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Proposal for a

Nuclear Research Facility

in the Medium Energy

(50 Mev) Range Utilizing

a Variable Energy

Multi-Particle Cyclotron

Department of Physics

Michigan State University

A PROPOSAL
to the
U.S. ATOMIC ENERGY COMMISSION
for a
NUCLEAR RESEARCH FACILITY
in the
MEDIUM ENERGY (50 MEV) RANGE
utilizing a
64" VARIABLE ENERGY MULTI-PARTICLE CYCLOTRON

DEPARTMENT OF PHYSICS AND ASTRONOMY

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CONTENTS

Introduction

In the Fall of 1956, a Committee on Nuclear Research was set up in the Department of Physics of Michigan State University to consider measures for expanding and strengthening the University's nuclear physics research and training programs. In June of 1957 this committee, in a formal report to the University administration, recommended the construction of a nuclear research facility centered on a medium energy fixed frequency cyclotron. This report was approved; funds were made available for improvements in facilities and hiring of additional staff necessary to accomplish design of the facility. Design studies were begun in the spring of 1958 by the staff of the Physics Department, with assistance from the Electrical Engineering Department of M.S.U. in the design of the r-f, from William Brobeck and Associates in engineering matters and from the Oak Ridge National Laboratory (under A.E.C. contract AT-(40-1)-2425) in the magnet design work. From these studies, plans have evolved for a research cyclotron facility of unusual precision and flexibility.

This is, then, an appropriate time to consider definite financial arrangements for the capitalization of the facility; we herein propose to the Atomic Energy Commission a plan for joint support of the capitalization by Michigan State University and by the Atomic Energy Commission.

The first section of this document summarizes the research potential and anticipated cost of the proposed facility and presents, formally, the proposal for joint support. Succeeding sections present detailed technical plans on which the estimates of research potential, cyclotron performance, and cost are based.

design in terms of their applicability to current nuclear problems; additional weight was given in the selection of the M.S.U. accelerator to those important experimental categories which would be least effectively attacked by these facilities in operation, or planned, elsewhere. It has in addition been deemed essential that the facility be highly flexible to assure capability for performing important research over many years in a changing and evolving field such as is nuclear research.

On the basis of these considerations a 50 Mev variable energy multi-particle cyclotron was selected for the accelerator, with the stipulation that stability and precision were to be emphasized in the design so as to meet the pervasive need for precise nuclear measurements at these energies. The cyclotron will accelerate protons and heavy ions with a two to one range of energy variation. A vast field of important and urgent studies are encompassed within this range as is described in detail in section II.

The two to one bandwidth for the energy variation was selected after careful reflection as to the relative merits of various alternatives. Design of a system of significantly broader bandwidth than this is a formidable task; if it were undertaken, completion of the cyclotron would be considerably delayed. Further broadening of the already prodigious research program which would be gained, would be quite unlikely to offset the disadvantages incurred by the delay, particularly in view of the important and urgent nature of the proposed research program.

Selection of the accelerator has been made on the basis of research capability, but it should also be borne in mind that the proposed facility will be of great value in the training of new scientists. Training in medium energy currents will be enhanced accordingly.

The precise energy definition of the external beam results from the resonant deflection system in conjunction with precise control of starting conditions and careful filtering of various supply voltages. Estimated currents are quite high considering the energy definition; the high currents result from the strong axial focusing provided by the particular pattern of azimuthal variations employed in the magnet. Rapid shifting of energy or particle is accomplished by a simple tuning mechanism on the r-f with servo control and with a network of trimming coils which make the required adjustments in magnetic field via a simple programmed adjustment in coil currents. Precision ancillary equipment is included in the initial proposal so that a strong research program can move directly into action as soon as beam is obtained. These and other characteristics of the facility are described in detail in section III.

Cost estimates for the cyclotron and for non-standard components of the ancillary equipment have been made by our engineering consultants, William M. Brobeck and Associates. Mr. Brobeck and his staff have wide experience in this field; we feel their estimates to be quite conservative. Estimates on standard items of the ancillary equipment have been made by the physics department staff from present list prices. The cost of the cyclotron building has been estimated by Mr. Donald O. Ross, Supervising Architect of M.S.U.

The costs are in summary:

Cyclotron	769,700	
Engineering design	135,000	
15% contingency	160,000	
Subtotal		1,064,700.

Commission should specifically not be committed, by virtue of assistance in capitalization of the facility, to future assistance in operation.

In the following sections the research potential, the feasibility studies, and the cost bases are discussed so as to evidence in detail the importance and the feasibility of the proposed facility.

progress is being made toward the automation of the mechanical aspects of data taking and preliminary analysis and that it should be anticipated that an accelerator installation such as that envisaged at M.S.U. will eventually include a digital computational facility specifically for this purpose.

A number of topics which may well appear to be obvious ones for this cyclotron have not been included in this section. The reasons for these omissions are best illustrated by considering the two examples of elastic porton scattering per se and element formation for $Z > 100$ say. In the first instance, in order to contribute significantly to our present knowledge very precise measurements requiring extensive instrumentation are required. Such measurements are, and have been, in progress on the Minnesota Linac for example,[2] and it does not appear reasonable to duplicate this effort unless the results obtained there indicate a particular need for the energy variation more conveniently available with the cyclotron. Similarly, in view of the lower energies, hence lower formation cross sections, available from the M.S.U. cyclotron for heavy elements, and the extensive program which Professor Seaborg and his colleagues[3] have underway on the Berkley Hilac, it does not appear reasonable to embark on an extensive series of studies in the transuranic field; there may well be specific problems however, pointed up by the Berkley results, to which the higher beam currents from the cyclotron may be particularly suited. Similarly at lower energies, there seems little point in detailed nuclear spectroscopic programs in energy ranges accessible to tandem Van de Graaff

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2. L.H. Johnston. Bull. Am. Phys. Soc. Ser. II, <u>3</u>, 170 (1958).
U. of Minnesota Physics Dept. Progress Reports 1956-1957
N.M. Hintz. Phys. Rev. <u>106</u> 1201 (1957)

3. G.T. Seaborg and A. Ghiorso, Conf. on Reactions between complex Nuclei, ORNL 2606 1958 Papers 3 and 4.

suited to the higher energy range and precise energy control of the cyclotron have been selected as representative.

II-A-1. Proton Induced Reactions and Nuclear Spectroscopy

Reference to a tabulation of Nuclear Reaction Q values[4] tabulated from currently accepted nuclear masses shows a number of high negative Q value, proton induced reactions which are beyond the range of present electrostatic accelerators. Of these (p, n), (p, d) and (p, t) are especially interesting.

In table I are listed a number of high threshold (p, n) reactions amenable to study using conventional threshold techniques[5] or via detection of the associated high energy β decay of the product nuclides. These measurements not only provide precise values for the product nuclear masses and decay energies but also establish calibration points on the analyzer magnet momentum scale. The specific importance of these masses of proton rich nuclides will be discussed presently.

Measurements on stripping (d, p) and pickup (p, d) reactions are one of the most powerful methods of contemporary light nuclear spectroscopy[6].

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4. D.A. Bromley and A.R. Rutledge "Nuclear Reaction Q Values" Chalk River Report C.R.P. 789 1958 unpublished

   Mattauch, Waldmann, Bieri and Everling. Z. fur Naturforschg. 11a 525 (1956); "Annual Reviews of Nuclear Science" Vol. 6, P179 (1956), Annual Reviews Inc. Palo Alto (1956)

5. J.B. Marion and T.W. Bonner. "Fast Neutron Physics" Chapt. 5 ed. Marion and Fowler Interscience Publishers, New York (to be published)

6. S.T. Butler. "Nuclear Stripping Reactions" John Wiley 1957

mechanisms pose formidable experimental difficulties because of the high ambient backgrounds; in particular cases the interest may well be sufficient, however, to justify the required effort for these measurements.

Similarly (p, t) reactions, with negative Q values ranging from 10 to 25 Mev have been little studied. These are particularly important because they provide a method for studying proton rich nuclides which are otherwise rather inaccessible. Precise measurements on the emergent triton energies, giving product nuclear masses, provide information on the nuclear mass surface off the stability axis. Particularly in the medium A region the available data on these nuclides is derived predominantly from relatively inaccurate K capture measurements; more accurate data is badly needed.

In the older semiemperical mass formulae of the Weizsacker type[7] a Coulomb energy term of the form $Z^2/A^{1/3}$ and a volume symmetry term $\frac{(A - 2Z)^2}{A}$ appear; if these are the only Z dependent terms a mass surface is obtained with a parabolic Z dependence for constant A. In more recent mass formulae such as those of Cameron and Green[8] a much more complex Z dependence is predicted. Accurate measurements on the nuclear masses off the stability line will suffice to fix the proper form of these and other terms in the mass formulae. The (p, t) measurements just discussed provide data on the proton rich nuclides. Similar measurements on (p, xp') reactions will provide data on the neutron rich ones. Present theoretical indications are that the nucleon binding energies are depressed on the neutron rich and elevated on the proton rich sides of the stability line. (p, xn) and (p, xnp) reactions will also provide useful information. (See also section II-A-2-C.)

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7. C. F. von Weizsacker. Z Physik 96 431 (1935)
   E. Feenberg. Revs. Mod. Phys. 19 239 (1947)

8. A. G. W. Cameron. Can. Jour. Phys. 35 1021 (1957)
   A. E. S. Green. Phys. Rev. 95 1006 (1954)

II-A-3. Experiments Requiring High Beam Intensity

The high proton beam currents anticipated from the M.S.U. cyclotron suggest a number of experimental studies specifically designed to utilize this feature. Typical examples, which are discussed in the following paragraphs, are polarization studies, neutron studies, and fission studies.

Polarization studies are especially important in view of the conclusive evidence from the successes of the nuclear shell model and from scattering experiments that the nuclear potential contains a spin orbit term of the form $a(r)\sum_j \tilde{I}_j \cdot \tilde{S}_j$ summing over the nucleons present. Normal scattering measurements utilizing unpolarized incident beams and randomly oriented target nuclides provide, at best, only indirect evidence on this potential feature and on the possible existence of other angular momentum dependent terms of the form $\tilde{S}_i \cdot \tilde{S}_j$ or $\tilde{I}_i \cdot \tilde{I}_j$ for example[12].

For these reasons a polarized proton beam poses very attractive possibilities as a research tool; a large variety of possible techniques for direct production of polarized protons followed by their acceleration have been proposed or are under development[13].

All of these have been specifically directed toward electrostatic accelerators, although Keller[14] has considered the possibility of cyclotron acceleration of polarized protons.

It has been demonstrated that by elastically scattering protons from light

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12. L. Wolfenstein "Annual Reviews of Nuclear Science" Vol. 6 p. 43 Annual Reviews Inc. Palo Alto (1956) and Phys. Rev. 75 1664 (1949) J. V. Lepore. Phys. Rev. 79 137 (1950)

13. E. Zavoiski. JETP (USSR) 5 338L (1957); 5 603 (1957) 32 408 (1957) G. Clausnitzer et al., Zeits, fur Physik 144, 336 (1956)

14. C. Keller. C.E.R.N. report. CERN - 5B (1958)

data given in the above two references it can be estimated that for a secondary target subtending $\simeq 3^{\circ}$ at the first, at an initial c. of m. scattering angle of $\simeq 80^{\circ}$, a flux of particles with polarization $\gtrsim 80\%$ of $\simeq 5 \times 10^{9}$/second may be readily obtained. This estimate corresponds to $\simeq 0.75$ Mev energy loss in the initial scatterer of a 40 Mev incident beam; there is every reason to expect that by properly choosing reaction angles, target thicknesses, etc. and incident energy (to which the predicted polarizations are highly sensitive) it will be possible to obtain polarized beams ($\gtrsim 80\%$) in the effective 10-100 $m\mu$ amp range with reasonable energy resolution. This is more than adequate for a wide variety of experiments.

The polarization P for an arbitrary target and energy may, of course, be readily obtained by noting that for identical first and second targets and scattering angles the observed azimuthal asymmetry R is given by

$$R = \frac{1 + P^2}{1 - P^2}$$

Future programs of the highest importance may develop from experimental work now in progress at Oxford University, at the University of British Columbia, and elsewhere, directed toward the production of aligned or polarized targets using cryogenic and microwave pumping techniques. Such techniques coupled with a polarized beam would make possible the complete elucidation of nuclear potential parameters in single-scattering experiments.

The availability of a high-intensity, controlled-energy proton beam immediately suggests its use for the production of intense monoergic neutron beams via (p, n) reactions and the subsequent use of these neutrons as experimental projectiles. The neutron energies obtained with this machine are not, however, amenable to study via normal time of flight methods and until a relatively high efficiency, high resolution neutron spectrometer becomes available for these topical experiments in the heavy ion field it will be convenient to accept a rough classification suggested by Flerov[20] who proposes these subdivisions: (i) Distant interactions, which are dominated by the effects of interaction of the nuclear coulomb fields; (ii) Contact interactions, comprising those wherein the nuclear surface effects are dominant, and characterized by relatively low energy transfer between the nuclides involved and by the transfer of a small number of nucleons; and finally (iii) Nuclear fusion reactions wherein a compound system is formed, usually at high excitation and with characteristic high angular momentum.

II-B-1. Distant Interactions

The Coulomb excitation process provides one of the most sensitive techniques for the study of the spectroscopy of low lying nuclear levels throughout the periodic table; in addition, it has the very considerable advantage of requiring limited experimental apparatus and of being relatively completely understood theoretically in terms of the mechanisms involved. An excellent compendium of the theoretical treatment and collected experimental information up to 1956 is given in the review article of Alder et al[21].

Classically the Coulomb excitation cross section is given by

$$d\sigma_{\left\{{E \atop M}\lambda\right\}} = \left(\frac{Z_1 e}{\hbar v_i}\right)^2 \left(\frac{Z_1 Z_2 e^2}{\mu v_i v_f}\right)^{-2\lambda+2} B\left({E \atop M}\lambda\right) \quad df_{\left\{{E \atop M}\lambda\right\}}(\theta,\xi),$$

20. G. N. Flerov. Geneva Conf. Paper 15/P/2299 USSR 1958

21. Alder, Bohr, Huus, Mottelson and Winther. Revs. Mod. Phys. 28 432 (1956)

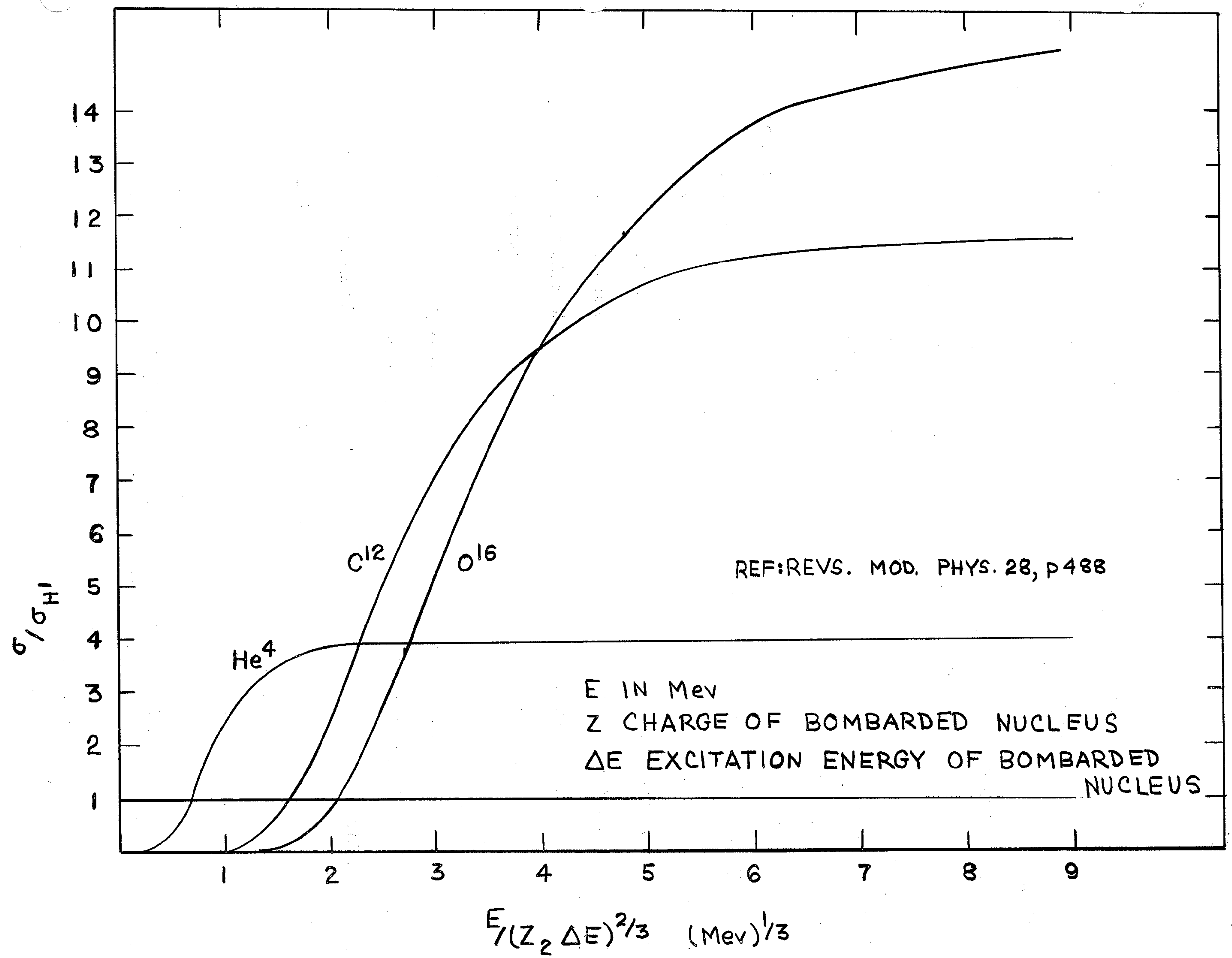

Fig II - 1: Coulomb excitation relative cross sections for different projectiles

Multipolarity determinations via relative cross section measurements are another type of experiment in which the cyclotron should lead to important nuclear information. Since some of the major difficulties in this work are those of target preparation, thickness determination, absorption corrections, and incident flux measurements, it was suggested by Bohr and Mottelson that the transition multipolarities be determined from the ratio of Coulomb excitation cross sections measured, using different projectiles, at energies chosen such that equal ξ values were obtained; from the equations given above it follows that the ratio is then a function only of the charges, masses, energies and the multipolarity involved. The technique has been used as yet only with relatively light projectiles[25].

In general, excellent agreement has been obtained with theory for E2 transitions; the only E1 transition so studied (110 Kev state in F^{19}, He^4 ions) shows marked deviations from the predictions which are as yet unexplained. Further measurements using C^{12} and N^{14} ions would be very valuable in deciding whether the E1 formalism is inadequate or whether the states involved in F^{19} have anomalous properties; either result would be of considerable interest. These measurements may also be useful in resolving higher multipoles (e.g. E3) in heavy nuclides. It should be noted, however, that relatively accurate $\simeq$ 2% measurements are required since the ratio difference between adjacent multipoles decreases with increasing incident mass.

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25. Bjerregaard and Huus p, d, He^4 on W^{183} Phys. Rev. 94 204 (1954)
Temmer and Heydenburg p, He^4 on F^{19}, Na^{23} Phys. Rev. 96 426 (1954)
Bromley, Kuehner and Almqvist He^3 and He^4 on F^{19}, Na^{23}, Ti^{47}, Mn^{55} Phys. Rev. to be published.

fission process, via both electronic and radiochemical techniques, as a function of the energy of the incident heavy ion to trace the transition from the Coulomb fission to direct fission following absorption of the incident ion. This latter is of particular interest because of the high angular momentum and relatively low compound system excitation energies involved. In particular, this fission should be characterized by relatively high transverse fragment momenta as compared to say proton fission at comparable excitation and should provide interesting insight into the collective model interpretation of the fission process[27].

Of particular interest would be a determination of the cross section for the particular fission mode wherein the incident heavy ion is transferred, essentially intact, to one or other of the fragments with a characteristic shift of the mass yield distribution.

As shown in Figure II-2 the maximum ion energies from the cyclotron are comparable to the Coulomb barriers of even the fissile nuclides.

A final set of experiments in the distant interaction category are studies of elastic scattering. The semi-classical sharp cut-off theory[28] has enjoyed remarkable seccess in fitting the elastic scattering differential cross sections for alpha particles and deuterons[29] and also for heavy ions (e.g. C^{12} on Au^{197}).[26]

In almost all of these heavy ion measurements on heavy targets to date, however, the instrumental resolution used had been inadequate to insure that only

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27. A. Bohr. Geneva Conf. Paper 7A/P/911 Denmark (1955)

28. J. S. Blair. Phys. Rev. 95 1218 (1954)

29. D. D. Kerlee, J. S. Blair and G. W. Farwell. Phys. Rev. 107 1343 (1957)

pure elastic scattering was included. Inclusion of inelastic scattering components would be expected to smear out fine diffraction structure which all the calculations predict for the pure elastic scattering. Indeed, in some of the measurements (e.g. C^{12} on Au^{197}) there is some evidence suggesting the presence of this fine structure but the energy resolution was inadequate to properly resolve it. With the precise energy control of the incident ion beam possible with the envisaged M.S.U. beam optics, and magnetic analysis of the elastically scattered particles, it will be possible to isolate the pure elastic scattering.

It will be of interest to carry out a systematic series of elastic scattering measurements at selected energies on targets throughout the periodic table to obtain information on the nuclear radii, potential parameters, surface difuseness, etc. Comparison of the scattering results for C^{12}, C^{13} and N^{14} with spins 0, $\frac{1}{2}$ and 1 respectively under classically corresponding conditions of momentum, etc. may provide a means of isolating specific spin dependent potential terms if these are present.

In many of these measurements the recently developed junction diode detectors may be extremely useful. It has been shown[30] that the response of these detectors is quite linear providing that the particle loses its energy within the junction layer. For alpha particles this sets an upper limit of $\simeq$ 10 Mev; for C^{12} for example the limit is 50 - 60 Mev. These detectors have the advantages of potentially large solid angle, high efficiency, fast output ($\simeq 10^{-8}$ sec.) for coincidence measurements, and almost trivial electronic requirements.

No information is available on the polarization of heavy ions by elastic scattering. This problem merits careful investigation and could provide a very

30. J. Mayer and B. Gossick. Rev. Sci. Instr. 27 407 (1956)

transfers involved. A study of the reaction mechanism as a function of the incident energy would be very useful in following the kinematics involved.

In the case of the $C^{12} + C^{12}$ reaction, for example, the interesting calculated Q values are the following:

a) $C^{12} + C^{12} \longrightarrow O^{16} + Be^{8} + 0.235$ Mev.

b) $\longrightarrow Ne^{20} + He^{4} + 4.620$ Mev.

c) $\longrightarrow C^{13} + C^{11} - 13.774$ Mev.

d) $\longrightarrow N^{13} + B^{11} - 14.012$ Mev.

e) $\longrightarrow N^{14} + B^{10} - 14.944$ Mev.

Cases c) d) and e) for neutron, proton and deuteron transfers are characteristically high endothermic with thresholds at $\simeq$ 30 Mev for the incident C^{12} ions. Consequently at lower energies only b) competes with a) and may be identified by the lack of $He^{4} - He^{4}$ coincidences. Reaction b) is typical of the (hi, He^{4}) reactions in light nuclei in that it has a relatively high Q value and, in the Oak Ridge measurements, relatively high probability of occurrence. This specific reaction for example will be very interesting in terms of nuclear spectroscopic measurements on Ne^{20}. With heavy ions it will be possible to populate states of higher angular momentum than have been accessible with lighter projectiles; the He^{4} - gamma - angular correlations in the formation and deexcitation of these states are particularly amenable to analysis since target, projectile and emergent particles all have spin 0. It will be possible in this way to identify and study the higher spin members of nuclear rotational bands and to examine the band structure in the vicinity of the terminations predicted by Elliott on the basis of shell model considerations (e.g. J = 8 for the ground state band).[33]

33. J. P. Elliott. Proc. Roy. Soc. A245 128 (1958), Proc. Roy. Soc. A245 562 (1958).

calibration of the beam analyzer system in terms of the accepted nuclear standards in energy regions where direct measurements are not available. From the $O^{16}(dn)F^{17}$ Q value of 1.836± 0.003 Mev, for example, the $H^2(O^{16}, n)F^{17}$ reaction provides equivalent proton energy calibration points at 14.47 and 9.33 Mev using the 3+ and 4+, O^{16} beams respectively. This technique will be of particular importance in calibrating the cyclotron beam optics, using a post acceleration stripper to obtain different change states.

Table II lists some of the relevant nuclear reactions of this type together with their Q values as observed or calculated from current nuclear mass tabulations[4].

Isobaric spin experiments are a third category of contact interaction which the cyclotron is well suited to investigate. As a result of the low carbon ion energies available with 5th harmonic acceleration, it will be possible to examine some of the consequences of the isobaric spin selection rules in light nuclei[37] and to obtain information on the isobaric spin mixing in nuclear states through partial violations of these selection rules. Thus, for example, in the $C^{12}(C^{13}, n)Mg^{24}$, and $C^{12}(C^{13}, p)Na^{24}$ reactions the prediction, assuming charge independence and neglecting isobaric spin mixing during the finite lifetime of the compound system, is that the ratio of the cross sections to corresponding states is given only by simple Clebsh-Gordan ratios in the isobaric spin quantum numbers; in this case the ratio is predicted to be $\sigma n/\sigma p = 2$. For similar measurements on $C^{12}(He^3\ n)$ and $C^{12}(He^3\ p)$ see Bromley et al[38].

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37. D. H. Wilkinson. Proceedings of the Rehovoth Conference. North Holland 1958

38. D. A. Bromley et al. Phys. Rev. 105 957 (1957)

the states decay before significant mixing can occur. At intermediate excitations $\simeq$ 10 - 20 Mev, neither condition is fulfilled and appreciable mixing may be expected. The energy variation available with the cyclotron and the range of suitable ions will make it a very powerful tool for these investigations.

II-B-3. Nuclear Fusion Reactions.

A particular interesting aspect of the fusion reactions is the high angular momentum of states formed in the reactions. Capture of a 50 to 60 Mev C^{12} or O^{16} ion by a target nucleus of A $\simeq$ 100 results in intermediate states with angular momentum $\simeq 50\hbar$ and excitation energies of $\simeq$ 50 Mev. Apriori, it might be expected that this excitation would be lost through multiple neutron emission, or charged particle, followed by neutron, emission; this, however poses a fundamental conflict in that nucleon emission cannot carry more than $\simeq$7-8 units of angular momentum corresponding to emission, from the nuclear surface, of a nucleon with energy corresponding to the Fermi surface and on the average a nucleon carries considerably less than this, $\simeq$3-4 units. Consequently, following the emission of a relatively small number of nucleons, a residual nucleus with $J \simeq 30\hbar$ and $E_x \simeq 20$ Mev remains. It can readily be shown as in Figure II-3 that the neutron penetrabilities P_L are such that gamma deexcitation then becomes the dominant mode (i.e. when $\Gamma \lesssim 1$ ev) via a multi-stage cascade through states of angular momenta decreasing by one or two units to the ground state value.

This process should be particularly interesting in regions of strong nuclear deformation where the cascades would consist predominatly of enhanced E2 transitions between successive members of rotational bands. (In these nuclei the limiting J values in the bands[33] are very high; the upper level spectrum would be expected, however, to be distorted in the direction to make cascade gammas involved in deexcitation of these levels all of roughly equal energy). Thus the gamma radiation following capture of heavy ions would be expected to have many features analogous to the bands observed in molecular spectroscopy. The characteristic moments of inertia and hence the level spacing in the bands will vary from $\simeq$ 1 Mev for A = 25 to $\simeq$ 100 kev in heavy nuclei.

Detailed study of this process will throw considerable light on the structure of the upper regions of the rotational bands now observed only at low excitations in these deformed nuclei and on the question of their termination. Russian measurements to date have verified the existence of a high yield of low energy cascade gamma radiation; no detailed measurements have been reported as yet. The Russian group under Flerov have coined the name, "neutron metastability", for this process. A search for nuclear systematics via this type of process would have important consequences for a more detailed understanding of nuclear structure.

In a somewhat different light, it will be of interest to examine closely the excitation curves for heavy ion capture on a thin target in the hope of finding relatively narrow "resonances" superimposed on the continuum yield corresponding to the formation of "metastable" states having appreciable lifetimes and as a consequence, relatively narrow widths.

Further information on the higher angular momentum states may be obtained by studying the multiplicity of nucleons emitted following heavy ion capture. Recent data from Saclay and Stockholm, for example,[40] on the bombardment of Cu^{63} and Cu^{65} by N^{14}, O^{16} and Ne^{20} ions shows that the probability of single nucleon

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40. Beydon, Chaminade, Crut, Faraggi, Olkowsky and Papineau. Nuclear Physics 2 593 (1957)
Atterling, Beydon, Crut and Olkowsky. Nuclear Physics 2 619 (1957)
Crut, Faraggi, Olkowsky and Atterling. Nuclear Physics 2 624 (1957)
Chaminade, Cros, Gratat and LePape. Nuclear Physics 2 634 (1957)

for heavy nuclides and have again found quite satisfactory qualitative agreement with theory[42] providing that Γ_n / Γ_f is assumed to be independent of the excitation energies involved. Further measurements of this type are clearly indicated in order to examine the behaviour as a function of nuclear distortion magnitude and sign for example. Such information would be of significance in a more detailed formulation of the theory of fission in terms of the collective model[27, 43].

II-C Other Research

A number of important research areas for which the proposed cyclotron is well suited would utilize both proton and heavy ion beams. Three examples of studies of this type are discussed in the following subsections.

II-C-1. Short Half Life Studies

Because of the high internal and external beam intensities, and the energies and particle types available, the cyclotron will consititute an efficient production facility for radionuclides throughout the periodic table. Many of these, of course, will have sufficiently long half lives ($\tau \gtrsim$ seconds) to allow their study by conventional radiochemical techniques. A large number of those far removed from the stability line, and consequently of particular interest, have high decay energies and half lives in the millisecond region. Utilizing the features of rapid withdrawal of an internal probe target via hydraulic means, or the possibility of either pulsing the arc source or the external beam, it will be convenient to carry out alternate bombardment and counting measurements in programmed sequence to study the formation and decay of these activities.

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42. See J.R. Huizenga and T. Sikkeland, Papers 1 and 2 Conf. of Reactions between Complex Nuclei ORNL 2606 Sept. (1956)

43. L. Wilets. Proc. Rehovoth Conf. ed. H. J. Lipkin, North Holland (1958)

The only high resolution excitation function measurements available in the literature at proton energies above $\simeq 5$ Mev are preliminary results on the Al^{27} (pn)Si^{27} reaction obtained with a tandem accelerator[36]. These show surprising resonance structure corresponding to excitation energies in the compound nucleus Si^{28} of 17.5 Mev, where the states are unbound for proton, neutron and alpha emission. With the cyclotron beam it may be possible in this way to obtain direct measurements on the level densities and nuclear strength functions at high excitations in relatively light nuclei.

II-D. Extensions of Present M. S. U. Research Programs

Preceding pages have discussed new programs of research specifically associated with the cyclotron. In addition to these studies, the cyclotron will allow important extensions of a number of present M. S. U. research programs principally by virtue of its capacity to produce isotopes and by virtue of the high flux of particles available for radiation damage studies.

The 1 ma internal proton beam incident on a Be target will produce about 3×10^{14} neutrons per second with an angular distribution strongly peaked forward. Using either the proton or the neutron beam, moderated if necessary, essentially any known isotope can be produced. In most cases it will be possible to use reactions in which the atomic number changes (p, n), (p, 2n), (n, p), etc. so that a standard chemical separation will give carrier free material of high specific activity. For charged particle induced reactions, the variable energy feature of the cyclotron will allow discrimination against unwanted activities of same atomic number, by the simple device of bombarding a thin target at the energy where the excitation function for the desired reaction peaks. Highly proton deficient fission product isotopes will be obtained, if needed, by bombardment of Uranium.

4. Other phenomena such as very low energy conversion lines can be studied as well as the usual studies of beta spectra and conversion lines at higher energies.

This program will be considerably augmented by availability of the cyclotron produced isotopes.

II-D-2. Fission Yields and Other Radiochemical Studies

In a previous study of yield patterns of 22 Mev proton induced fission, a number of inexplicable extreme deviations[47] occurred in the data and were rejected on statistical grounds. Substantial advances have since been made in both chemical separation and counting techniques which make it highly desirable to repeat the original work. The program will then develop into general studies of the behaviour of yields as a function of proton energy so as to determine characteristics of the transition between asymetric and symetric fission modes, as mentioned previously. Techniques have advanced to the point where fine structure on the yield curve can quite probably be detected.

Solutions of ferrous sulphate in 0.4 molar sulphuric acid have shown considerable promise as a proton dosimeter[48]. It would be highly desirable to extend these studies over a substantial range of proton energies. From a chemical point of view it would also be of important interest to compare the G value (number of ferrous ions oxidized per 100 ev absorbed) for the ferrous sulphate solution with that obtained from irradiation of aqueous solutions of

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47. W. H. Jones, A. Timnick, J. H. Paehler, and T. H. Handley. Phys. Rev. 99, 184 (1955)

48. A. Timnick, to be submitted for publication

such reactions is so high that polarization measurements can be made on the resonantly scattered gamma ray. These would be of considerable importance in determination of the multipolarity of the transitions, and the parities, of the states.

II-D-4. Bubble Chamber Studies

Although counter experiments on p-p scattering will probably not be included in the initial experiments for the cyclotron, the high energy physics group at M. S. U. plans to extend its bubble chamber experiments to studies of p-p and p-d scattering in the 10 to 40 Mev range. The experiments will exploit substantial advantages of the bubble chamber in the important angular regions close to 0° and 180° in the center of mass. (In other angular regions the chamber should attain accuracy comparable to counters, though not as conveniently).

In these experiments, the proton beam will be collimated to 1/8" diameter so that thin windows can be used both in the vacuum jacket and in the chamber wall. Precise experimental range data together with the highly resolved cyclotron beam, will give an accurate determination of the proton energy at the point of scattering.

Ninety degree stereo (two cameras at right angles) will provide angular measurements of high accuracy. The chamber used for these studies would be quite small ($\simeq$ 8" diameter) and so could easily be placed in a magnetic field, to add a momentum determination for the scattered particles. This together with angle measurements and some range measurements would provide overdetermination of the systematics of the scattering.

In contrast to counting experiments where information is accumulated at fixed energy points, the bubble chamber would accumulate data relatively uniformly over a wide energy range depending on the distance the proton travels in the chamber before undergoing scattering. The accumulation of several hundred

Experiments on the initiation of slip in silver halide crystals* have shown that the stress required to initiate and to propagate slip in crystals may be considerably different. Since slip initiates at the outside of the crystal it may be possible to irradiate a crystal in such a way as to pin the dislocations on the outside and greatly increase the strength of the crystal. The best type of radiation for this purpose is not known; a number of different types should be tried.

The high beam intensity envisaged for the machine makes it possible to study the flux region where "radiation annealing" becomes significant. This phenomenon is presently not well understood, and further work will be of considerable value.

Defects produced by irradiation should be quite effective in phonon scattering in the lattice of a crystal. This will produce changes in all processes which depend on the phonon conductivity either directly as in thermal conductivity or indirectly as in magnetic resonance relaxation times. It would be of considerable interest to extend the present M. S. U. program of magnetic relaxation measurements in this direction.

Extensive investigations of the paramagnetism of irradiation produced color centers have been made using electron and x-ray irradiations**. The availability of a neutron source would greatly extend the range of present experiments. Barium Chlorate, Sodium Chlorate, Gypsum, Barium, Lead and Strontium Sulfate, Lithium Sulphate, and Sodium Sulphate are among the crystals which have exhibited induced paramagnetism upon irradiation. In many cases bonds are broken

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* Nye, Spence, and Sprackling. Phil. Mag. 2, 772 (1957)

** J. A. Cowen. Bull. A.P.S. 2, 317 (1957). Wigen and Cowen. Jour. of Chem. Physics (in press).

III. THE RESEARCH FACILITY

The research facility, as was mentioned previously, is centered on a 50 Mev variable energy, multi-particle cyclotron. A modern building specifically laid out to house the cyclotron and associated research programs, will be erected at the south end of the present physics building. The cyclotron will be oriented with median plane vertical and with dees suspended from the top, thereby greatly easing mechanical problems in design and yielding, with the analyzing equipment planned, a very flexible experimental setup.

Detailed design studies have been carried considerably farther than is typically done as a basis for making a proposal. For the cyclotron, properties of the magnetic field have been accurately determined by measurement in a scaled model of the magnet; extensive calculations of orbit properties in this magnetic field have been made to insure that beam behaviour, stability limits, etc., are of acceptable form; properties of radio-frequency system have been calculated and an initial mockup has been constructed to verify major features of the computations; and a workable mechanical design has been prepared, insuring that structural requirements on components are held to acceptable limits and that reliability and ease of maintenance will be of a high level. Research facilities have been designed incorporating recent developments in nuclear instrumentation, with proper account for the optical properties of the cyclotron beam, and a building layout has been made and initial architectural studies performed. This program of study has established without question the feasibility of the proposed design, and, in addition, the advanced state of the planning has made it possible to give cost estimates which should have a high degree of reliability.

In the following subsections, the major divisions of the facility are described and the technical studies which have established the particular design reliably calculated, sources of difficulty can be pin-pointed and removed, and relatively major improvements in cyclotron performance thereby achieved.

The basic theoretical methods employed in the magnet design studies have evolved as an outgrowth of the MURA[54] studies of FFAG synchrotrons and, independently, and with specific application to the cyclotron, from studies by Welton[55]. The first application of these techniques to an actual cyclotron design problem met with gratifying success[56]. Subsequently, straight forward generalization of the techniques have been made to include the design of ferromagnetic cyclotron magnets, and the use of poleface windings to obtain the magnet variability characteristics[57] required for variable frequency multiparticle operation.

The techniques thus evolved have been used in arriving at the magnet design of the M.S.U. cyclotron. The computations have been carried thru using codes of Welton, codes of the Mura group, and codes set up for the M.S.U. computer, the Mistic[58].

The radio frequency system of the cyclotron is continuously adjustable over a frequency range from 15 to 21 mc. As mentioned previously, the particular range was selected after careful consideration of relevant factors, which in view of their paramount importance, we will discuss here in some detail.

For a cyclotron with fixed deflection radius, the kinetic energy

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54. Symon, Kerst, Jones, Laslett and Terwilliger. Phys. Rev. 103, 1837 (1956).

55. T.A. Welton. Phys. Rev. 99, 1623 T (1955)

56. Blosser, Worsham, Goodman, Livingston, Mann, Moseley, Trammel and Welton. R.S.I. 29, 819 (1958)

57. Blosser, Hudson, Lord, and Williams. Bull. A.P.S. II, 2, 233 (1958)

58. We are indebted to cooperative programs of Oak Ridge National Laboratory - Oak Ridge Institute of Nuclear Studies, of Midwestern Universities Research Association - International Business Machine Corp., and of the Michigan State University Computor Laboratory for making computing time available to us on the Oak Ridge computor, the Oracle, on the Mura IBM 704, and on the Mistic.

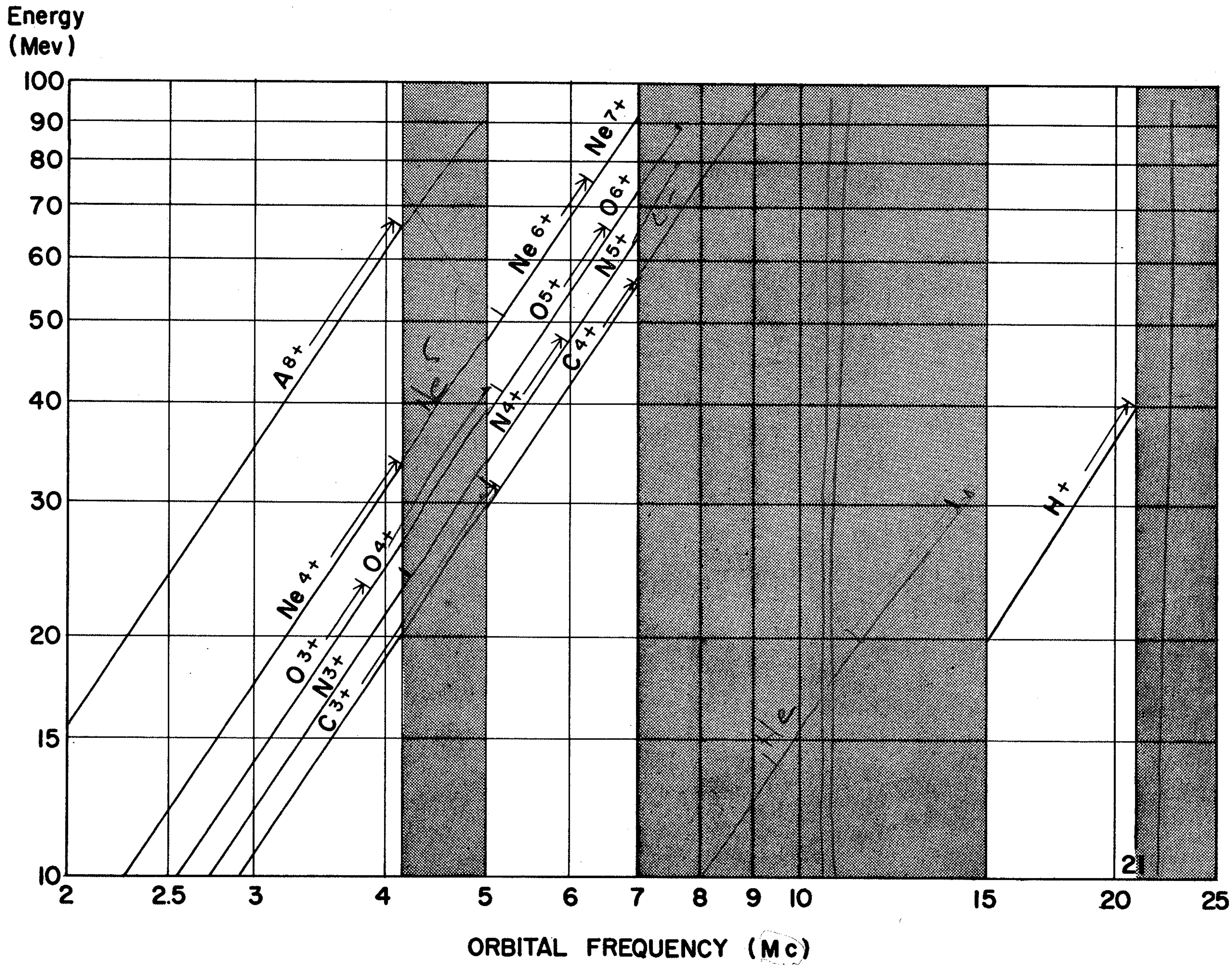

Fig. III – O: Energy vs. orbital frequency for MSU cyclotron

5. A possibility exists that some portion of 3 to 1 requirement can be eliminated by varying deflection radius as is discussed in section II-A-1-c. To our knowledge this approach is not being studied elsewhere; experience of the M.S.U. staff make it an appropriate item to explore here.

1. AVF magnet and regenerative deflector

The magnet for the cyclotron will be of conventional H yoke design with poles 64" in diameter. The azimuthal variations in the magnet will have three fold symetry (3 sector). In the design procedure models of the proposed structure are (excited to the design field strength,) (the field is measured,) and the properties of orbits in the full scale magnet are computed. Both the computation techniques and the corrective procedures have been described in detail elsewhere [56, 57, 59] and we therefore restrict ourselves to a presentation of results.

The pole tip shape used in the most recent model runs is shown in Fig. III-1. Field measurements are obtained by installing scaled tips in the model magnet facility of the Oak Ridge National Laboratory[59], the magnetic measurements being made with a Rawson rotating coil fluxmeter; the rotating coil is of 0.05" i.d. by 0.15" o.d. and 0.05" high so that errors due to averaging effects of the coil are negligible. Tests of the fluxmeter proper show a precision of 0.1%; other errors are introduced in the model facility such that the total rms error at a given point is about 0.6%. These errors are to a large extent averaged out in the data processing; improvements in precision would, however, be quite desirable and steps in this direction will be taken. Measurements are taken in a rectangular coordinate system and converted

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59. Oak Ridge National Laboratory Report #2598 (unpublished)

by polynomial interpolation to polar coordinates.

In Fig. III-2 the average field ($\langle B\rangle = \frac{1}{2\pi}\int_0^{2\pi} B(r,\theta)\,d\theta$) and flutter ($F = \langle (B - \langle B\rangle)^2\rangle / \langle B\rangle^2$) obtained at maximum field and also at a typical lower field are plotted. Also, for the maximum field, plots are given in Fig. III-3 of the azimuthal variation. The peak strength of 18 kilogauss (in hill regions) is determined by standard economic considerations with a factor included to approximately account for the generally increased ease of construction of smaller machines, i.e. machines with higher field.

a. Average Field Adjustment

The average field contours, Fig. III-2, obtained from the most recent model data increase more rapidly with radius than is desirable. If the orbital frequency is to be independent of energy, then the average field must have the form

$$\langle B\rangle(r) = \frac{m_0\omega_0}{e}\left(1-\beta^2\right)^{-1/2}\left(1+\frac{1}{2N^2}F\right)\left(1+\frac{1}{4N^2}\left[6F + 2r\frac{dF}{dr}\right]\right)^{-1},$$

where $\beta(r) = \frac{r\omega_0}{c}\left(1+\frac{1}{2N^2}F\right).$

This field, called the "isochronus" average field is plotted in Fig. III-4 for protons and for C^{4+} ions. The isochronus contours actually decrease with increasing radius at small radii due to the rapid build up in flutter which distorts the orbits from a circular shape more rapidly than the particles increase in mass; the non-circular orbits cause the particles to see an enhanced average field since the length of path in strong field regions is longer. The enhancement due to non-circular shape must be balanced by a decrease in the $\langle B\rangle$ to maintain exact isochronism. Poleface windings are used to adjust the actual field contour to the proper isochronus values for the various particles; for minimum power dissipation in these windings the field with coils off should be centered in the range between the two isochronus contours in Fig. III-4. The curve obtained from the model data is well outside the range, and in subsequent model runs, the tips will be modified

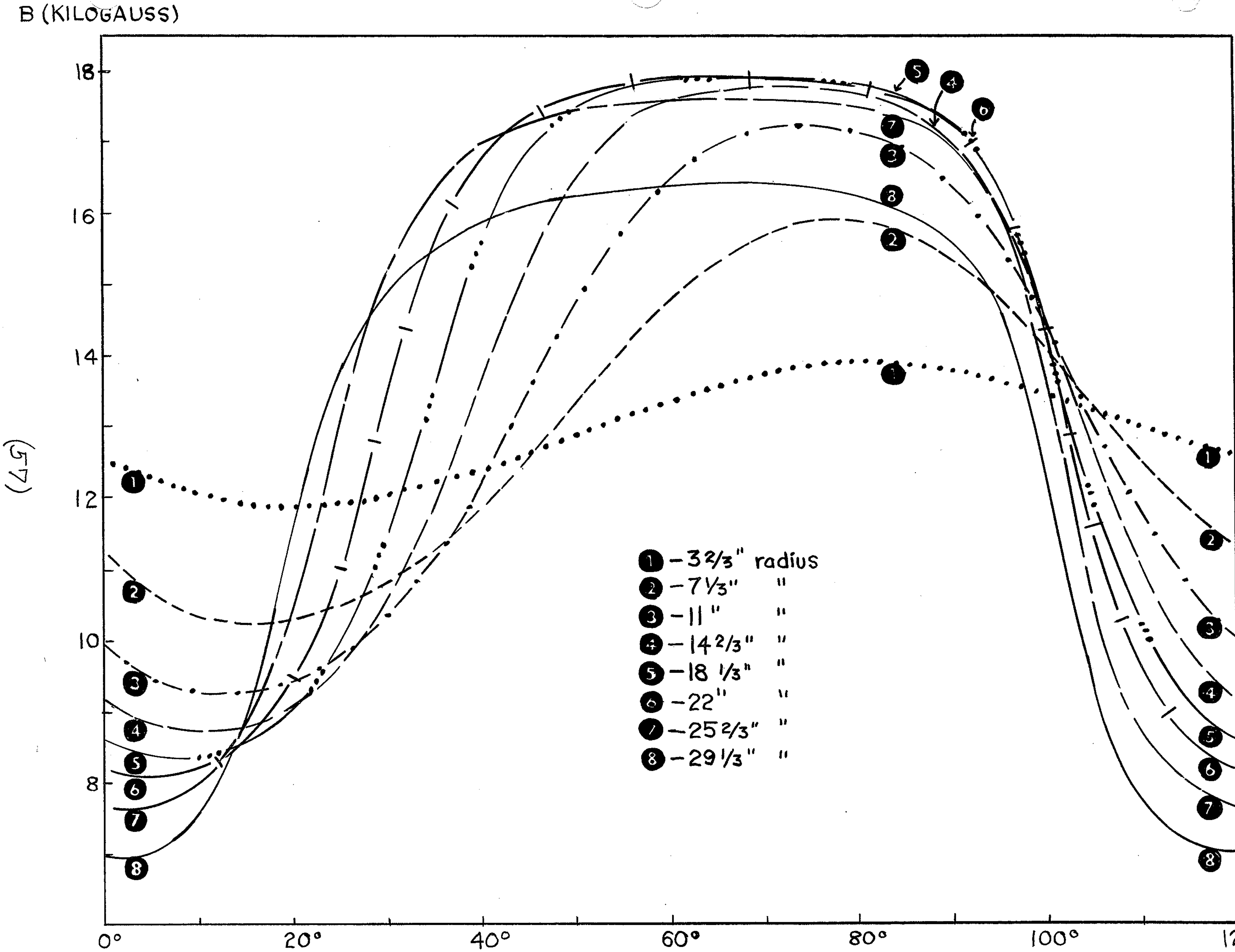

Fig. III-3 : Magnetic field vs. Azimuth at various radii using a generalization of the procedures of ref. 56, to accomplish the desired correction.

For determination of orbit properties, it is, moreover, completely acceptable to accomplish the required changes in average field entirely with the trimming coils. The only objection to application of this procedure in the actual cyclotron arises from the economic considerations mentioned above. This was, therefore, done in the calculations; the field thus obtained gives a realistic configuration in which to study major orbit properties at an early stage in the magnet design.

The proper settings for the trimming coil currents are determined by a standard least squares procedure as is also described in ref. 56. The calculation requires knowledge of the radial dependence of the average field of each trimming coil; the dependences assumed were based on model data of Hudson and Lord[60]. In a series of runs, the currents required to trim several extreme field shapes were computed, and from this the ampere turn capacity required in the trimming coils was specified for engineering design purposes. The field shapes used were sufficiently extreme so as to represent with factor of safety the maximum trimming required to compensate changes in saturation as the field is varied in strength and to provide, also, the variation required to adjust for different relativistic effects of the various particles.

On the full scale cyclotron, adjustment of the trimming coil currents will be accomplished in a similar analytical manner. To accomplish this it will be necessary, when the magnet is assembled, to measure (and store) the field profile at a sequence of field strengths distributed over the range of required

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60. E. D. Hudson and R. S. Lord (private communication).

severe beam disturbance; on the basis of these calculations a number of institutions have elected to use four sectors in their design. Subsequently, precise numerical calculations made at Oak Ridge by Gordon, Blosser, Cohen and Welton[58] showed acceptable behaviour of orbits in a three sector field quite similar to the field of the M.S.U. magnet. Three sectors are highly desirable in that vertical focusing in the central region of the cyclotron is strongly enhanced as will be discussed subsequently. To evaluate whether the advantages of the three sector design could safely be incorporated in the M.S.U. cyclotron, the precision calculation techniques worked out at Oak Ridge were applied to the measured model field of the M.S.U. magnet. (In this and following calculations the field used was that from the model plus trimming coil corrections, adjusted as described in the previous subsection to give isochronus acceleration.)

To perform these calculations it is first necessary to locate the equilibrium orbits for various momenta and, as a by product of this computation, the small amplitude focusing frequencies are obtained. The quantity (μ_r - 1), giving the deviation of the frequency from the resonant value, is shown in Table III for protons and for C^{4+} ions. Also, given for comparison, are the smooth approximation values which were assumed in the Stahlin calculations. The actual (μ_r - 1)'s are seen to exceed the smooth approximation values by a large factor indicating the particles to be considerably further from resonance and hence, raising at once the strong expectation that orbits will not be perturbed to nearly the extent predicted in the Stahlin calculations. This initial expectation was verified in a series of precise numerical calculations of trajectories for large amplitude deviations from the equilibrium orbits made with the Oracle[58]. The data from these runs are shown as phase plots in Fig. III-5 for protons and in Fig. III-6 for C^{4+} ions. Plotted in the figures are the quantities Δr vs Δp_r giving the deviation of radius and

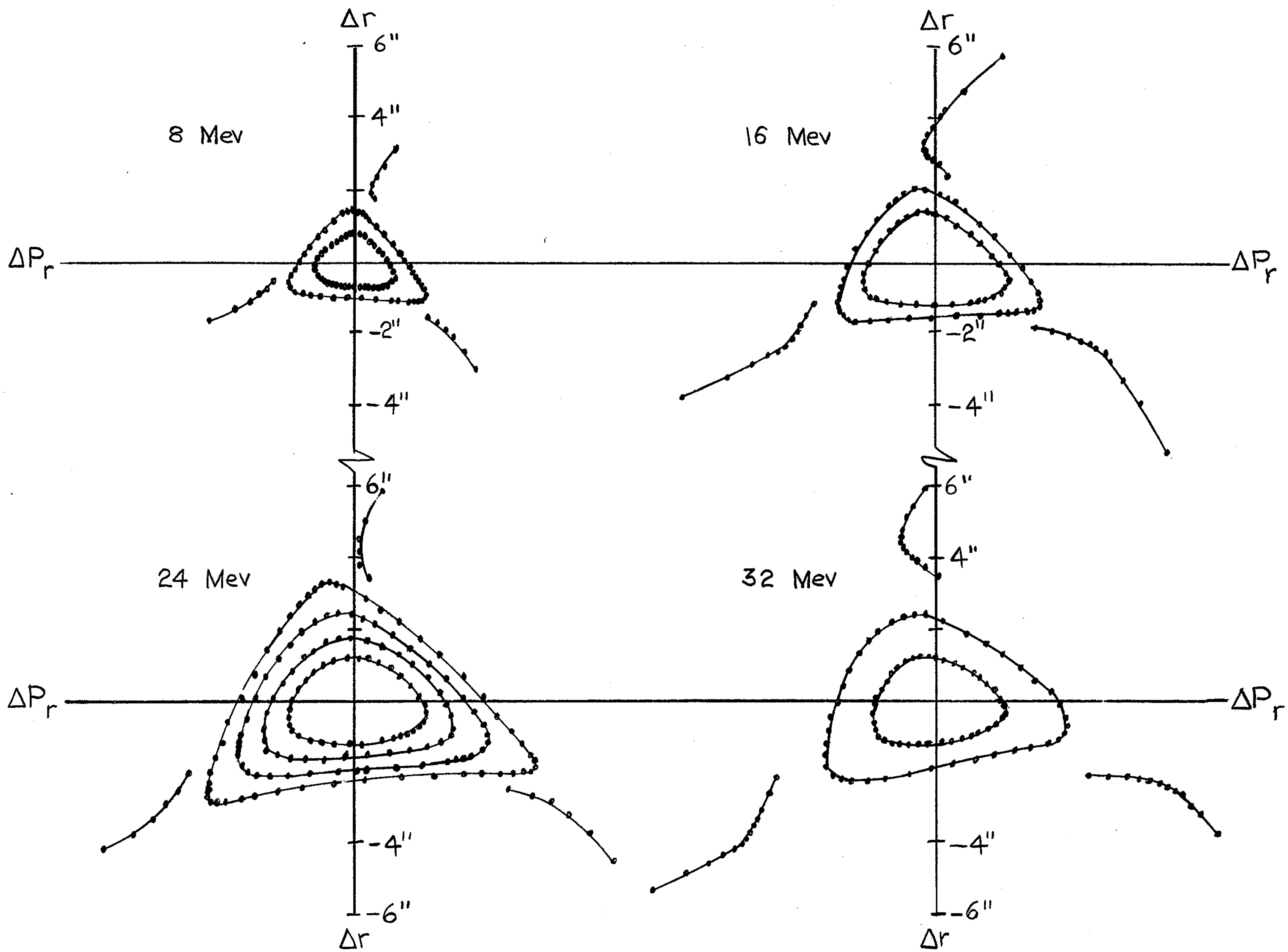

Fig. III-6: Radial phase space plots for C 4+ ions rapidly as is shown in the outer sequence of points in all plots except the one for 16 Mev protons. From the figures the maximum stable amplitudes for protons are seen to be approximately ± 1.8" at 4 Mev, ± 2.6" at 10 Mev, ± 3.6" at 16 Mev, and ± 4.4" at 22 Mev. For C^{4+} ions the corresponding amplitudes are ± 1.4" at 8 Mev, ± 2.0" at 16 Mev, ± 2.8" at 24 Mev, and ± 2.8" at 32 Mev.

For good performance the width of the band of stable amplitudes should in general be substantially larger than the range of amplitudes present in the cyclotron beam, else the amplitude of some particles will fall outside the stable region and will rapidly grow so that the particles are lost from the beam. The normal distribution of radial amplitudes in a cyclotron has been measured by Hough[62] and reconfirmed as a byproduct of central region studies of Blosser and Irwin[63]. The distribution of amplitudes can be separated into two components (as Hough shows), one component corresponding to a coherent amplitude in which the beam as a whole oscillates, the second component corresponding to the inherent spread in amplitudes from the source. The coherent amplitude arises from improper source location or first harmonic field and voltage errors, and can be eliminated by straight-forward correction of these errors. In the M.S.U. design a set of coils is provided to produce a first harmonic of adjustable amplitude and orientation; current settings can be straight forwardly claculated which will just cancel the cumulative effect of first harmonic errors. Source positioning errors are somewhat more subtle to handle in that the proper source position is a function of the dee voltage and if the source is properly positioned for particles emitted at the peak of the voltage wave it will be considerably off for particles emitted at other phases. As will

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62. P. V. C. Hough. Rev. Sci. Inst. 24, 42 (1953)

63. H. G. Blosser and R. Irwin. Bull. A.P.S. II, 3, 180, (1958)

growth takes place in the center and so effectively no growth in beam amplitude occurs. The difficulties predicted by Stahlin are hence conclusively shown not to be present in the proposed design; the particles will be smoothly accelerated out to the deflection radius.

III-A-1-c. Deflector design

In the deflection region, the radius gain per turn in the cyclotron will be about 0.09" for protons and about 0.30" for heavy ions with 70 KV dee voltage and phase at the r-f peak. The spread of betatron oscillation amplitudes at the deflection radius will be approximately equal to the turn separation for protons so that there would be an essentially continuous smear of particles at the outer radii. Convential electrostatic deflection is feasible in these circumstances as is evidenced by the Princeton cyclotron, among others. Such a system is not, however, a particularly attractive solution, since extraction efficiency would be inevitably quite small and the design and construction of a septum to handle near milli-amp currents would be a difficult and expensive task. In contrast, resonant magnetic deflection systems of the general type described by Gordon and Welton[65], offer promise of good extraction efficiency with comparatively simple hardware. Detailed studies of a system of this type are being made for the M.S.U. cyclotron. In the initial studies described herein, difficulties have been encountered as is to be expected in the exploration of new fields; remedies are being explored. If, as the studies progress, insurmountable problems are encountered at any stage, the design will revert to a conventional electrostatic system; deflected currents will be somewhat lower than estimated in section I.

who?

65. M. M. Gordon and T. A. Welton. Bull. A.P.S. II, 3, 57 (1958)

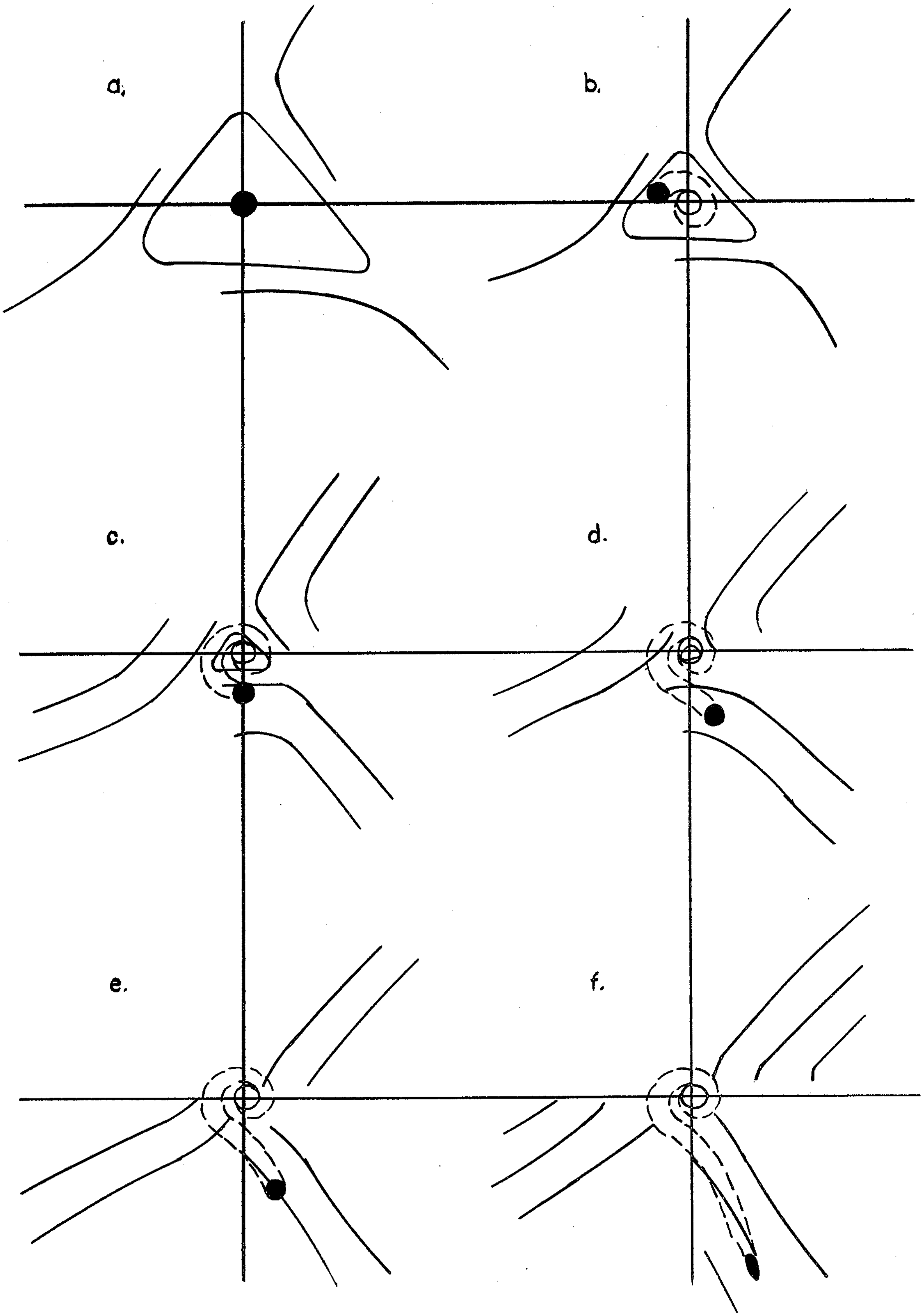

Fig. III —7: Deflection process (schematic)

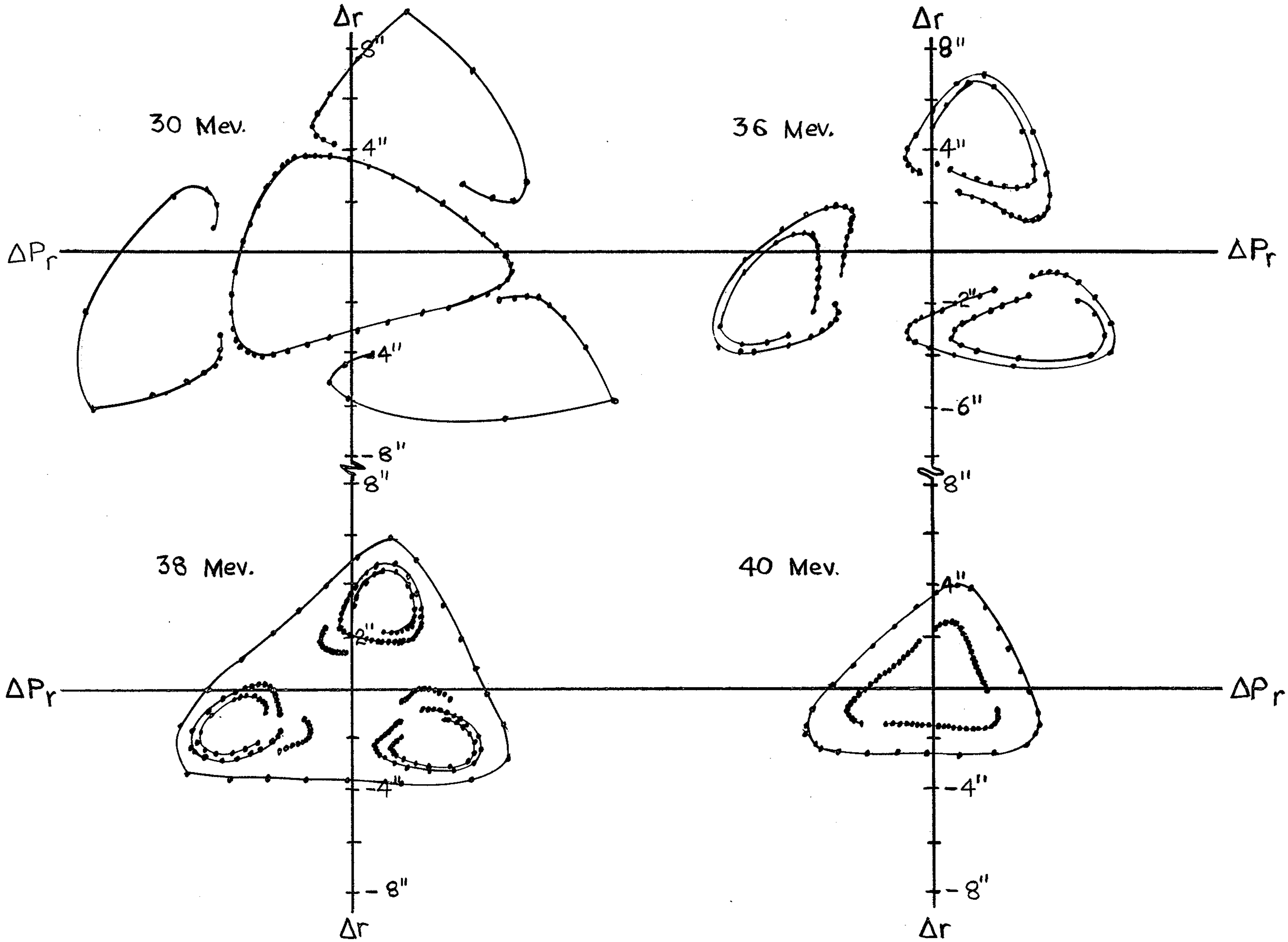

Fig. III — 8: Radial phase space plots for protons in deflection region move smoothly outward, the flow rate increasing with amplitude as is desired. The analytical revisions made in the field for these runs are then clearly of the proper character; the next step will be a revision of the pole tips to obtain a field in the model having the behaviour required to give proper phase plots. The revision will put more iron at the outer radius of the magnet in both hills and valleys, raising the average field and decreasing the flutter. Detailed form of the revisions will be gauged just as are corrections in the main part of the magnet [57, 59]; it is to be expected then that a brief series of iterative revisions will lead to a magnet configuration producing phase plots of the desired character.

Additional stringent requirements are placed on the deflector design in order to maintain proper vertical stability through the deflection process. The chief problem in this regard is the $\nu_r = 2\nu_z$ coupling resonance, the well known Walkinshaw[66] line. Frequency shifting terms in the vertical equations of motion cause the vertical frequency to increase as the radial amplitude is built up in the deflection process; a rapid shift of ν_z to the resonant value of one-half ensues. The effect can in principal be countered by a proper manipulation of the field beyond the deflection radius (only large amplitude orbits traverse this region) such that the vertical frequency for large amplitude orbits is depressed. A decrease in flutter is dictated which is fortunately consistent with the correction required by the radial motion.

The outlook for success in the overall problem of achieving a workable resonant deflection system is favorable on the basis of present results. It should be noted that the essentially radial character of the sectors in the M.S.U. cyclotron is quite probably a requisite for successful design of such a system.

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66. W. Walkinshaw. Harwell Report AERE, GP/R 2095, (unpublished)

conditions so that particles which would subsequently be lost are trimmed off early in the cycle and hence do not contribute to background and radiation hazard problems.

Preliminary results from the deflector transmission calculations indicate that the deflector system will probably function as a highly selective energy monochromater, which would correspond to synchro-cyclotron experience with regenerative deflectors. A range of energies of about ± 30% of the energy gain per turn would be transmitted, which for the protons is a spread of ± 80 Kev or ± 0.2%. There is considerable preliminary evidence to indicate that in addition to the energy selection, a requirement is also set that the number of turns be held constant. The two requirements together imply amplitude control on the dee voltage and careful selection of the phase at which particles are injected. The r-f amplitude would need to be controlled to ± 0.2%; provision has been made in the initial design for accomplishing this. A slit system will be required to accomplish the phase selection as was mentioned in the previous section. The phase selection slits may well be an integral part of the focusing grids and so discussion of possible geometric arrangements is deferred to section III-A-1-d where the focusing grids are discussed.

If subsequent calculations substantiate the 0.2% requirement on energy control as the correct requisite for transmission through the deflector, the phase selecting slits will have to include about 5 turns and the slit on the fifth turn would have a 1.0 mm radial aperture. Only particles emitted in a 7 degree phase interval would be transmitted through the slits. Experiments[63] with a system transmitting a 40 degree phase interval have shown a space charge limit of 2.8 ma, corrected to 2" vertical beam space. From this, for 0.2% control, a beam of 0.5 ma should be obtained through the slits and essentially all of this current would be transmitted through the deflector.

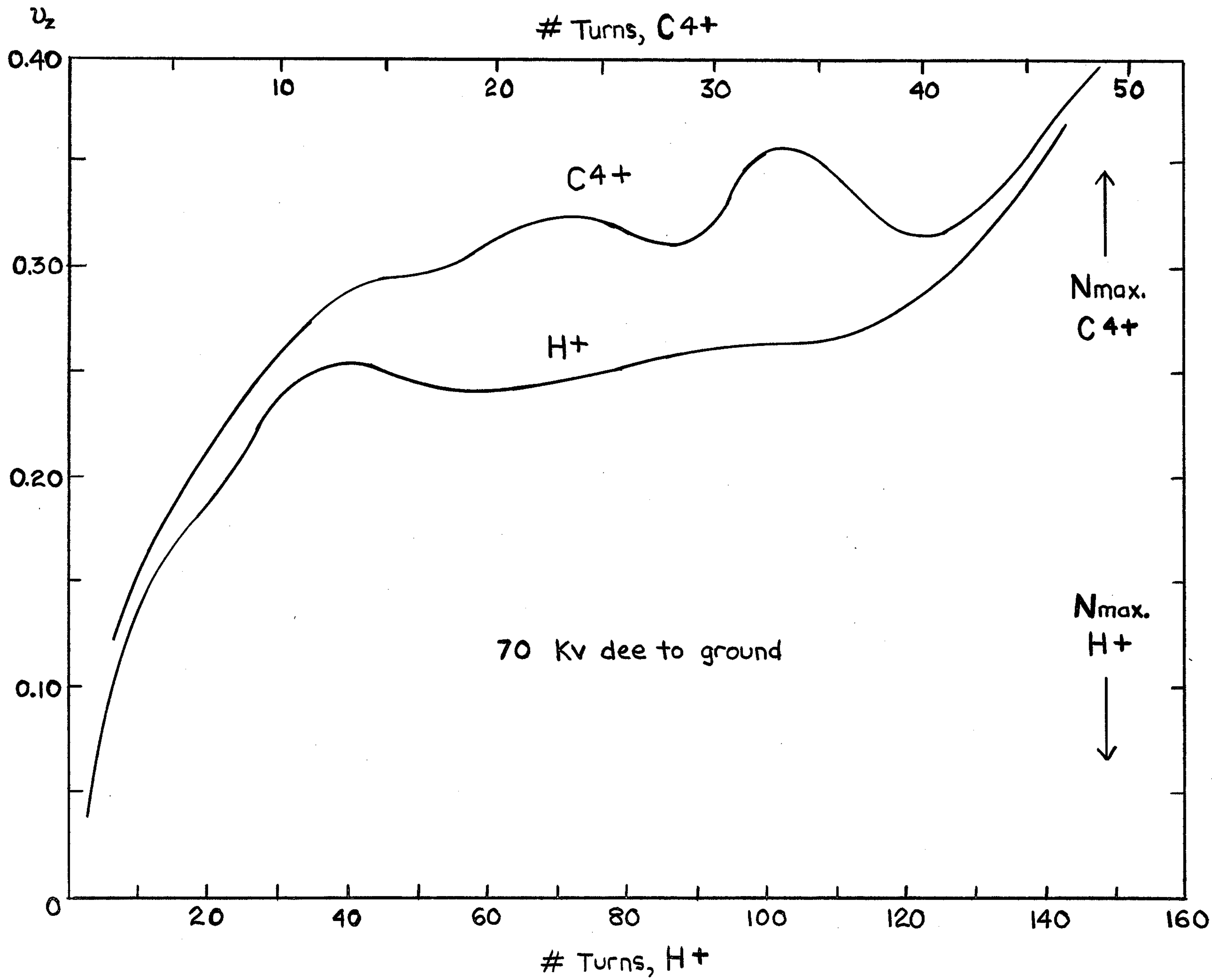

Fig. III-10: Axialfocusing frequency

up to essential equivalance with the focusing (i.e. weak defocusing) in the central region of a conventional cyclotron, but a possibly severe added problem is introduced in that the $\nu_r = 1$ resonance must be passed through at an intermediate radius. In contrast three sector magnets give focusing much stronger than conventional cyclotrons without introducing complex factors such as resonance passage. The discussion here is, of course, specifically restricted to protons, the difficulty arising from their rapid mass increase. Focusing for other ions is adequate with either 3 or 4 sectors.

The focusing grid geometry is shown in Fig. III-11. The grids are similar in principal to linear accelerator focusing grids, the entrant side of each dee being covered with a carbon structure which constitutes an essentially flat electrical surface, so that electrical field lines are shaped as in A-A'. At points where the beam passes through the grid, a slit is cut. If the slit is long axially as compared to its radial extent, the net axial focusing will be essentially unchanged from that of the uncut surface[69]. The particles progress through successive slits as shown in the sketch receiving an axial restoring impulse at each slit. The grids are continued until magnetic axial restoring forces reach an adequate level.

The narrow slits on the first and fifth turns are used to accomplish the phase selection. The phase selecting slits must, of course, be placed at nodes of the radial betatron oscillation. In the layout shown it is assumed that since ν_r is quite close to 1; the nodes would then coincide closely with the focusing grids, and so focusing and phase selection functions could be combined. If in detailed studies, the nodes of the radial oscillation are found to precess to azimuths away from the focusing grids, then separate phase selecting slits will be introduced. A number of effects, difficult to calculate, enter into

69. In passing through the slit the particles receive a small radially defocusing impulse but since magnetic radial focusing is strong in the cyclotron, the defocusing impulse is of little consequence.

determination of location of the betatron nodes and so as mentioned previously it may be necessary to perform experimental studies with electrons to determine the proper location for the slits.

Focusing grids and slits will be fabricated from graphite. Experience with such structures[63], show them to be essentially indestructable even when hit by large quantities of beam.

When changing the energy of the cyclotron, the dee voltage will be reduced in direct ratio to the output energy so that the total number of turns and the turn pattern are unchanged by the shift in energy. No change in slit position would then be required as the energy is adjusted. It is also quite probable that all heavy ions can, by proper adjustment of the dee voltage, be programmed to follow the same turn pattern so that a change of grids would be required only when shifting from protons to heavy ions and vice versa. A vacuum lock is provided in the design to accomplish this change rapidly.

A rough comparison of the relative performance of the M.S.U. design with that of conventional cyclotrons is obtained from the experiments of Blosser and Irwin[63]. In these experiments grids were used of design similar to the type which will be employed in the M.S.U. cyclotron. Results showed that 2 to 3 times more current was obtained in given phase band (3-4 ma in 30° phase interval with grids, 2-2.5 ma into 60° phase interval, without) than in a conventional cyclotron and that the effective ν_z of the grids was in the region 0.20 to 0.15. If five turns are programmed through the grids, the three sector field would give a ν_z on the sixth turn of 0.1 for protons and 0.2 for heavy ions, and hence the transmission through the composite system should be essentially the same as the transmission through the grids alone. On the basis of these rough arguments, for a prescribed phase interval and axial beam space, two to three times more current should be obtained in the M.S.U. cyclotron than in a magnet design is completely broad range - if the frequency range of the r-f is ever expanded to provide for acceleration of additional particles, no change in the magnet would be required.

II-A-2. Radio Frequency System

As has been mentioned in previous sections the r-f system of the cyclotron will be of two dee design operating at 140 KV dee to dee and tunable over a frequency range of 15 to 21 mc. The resonant system is shown in Fig. III-12. Dees and dee stems are suspended vertically from the top of the cyclotron, the dee stems being of rectangular cross section with rounded corners. The dees are open around their periphery so that the beam can move out of the dees as large radial oscillations build up in the deflection process[73]. A spacer is inserted at the lower corner of each dee to provide dimensional stability. The spacer is located in the shadow of the magnetic channel, as will be discussed subsequently, and so does not intercept beam. Each dee is cut back 10° on each side to further reduce the capacity. For the extreme low energy heavy ions which are running at an orbital frequency of 1/7th of the r-f, the voltage gain per turn is reduced to 35% of volts per turn on the fundamental. This reduction is of no consequence since in view of the low final energy, the ions would still be accelerated in fewer turns than the high energy heavy ions; the volts per turn would need to be further reduced by lowering of the dee voltage in order for low and high energy heavy ions to be accelerated in the same number of turns as is needed for deflection.

Tuning of the system is accomplished by changing the characteristic impedance of the dee stems in a manner suggested by Donaldson[74] and investigated

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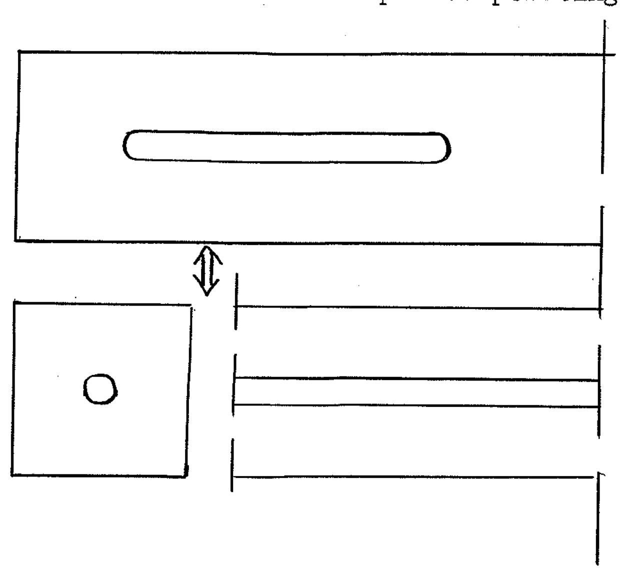
73. Once radial amplitude has begun to build up in deflection, the resonant magnetic effects predominate and it becomes of no concern whether the beam is given additional acceleration. Hence to reduce the dee capacity, dees are terminated 2" beyond the deflection orbit, and the sides left open to provide for the build up of radial amplitude. The dee periphery will be distorted slightly from circular shape to match the shape of the final orbit so that the 2" extension will be effective at all azimuths.

74. M. R. Donaldson. Ph.D. Thesis, Georgia Institute of Technology, (1957)

more recently by Lind et al[75]. A series of movable panels move in to the position shown by the dotted lines of Fig. III-12 for 21 mc operation and out to the position shown by the solid lines for 15 mc operation. Computations of the resonant frequency have been made treating the dee and stem as a non-uniform transmission line in the manner suggested by MacKenzie[76]. In the computations, the dee and stem are subdivided into sections of transmission line 1 foot in length beginning at the lower tip of the dee, and the standing wave currents and voltage computed step by step. With the linear panels in the high frequency position the characteristic impedance of each section of the line was gauged, for this calculation, by treating the dee and linear as a parallel plate capacity (edge effects neglected). With the panels in the low frequency position, the cross section for the upper portion of the line is as shown in the top portion of the sketch at bottom; in this region the characteristic impedance was computed assuming the line to be equivalent to a square line and a parallel plate line connected in parallel as in the lower part of the sketch.

The validity of computations of this type has been checked at numerous installations, and was reverified in an initial mockup built by the electrical engineering department of M.S.U. This initial mockup did not include the movable panels so that a check was obtained only at a single frequency; the resonant frequency of the mockup agreed quite closely with the calculated frequency. There remains essentially no question but what the proposed design will span the desired tuning range as calculated; this will be verified in a revised mockup incorporating the tuning panels.



The voltage standing wave pattern obtained in the resonant frequency calculations at 21 mc gives an essentially linear

75. D.A. Lind. (private communication).

76. K.R. MacKenzie, Rev. Sci. Instru. 27, 580 (1956)

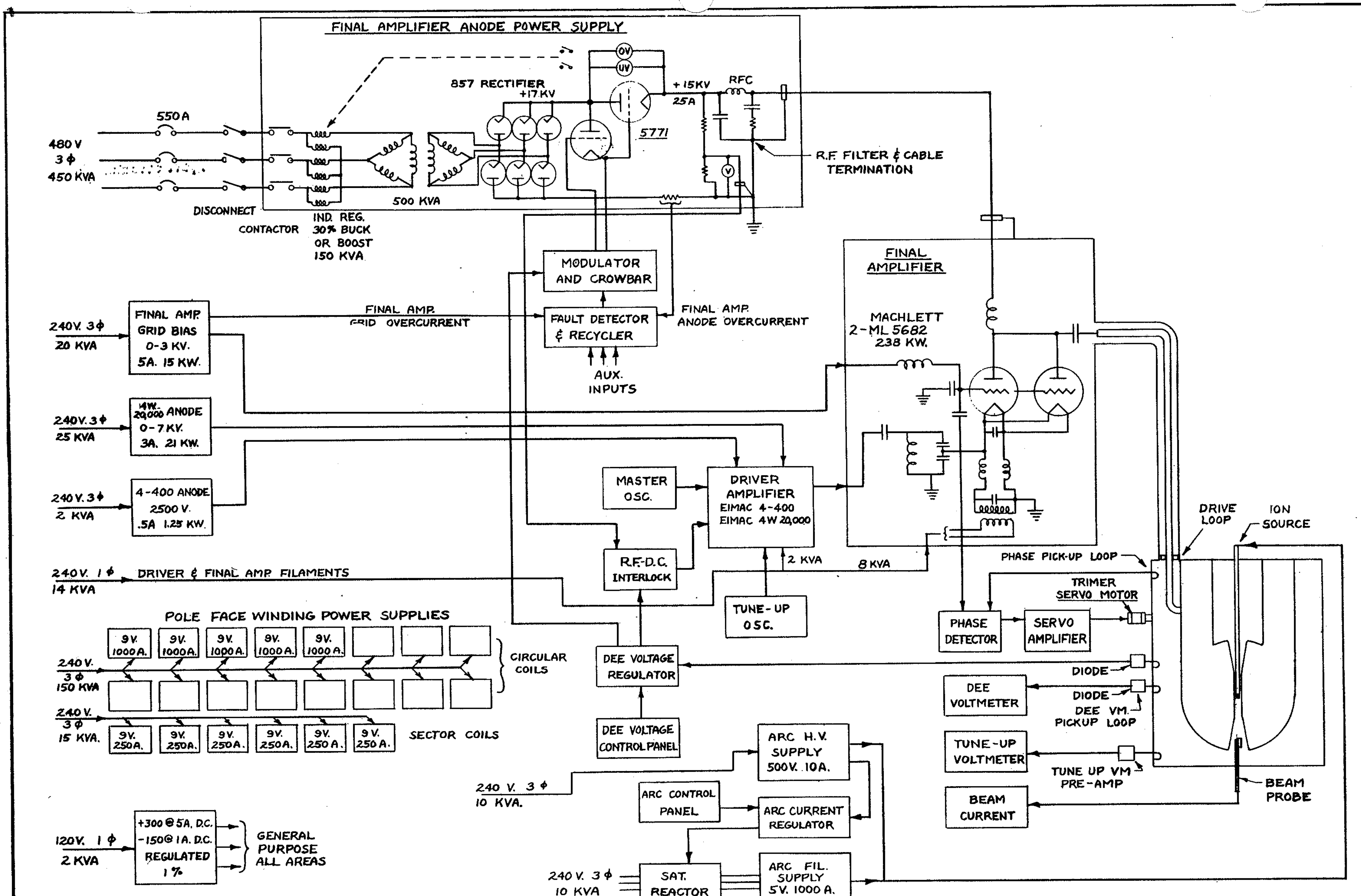
for each of the circular windings on each pole so that median plane errors, if any, can be corrected by an appropriate unbalancing of the currents in pairs of coils.

The r-f system in summary, is a straight forward application of established principles. Power dissipation is quite substantial; this is primarily caused by the high voltage and by the small dee to linear clearance (the minimum clearance required to hold voltage) which gives high dee capacity. The small clearance is used so that the magnet gap can be kept small which in turn is directly responsible for the high performance features of the magnet (Kw of r-f buy focusing in the magnet center). The enhanced usefulness of the cyclotron, by virtue of the precise beam thus derived, is felt to more than justify the expenditure for r-f power.

III-A-3 Mechanical Features

The basic mechanical layout of the cyclotron is shown in drawing 200-18-D1A. Many of the features are of standard character and can be understood simply from an inspection of the drawing. Remarks here will be restricted to unusual features.

The median plane of the magnet is vertical with yoke of conventional H design but oriented with a 20° tilt from the horizontal. The tilted orientation allows the r-f system to be suspended from the top in simple fashion while at the same time the beam can be brought out horizontally under the side member of the yoke. The yoke is supported on jacks, the jacks on one side being mounted on traversing bases as shown in Section B-B so that the yoke can be opened up 12" for installation of vacuum tank and liner, and for maintenance. Jack screws are provided to break the yoke apart for disassembly, and precision aligning pins provide precise positioning when reassembled. The pole bases are mounted to the yoke with a single central bolt; in the unlikely event that the beam fails to come



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MICHIGAN STATE UNIVERSITY
CYCLOTRON
ELECTRICAL SCHEMATIC DIAGRAM

WILLIAM M. BROBECK & ASSOCIATES
1920 PARK BLVD. OAKLAND, CALIF.

JOB NUMBER 200-18

DWG. NO. 200-18-D3A

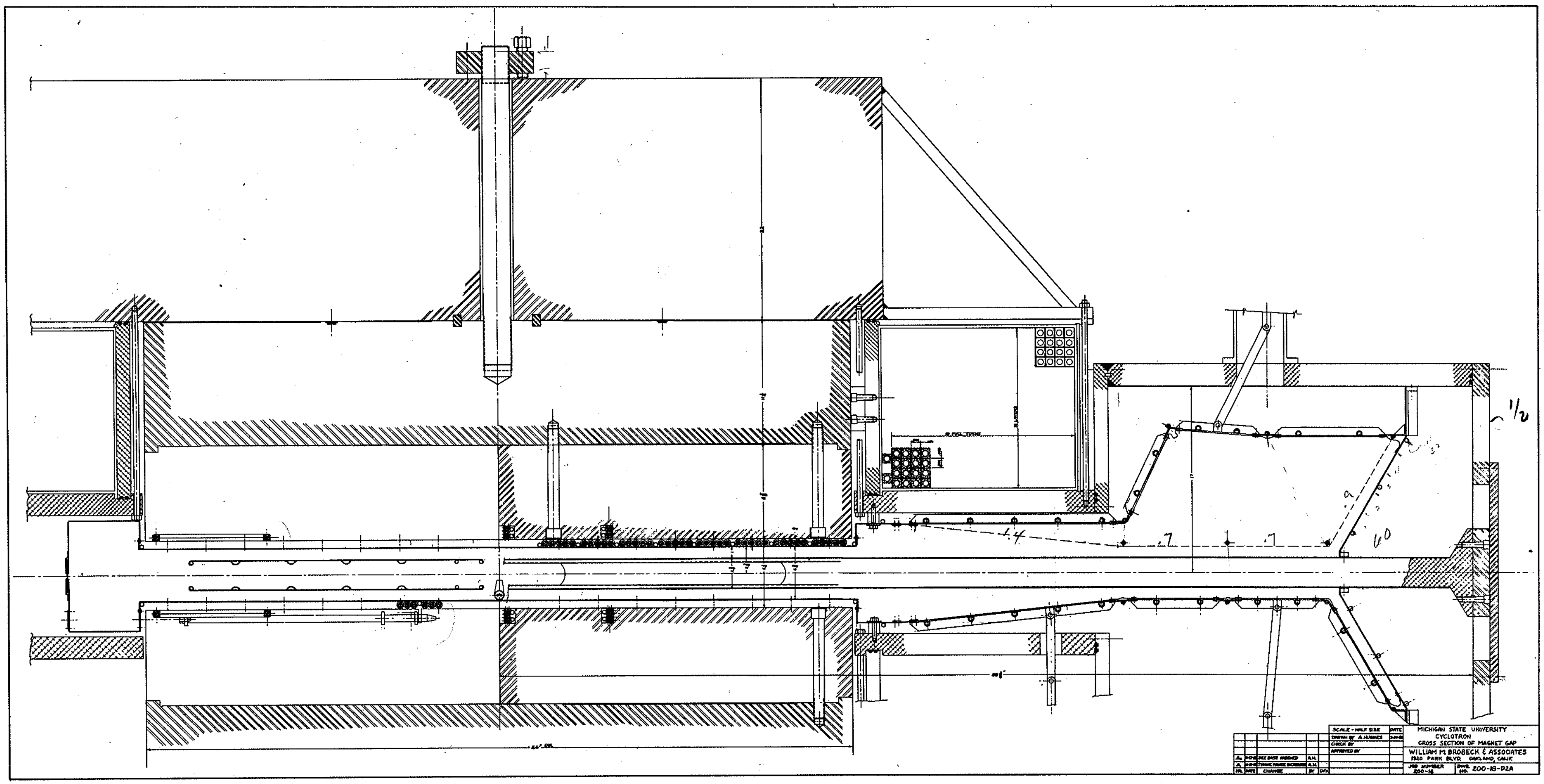
and by target design rather than by source output.

Mercury diffusion pumps with standard Freon and liquid nitrogen traps are used to evacuate the beam space to a pressure of 2×10^{-6} mm of Hg. The r-f liner forms a closed pocket with aperture protuding into the pump manifold so that the beam space is preferentially pumped.

The deflected beam is directed to a number of experimental positions as is discussed in section III-C. At an earlier stage in the planning, one of the beam paths passed back over the cyclotron coming through the upper end of vacuum tank and dee stems as shown in the drawing. The analyzing system has subsequently been rearranged to provide enhanced dispersive power; the beam path thru the cyclotron is not required in the improved arrangement.

Adjustment of the main liner tuning panels will be provided by motor driven linkage rather than the hand drive shown. In drawing 200-18-D2A a more detailed view of the liner structure is presented. The hinged joints are covered by thin flexible stock which deflects as the position of the liner panels is shifted. Current in the liner flows predominately parallel to the joints so that heating should not be a problem. The liner is water cooled, the water being fed from panel to panel by flexible metal hose. In the magnet gap, the poleface coils form an integral part of the liner, the cooling capacity being sized to handle both coil and r-f loads. The coils will be described further in a following paragraph.

The main vacuum tank for the cyclotron is arranged in a manner which permits both magnet tips and main coils to come close to the beam space as is highly desirable from the point of view of efficiency. The main coils are not in vacuum but the coil housing forms a part of the vacuum tank. Tank components are fabricated from aluminum with design such that the number of welded joints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MICHIGAN STATE UNIVERSITY
CYCLOTRON
CROSS SECTION OF MAGNET GAP
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electronic facilities can be shared, short lived isotopes produced in the cyclotron can be used in facilities such as the $\pi\sqrt{2}$ spectrometer located in the Physics building, an undesirable tendancy for a cyclotron faction to split off from the main staff is mitigated by enhanced mutual contact, and it is made considerably more convenient for members of the cyclotron staff to carry out normal teaching assignments. For these reasons both cyclotron and target areas have been shielded adequately to bring radiations well below biological tolerance immediately outside the shield walls in all directions; a site immediately to the South of the present Physics building has been selected as shown in the upper left of Fig. III-13. The site provides a comfortable area for expansion if such is ever required.

Fig. III-13 also shows the basement floor plan for the building. Fig. III-14 shows first and second floor plans and Fig. III-15 shows north-south and east-west vertical sections cut through the building. Both the cyclotron room and the target room are located below grade to minimize shielding requirements. The cyclotron room extends to sub-basement level, as is shown in the vertical sections.

The target area is "L" shaped extending around two sides of the cyclotron. Five beam positions (the steering mechanism will be discussed in the following section) and three avenues of access to the area are provided. Portable shielding designed for fork lift handling will be used to subdivide the room so that bombardments and set ups can proceed simultaneously. The basement level pit is used as an access area to bring heavy equipment into the west end of the target room and as a place to stack shielding blocks when it is necessary to uncover the main cyclotron pit. The wall separating the basement level pit from the target area is typical of the type of portable, fork lift adapted, shielding which would be used to subdivide the target area. One particularly well shielded area, designated "gamma cave," is provided in the target room for studies requiring low background.

A 15 ton overhead crane runs over the east end of the target room, the cyclotron room, the basement level pit, and on to a loading area beyond the pit. The crane is used for installation and maintenance of the cyclotron and for bringing heavy equipment into the east end of the target room. Shielding blocks over the cyclotron and the east end of the target area are sized for handling with the crane.

The cyclotron room is shielded with 5 feet of 210 pound per cubic foot concrete, the experimental room is shielded with 3 feet of the same concrete. Plug type doors of design similar to that employed for the Livermore cyclotron are provided at two points. Two coaxial pipes pass through the cyclotron shield wall along each beam path. The inner pipe which transmits the beam can be moved about in the outer pipe to provide adjustment of beam direction. The volume between the two pipes will be filled with water to minimize radiation leakage through the shield wall.

The building will be temperature controlled and a humidity maximum provided as required for stability of various sensitive electronic devices. Both cyclotron and experimental equipment control facilities will be housed in a single control room. Two desk type consoles are provided, one for the cyclotron and one for experimental equipment. The control room is lined with relay racks for housing electronic gear and an access way is provided behind the relay racks for hook up or maintenance work.

Offices and lab areas are included for staff members, a secretary, and a chief engineer. Shop facilities are included to augment facilities in the present Physics building. These and other features of the building shown in the Figures are of standard design and will not be discussed further. The

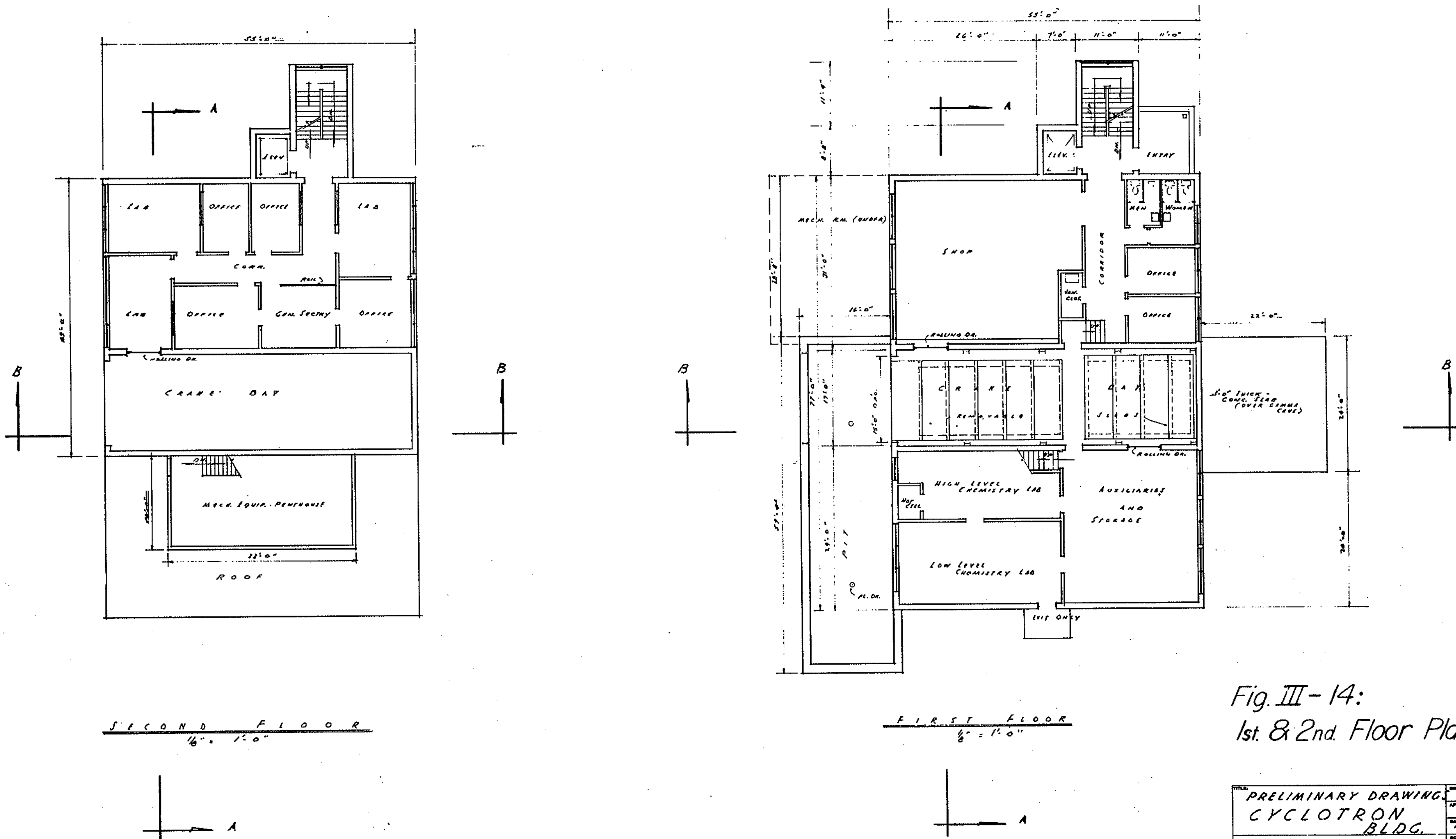

Fig. III - 14:
1st. & 2nd. Floor Plans

TITLE: PRELIMINARY DRAWINGS CYCLOTRON BLDG.	DRAWN BY: D. CROSS
	APP'D BY:
MICHIGAN STATE UNIVERSITY EAST LANSING, MICHIGAN BUILDINGS AND UTILITIES DEPARTMENT ENGINEERING SECTION	DATE: 10-30-58
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composite building will house adequately and with convenience the facilities necessary for a strong multi-pronged research program.

III-C. Experimental Facilities

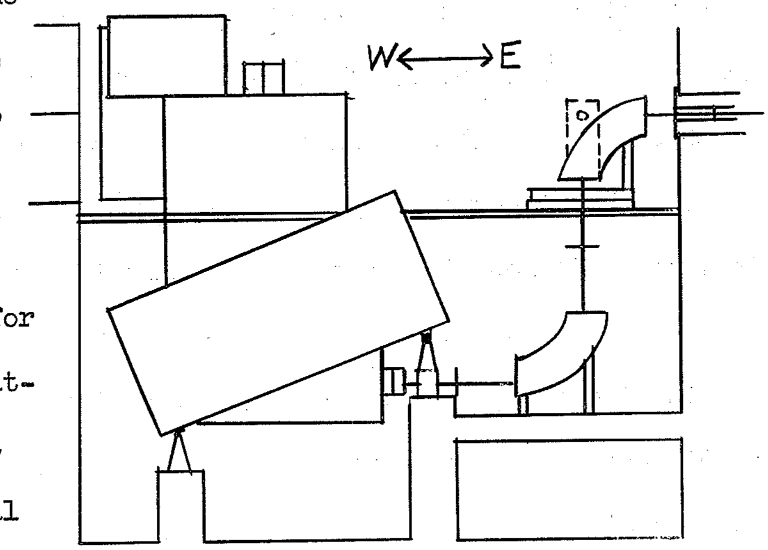
In a rapidly evolving field such as nuclear research, it is manifestly difficult to intelligently devise detailed plans for facilities to be used some years hence. In the face of this dilemma the most promising course of action is to plan facilities of flexible character; this is especially true for a versatile machine such as the proposed M.S.U. cyclotron.

Emphasis has also been placed on precision analyzing equipment. The important need for improved precision in innumerable nuclear experiments has been set forth in Section II. The M.S.U. cyclotron is particularly suited for such experiments due to the filtering action of the resonant deflection system which gives an initial external beam of unusually high precision so that further analysis can be made with much smaller attenuation than is normally the case. Well engineered facilities are provided for precision analysis and focusing of the primary beam and for handling of reaction products.

The initial design (and cost estimate) includes adequate equipment to move directly into a broad experimental program so that the total cost represents a complete operating research facility.

II-C-1. Beam Analyzing and Focusing Equipment

Magnetic analysis of the primary cyclotron beam is done entirely within the cyclotron room. The experimental area is then well shielded from both the accelerator proper and from the various slit systems for the magnets. These items are the major sources of background, assuming well designed beam stoppers are used as discussed subsequently. The experimental area should arrangement is shown in the sketch at the right. The position of the lower magnet is fixed with median plane coincident with the median plane of the cyclotron. The upper 90° magnet is mounted on a rotating carriage so that it can be used both as a switching magnet and for added resolving power. The rotating carriage is arranged so that the magnet turns about a vertical axis lying along the path of the incoming beam. Rotating the magnet then rotates the median plane about the vertical axis (the median plane remaining always vertical) and the output beam swings through a sequence of directions going successively to the positions labeled a, b, c, d, and e of Fig. III-13. (Beam pipes will, of course, be shifted from the position shown in the figure to provide for the relocation of the steering magnet in the east end of the room.) When the upper magnet is set with median plane at right angles to the median plane of the cyclotron and lower magnet (sending the beam to a position a. of Fig. III-13.) it is functioning purely as a steering magnet and does not add to the dispersive power; when the magnet is turned with median plane coincident with median planes of cyclotron and lower magnet, the dispersive powers add so that position e. of Fig. III-13 is used for experiments requiring maximum resolution. Before rotating the upper magnet it will be necessary to disconnect the exit beam pipe from the magnet. Valves will be provided in the beam pipes to isolate this section so that switching can be accomplished in minimum time without disturbing vacuum in either cyclotron or experimental equipment.



room and the gamma ray cave. A single quadrupole focusing stage will be provided in front of the magnet as suggested by Enge[81]. With the quadrupole off, the spectrograph functions in normal fashion; with the quadrupole on, high transmission is obtained over a restricted energy range for coincidence studies, etc. In heavy ion reactions the large center of mass energy will in many cases allow only a small laboratory range of θ to be accepted in high resolution work, due to the variation of energy with lab angle caused by the center of mass motion. For such work, provision has been made to turn the median plane of the spectrograph magnet through 90° about the scattered particle axis so that the axial aperture of the magnet defines the θ spread and radial aperture the azimuthal spread.

A differentially pumped gas target system will be provided specifically for heavy ion studies since they suffer prohibitive energy loss and straggle in traversing foil windows and, in addition, beam intensity is usually severely limited by the foils. Gas recovery will be provided for work with isotopically enriched gas targets i.e. N^{15}, C^{13} etc. These targets will be double ended in that the differential pumping will be applied both before and after the target to allow the main beam to continue to the shielded beam catchers. This facility will be particularly useful in the inverse reaction studies (see Section II) where targets of H^1, H^2, He^3, He^4 etc. will be used.

For initial studies a series of small, single purpose scattering chambers will be utilized. A stock of standard electronic equipment, including multi-channel analyzers and large gamma ray crystals will be provided. All equipment necessary to set in motion a strong research program is included.

The chemical lab will have the usual standard facilities and, in addition, an evaporator and an induction furnace will be included for target

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81. H. A. Enge. Rev. Sci. Instr. (in press).

IV. COST ESTIMATES

The total estimated cost of the proposed facility is, as stated previously, $2,204,200. Of this amount, $1,473,900 is requested from the Atomic Energy Commission and $730,300 will be supplied by M.S.U. The breakdown by categories is:

Category	A. E. C.	M. S. U.
Cyclotron with Contingency	$929,700	
Cyclotron Engineering Design	135,000	
Building		$488,000
Ancillary Equipment	303,400	
Cyclotron Development Studies	76,400	99,900
Project Management Costs		92,200
Scientific Supervision and Testing	50,200	29,400
	$1,473,900	$730,300

A detailed listing of items included in each category is given in tabular form at the end of this section. The estimates of staff salaries are based on a gradual increase in the cyclotron associated physics staff up to a level of four to six at the beginning of operation. This will in the main represent shifting of activities of present staff members; several new positions will also be included. The position of director of cyclotron research, in particular, is not presently filled, although an offer has been made to a person prominent in the medium energy physics field[82]. The University will, in any event, take all steps necessary to insure that the

82. A decision on this offer has been deferred (with consent of the University) until such time as definite information is available on scheduling and financing of the cyclotron; we are not, in the meantime, at liberty to divulge the recipient's name. The interest of this person in the proposed facility has been strongly stated to us and has been re-evidenced by the individual's substantial contributions to this proposal, made of his own volition.

were submitted to various accelerator groups for estimating, a wide range of figures would undoubtedly be obtained.

2. The real criterion is research per dollar; this must be judged from actual costs and can hence be done only after construction and operation.

3. In the proposal stage, a facility should be judged on the soundness of its conception and engineering since these are the quantities which will determine both its research output and the actual cost. If a facility is well conceived and well engineered it will certainly, in the long run, be economically attractive independently of initial cost estimates, which must at best be highly uncertain and reflect various prejudices and habits.

In the appendix, a listing is given of the scientific publications of the sponsors of this proposal. For recent, as yet unpublished work, references to abstracts of oral papers have been included.

W I L L I A M M. B R O B E C K & A S S O C I A T E S

M. S. U. Cyclotron	JOB 200-18	PAGE 1
Summary Cost Estimate - Cyclotron Proper	BY WMB	DATE 10/30/58

Magnet

Magnet Core Blocks, 200,000 lbs. @ 0.35		$ 70,000	
Bolts, Dowels, Brackets, etc.		2,500	
Jacking System		1,000	
Main Exciting Coil (including Terminal Box) 23,200 lbs. @ 3.50		82,000	
Magnet Installation (Rigging) 200,000 lbs. @ 5¢ lbs.		10,000	
Total			$ 165,500

Vacuum Tank and Pumping System

Aluminum Vacuum Tank and Magnet Coil Enclosure, 8700 lbs. @ 3.50		$ 30,500	
Vacuum Pumping System, 20" Diffusion Pump		20,000	
Lock and External Beam Tube Rough Pumping System		4,000	
Total			$ 54,500

Dees, Liner and Pole Face Coils

Dees			
Sheet Metal Matl. & Fab.	$ 10,000		
Support Hardware	4,000	$ 14,000	
Liner			
Liner Sheet Metal Matl. & Fab. 330 Ft.^{2} @ $40/Ft.^{2}	$ 13,000		
Liner Accessories - Tuners	5,000		
Coupling Loop - Internal Parts	2,000	20,000	
Pole Face Coils			
Conductor	$ 5,000		
Winding & Soldering	10,000		
Terminals	2,000	17,000	
Total			$ 51,000

Miscellaneous Mechanical Parts

RF Tuner Servo-drive		$ 10,000	
Beam Probe and Lock		7,500	
RF Pickup Probes (3)		3,000	
Gas Supply System		2,500	
Ion Source and Adjusting Mechanism		15,000	
Bending Magnets and Supports, 2 @ $13,250		26,500	
External Beam Tube and Valves		5,000	
Target Chamber		5,000	
Magnetic Deflector		10,000	
Manual Frequency Adj. Mech. (external)		5,000	
Dee Grid Changing and Adj. Device		15,000	
Platforms - Ladders		4,500	
Total			$ 109,000

Control Room Wireways	$ 8,700	
Control Wiring	5,500	
Spare Racks - 10 @ $200	2,000	
Total		$ 90,300

General Assembly and Check-out

Labor (not assignable to specific parts of the machine) 36 Man Months x 4.35 x 40 = 6,300 hours @ $6.00	$ 38,000

Unallocated

This item is to cover costs of minor changes and design additions for which funds must be available. This is an item which must be arrived at by judgement of the state of completeness of the design. We feel that 10% of the total cost of the cyclotron should be allocated for this purpose.

10% of $769,700	$ 77,000
Total Cyclotron	$ 769,700

Engineering Design

Engineering Services	$ 130,000	
Travel and Miscellaneous Expense	5,000	
Total		$ 135,000
Total Cyclotron Plus Engineering Design		$ 904,700

Contingency

15% of $1,064,700	$ 160,000
TOTAL With Contingency - 1958 Prices	$ 1,064,700*

* Note that this figure is based on 1958 prices. Allowance for price changes before the construction date should be made.

Cyclotron Development Studies

	M.S.U.	A. E. C.
10/1/57 to 7/1/59		
Services, supplies, and equipment	$34,700	
Labor and overhead	22,800	
Salaries and overhead	21,400	
7/1/59 to 7/1/60		
Services, supplies and equipment		$12,000
Labor and overhead		18,000
Summer Salaries and overhead		8,400
Academic Year Salaries and overhead	21,000	
Computor Rentals		38,000
Total	$99,900	$76,400

Scientific Supervision and Testing

7/1/60 to 7/1/62	M. S. U.	A. E. C.
Academic Year Salaries with Overhead	$50,200	
Summer Salaries		$29,400
Total	$50,200	$29,400

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