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PROPOSAL FOR THE NRL SECTOR FOCUSING CYCLOTRON

R. O. Bondelid, J. W. Butler, H. D. Holmgren
Van de Graaff Branch
Nucleonics Division

W. I. McGarry, R. B. Theus
Nuclear Reactions Branch
Radiation Division

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PREFACE

For several years some of the nuclear physicists at NRL have felt an increasing pressure to extend their research programs to an energy region not available with existing NRL particle accelerators. Thus, in September 1959, an ad hoc committee was formed consisting of personnel of the Nucleonics and Radiation Divisions. The function of this committee was to examine the characteristics of particle accelerators in terms of their suitability for extension of certain current research programs in both Divisions and in terms of their versatility for related problems in nuclear physics and allied fields. As the studies of the committee progressed, it became apparent that the accelerator which would satisfy the established requirements would also be a valuable facility for the investigation of many applied problems of interest throughout the Department of Defense. Some of the capabilities of such an accelerator are discussed in Chapter 1.

The committee concluded that the most important requirements of a suitable accelerator are (a) it must be able to accelerate a wide variety of particles including the helium isotopes, (b) the energy of the particles must be variable over a wide range from approximately the upper energy limit of Van de Graaff accelerators (about 10 Mev) up to an energy for protons in the neighborhood of 75 to 100 Mev, and (c) the machine should be one which can be obtained without the establishment of a large accelerator development program at NRL. On the basis of these criteria the committee decided that the most likely candidate is the sector focusing cyclotron (also referred to as flutter focusing, isochronous, spiral ridge, fixed-frequency alternating-gradient, and azimuthally varying field cyclotron).

Several groups in this country and abroad are currently engaged in projects leading to the construction of sector focusing cyclotrons. It was the decision of those writing this proposal that the accelerator best satisfying the needs of NRL is being developed at the Oak Ridge National Laboratory and is known as the ORIC (Oak Ridge Relativistic Isochronous Cyclotron). The authors therefore formally propose that NRL acquire a sector focusing cyclotron similar to the ORIC, for the purpose of augmenting its current program of research in nuclear physics and allied fields.

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PROPOSAL FOR THE NRL SECTOR FOCUSING CYCLOTRON

INTRODUCTION

One of the most important tools of the nuclear physicist is the particle accelerator. During the past fifteen years great strides have been taken in the production of fast charged particles. In order to produce mesons and antiparticles in the laboratory, it has been necessary for physicists to build higher and higher energy accelerators. Thus, during the past decade and a half, a great amount of the effort in support of nuclear science has gone into the development and construction of machines producing particles with energies in the Gev (or Bev) region. In this rush to the higher energies, the energy range between 10 Mev and 100 Mev has been largely overlooked. The importance of this energy region is shown in Chapter 1. Machines which have been constructed to produce particles in this energy range suffer from lack of beam intensity and/or beam quality. Among these are the proton linear accelerators, conventional cyclotrons, and FM cyclotrons.

One of the more exciting concepts in modern accelerator design currently undergoing extensive study is the sector focusing cyclotron, first proposed by L. H. Thomas. In order for scientists to realize the full potential of this principle, it has been necessary to apply modern computer techniques to the precise determination of the required magnetic field pattern.

Proton beams in the energy range from 7 Mev to 75 Mev will be available from the machine proposed in this report. Some of the other particles that can be accelerated by this machine and their maximum energies are as follows: deuteron, 39 Mev; helium-3, 100 Mev; helium-4 (α particle) 78 Mev; and krypton-84 (charge state +12), 145 Mev. The characteristics of the machine will permit energy variation of all of these particles over a relative range comparable to that for the proton (10 percent to 100 percent of the maximum energy). Circulating proton beam currents up to one milliampere are expected. Several tenths of the circulating beam can be extracted. Following extraction, and with proper beam handling equipment, 10 microamperes of ion beam current at an energy resolution of 0.02 percent will be available for precise nuclear physics experiments.

The anticipated initial cost of a sector focusing cyclotron and associated research facility is $5,488,546. This cost is detailed elsewhere in this report, but a coarse breakdown of the costs shows the following:

Sector focusing cyclotron	$2,097,000
Beam handling equipment	235,400
Experimental apparatus	486,380
Building and utilities	2,669,766

CHAPTER 1

SCIENTIFIC MOTIVATION

The prime motivation for the acquisition of a sector focusing cyclotron for NRL was the naturally evolved desire to extend present research programs. Consequently, the following section is mainly concerned with these programs and their extensions rather than with a survey of the many new research areas which will become accessible.

NUCLEAR INTERACTION MECHANISMS

During the last six years an active program of investigating the mechanisms of interaction of light nuclei (atomic numbers less than 8) with helium-3 and hydrogen-3 particles has been pursued in the Nucleonics Division, employing both the 2-Mv and 5-Mv Van de Graaff Accelerators. These experiments have been primarily concerned with the study of the energy dependency of the reaction probabilities and the angular distributions of the reaction products. This work has been quite fruitful in yielding information about the nature of the interactions of these particles with nuclei in this limited region of the periodic table, and at the low bombarding energies available. There are, however, large areas which cannot be investigated at these energies due to the strong effects of the repulsive electrical forces between nuclei. These forces severely inhibit the probability for the occurrence of a nuclear reaction until the kinetic energy of the incident particle is greater than the potential energy at the radius of interaction due to the electric forces. In Fig. 1, the energy necessary to overcome this coulomb barrier is shown for various nuclei. Furthermore, these forces often distort the observations to such an extent that the interpretation of the data is ambiguous. Both of these effects limit the range of the periodic table which can be presently investigated. Increasing the bombarding energies, however, overcomes these distortion effects and permits the extension of these investigations to heavier elements, where the nature of the interaction may be considerably different.

At higher energies, the incident particle's de Broglie wavelength (which is one measure of its effective size) becomes progressively smaller. This effect is shown in Fig. 2. Nuclear reactions may take on entirely new aspects as this wavelength becomes less than the diameter of the target nucleus, because the incident particle may then interact with subunits of the nucleus rather than with the nucleus as a whole.

The higher energies are also necessary for the study of reactions which require the addition of large amounts of energy. These reactions include those which result in the emission of complex particles, such as deuterons, tritons, and helium-3 particles. A systematic extension of the results obtained at NRL with low energy particles will allow one to gain a greater insight into not only the fundamental nature of the interaction mechanism but also the details of subunits in nuclear structure.

The NRL 5-Mv Van de Graaff Accelerator has been successfully used to measure the angular correlation functions between the directions of emission of the reaction products and the gamma-ray photons emitted as the excited nuclei decay to lower energy states. By detecting these radiations simultaneously, one is observing the interaction in greater detail; hence, a finer test can be applied to any theory of nuclear mechanisms. The accidental coincidence counts, which would plague the extension of these measurements to

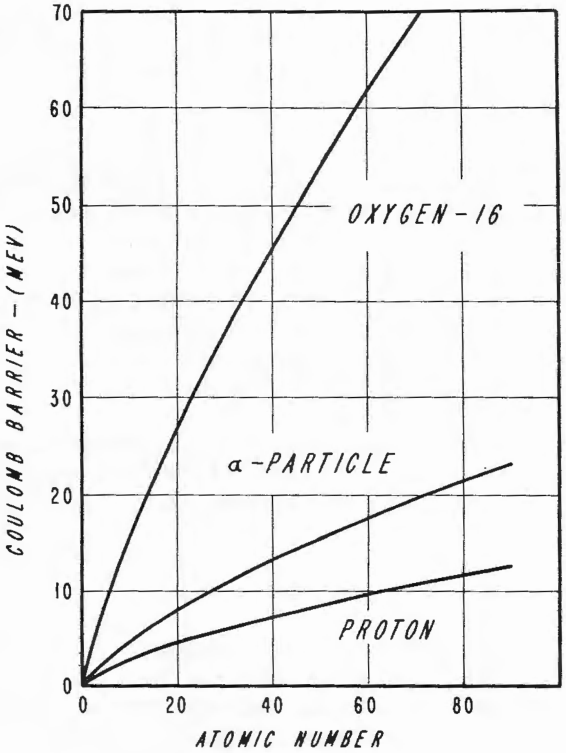


Fig. 1 - Coulomb barrier as a function of target atomic number for various beam particles

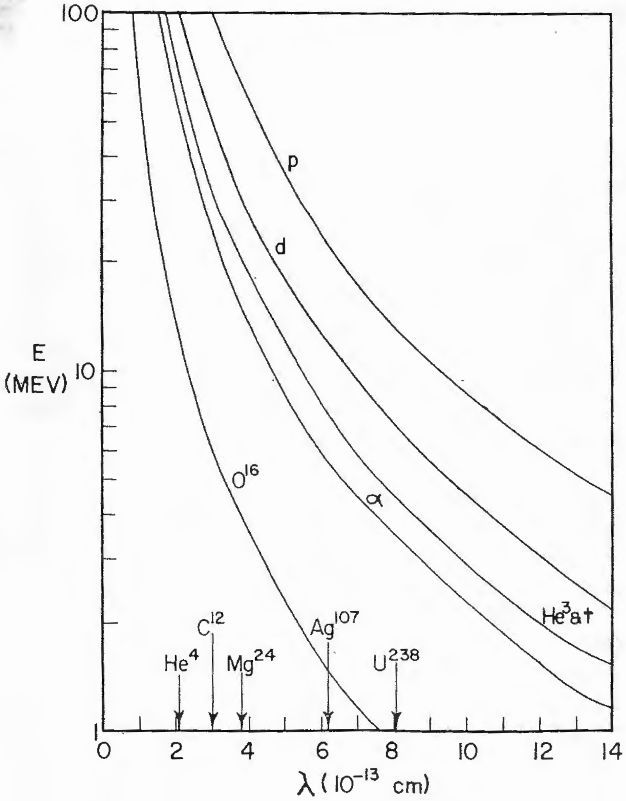


Fig. 2 - Particle wavelength as a function of bombarding energy. The arrows indicate various nuclear radii.

higher energy by the use of the excessively bunched beams of proton linear accelerators and FM cyclotrons, will be eliminated or reduced by the fixed frequency feature of the proposed accelerator.

Measurement of polarization of the spins of particles emitted in nuclear interactions is one of the more crucial tests which can be devised for any interaction theory. Since the analysis of the polarization of the particles requires a second nuclear interaction (usually the scattering of the emitted particles from some other nuclide), the rate of accumulation of data in these experiments is exceedingly slow with existing accelerators because of limited beam intensities. The characteristics of the proposed cyclotron are expecially suitable for such measurements. In view of the great interest in these observations, preliminary work at NRL has already begun on polarization measurements. This work will be expanded when the proposed accelerator is completed.

The extension of the preceding experiments, under conditions as similar as possible to those which have already been used, will afford a natural transition to further studies of nuclear interaction mechanisms.

NUCLEAR STRUCTURE

The study of nuclear structure may be divided into two general areas: nuclear spectroscopy and the study of the gross structure of nuclei. Nuclear spectroscopy is mainly concerned with the determination of the energy levels of nuclei and the measurements of the properties of these levels such as angular momentum and parity. The study of the gross structure of nuclei is the study of such properties as the size and shape, the charge distributions, and the mass distributions of nuclei, and more recently the study of the subunits of the nuclear structure and their location within the nucleus. These two areas are discussed in greater detail in the following paragraphs.

Nuclear Spectroscopy

The field of nuclear spectroscopy has been greatly exploited in the range of energies available with Van de Graaff accelerators by many groups during the last fifteen years. Immense progress has been made in the measurement of energy levels, the determination of their parameters, and the theoretical interpretation of these results. However, there still remain numerous problems to be investigated even in this energy range. One can anticipate that as experimental techniques continue to improve and more complex experiments are undertaken, considerably more information will be gained in this area, permitting greater theoretical progress. For about seven years various groups at NRL have been active in this field employing the 5-Mv and 2-Mv Van de Graaff Accelerators. The fact that these groups have made many significant contributions to this field is adequately indicated by the list of publications authored by them (see Appendix A).

Due to the high beam quality and great flexibility in energy and particles which can be accelerated, the proposed accelerator and the associated facilities will allow the extension of these programs to heavier elements, as well as to reactions in which large amounts of energy must be added to the system. This area cannot be investigated adequately with the existing accelerators in this range of energy (conventional cyclotrons, FM cyclotrons, and proton linear accelerators) due to the rather poor beam intensity and/or quality of these machines. With the proposed facilities, it will be possible to measure the position of energy levels excited by various incident particles for a very wide range of energies of excitation throughout the periodic table, to measure density of energy levels for many nuclei at various energies of excitation, and in some cases to measure the widths of these energy levels by observing the spectra of particles emitted from nuclear interactions. By examining the angular distributions of these particles, it will often be possible to gain indication of the angular momentum and parity of the corresponding level. In many cases, however, it will be necessary to measure the angular correlations between the particles emitted from the interaction and the gamma rays emitted during the decay of the level in the residual nucleus in order to determine the angular momentum. In some cases it may be even necessary to measure the polarization of the emitted particles, or to perform the experiments with beams of polarized particles in order to establish the angular momentum and parity of a level.

Spectroscopic investigations of the gamma rays emitted from the residual nucleus often yield a considerable amount of information about the level structure of a nucleus, and the level parameters. This statement is especially applicable if the excited level cascades to the ground state through one or more excited levels. In these cases, the measurements of the correlation functions between the gamma rays emitted are extremely useful in determining the level parameters. The proposed facilities will permit broadening the scope of these active spectroscopic studies.

Gross Structure of Nuclei

The study of the gross structure of nuclei is a relatively old field, although some of the most important progress has occurred only in the last few years, such as the investigations of the charge distribution within nuclei by Hofstadter and the work on various rotational aspects of nuclei by Bohr and others. One of the more promising fields of study in the area of nuclear structure is only, at present, in its initial stages of development. This field is the study of the subunits or substructure of particles within nuclei, as is suggested by the cluster-model theory of nuclear structure.

In the cluster-model theory of nuclear structure, it is envisaged that to some extent there are groupings of particles within nuclei resembling the form of alpha particles, helium-3 particles, tritons, or more complex structures such as subgroupings similar to the nuclei of oxygen-16. This model has met with considerable success in accounting for many of the energy levels of nuclei and their parameters, as well as several aspects of nuclear interactions. These particles certainly do not exhibit the same behavior as free particles of the respective type. However, if the theory is valid, some evidence of their existence should be seen in nuclear reactions also.

This model of nuclear structure has been of great interest to the group at NRL studying the mechanism of nuclear interactions, since it has allowed many heretofore unrelated experimental observations to be interpreted in a consistent manner. An example of this application is the fact that when nuclei (such as carbon-12 or oxygen-16), for which the cluster-model predicts a large probability for the existence of alpha particles, are bombarded with tritons or helium-3 particles, groups of alpha particles are observed orders of magnitude greater in intensity than from other reactions. These experimental observations made at NRL are among the strongest evidences existing for the support of this nuclear model.

One important question which must be settled is whether these subgroups exist only near the nuclear surface, as has been suggested by some people, or continue throughout the nuclear volume. In order to answer this question, it will be necessary, as was pointed out in the preceding section, to observe nuclear interactions at energies sufficiently high that the wavelength of the incident particle is of the order of the distance to which one is attempting to localize these groupings. From Fig. 2, it appears that it would be desirable to perform these experiments at as high a bombarding energy as is possible to attain. However, as the bombarding energy is increased, many new phenomena begin to occur, such as meson production, which make the interpretation of the observations more complex. It has been determined that the accelerator herein proposed represents an adequate facility for these experiments and that not a great deal is gained in the reduction of the wavelengths of the incident particles between the upper end of the energy range of this machine (see p. 1) and the energy threshold for meson production.

Since the investigation of subunits is a very new field, the exact nature of the experiments which will be employed is not envisioned at this time. It is however, expected that these studies will be closely related to those of nuclear interaction mechanisms, and that at least initially, the same types of experiments will be employed to study both areas of interest.

HEAVY-ION RESEARCH

The ability of the cyclotron to accelerate a large variety of charged heavy nuclei is summarized in Chapter 2. This valuable feature will allow the Laboratory to participate in the relatively new but rapidly expanding field of heavy-ion nuclear physics. Many of the experimental areas utilizing complex nuclei are logical extensions of present research surrounding the acceleration of helium ions. It should be stressed that many of the problems reported by some groups in this field of research, such as background radiations produced by the degradation of a fixed initial ion energy to the desired value and the uncertainty in the endpoint energy, will be eliminated or greatly reduced by the ability of the cyclotron to vary the energy of the ions over large intervals.

Coulomb Excitation

Recent studies of nuclear energy levels excited by the interaction of the coulomb field between the target and projectile have been immensely informative. The success of these studies utilizing mass-one through mass-four projectiles is indicative of the value of continuing such a program with heavy ions. This idea is especially applicable in the light of the advantages gained by exciting these levels with the heavier bombarding particles. The probability for coulomb excitation rapidly increases as the energy of the projectile is increased. The exploitation of this feature for studying weakly excited levels is limited when accelerating the lighter ions since the energy is soon reached at which the onset of contaminating nuclear reactions occur. These parasitic effects complicate the interpretation of the data since some of the gamma rays may be partly or completely due to nuclear reactions rather than coulomb excitation. However, if heavy ions are used, coulomb excitation cross sections of one or two orders of magnitude larger than those for light ions can be obtained while the probability for nuclear induced reactions are negligibly small.

The determination of the multipolarity of these transitions by the relative yields induced by the excitation of the same level with different ions has been discussed by many people and should be an important method for investigating level parameters.

The angular distribution of the inelastically scattered ions and the angular dependency of the de-excitation gamma rays provide one of the very few tools for the study of quadrupole moments of coulomb excited states. The theoretical implications of the perturbation of the excited target by the coulomb field of the incident projectile have been studied in detail by G. Breit.

Transfer and Exchange Interactions

The term "transfer interactions" refers to a collision event in which one or more nucleons are transferred from one ion to another, and the term "exchange interaction" refers to a reciprocal transfer in which each participating ion is both a donor and a recipient. The reaction mechanism for these types of complex ion interactions is interesting in its own right and provides a tool for the investigation of nuclear properties. At the lower energies, simple transfer interactions give a measure of the density of nucleons at the nuclear surface, and the angular distribution of the scattered ions is indicative of the type of interaction mechanism by implying the distances over which the transfers occur.

In the theory of direct neutron exchange interactions developed by Goldansky, the possibility of exciting hitherto unknown levels is noted. These levels would be characterized by being relatively low in energy, approximately one Mev, but having angular momenta differing greatly from the ground state.

Experimental results have been reported in which the bombardment of various nuclei indicated the net transfer of a proton and two neutrons in one case and two protons and three neutrons in another case. The first result is interpreted as involving the exchange of a proton and an alpha particle while the second observation is attributed to the double transfer of an alpha particle and a neutron. Similar experimental evidence for the transfer or exchange of more complex groups of nucleons would support and provide insight into some of the features of the previously discussed cluster model of the nucleus.

Evaporation Reactions

Evaporation interactions between complex nuclei are characterized by the emission of a number of light particles from the target zone. These particles may result from the formation of a compound nucleus in a highly excited state with the subsequent evaporation of nucleons or from a fragmentation effect in which the bombarding particle disintegrates in the vicinity of the target nucleus with some of the fragments continuing and some being captured. Most of the experimental results up to the present are consistent with the compound nucleus hypothesis. For example, the comparison of the excitation functions for proton and heavy-ion induced reactions having formally equivalent compound nuclei show good agreement on the low energy side. The high energy tail for the proton reactions is interpreted as resulting from knock-on cascades or multiple collision processes between the incident particle and the nucleons of the target nucleus. The peaking of these cross sections between bombarding energies of 20 and 75 Mev points out that the energy variation available with the proposed cyclotron is ideally suited for investigations in this field. One of the applications of these interactions is the measurement of the energy and angular distributions of the evaporated particles for the determination of the density of nuclear states and their dependency on even-odd nucleon effects.

NEUTRON PHYSICS

A useful group of reactions resulting from accelerated ions are those in which neutrons are produced. The ability of the cyclotron to generate these secondary particles over a large range of intensities and energies makes it a valuable instrument for investigations in the field of neutron physics. Its ability to contribute to this field is borne out by a comparison with the NRL Reactor, a facility which is predominantly devoted to neutron physics. The one-milliampere 75-Mev proton beam incident on an uranium target will yield a neutron production rate of 10^{15} neutrons/sec. Because of the peaked angular distribution of these neutrons in the direction of the ion beam, a flux density of approximately 10^{14} neutrons/cm^2 sec will be easily obtained over a small area. This is approximately ten times greater than the neutron flux at the core of the NRL reactor when it is operating at a power level of one megawatt, even though the total reactor neutron production rate is 7.5×10^{16} neutrons/sec.

The most important class of neutrons produced by the cyclotron will be those resulting from the proton and deuteron bombardment of light elements. Several of these reactions yield monoenergetic neutrons, the energy of which can be controlled with precision over a wide range by the variation of the energy of the incident ions. Because of the energy limitation of most Van de Graaff accelerators, there have been comparatively few neutron experiments between 8 and 14 Mev and above 20 Mev. These are relatively unexplored regions in which much remains to be learned regarding neutron interactions.

Cross Sections

Measurements of the total neutron cross sections are noticeably lacking in the region above 20 Mev as are the elastic and nonelastic cross sections. Simple transmission experiments allow the total cross sections to be determined and scattering by spherical shields is a common method for determining the nonelastic cross sections. A desirable quality of the results obtainable with the proposed facility will be a continuous measurement of cross sections over a large energy interval with one experimental setup instead of by the compilation of results from a variety of experiments, sporadically performed throughout the world.

Angular Distributions

In the last four years there has been a major effort to establish the parameters of the optical model of the nucleus by application of best-fit procedures to the data for the angular distribution of elastic neutron scattering. The principal limitation in this program is that most of the available data have been restricted to two energy islands: 3 Mev and 14 Mev. Consequently, there has been an excessive amount of ambiguity in the assignment of the potential-well parameters in going from element to element. Experiments which are strikingly lacking from this effort are the determinations of these angular distributions for single elements over large energy intervals. This type of experiment is the kind the cyclotron will allow.

For nonelastic scattering, the angular distribution of the reaction products is indicative of the reaction mechanism, and in the case of de-excitation gamma rays, it indicates the level spins.

Spectroscopy

The determination of the energy spectrum of inelastically scattered neutrons allows the effective temperature of the residual nucleus to be determined in the Weisskopf treatment. The shape of this spectrum on the high energy end is indicative of the interaction mechanism. It is desirable to know the relative contribution of compound nucleus formation, direct interaction, and cascade or knock-on interactions over the entire range of energies obtainable with the cyclotron.

This Laboratory is well represented in the areas of neutron physics discussed in these three preceding subsections with groups actively engaged in programs ranging from the study of reaction cross sections to the angular distributions of elastically scattered neutrons.

ELEMENTARY NUCLEON INTERACTIONS

Elementary nucleon interactions can be taken to include the scattering and polarization measurements as functions of the bombarding energies for all combinations of the following particles: protons, neutrons, deuterons, tritons, helium-3 particles, and alpha particles.

The studies of the interactions of elementary nucleons have been of great importance in determining information about the fundamental nature of nuclear forces, such as the range of the forces, the shape of the potential well, and the angular momenta involved. This field has been extensively explored by many laboratories in the range of energy available with Van de Graaff accelerators. Beyond this energy range, experiments have been performed at a number of fixed energies by various laboratories up to the highest energies available with particle accelerators. Although some of these observations have been of high quality, there still remain numerous experiments in this field accessible only for an accelerator with the characteristics of the one proposed.

At present, there is no existing program of research in this field at NRL. The techniques for performing such experiments are, however, very closely related to those used in the existing programs. Thus, it is quite likely that when the proposed accelerator is completed, experiments which appear to be particularly interesting in this field will be undertaken.

PRODUCTION OF RADIOISOTOPES

The supply of radioisotopes (excluding fission fragments), in the Naval Research Laboratory has grown from five curies in 1951 to approximately twenty thousand curies at present. These isotopes have been used over the entire spectrum of experimental programs supported by the Laboratory. The value of these isotopes as scientific tools to many diverse groups is illustrated by the more than one hundred radiation storage zones located throughout the Laboratory. At present, one is limited to using isotopes having relatively long half-lives except when the isotope of interest can be produced by neutron irradiation at the NRL Reactor or by the Van de Graaff accelerators.

The proposed cyclotron with its wide energy-ion combinations and large beam currents will be one of the world's most versatile producers of isotopes. This potential has been adequately demonstrated by the production for the first time of particular thallium and polonium isotopes and the transuranic element No. 102 by fixed-energy heavy-ion accelerators. The isotopes which can be produced by the positive ion beams are predominantly on the proton-rich side of the stability curve, a region generally inaccessible to production by reactor neutron irradiation.

At present several experimental groups at NRL are using radioactive isotopes for the study of fundamental nuclear properties. One such group is instrumented to measure the angular correlation between cascade gamma rays for isotopes having half-lives as short as one minute. Another group is instrumented to measure electronically the lifetimes of the excited states following beta-ray emission. This instrumentation allows the determination of these lifetimes with a resolution approaching 10^{-10} second. Resonance-fluorescence measurements, which yield the widths of γ-excited levels, are also being performed with reactor-produced isotopes. The increased availability of radioactive nuclides afforded by the cyclotron will augment these basic research programs.

ION INDUCED FISSION

The ability of the heavy ion beam to produce compound nuclei having high excitation energies and large angular momenta results in an increased probability for de-excitation via the fission mode. These properties have been exploited by the group at Moscow under Flerov, who observed large anisotropies in the angular distributions of the fission fragments, sensitive dependence on the Bohr-Wheeler parameter Z^2/A, indications for asymmetric mass yield curves, and the relative competition of evaporation processes. The purpose of these studies was the achievement of a better understanding of the laws governing fission. Because the de-excitation process for highly excited heavy nuclei proceeds by neutron and proton emission as well as by the fission mode, contributions to fission understanding will be made in many of the experimental areas that have been previously outlined.

SOLID STATE PHYSICS

When a solid state material is subjected to nuclear radiation, many of its physical properties may undergo appreciable changes. These properties include electrical characteristics (particularly in the case of semiconductors), diffusiveness, resistance to plastic deformation and corrosion, and resistance to brittle fracture and other mechanical failures. The information acquired in the study of these changes has aided reactor designers and in the future should aid in predicting the behavior of various structural members and instrument components when exposed to other nuclear radiations. These radiations may well include the protons found in the Van Allen layers and the intense proton emission associated with solar flares. Recent measurements show that appreciable portions of the energy spectra of these radiation fields fall within the proton energy range of the proposed cyclotron.

Crystal lattice displacements have been investigated at a few energies between 10 and 40 Mev for alpha, proton, and deuteron bombardment with microampere beam currents. The proposed cyclotron will allow the extension of these studies to higher energies and larger ion fluxes for a greater variety of accelerated particles. Among these beam particles the heavy ions have in recent years been regarded as highly desirable for use in radiation damage studies because of the relatively large lattice derangement that can be produced per collision as compared to that caused by nucleons. This feature has not been exploited in solid state studies simply because of the scarcity of machines capable of producing the necessary beams.

Another capability associated with the acceleration of heavy ions is the extremely rapid rate at which energy can be deposited in a small volume. It is estimated that for nitrogen-ion bombardment of a sample of intermediate atomic weight, ten megawatts/cm^3 can be obtained. This concentration of thermal energy will provide the sharp temperature gradients and the associated transient thermal stresses necessary for the study of thermal shock phenomena.

In summary, the facility herein proposed represents a powerful and versatile establishment for the study of basic nuclear physics and solid state physics, as well as an extremely useful tool for attacking many applied problems. In addition, the results obtained with this facility will provide information which will undoubtedly stimulate theoretical studies leading to a better understanding of the fundamental concepts in these areas. The experience of NRL in these and related areas highly qualifies it for the immediate and continued exploitation of the cyclotron's full potential.

CHAPTER 2

THE CYCLOTRON

HISTORY OF SECTOR FOCUSING CYCLOTRONS

In a conventional cyclotron, the ions, circling in a disk-shaped space, receive repeated additional increments of energy as they cross a gap between two hollow D-shaped electrodes (dees) on which is imposed a fixed-frequency rf voltage. These ions move in a curved path because of a magnetic field perpendicular to the plane of their motion. To a first approximation, this magnetic field is uniform, but actually it decreases slightly as a function of radial distance from the center, and it is this slight decrease in magnetic field as a function of radius that gives the conventional cyclotron sufficient focusing in the axial direction. As the energy (or velocity) of an ion increases, it spirals outward, thus traveling in a larger orbit. These two effects (increased velocity and increased orbit diameter) precisely cancel out if the ion mass is constant, so that the spiral rotations maintain phase with the rf field of the dees. However, for proton energies above about 10 Mev, the relativistic increase in mass of the accelerated ion becomes appreciable, and the proton therefore tends to lag the rf field in phase. This slipping in phase can be eliminated if the magnetic field is made to increase near the edge of the magnet. But, as mentioned, the focusing requirement demands a decreasing magnetic field near the outside.

Thus the designer of a conventional cyclotron faces the dilemma of needing a magnetic field which both increases and decreases with radius. In practice, a compromise has always been made, thus limiting the maximum energy of conventional cyclotrons. The highest-energy conventional cyclotron for protons is the ORNL 86-inch Cyclotron, which accelerates protons up to a maximum of about 25 Mev.

As early as 1938, L. H. Thomas pointed out a way of overcoming this dilemma by introducing azimuthal variations in the magnetic field. These azimuthal variations, accomplished by alternating sectors of high and low fields, can provide sufficient focusing to overcome the defocusing effect of a magnetic field which increases, on the average, as a function of radius. However, very little use was made of the Thomas idea until the 1950's for several reasons. In the first place, conventional cyclotrons worked satisfactorily in their limited energy range, and there was enough physics to be done in this region to occupy the physicists in the field during the 1940's. Then after World War II, when interest in meson physics grew rapidly, rf techniques, developed during the war, made it possible to overcome the cyclotron dilemma in another way, the introduction of frequency modulation on the accelerating voltage. In this solution to the problem of the accelerating ions slipping in phase, the rf voltage itself is made to decrease in frequency as the ions approach the end of their trajectory in the magnetic field, thus maintaining phase stability. This type of cyclotron, epitomized by the 184-inch Synchrocyclotron at Berkeley (730-Mev protons), allows very high particle energies, but they are achieved at the expense of beam intensity. Only one burst of particles is put out by the machine for each FM period, thus giving a very low duty cycle, and therefore a very low average beam intensity.

Another reason that the Thomas sector focusing idea was not developed before the 1950's is the great difficulty of computing particle orbits in such a complicated magnetic field, and therefore the great difficulty in designing such an accelerator. With the ready availability of large-scale digital computers, several research groups began feasibility studies of sector focusing cyclotrons, and a few are now in existence or being built. In

February 1959, a special "Conference on Sector-Focused Cyclotrons," under the joint sponsorship of the National Academy of Sciences-National Research Council and the American Physical Society, was held at Sea Island, Georgia. The proceedings of that conference, NAS-NRC Publication 656, give the design details of most of the sector focusing cyclotrons being designed or built at that time. A compendium of "Cyclotrons and High-Energy Accelerators – 1958" has been prepared by F. T. Howard of the Oak Ridge National Laboratory and is available as a document, ORNL-2644.

BEGINNING OF INTEREST AT NRL

When the limitation of particle energies of the existing NRL positive ion accelerators began to be felt as a severe restriction on the range and versatility of the nuclear physics experimental programs at NRL, several physicists in the Nucleonics and Radiation Divisions independently began to look into the possibility of obtaining an additional accelerator to meet these needs for higher energy particles. The results of these individual efforts was the formation of an ad hoc committee on accelerators under the joint chairmanship of M. M. Shapiro and C. V. Strain, in September 1959, to make a study of the various types of accelerators which might meet these needs at NRL, and to make a recommendation of the one most suitable.

Three types of accelerators were considered – positive ion linear accelerator, tandem Van de Graaff accelerator, and sector focusing cyclotron. After due study and deliveration, the committee unanimously recommended the sector focusing cyclotron because of its versatility and therefore its capability of meeting the anticipated needs of the NRL research program. Briefly, the reasons for rejection of the positive ion linear accelerator were the very limited number of types of accelerated particles, the limited energy variability, the low duty cycle, and low beam intensity. The principal reasons for rejection of the tandem Van de Graaff accelerator were its inability to accelerate helium ions in the tandem arrangement and the relatively low upper limit on beam energy, about 20 Mev.

Because the interest of the committee is primarily in the field of physics and the use of such an accelerator, instead of accelerator development, it was decided that the best course for acquisition of such an accelerator would be to copy one of the existing designs.

After careful consideration of the various designs for sector focusing cyclotrons, the design chosen as the one whose characteristics best meet the needs of the proposed research program at NRL is the Oak Ridge Relativistic Isochronous Cyclotron (ORIC). This cyclotron has 76-inch-diameter magnetic pole pieces and will accelerate protons over the energy range of about 7 to 75 Mev. It is an extremely versatile design, including capability of accelerating practically all nuclear species which can be introduced into the ion source in gaseous form. The circulating beam can be adjusted from zero to about 1 milliampere, and it is anticipated that several tenths of this amount can be extracted for energy analysis and precise experiments.

The magnet has a vertical gap, with pole pieces having three sectors in a weak spiral. Valley coils are used to oppose the magnetic field in the valleys, thus increasing the magnetic flutter, and hence the focusing power of the magnet. The isochronous field is achieved by the use of ten concentric trimming coils, coaxial with the pole pieces, each having a separate power supply.

Only two significant changes from the Oak Ridge design are proposed, and these changes are of a nature such that they will introduce a minimum of complicating ramifications. The proposed changes are the substitution of copper for aluminum in the main exciting coils and the substitution of NRL-type liquid-nitrogen cold traps for those on the ORIC. The copper will be used because it will result in overall economy over a 10-year period, since electrical power is more expensive in the District of Columbia than in Tennessee. The other change is based on experience with Van de Graaff accelerator vacuum systems at NRL.

NRL has employed William M. Brobeck and Associates, Oakland, California, to make a cost estimate for NRL to obtain a sector focusing cyclotron similar to the ORIC. Mr. Brobeck is eminently qualified to make such a study because of his experience at the Lawrence Radiation Laboratory, Berkeley, California, in the design of the 184-inch FM cyclotron and other accelerators. His firm has made similar cost estimates for Michigan State University and the National Bureau of Standards. The cost estimates made for NRL are presented in the first section of Chapter 6.

PERFORMANCE CHARACTERISTICS

The ORIC is a fixed-frequency, azimuthally-varying-field, variable-energy, 76-inch cyclotron designed to accelerate various particles with charge-state-to-mass-number ratios from 1 to 0.125 over a wide range of energies, up to 145 Mev (for krypton-84 in charge state +12). The machine is designed to accommodate large ion currents, with a total beam power up to 75 kw (one milliampere of protons at 75 Mev). The conditions associated with the acceleration of various particles to their maximum energies are tabulated below and presented graphically in Fig. 3, taken from "The Oak Ridge Relativistic Isochronous Cyclotron," by R. S. Livingston and F. T. Howard, ORNL-2648, September 1958.

Particle	Charge State	Max. Energy (Mev)	Energy Per Nucleon (Mev)	Orbital Frequency (Mc/sec)	Central Magnetic Field (kilogauss)
Proton	+1	75	75	22.5	14.8
Deuteron	+1	39	19.5	12.3	14.5
Helium-3	+2	100	34	15	14.7
Alpha	+2	78	19.5	12.3	14.5
Carbon-12	+4	115	9.5	8.6	17
Nitrogen-14	+4	100	7.3	7.5	17
Oxygen-16	+4	88	5.7	6.5	17
Neon-20	+5	108	5.7	6.5	17
Argon-40	+7	103	2.8	4.6	17
Krypton-84	+12	145	1.8	3.7	17

MAGNET AND FIELD COILS

Description of Magnet

The magnet in the ORIC has vertical pole faces and three sectors with a weak spiral as shown in Fig. 4 (ORNL 2648), a vertical section in the plane of the gap. The magnet is of a conventional closed-yoke design with a one-to-one ratio of pole base cross section to yoke cross section. The finished magnet, less coils and vacuum tank, weighs approximately 200 tons and is 180 inches high with base dimensions of 113 x 113 inches. The four 20-inch-thick yoke pieces are bolted together with through bolts.

The magnet is made of forged low-carbon steel, known as cyclotron analysis steel, whose nominal composition is as follows:

Impurity Element	Max. Content
Carbon	0.15%
Manganese	0.50
Phosphorus	0.04
Sulfur	0.05
Silicon	0.20
Nickel	0.08

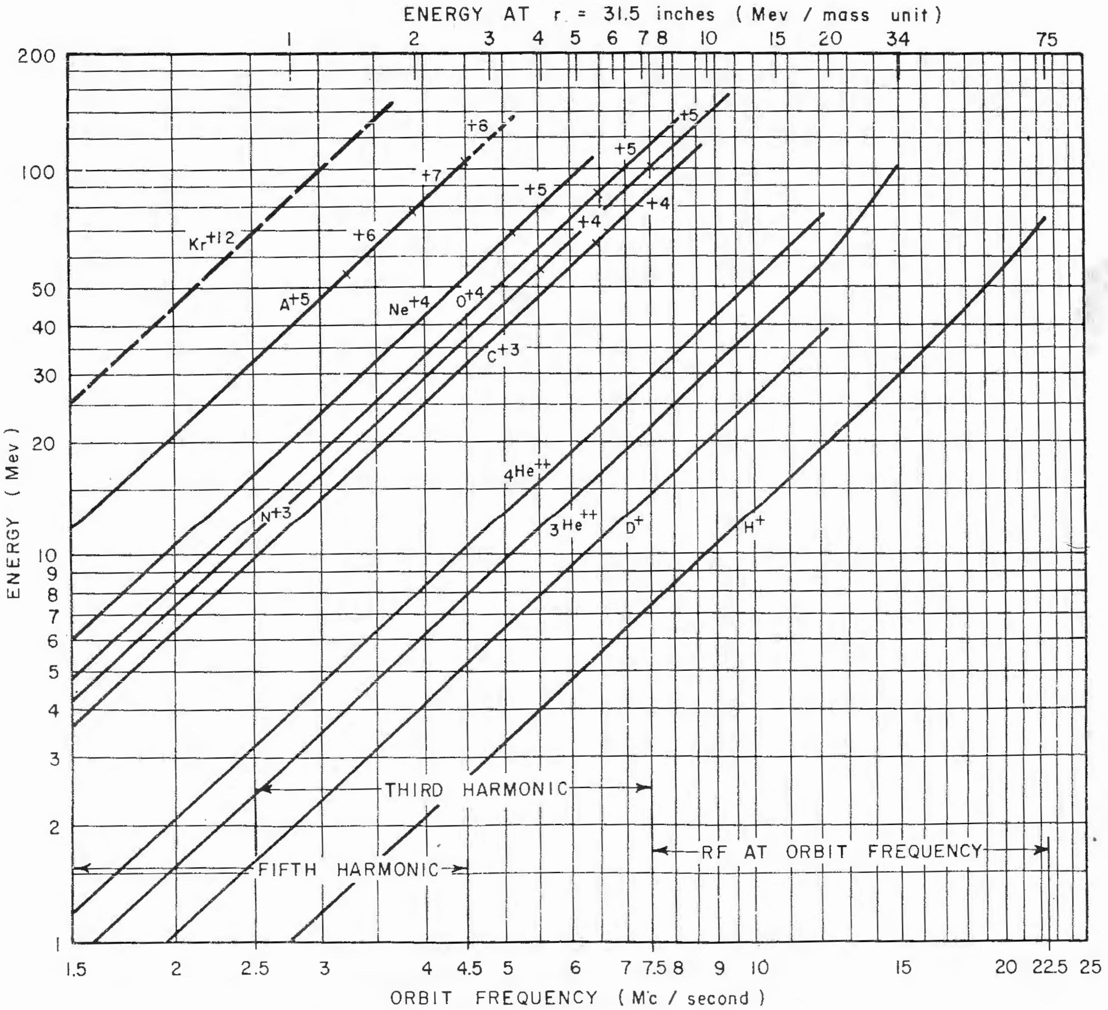


Fig. 3 - Accelerated particles and energies available in the ORIC (Reproduction of Figs. 3 through 6 was kindly permitted by the Oak Ridge National Laboratory, operated by Union Carbide Corporation for the United States Atomic Energy Commission)

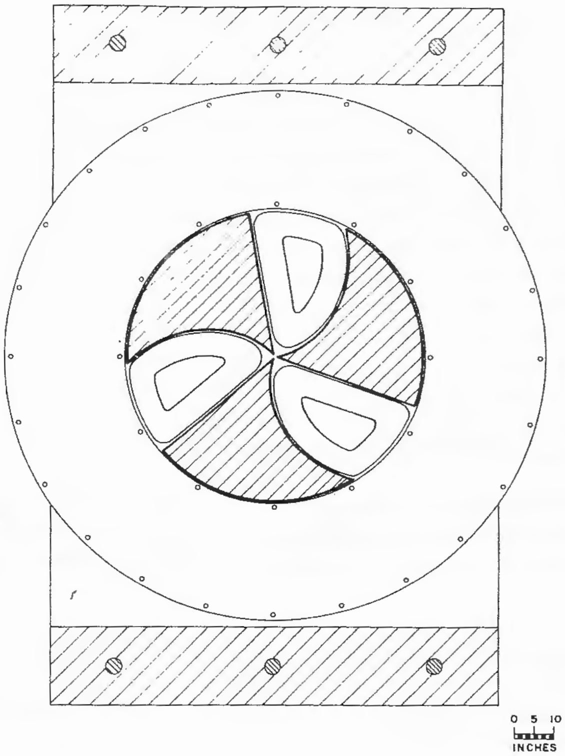


Fig. 4 - Pole configuration of the three-sector weak-spiral magnet

Main Exciting Coils

The main coils of the ORIC are designed with eight water and eight electric circuits each. Each circuit is a single conductor strand, 1170 feet long, wound as a double pancake so that all connections are external to the coil and pole piece. The pancake coils are securely mounted in a coil case and the entire assembly bolted to the yoke of the magnet.

Some of the design characteristics of the coils are listed at the end of this chapter.

Conductor Material

The ORIC has aluminum exciting coils because, at the time the coils were fabricated, the use of aluminum resulted in greater overall economy over a 10-year operating period. However, since that time the market prices of copper and aluminum have changed in a direction to decrease the initial price advantage of aluminum. Furthermore, the cost of power at NRL (about 1.1 cent/kw-hr) is considerably greater than at ORNL (about 0.5 cent/kw-hr), a fact which means that the use of copper over aluminum is relatively more important at NRL than at ORNL. A simple calculation shows that the total 10-year costs at NRL (initial costs plus operating costs) will be less for copper coils than aluminum. If it is assumed that the acclerator will be used 80 hours per week, 50 weeks per year, at an average of 75 percent of full power on the main magnet coils, the saving in power costs for copper coils instead of aluminum coils would be $13,000 per year, resulting in a net power cost of $21,000 per year for the main coils. The total power costs for operation of the entire accelerator will be about $75,000 per year. The extra initial cost of copper coils over the cost of aluminum coils would be less than $50,000. Also, the use of copper will allow a smaller power substation and the use of a smaller heat exchange unit and cooling tower.

It is therefore proposed that copper conductors of the same cross section and length as the ORIC aluminum conductors be used on the NRL cyclotron. By keeping other parameters the same (except the weight of the conductors, of course), the deviation from the ORIC design will be minimized, and it is believed that this simple change will not preclude the use of the ORIC engineering drawings in the construction of the NRL cyclotron.

The ORIC utilizes two "on hand" motor-generator sets to supply power to the main exciting coils. Regardless of whether or not the change to copper is made, it is not planned to copy these motor-generator sets because they are oversized, they are not "on hand," and rectifier sets are cheaper and require less maintenance than motor-generator sets.

Auxiliary Coils

An exploded view of a pole tip with coils is shown in Fig. 5 (ORNL 2648). (Here the pole face appears horizontal for the sake of clarity of presentation.) The increase in magnetic gap due to the presence of the valleys gives sufficient magnetic field variation (or flutter) to focus moderate energy protons (about 25 Mev) but does not produce sufficient flutter to focus the maximum energy protons which can be retained by the magnetic field. In order to increase the flutter, an auxiliary coil is placed in each valley, as shown in Fig. 5, and the current adjusted to counteract part of the existing magnetic field. The design features of these coils are such that they will be used at full design power opposing the main magnetic field only for 75-Mev protons. For acceleration of low-energy protons, or heavy nuclides at any energy, the current in the valley coils will be reversed, and adjusted to augment the magnetic field in the valleys; otherwise there would be too much flutter, resulting in axial instability in the beam. The valley coils are made of water-cooled copper windings enclosed in vacuum-tight stainless steel containers.

The harmonic coils, also of water-cooled copper and placed in the valleys, on the gap side of the valley coils, correct for the radial harmonics in the actual measured magnetic field configuration, thus compensating for any asymmetry of the ion orbits with respect to the geometric magnet-pole-piece axis.

There are ten circular concentric trimming coils, coaxial with the magnet pole pieces, located on the pole tips inside the vacuum tank. These coils are water-cooled unencapsulated copper windings, one conductor thick, and are used to increase the average magnetic field for larger radii, achieving the isochronous condition.

VACUUM SYSTEM

The vacuum tank is constructed of stainless steel with 76-inch-diameter, 4-inch-thick magnetic steel inserts to maintain magnetic continuity of the pole bases. The total vacuum volume, including vacuum tank, dee stem house, and diffusion pump manifold is about 700 cubic feet.

There are two 32-inch-diameter diffusion pumps, mounted one on each side of the ion source extension on the side opposite the dee stem. A 20-inch pump evacuates the other side (dee stem) of the system. The pressure in the accelerating region will be maintained at $\leqq 3 \times 10^{-6}$ tor (mm Hg).

Each diffusion pump will have over it either a water baffle or refrigerated baffle, and above this baffle will be a liquid-nitrogen cold trap of the NRL type, which utilizes thin re-entrant tubes for mechanical support, condenses the vapors inside an inner tube, and utilizes shields to minimize radiation heat transfer. The above characteristics give high trapping efficiency and long life on each filling of liquid nitrogen.

These changes from the ORIC design should result in a somewhat higher vacuum in the accelerating region, and less contamination of the vacuum system by vapors. It is not anticipated that these changes will interfere with any other components of the design.

ION SOURCE

The ion source is the standard Oak Ridge hot cathode type, and is described in the literature. The ion source consists of a heated tantalum filament, a carbon arc chamber, and a floating carbon anode.

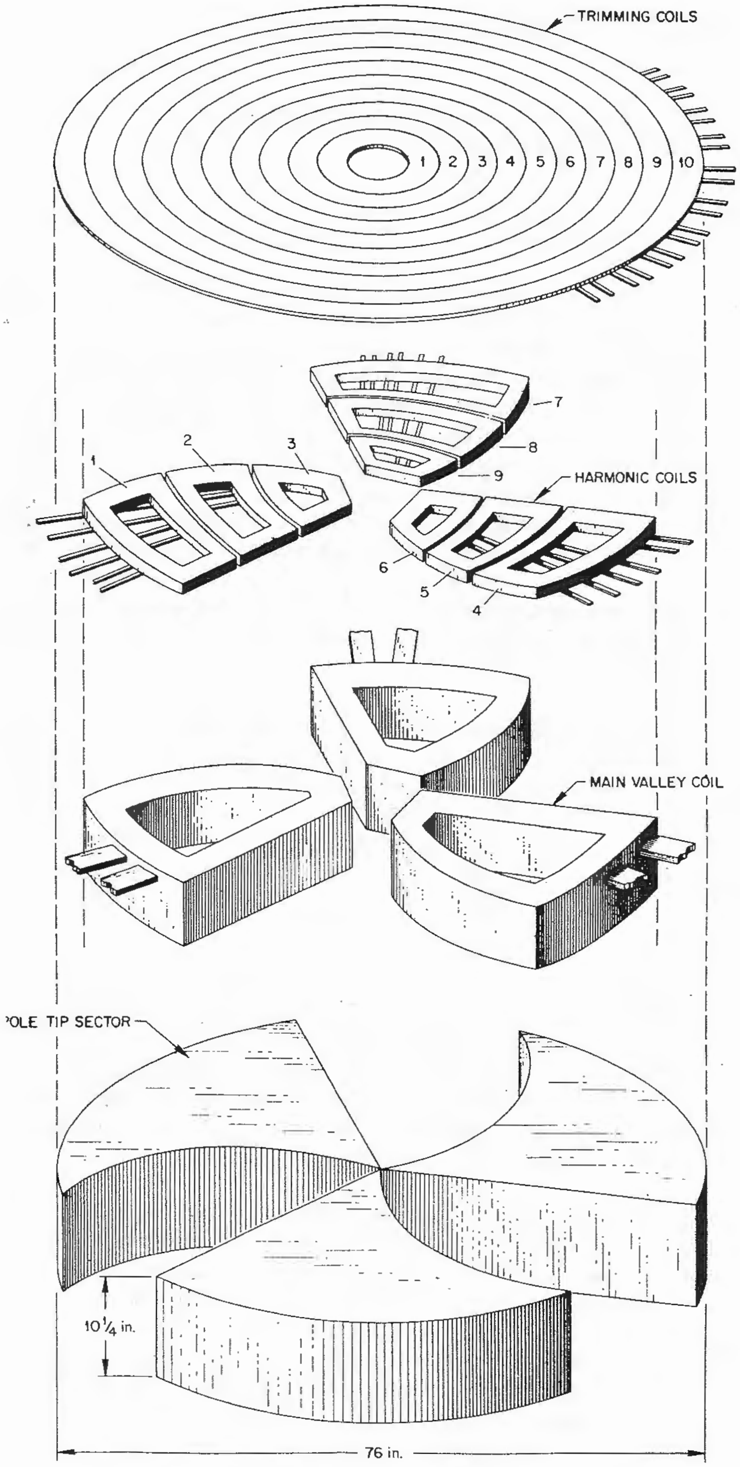


Fig. 5 - Exploded view of a pole tip with coils

A sequence of interlocks and automatic valves will allow remote removal and handling of the ion source, in case of a malfunction, in order that a new one might be installed without a waiting period for the induced radioactivity in the material of the ion source to diminish.

The source and probe enter the accelerating chamber on the horizontal center line on the opposite side from the dee stem.

RF SYSTEM

In the rf system, only a single dee of 180 degrees, shown in Fig. 6 (ORNL Drawing No. 2-02-015-810), is used for simplicity and mechanical convenience. The dee stem and liner are shaped to achieve minimum rf current densities and minimum excitation power, the excitation power being in the range from 60 to 360 kw, depending on circulating beam current and magnetic field. Coarse tuning of the resonant quarter-wave coaxial transmission line of the dee stem, over the range 7.5 to 22.5 Mc/sec, is achieved by a movable shorting mechanism of circular cross section, making contact to the inner and outer conductors through a series of "spiders" as illustrated in Fig. 6. A period of approximately five minutes is required to change the shorting mechanism from one end of its range to the other. Fine tuning is achieved by trimming condensers along each side of the dee.

The three-to-one frequency range, together with change in the operating mode from one-to-three rf cycles per revolution of the ions, permits covering a theoretical energy range of 81 to 1.

The power amplifier, utilizing an RCA-6949 tube, has its plate voltage controlled at the power supply, resulting in regulation of the dee voltage to about one part in 10^3. The peak rf voltage will be 100 kv, giving an energy gain of 200 kev per revolution. The frequency of the accelerating voltage is controlled to about one part in 10^6 by an oscillator located in the console. The simultaneous tuning of the various amplifier stages and resonator will be performed automatically.

BEAM EXTRACTION

The design for the beam extraction mechanism for the ORIC has not been completed. However, preliminary studies have been made of two conventional systems. One system consists of an electrostatic deflector channel combined with (or followed by) a magnetic channel. The other system consists of an electrostatic deflector channel followed by an electrostatic inflector channel. Graphical analysis of particle trajectories has been made for both systems, and both have been shown to be feasible.

However, a more sophisticated system, the so-called regenerative, or resonant, system using a magnetic spike near the extraction radius shows promise of simplifying the beam extraction and retaining beam quality during extraction. IBM-704 programs have been developed to evaluate all systems, and studies are under way. The beam quality for sector focusing cyclotrons is expected to be much higher than it is for conventional cyclotrons. The "beam brightness," defined as the number of particles per cm^2-steradian of angular spread, of conventional cyclotrons is poorer than Van de Graaff beams by a factor of about 10^3. The beam energy spread, defined as $\Delta E/E$, of conventional cyclotrons is about a factor of 10 poorer than that for Van de Graaff accelerators, giving an overall beam quality about 10^4 poorer than for Van de Graaff accelerators. It is anticipated that the beam quality for the ORIC will be a factor of 10^2 to 10^4 better than for conventional cyclotrons, thus bringing its beam quality within the range of Van de Graaff beams.

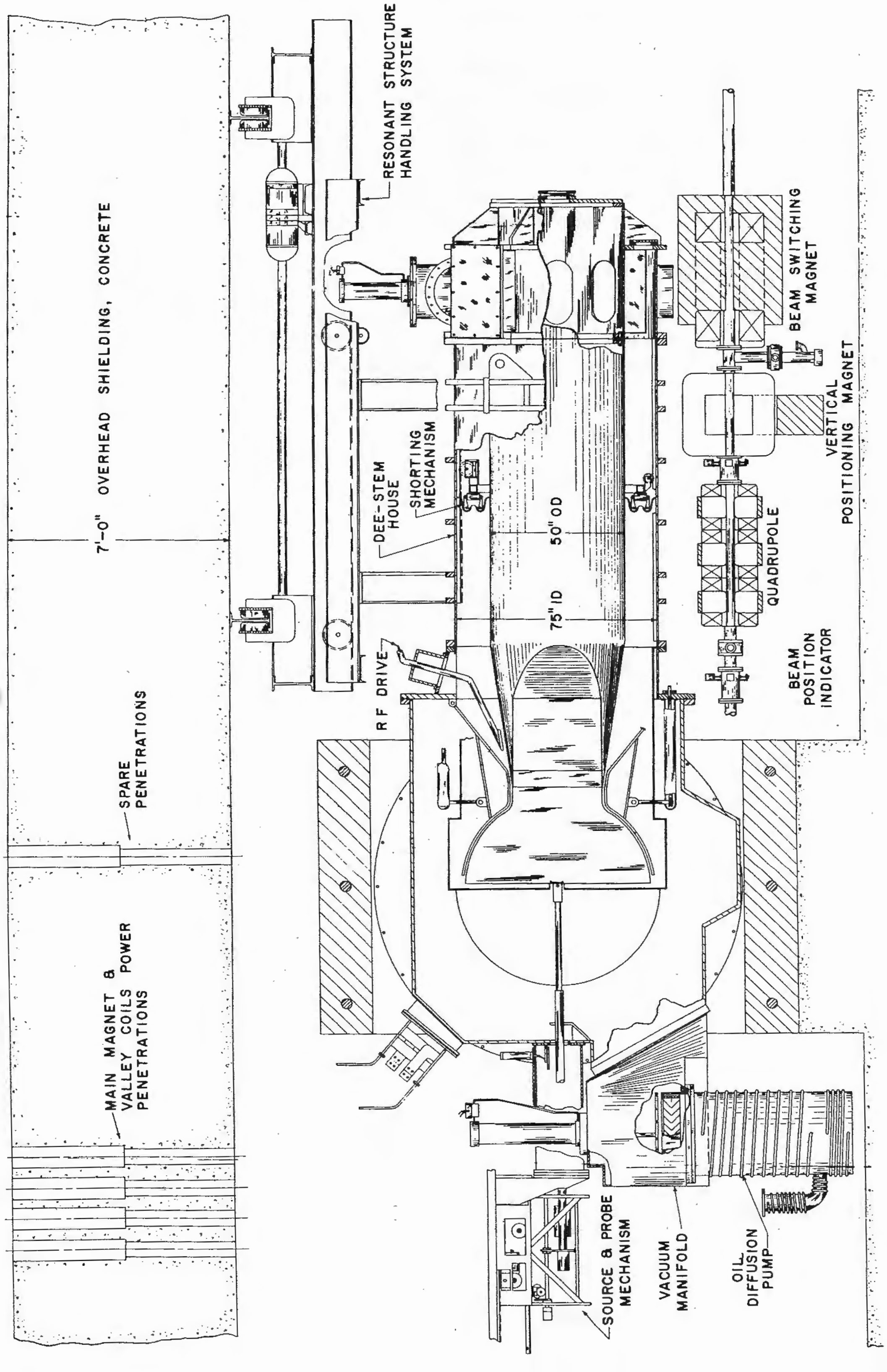


Fig. 6 - Vertical section through the ORIC, showing overhead shielding, method of supporting dee stem and house, and initial beam handling equipment

BEAM FOCUSING AND ANALYZING SYSTEM

The beam will be extracted near the bottom of the magnet gap, and go under the dee stem, as depicted in Fig. 6, toward the energy analyzing magnet and beam switching magnets. The beam is first focused by a magnetic quadrupole lens, then positioned and made horizontal by one (or perhaps two) vertical positioning magnet, and is then deflected by a beam switching magnet. In the total beam handling system, there are four beam switching magnets, whose function is to enable the experimenter to direct the beam to any one of several locations where a particular experiment is being conducted.

The analyzing magnet is of the double focusing type and deflects the beam through an angle of 135 degrees, precisely defining the beam energy. The resolving power of the analyzing magnet is adjustable, with a maximum value of at least 4000. The maximum Bρ (product of magnetic field strength and particle orbit radius) of the magnet is about 1400 kgauss-cm. The complete ion optics diagram is shown in Fig. 7.

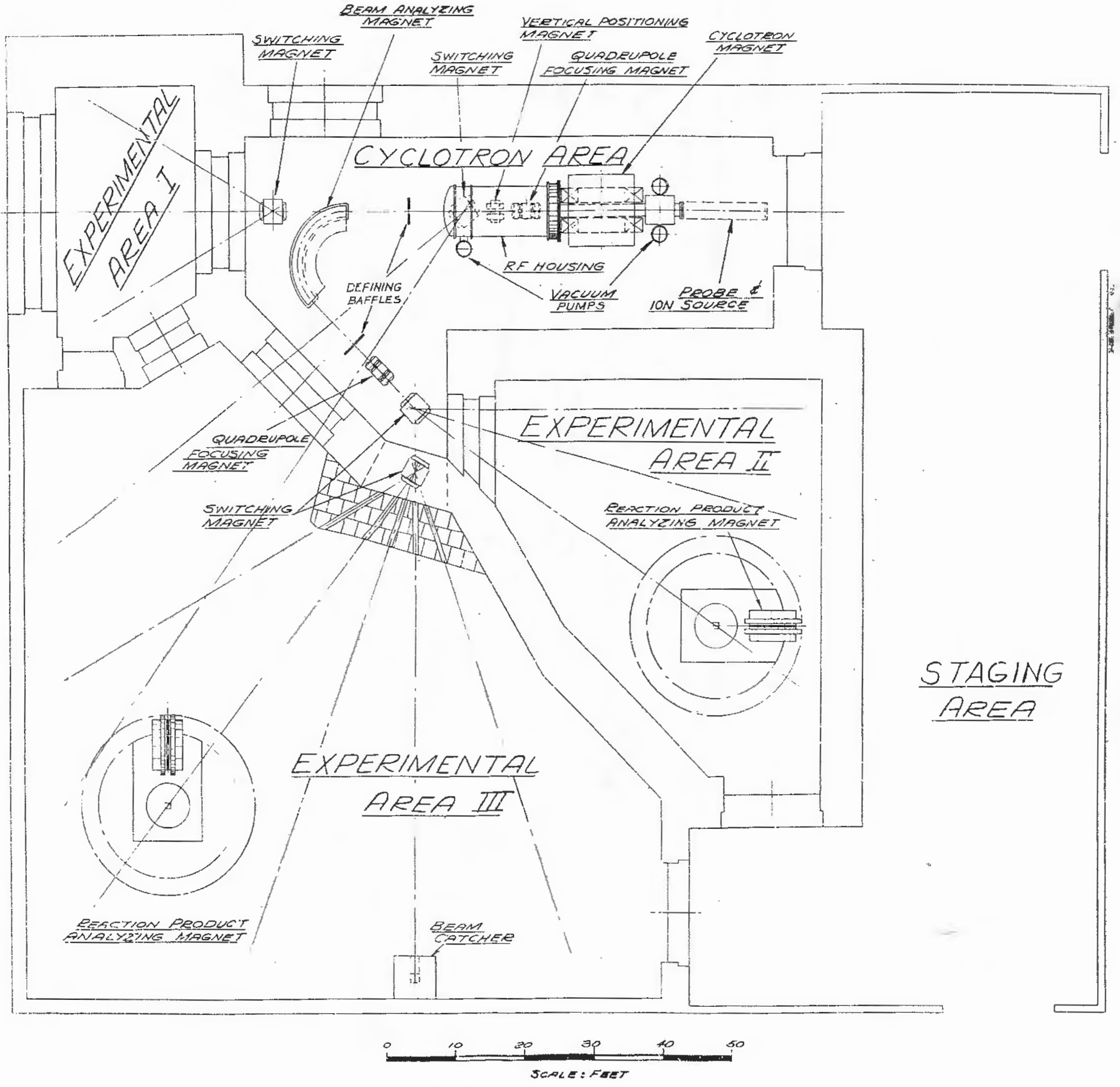


Fig. 7 - Ion optics arrangement

SUMMARY OF DESIGN CHARACTERISTICS

Magnet Data

Material	Cyclotron analysis steel
Magnet orientation	Vertical pole faces
Magnet field configuration	3 sector, weak spiral
Magnet core diameter	76 in.
Magnet pole tip diameter	76 in.
Beam radius, average max.	31.5 in.
Magnet gap, hill	7.5 in.
Magnet gap, valley	28.0 in.
Magnet field, max. average	17 kgauss
Magnet field, max. hill	22 kgauss
Magnet field, min. valley for max. hill	5 kgauss
Magnet field rise with radius, max.	8%
Magnet weight	208 tons
Magnet height	15 ft

Main Coils

Material	Copper
Weight	27 tons
Ampere-turns, max.	1.23×10^6
Total current, max.	3838 amperes
Current density	2113 amperes/in.^{2}
Total turns	640
Form factor	0.60
Turns, axial/coil	16
Turns, radial/coil	20
Total resistance	0.043 ohm
Total power, max.	631 kw
Cooling source	water

Auxiliary Coils

Valley coils, copper (total)	3 pairs
Number turns (each)	48
Current, max. (each)	5000 amperes
Power, max. (used only for 75-Mev protons)	900 kw

Harmonic coils, copper (total)	9 pairs
Number turns (each)	24
Current, max. (each)	200 amperes
Power, max. (total)	27 kw
Trimming coils, copper (total)	10 pairs
Number turns (each)	1
Core thickness (per pole piece)	0.5 in.
Current, max. (each)	500-1200 amperes
Power, max. (total)	160 kw

Vacuum System

Total volume	700 ft^3
High-vacuum pumps	Two 32-in. oil diffusion One 20-in. oil diffusion
Baffles	Refrigerated Freon
Cold trap	NRL type
Pressure in accelerating region	$\leqq 3 \times 10^{-6}$ tor

RF System

Number of dees	1
Angle of dee	180^{0}
Dee diameter	70 in.
Dee aperture	1.87 in.
Dee walls	11/32 in.
Liner aperture	5.75 in.
Liner walls	11/32 in.
Dee-to-liner clearance	1.59 in.
Power amplifier tube	RCA 6949
Power amplifier input power, max.	500 kw
Power amplifier output power, max.	360 kw
Frequency	7.5 to 22.5 Mc/sec
As 3rd and 5th harmonics	1.5 to 7.5 Mc/sec
Frequency instability	1 part in 10^6
Peak dee voltage	100 kv
Dee voltage instability	1 part in 10^3
Energy gain/revolution (protons)	200 kev

Beam Data

Ion source	Hot cathode
Type particle	Selectable
Particle energy	Adjustable
Beam current	Adjustable
Proton energy range	7-75 Mev
Proton current range	0-1 ma
Shielding	7 ft ordinary concrete
Beam extraction method	Regenerative and electrostatic
Resolving power, analyzing magnet, max.	4000

Power Requirements

Total, max.	2300 kw

CHAPTER 3

EXPERIMENTAL APPARATUS

In order to initiate a program of research with the proposed accelerator, it will be necessary to have certain foreseeable experimental apparatus of a very general and versatile nature. Although the development of experimental apparatus is undergoing a period of rapid change in many areas, one can reasonably estimate the type of equipment which will be necessary on the basis of present experience.

REACTION PARTICLE SPECTROMETER

A reaction particle spectrometer will be required for much of the proposed work in the field of nuclear spectroscopy as well as to assist in the study of gross structure of nuclei and the mechanism of nuclear interactions. Even though nuclear radiation detectors have undergone many recent improvements, the magnetic spectrometer remains the most accurate device for the energy determination of charged particles emitted from nuclear reactions. This precise energy analysis is required for the resolution of particle groups emitted from many of the individual levels of various target nuclei.

LARGE REACTION CHAMBER

Many experiments require a vacuum environment for elimination of air scattering effects. The design specifications of the proposed vacuum system will allow the enclosure of different arrays of detectors about the target area with a great degree of flexibility. Such a system will be necessary in many of the correlation and polarization experiments which have been proposed. Also, the measurement of the angular distribution of charged particles emitted from nuclear reactions as well as the relative yield curves can be accomplished with this facility.

DATA PROCESSING SYSTEM

For efficient utilization of the proposed research facilities it will be necessary to employ a small data processing computer and associated equipment for the purpose of reducing and performing preliminary analysis of data. Because of the vast amount of information which must be handled and the increasing complexity of many experiments, it will be often necessary to feed the data directly into the computer and to allow the computer to analyze these data during the process of accumulation. The information gained during a particular experimental run may dictate the future direction of the experiment or indicate faulty apparatus which can be repaired before accumulating large quantities of worthless data. Consequently, in order to eliminate costly delays in the operation of the cyclotron, it will be necessary to have a data processing system conveniently available and immediately accessible.

LARGE MULTICHANNEL PULSE HEIGHT ANALYZERS

The scintillation spectroscopy necessary in many nuclear experiments require the use of large multichannel analyzers. Improved techniques for performing time correlation measurements using time-to-pulse-height converters also demand a large number of channels. For simultaneous instrumentation of more than one experimental group, it is proposed that two 256-channel pulse height analyzers be provided.

SMALL FAST MULTICHANNEL PULSE HEIGHT ANALYZERS

In many experiments it is not possible to utilize the large multichannel analyzers due to their rather slow analysis time. In such cases it is necessary to use one or more fast, small-capacity multichannel analyzers. These analyzers are important for correlation-type experiments in which the rate of individual events is very large while the rate of coincidences is very small.

TARGET PREPARATION SYSTEMS

One of the major problems in many experiments is the preparation of ultra-high-purity targets of proper thickness made with very costly separated isotopes. Special and rather elaborate systems have to be frequently developed for each type of target. The equipment for the initial program will include high capacity evaporators, a vacuum manifold, an ultraclean electrodeposition system, a high temperature oven, and precision rollers.

SUPPORTING ELECTRONIC EQUIPMENT

Various other types of electronic apparatus will be required, such as amplifiers, power supplies, scalers, oscilloscopes, current integrators, coincidence circuits, time-to-pulse-height converters, and test equipment. Also included in this classification are scintillation crystals and their associated multiplier phototubes.

NEUTRON EXPERIMENTAL APPARATUS

To support the program in neutron physics, some special equipment is required. This will include gas target assemblies, heavily shielded and collimated detectors, and associated electronic equipment.

CHAPTER 4

BUILDING AND SITE

SHIELDING CONSIDERATIONS

For the type of accelerator being proposed, the problem of the suppression of the escaping radiation by means of shielding is dominated by the fast neutron production; that is, any shielding which is adequate to contain fast neutrons will be more than enough to suppress the slow neutrons and secondary gamma radiation coming from various parts of the cyclotron during its operation.

The proposed NRL sector focusing cyclotron is designed to deliver up to one milliampere of 75-Mev protons. The data of Crandall and Milburn (UCRL Report 4931) show a yield of about one fast neutron for four 75-Mev protons striking a thick target of high atomic number, for example, tungsten. Since one milliampere corresponds to 6.25×10^{17} protons/second, a one-milliampere beam of 75-Mev protons will produce a point source of about 1.5×10^{15} fast neutrons per second.

For cost and ease of construction, the most practical material for radiation shielding is ordinary structural concrete. Assuming an isotropic distribution of neutrons, if the distance between the source of 10^{15} fast neutrons per second and the nearest concrete wall is 10 feet, the neutron flux at the surface of the wall is 10^{9} fast neutrons per square centimeter per second. Also, if a broad, slab-type geometry is assumed for the shielding, the effective attenuation coefficient for ordinary structural concrete as a function of neutron energy is well known. For 14-Mev neutrons, the effective removal coefficient is 2.6 ft^{-1} Therefore, if 10^{9} fast neutrons per square centimeter per second are impinging on an ordinary structural concrete wall which is 7 ft thick, the neutron flux will be reduced by a factor of about 4×10^{8} , leaving an escaping flux of approximately 2 neutrons per square centimeter per second, which is less than the allowed biological dose to radiation workers. For a 40-hour week, the maximum permissible fast neutron dose for radiation workers is 10 neutrons per square centimeter per second, which corresponds to approximately 2.5 millirem per hour of gamma radiation.

Several assumptions that are not altogether correct were made in the foregoing statements. First, the distribution of neutrons from the target will not be isotropic but will be peaked in the forward direction. Furthermore, in certain instances the effective source, i.e., the beam stopper, could be closer to a wall than 10 feet. Therefore, localized intensities, higher than those cited, are possible. In these cases, the positioning of suitable amounts of portable shielding, for example, layers of iron or concrete, in the immediate neighborhood of the radiation source, becomes much more practical.

Second, fast neutrons with energies greater than 14 Mev, though fewer in number, will certainly be produced. For example, consider a one milliampere beam of 24-Mev deuterons striking a thick beryllium target. The total yield of neutrons will be approximately 1.85×10^{14} neutrons per second in a point source. This is a factor of 10 lower than the source cited earlier in this section; however, a considerable portion of the high energy neutron yield is in the forward direction. Nevertheless, it is concluded that the calculated shielding is adequate because the maximum of the neutron yield curve for this reaction occurs at about 3.5 Mev and drops off very rapidly with increasing energy.

For many experiments, full beam power of the accelerator will not be required, in which case the neutron intensities will be lower.

BUILDING SITE

Several factors are important in the choice of a site for the cyclotron. The first factor is the very nature of the building itself. The massive concrete walls that are required to keep the radiation level safe necessitate ground or footings which will support loadings the order of 4000 lb/sq ft. Second, the building must be isolated because of radiological safety and also possible interference with other experimental areas in the Laboratory.

The wall thicknesses have been calculated to reduce the neutron and gamma ray fluxes to well below that specified as tolerable for radiation workers. Nevertheless, it is recommended that the accelerator housing be located in an area which is relatively remote from other buildings; certainly no closer than 50 feet so that the radiation dose is lower than that acceptable to the general populace.

The escaping fluxes, though of low level and less than that specified for health tolerance, might still be high enough to interfere seriously with very low level counting experiments. The neutron flux intensity at 1000 feet from the proposed NRL sector focusing cyclotron is calculated to be one-tenth that from normal cosmic ray background; therefore, the cyclotron building should be at least 1000 feet from the nearest building which houses low level counting experiments, such as many experiments carried on by workers with radioactive tracers.

In view of the restrictions set forth for the site, it appears most unlikely that a building to house the proposed high intensity cyclotron could be accommodated within the present grounds of the Laboratory. A possible site, which fulfills the requirements previously set forth, is shown in Fig. 8.

In the sense of the aforementioned, the proposed site is isolated; yet, the remainder of the Laboratory will be accessible to it. Furthermore, the virgin ground will support the load without extensive use of pilings. (It is estimated by NRL's Public Works Division that at a cost of about $2700 per piling, the increase in price for putting the proposed building on unstable or filled ground would amount to $1 million for pilings alone.)

THE CYCLOTRON BUILDING

The floor plan of the proposed building, shown in Figs. 9 through 13, has been made consistent with the radiation levels, the needs of the research program, and the characteristics of the cyclotron. In addition to the thick concrete walls required to keep the radiation level from the cyclotron vault itself at a low value, it is necessary that the experimental areas, too, be adequately shielded since the intense ion beam is to be admitted to these areas. Since the experiments to be done with this machine are varied and complex, it is necessary that not only the cyclotron vault itself, but also the experimental areas be carefully planned so as to make the most efficient use of the accelerator.

Accelerator Room

It can be seen in Figs. 6 and 7 that the cyclotron requires a floor space of approximately 34 x 14 feet and is almost 18 feet high. The particle beam from the cyclotron must be focused, energy-analyzed, and directed into the experimental areas by means of steering magnets which comprise the ion optics system. Naturally, the high intensity beam will strike various parts of this system, thereby producing high intensity secondary radiations

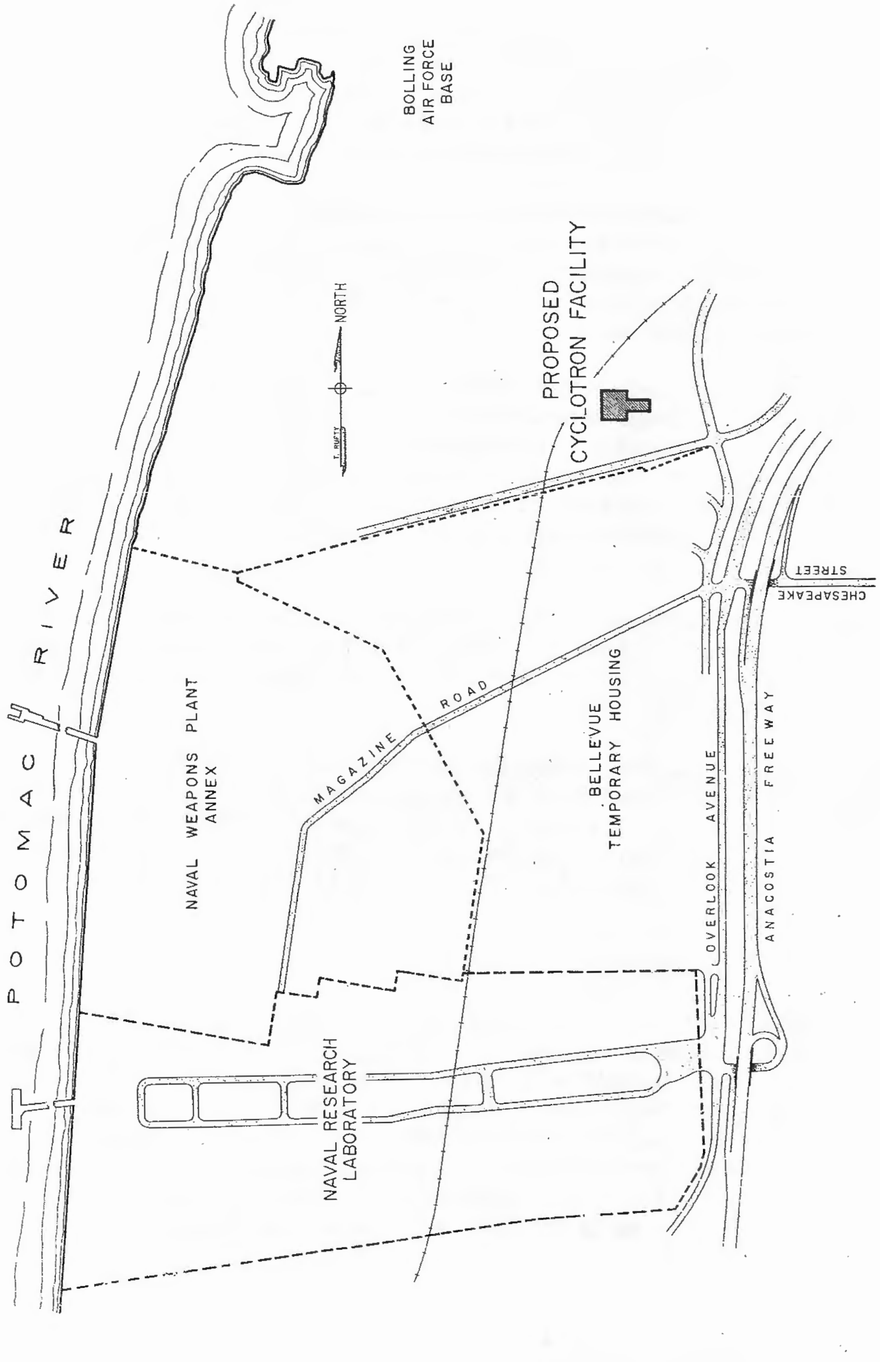


Fig. 8 - Building site

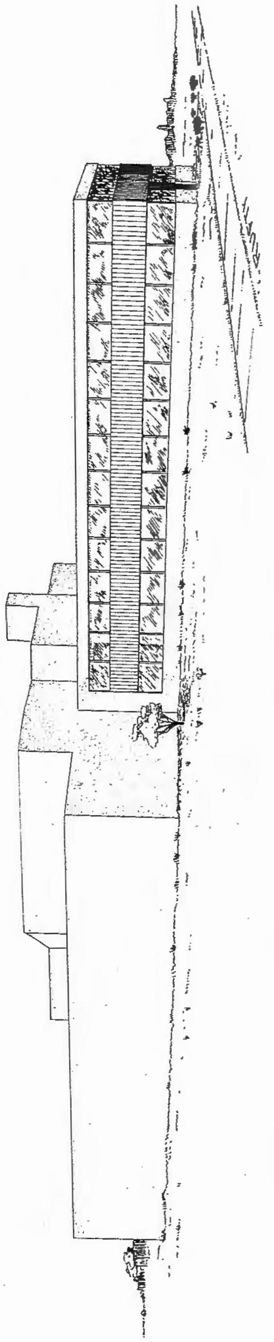


Fig. 9 - Artist's sketch of building

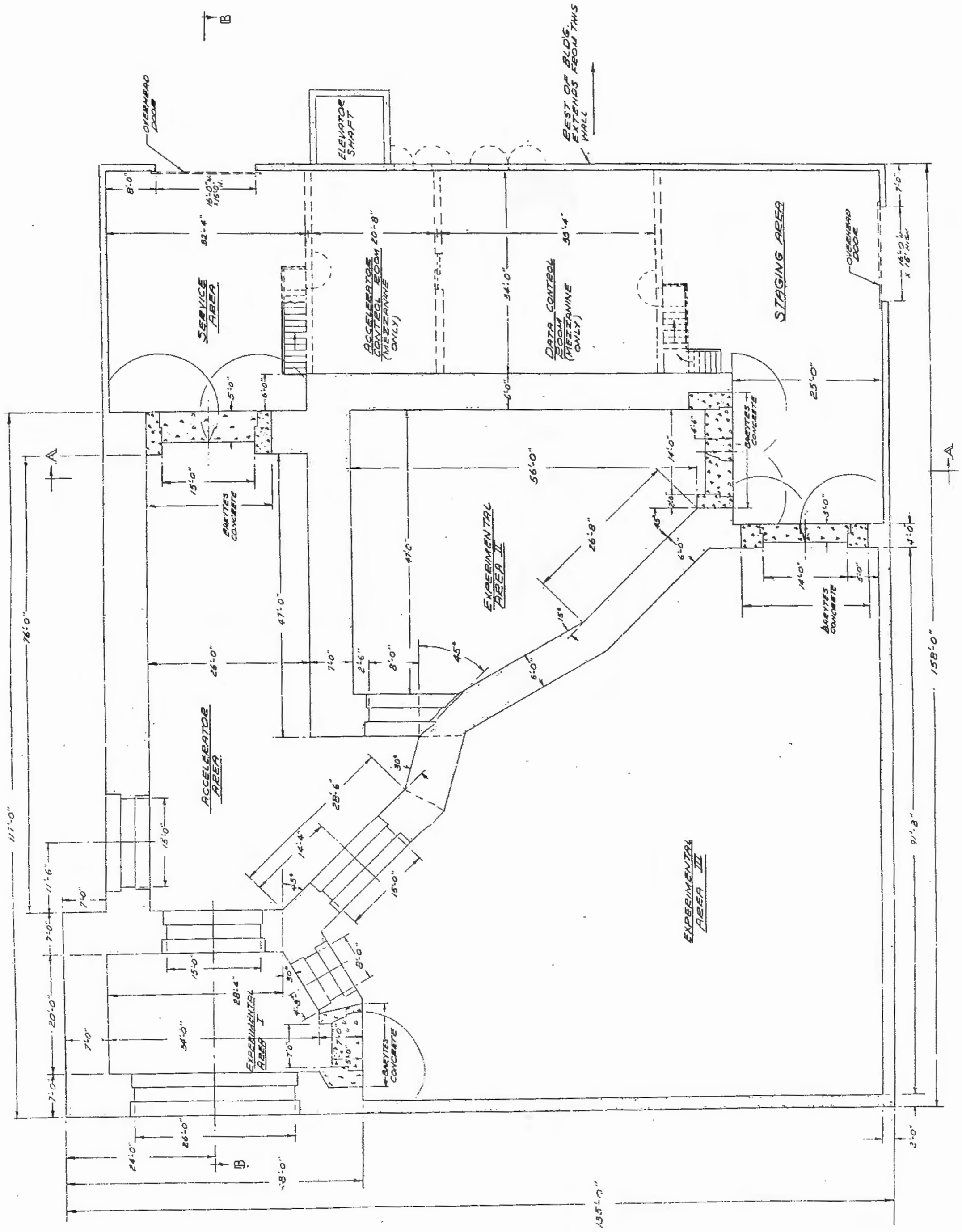
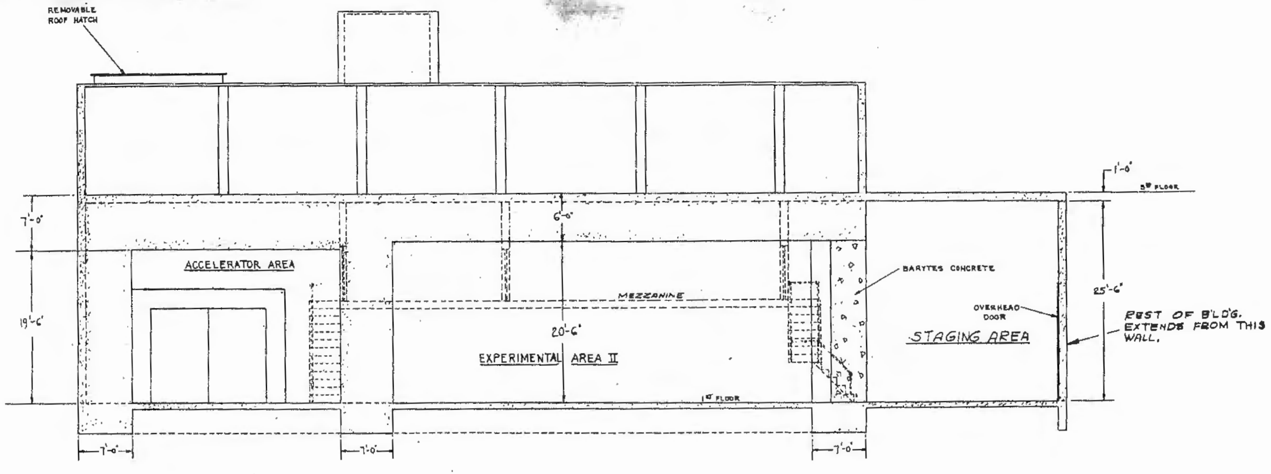
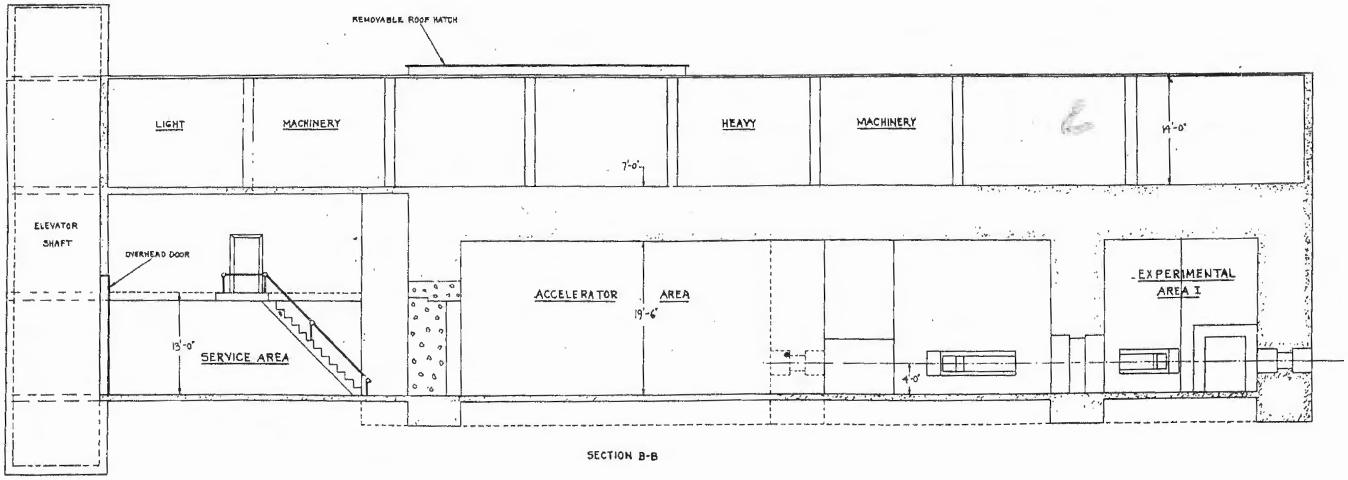


Fig. 10 - First floor and mezzanine of experimental wing, section through 4-ft level



SECTION A-A



SECTION B-B

Fig. 11 - Vertical sections of experimental wing. (Locations of sections A-A and B-B are shown in the previous figure.)

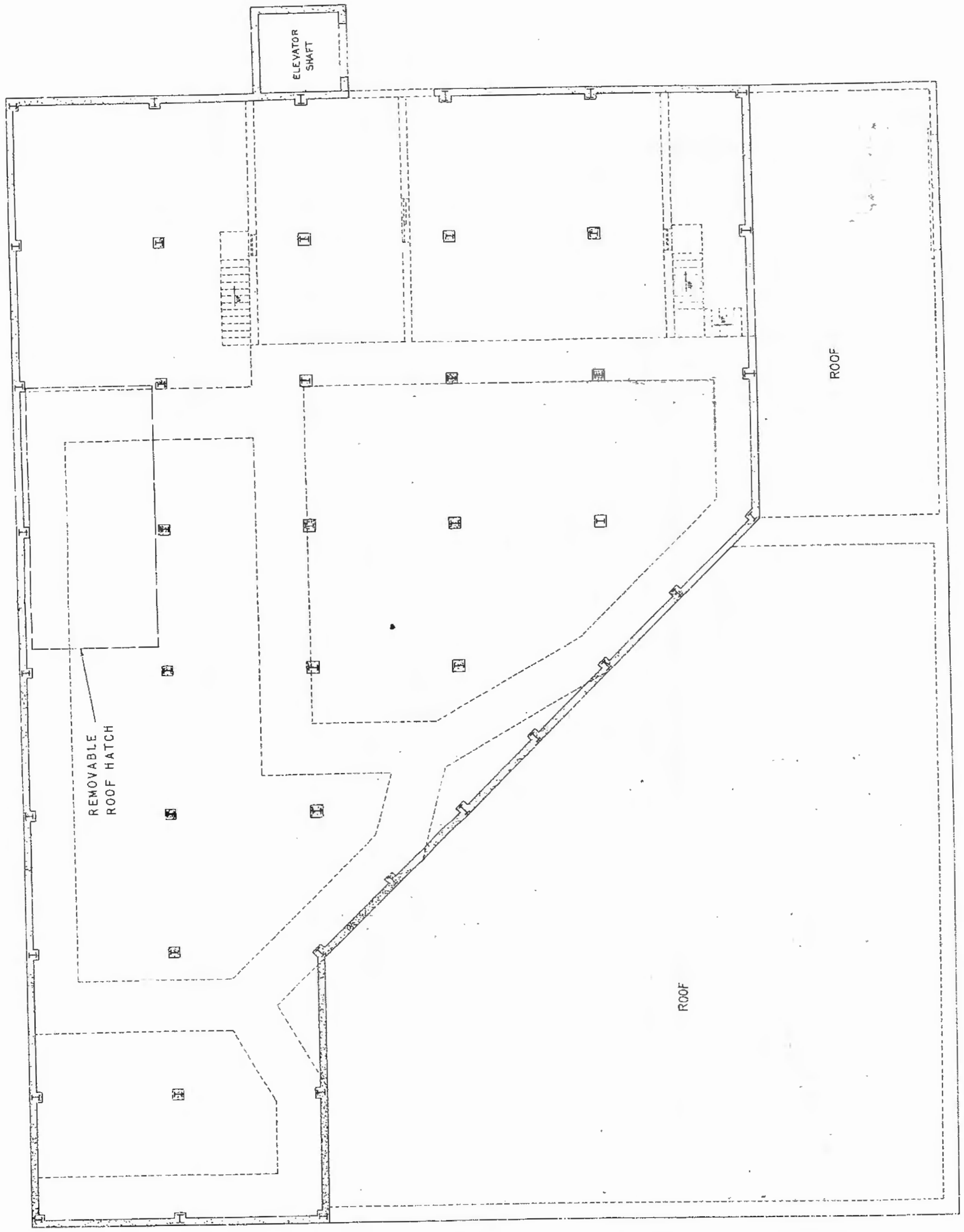


Fig. 12 - Third floor plan of experimental wing

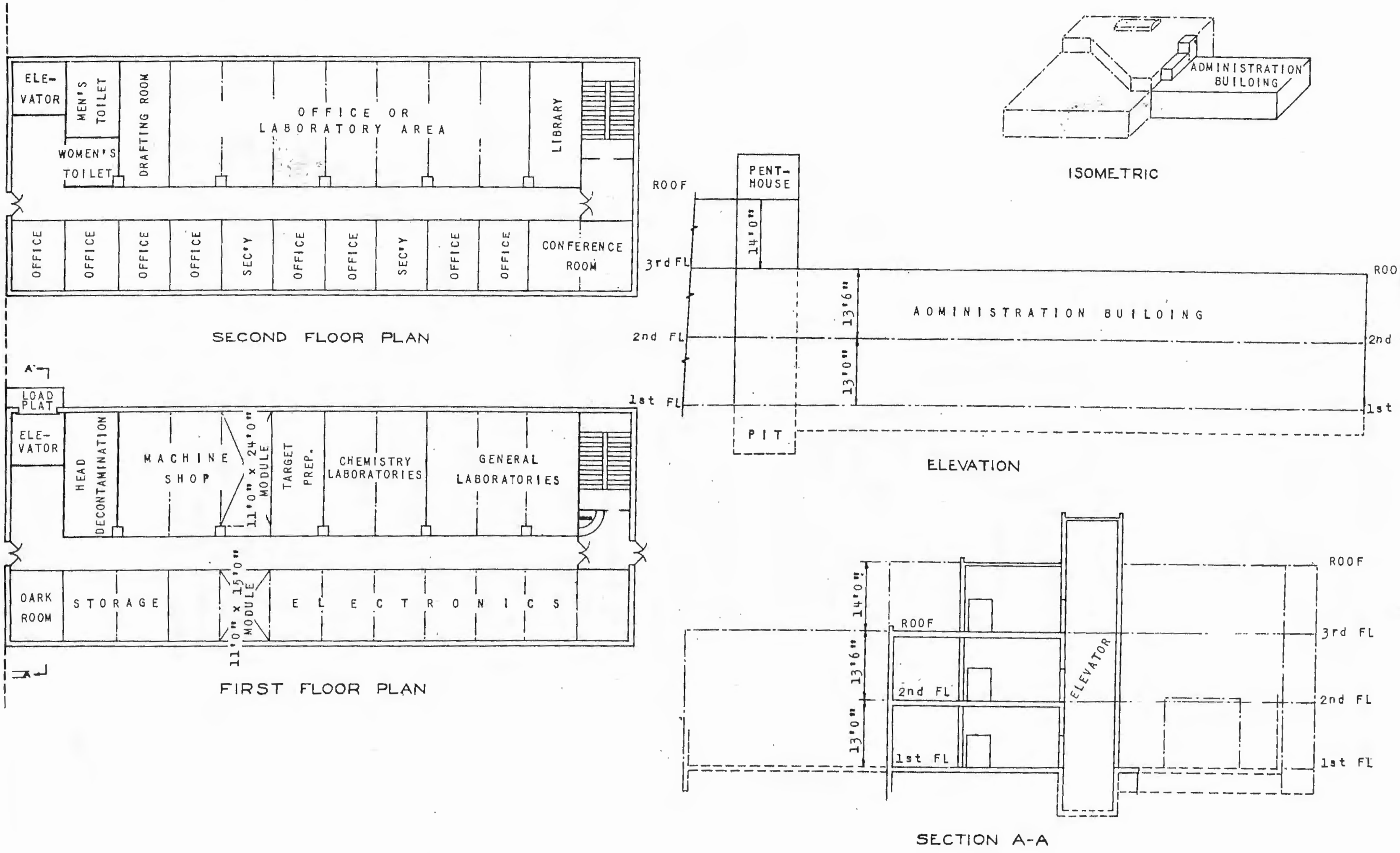


Fig. 13 - Administration wing floor plan and vertical section (laboratories and offices)

which would grossly interfere with the experiments in progress. Therefore, it is necessary that at least a portion of the ion optics system be contained within the cyclotron vault proper which has walls and ceiling 7 feet thick. It can be seen in Fig. 7 that the ion optics system has been arranged to provide minimum path lengths in the cyclotron vault consistent with adequate space and geometry in the experimental areas in order to minimize the amount of concrete shielding required.

Experimental Areas

It is essential that the experimenter have time enough to set up, align, and test thoroughly all experimental apparatus before taking data. Some of this equipment is necessarily very heavy, not counting the associated, complicated electronic equipment. Therefore, this testing must be carried on in the same room and in the same position where the actual experiment will be performed. At least three separate, well-shielded experimental rooms are needed. This arrangement will allow experiments to be performed in one room while preparations for subsequent experiments are being carried on in the other two. By adjusting the fields of the switching or steering magnets, the cyclotron operator can direct the beam into any one of the three experimental areas. The exact beam paths used will be chosen to fit the particular experiment in progress and the apparatus required. To allow for the flexibility desired, ports to admit the beam from one room to another, consisting of holes in the concrete walls, are specified in the building design. Except for the actual volume of the holes which carry the evacuated beam tubes, clearance around the tubes will be filled either with water or shielding blocks in order to minimize the leakage of radiation from the rooms. The three experimental areas are shown in Figs. 7 and 10.

Experimental Area I has been designed to accept the straight-through or only-slightly-deflected beam. This area is for very high intensity experiments where good energy analysis of the beam is not important. In this area, production of short-lived isotopes can take place; thermal shock studies, solid state studies, and radiation damage studies can also be done here. Because there will be little loss in beam intensity upon the beam's introduction into this room, the shielding is necessarily heavy. Since the type of experiments to be performed here does not require the large experimental equipment used in the more precise work carried on in Areas II and III, Area I is smaller than the other two.

Experimental Area II accepts only the highly analyzed beam and is shielded for high intensity experiments. Because of the loss of at least one order of magnitude of beam intensity in the energy analysis of the beam, this area requires only 6-foot-thick shielding. The higher precision experiments performed here frequently require large apparatus, such as the reaction product analyzing magnet shown in Fig. 7. Furthermore, more than one experiment of the type to be performed in this area can be set up at the same time. Area II is moderately large to accommodate double-scattering experiments and the large and complex apparatus mentioned earlier.

Experimental Area III has walls of only 2-foot thickness to accommodate those experiments not utilizing the full beam intensity or energy. An increasingly useful technique for energy measurement of a particle is the measurement of its time of flight. A large room is needed to accommodate this type of experiment in order to insure sufficiently long time intervals and in order to reduce background created by radiation scattered from the walls. Also, other experiments whose equipment requires a large amount of floor space can be performed here.

Staging Area

Experimental Area II is too small to accommodate permanently all the apparatus that will be used in it. In many cases it will be desirable to use a specific piece of apparatus for experiments in either Area II or Area III. Furthermore, while an experiment is being performed in Area III, it is desirable that the technical staff have the space, well shielded from radiation, in which to set up and test various experimental systems. Accordingly, a staging area is provided to service both Areas II and III. In this staging area, experimental apparatus can be made ready for rapid transfer into the appropriate beam positions in the experimental areas as soon as possible after cessation of bombardment in those areas.

Machine Service Area

Space must be allowed for the removal, adjustment, and repair of the cyclotron dee system, beam probe, extraction system, and ion source. Therefore, an accelerator service area is provided. Delivery access to this area is provided by a large overhead door to connect the room with the main loading platform.

Control Rooms

The cyclotron control and data rooms have been placed together on a relatively small mezzanine since it is desirable that the experimenter and accelerator operator be able to communicate visually. The area beneath these rooms provides staging space requiring less than 12-foot clearance.

Third Floor

In Figs. 11 and 12 is shown the third floor, which provides space for the mechanical and electrical equipment associated with the cyclotron. The areas over the 6- and 7-foot-thick ceilings will be used for the heaviest equipment, such as transformers, power supplies, pumps, and air-conditioning equipment. The region over the staging area will be used for lighter machinery and storage. Most of the aforementioned equipment can be raised to the third floor by means of the indicated freight elevator; however, for the installation of the heaviest and largest equipment, a removable hatch is specified for the roof.

Special Accesses

In addition to the personnel and equipment accesses shown in the figures, several special types of accesses are required for utilities, ventilating and vacuum pumping pipes, electrical control cables, pipes for circulating cooling water to the cyclotron magnet and rf system and the analyzing and switching magnets, and emergency exhaust outlets. Because ordinary feedthroughs would allow unacceptable neutron and gamma-ray leakage, special precautions must be taken to see that water lines go through the concrete walls at an oblique angle such that the length of water in the wall has the equivalent shielding effect of 7 feet of concrete and to see that all other feeds are curved in such a manner that any straight line drawn through the wall or ceiling would intercept at least 6 feet of concrete.

Laboratories and Offices

The general laboratory and office portion of the cyclotron facility is shown in Fig. 13 and follows as much as possible the modular concept that is to be employed by NRL in future construction. Offices and laboratories for the operating and scientific staffs are provided. Also included are a machine shop, electronic shops, decontamination showers, darkroom, conference room, reception room and control point, and a target preparation room.

Access to the freight elevator, control mezzanine, and staging area is provided. The floor-to-floor height of these rooms is such that rolling equipment may be moved from the conventional portion of the building into the specialized areas.

Miscellaneous

Although not shown in these preliminary figures, a water cooling tower which will handle about two megawatts is provided to dissipate the heat generated in the magnets and the rf system. The tower can be installed on the roof or at a site detached from the building.

Sufficient air conditioning is provided to maintain the building at 75° F and 50 percent relative humidity throughout the year.

All standard utilities are provided except that the main electrical feeds into the facility must provide up to three megawatts of power.

CHAPTER 5

CONSTRUCTION SCHEDULE AND PERSONNEL REQUIRED DURING CONSTRUCTION

It is anticipated that the building and cyclotron will be built and completed within two years from the time the project is authorized. This estimate is based on the experience of the groups at the Oak Ridge National Laboratory and the Lawrence Radiation Laboratory and is consistent with the estimate by the Public Works Division at NRL for the building and site. It is estimated that cyclotron- and beam-alignment, installation of beam handling equipment, and installation of experimental apparatus will be completed within one year following completion of the building. Thus, it is expected that the experimental research program utilizing the cyclotron would be initiated within three years following authorization of the project.

Since it is planned that practically all construction and fabrication work will be let out on contract with commercial firms, the number of NRL personnel involved in the project during the construction phase (first two years) will be as follows:

Physicists, 3 man-years/year

Scientific division engineer, 1 man-year/year

Public Works personnel, 1-1/2 man-years/year

Engineering Services personnel, 2 man-years/year.

During the third year, when the cyclotron and beam will be aligned and the beam handling equipment and experimental apparatus will be installed, the cyclotron group should be near its permanent strength (see Chapter 7) because these functions will be performed by the same people who will be performing and supporting the experimental research program.

CHAPTER 6

ESTIMATED COST OF RESEARCH FACILITY

CYCLOTRON

The cost estimate in this section for the cyclotron proper was prepared by William M. Brobeck and Associates, Oakland, California.

Magnet (76-inch Pole Diameter)		
Magnet core blocks 415,000 lb steel @ .30	$125,000	
Bolts, dowels, brackets, etc.	5,000	
Jacking system	3,000	
Main exciting coil (copper) 54,000 lb @ 3.50	189,000	
Magnet installation 470,000 lb @ .06	28,000	
		$ 350,000
Vacuum Tank		
Aluminum tank and magnet Coil enclosure 9,600 lb @ 3.75	$ 36,000	
Resonator tank, heads and dee stem	34,000	
Misc. covers, supports, etc.	10,000	
		80,000
Vacuum Pumping System		
Two 32-inch pumps and accessories	$ 19,500	
One 20-inch pump and accessories	7,000	
Mechanical pump	5,000	
Misc. piping and valves	7,000	
Freon refrigeration system	2,500	
		41,000
Dees, Liners, etc.		
Dee	$ 25,000	
Dee to stem transition	5,000	
Spider	20,000	
Coupling loop internal parts	2,500	
Stem tank to pole transition	5,000	
		$ 57,500

Auxiliary Magnet Windings		
Circular trimming coils and pole liner	$ 30,000	
Harmonic coils	5,000	
Valley coils 2,800 lb @ $5.00	14,000	
		$ 49,000
Miscellaneous Mechanical Parts		
RF tuner servo-drive	$ 10,000	
Beam probe and lock	10,000	
RF pickup probes	2,000	
Gas supply system	2,500	
Ion source and adjusting mechanism	18,000	
Target chamber	10,000	
Deflector	30,000	
Dee grid adjusting device	7,500	
RF transmission line	12,000	
		102,000
Cooling Water Distribution System (not including pumps, piping or exchangers)		
Flow switches, indicators, valves 60 circuits @ $100	$ 6,000	
Manifolds	1,500	
Piping at equipment	4,000	
		11,500
Magnet Power Supplies		
Main Coil Magnetic amplifier power supply, including switch gear installation, regulator, and wiring to magnet	$ 63,000	
Circular Trimming Coils 7 magnetic-amplifier power supplies (1,000 amperes each), 3 magnetic-amplifier power supplies (2,000 amperes each), including regulator and installation	88,500	
Valley Coils Magnetic-amplifier power supply, including dc switchgear, installation, and regulator	84,000	
Harmonic Coils 9 silicon rectifier power supplies including installation	27,000	
		$ 262,500

Auxiliary Coil Buses		
Water-cooled buses from auxiliary coil power supplies to coils, including vacuum seals through dee tank		$ 17,000
RF Power Equipment		
Power amplifier, with RCA 6949 tube	$ 38,500	
Master oscillator and driver amplifier	10,500	
Oscillator power supply	76,600	
Modulator, with RCA 5770 and 5771 tubes	10,400	
		136,000
Miscellaneous Power Supplies		
Ion source arc and filament supply	$ 2,700	
Deflector power supply (2) 120 kv @ 5 ma	10,800	
300V/150V regulated power supply for electronics	1,200	
Driver power supplies	3,000	
		17,700
Control and Low Power Electronic Equipment		
Equipment and racks 43 racks @ $2,400	$103,000	
Main control console (additional over standard racks)	1,500	
Control room wireways	13,000	
Control wiring	6,500	
Spare racks 10 @ $200	2,000	
		126,000
Total Cyclotron Components and Subassemblies		$1,250,200
General Assembly and Checkout		
Labor (not assignable to specific parts of the machine) 8,500 hours @ $7.00		59,500
Unallocated		
To provide for construction costs not included in above items 10% of total construction cost		145,500
Total Cyclotron Construction Cost (1960 prices)		$1,455,200
Accelerator Engineering		
Engineering and design services 15% of $1,455,200 construction costs	$218,300	
Full scale magnet testing labor	25,000	

Full scale magnet testing equipment	$ 50,000	
RF model testing, labor and equipment	25,000	
Construction supervision - 1-1/2 man-years	35,000	
Start-up supervision - 1 man-year	25,000	
Total Accelerator Engineering		$ 378,300
Total Construction Plus Engineering (1960 prices)		1,833,500
Escalation - 3 years @ 5% (15% of $1,833,500)		275,000
Contingency - 15% of $1,833,500		275,000
Total Cost - Cyclotron Plus Engineering		$ 2,383,500

If the Oak Ridge National Laboratory design is followed in detail and the ORNL drawings are made available, and if ORNL full scale magnetic testing equipment is made available complete in working condition, the following estimate shall apply:

Total Cyclotron Construction Cost (1960 prices)		$1,455,200
Accelerator Engineering		
Engineering and design services 5% of $1,455,200 construction costs	$ 72,800	
Full scale magnet testing labor	25,000	
Construction supervision - 1-1/2 man-years	35,000	
Start-up supervision - 1 man-year	25,000	
		157,800
Total Construction Plus Engineering		$1,613,000
Escalation - 15% of $1,613,000		242,000
Contingency - 15% of $1,613,000		242,000
Total Cost - Cyclotron Plus Engineering		$2,097,000

BEAM HANDLING EQUIPMENT

Beam deflector	$ 3,000	
Septum	300	
Magnetic channel	5,000	
Quadrupole focusing magnets (two)	4,400	
Power supplies for above (two)	12,400	
Vertical positioning magnet	12,800	
Power supply for above	10,200	
Beam energy analyzing magnet	46,500	
Power supply for above	11,800	
Beam switching magnets (four)	86,800	
Power supplies for above (two)	23,200	
Beam pipes	11,000	
Beam flaps (six)	3,000	
Beam port stoppers	4,000	
Beam position indicators (two)	1,000	
TOTAL COST		$235,400

EXPERIMENTAL APPARATUS

Reaction particle spectrometer	$ 58,300	
Large reaction chamber	65,600	
Data processing system	93,000	
Large multichannel pulse height analyzers	27,900	
Small fast multichannel pulse height analyzers	29,280	
Target preparation system	15,300	
Supporting electronic equipment	150,000	
Neutron experimental apparatus	47,000	
TOTAL COST		$486,380

BUILDING

Cyclotron Building First Floor

Excavation: footings and floor slabs approximately 2,000 cubic yards @ $5 per cubic yard (includes backfilling)	$ 10,000	
Reinforced concrete footings and first floor slab (in place), approximately 2,000 cubic yards of concrete @ $60 per cubic yard	120,000	
Concrete walls, approximately 2,900 yards (in place) @ $60 per cubic yard	174,000	
6- and 7-ft concrete floors - 1,984 cu yd	119,000	
2-ft concrete floors - 248 cu yd	14,800	
6 inch concrete roof - 172 cu yd	10,320	
Structural steel	28,000	
Heavy density (barytes) concrete	60,000	
Roof construction at the first floor level	6,400	
Building utilities:		
Plumbing: water, gas, steam, and compressed air	76,000	
Electrical: receptacles and wiring for lighting and power	51,000	
Telephones	600	
Intercommunication system	720	
Outside utilities:		
Underground ducts, storm and sanitary sewers, gas mains, water supply, and fire hydrants	127,000	
Electrical substation (based on 4 megawatts) including negotiations with Potomac Electric Power Company	225,000	
Ventilation, heating, and air conditioning	200,000	
Four complete isotope storage wells @ $900 each	3,600	
Surveying (includes alignment of cyclotron, magnets, and analyzers)	2,400	
Approximately 1,000 lineal feet of chain link fencing with barbed wire, 8 ft high @ $5 per ft	5,000	
Development of access roadways and parking areas	5,000	
Architect and engineer fee @ 5 percent	62,000	
Subtotal A		$1,300,840

Includes profit, overhead, insurance, social security, and bond

Cyclotron Building Mezzanine

General construction cost: 2,000 sq ft @ $40 per sq ft	$ 80,000	
Subtotal B		$ 80,000

Cyclotron Building Third Floor

General construction cost, approximately 12,000 sq ft @ $12 per sq ft	$ 144,000	
Subtotal C		$144,000

Special Utilities

Heat exchanger, water pumps, cooling tower, and water demineralizer		
AC power and cooling water stubbed in to accelerator equipment locations		
DC power conduit runs to accelerator equipment locations		
Conduits and wireways for accelerator control and instrumentation		
Compressed air and hazardous gas systems		
AC power and cooling water stubbed in to research equipment locations		
DC power conduit runs to research equipment locations		
Conduits and wireways for research, equipment control and instrumentation		
Subtotal D		$160,000

General Laboratory and Administration Space

One freight elevator, three stories	$ 50,000	
Two-story, modular building with gross area of 14,880 sq ft @ $30 per sq ft	446,400	
Laboratory furniture, fume hoods, chemistry sinks	50,000	
Additional shielding as may be required for a low level counting room	16,500	
Subtotal E		$562,900

Special Handling Equipment

Radiation monitors	$ 30,000	
Airborne particulate monitors	25,000	
Vacuum cleaners and filters	10,000	
Boom lift truck, self-propelled	10,000	
Remote controlled mobile manipulator	65,000	
Subtotal F		$140,000

Engineering Services		
Analysis of bids		
General and contractor supervision and coordination		
Scheduling	$ 14,000	
Cost estimating	3,000	
Subtotal G		$ 17,000

Summation of totals		
Subtotal B	$ 80,000	
C	144,000	
D	160,000	
E	562,900	
F	140,000	
G	17,000	
Subtotal B through G		$1,103,900
Applicable architect and engineer fees	$ 22,320	
Subtotal H	$1,126,220	
Subtotal A	$1,300,840	
Subtotal A and H	$2,427,060	
Allow 10% project management cost	242,706	
TOTAL COST (Building and Site)		$2,669,766

SUMMARY OF COSTS

The total estimated cost of the proposed research facility is stated below. The estimated cost of the cyclotron contains an escalation figure while the other costs do not. Because it is proposed that the ORNL design be followed closely, the lower figure for the cyclotron cost, given at the end of the first section is used.

Sector Focusing Cyclotron	$2,097,000
Beam Handling Equipment	235,400
Experimental Apparatus	486,380
Building and Utilities	2,669,766
Total Cost of Facility	$5,488,546

CHAPTER 7

RESEARCH SUPPORT LEVEL

As soon as the beam has been obtained from the accelerator, the research program can start. Because of the magnitude and the initial investment in this facility, it is recommended that a level of support be such that the research program can operate over an 80-hour week. No other sector focusing cyclotron group is planning less than 80 hours per week operation, and one group (Lawrence Radiation Laboratory) will operate on a 152-hour week.

For routine maintenance and operation, a staff of three is required for a given 40-hour week; thus, for 80-hour operation, a total operation staff of six is required. For similar operation the ORIC staff estimates 11 personnel; however, several of these are electricians and plumbers which at NRL would be drawn from Public Works Division.

It is recommended that the research staff consist of nine professional scientists and six supporting technicians. This number is less than that recommended by the ORIC group. However, it is anticipated that this staff will be supplemented by scientists from other groups located in the Laboratory who wish to use the research facility for specific programs. Based in part on the experience gained with the 5-Mv Van de Graaff Accelerator, it is estimated that the scientific staff of the cyclotron can handle three major programs, such as the study of nuclear interaction mechanisms, neutron physics, and nuclear structure. Each major research problem could be represented by five people, three of whom are nuclear physicists, one an electronic specialist, and the other member of the group a physical science aide. The preceding discussion is used to obtain an estimate of the degree of support required by a facility such as this cyclotron. It is recognized that experience might very well dictate a different distribution of personnel, and depending on the outside interest in problems utilizing the cyclotron, could very well demand an expansion of the support staff.

It is recommended that the secretarial staff consist of at least three people, two of whom would be of secretary status and the third a clerk-typist. One member of the secretarial staff could serve as building receptionist at the control point.

There should be at least two full-time machinists employed in the machine-tool shop located in the cyclotron building. In addition, at least one full-time draftsman will be required.

Summarizing the preceding we see that the building population would be 27 persons; three would be Engineering Services Division personnel, three secretarial, six accelerator maintenance and operation, nine professional scientists, and six supporting technicians.

In addition to the building population, a number of other individual scientists and groups at NRL would be interested in the occasional use of the accelerator facility or in the experimental results obtained with it. It is anticipated that the program of research with the accelerator facility would stimulate the interest of nuclear physicists at NRL other than those formally attached to the accelerator group. For example, several theorists would probably collaborate on a part-time basis with the experimentalists in the cyclotron group. A reasonable estimate would be three theorists, part time, one interested primarily in the results of each of the three experimental programs mentioned.

As discussed in Chapter 1, the accelerator is highly suitable for certain types of experiments in solid state physics and also for many types of radiochemistry experiments not feasible with other types of accelerators. (One of the principal uses of the sector focusing cyclotron at the Lawrence Radiation Laboratory will be in the field of the transuranic elements.) Therefore it is expected that such an accelerator would allow the scope of the research programs of the Solid State Division, the Chemistry Division, and others to be broadened.

It is anticipated that groups from other Department of Defense laboratories and from universities will occasionally wish to make use of the accelerator facility. In particular, such groups might be biophysicists, radio biologists, or university colleagues of the NRL nuclear physicists. Such collaborations in the past with the NRL Van de Graaff accelerators have been very fruitful.

It is estimated by the NRL Budget Branch that the annual budget required to support the proposed facility and research program is $530,000.00, exclusive of major procurements.

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APPENDIX A

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