20 KeV, 35 KeV, and 50 KeV. (See Figures 9, 10, and 11.) The values for $F_0$, $F_1$, $\sigma_0$, and $\sigma_1$ are obtained from those tabulated by Allison.\(^3\) (See Table IV.) $\sigma_0, \sigma_1$ are from the data of Stier and Barnett as referenced by Allison. Later works by McClure\(^5,6\) reaffirm the values of Stier and Barnett as well as Allison\(^3\) and several others.\(^7,8\) More recent experimental data by Payne and Rivere\(^9\) agreed to within 1% of the equilibrium fractions measured by Allison.\(^2,3\) $F_0$ and $F_1$ in this case were not calculated from actual cross sections used. These values were measured directly by Allison and are thought to be more accurate. Also, the thermocouple gauge pressure (G) is plotted and assumed to be twice the average pressure over the length of the canal. (The canal having a fixed total length of 20 cm.)

A similar method is used to calculate the production of $H^0$ from dissociation and charge exchange of $H_2^+$ in $H_2$. The process is more complicated since a total of ten possible reactions result in dissociation of $H_2^+$ to produce $H^0$. 

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 9.
Beam Fraction Versus PL and G at 20 KeV
PL is in micron-cm, G is the gauge pressure as indicated by the thermocouple vacuum gauge at position number 2 (TC2). G is assumed to be twice the average pressure over the length of the charge exchange canal.
Figure 10.
Beam Fraction Versus $PL$ and $G$ at 35 KeV
$PL$ is in micron-cm, $G$ is the gauge pressure as indicated by the
thermocouple vacuum gauge at position number 2 (TC2). $G$ is assumed
to be twice the average pressure over the length of the charge
exchange canal.
Figure 11.

**Beam Fraction Versus PL and G at 50 KeV**

PL is in micron-cm, G is the gauge pressure as indicated by the thermocouple vacuum gauge at position number 2 (TC2). G is assumed to be twice the average pressure over the length of the charge exchange canal.
Table IV

Cross Section Values Used for Calculation of Output Beam Composition

for \( \text{H}^+ \) Incident on \( \text{H}_2 \)

\[
\begin{array}{ccc}
E_i & 20 \text{ KeV} & 35 \text{ KeV} & 50 \text{ KeV} \\
F_{\omega \infty} & 0.797 & 0.680 & 0.525 \\
F_{\omega \frac{\infty}{\infty}} & 0.185 & 0.320 & 0.475 \\
* \sigma_{\beta} & 58.0 & 32.0 & 18.0 \\
* \sigma_{\gamma} & 12.8 & 16.0 & 15.8 \\
\end{array}
\]

*Units are \( 10^{-17} \text{ cm}^2 \) per molecule. These values are obtained from Allison.\(^3\) At 20 KeV, \( F_{\omega \infty} + F_{\omega \frac{\infty}{\infty}} \) does not equal one since a small amount of \( \text{H}^- \) is produced. However this contribution is neglected since it is less than 2%.
When $\text{H}_2^+$ ion traverses a gaseous target, it is dissociated in the following ways:

$$\text{H}_2^+ \rightarrow \text{H}^+ + \text{H}^0 \quad (\sigma_7) \quad (12)$$

$$\text{H}_2^+ \rightarrow 2 \text{H}^+ + \text{e} \quad (\sigma_8) \quad (13)$$

$$\text{H}_2^+ + \text{e} \rightarrow 2 \text{H}^0 \quad (\sigma_9) \quad (14)$$

The $\text{H}_2^+$ ion may also form a neutral molecule. Thus,

$$\text{H}_2^+ + \text{e} \rightarrow \text{H}_2 \quad (\sigma_{10}) \quad (15)$$

These primary reactions undergo subsidiary reactions

$$\text{H}^+ + \text{e} \rightarrow \text{H}^0 \quad (\sigma_{11}) \quad (16)$$

$$\text{H}^0 \rightarrow \text{H}^+ + \text{e} \quad (\sigma_{12}) \quad (17)$$

$$\text{H}_2^0 \rightarrow 2 \text{H}^0 \quad (\sigma_{13}) \quad (18)$$

$$\text{H}_2^0 \rightarrow \text{H}^+ + \text{H}^0 + \text{e} \quad (\sigma_{14}) \quad (19)$$

$$\text{H}_2^0 \rightarrow 2 \text{H}^+ + 2 \text{e} \quad (\sigma_{15}) \quad (20)$$

$$\text{H}_2^0 \rightarrow \text{H}_2^+ + \text{e} \quad (\sigma_{16}) \quad (21)$$

Again, the reactions refer only to the energetic reaction products;
the target molecule \( \text{H}_2 \) is omitted from both sides of the reaction equations. Reactions shown in equations (16) and (17) occur at half of the initial \( \text{H}_2^+ \) energy.

Four coupled differential equations can be written to predict each of the four beam components as the PL product of the target gas is varied. They are as follows:

\[
\frac{df}{dt} = F_3 (2\sigma_f + \sigma_g) + F_2 (\sigma + 2\sigma_f) + F_0 \sigma_f - F_0 \sigma_g \tag{22}
\]

\[
\frac{df}{dt} = F_3 (\sigma_g + 2\sigma_f) + F_2 (\sigma_f + 2\sigma_g) + F_0 \sigma_g - F_1 \sigma_f \tag{23}
\]

\[
\frac{df}{dt} = F_3 (\sigma_f) - F_2 (\sigma_f + \sigma_g + \sigma_f + \sigma_g) \tag{24}
\]

\[
\frac{df}{dt} = F_3 (\sigma_f) - F_2 (\sigma_f + \sigma_g + \sigma_f + \sigma_g) \tag{25}
\]

\( F_0, F_1, F_2, \) and \( F_3 \) correspond to the fractions of \( \text{H}^0, \text{H}^+, \text{H}_2^+, \) and \( \text{H}_2^0 \) respectively. The factor of two in the production terms involving \( \sigma_f, \sigma_g, \) and \( \sigma_f \) are required since two identical particles are produced in a single reaction.

Barnett\(^{10} \) proceeded with a similar calculation for \( \text{H}_3^+ \) ions. However, he assumed that \( \sigma_f, \sigma_g, \) and \( \sigma_f \) are equal to \( \sigma_f, \sigma_f, \) and \( \sigma_f \) respectively since the cross sections for the dissociation of \( \text{H}_2^0 \) were at that time unknown. Later McClure\(^5 \) found the cross sections for \( \text{H}_2^+ \) and \( \text{H}_2^0 \) to be quite different. McClure was not able to resolve all the separate cross sections but did measure the yield cross section; \( \sigma_{\text{H}_2^+}, \sigma_{\text{H}_3^+}, \) and \( \sigma_{\text{H}_2^0} \) which are combinations of \( \sigma_f, \sigma_g, \sigma_f, \) and \( \sigma_{10} \).\(^5 \)
They are:

\[
\begin{align*}
\sigma_{H_2^+} &= \sigma_{10} \\
\sigma_{H^+} &= \sigma_g + 2\sigma_f \\
\sigma_{H^0} &= 2\sigma_f + \sigma_g
\end{align*}
\]

In addition, the method McClure used for measuring the dissociation cross sections of fast H_2^+ ions (\(\sigma_1, \sigma_2, \sigma_3, \sigma_4\)) is accurate only to a few percent. He found that the results of the measurement depended upon the ion source settings. The dependence appeared to be associated with the excitation of internal vibration and rotational states in the H_2^+ molecular ions as these ions leave the ion source 4,5,6,11,12.

With the aid of a PDP-10 computer these equations have been solved by the use of the Runge-Kutta numerical technique. Results for 20 KeV, 35 KeV, and 50 KeV H_2^+ ions incident on H_2 gas are shown in figures 12, 13, and 14. Table V gives the values of \(\sigma\) for these computations. The results are plotted as the number of particles produced per incident H_2^+ ion versus pressure of the gas in the canal in microns times the length of the canal in centimeters. As before, the lower scale indicates the gauge pressure (G) as measured by thermocouple TC2. The gauge pressure is assumed to be twice the average pressure along the length of the canal. Note that when an H_2^+ ion dissociates the two identical products produced share the initial energy equally. Therefore, the H^0 and H^+ produced in the reaction are one-half the initial H_2^+ incident ion energy.

It should be noted here that the calculations used to obtain the output beam composition for H^+ and H_2^+ incident beams depend upon the
Figure 12.

Number of Particles Produced per Incident H²⁺ Ion Versus PL and G at 20 KeV.

PL is in micron-cm, G is the gauge pressure as indicated by the thermocouple vacuum gauge at position number 2 (TC2). G is assumed to be twice the average pressure over the length of the charge exchange canal.
Figure 13.
Number of Particles Produced per Incident $H_2^+$ Ion Versus PL and G at 35 KeV.
PL is in micron-cm, G is the pressure as indicated by the thermocouple vacuum gauge at position number 2 (TC2). G is assumed to be twice the average pressure over the length of the charge exchange canal.
Figure 14.
Number of Particles Produced per Incident H$_2^+$ Ion Versus PL and G at 50 KeV.
PL is in micron-cm, G is the gauge pressure as indicated by the thermocouple vacuum gauge at position number 2 (TC2). G is assumed to be twice the average pressure over the length of the charge exchange canal.
Table V

Cross Section Values Used to Calculate Output Beam Composition for $\text{H}_2^+$ Incident on $\text{H}_2$

$\begin{array}{cccc}
\text{E}_1 & 20 \text{ KeV} & 35 \text{ KeV} & 50 \text{ KeV} \\
\sigma_1 & 0.5 & 0.94 & 0.92 \\
\sigma_2 & 0.3 & 0.43 & 0.1 \\
\sigma_3 & 3.5 & 3.3 & 2.95 \\
\sigma_4 & 3.5 & 2.3 & 1.3 \\
\sigma_5 & 8.0 & 6.5 & 5.0 \\
\sigma_6 & 0.88 & 1.18 & 1.46 \\
\sigma_{H^+} & 0.45 & 0.65 & 0.70 \\
\sigma_{H^0} & 2.5 & 2.5 & 2.5 \\
\sigma_{H^2} & 0.4 & 1.2 & 1.5 \\
\end{array}$

*All cross sections are in units of $10^{-16} \text{ cm}^2$ per molecule. $\sigma_1, \sigma_2, \sigma_3,$ and $\sigma_4$ are obtained from McClure. $\sigma_6$ and $\sigma_2$ are obtained from Allison. $\sigma_{H^+}$, $\sigma_{H^0}$, and $\sigma_{H^2}$ are obtained from McClure. $\sigma_5$ and $\sigma_6$ are tabulated at $\frac{1}{2}\text{E}_1$. They are obtained from Allison's $\sigma_{H^0}$ and $\sigma_{H^2}$ respectively.
purity of the input beam. The calculations are based upon 100% purity of the beam from the ion source. This is not the situation with the ORTEC 320 radio frequency ion source. Approximately 85% of the output of the source is considered to be H\(^+\). Therefore, the calculations discussed above give a general indication of what range of pressure to operate the charge exchange canal.

It appears that a thermocouple gauge pressure (G) of 20 microns is suitable for producing an output beam with a large fraction of H\(^0\) with either an H\(^+\) or H\(_2\)\(^+\) input beam in the energy range of 20 to 50 KeV. This corresponds to a PL product of 200 micron-cm.

In addition, one is not limited to H\(_2\) as a target gas or H\(^+\) and H\(_2\)\(^+\) as projectiles. Other gases may be used as well. The reason for using H\(_2\) is that less scattering occurs. Greater scattering angles seem prevalent as the atomic weight increases.\(^9\)

A recent publication\(^12\) gives a collection of available literature dealing with the dissociation of various particles in various gases.
The angular spread of neutral atoms (H°) formed by electron capture and dissociation of H⁺ and H₂⁺ in H₂ defines in part the actual beam diameter at the output of the charge exchange canal. The angular spread of the H° beam produced is important in that a well collimated beam must reach the final bombardment chamber. If the beam is poorly collimated only a small fraction of the beam will enter the aperture of the bombardment chamber. This will lead to a very low output light intensity from the atoms being bombarded in the chamber.

Payne and Riviere⁹ show that with H⁺ incident on H₂ the neutral beam has little significant angular spread above 7 KeV. The scattering above 7 KeV became quite small and was difficult to measure. They plot their results to indicate the half-angle of an orifice (φₒ) to pass 50 percent of the neutral beam versus the energy per nucleon (KeV). At 20 KeV the angular spread is approximately one tenth of a degree with a PL product of 430 micron-cm in the canal.

In the present case with a PL product of 200 micron-cm in the canal, one would expect the angular spread to be no more than one tenth of a degree. The distance from the center of the charge exchange canal to the input aperture of the bombardment chamber is 60 cm. With one tenth of a degree half-angular spread (φₒ), 50 percent of the beam might be expected to pass through an aperture of 2 mm in diameter.
McClure measured angular distributions of H atom and H ion dissociation fragments of fast H ions incident on H gas molecules, under single-collision conditions. The data is presented as differential cross sections (cm$^2$ per steradian) plotted against lab angle in degrees at 5 KeV, 10 KeV, 20 KeV, 40 KeV, and 80 KeV H$_2$ incident energy.

In order to obtain from $\sigma(\theta)$, one must relate the differential cross sections per unit solid angle $\sigma(\theta)$ to the differential cross section per degree $\sigma'(\theta)$.

\[
\sigma'(\theta) \, d\theta = \sigma(\theta) \, d\Omega = \sin \theta \, d\theta (2\pi)
\]

\[
\sigma'(\theta) \, d\theta = \sigma(\theta) \sin \theta \, d\theta (2\pi)
\]

\[
\sigma'(\theta) = (2\pi) \sin \theta \{\sigma(\theta)\}.
\]

The symbol $\theta_{50}$ may be defined by the equation

\[
\int_{0}^{\theta_{50}} \sigma'(\theta) \, d\theta = \frac{1}{2} \int_{0}^{\infty} \sigma'(\theta) \, d\theta.
\]
In order to obtain $\theta_{50}$ from McClure's data, $\sigma'(\theta)$ versus $\theta$ was plotted as in the following diagram.

The angle $\theta_{50}$ is determined as that angle which bisects the area under the curve. At 20 KeV the $H^0$ beam produced by $H_2$ appears to have a half-angle spread ($\theta_{50}$) of four tenths of a degree. Increasing the energy to 40 KeV the half-angle narrows to three tenths of a degree.

Payne and Riviere determined that $\theta_{50}$ is four tenths of a degree for a 20 KeV $H^+_2$ beam incident on $H_2$ with a PL product of 430 micron-cm. This should be compared to the value $\theta_{50}^0 = 0.1^\circ$ quoted earlier for $H^+$ incident on $H_2$ with a PL product of 430 micron-cm. The diameter of the $H^0$ beam at the final bombardment chamber for $H^+_2$ incident on $H_2$ is expected to be approximately 8 mm. However, the $H^0$ beam diameter for $H^+$ incident on $H_2$ will be approximately 2 mm. Thus it is evident that the $H^+$ beam produced by neutralization of $H^+$ particles can have a much smaller diameter at the bombardment chamber than the $H^0$ beam produced by dissociation and neutralization of $H^+_2$.

In addition to angular spread of the output beam produced by charge exchange collisions and dissociation in the charge exchange canal, one must consider contributions to the beam diameter from the
lens and radio frequency ion source. It should be indicated here that if the charge exchange canal is not in use, there will always be a minimum beam diameter at the location of the bombardment chamber. The beam diameter is influenced by four additional effects. These are the ion source exit beam size, lens aberration, variations in the high voltage direct current lens power supply, and space-charge spreading.

The ion source is not considered a point source but in fact the exit beam has a dimension comparable to the diameter of the exit canal. The finite source size plus lens aberrations can increase the beam diameter. However, the ORTEC 3301 lens is considered to be one of the best designed to keep the aberrations and therefore the beam diameter to a minimum. Even without lens aberrations a finite source size would lead to a finite beam size down the beam line to the bombardment chamber.

The focusing power supply voltage can be adjusted to give a minimum beam diameter. Any variation of this voltage from its optimum value affected by drift or ripple of the high voltage may cause an increase in the beam diameter. In addition, there is in any well collimated charged particle beam a natural tendency for the beam diameter to increase due to a mutual repulsion from the space-charge effect. This effect would not be present for a neutral particle beam.

Collectively these four effects appear to produce a beam diameter of approximately 4 mm. That is, 50 percent of the beam intensity will fall within a spot 4 mm in diameter at the location of the
bombardment chamber.

It was estimated that with a $H^+$ input beam, the effect of the charge exchange canal will only produce a beam diameter of 2 mm. In the present case, one may expect the final beam diameter to be determined mainly by the four effects previously mentioned for charged particle beams. The final beam diameter might be expected to be 5 mm.

With an $H_2^+$ input beam, it was estimated that the effect of the charge exchange canal will produce a beam diameter of 8 mm. One may expect the final beam diameter to be determined mainly by the dissociation and neutralization process for $H_2^+$ rather than the four effects previously mentioned for the charged particle beam. The final beam diameter in the present case might be expected to be 10 mm.

One will obtain a better collimated $H^0$ beam using $H^+$ ions incident on the charge exchange canal rather than $H_2^+$ ions. It therefore appears worthwhile to use a radio frequency ion source which produces a high percentage of $H^+$ ions instead of a simple and more reliable PIG (Philips Ionization Gauge) source which produces predominately $H_2^+$ ions.
APPENDIX I

RECONDITIONING OF THE ION SOURCE

After many hours of operation the percentage of protons in the ion source beam will decrease. This is due to metal from the canal tip which is sputtered on the walls of the Pyrex discharge bottle and sapphire insulating sleeve. The metal deposit increases the recombination rate of atomic hydrogen forming into molecular hydrogen. A reduction in the percentage of protons from the source may not be a critical factor in operation. A molecular hydrogen beam may still be useful for producing the required excitation in the experiment chamber. However, continued operation will reduce the total beam current, and soon no output at all will be obtained. In addition to metal sputtering from the canal tip, erosion in the canal may actually close the canal or narrow it to the point at which little beam current, if any, will be obtained. Also, a high voltage flashover may occur due to metal deposits along the Pyrex vessel walls. Therefore, the source should be periodically cleaned and rebuilt.

The ion source is constructed such that the source may be dismantled for reconditioning. The source vacuum seals are of vinyl plastic which can be softened upon the application of heat. The source is then disassembled, cleaned, and rebuilt.

Once the ion source is removed from the lens mounting, use the snap ring pliers to remove the snap ring from the base of the source.
This will permit removal of the extractor tip. Place the bottle and base in an oven at 160°C. The assembly should be in the oven for one and one half hours. Using clean asbestos or cotton gloves, separate the base and probe cap from the bottle. A slight twisting motion and a direct pull will remove the bottle from the base. The sapphire sleeve will now be freed; be careful that it is not lost. The cap is removed by pulling it directly off. A slight twisting motion will help loosen it at first. But do not pry or tilt the cap as this may crack or chip the lip of the Pyrex bottle. Place all the parts on the wire oven rack to cool. Next, clean the vinyl off the Pyrex bottle by wiping it with acetone. Be careful not to allow acetone and the dissolved acetone-vinyl mixture to reach the inside surface of the Pyrex bottle. It is best not to soak the bottle in the acetone. This will deposit vinyl on the inside surface of the bottle which cannot be removed by the hydrofluoric acid treatment. The vinyl deposit would lead to considerable outgassing and would not permit the ion source to be pumped down.

Mix one part hydrofluoric acid with one part distilled water. Extreme caution should be used in handling hydrofluoric acid even when diluted. Beside avoiding breathing the fumes and taking care to avoid splashing it into one's face, care should be taken to prevent getting it on any part of one's body. Note the following quote from the Handbook of Poisoning.¹³
"Skin or mucous contact with hydrogen fluoride solution results in damage depending on the concentration. Concentrations above 60% result immediately in severe, extremely painful burns. Such are deep and heal slowly. Concentrations less than 50% may cause slight immediate irritation or none at all. The acid penetrates readily, however, and a deep-seated ulceration results if contact continues for more than a few minutes."

Pour the diluted hydrofluoric acid into a small plastic tray. Soak the bottle and the sapphire until the metal deposits are removed. If the soaking procedure takes more than ten minutes, etching of the glass will result. Therefore, limit the soaking time to less than ten minutes. Continually agitate the tray and rotate the bottle to expose all bottle surfaces evenly. The use of plastic gloves is mandatory in handling the bottle and sapphire when working with the hydrofluoric acid. Rinse the bottle and the sapphire in distilled water. Place them on a wire rack to dry. To speed drying time, the bottle and the sapphire may be placed in the oven at 160°C.

Completely clean the source base with acetone. Remember to handle all parts with clean gloves to avoid oil contamination. If using plastic gloves, be careful with the acetone which will dissolve the gloves and contaminate the source assembly. Cleanliness is essential.

Check the canal tip. If the tip is badly eroded, it should be replaced. ORTEC supplies new canal tips in glass vials. Break the vial and avoid touching the canal tip. Always use clean gloves and tools. If the used canal tip is in good condition, soak the tip in acetone for several minutes, remove and allow to dry.
Make a thick syrup with the vinyl beads and toluene (Union Carbide Bakelite Brand - AYAF available in small quantities from ORTEC). Several beads placed in a glass bottle and just covered with toluene will provide plenty of material for several reconditionings. The beads should soak in the toluene overnight as they are very slow in dissolving.

Using the vinyl syrup and a small brush, coat the ground surface on the bottom of the bottle. Apply a thick coat, one-quarter inch wide, just above the bulge near the top of the bottle. Coat the mating surface on the base of the source, being careful not to plug the gas feed canal. Finally, apply a coating to the inside of the outer ferrule of the probe cap. Do not allow any vinyl seal to touch the surface of the probe exposed to the discharge area.

Place all parts individually in the oven at 140°C. Bake for 2 to 2½ hours to remove the toluene solvent. While the parts are still warm, install the canal assembly from the bottom of the base and lock in place with the snap ring. Push the aluminum probe cap on the bottle by applying even pressure. The cap may not completely slide the required distance to the bulge due to adhesion of the vinyl seal.

Now place the sapphire sleeve over the canal tip. Place the bottle on the base and adjust its position until the bottle is centered around the sapphire insulating sleeve. Set the ion source assembly on the oven shelf with the shelf in the lowest position. Very carefully place the 10 pound assembly weight over the aluminum probe cap and check for clearance around the sapphire sleeve. This

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
force will, upon application of heat, push the aluminum cap further on the bottle to the bulge, as well as provide pressure to the base seal. Heat the complete assembly in the oven at 160°C for 2½ hours. At the end of this period turn off the oven. Leave the door closed and allow the source assembly to cool to room temperature. Finally, check base and probe cap seals for smooth fillet around both seals. Handle the ion source with gloves to avoid oil contamination. The source is now ready to be installed on the accelerator.
APPENDIX II

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Diffusion Pump Electrical Interlock System</td>
<td>88</td>
</tr>
<tr>
<td>16</td>
<td>Radio Frequency Oscillator</td>
<td>90</td>
</tr>
<tr>
<td>17</td>
<td>Radio Frequency Oscillator Power Supply</td>
<td>92</td>
</tr>
<tr>
<td>18</td>
<td>Magnet Coil Power Supply</td>
<td>94</td>
</tr>
<tr>
<td>19</td>
<td>Probe Power Supply</td>
<td>96</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 15.
Diffusion Pump Electrical Interlock System.
Figure 16.
Radio Frequency Oscillator
.001-SILVER MICA.
RFC-8.2 uH MILLER-4611.
RFC-1:45 TURNS NO.26
9/16 INCH DIA.
C: SPECIAL DESIGN-
TEFLON CAPACITOR
* E F JOHNSON 124-113
SCREEN BYPASS CAPACITOR
MOUNTED ON V1 AND V2.
L1- 2 TURNS 1/8 INCH
COPPER TUBING
3 INCH DIA.
Figure 17.  
*Radio Frequency Oscillator Power Supply.*
Figure 18
Magnet Coil Power Supply
RCA 40214

ALLIED 4A

MAGNET COIL

C - 900 MFD 165 VDC EACH

MAGNET COIL

0.2 AMPERE PANELMETER ON TERMINAL

2800 TURNS NO. 22 FORMVAR CLOSE WOUND
Figure 19
Probe Power Supply.
BIBLIOGRAPHY