A SMALL HELIUM-3 CYCLOTRON*

R. M. Main, M. R. Curtis, R. Grazier
P. B. Kennedy, B. H. Smith, D. A. Spence

Lawrence Radiation Laboratory
University of California
Berkeley, California

Summary

A 27-inch AVF cyclotron of fourfold symmetry designed specifically for use in helium-3 activation analysis is now in operation at the Lawrence Radiation Laboratory in Berkeley. The fixed energy and modest beam quality requirements have resulted in an instrument of minimum size, weight, power consumption, and fabrication costs.

New techniques were developed to construct edge-cooled tape-wound magnet coils which are housed inside the vacuum chamber. Other unusual design features include: unit construction dee liners hydraulically pressed to the pole tip contours; two 55° dees-in-valleys operating in push-pull; a removable top yoke assembly which allows complete access to the pole area; a narrow gap with an average spacing of 1.5 inches making possible maximum utilization of the pole diameter for stable orbits. In conjunction with the tape coils, the use of this small gap also results in a magnet of very high efficiency. The cyclotron operates with an average field of 16.6 kG and a grounded-grid triode provides 40 kV dee-to-ground (150 keV/turn).

Power is supplied by 220 V, 3-phase service. The magnet requires 17 kW, the RF system uses 17 kW, and the remaining instruments, pumps, and controls use an additional 6 kW. The complete system, including vacuum pumps and power supplies, weighs 10.7 tons and occupies a floor space of 37 x 64 inches.

Introduction

Recent advances in the techniques of charged-particle activation analysis have generated a high degree of interest in the production of an inexpensive light-ion accelerator. Further impetus has been provided by the demand for a similar instrument for isotope production, stimulated by the development of instruments and techniques for the use of short-lived positron emitters in biological research and medical diagnostics. The investigation of techniques for light-element activation analysis by Markowitz and Mahoney,[1] using ^{3}He beams from the Berkeley heavy ion linear accelerator and subsequent calculation of ^{3}He interaction cross sections with heavier elements, have indicated the broad versatility of this ion, both for activation analysis and for isotope production.

The 27-in ^{3}He cyclotron described in this report was designed specifically for use in these fields. We have, at the same time, attempted to develop methods of fabrication and design that will make possible its reproduction at the modest cost that will be necessary if these powerful analytical and diagnostic techniques are to have broad application.

Design Considerations

Although the utility of the instrument increases with increasing ion energy, most work is possible at about 10 MeV. We have chosen a maximum of 18 MeV to allow for the penetration of vacuum and target windows. Since a moderate energy spread is tolerable, energy can be varied with absorbers. A fixed-energy accelerator is thus acceptable. The restriction on beam divergence is modest, demanding only the ability for focusing on a spot about 0.75 in diam.

The primary design objectives for the ^{3}He cyclotron are high reliability coupled with simplicity of operation and maintenance. A secondary objective is low cost, which implies minimum instrument weight and size, minimum power consumption, and the utilization of fabrication methods that allow low-cost reproduction. These objectives are common to the design of all analytical instruments, but a cost analysis of the total installation and instrument operation must be given full consideration in order to indicate the degree of emphasis to be placed on each aspect of the design.

To be generally useful, the cyclotron must be capable of installation, with minimum building alterations, in existing laboratories. The necessity for heavy concrete neutron shielding is the predominant factor in the cost of the installation. The space requirements of either activation analysis or isotope production are relatively modest; clearance of a few feet around the cyclotron is adequate. Floor-area requirements of the cyclotron thus greatly affect the enclosure area requirements which, in turn, determine the total mass of shielding and, more important, the floor loading. The floor loading also depends on the height of the shielding, so that, if special foundations are to be avoided, restrictions on the instrument height and required overhead clearance must be observed. The floor loading under the cyclotron itself must also be minimum for the same reason.

Operational costs that are affected by design are those concerned with power consumption. In estimating the cyclotron operating costs, we have assumed a power cost of $0.015/kWh and 2.7 ft^3/kWh of cooling water at $.0015/$ft^3$. At 65% over-all efficiency each instrument kilowatt requires 1.5 kW of input power. Assuming a lifetime of 30 000 hours, the operating cost per instrument kilowatt is therefore $880, $700 for power and $180 for cooling water. For each instrument kilowatt an additional capital cost of $280 is estimated for power installation and power supplies. Conventionally designed cyclotrons of the size considered here generally require in excess of 100 kW and, over their lifetimes, the cost of power and power supplies exceeds the cost of the instrument.

These considerations have led to the extreme emphasis that we have placed on minimizing size, weight, and power consumption in the design of the ^{3}He cyclotron.

Magnet Construction

The magnet material is Type 1008 low carbon steel. The yoke and legs were cut from one 8-in thick slab and both poles from one 5-in thick slab. The tolerance requirements for these pieces are relatively lax, with the following exceptions: the inner surfaces of the yokes must be flat; the two legs must be of identical length with their ends flat and parallel; and the faces of the poles must be flat and parallel. The required precision of parallelism and flatness to within 0.0002 in and with a 16 μ-inch finish was easily and inexpensively achieved with a Blanchard grinder. For esthetics, other surfaces on the magnet were rough machined or rough ground. The poles were mounted on a mandril through center holes, which were used for adjustable magnetic center plugs, and turned together on a lathe, thus ensuring concentricity of the center holes and identical diameters of the poles.

The magnet was assembled with the poles coaxially aligned on the mandril to within a few tenths mil and positioning dowels placed in match-drilled holes at the mating surfaces of the legs and yokes. With the magnet excited to operating field strengths the pole tips are parallel to within about 0.0002 in across the 27-in diam. Repeated removal and replacement of the top yoke-pole assembly causes no detectable change in parallelism, and concentricity of the poles remains within 0.0005 in.

The Thomas pole hills are 35-deg sectors, truncated 0.75 inches from the center of the pole. These hills were produced as follows: the sectors were cut from a single piece of Type 1008 low-carbon steel, ground flat on one side, match drilled, and screwed to a flat, precision-drilled lathe-backing plate. A rough contour, derived by calculation and intuition, was machined on the hill surfaces with a tracer lathe. They were then positioned on the pole tips, measurements of the magnetic field were made, and B_{ave} as a function of radius was computed.[2] A thin (0.010-in) shim was placed under each hill and the field measurements were repeated. From this information the dependence of B_{ave} on hill height at all radii was derived, and contour corrections to the hills were calculated to produce the isochronous field which has been predicted by a second computer program.[3] The corrected contour was machined on the hills and the measuring process repeated with successively thicker shims placed under the hills to position the contour to the proper height. After the isochronous field was produced, a new set of shims was machined to the proper height and contour. Five measurements were required to produce the proper contour.

A minimum pole gap of 0.7-in was chosen as that necessary for beam clearance at the outer edge; more than adequate for the actual 1/4-in beam height experienced at extraction radius. Since no shims are used in the valleys, the Thomas hill shims are tapered in height and the resulting configuration allows for the extension to the dees over the hills at the center of the pole with adequate spacing for the high voltages, as shown in Fig. 1.

Magnet Coils

The emphasis we have placed on minimum cost and power consumption demands the design of a magnet system that is highly efficient. For the coils this requirement implies the use of copper with a high packing factor, the placement of the coils near the magnet's median plane, and the largest possible coil cross section consistent with efficient steel configuration. This latter restriction on coil cross section involves the use of the shortest possible pole height (and thus coil height) to achieve maximum magnetic efficiency and at the same time minimum steel weight.

These considerations have led to a coil system that is unconventional in three important aspects: first, the use of edge-cooled copper tape coils with a packing factor of about 90%; second, the placement of the coils to within 0.75-in of the pole-tip edge; and, third, the inclusion of the coils, with large areas of exposed epoxy, within the cyclotron's vacuum chamber.

The coils consist of 152 turns each of 0.027-in by 3.5-in copper tape wound on a 0.125-in copper mandril, with turn-to-turn insulation provided by a layer of epoxy (Hysol Type C-35) and 0.002-in glass cloth. After winding, the coils were resistively heated to progressively higher temperatures to cure the epoxy, with a final 2-h cure at 160°C. The edges of the cured coils were machined flat and parallel and subsequently etched with nitric acid so that the glass-epoxy insulation extended approximately 0.003-in beyond the copper. The cooling plate consists of a 0.5-in thick aluminum plate in which water channels were machined, and a 0.06-in thick cover plate welded at the inner and outer edges. The entire outside of the cooling plate was hard anodized to a depth of about 0.002-in to provide insulation between the plate and the coil edge. The plate was bonded to the coil with a thermally conducting grease (G.E. Insulgrease No. G-640) and sandwiched between the coil and magnet yoke. The grease bond also serves as a vacuum seal. Fig. 2 shows the details of the coil mounting.

The magnet power supply is located in the cyclotron stand-cabinet, and power is brought directly from the supply to the coils on a concentric bus system through the bottom yoke. Bussing between the bottom and top coils is inside the vacuum system. Removal of the top yoke-pole assembly to provide access to the cyclotron interior requires only a quick disconnect of this bussing.

The magnet operates at an average field of 16.6 kG with a current of 265 A (81 000 ampere-turns) and a current density in the coils of 2700 A/in^2. The total power of 16.0 kW is conducted across 800-in^2 of grease bond (20 W/in^2) with a temperature rise across the bond of about 15°C.

These coils have been in operation more than two years and no failures that can be attributed to the method of coil winding or cooling plate bonding have occurred. The failures experienced were caused by arcing in the bussing system.

Magnet Performance

With an average gap field of 16.6 kG approximately 80% of the reluctance is in the gap, with about three quarters of the steel reluctance at the pole bases. An increase in yoke thickness is thus not warranted, and calculations indicate that only minor improvement in over-all system efficiency would result from tapering of the pole.

The narrow gap allows achievement of isochronous fields to within 1 inch of the pole edge, resulting in a highly efficient system. The pole was shimmed to provide isochronous fields for ^{3}He (e/m=0.66) particles, but the fact that the Thomas shims are more saturated at the outer edge then at the center of the pole results in an unexpected advantage with regard to protons and α-particles. If the excitation is reduced slightly the central field is lowered, but the edge field remains constant. The resulting profile closely approximates the proton (e/m=1.0) isochronous field. Conversely, a slight increase in excitation produces the flatter profile necessary for e/m=0.5 isochronism. The instrument is thus adequate for all of the light particles without the necessity of auxiliary profile coils.

The shimming of the pole was accomplished with a precision such that, with the designed operating dee voltage of 40 kV the 0-deg particle phase excursion is limited to 15-deg. Correction of the phase slippage occurring at the center is made with the adjustable plugs and by adjustment of the radial field profile with excitation, as discussed above.

The azimuthal field profile at several radii is shown in Fig. 3. The narrow gap makes possible the production of flutter at a very small radius; significant focusing is available at 2.0 in. The vertical tune is approximately constant at about 0.16 from 2.5 to 10 in, then increases to about 0.23 at the extraction radius of 12.5 in.

The first and second azimuthal harmonics of the magnetic field are shown in Fig. 4. The relatively constant first harmonic amplitude at large radii is accounted for by the nonparallelism of the pole faces; the larger value at small radii is probably caused by misalignment of the shims at the center. The second harmonic is due to the two fold symmetry of the yoke-leg structure. Neither of these harmonics is large enough to be of significance.

Accelerating System

The removable top yoke-pole structure allows quick access to the entire interior of the cyclotron. Simple and accurate positioning of the RF structures is thus possible, and the system can be designed with relatively close spacing of the RF surfaces.

To minimize the RF power requirements, we have utilized the dee-in-valley configuration of MacKenzie.[4] This configuration requires a four-fold symmetry of the pole-tip, with the two dees in opposite valleys and operated in push-pull. The maximum gain-per-turn with 55° dee angles is $3.7\ V_{dee}$ eV. Following MacKenzie, we have also broadened the tips of the dees at the center of the pole where the minimum hill shim height allows adequate clearance (see Fig. 1). The first 1-1/2 turns thus receive full dee voltage gain from each dee, and the particles are rapidly accelerated away from the center and through the region of zero vertical magnetic focusing (about 1.5 inches radius).

The resonant system consists of the two dees and, for ^{3}He, a 6-turn coil, 28-in long and 6-in diam. The entire system is supported from the floor of the vacuum chamber by two 6-in long alpha alumina insulators at the outer ends of these dee stems and, at the center of the coil, by the coil-dee cooling-water coupling line. Frequency change of the system, necessary for acceleration of different ions, can be made by changing the coil.

The oscillator is a grounded-grid triode (EIMAC 3W5000), supported on the removable back wall of the coil chamber and capacitively coupled to one side of the coil by an adjustable shoe. A grounded balancing shoe, also mounted on the back wall, is capacitively coupled to the opposite end of the coil. Adjustment of these two coupling shoes provides for variable step-up ratio, dee balancing, and trim tuning of the system. An additional capacitive tuner for each dee is mounted on the side wall of the vacuum chamber. The entire back wall of the RF coil chamber is removable, allowing unobstructed access to the coil. The coil is held in position by six screws on each side, so that rapid change is possible.

A second EIMAC 3W5000 triode is used as a hard tube plate modulator for dee voltage regulation and high speed spark protection. The oscillator operates at approximately 70% efficiency, providing 8 kW of RF power to drive the dees to the normal operating potential of 40 kV, resulting in a maximum energy gain/turn of 150 KeV. An additional 7 kW is dissipated in the oscillator, modulator, and power supply.

The close dee-ground spacing and high RF voltages result in high VE values, and the fact that the system is frequently let up to atmosphere makes it mandatory that a method be provided for fast bake-in of the high voltage surfaces. During bake-in the energy that can be dissipated in sparks must be restricted, since high-energy sparking can produce pits in the copper surfaces. The system used allows delivery of power into glows but detects the fast current rise of a spark as a signal for RF turn-off and, after a delay to allow the gases produced by the spark to be pumped, RF turn-on. Both the turn-off time and the turn-on delay can be adjusted to provide for the most efficient bake-out. In practice, 5 to 10 sparks per second can be produced, and a very rapid bake-out results. After a normal let-down to atmosphere, stable RF operation is achieved after 10 minutes of bake-out and final pumping. The entire pump-down bake-out cycle takes about 25 minutes.

Each dee is made of two sheets of 0.030-in copper, hydraulically pressed to mirror-image dies, jigged together on 0.5-in OD water-cooling lines terminating in a machined copper bloc, and oven-brazed.

The dee-liners are also hydraulically formed to a die (the prototype hills and lathe-backing plate) identical to the pole tip, except for rounded edges added at suitable positions. The liners, of 0.030-in copper, are cooled only by contact with the pole tips (as shown in Fig. 1).

The method of hydraulic press forming proved to be quite inexpensive, and most rewarding is the fact that all contours are smooth in the high-RF field regions.

Vacuum System

The 27-in cyclotron design represents a variation from usual cyclotron vacuum-system design in two aspects: first, the inclusion of the magnet coils with relatively large areas of exposed epoxy within the vacuum chamber and, second, the requirement for frequent let-down to air which demands that the system be designed for rapid recovery from atmosphere.

The vacuum chamber consists of four walls with O-ring gasketing to the two magnet yokes, which form the top and bottom of the chamber. A 14-in extension of the chamber beyond the magnet contains the RF coil and also serves as a pumping manifold. This arrangement allows high pumping speeds all around the pole-tip edge. The single-sheet dee liners, which cover the magnet coils completely, prevent degassing of the undersurface of the liners, the pole shims, and the magnet coils directly into the region of the dees. The back wall of the extension, which supports the RF oscillator and coupling system, is removable to allow for quick change of the RF coil.

The pumping system consists of a 21-ft^3/min mechanical pump and an oil diffusion pump with an air speed of 1700 l/s, a ^{4}He speed of 2100-l/s and a fore-pressure tolerance of 0.5 torr. The pumps are coupled at one side of the RF coil chamber through a 10-in diam elbow equipped with a single-bounce louver baffle and a pneumatically-operated gate valve, 6-in in diameter. The mechanical pump is coupled to both the diffusion pump and the vacuum chamber through a three-way ball valve to allow its use in both rough and fore pumping.

The system has an air speed of about 1000 l/s and a ^{4}He speed of 1200 l/s, measured at the pole edge. With an ion source through-put of 4 torr-l/s the operating system pressure is about 3.5 x 10^{-5} torr.

The chamber pressure can be reduced from atmosphere to operating pressures within 15 min.

Ion Source

The ion source is of the dual cold-cathode hooded-arc PIG type, similar to the one used for the production of multiply-charged heavy ions at the Berkeley Hilac.[5,6] It is simple in construction, is long lived, and is particularly applicable for use in a small narrow-gap cyclotron where over-all height is restricted.

The plasma column is approximately 0.25-in in diameter by 0.75-in long and, with aluminum cathodes, operates at about 400 V with currents of about 0.1 A. With this arc-current a beam of 3 to 4 μA of He^{+2} is extracted from a 0.050-in diam hole in the center of the anode. Gas consumption is approximately 1 STP-cc/min. The operation of the cyclotron to date has been restricted to these low beam intensities because of a lack of shielding. However, with water-cooled cathodes to allow high arc currents, and an increase in the ion window area, the source is capable of producing currents of He^{+2} as high as the calculated space-charge limit of the cyclotron (approximately 75 μA).

This type of ion source is also capable of producing large currents of both positively and negatively-charged hydrogen and deuterium.[7]

Deflector

The deflector, positioned as shown in Fig. 5, is a conventional electrostatic channel, 6-in in length (23° arc) with a 0.005-in tungsten septum and a flattened 0.75-in in diameter copper rod as a high-voltage electrode. The channel conforms to the beam orbit, and its width may be varied from 1/8 to 1/4 in. The radius and entrance angle of the channel can be remotely adjusted during operation for maximum extraction. The beam exits the cyclotron approximately perpendicular to its front face.

The system was designed for 65 kV and, depending on channel width, operates with voltages from 30-50 kV. A 75-kV, 5-mA power supply, unregulated at present, is used.

Acknowledgments

We wish to acknowledge the valuable contributions made by W.J. Elwood in the fabrication of the instrument, by H.P. Robinson in the study of the beam characteristics. We also wish to thank the Hilac operations staff, directed by A. Ghiorso, for their assistance during construction. Special thanks is owed the members of the University of California, Davis, cyclotron staff, under the direction of J. Jungerman, for their counsel in all aspects of the design and assistance in preparation of the computer programs.

References

1. S.S. Markowitz and J.D. Mahoney, Anal. Chem. 34, 329 (1962).

2. J. Kibbe, DAMDEC, an IBM 7094-44 Code for Magnetic Measurement Data Reduction, University of California, Davis, Physics Department, 1965

3. A.A. Garren and A.S. Kenney, CYDE(DORO), Lawrence Radiation Laboratory Report UCID-2869-1967.

4. K.R. MacKenzie, National Research Council, 656, 146 (1959).

5. R. Jones and A. Zucker, Rev. Sci. Instr. 25, 562 (1954).

6. C. Anderson and K. Ehlers, Rev. Sci. Instr. 27, 809 (1956).

7. K. Ehlers, B. Gavin, and E. Hubbard, Lawrence Radiation Lab. Report UCRL-10385, July 1962.

18 MeV ^{3}He CYCLOTRON SPECIFICATIONS

Magnet

Dimensions	64-in x 37-in x 27.3-in high
Weight	7.4 tons Steel; 0.46 tons Coil
Pole	27-in diam x 4.75-in high
Gap	2.1-in max; 0.7-in min
B(ave)	16.6 kG
Shimming	4 - 35° Thomas sectors
Trim Coils	None
Power Supply	Full-Wave MagAmp, 1:5000 reg.

RF System

Dees	Two 55° in-valley push-pull
Resonant System	Dees & Coil in Vacuum
Operating Voltage	40 kV normal (50 kV max)
Frequency	17 MHz
Oscillator	EIMAC 3W5000 Grounded-grid
Coupling, Plate	Capacitive
Coupling, Cathode	Inductive
RF Power Supply	10 kV, 2.5 A
Modulator	EIMAC 3W5000, 1:1000 reg.
Dee Bias	0-1 kV, 5 mA

Electrostatic Deflector

Length	6-in (23° arc)
Septum	0.005-in Tungsten
Voltage	40 kV

Ion Source

Type	Cold-Cathode PIG
Arc	400 V, 0.1 A, 40 W
Gas Consumption	1 STP-cc/min

Vacuum System

Mech. Pump	21 ft^{3}/min Kinney (KTC-2)
Diffusion Pump	6-in Dresser (DPD 6-1800)
Baffling	Louver in 10-in elbow
Pressure (Operating)	3 x 5 x 10^{-5} torr
Normal Pump Down	15 minutes

Miscellaneous

Power Input	40 kW, 220 V, 3ϕ
Cooling Water	13 gal/min
Total Weight (inc. pwr. supplies)	10.7 tons

Fabrication Cost

Material			$22,000
Labor (inside)	3500 hr	@ $7.50	26,500
Labor (outside)	1500 hr	@ $8.00	12,000
Total Fabrication Cost			$60,500

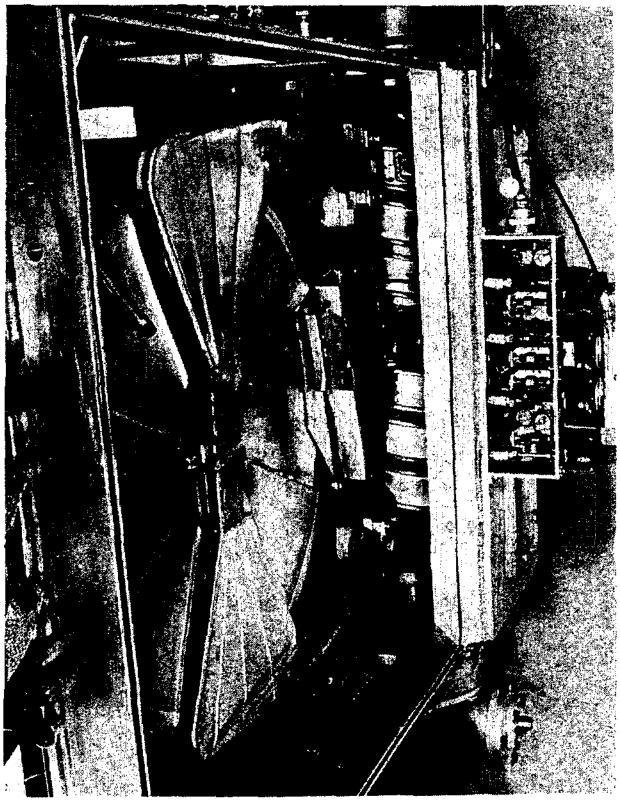

Fig. 1. 27-in ^{3}He cyclotron with top yoke-pole assembly removed for access.

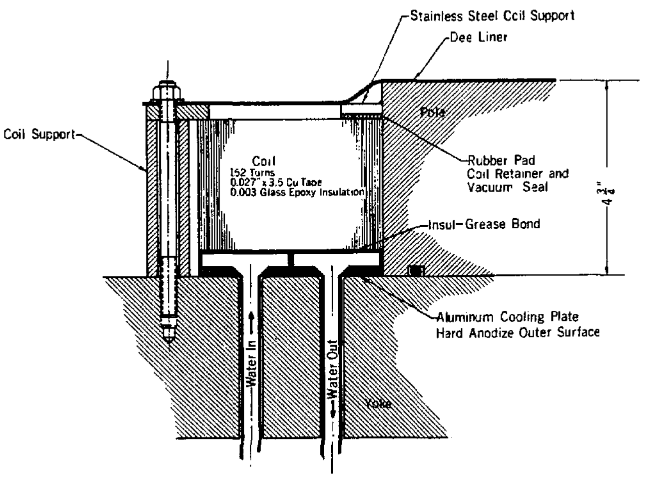

Fig. 2. Schematic cross section of coil mounting details.

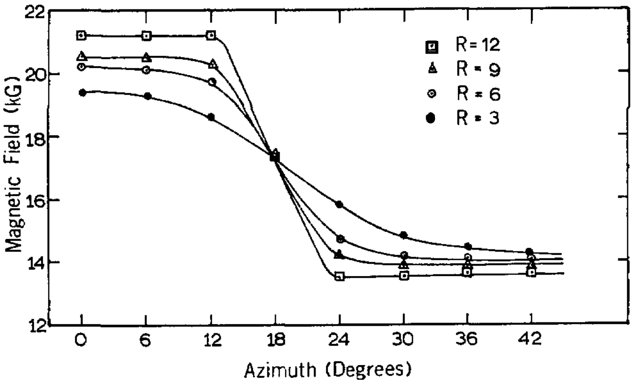

Fig. 3. Azimuthal magnetic field plotted at four radii.

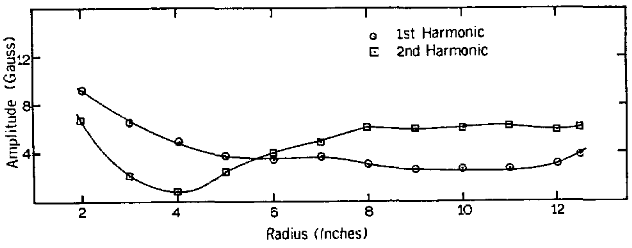

Fig. 4. The amplitude of the first and second magnetic field harmonics for radii between 2-in and 12.5-in.

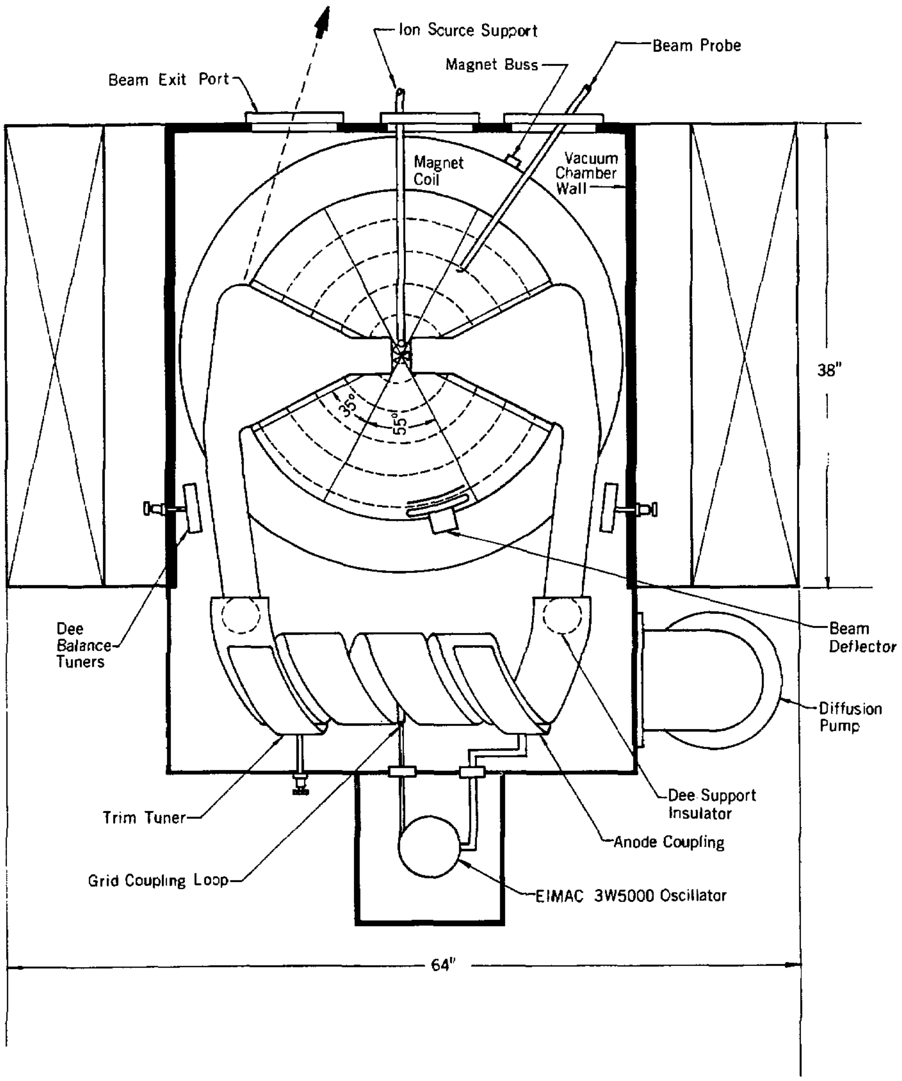

Fig. 5. Schematic showing ^{3}He cyclotron component layout.