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PROPOSALS

FOR

OPERATING SUPPORT

and

ADDITIONAL EXPERIMENTAL EQUIPMENT

FOR THE

MICHIGAN STATE UNIVERSITY
CYCLOTRON

July, 1963

Granted 2-5-64

7/63

PROPOSALS
to the
NATIONAL SCIENCE FOUNDATION

for

OPERATING SUPPORT
for the
MICHIGAN STATE UNIVERSITY
64" CYCLOTRON

from Oct. 1, 1963 thru Oct. 1, 1964

and for

EQUIPMENT
for
ADDITIONAL EXPERIMENTAL AREAS

Department of Physics
Michigan State University
East Lansing, Michigan

July 25, 1963

PREFACE

Beginning with an initial grant in October of 1961 the National Science Foundation has supported work on the design and construction of a variable-energy multi-particle cyclotron at Michigan State University. Additional funds are now needed to carry the operating program thru periods not covered by the previous proposal (referred to herein as the 1960 proposal), and also equipment funds are requested to provide additional experimental areas beyond those previously proposed.

The need for new funds is primarily a result of technological developments during the period since preparation of the previous proposal, augmented by the fact that the project has not proceeded as fast as had been hoped. The principal delay on the project has been the construction of the building which has taken approximately two years (including the architect's work) rather than the one year originally anticipated. The project staff has utilized the extended construction period to continue design studies with the result that the cyclotron will now be a vastly superior device to that originally proposed. The need for additional experimental equipment arises from a series of factors:

(a) The nuclear research experience of new project staff added since the preparation of the 1960 proposal made it clear that the experimental area, as proposed therein, was grossly undersized—this fact was also corroborated by discussions with workers at other nuclear physics laboratories.

(b) The enhanced capability of the cyclotron requires additional experimental rooms in order to achieve a balance between the cyclotron and the associated facilities.

(c) The evolution of nuclear research in the period since the previous proposal—particularly the need for greater precision and for rapid processing and assimilation of large amounts of data including determination of complicated correlations—has been such as to now require substantially larger experimental areas, more precise measuring equipment, and more automated processing in order to perform significant experiments.

As a result of these factors the size of the experimental areas planned for the cyclotron have been greatly increased; funds are requested herein for equipping these additional areas.

In order to comply with new procedural regulations of the National Science Foundation two proposals are given, one for operating funds for the period October 1, 1963 to October 1, 1964, and a second for the additional experimental equipment. For both of these proposals the principle justification rests on accomplishments with the previous grants. In view of this the initial section of this document consists of a progress report detailing accomplishments and progress to date. The two proposals follow, each containing a budget and a description of the purposes for which the funds will be used.

PROGRESS REPORT
on the
MICHIGAN STATE UNIVERSITY
CYCLOTRON PROJECT

Oct. 1, 1961 to July 31, 1963

Grant NSF-G19978

by
Project Staff
July 26, 1963

1.0 Introduction

In the process of finalizing the design of the cyclotron innumerable major and minor design improvements have been achieved which will result in increased versatility, higher energy, and improved precision and duty cycle as contrasted with the performance described in the original proposal[1). Specifically:

(a) the versatility has been enhanced by provision for the acceleration of deuterons and alphas,

(b) the maximum energy has been increased by approximately 20%,

(c) when accelerating protons and deuterons the cyclotron can, if desired, be operated in an alternate mode providing an approximate 15 fold increase in duty cycle (to a value of 25% or more),

(d) when accelerating protons and deuterons the energy resolution of the cyclotron can, if desired, be improved such as to provide workable counting rates for reaction studies at resolutions of approximately 1 part in 10,000 (this mode of operation is not compatible with (c) above),

(e) the building arrangement has been revised to provide a much larger number of target positions arranged in a system of separately shielded rooms such as to permit set-up work to go on at a number of

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1) The design work has proceeded on the philosophy that major hardware parameters (such as the size of the magnet core, the size of the magnet coils, the size of the rf tuning panels, the dee to ground voltage, etc.) should be held to the values specified in the original proposal so that design improvements result in improved performance. This is actually the only practical philosophy to adopt, since the major hardware components have long lead times and therefore must be ordered early in the evolution of a project before most of the design improvements have come to light.

positions concurrently with experimental work at others, and

(f) the cyclotron has been repositioned so that the median plane is horizontal rather than vertical thus improving the optical characteristics of the analyzed beam.

In the following sections these topics are discussed more fully, the discussion being grouped for convenience into items related to the cyclotron proper and items related to the associated experimental areas and equipment. In addition, a section is included summarizing cost experience and expenditures under the previous grant.

2.0 Cyclotron

The lower half of Fig. 1 indicates the variety of accelerated particles and final energies which the cyclotron is now expected to attain. For comparison the upper half of Fig. 1 is a reprint of the same graph taken from the previous proposal. The performance is seen to be notably improved. The gray areas in the graph (which are inaccessible due to rf system limitations) have been greatly reduced, due chiefly to a redesign of the dee shape and of the central region such as to permit acceleration of particles on even as well as odd subharmonics of the rf frequency; in addition, experimental measurements on a full-scale mockup of the rf system have shown the tuning range to be substantially broader than anticipated, i.e., 13.5 to 21.5 megacycles rather than 15 to 21 megacycles. The 20% increase in particle energy is a result of improved design of the magnet pole tips and revision of details of the resonant extraction system. In the following subsections each of these mechanisms is explained as well as the techniques used for obtaining the increased duty cycle for protons and deuterons.

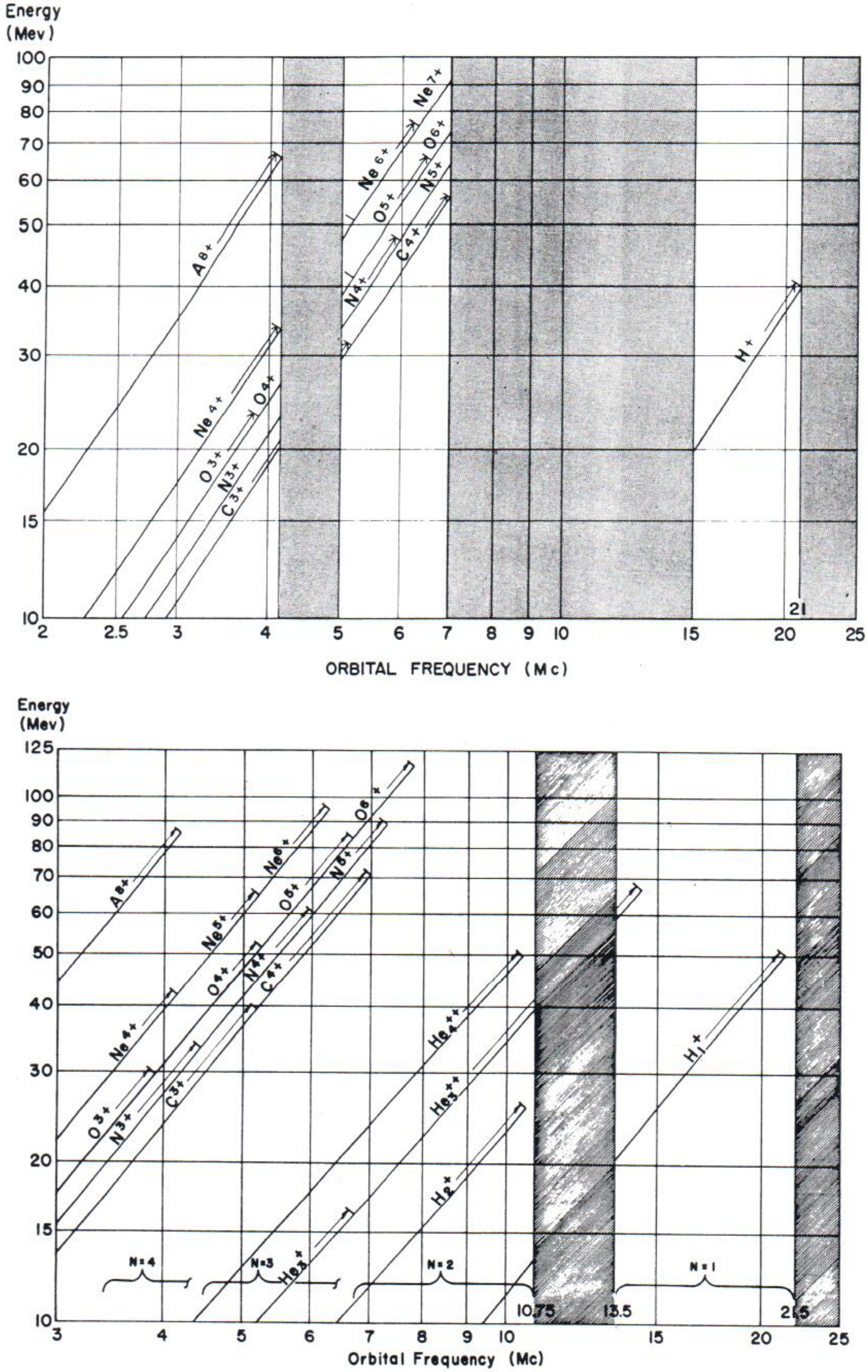

Fig. 1 — Upper Graph: energy versus orbital frequency for various particles as indicated in the December, 1960 proposal. Lower Graph: similar curves for the cyclotron as now designed.

2.1 Cyclotron Magnet

Fig. 2 is a photograph of the cyclotron magnet core being assembled in the plant of the Allis-Chalmers Corporation in Milwaukee. The factory inspection of the core has been completed—the results indicate a superb machining job. The 15" magnet gap, for example, was found to be uniform to within 0.002", the upper and lower pole bases were concentric to within 0.003", and the pole bases were aligned azimuthally to within 0.001". This exceptional machining accuracy should lead to minimal first harmonic content in the magnetic field of the fully assembled cyclotron.

Fig. 3 is a photograph of one of the main coil "pancakes" taken in the plant of the Westinghouse Corporation in Chicago, Illinois. Each of the main coils consists of eight such pancakes. At the present time (July, 1963) all of the pancakes have been wound and over half have been vacuum impregnated; the completed pancakes are in the process of being shipped to East Lansing.

Fig. 4 shows the form of the magnet pole tips. The pole tips are in process of fabrication by Allis-Chalmers Corporation and are scheduled for delivery in August. The contoured edge of the pole tips will be fabricated by a tape controlled milling machine. Allis-Chalmers guarantees that no dimension of any pole tip will differ from the corresponding dimension on any other pole tip by more than 0.003"; the characteristics of the machinery being used for fabrication of the pole tips indicate a substantial probability that the tips will actually be identical to within 0.001".

The main magnet power supply is completed and is presently undergoing factory tests in the plant of the Pacific Electric Motor Company in Oakland, California; delivery is expected in August. It is expected that assembly and hookup of the magnet coils and power supply will require approximately six weeks; hence, full scale magnet measurements should begin early in October.

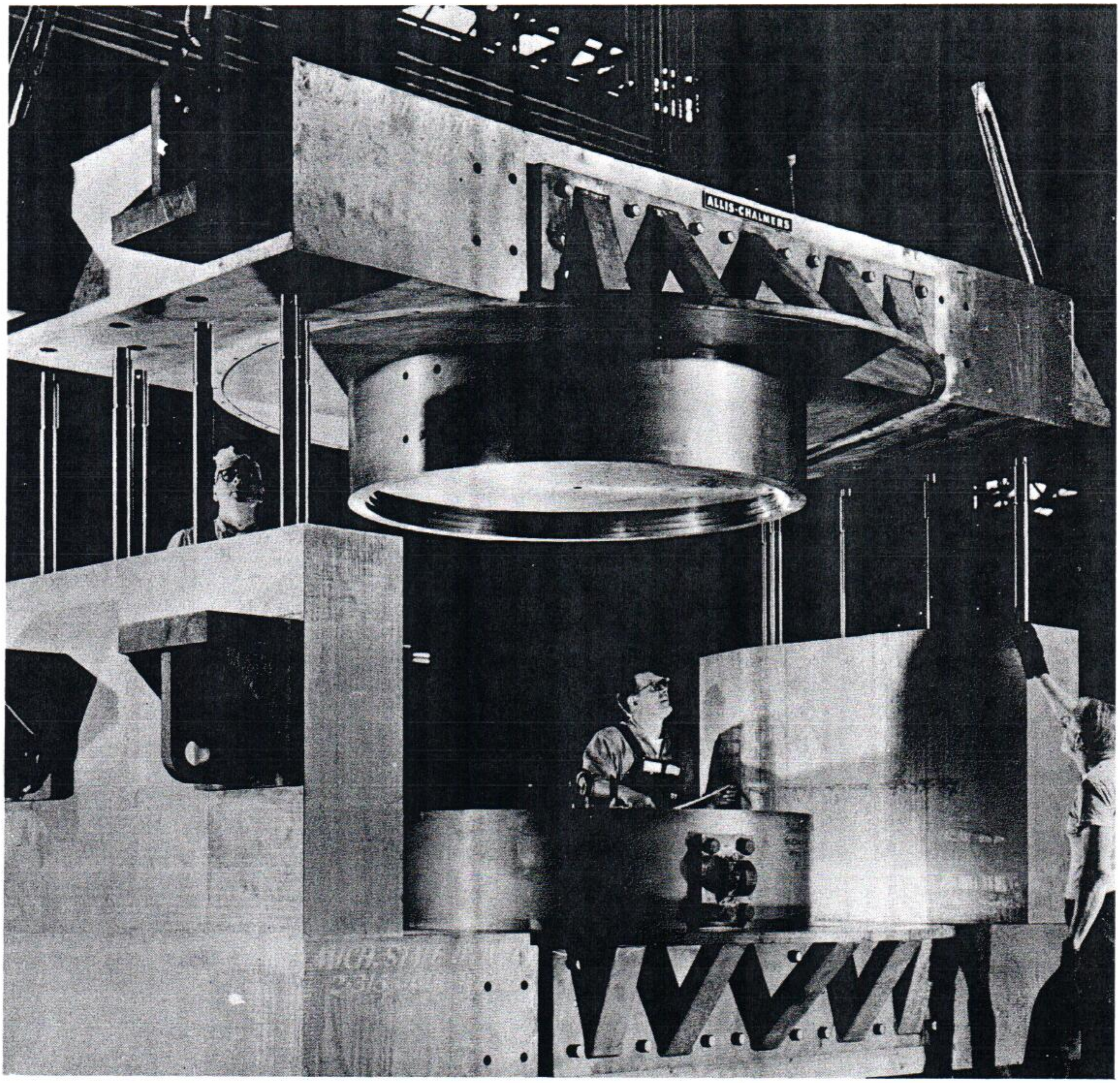

Fig. 2: Photograph of the cyclotron magnet core taken in the Allis-Chalmers plant in Milwaukee, Wisconsin. An overhead crane is in the process of lowering the 80,000 pound upper section into place.

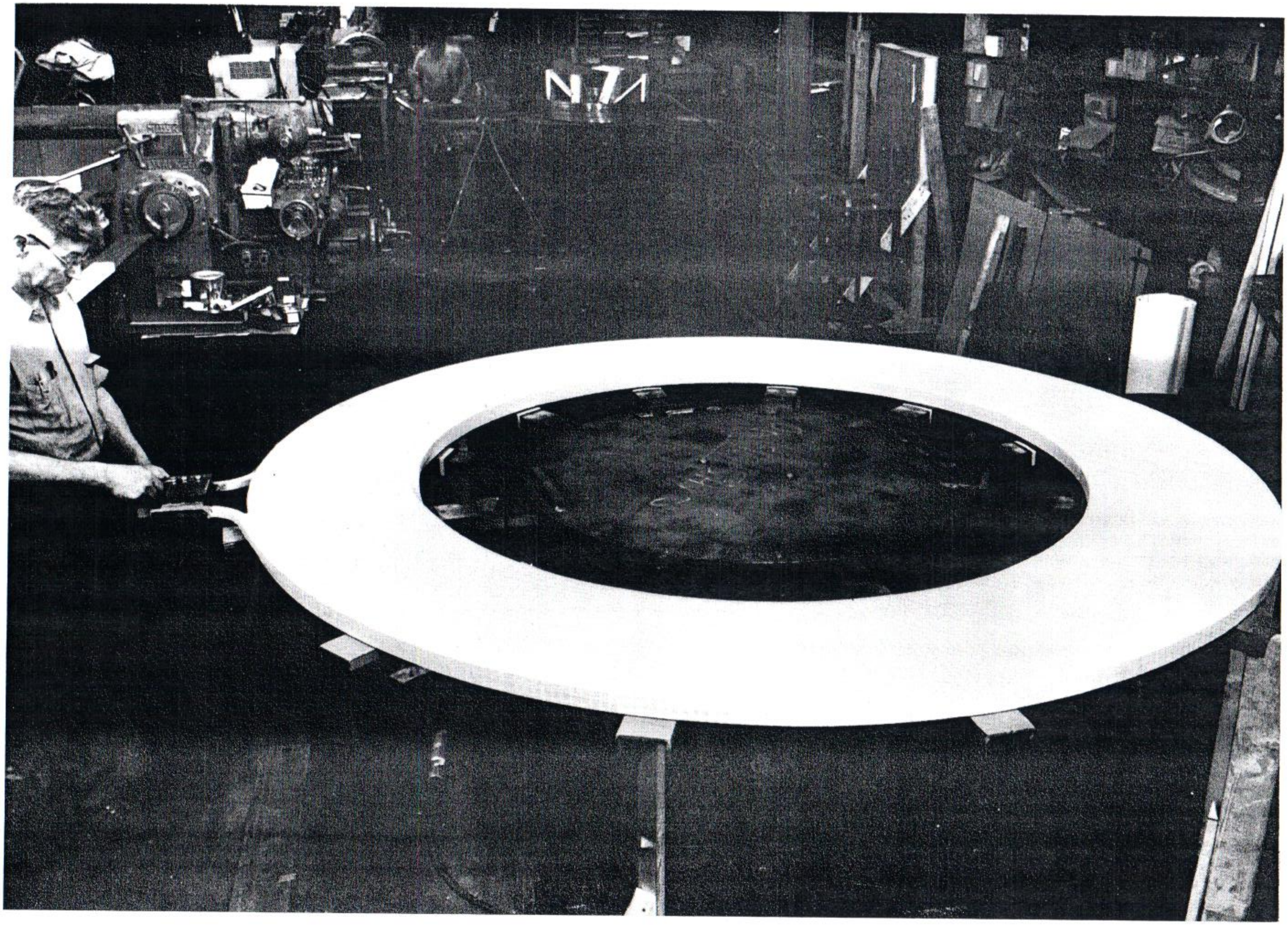

Fig. 3: Photograph of one of the main coil "pancakes" taken in the plant of the Westinghouse Corporation in Chicago, Illinois. Sixteen such pancakes, each containing approximately 1500 pounds of copper, are required to provide the main excitation for the cyclotron magnet. The "wire" used in winding the pancakes is of square cross-section, 0.8" x 0.8", and with an internal hole for the circulation of cooling water.

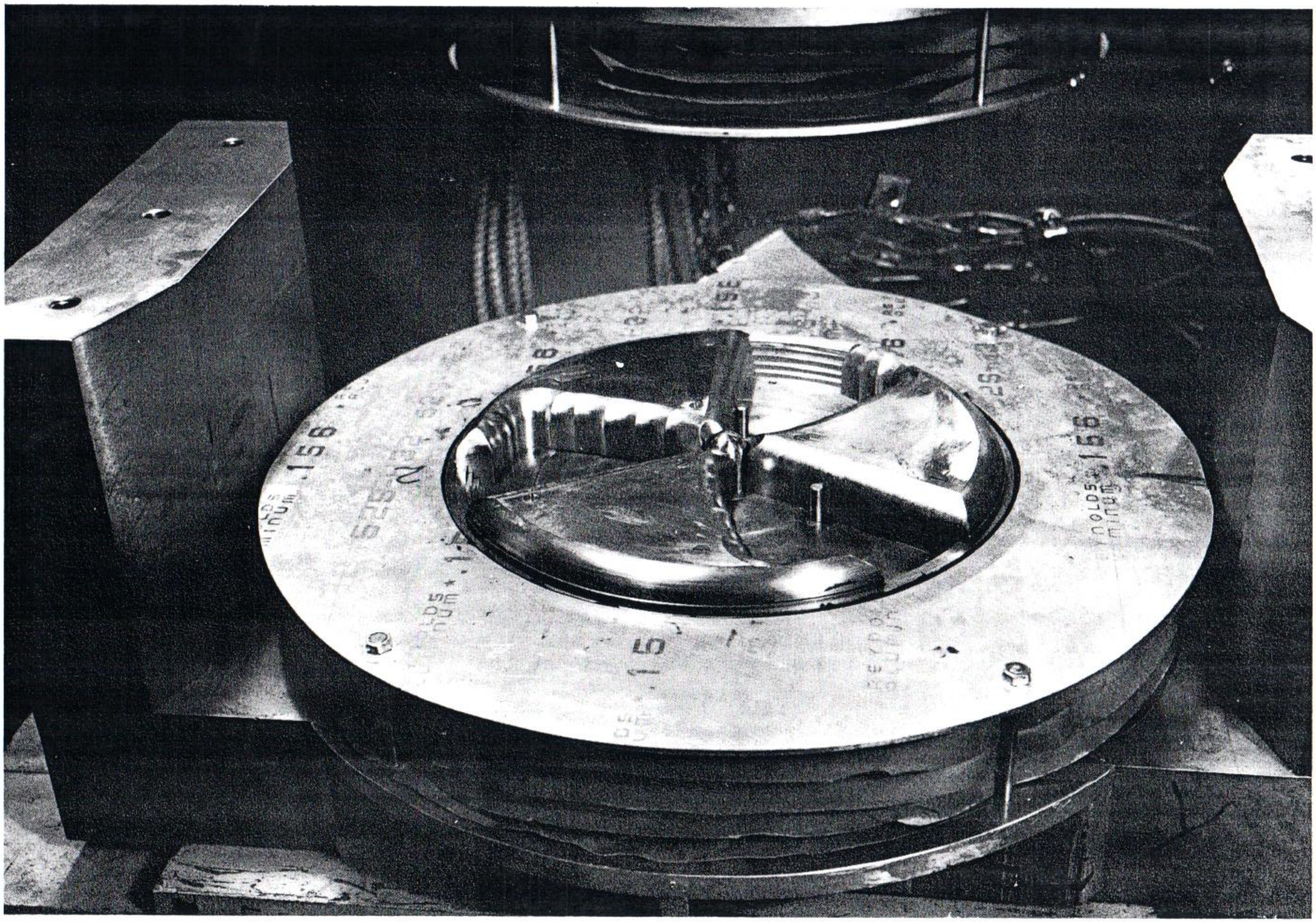

Fig. 4: View of the 1/6 scale model magnet used in designing the cyclotron. The upper half of the magnet is removed to give a clear view of the pole tips. The lower exciting coil is also in place.

The full-scale field measurements will be made using a specially constructed Hall probe assembly[2) with temperature compensation by means of thermoelectric coolers and with a positioning device borrowed from the University of Colorado. The Hall probe has been constructed and calibrated and the positioning device is on hand. The system will operate automatically in one coordinate (azimuthally) and will be manually moved in the other coordinate. As in the model measurements, data will be automatically digitized and recorded on punched cards by means of appropriate auxiliary equipment. Fig. 5 is a photograph of the positioning mechanism mounted in the Colorado magnet.

Referring again to Fig. 4 it will be noted that all protruding corners of the magnet pole tips are rounded. This rounding results in greatly reduced change in the field shape as the excitation of the magnet is varied (at high fields the equi-potential surfaces pull back from corners--if the magnet corners are cut to approximately conform to high field equipotentials, they will then remain in approximately the same form when the excitation is lowered). The effect of the rounded corners is illustrated quantitatively in Fig. 6 which shows the average field as a function of radius for four different excitations in the 1/6 scale model[3). The position of the outer field maximum, which determines the extraction radius, shifts by only 1/2" as the field strength is varied by approximately a factor of two (this is the maximum variation necessary in the magnetic field since lower energies can be obtained by shifting to lower e/m values of the accelerated ion). For

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2) J. A. Futhey, Michigan State Univ. Cyclotron Project Report No. 18 (July, 1963).

3) For more complete discussion of these studies, see Proc. of the 1963 CERN Cyclotron Conference, paper by H. G. Blosser.

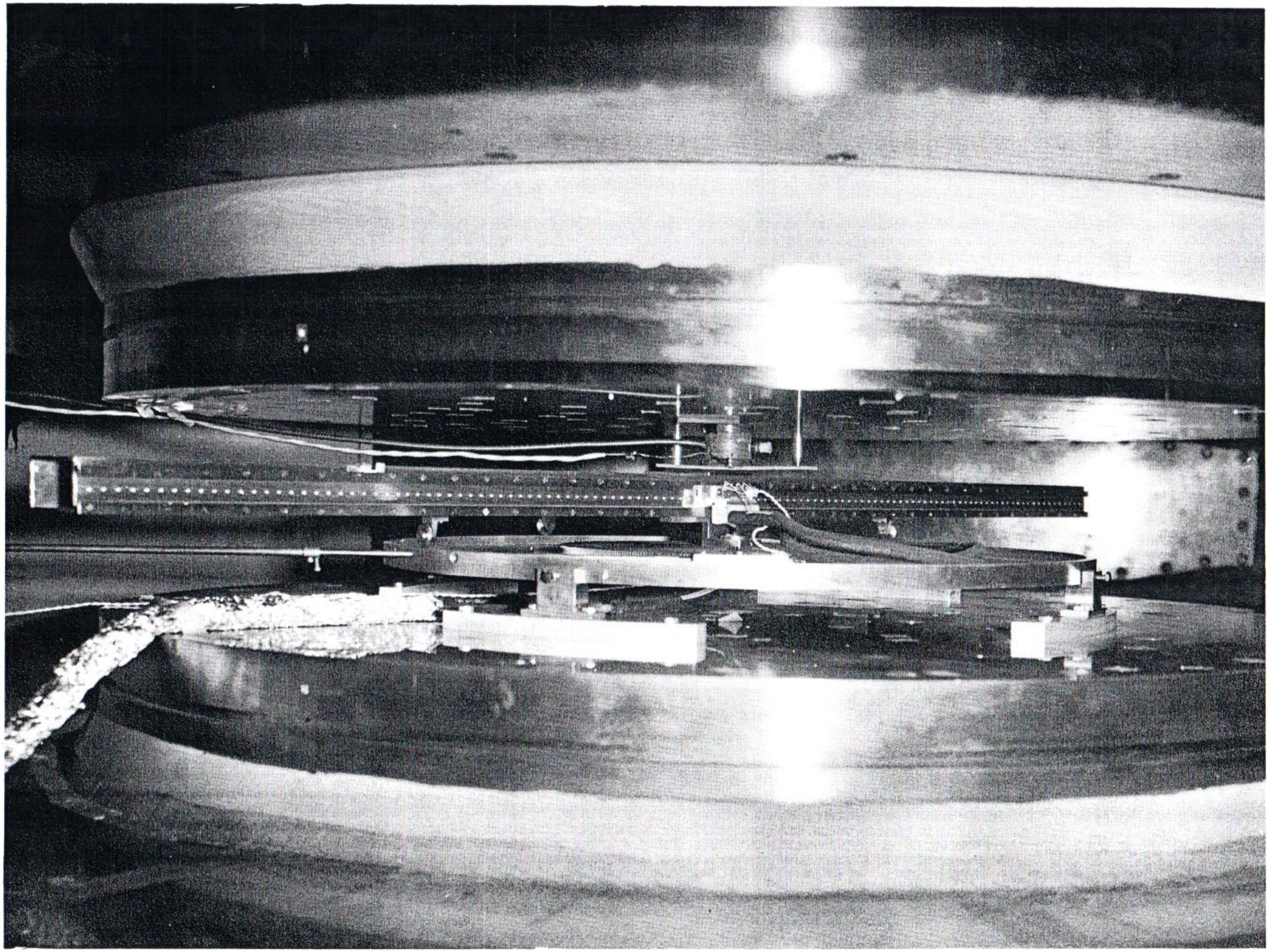

Fig. 5: Photograph of positioning equipment for field measurements borrowed from the University of Colorado. The equipment is shown in place in the Colorado cyclotron magnet.

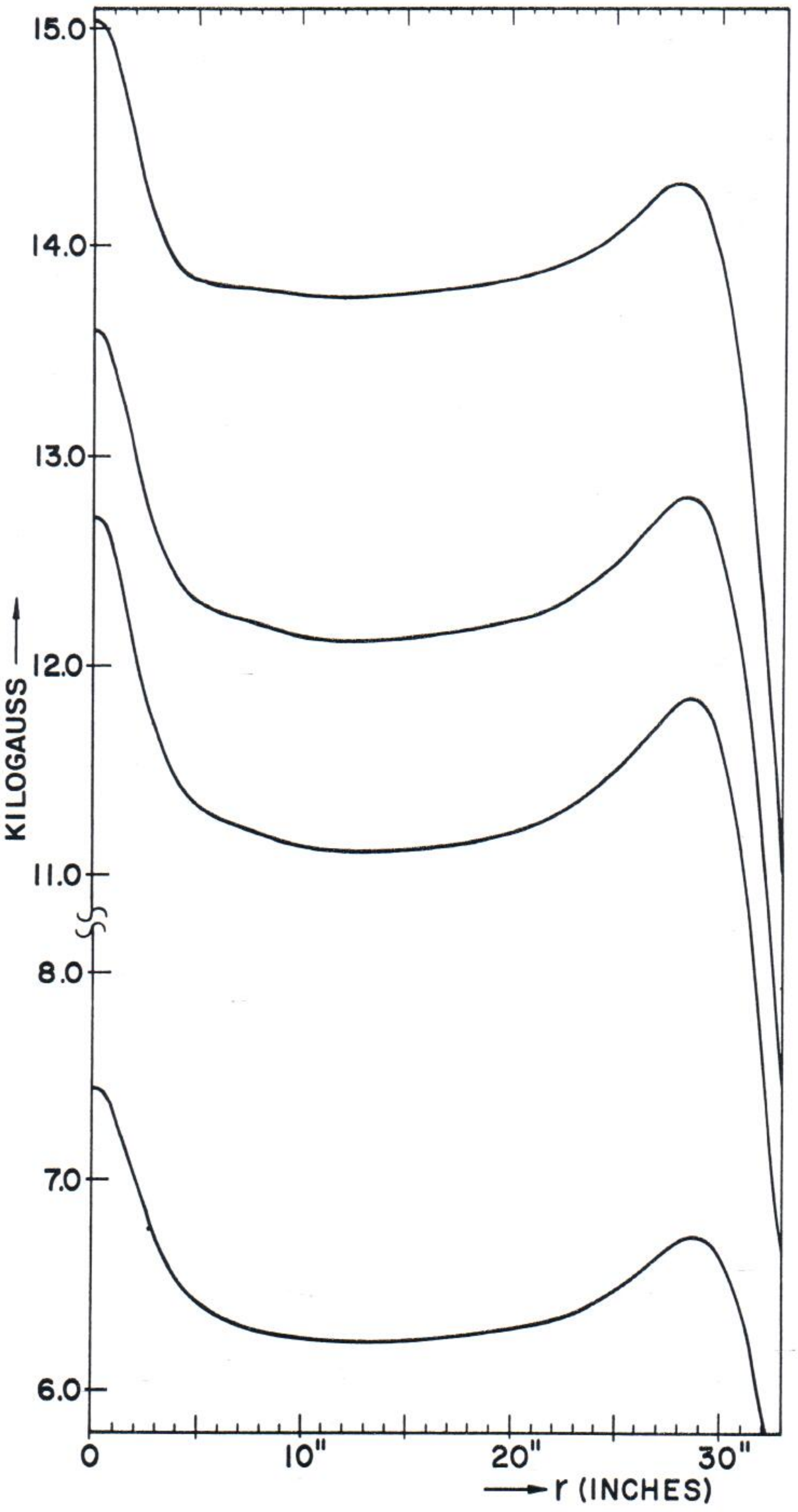

Fig. 6: Azimuthal average of the magnetic field at excitations of 415,000, 312,000, 264,000, and 120,000 ampere-turns.

comparison, the comparable shift with unrounded corners was in some cases as large as three inches. It should also be noted that one of the chief concerns in rounding of the corners—the cost of machining—proved to be unwarranted; the purchase cost of the pole tips for the MSU cyclotron is, for example, essentially identical to the cost of the considerably lighter pole tips for the Berkeley 88" Cyclotron.

The field data from the model magnet has been used to make an initial determination of the magnitude of the trimming currents required to adjust the field for acceleration of different ions. Since it is impractical to obtain measured data on trim coils in a 1/6 scale model, the computations have assumed air core coils which should result in an overestimate of the required currents. The results of these fitting calculations, together with computations of equilibrium orbit properties in the fitted fields, have been presented elsewhere3). The currents obtained were small; based on these results, the total connected power to the trimming coil sets has been fixed at 60 kilowatts—of this, it is expected that less than half will be in use at any given time.

2.2 Extraction

The character of the resonant extraction process has been changed considerably from the system described in the December, 1960 proposal4). The major physical change is the use of a much smaller field bump for triggering the resonance, i.e., roughly 2 gauss as compared with about 100 gauss. The smaller field bump produces substantially less turn separation than was obtained with the large bump (the separation is still adequate, however, to produce clean separation of individual turns), but

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4) For more complete discussion of these studies see Proc. of the 1963 CERN Cyclotron Conference, paper by M. M. Gordon and H. G. Blosser.

has the very favorable effect of increasing the extraction energy of the cyclotron and of decreasing the strength requirements on the electric and/or magnetic channel assemblies which pull the beam across the fringe field. Fig. 7 is a phase-space diagram showing the behavior of a beam-sized group of particles on the last several turns of the extraction process with the 2 gauss bump. The turn separation obtained is adequate for insertion of an electrostatic septum; in addition, the phase-space ellipse is seen to be relatively undistorted, as is needed to obtain clean images on external targets.

Recent studies on the extraction system have been devoted principally to detailed design of the electrostatic and magnetic channels. Results from Berkeley, Colorado, and Illinois5), establish that electrostatic deflectors having field strengths of 150 kilovolts/cm across a 1 cm gap are completely practical. In addition, model tests at MSU of possible magnetic channel designs indicate field reductions of up to 4 kilogauss are readily obtainable with simple, air-cored coils. In Fig. 8 the envelopes of two families of orbits are plotted on a magnetic field contour map, both groups of orbits having entered the deflector with a phase-space distribution corresponding to the last turn of Fig. 7. One of the groups is acted on by a continuing electrostatic deflector of strength 150 kilovolts/cm, while the other changes from electrostatic to magnetic deflection after an angle of 60°, the magnetic deflector having strength 4 kilogauss. The combination electrostatic-magnetic deflector bends the beam out of the cyclotron more rapidly than does the pure electrostatic

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5) See Proc. of the 1963 CERN Cyclotron Conf., paper by Bob H. Smith and discussion by D. A. Lind and J. S. Allen.

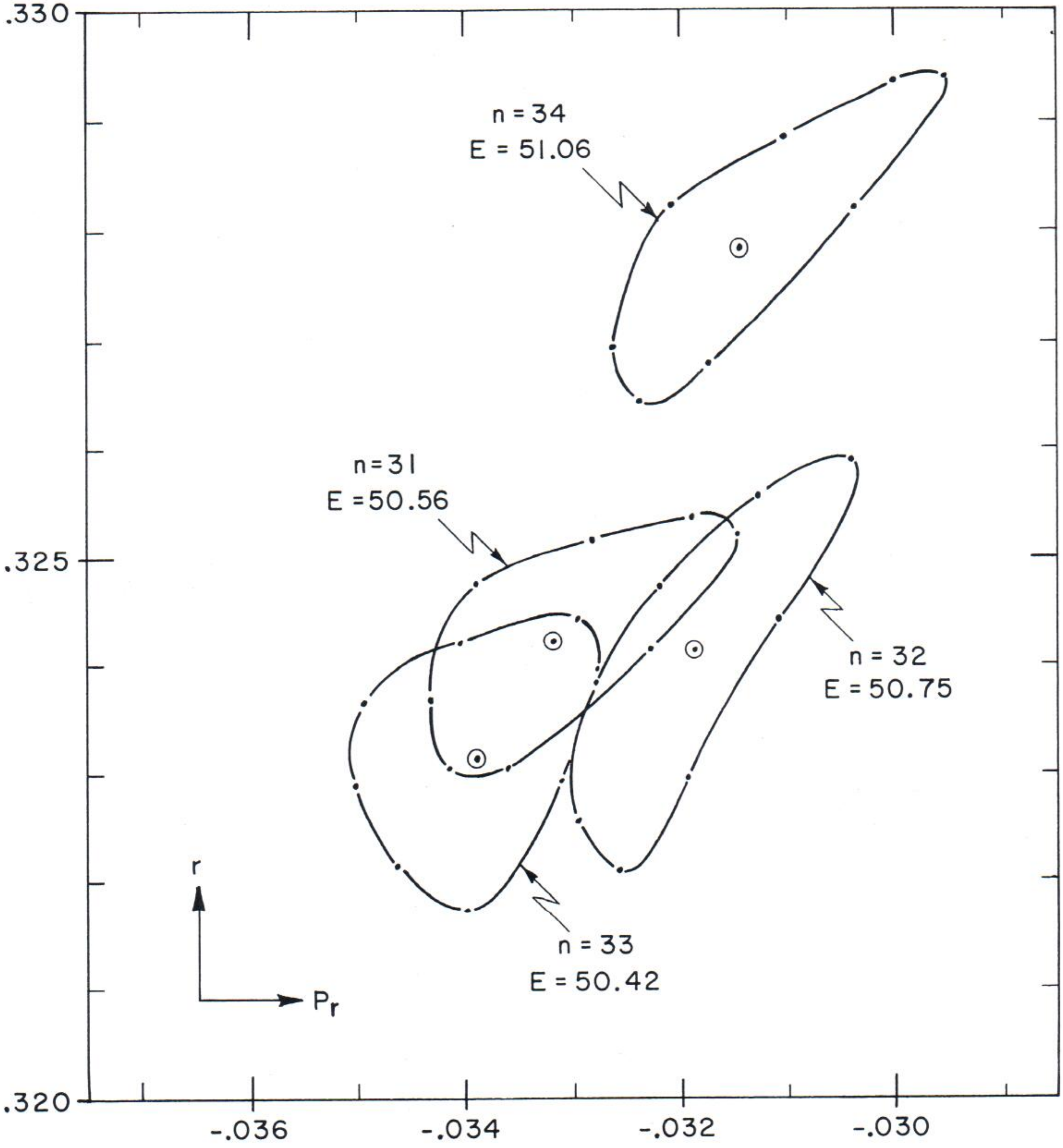

Fig. 7: Phase space plot (radius vs. radial component of momentum) showing behavior of beam sized group of protons on successive turns at the deflector entrance azimuth. The group of orbits originated at 43 Mev (7 Mev below the resonance energy); the number "n" in the figure is the number of revolutions from 43 Mev and E is the energy in Mev. The position of the central ray for the group on the successive turns is shown by the circled dot.

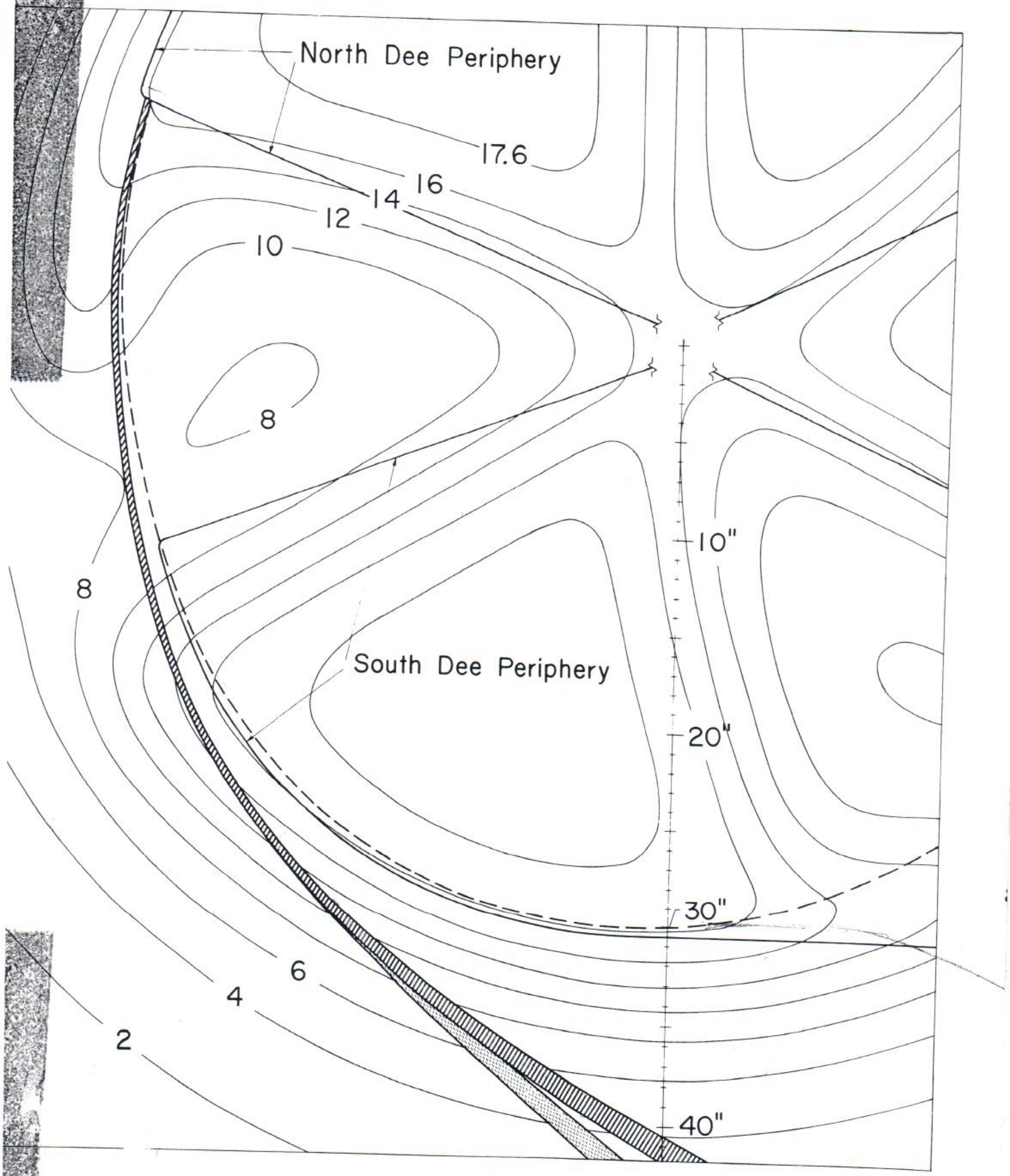

Fig. 8: Extraction orbits plotted on field contour map. The slant shading shows the region occupied by a family of trajectories continued from turn 33 of Fig. 7 and acted on by a 150 kv/cm electrostatic deflector. The deflector begins at the exit from the north dee and continues to the edge of the figure. The dashed shading shows the region occupied by a similar family of trajectories except that the electric field is terminated after an angular extent of 60° and a magnetic channel of strength 4 kilogauss begins. The dashed line inside the dees is the outer envelope of all of the trajectories on all previous revolutions.

system, as is desirable from the point of view of minimizing fringe field aberrations. Either of the two systems is, however, quite acceptable as can be seen in Fig. 9 which shows phase plots made at the end of the extractor in the two cases. The fact that both of the phase contours are quite nearly elliptical indicates that they can be refocused to a sharp image; design of an appropriate focusing magnet to be mounted between the main coils of the cyclotron is in progress.

At the present time, a final selection between a pure electrostatic deflector and a combination electrostatic-magnetic deflector has not been made. The pure electrostatic deflector is substantially more complicated mechanically since one or more hinge joints would be required—on the other hand such a system does not involve a stray field problem. Early in the measurement program on the full scale magnet, trial magnetic channels will be inserted and the stray field measured. If the stray field can be made sufficiently small, a final magnetic channel will be designed; otherwise, the electrostatic technique will be employed.

Present design thinking on magnetic channels is in terms of air core coils which are favored on the basis that such assemblies are the most readily calculable and are the most likely to perform properly in a variable energy machine, where saturation effects would presumably lead to difficult problems if magnetic materials were employed. Fig. 10 shows the air core magnetic field for several coil configurations under consideration. Model tests with a coil of configuration approximately corresponding to "A" in the figure actually indicate a much smaller external field than shown (corresponding to the external flux returning thru the magnet yoke rather than thru the magnet gap) and a higher internal field. These tests, as mentioned above, will be continued to a definitive conclusion, as soon as the full scale magnet is available.

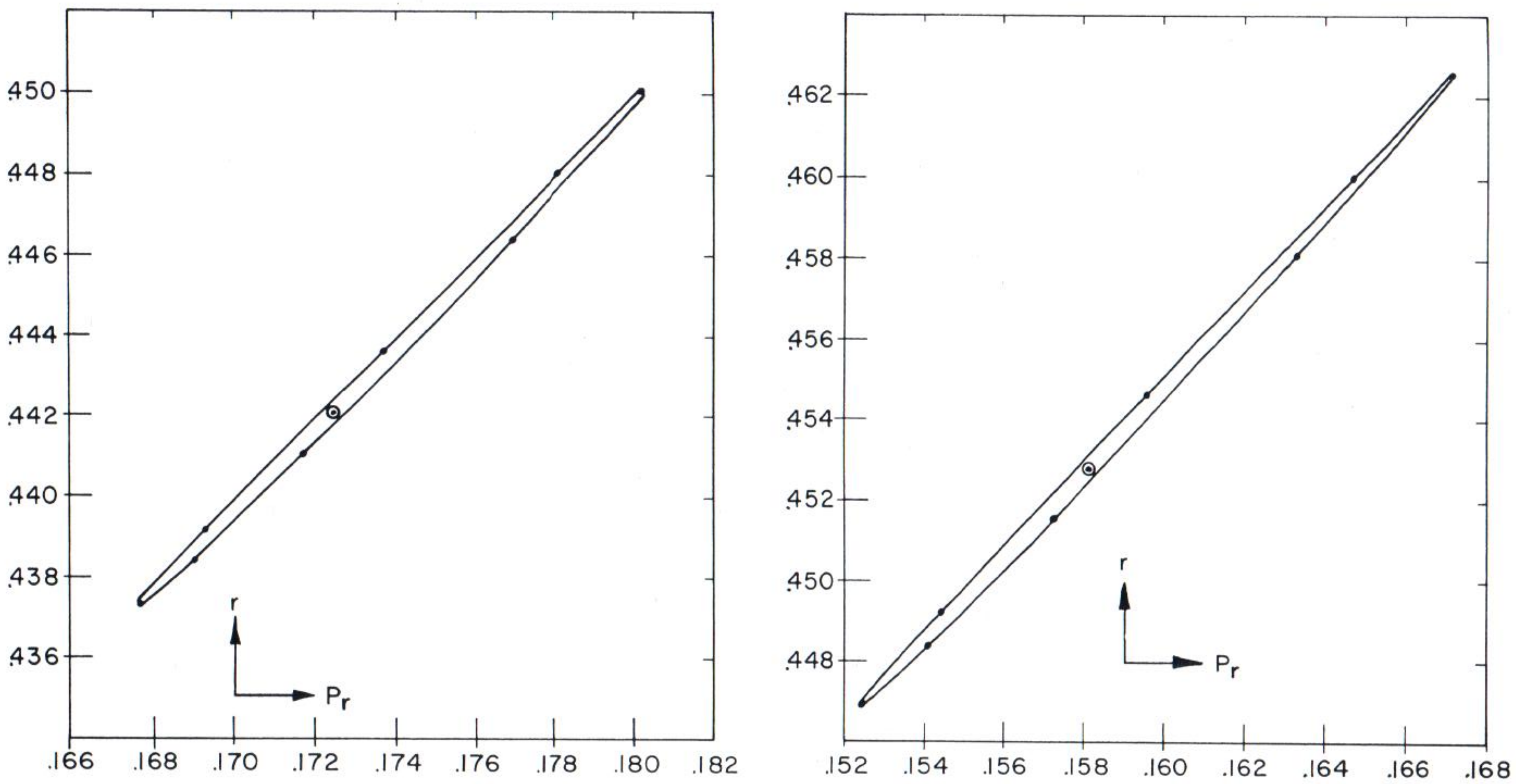

Fig. 9: Phase space distribution of the beams from Fig. 8 as they leave the extractor. Right: pure electrostatic deflector case. Left: combined electrostatic-magnetic deflector case.

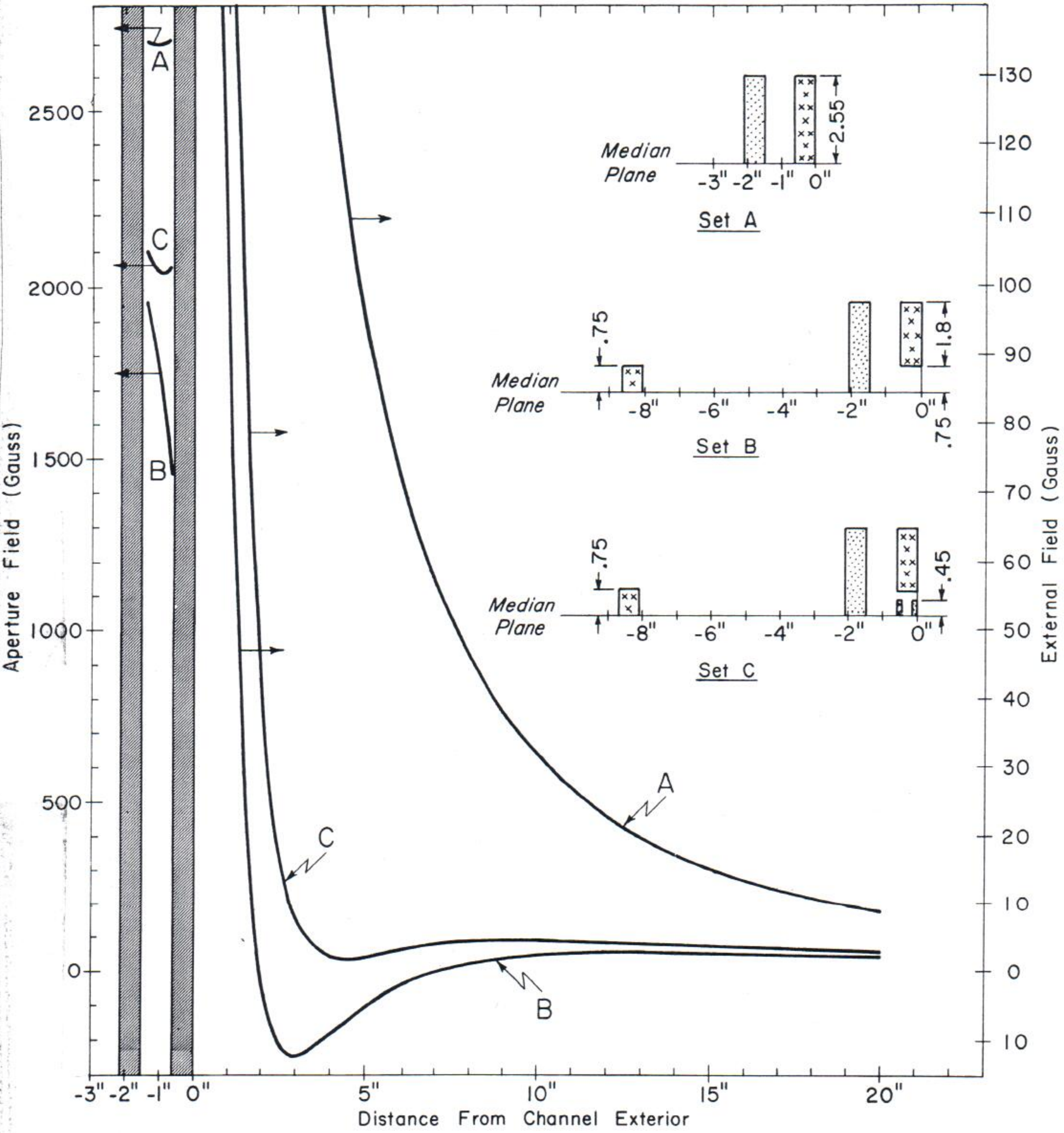

Fig. 10: Computed fields of several current distributions of interest in the design of a magnetic channel. The three distributions are shown at the upper right. All are symmetric about the median plane and are assumed infinite in length in the computations. The fields are for a normalized current of 1000 amps per "wire", a wire being 0.3" x 0.3" in size, including insulation. (The shaded area on the field graph denotes the region occupied by currents.)

The design of the electrostatic deflector will be copied after an arrangement developed by the group at Phillips of Eindhoven. The Phillips deflector has four adjustments, two controlling the aperture of the deflector at either end of the assembly, and two which move the two ends of the deflector in and out radially without affecting the aperture. The operator can adjust the deflector angle, for example, by moving the rear end of the deflector without affecting any of the other major parameters of the deflector. To accomplish this typical operational motion with other often used deflector designs would require carefully balanced adjustment of two controls.

2.3 Rf System

Fig. 11 is a photograph of the full-scale mockup of the rf cavity. The two dees are shown in the foreground while the tuning panels can be seen at the rear. The tuning range of the mockup matched prior design calculations to within approximately 5%. A difficulty with a resonance in the dee to dee coupling was eliminated by appropriate readjustments in the geometry of the resonant cavity6). A mockup of the final amplifier cabinet has been employed to drive the cavity, and the complete assembly has been scanned for unwanted modes up to a frequency of 100 megacycles. Several such modes were found—all have been successfully shifted from the operating frequency (or harmonics thereof) by appropriate geometrical corrections.

Fig. 12 is a diagram of the electrical circuitry of the rf system. The final amplifier employs two Eimac tetrodes in parallel driven by a Marconi broad-band amplifier of one

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6) See Proc. of the 1963 CERN Cyclotron Conf., paper by W. P. Johnson.

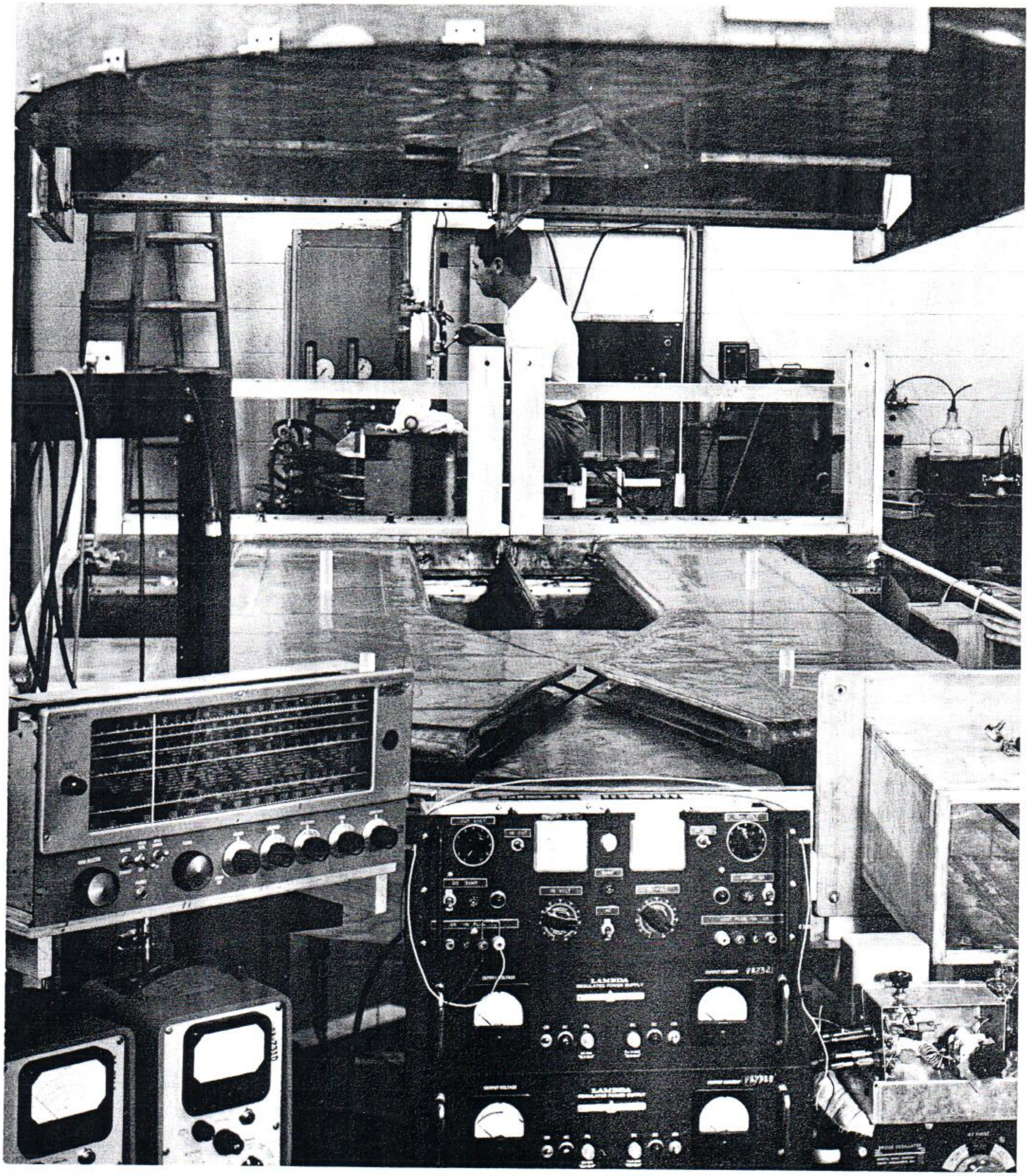

Fig. 11: View of full scale rf mockup. The 144° dees can be seen at the approximate center of the picture, with flat stems extending to the rear (the tuning panels are in the low frequency position). The upper half of the liner shows at the top of the picture. An early, breadboard mockup of the driver amplifier is at the lower right.

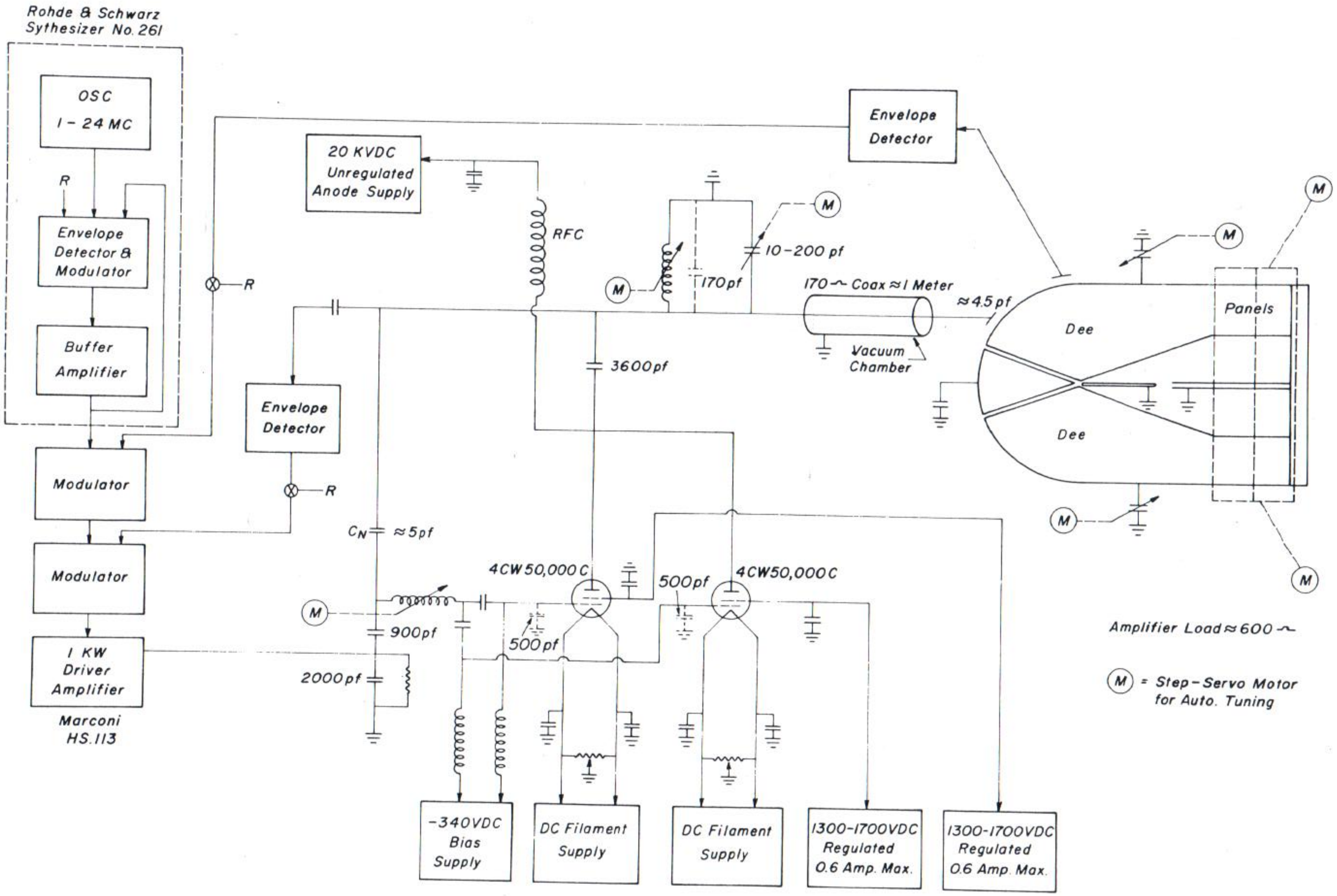

Fig. 12 Diagram of rf system circuitry.

kilowatt output. A Rohde and Schwarz frequency synthesizer is the frequency source for the amplifier system—since the system is operating in an essentially linear region, amplitude control can be accomplished by modulating the rf input to the Marconi amplifier. Both the synthesizer and the broadband amplifier are on hand and have been tested, and the modulators have been built. The Eimac tetrodes are due for delivery in early September. The mechanical design of the resonant cavity, including liner, tuning panels, and amplifier cabinet, is in an advanced state and should be completed and released for fabrication in the near future. The anode power supply for the rf system is presently on order and scheduled for delivery in December. The power supply is rated at 20 amperes at 21 kilovolts and is of solid state type.

The accelerative characteristics of the rf system on various harmonics are illustrated in Fig. 13. From the figure it is clear that the use of the second harmonic of the rf frequency for particle acceleration requires that the dee angle be less than 180° and, in addition, the dee system must be operated in the push-push mode. (A resonant cavity of the sort being employed for the MSU cyclotron always has such a mode with a Q essentially the same as that of the conventional push-pull mode—normally the push-push mode is regarded as a nuisance phenomenon.) The possibility of accelerating particles on even as well as odd harmonics was pointed out in the literature some time ago7). It is of course clear that the even harmonics involve a rather unusual problem in that, with the two dees always at the same instantaneous potential, there is a marked tendency for the electric field to vanish at the center of the cyclotron. In view of this, starting conditions must be carefully studied to insure proper performance in all modes as is discussed in the next subsection.

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7) M. J. Jakobson and F. H. Schmidt, Phys. Rev. 93, 303 (1954).

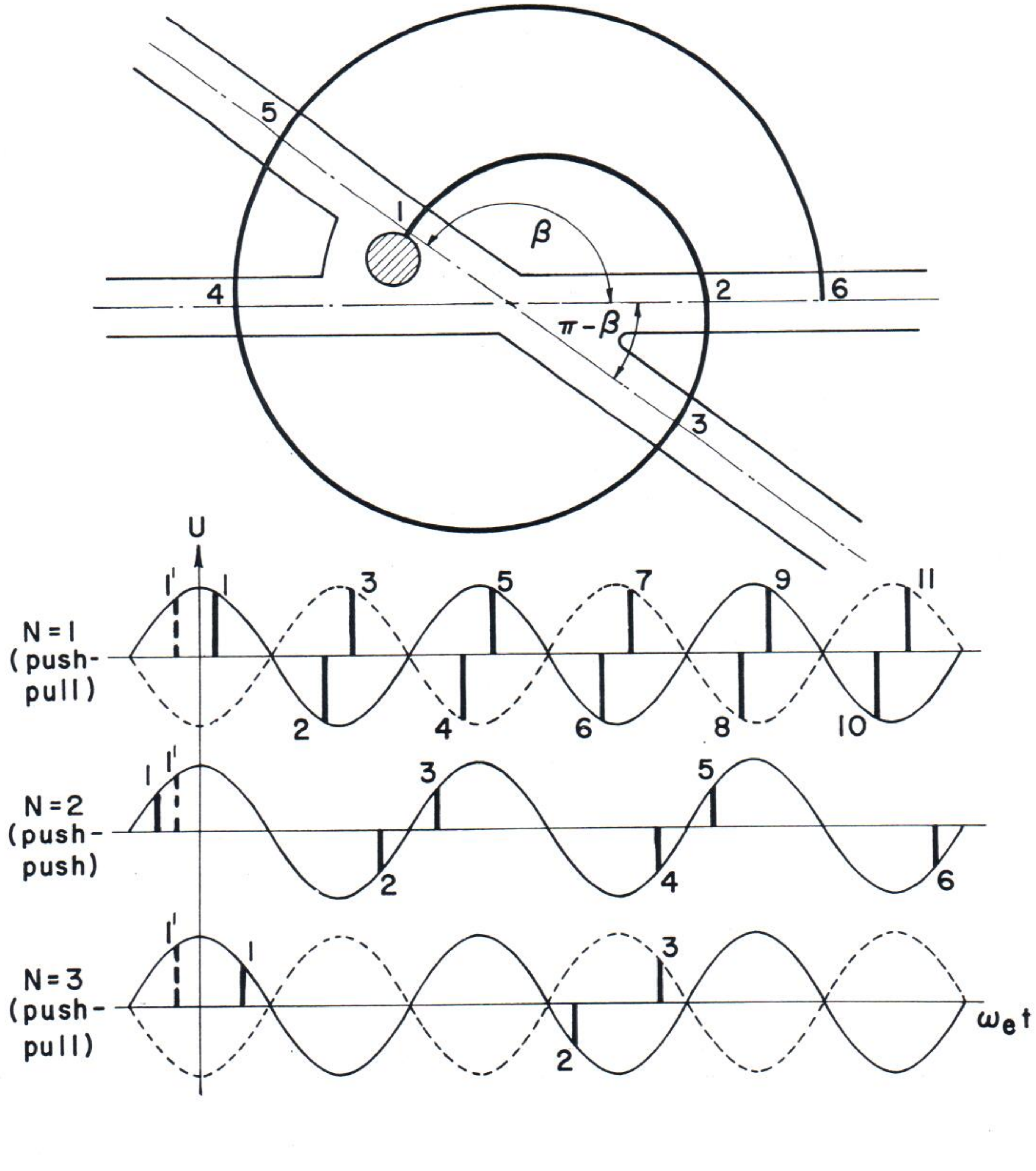

Fig. 13: Schematic drawing of acceleration sequence in a multi-mode dee system. Heavy vertical bars (1, 2, 3, etc.) mark gap crossing phase for maximum energy gain; dashed bar (1') marks the favorable starting phase.

2.4 Central Region Studies

As mentioned above there is a tendency for the electric field to vanish near the center of the cyclotron in the push-push mode. A system of slits is necessary to insure a proper electric field configuration. In addition, as can be seen by reference to Fig. 13, the phase at which maximum energy gain occurs lies on opposite sides of the rf wave for push-pull and push-push modes, whereas for all modes the optimum time for particles to leave the ion source occurs prior to the peak of the voltage[8) at approximately the position indicated by the dashed bars of Fig. 13. The phase of maximum energy gain per turn also marks the point of neutral first order electric focusing. On the early turns these electric forces are so strong as to have disastrous effects on the beam if they are allowed to produce defocusing; it is therefore necessary to rapidly shift the beam to a focusing phase. From Fig. 13 it is clear that differing amounts and direction of phase shift are required for the odd and even harmonics. To accomplish this shift in the actual cyclotron, a movable puller is attached to one dee, pivoting about an axis attached to the dee (the actual movement of the puller slit will be accomplished by engaging a coupling shaft which comes down along the axis of the magnet when the rf voltage is off). The movable puller slit and the configuration of electrodes are shown in Fig. 14. In addition to moving the puller, it is also necessary to move the source; this will be accomplished by providing two tracks thru one of the dummy dees, the source being inserted from the side of the vacuum tank as at Oak Ridge. A central hole has also been provided in the magnet core to allow for possible later insertion of a source along the magnet axis as at Berkeley, or for possible use with an external polarized ion source.

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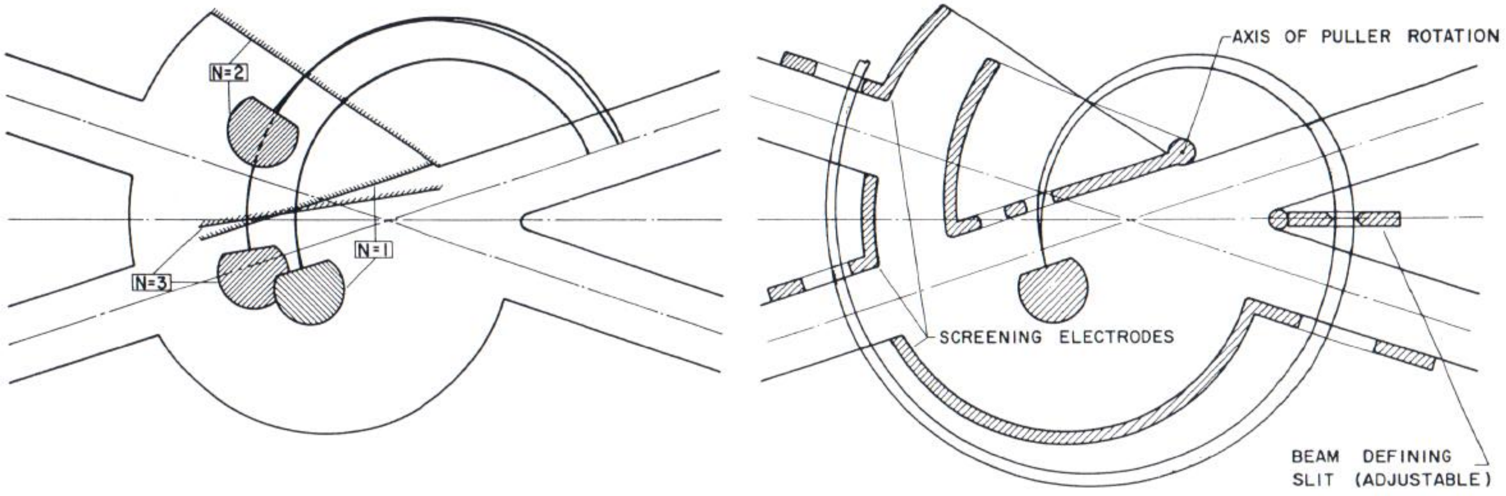
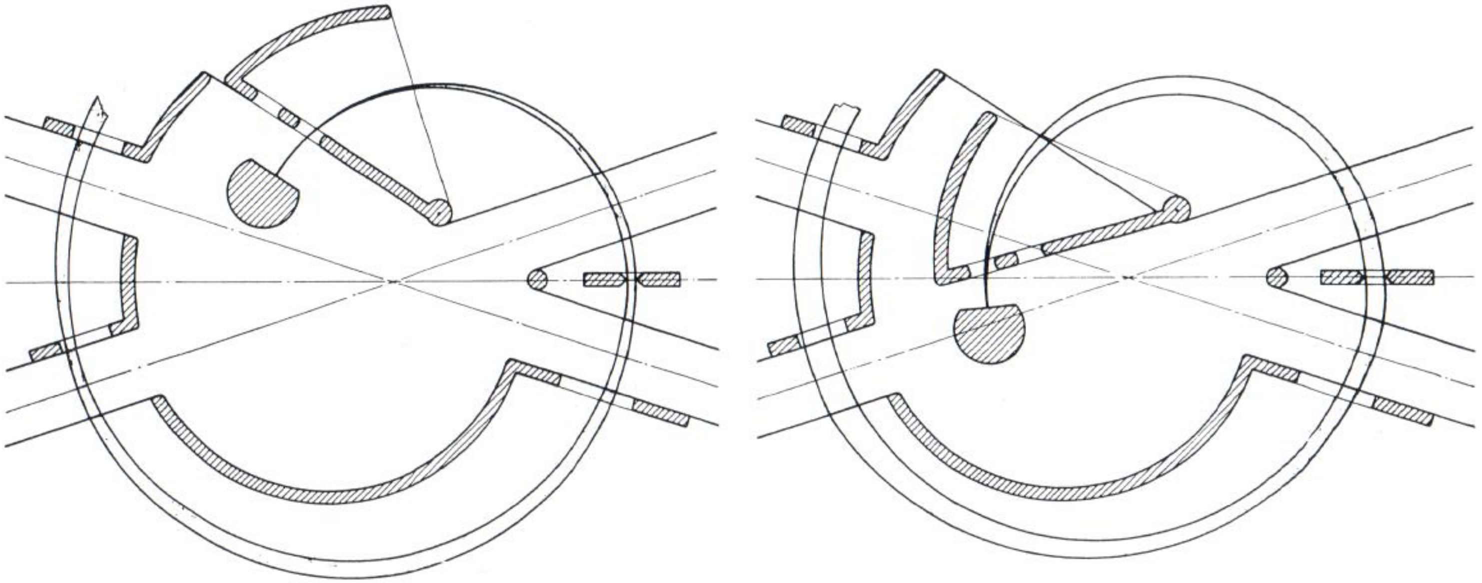
8) For more complete discussion see Proc. of the 1963 CERN Cyclotron Conference, paper by H. G. Blosser, M. M. Gordon, and M. Reiser.



a) Calculated optimum positions of source and puller

b) Central geometric arrangement with ion source, puller and defining slit in the N=1 position (push-pull mode)



c) Source, puller and defining slit in the N=2 position (push-push mode)

d) Source, puller and defining slit in the N=3 position (push-pull mode)

Fig. 14: Sketches showing, (a), calculated central geometry for the MSU cyclotron and, (b), (c), (d), the geometry of the actual electrode system with puller and source positioned for the three major modes. In each of the sketches the dees are at top and bottom and the dummy dees at right and left.

The dominant character of the electric field in the cyclotron central region makes the computer programs employed in the remainder of the cyclotron inadequate for detailed study of central region orbits (these programs approximate the electric field by a delta function acceleration). A series of special central region programs have, therefore, been prepared[9] as follows:

(a) For an initial survey of median plane motion in various central geometries a program known as "Cop" is employed in which the accelerating gaps are represented as square-wave fields (constant electric field within the gap, zero electric field out of the gap, sinusoidal time variation) and the magnetic field is uniform.

(b) For detailed survey of a particular geometry the "Cartwheel" program is employed. This program integrates complete median plane equations in arbitrary electric and magnetic fields. The fields are carried as a mesh of data points. The electric field is derived from electrolytic tank or other analog studies.

(c) The third program "Silax" also has complete median plane equations and, in addition, has axial equations accurate thru linear terms. The electric field in this case is restricted to a model based on the known conformal mapping solution for a standard accelerating gap. The field is a correct representation of 180° dees without puller slits, etc., and for other dee angles is qualitatively correct.

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9) T. I. Arnette, H. G. Blosser, M. M. Gordon and D. A. Johnson, Nuc. Inst. and Meth. 18, 19 (1962) 343.

To obtain accurate electric field information for use with the computer programs, a three dimensional electrolytic tank and a triple size mockup of the cyclotron central region have been constructed, and measuring apparatus has been assembled for determining the electric field to an accuracy of approximately 0.1%. Fig. 15 is a photograph of the central region model. The field in the tank is automatically scanned using the same positioning and recording equipment as in the model magnet studies.

Using the electric field data and the previously described computer programs, extensive studies have been made of the poorly understood central region of cyclotrons, the results of which have been recently reported 8). The studies establish that the proposed central geometry will provide well-centered orbits on all modes of operation.

The central region studies have also explored and established the feasibility of a system for accomplishing sensitive phase selection near the center of the cyclotron by means of axial slits. The system depends on the powerful influence of the electric field on the first several turns which causes the axial motion to be radically effected by rf phase, and thus allows selection of phase by means of slits placed to select certain axial trajectories 8). Since phase selection is equivalent to selection of particles which would survive the extraction process as against those which would not, the phase selection will be of great importance in minimizing activation of the cyclotron and in reducing background in experimental areas. The axial slits will be remotely adjustable so that they can be opened wide when using the high duty cycle mode of operation described in the next subsection. The phase selection process, in addition to improving extraction efficiency, opens the way for development of an extremely high resolution, time-of-flight capability.

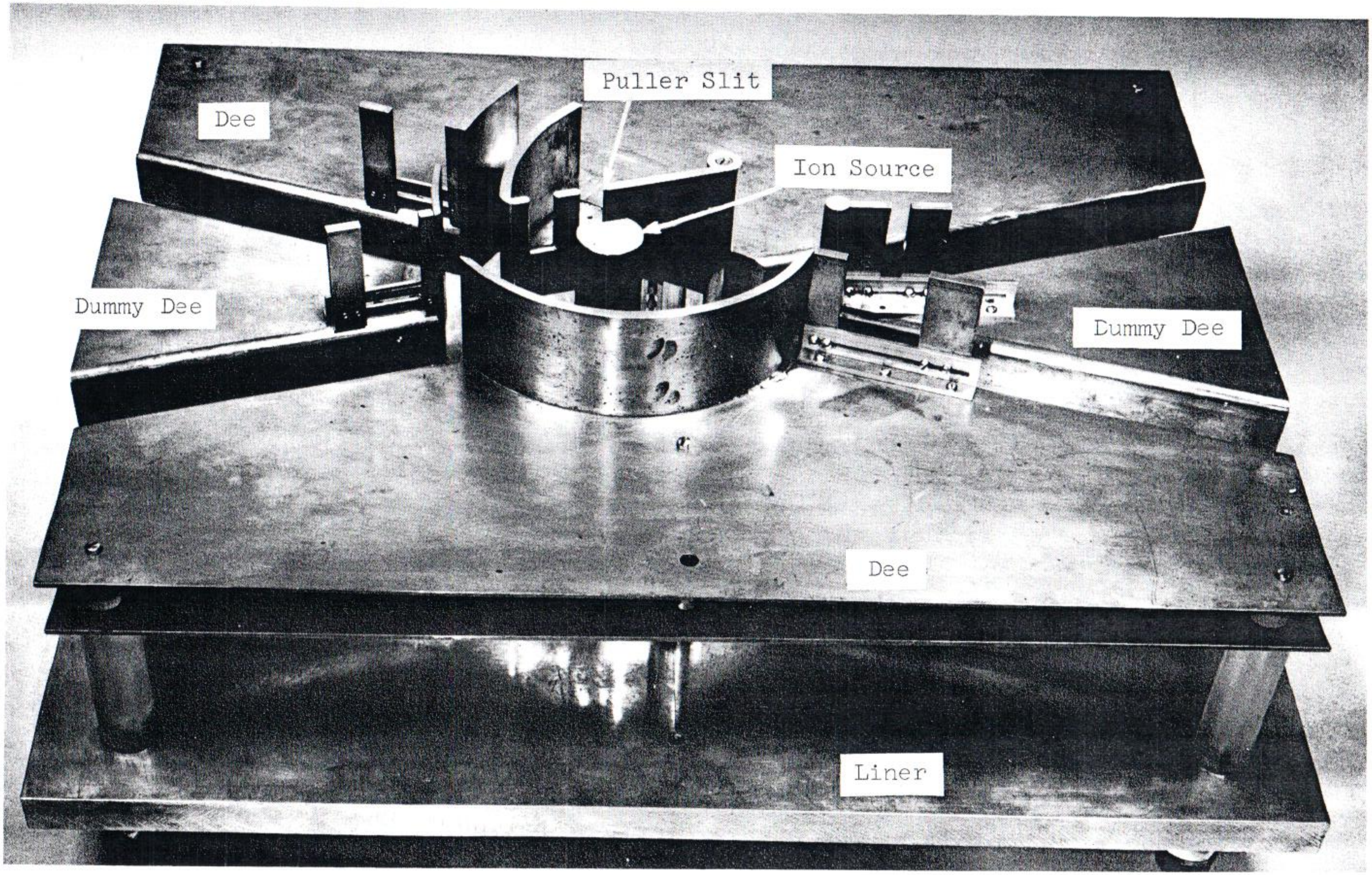

Fig. 15: Electrolytic-tank model of the central region with geometry as per Fig. 14 (source and puller in the $N = 1$ position). Due to the symmetry of the problem it is only necessary to fabricate the structures on one side of the median plane. The top surfaces of the various electrodes and slits at the center of the picture mark the median plane. This is also the water surface for the measurements.

2.5 Negative Ion Operation and High Duty Cycle

A large number of modern nuclear physics experiments involve the application of coincidence techniques. In such an experiment, a pulsed accelerator is always at considerable disadvantage since the signal-to-noise ratio in the experiment depends inversely on the instantaneous counting rate, and for given average current the instantaneous current in a pulsed accelerator is accordingly higher over the effective data collecting period. Though fixed frequency cyclotrons are "continuous" as contrasted with fm cyclotrons, nevertheless both internal and external beams are pulsed when viewed with equipment of high time resolution such as is presently in typical use in many nuclear experiments. The internal beam pulsing arises from (a) the fact that the voltage is decelerating in the cyclotron for half of each rf period, and from (b) a phenomenon known as phase grouping, which for conventional central geometries tends to pull particles together into a tight phase bunch. As a result of these two effects the internal beam of most cyclotrons has a duty cycle of about 10%. In addition to the internal beam pulsing, conventional extraction techniques introduce an even tighter grouping due to the fact that variation in energy gain per turn as a function of rf phase, shifts the turn pattern such that the beam, rather than passing cleanly thru the channel, exactly collides with the septum. The pulsing introduced by this phenomenon reduces the duty cycle to values which are typically in the 1 to 2% region. This pulsing by the extraction process follows directly from the presence of a septum, i.e., from the presence of a spatial region which can not be traversed without loss of beam. At the 1962 cyclotron conference in Los Angeles the Colorado group announced the successful acceleration of negative hydrogen ions in their cyclotron[10]. If negative ions are accelerated, a thin foil can

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10) M. E. Rickey and R. Smythe, Nuc. Inst. and Meth. 18, 19 (1962) 66.

be inserted to accomplish extraction of the ions by electron stripping. Such an arrangement is in effect a septumless extractor, since particles which miss the foil continue to accelerate, eventually hitting the foil and being extracted. With a system of this type the duty cycle in the external beam is then the same as that of the internal beam, since all particles are eventually successfully extracted. If this system is combined with a central region design which largely eliminates phase grouping, duty cycles of up to 25% can be readily achieved. Detailed studies of operation in this mode have been made for the MSU cyclotron and reported on11). The results establish the definite practicality of 25% duty cycle. (In addition, schemes have been proposed12) and are under study which could lead to duty cycles in the 60 to 80% range, i.e., equivalent to Van de Graaffs for all practical purposes.)

This high duty cycle mode of operation is unfortunately restricted to hydrogen ions, since these are the only ions which reach interesting energies in a cyclotron when accelerated in a singly charged state (which is certainly the only practical state to consider for negative ions). In addition, the high duty cycle mode of operation increases the energy spread in the external beam by a factor of about 5, up to roughly 1%. There is, nevertheless, a large class of experiments in which operation in this high duty cycle mode will represent a major improvement in the experimental situation.

In addition, the acceleration of negative ions makes feasible ultra-high energy-resolution experiments; this topic is further discussed in section 3.2.

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11) See Proc. of the 1963 CERN Cyclotron Conference, paper by M. M. Gordon.

12) J. R. Richardson, UCLA Report No. 52 (Sept., 1962).

2.6 Source Testing Facility

Development of cyclotron ion sources has been grievously neglected as contrasted with the diligent efforts devoted to improvement of Van de Graaff sources. As Cohen has pointed out[13], for a given experimental situation (fixed spatial, angular, and energy resolutions) the phase-space density of the accelerated beam is the quantity which determines the data collection rate (and hence often the feasibility of the experiment), and since the phase-space density of the external beam is in large measure determined by the ion source, it is of great importance to have an effective source. The fact that cyclotron type sources have received essentially no attention as regards improvement of phase-space density, leads to the expectation that such studies will prove highly fruitful.

A facility for testing cyclotron ion sources has been designed and is in the process of construction and assembly. The facility is of general purpose design and will allow testing of essentially any type of source. The facility will be used (a) for studies to improve the phase-space density of cyclotron sources, (b) for development of sources for novel ions including negative ions ,and (c) for testing of newly manufactured sources prior to insertion in the cyclotron, thereby minimizing loss of cyclotron time due to defective sources.

The magnet for the source testing facility has been completed and field measurements on the design of the shim-rings are now in progress. The vacuum chamber has also been completed and tested for leaks and found to be vacuum tight. Design and construction of the probes and of the initial source assemblies are in progress. "Calutron"

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[13] B. L. Cohen, R.S.I. 33, 85 (1962).

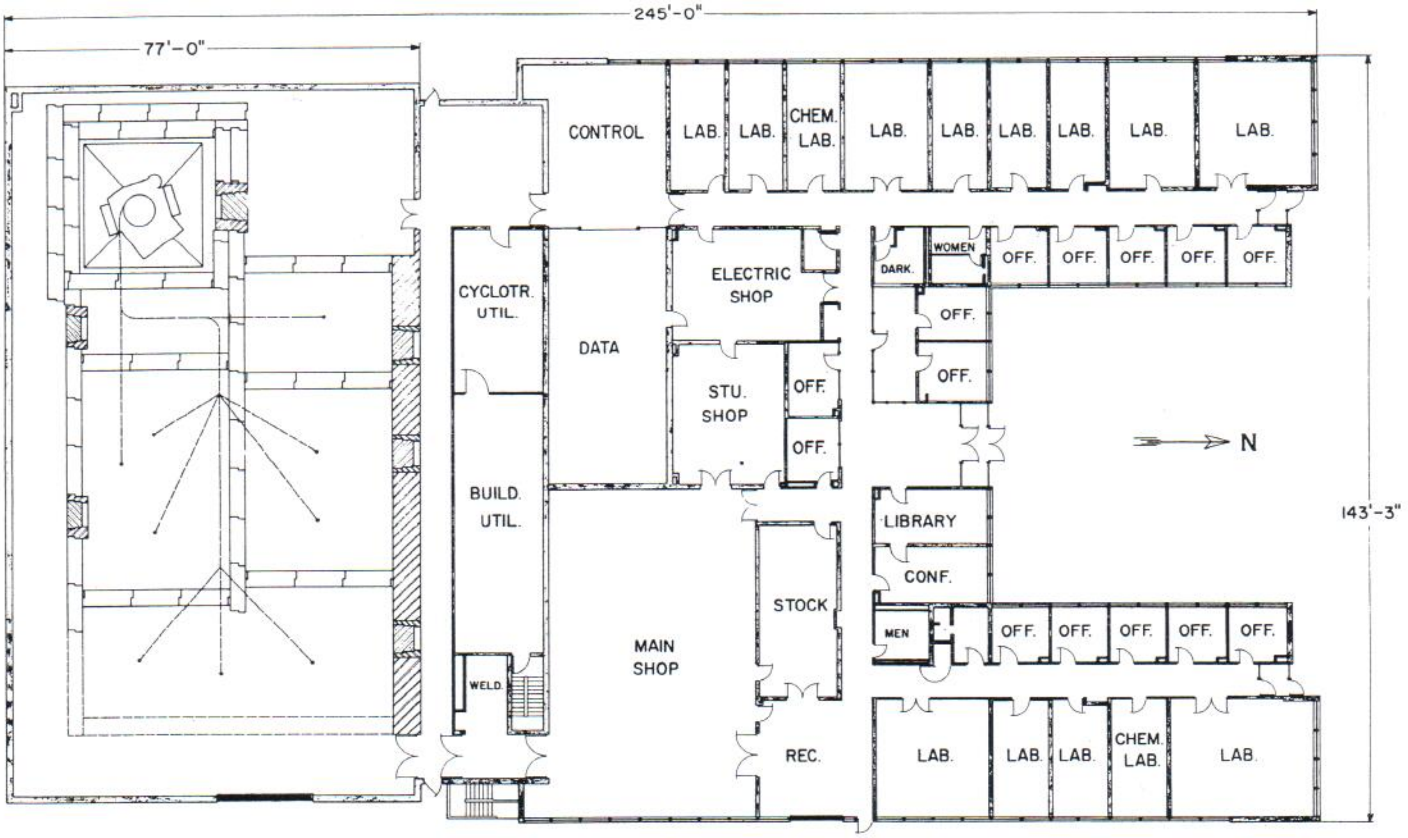
power supplies for the source, complete with high voltage isolation transformers, have been loaned by the Oak Ridge National Laboratory.

3.0 Experimental Areas and Equipment

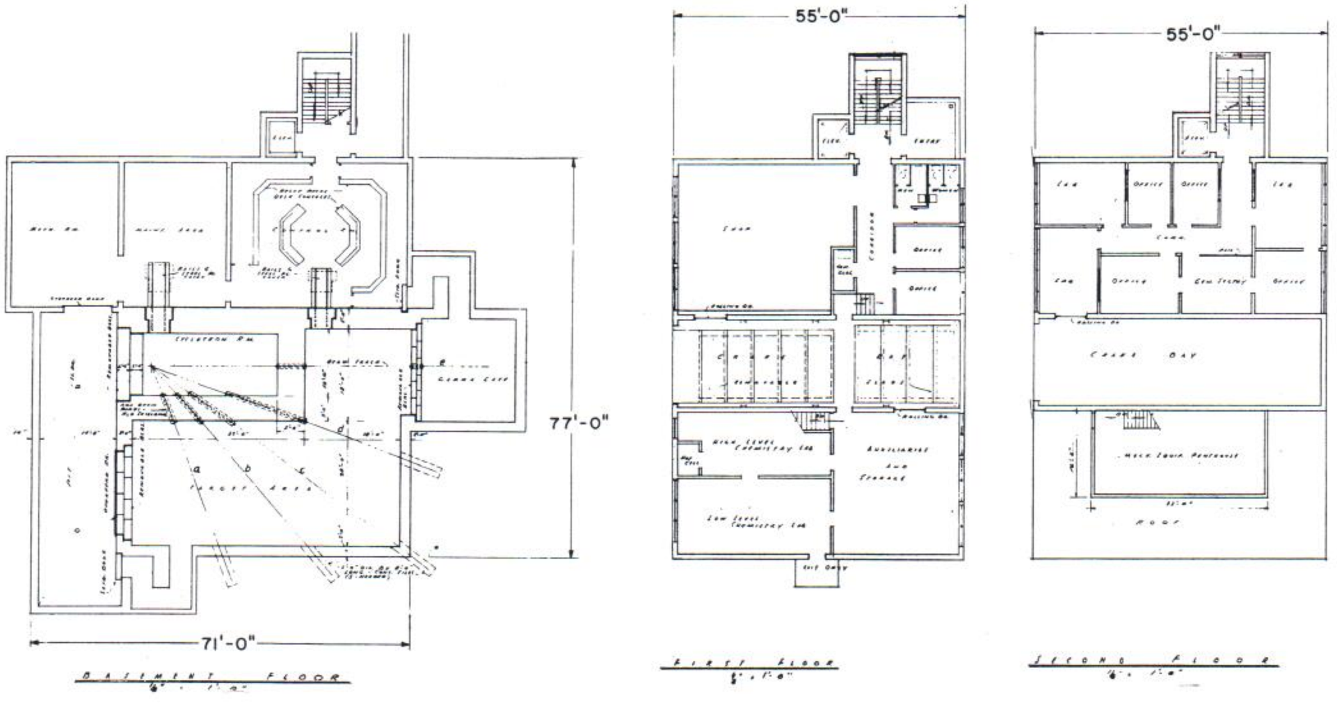
Due to a shift in site necessitated by long range campus planning considerations, a single floor arrangement became more appropriate for the cyclotron building than the previous multi-story plan. Fig. 16 shows both the present floor plan and that from the 1960 proposal. The present floor plan, in addition to the convenience of a one story arrangement, provides vastly more floor space (more than three times as much), thus achieving a better match with the enhanced versatility and energy range of the cyclotron. The cyclotron building is currently in an advanced stage of construction with completion scheduled for September.

3.1 Building Features

As can be seen in Fig. 16, the floor plan provides a ring of 14 offices looking onto an open courtyard. Across the halls from the offices are rows of general purpose laboratory rooms for use in initial assembly and testing of experimental apparatus and for equipment involved in experiments with radioisotopes (one of the lab rooms has a special 3-foot diameter, 100-foot deep hole for use in low background experiments). In the east-central portion of the building is located a shop cluster consisting of a receiving room, the main machine shop, a stock room, a student shop, and an electronics shop. The access path from the main shop into the experimental areas will normally be kept locked so that the only access to these areas is thru the control room at the upper center. The south third of the building is a high bay area for housing the cyclotron and experimental areas. A poured-in-place shield wall, indicated by the slant-shading in Fig. 16, separates the experimental areas from the remainder of the building; otherwise, shielding



PRESENT CYCLOTRON BUILDING PLAN



1958 CYCLOTRON BUILDING PLAN

Fig. 16 — Top: Floor plan of the present cyclotron building. Bottom: Floor plan of the cyclotron building as envisaged in the December, 1960 proposal. The total useful floor area of the 1960 design is smaller than the high bay area alone from the present design. (The high bay area is the 77' wide section at the south of the present building.)

is of stacked-block construction.

The shielding arrangement can be seen in Fig. 17 which is an artist's sketch of the building viewed from the southwest corner. The high bay area is spanned by a large overhead crane of 40-ton capacity which will be used both for assembly of the cyclotron and for handling of shield blocks. Each experimental room is provided with a hydraulically actuated shield door rising on a standard elevator-type ram from a below-floor pit (these doors are similar to doors used on the Argonne 60" Cyclotron and on the CERN Proton Synchrotron). Primary beam paths are indicated by the dashed lines in Fig. 16 and by the heavy black lines in Fig. 17.

3.2 Beam Analysis System

The primary beam analysis system consists of a pair of double focusing 90° magnets placed in a separately shielded room immediately downstream from the cyclotron. This system has the attractive property of providing either high resolution or high transmission simply by a repositioning of the object slit for the system, which will be accomplished remotely by providing two adjustable slits and appropriate quadrupoles for focusing the beam from the cyclotron on either slit. In the high transmission case the initial object is positioned at the focal point of the first 90° magnet, producing an image at the after focal point of the second 90° magnet. To first order, particles of all momenta image at the same point, hence yielding essentially complete transmission (limited only by nonlinearities and the finite aperture of the magnet). In the high-resolution case, the position of the initial object is shifted away from the first magnet such that an intermediate image is produced half way between the two 90° magnets; in this arrangement the dispersions of the two magnets add, yielding a momentum resolution, $\Delta p/p$, of 27 parts in 100,000 full width at half maximum for object and image slits of 2 mm aperture.

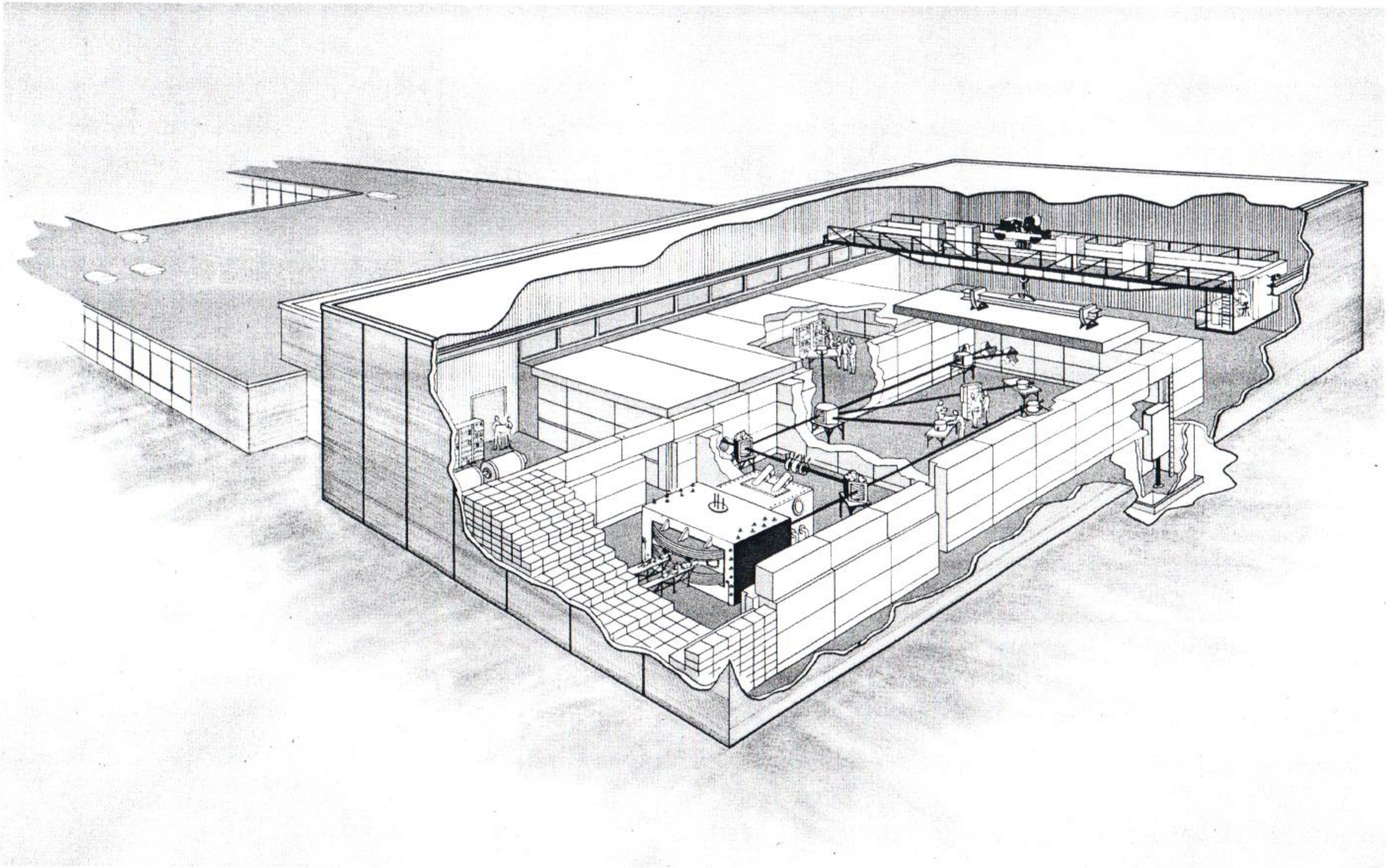


Fig. 17: Cutaway sketch of the high bay area of the cyclotron building showing the arrangement of stacked block shielding. The overhead crane has 40-ton capacity. One of the hydraulically actuated shield doors is visable in the cutaway at the right; the doors rise from pits on standard elevator rams.

It is presently planned to construct the double-focusing 90° magnets as a triplet consisting, in order, of (a) a vertically focusing quadrupole, (b) a flat-field normal-entry 90° magnet, and (c) a second vertically focusing quadrupole. The first order optical properties of such a triplet have been explored and found to be quite satisfactory, resembling quite closely the properties of an $n=1/2$ magnet. Moreover, as contrasted with the $n=1/2$ magnet, the triplet has advantages of (a) greater ease in construction, (b) ~~of~~ allowing proton resonance field control, and (c) ~~of~~ allowing electrical adjustment of the radial focal length so that the image plane can be made to precisely coincide with the location of the image slit (thus maximizing resolution of the system).

It is planned to correct aberrations in the analyzing magnet system by means of the same techniques employed in the design of the cyclotron, i.e., by accurate measurement of the magnetic field of the magnets and orbit computation in the measured fields. Exploratory studies of aberrations (and field corrections necessary to minimize same) using the above techniques have already been made and reported on14). The method appears to have important advantages over the normally used hot wire technique since (a) it affords much greater accuracy, (b) it allows rapid study of many possible corrective procedures, and (c) it affords a precise specification of the shimming correction needed (as contrasted with the essentially straight empirical procedures which must be employed with hot wires). The results already obtained indicate that aberrations can easily be reduced to a point where they constitute a minor contribution to the energy spread of the system.

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14) See Proc. of the 1963 CERN Cyclotron Conference, paper by H. G. Blosser and J. W. Butler.

3.3 Experimental Rooms and Target Positions

From the two 90° magnets, the beam is directed eastward down the approximate center of the high bay area and is switched to target positions at the right or left by means of a pair of steering magnets. The beam pipes entering each room will be provided with a heavy plug such that, with the plugs in place, interlocks will allow the shield door into the particular room to be opened independently of the state of operation of the cyclotron. With this system it will be possible to safely work on setups at a number of positions at the same time that an experiment is being conducted at some other position. The relatively large number of target positions allow the experimentalist to take as much time as he desires for setting up his equipment without the pressure of tying up valuable cyclotron time. This will hopefully result in more careful work and should be particularly valuable in allowing students to work out for themselves the problems of their equipment, which is a highly effective learning process.

For ease in shifting equipment from lab rooms to target positions and vice versa, each of the experimental areas is equipped with one or more "utilities clusters" which have available a 100-ampere, 120-volt electrical power panel, a 208-volt single and 3-phase outlet, hot and cold city water, deionized water supply and return, compressed air, and a rack for mounting gas bottles. The shielding doors to each of the experimental rooms provide a 5-foot wide passage. When it is necessary to install equipment too large to pass thru the doors, the overhead crane will be employed to remove a section of roof shielding, thereby permitting installation of equipment of indefinite size.

3.4 Negative Ion Reaction Experiments

As indicated previously, the acceleration of negative ions offers the possibility of performing ultra-precision reaction experiments with the cyclotron. This possibility was considered in some detail in a portion of a paper presented at the CERN accelerator conference.[14] In view of the considerable interest in this aspect of the cyclotron performance, the description presented at CERN is quoted here.

"At the Los Angeles Conference an interesting speculation was raised by the Colorado group[10] concerning the acceleration of H^- ions, with extraction by conventional means, so that thin foils can be employed downstream as slits for the analyzing system. The thin foils effectively eliminate slit scattering and the slit aperture can therefore in principle be as small as desired, giving beams of very high resolution. Since detailed estimates of the properties of the external beam of the MSU cyclotron are available from a previous performance study[15], an interesting speculative estimate of the parameters of a typical reaction experiment easily follows by applying the techniques of a resolution study by Cohen[13] to the situation posed by the Colorado group.

"The efficiency of negative ion sources gives rise of course to considerable uncertainty in the estimates. For purposes of computation the phase-space density of the H^- ion beam from the source was arbitrarily assumed to be 1/10 that measured for H^+ beams. With this assumption the properties of the external beam can be calculated from the known orbit dynamics of the cyclotron and extractor using the same techniques as previously employed. An external current of 250 μa of 50 Mev H^- ions is predicted with energy spread 60 kev, radial spot-size-divergence 0.004 radian-cm, and axial spot-size-divergence 0.02 radian-cm, all quantities being full widths.

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15) H. G. Blosser and M. M. Gordon, Nuc. Inst. and Meth. 13 (1961) 101.

"Fig. 18 depicts a typical reaction experiment using the negative beams. The size and divergence of the initial object are defined by the foils S_1 and S_3—particles penetrating either foil become positive and are deflected into the beam catcher, BC_1. The momentum spread is defined by S_4—particles penetrating S_4 are deflected into BC_2 by M_3 while the negative particles passing thru the aperture of S_4 are focused on the target. In the target, all particles become positive and a thick slit, S_5, must be provided in front of the reaction products analyzer, M_4, to define the scattering angle. This slit can fortunately be rather large even for an ordinary flat-field reaction products magnet, so that slit scattering from this slit is of small effect. Since all other stopping beam is steered into heavily-shielded beam catchers, the experimental situation should be extremely clean.

"Sources of error in such an analyzing system and reaction experiment have been tabulated by Cohen13). These include: (a) direct momentum error due to the size of S_1 and S_4, (b) kinematic errors due to variation in center-of-mass scattering angle allowed by S_3 and S_5, (c) target thickness errors due to variation in depth within the target at which scattering occurs and to fluctuations in energy loss, and (d) errors analagous to (a) and (b) due to finite axial size of the slits.

"With the situation shown in Fig. 18, the methods of Cohen predict a counting rate of 100/hour at a resolution of ± 2 kev when 30 Mev protons are inelastically scattered to a level of 10-Mev excitation, assuming S_1 to have an aperture of 0.005" by 0.750" (radially and vertically respectively), S_3 to be 1.000" by 0.900", S_4 to be 0.100" by 1.000", S_5 to be 0.600" by 0.900", the target to be of mass 170 and thickness 0.15 mg/cm^2 oriented at an angle α of 20°, the scattering angle θ to be 30°, and the cross section for scattering

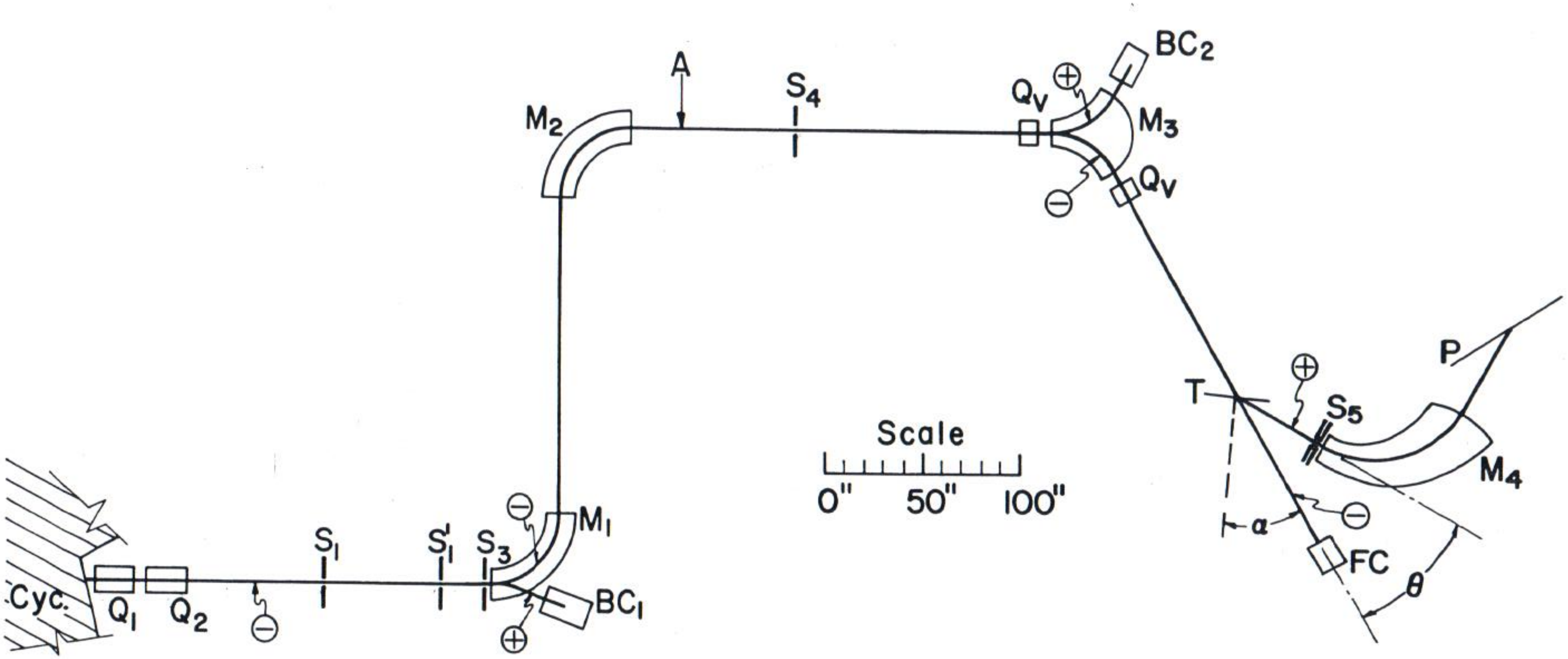

Fig. 18: Plan view of a portion of the beam analyzing and steering system. M_1 and M_2 are $n = 1/2$ bending magnets, M_3 and M_4 are flat field magnets, $BC_{1,2}$ are beam catchers, $Q_{1,2}$ are standard quadrupoles, the Q_v are vertically focusing quadrupoles, $S_{1,\ldots,5}$ are various slits, T is the target, θ is the scattering angle, α is the target angle, P is a photographic plate detector and FC is a Faraday cup and beam catcher. The + and - symbols on the beam denote beam polarity for a negative ion reaction experiment. The assumed radius of curvature is 36" in M_1, M_2, and M_3 and 50" in M_4.

from the particular level to be 0.1 mb/steradian. The resulting counting rate is approximately 2.5 times the minimum level considered workable by Cohen."

The ability to perform nuclear reaction studies at resolutions in the vicinity of 1 in 10,000 is expected to be of major significance to the research programs of the cyclotron. Complementary studies of inelastic scattering (p,p'), of pickup reactions (p,d), (p,t), (p,He^3), (p,d), (d,He^3), and of stripping (d,p) can be extended to innumerable nuclear states presently inaccessible due to the energy limitation (several of the reactions are highly endothermic) of lower energy accelerators or to the resolution limitation of higher energy machines (particularly in the high z region). Such studies can fix quantum numbers and determine basic wave function characteristics of the states, both of which are of great interest.

3.5 The Control Data 3600 Computer

Although not a direct part of the cyclotron program, the recent installation on campus of a Control Data Corp. type 3600 computer will be of enormous benefit to the project both in the construction of the cyclotron and later in the analysis of experimental data. Features of the 3600 include (a) a 32,000 word fast memory (expandible to 128,000 by addition of memory units), (b) a high degree of precision afforded by a 48 bit word (as contrasted with the 36 bit word for IBM computers), (c) an overall computing speed which is approximately four times that of the IBM 7090, and (d) an ability to accomodate up to 16 remote consoles thus permitting access to the computer from many widely scattered locations. Symbolic programming routines, including Fortran and Algol will be available thus permitting broad interchange of programs with other computers thruout the world.

The extensive library of cyclotron programs prepared for the University's old computer, the MISTIC, is now in the process of being rewritten for the new computer. The superior capabilities of the new computer will allow incorporation of many operational conveniences, greatly enhancing the ease with which problems can be set up for the computer and the results interpreted.

In the reasonably near future design computations for the cyclotron will taper off and the attention of the theoretical and programming staff will be directed to preparation of nuclear physics programs for optical model calculations, direct interaction studies with distorted waves, fitting of angular distributions, etc. In addition, there will of course be routine data processing programs to make center of mass corrections, pile up corrections, etc. Later, programs will be developed which, via a future computer console in the cyclotron building, will assist in the direction of experiments determining such things as the optimum placement of counters for angular distribution and correlation studies, etc.

4.0 Cost Experience

As indicated in previous sections, detailed design of the cyclotron proper is now in an advanced state such that the form of nearly all components is well established. In addition, most of the major components of the cyclotron are on order and accordingly on a firm cost basis. Table 1 presents a summary of costs itemized in the same way as in the original proposal showing presently estimated costs, costs as estimated in the 1960 proposal, and the allocation of previous grants from the National Science Foundation. In computing the "present estimate" a contingency factor has been included in each equipment item equal to 10% of the unexpended balance of the item.

Table I: Budget Summary

(All Figures rounded to nearest $100)	Present Estimate		Dec., 1960 Proposal		Previous NSF Grants Allocation
Equipment:	NSF	MSU	NSF	MSU	
Cyclotron	766,500		964,600		766,500
Cyclotron Engineering Design	106,100		138,000		106,100
Cyclotron Building		1,400,000		675,000	
Experimental Equipment	742,900		274,400		228,400
Equipment Total	1,615,500	1,400,000	1,377,000	675,000	1,101,000
Operation:					
Sci. Supervision and Testing					
(a) 2/15/62 to 7/1/63	207,000	115,000	144,000	74,000	207,000
(b) 7/1/63 to 10/1/63	65,000	35,000			65,000
(c) 10/1/63 to 10/1/64	245,000	178,300			
Operation Total	517,000	328,300	144,000	74,000	272,000
Budget Total	2,132,500	1,728,300	1,521,000*	749,000	1,373,000

Notes: * This total shown incorrectly in Dec., 1960 proposal as $1,411,000.

Referring to the table it is seen that the cyclotron and the cyclotron engineering design are now expected to cost considerably less than was estimated in 1960. Operating expenditures on the other hand are higher than anticipated due to the fact that (a) expenditures during the period covered by the 1960 proposal (ending July 1, 1963) have been $63,000 higher than anticipated, and (b) it has been necessary to cover operating costs for an additional period (July 1, 1963 to October 1, 1963) not included in the previous estimate. The budget is also complicated by the fact that grants from the National Science Foundation were $148,000 less than the total of items in the 1960 proposal budget. The net result of the several budget factors is that the combination of higher operating costs and smaller grants more than offset the savings on the cyclotron and cyclotron engineering, leaving a somewhat smaller amount of funds for experimental equipment than was originally requested. It should be noted that the increased operating costs are directly responsible for a large portion of the savings on the cyclotron proper due to design economies which have been achieved and also are responsible for the large performance improvements discussed in previous subsections. A more detailed breakdown of the equipment items from Table I is given in Table II.

The experimental equipment portion of the budget, as seen in Table II, is complicated by the fact that the shielding door arrangement is now a single system which, due to problems of construction compatibility and scheduling, had to be placed on order some months ago. In addition, the present building design involves a much larger amount of portable shielding than did the 1960 design. As a result of these factors the presently granted funds are barely adequate to bring the beam thru the analyzing magnet room, including only partial shielding for this room. No funds are available for such items as scattering chambers, experimental electronics, detectors, reaction products magnet, etc.

Table II: Itemization of Equipment Expenditures Against Previous NSF Grants.

I.	Cyclotron		
	A.	Magnet	179,500
	B.	Vacuum Tank and Pumps	59,600
	C.	Dees, Liner, and Pole Face Coils	49,900
	D.	Miscellaneous Mech. Parts	89,400
	E.	Cooling Water Distribution	9,000
	F.	Rf Supply	89,000
	G.	Miscellaneous Electronics and Electrical	38,700
	H.	Control and Low Power Electronics	91,800
	I.	General Assembly and Checkout	44,100
	J.	Shop Equipment	74,150
	K.	Contingency	41,350
		Total	766,500
II.	Cyclotron Engineering Design		
	A.	Consulting Engineers	97,000
	B.	Travel (Inspections and Consultants)	4,850
	C.	Contingency	4,250
		Total	106,100
III.	Cyclotron Building		
	A.	Construction Contracts	967,160
	B.	Architect	48,358
	C.	Site Investigation and Improvement	43,000
	D.	Utilities to Building	220,000
	E.	Furnishings	25,000
	F.	Bonds	5,688
	G.	Contingency	90,794
		Total	1,400,000
IV.	Experimental Equipment*		
	A.	Shielding Door System	70,000
	B.	Portable Shielding for Cyclotron Room	43,200
	C.	Portable Shielding for Analyzing Magnet Room (Partial)	9,100
	D.	Two 90°, n=1/2 Analyzing Magnets	36,000
	E.	Four 2 1/2" Aperture Quadrupoles	6,000
	F.	Magnet Power Supplies	17,000
	G.	Beam Tubes, Pumping Stations, Slits, Etc.	5,100
	H.	Mass Spectrometer Leak Detector	6,000
	I.	Source Testing Facility	17,100
	J.	Data Processing Equipment (for magnet measurements-later to be adapted for experimental data)	4,900
	K.	Contingency	14,000
		Total	228,400

* The distribution of funds under this item is based on carrying forward the construction of the planned facility in an orderly manner, presuming that additional equipment funds will become available to complete the facility. If such additional funds are not received, the above distribution will be drastically revised so as to in some way achieve a working nuclear facility within the funds available.

The proposal, in this document, for additional equipment funds attempts to remedy this situation.

5.0 Publications

Publications, reports, talks, etc. by the project staff for the first 22 months (October, 1961 thru July, 1963) of the grant are as follows:

PUBLICATIONS:

Effects of Field Imperfections on Radial Stability in a Three-Sector Cyclotron by M. M. Gordon and W. S. Hudec, Nuc. Inst. and Meth. 18, 19 (1962) 243.

Resonant Extraction from Three-Sector Low-Spiral Cyclotrons by H. G. Blosser, M. M. Gordon, and T. I. Arnette, Nuc. Inst. and Meth. 18, 19 (1962) 488.

The Electric Gap-Crossing Resonance in a Three-Sector Cyclotron by M. M. Gordon, Nuc. Inst. and Meth. 18, 19 (1962) 268.

Fixed-Point Orbits in the Vicinity of the $\nu_r = N/3$, $N/4$, and $N/2$ Resonances by M. M. Gordon, Nuc. Inst. and Meth. 18, 19 (1962) 281.

Acceleration of Particles into Stable Orbits in an Isochronous Three-Sector Cyclotron by M. M. Gordon and H. G. Blosser, Nuc. Inst. and Meth. 18, 19 (1962) 378.

Central Orbit Program for a Variable Energy Multi-Particle Cyclotron by M. Reiser, Nuc. Inst. and Meth. 18, 19 (1962) 370.

Cyclotron Programs for a Small Computer by T. I. Arnette, H. G. Blosser, M. M. Gordon, and D. A. Johnson, Nuc. Inst. and Meth. 18, 19 (1962) 343.

Performance Estimates for Injector Cyclotrons by H. G. Blosser and M. M. Gordon, Nuc. Inst. and Meth. 13 (1961) 101.

REPORTS:

MSUCP-11 Effects of Field Imperfections on Radial Stability, M. M. Gordon and W. S. Hudec (Nov., 1961).

MSUCP-12 Computation of Electric Field and Potential of an Idealized Dee Geometry, J. W. Beal (Oct., 1961).

MSUCP-13 First Order Study of Some Beam Analyzing Systems for a Medium Energy Cyclotron, K. Kosaka (Sept., 1962).

<u>MSUCP-14 Magnetic Coil Design for a Superconducting Air-Cored</u> 40-Mev Cyclotron, R. Berg (Jan., 1963).

<u>MSUCP-15 Ion Injection in a Cyclotron with Double-Mode Dee</u> System, M. Reiser (Feb., 1963).

<u>MSUCP-16 Initial Acceleration and Radial Focusing in the Nonuniform</u> Electric Field at the Ion Source of the Cyclotron, M. Reiser (Mar., 1963).

<u>MSUCP-17 Cyclotron Duty-Factor Improvement by Reduction of Phase</u> Bunching in the Central Region, M. Reiser (Mar., 1963).

<u>MSUCP-18 A Thermo-Electrically Cooled Hall-Effect Magnetic</u> Field Probe, J. A. Futhey (July, 1963).

BOOK REVIEW:

Principles of Cyclic Particle Accelerators, John J. Livingood, Van Nostrand, Princeton, New Jersey, 392 pp. (Reviewed in Nuc. Sci. and Engr. <u>16</u> (1963), 251 by H. G. Blosser).

INVITED APS PAPER:

Calculations of Closed Orbits in a Three-Sector Cyclotron, M. M. Gordon at Cleveland meeting of American Physical Society, Bull. APS <u>7</u> (1962) 547.

The following papers were presented at the 1963 CERN Cyclotron Conference and appear in the conference proceedings:

Magnet Design for MSU 50 Mev Cyclotron, H. G. Blosser.

Experimental Facilities and Resolution Capability of the MSU Cyclotron, H. G. Blosser and J. W. Butler.

Central-Region Studies for the MSU Cyclotron, H. G. Blosser, M. M. Gordon, and M. Reiser.

Central-Region Factors Influencing the Duty Cycle of a Cyclotron Beam, M. Reiser.

Orbit Calculations on the Extraction System for the MSU Cyclotron, M. M. Gordon and H. G. Blosser.

Limitations on Duty-Factor Improvement (Via Phase-Shifting) Using H^- Ions, M. M. Gordon.

Radio-Frequency System for the MSU Cyclotron, W. P. Johnson.

PROPOSAL

for

OPERATING SUPPORT

for the

MICHIGAN STATE UNIVERSITY
CYCLOTRON PROJECT

for the period

Oct. 1, 1963 to Oct. 1, 1964

by

Project Staff

July 26, 1963

PROPOSAL

It is proposed that operating expenses for the MSU cyclotron project for the period October 1, 1963 to October 1, 1964 be jointly supported by the National Science Foundation and the University, the National Science Foundation supplying $245,000 and the University supplying $178,295. The funds requested will cover expenses of the project staff as they proceed with design, construction, assembly and testing of the MSU cyclotron and related components, including costs of salaries, computing time, supplies and services, and travel to professional meetings. A detailed budget is given on the following page.

In the monthly payroll section of the budget, the project staff consists of: Professors—Blosser, Gordon, and Butler; Assistant Professors—Arnette, Benenson, and W. Johnson; Assistant Professors (Research)—Reiser and Stoltzfus; Chief Engineer—Schulke; Designers—Dickenson and Stork; Technicians—Harder, Rothmann, and Wescott; Computer Programmer—D. Johnson; and Secretary—Musich. In the regular labor category are: machinists, Mercer, Kittsmiller, and Wagner; eight graduate research assistants, on a half time basis; and undergraduate student labor. From the academic staff, Professors Butler and Gordon and Assistant Professor Benenson will have teaching duties averaging five class hours per week thru the academic year. Assistant Professor Arnette will have teaching duties averaging two class hours per week thru the academic year. Aside from these teaching assignments, all persons listed will work full time on the project. The academic year salaries of Professors Butler and Gordon and Assistant Professor Benenson will be paid entirely from University funds. The academic year salaries of Professor Blosser and Assistant Professor W. Johnson will be paid 1/2 from University funds and 1/2 from National Science Foundation funds. The academic year salary of Assistant Professor Arnette will be paid 70% from University funds and 30% from National Science Foundation funds. The salary of machinist

Revised (Sept. 10, 1963)

Table III: BUDGET

OPERATING EXPENSE OCT. 1, 1963 to OCT. 1, 1964

	NSF		MSU	
A. Wages and Salaries				
~~1~~. ~~Monthly Payroll~~ Faculty Salaries	38,033		64,352	
1 (~~a~~) ~~Tenured Staff~~	~~18,640~~		~~34,910~~	
(~~b~~) ~~Tenurable Staff~~	~~14,460~~		~~18,270~~	
2 (~~c~~) Research Associates	20,990			
3 (~~d~~) Engineers, Draftsman, ~~and~~ Technicians, and Secretaries	52,750 ~~49,100~~			
~~5 (e) Secretaries~~	~~3,650~~			
~~(f) New Staff~~	~~5,000~~	~~111,840~~	~~7,000~~	~~60,180~~
7 ~~2~~. TIAA	3,600	~~3,600~~	4,500	~~4,500~~
~~3. Other Payrolls~~				
4 (~~a~~) Regular Labor	20,910		8,400	
5 (~~b~~) Graduate Assistants	24,210			
6 (~~c~~) Student Labor	~~8,190~~ 8,257	~~53,310~~	———	~~8,400~~
8 ~~4~~. Social Security	4,100	~~4,100~~ 172,850	1,500	~~1,500~~ 78,752
B. Other Items				
1. Computer				
(a) Computer Time Charges	8,000		22,000	
(b) Card Equipment Rentals	1,200	9,200	———	22,000
2. Supplies and Services				
(a) Office	2,000		500	
(b) Machine Shop	4,000		3,000	
(c) Electronics Shop	2,500		2,500	
(d) Printing	1,700	10,200	1,000	7,000
3. Travel				
(a) Professional Meetings	3,750			
(b) Vendor Inspections	———	3,750	———	———
Subtotal		196,000		~~103,580~~ 107,752
Overhead (50% of wages and salaries - NSF contribution 25% of subtotal)		49,000		~~74,715~~ 76,801
Total		$245,000		~~$178,295~~ 184,553

Mercer will be paid entirely from University funds. All salaries not specifically mentioned above, including summer salaries for the academic staff computed according to the University's standard policy, are charged to the National Science Foundation.

Budget items for computer time and for supplies and services are based on expenditures in the 12 month period just completed. The travel to professional meetings is based on seven trips at an average cost of $250.00 each.

Several comments should be made relative to the operating budget proposed. First it should be noted that these expenses are completely essential to further progress of the project. Basic responsibility and know-how for all of the novel components of the cyclotron rests with the several senior staff. The supporting staff is at a minimum level consistent with the effective utilization of senior staff manpower. Second, the budget has already been trimmed substantially as a result of information transmitted by the National Science Foundation regarding general scarcity of funds. Expenditures for teaching relief for the senior staff have been reduced as compared with levels of previous years. Summer salaries for all graduate students are on a half-time basis as contrasted with the full time which has been customary in past years and supplies and services and travel to professional meetings have been trimmed to a minimal level. Third, the work load of the operating staff will be at a peak during the period covered by the proposed budget which includes the full assembly of the cyclotron. Any reduction in the staff during this peak period, such as would be necessitated by further budget reductions, would result in a prolonged construction period for the cyclotron which would be most unfortunate. In view of these several factors, it is requested that funds be granted in the amount proposed.

Of the new staff, who have joined the project since submission of the 1960 proposal, four are primarily interested in experimental nuclear physics, one is an accelerator physicist, and one is an engineer. Briefly the backgrounds of the new personnel are:

> Assistant Professor Walter Benenson obtained his B.S. degree from Yale in 1957, and his M.S. and Ph.D. degrees from Wisconsin in 1959 and 1962, respectively. At Wisconsin he studied under Professor Barschall and was concerned with several experiments studying neutron polarization. For the academic year 1962-63, Dr. Benenson has been engaged in a number of nuclear experiments at the Institut de Researches Nucleaires, Strasbourg, France.
>
> Professor James Butler received his B.S. degree from Georgia Tech in 1944 and his M.A. and Ph.D. degrees from Rice in 1949 and 1951, respectively. At Rice he worked with Professor Bonner. From 1951 to 1961 Dr. Butler worked at the Naval Research Laboratory, Washington, D.C. including responsibilities as head of the 2 Mev Van de Graaff section for a considerable part of this period.
>
> Assistant Professor William Johnson received his B.S., M.S., and Ph.D. degrees from Indiana University in 1955, 1956, and 1960, respectively. At Indiana he worked with Professor D.W. Miller on experiments studying polarization in (d,p) reactions. From 1960 to 1962 he worked with the cyclotron group at the University of Colorado as a Research Associate.
>
> Assistant Professor (Research) Martin Reiser received his M.Sc. and Ph.D. degrees from the University of Mainz in 1957 and 1960, respectively. From 1958 to 1962 he was associated with the group engaged in the

design and construction of the 50 Mev deuteron cyclotron at Karlsruhe. His responsibilities included design of ion sources, studies of central region orbits, and construction and operation of a small cyclotron for central region studies.

Chief Engineer A.A. Schulke was associated with the Washington University cyclotron from 1942 to 1957. He worked with Professor Thornton on construction of the machine and later served as Engineer-in-Charge for the project. From 1957 to 1963 he was at Argonne National Laboratory working under Dr. Ramler on the 60" cyclotron.

Assistant Professor (Research) Joseph Stoltzfus received his Ph.D. degree from the University of Iowa in 1961, where he worked with Professor Jacobs on experiments studying (p,α) reactions. From 1961 to 1963 he was an Assistant Professor at Virginia Polytechnic Institute. Also from 1961 to 1963 he spent extensive periods at Oak Ridge National Laboratory working with Dr. Goodman on the 86" cyclotron.

In addition to the staff already associated with the project, the University and the Physics Department plan to further augment the nuclear physics program by the early addition of two more experimentalists. One of the open positions is an extremely attractive professorship--the attractiveness of the position in combination with the superior characteristics of the cyclotron should make it possible to interest a senior nuclear physicist with both extensive experience and exceptional ability. The department maintains continuing informal contact with persons who would be appropriate, and expects to fill the position at approximately the time the cyclotron becomes operational. The second position is an assistant professorship for which a promising younger person is being sought. In addition to the experimental positions, the department plans to add another theoretical nuclear physicist to augment the group headed by Professor H. McManus.

ENDORSEMENT

This proposal has the support and approval of Michigan State University.

Henry G Blosser
Henry G. Blosser
Professor of Physics

Sherwood K. Haynes
Sherwood K. Haynes
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Milton E. Muelder
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Philip J. May
Vice President for
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PROPOSAL
for
ADDITIONAL EXPERIMENTAL EQUIPMENT

for the

MICHIGAN STATE UNIVERSITY
CYCLOTRON PROJECT

by
Project Staff
July 26, 1963

1.0 Introduction

It is proposed that the National Science Foundation make a grant of $389,000 for equipping additional experimental areas for the Michigan State University Cyclotron. The University is providing the building for the cyclotron from its own funds at a total cost of $1,400,000, of which $675,000 represents the building originally planned for the cyclotron and $725,000 is for added space to house the additional experimental areas and related setup labs, shops, and offices.

2.0 Budget

A budget for the proposed grant is given in Table IV. The items requested will provide shielding, beam transport equipment, and nuclear experimental equipment for three experimental rooms. Referring to the floor plan in Fig. 16 of the preceding progress report, the three areas are the south-central, the northwest and the north-central experimental rooms. In the light of information received from NSF as to anticipated severe shortages of funds, no equipment has been included for the eastern experimental areas shown on the floor plan even though these areas are felt to be urgently needed to achieve a proper balance between the versatility of the cyclotron and the capability of associated experimental areas and even though it appears that additional funds for this purpose will not be available from NSF for several ensuing years due to special budgetary plans. Quantity cost economies on items such as shielding, steering and focusing magnets, beam pipes, etc. will also be lost by doing the east rooms separately at a later date. The NSF budgets preclude, however, any possibility of including equipment for these rooms in this proposal.

The project staff will, of course, continue to exert every effort to realize the facility at minimum cost. It is

Table IV: Budget for Additional Experimental Equipment Proposal

I.	Beam Handling System	
A.	$\pm 60^\circ$, $n=0$, steering magnet	21,000
B.	Four 2 1/2" aperture quadrupoles	6,000
C.	Beam pipes, pumping stations, slits, etc.	9,200
D.	Controls and wiring	16,800
E.	Assembly and checkout	6,800
F.	Magnet power supplies (including reaction products magnet)	38,000
	Total	97,800
II.	Portable Shielding	
A.	Complete analyzing magnet room	5,000
B.	South-central experimental room	22,000
C.	North-west experimental room	15,700
D.	North-central experimental room	16,900
E.	Radiation warning system	4,700
	Total	64,300
III.	Electronics and Counters	
A.	Photo-tubes, power supplies, solid state and other detectors	9,000
B.	Preamps and amplifiers	12,000
C.	Coincidence circuitry	6,000
D.	Multi-channel analyzer(s)	40,000
E.	Current integrators	4,000
F.	Closed circuit TV system	6,000
G.	Miscellaneous	10,000
	Total	87,000
IV.	Mechanical	
A.	Scattering chambers	12,000
B.	Reaction products magnet core	36,000
C.	Reaction products magnet coils	14,000
D.	Reaction products magnet vacuum system	9,000
E.	Reaction products magnet miscellaneous	11,000
F.	Isotope production facility	6,000
G.	Assembly and checkout	5,500
	Total	93,500
V.	Target Preparation Equipment	
A.	Evaporation facility	4,000
B.	Chemistry supplies	3,000
C.	Miscellaneous	4,000
	Total	11,000
	Subtotal	353,600
	Contingency	35,400
	Final Total	$389,000

hoped that economies can be achieved, as on the cyclotron itself, such as to make available some funds for the east experimental areas within the framework of the present budget (hopefully at least sufficient to procure some of the items with substantial quantity discounts such as, for example, the steering magnets).

3.0 Estimating Procedures

Items in the budget are to a considerable extent self-explanatory—nevertheless some comments are in order both as to how the costs were estimated and as to plans for selection or construction of the equipment.

With respect to costs, there are many relatively standard items such as quadrupoles, shielding, vacuum pumps, etc. Major items of this type, such as the shielding, are based on vendor's estimates; minor items are catalog prices. The steering magnet and the reaction products magnet have been estimated by the project staff using estimating procedures of Brobeck and Associates. ($0.35 per pound for machined iron, $3.50 per pound for completed coils, and $2.00 per pound for machined vacuum tank valves, plate holder, etc.) It is planned to construct the large magnets in the same manner as the cyclotron magnet, i.e., by taking bids on individual components such as coils, core, etc. rather than on complete magnets. This procedure affords a much larger number of possible vendors resulting therefore in lower cost.

The cost estimates for the reaction products magnet have been prepared on the basis of a Bainbridge-Buechner design with central ray of radius 50", peak field of 12 kilogauss and aperture of 2 1/2". The magnet has not been designed in detail and prior to freezing the design one or more of the orbit experts from the staff will review the state of the art on such magnets with the objective of building a magnet of advanced design possibly incorporating double focusing, or built in kinematic corrections in addition to broad range.

Cost estimates for electronic equipment are difficult to prepare due to the rapidly changing state of the art. In view of this situation the estimates have been prepared by a combined process of considering equipment now available and by discussion with persons working in the field as to amounts which they considered reasonable. The budgeted amounts do not represent a specific selection of equipment and therefore individual items will be subject to fluctuation—on the other hand the total amount for electronics appears to be adequate and will be made accurate by requiring appropriate balancing of fluctuations in the final selection of equipment. This estimating procedure is by far the most reasonable to follow under the circumstances, since a specific selection if made at this time would without doubt be outdated nine to twelve months from now when the equipment is to be ordered. Selection of particular items at this time would also be inefficient due to the fact that the project staff, under the press of handling urgent problems related to construction of the cyclotron, are all somewhat out of contact with developments in nuclear instrumentation. Beginning in the coming fall Professors Butler and Benenson will devote essentially their full attention to a review of developments in this area with particular attention focused on multi-channel analyzers; the review will include visits and discussions with personnel from the several laboratories now in the forefront of developments in this area. Special attention will be directed to the question of whether multi-channel analysis equipment at MSU might best consist of essentially a special input link to the computer thus making use of the high-priority access which the cyclotron project will have on the 3600 computer.

4.0 Justification

The principal justification for the proposed grant lies in the achievements of the project to date—these achievements have been discussed at some length in the progress report section of this document. Clearly, the cyclotron, when completed, will be capable of sustaining a nuclear research program of tremendous breadth and interest; as has been discussed in considerable detail in our 1960 proposal. The capability of the facility (including the superb computational facilities now available on campus), if combined with an able experimental and theoretical staff will, without question, result in a leading nuclear physics research and training center. That the University is well along toward the realization of a staff of appropriate ability is evidenced by the progress and achievements to date on the construction of the cyclotron. This, in combination with the attractiveness of the as yet unfilled positions associated with the project, gives every assurance that the project will progress to full realization of its potential if accorded adequate financial support.

ENDORSEMENT

This proposal has the support and approval of Michigan State University.

Henry G. Blosser

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