DRAFT
Design Study of an Axial Injection System for the University of Washington MC50 Cyclotron

B.F. Milton, T. Kuo, R. Baartman
TRIUMF

R. Dawson
RjD Engineering

M. Dehnel
Dehnel Consulting Ltd.

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Chapter 1

Introduction

1.1 Goals

The University of Washington Hospital is interested in gaining the capability of producing alpha particle beams of sufficient intensity to produce clinically relevant quantities of the isotope Astatine-211. An external ion source using an axial injection system has been used on many other cyclotrons to improve beam quality and gain access to projectiles that are more difficult to ionize. This study is intended to be a detailed design and engineering feasibility study for an external ion source and injection system for the University of Washington MC50 cyclotron. The work reported here was performed under contact number 54812 between the University of Washington and TRIUMF.

From the point of view of cyclotron design, the three most important goals specified for this study were:

- Maintain or improve the existing 100 µA of extracted $^1$H$^+$ (protons)
- Maintain the existing ability to extract up to 50 µA of $^2$H$^+$ (deuterons)
- Develop the ability to extract up to 50 µA of $^4$He$^{2+}$ (alphas)

Since the objective is to find a retrofit for an existing cyclotron there is the special challenge of minimum disruption to the current operation. In particular, for a solution to be attractive it must be possible to implement and test the various changes during the three day intervals each week between regular patient treatments. In practical terms this means making changes only to components that were designed to be removed quickly such as the dee tips and centre plug, and no changes to the magnet.

1.2 Overview of the MC50

The MC50 cyclotron is a 3 sector, variable energy, positive ion cyclotron designed to operate in first harmonic mode for $q/A=1$, and in second harmonic
Figure 1.1: Lower half of the MC50 Showing poles, yoke and dees in relation to one another.

for q/A=1/2. Beams with a total energy between 28 MeV and 51 MeV can be extracted from the MC50.

The MC50 magnet is of an H-frame design with an overall size (in cm) of 239 h x 362 w x 155 d, and a pole diameter of 130 cm. (See figure 1.1). The flutter is provided by three spiral sector pieces with a hill gap of 11 cm and a valley gap of 20 cm. Central field values range between 1.0 T and 1.7 Tesla. There are 10 circular coils located on the pole face for the trimming of the magnet and another 4 coils sets located in the valleys for the generation of first and second harmonic fields.

The RF system consists of 2 independent 90 degree dees, and can operate at voltages up to 40 kV. Measurements indicate that it is currently operating in the region of 35 kV. The dees are cantilevered between the pole tips and dummy dees (ground planes) are mounted on the poles.

The MC50 presently operates with an internal PIG ion source with one cathode inserted from above and the other from below. The source anode is held in place between the two pole plugs, and consists of two separate chimneys, one for first and one for second harmonic operation. Changing between modes thus requires striking an arc with the cathodes in the other chimney location. The anode can be removed by lowering the pole plug. Views of the central region are shown in figure 1.2
Figure 1.2: Plan and section views of the MC50 Cyclotron central region as it current exists.
1.3 Axial Injection Systems

On a cyclotron, an external ion source system offers the ability to separate the production of ions from the initial acceleration of those ions. This allows for an ion source geometry that optimizes the ionization efficiency, and the increased space allows for considerably more ion source power. As well these systems can manipulate the beam parameters between the source and the cyclotron acceleration gaps allowing for significant improvements in beam quality.

Conceptually an axial injection system can be broken into three sections. First the ion source (or sources), where the atoms are ionized and then extracted using a set of accelerating lens. The second section is the transport line (known as the injection line) that takes this low energy beam from the ion source(s) to the median plane of the cyclotron. Finally in the median plane of the cyclotron is a set of electrode structures known as the central region that direct the beam into the median plane at the correct location and then provide the correct RF electric field conditions for clean beam acceleration.

The requirements of the MC50 are fairly basic. It is therefore reasonable to believe that we can find a single ion source capable of generating sufficient currents of protons, deuterons and alphas. Of course this also has benefits from the cost and operational points of view. With a single ion source and no need for mass selection after the ion source it is possible to design an injection line that is a simple straight line from the source up (or down) the central axis of the cyclotron. Such an injection line would then consist of basic optical elements such as quadrupoles and solenoids to provide the correct beam parameters at the entrance to the central region. An RF device known as a buncher can also be located in the injection line. Its purpose is to take the DC beam from the source and by applying a time dependent acceleration (or deceleration) to the particles, causes them to arrive at the entrance to the central region focused (bunched) in time. This puts more of the particles into the section of the RF waveform where they can be accelerated by the dees.

Table 1.1 provides an estimate of the beam currents that would be required at various stages in the system to meet the extracted beam currents set out in the goals section. In the table we have assumed that the accelerated phase spread is 10 degrees. In a positive ion machine this represents a reasonable compromise between acceptance and the loss of turn spacing with its effect on beam loss at extraction. Bunching efficiencies depend on a number of factors including the complexity of the buncher, energy of the beam and the beam current. At the relatively low injection energies practical for the MC50, our experience on the TR30 test stands indicates that a single harmonic buncher should be able to achieve a bunching efficiency of a factor of 2.
<table>
<thead>
<tr>
<th>Location</th>
<th>Effect factor</th>
<th>P (mA)</th>
<th>D,α (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracted</td>
<td></td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Internal</td>
<td>Ext Eff.</td>
<td>0.125</td>
<td>0.06</td>
</tr>
<tr>
<td>Injected</td>
<td>Inj Eff.</td>
<td>10/360</td>
<td>4.5</td>
</tr>
<tr>
<td>Source</td>
<td>Buncher</td>
<td>2</td>
<td>2.25</td>
</tr>
</tbody>
</table>

Table 1.1: Beam currents required at various points in the system in order to achieve the desired extracted beam currents
Chapter 2

Ion Source

As outlined in the previous section, we require an ion source capable of 2 to 4 mA of protons and 1 to 2 mA DC of alphas. While many ion sources are capable of producing protons and even deuterons in sufficient quantity to meet the 4 to 5 mA criteria, few are also capable of producing sufficient currents of \( \alpha \) beams. The TRIUMF ISAC test stand CUSP source achieved 3 mA of \( ^4\text{He}^+ \), however no \( ^4\text{He}^{++} \) was detected even at the nA level. Duoplasmatrons generate singly charged particles only, no data on doubly charged helium beam has been reported. ECR sources can provide medium intensity \( \alpha \) beam output (approximately 1 mA from LBNL Super ECR Source\cite{2}), however these are large and complex sources as well as expensive to build and operate. Almost all cyclotron \( \alpha \) beams are produced by variations of the PIG source which has been used to produce multiply charged ions for many decades. An ultra high power density version of the PIG source was developed by Kuo and Laughlin\cite{3} and has produced more than 4 mA DC of \( \alpha \) beams. This technique has been used to reliably achieve 1.5 mA DC \( \alpha \) beams for stable operation.

Figure 2.1 shows a simplified schematic of a PIG source. Two cathodes are located at either end of a 2.5 cm long anode chamber within an axial magnetic field. Electrons emitted from either cathode are accelerated into the anode. A large fraction of these electrons are trapped axially by the electrostatic well and

<table>
<thead>
<tr>
<th>Particle</th>
<th>DC Intensity</th>
<th>Arc Power</th>
<th>Magnetic Field</th>
<th>Extraction Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>7.5 mA</td>
<td>0.5 A @ 1 kV</td>
<td>7 kG</td>
<td>30 kV</td>
</tr>
<tr>
<td>d</td>
<td>7.5 mA</td>
<td>0.5 A @ 1 kV</td>
<td>10 kG</td>
<td>30 kV</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>1.5 mA</td>
<td>4.0 A @ 250 V</td>
<td>10 kG</td>
<td>30 kV</td>
</tr>
</tbody>
</table>

Table 2.1: Expected source output for sample source parameters
radially by the magnetic field. The electron beam ionizes the injected gas to form a dense plasma (arc column) from which ion beams are extracted. The ion source position is adjustable in four independent coordinates, horizontally (puller to anode gap), radially (ion entrance angle to puller), vertically (extraction slit to median plane), and axial angle. The axial angle control tilts the ion source head such that the opposite edges of the upper and lower anode openings are used to limit the arc column size. Rotating the source head while increasing arc power density also causes the arc column to retreat from the extraction slit in either direction of rotation, the slit surface also becomes oblique with respect to the puller. The Kuo and Laughlin PIG source, as shown in figure 2.2, uses a modified 6° angle bore anode which allows the ion plasma column to be close to the extraction slit for any operating angle while increasing the calculated arc power density from a few kW/cm³ at 0° axial angle (Penning mode) to greater than 140 kW/cm³ at 5.5° (high thermionic mode) at a constant arc power of 1 kW. Total lifetime is in the order of 100 hours for continuous operation in the high thermionic mode with much longer lifetime for the Penning mode (protons and deuterons). Sample operating parameters for the source are given in table 1.

The estimated normalized emittance at 30 kV with a source slit opening of 2mm x 4mm is 0.30 π mm-mrad in both planes. Emittance selection, reduction through collimation, beam transport losses, and deceleration is estimated to be about 25%. For protons and deuterons this reduction is of little consequence whereas for α beams this reduces the available injected current to 1.1 mA. A factor of two in the intensity required can be achieved through a buncher.

This type of PIG source could be easily adapted to an external ion source. A very similar source geometry could be located inside a 1 Tesla dipole magnet. The source would then be biased at the injection voltage (30 kV), and a grounded puller assembly would extract ions from the slit. A deflection channel would
Figure 2.2: section view of PIG source designed to achieve high plasma densities then probably follow to assist in extracting the ions from the dipole field. A conceptual design for such a source is shown in figure 2.3.
Figure 2.3: Conceptual design of an external PIG ion source capable of producing protons and deuteron beams in normal mode, and alphas in the high thermionic mode.
Chapter 3

Central Region

3.1 Basic Considerations

In a positive ion cyclotron the extracted beam energy is varied by changing the average magnetic field in the cyclotron. The final energy, $E$, is then given by:

$$E/u (MeV/u) \approx 48.243 \left(\frac{q}{u}\right)^2 (B_0 r_{ext})^2 \gamma$$

$$\gamma = 1 + \frac{E/u}{931.5}$$

with $B_0$ being the so called central field (or average field at $r=0$) in Tesla, $q$ being the particle charge in units of the electron charge, $r_{ext}$ is the extraction radius which is 0.58 m for the MC50, and $u$ the atomic mass in AMU ($1$ AMU $= 931.478$ MeV). The RF frequency is then adjusted to match the central field using:

$$f (MHz) = 15.36 \cdot h \left(\frac{q}{u}\right) B_0,$$

where $h$ is the harmonic number, or ratio of the beam orbit frequency to RF frequency.

In order to have a central region that will operate at all field levels (and thus all extracted beam energies), it is customary to operate in what is called constant turn mode. By fixing the number of turns to extraction regardless of the final energy, the radius gain per turn will be independent of final energy. In a machine where the flutter component scales linearly with average field, this means that the path taken by the ions on the first turn will be the same for all extracted energies. If we assign the maximum dee voltage of 40 kV to the 50 MeV case then we find that we need 442 turns in first harmonic. For first harmonic that gives us a scaling rule for the dee voltage of

$$V_{dee} (kV) = 0.8 (E/u)$$

and extending this to other harmonics for the MC50 dee geometry gives

$$V_{dee} = 0.8 (E/u) / \cos(h \pi / 4).$$
While constant turn geometry is standard practice in cyclotrons with axial injection systems, in many cases the central region geometry must be changed for each harmonic number. In our case we are looking for a single solution for both first and second harmonics.

In an axial injection system using an inflector it is also required that the injection energy and the voltage on the inflector be scaled so the orbit geometry in the inflector stays constant. The injection voltage is chosen so that the bending radius of the incoming particle is a constant and since a cyclotron acts as an energy multiplier for fixed bending radii at injection and extraction we can write:

\[
V_{\text{inj}}(k\text{V}) = \frac{30}{50}E_{\text{ext}}
\]

where we have selected an injection voltage of 30 kV to be used for the 50 MeV beam. The potential difference between the plates of a spiral inflector is given by:

\[
\Delta V(k\text{V}) = 2V_{\text{inj}}\text{gap}/A
\]

where the parameters \(\text{gap}\) and \(A\) are geometrical parameters of the inflector basically specifying the distance between the plates and the bend radius of the inflector. We thus find that the inflector voltage will scale directly with the injection voltage, which in turns scales directly with the final extracted total beam energy.

When designing a central region, it is common practice to maximize (for a given dee voltage) the energy gain on the first couple of gaps. For internal sources this is done to improve efficiency of ion extraction from the source, and in axial injection systems it is done to increase the clearance for the inflector. Since the MC50 operates for protons in first harmonic and the dees are nominally 90 degrees wide, the normal energy gain per gap is;

\[
\Delta V = V_{\text{dee}}\cos(\pi/4) = 0.707V_{\text{dee}}.
\]

The lost energy gain per gap due to the dee angle can be reduced by advancing the first gap in theta. This has the effect of increasing the dee angle towards 180 degrees where the maximum energy gain per gap would be achieved in first harmonic. (Note a dee angle of 180 degrees would give no energy gain in second harmonic.) If we make the effective dee angle 120 degrees then the energy gain in first and second harmonics will be almost the same, and the energy gain in first harmonic will be very close to the maximum possible for the dee voltage.

The gaps between the dees and the grounded structures in the MC50 central region vary between 3.2 mm and 8 mm in the median plane. It is therefore desirable to have all the gaps in the any new central region to be at least as large as 3.2 mm.

### 3.2 Electrode Structure

Finding the actual electrode shape is an iterative process. We used the orbit program CYCLONE[4] with electric field files generated using the program
RELAX3D[5]. A geometry using a first dee “puller”, that has an electric length of 120° is shown in Figure 3.1 along with a central trajectory. To determine the centring conditions required at the matching point (shown as a small circle in figure 3.1 a first harmonic particle was tracked backwards from a centred starting position 7 turns out. Both orbits have been calculated for a dee voltage of 40 kV and a central field of 1.7 Tesla. This means that the orbit geometry is not the same for first and second harmonics but as shown in the figure, there doesn’t appear to be a transmission problem for that harmonic.

In order to avoid problems with resonance crossings and to maintain reasonable beam for the extraction process, it is important that the beam be centred during most of the acceleration process. At low energy the beam orbit centre moves by large steps at each gap crossing, rather than in the more adiabatic fashion observed at higher energy. It is therefore convenient to follow the orbit centring by plotting the instantaneous centre of curvature. This is done in figure 3.2, for the first and second harmonic beams over the first 5 turns. The beam moves well onto the centre by this point, and what centring error remains can easily be removed using the harmonic coils provided in the MC50.

In the linear region of the cyclotron cyclotron designers use a construct known as the eigen-ellipse. This ellipse describes a possible beam shape in r,p_r (or z,p_z) space at a given energy and angle. This ellipse maps back onto itself after one turn, and the beam envelope over that turn is the minimum possible for the specified emittance. Beams that are significantly different from the eigen-ellipse will have much larger envelopes for the same emittance. In the absence of serious resonances and with small energy gain per gap, a beam that matches the eigen-ellipse at a given energy will adiabatically follow the eigen-ellipse as the energy increases. It is therefore desirable to have the beam as close to an eigen-ellipse as possible. The equilibrium orbit code GENSPEO
was used to compute 8 points that described the boundary of an eigen-ellipse at 0.6441 MeV (turn 7) with an area of $0.5\pi$ mm-mrad (normalized). The ellipse is centred on the accelerated orbit computed for that energy from a forward tracking run. The phase of each particle is corrected as per the procedure of Gordon\cite{9} (with $\nu_r \approx 1$);

$$\delta\phi = -\hbar\delta p_r/p.$$  

These particles are then tracked backwards to the matching point and the results at the matching point are shown in figure 3.3. These results show little distortion of the beam indicating clean passage through the electric lens of the central region. In figure 3.5 the orbits at the first gap are plotted for the rays describing the horizontal ellipse. Again we see that absence of shearing, and indication that the transit factors and electric lens effects are not producing a non-linear solution.

### 3.3 Inflector

Today the majority of axial injection system use what is called a spiral inflector at the centre of the machine. These devices use an electric field to bend the beam from the cyclotron axis into the magnet as an electric dipole would. However since we are in strong magnetic field, as the beam moves off axis it starts to spiral as well. To compensate for this the electric plates in the inflector are twisted to follow the beam trajectory so that the electric field is always locally perpendicular to the beam direction. As described by Pabot and Belmont\cite{6}, the resulting device has two free parameters. The first is the electric bend radius which is denoted by “A”. The second is the angle of the electric field in the plane that is perpendicular to the beam direction. This direction is called the tilt and is usually labeled $k'$. The tilt parameter can be used to adjust the final position (or orbit centre) of the beam. In some inflectors the gap between the electrodes is tapered in order to maintain a constant electric bend radius, however tapering
Figure 3.3: Matched radial ellipses. On the left are the initial matched ellipses at 0.67 MeV, and on the right are the results after tracking backwards to the matching point.

Figure 3.4: Matched vertical ellipses. On the left are the initial matched ellipses at 0.67 MeV, and on the right are the results after tracking backwards to the matching point.
the electrodes does reduce the aperture for the beam. In a practical design for the MC50, the inflector it would fit in the space currently occupied by the source chimney assembly. This constrains the overall height to about 4 cm. We would also like to have the source operating voltage and electric fields similar those used in the TR30 since it has demonstrated exceptional operational reliability.

The inflector design program CASINO [7] was used to find inflectors that would produce the desired centring at an injection voltage of 30 kV . Table 3.1 gives a list of inflectors that would give an orbit centre of $r=4.3$ mm which is the value from the CYCLONE runs. (Values in the table are for untapered electrodes, without fringe field compensation.) From this we find that a bend radius ($A$) of 3.2 cm gives reasonable operating values. An inflector with $A=3.2$, $k’=0.488$ is compared with the TR30 inflector in table 3.2. As can be seen, we are well within the safe operating margin. A more detailed search, using an approximate fringe field in CASINO, finds an inflector with $A=3.2$, $k’=0.518$ to have the correct centring, however since this is very similar, the results shown in figures such as 3.1 are for the $k’=0.488$ case.

To calculate the beam transport through the inflector we use a transfer matrix in the injection line calculations to represent the inflector. A number of possible arrangements can be calculated. Table 3.3 gives the transfer matrix for the $A=3.2$, $k’=0.518$ from $z=4.5$ (just before the fringe field), to the matching point in the cyclotron.

In practice the field along the cyclotron axis does not have a sharp edge and depends on the details of the axial hole. We have developed a TOSCA model of
Figure 3.6: Cut away View of the central region and inflector. The inflector shown has a gap of 0.8 and an aspect ratio of 1.7. No ground housing around the inflector is shown. Notice the proximity of the inflector to dee 2.
<table>
<thead>
<tr>
<th>A (cm)</th>
<th>k’</th>
<th>E (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>0.755</td>
<td>30.0</td>
</tr>
<tr>
<td>2.5</td>
<td>0.620</td>
<td>24.0</td>
</tr>
<tr>
<td>3.0</td>
<td>0.520</td>
<td>20.0</td>
</tr>
<tr>
<td>3.2</td>
<td>0.490</td>
<td>18.8</td>
</tr>
<tr>
<td>3.5</td>
<td>0.450</td>
<td>17.1</td>
</tr>
<tr>
<td>4.0</td>
<td>0.380</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Table 3.1: Inflectors with untapered electrodes that produce an orbit centre of r=0.43 cm. Beam energy is 30 keV.

<table>
<thead>
<tr>
<th>TR30</th>
<th>MC50</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (cm)</td>
<td>2.5</td>
</tr>
<tr>
<td>V_{inj}</td>
<td>25</td>
</tr>
<tr>
<td>gap</td>
<td>0.8</td>
</tr>
<tr>
<td>ratio</td>
<td>2.0</td>
</tr>
<tr>
<td>V_{inf}</td>
<td>8.0</td>
</tr>
<tr>
<td>k’</td>
<td>-.84</td>
</tr>
</tbody>
</table>

Table 3.2: Comparison of an inflector for the MC50 with the inflector used in the TR30

Table 3.3: Inflector transfer matrix in TRANSOPTR notation (units are cm, rad, cm, rad, cm, (dp/p)). The inflector has A=3.2, k’=0.518. The matrix is calculated from z=4.5 to the matching point. Matrix includes the entrance to the solenoidal field.
Figure 3.7: The magnetic field along the axis of the cyclotron bore. On the left is region close to the median plane and on the right is the low field further way.

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1753370</td>
<td>0.8478801</td>
<td>0.4514563</td>
<td>5.6585153</td>
<td>0.0000000</td>
<td>-0.4377152</td>
</tr>
<tr>
<td></td>
<td>0.3297465</td>
<td>2.8677545</td>
<td>-0.3017277</td>
<td>-2.0657076</td>
<td>0.0000000</td>
<td>1.3649478</td>
</tr>
<tr>
<td></td>
<td>0.6260910</td>
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<td>-1.2711353</td>
<td>-14.7449249</td>
<td>0.0000000</td>
<td>9.3316762</td>
</tr>
<tr>
<td></td>
<td>0.3606996</td>
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<td>-0.4090900</td>
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<td>0.0000000</td>
<td>3.1131329</td>
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<tr>
<td></td>
<td>1.0281920</td>
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<td>1.0000000</td>
<td>14.4366443</td>
</tr>
<tr>
<td></td>
<td>0.0000000</td>
<td>0.0000000</td>
<td>0.0000000</td>
<td>0.0000000</td>
<td>0.0000000</td>
<td>1.0000000</td>
</tr>
</tbody>
</table>

Table 3.4: Inflector transfer matrix from \( z=15 \) to the matching point. Axial field is that shown in figure 3.7

the cyclotron (see Appendix B) that has a 2cm radius hole in the centre plug. This means that the bore up to \( z=15 \) remains at 10 cm and then becomes 2cm from \( z=15 \) to \( z=7 \). The plug end could probably be shortened from \( z=15 \) but it must project below the \( z=10 \) point otherwise there will be a substantial loss of field on the median plane (there is a 2.4 mm gap under the pole tips at \( z=10 \)). The field along the axis is plotted in figure 3.7 using the TOSCA data. From this figure we see that a field of several hundred gauss extends out to \( z=90 \).

For injection calculations it is inconvenient to track in a field out to this distance so we have prepared a field \( \text{cp}_\text{axial.grid} \) that goes between \( z=15.1 \) and the median plane. (Note since the TOSCA model doesn’t include a chamfer on the bore radius the details near \( z=15 \) are probably incorrect, so we have zeroed the field at this point.) This field was then used in CASINO to compute a transfer matrix from the \( z=15 \) position to the matching point in the median plane. The resulting transfer matrix is shown in table 3.4.
Chapter 4

Injection Line

The injection line must take the beam produced by the ion source and transport it along the bore of the main magnet to the inflector entrance. In the above we estimated that the source should have a normalized emittance of $0.3\pi$ mm-mrad from a slit opening of 2mm by 4 mm. At the other end, the beam should arrive at the cyclotron matching point with beam shapes approximating the matched ellipses shown in figure 3.3. As well the beam envelopes and the optics elements are constrained by the space available in the magnet bore. The injection line should also provide the correct optics for a buncher to be located in the line. An overall concept of an injection line for the MC50 is shown in figure 4.1.

Compared with more modern cyclotrons with external ion sources, the MC50 has rather weak vertical focusing. This hurts in two ways. The matched vertical beam size is large, and since the inflector strongly couples all 3 dimensions, the bunch length can be no shorter than something like the transverse size and this is much longer than the longitudinal acceptance. It is not difficult to design a transport system which puts all of the beam into the transverse acceptance (see Figure 4.2). For these calculations, the source emittance is assumed to be $0.3\pi$mm-mrad normalized. The transverse acceptance is roughly 0.2 cm radially and 0.5 cm vertically. However, since the phase acceptance is only $10^\circ$, this would result in a transmission from the ion source to the beam circulating in the cyclotron of only $(1/36) \times 2.8\%$.

We can gain a factor of about 2 with a bunching system. It is difficult to bunch very much of the beam into the $10^\circ$ (= 0.26 cm) because the inflector couples all 3 degrees of freedom. This means that a vertical beam size of 0.5 cm will result in a minimum bunch (half-)length of about the same. Moreover, for short and compact injection line of about half a metre, the energy spread from the buncher contributes to vertical beam size because of the dispersion of the inflector. The result is a transmission of $\sim 6.5\%$, see Figure 4.3.

If the dispersion component is removed by using a debuncher or using the debunching properties of space charge, the transmission could be as high as 15%, but it is premature to depend on such a high number.

Since the injected bunch is long compared with the phase acceptance, it will
Figure 4.1: Section view of the MC50 showing a possible layout for the injection line including a quadrupole doublet in the magnet bore.

Figure 4.2: Beam envelopes for an ununched beam.
still be necessary to select the phase window in the centre region using radial slits downstream of the inflector. For the same reason, there is little to be gained in using more than just the first harmonic for bunching.

These matching calculations show that the source emittance could be matched to the cyclotron using three quadrupoles in the injection line. We have developed a design based on the TR30\[8\] injection quadrupole magnets, for a quad doublet that will fit in the space in the axial bore created when the existing centre plug is removed. These are shown in figure 4.4. Calculations show that these magnets should be capable of producing the focusing conditions at the entrance of the inflector necessary to match into the cyclotron.

In order to reduce the $\alpha$ current required from the ion source a buncher will be included in the injection line.

In order to keep the inflector orbit geometry constant, the injection energy will have to be scaled in the same manner as the dee voltage for the constant orbit mode. At low extraction energies (at present used infrequently) this results in very low source extraction voltages. This in turn will most likely reduce the source output current and increase the emittance. It therefore may be necessary to extract from the source at a higher energy and use the buncher to decelerate the beam to achieve high intensity $\alpha$ beams at low final energies. However since the MC50 currently operates at only a few fixed energies this is not an immediate problem.
Figure 4.4: View of a quadrupole magnet that would fit within the confines of the MC50 axial hole.
Chapter 5

Difficulties with the Solution

The MC50 is basically designed for small radius gain per turn when operating in first harmonic mode. This means that there is very little room for clearing the inflector with the first turn. This is well illustrated in figure 5.1 where the inflector and first harmonic orbits are plotted. In this figure the outline of an inflector with a gap of 8mm and an electrode aspect ratio of 2 are plotted. The edges of the inflector electrodes interfere with the grounded housing that surrounds it and in fact enters inside dee 2. Since it is very close to the orbit inside dee 2 it is not possible to move this dee further out.

A number of possible variants of the inflector can be tried to reduce the interference. Two of these are shown in figure 5.2. On the left is the same inflector but with the gap reduced to 6mm and the aspect ratio to 1.5. This reduction in electrode size solves the problem of the ground shield around dee 1 but the problem at dee 2 remains. The left side of the figure a much smaller inflector is shown. To get this small we have used an A for 2.0, an injection energy of 25 keV (instead of 30) plus the reduced gap and aspect ratio used in the left side of the figure. This inflector would have a higher electric field (25 kV/cm) and be much tighter and yet it still doesn’t provide for enough clearance. One could imagine shifting the beam centre away from the tight spot, however this doesn’t tend to work well because as the orbit centre is moved in one direction the exit of the inflector electrodes moves in the same direction.

One possible remedy would be to increase the available dee voltage however this probably means a large upgrade to the RF power chain and may have difficulties with voltage holding. In figure 5.3 we show the narrow inflector on a central region that has been scaled for 60 kV. Here there is sufficient clearance for the inflector although it is tight. It should be noted that this case is the same as would get if the maximum field where limited to 1.4 Tesla (which gives an energy of 33 MeV). Full energy could be achieved using a 40 kV dee voltage.
Figure 5.1: Median plane view showing the inflector and first harmonic orbits. Also shown are the dee electrode outlines and the outlines of the inflector electrodes. Notice that the inflector electrodes enter dee number 2.

Figure 5.2: On the left is an inflector with small gap and aspect ratios. On the right is a small inflector (A=2).
Figure 5.3: Two possible ways to make room for the inflector. On the left the narrow inflector with $A=3.2$ is shown with the central region scaled for 60 kV. On the right protons are run in second harmonic.

if it were run in second harmonic as show on the right side of figure 5.3. The difficulty with this is that it would require modifying the RF system to run at 51 Mhz, again a rather large job.
Chapter 6

Internal Source Options

Since the source technique discussed in Chapter 2 was originally developed on an internal ion source, it is reasonable to consider making modifications to the MC50 that would allow the PIG ion source to operate in such a mode.

Calculations of the first harmonic injection tend to indicate fairly marginal spacing at the nominal dee voltages. Figure 6.1 shows calculations of a nominal trajectory for 35 and 40 kV dee voltages for several starting phases. If fact the drawing of the first turn provided by UW shows significantly more spacing then we have been able to achieve with realistic conditions. In figure 6.2 an orbit using 35 kV on the first gap and 42 kV on all following gaps approaches the purple arcs, which are approximations to the curves on the provided drawing. While the absolute dee voltage is a scaling factor that can account for different magnetic field conditions etc., the need to have significantly larger energy gain on the second and third gaps from the first gap is hard to explain (the size of the effect would require more than a 1 kG field change over a few cm). Moving the dees from the strict 180 degree phasing can produce some of the same effect, but even the 20 degree difference shown in figure 6.2 doesn’t adequately explain the differences. While it is possible that there is some feature of the MC50 fields that we have not been included correctly in the CYCLONE model, it is also possible that the MC50 operates with marginal orbit spacing on the first turn when operated at the 1.7 Tesla field in first harmonic. If this is the case then it is probably also operating with poor centring.

From figures 6.3 and 6.4 it appears that the posts on the the upper and lower gap crossings are acting as a sort of phase selection slit. This effect might be enhanced by modifying the ground post on the lower gap, however it is hard to predict a dramatic effect. The phase distribution shown in figure 6.4 is certainly less than optimal for clean extraction so perhaps implementing a phase selection slit would be beneficial, particularly if the ion source intensity were also increased. The emittance ($0.15 \pi$ mm-mrad normalized) shown in figure 6.3 is about half of that which we used for the axial injection calculations. This probably suggests that an axial injection system should also stay at this level if we are to be assured that the acceleration and extraction processes are not
Figure 6.1: The MC50 central region with the source and post geometry as specified in the engineering drawings. On the left the dees are at 35 kV and on the right they are at 40 kV. Orbits for starting times of 230, 240, 250, and 260 degrees are shown.

Figure 6.2: On the left is shown an orbit with 35 kV on the first gap and 42 kV on the following gaps. The red curve in the right hand figure is a case with the second dee 20 degrees from nominal phasing (black curve is normal phasing). The purple arcs approximate the orbit shown on the figure provided by UW.
Figure 6.3: Estimation of the injection orbits for a dee voltage of 38 kV. On the left is shown the overall beam envelop and on the right are the final positions of those rays that survive.

Figure 6.4: On the left are rays with different phases at a dee voltage of 38 kV. Compare the crossing points of these rays with narrow points in the envelop plot in figure 6.3. On the left is an estimation of the surviving intensity as a function of phase.
Figure 6.5: Second harmonic orbits. On the left the dee voltage is 40 kV and the rays shown cover a 30 degree spread in starting time. On the right the dee voltage is 35 kV and the rays represent a large spread in initial position and angle.

affected.

There is less detailed information on the second harmonic rays, however it is easier to match the information we have. In figure 6.5 we see that the second harmonic geometry should accept quite a wide phase band. There is also room for a large transverse emittance since only the first posts seem to limit this. A check of the vertical focusing for this mode should be done, however it appears that the intensity in second harmonic will be only limited by the source output.

A brief review of the ion source drawings indicates that some basic modifications along with proper tuning and alignment of the existing source could substantially increase the output of the source for charge 2+ ions (singly charged ions are less demanding). For even greater output it should be possible to modify the source such that the type of plasma pinching described above can be performed in this source. As explained one could expect to achieve mA type currents of alphas in that mode.
Chapter 7

Conclusions

The high field and low energy gain per turn of the MC50 makes it very difficult to design a central region for axial injection that will operate in first harmonic mode. While it appears that it would not be difficult to design a central region for second harmonic mode, such a design would violate one of the study goals outlined in the first section. Modifications to the MC50 to allow axial injection in $h=1$ mode would be difficult and costly.

It should be possible to improve the ion source and perhaps the central region for second harmonic operation and thus substantially increase the accelerated alpha beam current. Expertise for this type of improvements exists at TRIUMF and could be applied to the MC50. This approach seems favourable compared to an axial injection system given the problems outlined above.
Appendix A

CYCLONE Parameters

The CYCLONE runs were done using two electric fields for a given geometry. The small field was used for the first gap crossing where the beam energy is very low. It had a point spacing of 0.2 mm in x and y and 0.5 mm in z. The switch to the large field took place inside the the enclosed section of the first dee at an angle of 80 degrees. The spacing used in the large field was .4 mm in x and y and 1 mm in z. The magnetic field used for the calculation shown in figure 3.1 was the 1.7 Tesla field described in the next appendix. The CYCLONE input file was:

```plaintext
! h=1 run V=40 kV
! in tosca field

PARTICLE 938.3,1.0
UNITS,CM,KG,
BFIELD,3,120,21,0.0,0.5,17.0,NO,
~/MC50/magnet/tcoil.bz
(8f9.5)
!electric field input
EFIELD,SMALL,1.0,
inf5_smallp
OFFSET,SMALL,0,
EFIELD,LARGE,1.0,1,2,
inf5_dee1
inf5_dee2
OFFSET,LARGE,0,
BOUND,LARGE,TRUE
! RF & DEE
HARMONIC=1
VOLTAGE=40.0
DEE=2,F,90.0,90.0,0.0
! approximate gap factor for MC50 dees
```
TIME,1.6,
! PRINT
PRINT=1,10
PRINT=2,12,0.0,30.0
PRINT=3,4,0.0,90.0
! Setting the puller to 100 means that it is never found
PULLER=100.0
! output files, format is unit#,on/off,formatted
! 35:ORBIT, 47:P_iii GAP DATA, 36:Centring, 50:PART_ii eflfd 51:PART_i eflfd
LOG=35,YES,T
LOG=36,NO
! transfer between parts - format is number,turn,angle,stop?
TRANSFER,1,0,80.,NO
!TRANSFER,2,2,46.,YES
! STARTING CONDITIONS
START=1
ETA=0
ENERGY=0.030
TURN=5
TAU=245.
XI=1.9
ALPHA=0.0
RUN

For the second harmonic runs the following lines were changed;

HARMONIC=2
ENERGY=0.015
TAU=140

otherwise they are the same as those above.
Appendix B

Magnetic Field Calculations

To obtain magnetic fields on the median plane in the machine centre and along the axial bore, a three dimensional magnetic model of the MC50 has been assembled using TOSCA. Results for the average field agree well with the measured data at full field. This model can also be used to evaluate the effect of making changes to the iron section of the centre plug.

A comparison between the TOSCA model (CP_HOLE) and the average field data that Scanditronix provided UW is made in figure B.1. Some details of the chamfering of the poles and centre plug in the region between r=5 and r=10 are inaccurate in this model. There is also a small clearance between the pole plug and the pole tips that is missing. The magnetic field in the median plane for a current setting of 834 Amps along with all the trim coils as per the “normal” 50.5 MeV settings is stored as P50.BZ and was used with CYCLONE calculations. (This field is reasonably isochronous out to r=15 for 25.9 Mhz.) The field from the I=535 case is stored as I535.BZ and is used for a low field run in CYCLONE.

The axial field along the bore of the magnet, when a 4.0 cm diameter hole is placed at the centre of the plug is shown in figure B.2 along with the iron geometry used along the axis. All changes can be accommodated by manufacturing a new centre plug element.
Figure B.1: Comparison between the average field (in kG) as computed by TOSCA with the field map data. On the left is a comparison for I=810 Amps and on the right is for I=535 Amps.

Figure B.2: Field along the magnet axis at the 1.7 Tesla field setting is shown on the left, and the iron geometry used is shown on the right.
Appendix C

Drawing Files

The electronic form of the drawings of the MC50 system and designs created for this study will be provided on a CD-ROM. Directory information will be provided here.
Bibliography


[2] Private communication between T. Kuo and D. Xie LBNL.


