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AN ELECTROSTATIC PARTICLE ACCELERATOR

A THESIS SUBMITTED FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY
AT THE UNIVERSITY OF AUCKLAND

BY HENRY NAYLOR

NOVEMBER 1968.
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Signed:  H. Naylor

Date:  14-8-49

NAYLOR, Henry: An electrostatic particle accelerator.

(PhD)
because the whole machine should march
Impelled by those diversely moving parts
Each blind to aught beside its little bent.

As from the welter of their time he drew
Its elements successively to view,
Followed all actions backward on their course,
And catching up, unmingled at the source,
Such a strength, ....

"Sordello", R. Browning.
PHOTOGRAPH ONE

General view of the accelerator laboratory. The beam line on the left goes through a shielding wall to the mass spectrograph room. In the right foreground, mounted in the neutron pit, is a spin-precession solenoid used in neutron polarisation experiments.
# CONTENTS

Introduction

<table>
<thead>
<tr>
<th>CHAPTER 1. HISTORY</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. Electrostatic Particle Accelerators</td>
<td>1</td>
</tr>
<tr>
<td>1.2. Origins of the AURA II High Voltage Generator</td>
<td>2</td>
</tr>
<tr>
<td>1.3. Auckland Proposals</td>
<td>3</td>
</tr>
<tr>
<td>1.4. Modifications to the N.I.R.N.S. Generator</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 2. THE SINGLE ENDED TANDEM ACCELERATOR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Tandem Accelerators</td>
<td>6</td>
</tr>
<tr>
<td>2.2. Terminal Magnet</td>
<td>7</td>
</tr>
<tr>
<td>2.3. Charge Stripping</td>
<td>8</td>
</tr>
<tr>
<td>2.4. Conclusion</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 3. BEAM OPTICS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1. General Design Considerations</td>
<td>12</td>
</tr>
<tr>
<td>3.2. Relevant Optical Theory</td>
<td>13</td>
</tr>
<tr>
<td>3.3. Transfer Matrices</td>
<td>17</td>
</tr>
<tr>
<td>3.4. Input Beam</td>
<td>24</td>
</tr>
<tr>
<td>3.5. Matching the Input Beam to the Terminal Magnet</td>
<td>26</td>
</tr>
<tr>
<td>3.6. Positive Ion Beam</td>
<td>33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 4. CHARGE EXCHANGE NEGATIVE ION SOURCE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1. History</td>
<td>38</td>
</tr>
<tr>
<td>4.2. Charge Exchange of Hydrogen Ions in Hydrogen Gas</td>
<td>40</td>
</tr>
<tr>
<td>4.3. General Arrangement of the Source</td>
<td>41</td>
</tr>
<tr>
<td>4.4. Charge Exchange Canal</td>
<td>42</td>
</tr>
</tbody>
</table>
4.5. Proton Source 44
4.6. Focusing the Positive Ion Beam 47
4.7. Ion Source Analysing Magnet 48
4.8. Performance 50

CHAPTER 5. ACCELERATION TUBES.
5.1. "Long Tube" or "Total Voltage" Effect 53
5.2. Non Uniform Field Tubes 56
5.3. Electric Field Design 58
5.4. Construction 63

CHAPTER 6. LENSES AND MAGNETS.
6.1. Matching Lens 65
6.2. Tube Entrance Lens 67
6.3. Strong Focusing Lens 68
6.4. 90° Analysing Magnet 70
6.5. Permanent Magnet Quadrupole Lens 72
6.6. Orientation of Optical Components 73

CHAPTER 7. PRELIMINARY TESTS.
7.1. Generator Voltage Runs 74
7.2. Tube Testing 76
7.3. Tests with Beam 76
7.4. Analysed Proton Beam 80
7.5. Energy Loss and Energy Spread in Carbon Foils 82
7.6. Early Energy Measurements 85

CHAPTER 8. ENERGY CALIBRATION.
8.1. Introduction 87
8.2. The Energy Reference 88
8.3. Calibration Reactions 90
8.4. Results of Threshold and Resonance Energy Measurements 91
8.5. Differential Hysteresis 93
8.6. Beam Position 95
8.7. Proposed Improvements to the Energy Scale 96

CHAPTER 9. PERFORMANCE AND FUTURE DEVELOPMENTS 98

9.1. Performance 98
9.2. Ion Sources 101
9.3. Target Stations 102

APPENDIX A. ENGINEERING ASPECTS OF THE ACCELERATOR 103

Introduction 103
A.1. Mechanical 103
A.2. Gas Handling 108
A.3. Vacuum 110
A.4. Electrical 111
A.5. Controls and Metering 112

APPENDIX B. TERMINAL MAGNET 116

APPENDIX C. RELIABILITY 119

References 124
INTRODUCTION.

This thesis is an account of the design, construction and testing of a particle accelerator which represents a minor variation on the now-familiar theme of the tandem van de Graaff. The machine has been very briefly described elsewhere (Naylor 1968).

Since the construction of an entire machine of this type is probably beyond the resources of this department, it was fortunate that the opportunity to purchase the basic high voltage generator for a very modest sum occurred at such a propitious time. Prof. R.E. White was instrumental in seeing that this opportunity did not pass unnoticed, and was involved in much of the administrative work entailed in ensuring that a suitable inventory of components was shipped with the generator, and in laying the foundation for the commencement of the project. Prof. D. Brown, as head of the department, managed to secure funds on a hitherto unprecedented scale, and has enthusiastically supported the work throughout, so that the enterprise was launched in singularly favourable circumstances.

It was the author's good fortune that most of this preliminary ground-work had been completed when he started working on the project, and also that he received so much willing and enthusiastic support from other members of the department. In particular, the help of my supervisor, Prof. E.R. Collins, is gratefully acknowledged. His timely comments frequently prevented my relying too heavily on intuition.
Technical assistance of a high standard has been available throughout the construction and testing phases, and special mention must be made of the three technicians employed almost entirely on this machine. M.J. Keeling was responsible for some of the installation and most of the maintenance of the vacuum systems, and has mastered the difficult art of making the thin carbon foils required for charge stripping. D. Skidmore has displayed great skill in making a wide variety of components in the departmental mechanical workshop. C.R. Young has done nearly all the electrical work, including the design and construction of many power supplies, among which the important terminal magnet current regulator is an outstanding example of the reliability and performance that can be achieved using solid-state circuits in a high voltage terminal. The assistance of J.F. Ayres of the Rutherford Laboratory, whose familiarity with the machine proved most valuable, is also gratefully acknowledged. Special thanks are also due to F.M. Blair and R.W. Noble, supervisors of the mechanical and electronic workshops, who have been most helpful at all times.

Anne Bell, who typed the script, deserves my sincere thanks for her quiet efficiency which has made the final stages of this work so much less troublesome than they might otherwise have been.

Financial assistance for the purchase of some of the equipment used was provided by the University Research Grants Committee.

H. Naylor.

Auckland, October 1968.
CHAPTER 1.

HISTORY.

1.1. Electrostatic Particle Accelerators.

It is unfortunate that such a misnomer as that of "electrostatic accelerators" should have persisted for so long, and that we are now almost forced to follow this usage. The term is, of course, used to describe accelerators using high voltages supplied by means of what can better be described as belt generators, of the type originally developed by R.J. van de Graaff (1931). Their wide-spread use in low-energy nuclear physics research during the last twenty years stems from the development of relatively compact generators insulated by gas at high pressure (Barton, 1932, Herb 1935). It was found possible to control the energy of particle beams from such machines quite precisely, (McKibben 1946) and this has been one of their main attractions as nuclear physics research tools.

Most pre-1958 accelerators were of less than 6 Mev energy, with the notable exception of two very large machines built at M.I.T. and at Los Alamos Scientific Laboratories (Livingston, 1962) which achieved energies of about 9 Mev.

Gove et al (1958) reported the first operation of a "tandem" accelerator, in which the D.C. potential produced by a belt generator is used to accelerate a beam of particles twice, and since 1960 the rapidly-increasing use of tandem accelerators has made precisely controlled beams of charged particles of energies above 10 Mev available
to a large number of experimenters. Much of the more recent
development work has been carried out by High Voltage Engineering
Corporation, which has manufactured at least 35 tandem accelerators
having maximum energy ratings of between 12 Mev. and 25 Mev. (Danforth,

Most of the electrostatic accelerators now in use are based on
high voltage generators very much like that described here, that is,
they consist of a high voltage terminal enclosed in a metal cap designed
to have the lowest possible field strength compatible with the required
voltage, supported by an insulating column of glass blocks separated by
equi-potential planes spaced about an inch apart. Resistors connected
across each insulating gap ensure that a constant electric field
appears along the length of the insulating column. The machines are
nearly all similar to those described in a review article by van de
Graaff et al (1948). Most positive terminal machines are operated
with maximum field strengths of about 500 kV per foot of column or
acceleration tube length, and use insulating gas pressures in the vicin-
ity of 200 pounds per square inch.

1.2. Origins of the AURA II Voltage Generator.

The accelerator described here (known locally as AURA II -
Auckland University Research Accelerator no.2.) is based on a high
voltage generator acquired by the Department of Physics in 1964.
Originally the generator was built as a test machine for development
work in connection with a large single-stage accelerator constructed by
the National Institute for Research in Nuclear Science for Oxford
University, described recently by Allen (1967). The test generator was assembled principally from spare parts for the Harwell Tandem accelerator (Allen, 1959), which accounts for its rather unusual proportions, the high voltage column being of exceptionally large diameter for its length.

During its period of usefulness in England, (Allen, 1962) the test machine was not used as an ion accelerator, but rather as a high voltage generator to test various methods of terminal voltage stabilisation. Some tests were also made on the voltage performance of acceleration tubes, and a few hours' operation with an electron beam was recorded.

All terminal voltage measurements during this earlier phase were made either using the column resistor current and measured values of resistors, or using a generating volt-meter calibrated from the resistor current measurements. Subsequent experience has led us to believe that these measurements were very optimistic. Nevertheless the generator is of fundamentally sound electrical design, if rather unnecessarily elaborate mechanically, and the quoted voltage performance from NIMNS of 4.6 MV with positive terminal operation seemed reasonable, although representing a rather higher column gradient than is usually achieved.

1.3. **Auckland Proposals.**

Preliminary discussions on the best way to make use of the generator were held during 1964, before the author's participation in the project. It was decided that the machine should be capable of
accelerating beams of polarised protons and deuterons, since much of
the recent nuclear physics research effort here has been directed
towards the study of polarisation in nuclear reactions and the
production of low energy polarised beams (Collins 1963, Collins 1964,
Glawish 1966). The possibility of installing a source of polarised
positive ions in the high voltage terminal of the accelerator was
considered, but was discarded because of difficulties involved in
tailoring such a complicated source to fit so confined a space. An
alternative was to mount a source of negative ions outside the generator
pressure vessel, and use a modification of the well-known two-stage
tandem principle as described by van de Graaff (1960). Although it
was not recognized until after the machine came into use, the proposed
method was just that originally suggested by Alvarez (1951) except for
the high voltage generator, for which Alvarez proposed an oil insulated
voltage multiplier. The accelerator will be described in detail in
the next chapter.

Discussions were at about this stage when the author became
involved at the end of 1964. It was then decided that construction of
the polarised ion-source would be left to the polarised ion source
group (Glawish 1968) while the author was to be responsible for the rest
of the machine, including an inexpensive unpolarised negative ion
source capable of producing sufficient current both to test the operation
of the accelerator, and for use in nuclear physics experiments not
requiring polarised ions.
1.4. **Modifications to the N.I.R.N.S. Generator.**

Although many additions and alterations were made to the generator, these were mainly of an engineering nature and are described in Appendix A. The most important change was that the high voltage column was lengthened by 34 cm. to 2.1 m., since the potential gradient along the acceleration tubes is usually the most important factor limiting the maximum energy available from pressurised van de Graaff accelerators. (Trump, 1967)
CHAPTER 2.

THE SINGLE-ENDED TANDEM ACCELERATOR.

2.1. Tandem Accelerators.

In conventional tandem accelerators (Gove 1958, Allen 1959) a negative ion beam travels from a source outside the pressure vessel housing the high voltage generator, through the first acceleration tube to the high voltage terminal, which is positive with respect to the pressure vessel. There some ions lose some or all of their electrons to become positively charged, in which state they are accelerated back to earth potential via the second acceleration tube. Apart from the small deviations required to focus the ion beam, the particle trajectories are essentially rectilinear between the ion source and the analysing magnet (fig. 2.1.1.) The final energy of the particles is

\[ E_F = E_S + 2eV_T \]

for the case of singly charged ions of each sign, where \( E_S \) is the energy of the negative ions emerging from the source (at ground potential) and \( V_T \) is the voltage on the high voltage terminal with respect to the pressure vessel, which is at ground potential. Although the two tandem accelerators of the UKAEA are constructed vertically, with ion sources above and analysing magnets below the pressure vessel, most other tandems are horizontal, which presents certain problems in engineering but allows easier access and reduces the cost of buildings.

The above "straight-through" type of tandem is undeniably the simplest, but the available resources were not sufficient to build
FIG. 2.1.1 "STRAIGHT" TANDEM ACCELERATOR

FIG. 2.1.2 FOLDED TANDEM ACCELERATOR
such a machine, it being necessary to use the N.I.R.N.S. generator without radical modification. Both financial and building limitations precluded the possibility of our extending the pressure vessel, so we were forced to try the single-ended tandem configuration illustrated in fig. 2.1.2. Here the two acceleration tubes are placed side by side in the high voltage structure, rather than end-to-end, and the beam is guided between the exit of the first tube and the entrance to the second by a magnetic field, produced by a 180° deflecting magnet inside the high voltage terminal.

2.2. **Terminal Magnet.**

The most critical element in determining the probable effectiveness of such a machine is the 180° magnet, since the required magnetic induction must be produced throughout a sufficiently large volume to make the transmission of a useful beam current feasible. To decide the values of gap width and induction required it is necessary to make some assumptions concerning the ion-optical quality of the charged particle beam, and the maximum anticipated magnetic rigidity of the particles there.

It was assumed that the maximum terminal voltage that could be hoped for with tubes in the machine was 5 MV, and that the accelerator would be used to accelerate mainly protons and deuterons, so that the highest mass-energy product expected for a beam at the terminal was 10 a.m.u.-Mev. This assumption really only limits triton energies in effect, as most heavier atoms would strip to multiply-charged positive ions, and their magnetic rigidity will thereby be reduced.
PHOTOGRAPH TWO

The heart of the "folded" tandem accelerator. The $180^\circ$ magnet is seen below the raised high voltage terminal cover. Immediately below the right-hand end of the magnet is the charge stripper, connected by a flexible bellows to the negative ion acceleration tube, which is just visible between gaps in the corona rings.
Discussion of the beam quality is deferred until the next chapter, but from the known characteristics of the existing polarised positive ion source it was inferred that a useful vacuum gap of 1.2 cm. would transmit most of the beam at all but low energies, provided that the beam quality would not be seriously degraded in the charge-changing process. Thus if an allowance of 3 mm. total is made for the walls of the magnet vacuum chamber, a pole gap of 1.5 cm. is required.

Two acceleration tubes could be accommodated in the high voltage column (as shown in Appendix A) with their centres 69.2 cm. apart, and there were already ports in the pressure vessel base and base plates in corresponding positions. There seemed to be little point in trying to achieve a greater tube separation than this, as a preliminary magnet design showed that a magnet fulfilling the above requirements could be made sufficiently compact to fit inside the existing high voltage terminal cover, together with the necessary power supply and current stabilising circuits. This preliminary design indicated that maximum power dissipation, at 13.3 kilo-gauss gap induction, would be in the vicinity of 3.5 kW. Engineering aspects of the magnet, its power supply, and mountings are given in Appendix B.

2.3 Charge Stripping.

In many tandem accelerators, electrons are stripped from the negative ions by passing the beam through a window-less gas target in the high voltage terminal (Gove 1958). However, for polarised ions Haeberli (1966) has shown that the use of a gas stripper results in loss of polarisation, since the beam particles may spend enough time in
the neutral state for the nuclear spins to couple to the electron spins, which are of course randomly oriented. This is not true if a solid foil is substituted for the gas target, as the foil should be as thin as possible to reduce the amount of energy deposited by the beam in the foil, and to minimise small angle scattering there. In the case of a carbon foil of 10 $\mu$ gm/cm$^2$ i.e. a thickness of $\sim 10 \mu$, a 1 Mev proton will spend $\sim 7 \times 10^{-14}$ seconds traversing the foil, which is the maximum possible time for the atom to remain in the neutral state, if it is to emerge as a positive ion. Since the time associated with atomic transitions is $\sim 10^{-10}$ secs. there is insufficient time for the electronic and nuclear spins to couple, and the nuclear polarisation is preserved. Gas strippers are, however, usually preferred for stripping unpolarised negative ions, because the target does not break, and can be made just thick enough to strip most of the ions to the required charge state. In the single-ended tandem, however, it is not possible to install a gas stripper because there is not sufficient length in the beam direction available to keep the gas consumption down to such a value that sufficiently low acceleration tube pressures can be maintained, as it is necessary to pump the gas down the tubes unless pumps are fitted in the terminal. Gas canals are usually about 1 m. in length, and gas consumption is approximately proportioned to the inverse square of the length, so that with only 20 cm. available here, the gas consumption would be much too high.

A foil stripper capable of holding 32 stripper foils was designed to occupy as little space as possible. In fig. 2.3.1. it will be seen that 16 foils can be mounted in each of two turrets.
Operating the change mechanism drives the ratchet wheel via a bellows-sealed lever and a spring-loaded pawl. Three pins at different distances from the centre are mounted in each turret, those of the lower turret engaging with corresponding holes in the ratchet wheel when the mechanism is assembled. The first fifteen strokes of the actuator drive the lower disc round, until at the end of the sixteenth stroke the pins fall into holes in the lower flange. The upper disc, which has until this time been locked in place by the upper ends of its pins engaging in holes in the top flange, is now able to fall the short distance required for the lower ends of its pins to engage in the holes in the ratchet wheel, so that it will be driven round while the lower wheel remains stationary.

From the point of view of charge stripping, the required target thickness is less than 1 $\mu g/cm^2$ (Rose 1967) but such thin foils cannot yet be made self-supporting over a large enough diameter for this application, and we have been forced to use foils of about 10 $\mu g/cm^2$. Foils are made by evaporation in vacuo from a low voltage carbon arc onto glass slides coated with glucose, mounted about 20 cm. from the arc. Southon (1966) has made foils of about 1 $\mu g/cm^2$ here using a similar technique, but these have been only 1 or 2 mm. in diameter, whereas 1.2 cm. foils are required for the stripper. Usually a large number of short bursts of arc current is allowed to pass between the electrodes to avoid too much general heating of the carbon rods and their holders, and hence of the substrate, causing stresses in the latter. After evaporation, the coated slides are removed from the vacuum vessel, and mounted at an angle of about 20° to the horizontal in a dish into
which warm water is allowed to flow slowly. As the glucose dissolves, 
the foils float off and one edge is then made to adhere to a special 
plate in which a foil holder is mounted. Withdrawal of the plate held 
close to vertical causes the foil to drape over the holder, and it is 
important that before the holder is completely out, the water should 
"break" cleanly from it, as otherwise the foil will be broken. After 
drying, the foil holder is removed from the plate, and is ready for 
mounting. The technique is similar to that used at U.K.A.E.A. Harwell, 
as described by Dearnaley (1959). All foils used in the machine have 
been made in this laboratory by M.J. Keeling.

2.4. **Conclusion.**

Having established the possibility of installing the necessary 
equipment inside the existing high voltage terminal cover, without 
having to modify the generator or the pressure vessel to any great 
extent, it was decided to proceed with detailed design on the basis of 
the above considerations. In view of the somewhat unusual effects to 
be anticipated from the use of a 180° magnet in the terminal, it was 
decided to start with the optical design, which is discussed in the 
next chapter. The acceleration tubes were designed at about the same 
time, as some delay in their manufacture was inevitable, but discussion 
of these is deferred until Chapter 5.
FIG. 3.11. BEAM PROFILE THROUGH ACCELERATOR.
CHAPTER 3.

BEAM OPTICS.

3.1. General Design Considerations.

In the single-ended tandem accelerator it is apparent that, since it is difficult to install a large aperture magnet in the high voltage terminal, the beam should be brought to a cross-over (or beam "waist" as it is often called) near the centre of the magnet. It will then follow that the beam diameter will not be much larger at the stripper foils, which is desirable as was indicated in section 2.3.

The laboratory building is such that the beam can most conveniently be directed to a number of target stations by rotating the 90° analysing magnet, about a vertical axis. In the interests of good energy homogeneity in the accelerated beam, it is desirable that the analysing magnet (which is actually the energy reference - see section 7.3) be used in a manner giving large dispersion, while at the same time transmitting as large a fraction of an incident beam as possible. It is generally agreed that the double-focusing condition is best, with cross-overs formed at an object slit above the magnet and at an image slit beyond it. This question is discussed more fully in section 6.4.

Since the beam will diverge beyond the waist in the terminal magnet, and since the "optical" strength of the second acceleration tube is low because the beam is already at high energy when it enters this tube, it is necessary to use a strong positive lens to form the required waist at the magnet object slit.
The above conditions define the optical requirements fairly completely, the essential elements being:

1. a lens or system of lenses to focus a suitably prepared beam from the ion source through the first acceleration tube to the terminal magnet,
2. the terminal magnet,
3. a strong-focusing lens to form a beam waist at the analysing magnet object slits,
4. the 90° analysing magnet,
5. further strong-focusing lenses to transport the beam to remote target stations.

Before proceeding to examine the above in detail, a brief summary of the necessary ion-optical theory will be given, together with some discussion of the useful concepts of phase spaces, emittance and acceptance. The treatment of these subjects will lean heavily on the work of Sturrock (1955), Pierce (1954) and Zworykin (1949), as well as the more recent work of Banford (1966) and Rose (1967) which had not been published before the accelerator came into operation.

3.2. Relevant Optical Theory.

The theory required in the design of such a simple machine as this is quite rudimentary compared with that used in the study of electron microscopes on the one hand, or proton synchrotrons on the other.

In the case of D.C. accelerators, we are not usually concerned with imaging as such, but rather with the volume enclosed by marginal
rays of the beam. Aberrations are important only if they lead to significant loss of beam, or to considerable reduction in current density at the target. Also, since the fields are constant in time, the equations of motion are of much simpler form than those required for cyclic accelerators. The dimensions imposed on electrostatic accelerators by electrical and mechanical considerations are such that particle beams are always nearly parallel and close to the optic axis, and focusing fields can usually be regarded as exerting forces on the particles which increase linearly with off-axis displacement. Thus we can make the great simplification of using first-order calculations through most of the machine.

A useful adjunct to keeping track of the particles in a beam is the concept of phase space. Generally a particle in a beam is completely specified if we know where it is and where it is going, as Banford so succinctly expresses it. Thus we require three position co-ordinates and three momentum co-ordinates to specify each particle, and we can think of each particle as being represented by a point in a six-dimensional phase-space. A beam, being an assemblage of such particles with finite bounds on each of the six co-ordinates, can be represented as a volume in this space. The concept would be of little utility were it not for the consequences of Liouville's theorem in statistical mechanics, which states that, under the action of forces which can be derived from a Hamiltonian, the motion of a group of particles is such that the local density of the representative points in the appropriate phase space remains everywhere constant. Most of the accelerator falls within the scope of this theorem, excepting parts
of the ion source, where space charge forces are important, and a very brief encounter with non-conservative forces as the beam passes through the stripper foil.

A further simplification is possible because the energy spread of a particle beam from an electrostatic accelerator is very low, so that the beam can be treated as essentially mono-ergic. Thus, using the convention that the z-axis coincides with a reference ray (usually, though not necessarily, thought of as an axis of symmetry or "undeviated" ray of the beam), and if x, y are orthogonal off-axis co-ordinates, and $p_x, p_y$ the conjugate momenta, the six-dimensional phase space referred to above has co-ordinates $x$, $y$, $z$, $p_x$, $p_y$, $p_z$. But, because of the energy homogeneity referred to, $p_z$ may be regarded as constant in regions of field-free space. The co-ordinate $z$ refers to the distance of a particle from some "mean" or reference particle of the beam, and in the case of constant $p_z$, $z$ is a constant of the motion. The above argument, used by Banford (1968) seems to be both unsatisfactory and unnecessary, as one can equally well assert, with Rose (1967) that each two-dimensional phase space can be treated separately in cases where forces due to interactions between the particles are not significant. The behaviour of the beam in the $z$, $p_z$ co-ordinates is, of course, usually of no interest, except for pulsed beam work, where such considerations can prove quite useful (Naylor 1965). A contour enclosing the beam in a two-dimensional phase space is usually referred to as an emittance diagram, and the area enclosed by the contour is called the emittance of the beam. Some authors choose to define emittance in terms of an upright ellipse drawn as in fig. 3.2.1, which
Actual emittance figure

Emittance = \pi x_{\text{max}} p_{\text{max}}

**FIG. 3.2.1.**

a. Beam defined by two apertures.

\[ \sigma \]

\[ x = 0 \]

b. At \( z = 0 \)

c. At \( z = 2L \)

d. At \( z = 4L \)

**FIG. 3.2.2. EMITTANCES DEFINED BY APERTURES.**
is sometimes a good approximation to the actual emittance figure, or which may be drawn as the minimum circumscribing ellipse to the actual figure. Since the procedures for transferring emittances are very simple in the cases considered here, we will not use this definition, but will generally consider polygon emittance figures. The use of ellipses sometimes simplifies calculations because ellipses always transform to ellipses in first-order transformations, and the whole ellipse can be transformed at once, whereas the vertices of a polygon must be transformed separately.

In the case of cylindrical symmetry, description of the beam in terms of the \( r, p_r \) co-ordinates is all that is needed, and the product \( r_{\text{max}} p_{r_{\text{max}}} \) at a beam waist then becomes identifiable with the Lagrange product used in some earlier treatments of accelerator optics (Johnson 1957) and also familiar in light optics from the theorem of Clausius. Here we shall use co-ordinates \( x \) and \( x' \) (where \( x' = \frac{dx}{dz} \)) as the co-ordinates for emittance figures, for reasons of practical usefulness, although this has the disadvantage that the emittance area is not preserved under acceleration. Since \( x' = \frac{p_x}{p_z} \) it follows that if, as is usual in particle optics, the potential is defined so that \( V = 0 \) where the particle velocity is zero, then the area of an emittance diagram describing a beam at a potential \( V \) is proportional to \( V^{1/2} \) in the non-relativistic case, which is the only one of interest here.

Corresponding to the concept of a beam emittance is that of the acceptance of an apparatus. This can be ascertained from the dimensions of its limiting apertures. Two apertures of radius \( 'a' \) separated by a field-free distance \( 2L(\text{fig. 3.2.2a}) \) have an acceptance as shown in fig. 3. 2.2b.
A large beam, of radius greater than 'a', containing trajectories of all slopes less than a/L has an emittance at B as shown in 3.2.2c, i.e. it is the same as the acceptance of the apertures viewed from the same point. If the same beam is examined at C, it is found to have the emittance of 3.2.2d. The emittance diagram has the same area in all three diagrams, and the change in shape is due merely to the progress of the beam through field-free space. It can be seen at once that the third figure corresponds to a position along the z-axis not containing a beam "waist", because the points corresponding to zero slope are not at the maximum radius.

3.3. Transfer Matrices.

The restriction to first order calculations mentioned earlier means that there exists a linear transformation between the co-ordinates of a particle in "object space" and those of the same particle in "image space", where the terms object space and image space are very loosely used. If \( z = z_1 \) and \( z = z_2 \) define two planes, then the 2 x 2 matrix

\[
\begin{pmatrix}
  x_2 \\
  x_2'
\end{pmatrix} = \begin{pmatrix}
  a_{11} & a_{12} \\
  a_{21} & a_{22}
\end{pmatrix} \begin{pmatrix}
  x_1 \\
  x_1'
\end{pmatrix}
\]

(3.3.)

is the general linear transformation connecting co-ordinates in the two planes. For the cases in which Liouville's theorem is valid, a two dimensional phase-space area remains constant. Since any such area can be resolved into triangles, we shall consider the effect of the above transformation on a triangular area. We can take one vertex of each elementary triangle at the origin. This is not necessary, but simplifies the algebra. Let \( x_1, x_1', x_3, x_3' \) be the other vertices
of such an elementary triangle in an emittance figure at \( z = z_1 \). Then
the area of the triangle 0, (\( x_1, x'_1 \)) (\( x_3, x'_3 \)) is just
\[
A_1 = \frac{1}{2} (x_1 x'_3 - x_3 x'_1)
\]
Transforming this elementary triangle to the plane \( z = z_2 \), where the
vertices become 0, (\( x_2, x'_2 \)) and (\( x_4, x'_4 \)), we have, using 3.3
\[
A_2 = \frac{1}{2} (x_2 x'_4 - x_4 x'_2)
\]
\[
= \frac{1}{2} (a_{11} x_1 + a_{12} x'_1)(a_{21} x_2 + a_{22} x'_2)
- (a_{11} x'_3 + a_{12} x'_2)(a_{21} x'_4 + a_{22} x'_1)
\]
\[
= \frac{1}{2} x_1 x'_3 (a_{11} a_{22} - a_{21} a_{12}) - x_3 x'_1 (a_{11} a_{22} - a_{21} a_{12})
+ x_1 x'_3 (a_{11} a_{21} - a_{12} a_{21}) + x'_1 x'_3 (a_{22} a_{12} - a_{22} a_{12})
\]
\[
= \frac{1}{2} (a_{11} a_{22} - a_{21} a_{12})(x_1 x'_3 - x_3 x'_1)
\]
and \( A_2 = A_1 \), as required by Liouville's theorem only if
\[
a_{11} a_{22} - a_{21} a_{12} = 1
\]
i.e. if the determinant of the transfer matrix has the value unity.
This is true if the co-ordinates of the emittance diagram are \( x, p_x \),
but only true for regions at the same potential (in the ion-optical
sense) if the co-ordinates are \( x \) and \( x' \). Evaluating the determinant
can therefore serve as a useful check on possible errors when multiply-
ing several matrices together. Some useful particular transfer
matrices will now be derived.
3.3.1. Field - Free Space.

Here \( x_2 = x_1 + (z_2 - z_1) x_1' \)

\[ x_2' = x_2 \]

so that the appropriate transfer matrix is

\[
A_{FF} = \begin{pmatrix} 1 & z_2 - z_1 \\ 0 & 1 \end{pmatrix}
\]  

(3.3.1)

3.3.2. Thin Lens.

Although most lenses encountered in particle optics are thick lenses, there are many cases where a thin lens approximation is sufficiently accurate, or where it is convenient to discuss an equivalent thin lens. We consider the case where our two reference planes co-incide with the mid-plane of the lens, so that

\[
x_2 = x_1
\]

\[
x_2' = x_1 - \frac{x_1}{f}
\]

using \( f \) negative for a converging lens and

\[
A_{TL} = \begin{pmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{pmatrix}
\]  

(3.3.2)

This matrix can be combined with two field-free space matrices to give the transformation between conjugate planes if required.

3.3.3. Transformation Between Conjugate Planes.

This is the case of optical imaging, i.e. \( x_2 \neq x_1' \) so that the matrix must be of the form

\[
A_{CP} = \begin{pmatrix} a_{11} & 0 \\ a_{21} & a_{22} \end{pmatrix}
\]
From 3.3.1. and 3.3.2. the required transformation is

\[
\begin{pmatrix}
  x_2' \\
  x_2
\end{pmatrix} = \begin{pmatrix}
  1 & v \\
  0 & 1
\end{pmatrix} \begin{pmatrix}
  1 & 0 \\
  -\frac{1}{f} & 1
\end{pmatrix} \begin{pmatrix}
  1 & u \\
  0 & 1
\end{pmatrix} \begin{pmatrix}
  x_1 \\
  x_1'
\end{pmatrix}
\]

where \( u, v \), are the conventional object and image distances.

i.e.

\[
\begin{pmatrix}
  x_2' \\
  x_2
\end{pmatrix} = \begin{pmatrix}
  1 - \frac{v}{f} & u - \frac{uv}{f} + v \\
  -\frac{1}{f} & 1 - \frac{u}{f}
\end{pmatrix}
\]

The condition for imaging is now

\[ u + v - \frac{uv}{f} = 0, \]

which is, in more familiar form

\[ \frac{1}{f} = \frac{1}{u} + \frac{1}{v} \]

or the Gaussian image condition.

The required transfer matrix is therefore

\[
A_{GP} = \begin{pmatrix}
  -\frac{v}{u} & 0 \\
  -\frac{1}{f} & -\frac{u}{v}
\end{pmatrix}
\]  \hspace{1cm} (3.3.3.)

and the diagonal elements are the linear and angular magnifications.

### 3.3.4. Uniform Field Acceleration Tube

Most modern acceleration tubes used in high voltage D.C. machines are constructed of a large number of equally-spaced similar electrodes with equal potential differences between adjacent pairs, so that the electric field near the tube axis is nearly constant, apart from end effects, which can be circumvented as described in Chapter 5.

If \( V = 0 \) when \( z = 0 \), at one end of a tube, of length \( L \), and \( V = V_T \) at \( z = L \), and we assume that the ion velocity is almost zero (e.g. thermal) at \( V = 0 \), then if \( E_x = E_y = 0 \), \( p_x \) is constant throughout the tube. Since relativistic effects can safely be ignored here, we have, for a particular ray,
\[ v_x = \text{constant.} \]

Also
\[ T_T = e V_T \]
and
\[ T_z = e V_T \frac{z}{L} \]

\[ \therefore v_z = \left( \frac{2aV_T}{mL} \right)^{\frac{1}{2}} \]

Now
\[ x' = \frac{dx}{dz} = \frac{v_x}{v_z} \]

i.e.
\[ x' = k z^{-\frac{1}{2}} \quad (3.3.4a) \]

where
\[ k = v_x \left( \frac{mL}{2aV_T} \right)^{\frac{1}{2}} \]

\[ \therefore x = 2kz^{\frac{1}{2}} + x_0 \quad (3.3.4b) \]

In a real tube, the initial ion velocity is not near zero, but has some energy \( T_0 = \frac{eV_T^2}{N} \), say, where, following \( \text{Elkind} \) \( (1953) \) we will call \( N \) the "energy amplification" of the tube. We can regard the part of the tube between \( z = 0 \) and \( z = L/N \) as a convenient fiction, although in practice this makes little difference for an input tube as \( T_0 \sim 50 \text{ keV} \) usually and tubes are operated at \( \sim 50 \text{ kV per inch} \).

We can now calculate the transformation from input to output as follows, using \( z = z_1 \), \( z = z_2 \) as input and output planes as before,

\[ x_2 - x_1 = 2k \left[ L^{\frac{1}{2}} - \left( \frac{L}{N} \right)^{\frac{1}{2}} \right] \quad \text{from } 3.3.4b \]

\[ = 2x_1' z_1^{\frac{1}{2}} L^{\frac{1}{2}} \left[ 1 - N^{-\frac{1}{2}} \right] \quad \text{from } 3.3.4a \]

\[ \therefore x_2 = x_1 + 2x_1' LN^{\frac{1}{2}} \left( 1 - N^{-\frac{1}{2}} \right) \]

Also \( x_2' = x_1' N^{-\frac{1}{2}} \)

and \( x_2' \ll x_1 \)

so that the matrix representing a uniform field tube is
$\beta_1$ positive, $P_1N_1$ on opposite side of trajectory from $C$.

$\beta_2$ negative, $P_2N_2, C$, on same side of trajectory.

**FIG. 3.3.5. SECTOR MAGNET FOCUSING**
\[ A_T = \begin{pmatrix} 1 & 2LN^{-\frac{1}{2}}(1 - N^{-\frac{1}{2}}) \\ 0 & N^{-\frac{1}{2}} \end{pmatrix} \quad (3.3.4) \]

3.3.5. 20° Double-focusing Sector Magnet.

The transfer matrices for a uniform field sector magnet were derived by Penner (1961). If \( \rho \) is the radius of curvature of a ray in the uniform field, \( \alpha \) is the sector angle, \( \beta_1, \beta_2 \) the angles between the ray and normals to the boundary at entrance and exit respectively, measured in the sense shown in fig. 3.3.5, then the transfer matrix for the field direction (i.e. perpendicular to the deflection plane) is given by Penner as

\[
A_B = \begin{pmatrix} 1 - \alpha \tan \beta_1 & \alpha \rho \\ -\frac{1}{\rho}(\tan \beta_1 + \tan \beta_2) & 1 - \alpha \tan \beta_2 \end{pmatrix}
\]

That this is incorrect may be seen at once by evaluating the determinant

\[ |(A_B)| = 1 + \alpha^2 \tan \beta_1 \tan \beta_2 \]

and this is 1 only when \( \alpha \), \( \beta_1 \), or \( \beta_2 \) is zero.

Penner's deduction is correct until the last step, where the \( a_{21} \) term should be

\[-\frac{1}{\rho}(\tan \beta_1 + \tan \beta_2) + \frac{\alpha}{\rho} \tan \beta_1 \tan \beta_2\]

The correct transfer matrix is therefore

\[
A_B = \begin{pmatrix} 1 - \alpha \tan \beta_1 & \alpha \rho \\ \rho^{-1}(\tan \beta_1 + \tan \beta_2) + \frac{\alpha}{\rho} \tan \beta_1 \tan \beta_2 & 1 - \alpha \tan \beta_2 \end{pmatrix}
\]

In the median plane of the magnet, the dispersion can lead to an appreciable increase in image size in some cases. The transfer matrix which includes the dispersion effects is a 3 x 3 matrix operating on the vector \( y, y', \frac{S_P}{\rho} \), but the last co-ordinate can, of course, be ignored subsequently when dealing with non-dispersive elements.
\[
A_{\rho} = \begin{pmatrix}
\frac{\cos(\alpha - \beta_1)}{\cos \beta_1} & \rho \sin \alpha & \rho (1 - \cos \alpha) \\
\frac{1 - \tan \beta_1 \tan \beta_2}{\rho \cos(\beta_1 + \beta_2)} & \frac{\cos(\alpha - \beta_2)}{\cos \beta_2} & \sin \alpha + (1 - \cos \alpha) \tan \beta_2 \\
0 & 0 & 1
\end{pmatrix}
\]

For the case of a symmetrical 90° double-focusing magnet, for which
\( \beta_1 = \beta_2 = \tan^{-1} \frac{1}{2} \) (Cross 1951), the above reduce to

\[
A_{B} = \begin{pmatrix}
1 - \frac{\pi}{4} & \frac{\rho \pi}{\rho} \\
\frac{\pi}{8\rho} & 1 - \frac{\pi}{4}
\end{pmatrix}
\]

and

\[
A_{\rho} = \begin{pmatrix}
\frac{1}{2} & \rho & \rho \\
\frac{3}{4\rho} & \frac{1}{2} & \frac{3}{2} \\
0 & 0 & 1
\end{pmatrix}
\]

(3.3.5a)

(3.3.5b)

3.3.6. 180° Magnet.

The 180° magnet used in the high voltage terminal has no focusing action in the field direction, because it is a uniform field magnet with \( \beta_1 = \beta_2 = 0 \). The sector magnet matrices therefore become

\[
A_{B} = \begin{pmatrix}
1 & \pi \rho \\
0 & 1
\end{pmatrix}
\]

which is the same as 3.3.1 describing a field-free region,

and

\[
A_{\rho} = \begin{pmatrix}
-1 & 0 & 2\rho \\
0 & -1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

(3.3.6)

This apparently trivial result contains the important fact that the only change in beam characteristics due to dispersion in this magnet is the addition of the term \( 2 \rho \frac{\delta \rho}{\rho} \) to the transverse
dimension of the beam. There is no change in beam angles as is the case with a $90^\circ$ magnet, for example. The well-known focusing property of a $180^\circ$ magnet ensures that if a beam waist is formed at the entrance boundary, there will be another waist formed at the exit boundary, whereas a $90^\circ$ sector magnet like that of the last section has object and image located $2\phi$ from the pole edges, so that the effect of the dispersion on the slope of a ray, $3/2 \frac{\phi r}{P}$ (from (3.3.5b)) can amount to quite a large increase in image size at the position of the waist in image space. Because of the difficulty of installing an elaborate stabiliser for the terminal magnet current, the (current) field stability cannot be made as high as is possible for a magnet at ground potential, and the effect of this current instability must be added to that of the variations in momentum of the beam particles.

3.4. Input Beam.

For reasons explained in Chapter 4, it was decided to make the ion source charge-exchange canal match the anticipated emittance of the polarised ion source output beam. It was also assumed that the unpolarised source positive ion beam would "blanket" the exchange canal, so that the emittance of the beam is the acceptance of the canal. For the sake of brevity, the donor canal acceptance transferred through various parts of the accelerator will be referred to as "the emittance". The ion source is described in detail in Chapter 4, but at this stage the important fact is that the donor canal is effectively a series of three apertures which serve to define the emittance shown as fig.3.4.1. At the exit of the canal is a very weak accelerating bi-potential lens,
FIG. 3.4.1. CANAL ACCEPTANCE

FIG. 3.4.2. VIRTUAL OBJECT FOR SOURCE ANALYSING MAGNET

FIG. 3.4.3. EMITTANCE AT INPUT LENS OBJECT
having a voltage ratio across it of approximately 2:1. From curves
given by Zworykin (1949b), for example, it is obvious that the focal
length of the lens is very large, at least 20 diameters, and the only
important effect will be the reduction of beam divergence by a factor
of $2^{-\frac{1}{2}}$. Fig. 3.4.2 shows how the marginal rays of the beam may
be projected back to form a "virtual waist" which may be taken as the
object for the $90^\circ$ source analysing magnet. This virtual waist is
situated 20 cm. away from the magnet entrance pole edge, so the image
will be 20 cm. away from the exit pole edge, since the radius of
curvature is 10 cm. for $90^\circ$ deflection in the magnet. The over-all
transformation from magnet object plane to image plane is therefore
given by the product of three matrices as follows.

$$A_{01} = \begin{pmatrix} 1 & 20 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} -215 & 15.7 \\ -0.0607 & 0.215 \end{pmatrix} \begin{pmatrix} 1 & 20 \\ 0 & 1 \end{pmatrix}$$

for the "plane" parallel to the magnetic field. For reasons discussed
later, (6.6) the plane of deflection of this magnet is set parallel to
the deflection plane of the terminal magnet, and since the apertures of
both magnets in the deflection direction are several times larger than
the apertures limited by the magnet pole gaps, we will confine the
discussion temporarily to the field "plane". The reference axis is
usually taken as a ray in deflecting magnets, so that the off-axis
co-ordinates are carried along with the beam i.e. they are not fixed in
space.

$$A_{01} = \begin{pmatrix} -1 & 0 \\ -0.0607 & -1 \end{pmatrix} ,$$

and we can transform the emittance
of the beam at the virtual object
for the magnet to the image position. The result of the transformation
is the emittance shown in fig. 3.4.3, and this can be regarded as the object for the input lens system.

Mechanical considerations (see Appendix A) place the negative acceleration tube entrance 2.5 m. from this beam waist. The most important problem in the optical design is that of ensuring that most of the beam will pass through the terminal magnet for a wide range of terminal voltage.

3.5. Matching the Beam to the Terminal Magnet.

The effective magnet aperture is 1.2 cm., and the separation of the ends of the vacuum box is 126 cm. in the beam direction. With a maximum radius of 0.6 cm. and maximum slope of .0096, the acceptance is as shown in fig. 3.5.1, for the field direction. Since the acceptance in the deflection plane is much larger, due to the greater width of the vacuum box, we will discuss the transmission in the perpendicular plane only. A superficial examination of the two diagrams of figs. 3.4.3. & 3.5.1. shows that the area of the emittance is much larger than that of the terminal magnet acceptance. Since the area of an emittance diagram is proportional to \( V^{-\frac{1}{2}} \), as indicated in section 3.2, there is some minimum terminal potential at which we can expect to match the beam emittance to the magnet acceptance. A perfect match will not be possible because of the different shapes of the two figures, but when the areas are equal we can expect to transmit a reasonably large fraction of the beam. The emittance area is \( 3 \times .045 \times .4 \text{ cm} = .054 \text{ cm} \), while the acceptance area is .012, so that the areas of the two figures will be equal when the potential at the terminal is \( V_T = \left( \frac{.054}{.012} \right)^2 V_{IN} \).
**FIG. 3.5.1. TERMINAL MAGNET ACCEPTANCE**

**FIG. 3.5.2. FORMATION OF INPUT LENS VIRTUAL IMAGE**

**FIG. 3.5.3. ACCEPTANCE AT NEGATIVE TUBE EXIT**

Negative ion acceleration tube

Virtual image

180° magnet
where $V_{IN}$ is the potential of the input beam, which is 40 kV in this case (see Chapter 4.). Thus when $V_T = 20 V_{IN} = 800$ keV the areas are equal, and we will consider the case $V_T = 1$ MV, making the energy amplification factor $N = 25$, as the first value at which to attempt the matching. Since the tube length is fixed by the mechanical design of the high voltage column, there is no means of varying the optical properties of the negative ion tube, and the only variables now available for matching the beam are the strengths and positions of whatever lenses are placed between the object and the entrance to the acceleration tube.

In most electrostatic accelerators, until the advent of tandems, the principle used in focusing the beam through the acceleration tube was the so-called "constant $N$" system advocated by Elkind. This meant that the input energy had to be changed in proportion to the terminal voltage. This method has been used in some tandems, (Collins 1959) but leads to a rather complicated ion source installation, since it is necessary to raise the source some 150 - 300 kV from earth potential, thereby almost eliminating one of the advantages of tandem accelerators viz. that the ion source is close to ground potential and readily accessible.

Fig. 3.5.2 shows some rays of a beam which just fills the terminal magnet aperture. (The $z$-axis has been "straightened out" in passing through the terminal magnet.). The input lenses must put as much of the input beam as possible into the envelope of these rays outside the tube. It is therefore convenient to transfer the terminal magnet acceptance backwards through the acceleration tube to the tube
entrance, in order that the effects of changes in the input lens arrangement can be seen readily. It is even more convenient, however, to consider the extension of these enveloping rays to the right, as they would appear in the absence of any electric field in the tube. They will then form a cross-over which might well be called the input lens virtual image. As we have seen earlier, a parallelogram emittance or acceptance figure represents the centre of a beam waist or cross-over when it is an upright diamond, as in fig. 3.2.b. To transform the terminal magnet acceptance into such a figure, then, we can first transfer it by means of a drift-space matrix (3.3.1) to the tube exit, then with the inverse of the tube matrix (3.3.4) to the tube entrance, then with another drift-space matrix to the input lens virtual image. The first step can be done by inspection to yield fig. 3.5.3, the acceptance transferred to the tube exit, regarded as coincident with the magnet entrance, which is not strictly accurate. Inserting the values \( N = 25, L = 210 \) in (3.3.4) gives

\[
A_T = \begin{pmatrix} 1 & 67.2 \\ 0 & 2 \end{pmatrix}
\]

whence \( A_T^{-1} = \begin{pmatrix} 1 & -336 \\ 0 & 5 \end{pmatrix} \)

We must now pre-multiply \( A_T^{-1} \) by another field-free space matrix to obtain the required upright diamond figure for the virtual image. If the length of this drift space is \( S \), then the total transformation is

\[
\begin{pmatrix} 1 & S \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & -336 \\ 0 & 5 \end{pmatrix} = \begin{pmatrix} 1 & 5S -336 \\ 0 & 5 \end{pmatrix}
\]

and in order that this may result in the point \((-0.6, .0096)\) being
transformed to \((0, x')\) we have
\[
\begin{pmatrix}
1 & 58 - 336 \\
0 & 5
\end{pmatrix}
\begin{pmatrix}
-0.6 \\
.0096
\end{pmatrix}
= \begin{pmatrix}
0 \\
.048
\end{pmatrix}
\]
so that \(58 - 336 = \frac{0.6}{0.0096} = 62.5\) cm and \(S = 80\) cm.

The required transfer matrix is therefore \(\begin{pmatrix}
1 & 62.5 \\
0 & 5
\end{pmatrix}\) and the resulting acceptance at the virtual image is shown in fig. 3.5.4. We can attempt to match the input beam to this acceptance by forming an image of the cross-over represented by fig. 3.4.3. with a single thin lens. As a first attempt, we could take a lens giving a magnification of 1.5 since this is the ratio of maximum \(x\) in the two figures. Thus, since the object-to-image distance is \(2.5 + .8\) m or 330 cm,

\[i.e. \quad u + v = 330\] cm.

Also \[v = 1.5u\]

\[u = 132\] cm., \(v = 198\) cm. and \(f = 79.3\) cm.

Substituting these values in 3.3.3, which is the transfer matrix between conjugate planes,

\[ A_{cp} = \begin{pmatrix}
-1.50 & 0 \\
-.0126 & -.667
\end{pmatrix}\]

and operating on the emittance of 3.4.3 the emittance shown by the dashed line of 3.5.4 is obtained. The result is a reasonable match, which could be improved somewhat by using a slightly lower magnification, and placing the beam waist rather than the Gaussian image at the position of the "virtual image." If the position of the "virtual image" is calculated for any \(N\), it is found that
FIG. 3.5.4: ACCEPTANCE AND EMITTANCE FOR N = 25

FIG. 3.5.5: ACCEPTANCE AND EMITTANCES FOR N = 100
\[ SN^{\frac{1}{2}} = 62.5 + 420 (1-N^{-\frac{1}{2}}) \]

and for \( N = 100, \) \( S = 44 \text{ cm}, \) i.e. the virtual image position is now 36 cm. closer to the tube entrance. Repeating the procedure that gave fig. 3.5.4 above, but this time relaxing the lens focal length from the calculated value of 73 cm. to 74 cm. to allow the beam waist to coincide with the virtual image position, one obtains the emittance and acceptance of fig. 3.5.5 with the lens in the same position as in the \( N = 5 \) case. It will be observed that, although the whole of the emittance figure lies within the acceptance, there would be considerably more margin for error if the lens could be moved closer to the object, resulting in smaller lateral magnification and larger angular magnification. It is therefore desirable that the lens should be movable.

With an object distance of 132 cm. and a maximum beam angle of .045 radian, the radius of the beam at the lens is 6 cm. To keep the distortion of emittance figures due to spherical aberrations within reasonable bounds, it is usually recommended that no more than one third of the aperture of a cylindrical electro-static lens should be used. If we follow this practice, the lens diameter will be 36 cm, which means that the vacuum enclosure housing the lens will have to be about 50 cm. in diameter. The situation of this very large lens would be inside the pressure vessel, close to the base plate. The use of a single lens becomes singularly unattractive in the face of these difficulties.

In most electrostatic accelerators, the field at the entrance of an acceleration tube is used to provide positive lens action, (Rose
1967, Elkind 1953) but this has serious drawbacks, because the lens so formed is usually far too strong. However, if a fine grid is placed across the tube entrance, this lens effect can be eliminated, or, if the grid potential is made variable, then a lens of any desired strength can be obtained at the tube entrance. This lens, which is discussed in detail in Chapter 6, can then be used as one of a pair taking the place of the large movable lens discussed above. If the strength of the two lenses is independently variable, then a good match between the beam emittance and the terminal magnet acceptance can always be obtained, since the two lenses are approximately equivalent to a thin movable lens placed between them. Furthermore, spherical aberrations can be kept low without having to resort to very large diameter lenses, and in fact this use of such a lens pair is much like that described by Zworykin (1949a) to reduce spherical aberration (in principle) below an arbitrarily low limit. The lens closest to the ion source is called the matching lens, while that at the tube entrance is called the entrance lens. The position of the matching lens can now be fixed by other considerations than purely optical, and in this case mechanical convenience was a factor which decided its situation inside the main high-vacuum tee-junction, just below the pressure vessel (see Appendix A). This places it 70 cm. from the ion source analysing magnet image, so that the two lenses are used approximately semi-telescopically for a wide range of terminal voltages, i.e. the beam is approximately parallel between the lenses. Since the focal point of the matching lens is close to its object, the strength of this lens affects the beam radius at the tube entrance strongly, whereas the entrance lens strength
has the greater influence on the slope of the rays inside the tube.

The transfer matrix for the two input lenses can be obtained by multiplying together, in reverse order, the matrices appropriate to the drift space before the matching lens, the matching lens, the drift space between lenses, and the entrance lens. Writing $M$ for the power (reciprocal focal length) of the matching lens, and $E$ for the power of the entrance lens, this product is

$$\begin{pmatrix}
1 - 180M & 250 - 12600M \\
180ME - M - E & 1 - 250E - 70M + 12600ME
\end{pmatrix}$$

If this matrix is multiplied by that representing the drift-space between the entrance lens and virtual image, the total transfer between ion source magnet image and the input lenses' virtual image is obtained. Using $M = 76^{-1}$, $E = 49^{-1}$, and the case for $N = 100$ quoted above, the emittance is as shown by the dashed line in fig. 3.5.5, and it will be seen that this "fits" the terminal magnet acceptance more comfortably than the emittance plotted for the single lens case. Similarly it could be shown that at some value of energy amplification between 25 and 100 it is possible to construct an emittance, using transformations appropriate to the two lens system, which represents a beam passing through the terminal magnet, whereas a beam corresponding to the single fixed lens would be intercepted by the vacuum chamber. The exercise would, however, be academic, because the case represented by these figures is a considerable over-simplification of what occurs. Aberrations in the lenses have not been allowed for, nor have imperfections in machining or alignment. Thus the above treatment should be regarded as indicating that the matching is reasonably satisfactory rather than
**Fig. 3.6.1. Terminal Magnet Acceptance at Positive Tube Exit**

**Fig. 3.6.2. Terminal Magnet Acceptance at Virtual Object of Strong-Focus Lens**
as prophesying complete transmission of the beam in certain circumstances.

3.6. **Positive Ion Beam.**

In the previous section the beam through the terminal magnet was treated as though it were the negative ion beam, but this is not the case, as the charge stripper is placed at the negative ion acceleration tube exit. Scattering from the foils must result in some increase in emittance, the magnitude of the effect depending, of course, on the thickness of the foils and the type and energy of the ions. It was assumed that, since foil strippers have been used satisfactorily elsewhere, the effects must be small enough to be ignored. The positive ion beam discussed here is therefore simply an extension of the negative ion beam.

It was shown in the previous section that the terminal magnet would sometimes present a limiting acceptance to the beam, and it is therefore reasonable to attempt to match this acceptance to the analysing magnet acceptance. We can transfer the terminal magnet acceptance as seen at the positive ion tube entrance, through the acceleration tube by using 3.3.3, which gives the acceptance figure at the positive ion tube exit shown as fig. 3.6.1. This becomes the dashed upright diamond figure of 3.6.2, corresponding to a beam waist, at $z = -334$ cm. from the tube exit and this is now the virtual object for the strong focusing lens.

Once the height above the laboratory floor of the horizontal beam from the analysing magnet has been decided, the dimensions of the
FIG. 3.6.3. LOCATION OF OUTPUT-SIDE OPTICAL ELEMENTS WHEN MAGNET SLITS SYMMETRICAL.
pressure vessel and the building height dictate the distance between
the positive ion acceleration tube exit and the analysing magnet.
Four feet was selected as the beam height, largely for convenience in
setting up targets and detecting equipment. The radius of curvature
of the central trajectory through the analysing magnet is 49 cm, and
the acceleration tube exit is 4 metres above beam height. In the
symmetrical double-focusing configuration for uniform field 90° sector
magnets, object and image are located at twice the radius of curvature
from the pole edges. In this case, the distance from tube exit to
magnet entrance slits is 2.53 m. (fig. 3.6.3).

The strong-focusing lens should be capable of handling any
particle that the accelerator can produce, and its design is discussed
in section 6.3, which shows that the necessary lens is rather long —
approximately 80 cm. in fact. If it can be regarded as a thin lens,
then the centre of the lens is at least 40 cm. below the positive ion
tube exit, so that the object distance is \(334 + 40\) cm, and the image
distance \(253 - 40\) cm. To transfer the virtual object to the entrance
of the analysing magnet, we use a matrix connecting the virtual object
and the magnet object slits, which are conjugate planes, and the drift
length 98 cm. The resulting product is

\[
\begin{pmatrix}
-1.31 & -174 \\
-0.0074 & -1.74
\end{pmatrix}
\]

and the resultant emittance figure is

shown in fig. 3.6.4. (solid line.)

Since the effective half-width of the magnet is 1.1 cm. this beam will
obviously not be transmitted, particularly since this result is rather
optimistic as the quadrupole lens is actually thick, and will therefore
have shorter focal lengths than those calculated above. The beam
Width of analysing magnet vacuum chamber

Fig. 3.6.4. Terminal magnet acceptances at analysing magnet entrance
divergence can be reduced, however, by reducing the height of the
magnet object slit. This in turn moves the next cross-over at the
image slit further from the magnet, with some increase in magnification
between slits. The position chosen for the object slit is 69 cm.
above the magnet pole boundary, and the transfer matrix for this
arrangement is \[
\begin{pmatrix}
-1.15 & -105 \\
-0.00675 & -1.52
\end{pmatrix},
giving the emittance figure
shown by the dashed line in
fig. 3.6.4.

This gives very much better transmission through the magnet, at
the expense of some increase in the size of the waists at the magnet
slits. If the deflection plane of the analysing magnet is perpendic-
ular to the deflection plane of the terminal magnet, then the effects
of dispersion in the latter will be to increase the emittance shown in
fig. 3.6.4, but it will be shown later that this is not an important
effect. Another advantage of the asymmetrical location of the
magnet slits is that the divergence of the emerging beam is less than
would be the case for the symmetrical configuration, so that the beam
can be more easily handled in subsequent optical elements because
their apertures can be reduced, or separation increased. (see section
6.5.)

Fig. 3.6.5 gives results of transferring the emittance of fig.
3.4.3 through the machine to the analyser image slits, for the case of
negative-tube energy multiplication \( N = 50 \), i.e. 2MV terminal
potential for 40 keV input beam. In performing this transformation
the correct form of the quadrupole transfer matrix was used, rather
than the thin lens approximation used above. It will be noticed that
--- in field direction.
- - - - - in deflection plane.
- - - - - - - - - in deflection plane with zero energy spread.

FIG. 3.65: BEAM EMITTANCE AT ANALYSING MAGNET IMAGE SLIT.
there is some astigmatism in the beam, and that the effects of beam
energy spread are almost negligible, using the value \( \frac{\sigma_p}{P} = \pm 10^{-4} \)
which corresponds to \( \pm 0.8 \) keV energy spread at 4 Mev beam energy. It
is reassuring to note that the areas of the input and output emittance
figures are proportional to the particle momenta before and after
acceleration. This not only shows that there is unlikely to have been
a serious error in the transformation, but also serves to emphasise
that the calculations are based on the simplest assumptions throughout,
no allowance having been made for the many aberrations and imperfections
which will cause the beam quality to deteriorate in its passage through
the three lenses, two magnets and two acceleration tubes involved.

It is not possible to make useful predictions concerning
expected output intensity without carrying out precise measurements on
the source emittance and intensity distribution. Usually the fact
that the beam emittance is reduced by 10% say, in passing through some
limiting acceptance means that the beam intensity will be reduced by
about 40%, but this again depends on the details of intensity
distribution.

Nevertheless the final output emittances shown in fig. 3.6.5
are useful in determining the best position to place subsequent strong-
focusing lenses between the magnet image slits and the target, in order
that a suitable combination of beam dimensions and divergences may be
obtained there. The emittances given apply to the orientation of the
analysing magnet which places its deflection plane perpendicular to the
terminal magnet deflection plane. Because of the intrinsic astigmatism
in the system, different emittance diagrams are obtained for other orientations, but the differences are not of great significance. It will be noticed that the conditions shown do not correspond exactly to the formation of a beam waist at the slit, but this could be achieved by slight alterations in the strengths of the two parts of the quadrupole lens, and under these conditions the beam would have a width of about 4mm. in each direction.
4.1 History.

Since the use of a negative ion source based on charge exchange from positive to negative ions may appear to be an anachronism, the reasons for constructing this source will be given.

During early discussions on the polarised ion source for this accelerator, it was decided to use a positive source, and convert the ion charge to negative by passing the positive ion beam through a suitable gas or vapour target. At this time most negative ion sources in use on tandems used hydrogen as the charge-exchange medium, and it was proposed to use this system here. Since the intensity available from polarised sources was then very low, it seemed advisable to be able to use an unpolarised beam for setting up beam lines and preliminary measurements with detectors etc., and to change over to the polarised beam only when the experiment was completely prepared. For this scheme to be at all effective, as many of the components as possible should be common to the two sources (polarised and unpolarised) and it was decided to make the input to the charge exchange canal the change-over point. To overcome de-polarisation which was known to occur when the ions spend too long in the neutral state (Glavish 1963), (Haebeli 1965), it was proposed either to provide a solenoidal magnetic field in the exchange canal, or, if the technical difficulties could be overcome, to use very thin carbon foils rather than hydrogen gas as
the exchange medium. The latter possibility was investigated by Southon (1966), and found to be fraught with many difficulties, chief among which is the large beam scattering angles which occur with practicable foils, whose thickness, at 1 μg/cm² is about ten times as great as that needed for an optimum negative ion yield. Thus the dimensions of the donor canal were based on the emittance of the polarised ion beam, which had not been properly measured at the time. Some measurements on passing the beam through apertures indicated that the emittance would correspond approximately to a diamond-shaped figure having $r_{\text{max}} r'_{\text{max}} = 3.0 V^{-\frac{1}{2}}$ where $V$ is the ion-optical beam potential.

Subsequently, the use of alkali metal vapours as the charge exchange medium (Donnelly 1964) has led to an increase of about a factor of 10 in negative ion yields, and it is proposed to use a potassium vapour canal for the AURA II polarised ion source, following some preliminary measurements by MacKinnon. However the unpolarised source had been installed and in use for several months before this information was available. A direct-extraction negative ion-source (Collins 1965, Lawrence 1965) is undergoing bench tests at the time of writing and will soon be installed in place of the source to be described. For this reason no attempt has been made to improve the exchange source, as it produces a beam of very inferior optical quality to that obtainable from a direct-extraction source (Collins 1966).
Equilibrium fractions for $H_1$, $H_0$, $H_T$ in $H_2$ gas

Charge-changing cross sections for $H$ ions in $H_2$ gas per target atom.

Fig. 4.2.1. Charge Exchange in $H_2$ Gas. (Allison, 1958)

The theory of charge distribution in a three-component system such as $H^+$, $H^0$, $H^-$ has been expounded by Alison (1958), whose review article summarises many measurements on cross-sections and equilibrium beam fractions. The processes involved are not well understood and it is only comparatively recently that some progress has been made towards a theoretical understanding. Since no investigation of charge exchange phenomena has been undertaken here, only those results relevant to the operation of this ion source will be mentioned. The most important information is that, of all the gases used as charge exchange media mentioned in Alison’s exposition, the highest negative ion yield for hydrogen ions comes from hydrogen gas, the maximum negative ion fraction being .02 obtained with an ion energy of about 15 keV. Fig. 4.2.1 reproduces Alison’s curves showing the dependance of negative ion fraction on the energy and on the gas target thickness.

Many negative ion sources use primary beams of $H_2^+$ or $H_3^+$ rather than of $H_1^+$ in the interest of greater $H^-$ output, but the use of these molecular ions results in greater energy spread and angular spread in the $H^-$ beam than exist in a beam of $H^-$ derived from $H_1^+$. For, in the case of $H_2^+$ incident beams, for example, it is desirable to carry out the charge exchange at an energy of 15 keV per proton, i.e. 30 keV for the $H_2^+$ ion. The charge exchange interaction is essentially between free electrons and ions, although the binding energy of the target electrons does have a slight effect. Thus the centre of mass of the reacting system moves with almost the velocity of the ion. Now although the dissociation energy is low ~1 ev, say, in the reaction
\[ H_2^+ + e^- \rightarrow H^+ + H^0 + e^- \], if \( v' \) = velocity of \( H^0 \) relative to the centre of mass, \( V = \) centre of mass velocity, then \( v = \) lab velocity of \( H^0 \),

\[
T_{Ho} = \frac{1}{2} m v^2 = \frac{1}{2} m (V + v')^2
\]

In the extreme cases, \( v_{\text{max}} = V + v' \), \( v_{\text{min}} = V - v' \)

\[
T_{Ho} (\text{max}) - T_{Ho} (\text{min}) = 2mVv' = 2mV^2(v'/V)
\]

\[
= 4E \sqrt{\frac{E(\text{dissoc.})}{E(\text{proton})}}
\]

where \( E \) is the lab energy of each proton.

In the case considered above, where \( E(\text{dissoc.}) \sim 1 \text{ ev} \) and \( E = 15 \text{ keV} \),

Maximum energy spread \( \sim 600 \text{ ev} \).

Similarly, for the case of \( v' \) perpendicular to \( V \) there is an increase in beam divergence of extreme value

\[
r' = v'/V \sim 10^{-2} \text{ in this case.}
\]

\( H^- \) beams derived from \( H_3^+ \) exhibit similarly poor quality.

On the other hand, the proton moves with almost the centre of mass velocity throughout in the case of \( H^- \) beams derived from \( H_1^+ \) so that the very small momentum transferred by the electron has little effect on the \( H^0 \) or \( H^- \) velocity, and \( H^- \) beams derived from \( H^+ \) have low divergence and energy spread.

4.3. **General Arrangement of the Source**.

Fig. 4.3.1 shows the arrangement of components which together comprise the negative ion source. The energy of ions at the exchange canal is \( e(V_X + V_{CH}) \) for \( H^- \) ions derived from \( H^+ \), and the energy of \( H^- \) ions in the source analysing magnet is \( e(V_X + 2V_{CH}) \). In the interests of modest beam dimensions through the input lenses it is
desirable that the beam energy there should be reasonably high, and
the easiest way of achieving this is to use a high $V_{ch}$, since this
keeps the over-all power supply requirements at a minimum, as with this
arrangement it is not necessary to have any of the proton source power
supplies isolated from ground.

4.4. **Charge Exchange Canal.**

We are interested in obtaining the maximum possible negative
ion output consistent with reasonable gas consumption and moderate
power supply loads. In the interests of gas economy, the gas must be
fed into the canal mid-way along its length. For a parallel-bore
canal, the conductance from the centre to either end is given by

$$G = 3.8 \ a^3 \text{L}^{-1} \ \text{litres sec}^{-1}$$

for hydrogen gas, using the long-tube expression (i.e. neglecting end effects) where the radius 'a' and
half-length L are both measured in mm. If $Q$ is the quantity of gas
admitted, the pressure at the centre is

$$P_c = \frac{Q}{2G} = \frac{QL}{7.6a^3} \ \text{torr if} \ Q \ \text{in torr liters/sec.}$$

and the pressure may be taken as approximately zero at either end, so
that the "target thickness"

$$T = \int P_z \ dz = P_c L \ \text{torr mm.}$$

and from fig. 4.2.1 a target thickness of about 0.7 torr mm. is
required

$$Q = \frac{0.7 \times 7.6a^3}{L^2} \ \text{torr litres sec}^{-1}.$$

or

$$Q \sim 5a^3 L^{-2} \ \text{torr litres sec}^{-1.} \quad (4.4.1)$$
The acceptance of a parallel-bore canal is the upright diamond figure shown in fig. 3.2b, having maximum $r \& r'$ values of $a$ and $a/L$, so that the product $r_{\text{max}} r'_{\text{max}} = a^2/L$. The maximum negative ion beam fraction is obtained at a proton energy of 15 keV, so that for the estimated polarised ion source emittance of 3 cm(volt)$^{1/2}$, we require
\[
\frac{a^2}{L} = 2.5 \times 10^{-2} \text{ cm}.
\]
If a canal $\frac{1}{2}$-length of 10 cm. is rather arbitrarily selected then
\[
a^2 = 0.25 \text{ cm}^2
\]
or $a = 0.5$ cm.
Substituting $a = 5$ mm, $L = 100$ mm in (4.4.1)
\[
Q = 0.0625 \text{ torr l.sec}^{-1}
\]
The decision to use a nine inch oil diffusion pump with a refrigerated baffle, having a rated speed of 1000 litres/sec. had been made, so that if a canal of these dimensions were to be used, the pressure in the source vacuum chamber would be $6 \times 10^{-5}$ torr, which is a little too high. The canal dimensions were therefore modified somewhat to those shown in fig. 4.3.2. The vacuum conductance of this canal can be calculated by regarding the tapered portion as a series of parallel tubes of gradually increasing diameter, and it is found that the quantity of gas needed to maintain a target 0.07 torr cm. thick is about $4 \times 10^{-2}$ torr litres sec$^{-1}$, giving a working pressure of about $5 \times 10^{-5}$ torr in the vacuum chamber, allowing a further $10^{-2}$ torr litre sec$^{-1}$ for the proton source gas.
Solenoid winding
Glass insulators
Low-density plasma
Oscillator tank coil

$\rho \sim 10^{-2}$ torr.

Anode ($V_x$)
Intermediate electrode
Cathode canal
Pyrex envelope

FIG. 4.5. PROTON SOURCE
4.5. Proton Source.

A useful negative ion current of about 5 to 10 \( \mu \)A was adopted as the design aim for the source, if this could be achieved in a simple inexpensive source that was likely to prove reasonably reliable. Since the negative beam fraction at the chosen energy and target thickness is about \( 1.8 \times 10^{-2} \), we need a proton beam through the donor canal, of about 500 \( \mu \)A. A high voltage power supply capable of delivering 2mA at 30kV was available for use on the canal, and in view of its rather low current rating, it is desirable to use a source having a high proportion of protons in its output, as other ions would only cause undesirable load currents on various power supplies. For this reason, as well as those of simplicity and low cost indicated above, a radio-frequency source seemed most suitable, as such sources can usually be made to deliver at least 80\% of their output as protons (Moak 1951, Thoneman 1955). The source of Moak et al. is still one of the best as far as output for a given gas consumption, high proton fraction, and low beam emittance are concerned, but suffers from the disadvantages of being expensive if purchased commercially and having a rather short life (\( \sim 200 \) hours) if operated continuously at high beam currents. The source is difficult to make as it requires the use of a sapphire sleeve in the extraction region. It was felt that most of these defects could be overcome, and some incidental advantages obtained, if a three-electrode extraction system were used. This type of extraction configuration was employed originally on heavy-ion sources used on isotope separators (Wakerling 1949) and has subsequently been adopted for high current positive ion sources. (Brooks 1964).
In the discussion that follows, it is assumed that the boundary of the ion source plasma from which the beam is extracted, behaves like a space-charge limited positive ion emitter (Kistemaker 1965) and thus can be treated in much the same way as the cathode in an electron gun. Best results are obtained if the plasma surface is concave towards the extraction electrodes, and this can usually be achieved by adjusting the plasma density to the appropriate value for the extraction field strength. The emitting surface then becomes similar to the spherical-cap cathode used in point-focus electron guns (Pierce 1954), and similar design procedures can be used here to predict the size and position of the beam waist in the source cathode. The canal surrounding this waist must offer sufficient impedance to the gas flow to limit the gas consumption to a reasonable value at the required source operating pressure ($10^{-2}$ torr.) Since the source is required to produce deuterons as well as protons, it is of some importance that the gas consumption be kept low.

Pierce gives design procedures for guns of this type, (i.e. point-focus electron guns limited by space charge) and also discusses in some detail the problem of forming a small beam waist when electron temperatures are important. When both space charge and temperature effects are significant, the problem of calculating the maximum current density in a beam becomes extremely difficult. This is the case with ion sources of this type (Liley, 1955). In view of the difficulty of the problem it was not thought worth while to attempt a rigorous design of the extraction system. Instead, experience with similar types of ion source (Naylor, 1956, 1963) served to indicate suitable dimensions
for the electrodes, those from other ion sources being scaled on the assumptions that the ion current output is proportional to the areas of the anode hole, and to $V_{EX}^{3/2}$. (Kowalewski, 1959).

The intermediate electrode is operated at about $-\frac{1}{3} V_{EX}$ and serves several useful purposes.

(1) It allows the use of a high electric field near the plasma boundary without a high final positive ion energy.

(2) It prevents electrons from near the cathode canal being accelerated back towards the anode, causing additional load on the extraction power supply and sputtering damage to the anode.

(3) It traps electrons in the region of the cathode canal, thereby contributing significantly to the reduction of space charge forces there due to the high density of positive ions in this region. Very effective space-charge neutralisation can occur for gas pressures as low as $10^{-5}$ torr, and since the pressure here is $\sim 10^{-2}$ torr, the neutralisation will have some effect despite the modulation of the positive ion beam intensity by the radio frequency oscillator which maintains the ion source plasma. (Phillips 1958)

An incidental advantage from the use of a high impedance power supply for the intermediate electrode is that the supply voltage drops quite sharply if the plasma density is too high, thereby providing a useful indicator for adjusting the r.f. power level. If it is assumed that all the electrons contributing to the space charge neutralisation are created by ionisation of the residual gas, then the time required for neutralisation is simply the beam density divided by the rate of electron production per unit volume (Kelley 1967)
or
\[ \tau = \frac{n_b}{n_0 \sigma_i v_b n_b} = \frac{1}{n_0 \sigma_i v_b} \]

where \( n_0 \) = gas density, \( \sigma_i \) = ionisation cross-section, \( v_b \) = beam velocity. For the case of a 2keV proton beam in hydrogen, \( \tau \sim 3 \times 10^{-8} \) s which is about the same as the period of the r.f. field, so that one would not expect complete neutralisation.

Some economy in r.f. power is achieved by using the solenoid magnet winding shown to increase the plasma density near the anode aperture, and the presence of this magnetic field also contributes to the effectiveness of the electron trapping referred to above.

4.6. **Focusing the Positive Ion Beam.**

Most of the positive ion beam should, of course, be made to pass through the donor canal, as we can anticipate that the load on the canal power supply will be several times the intercepted primary current, due to the emission of secondary electrons from the canal. A lens having low aberrations is therefore required between the source and the canal, and a grided lens was originally used in this position. (The use of grided lenses is discussed in Chapter 6.) Unfortunately the current density in the primary beam was such that the woven tungsten mesh used for the grid was evaporated near the lens centre after a few hours' source operation. It is probable that this could have been overcome by the use of higher transparency grids etched from continuous sheets of tungsten, but these are expensive and were not readily available. In the interests of reliability the grid was
abandoned, and the dimensions of the lens altered to compensate for the reduced strength. The voltage ratio across the lens must also be higher than that for the gridded lens, which, for a given energy at the donor canal, means that the energy of positive ions at the source cathode must be lower. The sum total of these effects was to reduce the negative ion output by about a factor of two.

4.7. **Ion Source Analysing Magnet.**

With the ion source operating at a canal potential $V_{CH}$ and extraction energy $V_{EX}$, a large variety of particles can emerge from the source, including the following.

1. the desired $H^-$ derived from $H_1^+$, having an energy
   \[ E = e \left( \frac{2}{3} V_{EX} + 2 V_{CH} \right) \]

2. $H^-$ ions formed by dissociation and electron capture from $H_2^+$, with
   \[ E = e \left( \frac{1}{2} V_{EX} + 1.5 V_{CH} \right) \]

3. $H^-$ ions formed similarly from $H_3^+$, with
   \[ E = e \left( \frac{1}{3} V_{EX} + 1.33 V_{CH} \right) \]

4. electrons from ionisation, charge exchange and secondary emission in the canal
   \[ E = e V_{CH} \]

5. $H^-$ ions formed from $H_1^+ \rightarrow H^0$ in source cathode canal, then $H^0 \rightarrow H^-$ in donor canal
   \[ E = e \left( V_{EX} + V_{CH} \right) \]

It is also to be expected that there would be small currents of $H^-$ and electrons formed in other ways, but the above represent most of
FIG. 4.6. ION SOURCE ANALYSING MAGNET
the beam intensity. In addition, of course, all the above components and almost as many again will be present when deuterium is used as the source gas. Since it is not desirable to permit this miscellaneous collection of particles to enter the acceleration tube, some form of energy or momentum selection is required.

With a vertical machine, it is mechanically convenient to mount the ion source horizontally, so that a 90° magnet seems the appropriate selector. High resolution is not a desirable feature of such a magnet, because energy spreads from the ion source result in increased beam emittance after the magnet, and the increase can be significant if the source energy spread or the magnet dispersion is large. The magnet was designed to deflect particles having magnetic rigidity up to that of 50 keV deuterons on a 10 cm. radius. Entrance and exit pole boundaries have their normals at \( \tan^{-1} \frac{1}{2} \) to the beam direction, in the well-known symmetrical double-focusing configuration (Cross 1951), which places object and image 20 cm. from the pole edges. An allowance of .7 inches was made at the entrance and exit pole edges to compensate for the fringing field, i.e. the pole pieces were made smaller than the geometrical sector by this amount. The cross-sectional view of fig. 4.6 shows how "homogenising" gaps have been included to give good field uniformity and also to decrease the amount of accurate machining required (Enge 1964). Windings are of 1 inch by .06 inch copper strip, insulated with paper and epoxy resin, in four coils each of 15 turns. Current is supplied by an ex-aircraft generator whose output is stabilised via the generator field in the usual way. Maximum current is about 190 amps for 50 keV deuterons.
4.8. **Performance.**

It was not thought worth while to attempt to overcome the many known deficiencies of this ion source, in view of the circumstances mentioned in 4.1. The source has proved reasonably reliable and has given sufficient output for some nuclear physics experiments. Analysed \( H^- \) beam derived from \( H_1^+ \) is usually about 5\( \mu \)A, although over 10\( \mu \)A was available with the gridded lens referred to in 4.6. Little maintenance has been necessary - the pyrex envelope has been cleaned three times, and some trouble has been experienced with surge limiting resistors in the donor canal supply on two occasions. If no attempt to exceed 5\( \mu \)A useful output is made, then quite long life can be achieved, as instanced by the fact that no attention at all was required in the 500 hours' operation immediately prior to the time of writing. That the conditions for focusing the positive ion beam through the canal are at least approximately correct is shown by the current load on the canal power supply, which is typically about 2mA at 5kV, falling to 0.5mA at 20 kV with no exchange gas. The load increases to about 1.2mA when exchange gas is added.

The source energy spread was measured at low exchange energies by using narrow slits on the 90° source analysing magnet, and a high precision 5kV power supply connected to the canal. Under these conditions, the FWHM was less than 100ev., but would probably be slightly in excess of this in operation at more usual exchange energies, as the manufacturers claim stability of 0.25% for the 30kV power supply. Since the load is fairly constant, however, and the mains supply voltage is also reasonably stable, the final energy spread is probably about
100 ev, as about 40 ev of the width referred to above could be attributed to slit geometry. The measured energy spread is fairly low for an R.F. source, and it seems likely that the use of an anode extraction aperture to determine the plasma potential rather than a probe at the opposite end of the source envelope may reduce the effects mentioned by Collins (1965), who reported large energy spreads with some methods of coupling the r.f. power to the plasma load.

Somewhat surprisingly, the source was found to have a rather higher output of D\(^-\) than of H\(^-\). When making D\(^-\) ions, only the source gas is changed, of course, as the consumption of the source is only about 10% of that of the donor canal. A possible explanation for the improved performance on D\(^-\) is the fact that the deuterium supply was much more pure than the hydrogen, which is only commercially pure. Better performance on hydrogen may well have been obtained if a nickel or palladium "leak" had been used in place of the needle valve.

Because high pumping speed is required in the source vacuum chamber, no high vacuum valve is used. A baffle cooled by a Peltier effect refrigeration unit seems to keep the system fairly free of oil. Base pressure is about 5 \(\times\) 10\(^{-7}\) torr, rising to 2 \(\times\) 10\(^{-5}\) torr when the proton source gas is admitted, and to 4 \(\times\) 10\(^{-5}\) torr when both source gas and donor gas are flowing. These are uncorrected (equivalent air) pressures measured on a triode ionisation gauge.

In conclusion, it may be claimed that the source was easily made at low cost, has a fairly low energy spread for sources of this type, and has produced sufficient beam current to test the operation of the accelerator and to provide a useful beam of either protons or
deuterons for nuclear physics experiments. However, the optical quality of the source output is not good, as must be expected from charge-exchange sources, since the emittance can certainly be no less than that of the initial proton beam, which is, of course, fifty times as intense. Some charge-exchange sources (Rose 1962) appear to achieve beams of greater intensity at lower emittance but this is usually done by selecting only a small fraction of the incident positive ion beam, using a canal of small acceptance. The resultant high power required means that liquid cooling of many components must be employed, and the whole installation becomes very much more costly, complicated, and bulky than that described above.
Glass insulators ~8 in. diameter

Aluminium electrodes ~3 in. inside diameter spaced ~1 inch apart over whole length of tube

Poly-vinyl acetate cement joints

FIG. 5.1. TYPICAL SIMPLE UNIFORM-FIELD ACCELERATION TUBE
CHAPTER 5.

ACCELERATION TUBES.

5.1. "Long Tube" or "Total Voltage" Effect.

It has been recognized for some years that the use of long acceleration tubes having potential differences in excess of about two million volts between their ends has led to a number of difficulties which have only comparatively recently been partly explained. (Cranberg 1959, Turner 1958)

The most distressing of these phenomena is usually called tube loading, and the presence and cure of the malady has led to much of the witchcraft associated with high voltage accelerators in the past. As described by Turner, the process involves electron multiplication in the following manner. An electron or some electrons are released from the tube cathode (it may be necessary to invoke the action of cosmic rays to account for the first electron), and are accelerated towards the anode. In passing through the residual gas they create ion pairs which separate under the action of the electric field. If the pressure in the tube is low, then the mean free path of electrons in the tube can be long enough to make this gas multiplication process relatively unimportant (e.g. at $p = 10^{-5}$ torr, the mean free path of electrons in air is 50 metres). In this case, the electrons are not appreciably slowed down or scattered by residual gas molecules, but travel along the tube until they collide with an electrode. For the simple tube illustrated in fig. 5.1, the transverse distance that the
electron must cover is about the inside diameter of the tube electrodes. Since the transverse momentum is low, and is little affected by the electric field once the electron has been accelerated to a few tens of keV, the time taken for the electron's free flight $t \propto r$ the radius of the electrode aperture. (Some electrons may proceed all the way to the anode, but this is rather improbable in long tubes.) Thus the length of the tube that the electron travels,

$$z = \frac{1}{2} \frac{eF}{m} t^2$$

so that the kinetic energy

$$T_e \propto z \propto r^2.$$ 

The electron slowing down in the electrode gives rise to bremsstrahlung whose distribution is strongly peaked in the forward direction. These X-rays in turn liberate further electrons from electrodes closer to the anode, and so the cascade is maintained. Since the forward intensity of the X-rays is approximately proportional to $T^2$, it follows that the number of electrons per unit area of target ejected by the X-radiation is $n \propto T^2 \propto r^4$. Only those electrons from near the inside edge of the electrodes are likely to be accelerated over more than one tube pitch, so that the effective target area is proportional to the aperture radius, and hence the total number of electrons released per incident electron is $N \propto r^5$. Turner commenced the investigations which showed this dramatic dependence of electron multiplication on $r$ after a beautifully constructed tube that he had designed for the 4MV injector for the Brookhaven proton synchrotron failed to reach more than 1.5MV over a seven foot tube length. In his case the situation was accentuated by the use of stainless steel for the tube electrodes, which
acted as a much more efficient target for X-ray production than the customary aluminium electrodes, because of the higher atomic number of the constituent elements.

Tube loading caused by processes like that described above usually sets in quite suddenly as the potential difference across the tube is raised. The ancient art of tube "conditioning" has been developed to improve the performance of tubes in this respect, and despite its apparently unscientific basis has enabled satisfactory performance to be achieved from what should really be regarded as unsatisfactory tubes! It is frequently not realised that the tube loading phenomena occur whether or not a beam of charged particles (i.e. "primary" beam) is present in the tube, although it is usually found that such tubes "condition" more quickly when the beam is on.

Many attempts have been made to overcome the difficulties associated with tube loading, and these have met with varying degrees of success. One obvious method is to use small apertures in the electrodes for the beam to pass through, and to use other apertures around these to provide the necessary vacuum conductance. These pumping holes must not, of course, be collinear or little improvement will be obtained. Tubes of this type have been used in the high energy regions of many tandem accelerators until the last few years.

McKibben (1964) has apparently succeeded in surmounting the problem by placing small apertures periodically along the length of the tube, thus limiting the free path available to electrons. Careful design of the electric field near the apertures ensures that secondary particles cannot subsequently acquire high energies. The large Los
Alamos Scientific Laboratories accelerator in which these tubes are used, is, however unusual in many ways, and this solution is not readily adaptable to other machines.

Many accelerators now in use have tubes using aperture diameters which are "waisted" near the middle of the tube, and this improves the performance over that of parallel-bore tubes for reasons not properly understood. Some experiments with tubes of this type have been reported by Chick et al. (1959.)

5.2. Non-Uniform Field Tubes.

The attempts to limit the effects of parasitic currents in acceleration tubes mentioned in the previous section have all been made on tubes having uniform potential distribution along their length, and cylindrical symmetry in their internal geometry. Other attempts have been made in which either the uniform potential distribution or the cylindrical symmetry has been abandoned. Perhaps one of the most startling was a proposal for an alternating gradient axial field tube (Boyd 1966) which is intended to confine the electrons within short sections of tube. This would lead to very considerable technical difficulties if any attempt to achieve the usual sort of average tube gradient (500 kV per foot) were made, as the fields would have to be at least twice as high along some parts of the tube.

It is sometimes proposed that the best way of confining the electron paths would be by arranging suitable magnetic fields in the vicinity of the tube axis to deflect the particles into the tube walls before they could attain high energies. (van de Graaff 1963, Howe 1965).
The author shared this view, but unfortunately no such tube had been adequately demonstrated, and neither the time nor the expense could be spared to undertake the development work which might be necessary to perfect such a tube. It does seem, however, that this is the method best suited to machines which are not required to accelerate electrons, as the effects of the "clearing fields" on the primary beam would be so much less than their effects on the unwanted secondary particles, in contrast to the case of suppression by electric fields where the effects on the primary beam may be considerable. Successful tubes of this type have been reported recently (Howe 1967, Reinhold 1967).

One of the best-tested methods of overcoming long tube effects has been the use of tilted electrodes to give a transverse component to the electric field — the so-called inclined field tubes. These fall into two main classes, the first being that advocated by Rose (1963) in which the transverse components all lie in a common plane, and the second that due to Allen (1962) who used a spiral disposition of electrode aperture planes. Both types were known to have their difficulties, but it seemed that those associated with the first variety could be readily overcome, while the second type appeared to have some fundamental limitations in that secondary particles created in the residual gas are not positively swept aside. The decision to use the first type seems rather fortunate now, in view of difficulties experienced with tubes in the Oxford University injector machine (Allen 1967.)
5.3. Electric Field Design.

Consider a tube made up of electrodes tilted as shown in fig. 5.3.1, and assume the potential uniformly divided along the tube. In any section of constant inclination, \( E_y = E_z \tan \phi \), and let the origin of \( z \) be so chosen that the primary beam energy is zero there. The problem is to find a suitable combination of tube segments having \( E_{y_1} = E_z \tan \phi \) and \( E_{y_j} = -E_z \tan \phi \) etc. such that secondary particles cannot be accelerated to high energies, while on the other hand the primary beam will remain close to the axis. In the interests of alignment of the whole machine it is certainly preferable that the beam should enter and leave the tube on the axis and parallel to it. It is also desirable, on more mundane financial grounds, that the two tubes should be identical, so that it would be necessary to have only one spare, since tubes of this size are rather expensive.

The time taken by a primary particle to travel a distance \( \hat{S}z \) is simply

\[
\hat{S} t = \frac{\hat{S}z}{v(z)}
\]

so that the time taken between two points \( z_i, z_j \) is

\[
t_j - t_i = \int_{z_i}^{z_j} \frac{dz}{v(z)}
\]

i.e.

\[
t_j - t_i = \frac{2m}{eE_z} \frac{1}{2} \left[ z_j^{\frac{1}{2}} - z_i^{\frac{1}{2}} \right]
\]

(5.3.1)

Hence if all electrodes between \( z_i \) and \( z_j \) are parallel, the change in transverse momentum in traversing the \( i, j \)th segment of tube is

\[
P_{y_j} - P_{y_i} = eE_z \tan \phi (t_j - t_i)
\]

\[
= (2mE_z)^{\frac{1}{2}} \tan \left( z_j^{\frac{1}{2}} - z_i^{\frac{1}{2}} \right)
\]
Let \( y' = \frac{\partial y}{\partial z} = \frac{P_y}{P_z} \)

\[
y_j' = \frac{P_{yi} + \delta F_y(i,j)}{P_{zj}}
\]

or \( y_j' = \left( \frac{z_i}{z_j} \right)^{1/2} y_i' + \tan \phi \left[ 1 - \left( \frac{z_i}{z_j} \right)^{1/2} \right] \quad \ldots \ldots \quad (5.3.2)\)

which gives the change in slope for a ray traversing the \( i, j \) th segment. For the change in transverse displacement,

\[
y_j - y_i = v_{y,i} (t_j - t_i) + \frac{e}{2m} E_z \tan \phi_i (t_j - t_i)^2
\]

\[
y_j' = y_i' v_{z,i} (t_j - t_i) + \frac{e}{2m} E_z \tan \phi_i (t_j - t_i)^2
\]

\[
y_j - y_i = y_i' 2z_i^{1/2} (z_j^{1/2} - z_i^{1/2}) + \tan \phi_i (z_j^{1/2} - z_i^{1/2})^2 \quad \ldots \ldots \quad (5.3.3)\)

In the transition regions between segments of opposite inclination, "straight" electrodes are placed so that there will be no great increase in field strength at these electrodes. The effect of the two wedge-shaped regions on either side can be regarded as cancelling each other to sufficient accuracy for this calculation.

Any calculations must be based on certain assumptions which must, unfortunately, be regarded as almost unattainable ideals in a practical machine of this type. Probably the most serious defect encountered is non-uniform potential distribution. The terminal potential is nominally divided down the high voltage column by a string of resistors having a total resistance of \( 3.7 \times 10^{10} \) ohms or about \( 5 \times 10^8 \) ohms per column plane. Unfortunately the resistance of all resistors suitable for use in this situation changes with increasing voltage in a manner which seems to depend on the conditions at the surface of the resistor. Leakage currents in parallel with the
FIG. 5.3.1. TUBE WITH TILTED ELECTRODES.

FIG. 5.3.2. PRIMARY TRAJECTORY IN TUBE WITH ONE LONG INCLINED FIELD REGION.
resistors across some planes can also result in incorrect potential distribution, while there is usually a time-dependent contribution due to uneven charge distribution on the belt which couples to the tube electrodes via the belt-column plate capacitance. The latter can, of course, lead to an output beam whose position is not steady, which is undesirable for some experiments. All these circumstances argue against the use of excessive excursions in the mean position of the primary beam, so that $\phi$ must not be too large. The path length of secondary particles is $\frac{d}{\tan \phi}$ where $d$ is the $y$-dimension of the tube aperture, so that $d$ should be made as small as possible. Since the inclined fields are intended to sweep secondary particles out in the $yz$ plane, the $x$ dimension of the aperture can be made large to provide the necessary vacuum conductance, without otherwise compromising the tube performance. Detailed consideration must also be given to the field strength at the electrode surfaces, that at the cathodes being kept as low as possible, and to the necessity for shielding the insulating surfaces from the beam. In order that the sweeping action may be effective there should be at least one long region of tube with electrodes inclined in the same direction, so that, if this is placed half-way up the tube, then the two halves are effectively isolated. If only one such region is used, it must be both preceded and followed by tube segments having the opposite inclination in order that the outgoing beam may be parallel to the ingoing. Such a tube will then give rise to trajectories like those illustrated in fig. 5.3.2, and it will be seen that these primary beam paths deviate rather a long way from the axis, unless the initial axial-field region is made long. In the
FIG. 5.3.3. ACCELERATION TUBE

Transverse displacement for "central" rays in negative tube (solid line) and in positive tube (dashed line)

Axially symmetric electrodes numbers 0–20 and 73–78

Tilted electrodes with slot apertures numbers 21–72

High voltage terminal

Electrode numbers

42

26

20

Earth plane

Off-axis displacement

3mm

Electric field directions in various tube segments
latter case, electrons coming from the cathode end will have quite a high probability of going right through the inclined field region.

Another possible configuration, which was finally adopted, is illustrated in Fig. 5.3.3.

Electrodes numbered 0-19 have circular apertures decreasing from 4.625 inches diameter at 0 to 3.750 at 19. The electrode inclination selected is 10°, giving an effective field angle near the axis of about 8°.

For a primary beam ray entering on the tube axis at an energy of 40 keV, the final direction and positions were calculated for the above tube when used

(1) as the negative ion tube

\[ y' = 0.000, \quad y'_p = 0.0015 \text{ inches} \], and

(2) as the positive ion tube

\[ y' = 0.000, \quad y'_p = -0.0013 \text{ inches} \].

Although there has been some discussion of additional focusing effects in inclined field tubes (Koltay 1965) these are generally so slight that they need not be considered (Rose 1967), particularly in the case of a machine such as this where the astigmatism introduced by the terminal magnet is very much more significant than that brought about by departures from cylindrical symmetry in the accelerating fields. With a slot width of 1.25 inches, the maximum distance that an electron starting in one of the long inclined field regions (e.g. at electrode 27 or 43) can travel is about 9 inches, or 9 tube pitches say, corresponding to an electron energy of about 470 keV for 4 MV terminal. The fate of electrons originating near electrodes 20-23 is not so clear,
FIG. 5.3.4: ELECTRON TRAJECTORIES IN INCLINED-FIELD ACCELERATION TUBE
although obviously those starting from about 24-26 will suffer a similar fate to those starting from near 27. Electrons starting from electrodes near the cathode will mostly be stopped at the first slotted electrode, but some will proceed further up the tube. Most of the latter will go right through to the terminal, when the voltage there is high, and in fact their lateral displacements will be less than those of the primary beam because of the relativistic increase in mass.

For example, with a terminal potential of 4 MV, the energy of an electron starting from electrode 0 is about 1 MeV at electrode 20, where its mass is $\sim 3 m_0$ and $\beta \sim 0.94$. Thus, although the velocity is now almost constant throughout the rest of the tube, the increase in mass means that the changes in transverse momentum will be less than those for the proton. When a non-relativistic particle has reached electrode 40, it is moving 1.4 times as fast as it was at electrode 20, but its mass remains the same, whereas an electron's velocity ratio is only 1.04, but its mass ratio is about 2, so that its deflection must be less than that of the primary beam particle. The probability of an electron's going through the slot in electrode 20 and subsequently hitting a tube electrode is therefore quite low, although there will be a few with trajectories like those shown in fig. 5.3.4, (where only the limits of the apertures in the electrodes are shown). Most of these few electrons will hit electrodes between about 20 and 30, and their X-rays will liberate most Compton electrons from electrodes still well within the first or second long inclined regions of tube, and these will quickly be swept aside. It is not necessary, of course, to eliminate all possible events of the type described in 5.1 in order
FIG. 5.4.1. TUBE CONSTRUCTION.
that the cascades may be limited to harmless proportions: it is merely necessary to reduce the probabilities of some of the reactions to the point where multiplication no longer occurs.

5.4. **Construction.**

Fig. 5.4.1 shows some details of the tube construction. Electrodes are pressed from a soft aluminium alloy (99% Al) having a low tensile strength. They are machined to thickness near the metal-glass interface area, and polished to a very high finish. The assembly process used by the specialist manufacturer, selected to make the tubes to the author's design, involves placing films of poly-vinyl-acetate about .001 inch thick between insulators and electrodes, two or three films per joint being preferred. An alternative technique uses dissolved poly-vinyl-acetate applied in liquid form, but this has a disadvantage in that it is difficult to pump the solvent out of the joints, so that several days' pumping may be required before the tubes come down to a low pressure. Sub-assemblies of tube 24 inches long were assembled in a jig, the sub-assemblies being subsequently joined to form a continuous tube. Alignment accuracy required from the makers was ± .005 inch.

To prevent stresses from tube mountings being transmitted to the glass insulators, the end flanges are made with a rather thin section between their stiff ends, as shown in fig. 5.4.1. Two O-ring gaskets are used on each flange, with a pump-out connection made to the space between them to assist in rapid and positive identification of possible leaks at these joints, which, since they are inside the
pressure vessel, could prove troublesome. A Kovar ring is inserted between each terminating flange and the adjacent electrode, to minimise the stresses induced by thermal shocks. The aluminium electrodes are sufficiently ductile for this to be no problem over the remainder of the tube.

Across each insulator are five spark gaps approximately equally spaced round the circumference. The electrodes forming the gaps (395 per tube!) are detachable, so that they can be used again when it becomes necessary to replace the tubes. A gap of .140 inch was chosen between electrodes having hemi-spherical ends of 4mm radius, which could be expected to spark across at about 150 kV at 200 pounds per square inch of nitrogen and carbon dioxide. Some difference of opinion exists as to the number of such gaps required, but it is certainly the case that if there are not sufficient, discharges can occur across the insulator surfaces sometimes causing serious damage. This is because such spark pulses have very low rise times, and a discharge, once started will always follow a low inductance path, i.e. it will be most unwilling to turn corners in order to find the spark-gaps thoughtfully provided for it!
CHAPTER 6.

LENSES AND MAGNETS.

The requirements for the optical components were set out in chapter 3, but only those pertaining to the negative ion source have been discussed in detail. In this chapter the remaining lenses and magnets will be described.


As indicated in 3.5, the matching lens, in conjunction with the entrance lens, is required to focus the beam from the ion source through the negative ion acceleration tube to the terminal magnet. A strong, large diameter lens will best preserve the optical quality of the beam, since it is important that only a small fraction of the lens diameter be used, to keep spherical aberrations low. The most convenient type of lens for this application is undoubtedly the "einzell" or uni-voltage lens, which leaves the beam energy unchanged outside the lens field. Most strong einzell lenses suffer from quite severe aberrations (Liebmann 1949) although the use of grids to eliminate the diverging part of the lens field can result in dramatic improvements (Moak 1959). The idea is by no means new, grid lenses having been reported by Cartan (1937) and Knoll (1938). It is the form used by Cartan and Knoll, with a single central grid, that is used here, as the lens with two grids seems to offer advantages only when a retarding voltage must be used on the central element. Fig. 6.1.1 shows the
FIG. 6.1.2. IMMERSION OR BI-POTENTIAL LENS

FIG. 6.1.1. MATCHING LENS
lens, which uses woven tungsten mesh of 1 mm. pitch, having 92% transparency, as the grid material. The effects of the "facet lenses" (Klemperer 1953) formed by each mesh unit cannot always be neglected, but may be calculated with sufficient accuracy for present purposes by regarding each mesh as an aperture separating regions of constant field. Fig. 6.1.2 shows the potential distribution found in an equi-diameter two-cylinder immersion lens, which is identical to that of the mid-grid einzel lens if the grid is substituted for the 50% equi-potential, and the field on one side of the lens is reversed. From this the field strength on either side of the grid can be obtained, and the well-known Davisson-Galbick equation then gives an approximate value for the focal length of a facet lens viz. \[ f = \frac{4V}{E_2 - E_1} \]

Here \( E_2 = -E_1 \), so \( f = \frac{2V}{E} \). From fig. 6.1.2 and the estimated grid potential (see later) we find \( f = 100 \) cm. Hence a particle passing close to a grid wire could be deflected by 0.5 mm in 100 cm. = 0.5 \( \times 10^{-3} \) radian. Since the emittance here has a half-angular width of .045 radians, it can be seen that the facet lens effect is small.

From the above remarks concerning the potential distribution, it will be seen that, since both halves of this lens are converging, whereas for the corresponding immersion lens one half is diverging, the power of the grid lens is at least twice as great as that of the corresponding immersion lens having twice the voltage ratio across it. From published curves of focal length vs. voltage ratio for the bi-potential lens (Zworykin 1945b) a voltage ratio of 3 gives a focal length of four lens diameters, so that we would expect a ratio of less
Negative ion acceleration tube

Tungsten mesh grid

Column planes

Earth plate

To lens power supply 0-50 kV

40 keV H⁻ beam from ion source

6.2.1. TUBE ENTRANCE LENS
than 1.5 to give a focal length of 2 lens diameters, which is the minimum likely to be required for the matching lens. The lens was designed to withstand 25 kV on the central electrode. In practice the usual value is about 13 kV for a 42 keV input beam, giving a lens ratio of 55:42 or about 1.3.

Because of the mirror symmetry of the lens, departures from planarity in the grid are not important, which is fortunate as it is difficult to keep the grids perfectly flat. The power supply for the lens was made in the laboratory from readily obtained television components, and is an 8 kHz voltage doubler having a maximum output of 17 kV at 200 μA.

6.2. Tube Entrance Lens.

To overcome the difficulties caused by the strong lens action which results from the electric field at the tube entrance, a grid is used in this lens also. Fig. 6.2.1 shows the lens, which is very much like half the matching lens. The effective lens diameter is that of the last tube electrode, 11.7 cm. so that the focal lengths required of the lens are between 3 and 7 diameters, depending on the terminal potential. If this lens is compared with the conventional cylinder lens whose potential distribution is shown in fig. 6.1.2, it will be seen that it is considerably stronger than the conventional lens having twice the voltage ratio, since the diverging part of the lens field has been eliminated. The curves referred to above give a focal length of 3 diameters for a voltage ratio of 3.5, so that we would expect a ratio of about 1.7 to be the maximum needed for the entrance lens. With an
input energy of 42 keV the maximum lens voltage is therefore about 30 kV. This is, of course only approximate and is intended only to furnish a guide to the power supply requirements. It is interesting to note that the potential as estimated here is not very different from that which the lens electrode would assume were it connected to the column potential divider. The "facet lens" focal length estimated on the same basis as in the previous section is about 20 cm, so that the increase in beam emittance here is more important than at the matching lens, giving a half-angle increase of about $2.5 \times 10^{-3}$ in $35 \times 10^{-3}$ radians. A commercially manufactured 50 kV 1 mA r.f. voltage multiplier provides the lens voltage. The low stored energy of supplies of this type is advantageous in reducing the likelihood of serious damage to the lens grids in the event of voltage break down in the vacuum.

6.3. **Strong-Focusing Lens.**

The requirements for this lens were indicated in section 3.6. Since the beam is at its maximum energy when it reaches the lens, it is not possible to produce a sufficiently strong lens in cylindrically symmetrical form, and a quadrupole lens is the most suitable. The choice lay between four types

1. electrostatic doublet
2. electrostatic triplet
3. magnetic doublet
4. magnetic triplet.

All quadrupole doublets suffer from so-called "image distortion"
FIG. 6.3 QUADRUPOLE LENS

Positive ion acceleration tube

Windings

Gimbal mounting

Flexible bellows

Windings

Pole piece

Vacuum pipe
(Enge 1961) i.e. from different magnification in two planes. This defect is not acceptable here because the 90° analysing magnet must be rotated about a vertical axis to direct the beam to various target stations, and a large beam dimension in the plane of beam deflection means that good momentum resolution requires excessive sacrifice of intensity. The use of a three-element lens overcomes this drawback, and enables an almost square image of a square object to be formed.

The beam diameter can be rather large (∼4 cm.) at the exit of the positive ion tube, and hence the lens should have a large aperture, preferably ∼8 cm. An electrostatic lens of such an aperture and of moderate over-all length would require very high voltages e.g. for a lens 1 metre in length, voltages of ±100 kV would be needed for a beam of 8 MeV singly-charged ions. The problems associated with supplying these rather high voltages to a lens situated inside the pressure vessel (where tank-pressure to vacuum and tank-pressure to atmosphere leads-throughs for each of four separate supplies would be needed) made the use of a magnetic triplet lens seem very attractive.

Such a lens was therefore designed on the basis of the very useful curves given by Enge (1961). The lens is able to focus a beam having a magnetic rigidity of 7 × 10⁵ gauss-cm. onto the magnet object slit. (This is the maximum rigidity beam that the analysing magnet will handle.) With an over-all length of 80 cm, an aperture of 8.7 cm and a weight of about 700 pounds, the lens is a fairly substantial instrument. Since hysteresis effects are not important here, boiler-quality mild steel plate is used for the iron path, not for its good magnetic properties but rather because its machining qualities and
FIG. 6.4.1. MAGNET POLE EDGE MODIFICATION.
homogeneity are superior to those of ordinary mild steel. Because it is difficult to machine the pole pieces to hyperbolic profiles, a circular arc approximation was used, the pole pieces being turned to shape in pairs on a special jig. There are two coils of 1\" x 1/16\" copper strip per pole, the windings on the eight end poles being connected in series, as also are those of the four centre poles. Current is supplied by two ex-aircraft DC generators each able to deliver 200 amps. They are driven by a single 10 HP motor, and have separate, variable current stabilisers using loops incorporating sampling resistors, transistor amplifiers, and the generator fields. Current stability is about $5 \times 10^{-3}$. Tank gas is used for cooling, no special provision being made to circulate it through the windings as there is a good draught from the charging belt near the lens, which is bolted rigidly to the positive ion acceleration tube, a gimballed bellows joint below the lens permitting the lens-tube assembly to be aligned as a unit. The vacuum tube is of stainless steel.

6.4. 90° Analysing Magnet.

The focal properties of this magnet were investigated by Dzedins (1968) who plotted the fringing field of the magnet and also traced trajectories through the gap, using the well-known floating wire analogy (Vogel, 1965). These investigations showed that the magnet had some deficiencies, which was not surprising in view of the low price for which it was purchased from an English manufacturer. It is equipped with rotatable inserts at the entrance and exit pole edges, so that the focal properties can be altered at will. The position of these
FIG. 6.4.2. ANALYSING MAGNET
pole tips does not define the effective inclination of the field boundaries very well, however, and the extent of the fringing field was greater than had been allowed for by the makers, so the pole tips were modified by having 0.5 cm. removed from each of them as shown in fig. 6.4.1.

This modification seems to have achieved the required result, as the beam has been observed to emerge within $2 \times 10^{-3}$ radian of horizontal, and this very slight error could easily be corrected by adjusting the position of the centre of the image slit.

The entrance and exit slits are supported from the magnet casting by a rigid frame of aluminium tubing. A two-inch mercury diffusion pump, with its associated liquid nitrogen trap and thermoelectrically cooled baffle, is mounted between the magnet and the exit slits as shown in fig. 6.4.2, which also shows the counter-balanced mounting arrangement, using a gun mounting as a turntable. The rotating mass is in excess of 4000 pounds, but the magnet can easily be rotated by pushing on the exit slit support with one finger. Four solid steel ½" diameter support columns 'A' transfer the magnet weight to the laboratory floor via the levelling and height adjustment screws L. Between the end of each column and its floor pad is a steel ball, which allows the columns to rock when adjustments are made to the horizontal constraining screws H. The counter-balance weight was necessary to overcome departures of the turntable from horizontal because of varying compression in the four support columns as the magnet was rotated.
6.5. **Permanent Magnet Quadrupole Lens.**

To enable the beam emerging from the analysing magnet to be focused on a target several meters away, another strong focusing lens is needed. A permanent magnet quadrupole doublet was purchased for this purpose (Jagger 1967). It makes use of blocks of ceramic permanent magnet material to produce a quadrupole field inside a non-magnetic vacuum tube. Lining part of this tube are short lengths (equal to the magnet length) of ferro-magnetic tubing which act as magnetic shunts. Each of the quadrupole elements can be moved along the pipe over its internal shunt, so that the effective length of magnetic field, and hence the lens strength can be varied, and a large range of focal lengths achieved. It is also possible to rotate each quadrupole about the lens axis, so that any desired orientation of the minimum image dimension can be obtained. This is of some importance as the doublet separation is almost a metre, and the magnifications in two planes can differ by a factor of 3 or 4 when short image or object distances are used. The lens has proved very convenient to use, and its aperture of $2\frac{3}{4}$ inches means that the beam could be transported considerable distances using just this lens between analysing magnet and target chamber. The most distant target station used at the time of writing was about 8 metres from the magnet, and the beam occupied less than one quarter of the lens aperture in this case, so that a target could be placed at least twice as far away if required.

It is, of course, usually desirable to adjust the strength of the 4-pole so that magnet image slit and target lie in conjugate planes, as otherwise it is possible that beam movement at the target may not be
negligible. The position of the lens along the beam path is usually determined, for a particular experiment, by the relative importance of linear and angular magnifications at the target.

6.6. **Orientation of Optical Components.**

In section 3.3 the effects of terminal magnet momentum dispersion were briefly discussed, and the possibility of beam position instability in the acceleration tubes was mentioned in 5.3. Since these produce disturbances in one plane only, as also does ion source energy variation, it was decided to orient the terminal magnet and source magnet so that their deflection planes coincide, and to mount the acceleration tubes so that this plane contains their off-axis electric field components. Hence the above effects will all produce beam movements in one direction only.

When the analysing magnet is set up with its deflection plane perpendicular to this direction, the beam will move along the image slit rather than across it. Since the analysing magnet is used as the energy reference for the accelerator, with error signals derived from the slits jaws in the usual way, these undesirable variations in beam position will not give rise to machine energy changes when this orientation is used. Thus experiments requiring good energy resolution should be set up with the analyser deflection plane at right angles to the plane containing the acceleration tube axes. Experiments requiring maximum beam current and not needing the utmost in resolution, are best carried out with the analyser rotated through 90°, as this allows the acceptance of all magnets to be used to the best advantage.
PHOTOGRAPH THREE

The 9\frac{1}{2} ton pressure vessel is suspended from its crane over the generator. When the intershield is used, it is supported by the plate situated half way down the high voltage column.
CHAPTER 7.

PRELIMINARY TESTS.

7.1. Generator Voltage Runs.

Installation of the equipment for storing and moving the insulating gas (see Appendix A.2) proceeded concurrently with the assembly of the generator column and belt charging system (Appendix A.1). This work was completed about the middle of 1966 and preliminary tests were started. Tracking and tensioning the charging belt proved to be a simple matter when the machine was open, but since the atmospheric humidity is usually high in Auckland, and the laboratory is not humidity-controlled, no tests other than the most rudimentary mechanical ones could be carried out in the air. The machine was therefore "closed up", (i.e. top of pressure vessel placed on base and bolted up) and the air pumped out for a few days using a 7 litre/sec. rotary pump. It was then pressurised to just over 1 atmosphere pressure $N_2 + CO_2$ (about 5:1 by weight), and it was found that evacuating the vessel had dried the belt and allowed it to stretch to such an extent that it no longer tracked correctly. After moving the insulating gas into the storage vessels, the generator pressure vessel was entered by means of a man-hole cover ostensibly provided for the purpose, and the belt re-tensioned. (This procedure of entering the pressure vessel has never been repeated, as it is more convenient to remove the whole top of the vessel.)

Voltage was measured by means of column resistor current only.
a notoriously unreliable method. Meters had been installed in the terminal to measure current collected from the charging belt there and also the current at the top of the resistor chain, as this can be quite different from that measured at the earth end if there is much corona current from the column. Tests were carried out for a total of about 20 hours only before the bearings supporting the pulley in the terminal failed. Discussion of this sort of catastrophe is deferred to Appendix C, which deals with reliability.

Results of the early voltage trials seemed to indicate that a terminal potential of about 4.5 MV could be attained with the inter-shield in place, but more recent measurements with the accelerated beam cast serious doubts on the validity of these measurements. The inter-shield was used in these attempts to assess the voltage capability of the machine, but attempts to improve on the above performance were abandoned when sparks caused severe damage to the charging belt, which had to be replaced. After the voltage runs, tests on terminal and pressure vessel cooling were carried out. The high-current DC generator for supplying terminal magnet current was installed together with its associated current stabilising circuits, three-phase alternator, and a dummy load comprising several feet of fencing wire. Temperatures were measured in the terminal and at the base of the machine, and were found to be very close to the maximum safe working temperatures for some components when the magnet current generator output was 3 kW. A water-cooled heat exchanger was therefore installed just below the level of the earth plane to remove some of the heat, and it does in fact take out about half the heat generated inside the vessel, the remainder
coming out through the tank walls. This resulted in much more satisfactory temperatures, and it was possible to increase the generator output to 6 kW, at which level the terminal temperature was 48°C, and 6 kW was being removed by the heat exchanger. Much of the input power goes into overcoming windage on the belt, the total input power for this test being about 13 kW.

7.2. Tube Testing.

The first acceleration tube was available just after the thermal testing had been completed, so the main vacuum system was installed (Appendix A.3) and the tube mounted in the high voltage column. Further voltage tests were made with the tube in place, together with X-ray measurements to give an indication of the onset of tube loading. Very low X-ray levels were observed with a monitor placed directly above the acceleration tube, the maximum level recorded being only six times background with a column resistor current reading corresponding to 3.8 MV. No tube spark-overs were observed, and the indications were that the tube was performing satisfactorily. A leak in the vacuum system made the internal tube pressure rather high at $2.5 \times 10^{-5}$ torr during these measurements.

7.3. Tests with Beam.

Installation of the second acceleration tube, charge stripper, terminal magnet, and lenses was completed a few months later. The components were all aligned to a primary reference which was taken as a vertical line passing through the intended centre of rotation of the
analysing magnet. Extensive use of a theodolite and suitable sighting targets ensured that the placing of tubes, lenses and terminal magnet was correct to within ± .015 inches. The charge exchange negative ion source was mounted below the pressure vessel after preliminary bench tests had shown that it was able to produce a few micro-amps of $H^-$ ions. A current collector placed just below the positive ion port in the pressure vessel terminated the beam path, and it was at this point that a positive ion beam was first detected. The current first observed was only $5 \times 10^{-8}$ amps at an indicated terminal potential of 2.5 MV. During the next few hours' running this was increased to $2 \times 10^{-7}$ amps by changes in the ion source alignment. It was noticed that if the terminal voltage was raised to over 1.6 MV when the tube entrance lens voltage was low, there was considerable X-ray production from the negative ion side of the machine. This was attributed to electrons from the lens grid, a hypothesis which was substantiated to some extent by the fact that the X-ray intensity fell by a factor of about 100 when the grid potential was raised to $V_t/80$, i.e. to about the potential which the grid would have assumed if it were connected to the column resistor chain rather than to its own power supply. Some measurements of the variation of X-ray production with acceleration tube pressure were made, with results as follows:

<table>
<thead>
<tr>
<th>Tube pressure (torr)</th>
<th>$1.5 \times 10^{-6}$</th>
<th>$4 \times 10^{-6}$</th>
<th>$8 \times 10^{-6}$</th>
<th>$1.6 \times 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistor current ($\mu$A)</td>
<td>52</td>
<td>54</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>Charging current ($\mu$A)</td>
<td>54</td>
<td>54</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>X-ray count rate.</td>
<td>$10^5$</td>
<td>$4 \times 10^3$</td>
<td>$3 \times 10^2$</td>
<td>$3 \times 10^2$</td>
</tr>
</tbody>
</table>
Fig. 7.2.1. MAGNETIC SUPPRESSION OF ELECTRONS FROM ENTRANCE LENS GRID
Pressure variations were achieved by partly closing the diffusion pump valve. The voltage "calibration" used was 27 $\mu$A resistor current/MV. The entrance lens grid was kept near zero potential. Background rate in the monitor used was 200, so that there appeared to be no significant X-ray production until the pressure was decreased to $4 \times 10^{-6}$ in the first set of results (≈ 2 MV terminal) or $1.8 \times 10^{-5}$ torr in the second series (≈ 2.2 MV terminal.) There is little significance in the fact that there is ≈ 10 $\mu$A difference between the charging currents and resistor currents in the second set, whereas there is little difference in the first set. These results were not very surprising, as there is every chance that electrons starting from the cathode end of the tube will proceed through to the terminal, as indicated in 5.3, particularly as some of them will start from near the tube axis. The local field will also be more nearly parallel to the axis at the point where the electrons start than would be the case for electrons leaving electrodes at an ungridded tube end. To minimise this X-ray production, some small permanent magnets were mounted outside the tube at the height of the gridded electrode. These produce a magnetic field strength of 9 to 10 gauss in the region of interest near the centre of the grid; the direction of the field being parallel to the long dimension of the slot apertures in the tube (Fig. 7.2.1.) The field distribution was measured using a Hall probe, and electron trajectories calculated.
(Lehnert 1964) near the grid, with the result shown for an electric field strength of 2MV/metre. The deflection so produced is sufficient to ensure that most electrons from the grid will stop at the first slotted electrode.

The variation of X-ray production with pressure seems to be common to almost all acceleration tubes, but still appears to lack a satisfactory explanation.

Although some X-rays were still present after the magnets had been placed on the tube, it was observed that the entrance grid could be "conditioned", in other words it was possible to apply the electric field in such a way that the electron currents causing the X radiation decreased with time, as shown by the following readings, which were taken at constant charging current.

<table>
<thead>
<tr>
<th>Time (mins.)</th>
<th>0</th>
<th>0</th>
<th>3</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistor current (μA)</td>
<td>95</td>
<td>90</td>
<td>95</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>Grid voltage (kV)</td>
<td>33</td>
<td>28</td>
<td>28</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

The technique used here was to reduce the grid voltage to such a value that about 5μA of electrons were drawn from it, then wait until the resistor current increased to its original value, whereupon the lens voltage would again be lowered. As is frequently the case with phenomena of this sort, a similar result was not achieved by running the grid at a very low voltage (i.e. high electric field strength) initially; the process must be carried out gradually or no improvement occurs. Once the grid has been conditioned in this manner, it will operate satisfactorily until the terminal has been run at a low voltage for many hours, after which, if high terminal potentials are again
FIG. 7.4.1. TERMINAL VOLTAGE STABILISER
required, it may be necessary to "condition" the grid again.

After such improvements in operating procedures, it was found that considerably enhanced beam transmission was obtained. Output beam currents rose to about half the input current, a maximum of 1.8 μA having been observed at this stage. The accelerator was operating at up to 85 μA resistor current at this time, and this we assumed to correspond to 3 MV terminal i.e. beam energy about 6 MeV.


Early in 1967 the analysing magnet was modified as described in 6.4, and mounted below the positive ion tube. Its position was established with respect to marks set out on the walls and floor of the laboratory at the time of tube installation. The task of moving the magnet into place was left to outside contractors, as its site is not accessible by the laboratory crane. Once the magnet was installed, the terminal voltage stabiliser described by Gummer (1967) was connected in, and measurements on terminal stability and beam energy spread were carried out. Fig. 7.4.1 is a block diagram of the stabiliser. These measurements showed that the principal contribution to the beam energy spread came from straggling in the stripper foils, and that the total energy spread was typically about 1 keV FWHM. The terminal voltage variations were found to be about ± 35 volts. Variations in the thickness and strength of the stripper foils are unfortunately quite considerable, due to technical difficulties in evaporating and subsequently mounting the foils. It is very easy to break foils even after they are mounted in the foil changer, when a careless bump may easily
cause several of them to rupture. Beam currents measured after the analysing magnet were 80-90% of those measured before it, depending of course on the magnet slit widths, which are variable between 0 and 0.6 inches. The over-all energy spread was inferred from the shape of gamma-ray yield curves near the well-known resonances in Al$^{27}(p,γ)$Si$^{28}$ at 991 keV and 1338 keV. When using such low energy beams it was found that the target current, as well as the energy spread, depended to quite a marked extent on the thickness of the stripper foil. On one occasion, when the proton energy was 1.34 MeV, there was an increase in target current from 0.4 μA to 2.0 μA when the foil was changed, and this was accompanied by a reduction in magnet image slit current of about a factor of eight. That this was due to a very thin foil is confirmed by the fact that the foil's life was very short! Thin targets of aluminium evaporated in situ onto carbon backings of about 50 μg/cm$^2$ were used for these measurements. Interposing a foil similar to the stripper foils in front of one such target showed that, with a proton energy of 1338 keV, the energy lost in the foil was about 1.5 keV and the extra energy spread introduced by it was ~1 keV. It was also established that the energy uniformity was substantially independent of slit width as long as sufficient current fell on each jaw to overcome pre-amplifier noise. This is a good test that the feel-back system is working correctly, and serves to emphasize the fact that the magnet is used as energy reference rather than as a momentum analyser. The above measurements are discussed more fully by Sumer, with whom the author collaborated in obtaining these results.

During further attempts to measure energy spreads in the beam
at low energy, it was found possible to obtain a beam of $10^{-8}$ amps above the analysing magnet with only 33 kV on the terminal, giving a total beam energy of 108 keV. Analysed beam was readily obtained with terminal voltages $\sim$ 100 kV, but the intensity is low at such energies since the dominant beam component at the charge stripper is $H^0$. Scattering by the foil will also increase the beam loss there (Southon 1966), and loss of $H^-$ ions to $H^0$ in the negative ion tube may also be important if the tube pressure is high where the energy is low.

7.5. **Energy Loss and Energy Spread in Carbon Foils.**

Rossi (1952) discusses the question of energy loss by ionisation for heavy particles, and most of this discussion is based on Rossi's treatment.

The following expression, based on the work of Bethe (1930, 1932) enables one to calculate the average energy loss

$$- \frac{dE}{dx} = \frac{2C m_0 c^2}{\beta^2} \left[ \log \frac{4m_0^2 c^4 \beta^4}{(1-\beta^2) I^2(z)} - 2\beta^2 \right]$$ 7.4.1

where $- \frac{dE}{dx}$ is the energy loss per g cm$^{-2}$, $C = 0.150$ Z/A and $I(z)$ is an average ionisation potential which has been calculated as 60 ev for the case of carbon. (Halpern 1948). This expression is based on a number of simplifying assumptions, not all of which can be adequately justified in this case. It assumes that the target atoms are independent, i.e. it neglects the screening effects of neighbouring atoms which have led several authors to attempt corrections to 7.4.1 for solid absorbers. 7.4.1 is actually the sum of two expressions for the energy loss due to
(1) distant collisions, in which the primary particle can be regarded as a point charge

(2) close collisions in which the atomic electrons can be regarded as free.

The dividing line between the two cases is taken as the case when the maximum energy that an ejected electron can have is \( y \), say. The close collision part is derived on the assumption that \( y \ll E'_m \), the maximum energy that an electron can be given by the primary particle in any collision. Now \( E'_m = 2m_0c^2 \frac{\beta^2}{1-\beta^2} \), and for the case of protons of \( \sim 500 \) MeV, \( E'_m \sim 1 \) MeV and \( y \) can be given a value between \( 10^4 \) and \( 10^5 \) eV. But for the case of protons (or \( \text{H}^- \) ions) of 1 MeV, \( E'_m = 2.16 \) keV only, so that if we take \( y \ll E'_m \), then \( y \) becomes of the same order as the K electron binding energy for carbon, so that these electrons cannot be regarded as free. Thus the part of 7.4.1 due to close collisions will be considerably in error here. At higher proton energies (e.g. 4 Mev where \( E'_m = 8.6 \) keV) 7.4.1 should be more accurate.

For the case considered above, viz. the \( \text{Al}^{27}(p,\gamma)\text{Si}^{28} \) resonance at 1338.6 keV, the \( \text{H}^- \) energy at the stripper foil is \( \sim 650 \) keV, and substituting the appropriate values into 7.4.1 we find,

\[
-\frac{dE}{dx} = 3.1 \times 10^5 \text{ keV cm}^2 \text{ g}^{-1}
\]

For the foil inserted in front of the target \( E_p = 1.34 \) MeV

\[
-\frac{dE}{dx} = 2.1 \times 10^5 \text{ keV cm}^2 \text{ g}^{-1}
\]

Thus the 1.5 keV energy loss referred to in section 7.4 corresponds to a foil thickness of about \( 7 \mu \text{g cm}^{-2} \), and a similar foil
Fig. 7.5.1. Energy straggling in 7 μg/m² cm² carbon foil.
at the stripper would account for 2.2 keV energy loss there.

Rossi also discusses the solution of the problem of the energy distribution of heavy particles passing through thin absorbers obtained by Symon (1948). Applying Symon's method to the case of protons in carbon foils 7 \( \mu \)g cm\(^{-2}\) thick, one arrives at the energy distribution curves given in fig. 7.5.1. The energy spread due to stripper foils of this thickness is clearly quite acceptable for \( H^- \) energies in excess of 2 MeV at the terminal, but could be embarrassingly large for high resolution experiments requiring final proton energies of less than 3 MeV. Symon's theory does not apply strictly to very thin absorbers, since it ignores fluctuations due to distant collisions in which electrons cannot be treated as free. Inclusion of all the effects which conspire to make this problem so intractable could probably only be carried out in a Monte Carlo calculation similar to that used by Costello (1964) in explaining the Lewis peak observed in the yield of gamma rays from a thick target just above a resonance.

The only way in which energy inhomogeneity in the beam can be reduced at low energies is by closing the analysing magnet slits so that the magnet becomes a true analyser. This, of course, can only be achieved at considerable loss of intensity, since, for example, energy resolution of \( \frac{\Delta E}{E} = 10^{-4} \) requires slit widths of \( \approx 5 \times 10^{-3} \) inch compared with \( \approx 8 \times 10^{-2} \) inch generally used, so that one might expect a reduction in intensity of a factor of ten.

Even with straggling in the stripper foil, the over-all energy spread cannot be regarded as unduly high, as most tandems achieve terminal voltage stabilities of \( \pm 1 \) kV and have \( \approx 500 \) eV energy
spread in their ion sources, so that the final energy spread is usually \( \sim 4 \) keV. There seems no reason to doubt that the energy spread in AURA II is \(< 500\) eV for \( E \geq 5 \) MeV, but this has not been demonstrated.

7.6. **Early Energy Measurements.**

The \((p, \gamma)\) resonances referred to in the last section established an energy scale at very low energies. A neutron threshold measurement, using the well known \( \text{Li}^7(p,n)\text{Be}^7 \) reaction gave another point at 1.8806 MeV (Marion 1966). On the basis of these measurements an approximate magnet energy calibration factor was worked out, and the value chosen was \( k = 0.404 \) in the expression for the proton beam energy

\[
E = k \left( \frac{f}{80 \times 10^{-5}} \right)^2 \text{MeV}
\]

where \( f \) is the frequency of a proton resonance measured in the NMR fluxmeter. The number in brackets is that actually read on a digital frequency meter, which is preceded by a fast scale of 4 and a 20x divider.

On the basis of these measurements, it was at once obvious that the previous estimates of terminal voltage had been wildly optimistic. The figure originally used was \( 27 \mu\text{A/MV} \) for the column resistors, based on the resistance of each of the 76 resistor "sticks" measured at 30 kV. A better figure was found to be about \( 31 \mu\text{A/MV} \). Hence it appears that the earlier voltage estimates were \( \sim 15\% \) too high, and it is possible that the same is true of the results obtained by the N.I.R.N.S. team at Harwell.

Although a great deal of development work remained to be done
after the energy spread measurements were completed, the accelerator had reached a stage where it could be used for nuclear physics experiments. One aspect urgently in need of improvement was the reliability. A total of about 600 hours' operation had been completed since the generator was assembled—as measured by an hour-clock which starts and stops with the belt drive motors. The only way in which reliability can be either demonstrated or improved is by running the machine for many hours, and eliminating short-comings as they show up. The question is discussed in Appendix C, but it was thought that the necessary hours of running could best be accumulated while the machine was being used for nuclear physics research, so the strictly developmental part of the machine's history can be regarded as finishing at this time (~ middle of 1967.)
8.1. **Introduction.**

For many nuclear physics experiments it is necessary that the energy of the bombarding particles be accurately known. There are many difficulties in making absolute energy measurements in the range of interest here, so that in most laboratories relative calibrations in terms of threshold or resonance energies for nuclear reactions are used. The accuracy and consistency of such measurements has improved so much in recent years that there is good agreement among those using absolute methods of measurement as to the energy values to be ascribed to these calibration energies. Comprehensive reviews of this improving art have been prepared periodically by Marion (1961, 1964, 1966) who is of the opinion that there is now little likelihood of there being any significant change in the values assigned to the most important points in the range up to a few Mev.

In view of the energy spread associated with the stripper foils discussed in section 6.4, there is little point in attempting to achieve the high precision that has been demonstrated by Donhowe (1967) using a single stage accelerator at Wisconsin, much technical ingenuity was invoked to minimise target problems so that resonance widths of a few tens of ev could be measured. The order of precision sought here has been about 1-2 keV in energy, i.e. about the same as the beam energy spread. It is not intended that the energy calibration measurements
described here should be regarded as final, as they are known to be considerably short of what can be fairly readily achieved, particularly with regard to target preparation, and it is intended to extend and improve the measurements as opportunities occur.

8.2. The Energy Reference.

Neither of the two obvious methods of measuring terminal voltage is capable of the accuracy required for the energy calibration. Generating voltmeters are affected by corona currents, mechanical instability both of their own parts and of the high voltage generator, and radiation-induced currents in the insulating gas (Turner 1955, Enge 1964b). High voltage resistor chains are also limited by leakage through various parallel leakage paths, and by radiation damage to the resistors in extreme cases, but mostly by the prodigious capital cost of a resistor chain having the required stability.

Since it is possible to measure magnetic fields accurately with fairly simple instruments, the use of an "analysing" magnet as the energy reference has become almost universal for accelerators of this type. The point has already been made in section 7.3 that magnets so used are not momentum analysers, but rather energy references, since the feedback system of the terminal voltage stabiliser adjusts the terminal potential to keep the beam in the centre of the image slit jaws, and the beam energy homogeneity may easily be an order of magnitude better than the spread which would be passed by the magnet and slit system in the absence of precise voltage control. A proton magnetic resonance fluxmeter was constructed for the magnet by R.W. Noble
under the supervision of Prof. E.R. Collins, and this has proved an extremely stable and reliable instrument. The stability of the magnetic field at the fluxmeter has been found to be considerably better than $10^{-4}$ after an hour's warm-up, and in fact the short term stability is sometimes close to $10^{-5}$, if there are no large transients in the mains supply. The magnet is current stabilised only, using a motor-generator set with series control transistors and a 'follow-up' circuit working through the generator field to limit the power dissipation needed in the control transistors.

If $B(s)$ is the value of the magnetic field over the beam path $s$, and $B(s)$ is assumed constant over the transverse dimensions of the beam, then the important quantity in determining the nett deflection of the beam is $G = \int B \, ds$, say, where the integral is to be evaluated over the whole of the path between entrance and exit slits. In practice, the induction becomes negligible about 8 inches beyond the pole boundaries, and the main contribution to $G$ comes from the region of uniform field in the magnet gap. It is usually assumed that the induction in the gap is the same as $B_p$, the value at the NMR probe position, but of course this is not necessary as no absolute energy measurements are to be made. The object of the calibration is to determine the value of the quasi-constant, $k$, in the expression

$$E = k f^2$$

where $f$ is the frequency of the proton resonance. This amounts to finding the relationship between $G$ and $B_p$ above.

The optical properties of the magnet have been investigated by Dzedins (1968) and the field stability was shown by Gummer (1967) to be adequate. Some important effects, such as differential
Fig. 8.4.1: Neutron Threshold at 4.234 MeV

\[ E_n = 4.234 \text{ MeV} \]

\[ N^{2}/N_{19} \text{ (p,n) } N_{19} \]

N = Neutron counts - background / \( N_{19} \) Coulomb

\( (\text{p,n) } N_{19} \)
hysteresis and beam position stability, will be discussed after the results of the calibration measurements.

8.3. Calibration Reactions.

The reactions selected from Marion's 1966 review, and the calibration energies associated with them are

\[
\begin{align*}
C^{13}(p, \rightarrow) N^{14}, & \quad 1747.6 \pm 0.9 \text{ keV} \\
Li^{7}(p,n) Be^{7}, & \quad 1880.6 \pm 0.7 \text{ keV} \\
C^{13}(p,n) N^{13}, & \quad 3235.7 \pm 0.7 \text{ keV} \\
F^{19}(p,n) Ne^{19}, & \quad 4234.3 \pm 0.8 \text{ keV} \\
Al^{27}(p,n) Si^{27}, & \quad 5796.9 \pm 3.8 \text{ keV}.
\end{align*}
\]

The detector used for the neutron thresholds was a Li\(^6\) and ZnS loaded plastic scintillator (NE421) mounted on a 10-stage 2 inch photomultiplier. The gamma efficiency of this detector is extremely low, so that the background rate was essentially zero below the lithium threshold, and even for some of the higher energies was still below the neutron rate a few kev above threshold. Thick, or semi-thick targets were used for all measurements, and a long, liquid nitrogen-cooled trap was used in front of the target to reduce the rate of build-up of surface films on the front face. It was not possible to detect the presence of such films during the course of the measurements. Only the C\(^{13}\) target was purchased commercially and this was the only isotopically enriched target used.

The gamma detector was a 4" x 3" Na I crystal. In all cases the detector (n or \(\gamma\)) was placed close to the target at 0\(^\circ\) to the proton beam. The efficiency of the neutron detector was somewhat
Fig. 8.4.2. Neutron Threshold at 5.797 MeV

$E_{th} = 5.796.9$ MeV

$^7_{Li}(p,n) ^7_{Li}$
increased by placing a small thickness (~1 cm) of moderator between it and the target as the laboratory energy of the neutrons at threshold is greater than 7 kev for all the reactions used.

For neutron thresholds, the procedure of extrapolating the \((\text{yield})^{3/2}\) vs. energy curve to zero yield is used to determine the calibration point, which, as Marion points out, is not necessarily the best value for the neutron threshold. The gamma resonance energy is taken as the energy where the yield is half the thick target yield, i.e. half the yield at energies above the Lewis peak, if this is observed. Both these procedures are those recommended by Marion as most suited to establishing an energy scale which can be confirmed at any laboratory where proton beams of good energy resolution are available.

8.4. Results.

Figs. 8.4.1 and 8.4.2 show the \((\text{yield})^{3/2}\) vs NMR frequency curves for the \(F^{19}(p,n) Ne^{19}\) and \(Al^{27}(p,n) Li^{27}\) reactions. The values ascribed to the constant \(k\) of the last section are shown in the table below.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Energy (kev)</th>
<th>(f/80)</th>
<th>(B(\text{k gauss}))</th>
<th>(k \times 10^{12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C^{13}(p,)N^{14})</td>
<td>1747.6 \pm 0.9</td>
<td>207660</td>
<td>3.9</td>
<td>40526 \pm 13</td>
</tr>
<tr>
<td>(Li^{7}(p,n)Be^{7})</td>
<td>1880.6 \pm .07</td>
<td>215465</td>
<td>4.05</td>
<td>40528 \pm 13</td>
</tr>
<tr>
<td>(C^{13}(p,n)N^{13})</td>
<td>3235.7 \pm 0.7</td>
<td>282700</td>
<td>5.5</td>
<td>40487 \pm 13</td>
</tr>
<tr>
<td>(F^{19}(p,n)Ne^{19})</td>
<td>4234.3 \pm 0.8</td>
<td>323740</td>
<td>6.1</td>
<td>40400 \pm 40</td>
</tr>
<tr>
<td>(Al^{27}(p,n)Si^{27})</td>
<td>5796.9 \pm 3.8</td>
<td>379240</td>
<td>7.1</td>
<td>40306 \pm 50</td>
</tr>
</tbody>
</table>
The number and accuracy of the calibration points are not sufficient for the shape of the calibration curve to be decided with certainty, but there is some indication that the effects of magnet saturation are becoming apparent even at about 9 k gauss. Dzedins (1968) shows how the "sharp cut-off" hypothesis field boundaries (Engs 1964c) recede as the gap induction is raised, in other words how the effective length of the magnetic field is reduced by saturation of the pole edges at entrance and exit. Unfortunately for their strict applicability to the present measurements, Dzedins measurements were taken only at 7 k gauss and at 14 k gauss, and were carried out before the pole tips were modified as mentioned in section 6.4. Nevertheless his results are interesting in that they give a guide to the magnitude of the effect which must be anticipated if it is necessary to use the magnet near its maximum rated induction of 14 k gauss. The apparent shift in the sharp cut-off boundaries amounts to about 0.15 inch at each end of the magnet. Thus there is a total reduction in effective field length of 0.3 inches in a path length of about 30 inches, i.e. a 1% reduction in the value of \( G = \int B \, ds \). To deflect particles of maximum magnetic rigidity would thus require a measured value of \( B_p \) too high, or a 2% error in \( E \) based on linear extrapolation. The main contribution to this effect will occur near \( B = 14 \) k gauss, but it is certainly not unreasonable to expect an effect about one tenth as large in the region already examined. It is possible that there may be some unintentional compensation for this effect because the flux meter probe is situated rather close to the edge of the pole gap, so that the induction measured there may be slightly less than the mid-gap induction.
when the iron is close to saturation.

It is perhaps of interest to note that the effective radius of curvature of the magnet, calculated assuming that \( B_p \) induction, is 19.20 in. This is to be compared with the "best" value of 19.23 in. suggested by Dzedins on the basis of measurements performed before the pole pieces were modified (as described in section 6.4) and with 19.0 ins, which is the manufacturer's design figure.

8.5. **Differential Hysteresis.**

In an iron-cored magnet, the induction in the gap is not a single-valued function of the magnetising force, due to the well-known phenomenon of hysteresis in the iron. The magnitude of the hysteresis effects depends quite strongly on a number of variables, in particular on the temperature and composition of the iron. The latter may vary significantly from place to place in a magnet such as this, where the poles and yokes are cast. There is thus the possibility that the value of the integral \( G \) may not bear a constant relationship to the value of \( B_p \) even at a particular value of \( B \), but may depend on the previous magnetisation history. Some tests were carried out in an attempt to ascertain the significance of such effects, using the lithium neutron threshold as reference energy, with results shown in fig. 8.5. The points lying on the line labelled 1 were taken in the usual way, i.e. the magnet current was set to the required value with no particular care or thought, although the field was left at about the right value for about an hour before the measurements were taken. Run 2 was taken after the magnet field had been taken up to about 12 k
FIG. 8.5. DIFFERENTIAL HYSTERESIS IN ANALYZING MAGNET

\[ \frac{f}{(\text{NMR} / \text{Hz})} \]

1 KeV

1.88 GeV

\[ N = \text{Neutron counts} / 500 / \text{C - background} \]
gauss and left there for three minutes, after which the current was reduced to produce the appropriate field strength and the results taken immediately. It is perhaps worth remarking that the magnet current supply reference potential is derived from a potentiometer comprising 5 decade resistor boxes, and that the stabiliser produces large overshoots with a period of about three seconds, thus producing a small sequence of converging hysteresis loops and possibly minimising the effects under discussion. Nevertheless, the shift between lines 1 and 2 is considerable. The magnet current was next reduced to 0.6 amps for ten minutes, then increased to 4 amps again, and the results labelled 3 were obtained. After this, the gap induction was raised to 13 k gauss for five minutes, then reduced to about 500 gauss for ten minutes, increased to 3 k gauss for 5 minutes, immediately after which the results lying on line 4 were recorded, and it will be seen that the threshold value is not different from that obtained with the previous set. A rather similar treatment was meted out before the results on line 5 viz. 16 amps (13.7 k gauss) for 5 minutes, 2 amps for 3 minutes and then up to 4 amps again. It will be seen that serious (i.e. >1 kev) errors can be induced only by quite drastic treatment of the magnet immediately before the required field value is set, and that, for most purposes, adequate accuracy can be obtained simply by approaching the required setting from below, or perhaps leaving the magnet running for 10 to 20 minutes near this setting if higher precision is needed. No shifts in the apparent energy of the threshold resulted from small magnet current changes immediately prior to doing the measurements.

The dispersion of the magnet is related to beam energy changes by

\[ x = 1.3 \frac{\Delta E}{E} \text{ metres, where } x \text{ is the beam movement across the image slit jaws.} \]

The magnification between the slits is 1.60, so that a change in beam position of 1.3 mm. at the image slit corresponds to a change of 0.8 mm. at the upper slit, and such a movement would have the same effect on the terminal voltage stabiliser as an energy change of \(10^{-3}\). It is therefore necessary that the beam should be centred accurately on the object slits to obtain precise calibration data, and some of the earlier results (e.g. the lithium neutron thresholds of fig. 8.5) were in error because the object slit jaws were set so wide that no beam current was intercepted by the jaws, and hence it was not possible to ensure that the beam was correctly centred there. The settings of the triplet 4-pole lens are quite critical, since it is easy with this lens, as with any other 4-pole, to obtain a badly distorted image if the relative strengths of the two parts of the lens are not correct. No steering is provided to move the beam across the object slit, as it has always been possible to obtain equal current on the slit jaws by correct adjustment of the lenses and magnets. Most of the beam current can usually be passed through object slits set at \(0.080\) in. for \(E_p > 2\) Mev, so that if the slit is set to this width, a considerable reduction in target current will result from a beam displacement of 0.5 mm. Hence the usual procedure of optimising the target current will ensure that the beam is correctly placed at the target entrance, except when the highest
accuracy is needed.

Since the entrance and exit slits are in conjugate planes, small variations in the angle at which the beam passes through the object slit do not affect the image position, so that although it may be possible to achieve slight deviations in this direction by judicious misadjustment of source and terminal magnets, there is no danger that such misadjustments will result in apparent energy changes provided, of course, that the beam remains centred on the object slit. Such effects could only be produced if the median plane of the analysing magnet is parallel to the planes of the other magnets, and for reasons mentioned in section 6.6 it is not expected that the energy homogeneity would be as high in this orientation as it is when the analyser is perpendicular to the other magnets. No measurements have been made to determine the extent of this defect, although it is intended to confirm that no serious change in the calibration occurs when the magnet is rotated.

8.7. Proposed Improvements.

It is proposed to repeat the measurements soon with targets evaporated in situ in the case of lithium, fluorine and aluminium, and also to extend the calibration to higher energies by threshold measurements on the $^3$H(p,n) $^3$He and Ni $^{60}$ (p,n) Cu $^{60}$ reactions at 6.451 and 7.024 Mev. Since some calibration of deuteron energies will probably be required soon it is intended to compare the magnetic rigidity of the deuteron beam with that of alpha particles, from sources whose energies are well known, in the split-pole spectrograph recently installed in the laboratory. (Müller.) The same method will probably be used as
a check on the proton calibration, although it is doubtful if the accuracy will be as high as that which can be obtained using neutron thresholds and resonances, except perhaps at low energies.

Data collection will be facilitated for excitation measurements over a small range by using a "staircase generator" to apply a voltage variation of 10 kV to the target, in steps of about 80 volts, the staircase being synchronised with the x analogue voltage of a multi-channel analyser operated in a multi-scaler mode. If the detector counts are fed into the multi-scaler input, then the excitation function is plotted automatically. The detailed shape of sharp resonances can probably be obtained more accurately by this method than by the more usual method of varying the analysing magnet current, as the latter method is subject to the effects of differential hysteresis. Also, since the period of the staircase wave-form can be varied at will between 1ms and 100 seconds, short-term energy fluctuations in the beam, if there are any, could in principle be averaged out. The staircase generator was constructed by C.R. Young in the laboratory. It has already been used in some calibration checks, and shown to give the same threshold energies as obtained by the other method.
CHAPTER 9.

PERFORMANCE AND FUTURE DEVELOPMENT.


Apart from the important question of reliability, which is discussed in Appendix C, the only aspects of performance that are of interest are maximum energy, and beam current and optical quality at the target. The maximum energy that has been attained at the time of writing is 7.3 Mev, but as this did not represent a serious attempt at achieving a high energy, there is good reason to believe that it will be possible to reach 8 Mev with the terminal cover, corona rings, and charging belt in better condition than they were on that occasion. The terminal cover, being made of aluminium alloy is much more easily damaged than a stainless steel one would be, and considerable effort is needed to remove from its surface scratches which may limit the terminal voltage.

It was hoped that it would be possible to reach higher energies, but for reasons mentioned in section 7.5 it is possible that these hopes were based on optimistic figures pertaining to earlier voltage tests. Assuming that it will be possible to operate the machine with 4 MV on the terminal, the tube gradient will be about 570 kV per foot, which is much the same as that reached in most commercially constructed ion accelerators of more than 2 Mev. If there is a definite need for higher energies then the intershield will be fitted to the high voltage column again if terminal-to-tank or terminal-to-liner sparks are the
limiting factor. This electrode has not been used since the accelerator was completed, as its use makes access to the terminal more difficult, and might possibly lead to overheating in the terminal.

Beam current performance has been reasonably satisfactory considering the rather poor optical quality of the beam from the charge exchange negative ion source. There was a period of some months when target currents were often low due to incorrect adjustment of the matching and tube entrance lenses. If the matching lens is too strong, then a cross-over may be formed between these two lenses, and the entrance lens strength will have to be increased to focus the beam through the terminal magnet. The facet lens effects at these two gridded lenses will be increased, and the optical quality of the beam diminished. Under these conditions the lowest slotted electrodes of the negative ion acceleration tube may intercept some of the beam.

Unfortunately, there is an optimum setting for the two lens strengths when this extra crossover is formed, which is why the error was perpetrated for so long. About one microamp. of beam current is usually available at the target, except, of course, when very small collimators are used. It is anticipated that when the duo-plasmatron ion source is installed, an increase of about a factor of 10 should be obtained, provided that no difficulty is experienced with stripper foil life at the higher currents. Considerable improvements in foil making techniques have recently been achieved in the laboratory by M.J. Keeling, who now evaporates sucrose onto the microscope slides rather than coating them with sugar solution or detergent, as was done previously. Besides obviating the difficulties which were previously
FIG. 8.1. BEAM PROFILE BEYOND IMAGE SLIT
caused by dust particles, the new method has the advantage of giving a foil containing fewer contaminating elements than those evaporated onto detergent, and this can be a decided advantage when the foils are used as target backings.

Although no proper measurements of beam emittance have been made, the size of the beam waists at the analysing magnet slits and at targets has generally been much as expected.

Only one measurement of the beam quality after the analysing magnet has been made. A wire scanner was used, to give the intensity distribution in the vertical plane shown in fig. 9.1, about 1.9 m. beyond the analysing magnet image slit, which was set at 2.5 mm full width. The maximum half-angle in the beam is therefore

\[ y' = \frac{16 + 2.5}{2 \times 1.9} \times 10^{-3} \text{ radian} \]

i.e. \[ y' = 5 \times 10^{-3} \text{ radian} \]

These figures give a smaller emittance than that shown in fig. 3.6.5, for which the most likely explanation is that the output of the positive ion source does not "blanket" the donor canal, and hence the emittance of the input beam is smaller than that shown in fig. 3.6.4.

The energy stabilisation has always worked well, as also has the terminal magnet current supply, and no difficulty from beam movement due to the action of the inclined field tube has been experienced. The machine has not been in operation for long enough to assess whether or not the tubes will have a satisfactory life, and although there is not as yet any indication of deteriorating
FIG. 9.2. DIRECT-EXTRACTION NEGATIVE ION SOURCE
performance, the negative ion tube shows considerably more
discoloration than does the positive ion tube, probably due to the
effects of electrons from the grid at the tube entrance, as much of
the discoloration is localised near the lowest slotted electrodes,
where such electrons are presumed to come to rest. With approximately
1900 hours of tube operation completed, at least it can be said that
the life of these expensive components is not catastrophically short!

9.2. **Ion Sources.**

It seems likely that most of the development for some time will
centre around new ion sources. The direct-extraction negative
hydrogen ion source mentioned in section 4.1 has been bench-tested and
shown to produce a beam of 20 μA of H⁻ into a very much smaller
emittance than the charge exchange source. Fig. 9.2 shows this source
as it will appear when coupled to the existing source analysing magnet.
The source head is a direct copy of a commercially manufactured version
of the duo-plasmatron. The source will probably be installed before
the end of 1968.

Work has been proceeding on the polarised negative ion source
(Gravish 1968) for some time, and it is expected that this source will
be completed in 1969.

There will probably be some interest in experiments using He³
and He⁴ beams soon, and since useful quantities of the metastable
negative helium ions can now be produced by charge exchange in alkali
metals, (Ennis 1967, F.A. Rose 1967, John 1967) a He⁻ source may be
constructed within the next year or two. The problem of injecting
the proposed He beam into the machine has not yet received any attention, although provision has been made for an easy change-over between the unpolarised and polarised hydrogen ion sources by injecting the polarised beam up through the source analysing magnet as shown in fig. 9.2.

9.3. Target Stations.

The ground floor plan of the laboratory, with existing and proposed target stations is shown in fig. 9.3. Some experimental work has been carried out using a small scattering chamber which can be bolted to the analysing magnet image slit box (Willey). To expedite changing target stations, another permanent magnet quadrupole lens has been ordered. At present considerable delay is incurred if the lens has to be moved from one beam line to another, and re-aligned each time it is moved. A 30 inch diameter scattering chamber of versatile design is nearing completion in the departmental workshops, and should be ready for use early in 1969. Preliminary measurements on the 60 cm. split-pole spectrograph should soon be completed, and it is expected that this powerful instrument will be available for experimental work in a few months' time.
FIG. A.1. AURA II TANDEM ACCELERATOR
APPENDIX A.

ENGINEERING ASPECTS OF THE ACCELERATOR.

Introduction:

Although the accelerator is fairly conventional in most respects other than those discussed in the text, some mention is made of various engineering problems encountered, largely to indicate the scope of the work done in Auckland. The generator arrived at the laboratory in a completely disassembled state. Sufficient extra components were obtained to enable the generator column to be rebuilt with an extra 12 column planes, resulting in a column length of 85 inches. The pressure vessel had been placed on its supporting floor by a mobile crane, access being gained through the removable end wall of the laboratory. When the author started working on the project, the vessel was not in its correct position. It was moved under the 10 ton crane (normally used for removing the 9.5 ton "lid" of the vessel) by outside contractors. The 5-ton base of the pressure vessel was then placed on its mounting pads and levelled to within ± .005 in. across the base plate.

A.1. Mechanical.

The supporting structure for the earth plate (see fig. A.1.) was modified to allow for the increased length of the generator column, and to permit the use of a very much less expensive belt drive motor arrangement than the inverted motor contained in the belt pulley which
had been used previously. Since this was not available, it was decided to use two three-phase 10 H.P. 2850 r.p.m. motors instead, for a cost of rather less than one tenth that of the inverted type of motor. The driving-end ball-races were replaced by roller races in the interests of long life with the fairly high radial loads created by belt tension. The motor shafts are keyed directly to flanges which are bolted to the driving pulley, a 24 inch length of 8 inch diameter steel bar, tapered slightly at the ends to ensure proper tracking of the belt. Separate star-delta starters are used for each motor so that the pulley speed can be increased gradually, thus avoiding excessive differential tension between the up and down-runs of the belt, which can occur when the moments of inertia of driven machinery in the terminal are fairly high, as is the case here. In extreme cases belt slip can cause serious damage to the belt. There is little danger in this case, however, as the driving pulley weighs 350 pounds. The heavy pulley also serves to reduce the load on the motor bearings due to belt tension which is usually maintained at about 600 - 700 pounds weight on each run of the belt, in the interests of reducing belt flap. Thus there is an upward force of 1200 - 1400 pounds on the pulley from belt tension. Some 700 pounds of this is supplied by the weight of the drive motors, pulley, and mounting beam, the remainder coming from four springs as shown in fig. A.2. The radial load on the driving-end bearings is thus about 500 pounds. One of the square steel bars transmitting the spring force to the mounting beam is bolted directly to the beam, but the other makes contact via a steel ball interposed between the bar and the beam, so
FIG. A.3. HIGH VOLTAGE COLUMN CONSTRUCTION
that no wracking stresses can be induced in the beam by the mounting. Thus the angular position of the motor assembly is determined by the relative compressions of the two springs at one end. Since the belt-charging screen and back-plate are also mounted on the motor assembly, this adjustment determines the pressure between belt and back-plate, which must be sufficient to ensure that the belt does not "bounce" off the back-plate, thus causing the charging screen to vibrate excessively and hence come to an untimely end from undue fatigue. A six-inch range of vertical adjustment allows for the considerable stretch which occurs in the 252 inch-long belt, which is 20 inches wide, and of continuous five-ply construction. It is made of rubber-impregnated cotton. Belt speed is one hundred feet per second.

The generator column structure comprises 75 cast aluminium equi-potential plates, spaced 1.09 inches apart by three insulators between each pair of plates. Each insulator assembly consists of a glass block cemented to a stainless steel flange at either end by polyvinyl-acetate cement. Brass plugs threaded into the steel flanges are used to join the insulator assemblies together, as shown in fig. A.3. The whole structure is prodigiously complicated but does have the advantage that each insulator is well protected electrically. The terminal plate essentially rests on the three glass-stainless steel-aluminium columns. There are slight variations in the lengths of the insulator assemblies and in the thicknesses of the plates, these variations being compensated for by periodic shimming to maintain the equi-potential plates horizontal during assembly. Many of the glued joints failed during assembly, and although a large number was repaired,
further joints failed later and these were not all repaired, thus pointing to one of the great advantages of a vertical machine. The lateral stiffness of the column was measured and found to be far below the calculated value. However, when the top plate was loaded with 3000 pounds of concrete, the stiffness more nearly approached the calculated figure, a deflection of $3.5 \times 10^{-3}$ inches being observed with a transverse force of 50 pounds weight. The longitudinal stiffness was about as expected after pre-loading of 1000 pounds had taken up some of the spurious deflection due to poor joints in the insulator assemblies. It was concluded that the column structure was satisfactory mechanically in view of the fact that the static compression on the column was expected to be about 9000 pounds weight.

The pulley in the high voltage terminal was extensively modified, and new supports were made so that it could be mounted close to the terminal plate, thus making more room available for the terminal magnet and its power supply. Both belt pulleys were dynamically balanced in the laboratory. Provision was made for V-belt drives from the belt pulley to the 200 amp. generator used to supply current to the terminal magnet, a motor-car alternator which supplies generator field current and 320 c.p.s. 3 phase A.C. for the magnet current stabilising circuits, and a centrifugal blower which is used to circulate insulating gas through the magnet current generator and onto the down run of the charging belt. A water-cooled heat exchanger is mounted just below the level of the earth plane, in a position where a good draught is created by the moving belt. This removes about half the total heat from the machine, the remainder escaping through the
tank walls.

Of the available driving power, about 7 H.P. is used in overcoming belt windage, while the D.C. generator (which compensates for its notable compactness by its very low efficiency!) needs almost 7 H.P. at 3 kW output. The alternator, blower, and charging power amount to another 3 H.P. so that there is a good reserve of power, particularly as the motors can quite safely be run at considerably above their atmospheric pressure rating due to the increased cooling effectiveness of the high pressure insulating gas.

Since it is difficult to maintain high accuracy in a structure like the high voltage column, it is desirable that such important components as acceleration tubes and the terminal magnet should be provided with adjusting screws to facilitate the initial alignment. This in turn implies that some flexibility is required in the vacuum plumbing, and this is provided here by four stainless steel bellows, located as shown in Fig. A.1. Lateral adjustments only are provided at the upper ends of the acceleration tubes, and both lateral and axial adjustments at the lower ends. The bellows have an effective cross-sectional area of 14.62 in\(^2\) so that, at a working pressure of 200 p.s.i. in the pressure vessel, a compressive force of almost 3000 pounds occurs across each bellows. In this case the load is transferred from the top flange of the upper two bellows to the 180° magnet, by means of two substantial bridge pieces and four studs on each side. The total load on the magnet supports is therefore about 6000 pounds + magnet weight of 1800 pounds. In order that the change in loading with tank pressure should not produce changes in the magnet position,
FIG. A.4. GAS HANDLING SYSTEM
its three support legs have cross-sectional areas proportional to the load they bear, and their "feet" are planted firmly over the tops of the glass columns. The supports for the terminal pulley shaft are also brought close to the same points for similar reasons.

A.2. Gas Handling.

A full charge of insulating gas is 620 cu. ft, the mixture used being the almost standard 80% N₂ and 20% CO₂ by weight. There is no evidence that the mixture is at all critical, but much evidence that more effective insulation can be provided by other gases at much lower pressures e.g. SF₆ at about 70 p.s.i. seems as effective as N₂ + CO₂ at 200 p.s.i. (Ashbaugh 1965). Most of the other gases (and especially SF₆) are more expensive, and some have toxic or corrosive products of decomposition which occurs in strong electric fields or, of course, during high voltage discharges. (Charpentier 1964). Since one fill of N₂ and CO₂ costs $160, it was decided to install a storage and transfer system in the interests of long-term economy. Most of the installation was carried out by a contractor. Two cylindrical vessels each having a capacity of 360 cu. ft. are mounted horizontally high up in the laboratory, and connected by two inch steel pipe through a series of valves to the 7.5 H.P. compressor which is used to move the gas either from the accelerator pressure vessel to storage or vice versa. The "circuit diagram" is shown in fig. A.4. Molecular sieve material is used as the gas drying agent in each of the two drier vessels. It can be effectively regenerated by gentle heating and pumping with the rotary pump to about 0.1 torr pressure. The material
selected also absorbs some CO₂ so no doubt the concentration of CO₂ will fall with repeated drying.

When the machine has been open to the atmosphere for a few hours, a considerable quantity of water is absorbed and adsorbed. Most of it can be removed by prolonged evacuation of the vessel after re-assembly, a pressure of about 0.2 to 0.3 torr usually being attainable after 50 or 60 hours' pumping if the pump's gas ballast facility is used judiciously. The compressor is usually used to reduce the pressure to about 1 atmosphere before switching over to the rotary pump. If the cooling water for the after-cooler is not turned on while the compressor is so used, most of the moisture collected in the after-cooler will be blown into the air, thus obviating the necessity for frequent draining. Even after this long pump-down there is usually sufficient water left in the charging belt to make the gas wet once the belt warms up, so that it is necessary to circulate the gas through the driers, using the small diaphragm pump mounted in the base of the pressure vessel. When the gas is sufficiently dry, its dew point is less than -50°C, which represents a concentration of about 4 x 10⁻⁵ parts of water vapour by volume. The charge of sieve material in each drier is 700 gms, and generally the gas can be made dry enough by passing it through one drier for a few hours, and then changing to the other drier for another hour or two. Charging belts can be irreparably damaged by operating the generator at high voltage before the belt has been properly dried.
All figures are conductances (26) or speeds in litre sec\(^{-1}\) for air.

[00] conductance between lettered points.

(00) nett pumping speeds [30]

Acceleration tubes

Quadrupole lens pipe

Liquid nitrogen-cooled trap

Refrigerated baffles

3in. diffusion pumps

To 7 litre/sec rotary pumps

↓ To 80 L/sec mercury diffusion pump.

**Fig. A.5. Vacuum System Conductances.**
A.3. Vacuum.

An advantage of the single-ended tandem configuration is that the ground-potential ends of the two acceleration tubes are close together, so that a single high vacuum pump can be used for both tubes, provided of course, that the conductance of the connecting lines is sufficiently high. Despite the fact that various gettering and sputtering pumps are now preferred for many vacuum installations, their use on low-energy accelerators is not yet very widespread, and it was thought advisable to use the well-tried mercury diffusion pumps for this machine.

A 9 inch mercury pump, having a speed of 500 liters per second above its refrigerated baffle and liquid nitrogen-cooled trap, pumps the main vacuum system from the negative ion tube side. The important conductances are shown in fig. A.5. The fact that the net pumping speed available below the positive ion tube is a factor of 10 lower than that on the negative ion side is of little consequence, since the beam energy is high there and the cross-sections for beam loss are very small. Base pressure of the main vacuum system is about $5 \times 10^{-7}$ torr, rising to $\sim 5 \times 10^{-6}$ when the accelerator is running. The pressure beyond the analysing magnet is typically $2 \times 10^{-5}$ torr with about 20 feet of beam pipe in use. All vacuum plumbing is of stainless steel inside the pressure vessel, and aluminium or stainless steel outside, except for the three magnet deflection chambers which are of copper with brass end flanges. Inert gas welding was used on all stainless steel and aluminium fabrications, and hard solder used on copper-brass joints. All gaskets are neoprene O-rings. Standard flange and pipe
sizes are used for all fittings beyond the analysing magnet, the
standard being compatible with flanges used in the other accelerators
in the department, AURA I and LEDA.

Commissioning of the vacuum system was agreeably uneventful,
due mainly to the fact that a helium mass spectrometer leak detector
was available at all times for leak testing. Some trouble has been
experienced with the 9 inch mercury diffusion pump, which has refused
to pump on a few occasions, due, apparently, to the presence of an oily
layer near the top of the condenser, which inhibits proper condensation
of the mercury there. Crawley (1967) has pointed out that this is
most probably due to back-migration of oil vapour from the rotary pump
when it has been left roughing the high vacuum side for too long at
low pressure. It appears that pump oil will back-stream at a consid-
erable rate once the pressure falls below 0.1 torr, whereas collisions
with gas molecules limit the back-migration rate at higher pressures.
A molecular sieve absorption trap has been made and will probably be
installed in the backing line soon to prevent recurrence of the trouble,
although it is noticeable that the diffusion pump has been performing
well since the practice of prolonged roughing was discontinued.

A.4. Electrical.

In most respects the electrical design of the generator is
conventional. The electric field design is perhaps a little unusual
in a modern machine in that an intershield is provided to reduce the
field strength at the high voltage terminal. This is a very well
finished aluminium fabrication, 62 inches in diameter and 78 inches
FIG. A.6. BELT CHARGING SYSTEM
long. It was designed to produce equal field strengths at its surface and at the terminal electrode surface when fitted 34 column planes up from the base, with the original 64-plane column. When the column length was increased by 12 planes here, it was not considered worth while to increase the length of the intershield, so its mounting plate is still located 30 sections down from the top. Although this is not the ideal configuration, (Boag 1953) the task of modifying the intershield is a difficult one, particularly as a good finish is required on the inside as well as on the outside. The use of a poor intershield can result in worse performance than that obtained without such an electrode.

Although the intershield was used during early voltage tests on the generator, the accelerator has not been operated with it as yet, for a variety of reasons, but principally because the accelerator performance appears to have been limited as much by tube or belt sparking as by tank sparks.

The belt charging system used is shown in Fig. A.6., and uses a high voltage power supply on the back-plate which is not required to supply any current. This is a considerable advantage as a rather crude 3-stage multiplier operated at 50 Hz can be used for the 40 kV supply. The extra screen just ahead of the charging screen is intended to remove charge induced on the belt by the driving pulley. The charging system is discussed more fully by Gummer (1967.)

A.5. Controls and Metering.

A great deal of time and effort has been saved by keeping the
controls as simple as is compatible with reasonable operator
convenience. All controls necessary for changing the beam energy are
provided at the control desk, but most of the ion source controls are
near the source itself. There is no remote control of any vacuum
equipment or cooling circuits.

Controls at the operator's desk in the control room are:

(1) belt drive motors - start, stop.

(2) belt charging system - back-plate voltage on, off, - charging
current manual adjustment.

(3) ion source analysing magnet - current adjustment.

(4) ion source output Faraday cup - in, out.

(5) matching lens high voltage - on - off, adjust.

(6) entrance lens high voltage - on, off, adjust.

(7) terminal magnet current - increase, decrease.

(8) electro-magnetic quadrupole - motor-generator start, stop,
current adjust (x 2)

(9) positive ion beam viewer or current collector - in, out.

(10) analysing magnet - motor generator set-on, off, current adjust.

(11) nuclear magnetic resonance flux meter - all controls.

(12) stripper foil changer - advance.

(13) terminal voltage stabiliser - liner power supply on, off and
set D.C., gain controls for slit amplifiers, difference
amplifier, slow amplifier and fast amplifier.

(14) terminal gas leak rate - increase, decrease.

(15) permanent magnet quadrupole - strength (x2) azimuth (x2).
Controls 7, 12, 14 require insulating links between the base of the pressure vessel and the high voltage terminal. Perspex rods through the column planes are used for all three: (7) being attached to a 3-turn helical potentiometer in the terminal and driven by a geared motor at ground potential, (14) is attached to a variable auto-transformer in the terminal and (12) transmits a reciprocating motion derived from a crank on a geared motor.

All ion source controls are located near the source except for (3) above, which is not duplicated near the source. The ion source controls are, in addition to on-off switches - source gas, exchange gas, r.f. oscillator power, extraction voltage and exchange voltage. Having the exchange voltage control at the source, and the source analysing magnet current control at the control desk means that the source output beam can be centred on the magnet image slits from either position.

A pico-ammeter is available for measuring currents at various places, and another sensitive current meter built around a photocell-stabilised operational amplifier is built into the control rack to monitor (a) source output current (b) positive ion current above analysing magnet (c) and (d) outer and inner slit jaw currents at analysing magnet object slit and (e) target current. A beam current integrator is also available (Summer 1967). Separate meters are provided for the voltages and currents appropriate to items 2, 5, 6, 7, 10 & 11 above and also for analyser image slit currents, column resistor current and down-charge collector current.
FIG. A.7. HIGH VOLTAGE LEAD-THROUGH.
To minimise the risk of damage by high voltage discharges, an earthed screen of perforated aluminium sheet is mounted at the level of the earth plate. Prior to its installation some trouble had been experienced with break-down across some lead-through insulators. Some low-power lead-throughs were supplied with the generator, but those for the belt drive motors (12 x 40 amps, 400 volts), the quadrupole lens (4 x 150 amps) and two high voltage lead-throughs for the entrance lens and charging screen (40 kV) were designed and made here. The high voltage lead-through is shown in fig. A.7.
FIG. B.1. HIGH VOLTAGE TERMINAL ARRANGEMENT
APPENDIX B.

TERMINAL MAGNET.

The problem of accommodating the required magnet inside the high voltage cover had to be considered in conjunction with its power supply requirements and the mechanical restrictions mentioned in Appendix A. Once the decision to use a compact, ex-aircraft generator for the supply was made, there was virtually no freedom of choice in the disposition of the terminal components, which is as shown in fig. B.1.

To deflect a beam of 5 MeV deuterons (or other non-relativistic particles of 10 a.m.u. Mev) on a radius of 34.6 cm. requires

\[ B = 3.334 \rho^{-1} (2Mc^2 T + T^2)^{1/2} \]

\[ \approx 13.3 \text{ k gauss.} \]

Thus, for a magnet gap width of 1.5 cm. the number of ampere-turns required for the gap is

\[ NI(\text{Gap}) = \frac{Bg}{a_4 NI} = 1.58 \times 10^4 \text{ ampere turns} \]

Allowing 10% for the magneto-motive force required in the steel, which may be approaching saturation in parts,

\[ NI_{\text{TOTAL}} = 1.76 \times 10^4 \text{ amp. turns.} \]

For a gap width of 1.5 cm, a pole face width of about 6 cm, is the minimum that will give an acceptable region of uniform field near the design centre trajectory. The maximum width that could be achieved is almost 7 cm, which is adequate. Fig. B.2 shows a
FIG. B.2. MAGNET CROSS-SECTION
Fig. 8.3. Magnet Excitation

Gap induction (gauss x 10^3)

Magnet current (amps)
cross-section of the magnet. Each of the six coils contains 22 turns of 1" x 1/16" copper strip, insulated with paper and epoxy resin. Some difficulty was experienced during their manufacture in obtaining adequate insulation resistance between turns, probably because the large thermal capacity of the winding did not allow the heat of reaction of the resin to raise its temperature to a high enough value to cure properly. This was largely overcome by prolonged heating of the windings but even then the coils did not seem entirely satisfactory. They seem to have improved steadily with use, however, and have given no trouble whatsoever in service, probably due to their very favourable environment in a high pressure atmosphere of dry gas. An excitation curve, taken with a Hall probe fluxmeter which was calibrated against a proton magnetic resonance, is given in figure B.3.

Much thought was devoted to the best method of construction for the vacuum chamber, which has to withstand the insulating gas pressure, viz. 200 pounds in $^{-2}$. Stainless steels were ruled out because their ferro-magnetic properties, particularly after welding, are notoriously unpredictable. Aluminium alloys were considered and rejected because of the difficulty of obtaining good elastic properties in high tensile alloys after welding. Finally, after some preliminary measurements on deflections of a suitable section, it was decided to make the chamber from $\frac{1}{8}$ inch 16 gauge copper pipe, which was left hard after bending and flattening. Care was taken, in hard-soldering the end flanges onto the pipe, not to anneal the flattened portion. Since the flats are only about half an inch wide, the section is quite favourable for withstanding the external pressure.
Two T-section mounting legs this side.

Tilt adjustment

One rocking column support this side.

Bridge piece and studs transmitting bellows compression force to magnet.

Acceleration tube

Column insulators

**Fig. B.4. 180° Magnet Mounting Details**
The magnet is mounted on three legs as described in Appendix A and illustrated in fig. B.4. Two of the legs are of 2" x ½" T-section steel, and are fitted with screw adjustments to set the lateral position of the magnet. A "rocking column" of 1" round bar is the third support, and it is equipped with a screw jack to permit adjustment of the median plane inclination, this being the only tilt adjustment required.

The magnet was constructed entirely in the departmental workshops except for the yoke side-plates which were too large for the available machines, and the outer yoke, which was bent from the 2 inch plate on a 600 ton press. Low-carbon steel plate was imported from Australia, and its analysis is compared below with that of some other magnet steels, where the figures are parts per cent by weight.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>M₆₀</th>
<th>S</th>
<th>P</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>This magnet</td>
<td>.06</td>
<td>0.40</td>
<td>.05</td>
<td>.04</td>
<td>Lysachts Aust.</td>
</tr>
<tr>
<td>Cosmotron magnets</td>
<td>.08</td>
<td>0.50</td>
<td>.05</td>
<td>.04</td>
<td>SAE 1010</td>
</tr>
<tr>
<td>Lintoll Ltd., quadrupoles</td>
<td>.10</td>
<td>0.50</td>
<td>.04</td>
<td>.04</td>
<td>BSS EN2A/1</td>
</tr>
</tbody>
</table>

Winding resistance at 35°C is 0.16 ohm so that the power required for 13.3 k gauss gap induction is about 2.8 kW and the current is 135 amps. The D.C. generator is capable of supplying 200 amps when run at 4,500 r.p.m. or more, so the V-belt drive is designed for 4,500 r.p.m. using a single small-section belt. Current for the generator field is taken from the rectified output of a motor-car alternator, via series control transistors, and a photo-chopper stabilised operational amplifier is used in the feedback loop as shown in fig. B.5. The supply was designed and constructed by J.R. Young and has proved absolutely reliable.
APPENDIX C.

RELIABILITY.

To serve as a useful research instrument, an accelerator must, of course, be sufficiently reliable. Almost any degree of reliability can be achieved if time and money for exhaustive testing and development are available, but neither of these two commodities was plentiful in the present instance, and consequently most of the testing has been carried out in actual operation of the machine. Many mistakes have been made, often resulting in time-consuming repairs and modifications having to be made, but against this must be set the fact that it was desirable to produce an accelerated beam as soon as possible to confirm that there were no unforeseen difficulties in operating a machine of this type.

Most of the serious failures have been mechanical, one of the most notable difficulties being that of obtaining sufficient life from the terminal pulley bearings. Tapered rollers, very generously rated, were originally installed, but the first set failed after only 5 hours running time, apparently because of faulty setting up. The next set, more carefully adjusted, lasted for 20 hours only, and it was suspected that the failure may have been due to pitting of the races caused by electric currents flowing through them from the charging belt to the terminal. Some confirmation of this was afforded by the fact that the next set of similar bearings lasted four times as long, "earthing" brushes having been placed on the pulley to provide an alternative
FIG. C1 TERMINAL PULLEY ASSEMBLY.

- Carbon Brush
- Insulating Sleeve
current path. The next modification consisted of insulating the bearings from the pulley, and placing an aluminium plate below the pulley, between the two runs of the belt, to shield the pulley more effectively from disturbances caused by tank sparks. These measures resulted in further improvement but the bearings failed again after 300 hours running. On this occasion one of the insulating bushes was damaged beyond repair, and the whole arrangement was scrapped, to be succeeded by bearings installed as in figure C, using two journal roller bearings at one end, and a journal ball and journal roller at the other. This has the advantage (in principle at least) that the pulley is constrained axially at one end only, so that differences in expansion between the pulley and its axle cannot produce stresses on the bearings. These bearings have given longer life than any of the others, although one set was replaced after about 500 hours use when it was necessary to install a new charging belt. The present set has been in use for about 1000 hours.

Another serious failure of a similar nature was due to insufficient precision in aligning the belt drive motors and pulley described in Appendix A.1. This caused a motor drive shaft to break inside the pulley flange, necessitating replacement of the motor and more careful alignment.

Charging belt life has also been a problem. During preliminary voltage tests a belt was ruined by taking the terminal to high voltage before the belt had time to dry out. This resulted in a tear which was about two feet long in the outermost ply of the belt, and punctured it completely for a few inches. Current practice is to run the belt for an hour or two at low voltage after the tank has been
off for repairs or maintenance. It is not yet understood why other belt failures have occurred. On one occasion, when the belt had remained stationary in the machine for several weeks, it was found that the generator would not charge satisfactorily, and the symptoms seemed to indicate that the belt had become partially conducting. When the tank was removed, it was discovered that in several places along its length there were black marks on the belt corresponding to places where light had reached the belt through windows in the pressure vessel. The pattern of marks and shadows was quite unambiguous and in one place there was a depression almost half the belt thickness deep. This alone was sufficient to render the belt useless. The depression occurred at a place where the direct light of the setting sun could have reached the belt through the equi-potential planes of the high voltage column, and it seems that this must have caused some damage to the rubber with which the belt is impregnated. Another belt failed subsequently, apparently with complete spontaneity! It is hoped that washing this last belt in detergent may have removed conducting layers from the surface, but it is difficult to devise tests that will indicate whether or not such treatments are effective. The only conclusive test is by installing the belt in the generator. Since about two days are needed to change a belt, a test on one, if unsuccessful, would require at least a week of otherwise potentially useful machine time. The fourth belt, which is in use at the time of writing, has had a rather longer life than any of the others despite an unfortunate early history, when it stretched so much that it failed to track properly and rubbed against a charging screen support.
This early accident probably led to partial failure of the belt after 600 hours' use, but on this occasion it was possible to "repair" the belt by cutting off a 3 cm. wide strip of belt from the damaged edge, right round its circumference.

Although considerable difficulty has been experienced in making adequate stripper foils, and frequently the machine has been closed up with only three or four foils in the changer, it has only once been necessary to remove the tank just to replace foils. Now the techniques have been more completely mastered, and better foils can be more easily made, it will be possible to mount a full complement of 16 foils in the stripper, and this should prove sufficient for normal operation even with considerably increased beam currents available from the duoplasmatron ion source. It seems probable that both the foil-holding wheels mentioned in section 2.3 will never be installed simultaneously.

No trouble has been experienced with vacuum leaks inside the pressure vessel since the accelerator was first assembled, with the exception of one occasion on which a leak developed in a nickel diffusion leak device which had been installed in the high voltage terminal to admit small quantities of hydrogen to the anode end of the acceleration tubes. This fault proved rather difficult to locate, as tank gas leaked through a valve gland into the hydrogen cylinder, and then through the leak in the nickel "leak" into the tubes. The vacuum system pressure did not follow changes in tank pressure for several hours, and helium would not diffuse into the cylinder at an appreciable rate until its pressure was less than atmospheric. The terminal gas
leak has not subsequently been reinstalled, although it is suspected on very slim evidence that its use may have improved tube performance above 6.5 MeV.

The belt motors have run for a total of 1950 hours, and the longest period of operation without removing the tank has been 470 hours. There has been a reasonably satisfactory tendency for the machine to be opened less frequently of late, but obviously there is still some improvement required before periods of about a thousand hours between major repairs or maintenance can be achieved.
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