Blosser
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PROPOSAL

FOR

SUPPORT

of the

NUCLEAR PHYSICS PROGRAM

FOR THE

MICHIGAN STATE UNIVERSITY

CYCLOTRON

June, 1964

6/64

PROPOSAL

to the

National Science Foundation

for

SUPPORT

of the

NUCLEAR PHYSICS PROGRAM

of the

Michigan State University Cyclotron

for the period

Dec. 16, 1964

to

Dec. 15, 1965

Department of Physics
Michigan State University
East Lansing, Michigan

June 12, 1964

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1. INTRODUCTION AND SUMMARY

Beginning in October 1961 the Michigan State University Cyclotron Project has been jointly supported by the National Science Foundation and the University. This document reports on progress during the approximate one-year period since the previous Progress Report and presents a proposal to the National Science Foundation for continuation of support for an additional one-year period beginning 16 December 1964.

Progress in the year since the previous report is impressive in two regards: (1) construction work on the cyclotron proper is proceeding smoothly and rapidly and (2) the nuclear physics staff has been greatly expanded and strengthened.

As regards the first of these, one year ago the cyclotron building was still in the midst of construction, the cyclotron group was dispersed around the campus in several areas, and work on the final engineering design was in an intermediate status. In October 1963 the building was released for occupancy and work began on the assembly of the cyclotron.

In the ensuing nine months: (a) the magnet has been assembled, (b) the magnet measurements program carried through, with results which establish that the field is of extremely high quality, (c) installation of the vacuum system is presently nearing completion, (d) the rf-drive chain is on hand and in final stages of assembly, (e) the tuning-panel network for the resonant cavity has been completed, and (f) the detailed engineering design has been completed. Work on fabrication of the dees and ion source (the remaining major items required for operation) is in progress in the MSU shops and it is expected to begin initial trials and tuneup of the cyclotron in the fall of this year. Work on the external-beam equipment has not progressed as rapidly as work on the cyclotron proper but since the resolution of solid-state detectors is a good match with the energy spread of the beam directly from the cyclotron, it will be possible to proceed immediately into a very interesting program of nuclear research using the direct beam from the cyclotron. The equipment required for such a program is in the process of procurement and/or construction.

The experimental program as presently anticipated is reviewed in Sec. 3.2. A partial list of the types of experiments includes correlation of nucleon pairs in nuclear matter, excitation of hole states, optical model experiments, angular correlation measurements on reactions with three-body final states, precision charged particle spectroscopy and decay scheme studies.*

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*) The decay scheme programs have previously been separately supported under direct NSF grants to Professor Haynes and Associate Professor Kelly. These groups have now combined with the cyclotron project to form a single nuclear experimental group (per NSF request).

The experimental staff associated with the project currently consists of Professors Blosser, Butler, and Haynes; Associate Professors Galonsky, Kashy, and Kelly; and Assistant Professors Benenson, Gruhn, and Johnson. The related group in nuclear theory† consists of Professors Gordon and McManus; Associate Professor Signell; and Assistant Professor Haybron. Four of these (Galonsky, Gruhn, Kashy, and Signell) have been added to the staff in the present year and all have been highly active in recent advances in nuclear physics, as is indicated in more detail in Sec. 3.3. In addition, work on the cyclotron is reaching a point such that the staff (Blosser, Gordon, and Johnson) who have in recent years worked primarily in accelerator development are beginning to re-orient their thinking to nuclear physics. The composite result is a tremendous increase in the total staff capability in nuclear research.

Estimated cost of the program for the one-year period is $782,100. Section 3.3 presents an itemization of costs. A total of $450,000 is requested from the National Science Foundation. The contribution of the University is estimated to be $332,100.

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†) Except for Professor Gordon the nuclear theory group is supported separately from the cyclotron project. (Atomic Energy Commission)

2. PROGRESS REPORT

2.1. Cyclotron Facility

2.1.1. Summary of Major Design Features

The MSU cyclotron is of the sector-focusing isochronous type. The cyclotron magnet has a nominal weight of 100 tons, nominal diameter of 64 inches, and three spiral-ridge sectors. The rf system is tunable by means of panels over the range 13.5 to 22.0 megacycles per second and will produce an energy gain per turn of 250 keV for singly-charged ions. Magnetic measurements on the full-scale magnet in conjunction with the above rf frequency range indicate a maximum proton energy of approximately 56 MeV. A variety of particles can be accelerated as is indicated in Fig. 1 (all energy values in Fig. 1 should be increased by 12%). Beam intensities are variable from very small values to a maximum in the vicinity of 800 microamps for protons. Extraction is accomplished in a single turn via a composite system: (a) turn separation is induced at the $\nu_r = 1$ resonance by means of a first harmonic field bump, (b) the separated turns enter a 60° electrostatic deflector and (c) the particles are steered out of the field by means of a two-foot long air-core magnetic channel. It is anticipated that extraction efficiencies in the vicinity of 90% will be achieved. Beam-energy analysis is accomplished by a pair

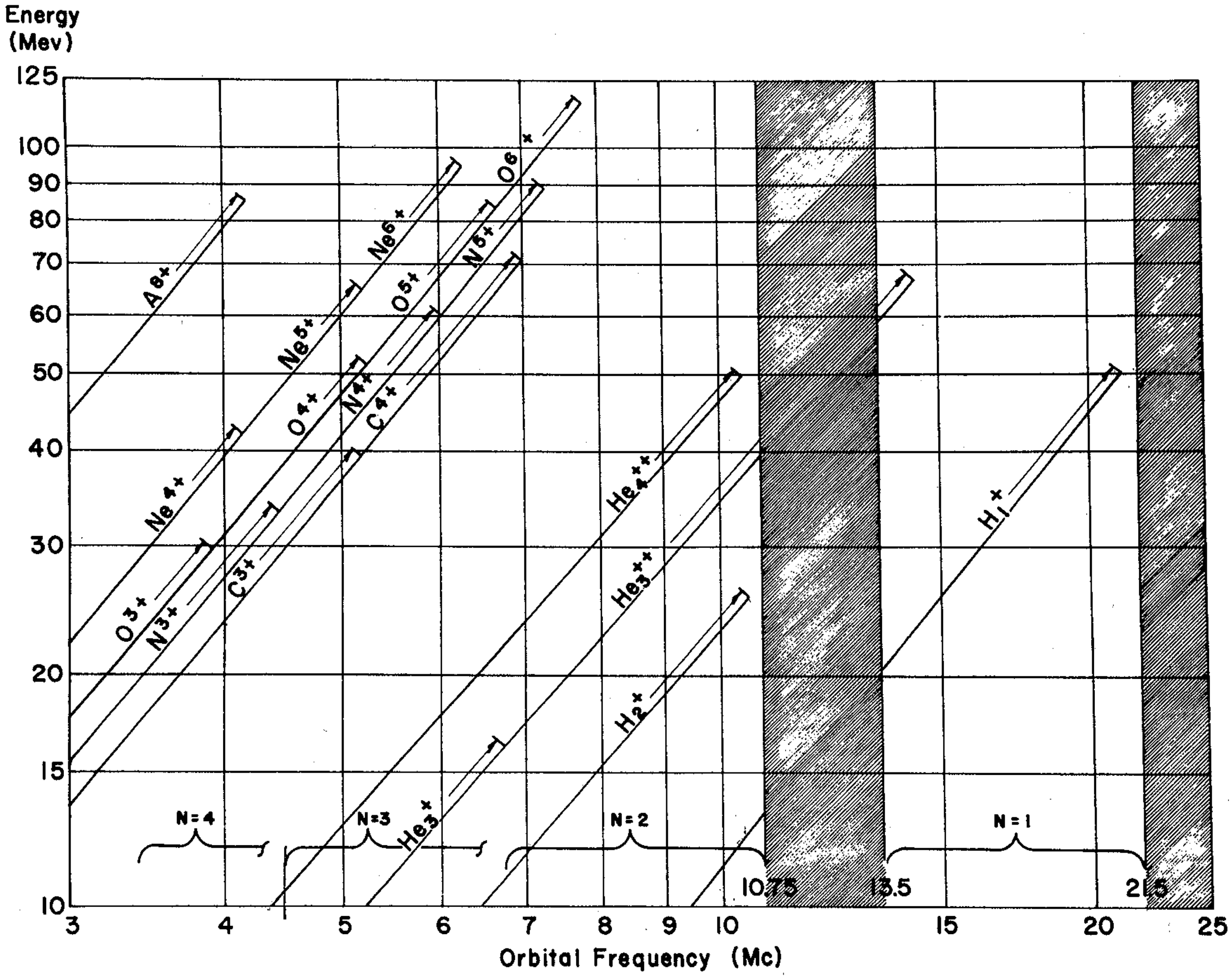

Fig. 1: Energy versus orbital frequency for various particles. Gray bands indicate areas unavailable due to tuning range limitations of the rf system (the energy scale should be shifted such as to increase all energy values by 10 to 12%).

of 90° magnets. The analyzed beam can be piped into any of four separately shielded experimental areas.

2.1.2. Cyclotron Magnet

Work on assembly of the main cyclotron magnet began in the late summer of 1963 immediately following release of the required work area by the cyclotron building contractor. The assembly work was performed entirely by MSU cyclotron personnel utilizing the 40-ton bridge crane in the high-bay area of the building. Figure 2 is a photograph of one of the main-coil pancakes being installed. The complete magnet was first placed under power in early December, 1963, and the field mapping program initiated.

Figure 3 is a view looking into the aperture of the main magnet with the magnet measuring gear in place. (The positioning gear was obtained on loan from the University of Colorado. Their cooperation in making this gear available was of great help.) The contoured pole-tip sectors are also clearly visible in Fig. 3. The sectors were fabricated on tape-controlled machines to a mechanical accuracy of 0.002". The rounded corners serve to greatly reduce saturation effects in the iron as can be seen from field results described in the following paragraphs.

The field measuring device consisted of a thermoelectrically cooled Hall-effect cell. The cooler provides the

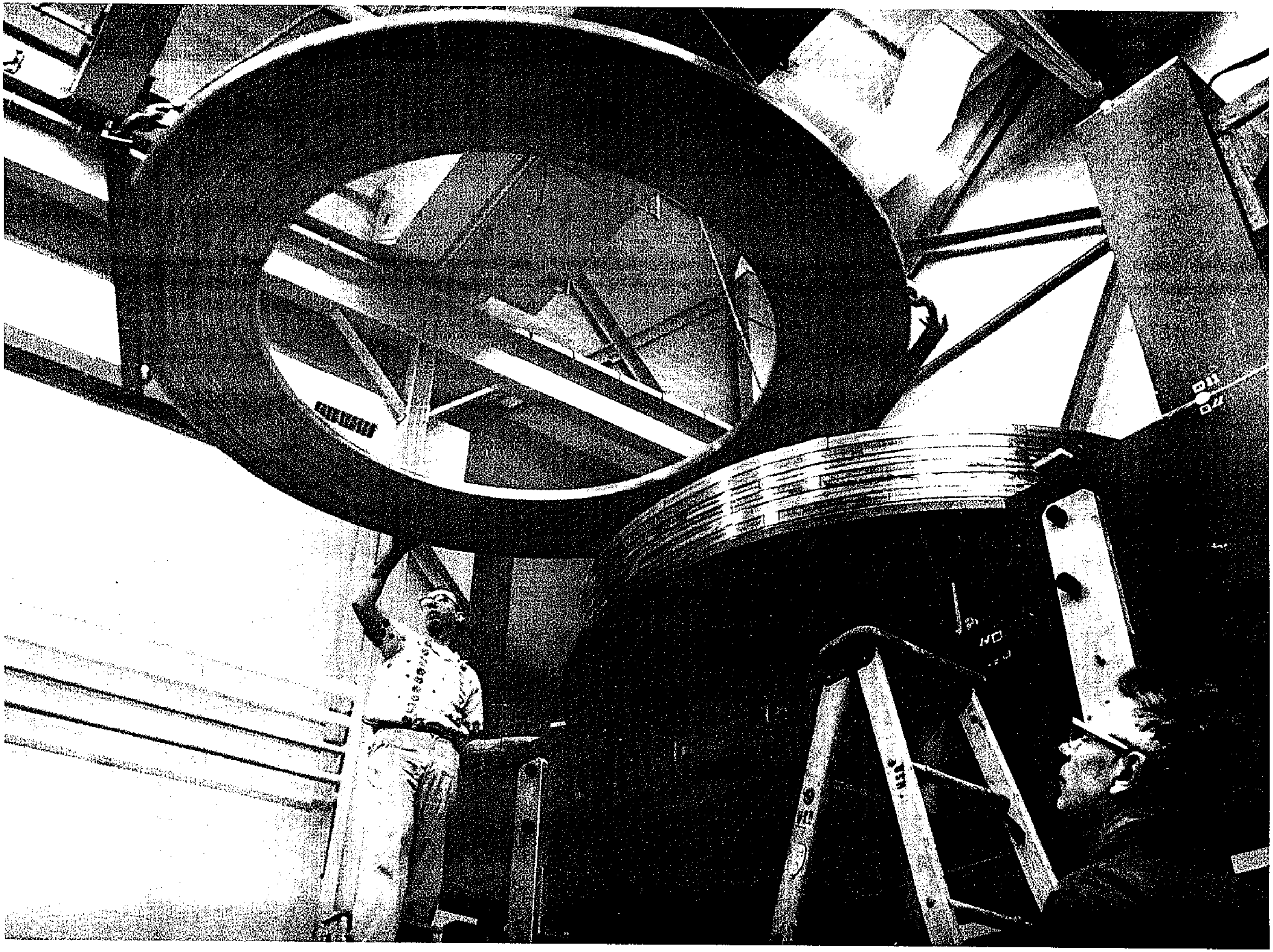

Fig. 2: One of the main-coil pancakes being installed.

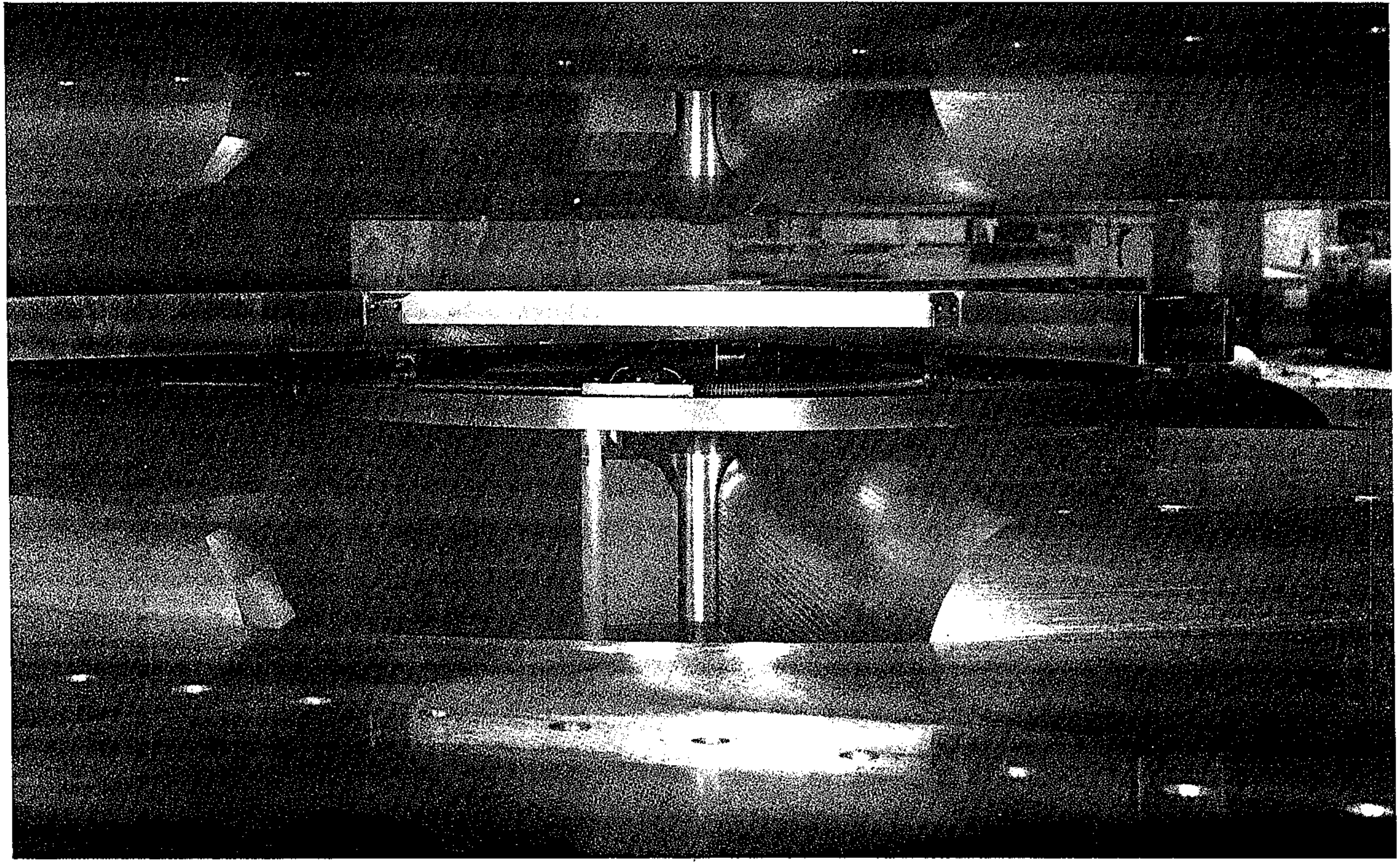

Fig. 3: The aperture of the main magnet with the magnet measuring gear in place.

necessary temperature control of the Hall plate while at the same time increasing the Hall-plate sensitivity by lowering the temperature. Electrical circuitry was arranged so as to provide approximate linearity between Hall voltage and field (of order 2%). The precision calibration curve employed for final data reduction was obtained by comparison with a commercial proton resonance fluxmeter.

Field measuring equipment was automated so that the Hall probe would be moved automatically in 4° azimuthal steps. The data was digitized via a voltmeter and punched via IBM card equipment. Radially, measurements were taken at 1" intervals out to 45". The field was measured at a total of eight excitations covering the operating range of the cyclotron. The field will be obtained at non-measured excitations by interpolation. A number of tests were made of measured vs. interpolated fields in order to be sure measurements were spaced sufficiently close in excitation to provide the required accuracy in the interpolated fields.

Raw data from the magnet measurements program were processed on the CDC-3600 Computer with the "Policy" program described elsewhere. Figure 4 presents results for the azimuthal average of the magnetic field at several excitations as obtained from "Policy." The field for the various excitations differs by a constant ratio to within

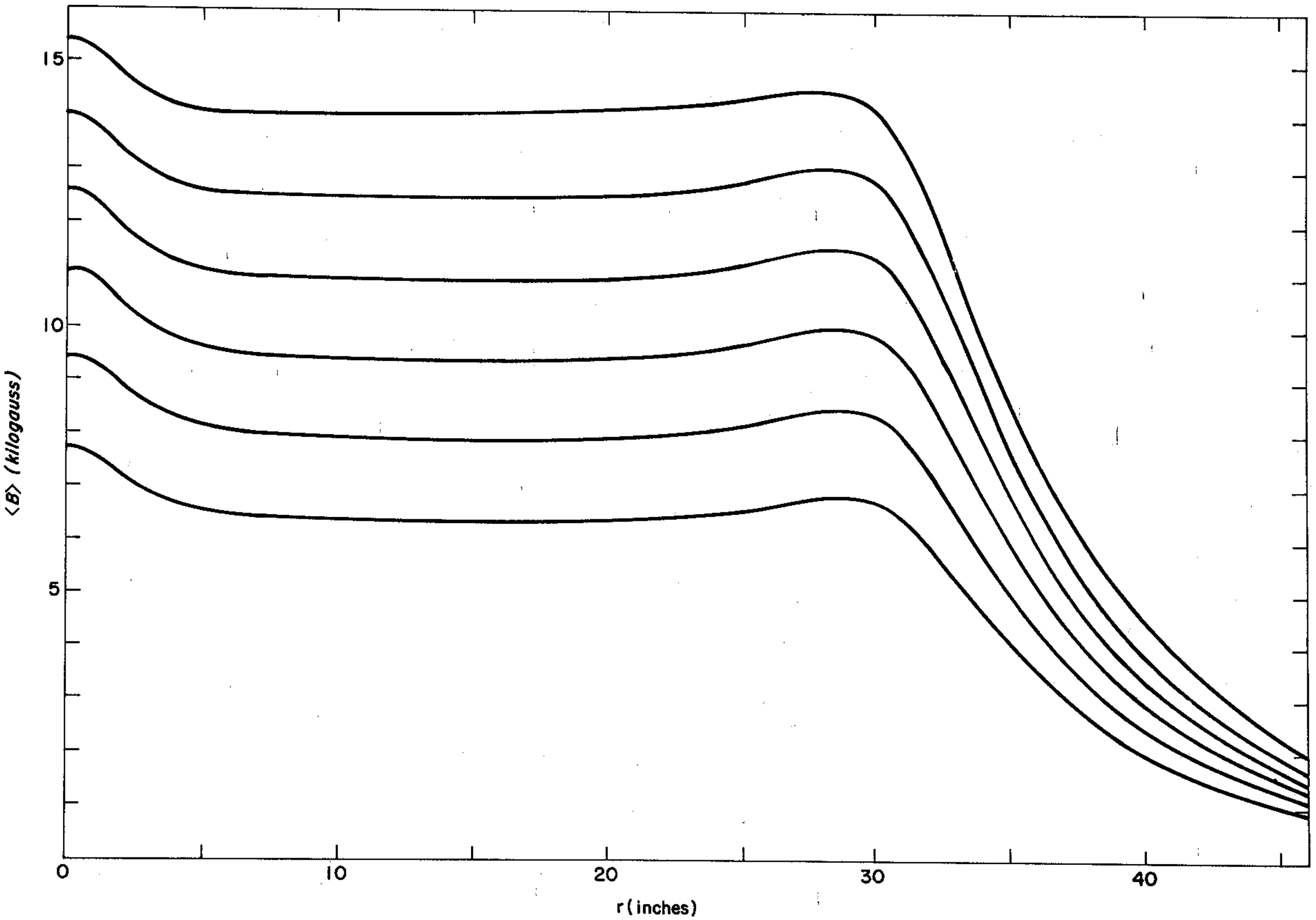

Fig. 4: The azimuthal average of the magnetic field at several excitations as obtained from "Policy."

an uncertainty of 2%, as contrasted with a figure of approximately 10% which would be expected from a magnet with square-cornered pole tips operated over a similar range of excitations. This characteristic of the magnet greatly reduces the magnitude of the correcting field to be produced by the circular trimming coils and results in major cost savings.

The accuracy of both the magnet and the measuring equipment can be inferred from a study of the azimuthal first-harmonic content of the field data. Figure 5 shows the phase of the first-harmonic content at four different excitations. Inasmuch as statistical errors lead to a random phase, whereas construction or positioning errors lead to a coherent phase, it is possible from study of the curve to qualitatively separate the two kinds of error. In the radius region from 5 to 20 inches, several of the phase curves are for example quite random in character. Figure 6 presents the associated first-harmonic amplitude data. From the curves for which the phase error was random, a statistical error of approximately 0.7 gauss is inferred.

Both Figs. 5 and 6 indicate an appreciable non-random first-harmonic content, particularly in the radius region beyond 30 inches. Both azimuthal location and dependence of amplitude on excitation are in accord with the hypothesis that this harmonic arises from the once-per-revolution

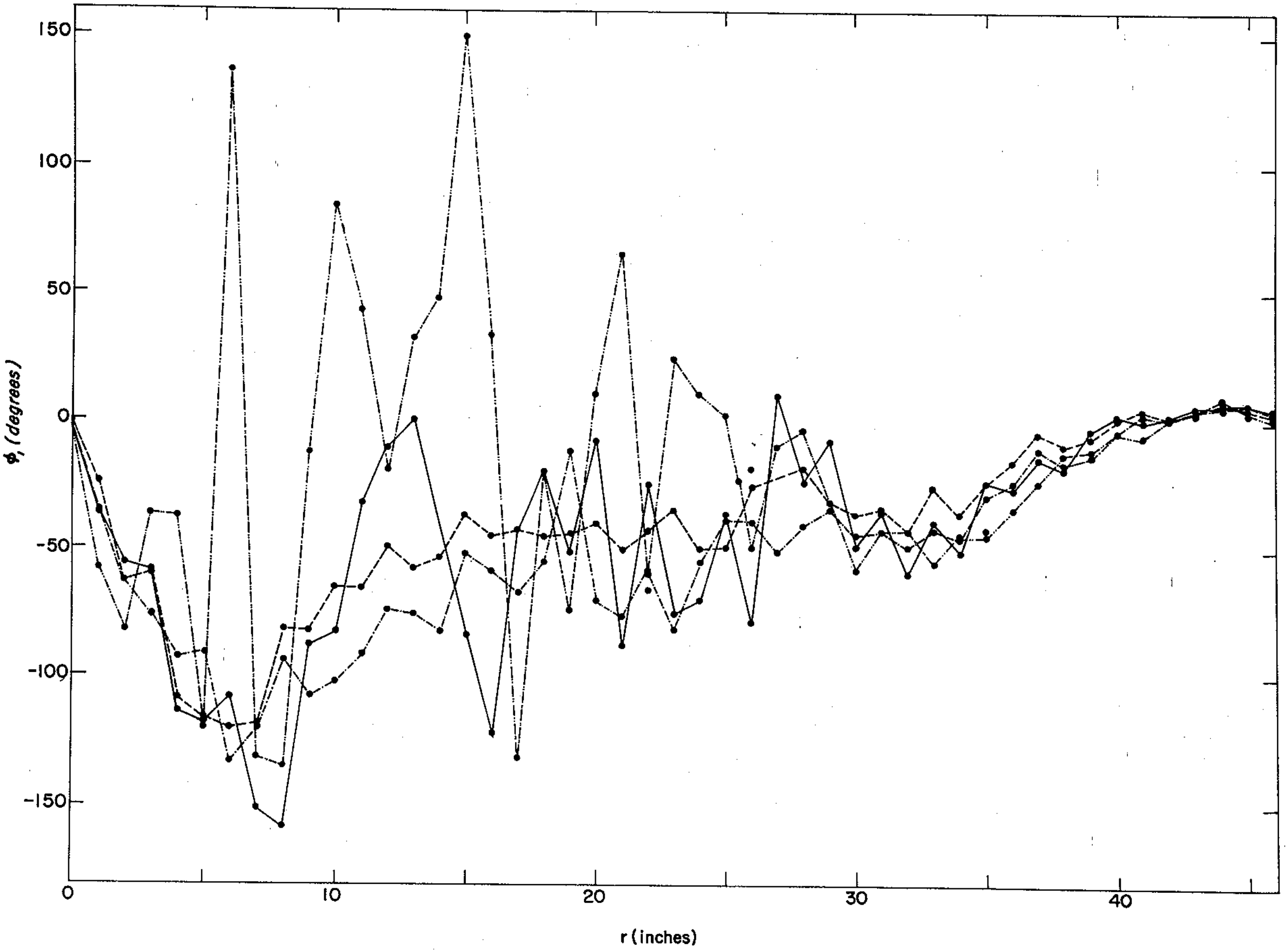

Fig. 5: The phase of the first-harmonic content of the magnetic field at four excitations.

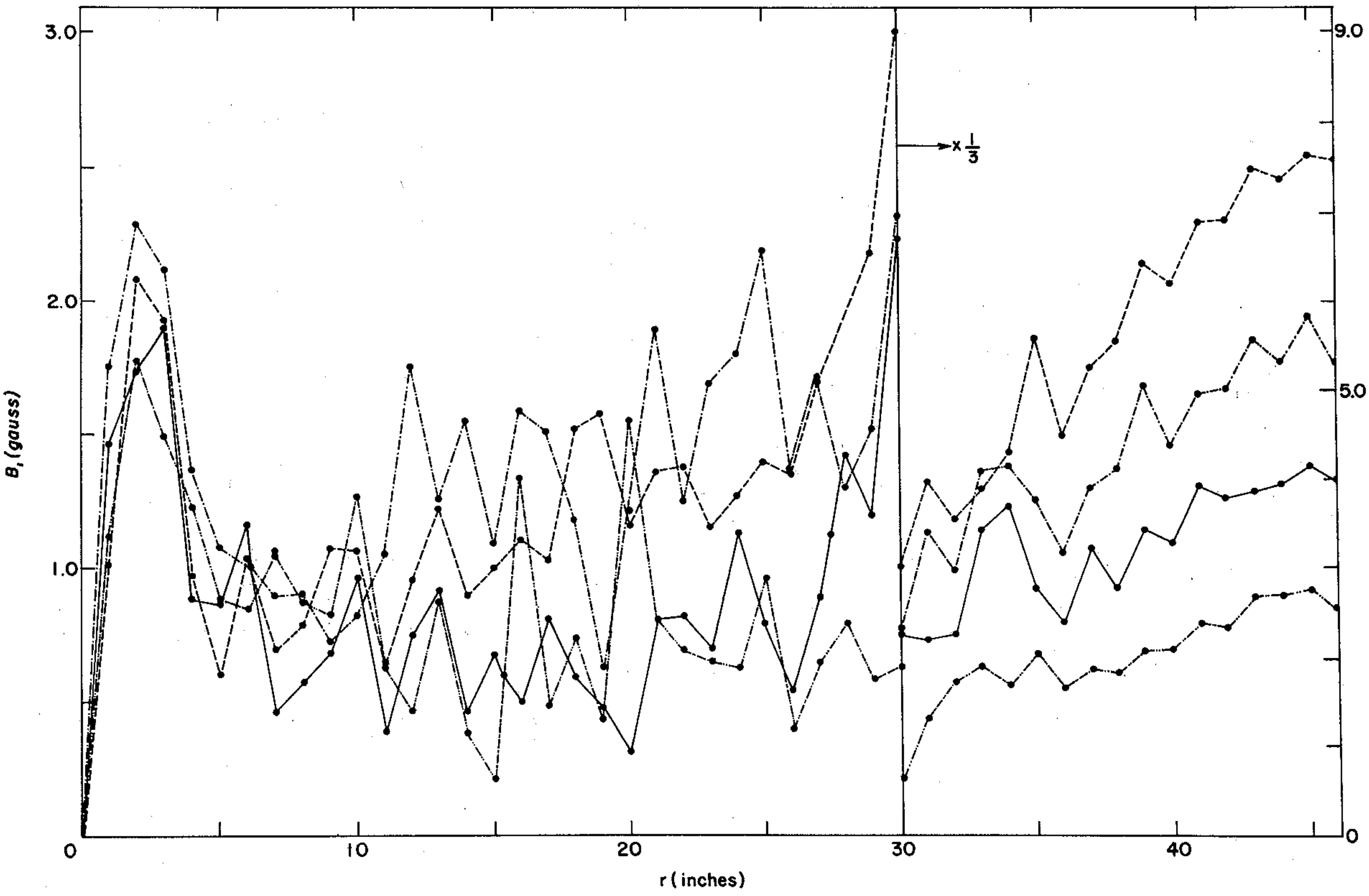

Fig. 6: First-harmonic amplitude data (excitations the same as in Fig. 5).

asymmetry of the main coil leads. From this assumption an air-core first harmonic can be subtracted from the data in order to ascertain the extent of errors in the construction and assembly of the iron. To the limit of accuracy imposed by the 0.7 gauss statistical measurement error, no first-harmonic contribution from the iron was detected, reflecting high quality workmanship both in the fabrication of the iron components (work by Allis-Chalmers Corporation) and in the installation and positioning (work by MSU).

Inasmuch as the measured first harmonic is very considerably smaller in amplitude than tolerance limits established on the basis of orbit computations, the results establish that the magnet is of extremely high quality relative to the requirements of the job which it is designed to perform. One of the major essential prerequisites toward achieving anticipated precision operation of the cyclotron has therefore been successfully realized.

As indicated in the introduction, final energies for all particles are now expected to be approximately 10 to 12% higher than had previously been indicated, i.e., a maximum proton energy of approximately 56 MeV, etc. This results from the fact that allowances were made in the specification of the magnet power supply to provide for a possible lower permeability of the iron as compared with the model magnet and a possible higher resistance in the coils. The full-scale field measurements show, however, that as regards both of these factors the full scale magnet is superior to the model and when the power supply is operated in its wide open condition, the field is such as to produce the 56-MeV protons. (Except for the permeability and coil resistance factors agreement between model and full-scale data is excellent. With appropriately scaled excitation, the main magnet and model fields can be made to coincide point by point to within 0.1%, i.e., the field shape, which is the essential factor in determining orbit properties, is quite accurately the same in the two magnets.)

At the present time, fabrication of the trimming-coil assemblies is nearing completion, and it is expected that the assemblies will be shipped to East Lansing for installation late in the month of June. Figure 7 is a recent photograph (May 1964) of one of the coil assemblies. The assemblies will require approximately one month to install in the cyclotron. The final step in the main-magnet program will consist of reinstalling the magnetic-field measuring gear for a program of check measurements on the coils; it is estimated that these measurements will require approximately one month.

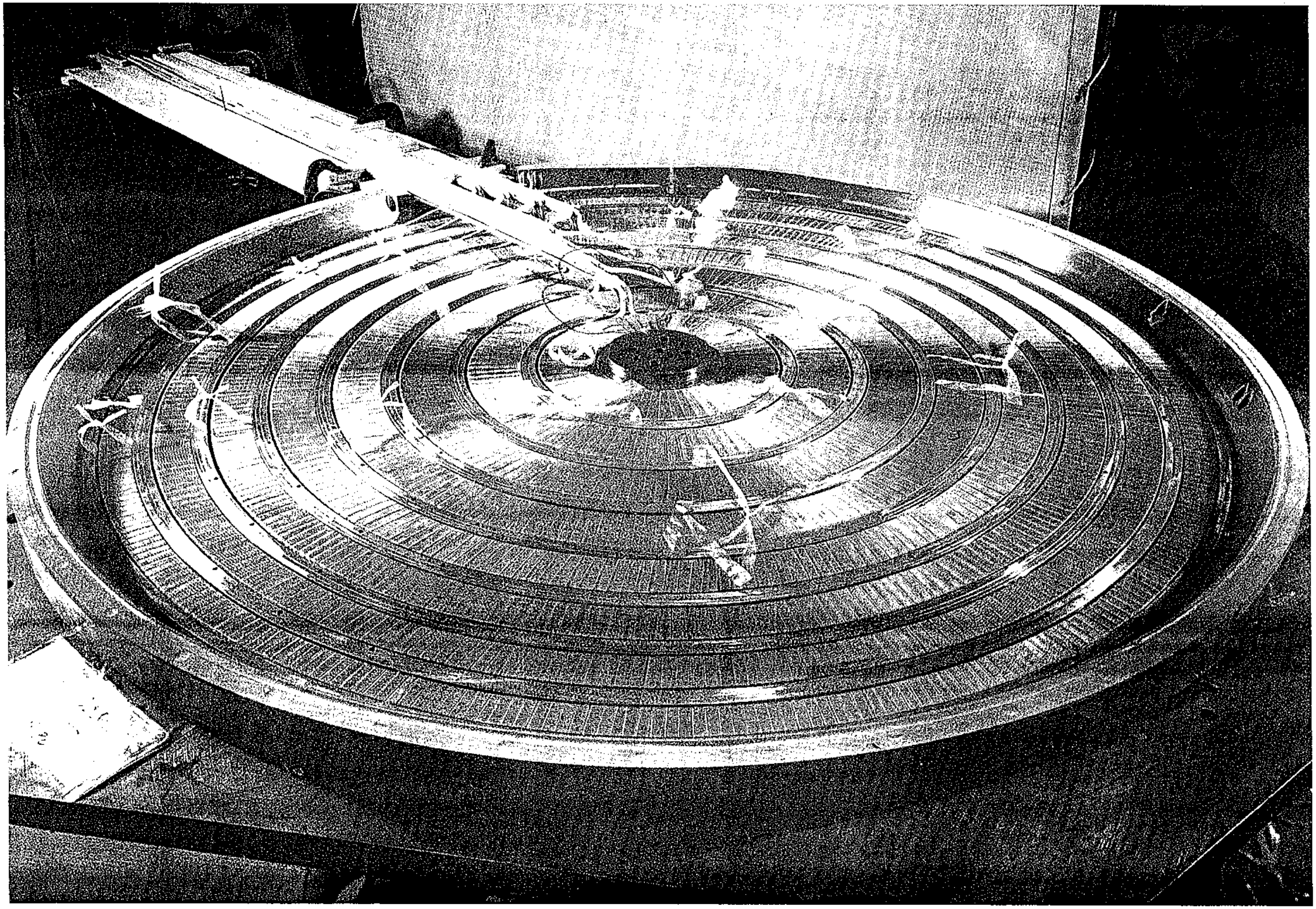

Fig. 7: One of the trimming-coil assemblies.

2.1.3. Rf System

The rf system, shown in the block diagram of Fig. 8, consists of a two-dee resonant cavity driven by a 250-kW rf amplifier. The tuning range of the cavity is 13.5 to 22.0 Mc/sec. A two-dee cavity may be excited in two modes—push-pull and push-push. In the latter mode, second-harmonic acceleration is possible for dee angles less than 180°; the effective MSU dee angle is 138°. The amplifier is capacitively coupled to one dee, and the pie-shaped section between the dees couples energy to the second dee. A very stable frequency synthesizer provides the excitation for a broadband amplifier which is the driver stage for the final amplifier.

Fabrication of the major mechanical components of the system is expected to be complete by the end of July, and their installation will begin immediately. The final amplifier cabinet has been tested under low power, and its performance is in good agreement with model studies.

The anode power supply was delivered in April. High-power tests of the final amplifier will begin in July with the anticipation of connecting the amplifier system to the dees as soon as the latter are installed in the cyclotron.

Major emphasis has been placed on design of a precision dee voltage regulation system. Regulation is accomplished by means of feedback signals from the dees and

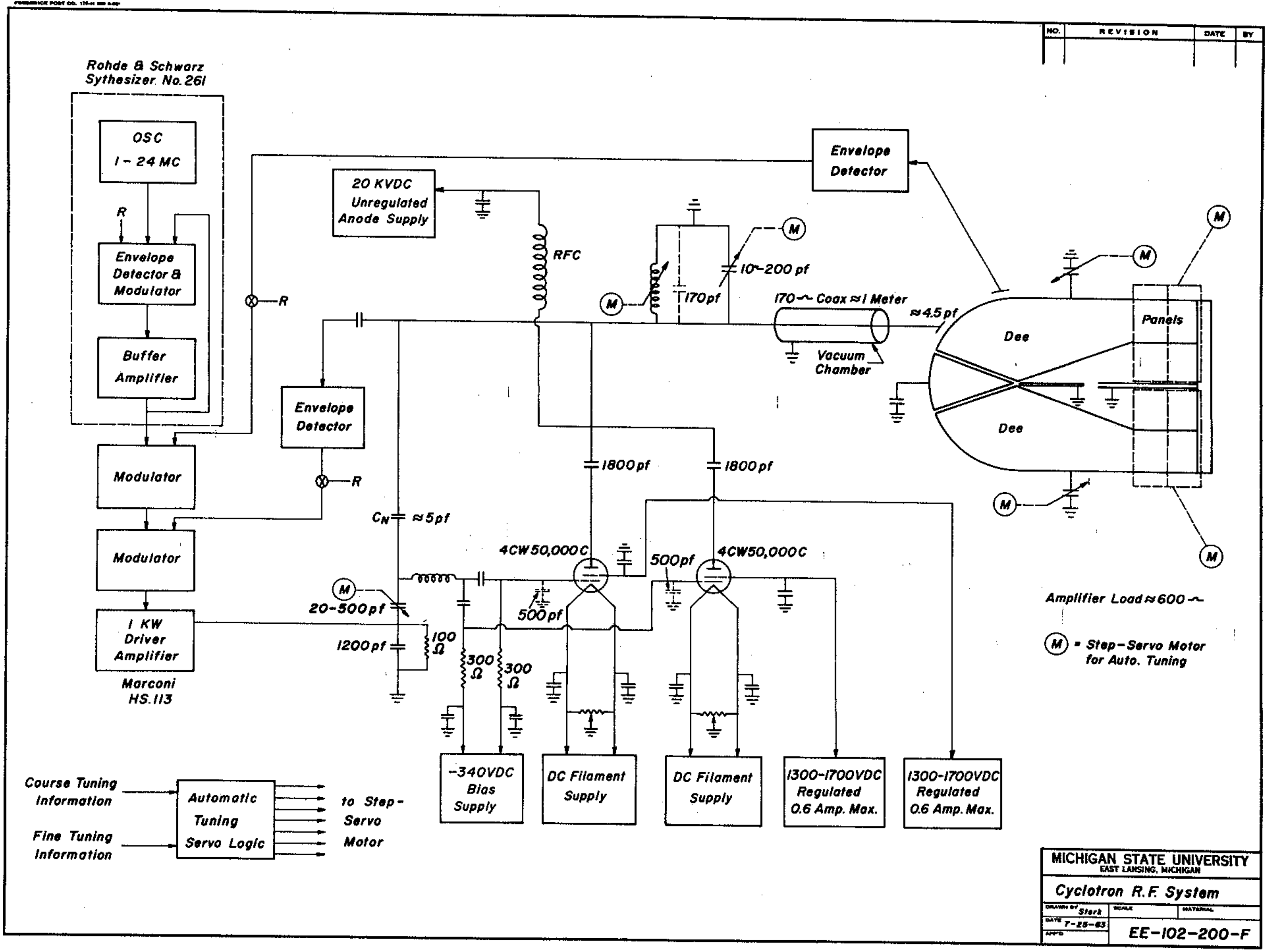

Fig. 8: Block diagram of the rf system.

final amplifier to the two modulators preceding the driver amplifier. The modulators in turn compare the feedback signal with a reference voltage, and the resulting error signal is used to control the input amplitude to the driver amplifier. Modifications in the commercially built components (frequency synthesizer and driver amplifier) have made possible the reduction of spurious noise and ripple on the rf voltage envelope to 0.1% of the peak rf voltage before the application of feedback signals. With the inclusion of feedback to the modulators, we now expect to regulate the rf voltage to 0.02%.

Design of the automatic tuning servo is in an advanced stage; final adjustments will be made when dees and tuning panels are installed in the cyclotron. The system employs digital logic to provide positioning information to step type servo motors. Wiring of the basic logic circuits is in progress.

About 90% of the rf-control circuitry has been designed. All electrical connections will be completed by the time high-power tests begin in July.

2.1.4. Central Region

The physical processes of ion injection and initial acceleration in the central region have long been the least understood and least investigated aspect of cyclotron operation. At the same time the starting conditions and the initial orbits of the ions are crucial in determining the overall performance of the cyclotron, particularly as regards the quality and precision of the external beam. For the MSU cyclotron major effort has been directed to the understanding and analysis of the central region problem including preparation of several special purpose computer programs and construction of a precision electrolytic-tank facility. The final cyclotron design has evolved by a successive approximation process in which the electric fields were in successive stages of approximation considered as a delta function, a square wave, a conformal mapping solution of the standard gap geometry and, finally, as measured data from the three-dimensional electrolytic-tank facility. In the median plane, single particle trajectories are computed using exact equations; axial motion has been treated in a semi-quantitative way, including a first order study in the conformal mapping acceleration gap field and including consideration of transverse space charge effects to first order via the MURA formalism. Results constitute a major improvement over previous cyclotron central-region studies.

Figures 9, 10, and 11 show computer results with the cyclotron operating in each of its three major modes. As can be seen from the figures it is necessary to move the source and puller over a considerable range in order to

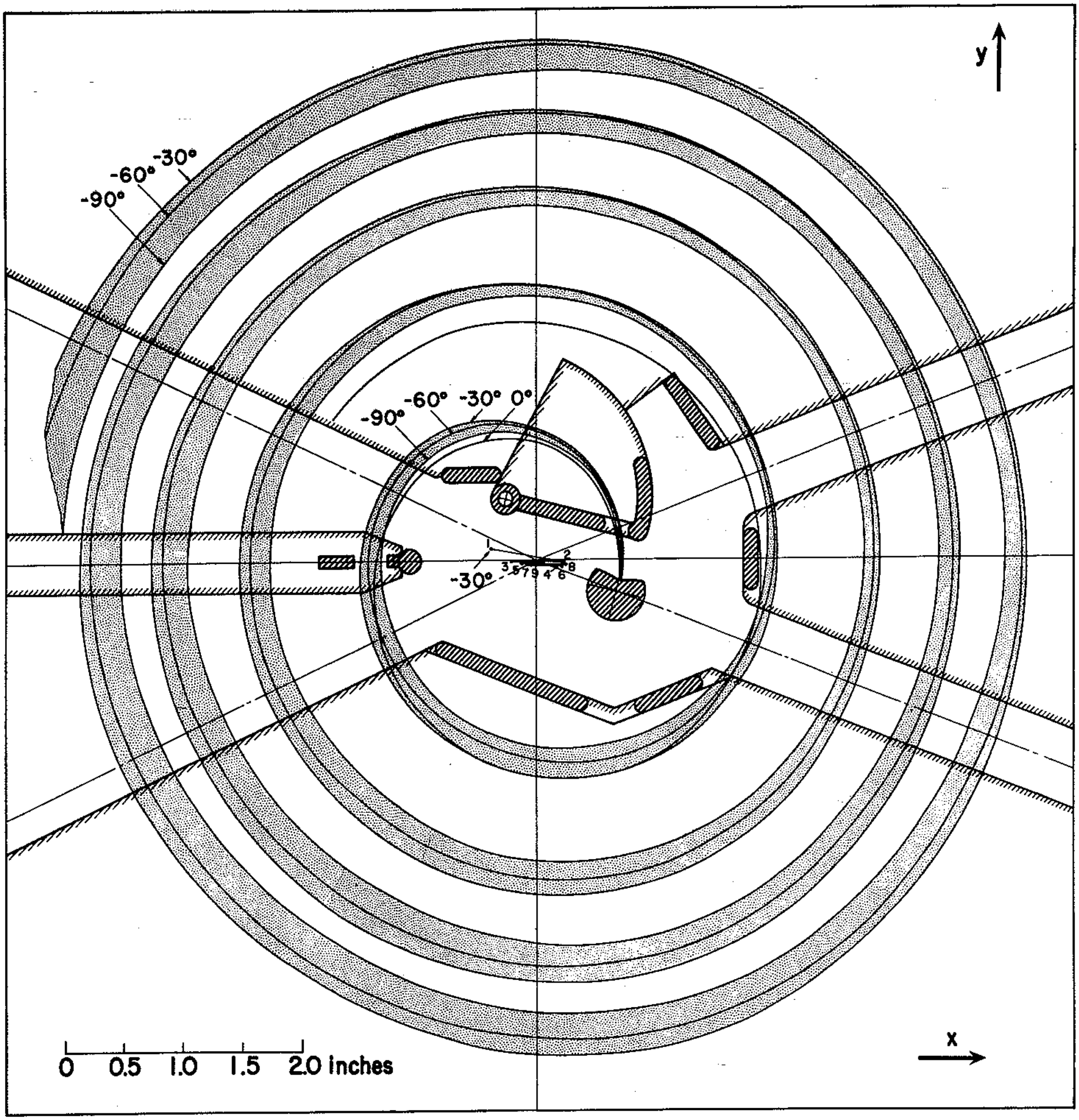

Fig. 9: Central geometry and initial orbits for protons with different starting phase in the first-harmonic mode of cyclotron operation.

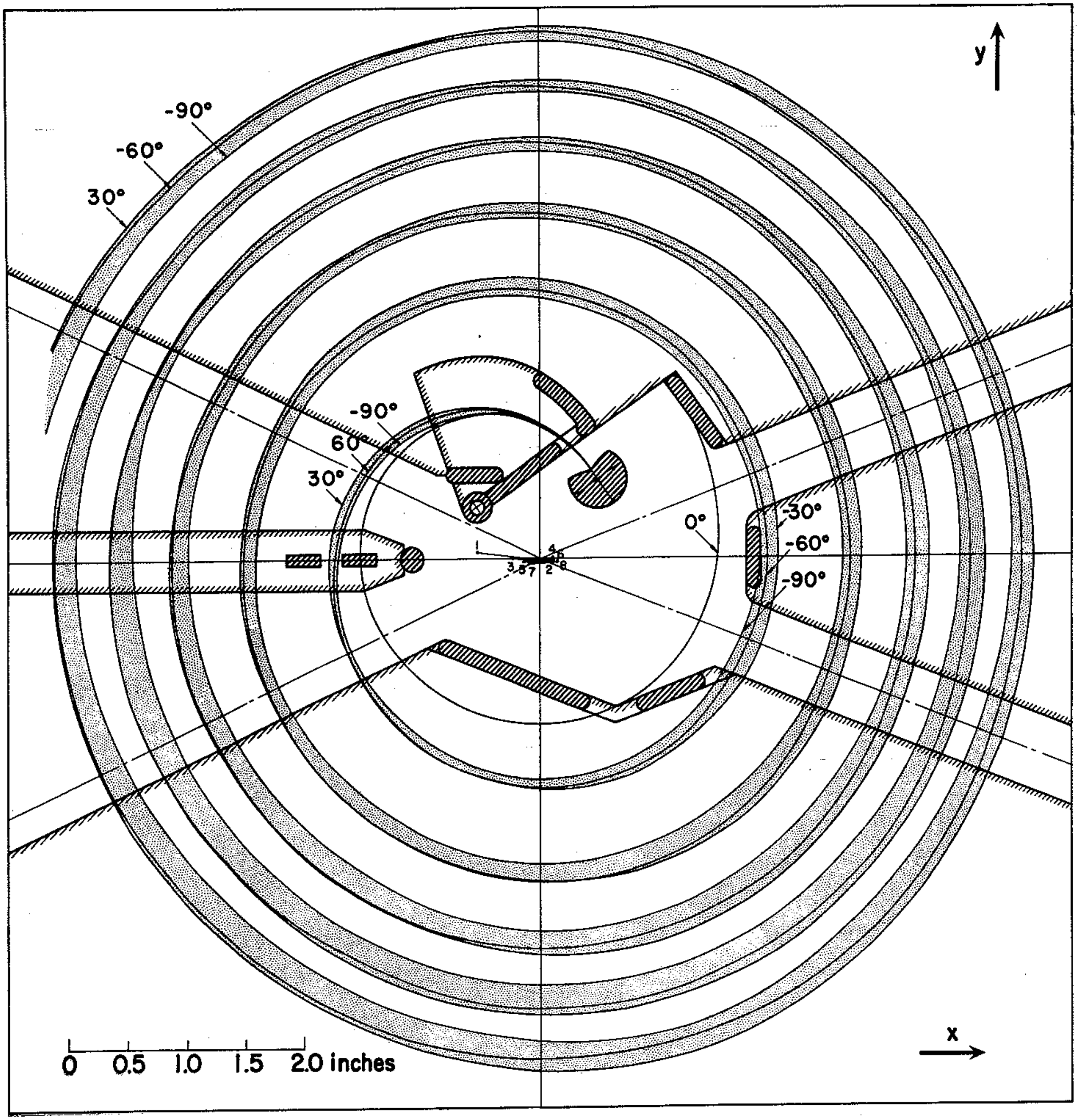

Fig. 10: Source-puller positions and central orbits in the second-harmonic mode.

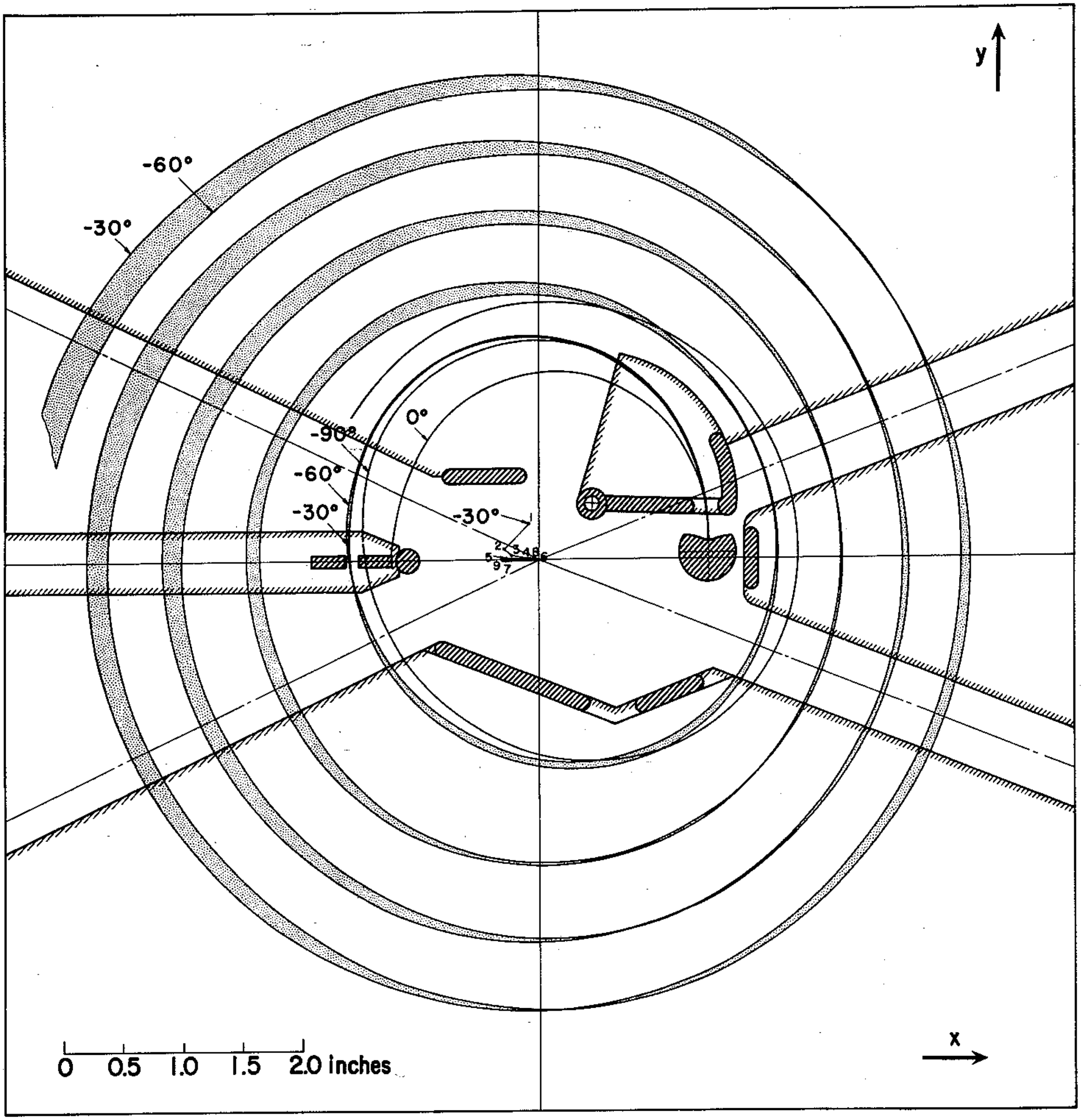

Fig. 11: Source-puller positions and center orbits in the third-harmonic mode.

obtain centered-orbits. Also due to the major importance of electric focusing on the early turns the ions must in each case be positioned in phase such as to be in the focusing region. A mechanical design for the source and puller has been evolved which allows the required motions to be accomplished without breaking vacuum so that operational shifts from one mode to another can be expeditiously accomplished.

As was indicated in our 1963 Proposal, provision is being made in the design for both "conventional" resonant extraction and for stripping extraction, the former to be employed on those experiments where precision is the dominant consideration, the latter to be employed in those experiments where duty factor is the dominant consideration. As a consequence it is desired to have a broad phase acceptance in the central region in the high duty cycle mode and a narrow phase acceptance otherwise. Figures 9, 10, and 11 demonstrate that the phase acceptance is inherently broad, particularly in the most important N = 1 mode where particles spread in phase by 90° successfully clear the several first turn electrodes. This in conjunction with the essential absence of phase grouping, which is also indicated by the computations, gives a 25% duty cycle as the particles leave the central region. It has also been demonstrated that appropriate manipulation of the rf-phase program can lead to an increase of the duty factor as the particles approach the stripping radius so that duty factors of approximately 30% are indicated for the stripping extraction mode.

To obtain single-turn extraction with the conventional resonant extraction system, it is necessary to limit the spread of the beam with respect to rf phase to approximately 7°. This will be accomplished in a two-step process:

(a) The slit which appears in Figs. 9, 10, and 11 at the end of the first 1/2 turn is adjustable in both radius and aperture from outside the vacuum system—this slit will be set with an aperture approximately the same as the source aperture thereby accomplishing a coarse-phase selection.

(b) Vertical-focusing studies have shown an extreme sensitivity of the dominant electric-focusing forces to rf phase. Typically the first node of the turn pattern shifts by approximately one revolution for each 15° shift in phase. A remotely operable axial slit assembly will also be mounted in the grounded dummy dee acting on the particles after they have completed 1.5 revolutions. By narrowing the axial aperture of this stop, the phase interval of the transmitted beam will be predominantly restricted to those ions which nearly come to an axial focus at the stop (such ions have an effective $\nu_z \approx 0.17$ due to the electric focusing on the first 1.5 turns). Inasmuch as the slits are all designed to be remotely operable it will be possible to change from the high to low duty cycle operating modes with a minimum of delay.

Design of all of the central region hardware is now completed and has been released to the shops for construction.

2.1.5. Beam Extraction

As indicated above, alternate extraction modes are being provided in the MSU cyclotron, the mode to be remotely selectable as determined by the requirements of a particular experiment. Extraction via negative-ion stripping, which will be employed for experiments in which high-duty cycle is of prime importance, is essentially trivial. A thin foil is inserted at the extrac-radius, the negative ions are stripped, the positive ions deflect sharply out of the field. The trajectories of the stripped ions have been calculated and appropriate ports for inserting the stripping foil and for passing the beam out through the vacuum tank are incorporated in the design. The azimuthal location for the stripping foil has been selected such that the trajectories for stripped and conventionally extracted particles become identical after the first 90° magnet.

The design of the conventional resonant extraction system is also completed. Extensive orbit calculations have provided a detailed understanding of the orbit dynamics and beam optics throughout the process; a report on these studies will soon be issued. The mechanism for generating turn separation is as follows: the ions are accelerated through the $\nu_r = 1$ resonance where a small (2 to 4 gauss) first-harmonic field-bump drives the orbits off center; as the ions accelerate farther out in the edge-region of the field, the value of ν_r drops sharply below unity such that the displaced orbit-centers precess with increasing rapidity; on the last turn the precessional displacement adds constructively to the energy-gain displacement at the channel aperture thereby providing sufficient turn separation for the beam to clear the septum. Beam deflection begins at $\nu_r \approx 0.75$ where the energy is approximately 10% greater than at the $\nu_r = 1$ resonance. Since the extraction process requires substantial ion acceleration into the non-isochronous edge-field, its greatest success demands a high energy-gain per turn, which is one of the distinctive features of the MSU cyclotron.

The first-harmonic field bump must be accurately controlled in order that the precessional motion be properly phased at the deflector entrance. This bump-field is produced by three sets of "harmonic coils," 120° apart, mounted on the liner plates and set into the magnet valleys. (These coils are an integral part of the profile coil assembly.) The currents in these coils are correlated so that the amplitude of the first-harmonic and the azimuth of its peak value can be independently varied. Because $(\nu_r - 1)$ passes through zero so rapidly, the resonance action of the bump-field is effective only over a narrow radius interval; calculations show that this critical interval is only 1.2 inches wide, and outside this interval such a small first-harmonic field produces a negligible orbit displacement. The position of this critical interval is known, and precise measurements will be made therein of the first-harmonic field component produced by the "harmonic coils" under various operating conditions. Computer results indicate that the beam may be as much as 0.4 inch off center (as a result of source-puller location and the electric gap-crossing resonance) prior to reaching the $\nu_r = 1$ resonance. This off-centeredness of the beam will be measured by three current probes which are located in the two dees and in the dummy dee. Computer calculations show that the first-harmonic field can be adjusted so that as the beam passes through the resonance, this off-centeredness is compensated such as to produce the desired final displacement. The $\nu_r = 2\nu_z$ coupling resonance (which follows the $\nu_r = 1$ resonance) limits the amount of orbit displacement generated at the $\nu_r = 1$ resonance; computations show that if the beam is more than 0.3 inch off center at the coupling resonance, axial growth will cause the beam to strike the dees. Since beam loss in this manner can readily be detected by the current probes, this coupling resonance provides a sensitive check on the settings of the harmonic coils.

For conventional beam extraction with an efficiency of 90% or better, it is essential that the energy spread within each turn be restricted so that $(\Delta E/E) < 1.5 \times 10^{-3}$; at the same time, such a restriction will of course yield an extracted beam of superior energy resolution. For this purpose, the rf phase interval of the accelerated ions must be limited to about 7°; this will be accomplished (as indicated in the previous section) by use of appropriate slits on the first turns.

After clearing the septum, the beam is deflected out of the cyclotron as rapidly as possible via an electrostatic channel followed by a magnetic channel. The detailed design of the electrostatic channel "shoe" is now complete and in the process of construction. This channel is 60° (30 inches) long, and should produce fields up to 150 kV/cm across a 1-cm aperture, although recent orbit calculations indicate a maximum field of 120 kV/cm is sufficient. The construction of the power supply is a copy of that used at the Berkeley 88-inch cyclotron and has the following features: low stored energy, which limits the energy supplied to sparks; and variable time constant, which permits spark duration to be optimized for fastest "bake out" of the system. The electrostatic channel will have a water-cooled copper septum adapted from an LRL design which has been found to tolerate 35 kw of beam power. Such a dissipation capability is essential if the cyclotron is to operate at its rated current output.

The magnetic channel is constructed from a set of coils and is designed to produce fields up to 4 kilogauss (recent studies indicate that a peak field of only 3 kilogauss is sufficient). The absence of iron from this channel minimizes saturation effects. A trial set of coils (Fig. 12) has already been constructed and installed in the cyclotron magnet; measurements of the field produced by these coils have established the adequacy of air-core design calculations. The data are now being analyzed to evaluate the first-harmonic component of the channel fringe-field in the critical radius interval near the $\nu_r = 1$ resonance (noted above). This harmonic is approximately 1 gauss; an appropriate correction will be made via the harmonic coils described above.

Computer calculations have been made to check the operation of the deflector when both ion energy and ion type are changed. A comparison of 51-MeV and 11.4-MeV

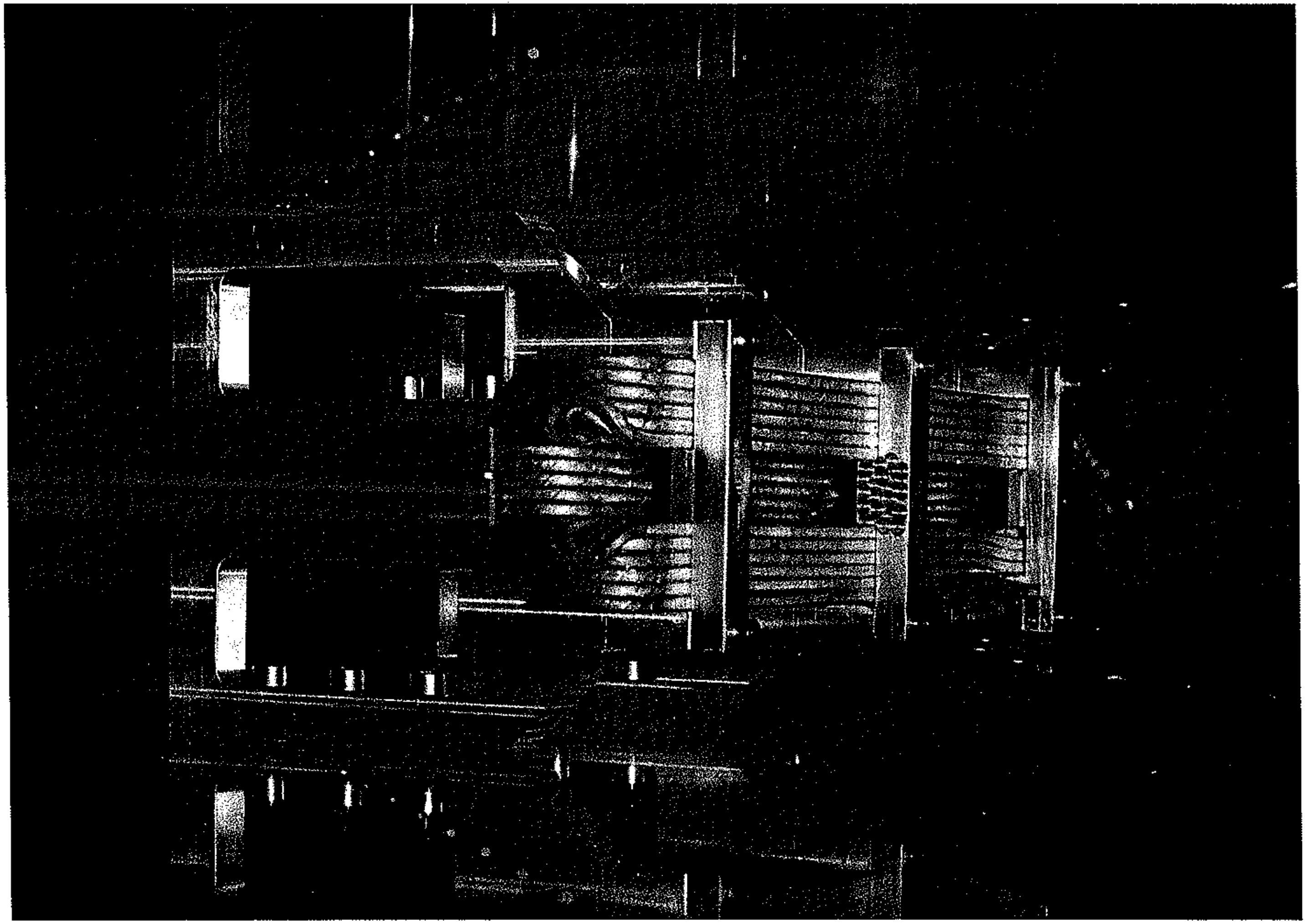

Fig. 12: The beam-extraction magnetic channel coils.

protons (high and low magnet excitations) in the deflector channels shows that the orbits can be made to coincide to within 0.042 inch by appropriate changes in field strengths. A similar comparison between 51-MeV protons and 68.6-MeV $(C^{12})^{4+}$ ions (which require the same magnet excitation) shows even closer coincidence between the deflection trajectories. These results indicate that only a minimal change in channel position is required for the variable-energy multi-particle operation of the cyclotron. The fact that a stabilized extraction trajectory can be obtained over such a wide variety of particle and energy reflects the general stability of the field shape resulting from the rounded magnet corners and is one of the major dividends of such rounding.

2.1.6. Vacuum System

The pumping system consists of a CVC Type PMC-50,000 oil diffusion pump, rated at 52,000 ℓ/sec. This is backed by two Kinney mechanical pumps: a KMBV-520 lobe-type rotary booster and a KDH-65 rotary-piston-type. The overall pumping speed of this backing-pump package is 185 ℓ/sec at 0.1 torr.

The entire system was designed to maintain a pressure of 5×10^{-6} torr in the acceleration chamber, with a total gas load (ion source plus air leaks) of 3 atm-cc/min.

The pumpdown time from atmospheric pressure to 5×10^{-5} torr is expected to be about one hour. An additional hour of pumping is expected to bring the tank to 5×10^{-6} torr.

A new ultra-low vapor pressure oil (10^{-10} torr), DC 705, will be employed in the diffusion pump. The low vapor pressure of this oil should minimize the problem of oil diffusion into the acceleration cavity. Initial trial operation will utilize water cooling on the baffles; in the event this proves unsatisfactory conventional liquid nitrogen cooling will be substituted (the baffle is designed for either coolant).

Experience on other cyclotrons has vividly demonstrated the important role of good vacuum to stable operation. The 36" diameter 50,000 liter/sec. pump selected for the MSU cyclotron gives the largest ratio of pump size to cyclotron size of any machine of which we are aware. It is also interesting to note that the pumping system was purchased within the limits originally budgeted for a 20" pump, reflecting a favorable cost trend in the vacuum equipment industry brought about largely by the emphasis which the environmental test laboratories of the space program have placed on large high-capacity pumping systems. (The importance of the additional pumping capacity was deemed to outweigh the alternate possibility of procuring the originally planned system at a considerable savings as compared with amounts budgeted.)

The various epoxy bonded coils utilized for field corrections are housed in a separate vacuum envelope with an independent pumping system (a CVC Type E70A, 19.3 ℓ/sec mechanical pump). Due to the stringent requirements on space in the magnet gap the diaphragm separating the two vacuum envelopes is unsupported in one direction such that atmospheric pressure in the coil envelope concurrent with vacuum in the beam space is not permissible. Appropriate fail-safe interlocks are provided to insure that this condition cannot occur.

All pumps have now been installed and most of the vacuum piping and valves are in place. Main power wiring and interlock and control wiring are in the process of installation. Figure 13 shows the fore-pump system and associated piping and valves, while Fig. 14 is a view with dee box removed looking into the large right angle valve at the top of the 36" pump. To facilitate leak testing a double gasket system is employed throughout the system with pump-out leads going to the space between the two gaskets. Leak checking can, therefore, be performed on a given joint as soon as it is made up by hooking the leak detector to the pump-out between the gaskets. Figure 15 shows leak detection work in progress on the dee stem box, while Fig. 16 shows a pair of the molded tee joints employed at corner points of the vacuum tank. The use of topological tees in the gasketing allows tanks to be made up out of independent plates

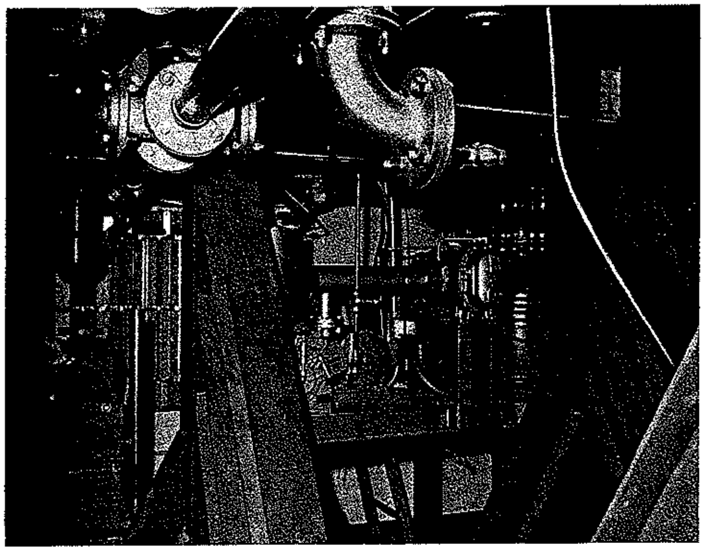

Fig. 13: Mechanical pumps and piping in the lower vault area. Lower section of PMC-50,000 pump is at righ-rear; Kinney KMBV-520/KDH-65 are center foreground.

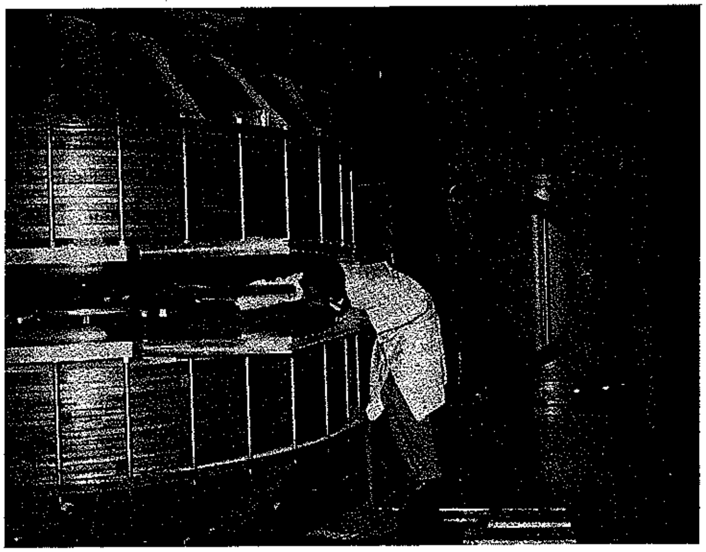

Fig. 14: Installation of dee-box cover plates. The 36" angle valve is at the right-rear atop the PMC-50,000 pump.

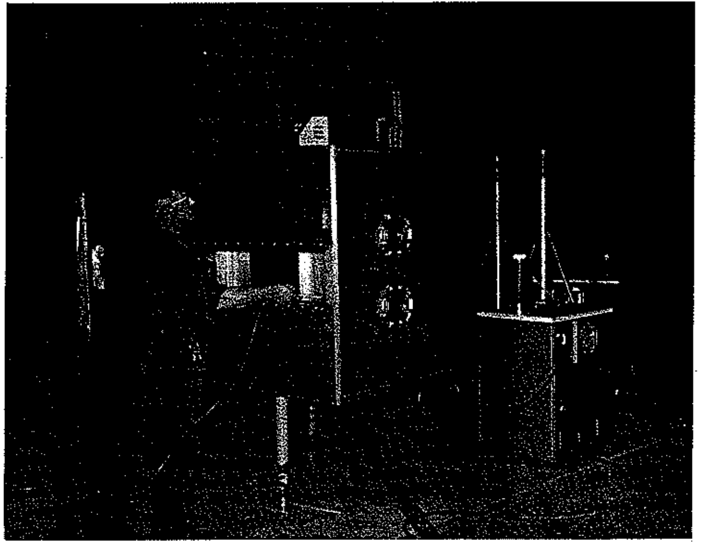

Fig. 15: Leak testing gasket assembly on rf panel-box.

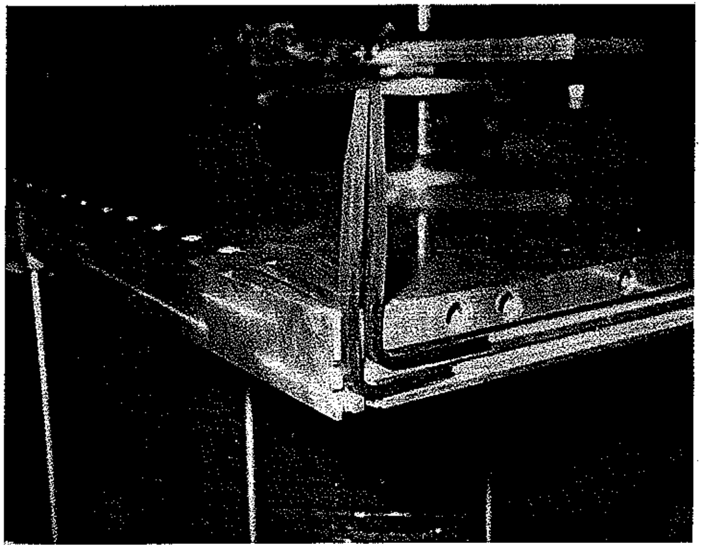

Fig. 16: Rf panel-box tee gaskets at one corner.

without welding (which would be a delicate and difficult operation on such large plates). An alternate joint technique in which straight sections of rectangular gasket material are butted together to form the tee has also been found to work satisfactorily.

Leak testing on the dee-stem box has been completed and the box found to be vacuum tight. Installation of the side plates of the accelerator tank is now in progress and should be ready for leak testing in the near future. Initial pump down of the complete cyclotron cavity should take place in early July.

2.1.7. Beam Transport System

The external beam handling system consists of two sections: the preparation system and the steering system (Fig. 17). The primary beam path runs from the cyclotron through two-double focusing 90° magnets and then into a system of steering magnets. The pair of 90° magnets produce zero dispersion if the object is placed at the focal point of the first magnet, while their dispersions add if the object is placed at the unit magnification position of the first magnet. The experimenter will be able to select either a highly resolved beam or a high intensity beam, depending on the position of the object slit. The beam-pipe hardware will include slits at each of the two positions with quadrupoles which can bring the beam to a focus at either slit so that selection of the zero-dispersion high-intensity mode or the high-resolution mode can be made remotely.

Magnetic elements in the beam-transport system are being designed by techniques similar to those employed in the cyclotron proper using a series of computer programs (described in Sec. 2.1.10) known as "Linop", "Cartax" and "Boptix". Determination of basic system properties, particularly the number and location of various elements, is made on the basis of linear optics calculations. Detailed design of individual elements and final adjustment of the complete system are accomplished by precision measurement of fields and digital computation of trajectories. Equations employed are exact in the median plane and accurate through third-order terms axially. With such a system it is possible to design corrective elements for an entire system or subsystem as a single unit, a tremendously easier task than the usually employed technique of attempting to achieve point by point realization of some specified analytical field distribution throughout all the magnets of the system. (Moreover the analytically prescribed field shapes so laborously sought after are themselves usually only approximations.)

Each of the 90° magnets in the MSU design is actually a magnet system consisting of a flat-field 90° magnet with single-stage vertically-focusing quadrupole elements at entrance and exit. Such a combination results in a dispersion equal to that of an $n = 1/2$ double-focusing magnet. For two such magnets (with the initial object positioned at the unit magnification point for the first magnet) the dispersion is double that of a single magnet. The quadrupoles have a maximum field gradient of 1700 gauss/in. and a focal length of 48 in. for 56-MeV protons, and they are large enough to permit a 2 in. x 2 in. beam space. A sample quadrupole built by Spectromagnetic Industries has been purchased, and the magnetic field measured to an accuracy of ±1 gauss at each measured point. The field gives good focusing over the 2 in. x 2 in. range as determined by calculated orbits, and the good-quality aperture could be extended by 15% by the addition of corrector conductors in series with the current in the coils of the quadrupole.

The 90° magnets are designed with wide pole faces to obtain a wide region of uniform field with a minimum of shimming. Correction of aberrations in the magnet system will be made by attaching specially shaped edges to the pole faces at entrance and exit. (The method is analagous to surface corrections in light optics.) It is expected that the circle of confusion can be reduced to the order of a few mils. The pole faces form the upper and lower cover of the vacuum box so that the entire magnetic gap is available for beam. The deflecting magnets and quadrupoles focus an energy-dispersed series of images of the entrance slit on the focal plane. An exit slit determines the energy range transmitted by the system. Both entrance and exit slits are adjustable horizontally (the dispersion direction) and vertically. For 56-MeV protons the dispersion is 400 keV/in. Thus with a 5-mil entrance slit and unit magnification, a 2-keV change in energy moves the image by one image width. Such a narrow slit can be used when a negative ion beam is extracted from the cyclotron since a negative ion passing through a thin foil is changed to a positive ion and is swept out by the following magnetic fields. An additional slit is provided at the focus of the first magnet to limit the amount of unwanted beam entering the second magnet. Suitable anti-scattering apertures are provided to reduce to a minimum the particles which can scatter from the slit edges and the walls of the tube and reach the exit slit.

The exit slit of the preparation system, or energy-range slit, forms the entrance slit of the steering system. The principal function of the steering system is to serve as a transfer lens to place an image of the energy range slit on the desired target. The steering system is being designed with small aberrations so that the energy-range slit determines the target spot rather than a slit near the target. An anti-scattering slit somewhat larger than the target spot is provided. A means for determining the position and direction of the beam near the target is required. A number of methods have been considered, but the choice will be made for each particular experiment. One possibility is an oscillating slit. Such a slit system would be of a size and thickness to interact with less than 10^{-2} per cent of the beam. The exact form of the steering system has not been determined, but will include one or more deflecting magnets capable of deflecting the beam into a number of beam pipes. Quadrupole magnets are provided for focusing. The principal difficulty in designing the steering system is obtaining long focal distances from the deflecting magnet with magnifications of approximately unity but without using a large number of elements.

Beam tubes for the MSU cyclotron will basically be of 4" diameter with localized sections of 3.5" diameter to reduce the cost of some components and to facilitate localization of beam spillage. All vacuum joints are interchangeable, and in addition both flanges of each joint will be identical. Coupling of the joints is by means of band clamps actuated by a single nut. All viewers probes, slits, etc., are mounted in standard all-purpose boxes.

The pressure in the beam tube will be maintained at less than 10^{-5} torr throughout by a series of suitably located diffusion pumps. At this pressure, calculations show that all undesirable effects due to interactions of the beam with the gas remaining in the beam tube are negligible (including the several stripping processes applicable to negative ion beams).

Methods for observing the beam spot include ZnS screens viewed by TV for small beam currents, bifilar scanning for larger beam currents, and ozalid burning for precision location of well focused beams. Slotted diaphragms will be used to observe the directional spread and uniformity of the beam, and to quantitatively determine phase space density.

Beam tubes and most other beam-pipe hardware will be constructed of aluminum which minimizes both cost and residual activity. Studies are in progress to determine the best material to use for slit jaws with positive ion beams, the selection to be made on the basis of minimizing slit edge scattering. (A dense material minimizes the solid angle subtended by the slit edge; a low Z material gives reduced multiple scattering.)

2.1.8. Experimental Equipment

Selection and procurement of equipment for use in initial cyclotron experiments is progressing on a schedule consistent with progress on construction of the cyclotron. Every effort is being made to foresee future developments as accurately as possible so that the equipment procured will be compatible with the ultimate complement of equipment to be assembled around the cyclotron. As a policy guideline preference is given to commercial equipment whenever such equipment is competitive in performance and economically reasonable as compared with construction of the equipment in the laboratory.

Negotiations are in an advanced state on procurement of a commercial 4000-channel two-dimensional analyzer. The analyzer will incorporate a digital-stabilization system which will essentially eliminate system drifts (including pre-amplifier, amplifier, and analyzer proper). The broad energy range of particles produced by bombardment at 50-MeV coupled with the high resolution obtainable with semiconductor counters requires one-parameter analysis with a large number of channels. With such a digital-stabilization system the analyzer can be used for 1000-channel single-parameter analysis with no problem of equipment drifts masking fine structure. The analyzer can, of course, also be used for all normal two-dimensional applications, particularly the study of reactions with three-body final states. The two-dimensional mode will also be invaluable in checking out the performance of analog circuits built for particle selection via dE/dx-E telescopes. The analyzer under consideration also has the capability of being expanded into a 10^3x10^3-channel two-parameter analyzer by the addition of a magnetic tape and buffer system (implying, of course, that the computer would be used to accomplish the actual sorting of events) and additional analog-to-digital converters can be added to allow analysis of more than two parameters. Small one dimensional analyzers are presently available as a part of the equipment associated with the decay-scheme program. These analyzers will also be used for checking out counters and detectors. In addition, in most experiments it is desirable to have a monitor counter to serve as a check on the Faraday cup and condition of the target. Small one-dimensional analyzers are now becoming available at very moderate cost. Purchase of such an analyzer for use with the monitor counter is presently under consideration.

Electronics for the various detection systems will be of modular type with a wide variety of circuits. Each experimentalist will interconnect the modules to suit the particular experiment. Except for special advanced-design circuits (such as analog circuits for particle identification), the electronics will be purchased commercially.

The modular approach provides a versatile electronics system which can be expanded as needed via gradual accumulation of compatible equipment.

Semiconductor-detector technology is at present in a state of rapid development and change. As a result commercially available detectors are generally either (a) inferior in resolution capability as compared with advanced laboratory produced detectors or (b) involve long and uncertain lead times on procurement. In view of this situation and of the fact that two of our staff have direct experience in production of detectors of advanced capability, a facility is being established for the fabrication of such detectors. The facility is intended to supplement rather than replace the external procurement process. Detectors will be procured externally whenever cost and performance are competitive. The internal facility will however always allow the project to remain abreast of the most advanced detector techniques, and in addition will allow experimentation with special types of detectors of particular interest in this energy range. As an example, it is planned to undertake preparation of a series of special counters designed to minimize the slit-scattering problems inherent in the collimation of 50-MeV proton beams, the approach consisting of surrounding the counter area of a lithium-drifted silicon detector by an anti-coincidence ring. The ring will act as a guard to reduce leakage current and, in addition, will act as a diaphragm to define the counter area, eliminating the necessity for a slit. Another special need is for an array of counters to be placed in the focal plane of the charged particle magnetic-spectrograph which is in the planning stage. It is also planned to assemble arrays of counters for simultaneous measurement of large portions of angular distributions.

A major recent advance in detector technology is the use of lithium-drifted germanium counters for gamma-ray detection. A detector produced (at another lab) by one of our staff has achieved a resolution of 6-keV on the Cs^{137} gamma. Overall resolutions of 4 to 8-keV appear obtainable. Production of such detectors is not difficult and will be of tremendous value in all experiments in which gamma-rays are detected. Since they must be kept at liquid nitrogen temperatures, it is particularly inconvenient to purchase these counters externally.

Most targets will also be made in the laboratory, utilizing (at least initially) much of the equipment assembled for detector production work. Provision has been made for inclusion of an electron gun in the vacuum-evaporator assembly in order to permit evaporation of materials that require very high temperature.

Realization of a suitable scattering chamber has posed a considerable problem. Ultimately, it is clear that an all-purpose, high-precision chamber is needed similar to chambers in use at Oak Ridge, University of Colorado, Princeton, and elsewhere. Such a chamber will be appropriate for essentially any semiconductor detector experiment. Unfortunately the cost of such a chamber is considerably outside the scope of amounts previously budgeted even if engineering costs are completely avoided by construction of a straight copy of a chamber from another lab. (Lack of funds for such a chamber constitutes, at present, the major equipment deficiency of the project—funds are requested in the Proposal section of this document.) To handle the scattering-chamber problem in the near future, negotiations are in progress to obtain a large chamber on loan from the University of Rochester. (The loan has been approved by the Rochester staff and the matter is now awaiting approval by the Atomic Energy Commission.) Assuming the arrangements proceed the chamber will arrive in mid-summer and will be fitted with equipment for the initially planned experiments.

2.1.9. Building

The Cyclotron Laboratory is a one-floor 34,500-square-foot structure. Construction on the building was begun in October 1962, and the building was occupied in October 1963. The floor plan, Fig. 17, shows the arrangement of offices, set-up laboratories, control room, shops, utilities space, and experimental areas. The nominal cost of the building was $1,400,000 of which $1,015,000 represent construction contracts and architects fee and the remainder consists of various internal site preparation and utilities expenses.

The cyclotron is located in one corner of a 35-foot ceiling high-bay area as is illustrated in the cut-away artist's sketch of Fig. 18. Four separately shielded target rooms are available to receive analyzed ion beams. Most of the shielding is provided by stacked-block concrete walls. A 5-foot-thick fixed poured-in-place wall separates the experimental areas from the remainder of the building. Each shielded room is provided with a heavy-concrete shielding door hydraulically raised and lowered by a standard elevator-type ram in a manner similar to doors employed on the CERN PS and on the Argonne 60" cyclotron. Installation of the shielding door system is now complete and the system has been under tests for some weeks. Performance is satisfactory. The total cost of the system ($70,000 for six doors) is competitive with

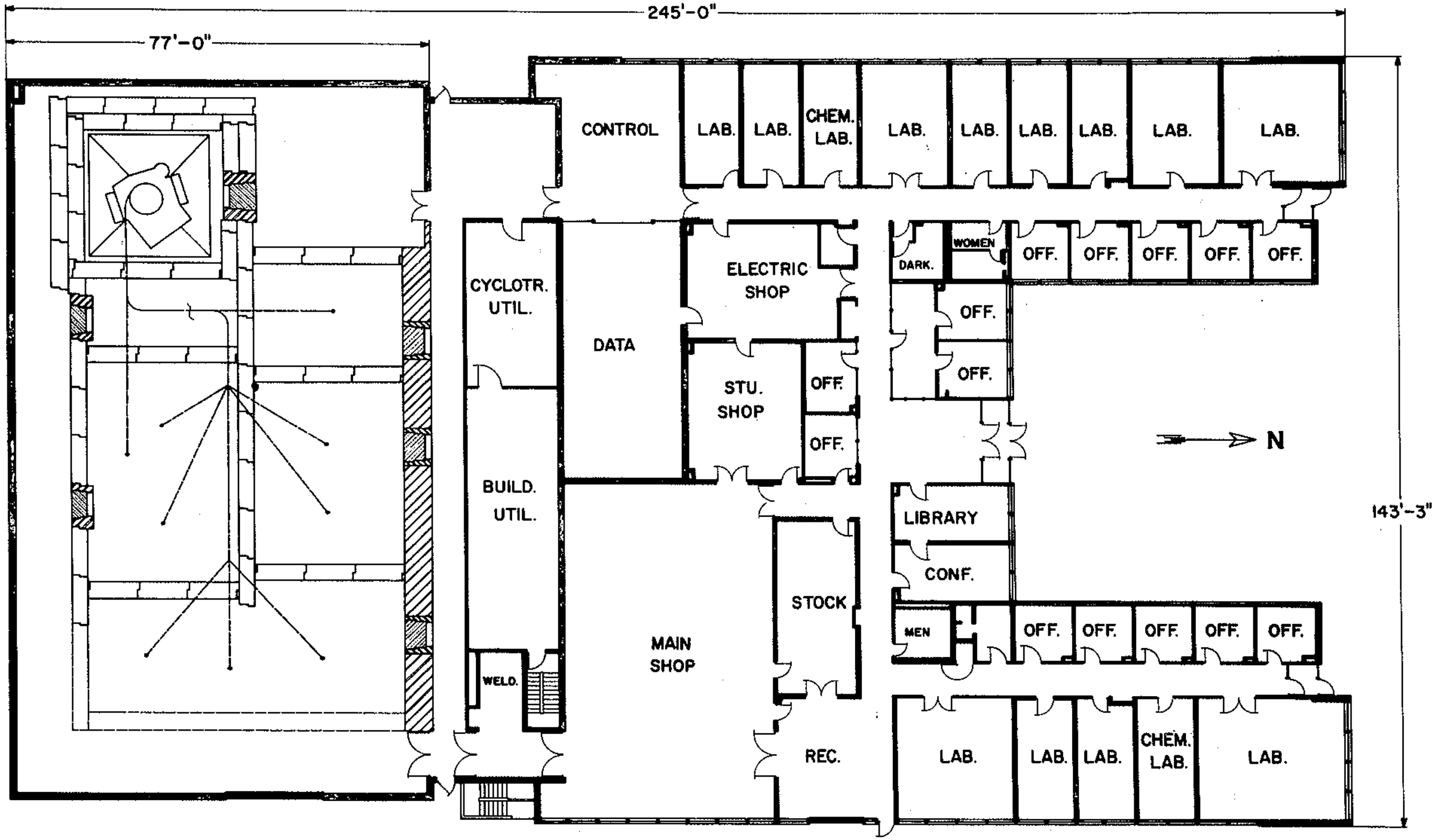

Fig. 17: Floor plan of the cyclotron building. Beam paths are denoted by heavy dashed lines running from the cyclotron to various target positions. The beam preparation system is located in the separately shielded room adjacent to the cyclotron magnet. The steering system employs large flat field magnets at each of the two fanning out points on the main beam pipe. (For simplicity orbit curvature in the vicinity of the fanning out points has been omitted.)

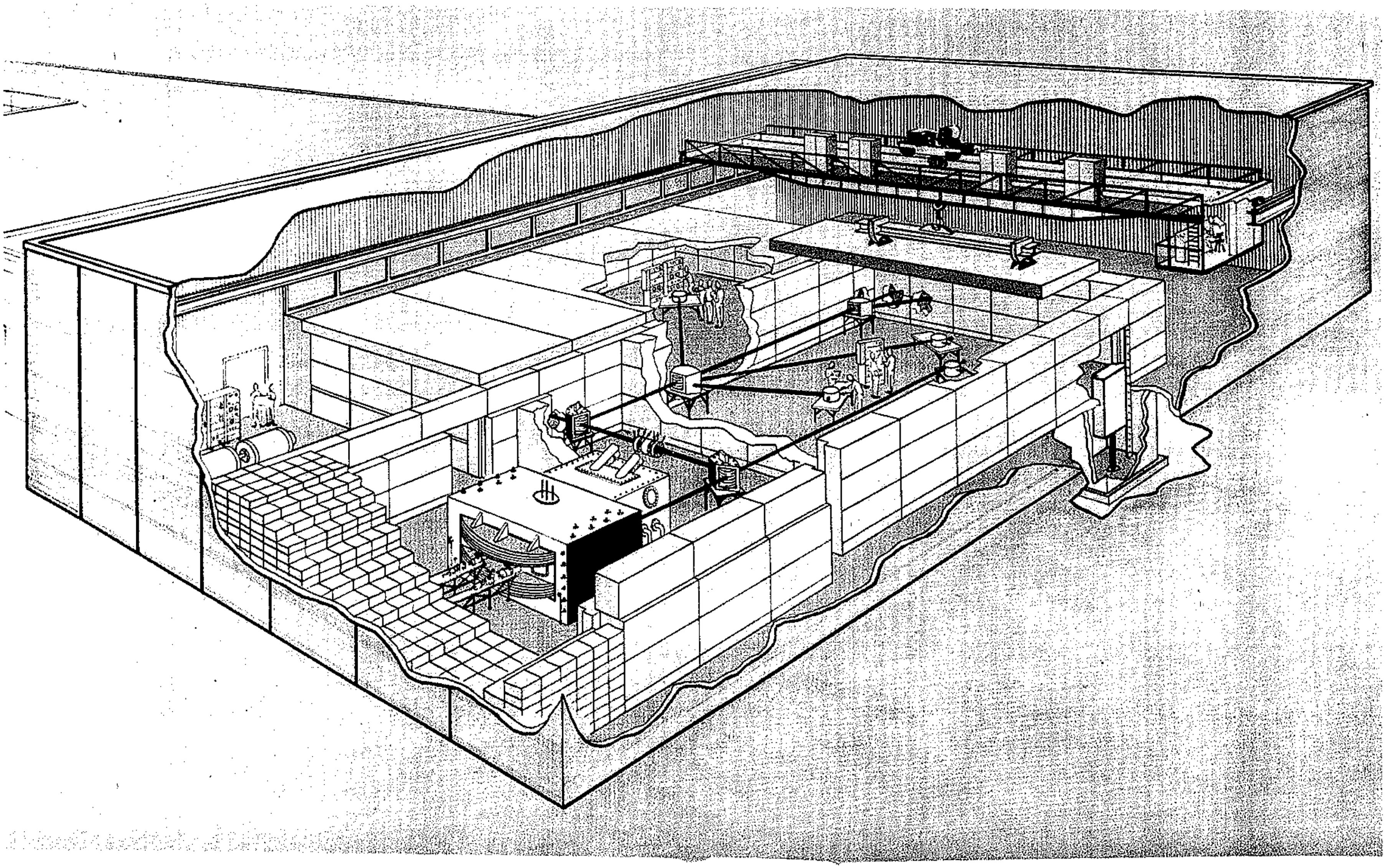

Fig. 18: Cutaway sketch of the high bay area of the cyclotron building showing the arrangement of stacked block shielding. The overhead crane has 40-ton capacity. One of the hydraulically actuated shield doors is visible in the cutaway at the right. The doors rise from pits on standard elevator rams.

that of other door techniques and has the advantage of requiring a great deal less floor space than alternate procedures involving horizontal motion of the doors.

Most of the high-bay area is accessible to a 40-ton bridge crane. Shielding blocks will be constructed in large sections corresponding approximately to the crane capacity. (The west wall of the cyclotron vault which is not accessible to the crane is an exception.) In the experimental areas, floor to roof block clearance of 12 feet has been provided.

An elaborate radiation-safety system is under construction, the most important features of which are the following: (1) When the cyclotron is operating the high-bay area is accessible only through the control room. (2) Remotely insertable iron "beam stopper" plugs are provided at each point where a beam pipe passes through a shielding wall. In order for the shielding door of a given room to be opened all beam pipes entering the room must be in the closed condition. (3) At each shielding door a panel of 15 keys is provided, all of which must be in place in order for the door to close. All personnel entering the given room will be under rigorous instructions to take one of the fifteen keys. Anyone with a key can be confident that the door will not be closed and the beam pipes activated while he is in the room. (4) Whenever the closing cycle on a door is initiated, room illumination within the particular shielded area will change from white to red and a warning siren will sound. (5) Within each room an emergency stop button is provided which will close the beam stopper plugs in all pipes entering the room and open the door, overriding all other interlocks.

The system as designed will permit safe occupancy of several experimental rooms for setup work at the same time that experiments are in progress in other rooms which should serve to greatly augment the total research capability of the facility.

Construction of the portable shielding is scheduled to begin in the late summer of this year on a schedule which should allow completion of shielding for the cyclotron vault, the magnet room and the south experimental room at approximately the same time as the cyclotron will be ready for initial operation. Due to funding limitations shielding of the east experimental room will continue to remain in a diferred status.

2.1.10. Accelerator Computer Programs

The new CDC-3600 computer was installed on campus in August 1963; the superior speed and versatility of the 3600 have been impressively demonstrated in work to date.

During the past year, efforts have been concentrated on transcribing the necessary cyclotron design programs to the new computer. In order to expedite this work so as to minimize delays in urgent cyclotron construction work, the new programs have all been written using the Fortran system. Even though Fortran programs are inherently inefficient, the new computer is so fast that the running time of these programs has turned out to be practically insignificant. At the same time, since Fortran is a nearly universal programming language, these new programs can be easily transcribed to any computer and should therefore be of considerable assistance to other groups undertaking the design and construction of sector-focusing cyclotrons.

The Fortran programs constructed during the past year cover all important aspects of cyclotron design work; many of these programs are simply improved and expanded versions of those developed here for our previous computer. The following is a list of those programs currently in use and a brief description of each.

(1) "Policy" processes the data from magnetic field measurements and computes the desired Fourier coefficients as a function of radius. It also computes accurately the isochronous average field which joins smoothly to the measured values near the magnet edge.

(2) "Cyclops" computes properties of equilibrium orbits and the associated linear (radial and axial) oscillations in a given magnetic field over a specified range of energies; the output provides basic design data such as the phase-slip per turn, and the radial and axial "tune" (ν_r and ν_z) versus energy. It also supplies values of $\alpha(\theta)$ and $\beta(\theta)$, as defined by Courant and Snyder, from which the radial and axial eigen-ellipses can be obtained at any azimuth θ for a given energy. This program can also compute the properties of other fixed-point orbits (stable or unstable) versus energy, with or without field imperfections; such results are important, for example, in determining stability limits.

(3) "Goblin" computes accelerated orbits by integrating complete median plane equations together with several sets of linearized axial equations; the acceleration routine simulates a two-dee rf system operating either in push-pull (odd-harmonic) or push-push (even-harmonic) modes. This program has several important overwrites including one for beam deflection studies using various combinations of electrostatic and magnetic channels. With the CDC-3600, Goblin tracks an accelerated orbit at about 150 turns per minute; hence, it is quite practical to compute orbits through the full 200 turn trajectory of the cyclotron.

(4) "Cartel" computes median-plane orbits in the central region starting from the ion source; the rf field is calculated from a cartesian map of the potentials as derived from electrolytic-tank measurements. This program is invaluable for designing source-puller and other electrode configurations in the central region of the cyclotron.

(5) "Trimco" computes current settings for the circular trimming coils such that the resultant field together with that of the magnet then matches as nearly as possible the prescribed form of the average field versus radius.

(6) "Phinal" computes the energy and phase-slip history of ions in a given magnetic field for a specified rf frequency; among the applications of this program is the determination of the specific rf frequency which minimizes the energy spread in the beam at extraction.

(7) "Linop" traces the optical properties of ion beams through specified sequences of focusing and deflecting magnets by using the appropriate transfer matrices; the program provides an analysis of the magnet system for analyzing and transporting the beam from the cyclotron to the target positions.

Other programs now in production should be completed by the summer of 1964; they are as follows.

(8) "Cartax" and "Boptix" compute orbit properties (including both radial and axial non-linear effects) and

beam optics in the fringe field of the cyclotron and through deflecting and focusing magnets. Measured field data are employed.

(9) "Silax" computes central-region orbits including axial electric as well as magnetic focusing; this program uses analytic electric fields which simulate those produced by a two-dee system. Improved versions of "Goblin" and "Cartel" are also under construction. Complete descriptions of all these programs will be issued as reports from this laboratory as soon as possible.

2.2. Decay-Scheme Studies

The National Science Foundation has previously supported the research programs of Professor S. K. Haynes and Associate Professor W. H. Kelly under separate grants. Beginning with the budget period covered by this proposal these groups will be combined with the cyclotron program (conforming to NSF request). The recent progress of these groups is reviewed in following subsections.

2.2.1. Iron-Free $\pi\sqrt{2}$ Beta-ray Spectrometer

During 1963, the iron-free $\pi\sqrt{2}$ beta-ray spectrometer came into full operation. Previous instrumental-drift difficulties were found to be due to various ambient temperature fluctuations, and these have now been effectively eliminated. Figure 19 is a photograph of the instrument.

Cs^{137} Conversion Lines. The complete conversion spectrum of Cs^{137} has been measured with a resolution of 0.04%. The L subshell ratios agree with those of Graham *et al.*,[1] taken with a resolution of 0.02%. However, no previous measurements of the M and N fine structure have been made with resolution as good as 0.04%. The data are now being analyzed and compared with theory.

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1) J. S. Geiger, R. L. Graham, F. Brown, Can. J. Phys. 40, 1258 (1962).

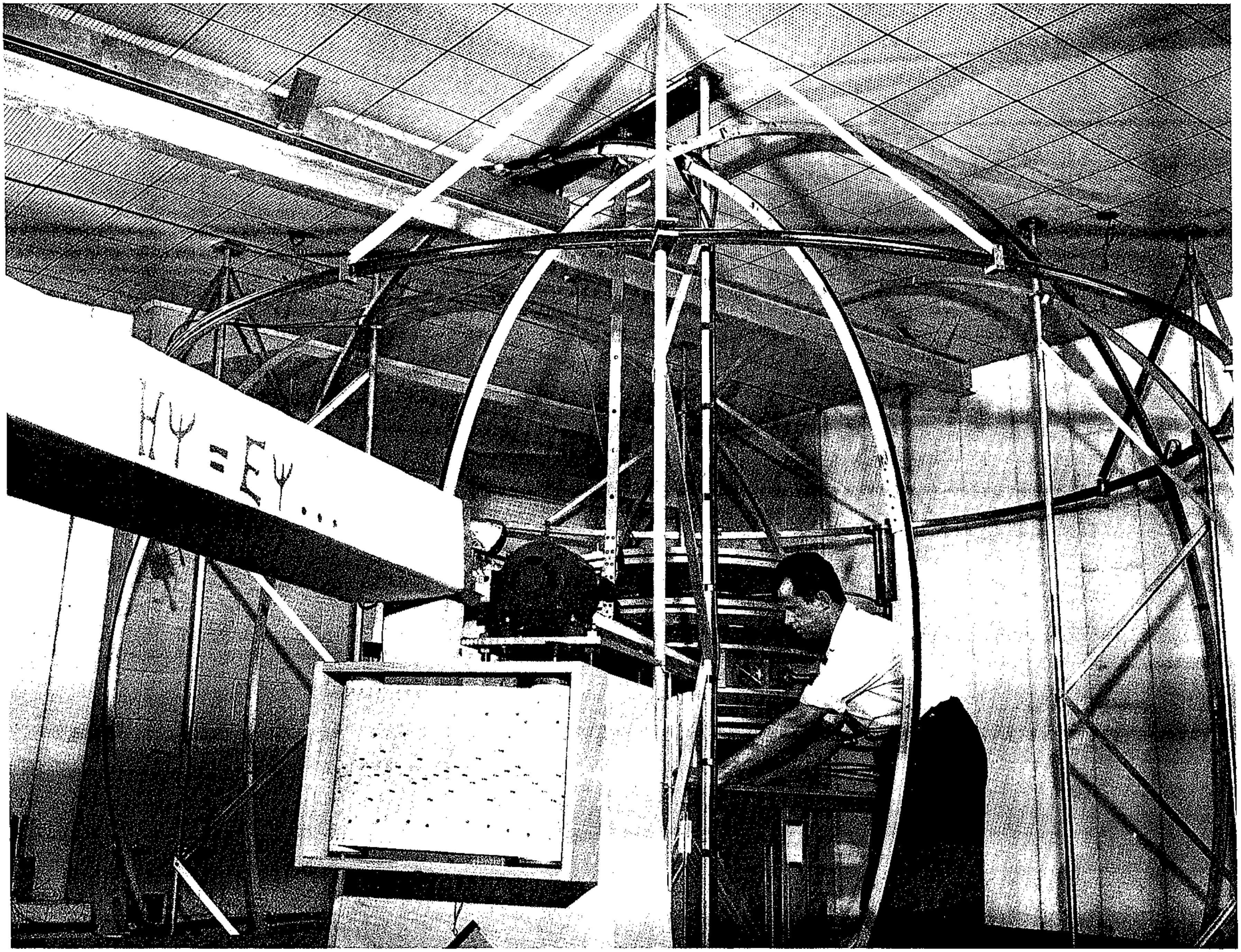

Fig. 19: View of $\pi\sqrt{2}$ air core beta ray spectrometer.

RaD Conversion Lines and L Auger Spectrum. The complete RaD spectrum (conversion lines and L Auger spectrum) has been measured with a resolution of 0.2%, better than any previous measurements. This L-Auger spectrum is of particular interest since there is no K conversion and 90% of the L conversions are in the L_1 shell. Thus these results when combined with those from a nuclide which has few L_1 vacancies (Au-199) should give quite accurate values of the Koster-Kronig coefficients f_{12}, f_{13}, and f_{23} for this part of the periodic table.

In^{113} and Sn^{113} Conversion Lines and K- and L-Auger Spectrum. We have found that sources containing 98% indium (In^{113m} has a halflife of 100 min) can be prepared by differential evaporation from a hot filament containing the orbital-capturing parent Sn^{113} (112 days). The plan is to study the Auger effect for In^{113} and then to study the orbital capture of Sn^{113} via its Auger electrons. Preliminary data have been taken for the conversion lines of the 392-keV transition of In^{113m} and will be taken for the K-Auger electrons (20 to 24 keV) and the L-Auger electrons (2 to 4 keV) from In^{113}. In the latter case, post acceleration of the electrons is necessary for efficient detection by the Geiger counter. The Sn^{113} sources were prepared in the Argonne isotope separator. The spectrum of Auger electrons from Sn^{113} is also being measured.

Effect of Source Chemistry on the Auger Effect. Preparations have been made for starting a program to determine the effect of source chemistry on the Auger effect. A vacuum chamber for the controlled evaporation of sources (10^{-10} to 10^{-9} torr) is under construction and is about 75% finished.

2.2.2. Scintillation Spectrometer Studies

Scintillation and electron spectroscopy techniques have been used to determine the decay schemes of several radioactive nuclides and isomers.

Decay Schemes of Te^{121} and Te^{121m}. The Te^{121} isomers decay to Sb^{121} states which are of considerable interest since they are a good test of shell-model predictions, Sb^{121} having a single proton outside the closed major shell of 50. In the course of these studies, five previously unreported gamma-ray transitions from the decay of Te^{121} and Te^{121m} were found. In addition, relative intensity measurements in singles and coincidence spectra have established the time order of a previously known 68- and 507-keV concident pair with the 68-keV transition preceding the 507. These results, when combined with results of previous studies, suggest excited states at 38, 507, 575, 948, 1038, and 1141 keV in Sb^{121}. Unambiguous spin assignments of 5/2, 3/2, 1/2 to the ground, 507- and

575-keV states were made possible by the results of angular correlation measurements for the 68- and 507-keV cascade combined with the results of recently published internal conversion and nuclear resonance fluorescence experiments.[2,3] The angular correlation data also gave a mixing ratio $\delta(E2/M1) = 0.17 \pm 0.06$ for the 68-keV transition. In addition, a weak positron branching has been found and assigned to the decay of Te^{121m}.

Spin and parity assignments for the ground, 38, 507, and 575-keV states indicate that these states are in good agreement with single-particle model predictions. On the other hand, the spins and parities of the 948, 1038, and 1141-keV states (suggested by log ft values) are $7/2^+$, $9/2^+$ or $11/2^+$, for each of these states. These positive parity states are not predicted by the single-particle model. However, these states do agree qualitatively with predictions of the core-coupling model when low-lying single-particle levels are coupled to an excitation of the even-even core. In the case of Sb^{121}, the even-even core is essentially the Sn^{120} nucleus, which has its first excited 2^+ state at 1180-keV. The ground state and first excited state of Sb^{121} have spins and parities $5/2^+$ and $7/2^+$, so a coupling of these states to the 2^+ core

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2) Y. Y. Chu, O. C. Kistner, A. C. Li, S. Monaro, and M. L. Perlman, Phys. Rev. <u>133</u>, B1361 (1964).

3) F. R. Metzger and H. Langhoff, Phys. Rev. <u>132</u>, 1753 (1963).

state would give rise to positive parity states lying in the vicinity of 1180 keV and having spins between 1/2 and 11/2.

A full description of these experiments and results has been accepted for publication (Nuclear Physics).

Excited States in Kr^{82}. Gamma-ray transitions in Kr^{82} following the 36-hour negative beta decay of Br^{82} and those gamma-ray transitions following electron capture by, and positron emission from, Rb^{82} (produced from the decay of 26-day Sr^{82}) have been studied by scintillation and internal conversion electron spectrometry. Two-parameter gamma-gamma coincidences, beta-gamma coincidences from the decay of 36-hour Br^{82}, and triple coincidences between the annihilation quanta and the gamma transitions from the decay of Rb^{82} to Kr^{82} have been measured. Angular correlations have been determined for the prominent gamma cascades in the decay of Br^{82}. Energies of the transitions from Br^{82} have been measured in 180° permanent-magnet electron spectrometers.

These data are still undergoing analysis. A number of new transitions have been identified, and these will require some revisions in the presently accepted decay schemes.

Excited States in Rb^{83}. The nuclide Sr^{83} decays (with a halflife of 34 hours) by electron capture and positron decay to excited states of Rb^{83}. The resulting beta and gamma-ray energy spectra have been measured by means of scintillation spectrometry and a lithium drifted germanium detector. Two-parameter gamma-gamma coincidence experiments, triple coincidence measurements with the annihilation quanta, and delayed coincidence experiments to determine the lifetimes of a few of the excited states have been performed. A proportional counter has been used to determine the internal conversion coefficients of one of the low-energy transitions.

The following gamma rays (energies in keV) have been identified as coming from Rb^{83}: 42, 94, 290, 300, 380, 388, 417, 423, 437, 530, 657, 673, 685, 710, 735, 760, 775, 818, 844, 887, 900, 925, 990, 1145, 1160, 1962, 2063, 2105, and 2160. The first three excited states have been found to exist at 42, 423, and 810-keV. Assignment of additional energy states are still tentative and will not be given here.

Lifetime measurements show that the 42-keV state has a halflife of $(5 \pm 2) \times 10^{-5}$ sec. The K-shell internal conversion coefficient and $K/(L \pm M)$ ratio of conversion coefficients of the 42-keV transition were found to be 17 ± 3 and 1.9 ± 0.2, respectively. These results indicate that the 42-keV transition is largely a single-particle E2 transition. Since the ground state of Rb^{83} is known to be $5/2^-$, these results suggest that the first excited state is a $1/2^-$ single-particle state. Because of the very strong electron capture branching to the 42-keV state, these results also suggest that the ground state of Sr^{83} is $1/2^-$. Talmi and Unna[4] have predicted the ground state of Sr^{83} to be $9/2^+$ with the $1/2^-$ lying 570-keV higher.

2.2.3. Multigap Beta-ray Spectrometer

A six-gap, iron-core electron spectrometer is under construction. This spectrometer, which is very similar to the orange-sector spectrometer first described by Nielsen and Kofoed-Hansen[5] and later by K. M. Bisgard[6], consists basically of six 20° wedge-shaped magnet gaps oriented around a circle. This arrangement has a number of advantages: (1) it can be used as a high transmission (10%) and a moderate resolution (1.4%) spectrometer; (2) the source and detectors can be placed on the axis of symmetry in a zero, or very low, magnetic field region; and (3) the arrangement is convenient for coincidence experiments (gamma conversion electron, or conversion-electron conversion-electron coincidences).

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[4] I. Talmi and I. Unna, Nucl. Phys. 13, 225 (1960).

[5] O. B. Nielsen and O. Kofoed-Hansen, Dan. Mat. Fys. Medd. 29, No. 6 (1955).

[6] K. M. Bisgard, Nucl. Instr. & Meth. 22, 221 (1963).

The spectrometer is being constructed so that the conversion electron source can be the cyclotron target. Thus the instrument can be conveniently used for Coulomb excitation experiments and studies of short-lived radioisotopes. Furthermore, by properly orienting the spectrometer with respect to the cyclotron beam direction (or with respect to a second coincidence detector) and by detecting the conversion electrons in the separate gaps with a system of several solid-state electron detectors, one can perform angular correlation experiments. The results of such experiments are valuable in the determination of the spins and parities of nuclear energy states.

The iron portions of the spectrometer (furnished by an outside vendor) are complete. The remaining portions of the instrument are being constructed in the MSU Physics Department shop. Full completion is scheduled for the late summer of 1964.

2.3. Publications

Publications have been divided into four categories in a mixed topical, chronological, and institutional grouping. Section 2.3.1 lists MSU publications in the general area of cyclotron design and accelerator technology. Section 2.3.2 lists MSU publications in experimental nuclear physics. Section 2.3.3 lists publications of the MSU staff pertaining to work performed at other institutions. For each of the above categories, the listing is restricted to 1961 and subsequent years and APS abstracts are cited only for cases where formal reports or papers have not as yet been prepared. The publications of Drs. Galonsky, Gruhn, and Kashy are not included in any of the above categories but rather are listed separately in Sec. 3.3 which discusses new staff.

2.3.1. MSU Accelerator Publications

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

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

The Electric Gap-Crossing Resonance in a Three-Sector Cyclotron by M. M. Gordon, Nucl. Instr. & Meth. 18, 19, 268 (1962).

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

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

Central Orbit Program for a Variable Energy Multi-Particle Cyclotron by M. Reiser, Nucl. Instr. & Meth. 18, 19, 370 (1962).

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

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

B, XV Magnet Design for MSU 50-MeV Cyclotron, H. G. Blosser, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

B, XVI Experimental Facilities and Resolution Capability of the MSU Cyclotron, H. G. Blosser and J. W. Butler, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

B, XVII Central-Region Studies for the MSU Cyclotron, H. G. Blosser, M. M. Gordon, and M. Reiser, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

Central-Region Factors Influencing the Duty Cycle of a Cyclotron Beam, M. Reiser, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

B XVIII Orbit Calculations on the Extraction System for the MSU Cyclotron, M. M. Gordon and H. G. Blosser, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

Limitations on Duty-Factor Improvement (Via Phase-Shifting) Using H^- Ions, M. M. Gordon, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

Radio-Frequency System for the MSU Cyclotron, W. P. Johnson, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

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).

MSUCP-14, Magnetic Coil Design for a Superconducting Air-Cored 40-MeV Cyclotron, R. Berg (Jan., 1963).

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

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

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

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

MSUCP-19, Electrolytic Tank Facility and Computer Program for Central Region Studies for the MSU Cyclotron, M. Reiser (May, 1964).

MSUCP-20, Central Geometry and Initial Orbits in the MSU Cyclotron, M. Reiser (June, 1964). (In press)

BOOK REVIEW:

E,

Principles of Cyclic Particle Accelerators, John J. Livingood, Van Nostrand, Princeton, New Jersey, 392 pp. (Reviewed in Nucl Sci. & Engr. 16, 251 (1963) 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 Socity, Bull. APS 7, 547 (1962).

Fortran Programs for Sector-Focused Cyclotron Calculations, M. M. Gordon, T. I. Arnette, and D. A. Johnson, BAPS 9, 473 (1964).

C XII Studies of Beam Deflection in a 3-Sector Cyclotron, J. W. Beal, M. M. Gordon, and H. G. Blosser, BAPS 9, 473 (1964).

C XIII Magnetic Measurements on the MSU Variable-Energy Cyclotron, H. G. Blosser, W. P. Johnson, and R. E. Berg, BAPS 9, 473 (1964).

2.3.2. MSU Nuclear Physics Publications

Magnetic Field at the Nucleus in Spinel-type Crystals, W. Kelly, V. J. Folen, M. Hass, W. N. Schreiner and G. B. Beard, Phys. Rev. 124, 80 (1961).

Nuclear Resonance Fluorescence Measurements on the 845 KeV Level in Fe^{56}, W. Kelly, G. B. Beard, Nucl. Phys. 27, 188 (1961).

Temperature Dependent Luminescence in $CaWO_4$ and $CdWO_4$, W. Kelly, G. B. Beard and M. L. Mallory, J. Applied Phys. 33, 144 (1962).

Self-Scintillation Studies of the Beta Decay of Rb^{87}, W. Kelly, G. B. Beard, Nucl. Phys. 28, 570 (1961).

The Neutron-Deficient Yttrium Isotopes Y^{82}, Y^{83}, and Y^{84}, W. Kelly, V. Maxia, and D. J. Horen, J. Inorg. & Nucl. Chem. 84, 1175 (1962).

Decay Characteristics of Ba^{131m}, W. Kelly, D. J. Horen and L. Yaffe, Phys. Rev. 129, 1712 (1963).

The Half-Life of the 1.27-MeV Level in Sn^{116} by Resonant Self-Absorption, W. Kelly, G. B. Beard, Nucl. Phys. 43, 523 (1963).

Lifetime of the 21.7 KeV-State in Eu^{151}, W. Kelly, D. J. Horen and H. H. Bolotin, Nucl. Phys. 43, 367 (1963).

Conversion-Electron Measurements in the Decay of 11.5 d Ba^{131}, W. Kelly, D. J. Horen, Nucl. Phys. 47, 454 (1963).

The decay of Te^{121} and Te^{121m}, W. Kelly, R. L. Auble, and H. H. Bolstin, Nucl. Phys., to be published (1964).

A Moussa-Bellicard Type Iron-free Double-Focusing Beta-ray Spectrometer, Q. L. Baird, J. C. Nall, S. K. Haynes, and J. H. Hamilton, Nucl. Instr. & Meth. <u>16</u>, 275 (1962).

Isomerism in Y^{85}, W. Kelly and D. J. Horen, BAPS <u>7</u>, 341 (1962).

Surface Escape Correction in "Self-Scintillation" Studies, W. Kelly, M. L. Spaeth, and G. B. Beard, BAPS <u>7</u>, 490 (1962).

Conversion Electron Measurements in the Decay of 11.5 d Ba^{131}, W. Kelly and D. J. Horen, BAPS <u>8</u>, 85 (1963).

Characteristics of the Decay of Ba^{131m}, W. Kelly, D. J. Horen and L. Yaffe, BAPS <u>8</u>, 861 (1963).

Lifetime of the 21.7 keV State in Eu^{151}, W. Kelly, D. J. Horen and H. H. Bolotin, BAPS <u>8</u>, 127 (1963).

Energy Levels in Sb^{121}, W. Kelly, R. L. Auble, H. H. Bolotin and D. A. Gollnick, BAPS <u>8</u>, 443 (1963).

2.3.3. Publications Concerning Work Done by MSU Staff While at Other Institutions

The Polarization of T(p,n)He^{3} Neutrons for Proton Energies from 2.9 to 12 MeV, R. L. Walter, W. Benenson, P. Dubbledam and T. H. May, Nucl. Phys. <u>30</u>, 292 (1962).

The Polarization of Li^{7}(p,n)Be^{7} Neutrons for 4 to 10 MeV Protons, W. Benenson, T. H. May and R. L. Walter, Nucl. Phys. <u>32</u>, 510 (1962).

Polarization in Neutron-proton Scattering at 16 and 24 MeV, W. Benenson, R. L. Walter and T. H. May, Phys. Rev. Letters <u>8</u>, 66 (1962).

Transitions Magnetique 8.88 MeV—6.06 MeV dans ^{16}O, S. Gorodetzky, P. Mennrath, W. Benenson, P. Chevallier, F. Scheibling, and G. Sutter, Phys. Letters <u>2</u>, 42 (1962).

Radioactive Corrections in the Angular Correlation of Monopole Pairs from O^{16} at Small Angles, S. Gorodetzky, G. Scheibling, R. Armbruster, W. Benenson, P. Chevallier, P. Mennrath, G. Sutter and J. Goldring, Phys. Rev. 131, 1219 (1963).

Polarization of $T(d,n)He^4$ Neutrons, R. L. Walter, W. Benenson, T. H. May and A. S. Mahajan, Bull. Am. Phys. Soc. 7, 268 (1962) and Nucl. Phys. (to be published).

Polarization of Neutrons Scattered by He^4, T. H. May, W. Benenson, R. L. Walter and P. VanderMaat, Bull. Am. Phys. Soc. 7, 268 (1962).

Transitions au Niveau 6.06 MeV des Etats de O^{16} Excites par $N^{15}(p,\gamma)O^{16}$, S. Gorodetzky, W. Benenson, P. Chevallier, D. Disdier, F. Scheibling, Phys. Letters 6, 269 (1963).

Measure de Probabilities de Transitions Electromagnetique dans le Noyan O^{16}, S. Gorodetzky, P. Mennrath, W. Benenson, P. Chevallier and F. Scheibling, Le Journal de Physique 24, 887 (1963).

(p,γ) Resonance-Curve Shapes and Measurements of Resonance Energies with H_2^+ Beams, R. O. Bondelid and J. W. Butler, Phys. Rev. 132, 1710 (1963).

(p,γ) Resonance-Curve Shapes and Measurements of Resonance Energies with H_1^+ Beams, R. O. Bondelid and J. W. Butler, Phys. Rev. 130, 1078 (1963).

3. PROPOSAL

It is proposed that the Michigan State University cyclotron research program for the period 16 December 1964 to 15 December 1965 be jointly sponsored by the National Science Foundation and the University, the National Science Foundation providing $450,000.00 and the University providing $332,100.00. The funds requested will enable the staff to pursue a vigorous research program utilizing the previously funded variable-energy multi-particle cyclotron.

3.1. Schedule Forecast

The status of major cyclotron components has been described in Sec. 2. Combining this information into a schedule forecast is, as is well known, an extremely uncertain process; nevertheless, to accomplish orderly forward planning, it is essential to make such schedule forecasts in as realistic a manner as possible. For the MSU cyclotron, current schedules indicate trial operation in late 1964 and full completion of the facility, including all beam optics, switching magnets, spectrometer-spectrograph magnet, etc., late in 1965.

The schedule statements with respect to trial operation of the cyclotron are believed to be firm. The overwhelming majority of the remaining work is to be handled internally by the project staff, which is a more controllable and predictable situation than arrangements with outside vendors. (Deliveries on major items procured from outside sources have typically lagged from three to nine months behind scheduled delivery dates. Of all major orders, only the vacuum tank has been delivered on time.) At present, the major schedule determining factor for the project is the machine shop time required to fabricate the innumerable small items involved in the design. This work is largely being handled internally in the project shop and is being expedited in every reasonable way.

As an indication of the present rate of progress, Figs. 20 and 21 show two photos of the high-bay area of the Cyclotron Building taken in April 1963 and April 1964, respectively. In the light of progress achieved in the previous year the present schedule forecasts appear reasonable.

We expect to achieve external-beam operation at essentially the same time as internal-beam operation. If necessary, this will be accomplished by accelerating negative hydrogen ions and employing stripping extraction. It also appears that the conventional-extraction apparatus will be ready at the same time as the rest of the machine in which case experimenters will from the beginning be able to select between the high-duty cycle and high-resolution modes of operation.

Work on the 90° analyzing magnets is proceeding on a considerably slower schedule than the work on the cyclotron proper, and as a result initial experiments will be performed with an unanalyzed beam coming straight out of the cyclotron and into the south experimental room. The energy spread (~0.1%) in the unanalyzed beam is a good match with the present resolving ability of semiconductor detectors. An active program of experiments with an overall resolution of better than 100 keV can therefore be initiated as soon as trial operation is achieved.

3.2. Research Program

Abstract

The varied capabilities of the cyclotron will obviously make possible a broad range of experiments. The specific programs discussed below represent present thinking of the staff; on a continuing basis programs will be expanded or curtailed, or new programs added, on the basis of staff judgement as to current significance of the particular activity.

The "pick-up" reactions discussed in Sec. 3.2.1 will provide valuable information on nuclear states and on the structure of nuclear wave functions. The (p,px) reactions discussed in Sec. 3.2.4 are aimed toward investigating clusters and other correlation effects in light nuclei. These experiments are all well suited to the proton beam expected in the initial operation of the cyclotron. The optical model studies described in Sec. 3.2.2 represent a relatively long-range program for improving the specification of the relevant interaction parameters; in addition to its general value, this program is of special interest to theorists (McManus and Haybron) on this campus.

After the completion of the cyclotron facility, the experienced magnet design group will undertake the design and construction of a spectrometer-spectrograph as discussed in Sec. 3.2.3; such an instrument will complement the energy resolution capability of the cyclotron and will make possible precision nuclear spectroscopy. The work of the programming group relevant to the cyclotron is nearing completion; this group will turn its attention to the development of nuclear physics programs as discussed in Sec. 3.2.6.

The decay scheme studies described in Sec. 2.2.2 will be continued; availability of short-lived activities and the multi-gap electron spectrometer will allow much broader selection of problems. The $\pi\sqrt{2}$ iron-free spectrometer program will continue with further studies of Auger spectra and electron capture ratios.

3.2.1. Pickup Reactions

Pickup reactions are extremely useful for obtaining nuclear spectroscopic information. For example, the strength of the excitation of the 0.593-MeV level of Ca^{43} ($J = 3/2^-$) in the reaction $Ca^{44}(p,d)Ca^{43}$ with 17-MeV protons reflects the configuration admixture of $2p_{3/2}$ neutrons in the Ca^{44} ground state, which on a simple model might be described as $(f_{7/2})^4$ neutrons outside a Ca^{40} core. The ability to obtain a quantitative measure of such configuration admixtures depends of course on the validity of the theory used in extracting the spectroscopic factors in the reaction.

J Dependence of Angular Distributions. An important aspect of the direct reactions used for nuclear spectroscopic studies lies in their J dependence. As was recently observed in the (d,p) reaction,[7] and later in the (p,d) and (d,t) reactions, the angular distributions of the outgoing particles show effects which are associated with the J value of the residual level. Some of our efforts will be directed toward investigating such J-dependent effects at our higher bombarding energies, and in so doing should lead to a better understanding of the interactions involved in producing these effects.

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7) L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. Letters 12, 108 (1964).

Many-nucleon Transfer Reactions. On an exploratory basis, it is intended to search for possible many-nucleon transfer reactions involving a large change in isotopic spin, i.e., (p,He^6) etc. In addition to the possibility of excitation of higher order analogue states (see Sec. 3.2.3 for additional discussion) such reactions can provide important information about nuclear wave functions. In the $Sc^{45}(p,He^6)Ca^{40}$ reaction, for example, the process can be expected to proceed by a pickup of everything outside the Ca^{40} core. The observation of a significantly large cross section for this reaction would lend support to the qualitative existence of such a core in the Sc^{45} ground state.

Correlation of Nucleon Pairs in Nuclear Matter. Two experiments are planned for the initial studies of the correlation of nucleon pairs in nuclear matter. The first experiment is a study of the importance of neutron pair correlations in the tin isotopes. These targets are ideal for this type of study because the proton shell is closed and the ten naturally occurring isotopes overlap with four neutron shells (2d 5/2, 2d 3/2, 3S 1/2, 1h 11/2). Specifically, we shall study the (p,d) and (p,t) reactions for all ten isotopes. For seven of these isotopes it is possible to make direct comparisons of the two reactions leading to the same final states.

The second experiment is to compare the correlation of a neutron-proton pair with a neutron-neutron pair, both outside a doubly magic core. For this study we shall use the reactions $Bi^{210}(p,He^3)$ and $Pb^{210}(p,t)$ both leading to the same final states in Pb^{208}. The experimental difficulties involved are considerable in that both target nuclides are highly radioactive.

Excitation of Hole States. Another important aspect of pickup reactions is seen when nucleons are removed from shells which on the basis of the shell model are filled. Experiments of this type have been done for the $1d_{3/2}$, $2s_{1/2}$ filled shell for a few targets whose last nucleons lie in the $1f_{7/2}$ shell.

The excitation of "hole" states in nuclides near the doubly closed Ca^{40} shell will be investigated by means of the reactions $Ca^{40}(p,d)Ca^{39}$, $K^{40}(p,d)K^{39}$, $Ca^{40}(d,t)Ca^{39}$, $Ca^{40}(d,He^3)K^{39}$, $Ca^{40}(p,t)Ca^{38}$, $K^{40}(p,He^3)A^{38}$, and $A^{40}(p,t)A^{38}$. We hope to obtain a comparison between the neutron-hole states of Ca^{39} and proton-hole states of K^{39}, and similarly the neutron-pair-hole states of Ca^{38} as opposed to the A^{38} proton-pair-hole states. In addition, such reactions will give direct information concerning the shell-model structure for the bound nucleons. This investigation will also include the excitation of hole states in the Pb, Sn, Ti, and Ca isotopes. The goal here will be twofold: (1) to determine the degree of configuration mixing and (2) to measure the degree of excitation of particular hole states by various reactions. The latter measurement will be carried out by use of different reactions that reach the same final states. For example, $Bi^{209}(p,He^3)$ and $Pb^{208}(p,d)$ are reactions which excite final states in Pb^{207}; the $Bi^{209}(p,\alpha)$, $Pb^{208}(p,t)$, and $Pb^{207}(p,d)$ reactions excite final states in Pb^{206}.

Experimental Procedure. For the above reaction studies, the experimental method will be as follows. A dE/dx - E counter-telescope will be used in conjunction with a fast analog circuit which will provide particle identification and selectively gate a multichannel analyzer displaying the total energy pulses. A third counter behind the dE/dx and E detectors will be used to provide an anticoincidence pulse to block the particle identification circuit. The particle identification circuit will thus analyze only those pulses resulting from a particle having stopped in the first two detectors. All the detectors will be semiconductor counters. With the present state of the art, it should be possible to achieve a system capable of 50-keV resolution at 50 MeV.

3.2.2. Optical-Model Experiments

Distorted-wave analysis of nuclear reactions requires the knowledge of wave functions derived from optical model potentials for protons, deuterons, alphas and other ions. These potentials must in turn be derived from experiments which fall under the general heading of "optical-model" experiments. When performed over a wide range of nuclei, these experiments can themselves reveal interesting insights into the structure of particular nuclei. The most basic of the optical-model experiments is elastic scattering, but total-reaction cross sections and polarization measurements are very useful as additional data. Computer programs are being constructed for the CDC-3600 computer to analyze these three types of data in terms of the optical-model parameters.

The measurement of the angular distribution of elastically-scattered protons is a relatively straight-forward experiment and there is a paucity of good data in the 25- to 55-MeV range. There is, furthermore, a desire by optical-model theorists for more precise data on elastic scattering throughout the periodic table.

Elastic-scattering measurements will be performed with an array of counters set to measure the whole angular distribution in a few runs. This procedure not only shortens the data-taking time but eliminates errors due to changes in the target or beam collection between runs.

Total reaction cross sections for protons can be used to eliminate some uncertainties in the optical-model analysis of the proton-nucleus interactions based solely on scattering angular distributions. Recent experiments[8] have shown a peak in the cross section for C, Al, Ni, Ag, and Au near 30 MeV. Between 30 MeV and 60 MeV there is a large gap in which no total reaction cross-section measurements exist. Measurements over the whole range of proton energies available with the cyclotron will indicate whether this peak is real or simply a discrepancy between laboratories and will provide more data for optical-model analysis in a relatively unexplored energy range.

The method for obtaining proton total reaction cross sections consists of measuring the transmission of a sample of the material by means of coincidence techniques. In addition, elastically-scattered protons must be sampled simultaneously at a fixed angle.

Besides complementing the measurements of angular distributionsof elastic scattering and total reaction cross sections, polarization measurements of elastically scattered particles are of interest in their own right since they are sensitive to spin-orbit and spin-spin interactions of the particle-nucleus system. In addition,

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8) M. Q. Makmo, C. N. Waddell and R. M. Eisberg, Nucl. Phys. <u>50</u>, 145 (1964).

measurements of the polarization of protons elastically scattered from a wide range of nuclei may result in the discovery of a useful proton polarimeter. For example, a measurement of the polarization of protons scattered from silicon is of considerable interest for the construction of a silicon solid-state polarimeter.

The initial polarization experiments would be of the double-scattering type with either carbon or helium as analyzer or polarizer. The polarization of scattered protons in the energy range from 25 to 55 MeV is not well known for these elements; some additional measurements will be necessary in the early stages of these experiments.

3.2.3. High-Resolution Charged-Particle Spectroscopy

With negative-ion beam acceleration and extraction, the cyclotron is capable of producing very highly resolved beams, $\frac{\Delta p}{p} \approx 0.01\%$ as was described in our 1963 Proposal. Such a capability, matched with a comparable heavy-particle magnetic spectrograph, will enable the precise measurement of energy levels related to charged-particle groups from reactions such as (p,p'), (p,d), (p,t), (α,He^3), etc. For example, the (p,t) reaction on target nuclei with $N = Z$ up to Ca^{40} is a fruitful method of investigating isotopic analog states. Most of these reactions have relatively high negative Q values, but the bombarding energies necessary are within the range of the MSU cyclotron. These (p,t) reactions lead to excited states in the $T_z = -1$ member of the $T = 1$ triplet. In many cases, the corresponding levels in the $T_z = +1$ member have already been investigated. In the investigation of states with T greater than $|T_z|$ very high resolution is essential because these states are usually at high excitation energies where the level density is high. In at least one case, these isotopic analog states have been shown to exhibit giant resonance behavior where, according to Wigner, excited levels of different T are mixed due to the Coulomb interaction.

Work has not yet started on the heavy-particle spectrograph, but as soon as other demands permit, a detailed study of the design problem will be initiated starting from a careful consultation with other workers now actively pursuing the problem. Field-measurement and orbit-tracking techniques will be employed as in design of the cyclotron proper in order to make a careful study of the various possible techniques for achieving broad range, high dispersion, and double focusing and thereby arrive at an optimized design. The magnet will be procured on an individual component basis; i.e., there will be separate bids on core, coils, power supply, vacuum tank, mounting structure, etc., with assembly and testing by our own staff. Experience with the cyclotron indicates that major economies can be achieved by this procedure. (Total cost of the 100-ton cyclotron magnet including core, coils, mount, power supply, vacuum tank, etc., is less than $200,000.00 or equivalent to frequently quoted costs of spectrometer-spectrograph magnets of half the size.) In addition, the capabilities of the project technical staff are admirably suited to handling the job as a result of their experience in the directly related and considerably more complex job of designing and assembling the cyclotron.

3.2.4. Angular Correlation Experiments on Reactions with Three-body Final States

Angular correlations in (p,2p) reactions have been measured over a wide range of incident proton energies. At higher energies (above 100 MeV) the motivation has been to obtain a direct measure of the nucleon-momentum distribution. The results of these experiments, when analyzed using plane waves and the impulse approximation, are in good agreement with the shell model. Experiments at 40 and 70 MeV have been performed[9,10] in reaction-

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[9] R. J. Griffiths and R. M. Eisberg, Nucl. Phys. 12, 274 (1959).

[10] D. Anderson, J. McKenzie and D. H. Wilkinson, Proc. Int. Conf. on Nuclear Structure, Kingston 1960, North Holland Publishing Co., Amsterdam, 1960, p. 319.

mechanism studies. It has been shown[11] that at these energies the reactions take place on the nuclear surface and that it is essential that distortion effects be taken into account. Analysis of the results is possible with the distorted-wave Born approximation. Such analysis gives information on the shell-model wave functions. Experiments that measure both the energy and angle of the emitted protons over a wide range have not been performed with good resolution. The high-duty-cycle beam of the MSU cyclotron is very well suited to such experiments on light nuclei.

Interpretations of the data from the $Li^6(p,pd)He^4$ reaction[12] imply the existence of clusters of nucleons in the nucleus. The correlation observed is consistent with quasi-elastic scattering. Reactions of the type $(p,p\alpha)$ are also of interest, in particular with C^{12} and O^{16}.

Experiments to study reactions of the type (p,px) may be performed with two solid-state detectors movable in the same plane. Analysis of the data is a complicated kinematic problem requiring a computer. However, use of particle identification and two-parameter pulse-height analysis allows simultaneous (p,2p), (p,pd) and $(p,p\alpha)$ experiments.

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11) I. E. McCarthy, E. V. Jezak and A. J. Kromminga, Nucl. Phys. 12, 274 (1959).

12) D. W. Devins, H. H. Forster, S. M. Bunch and C. C. Kim, Phys. Letters 9, 35 (1964).

3.2.5. Decay Scheme Studies

The program of decay scheme studies will in part be directed to further clarification and development of lines of research already in progress and in part to new areas arising out of the availability of cyclotron produced isotopes.

Studies of the energy levels of Sb^{123} and Sb^{125} are presently in progress via the decays of Sn^{123} and Sn^{125}, respectively. These studies are related to the work on the energy levels of Sb^{121}, discussed in Sec. 2.2.2. Since these nuclides differ only by neutron pairs, one would expect the level structures to be quite similar. One immediate aim of the present work, therefore, is the determination of these similarities or the reasons for any dissimilarities. With respect to Sb^{125}, the energies of the states are fairly well known, but the spin assignments are uncertain. Gamma-gamma angular correlation measurements on the various transitions are planned in an effort to remove some of the uncertainty in the spins and also to determine the multipolarities of the transitions. With respect to Sb^{123}, even the level scheme is not known satisfactorily. A comparison of the known levels in Sb^{123} with the level schemes of the other odd-A antimony isotopes leads one to suspect that there exist unobserved states in Sb^{123}. Scintillation detector coincidence techniques and lithium-drifted germanium semiconductor detectors will be employed in an attempt to locate the expected weak transitions to and from these postulated states. If feasible, angular-correlation and internal-conversion-coefficient measurements will be made to determine the spins and parities of these states.

Using cyclotron produced activities, the present program will be extended to include radionuclides of very short halflives in the spherical regions. Special emphasis will be placed on a systematic study of excited states of odd-odd nuclei in the tin region. The multi-gap electron orange-sector spectrometer will, in view of its high transmission capability, enable additional types of experiments to be done, such as angular correlations between groups of conversion electrons or between a group of conversion electrons and a gamma ray. In addition, excited-state lifetime measurements can be made by means of delayed coincidences and Doppler shifts.

The program of study with the $\pi\sqrt{2}$ spectrometer will include determination of conversion line fine structure, Auger coefficients, orbital capture ratios, and the effect of source chemistry on the Auger effect.

The usual difficulty in determining the Coster-Krönig coefficients related to the Auger effect is that one has a set of simultaneous equations with more unknown quantities than equations. We plan to obviate this difficulty by choosing beta emitting nuclides leading only to E2 gamma-ray transitions in the final nuclide. Most such transitions are only about 1% converted in the L_1 shell, no L_1 vacancies are created by K x-rays from K vacancies, and very few L_1 vacancies are produced by the K-Auger process. Hence one is concerned only with the L_2 and L_3 shells. The result is a set of four simultaneous equations in four unknown quantities, one of which is the f_{23} Coster-Kronig coefficient. The planned experiments should yield accurate values of this coefficient as a function of atomic number for the first time. Concurrent with the above experiments, we shall continue our efforts to measure K to L_1 to L_2 to L_3 capture ratios beginning with Sn^{113}.

Further studies will include the determination and comparison of high-resolution Auger spectra for a nuclide in two different chemical states.

3.2.6. Computer Programs for Nuclear Research

The availability of the CDC-3600 computer to the cyclotron laboratory greatly expands the capability for correlating and analyzing experimental data. The MSU computer is equipped with a 32K core memory, eight magnetic tape units, and a model 160A satellite computer for input-output operations. Such a computer makes feasible the utilization of large and sophisticated programs.

Since the programming work required for cyclotron construction is nearing completion, the major effort in the period covered by this proposal will be devoted to the design and construction of nuclear physics programs. A number of codes will be required for the routine conversion of raw experimental data to a form suitable for analysis and interpretation. A copy of one such program, developed at LASL, is now on hand; this code takes output data from a multichannel pulse-height analyzer and "unfolds" the spectrum. Small codes (e.g., conversion from lab to cms variables) can be anticipated and constructed as need arises; large programs, such as those described below, will require considerable time and effort.

Computer programs to perform optical-model calculations are essential for a proper analysis of elastic scattering (and total reaction) cross-section measurements; conversely, they can furnish useful wave functions or cross sections from given potential parameters. One such code, called "Abacus", has been obtained from E. Auerbach at BNL; the adaptation of this code to the CDC-3600 computer is underway.

Experiments on the inelastic scattering of protons, deuterons, and alphas as well as various stripping and pickup reactions will form an important part of the research program with the cyclotron. The analysis of such experiments requires "distorted-wave" and "coupled-channels" computer programs. These codes can be quite complex, but they are almost indispensable for deriving accurate spectroscopic information from the experimental data.

Useful computer programs which are available from other laboratories will be converted to the CDC-3600 whenever feasible. In the design and construction of new programs, considerable assistance will be obtained from Professor Hugh McManus and Dr. Ron Haybron (who is spending the current year at Oak Ridge National Laboratory working with Dr. R. Satchler). Furthermore, an attempt will be made to coordinate our programming effort with nuclear research groups at Argonne National Lab, which also has a CDC-3600 computer.

3.3. Staff

In accord with long range departmental plans discussed in previous proposals the nuclear physics faculty has undergone major expansion in the past year with the addition of three new experimentalists (Galonsky, Gruhn, and Kashy) and one new theorist (Signell) to the staff. Previous work of the new staff evidences in both quantity and quality a high degree of talent and a bright future in nuclear physics research. Brief resumes and lists of publications are given at the end of this section for the three experimentalists among the new staff. The credentials of Dr. Signell are not included since, as mentioned previously, the group in nuclear theory is supported separately from the cyclotron.

The new appointments in combination with the previous staff give a total of 13 faculty and 3 research associates in the area of nuclear physics. Of the faculty, 4 are in theoretical work (Gordon, Haybron, McManus, and Signell) and 9 are experimental (Benenson, Blosser, Butler, Galonsky, Gruhn, Haynes, Johnson, Kashy, and Kelly). The basic training and interest of all of this group is in nuclear physics, although 3 (Blosser, Gordon, and Johnson) have for some years been devoting their relatively full attention to accelerator development. The progress on the cyclotron is such that this latter group is now also able to re-activate their basic interest in nuclear physics, thereby further strengthening and broadening the group capability in this area.

In brief the experience of the three new experimental faculty is as follows:

Aaron Galonsky, Associate Professor. Dr. Galonsky received the Ph.D. degree from the University of Wisconsin in 1954. During the period 1954-59, he was a member of the Physics Division of the Oak Ridge National Laboratory working in nuclear reaction studies with the ORNL

Van de Graaff accelerators. From 1959 to 1964 he was a Group Leader at MURA in charge of planning the experimental program for the proposed MURA accelerator.

Charles R. Gruhn, Assistant Professor. Dr. Gruhn received the Ph.D. degree from the University of Washington (Seattle) in 1961. From 1961 to 1963 he was a Research Associate at MIT, and during the year 1963-64, he was an Assistant Professor at Boston University. During both of these periods, he worked with 30-MeV alpha particles from the MIT cyclotron to make a systematic study of alpha-particle scattering by nuclei near $A = 40$. He also studied the evaporation spectra of protons from α-induced nuclear reactions.

Edwin Kashy, Associate Professor. Dr. Kashy received the Ph.D. degree from Rice University in 1959. During the year 1959-60, he was an NSF Postdoctoral Fellow at MIT, and from 1960 to 1962 he was an Assistant Instructor at MIT. During the period at MIT, he worked on (d,p) stripping reactions with a broad-range high-resolution spectrometer and the 12-MeV Van de Graaff accelerator. From 1962 to 1964, he was an Assistant Professor at Princeton University, working with Professor R. Sherr on a study of (p,d) and (p,t) pickup reactions in the scandium and titanium isotopes.

3.3.1. Publications of New Experimental Staff

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n-p Scattering at 17.9 MeV, A. Galonsky and J. P. Judish, Phys. Rev. 98, 1168A (1955).

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3.4. Cost Estimates

The National Science Foundation is requested to provide a total of $450,000.00 to carry out the proposed research activities. Support derived from the University totals $332,100.00, yielding a program total of $782,100.00. A breakdown of these anticipated expenses is shown in the itemized budget on the following page.

The budget is unusual in that an exceptionally large fraction is allocated to salaries. Except for provision of one additional position in the research associate category, the amounts budgeted for salaries are based on the assumption that the project staff will remain at its present level through the budget period covered by this

BUDGET SUMMARY
NSF Supported Nuclear Physics Program
Michigan State University

		NSF		MSU
I. Salaries				
A. Regular Faculty	62,652		115,003	
B. Research Associates	37,905			
C. Technical Staff	31,333		10,590	
D. Operating Staff	31,350		1,075	
E. Machine Shop	31,060		15,115	
F. Electronics Shop	11,710		1,200	
Subtotal	206,010		142,983	
Retirement	12,051		10,116	
Social Security	4,100		1,840	
G. Graduate Assistants (16)	55,280			
H. Undergraduate Research Ass't.	22,500			
Salary Total		299,941		154,939
II. Indirect Costs (52.92% Salaries)		75,000		157,175
III. Supplies and Services		30,000		10,000
IV. Travel		5,000		
V. Publications		5,000		
VI. Equipment		25,100		10,000
VII. Computer		10,000		
		450,041		332,114
TOTALS (rounded to nearest $100)		$450,000		$332,100

proposal. As indicated previously, initial operation of the cyclotron is expected essentially concurrent with the beginning of the budgetary period, and it is expected that activity involved in assembly and installation of equipment in the various experimental areas will continue at a high level throughout the proposal period. This in conjunction with the large effort involved in startup of the nuclear experimental program requires that the staff be maintained at at least its present level.

Inasmuch as a maximum possible budget figure was available to us from information on Federal and University budgets the net result is to place a tremendous squeeze on equipment funds. In a normal year, provision of such a small number of dollars for equipment would be a highly inefficient arrangement. The year in question is, however, special in that the equipment required is largely provided under funds budgeted in previous years, and therefore the prime need for this proposal year is to maintain the staff at its present level.

Cost estimates on non-personnel and non-equipment levels (supplies and services, computer costs, printing, etc.) are based on current cost experience, and are of an essential nature in providing working materials for the staff. Travel costs are based on one trip per year per staff member for attendance at scientific meetings.

ENDORSEMENT

Henry G. Blosser
Professor of Physics

Truman Woodruff
~~Sherwood K. Haynes~~
Acting Chairman, Dept. of Physics

Philip J. May
Vice President for
Business and Finance

~~Note: Project is under joint direction of H.G. Blosser and S.K. Haynes.~~

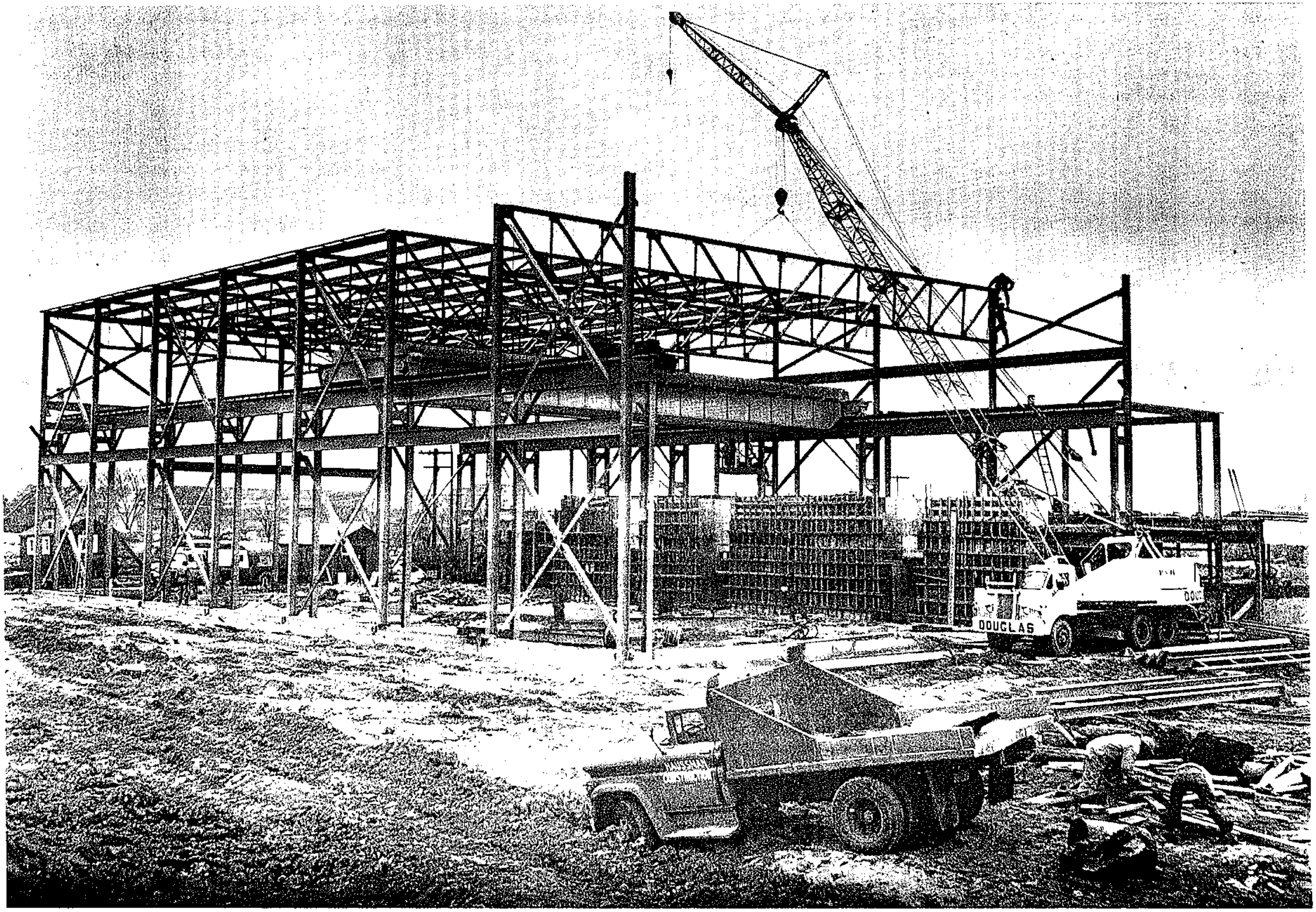

Fig. 20: The high bay area of the cyclotron laboratory in April 1963.

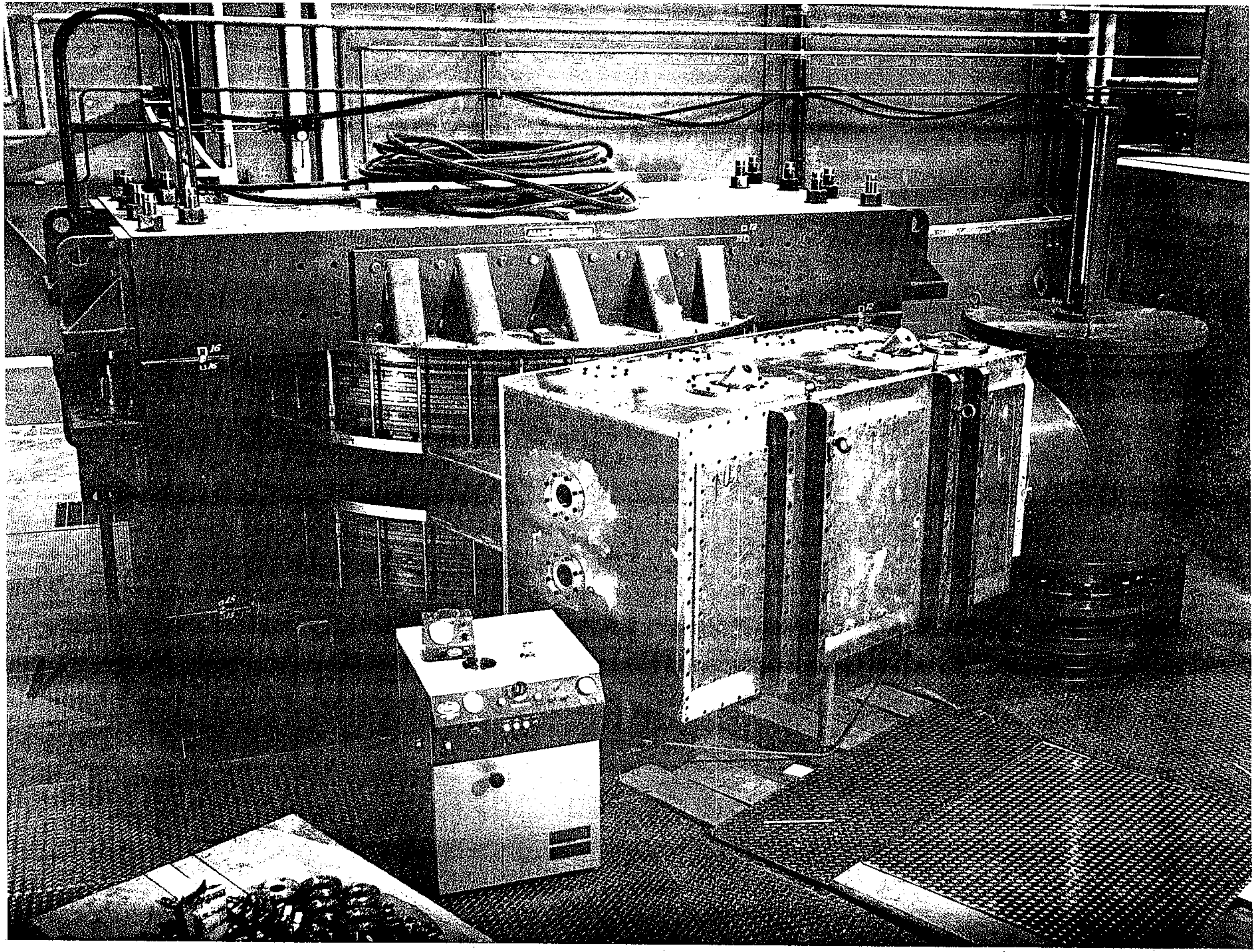

Fig. 21: View of the cyclotron taken in April 1964.