The center-region components of the Maryland cyclotron were designed with the maximum degree of flexibility permitted by geometrical restraints. Theoretical studies of initial orbits were based on electric field data, obtained with a fully automated electrolytic tank system. The desired magnetic field shape was determined in a 1/3 scale model magnet. A unique feature in the central magnetic field design is an adjustable cobalt-iron plug which permits to optimize the vertical focusing frequency at various field levels by balancing of the space charge forces. By proper positioning of the ion source and use of slits it is possible to operate either with large duty factor or to select a narrow pulse width.

1. Introduction

The Maryland University Sected Isocronous Cyclotron (MUSIC) has been designed as a multi-particle variable energy machine capable of accelerating protons to energies up to 145 MeV, and other ions (with charge number Z and mass number M) to maximum energies of roughly

\[ E_K = \frac{185 Z^2}{M} \text{ MeV} \]

It features a 4-sector magnetic field with a maximum spiral angle of about 4°. The R.F. system consists of two resonators with 90° dees which are driven separately by power amplifiers. Operation is possible in both push-pull as well as push-push modes over a frequency range of 9.5 to 21 MHz, with dees voltages up to 90 kV.

For the design of the center region of this type of cyclotron two special problems have to be solved: (1) Provide adequate vertical magnetic focusing which is intrinsically smaller in a 4-sector machine than in a 3-sector cyclotron. (2) Determine the best ion source position for each mode of operation and design the central-region components with the large degree of flexibility that is required for variable-energy multi-particle acceleration.

The central magnetic field was designed with the use of a model magnet at C.S.F. (France). A unique feature of the design is an adjustable cobalt plug which permits an optimization of vertical focusing frequency at various field levels while keeping the phase shift within tolerable limits.

The electric field configuration and central geometry was determined with the automatic electrolytic tank system at the University of Maryland and detailed orbit calculations with the PINWHEEL program.

2. Magnetic Field and Vertical Focusing

The main problems regarding the design of the central magnetic field in a sector-focused cyclotron are well known. Generally speaking a 3-sector field configuration provides better vertical focusing but may pose difficulties for the radial motion due to the 3/3 resonance. A 4-sector field, on the other hand, is better behaved in regard to the radial motion, but vertical focusing is intrinsically weaker due to the smaller flutter in the center.

For the Maryland cyclotron a 4-sector configuration was chosen. With 90° dees system this geometry avoids the gap-crossing resonance problems encountered in machines with three sectors and one-fold symmetry in the R.F. system.

The first model magnet measurements indicated that, as expected, the flutter was not sufficient for good vertical focusing inside the region of about 5 inches. It was, therefore, decided to add a bump of a few percent in the center to improve the situation.

Initial efforts were aimed at achieving a bump which provides a constant \( v_z \) curve with a value of about 1.5 from 6 in. inward reaching as close as possible to the center. Calculations showed, however, that in bumps of this kind the phase shift of the ions with respect to the R.F. was too large, especially in the higher harmonic modes of operation (N = 2 and N = 3). This concept was then dropped in favor of a desired \( v_z \) curve which rises sharply from zero to a peak value between 1 and 2 near the ion source (i.e. on the first ion orbit) and then is permitted to drop, passing through a minimum of about 1 or below between 4 and 6 inches and rising to a value of 2 thereafter. This design takes into account the velocity dependence of the defocusing space charge forces which change the \( v_z \) value according to the formula

\[
\frac{\Delta v_z}{v_z} = -\frac{1 - \frac{I}{P(n) L^2}}{2e \omega V_z Z \Delta \omega v_z \Delta v_z} \left( \frac{\Delta V_z}{v_z} \right)^2
\]

or, for small changes \( \Delta v_z \ll 1)\,

\[
\Delta v_z = \frac{I}{P(n)} \frac{\Delta V_z}{4e \omega V_z Z \Delta \omega v_z \Delta v_z}
\]

\( I \) is the average current, \( \Delta \phi \) the phase width, \( \omega \) is the cyclotron frequency, \( V_z \) the voltage gain per turn, and \( z \) the height of the beam. \( P(n) \) is a function which decreases with the number of turns approaching the value 1 at large radii. The dominant term at small radii is inversely proportional...
to $\sqrt{2}$, i.e., to the radius $r$, and hence the velocity $v$. The change in the effective $v_0$ is therefore largest at the ion source and decreases with radius until it reaches a constant value. From this consideration of space charge effects it follows that the maximum focusing is needed near the course on the first turn and that $v_0$ can be allowed to drop as $1/r$ initially.

On the basis of these considerations a desired curve for the average magnetic field, $B(r)$, was constructed which fits the isochronous field $v_0/r$ and hence the velocity $v$. The change in the effective $v_0$ is therefore largest at the ion source and decreases with decreasing radius reaching a peak of $4\%$ above the isochronous field at $r = 0$.

Lack of time and money did not permit an extensive program of model magnet studies to determine the iron shape which best fits the desired curve at all levels of excitation. An acceptable compromise was found by using a cobalt plug (diameter $2\%$ inches) which can be adjusted in height by as much as .6 inches thereby permitting a satisfactory optimization of the $v_0$ curve at all field levels.

The Maryland Cyclotron has 16 pairs of trim-coils for fitting the desired isochronous fields. The trim-coil currents are determined by a computer program which uses the magnetic flux as independent variable as proposed by the NRL cyclotron group.

In this calculation the cobalt plug is treated as an additional trim-coil where the plug height $h$ takes the place of the trim-coil current.

A description of the main magnetic field design is given in another paper. Studies on the effects of electric focusing are in progress and will be published in the future.

3. Central-Region Design Considerations

In a two-dee system with dee angle less than $180^\circ$ the optimum starting phase is different from the phase of maximum energy gain. This makes it necessary to provide a phase shift at the beginning of the first orbit by increasing (or decreasing) the path length between the ion source and the next r.f. gap. This change of the effective dee angle at the first turn is generally different for each mode of operation requiring a high degree of flexibility in the mechanical design.

A second consideration is whether to design the cyclotron with a constant-orbit geometry as was done at Michigan State University or to provide more options such as the NRL design where a different geometry was chosen for each mode of operation. It is known that the central geometry of a cyclotron is the dominant factor in determining the phase width of the beam. From the experimenter's point of view a machine which provides both a large duty factor as well as a narrow pulse would be most desirable. Unfortunately, these two requirements are incompatible and the possibilities of providing some flexibility in any given machine are rather limited. Most sector-focused cyclotrons have a central geometry which is somewhere between a large-gap situation, where phase bunching occurs, and the narrow gap with negligibly short transit time. Particles with different phase $\phi$ end up with different center points. In the case of a large gap with width $d$ the center point is given approximately by

$$r_0 = \frac{m v_0^2 \sin^2 \theta}{dB^2 q},$$

and for the narrow gap by

$$r_0 = \frac{1}{h} \left[ \frac{2mv_0 \cos \theta}{c} \right]^{1/2}.$$

In an actual machine with a geometry between these two extremes the spread in center points is thus proportional to $v_0^2$ with $2 < c < 1$. This means that, all other parameters being the same, the phase width that can be packed into a tolerable center spread $\Delta r$ decreases with increasing dee voltage $V_d$, or phrased in a different way, the higher the dee voltage the larger is the spread in center points (or the emittance) for a beam with given phase width $\Delta \phi$. To obtain a beam with narrow phase by means of phase-selection slits as is being done at Michigan State University and a high dee voltage is advantageous. On the other hand, lowering the dee voltage enhances the duty factor as long as large-gap phase bunching effects can be avoided. Other factors such as space charge effects, influence of magnetic field errors, resonance traversal, single-turn extraction capability, etc., of course, favor a high dee voltage.

In the design of the central geometry for the Maryland cyclotron it was attempted to strike a reasonable balance between these diverging requirements and to provide as much flexibility as was possible within the geometrical constraints. There are three modes of operation: first - harmonic, push-pull ($N = 1$, $\omega = \omega_0$); second - harmonic, push-pull ($N = 2$); and third - harmonic push-pull ($N = 3$). The maximum energy gain per turn in a 90$^\circ$ dee system with peak dee voltage $V_0$ is

$$\Delta E_p = 4v_0 \cos^2 \theta,$$

where

$$9m = 4v_0 \cos^2 \theta = .707 \text{ for } N = 1, 3$$

and

$$9m = 0, \cos^2 \theta = 1.0 \text{ for } N = 2.$$

The central region was designed for two basic constant-orbit geometries, one with approximately 600 turns for the $N = 1$ mode (high-energy protons) and one with 230 turns for the $N = 2$ and $N = 3$ modes. In addition, however, sufficient space was provided to permit raising the dee voltage at a given magnetic field by as much as 50$\%$ and move the ion source and puller to correspondingly larger radii. To achieve this flexibility of positioning it was necessary to make the shielding electrode in the dummy dee near the source adjustable.

In a constant-orbit geometry mode of cyclotron operation the magnetic field $B$, dee voltage $V_0$, and $q/m$ of the particles must be changed in such a way that $q/m$ remains constant, or more
With the PINWHEEL program were maze. In these modes of operation and a special puller was designed for each case. Two basic motions were provided for adjustment: a radial displacement and a rotation about an axis inside the puller. With these two motions it is possible to vary azimuthal and radial position of the puller slot and the spacing between puller and ion source in such a way that any desirable position between the two extreme orbit geometries within each mode can be approximated reasonably well. The ion source, which is introduced axially into the magnet gap, can be adjusted independently. It has three motions for radial position, azimuth angle and rotation of the source tube about its axis. The automatic electrolytic-tank system built for determining the potential distributions in the center was described in reference 2 which also contains a figure showing a typical equipotential map for the N = 1, push-pull mode. The PINWHEEL calculations were aimed at determining the source position for which the largest number of particles (with different starting phases) had orbit centers within a circle of a 2.5 mm radius. Rather than centering one particular phase we tried to obtain a small center spread for the largest possible phase width, $\Delta \phi$, i.e., to provide the best conditions for multi-turn extraction of a large duty factor beam. On the other hand, in the orbit geometries where single-turn extraction is feasible (N = 2, N = 3), the flexibility of the design permits to center and select (by slits) a narrow-phase beam comparable to that of the Michigan State University cyclotron.

Table 1 contains a figure showing a typical equipotential region geometry that was evolved from the studies for the N = 1 and N = 2 modes of operation (N = 3 is almost identical with N = 2). The turn patterns, source, puller and defining slit positions are for the small-orbit geometry. Displacements increasing the radial position by as much as 20% are possible without changing the pullers as was discussed above. In the N = 1 case, the puller protrudes from the dee to provide the required phase shift of about 180° between dee entrance and exit gap. When the machine is operated with high voltage (large-orbit geometry) in the N = 1 mode the electrode at the tip of the right can be retracted to prevent sparking to the puller edge.

Table 2 lists the source-to-puller spacing d, the puller angle $\alpha$ with respect to the gap center line, and the phase width $\Delta \phi$ of the beam with center spread within ± 2.5 mm for each of the 6 geometries that were studied in detail.

4. Electric Field Configurations and Initial Orbits

After the basic design concept had been evolved an electrolytic-tank model of the central geometry was built and detailed orbit calculations with the PINWHEEL program were made. In these studies two extreme positions of ion source and puller (corresponding to the smallest and largest orbit geometry) were investigated for each mode of cyclotron (i.e. six orbit geometries) operation. The geometrical peculiarities of the 90° system did not permit the use of a single puller for all modes of operation and a special puller was designed for each case. Two basic motions were provided for adjustment: a radial displacement and a rotation about an axis inside the puller. With these two motions it is possible to vary azimuthal and radial position of the puller slot and the spacing between puller and ion source in such a way that any desirable position between the two extreme orbit geometries within each mode can be approximated reasonably well. The ion source, which is introduced axially into the magnet gap, can be adjusted independently. It has three motions for radial position, azimuth angle and rotation of the source tube about its axis.

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Figsures 4 and 5 show the final central region geometry that was evolved from the studies for the N = 1 and N = 2 modes of operation (N = 3 is almost identical with N = 2). The turn patterns, source, puller and defining slit positions are for the small-orbit geometry. Displacements increasing the radial position by as much as 20% are possible without changing the pullers as was discussed above. In the N = 1 case, the puller protrudes from the dee to provide the required phase shift of about 180° between dee entrance and exit gap. When the machine is operated with high voltage (large-orbit geometry) in the N = 1 mode the electrode at the tip of the right can be retracted to prevent sparking to the puller edge.

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<thead>
<tr>
<th>Geometry</th>
<th>N = 1</th>
<th>N = 2</th>
<th>N = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$ [mm]</td>
<td>9</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>14°</td>
<td>15°</td>
<td>9°</td>
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5. Vertical Motion Calculations

In this paper and will be given in other reports and publications.

The first internal beam in the Maryland cyclotron was achieved on November 26, 1968. At this date particles were accelerated to full

$$r_0 = \frac{1}{n} \left[ \frac{V_0 \cos \phi}{B_0} \right]^{1/2}$$

(6)

$$r_0 (cm) = \frac{149}{5} \left[ \left( \frac{V_0 z^3}{B_0} \right) \right]^{1/2}$$

(7)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>N = 1</th>
<th>N = 2</th>
<th>N = 3</th>
</tr>
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<tbody>
<tr>
<td>$\cos \psi$</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>$r_0 (cm)$</td>
<td>2.1 to 3.6</td>
<td>3.9 to 5.9</td>
<td>5.9 to 8.4</td>
</tr>
<tr>
<td>$\Delta r (mm)$</td>
<td>0.2 to 1.3</td>
<td>2.5 to 3.7</td>
<td>5.5 to 8.7</td>
</tr>
<tr>
<td>Particle</td>
<td>proton</td>
<td>deuteron (N = 2)</td>
<td>deuteron (N = 3)</td>
</tr>
<tr>
<td>$V_0 (kV)$</td>
<td>60 to 70</td>
<td>56.5 to 84.8</td>
<td>56.5 to 84.8</td>
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<tr>
<td>$B_0 (kG)$</td>
<td>12.47</td>
<td>12.68</td>
<td>13.00</td>
</tr>
<tr>
<td>$a_0 (rad)$</td>
<td>14.00</td>
<td>13.00</td>
<td>13.00</td>
</tr>
<tr>
<td>$f_e (MHz)$</td>
<td>19.4</td>
<td>19.3</td>
<td>19.3</td>
</tr>
<tr>
<td>$E_k (MeV)$</td>
<td>115</td>
<td>125</td>
<td>125</td>
</tr>
</tbody>
</table>

Table 1

The radii $r_0$, number of turns $n$, and average turn separation $\Delta r$ at extraction radius (115 cm) for the smallest and largest orbit geometry within each mode of operation are listed in Table 1. As an example the values for $V_0$, central isochronous field $B_0$, average field at extraction, $B_0$, electric frequency $f_e$ in the case of 115 MeV protons (N = 1) and 52 MeV deuterons (N = 2) are also given in this table.

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5. Vertical Motion Calculations

In this paper and will be given in other reports and publications.

The first internal beam in the Maryland cyclotron was achieved on November 26, 1968. At this date particles were accelerated to full
radius (final energy 60 MeV) in the second harmonic mode. The orbit patterns were measured with a differential probe and found to be in excellent agreement with the calculations. At larger radii they were washed out somewhat due to the absence of r.f. voltage stabilization (which had not yet been installed) and r.f. interference with the trim coils (now eliminated by better shielding of the feedback amplifiers). Since that first run the extraction system has been installed, and further tests both for internal as well as extracted beam are scheduled for March.

Acknowledgements

The authors wish to acknowledge the many contributions made by other people to this work: J. Mullendore and J. Etter for building the electrolytic-tank facility; Dr. Hogil Kim who contributed through his advice and many helpful discussions to the design philosophy; Chang Han, T. White, D. Nelson, and R. Woody for assistance in numerous programming problems and computer calculations; Dr. Leboutet for helpful advice and suggestions; K. Jenkins who played the key role in the overall mechanical design philosophy, the design of the electrical power supplies for the ion source, and the control system for the central region; G. Bock for the mechanical design; R. Scesa for fabrication, and C. Meese for help in the assembly of the central-region components.

We regret that the scope of this paper and lack of time did not permit us to include a discussion of the mechanical features and other engineering aspects of the central region design.

References

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Figure 1.

Figure 2.
Figure 3.

Figure 4.

Figure 5.