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FINAL REPORT

UNIVERSITY OF MICHIGAN CYCLOTRON

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I. INTRODUCTION

On February 1, 1950, the date on which this contract began, we undertook to remodel our 42-inch cyclotron, which by all standards was in poor condition. The machine suffered from lack of maintenance during the war years, and in addition had not kept pace with improvements in cyclotron techniques. At the present time it can be reported that the rebuilding is essentially complete, the cyclotron is operating with larger internal and external beams than at any time in its history, and ideas new to the field, resulting from this work, are incorporated in the machine.

It was hoped that in addition to the rebuilding of the cyclotron a new program of research (centered around the machine) could be initiated. Unfortunately, lack of sufficient funds has caused this phase of the work to proceed much more slowly than desired. While the greatest part of our effort the past two years was devoted to routine engineering problems, some time was spent gaining an insight into those features of cyclotrons not previously understood. In the paragraphs that follow, the engineering items will be mentioned briefly, while a more complete discussion of the new features will be given.

II. CYCLOTRON REMODELING

A major item of the rebuilding program, from the standpoint of time, was the renovation of the magnet. The coils were removed, cleaned, reinsulated, and replaced, and a new method of cooling was adopted. The method consisted of imbedding 1/4 inch copper tubing in 3/8 inch thick copper plates, one such plate being placed between each two pair of coils with Consoweld MP-16 plastic sheet 1/16 inch thick used for insulation. Fourteen such plates were required. In addition to completely new plumbing, commercial-type flow switches were installed. Measurements at equilibrium indicate a 10° temperature rise at the center of the coils with full magnetic field. In Fig. 1 the assembled coils, the cooling plates, and the method of connection of the water lines may be seen.

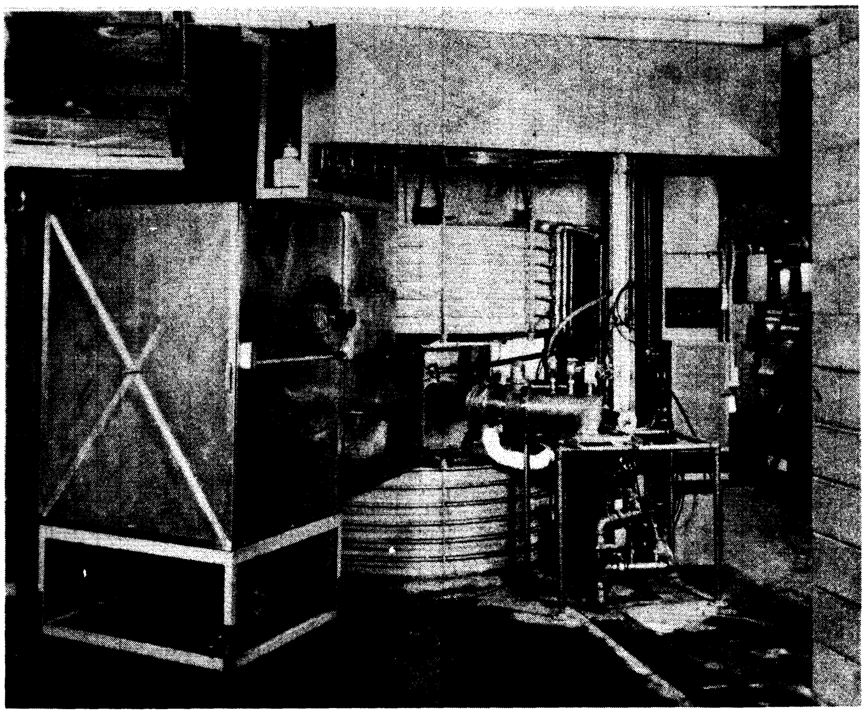

Fig. 1. The 42-Inch Cyclotron at the University of Michigan

The vacuum chamber and dees are in very poor condition and a source of difficulty both from the standpoint of frequent vacuum troubles and beam extraction. Unfortunately, sufficient funds were not available to replace these items during the period of the contract.

The vacuum system, aside from the cyclotron tank, is entirely new. The arrangement includes a Kinney VSD-778 mechanical pump, a DPI MB-100 booster, a DPI MCF-700 oil diffusion pump, a 6-inch vacuum valve and baffle with by-pass for roughing, a refrigerator, a liquid-air trap, and the necessary fittings, gauges, and safety interlocks. The chamber may be opened to air and pumped down to operating pressures in 20 minutes, whereas 6 hours were required previously. Part of the vacuum system may be seen in Fig. 1.

The oscillator for supplying the r-f voltage to the dees was rebuilt completely. The principal feature of the system is that it can be operated at either 11 or 18 megacycles per second, with approximately 30 minutes required to switch from one frequency to the other. The advantage of such an arrangement is that it makes available for research 5-mev protons, 10-mev deuterons, 20-mev alpha particles, and 16-mev protons. The system (standard tuned grid, tuned plate, push-pull oscillator) oscillates at 11 megacycles per second with a 1/4-wavelength line, and at 18 megacycles per second with a 3/4-wavelength line in the plate circuit. When a new vacuum chamber is available the higher frequency will be obtained with a 1/4-wavelength line at each end of the dees, a system which will yield higher dee voltages. The dees are supported at the vacuum chamber wall by cyclindrical polystyrene insulators, rather than by the more usual quarter-wave stub-supported line. Such an arrangement permits the rapid change-over in frequency, and adds to the overall simplicity of the system. The polystyrene insulators are much superior to the glass insulators previously used, both mechanically and electrically. The dee supports and part of the line may be seen in Fig. 2. At present the peak r-f voltage dee-to-dee is approximately 70 kv. This limit is set by arcing in the tank. New dees, properly designed, will allow two to three times the present peak voltage.

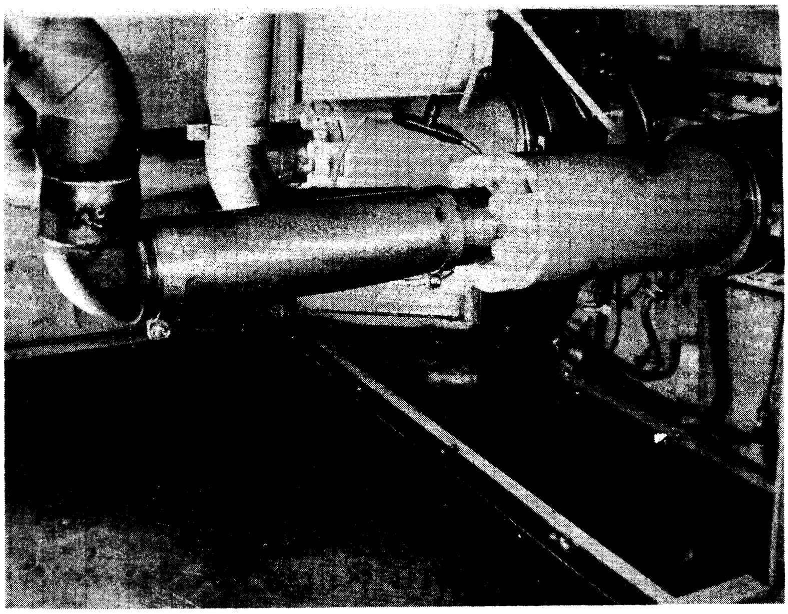

Fig. 2. The polystyrene Dee Supports and Part of the Oscillator Plate Line

It was necessary to install a compensator near one dee to compensate for changes in capacitance of the other dee when the deflector position was altered. Only in this way could the capacitances of the two dees to ground be made the same, and the oscillator be adjusted to operate in a balanced condition. The positioning of the compensator is critical and must be readjusted after any change in the deflector position. Oscillator balance is indicated when the r-f voltages from grid to filament and from plate to ground, respectively, are the same on each tube. F-124A tubes, which have a much larger power rating than necessary, are used because they were available at no cost. The amount of r-f feedback from plate to grid is adjusted by varying the tuning of the quarter-wave grid line. Fig. 3 is a view of the oscillator box, showing the tubes, r-f grid and plate meters, and quarter-wave grid line. Operating the oscillator in an unbalanced condition causes unequal heating in the polystyrene dee supports, and excessive heating in the external arc-source structure, which lies in the symmetry plane between the dee stems (Fig. 2). The r-f dee voltage is measured with a peak-reading diode rectifier circuit using a calibrated guard-ring-type pick-up condenser, for which the separation from the dee is accurately known.

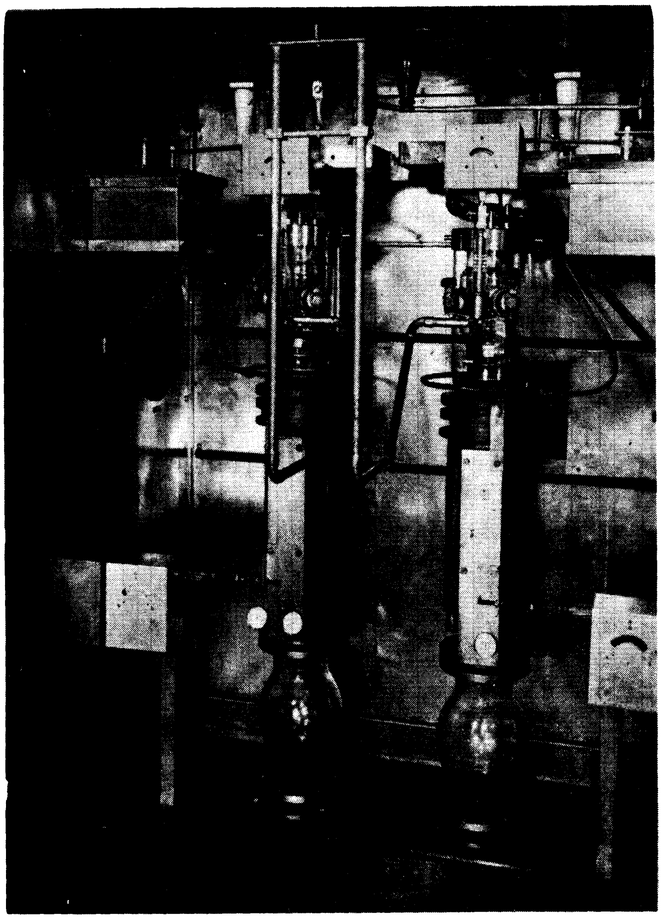

Fig. 3. The Oscillator Box, Showing the Tubes, Quarter-Wave Grid Line, and r-f Plate and Grid Voltage Meters

A new deflector shoe and mounting, as well as a new 60-kv power supply, was installed. The supply was purchased from Beta Electric Company and has proved to be very satisfactory. In addition to regulating the deflector voltage, it contains automatic overload protection, and meters the current to the deflector shoe, a valuable feature in beam-extraction studies. Cooling of the deflector shoe is accomplished in a convenient manner, due mainly to the remarkable properties of silicone oils. DC-200 (Dow-Corning Company) is circulated from the deflector through 2 feet of ceran tubing to a small heat exchanger. This closed system is a distinct advantage over the falling-water system previously used. The total leakage current is less than $30\,\mu a$ at 50 kv. The deflector is supported by a polystyrene cylinder similar to the dee supports.

The filament of the arc-ion source is now heated with direct current. Experience indicates that the filament life is as long as when heated with r-f. A new cathode-type arc source was developed which increases the life considerably (R.S.I. 22, 697 1951), although accurate data have not been obtained, since it has yet to be installed permanently in the cyclotron.

An important improvement from the viewpoint of operation is the complete revision of the wiring and control system, including the safety interlocks and overload cut-outs. The system includes a wire identification scheme, alarm system, and indicator panel. The interlocks prevent turning on the machine components in any but the proper order. As a single example of the safety devices, the oscillator shuts off if the doors to the cyclotron room are opened. A view of the control panel is shown in Fig. 4.

Fig. 4. A view of the control panel.

III. THE BEAM EXTRACTION PROBLEM

In this section a brief discussion will be given of the problems associated with obtaining large cyclotron beams. Details of the measurement and adjustment of the magnetic field, as well as the theory of radial oscillations, are given in the appendices. Two papers on this work are being presented at the annual meeting of the American Physical Society in New York. The abstracts appear as papers B-1 and B-2 of the Bulletin, vol. 27, No. 1.

At the conclusion of the remodeling phase a large circulating beam of deuterons was quickly obtained. Empirical shimming of the magnetic field yielded a beam external to the dees of approximately 100 μa. However, due to the poor geometry only 25 per cent of this could be obtained outside the walls of the vacuum chamber. The septum was then moved from 90° to 135° from the exit part. After this alteration it was somewhat surprising that even less beam was available. In the course of making adjustments two pecularities were observed: (1) Although the dee-to-dee voltage was sufficient to accelerate nearly all injected deuterons to terminal energy, the large internal beam began to decrease significantly at approximately 9 cm inside the septum. (2) Each time the vacuum chamber was let down to atmospheric pressure and re-evacuated, different azimuthal shimming was required to obtain the same beam external to the dees. Theoretical considerations suggested that large radial oscillations might be induced by a very small amount of first harmonic in the azimuthal variation of the magnetic field at a given radius. In particular an asymmetric settling of the iron lid of the vacuum chamber at evacuation could have accounted for the two peculiarities observed.

Three attacks were made on the problem simultaneously. A more extensive investigation was made into the theory of radial oscillations (Appendix I), a careful survey of the magnetic field was made which involved the construction and use of a magnetic resonance absorption apparatus (Appendix II), and an empirical shimming program was undertaken with the aim of correcting azimuthal field variations by observation on the beam itself.

The empirical shimming studies yielded essentially no information on the problem of radial oscillations, and did not improve the external beam appreciably. The reason for this failure, as was learned from later observation, was the loss of beam to the bottom of the dees, the loss varying with the shimming. Although the septum was burned at its center, indicating that the "median plane" at that radius was in the geometrical center, it did not follow that the same plane was defined at all radii. At smaller radii the bowing of the magnetic field is small, and very slight differences in the two poles of the magnet can cause a large vertical shift of the "plane", or more properly of the median surface. A simple method of adjusting this surface was devised (Appendix II), and beams of both deuterons and low-energy protons, for which no beams were obtained previously at large radii, were brought to the septum.

The magnetic resonance absorption apparatus proved to be extremely valuable for measuring the small but important variations in the magnetic field. It was from these measurements that the solution of the median surface problem was suggested, and the low-energy proton beam found. After making the necessary median-surface corrections and rough azimuthal corrections, beams of approximately 90 μa of deuterons and 120 μa of low-energy protons were obtained at the exit window, and about twice these values were obtained outside the dees. These figures indicate good performance by conventional cyclotron standards.

At this time a short program was instigated, the object of which was to make quantitative use of the theory of radial oscillations to extract a large fraction of the internal circulating beam. A more thorough mapping of the magnetic field was made, and asymmetries were reduced to the point where the shift of orbit centers should be only a few mm, provided the ions were injected on-center. The dee voltage was accurately measured, since this determined the distance an orbit center "walked" with the introduction of a specified asymmetry. An "angle probe" was designed to measure the direction of motion of ions as they crossed the line of dees at a given radius, and hence the displacement of orbit centers perpendicular to this line at that radius (Appendix III). At this writing only preliminary results or the measurement are available. These indicate that the ions are injected approximately 1.4 cm off the geometrical center, and their orbit centers precess, on a circle of this radius, about the geometrical center. The final pieces of information which should be obtained from the "angle probe" measurements are:

1. A knowledge of the mean center and spread of centers resulting from injection.

2. A detailed check of the theory of radial oscillations.

3. A knowledge of the displacement of centers required to cause the beam to approach the septum at the optimum angle for extraction.

With this information it should be possible to extract as much as 60-80 per cent of the internal beam, which would mean external beams of about 500 μa for deuterons, and about 700 μa of low-energy protons.

IV. INSTRUMENTATION

Due to insufficient funds only a limited amount of progress has been made on the basic instrumentation for the research programs. The design of a magnet for focusing the beam emerging from the cyclotron, and of a magnet for resolving the beam to 0.1 per cent in energy are complete. Funds for the purchase of the copper and steel were obtained only recently from the University, and the orders placed. Both magnets are of the double-focusing type, the focusing magnet having an angle of 50° and the analyzer magnet an angle of 90°. A window box at the exit port of the vacuum chamber is fitted with vacuum locks to permit the rapid removal of probes specially designed to carry target materials into the intense circulating beams. A double-walled steel pipe, 4 inches in inside diameter, fitted to the window box, carries the external beam to the position of the focusing magnet. The window box, vacuum lock, and steel pipe may be seen in Fig. 5.

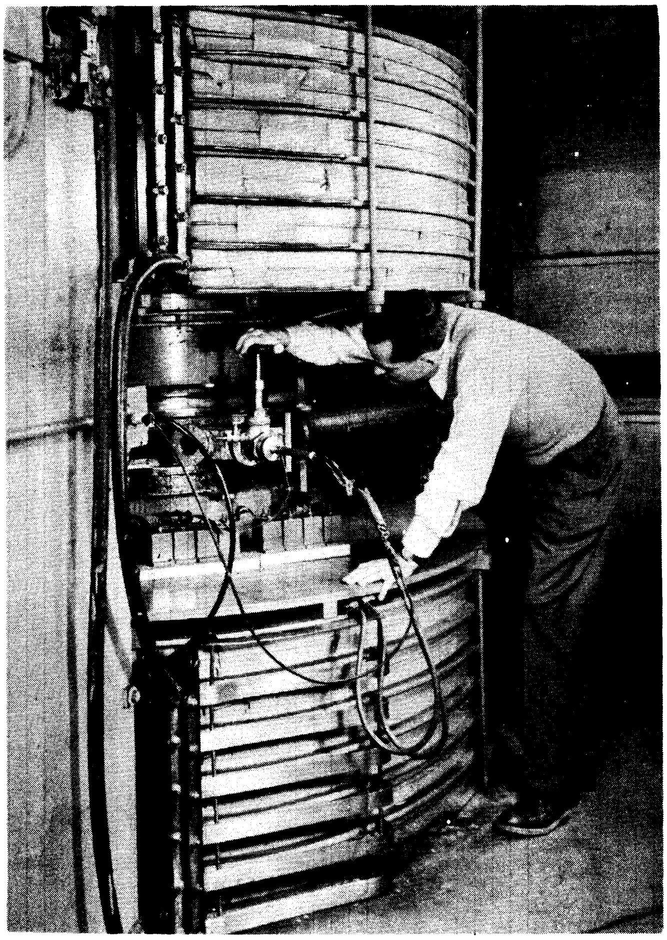

Fig. 5. The Window Box, and Beam Exit

A scattering chamber for use with the magnet system is designed and in the process of construction. It is intended for measurements of alpha particle and proton inelastic scattering as well as for measurement of energy distribution of the emitted neutrons in (α,n) and (p,n) reactions. An interesting feature of the chamber is that the scattering angle may be adjusted continuously from 20° to 160°. In previous scattering work measurements could be made only at definite predetermined angles. Any one of three types of particle detectors may be used with the chamber: coincident proportional counters, energy-sensitive neutron counters, and scintillation counters.

Considerable electronic instrumentation is complete. The circuitry for an investigation of (p,γ) reactions is complete, and that for use with the scattering chamber is being put into adjustment. The latter includes four pulse amplifiers, two 5000-volt electronically regulated power supplies, five decimal scalers, two single-channel differential discriminators, two counting-rate meters with pen recorders, and a coincidence circuit with a resolving time of 2×10^{-9} second.

V. SHIELDING

Because of the larger external beam it was necessary to improve the radiation shielding of the cyclotron unit. This was required not only for the safety of those using the cyclotron, but also for the safety of others inside and outside the building. Part of the cyclotron wing is being partitioned off, and concrete walls are being erected both inside and outside the building. Funds for this work are being supplied by the University.

VI. RESEARCH

While it was recognized that the purpose of this contract was to permit renovation of the cyclotron, radioactive samples were produced for a variety of studies. Sources were made for M. L. Wiedenbeck's group, working on angular-correlation studies, on which several letters have appeared in the Physical Review; for H. Gomberg's group working on radiography in conjunction with the Medical School; for E. Katz, who is studying diffusion problems in solid-state physics; and for W. Meinke for use in nuclear chemistry. In addition, some preliminary work was started by P.V.C. Hough on investigation of polarized gamma rays.

VII. PERSONNEL

Listed below are the names of those of staff or graduate-student rank who have been engaged in this program. Those associated with the project from its inception are indicated by (*). Those of staff rank are indicated by (+). In addition various part-time undergraduate assistants were employed on an hourly basis. Services of the Physics Shop, under the supervision of H. Roemer, were made available to us as needed by the Physics Department.

D. R. Bach	W. C. Jordan
E. H. Beach*	J. S. King
+H. R. Crane*	J. Nemarich
W. J. Childs	+W. C. Parkinson*
+P. V. C. Hough*	J. C. Rowley.

APPENDICES

APPENDIX I

THE THEORY OF THE RADIAL OSCILLATIONS

(By P. V. C. Hough)

A. The Equation of Motion and the Form of the Solution

We assume from the beginning that the vertical and radial motion of an ion in the cyclotron can be considered separately.* For the radial motion it is then easy to obtain a differential equation of motion, provided one assumes that the excursions of an ion from the equilibrium circle are small compared to the radius of that circle. Bohn and Foldy** have given the result, which is as follows:

$$\frac{d^2x}{d\theta^2} + (1-n)\, x = -r_o \sum_{s=1}^{\infty} h_s \cos\,(s\theta + \eta_s) \quad . \tag{1}$$

Here θ is the azimuthal angle of an ion from an arbitrary reference azimuth, x is the instantaneous radial displacement of an ion from the equilibrium circle, taken positive outward, $n = d\,(\ln B)/d(\ln r)$ is the "fall-off parameter" evaluated at $r = r_o$, and h_s and η_s are defined from the Fourier expansion of the magnetic induction near $r = r_o$, viz:

$$B(r,\theta;r_o) = B_o\left(\frac{r_o}{r}\right)^n\left[1 + \sum_{s=1}^{\infty} h_s \cos\,(s\theta + \eta_s)\right] \tag{2}$$

The parameters n, h_s, and η_s will in general be slowly varying functions of r_o, but they are assumed constant for the motion of the ion between the circles of radii $r_o - x_{max}$ and $r_o + x_{max}$. The origin of the polar

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* For a consideration of the possible transitions between the two types of motion, see Hamilton and Lyskin, RSI 22, 783 (1951). For the high dee voltages used with fixed-frequency cyclotrons, only the interchange at n = 0.2 can be important. It is quite possible, and as indicated in Section C it may be desirable, to prepare the magnetic field so n is always kept well below this value.

**Bohn and Foldy, Phys. Rev. 70, 258 (1946).

coordinate system is arbitrarily chosen at the geometric center of the cyclotron; it is important for the application of the theory to the experimental situation that any measurements of h_s and η_s be made using this origin.

When $0<\eta<<1$, as it will be for most cyclotrons, the forcing term with s = 1 in Equation (1) has nearly the natural frequency of radial oscillation, since the two frequencies in question are in a ratio $1: \sqrt{1-n}$. In consequence of this near resonance, the contribution of the term s = 1 to a resultant x is very much greater than any contribution for $s \neq 1$. (In the Michigan cyclotron, for example, the x resulting from s = 1 term is some 300 times larger than that from the s = 2 term). Therefore we may legitimately neglect in (1) all terms except s = 1 and obtain the simpler equation

$$\frac{d^2x}{d\theta^2} + (1-n)\, x = - r_o h \cos \theta \quad . \tag{3}$$

In (3) we have written h for h_1, and assumed that the axis of the first harmonic does not vary with r_o, so that it can be used for the reference azimuth. In Section B below this restriction is removed.

For motion at constant r_o, in which case n and h are constant, Equation (3) has the general solution

$$x = \frac{r_o h}{n}\left[\cos \theta + A \cos (\sqrt{1-n}\ \theta + \alpha)\right] , \tag{4}$$

where A and α are arbitrary constants. (If h = 0, the second term in the bracket is by itself the general solution).

A simple graphical representation of the motion given by (4) is useful. Since $\sqrt{1-n} \simeq 1 - 1/2\ n \simeq 1$, the two terms of (4) are of approximately the same frequency and may over any short period of time be combined by the vectorial addition of harmonic functions used in electric circuit analysis. Because the second "free oscillation" term in (4) is actually of slightly lower frequency, its representative vector must be made to rotate slowly in a direction opposite to the rotation of the ions themselves by n/2 revolutions per ion revolution. Fig. 6 shows the representation in the special case of no oscillation initially, i.e., A = -1, α = 0 in Equation (4). R is the resultant of the two component vectors, and when the diagram is rotated at the cyclotron frequency gives by projection on a vertical line the distance x of an ion from the equilibrium circle.

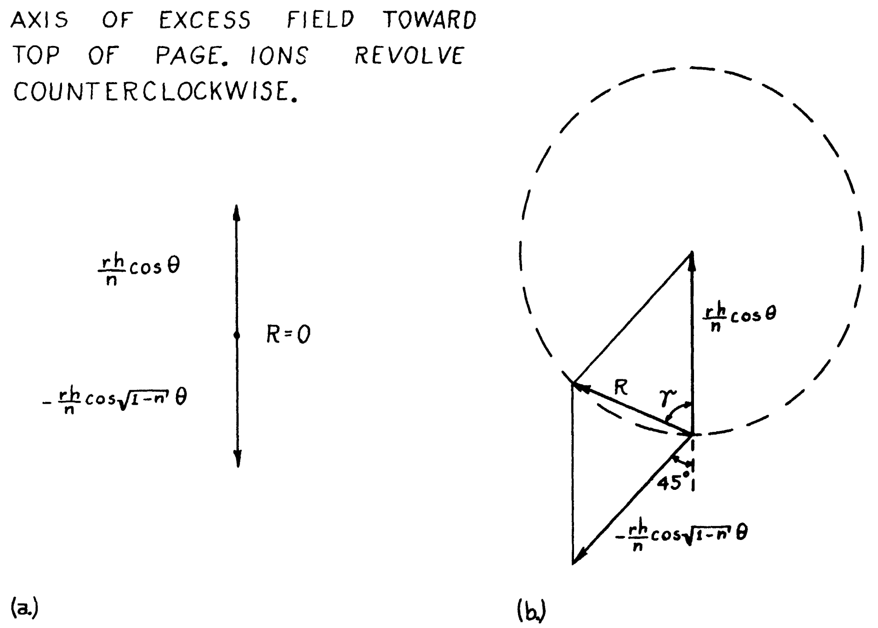


Fig. 6. Illustrating the development of radial oscillations in motion at constant r_0. (a) The component vectors initially, when there are no radial oscillations. (b) After the "free oscillation" component vector has precessed 45°, R, γ give the amplitude and phase of the oscillation.

It will be shown that the radial motion is, over a short period of time, of the harmonic type given by the vector composition above, even when the orbits are expanding. This can be expressed alternatively by saying that the ion moves temporarily in a circle of fixed, but displaced, center. The resultant vector R above is related to the position of the displaced center in the following simple way. In Fig. 4-b the resultant vector R shows that an ion at the axis of excess field is past its peak radial displacement and that the peak occurred eariler in aximuth by the angle γ. The magnitude of the peak displacement is equal to the magnitude of R. Therefore, the position of the instantaneous center is the mirror image in the vertical axis of the terminus of R. In the example illustrated by Fig. 6, the instantaneous center moves counterclockwise in the dotted circle by n/2 revolutions per ion revolution.

If now we consider the radial motion at one value of r_0 evolving into that at a larger value of r_0 as the orbits expand, we may note that the solution in each case is of exactly the form (4) but with different values of the arbitrary constants A and α. It is natural, then, to try to obtain from

(3) simpler equations determining the slow variation of A and α as the acceleration proceeds. One must, of course, at the beginning, replace $\sqrt{1-n}\,\theta$ by $\int\sqrt{1-n}\,d\theta$ in the argument of the second term of (4) so that α will really represent a slow variation of the phase of this term.

This program was carried out, but the techniques and results are too complicated to discuss in detail here. Historically this method of calculation was important to us because it showed that radial oscillations excited early in the motion can be (and usually are) retained as the orbits expand and n increases. The parameter $r_o h/n$ which determines the extent of the orbit-center displacement for motion at constant radius gives a very small displacement if measured values of h and n at the cutting edge are substituted. It is only when it is recognized that a large value of $r_o h/n$ for any part of the acceleration cycle can cause large final radial oscillations that the sensitivity of the orbits to azimuthal variation of the magnetic field is fully appreciated.

B. Simple Theory of the Motion

The kind of complication which developed in the calculation mentioned above suggested that a coordinate system fixed at the geometric center of the cyclotron is not the simplest possible for a description of the motion. We recall that for our purposes the magnetic field near $r = r_o$ is given by

$$B(r,\theta;r_o) = B_o\left(\frac{r_o}{r}\right)^n (1 + h\cos\theta) \quad , \tag{5}$$

where r and θ are measured from an origin at the geometric center of the cyclotron. If we introduce instead the polar coordinates R and Θ measured from a point M a distance m along the axis $\theta = 0$ (where $m << r_o$). Then (see Fig. 7)

$$r \simeq R(1 + m/R\cos\Theta) \simeq R(1 + m/r_o\cos\theta) \quad .$$

In terms of R, (5) becomes

$$B(R,\theta;r_o) = B_o(r_o/R)^n(1 - n\,m/r_o\cos\theta)\,(1 + h\cos\theta)$$

$$= B_o(r_o/R)^n\left[1 + (h - n\,m/r_o)\cos\theta\right] \tag{5-a}$$

in sufficient approximation.

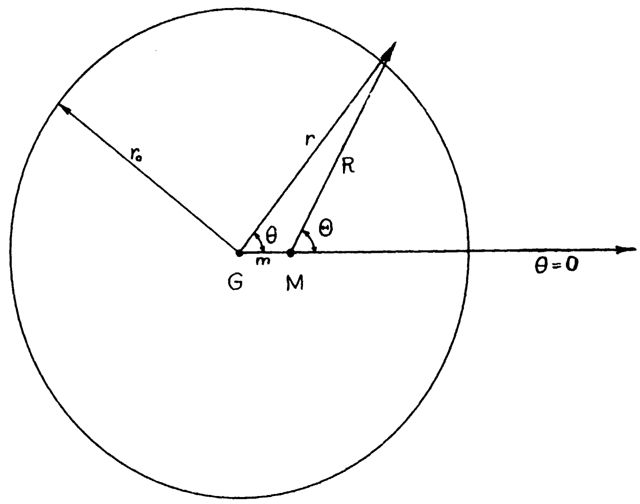


Fig. 7. The geometry for the transformation to a coordinate system with its origin at the magnetic center of the cyclotron.

Thus if m is chosen

$$m = r_0 h/n \quad , \tag{6}$$

then the new polar coordinate system origin is distinguished by the fact that an ion in an orbit centered on the new origin (and of radius $\sim r_0$) sees no first harmonic in the magnetic field. The point M may thus be called the "instantaneous magnetic center" of the machine. The position of M may be plotted as a function of r_0 when measurements of the magnetic field are available. In the uncorrected Michigan cyclotron, M started a few cm off-center, moved to a point about 5 cm off-center (in the same direction) and then at large radii, where n was large, retreated to the geometric center.

We now choose our coordinate system for description of the motion at M. About this origin the motion is a "free oscillation", or simply an advance of the instantaneous center by (1/2) M revolutions per ion revolution in a circle about M. With acknowledge of the rate of expansion of r_0 (which is determined by the dee voltage and the injection phase of the ion), M can be chosen always at the proper position in its path. If it is desirable to be very accurate it is possible, in calculating successive portions of the instantaneous orbit-center-displacement curve, to increase the radii of the circular arcs about M in proportion to $(1 - n)^{-1/4}$. This takes account of the increase in free-oscillation amplitude (as calculated by the WKB method) as the natural frequency decreases.

The advantage of the above picture is its simplicity, which allows an immediate determination of the effect of a given magnetic-field perturbation on the motion of orbit centers. A disadvantage, as presented here, is the failure to consider the question whether important "transport terms" arise because the motion is calculated relative to a moving coordinate system. There is good agreement between the simple theory and the more complicated calculation mentioned in section A for the one case where the latter has been used.

C. Applications

The primary use of the theory to date has been to indicate quantitatively the treatment of the cyclotron magnetic field necessary to obtain a reliable external beam. It showed first that very small azimuthal variations could, because of the near resonance between the rotation and radial oscillation frequencies, cause large radial oscillations; and it therefore suggested that the iron tank lid be wedged in place with precision. It showed the degree of accuracy needed in magnetic-field measurement control and thereby dictated the use of the magnetic field meter and guided the shimming. The effect of off-center injection was predicted and beam measurements were taken which can be used to position the arc source correctly. Finally, it indicates a way to extract a large fraction of the circulating beam (even in f-m cyclotrons) and to concentrate the extracted beam over a smaller area than is usual. The beam-extraction problem has not yet been attacked experimentally, but it may be worth while to describe the method proposed.

The experiments indicate that ions injected from the arc source at the geometric center of the machine have orbit centers grouped within a few mm of a point about 12 mm away from the arc source along the line of the dees. The first step is to slide the arc source along 12 mm to remove the off-center injection or "initial oscillations".

The magnetic field has been extremely well corrected for accidental first harmonic content. Therefore, during the middle part of the acceleration cycle no motion of the instantaneous orbit centers should occur.

As the orbits approach the septum, a strong, controlled first harmonic should be introduced which walks the orbit centers toward the septum. Fig. 8 illustrates how this can be done. The point $G \equiv 0$ indicates the instantaneous orbit centers at the geometric center after the middle acceleration period. The point M indicates the magnetic center produced by local shimming at the outside. The arrow shows the direction of

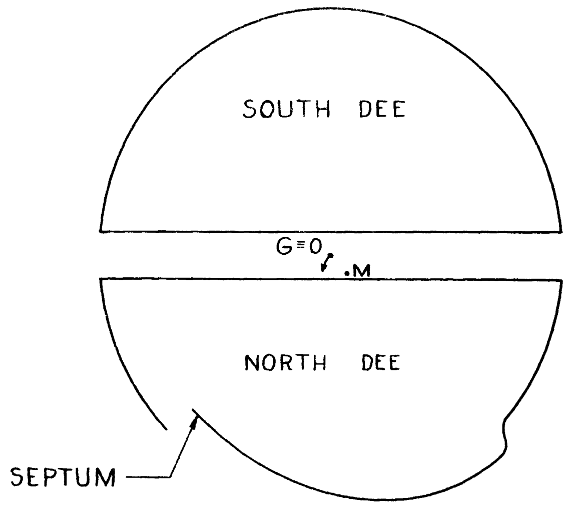


Fig. 8. Illustrating the method proposed for beam extraction.

motion of orbit centers for the last few turns. Evidently a walking of a cm or so per revolution, which should be easy to obtain, introduces just this much separation of successive orbits in addition to that caused by the energy added at the dee crossings, and for moderate dee voltages or in f-m machines would be the principal effect.

A difficulty arises in causing M to move suddenly from G to the position indicated. It is not necessary, of course, to accomplish this in a single orbit spacing, but it is necessary to do it rapidly enough so that the orbit centers do not walk too far around M in the meantime. Several ion geometries seem practicable, but n may have to be lowered near the cutting edge to reduce the rate of walking, or a complete revolution of orbit eenters may have to be used. With the angle probe (see Appendix III) to test the results, we are confident that this type of beam extraction can be realized.

APPENDIX II

MAGNETIC FIELD ADJUSTMENTS

A. The Median Surface Correction

Prior to the adjustment of the magnetic median surface, which will now be described, the internal deuteron beam decreased from 800 μa at a radius of 30 cm to about 200 μa at the septum (r = 44 cm). In addition, attempts to obtain a beam of protons at low magnetic field were unsuccessful. After searching for a proton beam, examination of the dees revealed a 1/2-inch diameter hole burned in the bottom of one dee. Because the deuteron beam always notched the septum at its center, the possibility of the beam shifting from the geometrical median plane was not previously considered. However, with this new evidence it became clear that the beam did not spiral out on a median plane, but rather on a curved or cupshaped surface, caused by an asymmetry between the top and bottom poles of the magnet. The amount of asymmetry necessary to cause such a shift is extremely small provided the bowing of the field lines is small, corresponding to a small value of the field fall-off parameter n, defined by $n = r\Delta H/\Delta r\ H_O$. In the case of deuterons, that part of the beam which missed the dees near r = 30 cm would arrive at the septum (where the value of n is much larger due to the fringe field) very close to the geometrical median plane. In the case of protons, for which the value of the magnetic field is just half that for deuterons, the fall-off is considerably less, resulting in complete loss of beam at r = 30 cm.

Fortunately this difficulty is easily corrected by inserting shims at the edge of either the top or bottom pole. In this case, since the beam was low at r = 30 cm, shims were placed between the top pole piece and the tank lid. That this is reasonable may be seen by considering the effect of such a shim on the magnetic flux. When the iron, at the outside edge of the top pole is increased, the flux redistributes itself, the density becoming greater at the edge of the magnet at the expense of that at smaller radii. This results in a vertical shift of the median surface. It is necessary that the shims be placed symmetrically (180° apart) in order to avoid producing a first harmonic term in the azimuthal asymmetry of the field (see part B below). By varying the amount of shimming and observing the current to an internal probe placed a few cm inside and septum and on the median plane, the optimum amount of iron can be determined. The shums used were 45° sectors, 3 inches wide and 1/16 inch thick. As the number of shims is increased the current rises, reaches a maximum, and then decreases. This is indicated in Fig. 9, where probe current is plotted as a function of the number of 45° shims. The two curves are for two different sets of center shims. With the larger set, the adjustment is less critical due to the fact that the fall-off parameter is larger. This may be seen in Fig. 10 where the value of n is plotted as a function of r for the two sets. With the smaller shims n is less than 0.005 out to a radius of 32 cm.

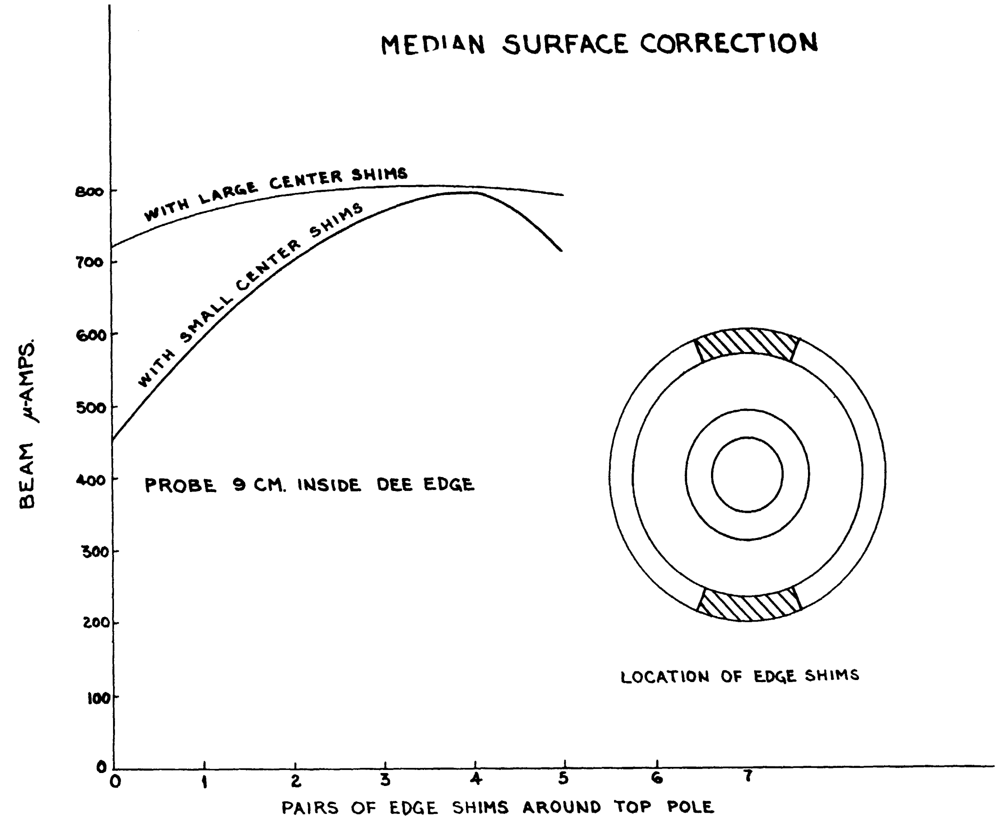


Fig. 9

After this simple correction of the median surface, beams of 700 μa of deuterons and 1000 μa of protons were obtained at the septum.

B. Azimuthal Asymmetry Corrections

The azimuthal variation of the magnetic field was measured by means of the magnetic resonance absorption technique, using the proton moment at the low magnetic fields and the lithium moment at the high field. The pick-up head was mounted on a sliding track on a boom which could be rotated through

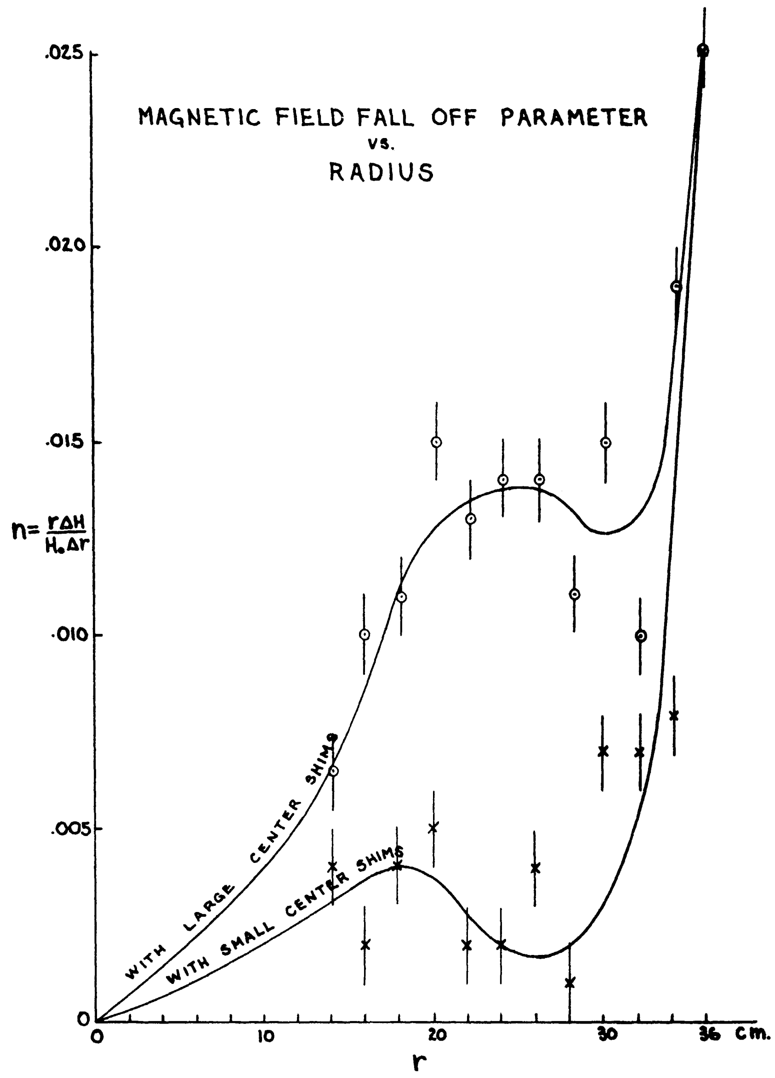
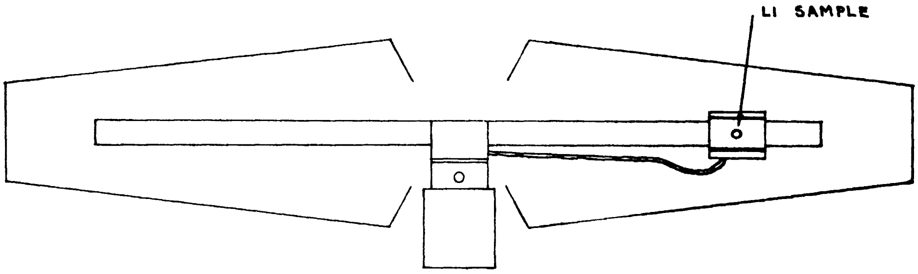


Fig. 10

360° of azimuth. A cross-sectional view of the apparatus is shown in Fig. 11. Shafts for varying the position of the pick-up both in radius and in azimuth were brought through the wall of the vacuum chamber by means of "O-ring" seals, so that measurements could be made with the chamber evacuated. The data are plotted in Fig. 12. The ordinate is half the frequency for which the resonance absorption occurs, and is proportional to the magnetic field. A variation of 0.1 per cent in the magnetic field occurs at an azimuth of 225°, which according to the calculations given in Appendix I would give rise to radial oscillations of several cm in amplitude. Small wedge-shaped shims were inserted between the tank lids and the pole pieces at this point. Fig. 13 is a plot of the azimuthal variation of the field at 29-cm radius before and after the correction.



CROSS SECTION THROUGH DEES SHOWING
MAGNETIC RESONANCE ABSORPTION HEAD.

Fig. 11

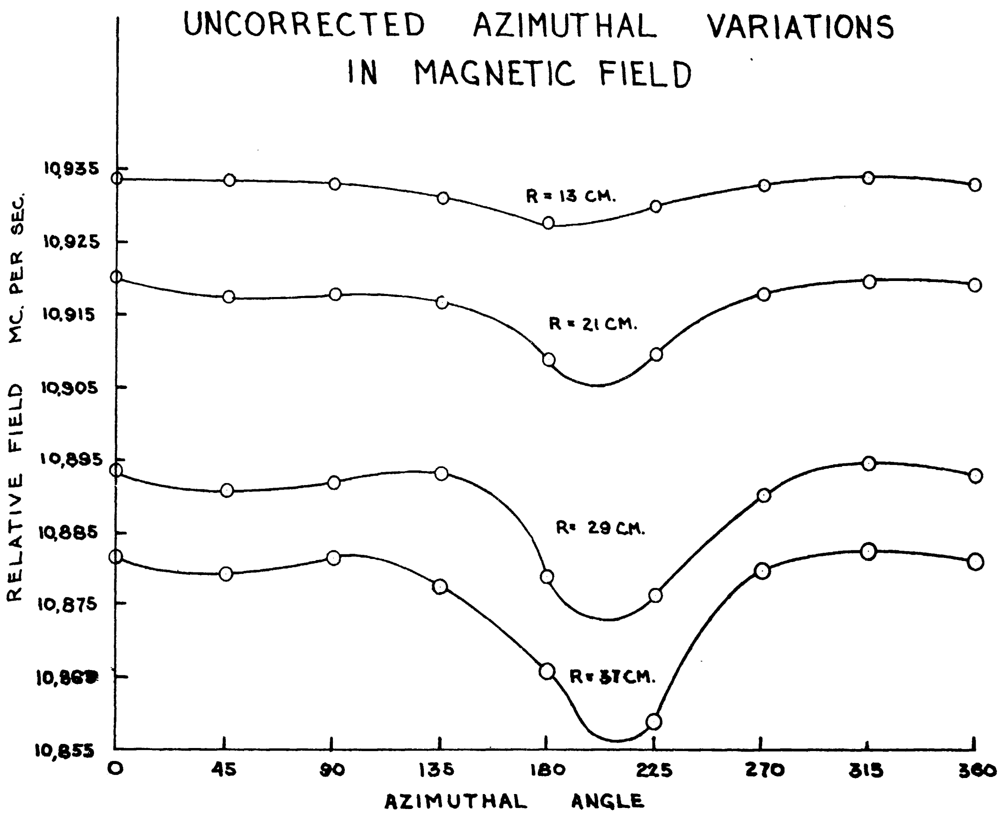


Fig. 12

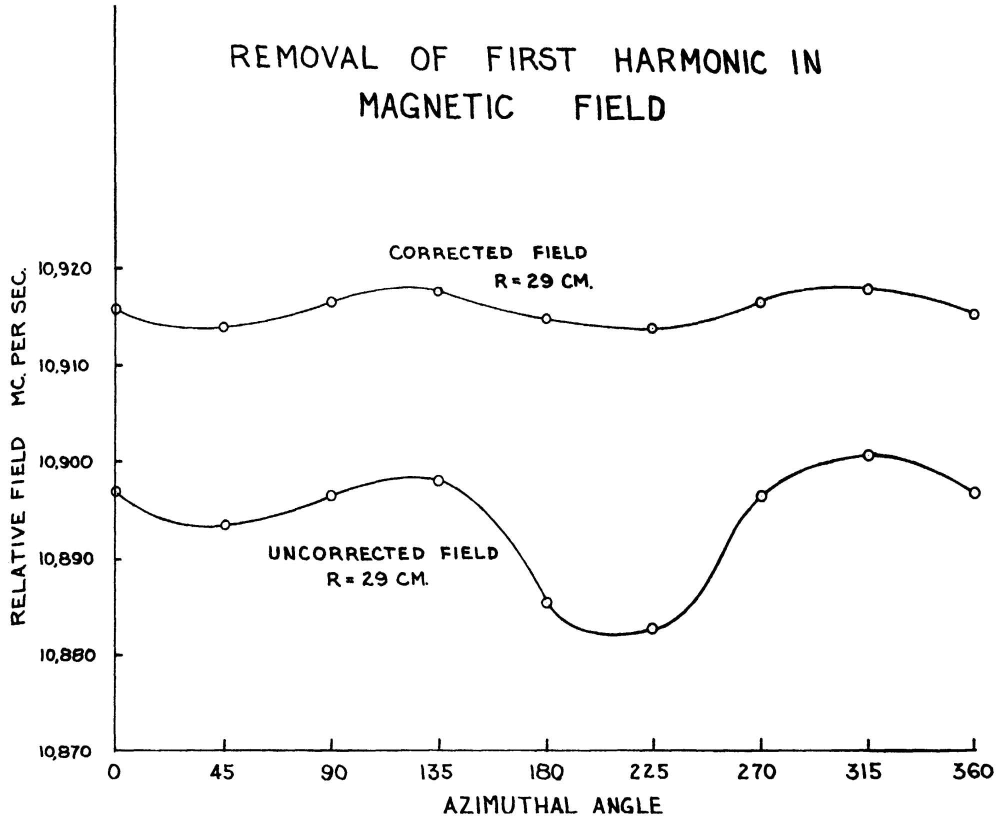

REMOVAL OF FIRST HARMONIC IN MAGNETIC FIELD
CORRECTED FIELD R = 29 CM.
UNCORRECTED FIELD R = 29 CM.
RELATIVE FIELD MC. PER SEC.
10,920
10,910
10,900
10,890
10,880
10,870
0
45
90
135
180
225
270
315
360
AZIMUTHAL ANGLE

Fig. 13

APPENDIX III

THE "ANGLE-PROBE" AND MEASUREMENTS OF RADIAL OSCILLATIONS

A detailed study of the motion of the accelerated particles in a cyclotron requires some method for determining the location of the instantaneous orbit centers of the particles, as well as a method of following the "walking" of the centers as the motion unfolds. This may be done in various ways. Two probes inserted in the vacuum chamber approximately 90° apart will determine the location of the line of centers, while three probes will determine the location of the center. The line of centers may also be determined by measuring the angle at which the particles cross a radius vector drawn from the geometrical center. While the three-probe method yields the most information, it is not generally convenient to insert three probes inside the dees simultaneously. For this reason a special "angle-probe" was devised. Details of the probe head are shown at the top of Fig. 14. The head of the probe contains a curved channel 0.002 inch wide with a radius of curvature of 40 cm. The channel terminates in an insulated collector plate, which is used to measure the current through the channel. The probe head may be set at any desired angle with respect to the axis of the probe shaft, which in turn lies on a radius from the geometrical center. In addition, the head can be set at any desired radius by sliding the shaft trough an O-ring seal in the wall of the vacuum chamber. At a given angle of the probe head, current from a particular region of orbit centers will be received by the collector. A plot of the collector current as a function of angle of the head then determines the line of centers, as well as the spread of the centers at a given radius. In addition, by taking data at successively increasing radii the progression or the "walking" of the line of centers may be determined.

The magnetic center and the geometric center of the system will coincide if the azimuthal asymmetries are removed. Should the ions be injected off this center the orbits will precess about a circle the diameter of which depends on the distance of the point of injection from the magnetic center. The effective injection point will not in general coincide with the position of the ion source due to the fact that the orbit center in the first few turns oscillates along the median line between the dees, the oscillations converging upon a point somewhat removed from the geometric center.

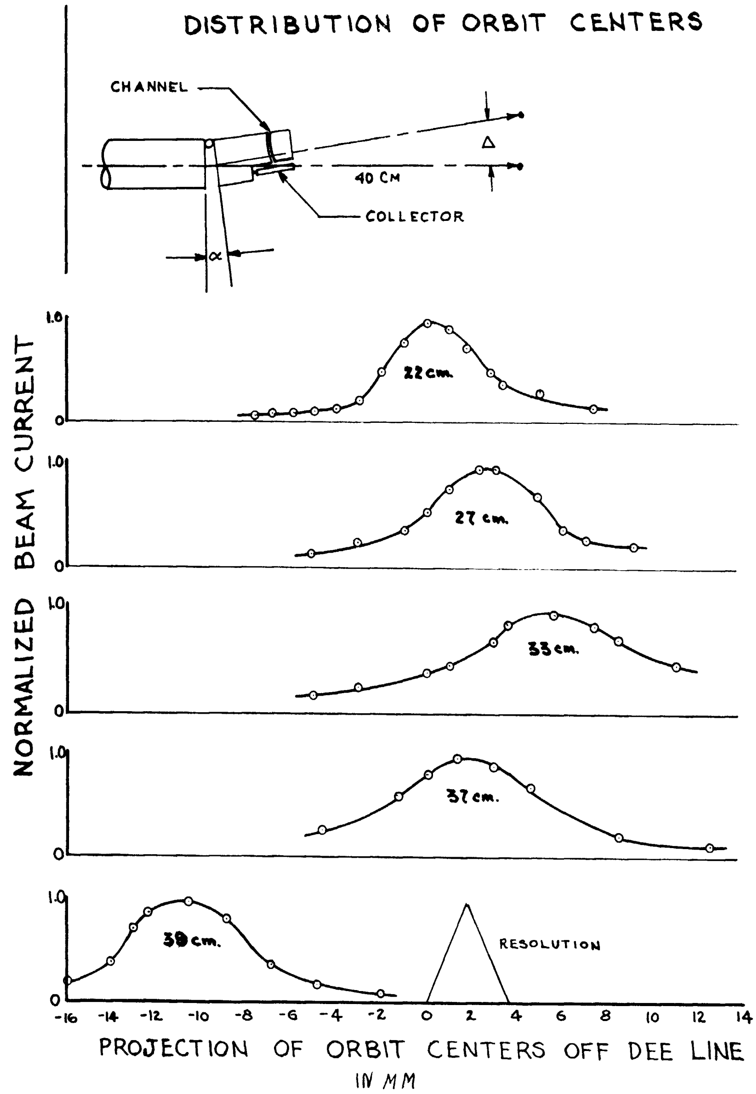


Fig. 14. Details of the "angle-probe" head, and probe-current data.

The curves of Fig. 14 give the results of the measurements made with the angle-probe. The beam currents have been normalized to unity. The abscissa, essentially the angle of the probe head, is expressed in terms of the perpendicular distance of the orbit centers off the median line between the dees. Note that as the instantaneous center precesses, this perpendicular distance moves first to the right then to the left. A knowledge of the dee voltage allows one to estimate the diameter of the precession circle, which in this case is approximately 3 cm. Accurate dee-voltage measurements were made using a guard-ring condenser pick-up as part of a capacitor voltage-divider network and a diode rectifier and meter.

It is clear that if the orbit centers precess on a circle of 3-cm diameter, the beam may reach the septum at an unfavorable extraction angle. Measurements of the external beam following the azimuthal correction indicated that only 10 per cent of the internal beam was being extracted. Two additional shims, 3/8 inch wide, 10 inches long and 1/16 inch thick, were introduced to attempt to shift the magnetic center toward the injection center and thus reduce the diameter of the precession circle. Under this condition 30 per cent of the internal beam was extracted. However, shifting the magnetic center is much less desirable than shifting the injection center to coincide with the geometric center, since this will introduce uncontrolled oscillations near the septum and hence the angle at which the beam approaches the septum may be unfavorable and will depend on dee voltage. (It may be desirable to introduce controlled oscillations at large radii, as suggested in Appendix I.) The injection center may be shifted easily by adjusting the position of the ion source along the median line between the dees. At this writing plans for constructing an adjustable ion source are in progress.