Title
AN ELECTRON MODEL PHASE-COMPENSATED C-W CYCLOTRON

Permalink
https://escholarship.org/uc/item/85c4n0mm

Authors
Pyle, Robert
Jungerman, John
Kelly, Elmer
et al.

Publication Date
1953-09-24

~~CONFIDENTIAL~~
SECURITY INFORMATION

UCRL 2241

UNIVERSITY OF CALIFORNIA

DECLASSIFIED

Radiation Laboratory

BERKELEY, CALIFORNIA

~~[illegible]~~

UNIVERSITY OF CALIFORNIA
Radiation Laboratory

Cover Sheet
Do not remove

INDEX NO. UCRL-2344
This document contains 85 pages
This is copy 45 of 69 series A
Date OCT 29 1953

DECLASSIFIED

Issued to Info. Div.

~~CONFIDENTIAL~~
Classification

Each person who receives this document must sign the cover sheet in the space below.

Route to	Noted by	Date	Route to	Noted by	Date
E Lofgren	E J L.				
A Andrew	Request		N		
	RKW	OCT 27 1955			

I-5(M)

~~CONFIDENTIAL~~
~~SECURITY INFORMATION~~

UCRL-2344
Particle Accelerators and
High-Voltage Machines Distribution

UNIVERSITY OF CALIFORNIA

DECLASSIFIED

Radiation Laboratory

Contract No. W-7405-eng-48

AN ELECTRON MODEL PHASE-COMPENSATED C-W CYCLOTRON

September, 1953

~~RESTRICTED DATA~~

~~This document contains restricted data as defined in the Atomic Energy Act of 1946. Its transmittal or disclosure of its contents in any manner to an unauthorized person is prohibited.~~

WORK DONE BY:

John Jungerman
Elmer Kelly
Robert Pyle
J. R. Richardson
Lawrence Ruby
Robert Thornton
Byron Wright

REPORT WRITTEN BY:

Robert Pyle

~~CONFIDENTIAL~~
~~SECURITY INFORMATION~~

Berkeley, California

CLASSIFICATION CANCELLED
BY AUTHORITY OF THE DECLASSIFICATION BRANCH USAEC
BY ______ 4-5-57
SIGNATURE OF THE PERSON MAKING THE CHANGE — DATE

Particle Accelerators and High-Voltage Machines Distribution

Standard Distribution: Series A	Copy Nos.
Argonne National Laboratory	1-8
Atomic Energy Commission, Washington	9-10
Brookhaven National Laboratory	11
California Research and Development Company	12-13
Carbide and Carbon Chemicals Company (ORNL)	14-19
Carbide and Carbon Chemicals Company (Y-12 Plant)	20-21
Chicago Patent Group	22
Chief of Naval Research	23
Columbia University (Failla)	24
Columbia University (Havens)	25
General Electric Company (ANPP)	26-27
Idaho Operations Office	28-29
Iowa State College	30
Knolls Atomic Power Laboratory	31
Los Alamos Scientific Laboratory	32-33
Massachusetts Institute of Technology (Evans)	34
National Advisory Committee for Aeronautics, Cleveland	35
National Bureau of Standards	36
Naval Research Laboratory	37
New York Operations Office	38-39
North American Aviation, Inc.	40-41
Patent Branch, Washington	42
UCLA Medical Research Laboratory (Warren)	43
University of California Radiation Laboratory, Berkeley	44-48
University of California Radiation Laboratory, Livermore	49-51
Westinghouse Electric Corporation	52-53
Yale University	54
Technical Information Service, Oak Ridge	55-69
	69

AN ELECTRON MODEL PHASE-COMPENSATED C-W CYCLOTRON

TABLE OF CONTENTS

Appendix

Particle Accelerators and High-
Voltage Machines Distribution

AN ELECTRON MODEL PHASE-COMPENSATED C-W CYCLOTRON

DECLASSIFIED

Robert Pyle

Radiation Laboratory, Department of Physics
University of California, Berkeley, California

September, 1953

ABSTRACT

A 33"-diameter cyclotron was constructed which accelerated electrons to v/c = 0.46 with a constant-frequency (61-megacycle) voltage on the electrodes. The design was based on an idea of L. H. Thomas, who showed that with the introduction of a suitable azimuthal asymmetry in the magnetic field it is possible for particles in all stable orbits to have the same period of revolution, and at the same time, adequate axial and radial focusing. The magnetic field of this cyclotron had three maxima and three minima, the analytical expression being given by:

$$H = H_0(1 + A(\omega r/c)\cos 3\theta + B(\omega r/c)^2 + C(\omega r/c)^3 \cos 3\theta$$

where $A = 1.35$, $B = 0.272$, $C \approx 0.5$ (variable). and $H_0 = 21.5$ gauss. ω is the angular frequency and θ the azimuthal coordinate.

The threshold voltage was found to be 59 peak volts on three 60°-wide pie-shaped "triants". These were oriented 120° apart, driven 120° out of phase, and gave a maximum energy gain of $3V_0e$ per revolution, where V_0 is the peak triant voltage. Under these conditions, beam which had an axial height of 1/8 in. at a radius of 5 inches had a maximum axial extent of 1/4 in. at larger radii.

By slightly modifying the magnetic field at large radii, 90 percent of the circulating beam was extracted from the cyclotron over a region 25°

wide in azimuth. The angular divergence of the external beam (in the median plane) was about 90°. Further shaping of the magnetic field concentrated 80 percent of the external current into a beam with an axial divergence of 3° and an apparent horizontal divergence of about 15°. The latter figure was obtained from the width of the beam two feet from the point where the electrons left the cyclotron. However, there was no single source for the horizontal trajectories.

The performance of this machine was promising enough that a second electron cyclotron of higher energy has been built.

UCRL-2344
Particle Accelerators and
High-Voltage Machines Distribution

AN ELECTRON MODEL PHASE-COMPENSATED C-W CYCLOTRON

Robert Pyle

Radiation Laboratory, Department of Physics
University of California, Berkeley, California

September, 1953

INTRODUCTION

Purpose

This report is concerned with an experimental investigation of the properties of a constant-frequency cyclotron capable of accelerating charged particles to highly relativistic velocities with little loss of beam during the process. The model work described here was initiated as a preliminary step to the possible construction of a high-energy, high-current deuteron accelerator for the MTA program. Energies of about 300 Mev and currents of perhaps fifty milliamperes were in mind for the heavy-particle machine. The model accelerated electrons rather than deuterons and was about a one-tenth scale model of the deuteron cyclotron.

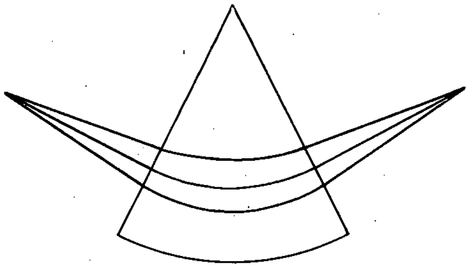
It is well known that a conventional fixed-frequency cyclotron cannot accelerate a large current of charged particles to highly relativistic energies, because of the inability to simultaneously provide the necessary focusing conditions and to maintain the phase relations between the particles and rf voltage which are required for energy gain. The frequency-modulated cyclotron reconciles these requirements but is subject to a duty cycle limitation which prevents it from delivering the currents desired.

L. H. Thomas* presented a possible answer to the problem of obtaining high energies and high currents in 1938, when he proved that a fixed-

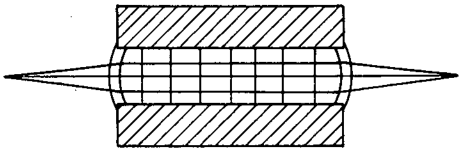
---

* L. H. Thomas, Phys. Rev. 54, 580, (1938)

~~CONFIDENTIAL~~ DECLASSIFIED



RADIAL FOCUSING



VERTICAL FOCUSING

WEDGE–TYPE FOCUSING.

MU-6538

Figure 1

frequency machine with a suitable azimuthal periodicity in the magnetic field could meet all the requirements for satisfactory acceleration. The work described here is based on this principle.

Thomas's work has been re-examined and extended by the UCRL theoretical group. The analysis is involved and will be covered completely in a future UCRL report by David Judd. Only those ideas and results necessary for an understanding of the experimental work are mentioned here.

Principle

The magnetic field (averaged over the orbit) should increase with radius to compensate for the relativistic increase in mass. In a conventional cyclotron such a field would be axially defocusing. However, it is possible to get both axial and radial focusing with wedge-shaped fields (Fig.1), and the idea developed by Thomas can be roughly described as the superposition of a form of wedge field on a field which increases with radius.

A magnetic field similar to that suggested above is described if the field at the median plane is represented by the expansion:

$$H = H_o \left(1 + A\left(\frac{\omega r}{c}\right)\cos M\Theta + B\left(\frac{\omega r}{c}\right)^2 + C\left(\frac{\omega r}{c}\right)^3\cos M\Theta + D\left(\frac{\omega r}{c}\right)^4 + \ldots\right.$$

where: H_o = the central magnetic field

ω = the angular frequency of the applied rf voltage

M = a constant equal to the azimuthal periodicity of the magnetic field

r = the distance from the axis of the cyclotron

c = the velocity of light

Θ = azimuthal displacement

A, B, C, etc. are constants.

It has been shown that if the coefficients A, B, C, etc. are properly chosen, the periods of revolution in all closed orbits will be the same, that is, particles will stay in phase with the accelerating voltage, and in addition both axial and radial focusing forces will exist. Satisfactory results can be obtained when M is any integer greater than two*. The theoretical upper limit on the energy obtainable is increased by increasing M, but the problems involved in the actual production of the magnetic field are such that M = 3 seems to be the only practical choice. Consequently, this value has been used in the experimental work.

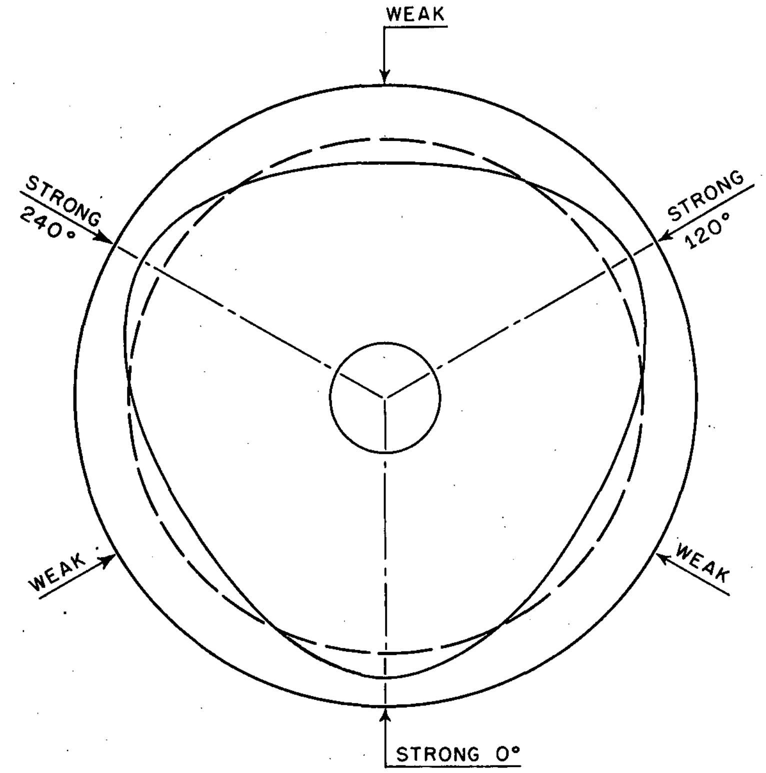
At the time the model was built, the C and higher order terms had not been investigated, and A and B had the values 1.35 and 0.272 respectively. Later, the correction corresponding to the C term was added by means of coils wound on the contoured faces of the poles, and accordingly could be varied over a considerable range.

The magnetic field at any closed orbit went through three maxima and minima, the percentage variation from maximum to minimum increasing with radius. The orbits in such a field are not circular (Fig. 2), and deviate increasingly from a circle as the radius increases. For example, when C = 0.5, the minimum radius is about 13-1/2 inches for the orbit with a maximum radius of 16 inches.

The net axial focusing force in this cyclotron is the sum of the positive effect of the wedge-type fields and the negative effect of the radially increasing average field, the former being larger in magnitude. The radial focusing force is the sum of a positive force from the wedge-type field and a positive effect from the average axial field, and increases faster with radius than the axial restoring force. Eventually an energy (or more properly

---

* L. I. Schiff, Phys. Rev. 54, 1114 (1938)



TWO TYPICAL ORBITS ARE SHOWN.
NEAR THE CENTER THE ORBITS ARE APPROXIMATELY CIRCULAR,
BUT DEVIATE CONSIDERABLY FROM A CIRCLE (DASHED) AT LARGE RADII.

MU-6539

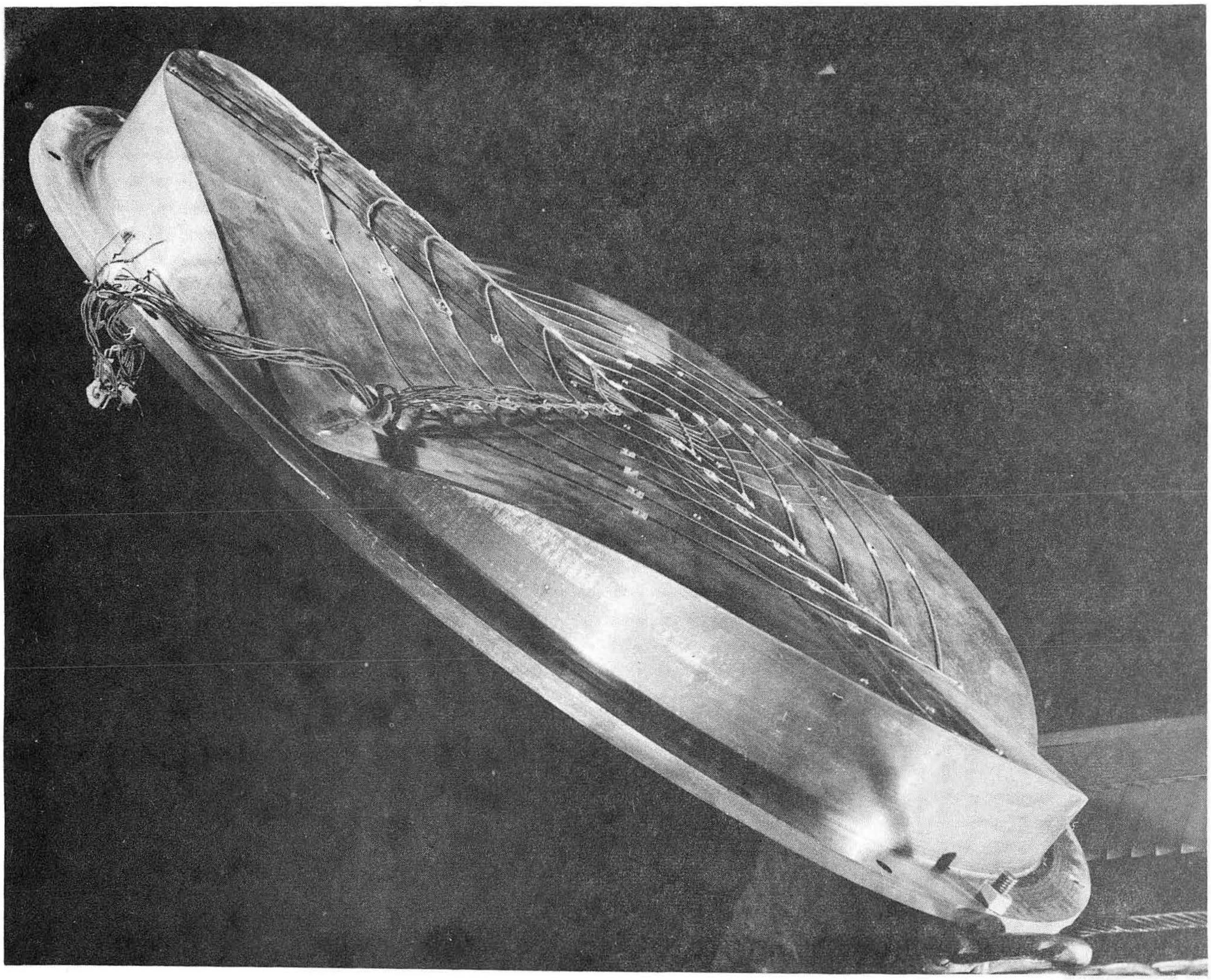
Figure 2

a velocity, the same for all particles,) will be reached at which the particles complete one-half of a radial oscillation in passing from one magnetic lens to the next. For stronger radial restoring forces, the amplitudes of the radial oscillations increase at an exponential rate. This is the effect which limits the maximum speed of the particle to that corresponding to a deuteron with an energy of perhaps 350 Mev. In practice, it appears that the cost of the machine would go up very sharply for deuteron energies much above 300 Mev.

A discussion of the factors considered in the choice of the coefficients used in the magnetic field expansion is given in Appendix I.

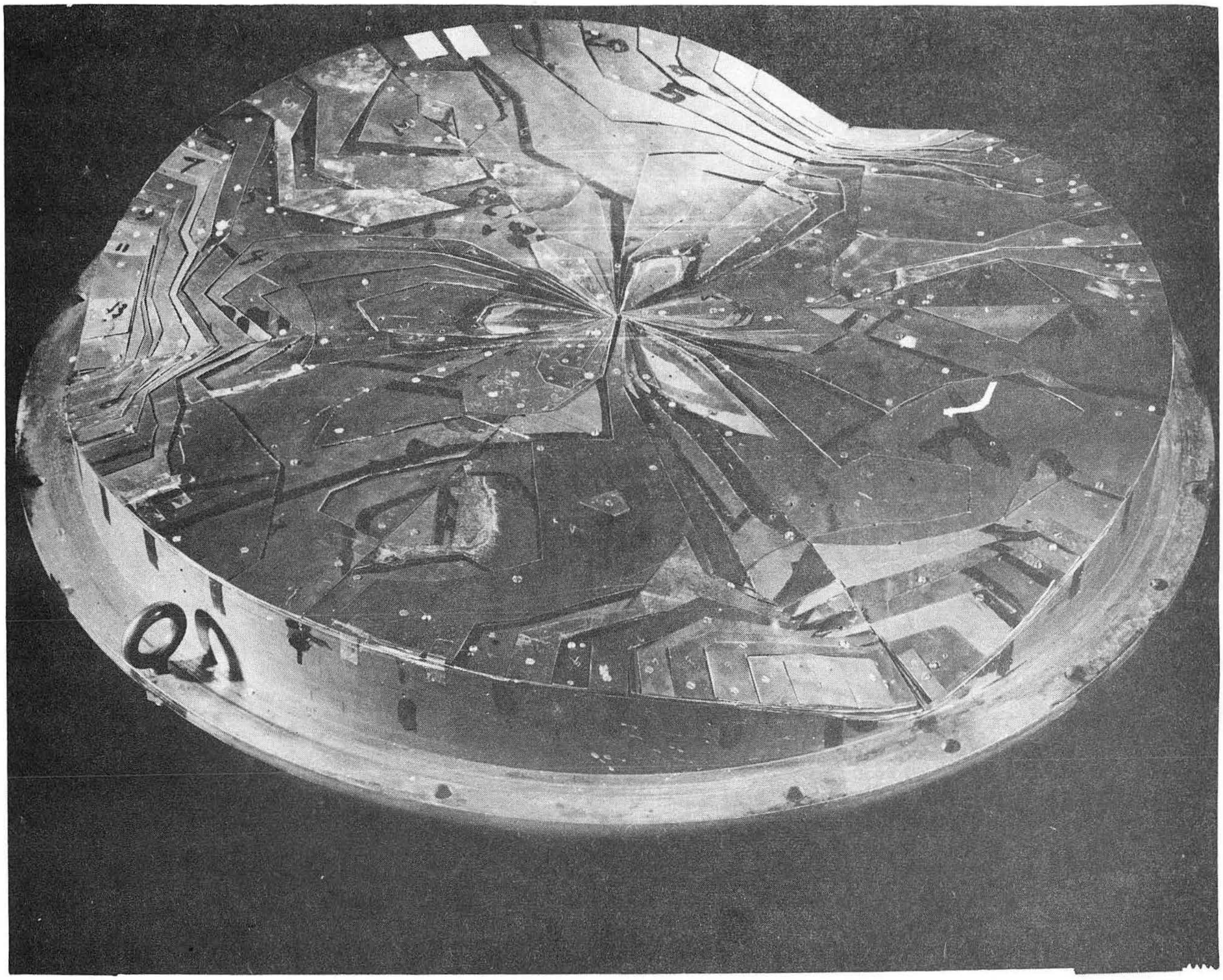
Scope of the Experimental Investigation

The broad regions for the experimental investigations of the properties of a cyclotron are (1) the starting conditions, (2) the acceleration to full energy, and (3) the extraction of the beam. An electron model does not lend itself well to an examination of the starting conditions. This work has been done in an azimuthally symmetric, 20-inch-diameter, three-phase machine using protons and deuterons (see UCRL 1889); there appeared to be no difficulty involved in starting a large current with an electrode configuration similar to that used in the electron model. Factors (2) and (3) have been examined in moderate detail with the electron model.



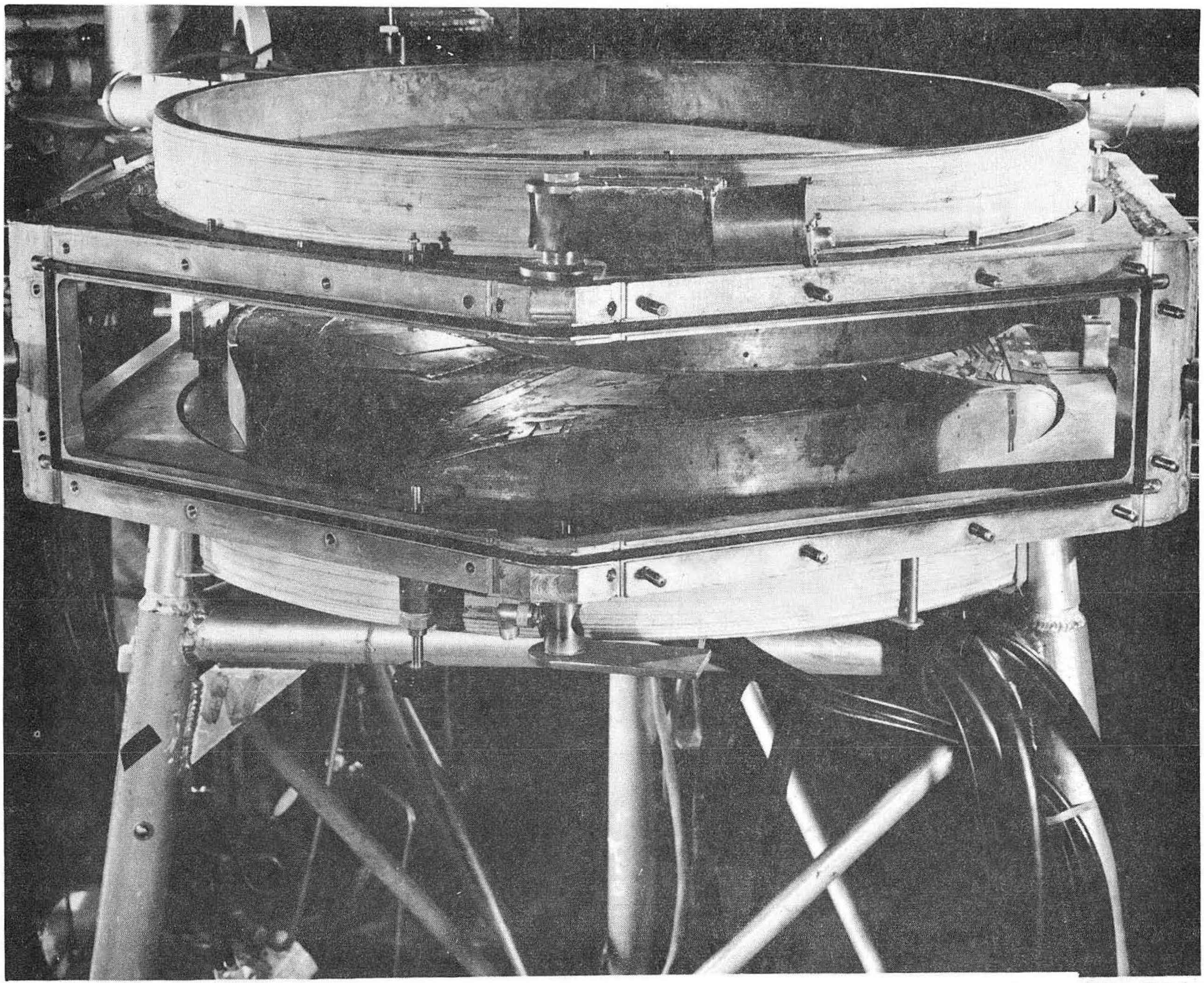
ZN-712

Fig. 3 Pole Without Shims



ZN-710

Fig. 4 Pole With Final Shims



ZN-724

Fig. 5 Poles and Energizing coils in place

APPARATUS

Magnet

The magnet was envisioned as an one-tenth scale model of the magnet required for a 250-Mev deuteron cyclotron. For this reason, no fundamental details of construction were considered unless they could be duplicated on the full-scale machine. Because the magnetic field was quite weak, with an average value of about twenty gauss and a minimum of seven gauss, it was necessary to choose a site well removed from sources of magnetic disturbance. The location chosen was Building 43, a small warehouse.

The return path for the magnetic flux was through the air rather than through a yoke. Such a design is economically feasible for the deuteron cyclotron, and very advantageous for the electron model, because otherwise the effects of residual magnetism would be much larger.

Poles

The design of the pole face contours was begun in May, 1950. The shape of the iron was calculated by assuming the field to be inversely proportional to the gap, with a correction of a few percent to allow for the curvature of the field lines. A plaster model of a 120° sector was constructed and used as a pattern for a three-dimensional pantograph milling machine. The blanks were four-inch-thick slabs of mild steel, which were heat treated before shaping. The finished poles had a maximum thickness of four inches and a diameter of 33 inches, exclusive of a flange where the vacuum seal was made (Fig. 3).

As more became known about the desired field, the pole faces were shimmed. The final appearance is shown in Fig. 4. Figure 5 shows the poles in place. The gap at the central axis was about two inches. The minimum gap on the "hill" at maximum radius was one inch and the maximum gap in the "valley" at this radius was about five inches.

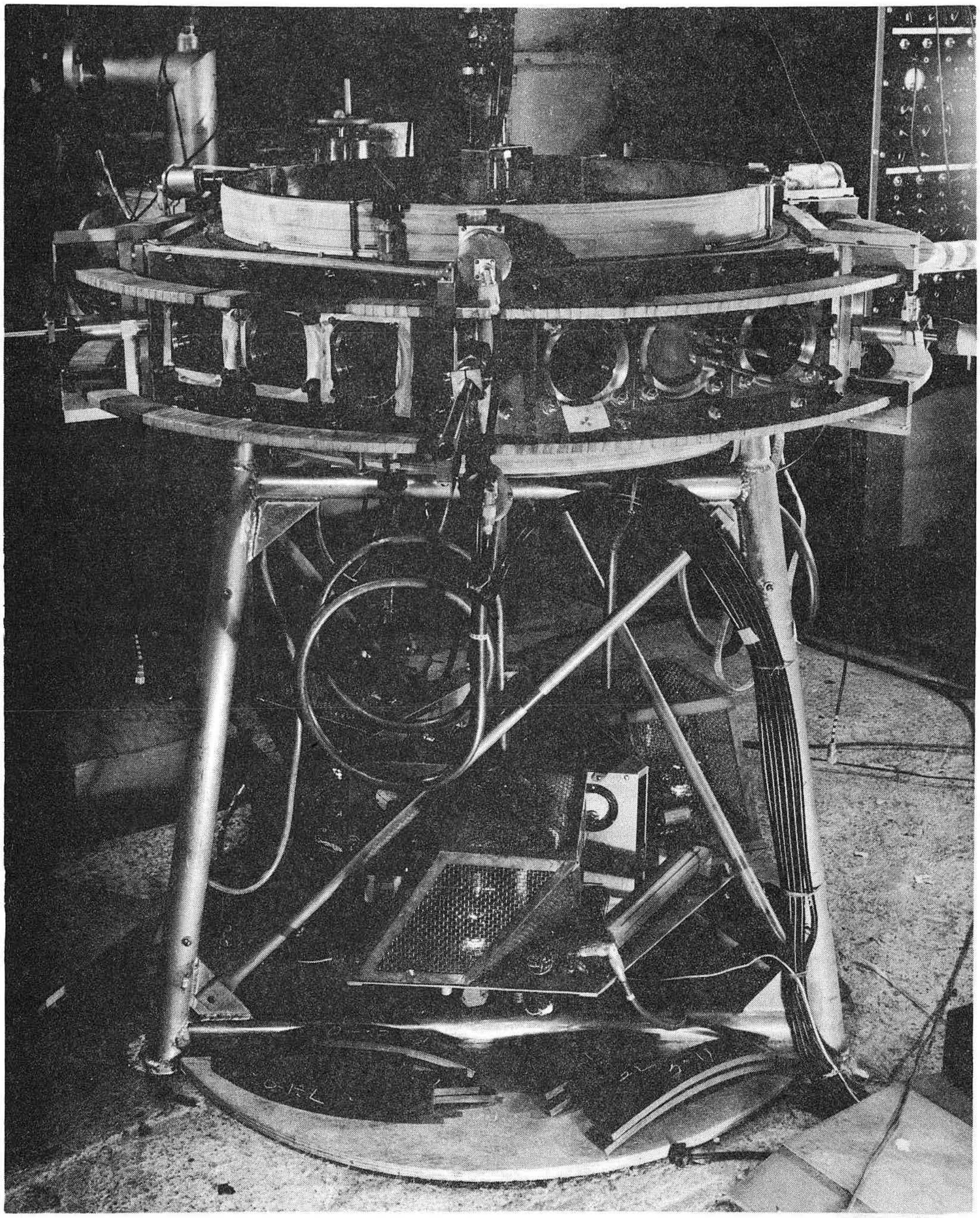
Coils

The two coils originally used to energize the magnet each consisted of thirty turns of 1/16 in. by 1/2 in. copper strap wound in the shape of a circle 54-1/2 in. o.d. They were separated axially by 6-1/4 inches and energized with 22 amperes of current supplied by a motor-generator set, which was stabilized by an external current regulator. The resultant field was not steady enough for good quantitative measurements.

The second set of coils, installed May, 1951, was mounted directly on the external pole surfaces. Each coil consisted of 660 turns of #16 formvar covered wire, wound on a brass spool 33-3/64 in. in diameter. The energizing current of 1.2 amperes was supplied at 55 volts by a rectifier, and regulated by a temperature-controlled electronic circuit to one part in ten thousand.

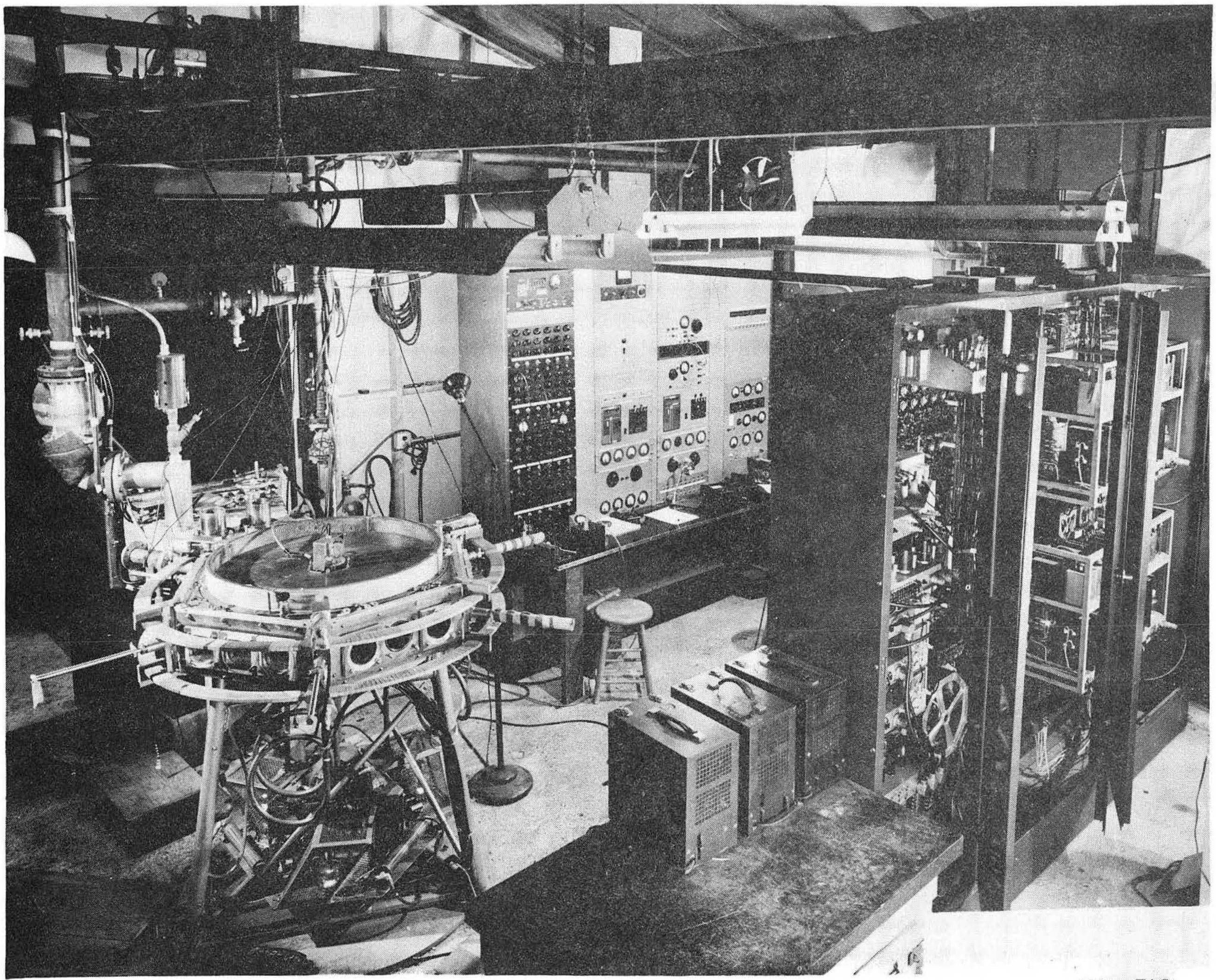
As would be expected, the appearance of the external beam was somewhat different in the two cases, but the field distribution in the gap appeared to be unchanged. The two pairs of coils are shown in position in Fig. 6 and again in Fig. 7.

A variety of coils was wound on the gap sides of the pole faces for the purpose of locally adjusting the magnetic field by a few percent. Identical coils of three turns each were mounted above and below the median plane and provision was made for adjusting both the total current through each set of coils and the difference between the top and bottom coils. The controls for adjusting these currents were mounted on a four-sided movable rack, two faces of which are shown in Fig. 8. These coils could be run up to three amperes, originally from storage batteries, and later from "Nobatron"



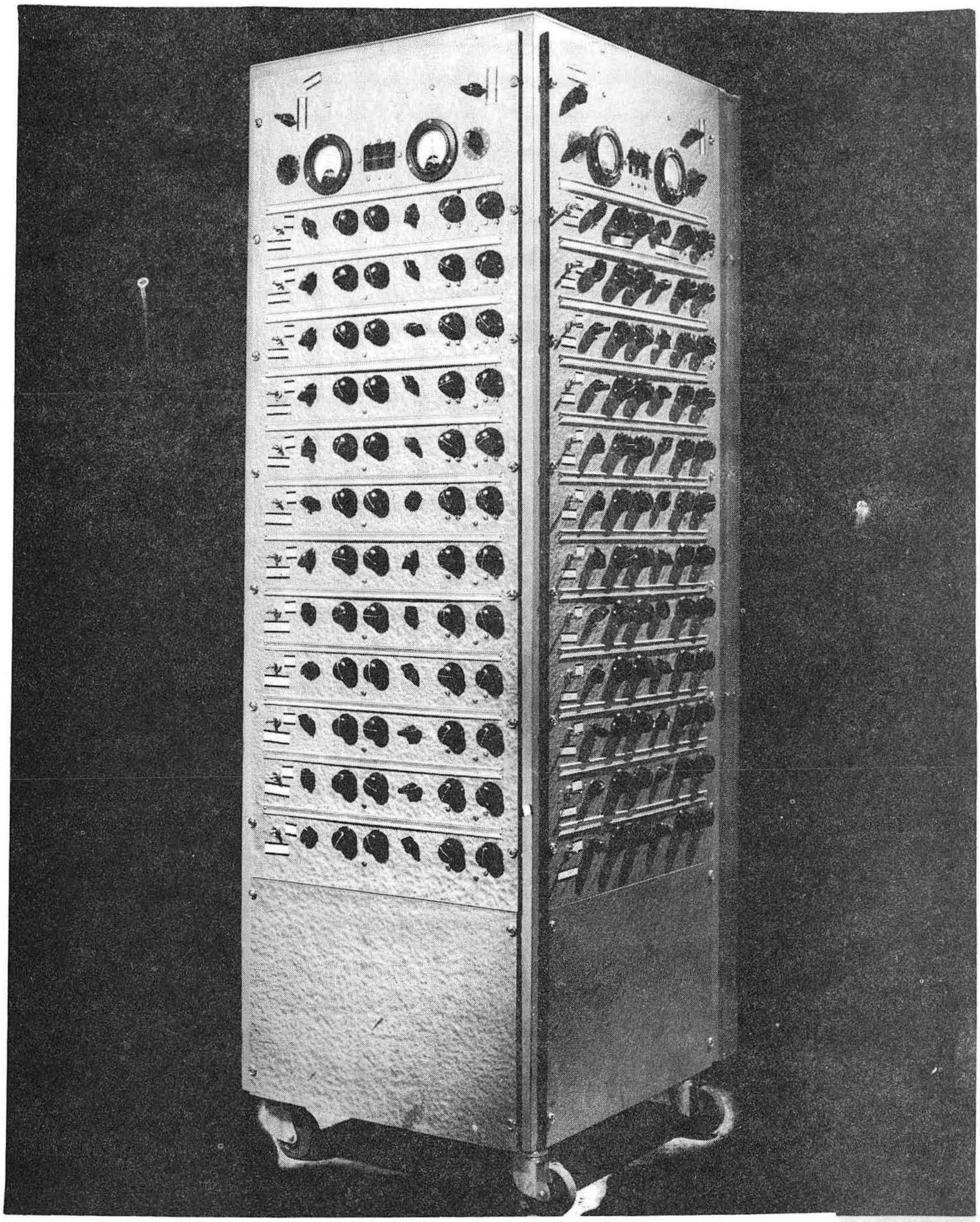
ZN-718

Fig. 6 Assembled Cyclotron



ZN-719

Fig. 7 General Room Layout



ZN-720

Fig. 8 Current Control Box.
Pole Face Winding.

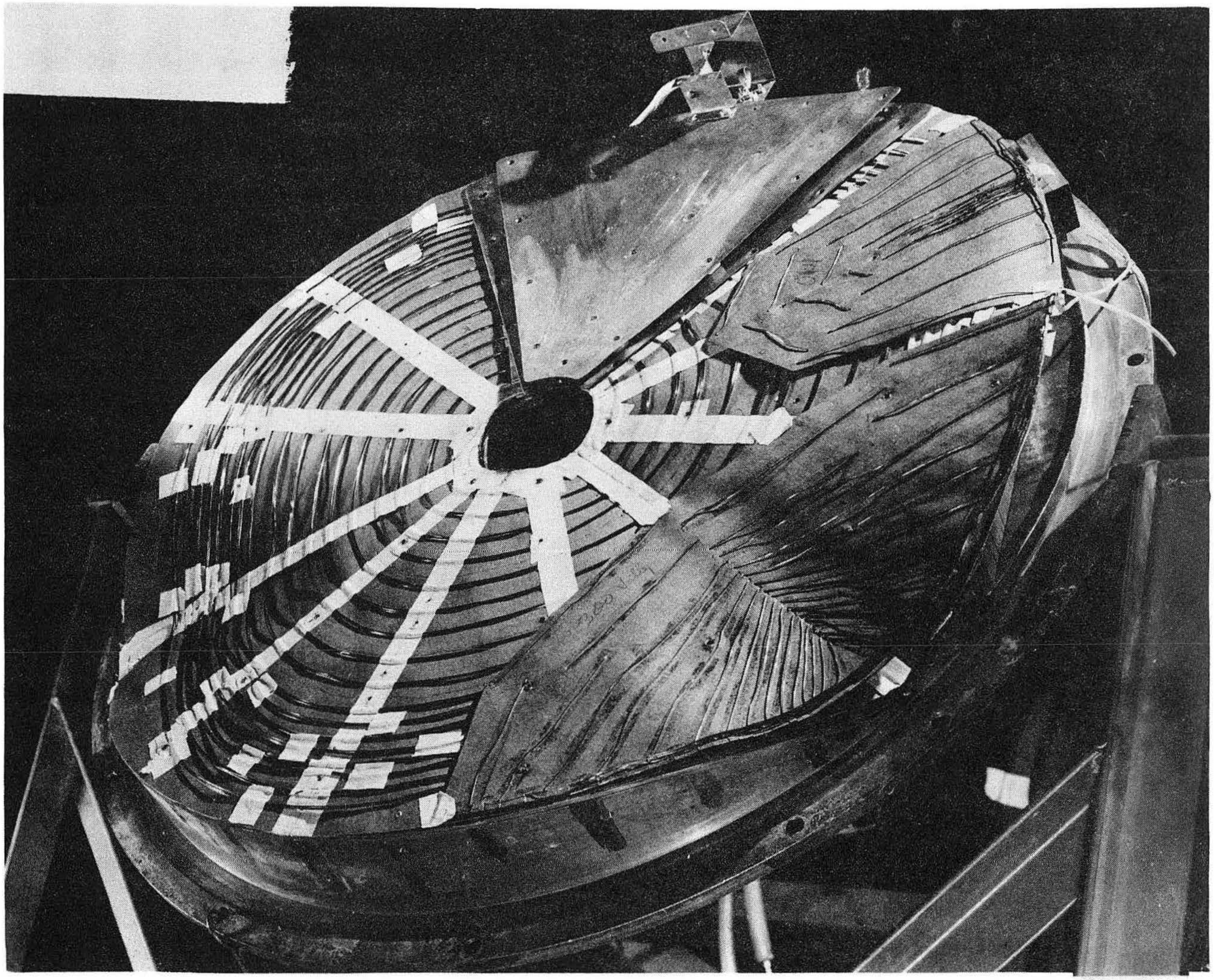
rectifiers. Initially, pairs of circular coils concentric with the axis of the cyclotron were spaced two inches apart from a radius of two inches to fourteen inches. In January, 1951 these coils were removed and new coils installed which were wound to the shape of the calculated orbits, and spaced every inch from two to fifteen inches radius on the "hills". A few months later additional coils of like design were added at 12-1/2 in., 13 1/2 in., 14 1/2 in, and 15 1/2 in.

Coils of a different nature were installed in June, 1951, the so-called "C-term" coils. These were spiral-shaped coils located top and bottom at the larger radii, one centered on each hill and valley center line. Their purpose was to extend the number of terms in the magnetic field expression through the C term, a total current of + 0.5 amperes in each set of hill coils and - 0.5 amperes in each set of valley coils making C=0.5. All coils were taped to fish paper. Figure 9 shows some of the orbital and C-term coils in place.

In addition to the previously mentioned coils, which were necessary for proper acceleration of the electrons, many other sets of pole-face windings were used at various times--for example, to adjust the field near the pole edge so as to aid in beam extraction.

Magnetic Field

The magnetic field was first measured in August, 1950. After one month of operation, the field was shimmed and remeasured. Errors of several percent existed at that time. The final shimming took place in March, 1951. The field was measured with a rotating coil fluxmeter capable of an accuracy of 0.5% for any given measurement. The grid system consisted of points every inch in radius along radial runs every ten degrees of azimuth. No field measurements were made except at the geometrical median plane. The



ZN-713

Fig. Pole face windings, showing the orbit coils, one "hill" C-term coil and one "valley" C-term coil. Half of one of the 60° triants is also shown.

final field was thought to agree with the theoretical field (A and B terms) to one percent. Not much is known about the field produced by the C-term coils, but spot checks (see Appendix III) indicate an accuracy of a few percent.

Unexpected behavior of the beam at certain radii prompted further investigation of the field and it was finally agreed that there was at least one spot in error by about 3 percent. In addition, all field measurements were made with the tank at atmospheric pressure, and it was eventually discovered that vacuum loading on the poles decreased the gap by 0.030 in. at the edge. This vacuum loading probably changed the field distribution by a small amount, even after the current in the main coils was adjusted.

Some of the errors were reduced by passing currents through pole-face windings and by placing iron on the external surfaces of the poles to give the best operation as determined by beam current and visual observation, presumably by canceling out the first harmonic produced by the bump mentioned in the preceding paragraph. The relatively low value ultimately obtained for the threshold voltage together with the good focusing of the circulating beam indicated that a reasonably good operating field was obtained by these trimming methods. The optimum operating field was never measured, however.

Vacuum System

The poles were mounted in and supported by a hexagonal dural structure 6 in. high inside and 40 in. from center to center of opposite faces. To one face was bolted a manifold containing two liquid-nitrogen traps with crude baffling, and connections to the pumps. Plates with windows and/or Wilson seals were bolted to the other five sides. Three-quarters-inch probes could be introduced at the median plane through Wilson seals at each corner of the tank. There were also access ports for three probes through the manifold. During the final external beam experiments an additional structure was bolted over two faces, which allowed beam observations to be made out to 44 inches radius over 120° of azimuth.

The system was roughed by a 43CFM air-cooled Kinney pump, then connected to a DPI MC500 oil diffusion pump backed by a 13CFM Kinney pump. A baffle cooled to -40°C was mounted above the diffusion pump. The operating pressure was 1 to 5 x 10^{-6} mm Hg.

It was essential that as little oil vapor as possible reach the main vacuum tank, as any nonconducting surfaces inside the machine quickly charged up and affected the operation. Before the diffusion pump was refrigerated to -40°C, there was good evidence that considerable oil was reaching the manifold. Even after the baffling appeared to be satisfactory, nonconducting layers were still built up at a slow rate. These may well have come from the considerable amount of organic material in the cyclotron tank.

Accelerating Electrodes and the RF System

Electrode Systems

Initial operation was with a single negatively-biased 180° dee, both with and without a dummy dee to compensate for the tendency of the dee bias to uncenter the beam (Fig. 10). The pole faces and pole-face coils were covered with copper sheet to complete the resonant system.

In April, 1951, "dees" or more properly "triants" consisting of three copper sectors 60° wide were installed, which extended from a radius of 2 inches to the edges of the poles. They were located in the valleys of the pole surfaces so that the vertical aperture available for the beam was determined by the contour of the iron rather than by the accelerating electrodes.

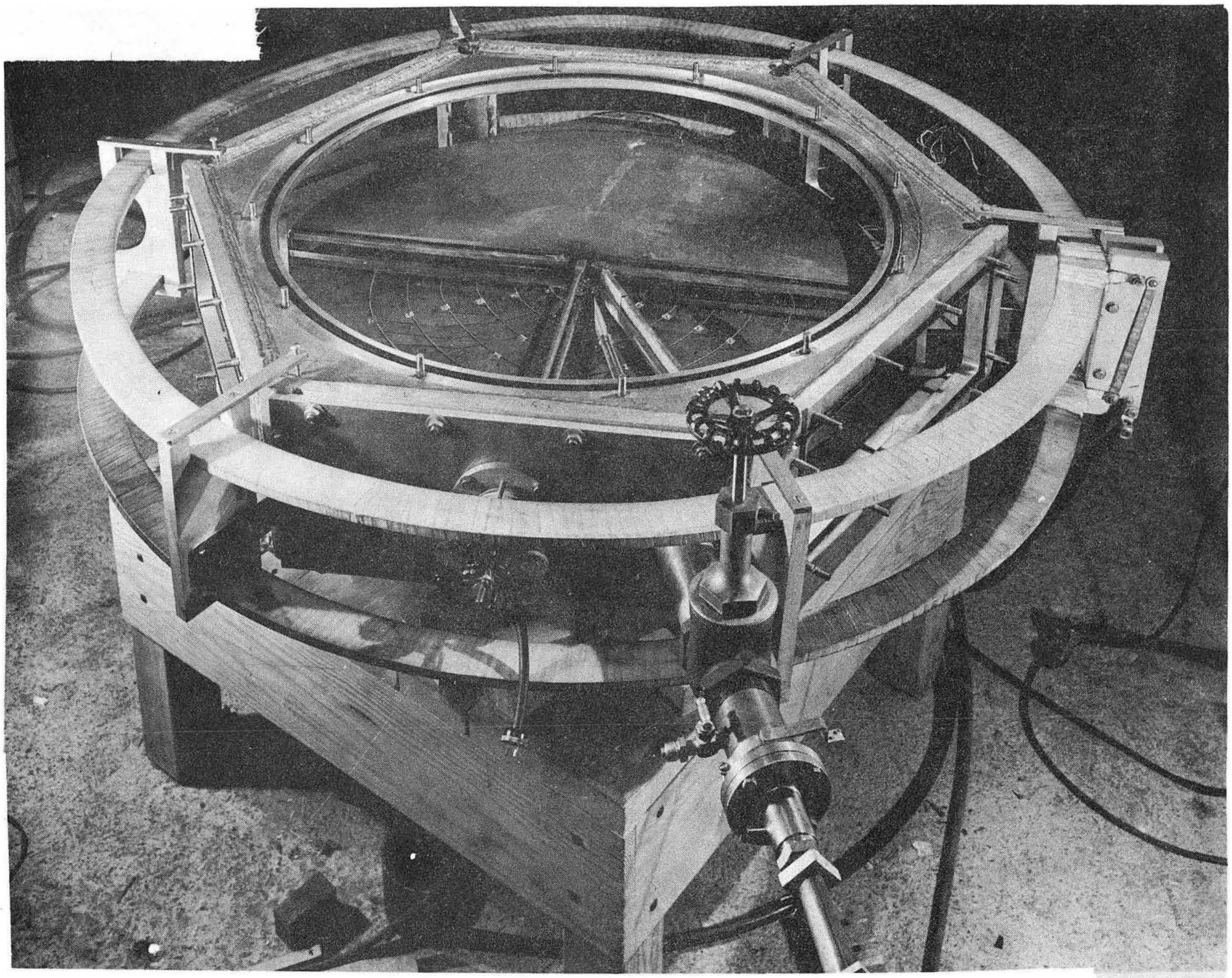
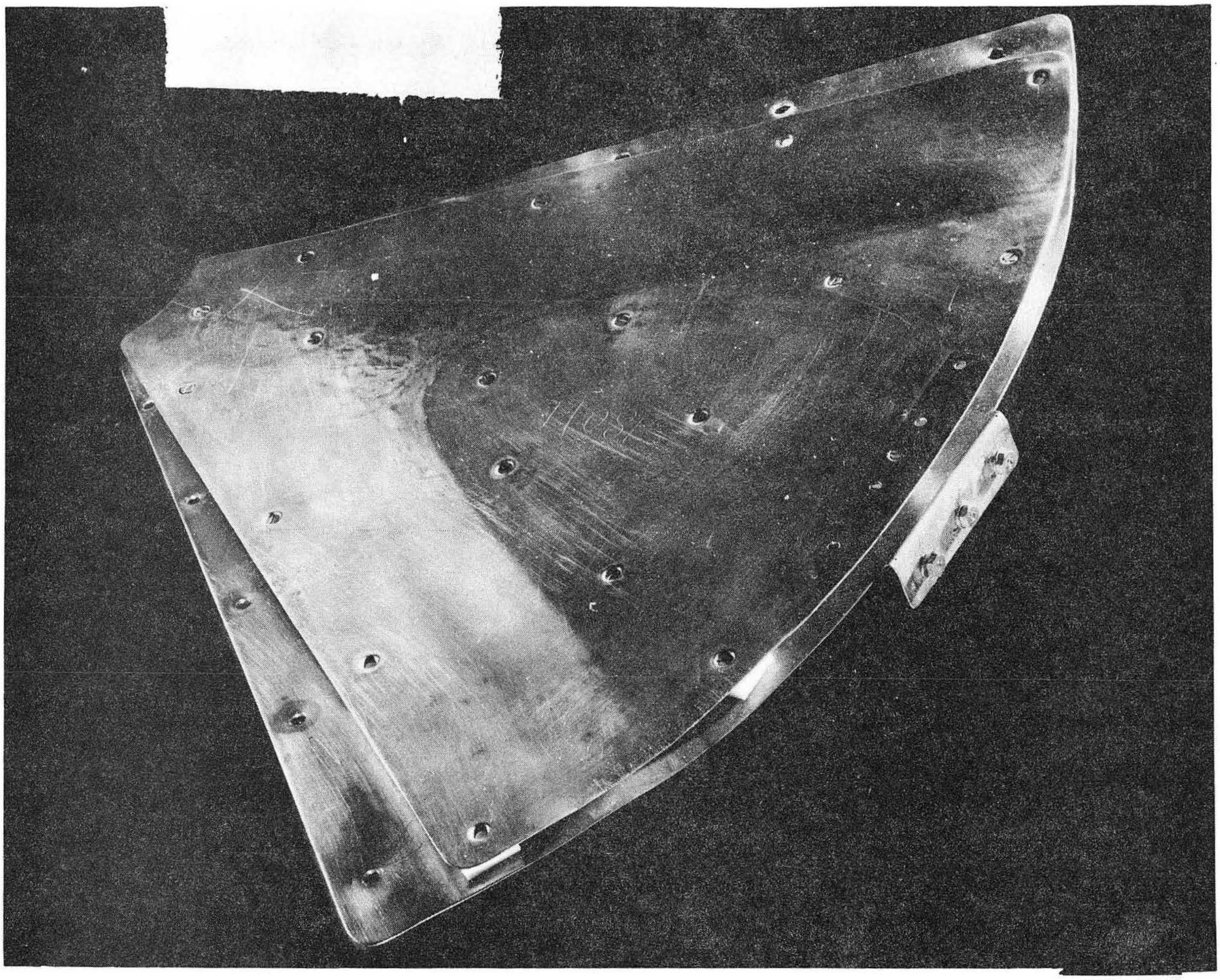
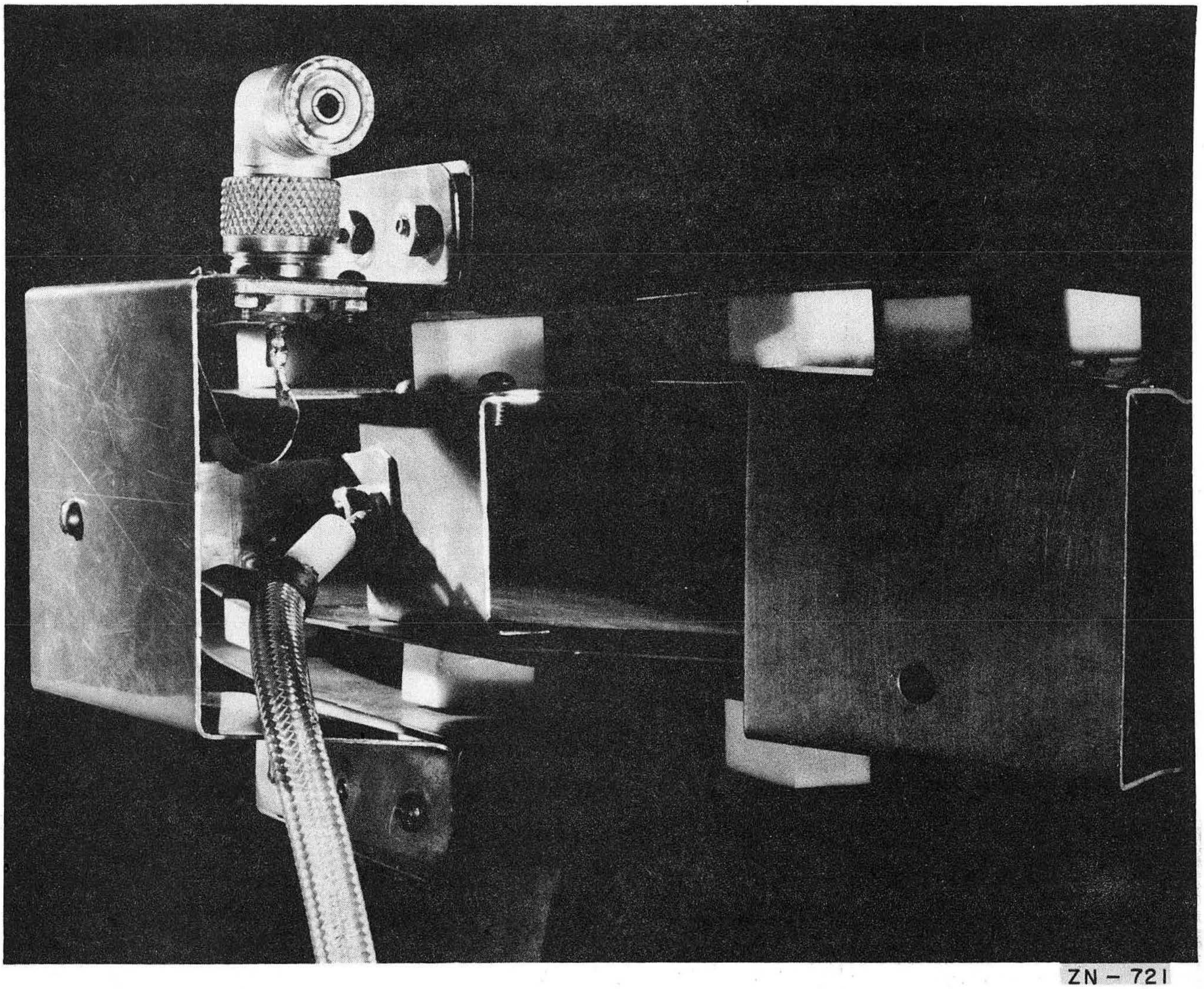


Fig. 10 The 180° dee in place. Note that the source structure was originally introduced through a face plate



ZN-714

Fig. 11 One-half of a 60° triant attached to its ground sheet.



ZN – 721

Fig. 12 Rear view of assembled 60° triant. The upper and lower surfaces are the ground sheets. The triant halves are tied together and connected to ground through a strap of the dimensions necessary to tune the system to 61 mc. Also shown are the drive line and phase pickup loop.

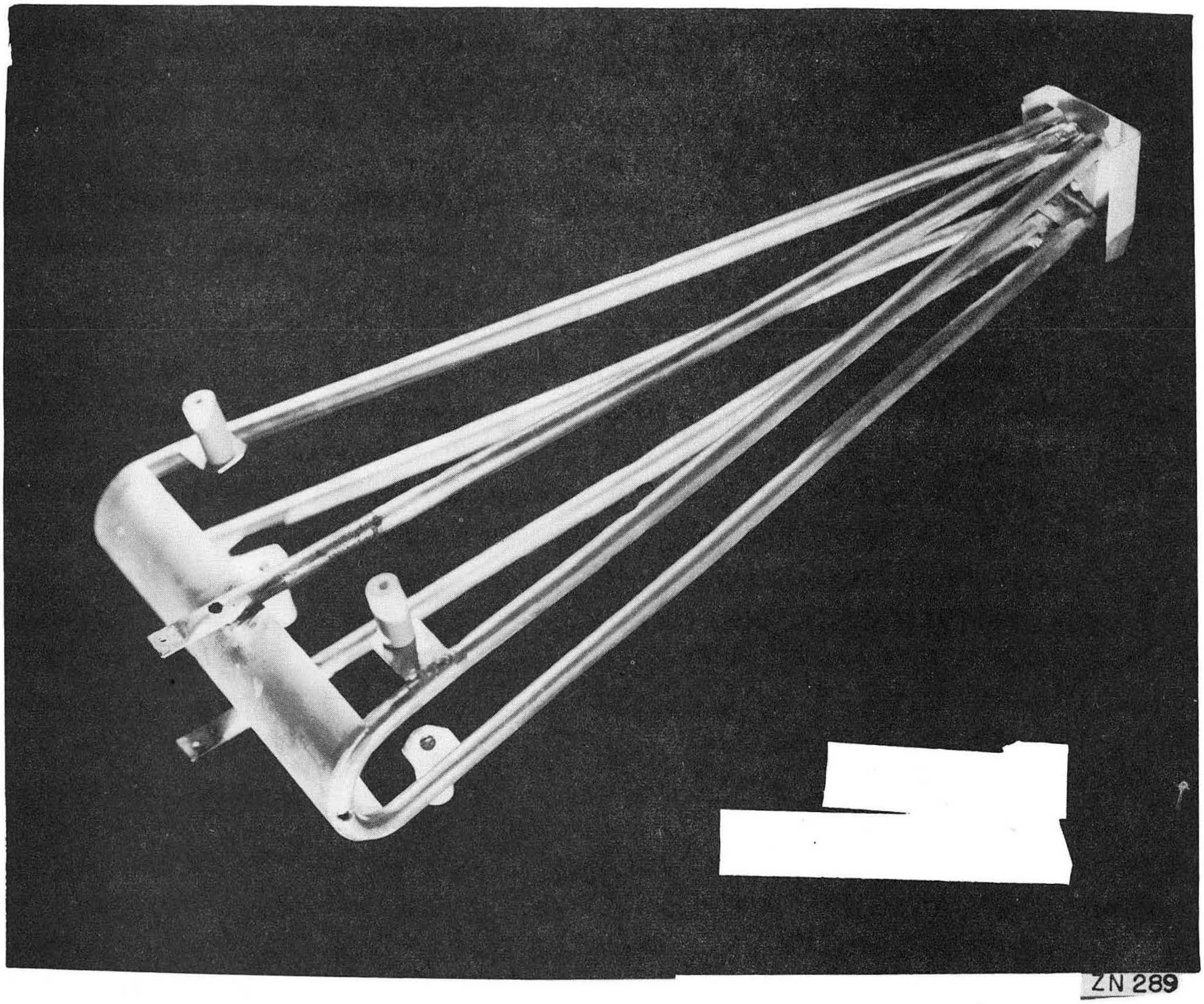
These electrodes were attached to ground sheets by 3/8 in. thick teflon spacers (Figs. 11, 12). Each triant had a capacity to ground of 240 micromicrofarads and a Q of about 400, and was tuned to the design frequency of 61Mc by adjustment of the inductance to ground. They were operated without bias.

This system was determined to have an energy gain per revolution of $3V_0e$, where V_0 is the peak triant voltage, by a simple stepwise calculation. This was verified by model measurements using a stretched rubber sheet, and later an electrolytic tank.

At one point it appeared that it might be mechanically and electrically advantageous to use triants constructed of spaced sets of tubing rather than of copper sheet. Some of the forms tried are shown in Figs. 13, 14, 15. For a given rod diameter, beam aperture, and number of rods, the azimuthal rod spacing for maximum energy gain per turn was determined from electrolytic-tank measurements. The energy gain per turn was $1.3V_0e$ for the electrodes of Fig. 13. The modifications shown in Figs. 14 and 15 were intended for tests of an electrode design that would provide large field-free regions near the center of the machine where space-charge neutralization of the beam could take place if necessary.

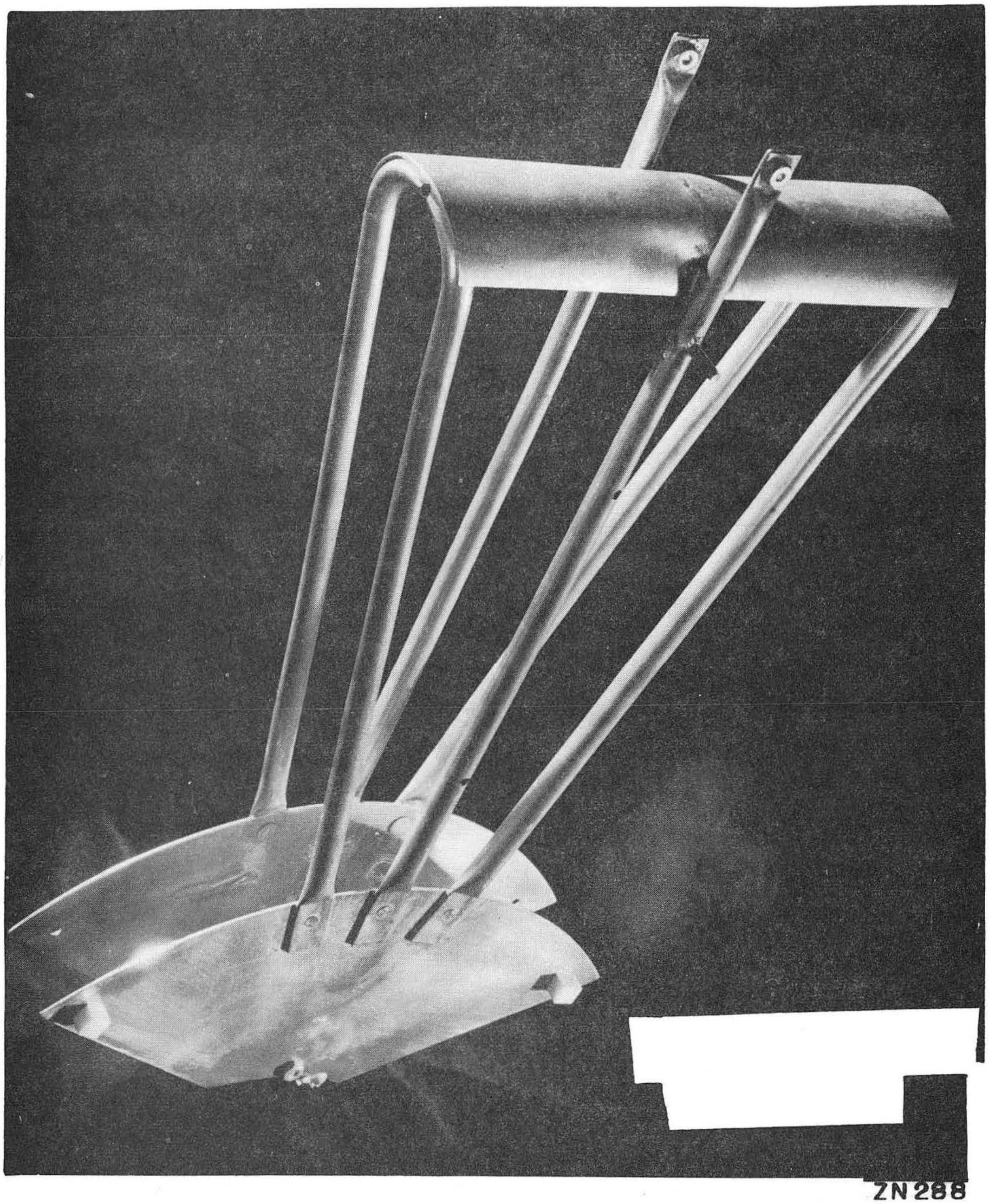
Adjacent triants were separated at the tips by 1/2 in., and there was consequently a considerable amount of capacitive coupling between triants. It caused excessive interaction and had to be neutralized. This was accomplished by tying the triants together at the tips with LC parallel circuits, which were tuned inductively to resonate with the intertriant capacitance.

Another type of system consisted of three 25°-wide triants connected together at the center of the machine and tuned to three times the



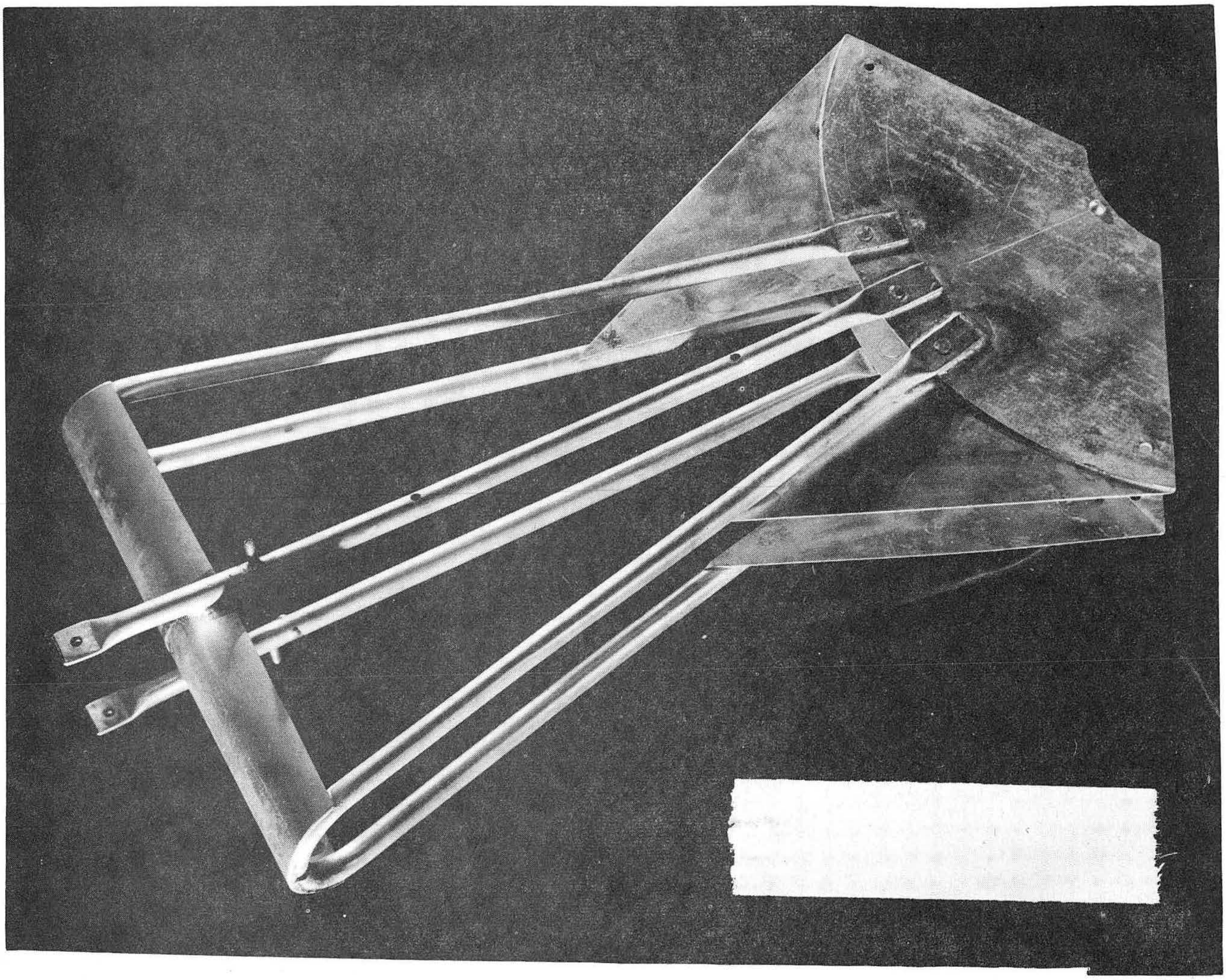
ZN 289

Fig. 13 Triant made of 3/8 in. Cu. tubing. The beam aperture is 1 1/8 in. and the azimuthal extent is 26°. The insulated cap at the small-radius end was grounded and served to reduce the interaction between triants. The calculated energy gain per revolution is 1.3 e V_0.



ZN288

Fig. 14 Rod triant with 100° tips from 2" to 6" radius.



ZN - 716

Fig. 15 Rod triants with modified 100° tips to provide a better transition from tip to rods.

cyclotron frequency, the configuration having a calculated gain per turn of $4\ e\ V_0$. Great difficulty was encountered in making them oscillate in phase with a usable voltage distribution along their length. No attempt was made to accelerate electrons with this arrangement.

Various other configurations were used for miscellaneous tests, e.g. a solid 90° quadrant and rod electrodes operated single phase. These are discussed under "Development and Operation".

Radiofrequency Setup

The 180° dee was driven by a grounded grid oscillator tuned to 61 Mc. The other sets of electrodes were driven by a crystal-controlled circuit. In three-phase operation, the output of the buffer amplifier was fed through terminated lines to three final power amplifiers located just below the cyclotron. The coaxial lines from the buffer to the final amplifiers were cut to lengths such that the output signlas were 120° out of phase. Power was then fed to the triants through half-wave-length coaxial lines. The voltage on each triant was monitored with a vacuum-tube voltmeter connected to the transmission line just outside the vacuum seal. The voltmeters were calibrated with a Hewlett-Packard model 410A VTVM (which had in turn been calibrated against a secondary standard) applied to the electrodes at a number of points around the edges top and bottom. The voltage was about 5 percent higher at small radii than at the maximum radius. Considerable care was required in measuring these voltages. In particular, the shield on the probe head had to be carefully grounded through a low-inductance path at the point of measurement. Under these conditions, the Hewlett-Packard readings were in good agreement with those from a simple peak-reading voltmeter.

To provide an indication of phases between triants, a signal was picked from the plate circuit of each final amplifier and mixed with the output of a local oscillator to produce audiofrequency voltages. These signals were then fed into oscilloscopes and the phase relations could be obtained from the Lissajous patterns. It was found after considerable operation that the best performance was not obtained when the phases appeared to be 120°, and investigation showed that the phase at the amplifier was not always the same as the phase at the triants. When measured, the lines from the amplifiers to the triants were found to be different from one-half wave length, and in fact one of them was off by 60°. This was apparently owing to material collected on the insulating spacers. The phase pickup leads were then removed from the amplifiers and inductively coupled to the triants themselves (Fig. 12).

Servo System

The phase relationships between the triants were not stable enough for satisfactory operation, and a servo system was designed that could maintain the phases to within two degrees. (See Bob Smith, UCRL 1484). Three servo networks were used (Fig. 16). One maintained the grid-to-plate phase difference of one amplifier at 180° for maximum efficiency. The others kept the outputs of the remaining amplifiers at any desired phase differences with respect to the first amplifier. Errors in phase were corrected by motor-driven condensers, which initially were attached so that they retuned the amplifier plate circuits (Fig. 16), but which were later moved to the vacuum tank and retuned the triants themselves through short lines. Most phase drift was found to be caused by some detuning inside the cyclotron, provided the amplifiers had come to constant temperature. In most cases this was due to a movement of one of the probes. Phase differences also could be

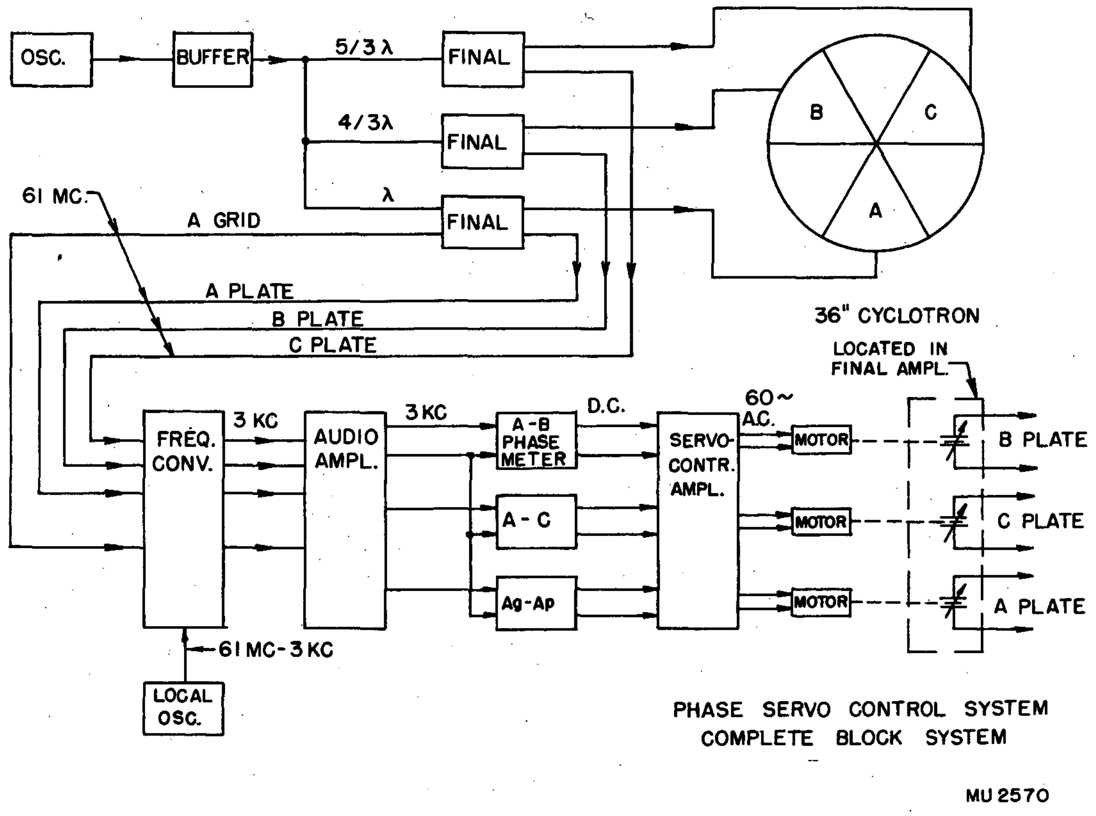


Fig. 16 Block Diagram of Servo System

read directly from meters in the servo circuits.

Probes

The most satisfactory probe handles were made of 3/4 in. o.d. ground and polished nonmagnetic stainless steel tubing. For visual observation of the beam, the probe head was simply a plate painted with a fluorescent material suspended in acetone with a few drops of Duco cement as a binder. This material is a poor conductor and, if a thick layer were applied, the probe head would charge and the beam would be deflected. There was no indication of any disturbance, however, even at very low energies, when thin layers were used.

Reliable current measurements were a serious problem, and no really satisfactory solution was found. Bare probes fashioned of a piece of copper sheet attached to a Kovar seal in the end of the probe gave spurious readings owing to rf pickup and rectification and, more especially, to large numbers of low-energy electrons (about 1 Kev), which were especially numerous at small radii and in the fringing field at the edge of the pole.

A probe enclosed in a wire grid at negative potential reduced the spurious currents but disturbed the circulating orbits. The solution seemed to be to cover the current electrodes with a conducting material thick enough to absorb the low-energy electrons. Aluminum foil or leaf was used as the absorber, insulated from the current electrode by either vacuum or 1.1 mg/cm^2 condenser paper. Because of pinholes, the smallest usable amount of shielding consisted of two layers of Aluminum leaf with a total thickness of 0.3 mg/cm^2. The smallest leaf thickness that gave results reproducible from one probe to another was 0.6 mg/cm^2, with a cutoff energy of about 17 Kev. In the cyclotron, the measured beam current through this thickness increased more or less linearly with radius above an energy of about 17 Kev until it flattened off at a radius corresponding to 35 Kev. Similarly, the current through a 1/2-mil Al foil

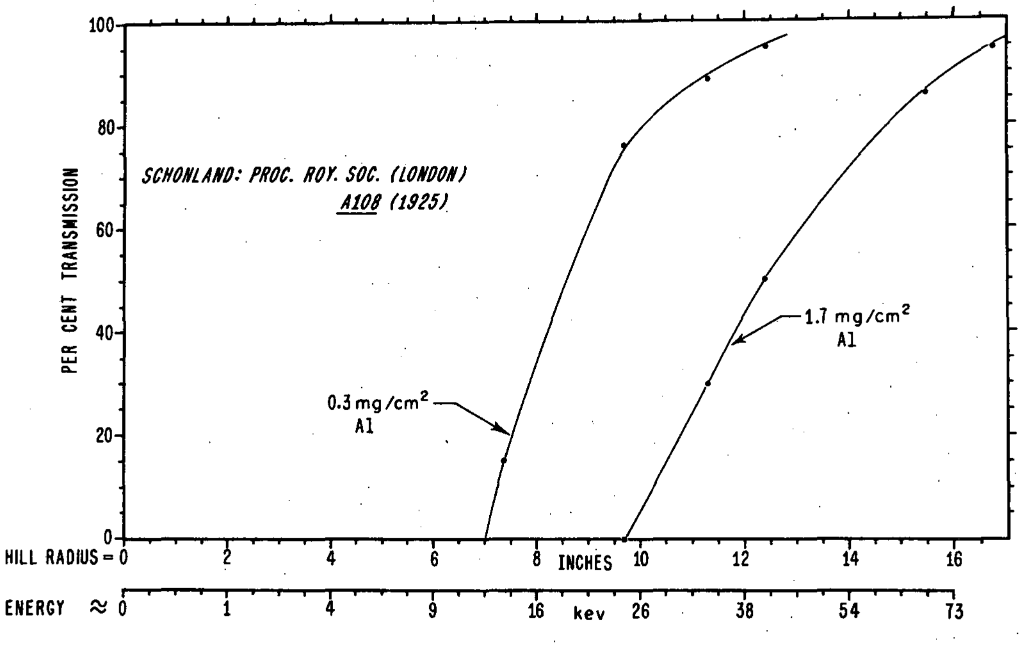
(3.5 mg/cm^2) increased from the calculated cutoff at 45 kev without reaching a plateau. The most commonly used shielding was 1/4-mil Al foil, which was reasonably sturdy and was thought to transmit a constant fraction of the electrons with more than 45 kev.

Current-vs-radius measurements did not show the expected form. When electrons were lost axially (as determined from visual measurements) the probe current was a maximum at intermediate radii, but with a well focused beam the measured current continued to increase with radius, except near the threshold voltage.

An auxiliary experiment was set up to calibrate the probes as a function of electron energy, but unfortunately no reliable data were obtained. Experimental evidence has recently been found that shows the transition from 0 to 100% transmission takes place much more slowly than we had supposed (Fig. 17).

Within the limitations set by foil transmission, there were two main sources of error in the measurement of the circulating beam. First, an unknown number of secondary electrons was produced when the beam struck the probe, many of which could have been lost. Second, there was a region several mils wide at the tip of each probe where electrons could be stopped without reaching the collecting electrode. This was a serious limitation in that it was found that beam with large radial oscillations gave larger readings than a well tuned beam. Galvanometer readings might increase as much as 50 percent as the probe was pulled from a circulating beam of small radial extent into the rather diffuse spill beam. Different probe heads of the same construction gave readings which agreed to within about 10 percent in the circulating beam and perhaps two percent in the external beam.

Currents were measured with L and N galvanometers with sensitivities of 0.0004 microamperes/mm deflection.



MU-6540

Figure 17

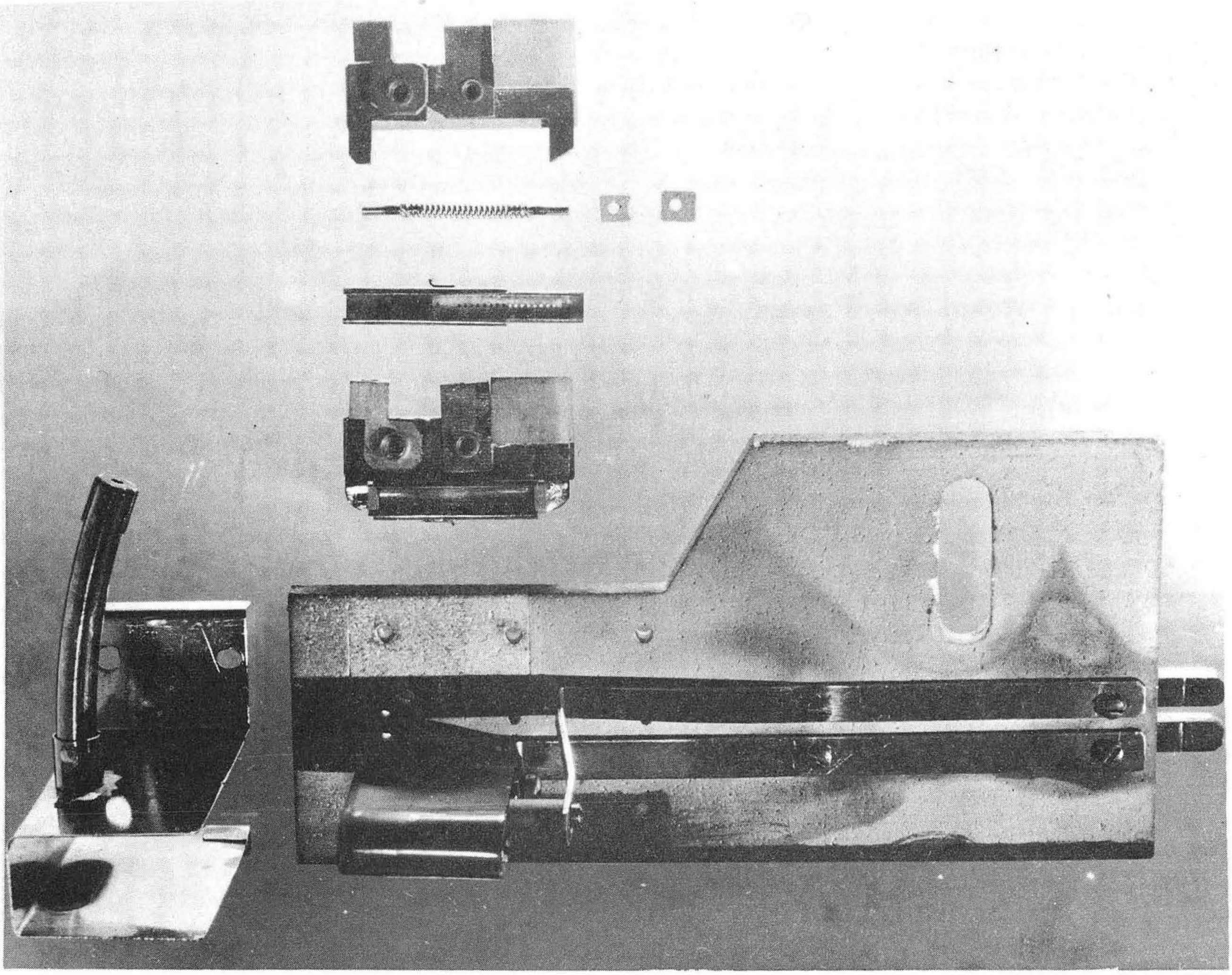
Sources

Many forms of electron sources were tried. At or near the center of the cyclotron bare tungsten filaments were satisfactory, provided they were so formed that the heater current would not produce objectionable magnetic fields. Most experiments were run with electrons injected two or three inches from the center, with an energy appropriate to the radius. A number of injection-type sources were constructed, in some of which the accelerating potential was applied between a filament and grounded field-shaping electrodes. Another form started electrons near the center of the cyclotron with a few hundred volts energy. After they were focused at the 180° point they were accelerated to final energy. This source had some structural advantages, but proved too difficult to keep in adjustment while the magnetic field of the cyclotron was being tuned.

The only reliable source developed is shown in Figs. 18 and 19. A W heater was packed in barium aluminate in a Ta capsule. The capsule was surrounded by a grounded shield and electrons were drawn through holes in the negatively biased capsule and emerged through a hole in the shield. A snout was used to collimate the beam.

The whole structure was mounted on a ceramic plate, which could slide on runners attached to the under side of the plug through the center of the top pole (Fig. 20).

These sources were operated up to 100 hours, with emission currents of about one ma. The current emerging from the collimator was not measured. The chief drawback was the impaired radial clearance for the first turn. It was necessary that the orbit increase in radius by at least 100 mils to clear, and at voltages near threshold, only a small current was accelerated.



ZN - 722

Fig. 18 Injection-type source with shield removed.
Also shown are the components of the emitting capsule

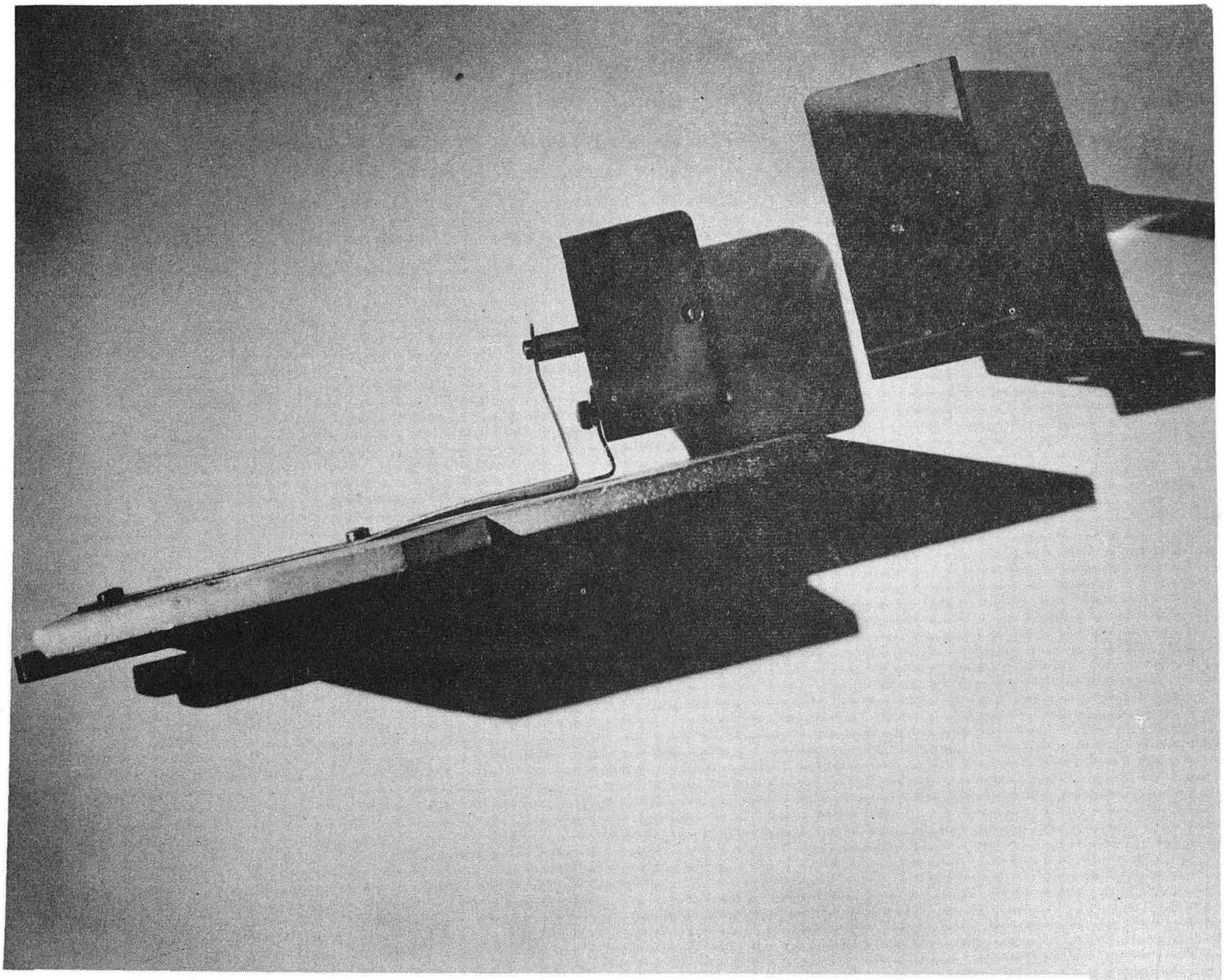
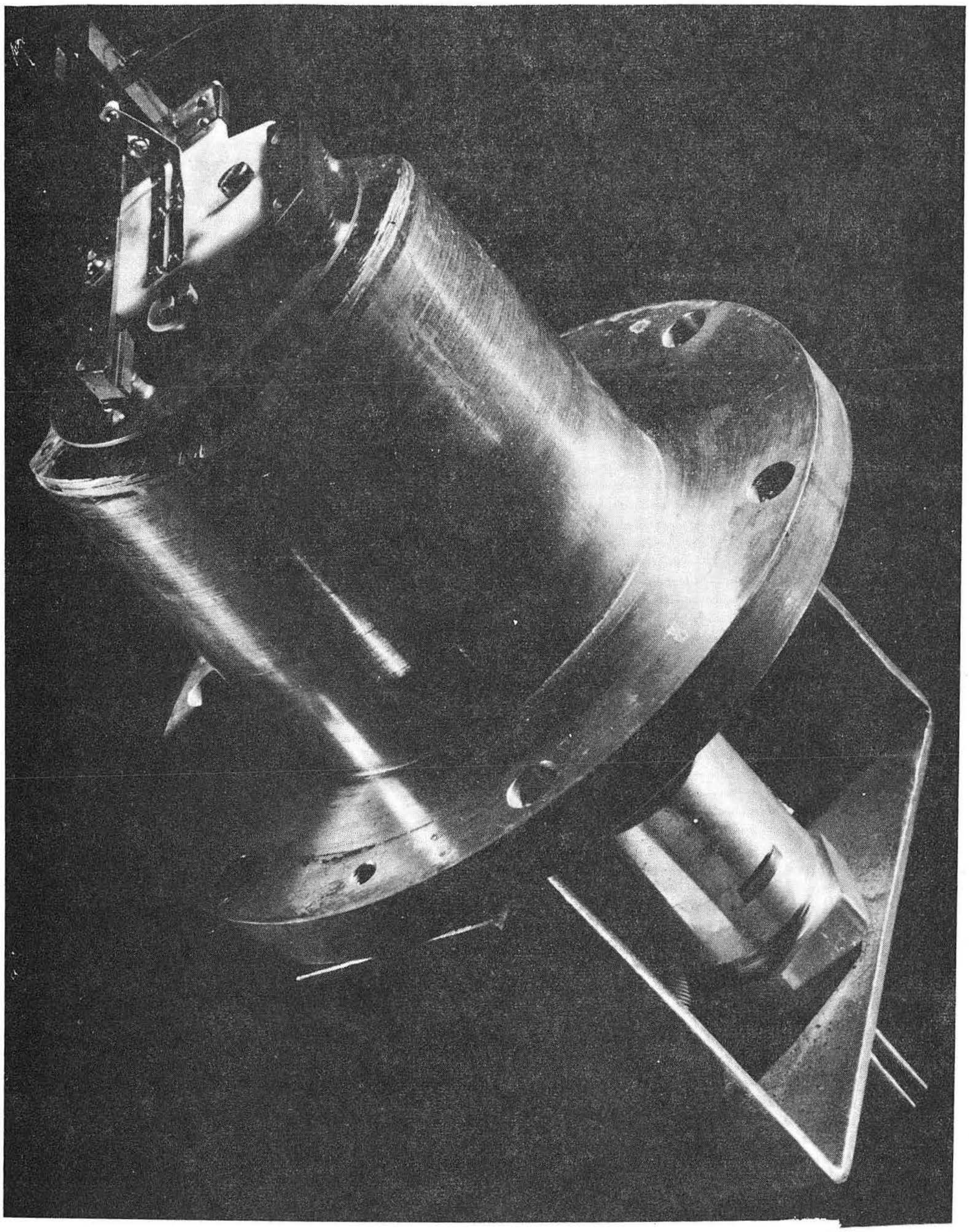


Fig. 19 Injection-type source with shield removed



ZN-715

Fig. 20 Source and source plug

Development and Operation

This section is broken down according to topics, rather than being presented as a chronological log, but a few remarks will be made for the purpose of orientation. The first beam was obtained Sept. 16, 1950. From this date until late in June, 1951 the accelerating system consisted of a single 180° dee. During this period several improvements were made in the magnetic field but only the A and B terms in the field expansion were included. The final shimming of the magnet with iron was finished April 19, 1951.

In June, 1951, the C-term coils were added and the three-phase electrode system was put into operation, using 60° triants. The main features of the cyclotron then remained pretty much unchanged for the remaining operation, except for a period during which a number of different types of accelerating electrodes were tried.

In May, 1952, a magnetic channel was cut in the poles, and the remaining operation was devoted to an examination of beam extraction by means of the magnetic channel.

The apparatus was dismantled and the poles destroyed on August 15, 1952, some of the equipment being needed for the next model.

See Appendix II for the energy-vs.-radius relationship.

The Central Region

No attempt was made to model the conditions that would exist in a full-scale deuteron cyclotron. The behavior of the initial orbits in existing heavy-particle machines is fairly well understood, and both deuterons and protons were successfully started in an auxiliary experiment in a three-phase cyclotron 20 inches in diameter with three 60° triants. (See UCRL 1889). However, electrons could be started fairly successfully with sources at the center, and in fact all of the 180° dee operation was of this type. A bare W wire central source was also used initially in the three-phase setup. An analysis of starting conditions with the triants extending inward to a radius of 2 in. was made by John Jungerman (unpublished). Somewhat better three-phase operation was obtained by adding tips to the triants so that they extended inward to a radius of 1/2 in. For the most part, however, the electrons were injected with energies of around 2 kev to avoid the problems peculiar to operation with low-energy electrons, in particular the effects of stray magnetic fields from the source structure, and electric fields from charges built up on the poorly conducting layers that were gradually deposited throughout the cyclotron.

The Region of Acceleration

Threshold Voltage

In principle, the threshold voltage can be very small because axial focusing is not obtained at the expense of the resonance condition, as it is in conventional cyclotrons. In practice, of course, the inaccuracies in the field shimming set some lower limit to the voltage at which beam can be accelerated to full energy; in addition the theoretical development of the field is in the form of a terminated infinite series, so that the exact field shape desired is not known for large values of v/c. There seems to be no easy way to predict what the threshold voltage will be from the magnetic field measurements, but one might hope that if the (positive and negative) field errors were random and, say, of one percent magnitude, as was roughly true in this cyclotron, the error in transit time per revolution would be smaller by a factor of perhaps ten. The performance of the machine indicated that something like this is true: If it is assumed that all the phase errors were in the same direction, then only 0.1 percent error per revolution would be required to make the phase between the electrons and the rf change by 90° during the acceleration to full energy at the experimental threshold voltage.

When the trimming coils were energized, the operating field was considerably improved. These coils had a twofold effect: First, they permitted adjustment of the magnetic median plane so that electrons were not lost to the pole surfaces, and second, they adjusted the average fields over groups of orbits so that the electrons remained in phase with the rf.

The magnetic field errors were of course not actually random as far as the orbits were concerned. The patches where the field was too high or too low had a minimum diameter roughly equal to the magnet gap. Therefore a number of revolutions could be made through approximately the same field errors, giving a cumulative effect.

The threshold voltage was arbitrarily defined as the minimum voltage required to give 5×10^{-9} amperes of beam outside the cyclotron. The outermost stable orbit was at a radius of about 15-3/4 in. This amount of current gave a deflection of about one centimeter on the most sensitive scale of the galvanometers. The beam would completely disappear from a fluroescent probe at a voltage about one percent lower than that for the above condition.

With this definition of threshold voltage it might be expected that the value of the threshold obtained would vary considerably with the filament emission. In all the sources tried, the maximum accelerated beam was obtained with two or three milliamperes total emission from the filament. The actual current injected into the cyclotron was much smaller. When the emission was run higher the output current would drop sharply, presumably because of some plasma defocusing effect in the source structure. All threshold measurements were made with the source emission optimized for maximum accelerated current.

The early threshold results are not of much importance except to show the sort of progress made as the field was improved. Before the final shimming of the pole faces, 520 peak volts were required to give 5×10^{-9} amperes at 14 in. radius, with a single 180° dee. After the shimming this current was obtained at 14 in. with 160 V on the same dee. It must be emphasized that in this cyclotron the operating conditions were adversely affected by any insulating layers on the surfaces of the dee or ground sheet. For example, after a few weeks of operation, the threshold voltage might be halved by thoroughly cleaning all surfaces. This behavior was not fully appreciated in the early operation.

A threshold voltage of 126 V was obtained for the full radius of 16-1/2 in. with the magnetic field as finally shimmed, but with the 60° triant, three-phase accelerating system. This corresponds to 190 V for the single 180° dee. With the addition of the C-term correction to the magnetic field, it was eventually possible to obtain 5×10^{-9} amps at 16-1/2 in. radius on one hill, with 59 volts peak voltage on the 60° triants. This is equivalent to 90 V on a single 180° dee in the electron model, and to about 225 kilovolts for a 60° triant deuteron cyclotron. This beam was not well centered at large radii, however. The currents in the C-term coils were adjusted so as to give the best beam on one particular hill probe, and a property of these coils was that the outer orbits could easily be displaced toward one hill. For the 59-V threshold quoted above, the circulating beam was at 14 in., 15 in., and 16 in. on the three hills; the maximum energy of the electrons was roughly that of a properly centered orbit at 15 in. radius. The operating conditions are given in Appendix IV.

When the rf voltage was reduced below threshold, the maximum radius at which the beam circulated was correspondingly reduced. No measurements of threshold voltage vs. radius were made with the cyclotron tuned for the 59-V spill beam threshold, because the initial orbits did not clear the source structure at voltages below 55 V. At this voltage the maximum beam radius was 14 in. A number of threshold voltage-vs.-radius measurements were taken before the final adjustment of the magnetic field, but have no significance for the field as finally shimmed.

Threshold measurements were also made with triants 26° across (Fig. 13). The energy gain per revolution was calculated to be 1.3 V_o from the electrolytic tank data. For coil settings which produced an off-centered beam the same as obtained with the 60° triants, the threshold for a spill beam was 132 V. Converting this to the 60° electrodes one gets 132 x 1.3/3 = 57 V, which is in good agreement. Using this set of electrodes, the threshold for spill beam with a well centered circulating beam was measured as 140 V peak. This corresponds to 61 V with the 60° triants.

A single solid 90° quadrant was used to accelerate the beam in an experiment to examine the radial restoring forces. This system had a calculated energy gain per turn of $\sqrt{2}\,V_o e$ and a measured threshold of 400 V peak for spill beam.

All the above measurements were made with 61 Mc rf and with the phases optimized with equal voltages on the triants. The phases were about 120° for minimum threshold, as expected, and just above threshold the tolerances on the phase angles were small. More exactly, the allowable variation in phase angle was small provided nothing else were varied, but even near threshold the character of the beam was changed only slightly if the phases were as much as ten degrees from 120° provided the triant voltages were readjusted.

It is easily shown that for 60° triants the energy gain per turn is $3eV_0$ when the phase differences are all 120°, and is reduced only 0.13% by changing the phase of one of the triants by 5 degrees. This loss in energy gain per turn can easily be compensated for by increasing the triant voltage, but a net force tending to drive the orbits off center will result. An increase in the amplitude of the radial oscillations was seen when the unbalance was large.

An example of the variation in output current which occurs when the phase difference between triants is changed from 120° by adjusting a single amplifier is given in the data of Table I. For a given triant voltage (V_T is the threshold voltage) and phase shift, the full-energy current decreased by the amount shown in the bottom row. The triant voltage was kept constant while the phases were being varied.

Triant Voltage	V_T	120% V_T	160% V_T	200% V_T
Phase Change	0.5°	1°	5°	6°
Decrease in Current	50%	7%	10%	$< 1\%$

Table I

The allowable phase of the particles with respect to the rf for acceleration lies in the range ± 90°, and it has been mentioned that in the ideal magnetic field the phase would not change with radius. Two attempts to measure the phase relationships as a function of radius were made by L. Wouters. In one experiment the photomultiplier was gated with rf whose phase could be adjusted with respect to the accelerating voltage on the triants. The phase signal from the beam was obtained by producing x-rays in a foil mounted on the end of a probe. In another case the source was pulsed with a signal whose phase relative to the accelerating voltage could be adjusted. In neither case was there any indication that the phase could be determined to closer than 45°; within these limits the phase did not change between the 12 in. radius and 15 in., and beyond 15 in. the electrons rapidly fell behind in phase. The adjustment of the cyclotron at this time was not optimum, but the crudity of the technique did not warrant more careful work.

With high triant voltages the radii of individual turns of the orbits could be measured, out to a radius of 9 in. The results were consistent with electrons in phase with the accelerating voltage.

It has been suggested that it should be relatively easy to measure the average phase between the beam and the rf by measuring the length of time for the electrons to be accelerated to full energy. This experiment was not carried out.

Axial Focusing

A basic requirement of a high-current, high-energy accelerator is that little or no beam be lost during the acceleration process, for in addition to the reduction of useful beam there would be severe radiation and cooling problems. As a consequence a large amount of time was devoted to the investigation of the axial focusing, and in particular to a search for a set of conditions in the cyclotron for which no beam would be lost to the pole faces.

With either an on-center or injection-type source, the beam filled the available gap after a few turns. Measurements of beam current vs. radius were not satisfactory, so that most of the information obtained came from visual observation. At radii greater than three or four inches, one hoped that the axial amplitude would decrease until it amounted to a small fraction of the available aperture, and that this axially restricted beam would not touch the pole surfaces at any point. As an aid to the tune up of the cyclotron, the vertical aperture was restricted somewhat by 1/8 in. high strips of metal attached to the upper and lower poles on the centers of the hills, i.e., at the positions of minimum gap. These extended radially from 2 in. to 16-1/2 in. and closed the gap to 1-1/4 in. at 3-inch radius and 3/4 in. at 16-inch radius. When these were coated with fluorescent paint it was possible to tell at what radii beam was lost axially. Fluorescent probes could be introduced to examine the beam distribution inside the gap.

In the early operation the beam filled the hill gap at all radii. After the final shimming (but before the addition of the C-term correction to the magnetic field) it was possible to adjust the auxiliary coils so that little beam was lost at radii less than 13 inches. At 13 inches the axial amplitude increased rapidly and most of the electrons were lost.

With the addition of the C term to the magnetic field it was possible to obtain a tuneup in which no current was lost to the gap-defining clippers between 3 inches and 13 inches, and very little at larger radii. However, the vertical extent was nearly equal to the gap at all radii.

A more informative technique was to limit the initial vertical height of the beam. This was done with adjustable strips of metal, extending from radii of 3 inches to 5 inches above and below the median plane. With a gap between these clippers of, say, 1/16 in., the individual turns beyond 5 inches could be seen as spots on a fluorescent probe, initially 1/16 in. x 1/16 in.

For a given triant voltage the trimming coils could be adjusted so that the spots did not grow in either dimension from 3 inches to 16 inches radii. This was true for all voltages from threshold to 500 V, although as would be expected the trimming coils had to be readjusted when the accelerating voltage was changed. Under these conditions the turns did not touch the poles and no beam was lost axially. (See Appendix IV for operating conditions.)

It was expected that the vertical extent of the beam would be greater in the valleys than on the hills, and so it was. At all radii, however, the heights in the valleys were more than 50 percent greater than on the hills.

Photographs of the orbits were taken on the hills and in the valleys by leaving the camera shutter open while fluorescent probes were pushed into the orbits. Examples are shown in Figs. 21 and 22. The center line of spots is the beam hitting the probe, the others are reflections from the top and bottom ground sheets. The radii included are 5 inches to 16 inches on the hill and 5 inches to 14-1/2 inches in the valley. Although photography under these conditions does not show up the first few turns, the bunched appearance of the beam at large radii is clearly visible. These photographs were taken with a peak voltage of 300 V on the 60° triants.

The frequency of the axial oscillation was measurable only at radii less than 8 inches. The successive turns in this region were observed to wander above and below the geometrical median plane. As the amplitude of the axial oscillations was small when the beam was started in the geometrical median plane and large when the beam was started off the median plane, it was clear that the observed phenomenon was actually a particle oscillation rather than a wandering of the median plane. Moreover the number of turns

Fig. 21 Hill beam, 3 in. to 16 in. The arrow indicates the first orbit.

Fig. 22 Valley beam, 3 in. to 14 1/2 in. The arrow indicates the first orbit.

involved in a complete oscillation was independent of the accelerating voltage, showing that the restoring force was magnetic rather than electrostatic at radii greater than 4 inches. The results at 5 inches were consistent with the theoretical frequency of 0.1 times the cyclotron frequency. As mentioned in Appendix I, one would expect the amplitude of the axial oscillation to be proportional to $(\nu_a)^{-\frac{1}{2}}$. The theoretical variation of ν_a with radius is given in Fig. 29. The height of the beam envelope should decrease with increasing radius except for the last inch or so. Under the best tuneups, a small decrease was found ~~out to a radius~~ of about 10 inches, beyond which the height did not change much.

An attempt was made to increase the electrostatic focusing at small radii with negatively charged rods, above and below the median plane, running radially out on the tops of the hills. No meaningful results were obtained.

The above investigations were made with the solid 60° triants. With the rod triants having solid tips out to 6 inches (Fig. 14) there was some indication of electrostatic defocusing at the transition radius of 6 inches for electrons more tha 1/8 in. from the median plane. This was not observed with the triants of Fig. 15.

As the theoretical analysis progressed it became clear that the axial restoring force would drop to zero at about 13 inches if only the A and B terms of the field expansion were included. For the C-term coils which were wound, it was predicted that currents of 0.5 and -0.5 amps or more in the hill and valley coils respectively would be satisfactory. With 0.25 and -0.25 in the hill and valley coils there was no evidence of an increase in beam height from 3 inches to 16 inches. The same was true for 0.75 and -0.75 amps in these coils; in fact the beam did not appear much different. With 0.5 and -0.5 amps the beam blew up vertically at about 14 inches radius, and in spite of several tries this blowup was not overcome. The reason for this is unknown, but it seems unlikely that there is anything wrong with this value of the C term as such.

The appearance of the beam was identical for the rod triants and the solid triants.

When the 60° triants were installed, considerable care was taken to position them accurately. It was later shown that the requirements on the geometry were not very stringent. To investigate this point, the lower half of one of the triants was extended azimuthally 1/2 in. The appearance and position of the orbits were found to be unchanged.

Radial Focusing

It has been mentioned that when the beam was collimated at small radii, the first few turns were distinct. The spacing between turns in all cases agreed with that calculated for the maximum energy gain per turn. When these distinct turns were first observed, it was found that the separation became smaller on one of the hills and increased on the other hills, starting at a radius of about 5 inches. An examination of the field measurements showed there was a magnetic bump, possibly as large as 3 percent, on the hill of smallest separation, and orbit plotting showed this could produce the observed effect. Rather than reshim the poles, the first harmonic was reduced by increasing the field at the same radius, but at an azimuth 180° away. An iron bar 2 in. x 2 in. x 12 in. placed on end on the top pole seemed to produce the desired result, and the orbits remained centered as they increased through this radius. At 9 in. or thereabouts, depending on the triant voltage, the change in radius per revolution was small enough that the radial oscillations caused the turns to overlap, and only the vertical and radial extent of the beam could be examined at the larger radii. Beyond 9 in., that is, at radii at which there was no possibility of seeing separate turns, it was found that spots of beam were still observed on the fluorescent probes. The orbits were well centered and therefore of the proper energies, so that these spots must be interpreted as beam bunching because of irregularities in the magnetic field.

The frequency of radial oscillation could not be measured and consequently the radial restoring force is unknown. In the initial operation, the beam lapped back on the probe up to 3/4 in., but as the magnetic field was improved it became possible with a careful tuneup to obtain a beam with a maximum radial extent of 1/16 in. on the fluorescent probes, indicating a small amplitude of radial oscillation.

Several electrode configurations were tried that gave strong off-centering forces to the orbits, and in such cases one would expect to see the radial amplitude of the beam considerably increased. For example, with the single 90° electrode, apparently normal orbits were found out to about 9 inches radius. Beyond 9 inches the radial extent of the beam on a fluorescent probe grew from 1/4 inch to 3/4 inch. Under these conditions the orbits were centered at large radii by adjusting the currents in the hill and valley coils. No attempt was made to preserve the axial focusing at large radii with this arrangement.

Beam Energy Determinations

The maximum energy of the external beam was measured in the first months of operation by the production and absorption of x-rays, and, was found to correspond to that predicted for electrons whose outermost stable orbit was at about 16 inches. Later, the circulating current was measured as a function of radius for different thicknesses of shielding, and when the results did not seem consistent with those expected from the predicted transmission of electrons through Al as a function of energy, there was some concern that the current measured might have a large energy spread.

One device proposed to measure the energy at any radius consisted of a small electrostatic spectrometer mounted on a probe. Peaks could be obtained but the resolution was very poor. No further work was done along this line.

Later the circulating and spill beam currents were measured with probes covered with two different thicknesses of Al. The current recorded on a probe covered with three layers of Al leaf (0.45 mg/cm^2) was twice that on a probe covered with 1/2-mil Al (3.5 mg/cm^2), but the ratio of spill beam to circulating beam was independent of the thickness of the shielding.

Shortly after this it was possible to examine the circulating beam turn by turn over the first 9 inches, and discrete orbits were found. In consideration of this finding together with the measurements of the preceding paragraph, it was concluded that no very large spread in the beam energy could exist.

Beam Extraction

The beam did not leave the cyclotron at all azimuths, but rather in the vicinities of the hills. Figure 23 shows some typical trajectories. These trajectories were determined in two ways: (a) with pinhole cameras containing photographic film inclined at a slight angle to the median plane, so that it was possible to measure the direction of the trajectories at any point; and (b) by casting shadows on surfaces covered with fluorescent material.

The detailed behavior of the spillout beam was dependent on the configuration of the magnetic field at large radii, which was changed from time to time, but the general behavior can be described as follows: The electron trajectories expanded around stable orbits until the field became incorrect owing to the proximity to the edges of the poles. In this machine the field on top of the hills began to weaken at a radius of about 15-1/2 inches. Within a few turns, the particles had obtained a large radial component of motion and left the pole gap on the near sides of the hills, in general over about 30° of azimuth preceding the center lines of the hills. No electrons emerged on the far sides of the hills, but some electrons outside the poles (up to 1/8 in.) did not break away from the poles until the next hill. The situation can be summarized by saying that the circulating beam sprayed out of the machine at three well defined azimuths, and after breaking away from the poles, each group diverged over a horizontal angle of roughly 90°, the outer edge of the spill beam being sharply defined.

As regards vertical motion, the "Thomas" focusing was weakened at 15-1/2 inches, but the fringing field at this point (on the hills) introduced some additional vertical focusing. The result was that the axial amplitude grew somewhat on the hills and even more in the valleys just before the electrons spilled out, the valley amplitude being about twice that on the hill. The radial extent of the region of increased axial amplitude was 3/16 in. in the valleys. As the electrons passed through the valley for the last time and out from between the poles on the near side of the hill they were very strongly focused vertically. The appearance of the spill beam of course depended on the form of the external field. With the large coils originally used, the field immediately outside the poles was not changing very rapidly ; the spill pattern at the top of a hill appeared as in Fig. 24. The

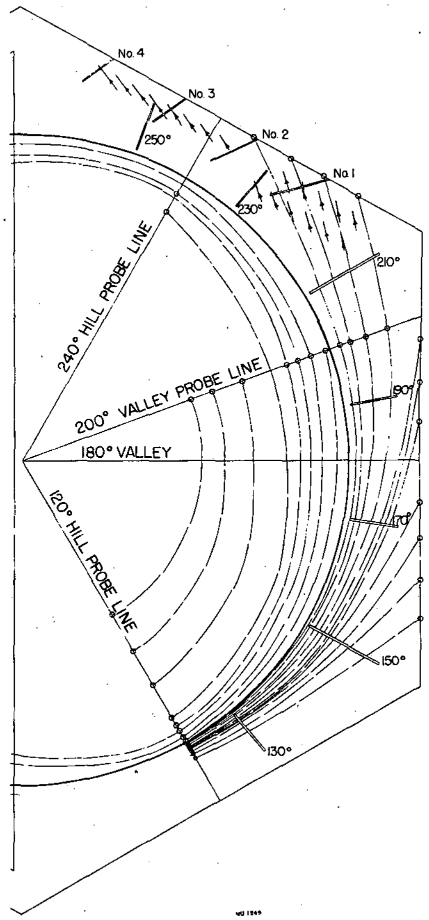


Fig. 23 Some Trajectories of the spill beam

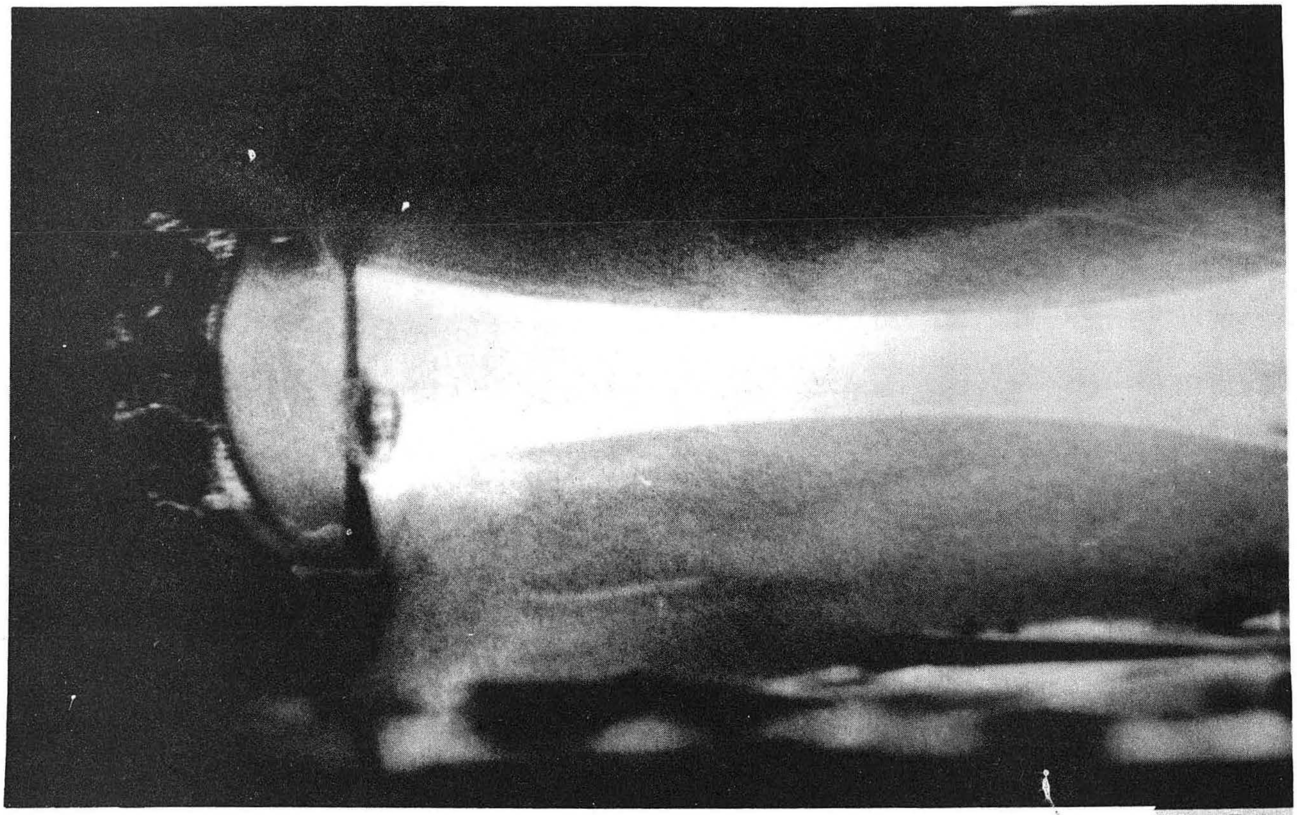


Fig. 24 Spill pattern with large coils.

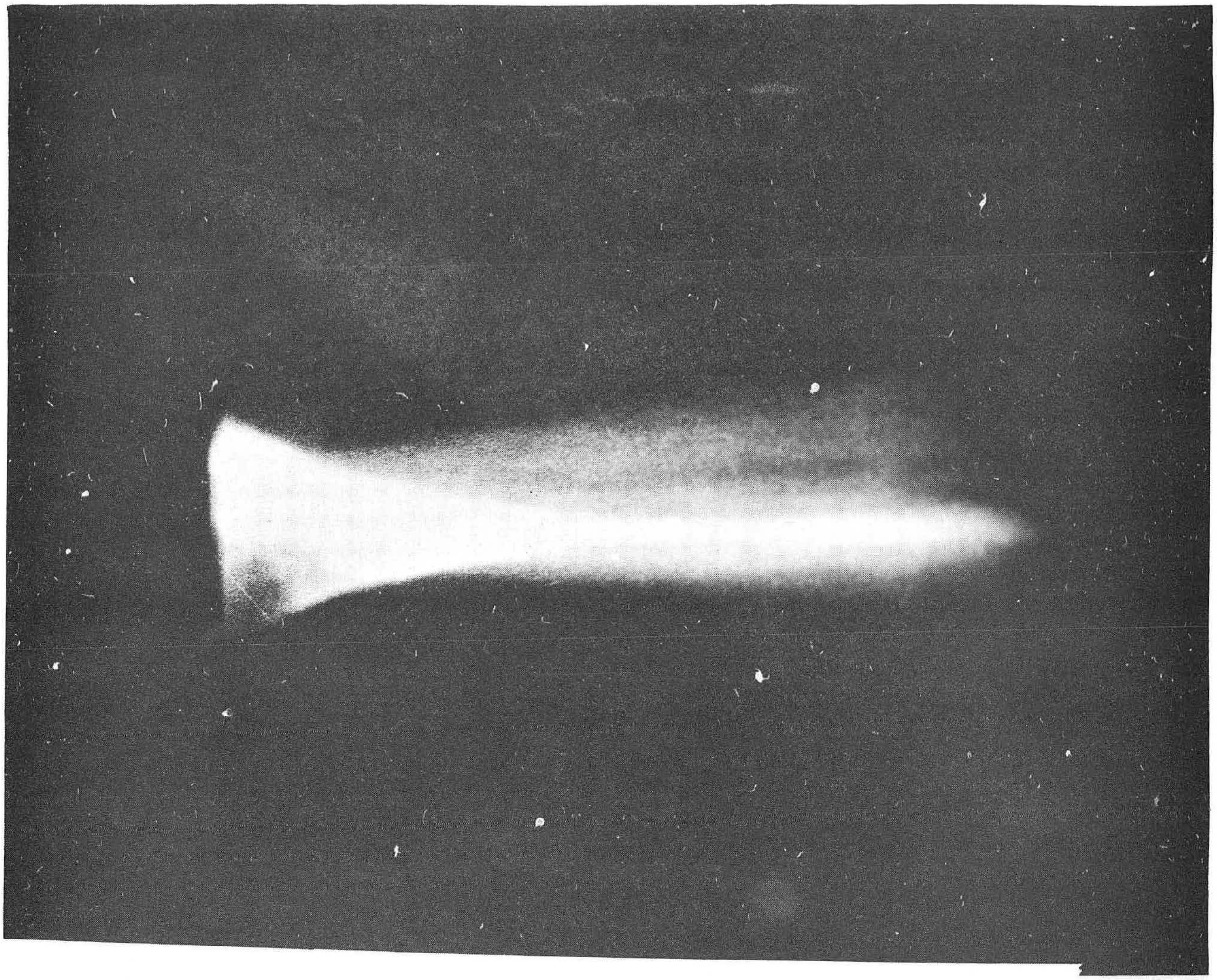


Fig. 25 Spill pattern with pole-size coils

radial extent of the pattern on the probe was 3 inches and the minimum vertical height was 1/4 in. In the case of the pole diameter coils, the field fell off very rapidly just outside the poles and the spill beam was much more strongly focused vertically. An example is given in Fig. 25, where the maximum vertical extent is 1/2 in. full scale and the length is 2 in. This was also taken on top of one of the hills. Both patterns start on the left at 16-1/2 inches radius, with larger radii to the right. Fig. 25 is a poor example of this particular pattern, in that it was taken under conditions of a rather poor tuneup. In general the diffuse background was absent and only the bright portion appeared.

The spill patterns from the three hills of this cyclotron were similar--but not identical--in both appearance and magnitude. An important discovery was that the beam could easily be made to come out chiefly on one hill by slightly modifying the magnetic field at large radii. In an ordinary cyclotron the orbits walk toward regions of stronger magnetic field but in this machine the orbits moved toward regions of weakened field. By either a slight decrease in the magnetic field on one hill or a slight increase of field in the opposite valley, or both, the electrons could be made to spill almost entirely on the hill in question. This could be achieved by changing the currents in the C-term coils, the maximum magnetic field change occurring at the largest radii and amounting to nearly 10 percent. The effect should be to reduce the axial focusing at the same time, but this was not particularly noticeable.

Considerable effort was devoted to an attempt to bring all the circulating current out on one hill. In general, one would expect that the C-term coils should be set up and then left untouched, and that the necessary field modification should be accomplished by some other means, so at times auxiliary coils were used to optimize the spillout. But because the axial focusing did not appear to be affected much, the adjustment of the C-term coils was often the method used.

There are two main questions of interest here: First, how much of the circulating beam gets out of the cyclotron, and second, how much of the spill beam can be intercepted outside the poles over a region small enough that it may be focused and collected in a single spot.

With a careful tuneup of the auxiliary coils it was possible to get nearly all the circulating beam out of the cyclotron. From visual inspection with fluorescent material painted on the surfaces the beam would most likely strike, it appeared that no electrons were hitting the pole faces. In a favorable tuneup 93 percent of the circulating beam at 14-1/2 inches radius was collected outside the poles on one hill. The circulating beam was driven rather badly off center under these conditions. Further attempts to extract the electrons without disturbing the circulating orbits will be described later.

Considering the second point, most of the spill beam came out on the near side of one hill. Some beam came out on the following hill, and in the intermediate valley. Several attempts were made to put this on a more quantitative basis with varying results, but in general 80 to 90 percent of the electrons came out in the few degrees preceding the center/line of the hill and the remainder in the next valley and ahead of the next hill. The simplest method of determining this beam distribution was to set a hill probe, say the 240° probe, at the edge of the pole. It was determined from shadow measurements that all beam intercepted by the probe in this position broke away from the poles. The 250° probe was then run in radially until the 240° probe current began to drop. The current to the 240° probe was then

80 to 90 percent of the sum of the two currents. More elaborate methods of measurement were tried but without any apparent improvement in reliability of results. A typical example follows: The beam was brought out on the 240° hill. No spray beam existed beyond the circulating beam at 60°, 120°, and 180°. The outer excursion of the beam for various azimuths was:

θ :	0°	60°	120°	180°	240°
R :	15-5/8 in.	13 in.	15-13/16 in.	13-5/8 in.	20-1/2 in.

The 250° probe was at R = 16-7/32 inches.

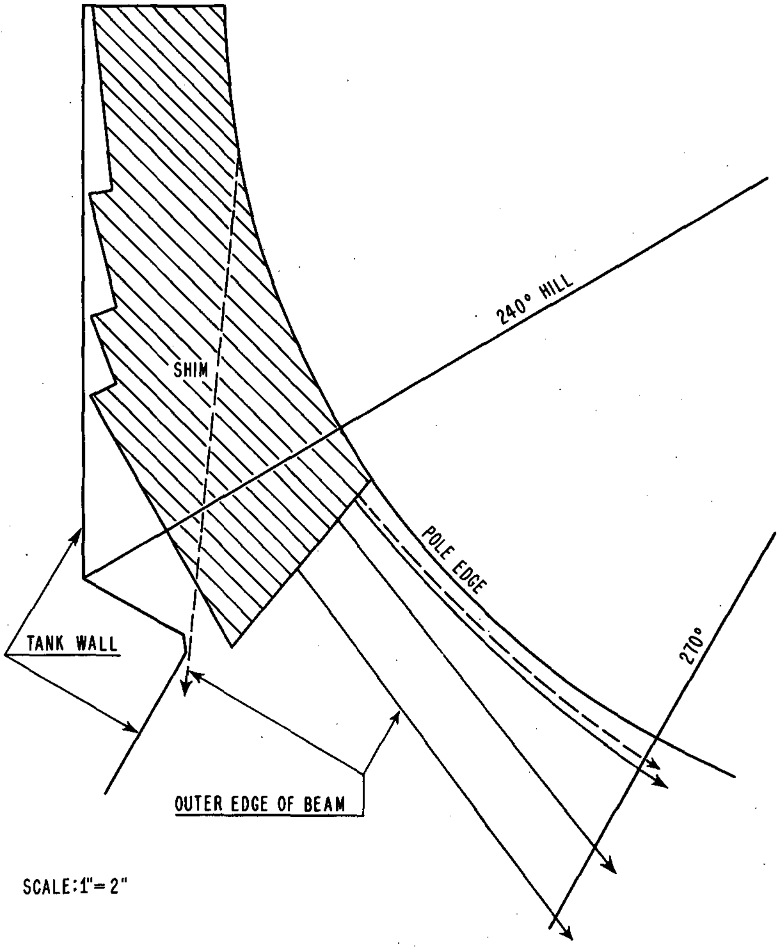
The auxiliary coil settings were:

COIL	13 in.	14-1/2 in.	15 in.	0°H	60°V	120°H	180°V	240°H	300°V
UPPER (ma)	9	13	23	370	0	115	-400	0	-225
LOWER (ma)	12	11	7	670	0	250	-225	0	-225

With a peak voltage of 250 V on the 60° triants, the current to the 240° probe was 9 cm and that to the 250° probe was 1 cm on the galvanometer. (Measurements of spill beam were reproducible from one probe to another within a few percent. Measurements of circulating current varied up to 10 percent from one probe to another, presumably because part of the current was lost in the insensitive area at the probe tip.) A further improvement in the percentage of the spill beam that could be collected on one hill was made with coils installed on the upper and lower pole surfaces at the hills. These extended 3 inches on either side of the hill center line and were 1 inch wide, extending from 15-1/2 inches to 16-1/2 inches. The purpose of these coils was to adjust the magnetic field over the last few orbits, and with them it was possible to make 98 percent of the spill beam leave on one hill. In this case, 80 percent of the beam circulating at 15 inches could be collected outside the poles.

Once it had been shown possible to get most or all of the electrons which got out of the cyclotron to spill from one hill, an attempt was made to focus this external current into a parallel beam. It was felt that not much could be done to the portion of the spill beam nearest the poles, so the magnetic field external to the poles at 240° was increased in such a way as to turn the outside edge of the external beam through a sufficient angle to make it parallel to the inner edge. Fig. 26 shows the shim that was added; the gap was the same as at the edge of the poles. On the drawing are shown some of the electron trajectories before (dashed) and after (solid) this shim was added. (The external distribution was similar but not identical to that of Fig. 23.) The appearance of the spill beam at 240° and 270° is sketched in Fig. 27. The beam was not parallel but the axial focusing was satisfactory. From shadow measurements it could be seen that most of the beam between 16-1/2 inches and 17 inches at 250° was directed back into the cyclotron, and from current measurements it appeared that this beam was lost into the pole faces before completing one revolution.

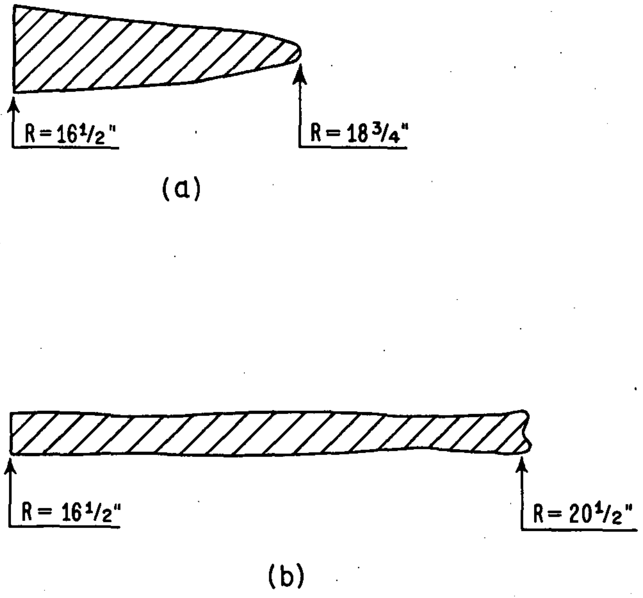
First one and later two coils were taped to the gap surfaces of the 240° shims to modify that field. Some improvement was made in both axial focusing and azimuthal distribution, but very little work was done along this line. While modifications were being made in the 240° shim, a wedge-shaped magnet was installed near the pole in the region of the 300° valley to focus the external beam into a spot. The useful acceptance area was 1 inch high and 6 inches wide; the fraction of the external beam that went through this



SHIM FOR FOCUSING THE EXTERNAL BEAM.
SOME TRAJECTORIES BEFORE (DASHED) AND AFTER THE ADDITION OF THE SHIM ARE SHOWN.

MU-6541

Figure 26



SPILL PATTERN FROM 240° SHIM. (a) 240° PROBE AND (b) 270° PROBE. FULL SIZE.

MU-6542

Figure 27

magnet was unknown, but from fluorescent measurements it was clear that neither vertical nor horizontal aperture was quite large enough. Of the beam which was transmitted, part could be focused into a sharp verticle line on a fluorescent surface 6 inches away, while the rest made a diffuse background. No current measurements were taken.

One method proposed for extracting the beam without uncentering the stable orbits was to extend two of the hills radially without changing the other, in the hope that the electrons would more or less suddenly find themselves in a region of weak magnetic field and leave the poles. To this end, two of the hills were extended radially 1 inch for 49° in each direction from the center lines. As a result the beam emerged preferentially from the unmodified hill, but some also came off the other hills. The distribution of spill beam was similar to that previously obtained. There appeared to be no improvement from this crude try, but a later investigation somewhat along this line with a more carefully planned magnetic field distribution gave encouraging results.

Members of the magnet group examined the displacement of the trajectories caused by various assumed perturbations in the magnetic field and were able to produce on paper a magnetic field configuration through which the spill beam emerged with quite small angular divergence in both the axial and horizontal directions, and which broke away from the poles rather sharply. The method by which this field was designed was to assume a configuration and plot the trajectories of electrons entering the perturbation under a number of assumptions as to energy and angular and radial displacements. The trial field was then modified to take care of particles that went astray and the whole process was repeated.

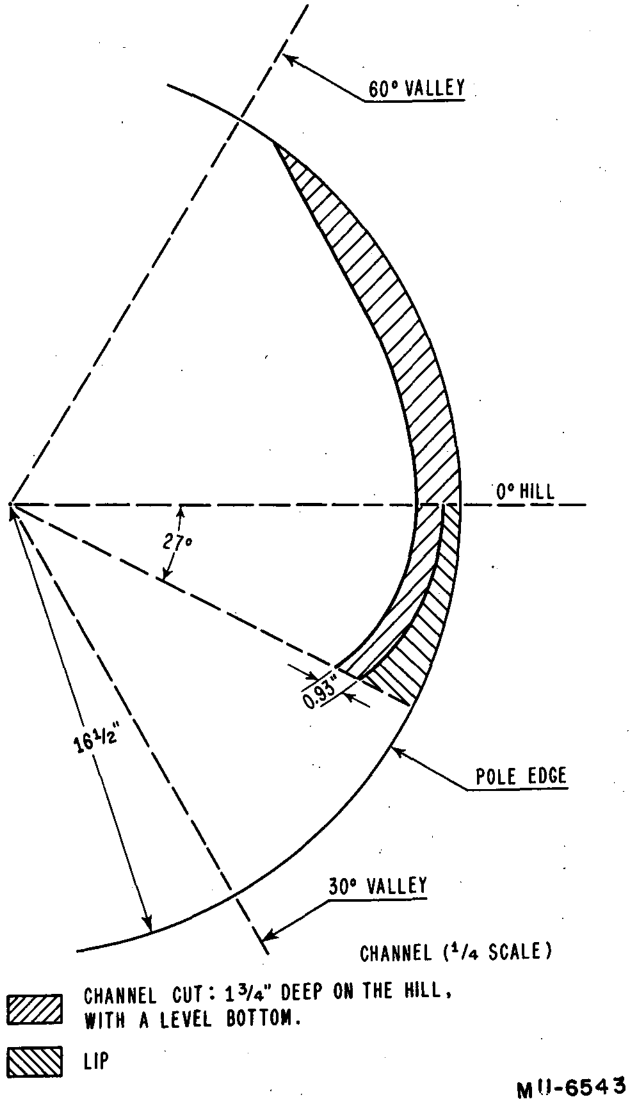

60° VALLEY
0° HILL
27°
0.93"
16½"
POLE EDGE
30° VALLEY
CHANNEL (¼ SCALE)
▨ CHANNEL CUT: 1¾" DEEP ON THE HILL, WITH A LEVEL BOTTOM.
▧ LIP
MU-6543

Figure 28

This is clearly a very difficult and lengthy business, and there is no way to tell if the assumed initial conditions are typical of those which actually would exist in the cyclotron. In addition, the proper technique to be used for drawing the trajectories was in doubt and each draftsman varied the method slightly to allow him to check with a calculated stable orbit. Before the magnetic field shaping was actually carried out, it was generally agreed that the spill distribution would probably have a large azimuthal divergence, but that the quantitative distribution might show some improvement.

To facilitate machining and subsequent changes in the field design, a large chunk of iron was cut from the upper and lower 0° pole tips. The cuts were then filled with iron to make the geometry of the pole faces the same as before. The magnetic field was not measured but the cyclotron was operated before further changes were made and the behavior seemed identical to that before the poles were cut. A crude version of the iron configuration necessary to produce the design field was modeled at six-tenths scale and the channel shown in Fig. 28 was cut into the upper and lower poles of the 0° hill. The maximum depth of the cut was 1-3/4 inches, the bottom of the channel being parallel to the median plane.

The position of the small-radius edge of the cut was supposed to correspond to the outermost stable orbit (15 inches maximum radius) between 333° and 0°. Following the 0° hill the electrons in stable orbits were inside the cut. The predicted (and observed) behavior of the electrons can be described as follows: The electrons entered the channel (from the left in Fig. 28) and found themselves in too low a magnetic field. As a result they were at too large a radius (compared to the stable orbit) on the 120° hill, at too small a radius on the 240° hill, and when they returned to the

0° hill were again at too large a radius and--more important--were inclined outward at an angle from the stable trajectory. This process was regenerative and the radial oscillation quickly increased until the electrons flew out of the cyclotron.

The channeled pole tips were replaced and a beam quickly obtained. The result was not very encouraging; beam sprayed out more or less uniformly over the whole sector from 0° to 120° with some beam leaving at 0° at a very sharp angle. The cut had also modified the field at smaller radii, as might be expected, so that beam, which was well centered, had radial oscillations up to 1/2 inch before entering the channel.

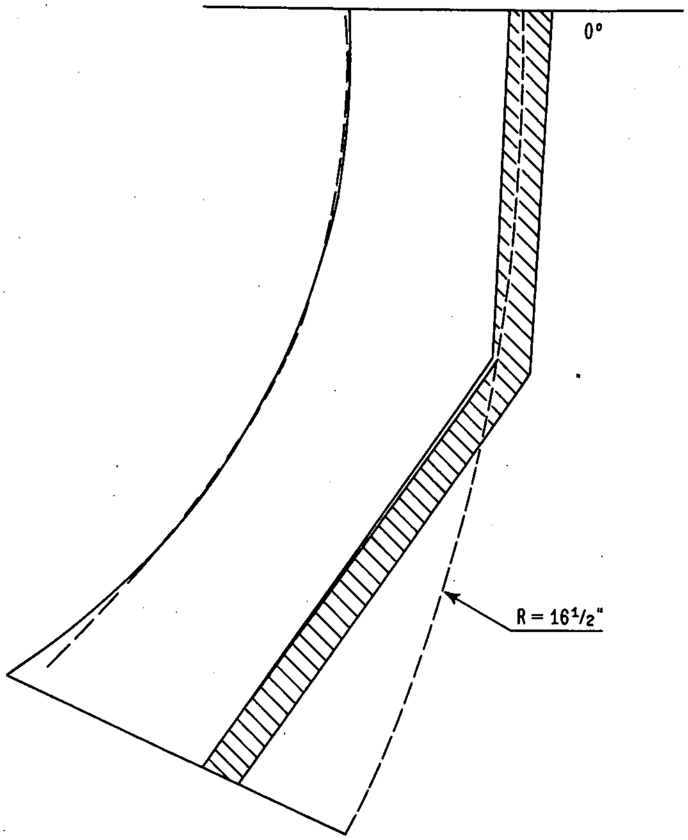
The magnet field clearly needed considerable modification and as no field-measuring device was available, the quickest empirical way to determine some of the necessary changes in the iron seemed to be by the use of an electrolytic tray. This method is applicable if the magnetic material used in the cyclotron can be considered to have infinite permeability. The geometry of the channel was set up and the field calculated from the measured equipotential lines. The result was in good agreement with that obtained from the model magnet work. With this technique, shims were designed which restored the magnetic field at radii smaller than the channel radius to something like its previous value. These shims were installed, and improved the appearance of the circulating beam without affecting the distribution of the spill beam.

There was some feeling that the channel would work considerably better if the field could be made to fall off more rapidly at the transition radius into the channel. To investigate this, all the iron on the outside of the channel was cut away (Lip of Fig. 28). The ratio of spill current between 0° and 60° to that between 60° and 120° was improved considerably, although the angular divergence of the spill beam was larger. A new outer edge of the channel was then installed (Fig. 29). This channel was considerably wider and therefore gave a larger gradient along the edge of the channel, and also was supposed to reduce the angular divergence of the beam. With this configuration the following typical set of data was obtained:

Circulating current at 14-1/2 in. 0°	60 cm	(1 cm = 5 x 10^{-9} amp)
Total spill beam	49 cm	
Spill beam on the 120° probe:	5 cm	
Spill beam found at radii of 20 inches or more over the azimuth range 0° to 60°	45 cm	

In short, something over 80 percent of the circulating beam was accounted for outside the cyclotron and 90 percent of the spill beam was at a radius of at least 20 inches over the azimuthal range 0° to 60°. The outer limit of the beam at 0° was 17 inches and at 30° was at 22 inches. All electrons at a radius of 16 inches or more on the 30° probe were included in the 0° to 60° figure given above. One could conclude that considerable progress had been made in breaking the beam away from the poles but that the angular divergence was still very large.

One might expect the magnetic channel to be poorer than predicted if the inner edge of the channel did not (magnetically) correspond to a stable orbit. Aside from actually trying a variety of iron configurations, there appeared to be two ways to investigate this point. First, the position and direction of the large-radius orbits could be changed considerably by adjusting the distribution of currents in the C-term coils. Also the magnetic field along the inner edge of the channel could be adjusted with current-carrying coils along the lip. Four sets of coils were distributed



MODIFIED MAGNETIC CHANNEL.

MU-6544

Figure 29

along the lip of the channel, at the upper and lower pole surfaces. In addition a coil was wound around the iron which formed the outside of the channel so that the outer excursion of the beam could be controlled. All these coils had an effect on the azimuthal distribution of the spill beam, but with the exception of the coil that adjusted the trajectories of the outside edge of the beam, the above measures only served to worsen the spill distribution.

As the beam that spilled toward the 120° hill passed through a large region inside the pole gap but outside the circulating beam, it seemed possible to increase the field in this region and so keep these electrons inside the cyclotron for another revolution, after which they could make another pass through the channel. To this end several coils were distributed over the upper and lower pole surfaces. While the experiment was exceedingly crude, the results were encouraging, and it was felt that following some careful trajectory plotting it would be possible to shim the magnetic field in this region to spill all of this beam in the desired direction. The possible vertical defocusing with such a field has not been considered.

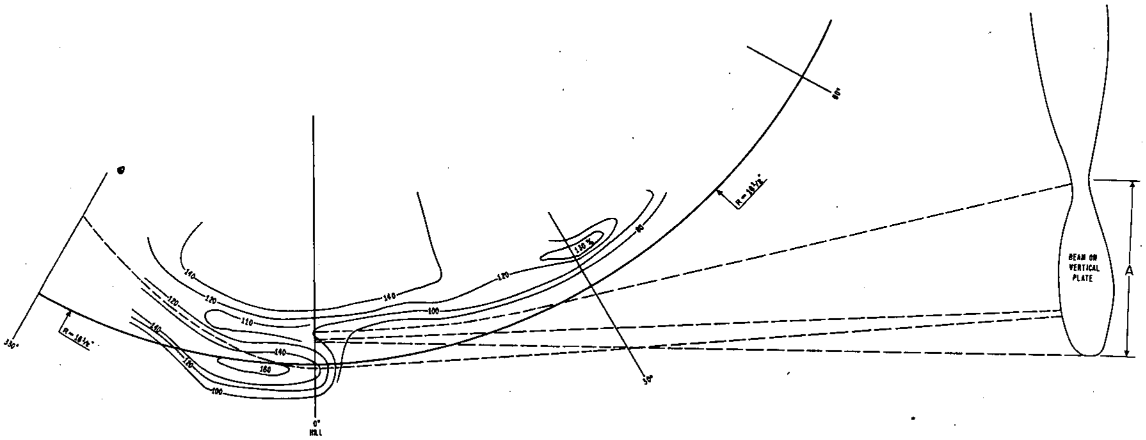
Somewhat along the above line was a short empirical investigation of the possibility of accomplishing the same result by adjusting the magnetic field over a relatively small region following the magnetic channel. Such a field distribution probably would not be as satisfactory as the more extensive field adjustment suggested in the previous paragraph, but still might serve to bring a larger fraction of the electrons out in the desired direction. To this end, mu-metal strips were placed on the pole surfaces over the azimuth range of 25° to 40° at such radii as were necessary to bring the beam spilling near 120° around for another try at the channel. Metal was added and subtracted at first according to shadow measurements, and finally by measuring current distributions. A coil was wrapped around the shim to allow the field to be varied up to 10 percent. Later an additional shim was installed closer to the 0° hill. The final field configuration is shown in Fig. 30. Before the channel was cut the field was symetrical across the 0° hill line. The vertical aperture in the shim closest to 0° was 3/4 in. and in the other shim was 1 inch. No electrons hit the shims.

The horizontal distribution of the spill beam is shown in Fig. 30 along with the appearance of the beam on a vertical fluorescent plate. Eighty percent of the spill beam fell in the region "A" with the rest nearer the poles. It should be noted that there was considerable crossfire in the horizontal plane, i.e., there was no single horizontal source point for all of the beam.

When a probe was inserted at 110° the circulating beam was picked up at 13 inches. A considerable amount of beam was in the range 13 inches to 15-1/2 inches; from there out there was no measurable or visible amount.

The field produced by the channel and shims was defocusing for some of the trajectories being recycled for another turn. Shadow measurements indicated that some of the electrons of this type would be lost into the pole faces. Current measurements, which were accurate to about 10 percent, showed that within the accuracy of the measurements all of the recycled beam came out of the cyclotron. The current recycled by the shims amounted to 20 percent of the total spill beam.

Threshold measurements showed that the channel cut had considerably affected the internal action of the cyclotron. The threshold for spill beam at 14-1/2 inches had been raised to about 200 volts, and the radial and axial oscillations were much larger. Just before reaching the spill radius



MAGNETIC FIELD CONTOURS IN PER CENT OF CENTRAL FIELD.
SOME ELECTRON TRAJECTORIES ARE SHOWN. 80% OF THE EXTERNAL BEAM
CURRENT WAS CONCENTRATED IN REGION "A"

MU-6837

Figure 30

the beam completely filled the gap on the hills. Under these conditions 80 percent of the beam circulating at 14 inches could be made to spill and 80 percent of the spill current could be collected in the region AB of Fig. 30.

It is expected that this result could be considerably improved. On the other hand, it does not seem possible to say whether the end result would be better than could be obtained with the rather simple focusing devise shown in Fig. 26. In both cases it appears that one could expect to concentrate most of the circulating current in a fairly small area some distance from the cyclotron.

APPENDIX

I Choice of the Constants Used in the Magnetic Field Expression

The material in this section consists of fragments of the theoretical investigation of L. H. Thomas and D. Judd.

Consider motion in the plane of symmetry with no electric fields acting. Take the magnetic field to be of the form:

$$H_z(r,\theta) = \frac{M_0 \omega c}{e}\left[1 + A\left(\frac{\omega r}{c}\right)\cos M\theta + B\left(\frac{\omega r}{c}\right)^2 + C\left(\frac{\omega r}{c}\right)^3 \cos M\theta + D\left(\frac{\omega r}{c}\right)^4 + \ldots\right]$$

where m is an arbitrary integer. It can be shown that $M \geq 3$ gives orbital stability. This expansion is fairly general, but is of course not the only possible once and has the limitation that it does not converge very rapidly for large-particle velocities. To decide upon the constants, it was first necessary to find a way to mathematically describe the stable orbits. Then these orbits were required to satisfy the "resonance condition" that the periods of all stable orbits should be the same, namely $2\pi/\omega$. From this requirement it is found that $B = -\frac{1}{2} - \frac{A^2}{M^2 - 1}$. Similarly D turns out to be a function of A and C, $F = F(A,C,E)$, etc. The higher the velocity of the particle, the more important are the higher-order terms in the expansion.

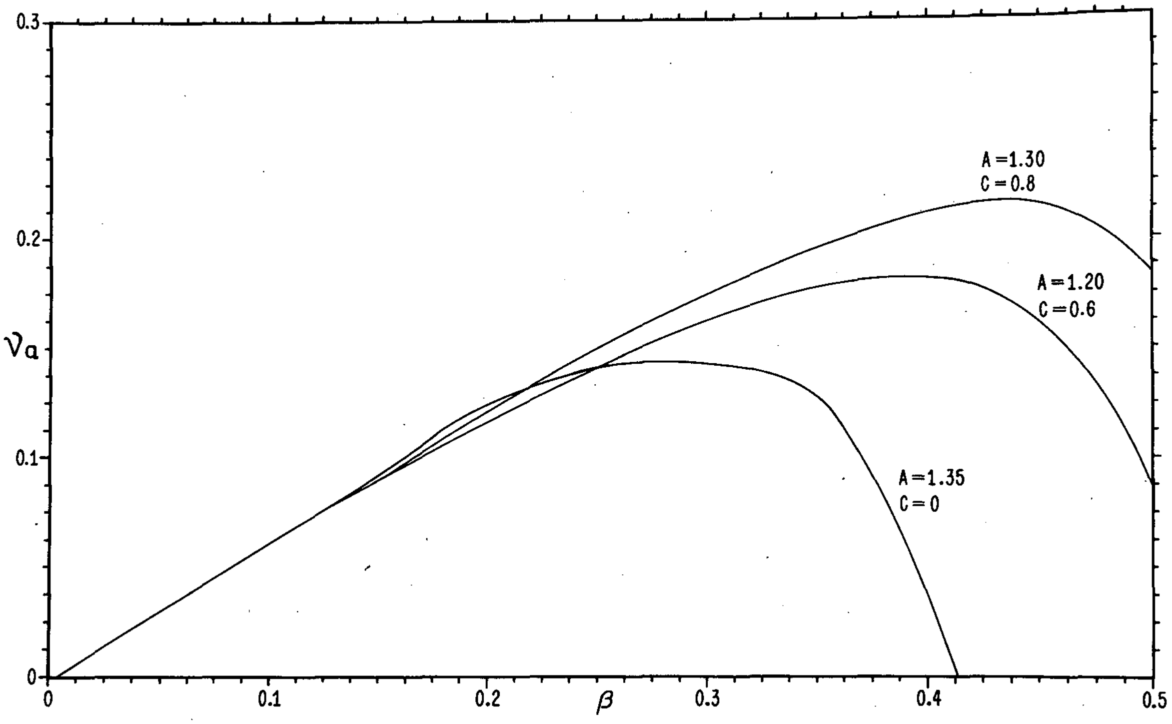
Expressions were then obtained for the axial and radial restoring forces in terms of the constants A, C, E, etc. The restoring forces are proportional to the squares of the frequencies of axial and radial oscillation. As has been mentioned in the report, the radial oscillations become unstable when ν_r, the ratio of the frequency of radial oscillation to the frequency of the orbital motion reaches 3/2, so that in the region of acceleration one requires $\nu_r < 3/2$. The velocity at which the point of $\nu_r = 3/2$ is reached decreases as A increases. The curve of ν_a, the ratio of the frequency of axial oscillation to the frequency of orbital motion, also rises more steeply for larger values of A. It can be shown that for ν_a to be positive, it is necessary that $A \gtrsim 1.115$ in a cyclotron with an azimuthal periodicity of 3. To decide on a value of A one then chooses a value as much greater than 1.115 as is possible without reaching the point where $\nu_r = 3/2$ before the particles have been accelerated to the desired energy. In the electron model the value A = 1.35 was chosen as a reasonable compromise. The value of B then turns out to be 0.272. If no higher order terms are included ν_a falls to zero at v/c = 0.41. Figure 31 shows the way in which ν_a varies with the choice of C. As the amplitude of the oscillation is proportional to $(\nu_a)^{-\frac{1}{2}}$ (according to the adiabatic theorem), it would be expected that at about v/c = 0.38 the axial amplitude would grow rapidly, when C = 0. This corresponds to a radius of 13 inches, and such a phenomenon was observed to occur at this radius, before the theory had been developed past the A and B terms.

The outermost stable orbit in this cyclotron corresponded to v/c = 0.46. For this value of v/c the choice of E and higher-order terms has little effect on the axial amplitude.

The point of radial instability was not reached with the coefficients used.

It is interesting to note that the axial restoring forces calculated for the electron model are very close to those existing in the Berkeley 184" cyclotron.

No transfer of energy from radial to axial oscillations, such as occurs in the 184" cyclotron at n = 0.2 was predicted or observed.



MU-6547

Figure 31

II Energy vs. Radius

The expressions relating energy and radius in a cyclotron of azimuthal periodicity three are given below:

$$E = M_o c^2 \left[\frac{1}{\sqrt{1 - \beta^2}} - 1 \right]$$

$$\beta = \frac{a\omega}{c} (1 + g_2 + g_4 + \ldots)$$

where $g_2 = 0.03516\ A^2 \left(\frac{a\omega}{c} \right)^2$

$$g_4 = \left\{ -0.02637\ A^2 - 0.00120\ A^4 + 0.07031\ A\ C \right\} \left(\frac{a\omega}{c} \right)^4$$

$$r = a(1 + f_1 + f_2 + f_3 + \ldots)$$

where $f_1 = 0.125\ A \left(\frac{a\omega}{c} \right) \cos 3\theta$

$$f_2 = 0.00658\ A^2 \left(\frac{a\omega}{c} \right)^2 \cos 6\theta$$

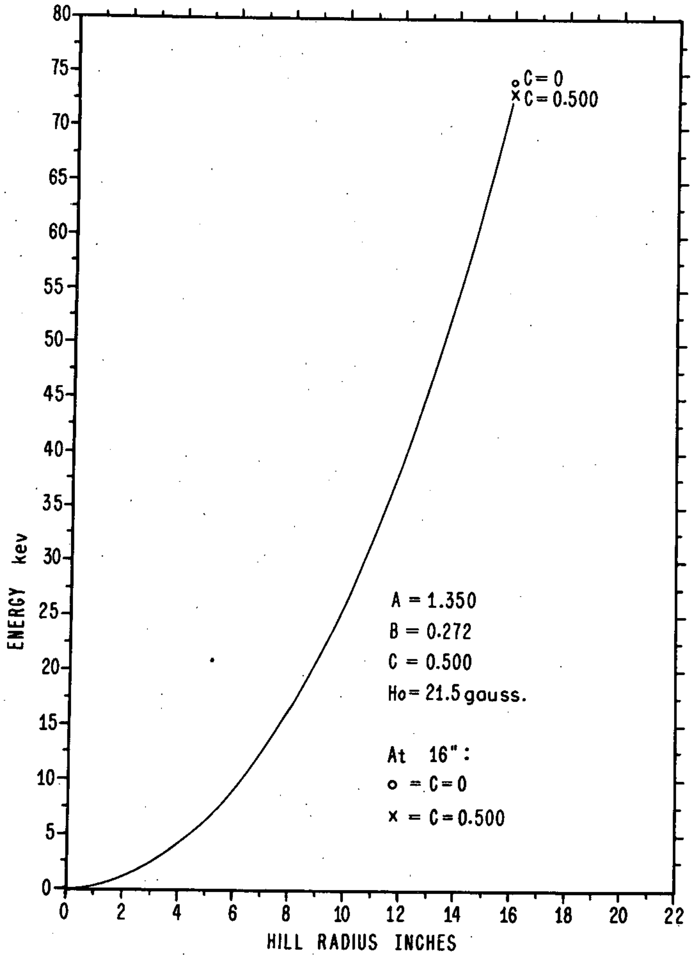
$$f_3 = \left\{ -0.0081\ A^2 - 0.04688\ A + 0.01250\ C \right\} \left(\frac{a\omega}{c} \right)^3 \cos 3\theta$$

$$f_4 = \left[\left\{ -0.00002\ A^3 - 0.00486\ A^2 + 0.01674\ A\ C \right\} \cos 6\theta - 0.00010\ A^4 \cos 12\theta \right] \left(\frac{a\omega}{c} \right)^4$$

For A = 1.350, B = 0.272, and C = 0.500, electron energy vs. the maximum radius of the stable orbit, i.e., the hill radius, is plotted in Fig. 32. Also shown is the change in energy at 16 inches if C is changed from 0.5 to 0.

III The Magnetic Field Produced By The C-Term Coils

The C-term coils were designed to produce a magnetic field corresponding to C = 0.5 when energized with a total of 500 ma in each set (upper plus lower) of coils. The detailed shape of the field actually created by such currents was never measured, but at the completion of the project a few spot measurements were made which indicated that at the azimuths



MU-6548

Figure 32

investigated the magnetic field was within a percent or so of that desired:

<u>240° Hill</u> : At a radius of 12.5 inches the magnetic field should theoretically be raised 2.1 percent with 500 ma in the C-term coils. The measured difference was 3.2 percent. At 15.5 inches the theoretical and measured fields were 3.4 percent greater than with only the A and B terms in the expansion.

The shape of the field as a function of radius for C = 2.00 is shown in Fig. 33. The experimental and theoretical fields are normalized at 12.5 inches.

<u>60° Valley</u> : At a radius of 14 inches the field was reduced 9 percent by passing -500 ma through the C-term coils. The expected change had been 10.9 percent. The valley field as a function of radius for $C \cong 0.680$ is shown in Fig. 34.

IV Operating Conditions For Threshold Beam With Good Axial Focusing

The following are the operating settings found for a threshold voltage of 60 V with the 60° triants. Under these conditions the radial and axial focusing were such that the extent of the beam on a fluorescent probe was never more than twice the value at 5 inches: 3/32 in. x 3/32 in. No beam was lost to the pole surfaces.

The spill beam was observed on the 120° probe.

Peak triant voltage: 60 V. Phases 120°

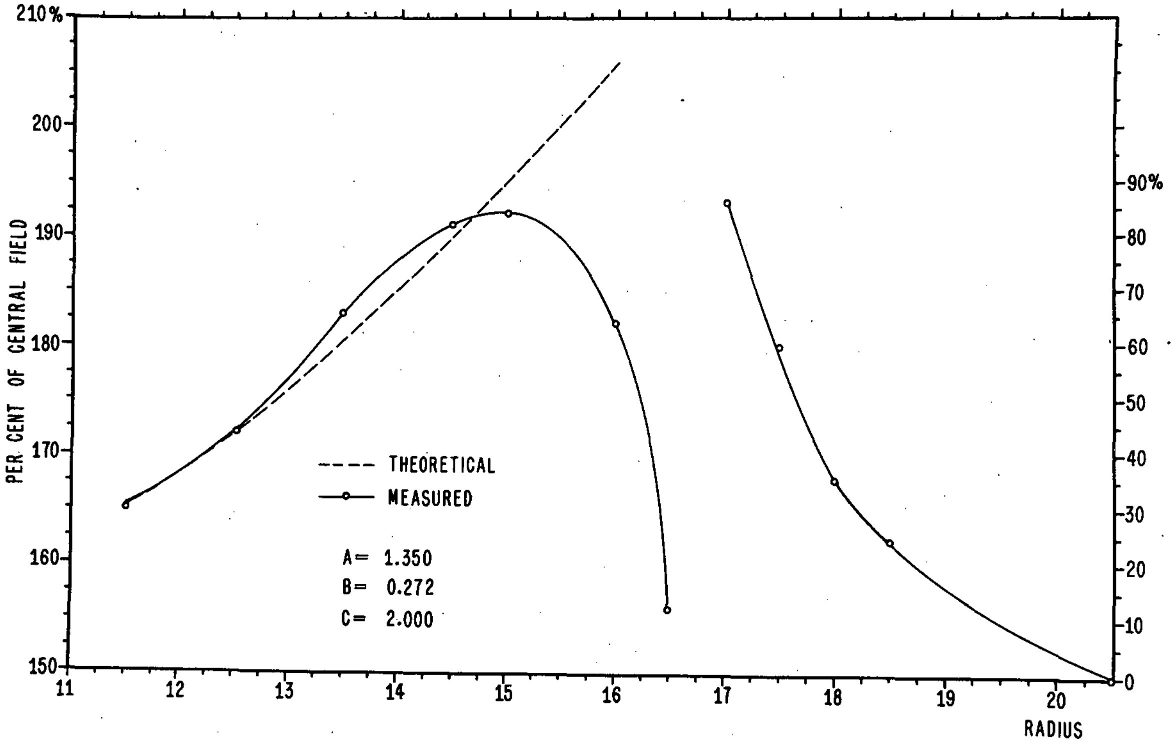
Main field coil current: 1.19 amps.

Total filament emission: 1.0 ma

Source injecting at a radius of 2 inches at an energy of 1.25 kev.

Tank pressure: 2×10^{-5} mm Hg.

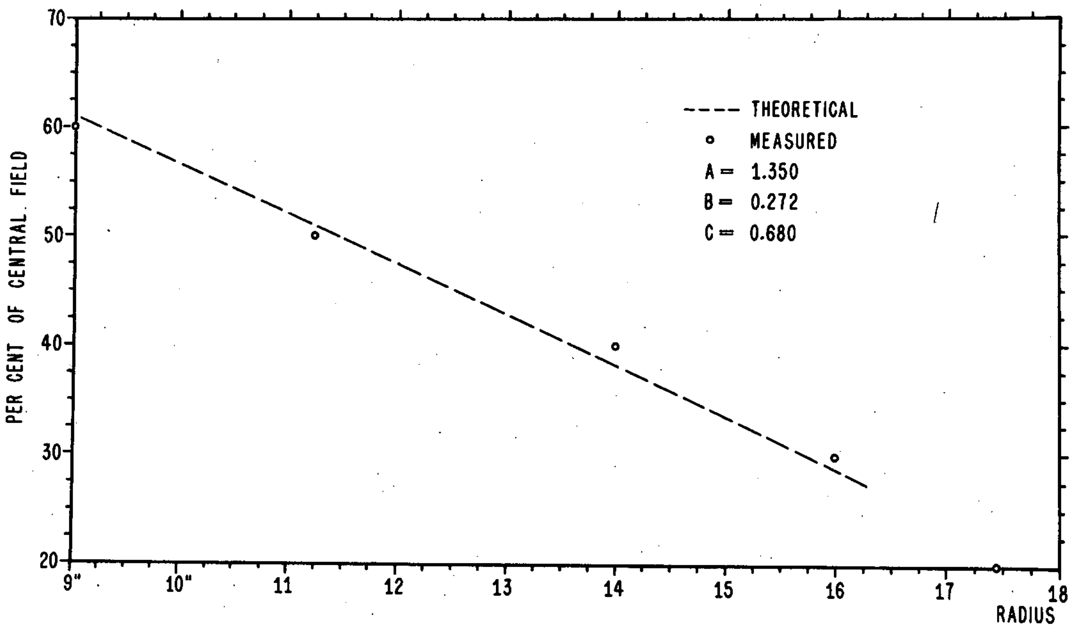
Shifting coil setting:



MAGNETIC FIELD AT 240° (HILL)

MU-6545

Figure 33



MAGNETIC FIELD AT 60° (VALLEY)

MU-6546

Figure 34

Auxiliary coil settings:

Coil	3 in.	4 in.	5 in.	6 in.	7 in.	8 in.	9 in.	10 in.
Upper (ma)	-280	70	25	42	-34	28	38	45
Lower (ma)	-390	210	12	38	-7	66	65	45

Coil	11 in.	12 in.	12-1/2 in.	13-1/2 in.	14 in.	14-1/2 in.	15 in.	15-1/2 in.
Upper	-70	50	-33	56	250	17	-170	-18
Lower	-107	45	35	-62	200	-10	-125	150

Coil	0°H	120°H	240°H	60°V	180°V	300°V
Upper	200	130	1180	-290	-700	34
Lower	250	110	940	-150	-620	-114

The azimuthal position of the source was unimportant.

The first harmonic at 5 inches and 240° was reduced by placing a 2 in. x 2 in. x 12 in. bar of soft iron on the external surface of the top pole at 5 inches and 60°, with the long axis vertical.

NOTE: The fields produced by the auxiliary coils are given by

$$H = \frac{\text{amp turns}}{0.4\pi\ \text{gap}_{cm}}$$

with an accuracy of about 15 percent (exptl.).

Information Division
9/25/53 plc

ACKNOWLEDGMENTS

We gratefully acknowledge the ideas and assistance of many others; among them:

Melvin E. Chun
Max E. Harris
Myron Heusenfeld
David Judd
Harry Keller
William Lauton
E. O. Lawrence
Edwin Mc Millan
Robert Ralston
Lazarus Ratner
Duane Sewell
Arthur Sherman
Robert Smith
Warren Stubbins
Dwight Vorkoeper

[redacted]

~~SECURITY INFORMATION~~

DECLASSIFIED

[redacted]