Studies for the Adaptation of a Field Ionization Ion Source for a Proton Microprobe

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by

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Abstract

A major factor limiting the resolution of the Scanning Proton Microprobe is the brightness of the primary beam supplied by the accelerator.

The recent development of a field ionization proton source, which is up to five orders of magnitude brighter than the present source, holds the promise of substantially improved resolution in MP.

The optics of the Pelletron accelerator were studied to determine the expected resolution improvement to the MP beam from the installation of the new source.

The optics of the field ionization source region were studied using the charge simulation method. First order effective source size was calculated for field ionization tips, and calculations carried out to determine the contribution of aberrations to source size. Tip size and applied voltage to maximize source brightness were also investigated.

The present electrostatic lens was investigated for use with the field ionization source, and found to be unsuitable unless very high voltages were to be applied. A range of alternative two and three element electrostatic lenses was investigated. Three element lenses were found to be more flexible, and generally had lower aberrations than two element lenses. Various designs of three element lenses were examined, and accelerating and decelerating modes discussed for all lenses. Accelerating lenses, although optically superior, were generally found to require unacceptably high applied voltages in order to achieve focusing.

Decelerating lenses were investigated in further detail, and the geometry of promising lenses varied to attempt to reduce aberrations. Calculations suggested the best alternative to the present lens to be a miniaturized variation of the decelerating Riddle lens.

A full scale version of this lens was studied on a specially constructed electron optical bench. The two grid method was used to measure cardinal points for the lens, as well as chromatic and spherical aberrations.
The values of measured optical properties were found to correspond well with theoretical calculations for the same lens over the voltage range of most importance, suggesting that a reduced scale version of the same lens would be suitable for use with the field ionization source.

The optics of the accelerating column were also investigated using the finite element method. Cardinal elements were extracted for a range of source lens operating voltages, permitting the calculation of accelerator object positions for a focus at the analysing magnet object slits.

Chromatic and spherical aberrations of the accelerating column were also determined, and their effect on beam brightness for various source and lens configurations discussed.

Finally all ion optical elements were combined and the final brightness, and expected MP beam resolution determined for a range of optical combinations. Conclusions were drawn on the most appropriate optical configuration of the accelerator. Further work required for the installation of the source was also discussed.

This thesis is less than 100,000 words in length.
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Chapter 1

Introduction

1.1 The Melbourne Microprobe

The scanning proton microprobe was first developed at Harwell in 1972 by Cookson et al. [Co72]. The Harwell Microprobe used a system of magnetic quadrupole lenses to focus a 3MeV beam of protons. Subsequently, many other microprobes have been developed around the World, using a range of lens types and configurations, and with the primary beam supplied by a wide variety of single and double ended particle accelerators. A review of microprobes has been carried out by Cookson [Co79, Co81] and more recently by Legge [Le84].

The Melbourne Proton Microprobe (hereinafter called MP) commenced operation in 1975 [Le79a]. The ion optical configuration of MP is similar to that of the Harwell probe, with a lens system consisting of an anti-symmetric Russian Quadruplet [Dy64]. The primary beam is supplied by a 5U Pelletron Accelerator.

MP has proved to be a flexible analytical tool which has found application in a wide range of multidiciplinary fields [Le80a, Le86a]. In its present state of development it combines sub-micron resolution with a variety of complementary micro-analytical techniques [Le79b, Le82b]. Continued development of MP and in particular continued improvements in resolution are necessary for continued expansion and diversification of MP applications.

Unlike other analogous devices such as electron microprobes and micro-
scopes no proton microprobe has yet had the benefit of a dedicated, specifically optimized beam source. The development of such a source holds the promise of substantial gains in MP resolution, and consequent broadening of its applications. The aim of this work is to investigate the production of a ‘brighter’ primary beam for MP by the adaptation of a ‘high brightness’ ion source to the Pelletron Accelerator.

1.1.1 Principles of MP Operation and Applications

A schematic of the Pelletron and MP is shown in Fig. 1.1. The object of the MP ion-optical system is formed by a diaphragm located at the entrance of the MP beam line. The object is illuminated by a $H^+$ or $\alpha^+$ beam supplied by the accelerator. A range of object diaphragms is available ranging from 5$\mu$m to 100$\mu$m. These diaphragms are drilled in a water cooled tantalum strip, which is thick enough to stop 3MeV protons. Beam divergence is limited by an aperture located 5m downstream from the object diaphragm. The aperture strip is constructed from .5mm thick tantalum, and bears a range of aperture sizes from .25mm to 5mm, thus permitting a range of possible beam divergences from 0.05 mrad to 1 mrad.

The MP lens system is located a further 3m downstream. The present system consists of 4 magnetic quadrupoles arranged in the Russian Quadruplet configuration. This configuration permits orthomorphic imaging, i.e. imaging with equal demagnifications in the XOZ and YOZ planes. The quadrupoles have been carefully manufactured with the aim of minimizing alignment errors and other parasitic aberrations. Details on the quadrupoles are given by Legge [Le82a, Le84].

The beam is focused by the quadrupole quadruplet onto the specimen plane located 236mm downstream from the lens exit. Between the lenses and specimen chamber are located two sets of magnetic saddle coils, which permit X and Y scanning of the beam in the chamber. In the most recent version of MP the specimen chamber consists of a main analysis chamber and a connected airlock chamber for specimen changing. Details of the MP chamber and specimen
Figure 1.1
Schematic diagram of Pelletron Accelerator and MP beamline.

Pelletron Accelerator:

MP beamline:

(From Allan [Al89a])
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handling systems are given by Legge [Le86a].

MP employs a variety of complementary analytical techniques, characterised by the different ways with which the incoming beam particle may react with specimen atoms.

Foremost among the techniques used is Proton Induced X-ray Emission (PIXE). This technique is reviewed by Johannson [Jo76]. PIXE has been used extensively on MP to investigate elemental distributions in medical, biological and botanical specimens [Le80a, Le82b, Ma82, Ma83, Ma85]. The present 1µm resolution for PIXE work has permitted intra-cellular investigations of animal cells 7µm in diameter [Ob81, Ob87, Co82, Al89b]. Semiconductor [Mc83a Mc83b, Br85], and geological [Lu83, Lu87, Sa87] samples have also been investigated. For PIXE work 3MeV protons are generally utilised. At this proton energy a good compromise is found between increasing x-ray ionization cross section with energy, and increasing Bremsstrahlung background for low to middle mass elements [Gu77, Gu78]. This compares with typical electron microprobe EIXE beam energies of up to a few tens of keV [Go81].

The detection of backward and forward scattered beam particles gives specimen elemental depth profile information. For backscattering work 2MeV α+ beams are preferred as alpha particles provide superior depth resolution to protons [Br85], although protons may also be used. The narrow convergence cone of the MP beam also permits channelling in crystalline materials. The construction of a 2 axis goniometer has enabled the development of Channelling Contrast Microscopy (CCM) as an analytical tool. CCM has been used to study dopant substitution rates in implanted and laser annealed polycrystalline silicon [Mc83a,b,c, Mc84, Mc86].

The third analytical technique involves the detection of nuclear reaction products and is used on MP for investigation of elements precluded from standard PIXE analysis [Ma82].

The final analytical technique is Scanning Transmission Ion Microscopy (STIM), first proposed for lower energies by Levi-Setti [Le74]. For STIM analysis the beam is 'stopped down' by reducing object and aperture diaphragms, then
run directly into a surface barrier detector located behind the specimen. For transmission thickness specimens, this yields density and thickness information, and has been used in the study of biological samples such as diatoms [Se87] and in specimen beam damage studies [Ch89].

1.1.2 MP Development and Resolution

For PIXE work using specimens with a biological matrix, a minimum current of approximately 100pA is required to permit reasonable irradiation times. With the present MP system the smallest probe diameter which may be achieved with this current is approximately $1\mu m$ FWHM [Ja85]. Jamieson found that by using smaller object and aperture diaphragms a resolution of $0.5\mu m$ is achievable, but the current of 10pA is unacceptably low for PIXE analysis [Ja85].

For STIM work, on the other hand much smaller currents are necessary. Such currents are typically $1.6 \times 10^{-16}$A or around 1000 protons/sec. Currents of this size are produced by inserting an aperture of 0.25mm and constricting the object by use of a set of ‘V’ shaped microslits [Be87]. The optimal resolution which has been achieved for STIM analysis is approximately $0.05\mu m$ [Be88].

To improve the flexibility and versatility of MP two broad (and related) aims arise: to increase the current available at the specimen for a given resolution, and to improve the resolution whilst maintaining usable current.

To achieve these aims, several different approaches have been pursued. Firstly, refinements have been made in the construction and alignment of MP and its peripherals and for the elimination of stray magnetic fields and vibrations in the vicinity of the beam. Careful construction of the magnetic quadrupole lenses by Legge [Le82a] has aimed to minimize aberrations due to pole irregularities and other lens errors.

Secondly, alternate lens designs and configurations have been analysed. The ultimate aim of these investigations has been to permit the aperture diaphragm to be opened up for a given object size, so as to achieve greater current in the image. With the present lens system, divergent rays suffer strongly from spherical and parasitic aberrations, and hence resolution may be expected to be...
rapidly degraded. Dix [Di83] investigated the alternative of a superconducting solenoid lens, which has the dual advantages of lower spherical aberrations and simpler alignment compared with conventional quadrupole lens configurations. Dix indicated that an improvement in resolution by a factor of 2 could be expected using such a lens. The practical difficulties and expense associated with superconducting windings and liquid helium cryostat make this unworthwhile in the present circumstances.

Alternate quadrupole lens configurations have been investigated systematically by Jamieson [Ja85]. The alternatives he considered included doublets, triplets and quadruplets. He concluded that no other configuration offered significant advantages over the present antisymmetric quadruplet system. Jamieson instead attempted to correct the aberrations in the present quadrupole lenses. Following the methods of Deltrap [De64] and Hardy [Ha67], Jamieson built and installed three magnetic octupole correctors between the quadrupole lenses [Ja85]. The octupoles were designed to correct the spherical aberration of the quadruplet, however it was found that the MP image is dominated by parasitic aberrations, not susceptible to octupole correction [Ja87]. Jamieson further found that the MP system is indeed not presently limited by spherical aberrations due to the low divergence of the beam produced by the accelerator when the accelerator’s electrostatic quadrupoles are not in use (See section 2.3).

A third approach is to increase the demagnification of the MP system, thus producing a smaller image spot for a given object and aperture selection. In the present configuration such increased demagnification is not practicable, since the image distance is already as small as possible to accommodate scanning coils, and the object distance is constrained by the dimensions of the experimental hall.

Moloney [Mo86] showed that image size reduction is possible using two stages of demagnification, employing two sets of quadrupole doublets or quadruplets. Geometrical considerations would permit a total demagnification of 100 to 150, however the large divergence angles induced in the beam would require careful spherical and chromatic correction in the lenses to achieve a substantial
improvement in resolution [Mo87].

The final approach to MP beam resolution improvement is to pursue improvements in the optical characteristics of the primary beam delivered by the accelerator [Le87]. There are two main considerations here. Firstly the characteristics of the ion source itself place an upper limit on the final characteristics of the image, since it is the source which is the ultimate object of the entire optical system. An improvement in the brightness of the source may lead to better resolution in MP. The second consideration is the accelerator itself, which must be optimized to ensure the beam from the ion source is transmitted to the MP line with minimum possible loss or degradation. Without the optimization of the accelerator's optical system, ion source brightness may simply be 'thrown away' in the accelerator.

1.2 The Melbourne Pelletron Accelerator

The Melbourne Pelletron Accelerator was constructed by the National Electrostatics Corporation, Wisconsin, and installed in the Melbourne University School of Physics in 1974. It is shown schematically in Fig. 1.1. It is a single ended light ion accelerator, designed for general low energy nuclear and applied nuclear research. The development of the Pelletron followed on technical and design breakthroughs in the 1950s [He74a, Br74] and had its genesis in Van De Graff type belt charged accelerators of the 1930s [Va48].

The principle of operation of the Pelletron Accelerator is very simple. A chain of metal cylinders joined by links of insulated plastic serves to inductively charge the high voltage dome. In the case of the Melbourne Pelletron, terminal potentials of up to 5MV may be obtained.

The accelerating column itself consists of five sections each capable of sustaining a 1MV voltage gradient. Each section in turn consists of three subsections, bolted together, utilizing metal gasket seals. Each subsection consists of alumina ceramic rings metal bonded to titanium. These bonding techniques and some of the accelerator tube's geometrical features have enabled the Pelletron
to largely overcome electron loading problems and the 'long tube effect' which limited early linear accelerators [He74a].

For use above 4MV all sections of the accelerator tube are required. For terminal potentials below 4MV the accelerator may be operated in two ways: either the entire column may be used at reduced voltage gradient, or else one or more accelerator sections may be 'shorted out' using stainless steel shorting rods. This latter technique allows the maintenance of high voltage gradients inside the operative sections of the tube and enhances the stability of the machine in some circumstances. For MP use, the accelerator is commonly used to provide 3MeV protons using all five sections, and 2MeV α⁺ using four sections although other beams are sometimes used. For example 4MeV protons produced using 5 sections are desirable for heavy element PIXE work due to higher K-shell ionization cross-sections at these energies [Li85].

Column gradient is regulated and made uniform by three sets of corona points, mounted on the column supports and on the acceleration column itself. This system was adopted rather than that of a chain of resistors due to the difficulty in obtaining sufficiently uniform resistors, and the problems of damage to resistors due to tank sparking. Recently however, some Pelletrons have been built with specially developed with resistor chains replacing the corona points [Sz88b]. This development has the added advantage of providing a further diagnostic for stability investigations.

Inside the terminal dome itself are located the ion source and gas bottles, as well as power supplies for the source, and the various electrostatic components associated with transport of the beam to the accelerating column (refer Chapter 2). Electrical power is supplied to the high voltage terminal by a perspex rotating shaft.

The entire dome/column system is located inside a steel tank filled with insulating SF₆ gas. For 3MV operation approximately 50 p.s.i. gas pressure is required. Voltage regulation of the machine is accomplished by voltage error signal feedback to the control grid of a corona triode mounted on the tank wall. The potential error voltage is generated either from the voltage signal from
the Generating Voltmeter, or by the ratio of high and low energy slit currents obtained from the horizontal slits at the exit of the beam analysing magnet located beneath the tank base [Na74]. Further details on the individual optical components of the Pelletron Accelerator are specified in following chapters.

1.3 Ion Source Development and Brightness

1.3.1 The Radio Frequency Ion Source

The present Pelletron ion source is a radio frequency source manufactured by Ortec Corporation, Oak Ridge, Tennessee. It is capable of providing up to 5mA of $\text{H}^+$ or 400µA of $\text{He}^+$ under optimal conditions [Or74], although it is in practice operated far below these limits. An applied RF electric field ionizes the source gas which is then extracted by an applied electric field from the extractor electrode. The geometry of the extractor electrode is designed to shape the plasma boundary so as to focus the maximum possible number of ions into the exit canal [Or74]. The object of the accelerator optical system may thus be regarded as a beam waist located approximately midway along the exit canal. Performance and stability of the RF source depends critically on the various parameters indicated above — viz. gas pressure, RF frequency and extraction (or 'probe') voltage. Source lifetimes are commonly of the order of 1000 hours without maintenance, and beam current output stability has proved suitable for MP use.

1.3.2 Brightness and Resolution

In order to quantify the optical performance of the ion source it is useful to introduce the concept of brightness. This quantity was first defined by Langmuir [La37] and has a direct analogy with the luminance used in light optics [Le80b].

Briefly brightness may be defined as the ‘emitted current density per unit solid angle of beam divergence’ [Ev67]. Brightness $B$ may be defined as
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\[ B = \frac{I}{\pi^2 r_o^2 \alpha^2} \text{Am}^{-2} \text{rad}^{-2} \text{V}^{-1} \]  
(1.1)

where \( I \) is the beam current,
\( r_o \) is the beam radius and
\( \alpha \) is the beam divergence.

The quantity \( B \) however is not constant in regions of differing potential, even in an idealized aberration-free optical system. To overcome this another quantity is generally introduced known as the 'specific' (or 'paraxial') brightness:

\[ \beta = \frac{B}{V} = \frac{I}{\pi^2 r_o^2 \alpha^2 V} \text{Am}^{-2} \text{rad}^{-2} \text{V}^{-1} \]  
(1.2)

By non-relativistic application of the Helmholtz-Lagrange theorem, \( \beta \) is found to be invariant for conjugate points of an aberration-free optical system, in the absence of limiting apertures. In this thesis the term 'brightness' will generally refer to the specific brightness as defined in equation 1.2.

It may be shown (refer Chapter 2) that \( \beta \) places an 'upper limit' on the optical performance of the system. Specifically for an apertured system, the Gaussian image size \( r_g \) is given by

\[ r_g = \frac{I_o^{\frac{1}{2}}}{(\beta V_p)^{\frac{1}{2}} \pi \alpha_p} \]  
(1.3)

where \( I_o = \) source current
\( V_p = \) image potential
\( \alpha_p = \) beam convergence angle.

Clearly \( r_g \) is limited by the specific brightness of the source, and for a given specimen current \( r_g \) is smaller for a brighter source. The specific brightness of the Ortec RF ion source was shown by Allan [AI89a] to be a function of source parameters, but typically lies in the range

\[ \beta = 1 \rightarrow 5 \text{Am}^{-2} \text{rad}^{-2} \text{V}^{-1} \]

Equation 1.3 indicates that a brighter ion source will lead to a reduction in first order probe diameter for a given specimen current, or alternatively a larger specimen current for a given first order probe diameter.
Guidance in the search for increased brightness sources may be gained from the fields of electron microscopy and electron microprobes. In these instruments heated tungsten hairpin cathodes operating at around 25kV have typical brightness in the range $\beta = 0.3 \rightarrow 4 \times 10^4 \text{Am}^{-2}\text{rad}^{-2}\text{V}^{-1}$ [Re85b], with LaB$_6$ cathodes an order of magnitude better than this. The field emission source has higher brightness again, although smaller available currents with $\beta \sim 10^8 \text{Am}^{-2}\text{rad}^{-2}\text{V}^{-1}$. By a combination of high brightness sources and careful design and construction of lenses, electron microscopes and microprobes have achieved sub-nanometer sized probes.

A survey of possible high brightness proton sources for MP was carried out by Allan [Al80]. He concluded that the Field Ionization Source, first proposed by Muller [Mu51] and Ingram and Gomer [In54], may provide a high brightness source suitable for microprobe use. Typical brightness of a field ionization source operated at 20kV is up to $10^6 \text{Am}^{-2}\text{rad}^{-2}\text{V}^{-1}$ which if transferred by an ideal optical system could deliver 100pA of current into an image spot size of 5.7nm using the present .25mm aperture.

A field ionization source was constructed by Allan [Al89a] and is shown schematically in Fig. 3.3. The principle of operation is straightforward. A high positive voltage is applied to the ionization tip which is immersed in a H$_2$ atmosphere. For electric fields in the vicinity of the tip in excess of $10^8 \text{V/cm}$ ionization of H$_2$ molecules and H atoms occurs by quantum mechanical tunnelling of the electron from the gas atom or molecule into the metal surface [Be77]. After this has occurred the atom or molecule is accelerated away by the electric field. The ratio of H$^+/H_2^+$ produced ions is an increasing function of the applied electric field and is given by Muller and Tsong [Mu69].

The performance of the field ionization source and its optics are discussed in Chapter 3. Fields in excess of $10^8 \text{V/cm}$ may be obtained by the application of 10kV to a tip of end radius 0.25µm. Allan was able to manufacture tips of these dimensions from polycrystalline tungsten by chemical etching using a 1M NaOH solution. Unfortunately both available current and tip lifetime have been low for these emitters. These factors are due mainly to bombardment from residual
gasses in the vacuum system, particularly H$_2$O causing etching and blunting of the tip [Al89a]. To overcome this Allan manufactured iridium tips by etching using a dilute solution of NaClO following the method of Orloff [Or84].

Allan has achieved lifetimes of 60 hours using Ir emitters, although total currents are still limited to around 21nA. Current increase by a factor of 4 could be expected by cooling the tip to liquid nitrogen temperatures [Cl62]. This was not attempted by Allan since the technical difficulties of locating a cryogenic system inside the high voltage terminal discouraged this alternative.

Even higher brightness sources have been reported by Bohringer et al. [Bo88] using a W 'supertip'. Such a source may eventually prove to have advantages over the presently developed field ionization using conventional tips although technical difficulties remain to be resolved before such tips are implanted in the high voltage terminal of an accelerator.

1.4 Motivation and This Work

The field ionization source developed by Allan [Al89a] is investigated in this Thesis as a possible alternative to the present source.

Such a source, since it produces a positive beam, would be unsuitable for a tandem accelerator, so would be unsuitable for many Microprobes currently operating around the world. In the Melbourne Pelletron however, this source holds the promise of improved resolution for the MP system. There are two limitations to this however. Firstly, the beam may be degraded, i.e. specific brightness lost, due to an imperfect beam transport system. Such 'imperfections' include geometric aberrations, chromatic aberrations, space charge spreading, diffraction effects and mechanical vibrations both in the accelerator itself and the MP beam line. Secondly, the beam may be insufficient initially, or current may be lost in the beam transport system, and hence insufficient current may be available at the specimen plane (i.e. an emittance/acceptance matching problem). In terms of equation 1.3, the defining aperture semi-angle $\alpha_o$ is given by

$$\alpha_o = \sqrt{\frac{I}{\beta \pi^2 r^2 \text{source} V_{\text{source}}}}$$

(1.4)
Total current \( I \) demands half-angle \( \alpha_a \); however accelerator optical acceptance must match source emittance.

The aim of the present work is to determine the suitability of the present accelerator optical system for a field ionization source, i.e. to determine whether the high brightness of the source is conserved by the accelerator. Where brightness or beam is lost, the aim is to redesign the optics to minimize such losses.

First order optics and aberration theory of cylindrically symmetric systems are discussed in Chapter 2. The overall first order optics of the Pelletron is considered and possible alternative configurations are discussed.

Chapter 3 contains a full ion optical discussion of the field ionization source region. Electrostatic potential calculations are carried out using the charge simulation programs of Kasper [Ka79], and trajectories traced by an accurate predictor-corrector method. General beam characteristics and source parameters are also discussed.

Chapter 4 contains an analysis of the present electrostatic lens, and discusses its suitability for operation with a field ionization source. There follows an analysis of a range of 2 and 3 element electrostatic lenses to determine possible alternatives. The optimization of 2 of these lenses is discussed and applied, and calculations performed to determine brightness downstream of the lens for differing source and lens configurations.

Chapter 5 contains an analysis of the accelerating column. The importance of the aberrations on overall brightness loss is analysed. Aberration minimization is also discussed.

Chapter 6 discusses the construction of a prototype lens and lens support system for the ion source. It also presents the development of an ion optical test bench to permit the testing of the lens.

Chapter 7 covers the testing of the prototype lens using the two grid method. The results of measurements of lens cardinal elements and aberrations are presented and discussed.

Chapter 8 reviews the present work, and briefly discusses further problems which must be considered.
Chapter 2

Ion Optics Theory of Cylindrically Symmetric Electrostatic Systems

2.1 Introduction

The focusing action of cylindrically symmetric electrostatic fields was first recognised in 1931 and 1932 by Davisson and Calbick [Da31, Da32] and independently by Bruche and Johannson [Br32]. Since that time enormous development has taken place in the field of electrostatic electron and ion optics. This development has resulted in the evolution of a wide range of components and instruments exploiting electrostatic lenses, which have found application in almost every branch of science.

The theoretical basis of charged particle optics has been derived from two fundamentally different approaches. These are the trajectory method as favoured by Scherzer [Sc36] and the eikonel method as developed by Funk [Fu36], Rogowski [Ro37] and Glaser [Gl52]. The final results of these two approaches may however be proved equivalent [Ha86].

By applying optical principles to particles moving in electrostatic fields the problems can be simplified conceptually and an array of techniques evoked for light optics can be employed. This chapter discusses the optical formalism of cylindrically symmetric electrostatic fields and discusses some first order results for the present Pelletron system.
2.2 First Order Optics

2.2.1 Definition of Cardinal Elements

The electrostatic potential distribution in a vacuum obeys Poisson’s equation

\[ \nabla^2 V = -\frac{\rho}{\varepsilon_0} \]  

(2.1)

where \( \varepsilon_0 \) is the dielectric constant of vacuum, and \( \rho \) is charge density. In the absence of space charge this reduces to the Laplace equation

\[ \nabla^2 V = 0 \]  

(2.2)

Expressed in cylindrical co-ordinates this becomes

\[ \frac{\partial^2 V}{\partial z^2} + \frac{1}{r} \frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial r^2} = 0 \]  

(2.3)

The equation of motion of a particle of mass \( m \) and charge \( q \) in an axially symmetric electrostatic field may be written

\[ m\ddot{r} = qE_r \]  

(2.4)

\[ m\ddot{z} = qE_z \]  

(2.5)

where

\[ E_i = -\frac{\partial V}{\partial x_i} \]  

(2.6)

Eliminating time from equations 2.4 and 2.5 using energy conservation we obtain

\[ r'' + \frac{1 + r^2}{2V} \left( \frac{\partial V}{\partial r} - r \frac{\partial V}{\partial z} \right) = 0 \]  

(2.7)

known as the General Ray Equation.

This equation is valid for non-relativistic, cylindrically symmetric electrostatic systems in the absence of space charge. Writing the potential as the well-known series expansion in terms of the axial potential \( (V_0) \)

\[ V(r, z) = V_0(z) - \frac{r^2}{4} V_0''(z) + \frac{r^4}{64} V_0^{(4)}(z) - \ldots \]  

(2.8)
and retaining only terms up to second order, equation 2.7 reduces to

\[ r'' + \frac{V_o'}{2V_o} r' + \frac{V_o''}{4V_o} r = 0 \] (2.9)

where differentiation is with respect to \( z \). Equation 2.9 is known as the Paraxial Ray Equation (PRE), and is a linear homogeneous second order differential equation.

A number of important implications flow from equation 2.9. Firstly the PRE (or indeed equation 2.7) does not contain either the mass or charge of the moving particle, hence the trajectory followed is the same for all charged particles which enter the field with the same kinetic energy. This implies that results in electron optics are directly applicable to protons provided the signs of all potentials are reversed.

Secondly the equation is homogeneous in \( V \) which means trajectories are unaltered if \( V \) is increased proportionally on all electrodes. This implies optical properties depend on voltage ratios only, not absolute voltages providing the ‘zero’ energy of the trajectory particle corresponds to the zero of the defined potential, and the particle speeds are non-relativistic.

Thirdly the equation is homogeneous in \( r \) and \( z \) which means that optical properties will simply scale with the physical dimensions of the lens (providing object and image distances are also scaled).

Finally any solution of equation 2.9 may be written as the linear combination of two independent solutions. It may be shown from this [Ka70] that the trajectories have the properties of focusing. We may write:

\[ r_i = a_{11} r_o + a_{12} r_o' \] (2.10)

\[ r_i' = a_{21} r_o + a_{22} r_o' \] (2.11)

Electrostatic lenses must generally be represented as ‘thick’ lenses, i.e. lenses whose entrance and exit principle planes do not coincide.

Fig. 2.1 defines the cardinal points of a lens as they are used throughout this work. Subscripts ‘o’ and ‘i’ will generally be used for object and image...
Figure 2.1

Definition of cardinal points for an electrostatic lens. PP₁ and PP₂ depict the first and second principal planes. Note that these are shown as having planar cross-section. In fact, in general, these surfaces will be closer to paraboloids [Li49] (see also Fig. 7.1). f₁ and f₂ are the focal lengths. Object and image potentials are given by V₀ and Vᵢ respectively. Ray paths are shown as dashed lines. Cardinal planes and asymptotic rays are shown as solid lines.
plane quantities respectively, but '1' and '2' are also used when confusion might otherwise arise.

Linear magnification may be defined by

\[ M = \frac{r_i}{r_o} \]  \hspace{1cm} (2.12)

Angular magnification may be defined as

\[ M_a = \frac{\alpha_i}{\alpha_o} = \frac{1}{M} \sqrt{\frac{V_o}{V_i}} \]  \hspace{1cm} (2.13)

In this Thesis, the term 'Gaussian image' will refer to that image formed by paraxial rays which have the median energy of all particles comprising the beam.

2.2.2 Methods of Calculation

The majority of Gaussian lens calculations in this thesis have been performed using a modified version of the program suite of Munro called F11 [Mu73c, Mu75]. This program calculates the potential at all points of a user-specified mesh using the finite element method. Boundary values, including electrode geometries, are pre-specified by the user. The mesh and boundaries represent a 'slice' through a cylindrically symmetric electrode system. Paraxial raytracing may then be performed either forwards or backwards through the lens by a fourth order Runge-Kutta algorithm and using the calculated axial potential distribution. Focal lengths, principle plane locations and magnification are then derived from the raytraces.

For emitter tips, calculations were performed using the Kasper suite of programs [Ka81a] (refer Chapter 3). Gaussian image positions and focal lengths were calculated from these programs by extrapolating 'low divergence' rays to the axis. This method has proved reliable for magnetic lens studies [Di83].

Finally, for calculations involving the overall first order optics of the Pelletron system (refer Section 2.4), the matrix method was used, with focal and mid-focal lengths for 2 and 3 cylinder lenses obtained from the polynomial expressions of Harting and Read [Ha76]. These expressions were implanted into the
optical matrix program PRAM [Ja82]. This program provided the advantage of
erapid overall first order calculations of the system with convenient element ma-
nipulation. All calculations were performed either on a DG MV8000 computer
or on a DEC VAX 11/780.

2.3 Aberration Theory

2.3.1 Trajectory Calculations and Aberration Coefficients

Consider a meridional ray which enters a cylindrically symmetric electrostatic
lens and whose radial position and divergence are specified by \( r_1, r'_1 \) when pro-
jected onto the first focal plane of the lens. If the outgoing ray is specified by \( r_2, r'_2 \)
when projected onto the second focal plane, \( r_2, r'_2 \) are given by [Ve63, Re86]

\[
\begin{align*}
    r'_2 &= -r_1/f_2 + m_{13}r_1r^3 + m_{14}r_1^2r_1/f_2 + m_{15}r_1r_1^2/f_2^2 + m_{16}r_1^3/f_2^3 \\
    &\quad + q_{11}r_1r^5 + q_{12}r_1^4r_1/f_2 + q_{13}r_1^3r_1^2/f_2^2 + q_{14}r_1^2r_1^3/f_2^3 \\
    &\quad + q_{15}r_1r_1^5/f_2^4 + q_{16}r_1^5/f_2^5 + \cdots
    \end{align*}
\]

(2.14)

\[
\begin{align*}
    r_2/f_1 &= r'_1 + m_{23}r_1r^3 + m_{24}r_1^2r_1/f_2 + m_{25}r_1r_1^2/f_2^2 + m_{26}r_1^3/f_2^3 \\
    &\quad + q_{21}r_1r^5 + q_{22}r_1^4r_1/f_2 + q_{23}r_1^3r_1^2/f_2^2 + q_{24}r_1^2r_1^3/f_2^3 \\
    &\quad + q_{25}r_1r_1^5/f_2^4 + q_{26}r_1^5/f_2^5 + \cdots
    \end{align*}
\]

(2.15)

where \( f_1, f_2 \) are the first and second focal distances as defined in Section 2.2, and
\( m_{ij}, q_{ij} \) are dimensionless coefficients related to 3rd and 5th order aberrations
respectively.

Considering up to the 3rd order coefficients only, then in the general case
of a ray from an object located at position \( P \) (measured from the first principal
plane), and a defining aperture located in a plane \( S \), downstream from the first
focal plane we may write

\[
\begin{align*}
    r_i &= -\frac{f_1}{f_2-1}r_o \quad \text{First order image size} \\
    &+ Jr_0^3 \quad \text{Spherical Aberration} \\
    &+ Jr_0^2r_o \quad \text{Coma} \\
    &+ Kr_o^2 \quad \text{Field curvature and Astigmatism} \\
    &+ Lr_o^3 \quad \text{Distortion}
    \end{align*}
\]

(2.16)
where $r_*$ is the radial position of the ray at the aperture and $I, J, K, L$ are functions of $m_{ij}$ and are given by Verster [Ve63].

### 2.3.2 Spherical Aberration

Considering now a point object situated on the axis, the deviation from the Gaussian point image in the image plane $r_i$ is given from equation 2.16 as

$$
\Delta r_i = I r_*^3
$$

(2.17)

In terms of the divergence in the first focal plane we may define the spherical aberration coefficient $C_s$ by

$$
\Delta r_i = M C_s r_i^3
$$

(2.18)

where $C_s$ may be expanded as a polynomial in reciprocal magnification as follows:

$$
C_s(M) = C_{s0} + C_{s1} M^{-1} + C_{s2} M^{-2} + C_{s3} M^{-3} + C_{s4} M^{-4}
$$

(2.19)

Providing only 3rd order aberrations are considered, we may write [Ve63]:

$$
\Delta r_i = -M \Delta r_o
$$

(2.20)

Now from equations 2.18, 2.20, we may define

$$
\Delta r_o = C_{s0} \alpha_o^3
$$

(2.21)

$$
\Delta r_i = C_{si} \alpha_i^3
$$

(2.22)

where $C_{s0}$ is the spherical aberration coefficient related to the object,

$C_{si}$ is the spherical aberration coefficient related to the image,

$\alpha_i$ is the convergence semi-angle,

$\alpha_o$ is the divergence semi-angle

and [Go85]

$$
C_{si} = C_{s0} M^4 \left( \frac{V_i}{V_o} \right)^{\frac{3}{2}}
$$

(2.23)

In this work $C_{s0}, C_{si}$ and $C_{sco}$ are all used, with the actual choice of appropriate $C_s$ coefficient depending on the particular circumstances of each situation.
Chapter 2. Ion Optics Theory of Cylindrically Symmetric Electrostatic Systems

For an apertured system of negligible object size, the circle of least confusion is located upstream of the Gaussian image plane, where the beam diameter is a minimum. It may be shown that the beam radius at the circle of least confusion is given by

\[ r_{sc} = \frac{1}{4} C_s\alpha_{max}^3 \]  

(2.24)

where \( \alpha_{max} \) is the most strongly convergent ray permitted by the aperture and is located a distance upstream from the Gaussian image plane a distance

\[ z_{sc} = \frac{3}{4} MC_s\alpha_{max}^2 \]  

(2.25)

A derivation of this is given by El Kareh and El Kareh [Ka81].

In Munro's original program, the coefficient \( C_s \) or \( C_{st} \) is determined by numerical evaluation of the well-known integral

\[ C_s = \frac{1}{16} V_o \int_{z_o}^{z_i} \left( \frac{5}{4} \left( \frac{V''}{V} \right)^2 + \frac{5}{24} \left( \frac{V''}{V} \right)^4 \right) r^4 + \frac{14}{3} \left( \frac{V''}{V} \right)^3 r' r_\alpha^3 - \frac{3}{2} \left( \frac{V''}{V} \right)^2 r'^2 r_\alpha^2 \right) \sqrt{V} dz \]  

(2.26)

As stated above however, \( C_s \) is a function of object position, or magnification, for any given lens.

The integrands to evaluate the coefficients of equation 2.19 were implanted into F11. It was found however, that these coefficients were not particularly useful in the attempt to optimize lenses, due to the large number of variables involved.

For the case of ionization tip calculations, the ordinary aberration integrals cannot be evaluated due to the divergence of the integrand in the region of the tip, unless special precautions are taken [Ta84, Ju84]. In this case, therefore, the geometric aberration coefficients were obtained by least-square fitting of polynomials to the axial or radial displacement of image plane rays.

2.3.3 Chromatic Aberration

The focal length of an electrostatic lens depends on the energy of the incoming particle, as well as excitation of all electrodes. In analogy with light optics, aberrations due to a variation in these factors are called chromatic aberrations.
It is usual to define an axial chromatic aberration coefficient such that

$$\Delta r_{ci} = \frac{1}{2} \alpha_i C_{ci} \frac{\Delta V}{V_i} \quad (2.27)$$

where $\alpha_i$ is the half angle of convergence,

$\Delta V$ is the energy spread of the beam,

$V_i$ is the image potential,

$C_{ci}$ is the axial chromatic aberration coefficient referred to the image,

$\Delta r_{ci}$ is the increase in image radius due to chromatic spread.

We may also define

$$\Delta r_{co} = \frac{1}{2} \alpha_o C_{co} \frac{\Delta V}{V_o} \quad (2.28)$$

where $\alpha_o$ is the half angle of divergence,

$\Delta V$ is the energy spread of the beam,

$V_o$ is the object potential,

$C_{co}$ is the axial chromatic aberration coefficient referred to the object,

$\Delta r_{co}$ is the increase in object radius due to chromatic spread.

which implies [Go85]

$$C_{ci} = M^2 \left( \frac{V_i}{V_o} \right)^{\frac{3}{2}} C_{co} \quad (2.29)$$

It is noted in passing that the factor $1/2$ is incorporated into equations 2.27 and 2.28 in line with the traditional definition of $C_{co}$. As pointed out by Orloff [Or83], this factor is incorrectly omitted in much of the literature.

In Munro's original program, $C_c$ is evaluated by the well known integral

$$C_c = \sqrt{V_o} \int_{z_o}^{z_i} \left( \frac{1}{2} \frac{V''}{V} r''_a + \frac{1}{4} \frac{V'''}{V^2} r''_a \right) \frac{r_a}{\sqrt{V}} dz \quad (2.30)$$

In the case of ionization tip calculations, chromatic aberration coefficients were obtained by permuting the initial energy of particles and fitting curves to the Gaussian image radius as a function of change in energy. Following the definition of 'Gaussian image' in Section 2.2 above, it may be seen that the effect of chromatic aberration does not alter the location of the image plane.
2.3.4 Addition of Aberrations

If the aberrations are statistically independent it is usual to add aberration discs and the Gaussian image in quadrature [Gr65, Wi73a]. Although not precisely correct, this method has been shown to yield results close to those of more complicated methods [Vo38, Sm56, Pe65].

For axial aberrations we write

\[ r_t = \sqrt{r_g^2 + r_s^2 + r_c^2 + r_d^2} \]  

(2.31)

where

- \( r_g \) = radius of the Gaussian image,
- \( r_s \) = radius of circle of least confusion of spherical aberration,
- \( r_c \) = radius of circle of chromatic aberration,
- \( r_d \) = radius of diffraction disc and
- \( r_t \) = total image disc radius

The radius of the diffraction disc referred to the object for a field ionization source is given by

\[ r_d \approx \frac{0.6\lambda}{\alpha_o} \]  

(2.32)

where \( \lambda \) is the wavelength of protons produced by the ion source

\( \alpha_o \) is the maximum divergence angle of beam from the source

2.4 First Order Pelletron Optics

The Pelletron Accelerator may be broken up into a sequence of discrete optical elements. These elements are illustrated in Fig. 2.2.

Fig. 2.2A shows the present Pelletron configuration. In this situation the focus from the source lens is located at the 1mm aperture at the exit of the velocity selector. This focus serves as the object for the accelerating column at a distance of 125mm upstream from the entrance. In this configuration, and with commonly used injection and acceleration voltages, the object is well outside the focal plane of the accelerator column and a crossover occurs inside the tube. This being the case, a further lens is required to produce a focus at the
Figure 2.2

First order beam envelopes for the Pelletron accelerator.

Radial scale is exaggerated for the purposes of illustration. Vertical scale upstream of the Steerer exit is also exaggerated by a factor of 5 compared with the section downstream of this aperture. Components depicted are:

IS: Ion source exit canal.
VS: Velocity selector exit aperture plane.
S: Steerer exit aperture/accelerator entrance aperture.
X: Accelerator column exit.
OS: Plane of analysing magnet object slits.

Maximum beam divergence depicted is 0.3 rad.

A:
Present configuration — Lens focus is at exit of velocity selector.

B:
Lens focus moved into Steerer — Final focus located at analysing magnet object slits.

C:
Lens focus moved to Steerer exit.
exit of the accelerator (i.e. the object slits of the analysing magnet). Originally an electrostatic quadrupole doublet was used for this purpose. This doublet was located inside the accelerator tank, immediately below the accelerating column. The electrostatic doublet however suffered from persistent alignment problems, and steered the beam away from the exit slits. Moreover, instabilities in the quadrupole strengths resulted in periodic beam loss. Once such loss had occurred, the reestablishment of the beam was rendered far more difficult and non-reproducible by the presence of the steering in the quadrupole doublet, combined with the steering by the electrostatic plates in the terminal. Since for MP use all but the core of the beam is discarded in the beam line in any case, it has proved advantageous to run without the electrostatic quadrupoles at all.

For this geometry therefore the final beam parameters are dictated by the magnet image slit settings. For 3 MeV acceleration and typical 'acceleration mode' settings of the ion source lens (refer Chapter 4), final divergence and beam radius are of the order of up to 2mrad and 8mm respectively [Co82]. For such settings, currents of 5µA through analysing magnet object slits of 2mm separation may typically be obtained for H\(^+\) beams.

A second possible mode of operation is to relocate the 1mm defining aperture to the exit of the beam steerer, a further 12.5cm downstream from the velocity selector exit. This configuration is illustrated in Fig. 2.2C. In this case the beam crossover occurs inside the focal plane of the accelerating column and so no real image is produced by the column at all. Once again a supplementary lens is required if a focus is to be obtained at the accelerator exit. Typical final radius and divergence of the beam are 9mm and 1.4mrad [Co82].

A third possible mode, illustrated in Fig. 2.2B, is to use the strong focusing properties of the acceleration entrance aperture to form the desired image at the accelerator exit. This is the technique used in many tandem accelerators to achieve a beam focus at the stripper [Co59]. In practice this focus may be achieved by moving the image formed by the electrostatic lens to an intermediate position between situations 1 and 2 above, with associated removal or relocation of the defining aperture. The actual location of this focal point is a function of
the initial emittance of the beam object as well as all other voltage parameters
[Re88c], but is located approximately 50mm inside the steerer for 3MeV protons,
5 sections of acceleration and an injection voltage of 20kV. This configuration has
advantages in that beam transmission of the Pelletron may be maximized with
a minimum number of lenses. If the RF source is replaced with a field ionization
source, the necessity to produce a focus at the accelerator exit is greater than at
present since the source inherently produces low current.

A final design possibility is to remove the ion source lens altogether and
inject the beam directly into the accelerator entrance. This configuration was
originally proposed by Van De Graaf [Va48]. The inflexibility of this configura-
tion and other practical difficulties have restricted its use in practice [Ga67], and
it will not be considered further.

### 2.5 Accelerator Brightness and MP Resolution

In an apertured MP system, with source reduced brightness $\beta$, the Gaussian
image size $r_9$ is given by equation 1.3. To this must be added the spot size con-
tributions due to aberrations in the MP quadrupole lenses, according to equation
2.31.

The theoretical minimum spot radius for chromatic aberration dominated
beams may be derived using equation 2.31 as

$$ r_{\text{min}} = \left( \frac{1}{\pi} \right)^{\frac{1}{2}} \left( C_c \frac{\Delta E}{E} \right)^{\frac{1}{2}} \left( \frac{I_0}{\beta E} \right)^{\frac{1}{4}} $$

(2.33)

where $E$ is the final energy of the beam, and $\Delta E$ is the energy spread.

Some important points follow from equation 2.33. For the chromatically
limited image, spot size reductions may be achieved by reduction or correction
of the aberration coefficients in the quadrupole lenses, or by reduction in energy
spread of the beam. Smaller improvements however are achieved by increasing
primary brightness of the beam or decreasing target current, since minimum
beam radius varies only as the fourth root of the quantity $I_0 / \beta$. For a given
minimum spot size, the current available on target is directly proportional to the
brightness of the beam provided by the accelerator. For STIM work, however,
increased beam brightness would be used for spot size reduction rather than current increase, as count rates are limited by the particle detection system [Se87].

An improvement in source brightness of several orders of magnitude is achieved with a field ionization source. If this brightness may be transferred to the start of the MP beam line, then improvements may be found in $r_{min}$ for STIM applications.

To obtain currents suitable for PIXE imaging, both object and aperture must be substantially increased in size compared with those suitable for STIM imaging. As the aperture is opened up, spherical aberration becomes the dominant lens aberration, as it varies as the cube of beam divergence.

In this situation, where spherical aberration is dominant, the theoretical minimum spot size is given by

$$r_{min} = \left(\frac{16}{27}\right)^{\frac{1}{2}} C_s^{\frac{1}{4}} \left(\frac{I}{\pi^2 \beta E}\right)^{\frac{1}{8}}$$  \hspace{1cm} (2.34)

Transposing, we obtain

$$I = \left(\frac{27}{16}\right)^{\frac{1}{8}} \frac{\pi^2 \beta E}{C_s^\frac{1}{8}} r_{min}^{\frac{3}{8}}$$  \hspace{1cm} (2.35)

It should be noted that the MP spot size is not presently limited by spherical aberration for PIXE currents [Ja85] as accelerator beam divergence is low. This point is discussed further below.

From equations 2.34 and 2.35 it is apparent that once again reduction in $r_{min}$ is achieved by increasing brightness. In the case of PIXE work however, greater spot size reduction is achieved compared with STIM work as $r_{min}$ now varies as $1/\beta$ to the $3/8$ power. On the other hand, a smaller improvement can be expected in the case of a reduction in the spherical aberration coefficient, as pointed out by Dix [Di83].

Once again, equation 2.35 indicates that for a given optimum probe size, target current varies directly as the brightness. In the case of PIXE work, improved brightness may prove to be of great practical benefit, as scan times required are inversely proportional to the target current.
It should be noted that if parasitic aberrations could be removed from the MP magnetic quadrupoles, then for the existing MP beam line (MP I), divergence at the aperture would not always be sufficiently large for optimum convergence angles to be achieved for a given required target current (i.e. for the optimum situation of equation 2.34 to be realised) [Ja85].

This could be overcome by making use of the existing electrostatic quadrupole doublet situated below the column, following suitable correction of its steering problems. This is not a possible option, however, for the redesigned Accelerator, in which the focus at the analysing magnet object slits is formed by the accelerating column (configuration 2 in Section 2.4). Furthermore for this situation, the final divergence is expected to be much smaller than is presently the case (refer Section 5.4). Nor could specimen plane convergence angles be increased by strengthening of the MP quadrupole lenses and reducing working distance, as discussed in section 1.3. These limitations may be overcome on a second MP beam line (MP II) which provides two stage demagnification. This beamline is presently under construction. The theoretical aberrations of this line are given by Moloney [Mo86, Mo87].
Chapter 3

The Field Ionization Source

3.1 Introduction

A prototype field ionization source has been constructed by Allan [Al89a]. The ionization tip provides the object for the entire Pelletron and MP optical system. As detailed in section 2.5, the optical properties of the field ionization diode thus establish upper limits on the MP optical performance, and an analysis of this region is critical to an understanding of overall accelerator optics.

The field ionization diode is located closely upstream of the ion source lens. Strictly an investigation of the source region must also include the effect of the subsequent electrodes in the source lens, and they should be included as boundary conditions. There are however, advantages in considering these two elements separately.

Firstly, the calculations are considerably simplified due to the less stringent boundary conditions, and far fewer variables are involved in calculations. Secondly, optimization is simplified due to the smaller number of variables in the calculation. Thirdly, physical insights may be obtained by considering the properties of each element separately, then subsequently combining them.

Support is lent to this 'decoupled' approach by the investigations of Kern [Ke78] who performed calculations on a field emission diode and lens, both coupled to and decoupled from each other. He concluded that to a good approximation the two results gave the same optical properties, even with the emission tip
located as close as 3.2mm upstream from the inside of the first electrode. These results are further supported by measurements by Kurz [Ku79] and by aberration calculations performed by Eupper [Eu80]. These results are explained by Kasper [Ka82] and Szilagyi [Sz88] as being due to the low curvature of the particle trajectories in the weak 'stray' field of the bore region of the first electrode which separates the strong field regions of the source lens and the emitter tip itself. As a check however, calculations were performed for the optical system by full analysis of the diode and lens together with full satisfaction of all boundary conditions, and for the diode at its closest working distance. The results of these calculations, presented in Chapter 4, support the two stage approximation discussed above. In the light of the above considerations the Field Ionization diode and electrostatic lens are analysed as separate entities in this work.

3.2 Analysis of Field Ionization Diodes

3.2.1 Introduction

An investigation of field ionization gun characteristics may draw upon the large bodies of work concerning Field Ion Microscopy, Field Emission Sources, and Liquid Metal Ionization Sources. This is so, despite the different physical processes involved in beam formation in each case, due to close similarities in source geometries and therefore optics. Allowance of course must be made for potential sign changes where appropriate.

Analysis of the optics of field emission and field ionization devices has long been problematic due to the difficulties in accurately modelling the important high field region in the vicinity of the microscopic tip, and at the same time matching boundary conditions imposed by the surrounding electrodes.

Early models represented the tip as a sphere or as a paraboloid [Wo69] or hyperboloid [Gi73] of revolution. Using a hyperboloid source and a planar extractor, Miskovsky et al. [Mi81] have presented paraxial calculations for liquid metal ion sources. These methods however, fail to accurately represent shank geometries. A more realistic tip representation is obtained using an equipotential
from the analytical field obtained from a sphere on an orthogonal cone (SOC). Using this model a number of workers have performed calculations of field emission diodes [Dy53, Wi70, Ke78] and liquid metal ion sources [Wa85]. Wiesner and Everhart [Wi73a] performed a full analysis of geometric and chromatic aberrations for an emitter tip using this model. The SOC model, though widely used, suffers from a number of deficiencies, the most serious being that the solution of the SOC field is an infinite series of Legendre polynomials, and the extracting electrode boundary may be accurately modelled only if a large number of terms are taken in this series [Ke78]. Unfortunately Wiesner and Everhart and earlier investigators considered only the lowest order term, and boundary conditions are not met, rendering the accuracy of these calculations uncertain.

The standard methods for solving Dirichlet problems, the finite element method, and the finite difference method have also been applied to emission diodes and liquid metal sources [Wa81]. The major problem with the standard finite difference method is that the requirement of a uniform mesh size precludes simultaneous modelling of the microscopic tip and the macroscopic surrounding electrodes for realistic computer memory capacities. Kang [Ka81c] has overcome this problem by introducing a spherical coordinate system with geometrically increasing radial mesh size (the 'SCHWIM' model), and has performed calculations on rounded and faceted field emission tips [Ka81c, Ka83] using this model.

The finite element model has been used by Gipson [Gi79] and also Ward and Seliger [Wa81] to calculate the potential in a field ion microscope and liquid metal ion source using finite element meshes which increase geometrically in period in the region of the tip. The application of finite element methods to such geometries has been questioned however by Ozaki [Oz81] and Kasper [Ka82] on the grounds that inaccuracies introduced by interpolation in the triangular elements in the vicinity of the ionization tip render the calculations invalid. Munro [Mu87] has attempted to remedy this by introducing a more accurate triangular interpolation algorithm. Recently Eupper [Eu85] performed detailed 3-D calculations of an emitter tip, including the shank and hairpin support by triangulation of the whole cathode surface.
Chapter 3. The Field Ionization Source

The final methods applied to emission and ionization guns are the charge simulation methods. In these models a charge distribution is solved as the source of the potential field, such that the prescribed boundary conditions are met.

Ozaki et al. [Oz81] have investigated the emission properties of a field emission gun, solving for the field by computing charges on the surfaces of the electrodes. Hoch [Ho78] on the other hand shifted the singularities into the interior of the electrodes. This method has been refined by Kasper [Ka76, 79, 81a,b] and applied to field emission guns by the addition of logarithmic singularities in the tip interior.

In this chapter results are presented of calculations performed using the methods of Kasper. These models appear to be currently the most flexible and accurate for field ionization gun calculations, and permit close modelling of all boundary surfaces.

The calculations performed assume a rotationally symmetrical field. In fact, apart from any slight irregularities in the symmetry of the tip region, an asymmetry occurs due to the semi-circular support bar upon which the ionization tip is spot welded. A typical value of the separation of the tip from the support for tips used in the Melbourne source is 5mm, with a bar radius of curvature of 5mm. This bar is located well outside the strong field region. Calculations by Ozaki et al. [Oz81] which allowed for a rough modelling of a support bar indicate the asymmetry could be safely ignored if shank length exceeds 1.7mm for a bar with radius of curvature 300µm. Investigations by Eupper [Eu85] also found that the astigmatism could be ignored for field calculations for a tip cathode welded onto a hairpin support under similar geometries. Since the support bar in the Melbourne source is located typically 5mm from the tip it will be assumed that it may be ignored in the field calculations which follow.

3.2.2 Method of Calculation

In the program suite of Kasper, the electrostatic field is obtained by a linear combination of a number of analytic solutions of Poisson's equation. These elementary fields are derived from distributions of infinitely thin plane apertures,
charged rings and cylinders, an axial charged wire with constant, but different, charges per unit length, and a point charge located at the end of the wire. All field singularities are located within electrodes. Details on these fields are given by Kasper [Ka76, 79]. Boundary specification and selection of singularities is carried out using program HP1. Boundary values are specified at a series of 'control points' (marked as “x’s” in Fig. 3.3) and charges on singularities are automatically adjusted by program HP2 to ensure boundary values are met. Care must be taken to ensure that a balance is found between increasing the number of charge rings and control points to produce high field accuracy, and matching of asymptotic conditions, and limitation in the number of rings to keep calculation times low. Generally, positioning of ring charges was carried out automatically by program HP1 but occasionally it was found preferable to override these distributions manually. Takoaka [Ta84] has pointed out that for optimal efficiency for ring use, ring separation should be inversely related to electrode surface field intensity, which in practice requires the clustering of points close to sharp edges and gaps.

The crucial region of the ionization tip is modelled by a point charge and a wire of uniform charge distribution. Following Kasper [Ka76, 79], assuming that the origin point (0, 0) lies at the tip 'centre' (note that this point is given as -1 in Fig. 3.2), the potential in the region close to the tip is given by

\[ V(r, z) = q \left( \ln \left( \frac{z + \rho}{2a} \right) + \eta \left( 1 - \frac{a}{\rho} \right) \right) \]  

(3.1)

where

\[ \rho = \left( r^2 + z^2 \right)^{\frac{1}{2}}, \]

\[ a \] is the tip apex radius of curvature,

\[ q \] is the charge density (charge per unit length) of the line of charge terminating at the tip apex 'centre' and

\[ \eta \] is a shape parameter of the tip.

The boundary condition \( V(0, a(1 + \epsilon)) = 0 \) determines that

\[ \eta = (1 + \frac{1}{\epsilon}) \ln \left( \frac{2}{1 + \epsilon} \right) \]  

(3.2)

and results in the series of 0kV equipotentials shown in Fig. 3.2.
Figure 3.1
Electron Micrographs of the Ir field ionization tip.

A:
Micrograph showing Ir emitter and shank mounted on W support bar. Radius of curvature of support bar is approximately 5mm.

B:
Micrograph of the tip end taper.

C:
Micrograph of tip region.

D:
Micrograph of tip region.

E:
Micrograph of tip region.

F:
Micrograph of the tip region, for a ‘re-etched’ tip.
3.2.3 Gaussian Optics

Fig. 3.1 shows SEM micrographs of Ir tips, produced by the technique developed by Allan [A189a]. Due to the nature of the etching process, as well as the crystalline variation of the Ir wire, a degree of variation in tip profile and size is observed. Experience shows that sharp protuberances and irregularities on the tip and shank are removed by field evaporation and ion-bombardment during operation in the source. Overall tip shape however, may be expected to remain constant providing spark damage does not occur [A189a].

Tips with profiles similar to Fig. 3.1D are chosen in preference for source operation as they may be expected to produce more strongly forward peaked emission than tips of profile shown in Fig. 3.1F. Table 3.1 shows the tip parameters used in program HP1 as obtained by a match of a 'typical' forward-peaked tip profile to the 0kV equipotential.

A shape factor ε (see Kasper [Ka76, 79] and Fig. 3.2) of 0.3 was found to be most suitable for such tips. Fig. 3.3 shows the overall gun geometry used for modelling a tip of distance 3mm from the 2mm diameter cathode aperture. All dimensions were taken directly from the source built by Allan. Voltages in Fig. 3.3 are assumed to be -20kV on the aperture with the tip grounded.

It may be noted that although the Kasper suite was written for electron ray tracing, and assumes the tip to be at zero potential with a positively biased extractor electrode, equipotentials for a positively biased tip are identical in shape and are obtained by simply reversing the sign of the equipotential. Fig. 3.4A shows a magnified view of the tip region, with equipotentials indicated in 1kV steps.

Kasper [Ka82] has pointed out that conceptually a field emission or field

<table>
<thead>
<tr>
<th>Shaft length (mm)</th>
<th>Shaft width (mm)</th>
<th>Taper length (mm)</th>
<th>Shape factor</th>
<th>Tip radius (μm)</th>
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<td>0.9</td>
<td>0.3</td>
<td>0.1→ 0.4</td>
</tr>
</tbody>
</table>

Table 3.1: Field Ionization tip parameters as used for final optical calculations
Figure 3.1 continued.
ionization diode may be considered to consist of two roughly distinct regions. The first region consists of a nearly radial field with high initial particle acceleration. For the geometry of Fig. 3.4A the ions have gained 25% of their kinetic energy within 1.3 tip diameters and 50% of their energy within 24 tip diameters of the source. The second region, at larger distances from the tip consists of mainly transverse field components. However, the particles have already gained too much kinetic energy to be strongly deflected in this region. The overall effect of these fields is one of weak focusing, with a virtual source located somewhere behind the tip. To these must be added the weak defocusing effect of the transition from the accelerating region in the field ionization diode to the field-free region downstream from the extracting aperture.

Raytracing was carried out using a modified version of program BAHN, which calculates trajectories using an accurate predictor-corrector method. The location of the virtual image for each ray was obtained by ‘tracing back’ the tangential ray to the point where the tangent crosses the optical axis. Such traces are shown in Fig. 3.4A.

Fig. 3.4B defines three important groups of particles emitted from the ionization tip (or rather from just above it — see Section 3.2.5). Firstly there are those emitted at right angles to the tip surface, at points away from the apex. Secondly there are those emitted from the same points, whose initial velocity is tangential to the tip surface in the meridional plane. Thirdly there are those emitted from the tip apex (i.e. on axis) at a range of angles between 0 rad and π/2 rad.

The position of the Gaussian image plane is obtained, following the method of Wiesner and Everhart [Wi73a], by considering virtual image positions for ions commencing at right angles to the tip’s surface at various starting inclinations to the optical axis and extrapolating to zero angle.

Angular magnification may be obtained by evaluating

\[ M_a = \frac{\theta_v}{\theta_c} \]  

(3.3)

Where \( \theta_c \) is the inclination angle of the ray starting point on the tip.
Figure 3.1 continued.
Figure 3.2

Variation in emitter tip end profile for different values of $\epsilon$, as used by the Kasper suite of programs.

The tip end is 'centered' at -1 on the horizontal axis. Numbers on the curves indicate the values of $\epsilon$.

(After Kasper [Ka79]).
**Figure 3.3**

Field ionization gun geometry in radial section.

Control points (labelled 'C') are shown as crosses. Charged rings (labelled 'R') are shown as squares. 'A' marks charged apertures. The shank of the Ir emitter lies along 'OT', with the centre of the tip located at 'T'.

Equipotentials are labelled in kV along the left hand margin. Tip potential is 0kV.

Note the different scales for radial and transverse coordinates.
Figure 3.4A

Magnified view of the tip region, for a tip specified by parameters listed in Table 3.1.

'A' denotes tip apex location. Macroscopic geometry is identical to Fig. 3.3 with extraction aperture voltage of -20kV. Absolute values of equipotential voltages are shown in kV along the box margin.

Heavy arrows denote raytraces from the tip surface. Dashed lines show tangents from rays traced to 0.1mm downstream of 'A'.

The scale is the same in radial and transverse directions.
Figure 3.4B

Figure defining important categories of initial conditions for beam particles.

These initial conditions are:

(1): Particles commencing at off axis locations on the tip, with initial velocity at right angles to the tip surface. This is shown in the Figure as ray 1, commencing at point $P$, with initial direction $N$, at initial divergence $\theta_c$.

(2): Particles commencing at off axis locations on the tip, with initial velocity parallel to the tip surface. These are shown as rays 2 and 3, commencing at point $P$, with initial directions $T_1$ and $T_2$ respectively.

(3): Particles emitted from the tip apex. These are shown as rays 4 and 5, commencing at the apex point $A$. The initial divergence of ray 4 is shown, and is of value $\alpha_o$. The initial divergence of ray 5 (not shown) is $\pi/2$.

Point $F$ is assumed to be in field free space. The final field free divergence of ray 1 is indicated as angle $\theta_u$. 
\( \theta_v \) is the final, field-free ray divergence for each ray, and once again extrapolating to zero angle.

The apparent source size of the Field Ionization tip is much smaller than the tip radius, since a radially outstreaming ion appears to come from a virtual point close to the centre of the tip. Using conservation of angular momentum, Gomer [Go61] showed that for ions of gas temperature \( T \), the virtual source has radius \( r_* \) given by

\[
   r_* = 4 \chi r_t \frac{kT^{1/2}}{eV_s}
\]

where \( V_s \) is the final particle energy,

\( k \) is Boltzmann's constant,

\( r_t \) is the tip end radius,

\( \chi \) is a tip geometric factor, typically \( \sim 1.5 \).

Wiesner and Everhart [Wi73a] however point out that below a certain emission angle, equation 3.4 no longer provides an accurate value of apparent source size. Instead, at low angles, the virtual source size is determined by the size of the waist formed by backward tracing of tangentially emitted particles. This waist is located approximately half way between the tip surface and its centre. For this condition, the size of the Gaussian virtual source, for a final ray divergence \( \theta_v \), is given by

\[
   r_* \simeq \frac{1}{2} r_t \theta_v
\]

For the calculations performed on the Field Ionization source, the half angle at which these two expressions give equal values (and hence below which equation 3.5 limits spot size) is approximately 0.01rad. Of course the object position of the optical system is thus shifted slightly between the two situations described above, but the displacement is small enough to be negligible (see Table 3.3).

To determine the Gaussian image size from equation 3.5 the magnification \( M \) must also be known. This may be determined by a fit to the data from a group of particles emitted from the apex of the tip at a range of angles of the
Abbe sine condition:

\[ M = \frac{v_o \sin \alpha_o}{v \sin \theta_v} \]  

(3.6)

where \( \alpha_o \) is the divergence angle of rays emitted from the tip apex,
\( \theta_v \) is the final field-free ray divergence,
\( \frac{v_o}{v} \) is the ratio of initial to final particle velocities.

Although this expression is strictly correct for aberration free imaging only, negligible errors are encountered for its use for rays of low divergence (i.e. below 0.01 rad) [Wi73a].

The investigation of the Gaussian optical properties was carried out systematically for a range of geometries and voltages, and in each case the values of virtual object, angular and lateral magnification extracted. The results are presented in Table 3.3.

3.2.4 Geometric Aberrations

From equation 2.16 the increase in image radius due to third order aberrations may be written:

\[ \Delta r_i = L r_o^3 + J r_o^2 r_s + K r_s r_o^2 + L r_o^3 \]  

(3.7)

where \( r_o \) refers to radius in the object plane,
\( r_s \) refers to radius in an aperture plane.

Considering an aperture plane in the field free region behind the extraction aperture then

\[ r_s \propto \tan \theta_v \]  

(3.8)

where \( \theta_v \) is the final, field free divergence.

Since the axis crossing displacement \( \Delta z \) from the image position is given by

\[ \Delta z = \frac{\Delta r_i}{\tan \theta_v} \]  

(3.9)

equation 3.7 may be rewritten as

\[ \Delta z = \frac{Mr_o^3}{\tan \theta_v} + J' \tan^2 \theta_v + J' r_o \tan \theta_v + K' r_o^2 + \frac{L' r_o^3}{\tan \theta_v} \]  

(3.10)
For calculations on normally emitted protons from the tip surface the axis crossing displacement $\Delta z$ was plotted against $\tan \theta_v$ for all geometries investigated below, and in all cases a good fit was found to the relation $\Delta z = -C \tan^2 \theta_v$ independently of $r_o$. In each case a plot was also made of $\Delta z$ against $\theta_v$ for protons emitted from the tip apex at a range of starting angles. The fit indicated an index of $\theta_v$ of almost precisely 2 and also gave values of $C_v$ in good agreement with $C$ obtained from the normally emitted protons. It may be concluded therefore, following Wiesner and Everhart [Wi73a], that all geometric aberrations other than spherical are negligible. The values of $C_v$ obtained are discussed in Section 3.3 below.

3.2.5 Chromatic Aberrations

The change in beam radius for a change in initial energy of a beam may be written [Sh83]

$$\Delta r_v = \frac{\Delta V}{V}(C_1 r_v + C_2 r_v)$$

(3.11)

In practice for a Field Ionization source there are two distinct components of momentum spread in the initial beam. These are tangential and normal. These momentum spreads may be of greatly different sizes and caused by different physical processes. In addition, the resulting aberration coefficients are found to be of different magnitudes and opposite signs.

For all but very small angles the tangential spread directly determines the 'Gaussian' image size as defined in Section 3.2.3. For angles below the threshold discussed in that section, the tangential momentum spread is not included in the derivation of the Gaussian image size and so must be explicitly included. For this reason, and also for completeness, the tangential aberration coefficients were calculated for all investigated geometries and voltages.

Following Uchikawa [Uc83], the tangential momentum spread was assumed to obey a thermal Maxwellian distribution, with most probable particle energy at 290K being 0.038eV.

In the normal direction, momentum spread is dominated by the intrinsic energy spread of the field ionization process. Studies by Hansen [Ha74] and
Beckey [Be77] indicate that field ionization takes place in the region immediately above the surface and not on it. As a result H\(^+\) energy is less than the applied voltage. The spread in particle energies is due to two processes. Firstly, it is caused by vibrational and rotational motions of the diatomic H\(_2\) molecules during dissociation [Ha74]. Secondly there is further spread due to enhanced ionization of atoms at certain distances from the surface where atom-surface well energies are in resonance with the energy of the electron in the H atom [Be77]. It should be noted that these are inherent energy spreads of the field ionization process, and exist independently of energy spread due to gas temperature, power supply instability or particle relaxation due to space charge effects.

Only the second process of momentum spread is sensitive to gas temperature [Ha74]. Measurements by Hansen [Ha74] identify the peaks in the H\(^+\) field ionization energy spectrum which are due to each process, and hence permit the calculation of H\(^+\) energy spread at room temperature. The full width of the main vibrational-rotational peak is approximately 2.1eV at a field of 22V/nm, increasing to 5.7eV at 28V/nm. The full spread of the beam including 'resonance broadening' increases from 15eV for 22V/nm to in excess of 40eV at 28V/nm at 21K. Details of central peak beam spread, as a function of tip apex field may be derived from figures provided by Hansen.

Initially the effect of an energy deficit on the particles was modelled for the Field Ionization source by starting particles with Maxwellian initial energy from the appropriate equipotential above the tip surface. The chromatic aberration coefficient for such an energy deficit however is the same as for an energy surplus, so for simplicity in later calculations particles were traced from the region between the tip and the 10eV equipotential with energy spread represented by a particle energy surplus (i.e. by non-zero initial particle speeds). To separate the effect of tangential and normal chromatic spreads from each other, and to separate them both from the effects of geometric aberrations, rays were traced from a range of starting regions on the tips, both normally and tangentially emitted, and with a range of initial energies. The shift in axis crossing location, \(\Delta z\), was noted from the axis crossing position of a normally or tangentially emitted ray,
as appropriate, of unshifted starting energy, at the angle of emission in question. It was found that for low energy spreads $\Delta z$ is linearly related to $\Delta V/V$ such that we can write

$$\Delta z = +C \frac{\Delta V}{V}$$

(3.12)

and using equation 3.9 we obtain

$$\Delta r = -C \frac{\Delta V}{V} \tan \theta_o$$

(3.13)

This equation indicates that in equation 3.11 only the on axis chromatic aberration effect is important for these energies for the tip geometries investigated. The constants $C$ in the case of tangentially emitted and normally emitted rays are of different magnitude and of opposite sign. Values of chromatic aberration coefficients for a range of tip sizes and working distances are given in Table 3.4.

The analysis so far has ignored the effect of the beam itself on the electric field. Space charge has two effects. Firstly it causes radial spreading of the beam due to the mutual repulsion of the particles, and secondly it causes radial and transverse energy spreading due to the conversion by particles of potential to kinetic energy [Kn79, Kn81]. These effects are expected to be most significant in the region of the tip since the charge density is highest there, the particles are moving relatively slowly and they are in an ‘unrelaxed’ state due to the inhomogeneity of their emission. Calculations by Yau et al. [Ya83] suggest energy broadening effects on keV ion beams are significant only in the first 0.2mm of flight.

The energy spreading in divergent, collision free ion beams has been investigated by Knauer [Kn79, Kn81]. The beam from the Melbourne field ionization source falls into Knauer’s ‘single file’ regime of low space charge effect due to its low angular current density. Yau et al. performed calculations for H$^+$ beams for a spherical emitter tip and found negligible energy spreads for beams up to 1$\mu$A for a 2000nm radius source with tip field of 10V/nm. These results are supported by measurements by Okutani et al. [Ok83] and calculations by Sasaki [Sa86] for Ga$^+$ for a LMI source, which may be used as a upper bound for the spreading of energy in H$^+$ beams. Finally experimental work by Hanson and
Siegel [Ha79, Ha81a] support the conclusion that the beam spread due to space charge in 'conventional' (i.e. non-'supertip') H+ field ionization beams is small enough to neglect.

To correctly model the beam energy spread due to trajectory displacement by space charge repulsion requires an iterative field calculation and raytracing routine. Calculations for beam spread of electrons from field emission guns have been carried out by Kang [Ka83] amd Killes [Ki84]. It is expected that the beam spread for ions is worse than for electrons since broadening increases for higher \( m/q \) ratios. Yau et al. [Ya83] have performed calculations for an H+ source with an emission semi-angle of 20mrad and a tip field of 10V/nm. They found significant target spot radius increase for the gun for H+ currents only in excess of approximately 30nA. The Melbourne field ionization source typically operates with a tip field in excess of 20V/nm and a maximum achievable current of less than 1nA into a cone of semi-angle 20mrad. Consequently the effects of space charge are safely ignored in the calculations for the Melbourne field ionization source. Such would not necessarily be the case for a source operating with a 'supertip' however. Measurements by Schwoebel and Hanson [Sc86] suggest total beam currents in excess of 100nA are possible with such tips.

3.3 Beam Characteristics of the Field Ionization Ion Source

3.3.1 Current Characteristics

Theoretically, the total beam current for H+ for a field ionization source falls into two domains. At low applied fields current is limited by the mean lifetime for ionization of molecules near the apex, and the gas supply function to the tip [Be77]. Since both factors are strong functions of apex field, total current is a very strongly increasing function of applied voltage. On the other hand at high fields, the probability or ionization of a molecule near the apex is 1 and current is limited by the gas supply function only. The gradient of the current/applied voltage curve is consequently lower in this region. Measurements of total field ionization current as a function of applied voltage for the Melbourne ion source were made
by Allan [Al89a]. These measurements clearly showed the two different domains discussed above. Allan however found a degree of variability between tips, with each tip having slightly different emission characteristics and hence curve shape.

The region of the gradient change in the current/voltage curve is often referred to as the 'cut off point' and occurs at a characteristic tip apex field strength for a given ionizing gas, tip metal and temperature. Room temperature measurement by Muller and Bahadur [Mu56] placed the cut off point at 17V/nm for H₂ above W. Later measurements by Tsong and Muller [Ts66] referred to constant field by Levi-Setti [Le80c] give a value of 25V/nm also for W. Measurements by Orloff and Swanson [Or75a] using Ir emitter tips place the knee at 21.3V/nm. This last value will be used in this thesis. The position of the cut off point was shown by Southon [So63] to be unaffected by gas pressure.

The position of the cut off point in the total current curve thus permits the voltage as measured by Allan to be calibrated against tip field for each ionization tip. From a knowledge of the tip-aperture separation a value of the radius of the tip may be determined. An examination of Table 3.2 below indicates a typical tip radius as used by Allan of between 0.15µm and 0.20µm.

Allan’s [Al89a] voltage measurements were made with an error below ±0.5% and tip aperture separations within an error of ±0.1mm. The location of the cut off point in the current/applied voltage curves could be typically located to an accuracy of ±0.4kV. As a result, the final tip size from each set of measurements by Allan may be determined within an error of approximately ±0.01µm.

Beckey [Be77] has shown that in the region of the cut off point the total ion current is approximately proportional to \( r_t^{-2.5} \) for a given gas pressure. Since the maximum possible current is required from the source it is best to operate with a relatively large tip radius. Unfortunately the apex electric field decreases with increasing tip radius as approximately \( r^{-1} \). To compensate for this decrease in field the tip may be moved closer to the aperture or the applied voltage may be increased. In order to quantify the options available (as well as to determine the size of the tips in use), program FELD was used to calculate the apex field
as a function of tip radius, applied voltage and tip-aperture separation for the
tip geometry described above and a 2mm diameter aperture. The results are
presented in Table 3.2.

The table also shows the impossibility of obtaining significantly greater
current by further increasing $r_t$ and decreasing the tip-aperture separation for
a given applied voltage. The reason for this is the marked insensitivity of the
apex field to the separation of tip and aperture. This is because in all cases the
high tip field value is due principally to the small absolute size of the tip rather
than the proximity of the grounded aperture, due to the extreme scale difference
between the tip and the relatively distant aperture. Thus for example for a tip
of radius 0.1µm, a reduction in the tip-aperture plane separation from 5mm to
1mm increases the apex field by only 10%. In contrast, an increase in tip radius
from 0.1µm to 0.15µm for a given separation decreases the apex field by 31%.
At the same time, the bringing in of the tip from 5mm to 1mm greatly increases
the danger of sparking for a given applied voltage.

Nor is it possible to simply increase both tip radius and applied voltage
for a fixed separation, thereby maintaining constant tip field. Hawley [Ha68]
showed that the likelihood of vacuum electrical breakdown over distances of
several millimetres is not simply a function of electric field, but also the total
applied voltage. The possibility of breakdown in other parts of the apparatus
also increases with an increase in absolute applied voltage.

A reduction in aperture radius may be expected to produce similar, small
increases in the apex field, of the same order as those produced by the reduction
in the tip/aperture plane separation discussed above.

Measurements of the angular distribution of ions from the field ionization
tip were made by Allan [Al89a]. Making corrections for the total annular emission
area these results may be used to determine current angular density as a function
of emission half angle. By this method peak current density was determined as
approximately .15µA sr$^{-1}$. This value, as expected, lies approximately a factor of
4 below the peak current densities achievable using a field ionization tip cooled to
liquid N$_2$ temperatures [Ts66]. Fig. 3.5A displays typical angular current density
Table 3.2: Fields at the apex of a Field Ionization Emitter for a range of tip radii, tip to aperture distance and applied voltage. In all cases the tip shape factor, taper length, shaft diameter and aperture size are as specified in Table 3.1. Calculations were carried out using Program FELD. Two field values are important: 1: The steep section of the current/voltage curve lies below $F = 21.3\text{V/nm}$. (It is therefore desirable to operate the ion source above this field threshold). 2: Field evaporation of Ir occurs at approximately $50\text{V/nm}$ (so fields above this will not be achievable in practice).
Figure 3.5

A:

Typical current density for the field ionization source as a function of acceptance half angle.

'Differential current density' denotes the differential current density as a function of half angle. Values are taken from measurements by Allan [A188], and averaged either side of the central maximum to give half angle results. 'Average current density' is derived from integrated current divided by total solid angle.

B:

Typical total beam current for the field ionization source as a function of acceptance half angle for the source in Fig. 3.5A.
A

Angular Current Density (nA sr⁻¹)

Differential

Average

B

Total Beam Current (nA)

\[ r = 0.17 \text{ microns} \]

\[ H_2 \text{ pressure} = 1 \text{ mTorr} \]

\[ T = 293 \text{K} \]

\[ V = 17 \text{kV} \]
from the source, showing both differential and average current density ($\frac{dl}{d\theta}$ and $I_\theta$). It may be seen that the current density falls off only slowly with emission half angle, reflecting the broadly divergent nature of the source.

The irregularities in the density and total current curves are the result of irregularities on the tip surface, due largely to the random alignment of Ir crystals in the tip region [Al89a].

Orloff and Swanson [Or75a] and Lewis et al. [Le86b] also found broad divergent field ionization beams, characterised by strong off axis emission due to crystal orientations in the tip. The use of aligned single crystal Ir wire for emitter manufacture should reduce these inhomogeneities as well as make the current distribution more strongly forward peaked [Bo88]. Further details on tip behaviour and current measurement are given by Allan [Al89a].

Despite the inhomogeneities discussed above, Fig. 3.5A may be taken as typical of ‘high current’ beam profiles as measured by Allan. Fig. 3.5B displays the total current as a function of emission half angle determined for the same field ionization tip. By applying mass spectrometry to field ionization sources Clements and Muller [Cl62] found that the beam produced is a mixture of $H^+$, $H_2^+$ and $H_3^+$ ions, the proportions of which vary strongly as a function of tip field strength. Current attenuation factors as a function of field strength are given by Clements and Muller [Cl62]. These factors were used in the total $H^+$ current calculations performed in the brightness calculations below.

### 3.3.2 Optical Properties

Optical calculations were carried out for a range of tip-aperture separations, tip sizes and applied voltages. In each case all Gaussian and chromatic and spherical aberration coefficients were extracted from polynomial fits to the data as discussed above.

Tables 3.3 and 3.4 show the result of calculations for geometries and applied voltages commonly used by Allan in operating the field ionization ion source.

The results show that the distance behind the tip of the virtual image
### Table 3.3:

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<th>V (kV)</th>
<th>$D_o$ (mm)</th>
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Table 3.3: Table showing some results of Gaussian calculations for field ionization sources. Results are presented for a tip with parameters specified in Table 3.1 showing the effect of change in tip radius, tip to aperture distance ($D_o$) and applied voltage. The value $\Delta z_{oo}$ represents the Gaussian image location in millimetres behind the tip 'centre'. $M$ and $M_\alpha$ represent the transverse and angular magnifications respectively.
Table 3.4: Table showing some results of aberration calculations for field ionization sources. Results are presented for a tip with parameters specified in Table 3.1, showing the effect of change in tip radius, tip to aperture distance and applied voltage. $C_{c\perp}$ and $C_{c\parallel}$ represent the chromatic aberration coefficients for particles commencing at right angles to and parallel with the tip surface respectively. All coefficients are shown as positive although $C_{c\perp}$ and $C_{c\parallel}$ are in fact of opposite sign.
increases strongly with increasing tip-aperture separation, although it shows little variation with applied voltage. It also weakly increases with increase in tip radius. For a tip 1mm from the aperture plane, the virtual object lies approximately 4.5μm behind the tip apex for almost any tip size or applied voltage.

Angular and transverse magnification also show little variation, with the value of $M$ lying between .6 and .71 and the value of $M_\alpha$ lying between .33 and .41 for all situations investigated.

Spherical aberration is also shown to increase strongly with increased tip-aperture separation, and less strongly with increased tip radius and decreased applied voltage. Thus an increase in tip-aperture separation from 1mm to 3mm results in an approximately 6 fold increase in the spherical aberration coefficient, whilst a doubling of tip radius results in a 30% increase only. A further increase in separation from 3mm to 5mm results in a further 3 to 4 fold increase in $C_\alpha$. For comparison, calculations by Takaoka and Ura [Ta84] for an emission tip with apex field 4V/nm and tip-anode separation of 10mm gave a $C_\alpha$ of 400μm.

The perpendicular $C_\perp$ coefficient behaves in a similar way as $C_\perp$ with an increase in tip-aperture separation from 1mm to 3mm resulting in a doubling of the coefficient with further small increases for increasing tip-aperture separation. An increase in tip radius or decrease in applied voltage generally produces only a slight increase in aberration coefficient. Trends in the parallel $C_\parallel$ coefficient are not so pronounced, but the coefficient is more sensitive to changes in tip/aperture separation at small radii than at large.

The perpendicular $C_\perp$ coefficient is in all cases considerably smaller than, and of opposite sign to, the parallel $C_\parallel$ coefficient.

3.3.3 Effective Source Size and Brightness

The total apparent source radius may be obtained by using equations 2.31, 3.7, 3.10, 3.13 and 2.32 giving

$$r_a = (r_p^2 + (\frac{1}{2} C_{\parallel} \frac{\Delta E_{||}}{E} \tan \theta_v)^2 + (\frac{1}{2} C_{\perp} \frac{\Delta E_{\perp}}{E} \tan \theta_v)^2 + (\frac{1}{4} C_\parallel \tan^3 \theta_v)^2 + (\frac{0.6\lambda}{\theta_v})^2)^{\frac{1}{2}}$$

(3.14)
Figure 3.6

Source effective radius contributions for a field ionization source as a function of divergence half angle. Radius of tip = 0.2µm. The curves indicate the following source size contributions:

- $r_g$: Gaussian radius.
- $r_d$: Radius of diffraction disc.
- $r_c$: Radius of chromatic aberration disc.
- $r_s$: Radius of spherical aberration disc.
- $r_t$: Total effective source size.

Tip/extraction aperture distance, $D_o$ and applied voltages are:

A: $D_o = 1\text{mm}, V_{ap} = 16.3\text{kV}$
B: $D_o = 5\text{mm}, V_{ap} = 18.1\text{kV}$
Tip apex field = 25 V/nm
Tip radius = 0.2 microns
$D_o = 1$ mm

**Graph A**

Effective Source Radius (mm)

- $\Gamma_t$
- $\Gamma_s$
- $\Gamma_c$
- $\Gamma_d$
- $\Gamma_g$

Half Angle (Radians)

**Graph B**

Tip apex field = 25 V/nm
Tip radius = 0.2 microns
$D_o = 5$ mm

Effective Source Radius (mm)

- $\Gamma_t$
- $\Gamma_s$
- $\Gamma_c$
- $\Gamma_d$
- $\Gamma_g$

Half Angle (Radians)
where $\Delta E_\perp$ and $\Delta E_\parallel$ denote the energy spreads in the perpendicular and parallel initial trajectories, and $E$ the final beam energy.

This equation was evaluated using the values for aberration coefficients from Table 3.4 and with the geometric parameters listed in Table 3.1.

Fig. 3.6 shows the individual contributions to effective source size for a tip with $r = 0.2 \mu m$. Diffraction effects are shown to be negligible for all angles above $\sim 1\text{mrad}$. Above $\alpha = 0.06\text{rad}$ spherical aberration of the source dominates spot size, and source size rapidly increases above this angle. Below this angle source size is determined by the Gaussian spot size calculated using equation 3.4, and below $\alpha = 0.01\text{rad}$ by the smaller Gaussian spot size determined by equation 3.5. In no region is the chromatic contribution dominant for an energy spread of 10eV. A comparison of Figs. 3.6A and 3.6B show that as tip-cathode separation increases the angle at which spherical aberration becomes dominant decreases.

Current angular distribution was determined from Fig. 3.6 and the corrections $r^{2.5}$ made for the tip radius. Corrections to the total current were also made for the fraction of the beam which is $H^+$, from the results of Clements and Muller [C162]. Using the resultant $H^+$ current as a function of angle, and the effective radius as calculated using equation 3.14, $\beta$ was determined over the range of tips analysed.

The resultant brightness as a function of angle, and as a function of $H^+$ current for tip geometries of importance is shown in Fig. 3.7. It should be noted that the calculations assume total beam transmission, whereas in fact for a 1mm working distance emission is restricted to 1rad and for a 5mm working distance it is restricted to 0.2rad.

An examination of Fig. 3.7A shows a fairly uniform high brightness of $10^6 \text{Am}^{-2}\text{rad}^{-2}\text{V}^{-1}$ for small angles, with rapid fall off occurring at larger angles due to the rapid increase in effective source size due to spherical aberration along with a decrease in angular current density. Closer tip/aperture working distances clearly provide a brighter source at high divergence angles for a given applied tip apex field. The increase in brightness below 0.01rad reflects the small Gaussian source size determined using equation 3.5 at low angles, but Fig. 3.7B
Figure 3.7

A:  
Source brightness as a function of divergence half angle, for a tip with radius 0.2\(\mu\)m. Labels on curves denote tip/extraction aperture separations.

B:  
Source brightness as a function of total current. Labels on curves denote tip/extraction aperture separations.
Figure A: Brightness (A m⁻² rad⁻² V⁻¹) versus Half Angle (Radians) for different tip lengths (0.1 mm, 1 mm, 3 mm, 5 mm) with tip electric field of 25 V/nm and radius of 0.2 microns.

Figure B: Brightness (A m⁻² rad⁻² V⁻¹) versus Current (nA) for different tip lengths (0.1 mm, 1 mm, 3 mm, 5 mm) with tip electric field of 25 V/nm and radius of 0.2 microns.
indicates that total current is restricted to below 10pA in this region.

Fig. 3.7B indicates that a fall off in brightness occurs for all working distances at approximately 500 → 600pA but that once again the rate of drop off is considerably lower for smaller working distances than for larger.

From Fig. 3.7B it is seen that the source may be expected to produce a current of 1000pA with a brightness in excess of $5 \times 10^5 \text{ Am}^{-2}\text{rad}^{-2}\text{V}^{-1}$ at half angle of approximately 100mrad for tip radius of .2µm and a working distance of 1mm.

Calculations were performed to determine the effect of changes in tip radius and tip field on source brightness. It was found that for currents below approximately 500pA an increase in tip radius produces a small increase in brightness. For an increase in radius from .15µm to .2µm brightness increases by 40%. A further increase in tip radius produces only a negligible increase in brightness. For high currents, a substantial decrease in brightness occurs for small tips since for these tips large currents require a significant increase in beam angle acceptance. These results are illustrated in Fig. 3.8.

Brightness is also found to increase with increasing tip apex field. The strong increase in beam energy spread with increasing field however limits the increase in brightness in the region 1 → 5nA above fields of 30V/nm. For currents below or above this region, the effective spot size is dominated by Gaussian and spherical aberration discs respectively and hence brightness continues to increase with increasing apex field. It is seen in Chapter 4 however that chromatic aberrations in subsequent optical elements negate the advantage of operating the source for high currents at fields above 30V/nm.
Figure 3.8

Source brightness as a function of half angle and total current, with variations in tip size and tip apex field. Curves correspond to:

1: $r = 0.15\mu m$, $F = 25V/nm$.
2: $r = 0.20\mu m$, $F = 25V/nm$.
3: $r = 0.25\mu m$, $F = 25V/nm$.
4: $r = 0.20\mu m$, $F = 30V/nm$. 
4.1 Introduction

The present Pelletron electrostatic lens serves to extract, accelerate and collimate the beam from the RF ion source, and to produce a beam focus which serves as an object for subsequent optical elements. The field ionization ion source was shown in Chapter 3 to be considerably brighter than the RF source. At the same time however, the beam is considerably more divergent, more energetic, and produces approximately 3 orders of magnitude less current than the RF source. These three factors combine to make the optics of the electrostatic lens critical to the performance of the whole redesigned Pelletron optical system.

The importance of the source lens has long been recognised in the area of field emission microscopy where very bright W field emission tips are employed. Special low aberration lenses have been developed for microscopes using these sources [Bu66, Cr68, Cr70] and, for the design of a field ionization lens, much use may be made of experience gained in the field of electron microscopy. There are however, some important differences. Firstly the mechanism of field ionization requires higher fields (i.e. smaller, sharper tips, with larger applied voltages) than does field emission. Secondly, the field ionization tip must be immersed in an atmosphere of H₂ of the order of 1mTorr, compared with the UHV conditions of field emission sources. Finally the ion source is also required to be located in a high voltage accelerator terminal. In the Melbourne University Pelletron it is
located in a dome inaccessibly located in a pressurised tank.

Orloff and Swanson [Or75a,b] have investigated lens systems for a field ionization source, but were not concerned with high currents or subsequent acceleration of the beam as they were concerned with development of a low energy, low current ion implanter. Other designs for field ionization ion source lenses have been considered by Blackwell et al. [Bl85], Lewis et al. [Le86b] and Hanson and Siegal [Ha81a]. Other authors have investigated a number of lenses for use with liquid metal ion sources designed generally for secondary ion mass spectroscopy applications [Ku85, Ah85, Cu87]. Read et al. [Re88c] however, have proposed a lens design for operation with a LMI source within a 5MV Laddertron Accelerator. Besides these investigations there is a broad range of data published on different designs for electrostatic lenses for a wide variety of applications in areas of electron microscopy and electron and ion spectrometry, and other related fields. A survey of electron lens designs and techniques was made by Baranova and Yavor [Ba84].

The aim of this chapter is to investigate the present electrostatic lens, as well as alternatives, to find a workable lens to satisfy the requirements of use in a 'field ionization gun'.

During this analysis it is worth bearing in mind the comments made by Kasper [Ka82], when investigating the design of tips and lenses for field emission guns. He concluded, after a survey of possible designs, that 'the value of ... theoretical considerations ... is not the presentation of the “optimum ” field emission electron gun, which does not exist, but the illustration of the necessary compromises in any practical design' (my emphasis). The same can be said as convincingly for field ionization guns.

### 4.2 The Present Electrostatic Lens

The existing lens shown in radial cross section in Fig. 4.1 consists of 4 coaxial cylinders, with the first element having a conical bore and a tapered entrance snout. The ion source exit canal is located 5.5mm upstream of the entrance of
Figure 4.1

Present Pelletron RF source lens and canal exit.

Outlines of lens electrodes and supports are shown in heavy lines. Finer lines indicate the finite element calculation grid. The uppermost electrode corresponds to the RF source exit flange. Letters indicate control voltages for lens operation. Voltages shown in brackets denote the voltages as discussed in the text.

P: Probe ($V_{(0)}$)
E: Extractor ($V_{(1)}$)
F: Focus ($V_{(2)}$)
B: Bias ($V_{(3)}$)
Chapter 4. Ion Source Lenses

this lens. However the shape of the source plasma and the length of the canal place the effective source a further 6.1mm upstream [AI80].

The first and third electrodes are wired at the same potential. There are thus 3 control voltages called ‘Extractor’, ‘Bias’ and ‘Focus’ which are varied by the operator to obtain a required beam focus. This permits 2 degrees of freedom for any particular setting of the probe voltage. Of course although a focus may be obtained, the image is not necessarily an optimum one, there being a wide variation in magnification and aberrations for the different possible sets of electrode settings. These degrees of freedom are indeed found when operating the accelerator. For a given probe setting there is a wide range of settings which give a local maximum of current (and hence a focus) at the velocity selector aperture. Moreover it is noted, as expected, that a satisfactory focus may be obtained when one or other of the electrode power supplies is inoperative, by using appropriate settings of the other voltages.

The mesh used for lens analysis is shown in Fig. 4.1. Care was taken to ensure correct boundary conditions were achieved, particularly in the gaps between the electrodes. Rather than assume a linear potential gradient between electrodes at the tube walls, the tube elements were ‘hung’ from their support structure with a linear potential gradient assumed between these supports. The tube support geometry was taken directly from engineering diagrams of the lens structure. Fig. 4.2 shows an example of an equipotential plot for the lens with an accompanying ray trace.

A full ion optical analysis of this 4 element lens was complicated by the 3 degrees of freedom present in the system. Final to initial energy ratios were kept in the range of 1 → 16. Extraction voltages were then varied and using the general function minimization program STEPIT [Ch65], the ‘Focus’ potential was adjusted to produce a focus at the velocity selector aperture plane. Fig. 4.3 indicates the locus of calculated voltages. In this section, the voltages discussed are defined as those on the Probe ($V_0$), Extractor ($V_1$), Focus ($V_2$) and Bias ($V_3$) (see Fig. 4.1).

As noted by Read [Re70] and Heddle [He74b] for 3 element lenses, in
Figure 4.2

Example of equipotential plot and ray trace for the present Pelletron lens, operating in a decelerating focus mode. The maximum divergence of rays is 120 mrad.
general for a given set of other voltages there are 2 values of the ‘Focus’ which produce the required beam focus, termed ‘acceleration’ and ‘deceleration’ modes.

For the Pelletron lens in acceleration mode, several remarks may be made following Fig. 4.3. Firstly, for the case where no beam crossover occurs in the lens (termed ‘zero crossover’) voltage ratios of up to about 15 are required for the focus. Secondly, for zero crossover it is found (as expected) that high voltage ratios of $V_2/V_0$ (and hence $V_3/V_1$) produce a strong second ‘immersion lens’ and hence permit focusing with a smaller $V_2/V_1$ Einzel lens ratio. Thirdly, for values of $V_1/V_0$ greater than approximately 5.5 the initial converging effect becomes so strong that zero crossover foci become impossible for any value of $V_2/V_0$, and a crossover must occur. Finally, a focus with single crossover generally requires high voltage ratios in the order 50 → 120 which is prohibitively high even with low $V_0$. Hence the single crossover investigation was not extended below $V_1/V_0=3$ as a low energy alternative is readily available at these values. Nor were modes involving 2 or more crossovers investigated.

For the deceleration mode, similar trends are apparent, although focus voltages are now mostly in the range 0.1 → 5. Once again, above $V_1/V_0 \approx 5.5$ a focus with zero crossovers is impossible. In contrast to the acceleration mode, for values of $V_1/V_0$ less than approximately 6.5, single crossover modes are not easily obtained as negative voltages must be applied to the focus electrode which is certainly not performed in practice. Once again modes involving 2 or more crossovers were not investigated.

Fig. 4.4 shows magnification for the accelerating and decelerating modes. For both the zero and single crossover cases, maximum magnification occurs for $V_1/V_0$ in the range 4 → 6. For a particular value of $V_1/V_0$ magnification generally increases with decreasing $V_3/V_0$. This occurs because for a given image distance the weakening of the immersion lens dictates a strengthening of the Einzel lens. Since this is located closer to the object, magnification is larger.

---

1A two element electrostatic lens

2A three element lens, with the same voltage on the first and third electrodes
Figure 4.3

Loci of voltage ratios, $V_2/V_0$, required to produce a focus at the velocity selector exit for the present Pelletron lens. Numbers on curves represent voltage ratios $V_2/V_0$. Zero crossover lines terminate at a value of $V_1/V_0$ beyond which no focus is possible without an internal crossover.

Voltages correspond to:

- $V_0$: Probe
- $V_1$: Extractor
- $V_2$: Focus
- $V_3$: Bias

A:

Acceleration mode

B:

Deceleration mode
Pelletron lens, Focus at velocity-selector exit.
Accelerating mode.

Pelletron lens, Focus at exit of Velocity-selector. Decel mode.
**Figure 4.4**

Magnification for the present Pelletron lens. Curves correspond with those of Fig. 4.3.

**A:**

Acceleration mode

**B:**

Deceleration mode
Pelletron lens,

Accel. mode.

\[ \text{Magnification} \]

\[ v_1/v_0 \]

One Crossover

Zero Crossover

---

Pelletron lens,

Decel. Mode.

\[ \text{Magnification} \]

\[ v_1/v_0 \]

One Crossover

Zero Crossover
Peak magnifications available are of the order of 25 in all cases.

Spherical and chromatic aberration coefficients referred to the object are shown in Figs. 4.5 and 4.6 for both acceleration and deceleration modes. Spherical aberration is found to be a strong function of $V_1/V_0$ or the first accelerating voltage. As expected, with no crossovers, $C_{80}$ decreases sharply for increasing $V_1/V_0$. This is because as stronger focusing occurs in the initial accelerating gap, rays remain closer to the axis for a given initial divergence. Where a beam crossover occurs within the lens however, further strengthening of the first lens produces a higher $C_{80}$. For small values of $V_1/V_0$ and no crossover $C_{80}$ increases strongly with $V_3/V_0$ (in the case of the acceleration mode). This is because the strengthening of the immersion lens dictates a weakening of the Einzel lens and permits rays to move further off axis inside the lens. Overall the acceleration mode produces a lower value of $C_{80}$ than the deceleration, although for larger values of $V_3/V_0$, this effect is less pronounced. The minimum value of $C_{80}$ obtainable with the lens in its present configuration is approximately 25mm both for acceleration and deceleration modes. This requires a value of $V_1/V_0$ of 4 and is quite insensitive to choice of $V_3/V_0$ for the minimum $C_{80}$ region.

Chromatic aberration shows a similar decline for $V_1/V_0$ increased from 1 to 4 or 5. However, in this case lower values are usually obtained for $V_3/V_0$ larger rather than smaller. Once again the accelerating case is usually better than the decelerating case although minimum values for both cases are similar. Optimum operating conditions are predicted to be with values of $V_1/V_0$ between 3 and 6 in the accelerating case and 4 and 6 in the decelerating case. The minimum value of $C_{80}$ obtainable with the lens in its present configuration is approximately 7mm. This requires a value of $V_1/V_0$ of 5 and is once again quite insensitive to choice of $V_3/V_0$.

For operation with a field ionization source, the source could be located with the extraction cathode at any position upstream from the entrance snout. Two particular situations will be considered: firstly with the cathode located at the present ion source exit location, and secondly with the cathode formed by the entrance snout itself. In the first situation voltage data for operation may be
Figure 4.5
Spherical aberration for the present Pelletron lens. Curves correspond with those of Fig. 4.3.

A:
Acceleration mode

B:
Deceleration mode
found directly from the curves of Fig. 4.3. For the second situation guidance may also be obtained from Fig. 4.3, but due to the direct injection of the ion source, \( V_1/V_0 \) is limited to 1.0. In this situation voltage ratios more extreme than those of Fig. 4.3 will be required as the working distance is smaller.

In the first situation, the cathode is located 5.5mm upstream of the lens entrance, with the emitter a further 6mm upstream. Assuming a source energy \( V_0 \) of 20kV, Fig. 4.3 indicates that voltages of at least 100kV either on extractor or focus electrodes are required for focusing in acceleration mode with final to initial energy ratios of below 4. An increase in \( V_3/V_0 \) to 8 permits Focus and Extractor voltages to remain below 40kV, but Figs. 4.5 and 4.6 indicate particularly high aberrations for this configuration, as principal focusing occurs far downstream in the lens.

Electrode voltages may be kept lower by operating in decelerating mode. Fig. 4.3 indicates that the ratio \( V_2/V_0 \) remains below 2 for all values of \( V_1/V_0 \) below 4 and all values of \( V_3/V_0 \) below 8. The voltage across the 4mm gap between Extractor and Focus electrodes however steadily increases with increasing \( V_1/V_0 \). For \( V_1/V_0 = 2 \) this voltage gap is nearly 40kV for \( V_3/V_0 \leq 4 \).

Figs. 4.5 and 4.6 show that the critical ratio for aberrations is \( V_1/V_0 \). Minimum values of \( C_\infty \) and \( C_{\infty} \) of 25mm and 7mm respectively occur for \( V_1/V_0 \) in the range 4 → 5. In accelerating mode a \( V_1/V_0 \) of 4 requires \( V_2/V_0 \) in excess of 10 for all values of \( V_3/V_0 \). Thus there is considerable advantage in increasing \( V_1/V_0 \) to 5.5 whereby all values of \( V_2/V_1 \) drop to 1 irrespective of \( V_3/V_0 \). A similar situation occurs in decelerating mode. For \( V_1/V_0 = 4 \) and a source voltage of 20kV, a voltage gap of 70kV occurs between the Focus and Extractor electrodes. This gap is reduced to zero volts by once again increasing \( V_1/V_0 \) to 5.5.

The operation of the lens with \( V_1/V_0 = 5.5 \) reduces its action to that of a single accelerating gap with a voltage jump of 90kV occurring across the first 5.5mm. It may of course be possible to increase this gap slightly without increasing aberrations by moving the cathode closer to the ionization tip.

Operating with single crossover also produces low aberrations for \( V_1/V_0 \sim 5 \). The excessively high voltages required for a focus in this mode however would
Figure 4.6
Chromatic aberration for the present Pelletron lens. Curves correspond with those of Fig. 4.3.

A:
Acceleration mode

B:
Deceleration mode
**A**

Pelletron lens

Accel. mode.

![Graph](image.png)

- $C_{oo}$ vs. $v_1/v_0$
- Zero Crossover
- One Crossover

**B**

Pelletron lens

Decel. mode.

![Graph](image.png)

- $C_{oo}$ vs. $v_1/v_0$
- Zero Crossover
- One Crossover
In the second situation, in which the cathode is formed by the entrance snout, \( V_1/V_0 \) is limited to 1.0. For this configuration, for the acceleration mode, Fig. 4.4 indicates a requirement of the Focus or Bias in excess of 100kV for a source of 20kV. For the deceleration mode however a focus is possible with a Focus voltage of below 2.0kV. Once again however, in both cases the lens is operating in far from optimal aberration conditions, with no option of reducing aberrations by an increase in Extractor. Fig. 4.5 indicates a \( C_{sp} \) of at least 800mm in decelerating mode for \( V_1/V_0 = 1 \) irrespective of \( V_2/V_0 \), and in accelerating mode \( C_{sp} \) cannot be reduced below 200mm. Chromatic aberration coefficients in excess of 50mm and 200mm occur for the decelerating and accelerating modes respectively for \( V_2/V_0 \leq 4 \). In decelerating mode chromatic aberration may be reduced by a factor of 2.5 by increasing \( V_3/V_0 \) to 8, but spherical aberration is sharply increased at this value.

Aberrations may be reduced by bringing the source closer to the lens; however the required voltage ratios become more extreme and the lens is operating so far from its optimal voltage configuration that substantial improvements are unlikely.

In both situations discussed above the limitations imposed by the operating voltage of a field ionization source make it difficult to operate the present Pelletron lens in its optimal voltage configuration. It is necessary therefore to investigate alternative lens designs to determine whether optically superior electrostatic lenses may be constructed.

### 4.3 Two Element Lenses

The simplest possible lens design consists of two electrodes, either cylindrical or planar in geometry. Theoretical and experimental optical properties of a wide range of such lenses are listed in the literature. (For example Re69, Re70, Ka70, Ha76, Bo79). Butler [Bu66] and later Crewe [Cr68] proposed a design consisting of two parabolically shaped electrodes which they found to give minimum \( C_{sp} \) for
an accelerating field. The analytical model of Crewe assumed infinitely small electrode aperture bores. Field emission microscopes have been constructed employing a Butler type lens with finite apertures, and using the first lens element as the extraction anode of the field emission gun [Re85b]. A field ionization microscope for STIM work was designed by Levi-Setti [Le74] using a 100kV accelerating Butler lens, and similar instruments have been built by Eskovitz et al. [Es76] and Schwarzer and Gaukler [Sc78].

Kuroda and Suzuki [Ku74c] investigated Butler lenses, and showed that there is little difference in the properties of lenses between the true Butler shaped electrodes and those with a more easily machined conical bore. Munro [Mu73c] has compared a number of alternative 2 electrode geometries, including Butler's, and found (for small magnifications at least) that for an object distance of 10mm $C_*$ and $C_0$ are smaller for a particular asymmetric shaped lens. This lens is shown in Fig. 4.7. The design proposed by Munro has also been used in a number of scanning electrode microscopes. Considering construction practicalities, the Munro design lens appears the most attractive 2 element lens for field ionization applications, and was analysed for this use.

Fig. 4.8 shows optical parameters for the Munro lens calculated for the case of an image located 200mm downstream from the lens entrance aperture.

In the acceleration mode, working distance decreases strongly and magnification increases strongly with increasing voltage ratio — particularly below $V_2/V_1 = 5$. Both spherical and chromatic aberrations also decrease strongly with increasing $V_2/V_1$. For $V_2/V_1 = 8$, $C_{so}$ is 177mm and $C_{co}$ is 22.5mm. If image distance is permitted to increase, these aberrations may be further reduced. Lower limits, given by $C_{s\infty}$, and $C_{co\infty}$ are 104mm and 17.1mm respectively for $V_2/V_1 = 8$ (see Fig. 4.9). For comparison, Levi-Setti proposed a Crewe lens for use with a field ionization source, with $V_2/V_1 = 7$, giving a $C_{so}$ of 222mm and $C_{co}$ of 29.1mm, although he found he had to keep acceptance half angle to 1mrad in order to reduce spherical aberration to below that of other spot size contributions [Le74].

Fig. 4.8 shows that running the lens at a higher voltage ratio greatly
Figure 4.7

Lens proposed by Munro.

$V_1$ was set at 10kV and $V_2$ at 100kV. Equipotentials are indicated in 5kV steps, with 11, 12.5, 97.5 and 99kV lines also shown.
Figure 4.8

Optical parameters for the Munro lens for image distance 200mm downstream of the lens entrance. The parameters shown are:

- $D_o$: Working distance (object/entrance aperture plane separation)
- $M$: Transverse magnification
- $C_{so}$: Spherical aberration referred to the object
- $C_{so}$: Chromatic aberration referred to the object.

The ordinate scale is in mm for all parameters except magnification.

A:

Accelerating lens.

B:

Decelerating lens.
reduces aberrations (particularly $C_{oo}$), but high voltage ratios rapidly become impractical for a source operating around 20kV.

For parallel plates of separation over 2mm in UHV, Latham [La81] found an expression for maximum applied voltage prior to breakdown given by

$$V_b = Kd^\alpha$$

(4.1)

where $d$ is the plate separation in m,

$K$ and $\alpha$ are constants depending on the materials involved and their preparation.

Latham found $K$ to lie in the range $40 \rightarrow 45\text{MVm}^{-\alpha}$ and $\alpha$ is in the range $0.4 \rightarrow 0.6$. The achievement of maximum breakdown voltages requires careful electrode surface preparation. It is dependent also upon electrode material, with refractory materials such as stainless steel providing voltages in the upper part of the range. For the full scale Munro lens, with a source voltage of 20kV this suggests maximum achievable voltage ratios in the range $5 \rightarrow 10$.

Voltage ratios required for a focus may be brought closer to unity by reducing the scale of the lens. This results in an effective increase in working distance $D_o$. A scale change of the lens produces a similar scale change in working distance for a given voltage ratio, thereby permitting a lower voltage ratio for a given absolute working distance. Although voltage ratios are reduced however, for a lens in the region $V_2/V_1 = 4 \rightarrow 8$, calculations show that an increase in lens field of approximately 10% is needed to maintain absolute working distance with a 50% scale reduction. Furthermore, Fig. 4.9 shows that both aberration coefficients increase more rapidly than working distance with decreasing lens strength indicating that the final aberration coefficient for a scaled down lens will be greater than that for the full scale lens for any given working distance. These results agree with the findings of Shimuzu [Sh83]. Fig. 4.9 shows that for $C_\varepsilon$ these effects will be small. For $C_\ast$, however, the effect is large and a 50% scale reduction for $V_2/V_1 = 8$, maintaining constant working distance, increases $C_\ast$ by a factor of 3.
Figure 4.9

As for Fig. 4.8A, except the lens is operated in infinite magnification mode. 'F' represents entrance plane focal length.
Alternatively the lens may be run in decelerating mode. The decreased voltages result in a much reduced likelihood of electrical breakdown. However in this mode the particles travel much further off axis and Fig. 4.8B indicates spherical and chromatic aberrations are considerably larger for a given lens strength. Calculations indicate a $C_{so}$ in excess of 1000mm and a $C_{co}$ of greater than 100mm for zero working distance, so for all practical situations aberrations will be larger than this. A further disadvantage of deceleration mode is that angular demagnification will be small, thereby increasing the contribution of angle dependent aberrations in subsequent optical elements (refer Chapter 5).

4.4 Three Element Lenses

A problem of operating with a 2 element lens is the lack of variable lens parameters. Experience with the field ionization source indicates that different tips have optimal performance at different ion source energies, depending upon the precise tip size and shape and tip-cathode separation [Al89a]. For a given source extraction voltage only two possible lens voltages (an accelerating and a decelerating mode) will produce a focus at the required image plane. A 2-element lens therefore cannot produce a given image plane location as well as a specified final energy. Calculations in Chapter 5 shows that this would therefore preclude the use of a fixed aperture upstream of the accelerating column, serving as the accelerating column object. It may also prevent full optimization of the ion source lens for the particular source in use.

Read [Re70] and Heddle [He74b] demonstrated for a three aperture lens, for given object and image positions, and a given final to initial energy ratio, there are generally two central electrode voltages which produce the required focus. These are termed the 'acceleration' and 'deceleration' modes. As a result of the flexibility of three element lenses, a large number of geometries have been investigated for a wide range of applications.

Read [Re69, Re70], El Kareh [Ka70] and Bonjour [Bo79] have published data on tubular and planar lenses, including spherical and chromatic aberration...
coefficients. Harting and Read [Ha76] have published data for 6 electrostatic lenses consisting of 3 cylinders or apertures of different geometries. General 3 element lens data was also published by Berger and Baril [Be82] and Werner [We71]. Variations on lens geometries to minimize aberrations have been systematically attempted by Riddle [Ri78], Mulvey and Wallington [Mu73b] and Shimuzu [Sh83] for asymmetric Einzel lenses. Studies of 3 element lenses for particular use with field emission sources have been carried out by Kuroda and Suzuki [Ku74a, Ku74b] and Roques et al. [Ro83a, Ro83b]. For field ionization or liquid metal ionization sources, lenses have been investigated by Orloff and Swanson [Or79], Kang and Sheng [Ka87] and Mayer and Gaukler [Ma87]. A low aberration, low voltage ratio 3 element lens has been designed by Szilagyi [Sz84a] by a dynamic optimization technique. A design to obtain a low aberration 3 element lens by combination of back to back Crewe lenses was published by Kuroda and Suzuki [Ku74a, Ku74b].

It was decided to investigate in detail 3 lenses – those designs proposed by Orloff and Swanson, by Riddle, and a variation of the double Crewe lens proposed by Kuroda and Suzuki. These lenses were selected because they were claimed to have intrinsically low spherical and/or chromatic aberrations. In each case the lens was modelled using the modified Munro program F11. Mesh size and integration lengths were set to a region where further alteration in size produced insignificant changes in optical parameters. Object distances were set, and program STEPIT used to adjust voltages to obtain the required image location. Other optical parameters such as magnification and spherical and chromatic aberrations were then extracted. Coefficients were generally referred to object coordinates rather than image coordinates to remove the effect of magnification on the image aberrations, and to permit calculations to be performed as a function of lens acceptance angle.

A preliminary calculation however was carried out to determine the effect of the non-uniform field in the vicinity of the ionization tip on the validity of the Munro calculations. Since the effect of the tip field is expected to increase with decreasing tip/aperture separation, calculations were carried out for separations
Figure 4.10

Kasper and Munro calculations for the Riddle lens, operated as an Einzel lens in decelerating mode.

A:
Reciprocal image location as a function of voltage ratio $V_2/V_1$. Both working distance and image distance are measured from the entrance aperture of the lens. Calculations are shown for working distances of 1mm and 3mm.

B:
Spherical and chromatic aberrations referred to the image, as a function of reciprocal image location for the Riddle lens. Only the 1mm working distance results are shown, although the 3mm results show similar trends.
of 3mm and 1mm.

Calculations were performed on the Riddle lens (refer Fig. 4.18) using program F11, and also using the Kasper programs. In the latter calculations, full modelling of a 0.1μm radius ionization tip was included, as well as all lens electrodes. For these calculations image position was determined from extrapolation of rays to zero angle, and aberrations determined by 5th order polynomial fits to axis crossing locations in the manner of Chapter 3. The results for the calculations are presented in Fig. 4.10.

Fig. 4.10A shows quite good agreement for the image distances between the two models, although the Kasper calculation generally suggests a slightly weaker lens for a given voltage ratio, with the discrepancy slightly increased for the shorter working distance (for \( D_o = 1 \text{mm} \) and real images, the Kasper model requires a reduction in voltage ratio by approximately 10% to achieve the same focus).

Fig. 4.10B displays spherical and chromatic aberrations referred to the image for the case \( D_o = 1 \text{mm} \). To remove the effect on the aberrations of the slight weakening of the Kasper lens, the aberrations are plotted as a function of reciprocal image location. The results suggest good agreement except for weak virtual images, where the Kasper calculations show consistently larger aberrations. Indeed for a further weakening still, calculations show closer agreement between the models.

These calculations support the use of the Munro programs for the lenses, with the proviso that voltage ratios for close working distances must be slightly strengthened for a required image location.

In decelerating mode particles move far off axis in the central bore region of the lens. The beam 'filling factor' may be defined as the maximum radial extent of the beam within the lens bore region, as a percentage of the bore radius. In decelerating mode, lens filling factor may be very high. For \( V_2/V_1 = 0.1 \) and a working distance of 1mm the filling factors for 0.1rad and 0.2rad beam divergence are 40% and 99% respectively. Fifth order aberrations (refer equation 2.15) were extracted from the polynomial fits to Kasper raytraces to determine whether
Figure 4.11
The double Crewe or 'Butler' lens. The lens is shown with the following voltages:

\[ V_1 = 10kV \]
\[ V_2 = 100kV \]
\[ V_3 = 20kV \]
they are significant for the lens used in this mode. For a working distance of both 1mm and 3mm, the 5th order aberration coefficient referred to the image was found to be between .24 and .26 of the spherical aberration coefficient (also related to image). Since angles will in practice be kept below 100mrad, it was therefore concluded that 5th order effects are negligible for this lens.

4.4.1 The Butler Lens

The double Crewe lens (here referred to as a 'Butler' lens) is shown in Fig. 4.11. Fig. 4.12 shows the loci of voltages $V_2/V_1$ required for a focus 200mm downstream from the entrance aperture for object distances 1, 3 and 5mm upstream of the aperture, as a function of $V_3/V_1$. Magnification and spherical and chromatic aberrations for the lens are displayed in Figs. 4.12B, C, D. Fig. 4.12A shows that for low values of $V_3/V_1$, there is a considerable shortening of working distance compared with the Munro lens for a given ratio $V_2/V_1$. For $V_3/V_1 = 1$ a $V_2/V_1$ of 4.3 permits a working distance of 5mm compared with a $V_2/V_1$ of 12 for the Munro lens, although $V_2/V_1$ rapidly increases with increasing $V_3/V_1$. Fig. 4.12C indicates spherical aberration decreases strongly with $V_3/V_1$ in the acceleration mode, remaining below that of the Munro lens for any particular value of $V_2/V_1$. In deceleration mode however $C_{oo}$ is nearly constant and in excess of 100mm for all voltages.

The chromatic aberration shows a similar tendency with the acceleration mode being generally a factor of 3--8 lower than the deceleration mode. In both modes $C_{oo}$ is not a strong function of working distance. In accelerating mode, with $V_3/V_1 = 1$, and a working distance of 5mm, a $V_2/V_1$ of 4.4 gives a focus with $C_{oo} = 10mm$, $C_{oo} = 38.4mm$. Equation 4.1 suggests a maximum possible accelerating ratio of $3.9 \rightarrow 4.9$ for this lens with a source energy of 20kV.

4.4.2 The Orloff Lens

The Orloff lens is shown in Fig. 4.13. Fig. 4.14A shows the loci of voltage ratios as before which produce a focus 200mm downstream of the inside of the first electrode. Fig. 4.14B shows the magnification for the voltages calculated for Fig.
Figure 4.12

Optical results for the lens of Fig. 4.11.
Calculations are shown for object distances of 1, 3, 5mm and an image distance of 200mm. All distances are measured from the lens aperture.

Displayed quantities are:

A: 
Focusing voltage, $V_2/V_1$.

B: 
Magnification.

C: 
Spherical aberration referred to the object.

D: 
Chromatic aberration referred to the object.
Butler Lens, $D_i=200\text{mm}$

**A**

$V_2/V_1$ vs. $V_3/V_1$

- $D_o = 1\text{mm}$
- $D_o = 3\text{mm}$
- $D_o = 5\text{mm}$

**B**

$M$ vs. $V_3/V_1$

- $D_o = 1\text{mm}$
- $D_o = 3\text{mm}$
- $D_o = 5\text{mm}$
Figure 4.12 continued.
Butler Lens, $D_i=200\text{mm}$

**Graph C**

- Decel.
- $D_o = 1\text{mm}$
- $D_o = 3\text{mm}$
- $D_o = 5\text{mm}$

**Graph D**

- Decel.
- $D_o = 1\text{mm}$
- $D_o = 3\text{mm}$
- $D_o = 5\text{mm}$
4.14A.

With an electrode separation of 3mm, equation 4.1 suggests a maximum possible accelerating voltage ratio of between 4 and 5.4. For close working distances, these values must be reduced by a further 10% to compensate for the slight overstrengthening of the lenses in the Munro calculations noted in Section 4.4. This effectively keeps \( V_3/V_1 \) below 1.5 for all working distances below 5mm. Fig. 4.14A shows there would be great advantage in operating with \( V_3/V_1 \leq 1 \) as \( V_2/V_1 \) rapidly decreases with decreasing \( V_3/V_1 \). All decelerating voltages could be easily reached and \( V_3/V_1 \) is the limiting ratio in this mode.

Magnifications, as shown in Fig. 4.14B are not a particularly strong function of working distance for either deceleration or acceleration modes, due to the first principal plane of the lens lying well inside the lens entrance aperture for most values of \( V_3/V_1 \). Figs. 4.14C and 4.14D present spherical and chromatic aberrations, referred to the objects, for the Orloff lens for the conditions of Fig. 4.14A. Fig. 4.14C shows that \( C_\infty \) strongly decreases with increasing \( V_3/V_1 \) in the accelerating mode, but is more or less independent of \( V_3/V_1 \) in the decelerating mode. For decelerating operation \( C_\infty \) strongly decreases with decreasing working distance as this ensures that rays emanating at a certain angle are considerably closer to the axis when they enter the lens field, thereby ensuring integrand terms 3 and 4 of equation 2.26 remain small.

Accelerating mode values of \( C_\infty \) are smaller than decelerating modes for \( V_3/V_1 \) in excess of between 1.2 and 3 for working distances between 5 and 1mm. Since large accelerating mode values of \( V_2/V_1 \) preclude a \( V_3/V_1 \) of greater than approximately 2, Fig. 4.14C indicates an optimal practical value of \( C_\infty \) is obtained with decelerating mode with \( V_3/V_1 \) between 1 and 2.

Chromatic aberration is shown in Fig. 4.14D to be a strongly decreasing function of \( V_2/V_1 \) in accelerating mode and a weakly decreasing function in the decelerating mode. In both cases it is a weak function of working distance. For \( V_3/V_1 = 1 \) the accelerating mode \( C_\infty \) is a factor of between 4 and 5 lower than the decelerating mode. For a working distance of 5mm, with \( V_3/V_1 = 1.5 \) and \( V_2/V_1 = 5.17 \), a focus may be obtained with \( C_\infty = 60.9 \text{mm} \) and \( C_\infty = 8.24 \text{mm} \).
Figure 4.13

The 'Orloff' lens.

Surfaces marked by numbers and arrows are those varied by STEPIT, in order to minimize aberrations.
Figure 4.14
Optical results for the lens of Fig. 4.13.
Calculations are shown for object distances of 1, 3, 5mm and an image distance of 200mm. All distances are measured from the lens aperture.
Displayed quantities are:

A: 
Focusing voltage, $V_2/V_1$.

B: 
Magnification.

C: 
Spherical aberration referred to the object.

D: 
Chromatic aberration referred to the object.
Figure 4.14 continued.
As seen in Fig. 4.14A, higher values of $V_3/V_1$ may be used only if working distance is increased, but such an increase also increases aberrations. An increase in working distance to 7mm, with a $V_3/V_1$ of 2 and focusing ratio $V_2/V_1$ of 5.16 gives $C_{co} = 62, C_{so} = 8.2$.

In the important region of $V_3/V_1 = 2$ where both accelerating and decelerating modes give comparable values of $C_{so}$ the effect of changing working distance or lens scale may be investigated using Fig. 4.15 which displays optical parameters for infinite magnifications. Fig. 4.15B clearly shows the minimum of $C_{so}$ at $V_3/V_1 = 2$ for accelerating mode is around $V_2/V_1 = 6$ and does not occur at minimum working distance. In decelerating mode, as the lens is strengthened working distance rapidly falls, partly due to decreasing focal length, but mainly due to the movement downstream of the first principal plane. Fig. 4.15A shows that the minimum of $C_{so}$ cannot be reached in practice as the object lies inside the lens for this value.

Although $C_{co}$ is relatively large for the decelerating mode, Fig. 4.15A suggests a reduction in $C_{co}$ is possible through a scale change of the lens, since the gradient of $C_{co}$ is considerably less than that of $D_o$ especially for small working distances. To investigate this, calculations were carried out for the Orloff lens in decelerating mode, assuming a fixed working distance of 2 or 4mm and assuming a scale reduction of up to 5. Fig. 4.16 displays the chromatic aberration results for $V_3/V_1$ equal to 1 and 2 as a function of magnification, and Fig. 4.17 displays $C_{so}$ for similar conditions.

As expected, Fig. 4.16 indicates that a reduction in scale, with the maintenance of absolute working distance results in a significant reduction in $C_{co}$. For large magnifications the improvement is by a factor of 2 to 3, with larger improvements for low magnifications. The small effect of a doubling of working distance on the coefficients is also apparent from the graph.

In contrast Fig. 4.17 shows that although $C_{so}$ is considerably reduced by a reduction of relative working distance, or by a reduction of scale with maintenance of relative working distance as expected, a reduction of scale with maintained absolute working distance in fact results in increased aberrations.
Figure 4.15

Orloff lens, infinite magnification mode, for $V_3/V_1 = 2$. Optical parameters are shown as a function of $V_2/V_1$ for:

A:
Decelerating mode.

B:
Accelerating mode.
Orloff lens, \( \frac{v_3}{v_1} = 2 \), decelerating mode.

Infinite magnification.

\[ v_2/v_1 \]

Orloff Lens, \( \frac{v_3}{v_1} = 2 \), accelerating mode.

Infinite magnification.
Figure 4.16

Chromatic aberration as a function of magnification for the Orloff lens, for full and reduced scales, in decelerating mode. The curves shown are for:

1: \( \frac{V_3}{V_1} = 1, \ D_o = 2\text{mm}, \) full scale lens.
2: \( \frac{V_3}{V_1} = 2, \ D_o = 2\text{mm}, \) full scale lens.
3: \( \frac{V_3}{V_1} = 3, \ D_o = 2\text{mm}, \) full scale lens.
4: \( \frac{V_3}{V_1} = 1, \ D_o = 4\text{mm}, \) full scale lens.
5: \( \frac{V_3}{V_1} = 2, \ D_o = 4\text{mm}, \) full scale lens.
6: \( \frac{V_3}{V_1} = 3, \ D_o = 4\text{mm}, \) full scale lens.
7: \( \frac{V_3}{V_1} = 1, \ D_o = 2\text{mm}, 1/5 \text{ scale lens}. \)
8: \( \frac{V_3}{V_1} = 2, \ D_o = 2\text{mm}, 1/5 \text{ scale lens}. \)
9: \( \frac{V_3}{V_1} = 3, \ D_o = 2\text{mm}, 1/5 \text{ scale lens}. \)
Figure 4.17

Spherical aberration as a function of magnification for the Orloff lens, for full and reduced scales, in decelerating mode. The curves shown are for:

A:

1: $V_3/V_1 = 1, D_o = 2\, \text{mm}, \text{full scale lens.}$
2: $V_3/V_1 = 2, D_o = 2\, \text{mm}, \text{full scale lens.}$
3: $V_3/V_1 = 3, D_o = 2\, \text{mm}, \text{full scale lens.}$
4: $V_3/V_1 = 1, D_o = 4\, \text{mm}, \text{full scale lens.}$
5: $V_3/V_1 = 2, D_o = 4\, \text{mm}, \text{full scale lens.}$
6: $V_3/V_1 = 3, D_o = 4\, \text{mm}, \text{full scale lens.}$

B:

1: $V_3/V_1 = 1, D_o = 2\, \text{mm}, 1/5 \text{ scale lens.}$
2: $V_3/V_1 = 2, D_o = 2\, \text{mm}, 1/5 \text{ scale lens.}$
3: $V_3/V_1 = 3, D_o = 2\, \text{mm}, 1/5 \text{ scale lens.}$
4: $V_3/V_1 = 1, D_o = 2\, \text{mm}, \text{full scale lens.}$
5: $V_3/V_1 = 2, D_o = 2\, \text{mm}, \text{full scale lens.}$
6: $V_3/V_1 = 3, D_o = 2\, \text{mm}, \text{full scale lens.}$
In conclusion, for the decelerating mode, although aberrations may not be reduced arbitrarily by reduction in working distance alone, a combination of scale reduction and appropriate reduction in working distance will result in reduction of $C_{co}$ by a factor of 2 or 3. Below 0.5mm electrode separation, Latham [La81] found breakdown voltage between parallel plates in vacuum to be dependent only upon applied electric field with

$$V_b = E_b d$$

(4.2)

$E_b = 6 \rightarrow 8 \times 10^7 \text{Vm}^{-1}$. This corresponds to $60 \rightarrow 80 \text{kV/mm}$, and would thus permit electrode separation to be reduced to as little as 0.25mm in decelerating mode.

For the accelerating mode Fig. 4.17 suggests a scale reduction of 3 with $D_o$ remaining 1mm and $V_2/V_1 = 7$ will reduce $C_{co}$ and $C_{co}$ greatly, however the likelihood of breakdown is much increased with an equivalent fullscale $V_2/V_1$ of 19.

The preceding calculations indicate that the aberrations in the Orloff lens in decelerating mode are consistently lower than those of the Butler lens under similar operating voltages.

Following initial calculations with the Orloff lens, program STEPIT was used to vary the geometry of the lens in order to reduce aberrations further. Program F11 was modified so that electrode corners of surfaces could be varied in both $r$ and $z$ directions, either singly, or in groups of up to 10 at a time. Program STEPIT was used to minimize a figure of merit which could be selected from a range introduced into program F11. For the Orloff lens the figures of merit investigated in this way were $C$, $C/f$, $C/D_o$, $1/M$ and $f$, where $C$ represents either $C_{co}$, $C_{co}$, $C_{oo}$ or $C_{co}$.

It was found that quite different final results were obtained using the different figures of merit. Minimization of $C_{co}$, $C_{co}$ or $f$ tended to strengthen the lens, thereby moving the object inside the first electrode. Conversely, minimization of $C_{co}/f$ or $C_{co}/D_o$ tended to weaken the lens and did not generally produce a result with low $C_{co}$. In order to remove the effect of this change in lens strength
the final calculations were performed by varying one electrode surface at a time, with each geometry variation followed by a modification in potential $V_2$ (also by STEPIT) to restore the required object and image distances. Electrodes were constrained so as not to touch each other or touch the axis, although no overriding control on field strength was imposed at this stage. Since the variation of each surface produces only a local minimum in the selected figure of merit, the order of variation of the surfaces is important. Hence the order of surface variation was itself varied to attempt to ensure that the final result produced was a 'global' minimum for the lens. In Fig. 4.13 the numbers 1 – 8 indicate the final order in which surface variation took place. The mesh used in the calculations was made as fine as possible within the constraints of computing time to minimize inaccuracies caused by distortions in the mesh. Calculations to minimize a figure of merit required approximately 5 hours of CPU time on a DG MV8000 computer.

Calculations were concentrated on the decelerating mode as accelerating mode calculations almost invariably led to unacceptably high voltage gradients. This is because accelerating mode aberrations are almost invariably reduced by increasing voltage gradients, which is not the case for the decelerating lens.

In the decelerating mode, for $V_3/V_1 = 1$ and $D_o = 1$mm it was found that the strongest factor governing aberrations is the gap between the first 2 electrodes. A reduction in the gap width actually weakens the decelerating lens slightly requiring a compensating decrease in $V_2/V_1$ to maintain lens strength. A 50% decrease in this gap reduces final $C_{so}$ by approximately 45% and $C_{co}$ by approximately 15%. Further reduction in the gap produces slight further reduction in $C_{so}$ (by up to 12%) but no significant change in $C_{co}$.

In contrast, both aberrations are considerably less sensitive to the separation between electrodes 2 and 3 and the position of the third electrode is important mainly for its effect on other electrode variations. A reduction in separation to close to zero results in a decrease in $C_{co}$ and $C_{so}$ of between only 5 and 6%.

The spherical aberration is also quite insensitive to the location of the back
surface of the central electrode (surface 4 in Fig. 4.13). Chromatic aberrations may be reduced by approximately 4% by halving the width of this electrode.

In the radial direction aberrations are most sensitive to the bore radii of the central electrode. An increase in the smaller bore radius (surface 5 in Fig. 4.13) weakens the power of the lens for given $V_2/V_1$. A decrease in lens bore tends to decrease $C_{so}$ and increase $C_{co}$. A large increase in bore radius (say to 5 or more millimetres) considerably weakens the lens, with final $C_{so}$ increased by a factor of 2 or 3, but with substantial reductions in $C_{co}$.

The effect of change on a larger bore radius is largely dependent on the location of electrode 3. If electrode 3 is 4.5mm from electrode 2, an increase in bore radius results in a considerably weaker lens. The subsequent compensating strengthening of the lens may reduce $C_{so}$ by up to 35% (from 15mm to 9.8mm) with a smaller decrease in $C_{co}$. If the two electrodes are very close, an increase in bore radius may produce a slight increase in $C_{so}$ with approximately 5% decrease in $C_{co}$.

The size of the entrance and exit apertures has only a small effect on aberrations – with a decrease in entrance bore marginally reducing $C_{so}$ and $C_{co}$, and with an increase in bore reducing $C_{so}$ and increasing $C_{co}$ by small amounts.

The overall conclusion which may be reached supports that of Riddle [Ri78] who found that the process of reduction of one aberration in a lens tends to simultaneously worsen the other.

The minimum value of $C_{so}$ obtainable by this method is 8.1mm with a $C_{co}$ of 39.3mm, although electrode separations are very small. For a minimum first electrode gap of half the starting value, minimum $C_{so}$ obtainable is 12mm. Magnification is 21.5. For minimum $C_{co}$, with a minimum first gap width of 1.5mm, the values are $C_{so} = 15.4mm$, $C_{co} = 27.7mm$. Magnification is 35, $V_2/V_1 = .05$.

The suitability of such a modified lens for use with a field ionization source is discussed further in Section 4.5 below.
4.4.3 The Riddle Lens

The 'Riddle' Lens is shown in Fig. 4.18. Voltage loci for an image 200mm downstream of the first electrode are shown in Fig. 4.19A and magnifications are shown in Fig. 4.19B.

Voltage ratios in the decelerating mode differ very little from those of the Orloff lens. It may be seen from Fig. 4.19A that accelerating mode ratios vary little with \( V_3/V_1 \) and are much lower for large \( V_3/V_1 \) than those of the Orloff lens.

Decelerating magnifications of the Riddle lens are also very small compared with those of the Orloff lens, however accelerating mode magnifications are considerably increased. Once again in the decelerating mode \( M \) is not a strong function of \( D_o \) as the first principle plane lies well inside the lens (at 5.9mm inside the lens entrance for \( V_3/V_1 = 1 \), \( V_2/V_1 = .2 \), and 8.0mm inside for \( V_2/V_1 = .1 \)).

The spherical and chromatic aberrations are shown in Figs. 4.19C and D as functions of \( V_3/V_1 \) and working distance.

The Riddle lens in accelerating mode differs significantly from the Orloff lens in that spherical aberrations are virtually constant for different \( V_3/V_1 \). This reflects the close to constant values of \( V_2/V_1 \) required for focusing indicated in Fig. 4.19A, and partially negates the advantage of the lens having relatively low focusing voltages in this region. In the decelerating mode the aberrations are very similar to those of the Orloff lens, but are in all cases slightly lower. The accelerating and decelerating mode values of \( C_{oo} \) are very similar to each other for large working distances, but with a working distance of 1mm for decelerating mode is two to three times larger than the accelerating mode value.

The chromatic aberrations in the decelerating mode are virtually identical to those of the Orloff lens for all but large values of \( V_3/V_1 \). In the accelerating mode, once again, the aberrations are almost constant over the greater part of the range of \( V_3/V_1 \).

The electrode separation in the standard lens is 2mm. Equation 4.1 indicates a maximum possible accelerating voltage ratio of between 3.6 and 4.4. For a working distance of 5mm, this permits a \( C_{oo} \) of 109mm and \( C_{oo} \) of 8.6mm for
Figure 4.18

The standard ‘Riddle’ lens.

Surfaces and corners marked by numbers and arrows are those varied by STEPIT in order to minimize aberrations.
Figure 4.19
Optical results for the lens of Fig. 4.18.
Calculations are shown for object distances of 1, 3, 5mm and an image distance of 200mm. All distances are measured from the lens aperture.
Displayed quantities are:

A:
Focusing voltage, $V_2/V_1$.

B:
Magnification.

C:
Spherical aberration referred to the object.

D:
Chromatic aberration referred to the object.
Riddle Lens, $D_i = 200$mm

**A**

- **V2/V1** axes
- **V3/V1** axes
- **Accel.**
- **Decel.**

- $D_o = 1$mm
- $D_o = 3$mm
- $D_o = 5$mm

**B**

- **M** axes
- **V3/V1** axes
- **Accel.**
- **Decel.**

- $D_o = 1$mm
- $D_o = 3$mm
- $D_o = 5$mm
Figure 4.19 continued.
In the accelerating mode, by increasing the separation of the first 2 electrodes to 6mm, voltage ratios up to 7.5 may be expected to be sustained for a 20kV source energy. With a working distance of 1mm, this permits a focus with $C_{so} = 21.9\text{mm}$ and $C_{co} = 8.4\text{mm}$. $M$ however is a relatively low 12.4, resulting in significant accelerator aberrations (refer Chapter 5). An increase in working distance to 3mm permits a reduction in $V_2/V_1$ to 5.8, but $C_{co}$ increases to 10.5mm and $C_{so}$ doubles to 46mm.

As before, program STEPIT was used to minimize lens aberrations by variation in lens geometry and applied voltages. Fig. 4.18 indicates the surfaces which were varied by the program.

In the decelerating mode for $V_3/V_1 = 1$ it was found, as with the Orloff lens, that both aberrations are most sensitive to a change in separation between the first two electrodes. This confirms Riddle's findings in his original study of the lens [Ri78]. For a fixed object, $C_{so}$ is reduced by 35% by reducing the gap width by 50%, and by a further 10% by reducing gap width to close to zero. $C_{so}$ is also minimized by reducing the thickness of the first electrode to a minimum, with a halving of thickness producing a 6% decrease in aberration coefficient. Equation 4.2 indicates that it may be expected that electrode separation may be reduced to 0.3mm in the decelerating mode.

Chromatic aberration is reduced by 20% by halving the first to second electrode gap, but was found to be relatively insensitive to the thickness of the first electrode. As found by Riddle [Ri78] the effect on aberrations of the size of the gap between second and third electrodes is much less significant. Both $C_{so}$ and $C_{co}$ are slightly decreased for an increase in electrode separation.

The aberrations are remarkably insensitive to the size of the final aperture. A doubling in aperture size from 6 to 12mm with compensating adjustments of $V_2/V_1$ for the required focus, changes $C_{so}$ and $C_{co}$ by less than 1% (decreasing both of them).

The effect of the entrance aperture on both $C_{so}$ and $C_{co}$ is also very small, with a halving of the aperture radius producing a reduction of approximately
3% in each.

The radius of the bore of the central electrode is once again the most important radial dimension. Increasing this significantly improves $C_{\infty\infty}$ but worsens $C_{\infty 0}$. For finite, fixed object aberrations, the consequent strengthening or weakening of the lens to compensate for bore changes reduces the size of the change in aberration. The final result of increasing the bore radius by .85mm decreases $C_{\infty 0}$ by 11% and increases $C_{\infty\infty}$ by 13%. On the other hand a reduction of radius from 2 to 1.5mm increases $C_{\infty 0}$ by 21% and decreases $C_{\infty\infty}$ by 12%.

The angle of the bore cone was found by Riddle to be optimal for values of $C_{\infty\infty}/D_0$ for one particular set of lens voltage ratios. For $D_0 = 1$mm the aberrations of the lens are quite insensitive to changes in the cone angle, with $C_{\infty\infty}$ slightly reduced and $C_{\infty 0}$ slightly increased for increasing the cone angle from that in Fig. 4.18. The magnitude of changes are both less than 2% for a ±10° change of angle. A doubling of bore angle from 26° to 52° for fixed $V_2/V_1$ produces a marked weakening of the lens, and strong increase in $C_{\infty\infty}$ and decrease in $C_{\infty 0}$. Once $V_2/V_1$ is readjusted for 200mm image distance, $C_{\infty 0}$ is increased by 14% and $C_{\infty\infty}$ decreased by 5%. This kind of interplay between finite and infinite aberration coefficients has also been noted by Scheinfein and Galantai [Sc86a].

The minimum value of $C_{\infty 0}$ for a lens with a 'substantial' electrode gap separation (i.e. ≥ 1mm) is found to be 11.7mm with a $C_{\infty\infty}$ for this lens of 42.7mm, $M = 22.0$, $V_2/V_1 = .089$. The minimum value of $C_{\infty\infty}$ is found to be a lens with $C_{\infty\infty} = 24.0$mm, $C_{\infty 0} = 29.2$mm, $M = 30.0$, $V_2/V_1 = 0.15$. This represents a reduction of $C_{\infty\infty}$ of 38% from the standard Riddle lens with an increase in $C_{\infty 0}$ of 33%. $C_{\infty 0}$ may be reduced by approximately 10% by a gap narrowing, and a total of 10% from all other optimised changes, the combined effect of all variations being less than the sum of each individual variation.
4.5 Comparison of Electrostatic Lenses

From Chapter 3 it is found that the total H⁺ current available from a given ion source configuration and half angle may be written

\[ i_{H^+}(\alpha, r_t, F, \Delta E, D_o) = i_r k_o k_1 k_2 k_3 k_4 k_5 \]  

(4.3)

where

\[ i_r(F_0, P) \] is the raw current at cut-off point field \( F_0 \) as measured by Allan [Al89a]. It is proportional to pressure, \( P \) [Le74].

\[ k_o = \left( \frac{r_t}{r_s} \right)^{2.5} \] is the tip size correction for total current [Be77]. \( r_s \) represents the 'standard' tip size represented in Fig. 3.5. \( r_t \) is the radius of the tip under consideration.

\[ k_1(F/F_0) \] is the correction on the raw current for change in tip apex field \( F \), and is taken from the measured current/voltage curves.

\[ k_2(\Delta E, F) \] is the correction for the fraction of H⁺ lying within \( \Delta E/2 \) of the mean energy of the source. \( k_2 \) is a function of tip field \( F \), and values may be read off data presented by Hansen [Ha81a] (refer Chapter 3).

\[ k_3(F) \] is the proportion of the total beam that consists of H⁺ This is a given as a function of apex field by Muller and Tsong [Mu69].

\[ k_4(\alpha) \] is the fraction of current within half angle \( \alpha \) and is derived from current density measurements made by Allan [Al89a].

\[ k_5(D_o, \alpha) \] represents the limiting of divergence by the extraction aperture or lens bore and is a function of source working distance \( D_o \). For small angles \( k_5 = 1 \).

The final current is thus a function of a broad range of parameters. Total current is found to increase with increasing tip radius, apex field and angle of divergence. The fraction of H⁺ of total beam also increases with increasing field.
With increasing apex field and selected current comes an increase in beam energy spread. As divergence and energy spread increase, lens aberrations also increase. Brightness is reduced by this, as well as by increased tip size and increased applied voltage.

Calculations displayed in Fig. 4.20 indicate two distinct regions for operation of the ion source lens. At low angles effective source radius is dominated by chromatic aberration, and at large angles by spherical aberration. The ‘trade off’ angle is given by

\[
\alpha = \left( \frac{2C_c \Delta E}{C_s E} \right)^{\frac{1}{2}}
\]

(4.4)

In the first region, for low final currents, a source mode with low current and low energy spread will generally be advantageous. For the second region a high current, higher energy spread is preferable, since it is most important that beam divergence be kept low. For MP use, these regions broadly correspond to those of STIM and PIXE operations.

It is clear that brightness is always enhanced, for given energy spread and tip field, by the use of the largest possible radius tip consistent with operation in or above the beam ‘cut off’ region. For an applied voltage of 20kV, using the Melbourne source, Table 3.2 determines a maximum tip size of approximately 0.25µm. Fig. 4.20 displays brightness calculations carried out for the Riddle decelerating lens with a working distance of 1mm. With one exception all curves are for a tip with radius 0.25µm. For comparison calculations were also performed assuming a source using ‘supertips’ as tested by Jousten et al. [Jo88]. For these tips a peak current density of 20µA sr⁻¹ was assumed.

For a given tip field, as higher currents are required, maximum brightness is achieved by the selection of the less divergent, but more highly energy spread region of the beam phase space.

It should be noted that it would not in practice be possible to select the low energy spread phase space ‘core’ of the beam in the source region of the accelerator. Calculations by Allan [Al88b] have shown that the consequent requirements for energy separation of a Wien filter in this location are prohibitive. Nor would such beam filtering be necessarily advantageous, as ‘outer’ regions of
**Figure 4.20**

Brightness as a function of source current for the Riddle standard lens in decelerating mode, $D_o = 1\text{mm}$. The curves display the following source configurations:

1: $r_t = 0.15\mu\text{m}$, $V_{ap} = 11.0\text{kV}$, $F_t = 22\text{V/nm}$, $\Delta E = 1.07\text{eV}$.
2: $r_t = 0.25\mu\text{m}$, $V_{ap} = 17.5\text{kV}$, $F_t = 22\text{V/nm}$, $\Delta E = 1.07\text{eV}$.
3: $r_t = 0.25\mu\text{m}$, $V_{ap} = 17.5\text{kV}$, $F_t = 22\text{V/nm}$, $\Delta E = 6.38\text{eV}$.
4: $r_t = 0.25\mu\text{m}$, $V_{ap} = 20.6\text{kV}$, $F_t = 26\text{V/nm}$, $\Delta E = 1.00\text{eV}$. †
5: $r_t = 0.25\mu\text{m}$, $V_{ap} = 20.6\text{kV}$, $F_t = 26\text{V/nm}$, $\Delta E = 1.4\text{eV}$.
6: $r_t = 0.25\mu\text{m}$, $V_{ap} = 20.6\text{kV}$, $F_t = 26\text{V/nm}$, $\Delta E = 5.7\text{eV}$.
7: $r_t = 0.25\mu\text{m}$, $V_{ap} = 20.6\text{kV}$, $F_t = 26\text{V/nm}$, $\Delta E = 11.5\text{eV}$.
8: $r_t = 0.25\mu\text{m}$, $V_{ap} = 20.6\text{kV}$, $F_t = 26\text{V/nm}$, $\Delta E = 15.0\text{eV}$.
9: $r_t = 0.25\mu\text{m}$, $V_{ap} = 22.3\text{kV}$, $F_t = 28\text{V/nm}$, $\Delta E = 1.43\text{eV}$.
10: $r_t = 0.25\mu\text{m}$, $V_{ap} = 22.3\text{kV}$, $F_t = 28\text{V/nm}$, $\Delta E = 11.5\text{eV}$.

11 and 12 are supertips with an assumed $\Delta E$ of 1.43 and 11.5 eV.

†$\Delta E$ of source alone is 0.7 eV. Power supply ripple is approximately 0.8 V for 20 kV producing a larger effective energy spread.
the beam would generally be required for the energy stabilization of the Pelletron. Rather, beam core selection would have to take place in the beam line of MP using finely adjustable object and image diaphragms, as is presently the practice.

The final $\beta$ measured in the beam line for a given tip apex field, $F$, (assuming zero loss of brightness in the accelerating column and analyzing magnet) would be given by the envelope of all curves for that field given by Fig. 4.20. Brightness envelope calculations were carried out for a tip apex field of 26V/nm for all major lenses analysed in this chapter. The lenses investigated are listed in Table 4.1. The results of the calculations are shown in Fig. 4.21.

To determine the usefulness of each lens for PIXE analysis, brightness was extracted for final beam currents of 100pA for each lens using equations 4.3, 1.2 and 2.31. The results are displayed in Table 4.2. The ratio $(\beta/5)^{3/8}$ is also included to permit direct spot size comparison with that presently achievable with the spherically limited quadrupole quadruplet. Also for comparison, brightness calculations for lens $p$ using a $20\mu$A sr$^{-1}$ supertip are included. Such a source is represented by curves 11 and 12 in Fig. 4.20.

Table 4.2 shows that brightness at 100pA lies below 2000 Am$^{-2}$ rad$^{-2}$ V$^{-1}$ for all lenses with conventional tips. This represents an improvement in resolution in the MP beamline of less than 10 for all lenses. Greatest improvement is for lens $r$, the accelerating mode standard Riddle lens with a working distance of 1mm. This lens in turn is approximately a factor or 2 better than the accelerating Riddle lens with increased first to second electrode gap and working distance of 1mm. The second highest final brightness is achieved with a decelerating Riddle lens, at 1/4 scale with a working distance of 0.25mm. A final beamline resolution improvement of a factor of 7 could be expected with such a lens. The present Pelletron lens in optimal configuration, and the reduced scale Orloff lens (lens $l$) also show an improvement over the present resolution by a factor of more than 5. All other lenses show an improvement of less than a factor of 4.

Using a supertip, Table 4.2 indicates improvements in resolution by 2 orders of magnitude could be expected using the full scale decelerating Riddle lens.
Figure 4.21

Brightness as a function of current for the lenses listed in Table 4.1, for a tip apex field of 26V/nm. In each case the curve shown represents the 'envelope' of 26V/nm curves for the lens, as for example shown in Fig. 4.20 for the standard Riddle decelerating lens. Brightness values extracted from these curves are listed in Table 4.2. The labels on the curves correspond with the labels listed in Table 4.1.
Lens Image Brightness
Tip Field = 26V/nm
Tip radius = 0.25 microns

Current (pA)

Brightness (Am\(^{-2}\cdot rad\cdot V^{-1}\))

A

B

Lens Image Brightness
Tip Field = 26V/nm
Tip radius = 0.25 microns

Current (pA)

Brightness (Am\(^{-2}\cdot rad\cdot V^{-1}\))
Figure 4.21 continued.
Lens Image Brightness
Tip Field = 26V/nm
Tip radius = 0.25 microns

C

D

Current (pA)

Brightness (A m^-2-rad^-2 V^-1)
Figure 4.21 continued.
Lens Image Brightness
Tip Field = 26V/nm
Tip radius = 0.25 microns

Brightness (Am^{-2}rad^{-2}V^{-1})

Current (pA)
Table 4.1

Table displaying optical parameters for the finally selected range of lenses. Image distance is 200mm. \( g_{\text{min}} \) shows minimum inter-electrode gap width. \( V_{\text{gap}} \) shows voltage difference across this gap. \( D_o \) shows working distance. Those lenses displayed are:

a: Present Pelletron lens, minimum aberration mode.
b: Munro standard lens, \( V_2/V_1 = 8 \).
c: Munro standard lens, \( V_2/V_1 = 4 \).
d: Butler standard lens, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
e: Butler standard lens, accelerating mode, \( V_3/V_1 = 1, \ D_o = 5\text{mm} \).
f: Orloff standard lens, accelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
g: Orloff standard lens, accelerating mode, \( V_3/V_1 = 1, \ D_o = 5\text{mm} \).
h: Orloff standard lens, accelerating mode, \( V_3/V_1 = 1.5, \ D_o = 5\text{mm} \).
i: Orloff standard lens, accelerating mode, \( V_3/V_1 = 2, \ D_o = 7\text{mm} \).
j: Orloff optimized \( C_{\infty} \) lens, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
k: Orloff optimized \( C_{\infty} \) lens, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
l: Orloff standard lens, 1/5 scale, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
m: Orloff standard lens, 1/5 scale, decelerating mode, \( V_3/V_1 = 1, \ D_o = 2\text{mm} \).
n: Orloff standard lens, 1/10 scale, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
o: Orloff standard lens, 1/20 scale, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
p: Riddle standard lens, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
q: Riddle standard lens, decelerating mode, \( V_3/V_1 = 2, \ D_o = 1\text{mm} \).
r: Riddle standard lens, accelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
s: Riddle standard lens, accelerating mode, \( V_3/V_1 = 1, \ D_o = 5\text{mm} \).
t: Riddle optimized \( C_{\infty} \) lens, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
u: Riddle optimized \( C_{\infty} \) lens, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm} \).
v: Riddle lens, accelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm}, 6\text{mm electrode gap}\).
w: Riddle standard lens, 1/2 scale, decelerating mode, \( V_3/V_1 = 1, \ D_o = 0.5\text{mm} \).
x: Riddle standard lens, decelerating mode, \( V_3/V_1 = 1, \ D_o = 0\text{mm} \).
y: Riddle standard lens, 1/4 scale, decelerating mode, \( V_3/V_1 = 1, \ D_o = 0.25\text{mm} \).
z: Riddle standard lens, decelerating mode, \( V_3/V_1 = 1, \ D_o = 1\text{mm 'supertip'} \).
## Chapter 4. Ion Source Lenses

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These results suggest that lenses $a$, $l$, $v$, $y$ and $n$ would be best for PIXE work. Lens $r$, despite having greatest resolution improvement, would require unacceptably high voltages applied across the first inter-electrode gap.

For STIM imaging, currents of tens of kHz of protons are required. With a source angular current density of $150\text{nA}\text{s}^{-1}\text{sr}^{-1}$, source acceptance half angle is of the order of $0.01\text{ mrad}$ for an apex field of $26\text{V}/\text{nm}$. In this region spot size is diffraction limited for all lenses for currents below a few kHz. Table 4.2 shows brightness for currents of $10\text{kHz}$, as well as current (in kHz) produced for maximum brightness achievable in the low current region.

For a current of $10\text{kHz}$, diffraction may be reduced from the situation in Table 4.2 by increasing acceptance angle. The results from Allan [Al89a] in the voltage region above the field ionization current 'cut off' point indicate $i \sim V^n$ where $n \approx 7$. By reducing $V$ slightly therefore, the acceptance angle may be increased to that where diffraction and chromatic aberration spot size contributions are equal. However, the consequent loss of brightness due to increased acceptance angle, coupled with an offsetting increase in diffraction due to decreasing beam energy, results in a final brightness a factor of between 2 and 5 lower than those shown in Table 4.2 for all lenses investigated.

Equation 2.33 indicates that without alteration to the MP beamline, or reduction in Pelletron energy spread, final STIM spot size varies as $(1/\beta)^{1/4}$. This reduces the range of spot size improvement available from brightnesses listed in Table 4.2 for conventional tips to between 17 and 36 over the present optimum resolution. For supertips there is no improvement over conventional tips for resolution at currents of $10\text{kHz}$ as increases in diffraction cancel out the improvement due to increase in current angular density. The optimal low current brightness however, shows a final beamline resolution improvement of a factor of 3 over the best conventional tip low current spot size achievable with any of the lenses.

For conventional tips, the lenses giving greatest resolution improvements are lenses $r$, $o$, $n$, $y$ and $a$ — i.e. the Riddle accelerating lens with $1\text{mm}$ working distance, Orloff and Riddle reduced scale lenses, and the present Pelletron lens.
Table 4.2

Table displaying brightness for a tip apex field of $26\text{V/nm}$, for lenses listed in Table 4.1. The values of brightness are given for currents of $10\text{kHz}$ and $100\text{pA}$, as well as for the maximum brightness achievable for the lens and source. The current (in kHz) for the condition of maximum brightness is also listed, as is the value $(\beta/5)^{3/8}$ for $100\text{pA}$ brightness. Units for brightness are $\text{Am}^{-2}\text{rad}^{-2}\text{V}^{-1}$. 
## Chapter 4. Ion Source Lenses

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<th>Lens</th>
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<th>$\beta_{max}$ (low curr.)</th>
<th>$I_{\beta_{max}}$ (kHz)</th>
<th>$\beta$ (100pA)</th>
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It should be noted that except in the case of lens $r$, all optimum brightnesses occur for currents of greater than 100kHz. For counts of 10kHz, all lenses are diffraction limited, and resolution improvement is approximately 17 in all cases.

The best lens either for PIXE or STIM work however cannot be finally determined until the effect of the accelerating column on beam brightness is included. That effect is the subject of the following chapter.
Chapter 5

The Accelerating Column

5.1 Introduction

A major difference between the proton microprobe and the electron microprobe (EMP) is the far higher energy required for elemental analysis using protons [Jo76]. Whereas the acceleration of the beam of a typical EMP may be achieved across a single voltage gap [Re85b, Co87], for practical purposes the production of 3 MeV protons requires a full multi-electrode accelerating column [Va48].

Historically, the development of accelerator columns has been dominated by the twin requirements of voltage insulation, and the control of column loading caused by secondary particles. The optical properties of columns have been regarded as an important but only secondary consideration [Ga67]. As a result, much of the focusing data for accelerator design has been acquired empirically (with theoretical optical analysis following only afterwards). Where calculations have been performed, for many applications the optical parameters have been determined using the simplifying assumption of a uniform accelerating field terminated by abrupt transitions to field free regions [El51, Mo74, Se77]. For the present calculations, overall design was performed using this model also (Refer Chapter 2).

More precise optical calculations have been performed however by a number of workers [Ro64, La77a, Ki83]. These have included the determination of the acceptance of accelerator tubes for various lens configurations [La77a] and for
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determining the effect on column loading of the production of secondary particles [Ki83]. Calculations have also been made investigating the effect of space charge in intense accelerated beams [Wi73b]. Direct experimental verification of such theoretical studies is difficult, due to the inaccessible nature of most accelerator tubes, but studies have demonstrated the usefulness of theoretical calculations as an accelerating column design tool [El51].

For MP design, an investigation of the acceleration column is crucial for overall understanding of the optical system. The aim of this chapter is threefold — to calculate the Gaussian and higher order optical properties of the present acceleration column; to determine the contribution of the acceleration column to overall degradation in beam brightness or contribution to beam loss; and to investigate optimization of the acceleration column from an optical standpoint, where consistent with practical limitations.

5.2 Gaussian Optics

A tube element is shown diagramatically in Fig. 5.1. Each element consists of 12 titanium rings, with inner diameter 6.7cm, separated by, and metal-bonded to 1.25cm long alumina ceramic cylinders. A flange of titanium is also located at each end of each section for the purposes of secondary electron suppression. Between each tube section is a 'decoupling' section 52mm long and containing a 2.5cm diameter diaphragm. This diaphragm may be heated by an induction current using power from the rotating shaft, however such heating has proved unnecessary for column outgassing in practice, except during installation, as outgassing occurs during 'conditioning' of the column prior to operation. Each titanium ring is fitted externally with a torroidal spark gap and a mounted corona point to maintain voltage linearity along the tube. Three tube elements together make up a single accelerator section. The Melbourne Pelletron consists of 5 sections, or 15 tube elements.

Theoretical calculations by the manufacturer prior to construction of the accelerator were performed using 'Gan's' method and matrix formalism [Na75].
Figure 5.1

Entrance region of the Pelletron Accelerator column, shown in radial section. E denotes the tantalum entrance aperture (lying at the Steerer exit). The second small aperture at the end of the first section is also made of tantalum, with all other electrodes made from titanium.

The entrance potential is 10kV. The potential at the lower tantalum aperture is 210kV. Total voltage on the full accelerating column is 3MV.

Equipotentials are shown every 10KV, except around the entrance region and the first ‘decoupling section’ where intermediate lines are included. Around the entrance, these voltages are 15kV, 12.5kV, 10.5kV, 10.1kV and 10.02kV. In the ‘decoupling section’ equipotentials are shown for 205kV, 209kV, 211kV and 215kV.
In order to model the accelerator more carefully, Munro's program was modified to permit the calculation of relativistic particle trajectories and aberration coefficients using the equations of Zworykin et al. [Zw45]. The effect of relativistic particle speeds is to render the optical properties of the tube no longer dependent only upon the ratio of final to initial energies for a given geometry, but dependent upon the absolute injection and acceleration voltages.

The effect for 3 MeV protons however is small. Such particles have a speed of 0.08c. Calculations showed that the relativistic shift in focal length is typically less than .1%, and spherical and chromatic aberration coefficients were found to increase by around .4% and .2% respectively for relativistically corrected calculations compared with non-relativistic calculations. Such effects are small, and indeed within the error of the finite element method [Mu87]. For the sake of simplicity and with small error therefore, optical parameters are displayed in this Chapter as functions of the voltage ratio (as in other Chapters) rather than as absolute voltages.

Optically the most important region of the accelerating column is the first section and particularly the entrance aperture and fringing fields [El51]. A single accelerator section was initially modelled using a finite element grid of size $30 \times 200 (r \times z)$. Fig. 5.1 shows equipotential plots for this first section assuming an injection voltage of 10kV and final acceleration voltage of 3MV. The entrance aperture fringing fields which produce the strong focusing are clearly seen.

Focal length and spherical and chromatic aberrations proved to be relatively insensitive to changes in grid mesh size and spacing. A grid reduction to size $18 \times 60$ resulted in the variation in focal length by less than 1.5% and in $C_s$, $C_c$ of less than 2.0%. A mesh of this size permitted the modelling of the entire acceleration column as a single entity using an $18 \times 950$ array which was large enough for accurate calculations and permitted reasonable program running times. Fig. 5.2 shows the whole accelerator stack as modelled by this array. The horizontal scale has been much exaggerated for the purposes of plotting. Each minor section in fact expands to a single section geometry similar to that of Fig. 5.1.
Figure 5.2

Full Pelletron Accelerator column, showing the 15 accelerating elements.

VS represents the velocity selector exit, E the accelerating column entrance aperture, X the column exit and X' the end of 3 major sections.

A first order raytrace is shown assuming an injection voltage of 20kV and final accelerating voltage of 3MV. The focus upstream of the accelerator is at the velocity selector exit (its present location) and maximum divergence is 50mrad. The scale of the diagram is much exaggerated in the radial direction for the purpose of illustration.
The dominating effect of the entrance aperture 'lens' on ray paths is clearly seen in Fig. 5.2. In this region strong focusing occurs. A corresponding defocusing effect occurs at the exit aperture of the column. The effect on particle trajectories however, is far smaller than at the entrance, due to the high energy of the beam downstream of the column. Between these regions, protons follow approximately parabolic paths, and the focal length of the central accelerating column is effectively infinite.

The results of the Gaussian calculations are shown in Fig. 5.3. This presents a series of curves displaying object and image positions as well as magnification for various final to initial voltage ratios and using all 5 acceleration sections. Object and image distances are measured from the entrance aperture of the accelerator in all cases. The dotted line marked by an 'X' indicates the exit aperture of the accelerating stack. Below this line the crossover occurs inside the acceleration column. The line marked 'Slits' indicates the present location of the exit slits below the accelerator tank base. For an image located near this position, magnification is relatively large and image position is shown to be a sensitive function of object position for much of this region since the object position is located close to the focal point of the accelerator. For final voltage of 3MV and injection voltages of 20kV and above, both principal planes lie upstream of the entrance aperture (e.g. for an injection voltage of 40kV, \( PP_1 \) lies 650mm upstream and \( PP_2 \) lies 13mm upstream of the entrance).

For the purposes of accelerator design, for a given voltage ratio and required image position, object location may be read off these curves. For example for an injection voltage of 40kV and final voltage of 3MV and for an image located in the plane of the analysing magnet object slits, the accelerator would require an object located 19cm upstream from the entrance aperture. The magnification of the column is 2.8 for this configuration.

In the conditions depicted above the voltage gradient along the accelerator is well below its practical limit. The accelerator column may be modified by electrically 'shorting out' sections, particularly those sections at the entrance or exit of the stack. These changes would not only alter the effective entrance or
Figure 5.3

Object/Image curves (solid lines) for the full accelerating column.

P represents object distance, and Q the resultant image distance (in mm). P and Q are measured from the entrance aperture of the accelerator. Numbers associated with solid lines (small figures) denote final-to-initial voltage ratios. (Assuming a final voltage of 3MV, the 75 line denotes particles with an injection voltage of 40kV). Dashed lines indicate magnification, with values shown in small figures.

X locates the exit aperture plane of the accelerating column and 'slits' the plane of the analysing magnet object slits.
exit position of the accelerator tube, but also the focal properties of the tube by altering the voltage gradient.

Fig. 5.4 shows Gaussian properties calculated for the accelerator stack shortened in this manner to 3 consecutive sections and operating at 3MV. As expected, focal lengths are reduced compared with the 5 section accelerating tube, principally because the dominating entrance aperture lens is now stronger. Magnification is also smaller for all object distances and values of injection voltage, but larger for a fixed image position and given injection voltage. Object and image positions as shown in Fig. 5.4 are measured from the entrance aperture of the first non-shorted section.

Fig. 5.4 may be used for configurations where either the first two or the last two accelerator sections are shorted out. In the first situation, both object and image distances are measured from the aperture at the entrance of the third section. In this case the closest focus possible which does not lie inside the column (i.e. the focus which occurs at the exit of the accelerating column) is indicated by line ‘X’. The location of the exit slits for this case is given by the line marked ‘Slits’. For the second case, where the last two accelerator sections are shorted out, slits and column exit planes are the same as those in Fig. 5.3, and are given by the lines marked ‘slits’ and ‘X’ in Fig. 5.4.

The overall first order effect of operating with the final two sections of the accelerator shorted and the present image slit locations is to increase the magnification (to 4.3 for an injection voltage of 40kV) and decrease the required accelerator tube object distance (to 10.1 cm for the same injection voltage). Fig. 5.4 shows that if desired however, magnification could be reduced by shorting out the first two sections and moving the accelerator object into the accelerator tube itself.

The acceptance of the accelerator tube is a measure of the area of phase space which is transmitted unimpeded by the tube. For operation with a low current field ionization source, it is important that accelerator tube acceptance be greater than injection beam emittance so no beam is lost. Acceptance ellipses were calculated for the accelerator for a range of beam injection voltages using
Figure 5.4

Object/Image curves for the shortened accelerating column. The diagram is of the same format as Fig. 5.3 with line $X'$ representing the exit plane 3 major sections downstream of the entrance aperture.

If the final two accelerating sections are shorted out, the location of the accelerator exit is given by line $X$, and the slits by the line marked 'Slits'. If the first two sections are shorted out, then the location of the accelerator exit (measured from the aperture at the entrance of the third accelerating section) is given by line $X'$, and the slits plane by the line marked ‘Slits’.
the methods of Larson and Jones [La77b] and Banford [Ba66] and equations 2.10 and 2.11. The resultant phase spaces were transformed back by matrix manipulation to the object point required for a focus at the exit slits for each injection voltage. The results are shown in Fig. 5.5.

The difference in the magnitude of the acceptance (i.e. the area of the acceptance ellipse) for different injection voltages is a consequence of Louiville's theorem. The small radial extent of the beam from the Field Ionization source, even at large magnification ensures that emittance is smaller than acceptance for the radial coordinate. The maximum divergence accepted by the accelerating column decreases rapidly with increasing injection energy (acceptance angle varying as approximately the reciprocal of the injection energy). On the other hand, the maximum divergence of the beam is given by

$$\alpha_m = \frac{\alpha_o}{M} \sqrt{\frac{V_o}{V_t}}$$

(5.1)

where $\alpha_o$ is the acceptance half angle of the source aperture,
$M$ is the transverse magnification of the source lens,
$V_o$ is the source voltage and
$V_t$ is the accelerating column injection voltage.

For a source voltage of 20kV, and source acceptance half angle of .1rad, Fig. 5.5 and equation 5.1 together show that a source/lens magnification of 1 is sufficient to ensure complete beam transmission. Since it is anticipated that magnifications larger than 1 and source applied voltages of not substantially greater than 20kV would be used in practice, complete beam transmission under all source and lens configurations may be expected.

5.3 Aberrations

Calculations were carried out for spherical and chromatic aberration coefficients for the accelerating column. Of primary interest were the values of $C_{ao}$ and $C_{co}$ for different possible object and image locations over a range of injection voltages. Figs. 5.6A and 5.7A show $C_{ao}$ as a function of accelerator magnification for the
Figure 5.5

Accelerator Acceptance

Acceptance ellipses for the full length Pelletron Accelerating Column. Upright ellipses indicate acceptance in the entrance aperture plane of the accelerating column. Skew ellipses indicate the same acceptance ellipses transformed back to the object plane corresponding to a beam focus at the analysing magnet object slits. Beam injection voltage (in kV) is denoted for each ellipse by the number adjacent to the curve. Final acceleration voltage is 3MV.
Figure 5.6

Full length accelerator column aberrations.

A:

Spherical aberration curves for the full length accelerating column, as a function of column magnification. Large figures indicate final-to-initial accelerating voltage ratios. Dashed lines show lines of constant image location at the column exit, as well as 4m and 8m downstream of the exit. The plane of the exit slits of the accelerator lies half way between the 'X' and '4m' lines on the logarithmic scale.

B:

Chromatic aberration curves for the full length accelerating column. Figure is of similar format to Fig. 5.6A.
full length and shortened columns. Also plotted are curves corresponding to conditions of constant image plane location. These curves thus indicate the aberration for a particular image plane as a function of injection energy.

It is apparent from Fig. 5.6A that $C_{so}$ decreases both with increasing magnification and with increasing voltage ratio. These observations are consistent with the behaviour of electrostatic lenses observed in Chapter 4, where $C_{so}$ was found to decrease with decreasing object distance and increasing lens acceleration ratios. The effect of object distance on $C_{so}$ is generally small however. It was found that only a small reduction in $C_{so}$ would be gained by increasing the drift length of the beam after the accelerator exit aperture. For example Fig. 5.6 indicates that a reduction in $C_{so}$ of between only 20% and 40% is achieved by positioning the exit slits 4m past the present location for typical injection energies.

Comparing the shortened to the ordinary column for a final accelerating voltage of 3MV, there is a reduction in $C_{so}$ by a factor ranging from 2 for injection voltages of 20kV up to 3 for injection voltages of 160kV for a given column magnification. This is once again consistent with the findings in Chapter 4. Calculations below show the principal contribution to $C_{so}$ occurs in the entrance region where energies are relatively low, and an increased rate of acceleration reduces the aberration integral. Further increase in the overall acceleration voltage gradient could be expected to further reduce $C_{so}$. Spherical aberration is more strongly affected however by the injection voltage, with $C_{so}$ varying as approximately $V_o^2$ for constant magnification.

Figs. 5.6B and 5.7B show $C_{oo}$ as a function of accelerator magnification for the full length and shortened columns. Once again curves of fixed image location are also shown. It is apparent from these results that $C_{oo}$ decreases both with increasing magnification and decreasing injection voltage. Once again these findings are consistent with the findings for electrostatic lenses in Chapter 4. A 4m increase in drift length following the accelerator exit decreases $C_{oo}$ by 30% for 40kV injected ions, and 50% for 80kV injected ions. Magnification is increased by a factor of 3 and 4 for these cases. $C_{oo}$ is also found to decrease
Figure 5.7
Shortened accelerator tube aberrations.

A:
As for Fig. 5.6A, for the 3 section accelerating column.

B:
As for Fig. 5.6B, for the 3 section accelerating column.
with decreasing injection energy and hence decreasing focal length. To a good approximation, for a given magnification, $C_{co}$ is found to vary directly with the injection voltage. The advantage for a chromatically limited beam in running the accelerator with a low injection voltage however, will depend upon the source of the energy spread in the beam, as well as the working voltage and magnification of the injecting lens. These effects will be discussed in section 5.4 below.

5.3.1 Reduction of Aberrations

It is of interest at this point to investigate whether the intrinsic aberrations of the accelerating column may be readily reduced. The integrals used to calculate spherical and chromatic aberrations coefficients are specified in equations 2.26 and 2.30. Relativistic corrections were found to be small since critical aberration contributions were shown to occur in low energy regions.

It is evident that in the case where the rays are emanating from a point source near the focal point of the accelerator, the slope of the trajectory $r'$ will be greatest and $r$ least in the fringing fields upstream of the entrance to the column. Due to the strength of the 'aperture lens', $r$ will be greatest and $r'$ will be least in the region of the aperture and immediately downstream of it. For large magnifications $r$ remains relatively large and $r'$ small and negative for much of the length of the accelerating column. For both aberrations the presence of $V$ to a power greater than unity in the denominator of all terms ensures that for a high energy accelerating tube the integrand rapidly falls along the length of the column and is in fact negligible at the exit aperture.

Fig. 5.8 displays $V''$ and positive $V'$ dependent terms of the spherical aberration integrand (i.e. terms 1 and 2 in equation 2.26), for a 40kV injection voltage. The positive term dependent on $V'$ in equation 2.26 falls off with the 7/2 power of the potential. The negative $V'$ terms in equation 2.26 (not shown in Fig. 5.8) are in fact of greater magnitude than this term for all sections of the accelerator downstream of the entrance region and thus the total contribution of $V'$ dependent terms is negative for all sections. The value of $V''$ is large in the entrance, exit and field transition regions between each accelerator tube element,
Figure 5.8
Aberration integrands for the full length accelerator.

A:
Spherical aberration integrand, showing $V'$ and $V''$ terms. Negative contributions to the integrand are not shown. $E$ denotes the entrance aperture plane of the accelerator. The zero of the $X$ axis corresponds to the centre of the accelerating column.

B:
Chromatic aberration integrand, showing $V'$ and $V''$ terms. $E$ denotes the entrance aperture plane of the accelerator. Integrands downstream of -1200mm are multiplied by 20 for the purposes of display.
Aberration Integrands, (Positive terms).

V' terms

V'' terms

Aberration Integrands, Full Accelerator.

V' terms

V'' terms

Chromatic Aberration Integrand (Arb. units)
and large positive contributions to the integrand occur in these regions.

It is apparent that spherical aberrations would be reduced for a tube of constant potential gradient. Such reduction would be only slight however because of the rapid fall off in the integrand along the tube. Practical problems associated with achieving a more uniform column field further discourage this alternative.

Most important however is the contribution of the region of the entrance aperture and fringing fields where the potential is low, and it may be seen from Fig. 5.8 that the $V''$ terms in this region dominate the aberration integrand. The effect of the fringing fields may be removed by placing a beam transparent grid across the entrance aperture of the tube [La77b, Br65]. This greatly decreases the focal power of the tube however, and would require the introduction of a further lens into the system. It also introduces further aberrations due to the 'facet lens' occurring in each grid element [Br65].

Fig. 5.8B displays the chromatic aberration integrand terms for a 40kV injection voltage. The first integrand term in equation 2.29 is negative in all regions downstream of the aperture due to $r'$ being negative. The integrand is once again dominated by the large $V''$ term, particularly in the entrance aperture area. In the case of chromatic aberration however it is seen that large negative contributions to the integrand occur where $V'' < 0$. These areas are matched in pairs, so the overall contribution from each decoupling region is zero and no advantage is gained in the reduction of chromatic aberration from a constant gradient accelerator.

In order to reduce spherical and chromatic aberration integrands, the entrance fields may be modified by variation of the electrode geometry and applied voltage for the important first few acceleration rings. For a single tube element such variation was performed using the technique outlined in Chapter 4. Using program STEPIT, program F11 was used to vary geometries and potentials of up to the first 7 electrodes in order to minimize a specified figure of merit. No limits on focal length were specified, however the initial and final beam energies were required to be unchanged. Using this method, modifications to the present
entrance configuration to reduce $C_\infty$ and $C_c$ were investigated.

With no restriction on the object position, a minimum of $C_s$ and $C_c$ may be obtained by setting several electrodes downstream of the entrance aperture to zero, thereby ensuring the steepest possible voltage gradient in the initial beam acceleration region. This keeps particles closer on axis and reduces the region of non-zero second differential of the potential. For example for an injection voltage of 10kV, by setting electrodes 2 to 5 to zero volts, while maintaining voltages unaltered on electrodes 6 and 7, $C_\infty$ may be reduced from 119mm to 57mm and $C_c$ from 50mm to 36mm whilst moving the object position from 50mm upstream of to 10mm downstream of the entrance aperture. Thus in analogy with accelerating lenses discussed in Chapter 4 it is seen as advantageous in minimizing $C_s$ and $C_c$ to have high values of $V'$ in the entrance region of an optical element. The voltage gap between electrodes 5 and 6 however is 82kV. By insisting that the object remains upstream of the aperture (for example by minimizing the figure of merit $C_\infty/D_o$) a local minimum may be found for $C_\infty$ of 76mm. The maximum voltage gap between electrodes is 55kV in this case, and object position is 43mm upstream of the entrance aperture.

The spherical aberration is especially sensitive to the initial acceleration region. If a further electrode downstream were grounded, the initially steep acceleration region would reduce $C_\infty$ further to 16mm. If electrodes downstream of the first 7 electrodes are grounded to minimize aberrations, then spherical aberration is minimized by having the entrance aperture region in a smoothly decelerating mode, thereby reducing the size of $V''$ terms in the intergrand. On the other hand, a $C_\infty$ of below 20mm is achievable by placing a strong 3 element lens in the entrance region, with $V_3/V_1$ close to zero and $V_2/V_1$ very large. This strong lens ensures that incoming particles have negative $r'$ in regions of large positive $V''$, thereby reducing the aberration integrand in the entrance region.

Although the above calculations were performed assuming an injection voltage of 10kV, comparable reductions in $C_\infty$ and $C_c$ may be expected for cases with higher injection voltages for similar voltage modifications to those discussed above.
5.4 The Combined System

In a system of two (or more) lenses, the aberration coefficients of individual lenses may be combined into one single coefficient. The formulae given by Orloff [Or83] corrected earlier commonly used but incorrect expressions. For two lenses with aberration coefficients \( C_{so}^{(1)} \), \( C_{co}^{(1)} \) and \( C_{so}^{(2)} \), \( C_{co}^{(2)} \) respectively we may write

\[
C_{so}^{(t)} = C_{so}^{(1)} + \frac{(V_o^{(1)}/V_i^{(2)})^{\frac{2}{3}}}{M^4} C_{so}^{(2)}
\]

(5.2)

\[
C_{co}^{(t)} = C_{co}^{(1)} + \frac{(V_o^{(1)}/V_i^{(2)})^{\frac{2}{3}}}{M^4} C_{co}^{(2)}
\]

(5.3)

where \( C_{so}^{(t)} \), \( C_{co}^{(t)} \) are total spherical and chromatic aberration coefficients,

\( M = M^{(1)}M^{(2)} \) is the total system magnification and

\( V_o \) and \( V_i \) denote the object and image voltages of the lenses respectively.

In both cases, it is apparent that the contribution to total aberration of the second lens is strongly reduced both by increased magnification and increased voltage accelerating ratio of the first lens. This is primarily due to the variation in angular magnification of the first lens, given by equation 2.13. For spherical aberration the dependence on the angular magnification is particularly strong as the radius of the aberration disc varies as the cube of the divergence.

In the case of chromatic aberration equations 5.4 and 5.5 only give a complete description of beams where the total energy spread is dominated by the energy spread intrinsic to the ion source. In the case of a field ionization source, this spread is of the order of 10eV for a tip field of 25V/nm and applied voltage of 15kV. This represents a total particle energy variation of approximately 0.07%.

For the Pelletron Accelerator however a much greater contribution to final energy spread is caused by voltage fluctuations in the high voltage terminal. The total energy variation of the Melbourne University Pelletron at 3MV is given by
Chapter 5. The Accelerating Column

Jamieson [Ja85] as 0.005% or 150eV. Assuming an RF ion source with an energy spread of approximately 70eV [Al89a], this gives a terminal energy fluctuation of the accelerator of approximately 130eV. Hence the final contribution to the chromatic disc radius must be calculated by an application of equation 5.5 for the ion source, lens and column, along with a separate application of equation 2.28 for the accelerator stack alone.

For chromatic aberration it was found in section 5.3 that $C_{co}$ of the accelerating column varies as approximately $V_o^{(2)}$ for constant $M^{(2)}$. Referring the aberrations to the ion source, equation 5.5 combined with equation 2.28 for the contribution to source size from the terminal energy fluctuations may be rewritten approximately

$$\Delta r_c \approx \frac{1}{2} \alpha_v \frac{F_c(M^{(2)}) \Delta E V_o^{(1)} \Delta E / E}{M^{(1)^2} V_v^{(2)^{1/2}} V_v^{(2)^{1/2}}}$$

(5.6)

where $\Delta r_c$ is the increase in beam radius referred to the ion source,

$V_v^{(1)}, V_v^{(2)}$ denote ion source applied voltage and accelerating column injection energy respectively,

$F_c(M^{(2)})$ is a function of the accelerating column magnification,

$\alpha_v$ is the acceptance half angle and

$\Delta E / E$ is the ratio of terminal energy fluctuations to ion source exit energy.

Similarly for spherical aberration it was found in section 5.3 that $C_{so}$ of the accelerator varies as approximately $V_v^{(2)^2}$ for constant magnification. Thus equation 5.3 may be rewritten approximately

$$C_{so}^{(1)} \approx C_{so}^{(1)} + \frac{V_v^{(1)^{1/2}} V_v^{(2)^{1/2}}}{M^{(1)^4}} F_s(M^{(2)})$$

(5.7)

where $F_s(M^{(2)})$ is a function of the accelerating column magnification.

The chromatic and spherical aberration contributions of the accelerating column are thus both increasing functions of the injection energy of the beam. They are also strongly decreasing functions of the magnification of the ion source lens.

For total aberration calculations the ion source lens image distance was fixed at 200mm. For most lenses studied this provides an ion source/accelerating
column separation approximately equal to that which presently occurs in the Pelletron, although it may be possible to increase this separation somewhat by suitable rearrangement of the high voltage terminal.

Fig. 5.9 shows the contributions to final spot size, referred to the source, for three contrasting optical configurations.

In Fig. 5.9A the Riddle lens is shown in 'low current' operation. In this situation, the accelerating column chromatic aberration contribution to spot size is virtually as large as that of the lens. \( C_{30, \text{acc.}} \) is completely negligible according to equation 5.3 due to the high magnification of the source lens.

Fig. 5.9B shows spot size contributions for the same lens in 'high current' mode. Chromatic aberration of the source lens is increased dramatically with increased source energy spread. The effect on the accelerating column contribution however is minimal as this contribution is dominated by beam spread due to terminal energy fluctuations.

Fig. 5.9C shows the contributions for the Munro lens for \( V_2/V_1 = 8 \) and low current mode. In this case, \( M^{(1)} \) is much lower than previously, and \( V_0^{(2)} \) higher, resulting in a dominant term in the source radius being the accelerating column chromatic aberration term. Accelerating column spherical aberration is much larger than before, but still a smaller term than the lens spherical aberration. If the Munro lens were to be used in the Pelletron, with an accelerating ratio of 8 and in low current mode, the source lens image distance would have to be increased by approximately a factor of 10 to reduce the accelerating column chromatic aberration to below that of the lens.

Calculations similar to those above were performed for the range of lenses presented in Table 4.1. In each case brightness envelopes for the pre- and post-accelerator beams were extracted. Fig. 5.10 illustrates brightness for 4 lenses, showing the differing effect of the accelerator on the brightness of each beam.

For lenses a and c, brightness loss in the column is large at low currents, following equation 5.5, because injection energy of the beam is high. For lenses c and d substantial loss of brightness also occurs, following equation 5.5, because lens magnification is relatively low. For lens t, magnification is high and injection
Figure 5.9

Curves showing contribution to the beam spot size downstream of the accelerator exit. All contributions are referred back to the object (i.e. the ion source). All curves are for the region of low current (diffraction and chromatically limited) operation of the source.

The curves shown are:

- $r_{ts}$: total radius of ion source object.
- $r_{sl}$: lens spherical aberration disc radius.
- $r_{cl}$: lens chromatic aberration disc radius.
- $r_{al}$: accelerator spherical aberration disc radius.
- $r_{ca}$: accelerator chromatic aberration disc radius.
- $r_t$: total disc radius.

The figures shown are for:

A:
The Riddle standard lens, decelerating mode (lens $p$ of Table 4.1).

B:
The Munro standard lens, $V_3/V_1 = 4$ (lens $c$ of Table 4.1).

C:
The Munro standard lens, $V_3/V_1 = 8$ (lens $b$ of Table 4.1).
Riddle Standard Lens, $V3/V1=1$

Munro Standard Lens, $V2/V1=4$
Figure 5.9 continued.
Munro Standard Lens, V2/V1 = 8

Half Angle (mrad) vs. mm

Graph showing various curves for different parameters labeled with Greek letters.
Figure 5.10

Brightness as a function of final beam current for lenses $a$, $c$, $d$ and $t$ of Table 5.1.

For each lens 2 curves are shown — the upper curve indicates brightness for the beam at the accelerating column entrance, and the lower curve indicates brightness downstream of the accelerator exit.
energy relatively low, since \( V_3/V_1 = 1 \). Hence little loss of brightness occurs in the accelerating column.

The total accelerating column aberration coefficients and magnifications were calculated for all lenses presented in Table 4.1. Table 5.1 shows aberration coefficients related to the object (i.e. the ion source) for all lenses. It also lists total magnification for the combined lens/accelerating column system, assuming a source lens image distance of 200mm.

Table 5.2 displays final brightness, calculated for the beam downstream of the accelerator exit, for typical STIM currents, for the range of lenses in Table 5.1. The amount of brightness loss occurring in the accelerating column may be gauged by comparing final brightness values with those listed in Table 4.2.

Table 5.3 displays final brightness, calculated for the beam downstream of the accelerator exit, for typical PIXE currents (100pA), for the range of lenses in Table 5.1. Also displayed in Table 5.3 are the expected beam spot sizes and divergences at the accelerator exit for a beam current of 100pA.

In Chapter 4 it was found that for currents of 100pA, brightness downstream of the lens is limited by both \( C_c \) and \( C_r \) in the lens. Equation 5.2 ensures that \( C_r \) of the accelerator is small in all cases. The accelerator chromatic aberration, however may still be significant for lenses with low magnification, for currents of 100pA. For example, for lens \( y \), the Riddle accelerating lens with electrode separation 6mm, the accelerating column chromatic aberration reduces brightness by 40%. Equation 2.34 indicates an increase in optimum beamline spot size of approximately 20% in this case.

In contrast, for the low current brightness maximum, (i.e. STIM currents) the accelerator causes a reduction in maximum brightness by up to a factor of 5. This represents approximately a 50% decrease in final optimum resolution in the beam line. In all cases the current at which the brightness maximum occurs is found to decrease with the addition of the accelerating column into the optical system, by approximately the same factor as brightness is reduced by the accelerating column.
Table 5.1

Table displaying accelerator column spherical and chromatic aberrations, referred to the source, for lenses listed in Table 4.1. Total magnification of the lens/accelerator system is also shown.
Chapter 5. The Accelerating Column

<table>
<thead>
<tr>
<th>Lens</th>
<th>$C_{so}$ (acc.) (mm)</th>
<th>$C_{co}$ (acc.) (mm)</th>
<th>$M_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$1.0 \times 10^{-2}$</td>
<td>$7.6 \times 10^{-4}$</td>
<td>61</td>
</tr>
<tr>
<td>b</td>
<td>$1.8 \times 10^1$</td>
<td>$2.5 \times 10^{-2}$</td>
<td>7</td>
</tr>
<tr>
<td>c</td>
<td>$9.3 \times 10^1$</td>
<td>$1.2 \times 10^{-1}$</td>
<td>6</td>
</tr>
<tr>
<td>d</td>
<td>$1.2 \times 10^{-2}$</td>
<td>$4.2 \times 10^{-3}$</td>
<td>82</td>
</tr>
<tr>
<td>e</td>
<td>$4.5 \times 10^{-2}$</td>
<td>$8.1 \times 10^{-3}$</td>
<td>59</td>
</tr>
<tr>
<td>f</td>
<td>$2.4 \times 10^{-2}$</td>
<td>$7.0 \times 10^{-3}$</td>
<td>63</td>
</tr>
<tr>
<td>g</td>
<td>$3.0 \times 10^{-2}$</td>
<td>$6.6 \times 10^{-3}$</td>
<td>66</td>
</tr>
<tr>
<td>h</td>
<td>$2.4 \times 10^{-2}$</td>
<td>$4.0 \times 10^{-3}$</td>
<td>65</td>
</tr>
<tr>
<td>i</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$3.0 \times 10^{-3}$</td>
<td>60</td>
</tr>
<tr>
<td>j</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>140</td>
</tr>
<tr>
<td>k</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$5.4 \times 10^{-4}$</td>
<td>228</td>
</tr>
<tr>
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<td>734</td>
</tr>
<tr>
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<td>958</td>
</tr>
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<td>130</td>
</tr>
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<td>59</td>
</tr>
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</tr>
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<td>104</td>
</tr>
<tr>
<td>t</td>
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<td>$7.4 \times 10^{-4}$</td>
<td>196</td>
</tr>
<tr>
<td>u</td>
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<td>$1.4 \times 10^{-3}$</td>
<td>143</td>
</tr>
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</tr>
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<td>$1.1 \times 10^{-4}$</td>
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</tr>
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<td>z</td>
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<td>$1.7 \times 10^{-1}$</td>
<td>130</td>
</tr>
</tbody>
</table>
Table 5.2

Table displaying brightness downstream of the accelerator for a tip apex field of 26V/nm, for lenses listed in Table 4.1. The values of brightness are given for currents of 10kHz, as well as for the maximum brightness achievable for the lens and source. The current (in kHz) for the condition of maximum brightness is also listed. Units for brightness are $\text{Am}^{-2}\text{rad}^{-2}\text{V}^{-1}$.
### Chapter 5. The Accelerating Column

<table>
<thead>
<tr>
<th>Lens</th>
<th>$\beta$ (10kHz)</th>
<th>$\beta_{\text{max}}$ (low curr.)</th>
<th>$I_{\beta_{\text{max}}}$ (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
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<td>139</td>
</tr>
<tr>
<td>b</td>
<td>$1.08 \times 10^5$</td>
<td>$1.33 \times 10^5$</td>
<td>5</td>
</tr>
<tr>
<td>c</td>
<td>$6.28 \times 10^3$</td>
<td>$2.86 \times 10^4$</td>
<td>1</td>
</tr>
<tr>
<td>d</td>
<td>$4.19 \times 10^5$</td>
<td>$5.30 \times 10^6$</td>
<td>21</td>
</tr>
<tr>
<td>e</td>
<td>$3.69 \times 10^5$</td>
<td>$4.07 \times 10^5$</td>
<td>16</td>
</tr>
<tr>
<td>f</td>
<td>$3.96 \times 10^5$</td>
<td>$4.68 \times 10^5$</td>
<td>18</td>
</tr>
<tr>
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<td>$5.08 \times 10^5$</td>
<td>$5.02 \times 10^5$</td>
<td>19</td>
</tr>
<tr>
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<td>32</td>
</tr>
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<td>$4.89 \times 10^5$</td>
<td>$1.08 \times 10^6$</td>
<td>42</td>
</tr>
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<td>42</td>
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<td>$8.33 \times 10^6$</td>
<td>32</td>
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<td>s</td>
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<td>$1.25 \times 10^6$</td>
<td>49</td>
</tr>
<tr>
<td>t</td>
<td>$5.07 \times 10^5$</td>
<td>$1.82 \times 10^6$</td>
<td>71</td>
</tr>
<tr>
<td>u</td>
<td>$4.86 \times 10^5$</td>
<td>$1.02 \times 10^6$</td>
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</tr>
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<td>y</td>
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</tr>
<tr>
<td>z</td>
<td>$5.20 \times 10^5$</td>
<td>$4.80 \times 10^8$</td>
<td>$2.3 \times 10^6$</td>
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</tbody>
</table>
Table 5.3

Table displaying brightness downstream of the accelerator for a tip apex field of 26V/nm, for lenses listed in Table 4.1. The values of brightness are given for currents of 100pA. The value \((\beta/5)^{3/8}\) is also listed for each lens. Units for brightness are \(\text{Am}^{-2}\text{rad}^{-2}\text{V}^{-1}\).

Also listed are the values of final beam spot size \(r_f (\mu\text{m})\), and divergence \(\theta_f (\text{mrad})\), for 100pA current, at the accelerator exit for the lenses and configurations specified.
<table>
<thead>
<tr>
<th>Lens</th>
<th>$\beta$ (100pA)</th>
<th>$(\beta/5)^{3/8}$</th>
<th>$\theta_f$ (mrad)</th>
<th>$r_f$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>500</td>
<td>5.7</td>
<td>.03</td>
<td>2.8</td>
</tr>
<tr>
<td>b</td>
<td>8.2</td>
<td>1.2</td>
<td>.23</td>
<td>2.7</td>
</tr>
<tr>
<td>c</td>
<td>.03</td>
<td>.15</td>
<td>.27</td>
<td>39</td>
</tr>
<tr>
<td>d</td>
<td>7.2</td>
<td>1.2</td>
<td>.022</td>
<td>31</td>
</tr>
<tr>
<td>e</td>
<td>18</td>
<td>1.7</td>
<td>.028</td>
<td>16</td>
</tr>
<tr>
<td>f</td>
<td>5.8</td>
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<td>.026</td>
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<td>.025</td>
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<td>.012</td>
<td>19</td>
</tr>
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<td>k</td>
<td>110</td>
<td>3.2</td>
<td>.008</td>
<td>22</td>
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<td>l</td>
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<td>.003</td>
<td>38</td>
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<td>o</td>
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<td>u</td>
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<td>v</td>
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<td>.008</td>
<td>22</td>
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<tr>
<td>x</td>
<td>65</td>
<td>2.6</td>
<td>.014</td>
<td>17</td>
</tr>
<tr>
<td>y</td>
<td>990</td>
<td>7.3</td>
<td>.0035</td>
<td>17</td>
</tr>
<tr>
<td>z</td>
<td>$\sim 10^6$</td>
<td>$\sim 100$</td>
<td>.0025</td>
<td>.73</td>
</tr>
</tbody>
</table>
For high currents (PIXE work) Table 5.3 indicates that best final resolution improvement would be achieved by the accelerating Riddle lens. For this case, assuming final spot size is limited by spherical aberration in the beam line, a reduction in minimum spot size by a factor of 9 could be expected over the present source and lens. Calculations in Chapter 4 however, indicated that this lens would require unacceptably high applied voltages on the second electrode for operation with the field ionization source. The case of reducing the central electrode voltage by permitting an increase in object distance (i.e. tip/lens electrode separation) is represented by lens s. To achieve acceptable central voltages $D_s$ must be increased to 5mm. From Table 5.3 it may be seen that the expected resolution improvement over the existing situation is reduced to 2.3 for this lens. Increasing first to second electrode gap in the accelerating Riddle lens permits the maintenance of a small object distance, whilst permitting the required voltage to now be applied across the electrode gap (refer discussion in Section 4.5). This lens is represented by lens v. It may be seen in Table 5.1 however that aberrations are substantially increased over lens r due to the enlarging of the electrode gap. Final resolution improvement is by a factor of 4.5 over the present case for lens v.

Lenses g, h and i represent accelerating mode Orloff lenses, with object distances large enough to permit achievable voltages on the central electrode. Improvement in resolution over the present source/lens configuration is approximately 3 in each case.

As discussed in Chapter 4, decelerating lenses provide the advantage of having easily achievable applied voltages, although their aberrations are relatively high compared with accelerating lenses.

The full scale decelerating Riddle lens with 1mm object distance for example, represented by lens p, may be expected to provide only comparable brightness to the present Pelletron source/lens configuration. Reducing object distance further (lens x) does not significantly reduce aberrations and improve brightness.

Aberrations may be reduced however by reduction in the scale of the lens along with a similar reduction in object distance. Lenses w and y represent
Riddle lenses in decelerating mode, reduced to \(1/2\) and \(1/4\) scale respectively. It should be noted that the full scale Riddle lens discussed here differs slightly in design from that shown in Fig. 4.8 in that the first to second electrode gap is 2mm for the full scale lens. For PIXE currents, lenses \(w\) and \(y\) may be expected to produce final minimum spot sizes approximately a factor of 3.2 and 7.3 smaller than at present respectively. At \(1/4\) scale, for 20 kV source voltages, the voltage applied across the 0.5mm first to second electrode gap in the lens is 17.8kV. This voltage lies within that achievable across the gap according to equation 4.2 (equation 4.2 suggests a minimum possible separation of 0.3mm for this case). For similar scale reduction, the Riddle decelerating lens is superior to the Orloff decelerating lens at PIXE currents, as aberrations (particularly spherical) are larger for the Orloff lens.

A further reduction in lens scale by a factor of 0.6 may be possible for lens \(y\). Such a further reduced lens would be at the inter-electrode breakdown limit. Calculations indicate that minimum spot size for this lens would be approximately a factor of 11 below that of the present source/lens configuration for PIXE currents.

Table 5.2 indicates that best low current (STIM operation) final resolution is provided by lenses \(l\), \(n\) and \(o\), the scaled down decelerating Orloff lenses, and lens \(y\), the \(1/4\) scale decelerating Riddle lens. Beams using these lenses suffer no significant loss of brightness in the accelerating column as lens magnification is high (in excess of 75 for each lens). The \(1/10\) scale decelerating Orloff lens with 1mm object distance (lens \(n\)) is slightly superior to the \(1/4\) scale decelerating Riddle lens, however equation 2.33 determines that there is no significant difference between the final minimum spot size of the two. The \(1/4\) scale Riddle lens could be expected to reduce the minimum spot size by a factor of 31 over the present case at low currents.

It may be seen that no single lens provides optimum performance at both high and low currents. This is because the attainment of lower \(C_a\) generally implies higher \(C_c\) and vice versa. These findings were also noted by Riddle [Ri78].
As a consequence of investigations carried out above, and of those in Chapter 4, it was concluded that the most promising lens for use with the field ionization source is the reduced scale, decelerating Riddle lens; either lens $y$ or a version of lens $y$ reduced by a further factor of 0.6.

It was decided to construct a full scale version of the lens, to permit the testing of the design and a check of calculations. Flexible design of the lens cradle and mounting will permit the reduction of lens scale in future, when the final lens is constructed.
Chapter 6

Ion Source Lens — Design and Construction

6.1 Introduction

The analysis in Chapters 3 to 5 indicated that a substantial improvement in the brightness of the Pelletron proton beam might be expected from the installation of a field ionization ion source coupled with appropriate modifications to the Pelletron Accelerator. The analysis also indicated that the most crucial modification to the optical system is that of the electrostatic ion source lens. A prototype field ionization source has already been built and tested by Allan [Al88a]. The utilization of this source requires the construction of a lens based on the design of Chapter 4, and compatible with the working environment of the Pelletron High Voltage terminal. The calculations in Chapters 4 and 5 indicated that a reduced scale version of the Riddle lens may be expected to provide the best final MP resolution with practicable lens applied voltages.

Before installation of such a lens however, the design must be tested extensively in the laboratory. It was decided to construct a full scale version of the lens, to permit the testing of the design and a check of calculations. Flexible design of the lens cradle and mounting will permit the reduction in lens scale in future when the final lens is constructed. This Chapter describes the design and construction of the ion source lens, and the associated optical test bench.
6.2 Design and Construction of the Lens

6.2.1 Ion Source and Housing

The prototype field ionization source was developed by Allan [Al88a]. The lower flange of the source housing is of the diameter required for mating onto the upper flange of the Pelletron velocity selector or steerer. The associated test bench is a modified version of equipment originally designed for the investigation of the properties of an RF ion source [Al80].

The source housing itself (shown in Fig. 6.1) is constructed from a cylindrical piece of stainless steel and is provided with four ports. These ports are ordinarily used to mount a cold cathode vacuum gauge, a mass spectrometer head, a window and a linear motion drive. Three radial electrical feedthroughs were also incorporated in anticipation of the installation of the electrostatic lens.

The source region itself is enclosed in a cylindrical ceramic block capped by a stainless steel snout with a central differential pumping aperture. The introduction of H₂ gas is possible via a vent machined in the upper surface of the source. The field ionization tip is mounted opposite the differential pumping aperture, resulting in a beam directed down the axis of the source. Voltages are applied to the ionization tip by means of an axial electrical feedthrough situated at the top of the source. Further details on source design and performance are given by Allan [Al88a].

6.2.2 Lens and Lens Mounting

The lens was required to be located directly below the ion source, and mounted on the ion source housing. The entire system was also required to be designed for maximum flexibility of usage, as well as compatibility with Ultra High Vacuum (UHV) and high voltage requirements. The problem of electrical breakdown was expected to be an important limitation, due to the high voltages and small electrode gaps required by the optically superior lenses suggested by theoretical calculations.

The lens and lens support structure is illustrated in Fig. 6.1. The lens
Figure 6.1
Schematic diagram of the test bench and lens (to scale). The diagram shows

A: Thermionic electron source
B: Anode
C: Pactene anode support ring
D: Lens electrodes
E: Ceramic lens block
F: Aluminium lens cradle
G: Stainless steel lens sleeve
H: Aperture strip
I: X-Y adjustment opposing spring
J: Lockable X-Y adjustment screw
K: Ceramic HV feedthrough
L: Pactene HV plug
M: Cold cathode vacuum gauge (not shown)
N: Varian linear motion drive (not shown)
O: Multi-position target locator (not shown)
P: Grid holder
Q: Turbo molecular pump (not shown)
R: Auxiliary port
S: Target phosphor screen
T: Lower viewing port
U: Voltage feedthrough wire.
electrodes were manufactured from stainless steel, chosen for its good vacuum breakdown properties [Ha68]. Measurements by Cranberg [Cr52] indicate vacuum breakdown fields of up to $10^5 \text{V/mm}$ for parallel polished stainless steel plates separated by 1mm, although careful conditioning is required to reach these values. Even higher fields are found for W [Ha68], but machining difficulties discouraged its use for electrodes. Conditioning of the lenses was not generally carried out due to practical difficulties. All electrodes were carefully polished and cleaned prior to use, and all sharp edges rounded off. The electrodes used in the lens prototype are shown in Fig. 6.2A. The ports located around the circumference of the larger electrodes were designed to maximize pumping conductance.

The electrodes were mounted in a ceramic support block, shown in Fig. 6.2B. The block is manufactured from a single piece of Macor ceramic. This material was chosen as an insulator as it can be accurately machined, and for its compatibility with UHV conditions. The inside surface of the block is machined to 3mm cylindrical 'steps'. The electrodes are then located on each step with a "push fit", and alignment of electrode apertures is ensured by careful block machining. Electrical connection is achieved by spring loaded stainless steel contacts, mounted inside threaded feedthroughs in the walls of the block. The nature of the electrode/support block structure was designed to facilitate alteration of electrode geometry. Providing their sizes and spacing do not vary too drastically, new electrodes may be constructed, then simply exchanged for the existing electrodes in the block. In the unlikely event of damage to an electrode, it is also easily replaced.

The support block is mounted inside a cylindrical aluminium cradle, shown in Fig. 6.2C. As before, accurate axial alignment is ensured by close fitting between the ceramic block and the aluminium cradle. To increase pumping speeds and to reduce the "virtual leak" created by close fitting surfaces, the cradle is provided with numerous pumping ports, as well as milled pumping grooves located on its inner and outer surfaces. Three 12mm ports in the wall of the cradle accommodate electrical feedthroughs. The Macor block is secured inside
Figure 6.2

Components of the prototype electrostatic lens.

A:

Lens electrodes. Illustrated right to left are the first, second and third electrodes. All electrodes are showing ‘downstream’ surfaces. The holes drilled around the circumference of the first and second electrodes serve to increase pumping conductance. The conical bore of the central electrode is also visible. The largest electrode is 40mm in diameter.

B:

Ceramic electrode block and aluminium cradle. The block is machined from a single piece of ‘Macor’ ceramic. The three cylindrical steps designed to support the electrodes may be seen. The ends of two electrical feedthroughs are also visible.

Milled pumping grooves may be seen on the inside and outside surfaces of the aluminium cradle. Smaller holes in the sides and base are pumping ports. Larger holes are for electrical feedthroughs.
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the cradle by 3 screws in the cradle base.

The cradle itself is located within a cylindrical stainless steel sleeve shown in Fig. 6.2D. The design of the sleeve permits adjustment in axial cradle position by up to 36mm. Elongated slots in the sleeve accommodate the movement of the electrical feedthroughs. The axial adjustment of the lens and its cradle is necessary for flexibility of usage of the lens, as well as for the measurement of lens properties (Refer section 7.2).

Variation in the cradle position is achieved by the adjustment of a lockable threaded ring located immediately below the cradle. The correct orientation of the lens feedthroughs vis-à-vis the cylinder is ensured by a vertical alignment groove in the outer surface of the cradle. Once again, numerous pumping ports are provided in the stainless steel cylinder, and three slots are available for insertion of aperture strips. The aperture strips are also manufactured from stainless steel and are machined to close-fitting thickness to ensure precise axial location of apertures. Each aperture strip may be moved through approximately 50mm by use of a Varian linear motion drive. Two viewing ports are also provided in the upper portion of the sleeve, corresponding with the ports on the test bench housing.

The upper surface of the cylinder which mates with the ion source housing is accurately machined to ensure axial alignment of the lens with respect to the ion source and subsequent optical elements. The cylinder locates into the upper part of the housing with a push fit, and the uppermost flange is provided with push out screws. All locating screws are axially drilled to minimize virtual leaks.

6.2.3 High Voltage Supply

High voltage supply to lens electrodes is achieved via three electrical feedthroughs situated in the side wall of the ion source housing. These feedthroughs are custom built, consisting of an axial wire surrounded by a 22mm diameter Macor plug, Torrsealed into position. The corresponding socket for the power supply is a close fitting Pactene block which may be screwed rigidly onto the feedthrough. Connection to the stainless steel electrode contacts is by ceramic bead encased
Figure 6.2 continued.

C:

The stainless steel lens sleeve, aluminium lens cradle and locking ring. Smaller holes in the lens sleeve are pumping ports. The larger hole is the viewing port. The alignment screw on the lens sleeve and the alignment groove on the lens cradle are also visible.

D:

The lens sleeve, viewed from the opposite side to Fig. 6.2C. The elongated slots are placed to accommodate electrical feedthroughs. An aperture strip, with linear motion drive adaptor, is also shown.
steel wire, of sufficient length to accommodate lens movement.

Electrode voltages are provided by up to three Bertan 612A power supplies. These supplies are extremely stable with rated voltage ripple of .004% at 20kV and voltage stability of .01% per hour. Field ionization current is also supplied by a Bertan 612A-500P power supply. Spark protection is provided by the incorporation of series resistors of $10^8$ or $10^{10}\Omega$ in all electrode circuits, as well as in the field ionization source supply line. These are required since sparks due to voltage breakdown may cause damage to electrodes and destruction of the ionization tip [Al88a]. Since electrode operation is static, the presence of resistors has no effect on ordinary operation. Further, since maximum field ionization currents are of the order of $10^{-8}$A there is insignificant voltage drop over the protection resistor in the source circuit [Al88a].

6.2.4 Vacuum

The source and lens are pumped by a 170 l/s Pfeiffer turbo molecular pump. The pump is mounted on a right angled 2½” diameter beam tube adapted onto the bottom of the lens housing (refer Fig. 6.1). Base pressures are limited by pumping speed, the intricacy of the lens and the large area of close fitting surfaces. Unfortunately, the precision of manufacture and the presence of Torrseal seals precludes high temperature baking of the system. Attempts to improve pumping speed of the ion source by the introduction of a 25 l/s ion pump by Allan [Al88a] did not show significant improvement. Nevertheless, pressures of around $3 \times 10^{-7}$ Torr measured at an upper port are achieved after a pumping period of 24 hours. Base pressures of $5 \times 10^{-8}$ Torr are obtained after a period of approximately 10 days. Allan [Al88a] found base pressures in the low $10^{-7}$ Torr range suitable for operation of the field ionization source.

For operation inside the accelerator, a pump would be required to be located inside the terminal dome, preferably immediately below the lens. In this location the pumping speed would benefit over the present situation from enhanced conductance through the 6” flange on the bottom of the source. An appropriate pump would be an ion or sublimation pump. Without this pump,
very long pump down times could be expected for the existing pump geometry, due to the high impedance of the accelerator column.

6.3 The Ion Optical Test Bench

6.3.1 The Electron Source

The beam produced by the field ionization ion source has a maximum current of approximately 21nA at an applied voltage of 20kV with H₂ partial pressure of 1 Torr [A188a]. The beam conducted by the lens is expected to be an order of magnitude below this (refer Chapter 4). At such currents, and at the high source and electrode voltages required for operation, a systematic investigation of lens properties is difficult. The most convenient method of investigation of lens properties is the 2 grid method (refer Chapter 7), which requires the projection of beam grid shadows onto a scintillation screen. Such low beam currents and long pumpdown times would render this method impracticable. Since at non-relativistic velocities lens properties are independent of beam particle mass, electrons may be used to investigate the lens, providing all electrode voltages are reversed. It was also expected that substantial electron beam currents could be obtained relatively easily.

Initially, the field ionization source was operated as a field emission source by the application of negative voltages to the tip. This method did not produce promising results however, for several reasons. Stable field emission gun operation requires a pressure in the tip vicinity in the range 1 → 3 × 10⁻¹⁰ Torr [Cr52]. Alternatively, field emission guns may be operated in the low 10⁻⁸ Torr region providing the tip may be “flashed” by the application of a high transient AC voltage, and tip power supply circuitry has protection against sparking [Ly87]. The “flashing” of the tip is important due to the occurrence of surface contaminants on the emission tip, which if not removed lead to electrical breakdown between the tip and the anode.

Pressures in the low 10⁻⁸ Torr region could be reached in the ion source after a pump down period of 10 days. Pumping times could not be reduced below
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this because of the inability to aggressively bake the ion source due to the delicate seals and accurately machined lens assembly. Nor could the tip be flashed due to the existence of only a single tip electrical feedthrough. Nevertheless, field emission was attempted using the ion source. Although catastrophic breakdowns which would destroy the tip were avoided by the use of a series protection resistor, the current was found to fluctuate wildly and unpredictably. These fluctuations were thought to be caused by a combination of the effect of tip surface contamination and the deformation of the tip shape by the bombardment of residual ions. Moreover, the prohibitively long pump down periods are unsuitable for the 2 grid method, where repeated opening of the source and repositioning of the lens is required. Without substantial redesigning of the ion source, it was concluded that its operation in field emission mode for the testing of the lens was impracticable. Instead, following the example of optical test benches built elsewhere, a thermionic electron gun was adapted to the system. Such a source may readily produce a high current, high brightness beam, without the need for UHV conditions. Hence pumping times may be expected to be substantially less. The particular gun was obtained from a decommissioned Siemens scanning electron microscope.

The electron gun is adapted onto the ion source housing by an aluminium cylinder equipped with “O” ring seals (refer Fig. 6.1). Alignment of the electron gun is possible using lockable X and Y screws fitted with opposing springs. The gun anode is mounted on an insulating Pactene cylinder and is located on the end of the ceramic snout. Threading of the cylinder and mount permits continuous adjustment of cathode/anode separation. By this method the separation could be varied between 6mm and 15mm.

Since it was intended that much lower voltages would be used than those of the original SEM the gun electronics had to be substantially modified. As a result of these modifications, the gun could be used to operate with an extraction voltage of 2—10kV.

Fig. 6.3 shows a view of the ion source housing, with the mounted electron source. The electron source is supported from above to prevent distortion of the
Figure 6.3

A photograph of the ion optical test bench.

From top to bottom the elements are: Electron gun (supported from above by a chained plate); Lens housing, with linear motion drive and viewing port; Beam tubing, with multi-position locator for targets. The bottom window and phosphor screen may be seen reflected in the mirror below the beam tube bottom flange.
carefully constructed ion source housing and lens support by the weight of the source and the adaptor cylinder. Fig. 6.1 is a diagram of the whole electron optical test bench including electron gun and electron 'beam line'.

Electrons of energies $2 \rightarrow 10$keV are strongly affected by the Earth's magnetic field, as well as by stray magnetic fields. The effect of such fields was minimized by ensuring all construction materials were non-magnetic, and by removing magnetic items (such as the cold cathode gauge head) as far as possible from the test bench. Finally, two sets of Helmholtz coils, positioned at right angles, were mounted around the chamber. These coils may be seen in Fig. 6.4.

At the start of each data-collection run, the spot was observed without lens applied voltage and the coil current adjusted to obtain axial positioning of the beam spot. When the lens was used in decelerating mode the low-energy beam was further sensitized to the Earth's field, and fine readjustments to the coil currents were occasionally necessary during operation.

AC magnetic fields were investigated using a wire coil and oscilloscope, and were found to be negligible.

6.3.2 Beam Detection and Measurement

A number of possible beam detection modes are available. Firstly, the lens assembly may be replaced by a Faraday cup. This cup has electron suppression and a triaxial feedthrough permits the measurement of currents down to the pA range [Al88a]. By means of moving an aperture strip across the beam a source beam profile may be obtained. This was the means of measurement of the profile for the field ionization source by Allan [Al88a] from which the results in Fig. 3.5 were derived.

When the lens assembly is in place a rough measurement of source current may be made from the beam falling on electrode 1. A nonsuppressed Faraday cup may also be mounted on a 3-position locator situated either 78mm or 140mm below the bottom flange of the ion source housing. Using this locator, either the Faraday cup, or a grid mount may be positioned on the beam axis. Finally, a
Figure 6.4

Overall view of the experimental area. Along with the test bench chamber can be seen Helmholtz coils and power supplies, electron source power supply and controller, and microscope camera and controller. A perspex box containing a series protection resistor is visible beside the coil power supplies. A 50mm aluminium spacer is located immediately below the electron source lower flange.
Faraday cup may be mounted on the bottom port of the optical beamline. Grids may be mounted both on the aperture strip located between the source and the lens, and on the 3-position locator in two positions downstream from the lens.

Observation of the beam spot or of grid shadows occurs on the window located at the end of the beamline. On the inside of this window is mounted a microscope coverslip with its upstream surface covered with a thin film of P1 phosphor.

The phosphor was carefully laid to ensure high resolution of the grid shadows. The phosphor film was formed by precipitation of SiO₂ from a suspension of KSiO₂ in a BaNi buffer. With the coverslip held horizontally, the buffer was then syphoned off to ensure as even as possible a layer of phosphor on the coverslip.

P1 phosphor was chosen for its high luminance under bombardment of electrons of several keV and its suitability for photography. The grid shadow or spot is observed using a mirror with an optical microscope located at the bottom of the apparatus. This microscope also has a camera mounting facility. The microscope and camera may be seen in Fig. 6.4.
Chapter 7

Performance of the Ion Source Lens

7.1 Introduction

The two-grid method for determination of lens parameters was first proposed by Epstein [Ep36]. Subsequently it has been used by Spangenberg and Field [Sp42] to investigate first order properties of electrostatic immersion lenses. It was subsequently used by Heise and Rang [He49] and Everitt and Hanssen [Ev56]. It was used by Munro [Mu71] and Hill and Smith [Hi82] to investigate chromatic and spherical aberrations of magnetic lenses. It has also been used by Rempfer [Re85a] to measure cardinal elements, as well as chromatic and spherical aberrations of symmetric, electrostatic Einzel lenses.

It had the advantage of simplicity in the presently set up test bench, as positions for the location of aperture strips already existed. Further, it has the advantage over the parallel beam method by not requiring a supplementary lens in the optical system to produce a parallel beam of electrons.

This chapter describes the extension of the theory of Rempfer [Re85a] to cover the application of the two grid method to the measurement of the magnification independent chromatic and spherical aberration coefficients of asymmetric Einzel lenses. It then presents the results of measurements using the two grid method of cardinal elements, as well as chromatic and spherical aberrations, for the prototype lens discussed in Chapter 6.
7.2 Measurement of First Order Characteristics

7.2.1 Introduction

The double grid method determines the characteristics of the lens based upon the measurement of the magnification of the shadows cast by the grids on a phosphor screen. The geometry of the situation is illustrated in Fig. 7.1.

The method itself requires 2 observations of the grid shadows, with the location of the object changed between observations.

Referring to Figs. 7.1 and 2.1 it may be seen that object and image distances may be expressed in terms of the magnification, $M$, by

\[ u = f_2(1 + \frac{1}{M}) - P_2 \]  \hspace{1cm} (7.1)

\[ v = f_1(1 + M) + P_1 \]  \hspace{1cm} (7.2)

Angular magnification is given by

\[ M_\alpha = m_1 \frac{a}{c + d} \]  \hspace{1cm} (7.3)

where $m_1$ is the shadow magnification of the upper grid.

The expression for $c$ depends upon whether crossover occurs before or after the second grid. This may in turn be determined by observation of the lower grid shadow as lens strength is increased. An increase in shadow bar separation with increasing lens strength indicates the crossover is located upstream of the second grid. For the geometry used in the present experiments, this was generally the situation. The distance $c$ for this case is given by

\[ c = \frac{d}{m_2 - 1} \]  \hspace{1cm} (7.4)

where $m_2$ is the shadow magnification of the lower grid. This permits the determination of image distance $v$. Lateral magnification $M$ may be calculated from angular magnification by application of Lagrange's law. All unknowns in equations 7.1 and 7.2 may be determined by the measurements of two sets of $u$, $v$. 


Figure 7.1

Schematic diagram of the geometry used for the lens measurements.

The electron source is located at point ‘p’. The reference plane ‘R’, is taken as the inside of the first electrode. ‘S’ is the phosphor screen. The values ‘P₁’ and ‘P₂’ represent the distances of the first and second principal planes respectively from the reference plane at height ‘II’. ‘G₁’ and ‘G₂’ denote the upper and lower grids respectively.

Refer to Figure 2.1 for the definition of first and second focal lengths.

‘u’ and ‘v’ denote the object and image distances referred to the reference plane.
Chapter 7. Performance of the Ion Source Lens

$v$ and $M$ for a given voltage ratio. The following expressions for the cardinal points may be derived:

\[ f_1 = -\frac{v_1 - v_2}{M_1 - M_2} \quad (7.5) \]
\[ f_2 = \frac{u_1 - u_2}{1/M_1 - 1/M_2} \quad (7.6) \]
\[ P_1 = \frac{u_1 M_1 - u_2 M_2}{M_1 - M_2} - f_1 \quad (7.7) \]
\[ P_2 = f_2 - \left(\frac{v_1}{M_1} - \frac{v_2}{M_2}\right)\left(\frac{1}{M_1} - \frac{1}{M_2}\right) \quad (7.8) \]

The object was formed by an image of the filament tip of the electron gun. The location of the tip was determined in each position by careful measurement. The position of the tip image however, had to be determined by measurement of its location from shadow patterns. This determination is discussed further below.

The upstream grid was mounted on an aperture strip inserted through the stainless steel lens sleeve and connected to a Vacuum Generators linear motion drive. Three upstream locations were possible for this strip. The second upstream grid, when required, was mounted on a separate stainless steel block supported by and electrically connected to the first electrode itself. One downstream grid was located on an angled arm, mounted on a Varian flange supported by bellows and a three-position locator. Hence it was possible to move upper and lower grids into and out of the beam separately. This was useful for the observation of faint shadow patterns. The location of the downstream grid was variable by ±30mm along its angled arm mount.

For large object distances and high lens strength, image locations lie closely downstream of the lens, or may occur within the lens itself. In such cases, in order to reduce errors in the measurement of image location, a further grid was mounted on the lens cradle locking ring, 4.5mm below the lowest lens electrode.

Three types of grid were used in the course of the experiments. These grids were nominally 400 mesh\(^1\) parallel bar grids, and nominally 200 mesh and

\(^1\)lines per inch
Chapter 7. Performance of the Ion Source Lens

2000 mesh square grids. All grids were made from copper. The periodicity of the grids was carefully checked and the 200 mesh and 400 mesh bar separations were measured to be \(0.1264 \pm 0.0002\text{mm}\) and \(0.0619 \pm 0.0002\text{mm}\) respectively.

The lower grid was mounted in a specially constructed stainless steel target holder. Care was taken to ensure the grids and holders were clean and free from insulating material. It was found that even small regions of such material on the edge of a grid (outside the screen shadow viewing area) charged up under beam irradiation and significantly affected beam trajectories such as to render shadows meaningless. Grids were electrically connected to the target holders by spots of silver-dag.

The shadows were observed via a 45° angled mirror below the final window using an Olympus stereo zoom microscope. They were photographed with an Olympus microscope camera attached to the trinocular eye piece. Exposure times were controlled automatically, and were typically a few seconds using ASA 3200 film and a 5kV beam.

No damage to or distortion of grids was observed due to action of the beam on any occasion during the measurements.

The printed photographs were then digitized, and bar shadow separation determined by the fitting of polynomials to grid shadow position. Final shadow magnification was calculated using a scale defined by the location of two fiducials scratched in the phosphor. The separation of the fiducials was measured using a travelling microscope. Square mesh grid photographs were digitized along both grid axes.

The filament voltage was monitored using a 4 digit Keithley voltmeter connected across a voltage divider in parallel with the filaments. Since voltage ratios rather than absolute voltages were important, the voltmeter was first calibrated against the lens power supply. Drift in the calibration due to changes in the values of resistors in the divider chain with time was investigated before running using the lens power supply. It was found that a drift in the calibrated voltage of 0.7% in an hour took place in the chain for an applied voltage of 5kV. Since experimental durations of less than half this time were typically used, drift
in the divider was assumed to account for less than 1% uncertainty in the beam voltage.

Voltage was controlled using a Variac, and was maintainable to the last digit on the Keithly voltmeter. At 5kV this represents a further ±0.08% uncertainty in the beam voltage. Voltage on the lens was measured using the voltage monitoring output of the power supply, and a digital voltmeter, to an accuracy of ±5V or 0.1% at 5kV.

Object position could be varied by movement of the lens cradle within the cradle sleeve. This however alters relative lens/grid locations, and it was found to be quicker and more convenient to leave the lens position fixed and insert or remove a 50mm aluminium spacer located below the electron gun lower flange (Refer Fig. 6.4).

Measurements were made for the lens described in Chapter 6. Typical grid shadows photographed with the lens operating in decelerating mode are shown in Fig. 7.2.

For zero applied lens voltage, linear fits were made to the grid shadows, and from these object positions were determined. The virtual object of the optical system is formed by an image of the cathode filament tip which occurs downstream of the tip. Virtual object position, size and shape depend on the height of the cathode filament in the Wehnelt bore, tip anode voltage and Wehnelt bias [Re85b]. In the present case the Wehnelt electrode was self biased (i.e. Wehnelt/filament bias was determined by the voltage drop across a connecting resistor). For fixed cathode voltage therefore, object position was determined by the heating power applied to the cathode [Re85b]. As a consequence of this, instabilities in the heating current or variation in the resistance of the cathode or of the biasing resistor may result in variation in virtual object location.

Moreover for the case of close cathode/lens working distances, voltages applied to the lens electrodes may affect object position. It was considered that in the present case this latter effect was small since the cathode filament region was shielded from the second electrode by the first electrode, the aperture strip and grid and the anode. Filament to lens working distances were kept above
Figure 7.2

Grid Shadow Photographs

A: Lens in Decelerating Mode. Two bar grids are in use. The upper grid casts the diagonal shadows, whilst the lower grid casts the finer, close to horizontal shadows.

Some distortion due to spherical aberration is evident in the pattern. Some distortion is also evident, however, in the lower left corner due to some charging up of the lower grid holder.

Object distance 88mm. $V_2/V_1 = 0.2$.

B: Lens in Decelerating Mode, object spacer in. The shadows of three grids are evident. Shadows from top right to bottom left (aa) are those of the upper bar grid. Shadows from top left to bottom right (bb) are those of the supplementary lower bar grid, located 4.5mm downstream from the lens exit. The other shadows are cast by the lower square mesh grid (shadows cc and those shadows at right angles to cc, with the same period).

The light area in the centre of the photograph is a bright spot on the phosphor screen. This area is illuminated by the glowing tungsten cathode shining directly down the bore of the lens.

Object distance is 62mm. $V_2/V_1 = 0.15$. 
20mm. Photographs of grid shadows with no applied lens voltage were taken before and after each set of measurements to measure object position. It was found in early measurements that instabilities in object position did occur during the course of some sets of measurements.

To overcome these problems, two approaches could be adopted. Firstly, further investigations could be carried out into the stability of the Wehnelt power supply and biasing, as well as the heating current. Secondly, a further lens and aperture system could be introduced upstream of the lens under investigation. This latter option would be the preferred one for any future development of the test bench, and will be discussed further below.

For non-zero applied lens voltage the magnification of the front grating may be expressed as [Re85a]:

$$ M = M_o(1 + \beta n^2) $$

(7.9)

where $M_o$ is the paraxial magnification, $n$ is the bar shadow number and $\beta$ is a distortion coefficient.

Since in each case the precise location of the central part of the pattern was uncertain, a fit of

$$ M = M_o + K(n - n_o)^2 $$

(7.10)

was performed for all shadow patterns. The resultant values of the paraxial shadow magnification $M_o$ were used in cardinal element calculations.

For the lower grid the magnification may be expressed by [Re85a]:

$$ \frac{1}{M' - 1} = \frac{1 + \beta' n^2}{M'_o - 1} $$

(7.11)

where the value $n$ for a given lower grid shadow is that of the corresponding bar shadow on the upper grid. The value of $n$ for each lower shadow is thus derived from extracting the real root (or in the case of there existing 3 real roots, the 'middle' root) of the cubic equation

$$ E = x_1(n - n_o)M_o + x_1(n - n_o)^3M_o\beta $$

(7.12)

where $E$ is the distance on the phosphor screen of the lower grid bar shadow.
from the centre of the lower grid shadow pattern,

\( x_1 \) is the bar separation of the upper grid and

\( n_o \) is the upper grid shadow central bar grid number (generally not a whole number).

The paraxial values \( M_o' \) attained from the measurements were used in the cardinal element calculations.

### 7.2.2 Results and Discussion

Fig. 7.3 shows the measurements of image position and lateral magnification for the lens operating in decelerating mode with \( V_3/V_1 = 1 \), as a function of \( V_2/V_1 \). Results are shown for filament distances of 20.6mm and 70.7mm.

Measurements of virtual object location were made from grid shadows photographed with no applied lens voltage. These photographs were taken before and after each complete set of measurements. It was found that the object tended to drift during the course of the experiments, even over short time intervals. In order to minimize errors the experiments were repeated several times. The final results used were those in which the errors due to object drift and errors due to close working distances were lowest. For the final experiments carried out with the aluminium spacer in position, object position was measured as \( 62.0 \pm 0.8 \)mm. Measurements before and after the run agreed within error bars.

For the final run without the spacer however, measurements before and after the experiment found a change in the object position from \( 18 \pm 2 \)mm to \( 16 \pm 2 \)mm.

Errors in the latter two measurements were larger than the first object measurements due to the greatly increased uncertainty in the location of the grid bar shadow edges for short object/grid distances due to the size of the virtual source.

The drift in object location during the second set of measurements greatly increased the uncertainty in the final optical results. Figs. 7.3A and 7.3B show the results of the measurement of image position for the decelerating lens for
Figure 7.3

Magnification and image location for the decelerating prototype lens in Einzel lens mode, as a function of $V_2/V_1$.

Data points were measured by the two grid method. The solid lines show calculations made using program F11. All distances are referred to the inside surface of the first electrode. Errors in the $V_2/V_1$ direction are approximately $+0.005 -0.011$ for all points.

A: Image location for an object distance of 62.0mm.

B: Image location for an object distance of 16mm. The dashed line indicates calculations for a working distance of 18mm. Note that data points are determined from an analysis of grid shadow measurements assuming an object distance of 16mm. Reanalysis of patterns assuming a working distance of 18mm reduce magnification by 14%.

C: Magnification for an object distance of 62.0mm.

D: Magnification for an object distance of 16mm. The dashed line indicates calculations for a working distance of 18mm.
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70.7mm and 20.6mm filament working distances. In Fig. 7.3B results of image position calculated using program F11 are shown for the initially measured object distance. Also shown for higher values of $V_2/V_1$ are the calculated image distances for an object distance of 18mm. It can be seen that the measurements below $V_2/V_1 = 0.175$ agree well with theory for the shorter object distance. Above $V_2/V_1 = 0.175$ the experimental results differ systematically from the calculated results, for an object distance of 16mm, but are in excellent agreement with the theoretical results for the increased object distance.

Measured magnifications shown in Fig. 7.3D for this case are in good agreement with theory between $V_2/V_1 = 0.1$ and 0.2 for an object distance of 16mm. Above this there is once again systematic disagreement between theory and experiment. The dashed line in Fig. 7.3D shows the magnification for an object distance of 18mm. All data shown were determined using equation 7.3 assuming an object distance of 16mm. If the data were reanalysed assuming an object distance of 18mm, then magnifications would be decreased by 14% for all points, and points between $V_2/V_1 = 0.175$ and 0.225 are once again found to be in good agreement with theory (agreement at 0.2 is within 1%). All distances in Fig. 7.3 are measured from a reference plane, taken as the inside surface of the first electrode.

Error bars result from uncertainties in the digitizing process, and in the measurement of the photographic scale. Uncertainty in digitizing the very faint upper grid shadows for the cases of $V_2/V_1 < 0.1$ results in the increased errors for the measured magnification of these points. Errors in Fig. 7.3 in the $V_2/V_1$ direction are not shown but are approximately $+.005 -.011$ for all points.

In general, equations 7.3 and 7.4 ensure that errors are lowest for image position and magnification when grids are closest to image position and object location respectively. Hence errors are lower in Fig. 7.3A than in Fig. 7.3B, as the supplementary grid 4.5mm below the final lens element was used. In Fig. 7.3A it can also be seen that error bars diminish with increasing $V_2/V_1$ as the image position approaches the lower grid location for higher $V_2/V_1$.

For close working distances magnification is relatively large, and it was
found that the size of the virtual source reduced the sharpness of the bar shadows. This effect, combined with the decreased number of bars illuminated by the beam, increased errors for close working distances, and precluded the use of the first lower grid located 4.5mm below the final lens element.

This problem could be overcome in two ways. Firstly a coarser grid might be used. Such a grid however would result in fewer bars being illuminated, which would increase the digitizing and curve fitting errors. In the present configuration at close working distance fewer than 8 bars of the upper 61.9µm period grid are visible on the phosphor screen.

Secondly the source could be made smaller by introducing a further, demagnifying, lens and aperture system upstream of the lens under study. This latter option would require substantial redesigning of the upper section of the test bench. It was considered that such rebuilding should be undertaken only if measurements suggested that further, more accurate, experimental results were required. It may be seen that within the errors as discussed, particularly with regard to object position, the measured values of image location and lateral magnification, are in good agreement with the theoretically derived results.

Using equations 7.5 to 7.7, and from the results depicted in Fig. 7.3 focal lengths and first principal plane location were calculated for the lens in deceleration mode. For an Einzel lens, \( f_1 = f_2 = f \) and equation 7.8 may be rewritten:

\[
P_2 = f - \left( \frac{v_2 + (M_1 - M_2)f}{M_1} - \frac{v_2}{M_2} \right)/\left(\frac{1}{M_1} - \frac{1}{M_2}\right)
\] (7.13)

Use of this expression provides a more accurate value for the second principal plane location than equation 7.8, since as discussed earlier, the errors in measurement of \( v_2 \) are smaller than those of \( v_1 \) (\( v_2 \) here referring to the measurements taken with the greater working distance).

Equations 7.5 to 7.8 and equation 7.13 indicate that smallest uncertainty in cardinal points is obtained by selecting object locations giving as large as possible a range of image position and magnification for a given \( V_2/V_1 \). Using the 50mm spacer it was found that a minimum object distance of above 40mm gave unacceptably large errors in cardinal elements, due to the relative insensitivity of
image distance and magnification to object position above this working distance. The results of Figs. 7.3 and 7.4 were taken for a minimum working distance of 19.2 mm. For working distances below this, increased digitizing errors due to the effects of relatively high source magnification discussed above negated the advantage of the increased spread in magnification and image location between the two measurements.

Fig. 7.4 displays principal surface locations and focal length derived from the decelerating lens data.

Both theory and experiment indicate that the variation of focal length with $V_2/V_1$ is quite weak. Good agreement is found between the experiment and theory for values of $V_2/V_1$ below 0.225. Good agreement is also found for the value of $P_1$. Agreement between experiment and theory for the value of $P_2$ for values of $V_2/V_1$ between 0.1 and 0.2 is reasonable. Outside this range the agreement is less conclusive. Unfortunately errors in equation 7.13 are large due to the repeated subtraction of terms of similar magnitude.

All cardinal element calculations were initially carried out assuming an object distance in the first set of measurements of 16 mm (i.e. no allowance was made for the observed drift in object distance in these measurements). However reanalysis of results for an object distance of 18 mm for high values of $V_2/V_1$ for the second set of measurements produced much closer agreement for cardinal points for $V_2/V_1 \geq 0.2$.

From the measurements discussed in this section it may be seen that subject to the uncertainty limits discussed, the theoretical calculations carried out using program F11 are in good agreement to first order with experimental data for the lens. These results help support the validity of the first order calculations presented in Chapters 4 and 5.
Figure 7.4

Cardinal points of the decelerating prototype lens in Einzel lens mode, as a function of $V_2/V_1$.

A:  
Axial Principal plane location (refer to Fig. 7.1 for definition of principal planes).

B:  
Focal length.
7.3 Chromatic Aberration

7.3.1 Introduction

From Fig. 7.1 it may be seen that the object and image locations \( u, v \) are related by

\[
(v - P_1 - f_1)(u + P_2 - f_2) = f_1 f_2 \tag{7.14}
\]

Differentiating equation 7.14 and noting that

\[
\frac{f_2}{u + P_2 - f_2} = m = \frac{v - P_1 - f_1}{f_1} \tag{7.15}
\]

we obtain

\[
\Delta v = \Delta P_1 + \Delta f_1 (1 + m) - \Delta P_2 m^2 \frac{f_1}{f_2} + \Delta f_2 (m \frac{f_1}{f_2} + m^2 \frac{f_1}{f_2}) - \Delta u m^2 \frac{f_1}{f_2} \tag{7.16}
\]

Assuming \( \Delta u = 0 \) (i.e. the object position is unchanged) and noting that for an Einzel lens \( f_1 = f_2 \) and \( \Delta f_1 = \Delta f_2 \) we obtain

\[
\Delta v = \Delta P_1 - \Delta P_2 m^2 + \Delta f (1 + 2m + m^2) \tag{7.17}
\]

Now we define

\[
\Delta f = C_f \frac{\Delta v}{\nu} \tag{7.18}
\]

\[
\Delta P_1 = C_{g1} \frac{\Delta v}{\nu} \tag{7.19}
\]

\[
\Delta P_2 = C_{g2} \frac{\Delta v}{\nu} \tag{7.20}
\]

where \( \nu = V_2/V_1 \). Noting that

\[
\Delta c r_i = \Delta c \nu \alpha_i \tag{7.21}
\]

where \( \alpha_i \) is the beam half angle of convergence at the image, we obtain

\[
\Delta r_o = \frac{\Delta v \alpha_o}{\nu^2} (C_{g1} + C_{g2} + C_f (1 + \frac{2}{m} + \frac{1}{m^2})) \tag{7.22}
\]

Where \( \alpha_o \) is the beam half angle of divergence at the object,

\( \Delta r_o \) is the increase in beam radius referred to the object.
Comparing equation 7.22 with equation 2.28 we find

\[ C_{co} = \frac{C_{g1}}{m^2} - C_{g2} + C_f(1 + \frac{2}{m} + \frac{1}{m^2}) \]  

(7.23)

By noting that focal plane positions are given by \( F_1 = P_1 + f_1 \) and \( F_2 = -P_2 + f_2 \) it may be seen that equation 7.23 reduces to that derived by Rempfer [Re85a] for the special case of symmetric unipotential lenses. In the present situation of an asymmetric lens, both principal plane terms must be retained. It may be noted that in contrast with the expression derived by Rempfer, by maintaining explicitly the locations of principal plane in the present formulation, the aberration coefficient retains a focal length aberration term even at high magnification.

7.3.2 Results and Discussion

The coefficients \( C_f, C_{g1} \) and \( C_{g2} \) were determined as a function of \( V_2/V_1 \) from the results presented in Section 7.2. Figure 7.5 shows plots of the chromatic aberration coefficient, referred to the object, as a function of object distance, as determined from these results. For the experimental graphs, magnification was calculated as a function of object distance using equation 7.15 and using the results displayed in Fig. 7.4. For each point, the chromatic aberration coefficient was then calculated using equation 7.23. Also presented in Fig. 7.5 are theoretical values of \( C_{co} \), calculated using program F11. For each increasing value of \( V_2/V_1 \) the above 0.05 plots in Fig. 7.5 are displaced upwards on the \( C_{co} \) axis by a factor of 10 in order to separate them for display.

Errors arise in the experimental values as a result of uncertainty in \( m, f \) and \( P_2 \) as well as in constants \( C_f, C_{g1} \) and \( C_{g2} \). Errors in these latter coefficients however contribute the most strongly to overall error as the values result from the measurement of gradients of the cardinal elements. In the case of values of \( V_2/V_1 \) of 0.05 and 0.25, extra uncertainty occurs since the gradient may not be measured symmetrically around the data point, and the interpretation of a line of best fit is difficult for these points. Errors for the curves of \( V_2/V_1 = .1, .15, .2 \) are estimated to be ±15%. Errors for the curves of \( V_2/V_1 = .05, .25 \) are estimated
Figure 7.5

Chromatic aberration for the prototype lens, as a function of object distance.

Solid lines indicate theoretical results, calculated using program F11. Dashed lines indicate results calculated from measured cardinal points and measured chromatic aberration coefficients of $f$, $PP_1$ and $PP_2$.

Numbers on the plots denote values of $V_2/V_1$. Subsequent pairs of curves above $V_2/V_1 = 0.05$ are displaced upwards by a factor of 10 to separate them for the purposes of display.

Object distances are measured from the inside surface of the first electrode, and the lens entrance plane is indicated.
to be ±40%.

For low magnifications (i.e. large working distances), equation 7.23 reduces to

$$C_{co} \approx \frac{C_{g1} + C_f}{m^2}$$

(7.24)

For high magnifications equation 7.23 reduces to

$$C_{co} \approx C_f - C_{g2}$$

(7.25)

For low values of \(V_2/V_1 \leq 0.15\), it is found that \(C_{g1} \gg |C_f|\) and hence chromatic aberration of \(P_1\) dominates total chromatic aberration at low magnification. For high values of \(V_2/V_1\) both \(C_{g1}\) and \(C_f\) are of similar magnitude and the same sign. Thus, as expected, \(C_{co}\) is not zero for any voltage ratio. For high values of \(V_2/V_1 \geq 0.2\), it is found that \(C_f \gg C_{g2}\) and hence chromatic aberration of \(f\) dominates total chromatic aberration at high magnification. For values below this, \(C_f\) and \(C_{g2}\) are both important for the calculation of \(C_{co}\). For low values of \(V_2/V_1\) (below 0.1), \(C_f\) and \(C_{g2}\) are of the same sign. They are never equal, and as expected, \(C_{co}\) is non-zero for all magnifications and all voltage ratios.

Within the errors stated above it may be seen from Fig. 7.5 that agreement is good between theory and experiment for lens excitations of \(V_2/V_1 = 0.1, 0.15, 0.2\) for all working distances. For lens excitations of \(V_2/V_1 = 0.05, 0.25\), agreement is only within a factor of approximately 2 over the range of object distances. Due to the large size of the errors in experimental results however, the data remain inconclusive for these values. For \(V_2/V_1 = 0.25\) an additional uncertainty arises due to the drift in object location during experiment, as noted in Section 7.2.

7.4 Spherical Aberration

7.4.1 Introduction

To second order, the variation of \(f_1\), \(f_2\), \(P_1\) and \(P_2\) with height may be expressed as [Li49, Re85a]

$$\Delta f_1 = S_{f1} \frac{\Pi^2}{f_o}$$

(7.26)
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\[ \Delta f_2 = S_{f2} \frac{\Pi^2}{f_o} \quad (7.27) \]

\[ \Delta P_1 = S_{s1} \frac{\Pi^2}{f_o} \quad (7.28) \]

\[ \Delta P_2 = S_{s2} \frac{\Pi^2}{f_o} \quad (7.29) \]

where \( S_{f1}, S_{f2}, S_{s1} \) and \( S_{s2} \) are dimensionless aberration coefficients of first and second focal length and first and second principal planes respectively and \( \Pi \) is the height of an incident ray at the principal planes (refer Fig. 7.1).

The value of \( \Pi \) for an Einzel lens is given by

\[ \Pi = f(1 + \frac{1}{m}) \quad (7.30) \]

Differentiating equation 7.15 (see Appendix A) we obtain

\[ \Delta f_1 = \frac{f_{o1}}{m_o + 1}(m_o C_1 - C_2 - \frac{\Delta P_1}{f_{o1}}) \quad (7.31) \]

\[ \Delta f_2 = \frac{f_{o2}}{m_o + 1}(C_1 + m_o \frac{\Delta P_2}{f_{o2}}) \quad (7.32) \]

where

\[ C_1 = \beta - \frac{\beta'}{M_o} \quad (7.33) \]

\[ C_2 = C_o \frac{\beta'}{f_{o1}} \quad (7.34) \]

For an Einzel lens, \( f_{o1} = f_{o2} \). For a symmetric Einzel lens, we note in addition that \( \Delta P_1 = -\Delta P_2 \) and \( \Delta f_1 = \Delta f_2 \). These expressions reduce the number of unknowns in equations 7.31 and 7.32 to two, permitting the determination of \( S_{f1}(= S_{f2}) \) and \( S_{s1}(= S_{s2}) \) from one set of grid bar distortion measurements\(^2\).

For the case of lens asymmetry, either in voltage or geometry, two separate sets of measurements of bar distortion, with different magnifications, are needed to solve equations 7.31 and 7.32.

Furthermore, both focal length differentials must be explicitly retained in equations 7.31 and 7.32. This is because although for the case of an Einzel lens

\(^2\)Although of course two independent measurements are needed to ascertain \( f_o \) and \( P_o \).
\[ f_{o1} = f_{o2} \], for an asymmetric lens, it is not valid to assume that \( \Delta f_1 = \Delta f_2 \). Indeed, calculations below show these differentials may be of opposite sign.

For the first grid measurement, the value of \( \Pi \) is chosen such that

\[
\Pi = (1 + \frac{1}{m_0}) f_{o1} \tag{7.35}
\]

where \( \alpha_1 \) is the angle subtended at the source by one upper grid bar period. (Note also that the subscript has been dropped on the paraxial focal length).

In the second measurement, the value of \( n \) in equation 7.9 is given by

\[
n = \frac{\alpha_2 a_2}{x_2} = \frac{a_2(1 + \frac{1}{m_0(1)})}{x_2 (1 + \frac{1}{m_0(2)})} \tag{7.36}
\]

Where \( a_2 \) is virtual object/upper grid distance in the second measurement, \( x_2 \) is the period of the upper grid in the second measurement and Numbers (1) and (2) refer to the first and second measurements.

The values of the principal plane differentials are then given by

\[
\Delta P_1 = f_o(K(m_o(2)C_{1(2)} - C_{2(2)}) - m_o(1)C_{1(1)} + C_{2(1)})/L \tag{7.37}
\]

\[
\Delta P_2 = f_o\left(\frac{KC_{1(2)} - C_{1(1)}}{L}\right) \tag{7.38}
\]

where

\[
K = \frac{1 + m_0(1)}{1 + m_0(2)} \tag{7.39}
\]

\[
L = \frac{m_o(1) - m_o(2)}{1 + m_o(2)} \tag{7.40}
\]

Values of \( \Delta f_1 \) and \( \Delta f_2 \) are then obtained by substitution back into equations 7.31 and 7.32.

The values of \( S_{f1}, S_{f2}, S_{g1} \) and \( S_{g2} \) may then be calculated from equations 7.26 to 7.29. Substituting for these coefficients into equation 7.16 gives

\[
\Delta v = (1 + \frac{1}{m})^2 f_o^2(S_{g1} - m^2S_{g2} + S_{f1}(1 + m) + S_{f2}(m + m^2)) \tag{7.41}
\]

The radius of the circle of least confusion, related to the object is given by

\[
\Delta_s r_o = \frac{1}{4m^2} \Delta_s v \alpha_o \tag{7.42}
\]
which implies

$$\Delta r_o = \frac{1}{4}(1 + \frac{1}{m})^2 f \alpha^2 \left( \frac{S_{g1}}{m^2} - S_{g2} + S_{f2}(1 + \frac{1}{m}) + S_{f1}(\frac{1}{m} + \frac{1}{m^2}) \right)$$  (7.43)

Equating this expression with equation 2.21 we obtain

$$C_{so} = -\frac{1}{4}(1 + \frac{1}{m})^2 f \alpha^2 \left( \frac{S_{g1}}{m^2} - S_{g2} + S_{f2}(1 + \frac{1}{m}) + S_{f1}(\frac{1}{m} + \frac{1}{m^2}) \right)$$  (7.44)

(The minus sign arises from a convention that the aberration coefficient is positive). Once again this equation reduces to that of Rempfer [Re85a] for a symmetric Einzel lens where for any value of $\Pi$, principal planes are equidistant from the midpoint plane of the lens, and $\Delta f_1 = \Delta f_2$. A full expansion of equation 7.44 gives the magnification independent spherical aberration coefficients of equation 2.19.

### 7.4.2 Results and Discussion

The values of the distortion coefficient $\beta_1$, $\beta'_1$, $\beta_2$, $\beta'_2$ were determined using equations 7.9–7.12, and the digitized grid shadow data for the decelerating lens experiment.

Fig. 7.6 shows an example of a fit to a lower grid magnification pattern. The error bars are due to digitization uncertainties. The $x$ axis displays the upper grid shadow bar number, calculated according to equation 7.12. The effect of the distortion in the upper pattern on the fit to the lower is seen by the increasing distance between points on the $x$ axis with increasing absolute bar number. Using equations 7.31 to 7.40, values of $\Delta f_1$, $\Delta f_2$, $\Delta P_1$ and $\Delta P_2$ were calculated to the values of $V_2/V_1$ of 0.1, 0.15 and 0.2. The values of the aberration coefficients $S_{f1}$, $S_{f2}$, $S_{g1}$ and $S_{g2}$ were also calculated from equations 7.26 to 7.29.

Table 7.1 shows values of these aberration coefficients for $V_2/V_1 = 0.1$, 0.15 and 0.2. An examination of Table 7.1 indicates that the signs of $S_{g1}$ and $S_{g2}$ are both positive for values of $V_2/V_1 \geq 0.15$, indicating that both principal planes are convex towards the lens entrance aperture for these values. For $V_2/V_1 = 0.1$, the planes are 'back to back' convex — similar to the planes shown in Fig. 7.1.
Table 7.1

Table showing the measured spherical aberration coefficients of principal surfaces and focal lengths, for the decelerating prototype lens.

The coefficients are defined in equations 7.26 → 7.29.

Figure 7.6

Example of the results of a fit to a lower grid magnification pattern.

Each data point represents a digitized grid bar shadow, for the lower grid. Horizontal bar numbers correspond to the equivalent upper grid bar number, calculated according to equation 7.12.

The effect of the cubic term in equation 7.12 may be seen by the increase in separation of the shadow points away from the origin of the horizontal axis.

Error bars are principally due to digitization uncertainties. The fit shown is a function of the form of equation 7.10.
<table>
<thead>
<tr>
<th>$V_2/V_1$</th>
<th>$S_{f_1}$ (mm)</th>
<th>$S_{f_2}$ (mm)</th>
<th>$S_{g_1}$ (mm)</th>
<th>$S_{g_2}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1</td>
<td>-81</td>
<td>100</td>
<td>-33</td>
<td>116</td>
</tr>
<tr>
<td>.15</td>
<td>-102</td>
<td>115</td>
<td>1.6</td>
<td>176</td>
</tr>
<tr>
<td>.2</td>
<td>-85</td>
<td>154</td>
<td>7.2</td>
<td>212</td>
</tr>
</tbody>
</table>
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Errors in the calculation of the aberration coefficients of principal plane and focal length arise principally due to the uncertainties in digitizing and fitting the shadow patterns.

For all grid patterns, distortion coefficients are a small correction on an otherwise linear magnification fit. For example, for a nominal working distance of 16mm, $\beta$ was found to be smaller than $1.5 \times 10^{-2}$ for all voltage ratios investigated. At such small values the fitting routine employed required the manual variation of $n_o$ along the function until the maximum absolute value of $\beta$ was determined. Similarly, for the short working distance there was uncertainty as to the centre of the pattern in the normal direction, and hence uncertainty as to along which normal line digitization should be performed. As a result, multiple digitizations were performed along lines normal to the direction of the upper bar shadow pattern, and the maximum absolute value of the distortion coefficient determined by fits to the data.

For the data taken with the aluminium spacer in place, the centre of the pattern was determined by the location of the bright region in the pattern (refer Fig. 7.2B), as this is axially located.

Curve fitting errors were larger for the close working distance results than for the larger working distance, as fewer grid bars were visible for the patterns in the first set of measurements.

Errors were compounded for the calculation of spherical aberration coefficients by the subtraction of similar sized quantities in the evaluation of equations 7.37 and 7.38. Furthermore, in the calculation of $C_{so}$ in equation 7.44, further subtraction occurs. The result of these subtractions is that the final percentage error is relatively large, particularly at large magnifications. For example, an increase in $\beta'(1)$ by 20% for the case of $V_2/V_1 = 0.2$ produces a change in sign in the final aberration coefficient for large magnifications. Overall errors in the determination of $C_{so}$ from these measurements was estimated at ±50%. As a result of such error, it appears that this method of determination of $C_{so}$ is insufficiently accurate for a definitive determination of $C_{so}$ for the lens under investigation.

Nevertheless, an investigation of Fig. 7.7 indicates reasonable agreement
Figure 7.7

Spherical aberration coefficients, related to the object, for the prototype lens, as a function of object distance. Data points are derived from the coefficients listed in Table 7.1 using equation 7.44, with magnification determined by application of equation 7.15.

Solid lines represent calculations performed using program F11.

Object distances are measured from the inside surface of the first electrode, and the lens entrance plane is indicated.

A: $\frac{v_2}{v_1} = 0.1$

B: $\frac{v_2}{v_1} = 0.15$

C: $\frac{v_2}{v_1} = 0.2$
Spherical Aberration

Entrance plane

$V_2/V_1 = 0.1$

$C_{se} (\text{mm})$

Object Distance (mm)

$V_2/V_1 = 0.15$

$C_{se} (\text{mm})$

Object Distance (mm)

$V_2/V_1 = 0.2$

$C_{se} (\text{mm})$

Object Distance (mm)
between the calculated and measured values of spherical aberration coefficient over a wide range of working distances, within the error bars stated.

For the evaluation of $C_{so}$ for $V_2/V_1 = 0.2$, a working distance of 18mm in the first set of measurements was assumed (Refer Section 7.2).

For low magnifications (i.e. large working distances) equation 7.44 reduces to

$$C_{so} \simeq \frac{f}{4m^4}(S_{g1} + S_{f1})$$

(7.45)

An examination of Table 7.1 indicates that although $S_{g1}$ and $S_{f1}$ are of opposite sign, $S_{f1}$ is for all voltage ratios much larger in magnitude than $S_{g1}$, and hence dominates $C_{so}$ for low magnifications.

For large magnifications (i.e. small working distances) equation 7.44 reduces to

$$C_{so} \simeq \frac{f}{4}(S_{f2} - S_{g2})$$

(7.46)

The closeness of the absolute values of the aberration coefficients being added and subtracted in these cases accounts for the relatively large percentage error in the final results. $S_{f2}$ cannot however equal $S_{g2}$ for any value of $V_2/V_1$ or of $M$, as $C_{so}$ cannot equal zero.

Within the errors stated above, it may be seen that there is reasonable agreement between theoretical and experimental values of $C_{so}$, over a broad range of object distances. Therefore, within errors, these results help support the validity of the calculations performed in Chapters 4 and 5.
Chapter 8

General Conclusions and Future Work

It is significant that despite the development of field ionization more than thirty five years ago [Mu53], and the scanning proton microprobe nearly twenty years ago, no scanning proton microprobe has yet come into operation using a field ionization source.

The aim of this Chapter is two-fold. Firstly, it will briefly give an overview of the main conclusions in this Thesis regarding the optical limitations to the achievement of improved resolution for the Melbourne SPMP using a field ionization source. Secondly, it will discuss some of the further technical problems involved in the source installation, which have yet to be addressed. Most or all of these further problems will have to be overcome before a Microprobe using a field ionization source can finally be commissioned.

The first critical component is the field ionization tip itself. The calculations in Chapter 3 indicated that based on measurements by Allan [Al89a], a brightness in excess of $10^6 \text{ Am}^{-2}\text{rad}^{-2}\text{V}^{-1}$ could be expected from the ion source for currents of around 10mA. Source brightness for currents below approximately 500pA was found to vary primarily with tip size and applied voltage. Only above 500pA do aberrations sensitive to tip/aperture separation become significant.

Combined with calculations in Chapter 4, these calculations indicate that an applied tip field of 26V/nm may be expected to produce the brightest final beam at currents of 100pA.

The analysis of Chapter 3 indicated that for these tip fields, tip sizes
within a fairly narrow range are required — not too small as currents are too low, nor too large as required source voltages are prohibitively high.

Unfortunately no method has yet been devised for reliably predetermining the Ir tip size in the etching process. Further work would be required to attempt to achieve this. The major problem is posed by the inherent irreproducibility of the etching technique, along with variations due to the random alignment of crystal grains in the Ir wire. Single crystal Ir wire for emitter manufacture may help considerably here.

Experience with the present etching technique suggests that tips with an end radius of approximately 0.15µm are typically produced. Calculations in Chapters 3 and 4 indicate an optimum tip end radius of around 0.25µm. A possible procedure to produce such tips may be to first manufacture very fine tips (see for example Fig. 3.1E), then follow with a controlled increase in tip size (i.e. tip blunting) by bombardment by introduced gas. The control of such a process however may be difficult. A similar tip reshaping technique is successfully used by Jousten et al. [Jo88] for the manufacture of W supertips. A possible alternative is the manufacture of fine tips by etching, followed by slow blunting of the tip by further etching. This process produced tip F in Fig. 3.1. It is found in practice however, that this process is difficult to control, and is liable to over enlarge the final tip due to the violence of the final stages of etching.

Prior to installation into the accelerator terminal, tips would need to be routinely inspected under an electron microscope to select appropriate tip shape and, if possible, size. The present method of inspection under an optical microscope is inadequate since tip-end size is generally close to the resolution limit of the microscope.

Tips should also preferably be tested for field ionization currents and beam profile on a test bench prior to insertion into the accelerator.

An associated problem with tip size is the irregularity of end shape due to the random alignment of Ir crystals. The forward peaked distributions discussed in Chapter 3 tend to be best case examples, and experience shows that strongest emission is not necessarily axial. Indeed Lewis et al. [Le86b] found the current
in a field ionization source and associated lens to be primarily limited by the
difficulty in ensuring peak emission occurs down the axis. In the present source
it was found that operation of the source in field emission mode caused widely
spread discolouration spots on the inside of the differential pumping aperture.
These discolourations indicated strong off-axis electron emission, and would, in
all likelihood produce similar effects for field ionization. Redesigning of the ion
source to permit tilting of the emitter tip from the Pelletron control desk to
maximize current would thus probably be necessary for practical operation of
the source.

Coupled with this problem is that of axial tip alignment. Although the
lens electrodes were, as far as possible, carefully and rigidly aligned along the
optical axis, there is no present method of ensuring that the emitter tip is located
on the same axis. Tip misalignments cause steering of the beam (which may be
corrected), and off axis aberrations which may degrade the beam and reduce
brightness. This problem would be more acute if a reduced scale lens were to
be used. Close working distance (i.e. large magnification) and a small entrance
aperture would ensure that accurate tip/lens alignment would be critical.

Due to the variability between tips and the impossibility of pre-alignment
to the accuracy required, dynamic alignment of the tip, with working voltage on
it, would need to be carried out by the accelerator operator upon the installa-
ton of a new tip.

Location along the optical axis is also critical, and with a reduced scale
lens such location would be required to within a fraction of a millimetre. Indeed,
calculations in Chapter 3 indicate that the optimal location of each tip may vary
over the lifetime of the tip as tip size and shape vary. Thus, for example, it may
be necessary to move a tip slightly closer to the first lens element as the tip ages
and its end radius increases.

For these reasons, the tip support assembly should be mounted on a servo-
motor driven XYZ stage. If vacuum requirements can be readily met, it may be
preferable to run alignment tests with negative applied voltage, due to the far
greater currents which may be achieved using a tip in field emission mode.
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The final tip problem is that of lifetime. Measurements by Allan [Al89a] indicate typical lifetimes in excess of 60 hours. Catastrophic sparks may destroy tips, although the inclusion of series protection resistors has virtually eliminated this risk. Nevertheless, tips may be destroyed by mishaps during the alignment process. Furthermore, tips will gradually increase in end size due to residual gas (particularly H₂O) bombardment during usage, until they are too large for field ionization. Modifications such as source replacement inside the HV terminal of the accelerator require pumping out of the insulating gas and physical entry into the tank. Loss of gas in the exchange process as well as labour means a cost of approximately $1000 per tank opening. Combined with this is the loss of at least one to two days of accelerator running time in the changeover.

As a consequence of this, it would almost certainly be impractical to operate the source inside the accelerator with only a single tip available at a time. Some mechanism of remote tip replacement would therefore be necessary. Such a mechanism may consist, say of a carousel upon which are mounted a number of tips. To replace a damaged or destroyed tip would then simply be a matter of withdrawing the tip from the proximity of the lens and rotating another into place. Such a method may also permit the selection of the brightest tips for experiments which require the highest resolution, yet permit the superior tips to be kept in reserve when such high resolution is not needed.

The final comment on tips is that alternatives to the present poly-crystalline Ir tips should be further investigated. Firstly the use of single crystal Ir wire for tip fabrication should be considered. Although substantially more expensive than poly-crystalline Ir tips, such single crystal tips may prove more readily reproducible than the present ones as well as brighter and more easily aligned inside the accelerator. Secondly 'supertips' should be investigated. Calculations in Chapters 4 and 5 indicate that 'supertips', should they prove reliable and practical, would provide vastly improved resolution in MP over the present tips. The dynamic nature of their manufacture may however, preclude their routine use inside an accelerator terminal.

Calculations in Chapter 4 indicated that the present Pelletron lens would
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not be suitable for use with a field ionization source, unless it were operated at impractically high voltage. Calculations on possible alternative lenses indicate a three-electrode lens is preferable to a two-electrode lens. For all lenses it was found that spherical and chromatic aberrations would significantly reduce the brightness of the beam downstream from the ion source. At low currents for STIM work, diffraction and chromatic aberration would limit the resolution. At high (PIXE) currents, spherical and chromatic aberrations both contribute to the limitation.

Aberrations were almost universally found to be smallest for short working distances. They were also found to be smaller for accelerating three-element lenses than for decelerating. Since source voltages are high, however, the large voltage ratios required for accelerating mode would almost certainly lead to electrical breakdown, either between electrodes, or elsewhere in the vacuum system.

Calculations in Chapter 4 suggest that reducing the voltage ratios required, either by increasing working distance or by scaling up the lens, would increase aberrations and negate the advantage of operating with an accelerating lens.

Decelerating lenses overcome the breakdown problems, but unfortunately have substantially higher chromatic and spherical aberrations than the accelerating alternatives. Attempts in Chapter 4 to reduce aberrations by geometrical variation did not result in aberrations which matched those of accelerating lenses. Moreover, it was consistently found that alterations resulting in improvement in one aberration worsened the other. Since the lens would be required to operate with both high and low beam currents, such tradeoffs are unacceptable.

Miniaturization of decelerating lenses appears the most promising alternative, and calculations in Chapter 4 indicated that substantial scale reduction (by at least a factor of 5) could be achieved without risking breakdown problems. Providing the field ionization tip could be placed accurately closely upstream of such a lens, calculations suggest substantial brightness improvements could be achieved over the full-scale lenses.

The full analysis in Chapter 5 indicated that no single decelerating lens
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provides optimum performance in both high and low current modes. For high currents the reduced scale Riddle lens is found to be superior. For low currents reduced scale Riddle and Orloff lenses give comparable results.

For a scale reduction by a factor of 1/4 and object distance of 0.25mm (lens y in Table 5.3), the Riddle lens may be expected to give a reduction in minimum spot size for PIXE currents of 7.3 and for STIM currents of 31 over the present Pelletron source and lens. Further reduction of the lens below this size may be possible. Equation 4.2 indicates that reduction in first to second electrode gap separation to 0.3mm for a 20kV source voltage should be possible. This represents a final scale reduction of 6.6 over the full scale Riddle lens. At such a scale final reduction in PIXE minimum spot size may be expected to be as great as a factor of 11 over the present case, however great care would need to be taken in the construction of such a miniaturized lens.

Measurements in Chapter 7 of the optical characteristics of a full-scale variation of the Riddle lens supported the values of the first order properties of the lens calculated using the program F11. The measured values of the chromatic aberration coefficient also supported the theoretical values obtained, even for low working distances and high magnifications.

Spherical aberration measurements also gave reasonable confirmation of theoretically determined coefficients, although errors in the method of measurement are large.

The primary experimental factors limiting accuracy in the technique employed were the low brightness of the electron gun and the drift in the virtual object position. The first of these factors meant that at close working distances (with large magnifications) the beam was too diffuse, and grid shadow edges became ill-defined. As a consequence, with large magnifications, fine grids located closely downstream of the lens could not be used as the bars could not be resolved at all. Greatest accuracy for the determination of all coefficients (first and third order) is achieved from two measurements as widely as possible at variation in magnifications. Thus, the inability to use the lens in a very high magnification mode with the electron source limited the accuracy of the measurements
undertaken.

This problem could be overcome using the present electron source by introducing a further lens upstream of the lens under test. Since the aim of the overall work however, would be the implementation of the lens in a field ionization gun in the accelerator, it is not expected that further development of the electron gun or electron test bench would be fruitful. In any case the reasonable confirmation of the theoretical results by the present measurements supports the reliability of the calculations.

Errors in the determination of image location were too large however to measure any axial astigmatism in the beam. If the bar mesh grid located immediately below the lens were to be replaced by a square mesh grid, then measurements in Chapter 7 indicate that astigmatism coefficients of below 0.25mm could be determined for working distances of over 60mm for decelerating voltage ratios greater than .225. It would be expected that astigmatism would be considerably smaller than this however [Mu71], and at lower voltage ratios and shorter working distances the present technique would be unsuitable for measurements of lens astigmatism. Nevertheless, with reduced scale lenses, the likelihood of electrode misalignments or irregularities is increased, and the possibility of introducing a stigmator into the beamline at some point downstream of the lens should be considered.

Calculations in Chapter 5 indicated that providing lens magnification is high, aberrations in the accelerating column should not limit final beam brightness. If a miniaturized lens were used, calculations in Chapter 4 indicate that magnifications would be large (> 50 for a 200mm lens/accelerator working distance) and so the accelerating column aberrations would be indeed negligible.

Although chromatic aberration in the column in this case is small, the chromatic aberration in the MP quadrupole lenses provides a limit on the final beam resolution in the case of STIM imaging. Equation 2.33 indicates that the most effective means of improving final, chromatically limited, resolution is the reduction in accelerator beam energy spread.

As discussed in Chapter 5, the beam energy spread downstream of the
The accelerating column is dominated by terminal energy fluctuations. Compared with this spread, the inherent energy spread of the field ionization source is negligible providing well stabilized power supplies are used. Thus an important line of investigation is the stabilization mechanism of the accelerator.

There is an additional, important reason for the investigation of energy stabilization. The field ionization source can produce at most the order of 20nA of current, which at a tip field of 26V/nm may be expected to be \( \approx 80\% \) H\(^+\) [Mu69]. The present stabilization circuitry is based on a high and low energy slit current difference feedback signal, controlling a corona triode.

Experience with the machine has established that with this circuitry, stabilization is achievable for beam currents of a few nanoamps. Since substantially lower currents may be used in certain circumstances, however, difficulties may be encountered in stabilizing the machine with the present method.

Investigations carried out by Baker [Ba86] on the feedback signals of the Melbourne Pelletron found no readily identifiable correlation between the stabilization circuitry feedback signals and the energy variation of the terminal.

One alternative means of stabilization, adopted on many accelerators, is control by feedback from a generating voltmeter (GVM). The present GVM circuitry is designed only to keep the terminal voltage within a relatively broad 'dead band' or energy window. Modifications to upgrade the present GVM would include increasing the present number of stator blades from two active blades to four. Modifications would also need to be made to the feedback electronics to ensure optimal stability from this method [Pe84]. One weakness of GVM based stabilization is that the stators sense not only the terminal dome, but possibly also the upper section of the accelerating column itself. Thus fluctuations in the voltage gradient in the column, possibly due to worn corona points, may increase instability in the accelerator.

One means of reducing this effect is the replacement of corona points by resistors along the accelerating column. This change has now become standard practice in new Pelletrons. The change to resistors would also provide an additional means of monitoring energy fluctuations in the terminal.
Finally, mechanical vibrations in the accelerator should be investigated. Since a field ionization tip with electrostatic lens has an effective virtual source size of approximately 0.1µm, vibrations in the ion source region of this magnitude may cause reduction in the brightness of the beam. The major source of vibrations in the Pelletron tank would undoubtedly be the charging chain. Transverse vibrations in the accelerating column may also cause enlargement of the beam, although the large magnification of the ion source lens serves to minimize this effect.

Care would need to be taken to differentiate between those vibrations which move elements relative to a straight optical axis, and those which involve motion of the axis itself — for example a rocking of the whole column. These latter vibrations would not degrade brightness within the accelerator, although they present problems upon presentation of the beam to the MP beam line.

It should be possible to investigate these problems by mounting the field ionization source and lens on the accelerating column and running with a stopped down beam. By comparison of measured beam brightness in the MP beam line with that expected from the source, information may be gained on accelerator vibrations and instabilities. Further beam brightness measurements may be subsequently made with increased source acceptance angles.

Despite the difficulties associated with a field ionization source, with the additional developments discussed above, it may be expected that an accelerator provided with such a source will provide the beam for the next generation of Proton Microprobes.
Appendix A

Derivation of Spherical Aberration Differentials

Derivation of equations 7.30 and 7.31 for the differential focal length:

Differentiating the first part of equation 7.15, we obtain

\[ \Delta f = \frac{\Delta (v - PP_1)}{m_o + 1} - f_{o1} \frac{\Delta (m + 1)}{m_o + 1} \]  \hspace{1cm} (A.1)

The first term in equation A.1 may be evaluated noting that (refer to Fig. 7.1):

\[ \Delta v = \Delta C \]

\[ = -d \left( \frac{1}{M'_o - 1} - \frac{1}{M' - 1} \right) \]  \hspace{1cm} (A.2)

It follows from equation 7.11 that we can write

\[ \Delta v = f_{o1} C_2 \]  \hspace{1cm} (A.3)

where

\[ C_2 = \frac{C_o \beta'}{f_{o1}} \]  \hspace{1cm} (A.4)

The last term in equation A.1 may be evaluated by noting that

\[ \frac{\Delta m}{m_o} = \frac{m}{m_o} - 1 \]  \hspace{1cm} (A.5)

\[ = \frac{M'C}{(1 + \beta)M'_o C_o} - 1 \]  \hspace{1cm} (A.6)
Appendix A. Derivation of Spherical Aberration Differentials

Since
\[
\frac{C}{C_o} = 1 + \beta' \tag{A.7}
\]
equation A.6 may be rewritten
\[
\frac{\Delta m}{m_o} = -\beta + \frac{\beta'}{M_o'} \tag{A.8}
\]
Since \( \beta \ll 1 \) we may write approximately
\[
\Delta m = -m_o C_1 \tag{A.9}
\]
where
\[
C_1 = \beta - \frac{\beta'}{M_o'} \tag{A.10}
\]
Substituting into equation A.1 from equations A.3 and A.9 we obtain
\[
\Delta f_1 = \frac{f_{o1}}{m_o + 1} (m_o C_1 - C_2 - \frac{\Delta P P_1}{f_{o1}}) \tag{A.11}
\]
which is equation 7.30.

Differentiating the second part of equation 7.15 we obtain
\[
\Delta f_2 = \frac{\Delta u + \Delta P P_2}{1 + \frac{1}{m_o}} + f_{o2} \frac{\Delta (1 + \frac{1}{m})}{1 + \frac{1}{m_o}} \tag{A.12}
\]
The final term in equation A.12 may be evaluated by noting:
\[
\Delta \left( \frac{1}{m} \right) = -\frac{1}{m_o^2} \Delta m \tag{A.13}
\]
\[
= \frac{C_1}{m_o} \tag{A.14}
\]
Assuming \( \Delta u = 0 \) (i.e. no change in object position) equation A.12 may be rewritten
\[
\Delta f_2 = \frac{f_{o2}}{m_o + 1} (C_1 + m_o \frac{\Delta P P_2}{f_{o2}}) \tag{A.15}
\]
which is equation 7.31.
Bibliography


[Be88] Bench, G.: Private Communication


[Ch65] Chandler, J.P.: 'STEPIT - A Fortran Subroutine for finding Local Minima of almost any Real Function', Quantum Chemistry Program Exchange, Dept. of Chemistry, Indiana University, Bloomington, Indiana (1965)


[Cr73] Crewe, A.V.: 'Progress in Optics' 11 (1973) 225


[Ha79] Hanson, G.R., and Siegel, B.M.: J. Vac. Sci. Technol. 16 (1979) 1875


[He49] Heise, F., and Rang, O.: Optik 5 (1949) 201


[Ho73] Houtman, H., Kost, C.J.: ‘RELAX3D, A Program to Solve 2 and 3 dimensional Poisson and Laplace Equations’. TRIUMF, UBC, Canada (1973)


BIBLIOGRAPHY


[Ki84] Killes, P.: Optik 70 (1985) 64


BIBLIOGRAPHY


BIBLIOGRAPHY


[Ly87] Lynch, D.: Private Communication


[Or74] Ortec Technical Information Centre (1974) 'Ion Sources and Systems' IS505 Tennessee


[Or84] Orloff, J.: Private Communication


[Re88b] Rempfer, G.: Private communication


[Ro37] Rogowski, W.: Arch. Elektrotechn. 31 (1937) 555


[Ro83a] Roques, S., Denizart, M., Sonier, F.: Optik 64 (1983) 51


[So63] Southon, M.J., and Branton, D.G.: Phil. Mag. 8 (1963) 579


[Sz88b] Szymanski, R: Private communication


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