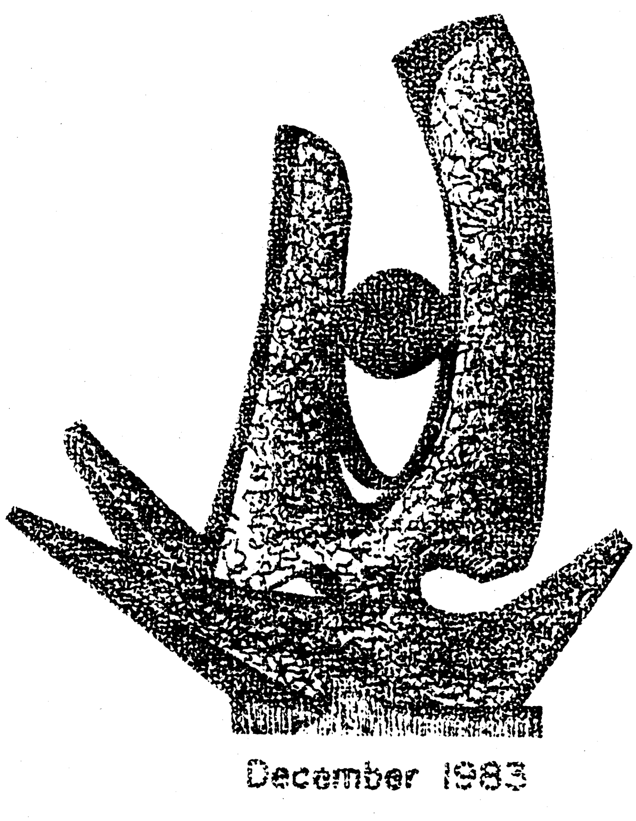
MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

Proposal to Construct a Superconducting Cyclotron System for the Radiation Oncology Center of Harper Grace Hospitals



December 1983

MSUCL-440

PROPOSAL TO HARPER-GRACE HOSPITALS

REQUESTING FUNDING FOR A JOINT PROJECT TO CONSTRUCT

A SUPERCONDUCTING CYCLOTRON SYSTEM

TO PROVIDE

A NEUTRON THERAPY MODALITY

FOR

CLINICAL RADIATION ONCOLOGY APPLICATIONS

FROM

NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY

OF MICHIGAN STATE UNIVERSITY

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I. INTRODUCTION

Approximately one-half of U.S. cancer patients are treated via radiation therapy, the procedure sometimes being used alone and sometimes being used in conjunction with other treatment modalities, such as surgery or chemotherapy. Most present radiation therapy treatment protocols utilize electromagnetic radiation (photons) as the interactive mechanism for affecting human tissue. The photons are derived either from radioactive materials, such as cobalt or radium, or from electron linear accelerators in the form of target x-rays. (A few protocols also involve direct treatment with electron beams from the linear accelerators.) Alternate therapy modalities in which the impact on tissue is derived from protons, neutrons, pi mesons, and heavy ions have been used in exploratory situations. The results of these explorations establish neutron therapy as a likely technique for accomplishing a broad improvement in treatment effectiveness relative to techniques presently in use.

The neutron therapy explorations are, in more detail, generally viewed as establishing a very dramatic improvement in treatment effectiveness for a few types of cancer and modest improvements for a much broader spectrum of cancer types. The neutron results are moreover achieved in the face of a very significant technical handicap in that the facilities used for neutron treatments do not for the most part allow the treatments to be administered with a level of treatment planning sophistication at all comparable to that normally utilized with photon facilities. In spite of this significant handicap, neutrons have done at least as well as photons in every circumstance in which they have been tried. There is thus the implication that further advantage for neutrons, relative to photons, will develop when facilities are available which allow treatment planning at a level of sophistication comparable to that in use for photons.

A major impediment to the further exploration of the effectiveness of neutrons as an alternate cancer therapy modality is the cost of currently available commerical units. Specifically commercial neutron therapy equipment, in a configuration regarded as appropriate for modern treatment planning, involves an expenditure approximately double that required for the best photon equipment. As a consequence neutron studies to date in this country have been largely performed in physics laboratories, although several modern hospital units are just now at the point of starting up, the expense of these units being largely handled through grants from the National Cancer Institute.

Recently a major new breakthrough in cyclotron technology has occured, namely the use of superconducting coils to provide the excitation for the cyclotron magnet. Using these techniques cyclotrons can be constructed at a cost which is one-third to one-half of the cost of a cyclotron of the same energy built with room-temperature coils. Superconducting cyclotrons are also more compact and the overall weight is typically only one-quarter or one-fifth of that of a corresponding room temperature cyclotron. The approach of using a superconducting cyclotron as the neutron source for a hospital based neutron therapy system then promises to bring the price of such systems down to a level approximately equal to that of the better, presently used, photon systems. In addition the superconducting cyclotron neutron therapy unit is both more compact and lighter than a neutron therapy unit based on room temperature cyclotron technology. Given that Michigan State University is a leading center for development of superconducting cyclotrons and that Harper-Grace Hospitals is a leading radiation therapy center we herewith propose to Harper-Grace a joint program for design, construction and testing of a neutron therapy system using a superconducting cyclotron.

Details of the technical aspects of the facility and a proposed work plan are given in Sections II and III of this proposal. Briefly, the MSU role in the proposed project is 1) to make available techniques and know-how relative to the design and construction of superconducting cyclotrons, 2) to make available the equipment and facilities of MSU's National Superconducting Cyclotron Laboratory and 3) to provide management responsibility and technical direction for the project. The Harper-Grace role involves 1) providing a technical team to perform the bulk of the actual design, fabrication and testing work on the project (under the direction of the MSU project leader) and 2) providing funding for all costs associated with the project, including costs of services performed by MSU personnel. (The later will consist mostly of management and procurement work plus a small technical assistance component in situations involving sensitive equipment or critical skills.) All use of MSU facilities and all work by MSU personnel for the project will be in all circumstances subject to the stipulation that the work not interfere with the on-going major

National Science Foundation programs at the National Superconducting Cyclotron Laboratory.

Briefly the proposed plan of work involves:

1) Preparation of design drawings and specifications by the Harper technical team with some use of special MSU facilities where needed.

2) Manufacturing of components by commerical vendors based on procurement contracts negotiated and administered by the NSCL purchasing department.

3) Delivery of components to NSCL.

4) Assembly of components by the Harper technical team with assistance from NSCL personnel in critical or sensitive functions, such as use of heavy lifting equipment, connections to the helium refrigerator, etc.

5) Magnet testing by the Harper technical team, first, operating the magnet and mapping the magnetic field to insure conformance with cyclotron requirements, then testing the ability of the gantry system to move the magnet to the various locations required by therapy protocols and verifying that these motions do not change the shape of the field.

6) Testing of the cyclotron radio frequency system by the technical team to insure that the system operates at the required frequency and that it will produce the design dee voltage.

7) (When tests 5) and 6) have been completed) testing of the accelerated beam . For these tests the ion source will be activated and a test beam will be accelerated to a partial radius such that beam intensity requirements can be verified without producing harmful levels of ionizing radiation.

8) Brief full energy testing, performed by clearing an appropriate area so that radiation exposure to personnel will not exceed allowed levels, or alternatively, if a temperary shielding hut can be erected, without interfering with the ongoing NSF-NSCL program, a longer full energy test will be performed.

9) Disassembly and shipping. Upon completion of the testing phase, components will be disassembled, crated, and conveyed to the respective parties in accord with arrangements described in section IV of this proposal.

This proposal asks Harper-Grace to provide a technical group with appropriate qualifications and to provide full cost reimbursement for all work by MSU personnel and for all procurements made by MSU for use in the program, including fringe benefits and overhead where applicable, all of the above in accord with established MSU procedures for research grants. MSU will make available technical knowhow, space in the Cyclotron Laboratory, and use of the specialized facilities of the Laboratory, such as diagnostic equipment, measuring devices, etc, all such use subject to the condition that the medical cyclotron program not interfere with the ongoing NSF sponsored programs of the National Superconducting Cyclotron Laboratory.

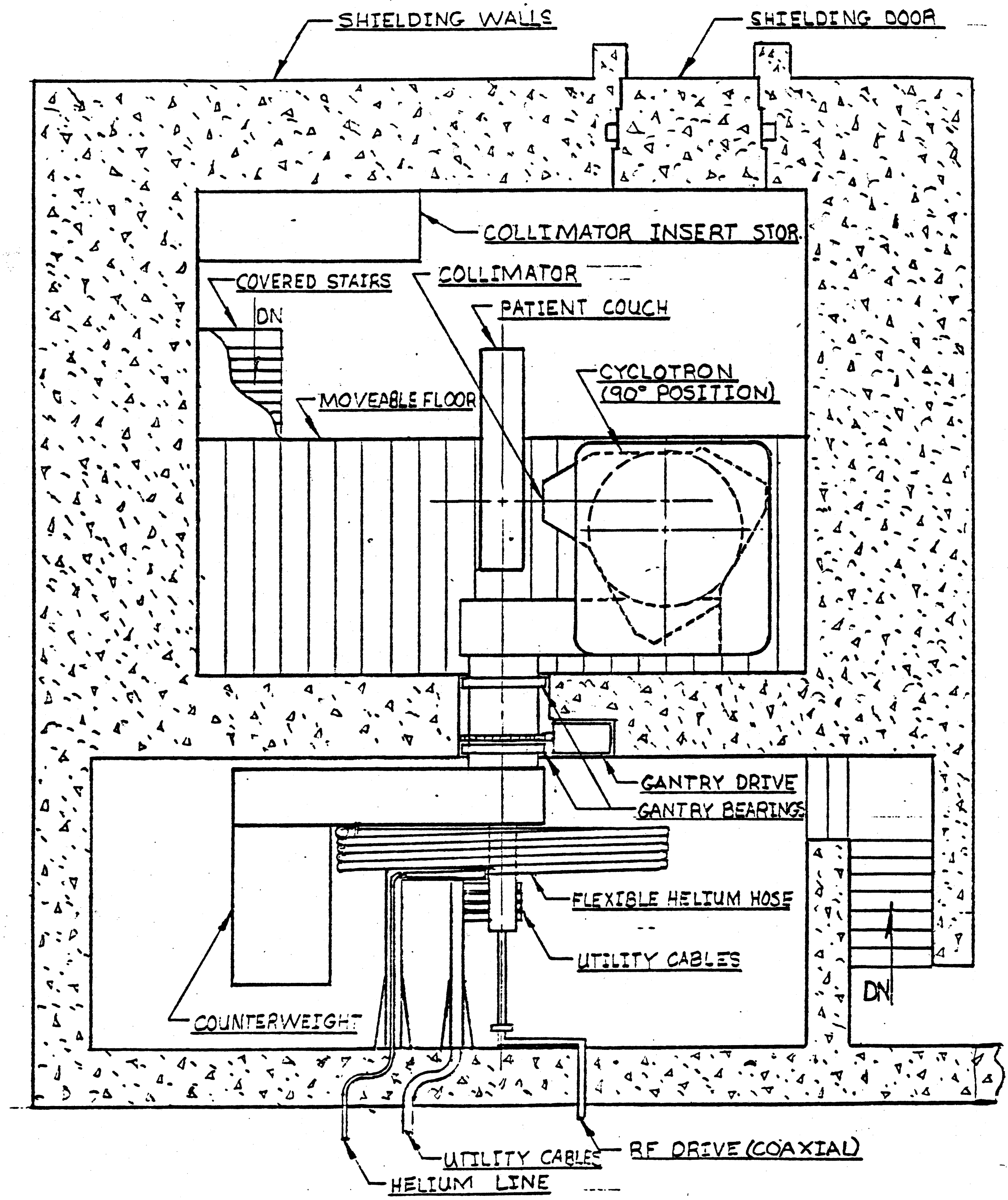
Results of the program will be published and/or patented by the group of investigators with appropriate indication of the joint Harper, MSU sponsorship and of the essential underlying role of the NSF program. The program objective is to definitively establish the feasibility of a low cost neutron-therapy unit based on the NSF/MSU developed superconducting cyclotron technology. Upon completion of the program the cyclotron unit will be transfered to Harper Hospital and put into use in an actual therapy program thus leading to an improvement in treatment procedures in one of the largest U.S. Radiation Oncology Centers.

II. TECHNICAL DESCRIPTION OF THE NEUTRON THERAPY SYSTEM

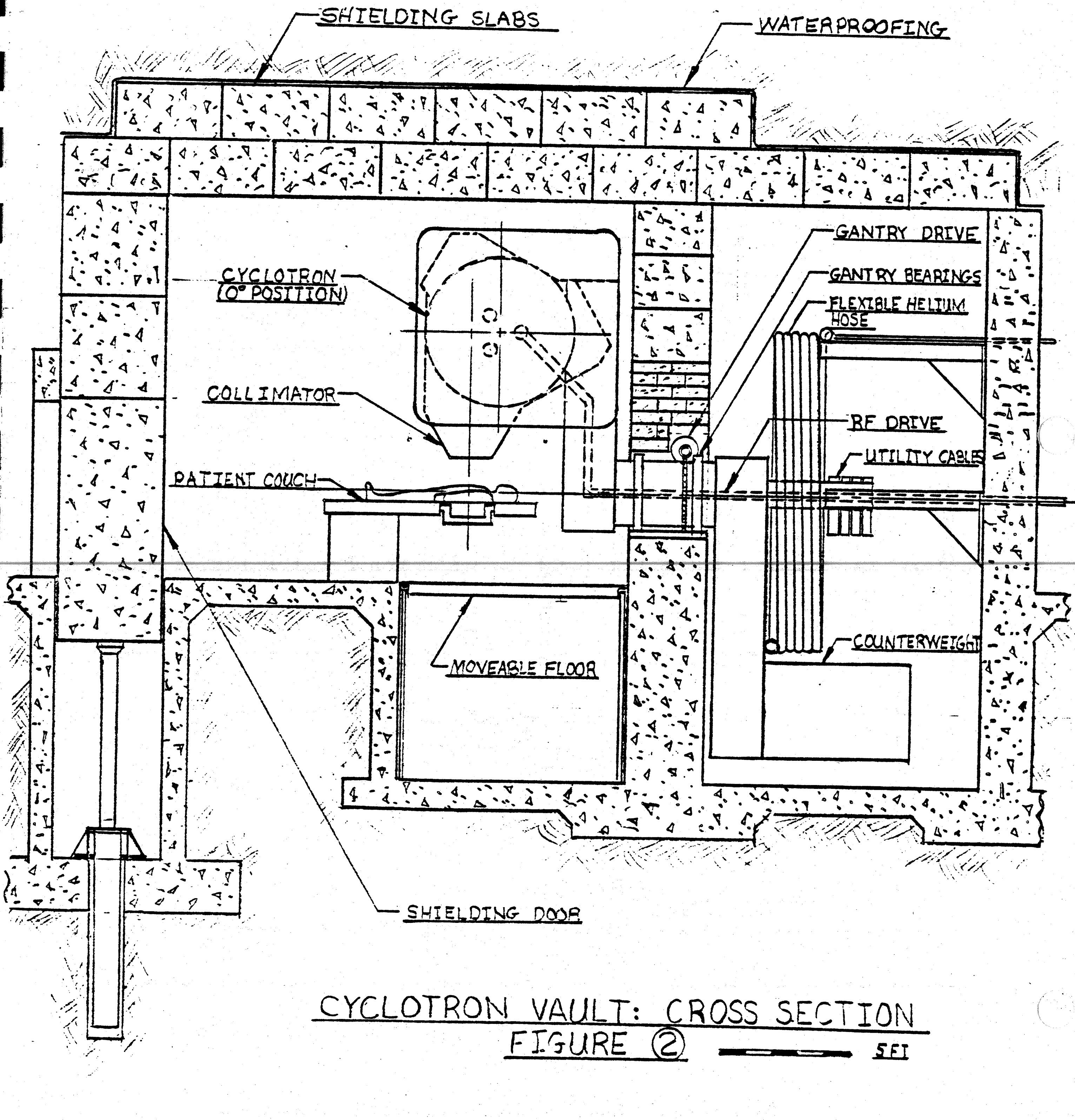
The proposed neutron therapy system will consist of a 50 MeV deuteron cyclotron mounted with a matching counterweight on a "bicycle crank" type support system. This support system moves the neutron source (the cyclotron's internal target) in a 144 inch, 355 degree circle with respect to the axis of the bicycle crank. (Neutron source 183cm from the system isocenter.) The arrangement includes a neutron collimator holder and a set of collimators of various sizes and appropriate space for later installation of an adjustable patient table to accurately position tumourous tissue at the system isocenter.

The cyclotron will be of the superconducting type and will operate at a magnetic field of 4.6 tesla and an rf frequency of 105 MHz. Utilities will feed to the cycloton through a custom designed helical system which allows the coil of cables to wind up or unwind as the cyclotron rotates. Figures 1, 2, and 3 give overall plan, elevation, and end views of the cyclotron, gantry, and patient table system. These figures show the therapy system installed in a facility which utilizes a proprietary, moveable floor system (available from NorPac Engineering of Seattle, Wash.) to cover the pit below the patient table (the pit being required to provide space for the cyclotron as it moves below the patient).

A possible alternative floor system is shown in Fig. 4. In this arrangement a smaller, less expensive, moving floor rotates around the patient table. The motion of the floor is directly driven by the movement of the cyclotron thus eliminating the relatively expensive,



CYCLOTRON VAULT: PLAN VIEW
FIGURE (1)



CYCLOTRON VAULT: CROSS SECTION
FIGURE ②

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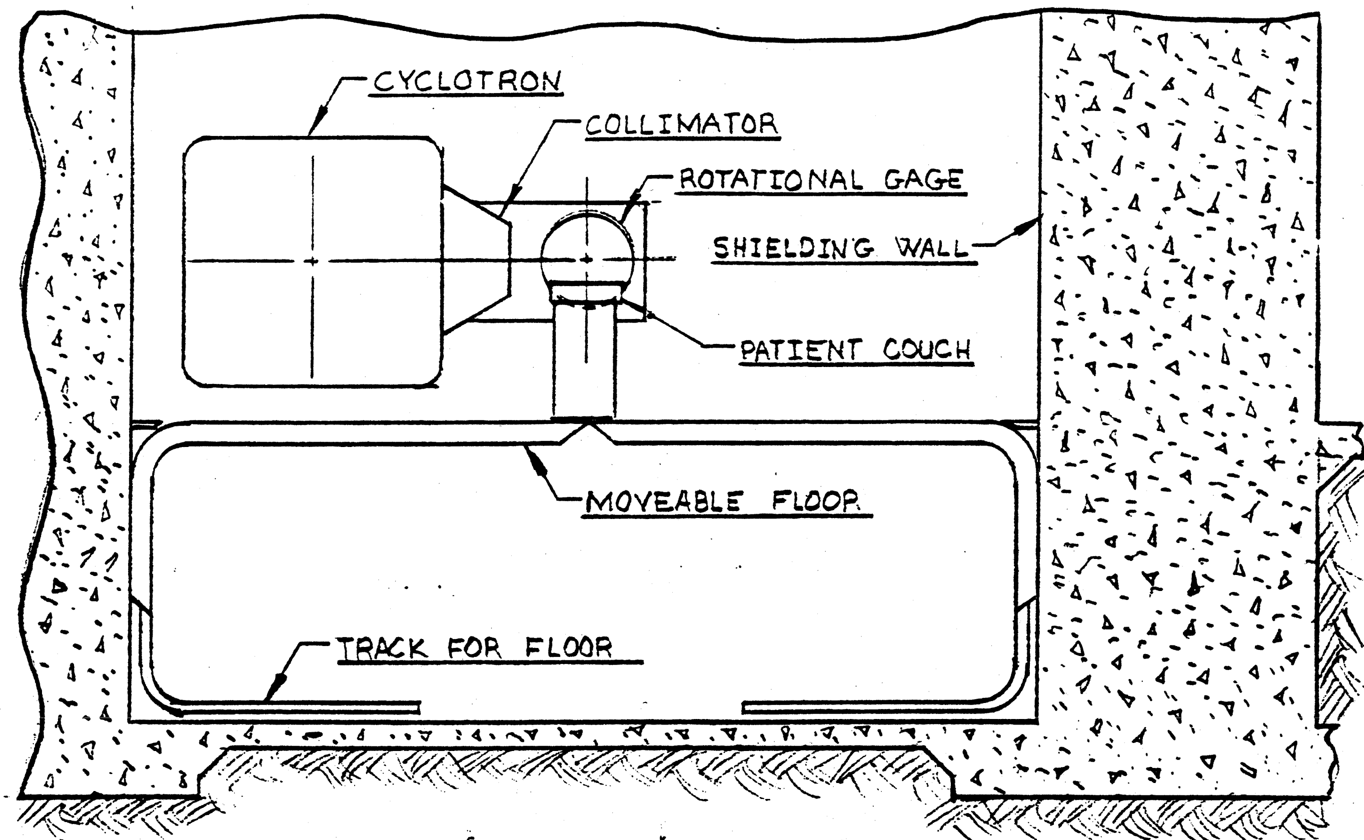


CYCLOTRON IN 90° POSITION

180° POSITION

-120° POSITION

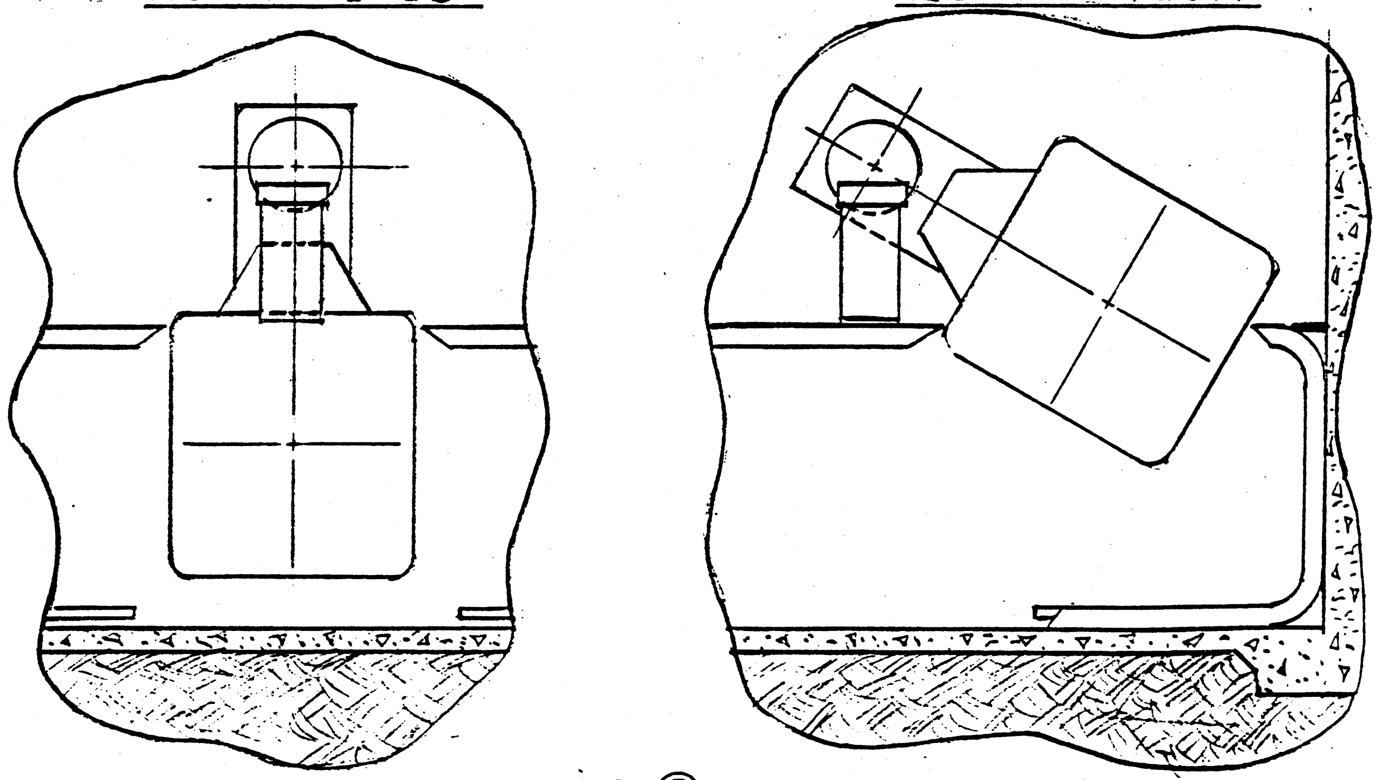
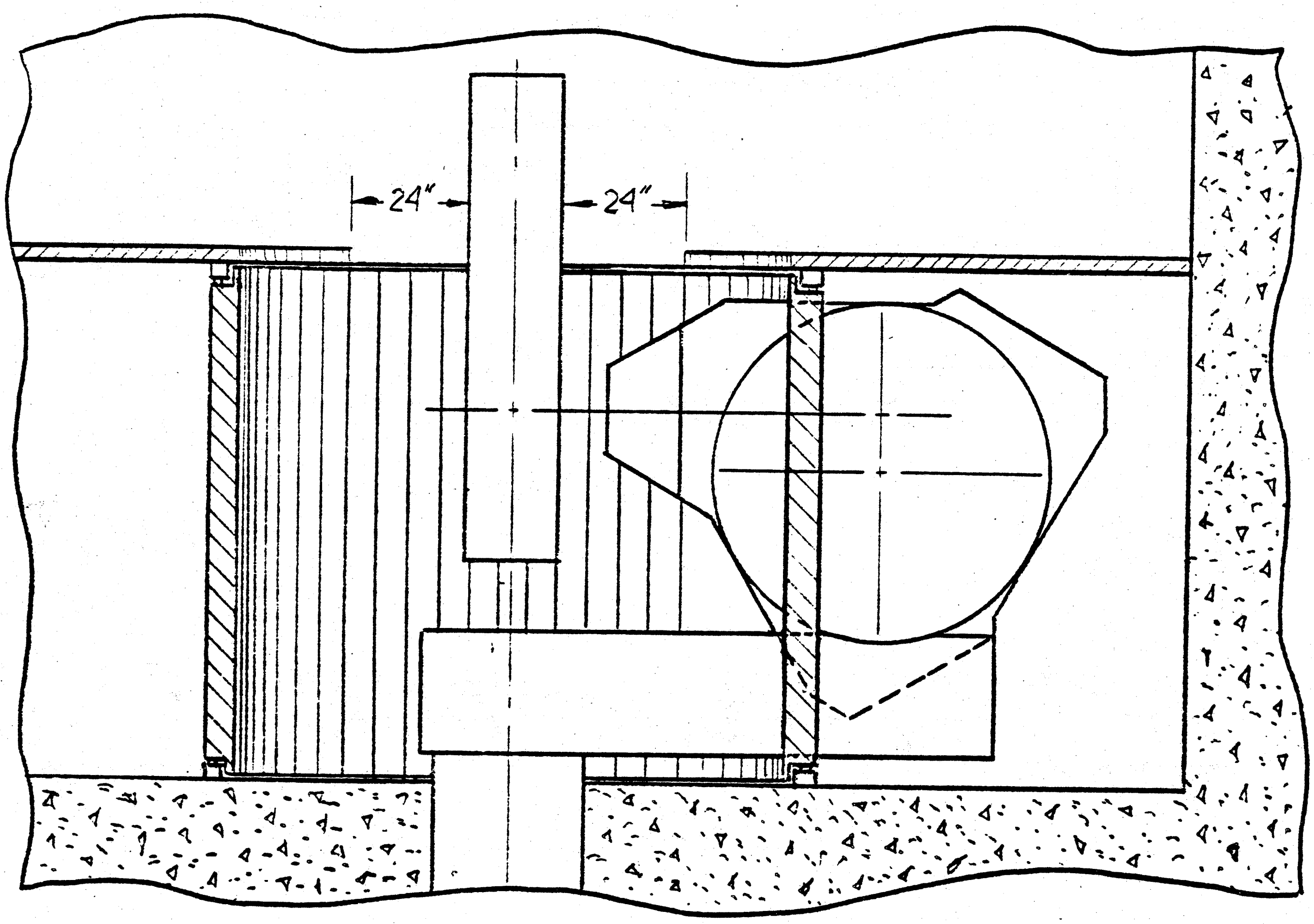
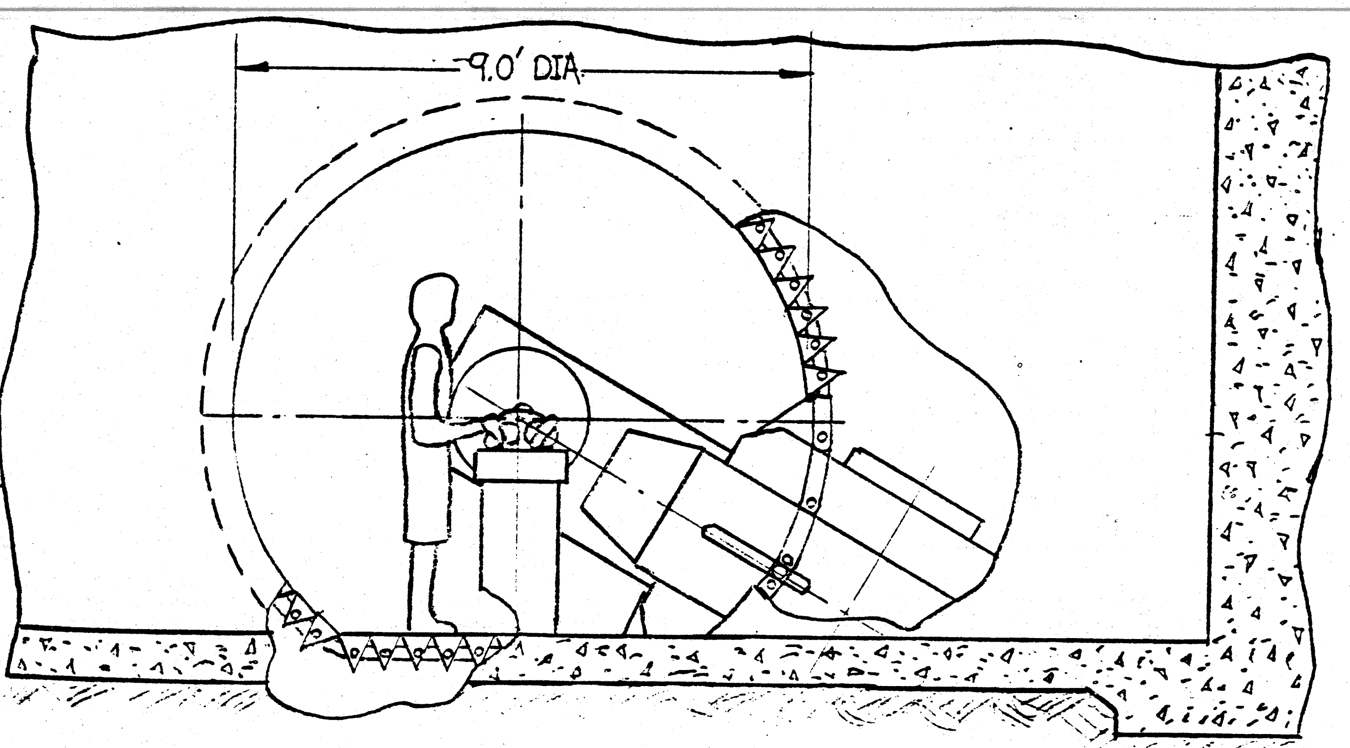


FIGURE ③



TOP VIEW (CYCLOTRON IN 90° POSITION)



END VIEW (CYCLOTRON IN -120° POSITION)

FIGURE (4)

3 FT

intelligent floor drive required for the configuration shown in Figure 3. Access to the patient table is restricted as compared to the arrangement of Figure 3, but is perhaps adequate. Another feature of the Figure 4 arrangement is that a thin wall is used to shield most of the cyclotron pit from the remainder of the treatment room. (Note that the system to be constructed in the Harper-MSU study does not include either moving floor arrangement and also does not include the patient table--it does include all the components needed to construct and operate the cyclotron and to move it about on the gantry mounting, assuming basic utilities, such as AC power and cooling water, are furnished from another source and also that liquid helium is furnished from a separate source-- the rotation drive will be sized to provide power for the Figure 4 type floor system so that either floor arrangement can later be selected.)

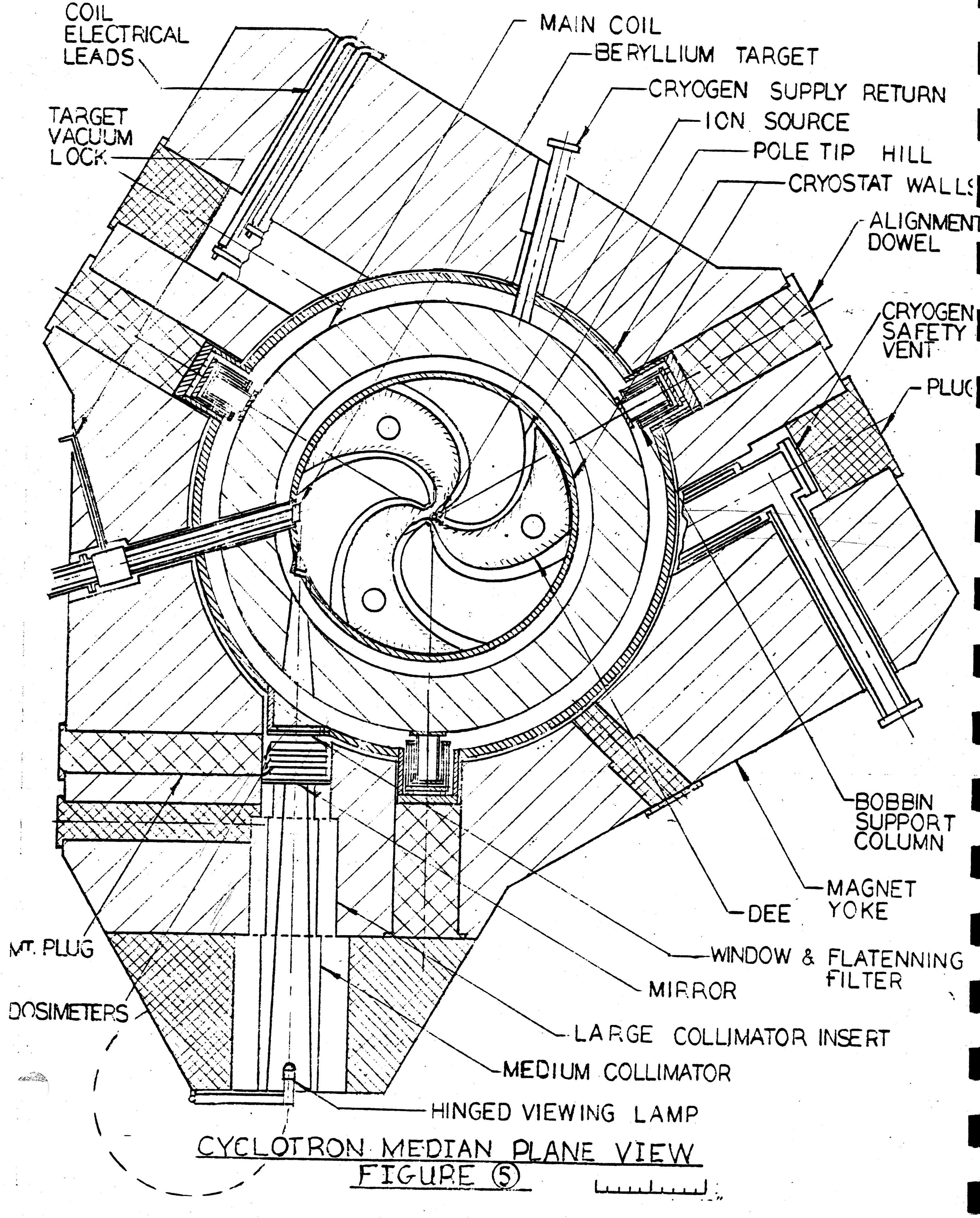
Following subsections describe the cyclotron, the gantry and counterweight, the collimator, the control system, and overall system specifications.

A. The 50 MEV Deuteron Cyclotron

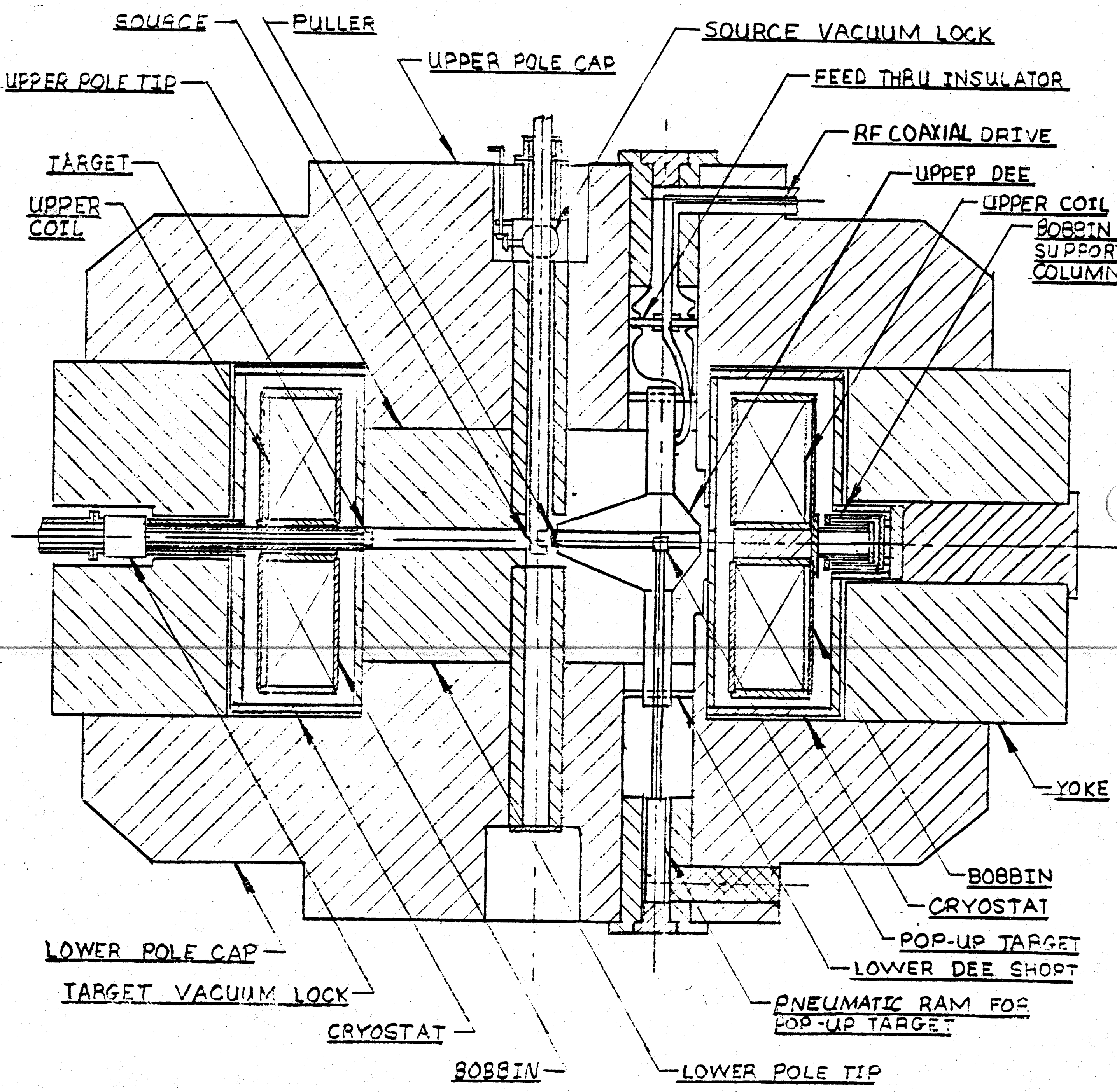
The design of the cyclotron system closely follows the concepts used in the first operating superconducting cyclotron, the MSU K500. Interestingly, this design has many features which are naturally well adapted to the therapy cyclotron requirements. These include a very lightweight magnet, a dee-in-valley RF system which minimizes rf power consumption, a fully enclosing, closed yoke which is magnetically efficient while at the same time serving as a significant radiation shield, etc.

Figures 5 and 6 give a plan view and an axial section view of the cyclotron and show major features such as the arrangement of the hills and valleys of the magnet, the location of the ion source, the location of the target, the arrangement of the superconducting coil and cryostat, etc. The cyclotron is exceedingly simple in comparison with most modern cyclotrons, the magnetic field being entirely controlled by setting one variable, the magnet current, and the radio frequency system being similarly controlled by setting one variable, the rf voltage. Computation techniques which have been developed at MSU for superconducting cyclotrons allow the magnet iron to be predesigned to produce a magnetic field shape satisfying the cyclotron isochronism requirements without need for the usual array of "trimming" coils which are found in most cyclotrons. Producing the neutron beam in an internal target is a further major simplification which eliminates the array of adjustable elements required to extract the beam from a cyclotron.

The ion source for the cyclotron will be a conventional, cold-cathode source with independent controls for voltage and current and with a special, dual, gas-feed system to provide both deuterium and nitrogen. With this arrangement, the nitrogen serves as an arc support gas so that beam intensity can be varied over a wide range by varying the flow of deuterium without affecting other source operating parameters. A vacuum lock will also be provided so that the source can be removed for weekly cleaning and cathode replacement without disturbing the main cyclotron vacuum.



CYCLOTRON MEDIAN PLANE VIEW
FIGURE (5)



CYCLOTRON VERTICAL SECTION
FIGURE (6)

The vacuum pumping system for the cyclotron will use a titanium getter pump which has excellent performance for both hydrogen and nitrogen plus a small ion pump to handle the trace quantities of noble gases which the system will contain. Both of these pumps have the advantage of being able to operate in any orientation so that pumping problems associated with the rotation of the cyclotron are eliminated. Initial pump down of the cyclotron will be accomplished with an external mechanical pump mounted separate from the gantry on the floor and coupled through a flexible hose in the utility cluster. (In normal operation this pump would not be needed and would be valved off.)

The superconducting coil for the cyclotron will be an open-lattice, helical winding of the same basic structure as the K500 and K800 coils at MSU. With this design, liquid helium penetrates through the coil in a set of passages formed between spaced strips of insulation, these strips being arranged in a "picket fence" structure separating succesive coil layers. Coils of this type are known to be extremely rugged and reliable and free of the "quenching" phenomena which is a troublesome aspect of some superconducting coil systems.

The coil will use a "subcooled liquid" cooling concept in order to avoid problems associated with gas bubbles (from liquid boiling) collecting in a trapped upper pocket as a consequence of the continuously variable range of possible orientations of the coil container. In this subcooled system, the liquid helium will circulate at a pressure of 1.8 atmospheres and a temperature of 4.5 degrees, these corresponding to conditions in which the liquid can remove heat without boiling so that gas bubbles will not develop. The subcooling will be achieved by allowing the outflowing liquid from the coil to expand to 1.2 atmospheres in an internal Joule-Thompson valve, becoming in this process a two-phase, gas-liquid mixture. This boiling, 4.5 degree mixture will then circulate through a "subcooler" piping loop, which weaves through the helium reservoir section of the main coil helium vessel, just outside of the area occupied by the actual coil winding.

Electrical leads for the coil will be of the gas cooled type with the important length-to-area ratio, selected to provide broad insensitivity to misadjustments in the gas flow.

The radio frequency system for the cyclotron will utilize a commercial prepackaged amplifier system from the Harris Corporation of Quincy, Illinois or equal. A descriptive brochure on the Harris unit is attached (Appendix A.). The required frequency and the rf power level match values normally used in the transmitters of standard FM radio stations. The output of the transmitter will feed through a rigid, air-insulated, coaxial line to a sliding contact rotating rf joint mounted on the rotation axis of the gantry system. From the rotating seal additional rigid coax will feed out through the gantry arm and then through a conventional feedthrough insulator into the cyclotron vacuum system.

The internal accelerating electrode system will be a dee-in-valley design as in the K500, but the rf will operate always at three times the rotation frequency of the particles. With this frequency choice, optimum phasing of a three dee system occurs when all the dees operate at the same phase; this requirement is easily insured by including an actual metallic connection between the dees at the cyclotron center. (Systems of this type have been very successfully used for many years in the several European cyclotrons manufactured by AEG Incorporated of West Germany.) The rf power provided by the Harris amplifier will produce a peak voltage to ground of approximately 40,000 volts on the resonator system. This gives a deuteron energy gain of 240 keV/turn and 210 turns are then required to reach 50 MeV. This figure, 210 turns, implies comfortable isochronism tolerances for the cyclotron magnet.

The orbital pattern in the cyclotron will be pre-computed using computation techniques which accurately predict both magnetic and electric fields. Orbits should then be well centered in the cyclotron, and this condition in turn corresponds to a reproducable and stable left-right distribution of the neutrons emitted from the beryllium target. The cyclotron design as an extra safeguard will also include two sets of magnetic compensating shims. If necessary, these can be used at the time of the start up tests to make a permanent experimental correction for inadvertant construction errors which might affect beam centering. The cyclotron design also includes a pop-up target at partial radius to allow the operator to check beam intensity before passing the beam to the main production target.

B. Gantry and Counterweight System

As shown in Figures 1 and 2, the support system for the cyclotron utilizes a structure similar in form to the crank and bearing assembly connecting the pedals of a bicycle, the cyclotron being placed at the location of one pedal, the counterweight at the location of the other.

A large central bearing supports the weight of both cyclotron and counterweight. The system is designed to be accurately balanced to within a few pounds by making small adjustments to the counterweight so that the drive system, which rotates the complete assembly, needs only to overcome frictional forces. The main load bearings are a standard commerical product rated to take both the radial and thrust loads of the combined cyclotron and counterweight.

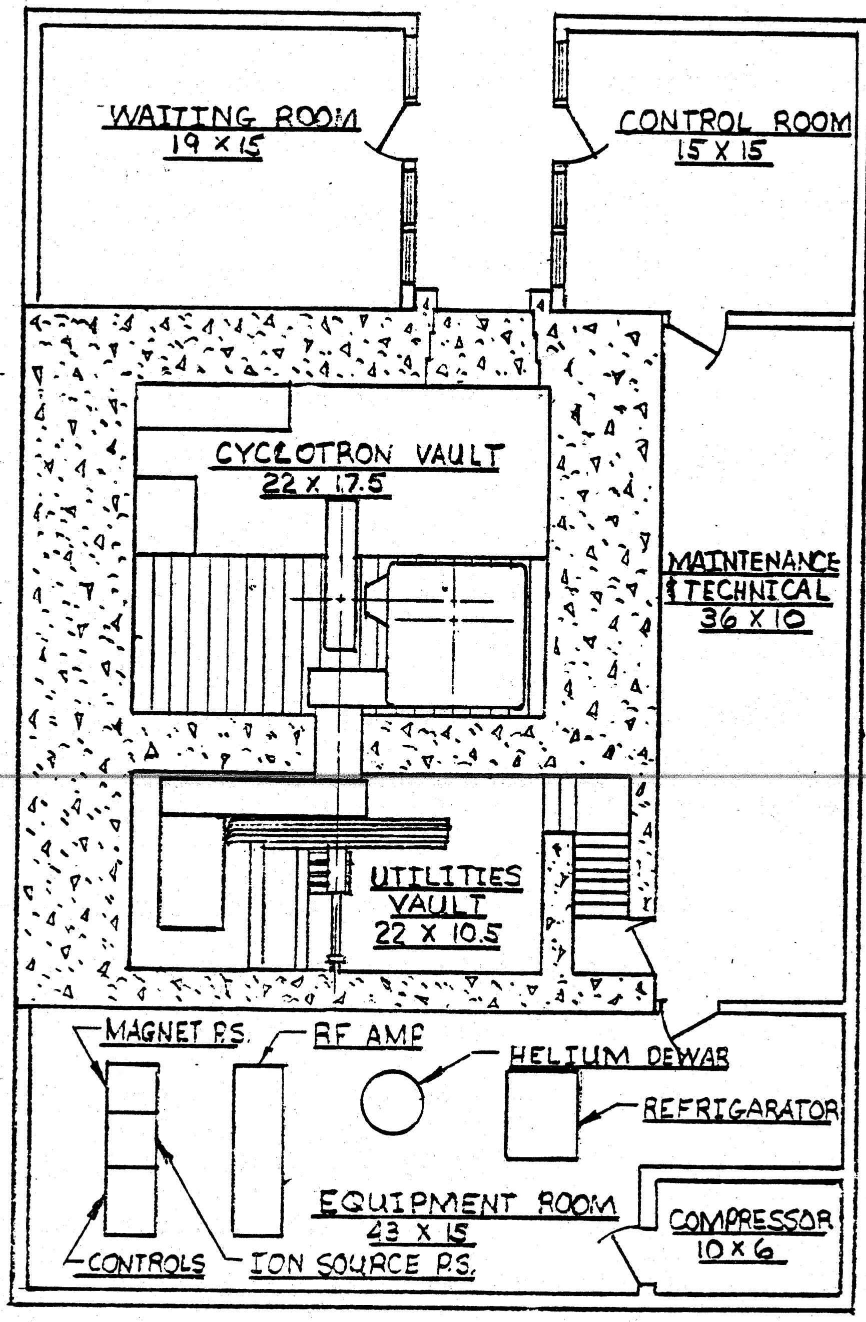
The gantry arm supporting the cyclotron is a large, rectangular, welded beam with internal reinforcing ribs, the dimensions and wall thickness of the beam set on the basis of stress and deflection analysis to conform to the aiming accuracy specification on the neutron beam (see section II.E.). The gantry arm bolts to both the cyclotron proper and to the center core of the bearing assembly. A similar welded arm supports the counterweight structure on the opposite side of the wall.

Utilities connections to the cyclotron feed through the hollow center of the gantry arm and central bearing shaft and onto a specially designed utilities hub on the counterweight side of the crank system. General characteristics of the utilities hub are shown in Figure 1. A central, on-axis, coaxial line carries the rf drive power through a rotating joint as noted above. Highly flexible lines such as water hoses, air hoses, electric cables, etc. are wrapped and unwrapped on a small drum. The relatively stiff, quadrupole walled, helium and nitrogen hoses are carried on a large helical spring supported by a system of rollers. This spring unwinds and expands as the cyclotron rotates so that the number of turns varies by plus or minus one-half. The rigidity of the spring prevents the cryogenic hoses from bending in too small a radius, a condition which would short circuit the thermal insulation system which is built into the lines.

Beyound the utility pod, all utility systems feed through a second supplementary shield wall designed to atenuate the neutron flux which leaks through the center of the main bearing shaft. In an adjacent room these utilities connect to power supplies, refrigerators, vacuum pumps, nitrogen storage dewar, etc. A possible schematic layout for these arrangements is shown in Figure 7. (Reminder: the system which will be set up at MSU may or may not include a shielding system and, if one is included, it will be a hut constructed of moveable blocks in a configuration quite different from that shown in Figure 7--the arrangement of power supplies, refrigeration lines, etc. will also be different at MSU, to match the characteristics of the available space, and cryogenic fluids will be obtained by connecting to existing MSU systems.)

C. Target and Collimator System.

The target assembly for the cyclotron utilizes a stopping thickness of beryllium metal electroplated on a copper housing which is directly watercooled. Since no significant radioactivity is produced in the beryllium itself, and since the beam does not penetrate into the copper, the level of radioactivity from the target will be low and special shields to protect the staff from this activity will not be required. The target system includes a vacuum lock so that the target can be withdrawn for inspection and/or replacement without disrupting the main cyclotron vacuum.



TYPICAL FLOOR PLAN
FIGURE (7)

10 FT

After leaving the target the neutron beam penetrates through a thin Aluminum window which separates the acceleration chamber vacuum from the main coil insulation vacuum. At the outer edge of the coil, the neutrons exit to atmospheric pressure through a second window. This second window will have a thickness which varies with distance from the neutron beam axis so that the window also serves as a flattening filter, giving a more rugged window and also saving space along the neutron path.

The collimator system which will be included as a part of the project copies the system in use at the Fermilab neutron therapy facility in which molded inserts of plastic loaded concrete are placed in the iron outer collimator housing. The inserts are arranged in stepped sizes, the smaller, most frequently used inserts being light enough to be handled by regular radiation oncology personnel. For the less frequent occasions when a large insert needs to be changed the assistance of additional personnel, such as hospital orderlies will be useful. Table I lists the characteristics of the set of inserts which will be furnished giving both the treatment area at the isocenter and the weight of the insert.

The collimator system is designed for easy adaptation to the customized collimator techniques now in use in the Radiation Oncology Center. The planned process for fabricating a customized collimator would involve 1) casting of a Cerrobend, irregular cone matching the desired final aperature of the collimator, 2) centering this formed cone in an aluminum mold matching the required outer dimensions of the collimator, and 3) pouring in the plastic loaded concrete mixture. When the concrete has hardened the Cerrobend would be removed by

TABLE I: COLLIMATORS TO BE PROVIDED

Housing Size*	Beam Size at Isocenter (centimeters)	Collimator Weight** (pounds)
large	30x20	81
large	20x20	96
large	20x15	104
large	20 dia	103
medium ***	16 dia	35
medium	15x15	30
medium	15x10	38
small***	12x8	14
small	12 dia	13
small	10x10	14
small	10x6	17
small	8 dia	17

*Molds will be included for each outer housing size so that customer can make additional inserts of any size.

**Weights are for "polyethelene cement" collimators. Composition by weight: 50% Portland cement, 20% 1/8" dia. Polyethelene pellets, remainder water. Density of composite 1.6 gm/cm^3.

***Holder for "medium" inserts weighs 77 lbs--must be removed to use large collimators. Holder for "small" inserts weighs 29 lbs--must be removed to use medium collimators.

heating and the collimator would be ready for use. The Cerrobend cone would be fabricated with the same styrofoam form procedure now used at the ROC except that the styrofoam would be the outer part of the mold and the Cerrobend would be in the center. The aluminum outer molds for the collimators will be furnished as a part of the project.

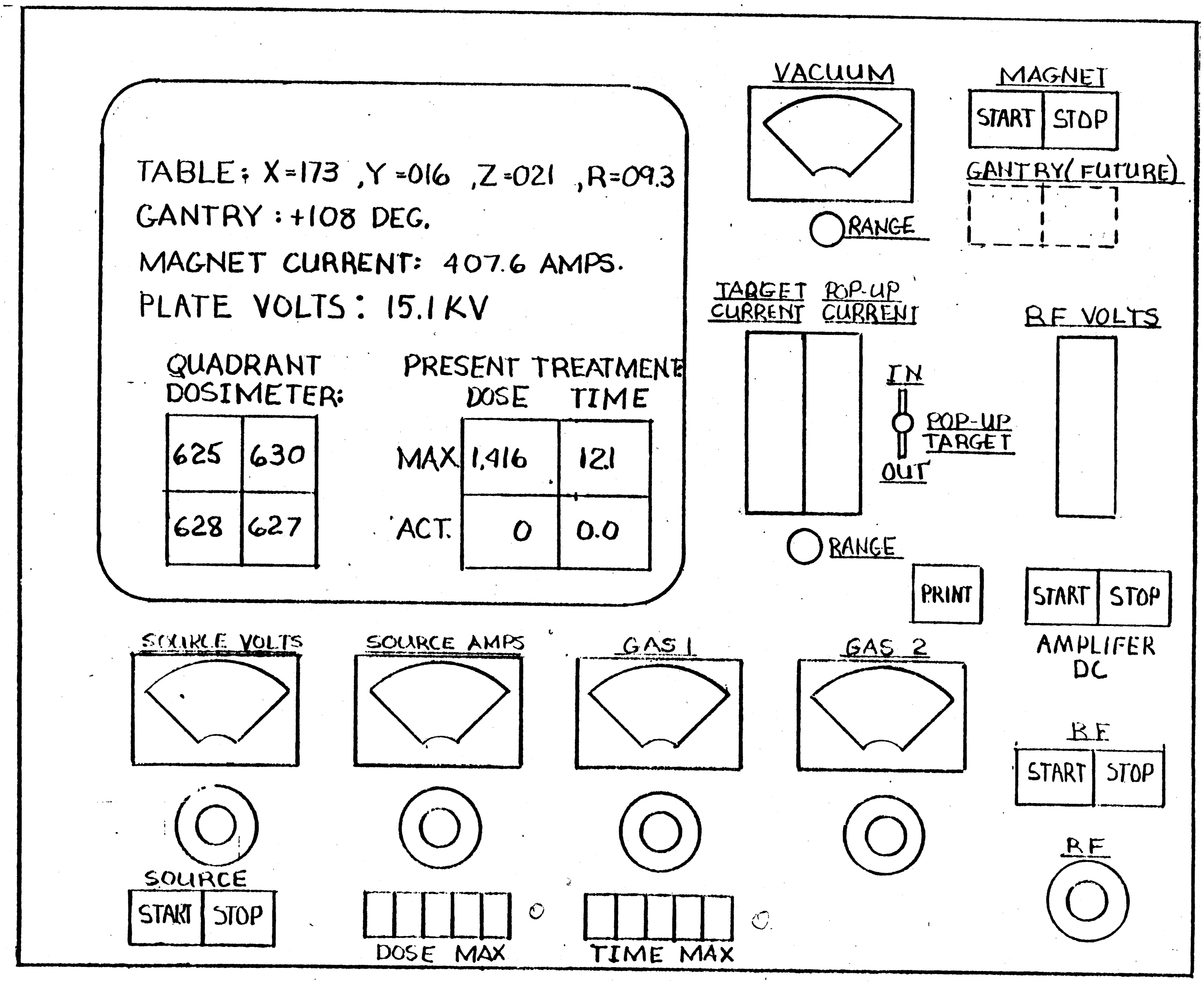
Between the neutron exit window and the collimator, space is provided for a flux monitoring package to be provided by Harper. This package will be mounted on a removeable insert in the side of the magnet. The insert includes provision for the necessary electrical feeds and signal cables.

An optical alignment system is included in the collimator arrangement, the system consisting of a thin, front-surface mirror located at the target end of the collimator and a hinged, flip-in, light source and cross hair assembly, which swings into place at the entrance of the collimator. The distance from light source to mirror just matches the distance from target to mirror and the resulting light cone therefore accurately corresponds to the actual neutron cone produced by the selected collimator.

A tentative feature of the proposed configuration which will be explored using existing MSU power supplies, but is not a final part of this project, involves testing an electron gun system designed to produce X-rays directly in the neutron target by inserting a high voltage cathode thru an axial hole in the magnet. The cathode will be designed to operate at a potenial of 120 kilovolts. The ultra-strong magnetic field from the main superconducting coil will accurately collimate the emitted electrons into a beam directed at an X-ray anode located on the downstream side of the main neutron producing target. An X-ray film at the far side of the patient would then accurately show the alignment of the patient relative to the collimator and neutron beam. If the test system works successfully, a final system of this type can be added to the therapy unit at a small additional cost by procurement of an appropriate high voltage power supply. In addition, provision will be included for mounting a commercial X-ray unit on the side of the cyclotron gantry. (The actual X-ray unit is not a part of this project.)

D. Control System

The control system for the proposed neutron therapy system will be based on a conservative design concept in which all interlocks and safety systems are "hardwired" using real limit switches, relays, etc. Similarly, direct control of all key systems will flow through hardwired buttons and knobs with all system logic arranged in "fail-safe" patterns. A computerized readout and monitoring system will display the setting of all system parameters and provide a printed record on request. Full software documentation will be provided for all computer programs and later the system can, if desired, be modified to interconnect with a computerized patient record keeping system, so that run parameters could be directly entered in the patients medical record to eliminate possible transcribing errors. Figure 8 shows the control panel arrangement as presently envisioned.



CONTROL PANEL
FIGURE (8)

At the beginning of a working day cyclotron start-up would consist of:

1. Pressing the magnet "START" button and waiting for approximately 10 minutes for the magnet to come to full current--at all times, the actual value of the current would be continuously indicated on the magnet current display.

2. With the magnet at operating current and the ion source voltage and current controls set at operating values, the source "START" button is pressed. This will cause readings of approximately 1500 volts and 0 amps to show on the source voltage and current meters. The source gas is then slowly increased by turning up the source gas control until the arc strikes, the striking point being identified by a sudden drop in voltage to a value of about 400 volts and a sudden rise in arc current to a level of approximately 2 amperes. After striking the source, the gas is next slowly reduced until the voltage reaches the operating value of about 700 volts at which point the current will fall to a value of approximately 1.5 amps. (Striking the source can be done with either of the dual gas controls and after striking the two gas controls should be adjusted so that the gas flow is approximately half from each in order to have maximum adjustment range.)

3. With the rf voltage control at a low level the DC "START" button is pressed and a voltage indication of 15 kilovolts will appear on the plate voltage display. The rf "START" button is then pressed and a low voltage will appear on the dee voltage meter corresponding to the setting of the rf voltage adjusting knob.

With the pop-up target "IN", the voltage is then raised to the operating value and beam currents will appear on the pop-up target current meter.

4. If the beam current is not at the level desired the dual source gas controls are adjusted, raising or lowering the deuterium fraction to raise or lower the current level.

5. A reproducability check is made by turning off the rf, waiting for some period and then turning back on, leaving all other controls at their previous settings. Beam current on the pop-up target should go back to the previous value.

6. Next the pop-up target switch is moved to the "OUT" position--beam should immediately appear on the main target current meter and at the same time readings should appear on the dose monitoring displays. These readings are checked for proper level, the rf "OFF" button is actuated and the machine is then ready for use. Subsequent patient exposures are then initiated by pressing the rf "START" button.

The system will be fully interlocked in a way which is designed to prevent damage to components irrespective of actions of the operator. When an interlock fault condition exists the "START" button for that system will change to blue and pressing the button will cause a display of the interlock chain for that system to appear on the console display with the fault elements marked by a flashing display. As an example, the "RF START" button will change to blue, indicating a system fault, if the target is not installed, or if water flow monitors in any of the rf cooling circuits signal inadequate flow or if either the length-of-run timer or the dose-integrating timer for patient exposures have reached preset values, etc. Remedial action for each interlock fault condition will be given in an operating manual, listed in the same sequence as on the console monitor display, thus enabling the operator to quickly identify the system component which is producing the interlock interruption. All interlocks will also be of the "latching" type so that a record of a quickly dissapearing transient fault will be preserved until cleared by the operator.

Control of the Helium refrigeration system is accompolished from a separate control panel at the refrigerator. The only coupling to the main cyclotron control console is through the interlock chain for the magnet "START" button, where either a "temperature out of range" or a "helium level out of range" condition would prevent the magnet current from being turned on, if the magnet was off, or would turn the magnet current off, if the magnet was on. (In this situation, an interlock fault indication would of course also appear on the magnet "START" button.) Actual operation of the helium liquifier will follow the instructions in the manufacturer's manual and after initial cool down the liquifier will normally typically operate on a continuous 24 hour per day basis with no adjustment of controls. Once a day reading and recording the values of the various pressure and thermometer indicators on the liquifier is recommended. (If the liquifier is used for other purposes in addition to the cyclotron and step changes are made, such as for example, withdrawing a dewar of liquid from the system, adjustments of liquifier controls would be needed, but procedures are relatively simple and training assistance would be provided.)

The patient table system is not a part of the joint MSU-Harper project but the control system will include input channels to allow the coordinates of the patient table to be read and displayed by the control system and included in the paramater printout. (It is assumed that actual movement of the table will be controlled only from the table stand itself so that the operator would have a direct view of any conflicting physical objects which might conceivably lead to patient injury if the table were improperly moved.) It is also assumed that the reset button for the "exposure limit" interlocks will be located near the patient table to reduce the possibility of the button being inadvertantly or incorrectly utilized.

E. System Specifications

Specifications for the medical cyclotron system are given in Table II. All specifications correspond to component operating conditions which are well within the levels which have already been achieved in other cyclotron projects or are based on routine implementation of standard engineering techniques. It is then highly probable that all specifications will be successfully accomplished. At the same time all parties involved in this project recognize that any first-of-a-kind effort inevitably includes some element of risk from unanticipated difficulties. MSU, in undertaking to manage and direct the design, fabrication and testing of this unit, does so on a "best effort" basis and subject to the previously stated understanding that work on this project must always be noninterferring relative to

TABLE II: SYSTEM SPECIFICATIONS

CYCLOTRON

Magnetic Field: center 4.6 tesla, hill 5.4 tesla

rf System: frequency 105 Mhz, dee voltage $\pm$40 kV peak, rf power 25 kw

Vacuum: source gas off 5×10^{-6} torr, source gas on 1.5×10^{-5} torr.

Beam Energy: 50$\pm$0.3 MeV deuterons

Maximum Beam Current: Pop-in target 50 microamperes, Be target 20 microamperes

Beam current reproducibility: for beam current greater than 5 microamps the beam current setting will reproduce to within 5% of the previous value when the cyclotron is turned on after an off period of up to 30 minutes (without adjustment of ion source parameters).

SUPPORT SYSTEM

Rotation Range: +180°to -175° (355° total travel)

Mechanical Rigidity: the extended central axis of the neutron collimator will intersect with a single sphere of 3 mm dia irrespective of the gantry rotation angle

Rotation Speeds: fast 90° /min, slow 22 1/2° /min.

Angular Accuracy: The readout of the gantry angle will be accurate to 0.5°.

NEUTRON FLUX

Spatial Reproducibility: the dose distribution at the isocenter will reproduce on five successive days within a total variation of 6%, as observed in a test performed with neutron collimator set for a 10x10 cm field at the isocenter and using a 17 member array of detectors, (one detector at the isocenter and four lines of four detectors extending from the central detector on lines perpendicular to the collimator axis at 1 cm spacing).

Angular Stability: The neutron flux as measured at the isocenter will be constant to within 5% as the cyclotron is successively moved in 30° steps through its full angular range.

RELATED EQUIPMENT NOT INCLUDED IN THIS PROJECT

- Moving Floor System
- Patient Table System
- X-ray System
- Low Conductivity Cooling Water System
- Primary AC Switchgear
- Dose Monitoring Instruments
- Helium Refrigerator System

the ongoing National Science Foundation nuclear science program at the National Superconducting Cyclotron Laboratory.

III. WORK PLAN

The proposed plan of work for the project was outlined in the "INTRODUCTION" of this proposal. Key elements of the plan are:

1) MSU will provide the services of Dr. Henry Blosser on a 5% of total effort basis as director of the project and will provide approximately 3,000 hours of on-call effort by procurement personnel and technical personnel, the later to be used only in situations requiring special skills or special knowledge of MSU equipment.

2) Harper-Grace will provide most of the manpower for the project in the form of a technical team consisting of engineers, technicians, and expert consultants. (The schedule given herein is based on a Harper technical team work force of five full time people plus 100 hours/month of expert consultant effort.)

3) MSU will provide its technical know-how and access to the facilities of the National Superconducting Cyclotron Laboratory subject to the condition of noninterference with the Laboratory's National Science Foundation program.

4) Harper-Grace will provide full funding for the project, detailed arrangements to be in accord with standard MSU procedures for sponsored research projects. (The proposed budget is given in Section IV of this proposal.)

Table III shows the anticipated work plan and schedule for the project--some explanatory comments will help in digesting the material in this table. A first point to note is the block of information in

TABLE III

0) MAGNET STEEL
01 Yoke
02 pole tips
03 non-mag. plugs
04 jacks
05 mounting brackets
06 pole cooling plates
07 centering rods

1) MAIN COIL
11 bobbin
12 conductor
13 electrical insulation
14 wind coil
15 thermal insulation
16 coil supports
17 coil leads
18 nitrogen shield

2) RF
21 low power mockup
22 25 kw amplifier
23 coax line
24 feed thru insulator
25 rf trimmer
26 dee structure

3) SUPPORT SYSTEM
31 gantry arms
32 bearings
33 bearing housing
34 counterweight housing
35 counterweight mass
36 drive gear motor

4) UTILITIES
41 He hose
42 LN hose
43 hose support coil
44 flow switches
45 valves
46 pressure gauges
47 conductor
48 magnet power supply

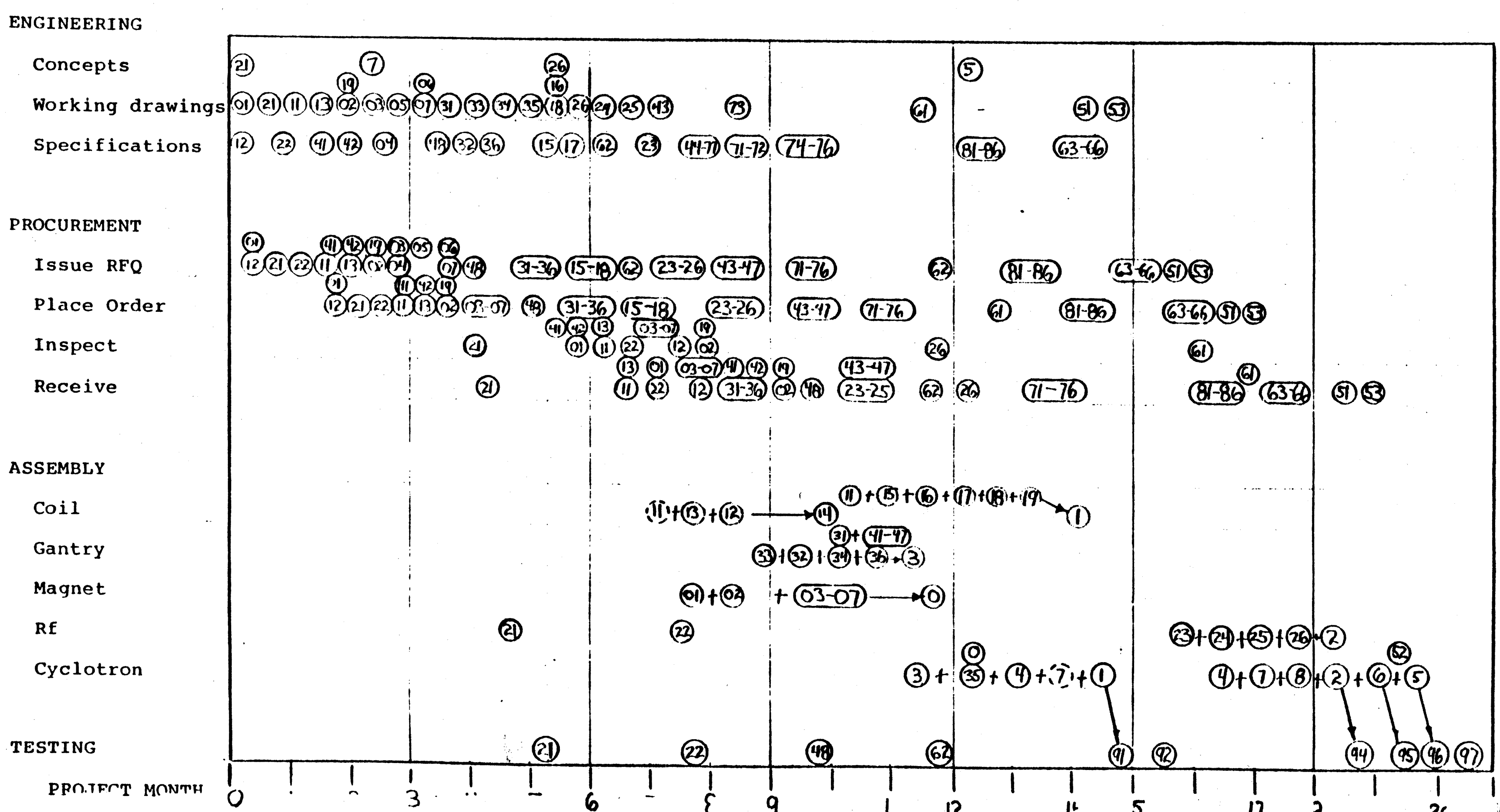
5) COLLIMATORS
51 main housing
52 inserts
53 insert molds

6) MISCELLANEOUS PARTS
61 ion source
62 source power supply
63 pop-in target
64 probe
65 target
66 viewing light

7) CONTROL SYSTEM
71 Modicon controller
72 68000 computer
73 main control panel
74 meters & buttons, etc.
75 cross connect rack
76 wiring

8) VACUUM SYSTEM
81 mech. pump
82 TiBall pump
83 ion pump
84 guages
85 plumbing
86 valves

9) PERFORMANCE TESTS
91 main coil cold
92 magnet maps complete
93 40 kV on dees
94 beam on pop-up target
95 beam on Be target
96 picked up by shipping firm



the upper half of the table listing the work elements into which the project will be divided. This listing also gives the numerical identification codes assigned to each work element, viz. "11" for the coil bobbin, "31" for the gantry arms, etc. The material at the bottom of the table lists on the left side the major kinds of activities required to complete the project, viz. "engineering", "working drawings", "procurement", etc. A time line drawn horizontally from each of these activities shows the sequence of work for each activity in terms of the numerical codes. As an example looking across the "working drawing" time line, one notes that the drawings for the magnet pole tips, code 02, will be prepared in the 2nd month, looking on the "place order" time line one sees that the pole tips will be ordered in the fourth month of the project, etc.

Studying the various entries in the table one sees that the initial activity for most components is preparation of working drawings and specifications; this category of work will be performed by the engineers, designers and detailers of the Harper technical team with review by the technical team consultants. For most components, the next step is procurement. This involves taking bids and placing orders based on the drawings and specifications from the engineering group, the actul process to be handled by the NSCL purchasing group following standard NSCL and MSU procedures. The usual next step, monitoring of external vendor activity, is again an activity which will be handled by the Harper technical team, using either periodic telephone contacts with vendors to check on progress or actual inspection visits in the case of particularly sensitive items. When a vendors product meets specifications, the inspector will give a shipping authorization and the item will be shipped to NSCL.

As equipment arrives at NSCL, it will first of all be checked by the NSCL receiving department for shipping damage, missing items, etc. After these formalities have been completed, the item will be delivered to a designated member of the Harper technical team who will have responsibility for final technical inspection and payment approval.

At this point, the assembly work begins or, in the case of components programmed for internal fabrication, the appropriate fabrication work will continue. The main coil is an example of a frequently occuring pattern of external procurement/internal fabrication activity; after the bobbin, the internal coil insulation, and the conductor have been received from external vendors, the bobbin will be installed in the NSCL coil winding facility and prepared for winding. This involves placing the bobbin on the large vertical lathe and installing the insulating and inspection devices on the lathe tool arm. Next the actual coil winding begins under the guidance of the Harper technical team construction manager with assistance from one of the technical team technicians. Coil winding will require approximately four weeks--when it is completed the next step is to install the cold gas distribution system and the subcooling loop and then the bobbin covers are welded into place. At this point a sensitive leak checking operation occurs-- the MSU, mass-spectrometer, leak-detector system will be used for the tests and NSCL technicians, experienced in using the equipment will make the actual tests. When the bobbin has been determined to be 100% leak free, it is ready for application of super insulation. After this, the liquid nitrogen shield is installed with a further application of super insulation outside of this shield and the whole assembly is then ready to be fitted into the cryostat. Following this, the cryostat is welded shut and checked for leaks in the same fashion as described for the bobbin and with this operation, the procurement/fabrication cycle for the main coil assembly is fully complete.

Other major sub-assemblies involve procurement and/or fabrication cycles much like that just described for the main coil. The sequence of these operations is programmed, as shown in Table III, such that major sub-assemblies will come together on a schedule matching the requirements of the series of operating tests which will be preformed on various sub-systems.

The first such operating test will be the powering of the magnet to full design excitation and mapping the magnetic field. This test requires the magnet steel, the main coil, and the support system to all be fully complete and assembled to each other and much of the utilities system also needs to be in place. The instruments which will be used to actually measure the magnetic field are an existing standard NSCL system; characteristics of the system are such that operation can be handled by the Harper technical team based on instructions and guidance from experienced NSCL personnel. The mapping apparatus feeds the magnetic field information directly into the computer system where the data will be processed and interpreted in terms of conformity with cyclotron requirements. While waiting for the processing of the field mapping data, the magnet operation group will proceed with moving the gantry to various orientations rechecking the magnetic field at each orientation.

One of the numerical checks which will take place at this time involves a computation of orbit centering in the measured magnetic field. If a field adjustment is needed to correct for fabrication errors, the Chalk-River-type centering rod system will be reset based on the orbit computation results and after this the magnet measuring process will be recycled to confirm that the correction has been properly made.

When the magnetic field configuration is in proper form the magnet will be reopened and the rf system and vacuum system components will be installed and remaining utilities connections made. This then brings the system to a status where it is ready for rf system performance tests.

The first step in the rf tests consists of adjusting the rf trimmer system to bring the resonant frequency of the dee system to an exact match with the frequency of the crystal-oscillator-driven rf amplifier. After this a "baking in" process begins in which the rf voltage is slowly raised over a period of days to drive out fabrication impurities from the various resonater surfaces. In this operation the structure will be overbaked by approximately 20% so that the bake-in cycle should not have to be repeated for the life of the cyclotron. In these tests an NSCL X-ray type, dee-voltage calibrating system will be used, the system having the capability of calibrating the dee voltage to within 2%. When the dee system is fully baked-in and calibrated, the "turn on" voltage program will be fine tuned to match the speed of the tuning electrode servo so that thereafter the rf system will be able to be turned on with the controls set for full voltage. (An exception is the circumstance where some component has been out of the cyclotron for service, such as the typical once a week service of the ion source, in which case a slower turn on cycle requiring perhaps one-half to one hour will be required.)

With the rf system operating properly, the cyclotron will be prepared for the next series of tests by installing the ion source, the probe, and the pop-in target. This then readies the cyclotron for partial radius beam tests, including runs going to the full 50 microampere, maximum beam current design value. In the process of performing this test, the orbit pattern in the cyclotron will be observed with the probe and compared to the calculated pattern to determine if the beam is centered and that all systems are functioning in accord with specifications.

At this stage, if shielding blocks can be borrowed without disturbing the NSCL nuclear science program, a shielding hut will be erected around the cyclotron and, when this is in place, operating tests will resume and the beam will be passed to the full energy target. At this point the performance of the collimator system and the dosimeter system will be checked, and the field flattening filter will be designed and installed. In the event that a shielding hut can not be erected, the full energy test will be accomplished by clearing a necessary area on an evening or weekend and the tests will be very brief, lasting approximately one hour. In this event most of the dosimeter testing, and the design and testing of the field-flattening filter would be deferred until the cyclotron is installed and operating in its vault at Harper Hospital.

At this point, with the concurrence of the Harper Radiation Oncology Physics Group, the MSU testing portion of the joint Harper-MSU project would be declared complete. The cyclotron system would then be disassembled and packaged for shipment and the group of investigators would undertake the preparation of appropriate reports, publications, patent declarations, etc., all of these steps in accord with the terms of the working agreement between Harper-Grace and MSU (the envisioned provisions of this agreement are described in Section IV of this proposal).

D R A F T

IV. BUDGET AND CONTRACTUAL ARRANGEMENT CONCEPTS

The budget for the proposed joint Harper-MSU project is given in Table IV and totals $707,565. On receiving indication from Harper-Grace of intent to accept this proposal MSU will draft a formal legal agreement specifying contractual details of the jointly sponsored project. The contract will include provisions providing for the following:

1. Work under this contract is to be conducted in a way which will not interfere with the ongoing National Science Foundation program at NSCL.

2. Contract is on a "best effort" basis--no penalty to either party if project fails to achieve technical goals. Project is considered completed when performance tests described in Section III have been jointly declared to be satisfactorily completed by the MSU project director and by the head of the Harper Radiation Oncology Center and all equipment has been packaged and picked up by a carrier (except equipment provided for NSCL under the unexpended funds provision below).

3. Publications to indicate joint Harper-Grace, MSU sponsorship. Authors to be persons actually involved in technical developments. All publications to acknowledge National Science Foundation support of basic research underlying development of the superconducting cyclotron technology.

4. To provide working capital, Harper to convey to MSU on signing of the contract, funds in the amount of 15% of the total project budget. On approximately the 15th day of the second month of the project, and each succeeding month therafter, MSU will bill Harper for the actual costs incurred for the project in the previous month, including a copy of monthly ledger sheets for the project listing all expenditures. Payment of all invoices will be due 30 days from date of the invoice.

5. Obligations incurred by MSU in the course of carrying out this project are not to exceed total funds budgeted. If the project is completed without fully expending the budgeted funds, one-half of the unexpended amount will be used to purchase new equipment needed for the NSCL program (to offset wear and tear on the Laboratory's equipment due to the project) and one-half will be left unexpended thus reducing the total project cost to Harper-Grace.

6. To the extent permitted by U.S. law and our agreement with the NSF, ~~P~~atents, if any, to be applied for by, and to be property of, MSU. MSU will grant to Harper an exclusive license, including right to sublicense, to use all techniques and know-how needed to manufacture additional copies of the therapy unit, at a royalty of 1% of the gross sales price of the unit.

7. Harper-Grace to provide insurance coverage for its personnel working at NSCL on same basis as required of other contractors working on MSU property.

8. Either party to have right to terminate based on 30 day notice. At termination all items procured using funds from this grant and all rights to technical know-how to be property of Harper-Grace. If terminated by Harper-Grace prior to completion, 10% of the amount budgeted for the project is to be made available to NSCL for the same purpose as stated above relative to distribution of unexpended funds on completion of the project.

TABLE IV--BUDGET FOR MSU MEDICAL CYCLOTRON PROJECT

A.	Personnel expenditures	
	Supervision--H. Blosser 5% time--18 months plus actual hours spent by purchasing personnel, vendor inspectors, and operatiors for special devices estimated at 3,000 hrs total	$49,596
B.	Fringe Benefits on A. @ 21%	10,415
C.	Expendable Supplies	15,000
	Subtotal	75,011
D.	Equipment	539,000
E.	Indirect Costs (39.4% of Subtotal)	29,554
F.	Reserve for overlooked equipment items	64,000
	TOTAL PROJECT	$707,565

APPENDIX A

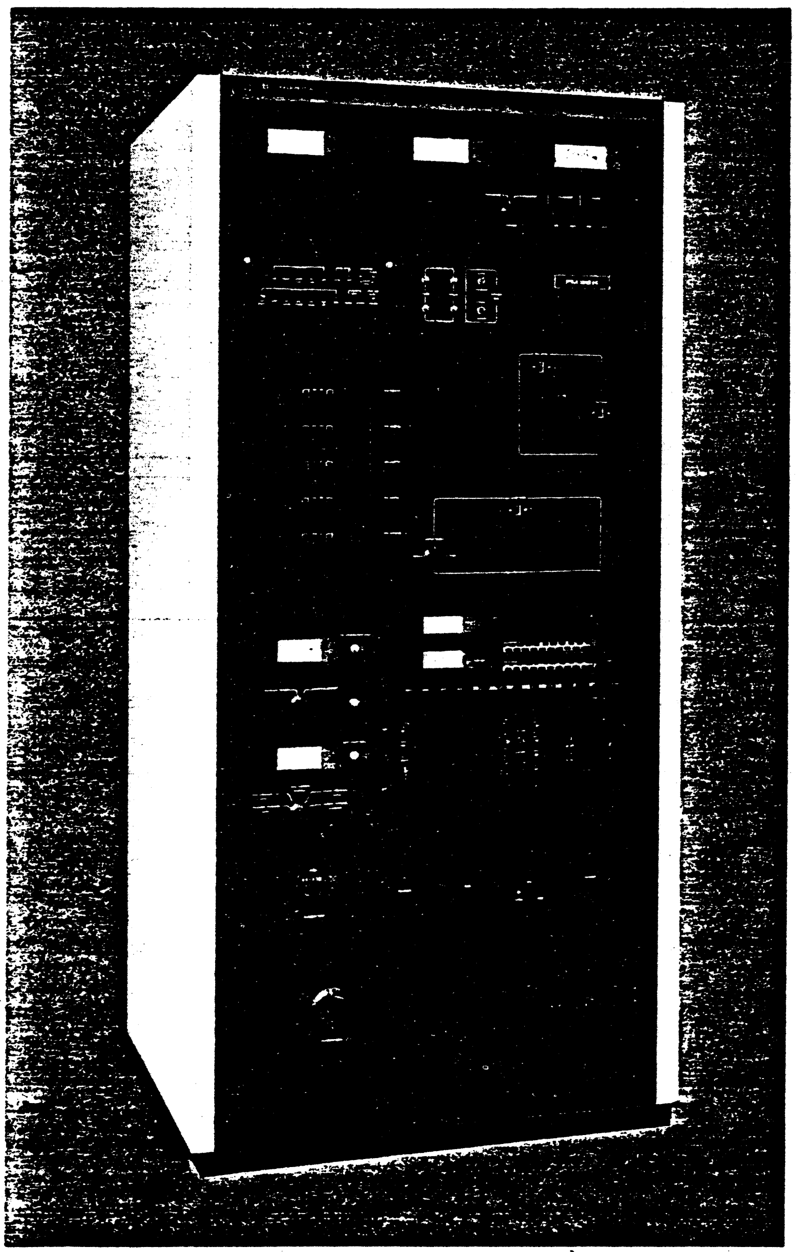
Manufacturer's brochure describing the type of amplifier system which will be used to provide rf drive for the dee system.

Eimac 8990

HARRIS
COMMUNICATION AND
INFORMATION PROCESSING

FM-25K

25-Kilowatt FM Broadcast Transmitter



- **First one-tube high-power FM transmitter**
- **High efficiency, low operating cost**
- **Solid-state, redundant IPA**
- **Wide RF bandwidth, minimum tunable components**
- **Driven by the most advanced FM exciter in the world—MS-15**
- **Patented DSM stereo generator . . . stereo separation 40 dB minimum, 50 dB typical**
- **DTR filter technique limits overshoot to 2% or less**
- **Solid-state control logic**
- **Automatic power control standard**

Harris' technology has combined advances in both tube and transistor designs, to bring you a major step forward in high-power FM transmitters. Transistors are now available which provide 50 watts of RF power at reasonable gain and low junction temperatures. By combining several of these transistors in wideband RF circuits, enough power can be generated to drive an advanced high-gain Eimac tetrode tube, the 8990. This tube, when grid driven in a grounded cathode, quarter-wave cavity, can produce 25 kilowatts with 350 watts of drive at nearly 80% plate efficiency!

The FM-25K, twenty-five kilowatt FM transmitter reflects Harris' design philosophy that FM transmitters should deliver RF power efficiently, should not limit exciter performance, and should integrate dependable solid-state control logic. In the FM-25K, these features are teamed with efficient, single-tube design, and with the world's most advanced exciter—the MS-15.

The FM-25K was designed for applications with tower limitations or specific coverage requirements. The higher RF power output reduces the number of antenna bays required for a given ERP; and fewer bays mean a reduction in windloading and mounting area, so that tower size and/or height may be reduced. Also, fewer antenna bays, with less gain, can mean improved close-in coverage and the elimination of null fills.

SINGLE TUBE DESIGN. The FM-25K is the first high-power FM transmitter to utilize a single-tube design. A high-gain, highly efficient 8990 tetrode is the only tube in the entire transmitter, and is used as the final power amplifier. The tube uses a

Harris' FM-25K...high efficiency...

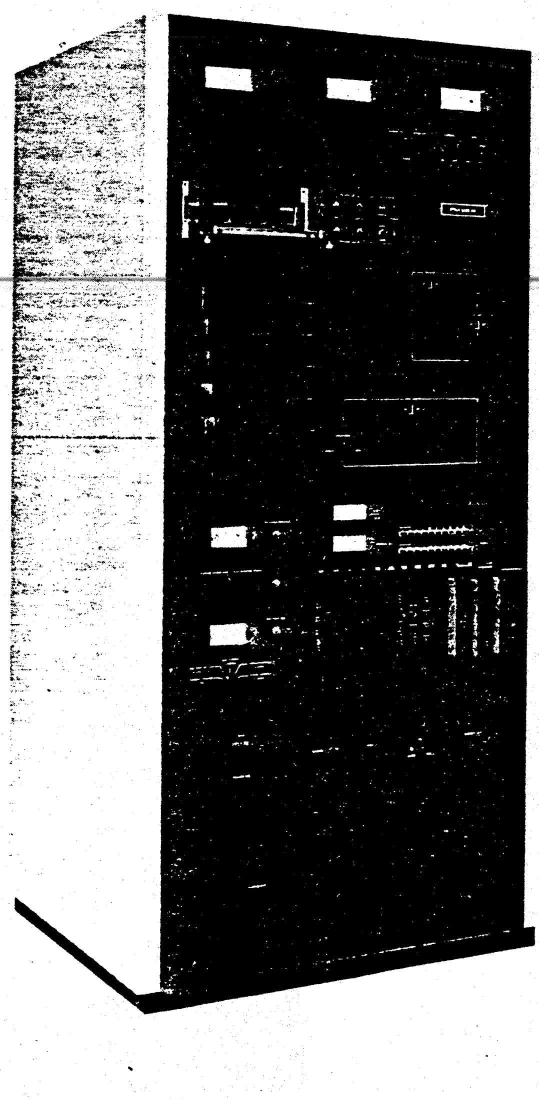
wavy fin radiator which provides exceptional cooling at reduced air requirements, for quiet operation. The quarter-wave PA cavity design eliminates troublesome sliding contacts for tuning, and assures wide RF bandwidth. This results in a signal path that is transparent to the MS-15 exciter.

SOLID-STATE IPA. Five solid-state power amplifier modules (2 amplifiers per module) are combined to produce 350 watts of drive power, with plenty of reserve. One module functions as the IPA driver, and the other four as driver power amplifiers. All of these modules are identical, so that in case the IPA driver should fail, one of the power amplifier modules may be inserted in its place. Loss of one of the four driver amplifier modules will not result in an off-air condition, as these solid-state amplifiers are isolated from each other. All five solid-state amplifier modules are broadbanded, and require no individual tuning over the entire 88-108 MHz FM band. The solid-state, modular concept affords back-up capability for greatly improved reliability, and reduces overall transmitter tuning requirements.

LOW OPERATING COST. With today's mounting energy costs, transmitter efficiency must be a major consideration in any purchase. 77% efficiency in the final power amplifier, high efficiency in all amplifier circuits, and conservatively rated components result in comparatively low power consumption and low operating stress on heat generating components in the FM-25K. This adds up to very impressive savings in operating and maintenance costs.

AUTOMATIC POWER CONTROL. The FM-25K automatically monitors power output, and maintains the output at the desired level. This standard feature insures against out-of-tolerance power conditions. Furthermore, the power set point can be remotely adjusted independently of the limit points to allow operator control of power output. During maintenance periods, the automatic power control may be switched off.

VSWR PROTECTION. VSWR protection is mandatory in any high-power transmitter—therefore, Harris has incorporated this as a standard feature in the FM-25K. A high VSWR condition will cause the transmitter to recycle... if three overloads occur within a given time period, the transmitter will shut down until manually restarted. The transmitter may also be programmed for single VSWR overload shutdown.



CONTROL CIRCUITRY. The FM-25K is controlled by solid-state logic circuitry. The logic circuitry not only controls basic On/Off functions, but also monitors critical stages for overload conditions. Should an overload occur, the transmitter will recycle automatically, according to the number of times pre-set (one or three).

The control logic used in the FM-25K interfaces directly with most remote control systems, eliminating the need for an additional remote control interface. The control signals are momentary low current contacts to ground. The transmitter output parameters are buffered, and all status indicators are remoted.

METERING AND VISUAL AIDS. Major functions, including RF output, VSWR and PA parameters are displayed on easy-to-read four-inch meters. Low-level parameters are displayed on a multimeter, and IPA RF output and reflected power are indicated on another meter. Filament voltage is measured by a true RMS circuit.

The FM-25K provides a variety of indicators as trouble shooting aids and quick references. These include four illuminated On/Off pushbuttons and 26 LED's not including those on the MS-15 exciter.

HV POWER SUPPLY. The high voltage power supply is housed in a separate cabinet, and provides the plate and screen supplies. The conservatively-rated three-phase plate supply uses silicon rectifiers with AC line transient protection.

COMPACT SIZE. The trim PA cabinet can fit as a replacement for all older 20- to 25-kilowatt FM transmitters. The cabinet is only 35 inches wide, 72 inches high and 31 inches deep. Additionally, the HV power supply may be located in any convenient spot remote from the PA cabinet.

GENERAL. There are many other operational and convenience features incorporated into the FM-25K. These include:

Line Loss Protection—Built-in protection against total AC failure and loss of

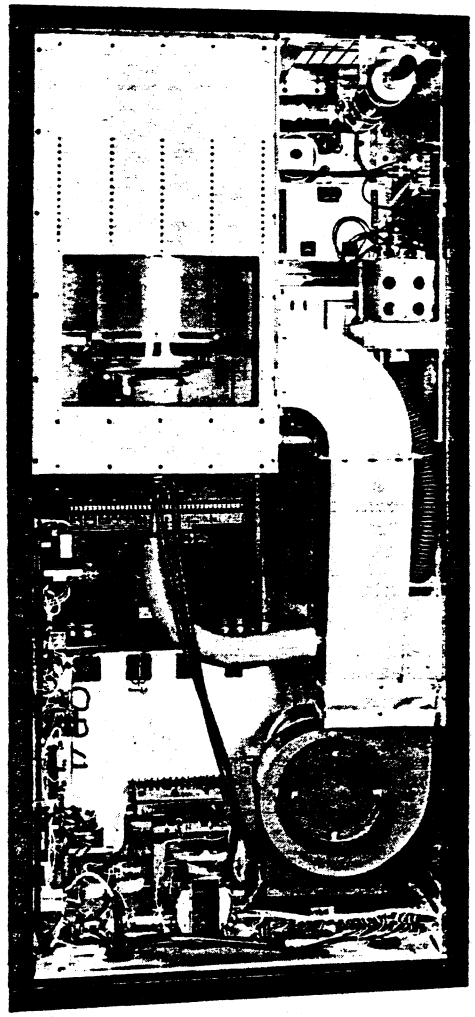
nly one tube . . . wide RF bandwidth

phase is provided. The FM-25K will restart automatically following a total power failure, while loss of a single phase will shut down the transmitter.

High Altitude Rating—A high-capacity, direct-drive blower delivers sufficient air to cool the transmitter at altitudes up to 10,000 feet (3048 meters).

Additional Protection—Four magnetic circuit breakers are utilized to protect the blower motor, the filament supply, the IPA supply and the bias supply. A wide-ranging interlock system and a drop solenoid system quickly discharge power supplies to safe levels.

ATS Compatibility—The simple control logic interface and full metering in the FM-25K permit ATS operation.

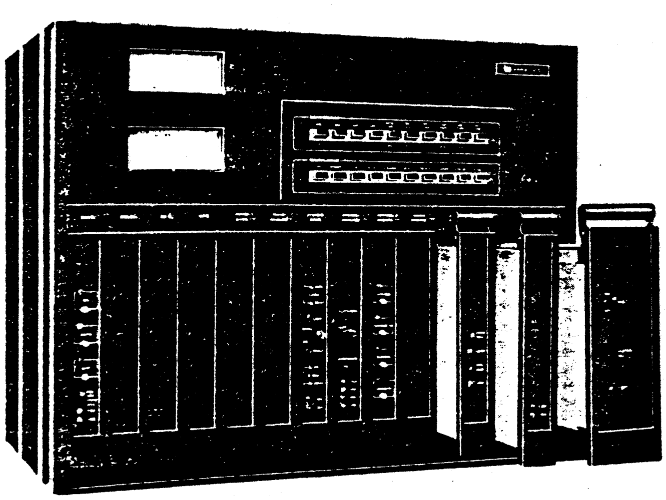


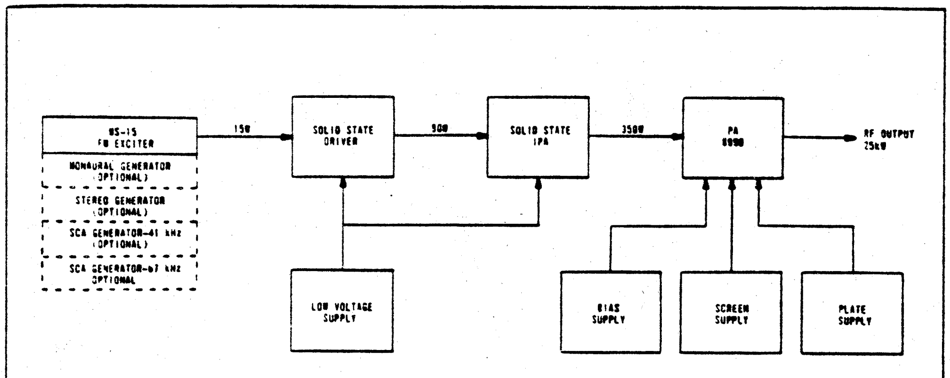
MS-15 EXCITER. The solid-state MS-15 exciter employs Digitally Synthesized Modulation (DSM), overshoot compensation, and other Harris exclusive design techniques, to give you an FM sound that is noticeably cleaner, noticeably louder than any competitive signal.

The DSM stereo generator is a Harris development which eliminates the tradeoff that exists between switching type stereo generators (poor separation at high frequencies) and balanced modulator types of stereo generators (poor harmonic rejection and SCA crosstalk). The DSM stereo generator is capable of both 50 dB separation (typical) through 15 kHz and an exceptionally clean baseband, promoting minimal interaction between stereo and SCA service. Also, pilot phase is automatically controlled so that high separation can be maintained under varying operating conditions.

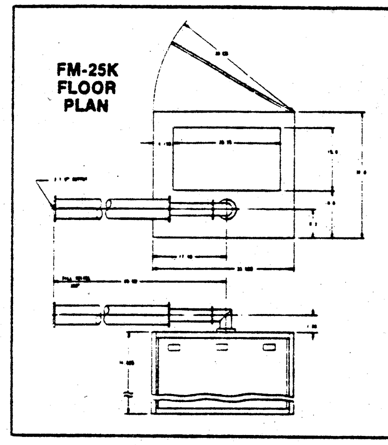
A Dynamic Transient Response (DTR) filter has been developed by Harris for FM stereo, which holds overshoot to 2% or less on any program material processed by any limiter. As a result, a 2 to 6 dB increase in loudness can be achieved without degradation of audio quality. Controlled transient response, high stereo separation, low crosstalk and low intermodulation distortion are all maintained with increased loudness. For monaural stations wishing to protect 41 and/or 67 kHz SCA channels, a defeatable linear phase lowpass filter is provided for optimal linear control of overshoot.

The MS-15 is available for wideband, mono or stereo operation, with or without SCA. The modular construction of the MS-15 allows you to change the mode of operation or to add SCA at any time, by simply plugging in the appropriate module(s).





FM-25K BLOCK DIAGRAM



FM-25K FLOOR PLAN

FM-25K SPECIFICATIONS

GENERAL

POWER OUTPUT: 10 kW to 25 kW.
FREQUENCY RANGE: 87.5 to 108 MHz, tuned to specified operating frequency. Exciter programmable in 50 kHz increments.
RF OUTPUT IMPEDANCE: 50 ohms.
OUTPUT TERMINATION: 3⅛″ EIA flange.
FREQUENCY STABILITY: ±300 Hz 0° to 45°C TCXO.
TYPE OF MODULATION: Direct Carrier Frequency Modulation.
MODULATION CAPABILITY: ±100 kHz.
AC INPUT POWER: 208/240 V, 3-phase, 50/60 Hz and 360/415 V, 3 phase. 50/60 Hz, 4-wire. Power consumption: 40kW typical.
RF HARMONICS: Suppression meets all FCC requirements.
ALTITUDE: 10,000 feet (3048 meters).
AMBIENT TEMPERATURE RANGE: −20°C to +50°C. Maximum temperature 50°C @ sea level, decreasing 2°C per 1000 feet (305 meters) to 30°C maximum at 10,000 feet (3048 meters).
MAXIMUM VSWR: 1.7 to 1.
SIZE: Transmitter cabinet, 34.6″ W (87.8 cm) x 71.7″ H (182.1 cm) x 31.0″ D (78.7 cm). HV power supply cabinet: 48.0″ W (121.9 cm) x 60.2″ H (152.9 cm) x 24.2″ D (61.5 cm).
FINISH: White, blue and black.
WEIGHT AND CUBAGE: (Estimated) Export: 3000 lbs. (1361 kg). Domestic: 2700 lbs. (1225 kg). Cubage: 150 cubic feet.

MONAURAL MODE

AUDIO INPUT IMPEDANCE: 600 ohms balanced, resistive, adaptable to other impedances.
INPUT FILTER: Controlled response LPF, defeatable.
AUDIO INPUT LEVEL: +10 dBm ±1 dB for 100% modulation at 400 Hz.
AUDIO FREQUENCY RESPONSE: Standard 75 microsecond FCC pre-emphasis curve ±0.5 dB, 30-15,000 Hz. Selectable: flat, 25 or 50 microsecond pre-emphasis.
HARMONIC DISTORTION: 0.2% or less, 30-15,000 Hz.
IMD: 0.2%, 60/7000 Hz, 4:1 ratio.
FM NOISE: 68 dB below 100% modulation (ref. 400 Hz @ ±75 kHz deviation).
AM NOISE: 55 dB below reference carrier AM modulation 100%.

STEREOPHONIC MODE

TYPE OF MODULATION: Digitally Synthesized Modulation (DSM).
AUDIO INPUT IMPEDANCE: (left and right) 600 ohms balanced, resistive. Adaptable to other impedances.
AUDIO INPUT LEVEL: (left and right) +10 dBm ±1 dB for 100% modulation at 400 Hz.
AUDIO FREQUENCY RESPONSE: (left and right) Standard 75 microsecond, FCC pre-emphasis curve ±0.5 dB 30-15,000 Hz. Selectable: flat, 25 or 50 microsecond pre-emphasis.
INPUT FILTERING: 15 kHz LPF, 45 dB rejection at 19 kHz.
OVERSHOOT PROTECTION: Dynamic transient response (DTR) filter.
AUDIO TRANSIENT RESPONSE: 2% maximum overshoot beyond steady state. Defeatable for test purposes.
HARMONIC DISTORTION: (left or right) 0.4% or less, 30-15,000 Hz.
IMD: 0.4%, 60/7000 Hz, 4:1 ratio.
FM NOISE: (left or right) 65 dB minimum below 100% modulation. Reference: 400 Hz, 75 microsecond de-emphasis, ±75 kHz deviation.
PILOT OSCILLATOR: Crystal controlled.
PILOT STABILITY: 19 kHz ±1 Hz, 0° to 45°C.
PILOT PHASE: Automatically controlled.
STEREO SEPARATION: 40 dB minimum 30-15,000 Hz, 50 dB typical.
CROSSTALK: (main to stereo sub-channel or stereo sub-to main channel) 45 dB below 90% modulation.
SUB CARRIER SUPPRESSION: 50 dB below 90% modulation.
76 kHz SUPPRESSION: 60 dB minimum below 100% modulation.
MODES: Stereo, mono (L + R), mono (L), mono (R). Remoteable.

SCA SPECIFICATIONS

MODULATION: Direct FM.
FREQUENCY: 41 or 67 kHz programable, any frequency between 25 and 75 kHz on special order.
FREQUENCY STABILITY: ±500 Hz.
MODULATION CAPABILITY: ±7.5 kHz.
AUDIO INPUT IMPEDANCE: 600 ohms balanced (AC coupled) and 2000 ohms unbalanced (DC coupled).
AUDIO INPUT LEVEL: +10 dBm ±1 dB for 100% modulation at 400 Hz.
AUDIO FREQUENCY RESPONSE: 41 kHz and 67 kHz, 150 microsecond pre-emphasis ± 1 dB, standard. Selectable: flat, 50 or 75 microsecond pre-emphasis.
INPUT FILTERING: Programable LPF, 4.5 kHz standard.
DISTORTION: Less than 1%, 30-4500 Hz. ±5 kHz deviation.
FM NOISE: (main channel not modulated) 55 dB minimum (ref: 100% = ±5 kHz deviation at 400 Hz).
CROSSTALK: (SCA to main or stereo sub-channel): −60 dB or better.
CROSSTALK: (main or stereo sub-channel to SCA): 50 dB below ±5 kHz deviation of SCA, with mono or stereo channels modulated by frequencies 30-15,000 Hz, SCA demodulated with 150 microsecond de-emphasis.
CROSSTALK: SCA to SCA (41 kHz/67 kHz) 50 dB demodulated with 150 microsecond de-emphasis.
AUTOMATIC MUTE LEVEL: Variable from 0 to −30 dBm.
MUTE DELAY: Adjustable 0.5 to 20 seconds.
INJECTION LEVEL: 1% to 30% of composite. Adjustable.

WIDEBAND MODE

INPUT IMPEDANCE: Greater than 5000 ohms resistive, unbalanced.
INPUT LEVEL: 1.0 VRMS nominal for ±75 kHz deviation.
AMPLITUDE RESPONSE: ±0.25 dB, 30 Hz to 75 kHz.
PHASE LINEARITY: ±2°, 30 Hz to 75 kHz.

ORDERING INFORMATION

FM-25K, 25,000 watt FM broadcast transmitter with MS-15 exciter, for wideband operation, 50/60 Hz (specify 50 or 60 Hz)	**994-8258-001**
Spare tube	**374-0151-000**
Mono generator (add for mono operation)	**994-8019-001**
DSM stereo generator with DTR (add for stereo operation)	**994-8020-001**
SCA generator (add for SCA operation, specify 41 or 67 kHz)	**994-7992-001**

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SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE.