Title
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Publication Date
1960-11-22

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BERKELEY, CALIFORNIA

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ABSTRACT

A standing-wave linear accelerator that accelerates ions in the mass region from helium to argon to an energy of 10 Mev/nucleon is described.

HEAVY-ION LINEAR ACCELERATOR*

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INTRODUCTION

For many years nuclear reactions have been studied with neutrons, protons, and alpha particles as projectiles. However, heavier projectiles are particularly useful for studies in Coulomb excitation, transuranic and neutron-deficient element production, and the many problems of interactions of complex nuclei.[1] For these experiments, heavy-ion beams of energies up to about 10 Mev/nucleon are required. These can be produced by cyclotrons or radio-frequency linear accelerators.

Cyclotrons using gas stripping have been used to accelerate carbon and other ions to energies as high as 10 Mev/nucleon. The cyclotrons used at Berkeley[2-7], Birmingham[8,9], Stockholm[10,11], and Saclay[12,13] were originally designed for light ions. When used for heavy ions, they accelerate doubly charged ions, as produced by the source, at a "sub-harmonic" of the

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*This work was done under the auspices of the U.S. Atomic Energy Commission.

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cyclotron frequency. Within a few orbits these ions are stripped of several electrons and are further accelerated to full energy with the fundamental frequency of the cyclotron. The random nature of the stripping process results in a large energy spread in the circulating beam and leads to difficulties in extraction.

The cyclotron at Oak Ridge[14] was designed for heavy-ion acceleration and utilized an ion source[15] that directly produced a multiply charged ion, nitrogen 3+. Since this cyclotron had a beam energy of 29 Mev., it could not produce reactions with heavy target nuclei. A larger cyclotron of this type was constructed at Moscow.[16, 17] It uses an ion-source producing carbon-4+, nitrogen-5+, or oxygen-5+ ions and gives beam energies of 90, 115, and 103 Mev, respectively. This cyclotron is sometimes operated with "sub-harmonic" acceleration.

In 1953 we began a study of accelerators to produce 10 Mev/nucleon heavy ions. We hoped to obtain beams of high intensity and good quality for many ions. Our preliminary considerations led us to conclude that to obtain a large variety of ion beams of good quality at the desired energy would be a formidable problem for a cyclotron. A linear accelerator of the Alvarez design seemed to be a more promising solution.[18, 19] Not only does a linear accelerator naturally produce a well-focused monoenergetic beam, but also the requirements on the ion source are relaxed, since electron stripping can be done at definite stages in the accelerating process without introducing appreciable energy spread or loss of beam intensity.

In 1954 the design study was completed, and subsequently two essentially identical heavy-ion linear accelerators were built. One, at the Lawrence Radiation Laboratory of the University of California, began operation in April 1957 and is used primarily for research in nuclear chemistry. The other, at Yale University, began operation in March 1958 and is used primarily for research in nuclear physics. Both machines produce beams of any ion from helium to argon mass at 10 Mev/nucleon. The beam intensities for carbon or nitrogen are about 1 μa (average). Recently a somewhat similar accelerator has been built at Kharkov.[20]

A simplified sketch of the Yale accelerator is shown in Fig. 1, and a photograph of the Berkeley accelerator is shown in Fig. 2. The linear accelerators consist of a Cockcroft-Walton injector and two 70-Mc cavity resonators of the Alvarez design. A 2-msec pulse of ions from the source, with $e/m \geq 0.15$,[21] is injected 10 to 15 times a second into the first cavity. This cavity, called the prestripper, contains 37 grid-focused drift tubes as shown in Fig. 3. In the prestripper the ions are accelerated from an energy of 0.07 Mev/nucleon to 1.0 Mev/nucleon. Before entering the second cavity, called the poststripper, the ions are passed through a thin layer of matter to increase their e/m ratio to 0.3 or more. The poststripper contains 67 drift tubes (Fig. 4), each of which encloses a focusing magnet, as shown in Fig. 5. The rf power used in the two cavities during the 3-msec pulse is about 3 Mw.

As in all accelerators, the final design represents a compromise between physically possible and economically feasible solutions. The choice of the acceleration frequency was determined by the availability of power tubes and by the size of the drift tubes into which quadrupole magnets would have to be installed. The duty factor of the accelerator was determined by the cost of radio-frequency power and the need for special cavity cooling tempered by the desire for a large average beam current. The velocity at which stripping occurs was set by two factors: the relation between ion velocity and its equilibrium charge state, and the need to convert to strong focusing as soon as possible in order to reduce beam intensity losses due to grid interception.

It was not thought feasible to use strong focusing in the prestripper. Finally, the charge-to-mass ratio of the ions to be injected into the accelerator was determined by the charge states that could be produced by the developmental ion sources. All of these considerations are strongly dependent on the ions for which the machine is designed. These accelerators are optimum in the nitrogen-neon region. For lighter ions they are more complex than necessary and for heavier ions the performance (i.e., beam current) suffers.

ION SOURCE

The multiply charged ions are produced in a pulsed, cold-cathode discharge operating at high arc voltage and low gas pressure. The details of the source have been published elsewhere.[22] The magnet that supplies the field for the discharge is also used to select the desired ions for acceleration by the Cockcroft-Walton injector and thus to minimize space-charge blowup in the accelerating column. The extracting electrode is curved to produce a vertical focus near the horizontal focus of the analyzing magnet. Figure 6 is a sketch of the ion source and lens system used at Berkeley to inject ions into the column. The electrostatic lens is oval-shaped in an attempt to further overcome astigmatism of the beam, but the primary purpose of the lens is to provide additional control of beam optics. At Yale, this lens is not present, and a space-charge-neutralized beam is carried to the entrance of the column. Both systems work well and present a diverging beam to the column in order to obtain a real image[23] beyond its ground end. Additional focusing has been found necessary at both accelerators to obtain maximum beam output from the prestripper. Magnetic-quadrupole lenses are placed between the ground end of the accelerating column and the input to the prestripper. Since charge exchange causes appreciable loss of the multiply charged ions at pressures above 10^{-5} mm Hg, diffusion pumps must be used both at the ion source and the ground end of the column.

COCKCROFT-WALTON INJECTOR

The ion source and its associated equipment are located in an 8-by 8-by 10-ft aluminum-alloy high-voltage shell with 1-ft corner radii. The shell structure is mounted on four 10-in.-diam textolite columns 6 ft high, and the high-voltage power supply is located between these columns and directly below the shell. Local power in the shell is supplied by a 35 kw generator driven by special graphite-free V-belts from a 50 hp motor mounted below the ground-plane. The heat load of the magnet, diffusion pump, and baffle refrigerators is removed from the shell by a 3 hp air-cooled refrigerator at Yale, and by pumping oil-free freon refrigerant from the ground plane to the shell at Berkeley. The injector is located in a metal-sheathed room with 6 ft clearances at the shell sides and top. Dry cooling air circulates through the room. There is a provision for quick access through this room to the shell to allow changes of ion-source gas cylinders. All other operating controls are brought outside by means of insulated shafts.

The accelerating column is 4 ft long. It consists of 18 stainless steel electrodes and zirconia insulators joined by epoxy resin. The joints are vacuum-tight and are exceedingly strong, for although the column is supported at both ends, it is not under compression. The electrodes are connected to gradient hoops and to a string of voltage dividing resistors connecting the shell to ground.

The correct ion velocity at the input to the prestripper accelerator is obtained by using different values of the injector high voltage for different ions (see Table I). Because the maximum high voltage required is 472 kv, the injector was designed to operate up to 500 kv. The source of this voltage is a stack of 14 voltage doublers in cascade. The mechanical design of these units is similar to that used in the Bevatron injector.[19] Instead of the vacuum tube rectifiers described by Cork,[19] each of the four rectifiers in a voltage doubler consists of 1000 1/4-in.-diam selenium cells instead of a vacuum-tube rectifier. The bottom unit is driven by an 800-cycle, 20-kv (peak) voltage from a transformer fed by a motor-generator. The voltage-doubler stack will supply 1 ma at 500 kv with about 1-kv ripple.

When the ion beam is injected directly into the prestripper cavity from the Cockcroft-Walton, it is necessary to hold the high voltage of the injector constant to 4 kv to prevent a 10% loss in beam. Normally an rf buncher is used between the injector and the prestripper. Use of the buncher increases the sensitivity to voltage so that a 10% loss in beam occurs for a change of 0.7 kv or 0.15%. To achieve this stability a regulator is required. The regulator receives its error signal from a 3.0×10^9-ohm voltage divider connected from the high-voltage shell to ground, and controls the field of the 800-cycle alternator. The total capacitance (0.009 μf) from the shell to ground limits the drop in the high voltage to about 200v during the 2-msec beam pulse.

BUNCHER

The interval in phase of the rf accelerating voltage during which ions with the synchronous velocity are accepted by the prestripper linac is approximately $3\phi_s$, where ϕ_s is the phase of the synchronous ions. Since the beam from the injector is uniformly distributed in phase, only the fraction $3\phi_s/2\pi$ of the injector beam is accepted by the prestripper. The optimum synchronous-phase of a grid-focused linac is difficult to calculate, but the work of Smith and Gluckstern[24] and measurements on the Berkeley machine indicate that the synchronous phase of the prestripper is about 10 deg. Therefore, about 1/12 of a continuous monoenergetic beam should be accepted by the prestripper.

The fraction of the beam from the injector which is accepted by the prestripper can be increased by phase bunching. Bunching is done with an rf accelerating electrode operating at the same frequency as the linac. This electrode is separated from the prestripper by a drift space. As in a klystron, the buncher increases the velocity of ions that pass through late in phase and decreases the velocity of the ions that are early in phase. The faster ions overtake the slower ones in the drift space, and the beam accepted by the prestripper is increased. In operation this increase is by a factor of three.

The buncher electrode is a single drift tube mounted as shown in Fig. 7. It resonates at 70 Mc as a capacity-loaded quarter-wave line. The drift space is 48 in., and the operating voltage is 5000 v. The 1.5 kw of rf power required is obtained from a small coupling loop in the prestripper. The buncher voltage is adjusted by rotating this loop, and the phase of the bunch at the first gap is adjusted by varying the drift distance at Berkeley and with a line stretcher at Yale. Grids are used at the bore of the electrode to reduce rf defocusing.

PRESTRIPPER ACCELERATOR

Ions entering the prestripper with $\beta = 0.012$ (0.07 Mev/A) are accelerated to $\beta = 0.045$ (1 Mev/A). (A is the number of nucleons in the nucleus of the ion being accelerated). This cavity was designed to have a peak electric field in the gaps of about 2 Mv/ft, which was selected as being the practical maximum (at 70 Mc) as determined from a semiempirical analysis of vacuum sparking data.[25] The length of the cavity is determined by the desired velocity increase for the ions, their charge-to-mass ratio, the peak gap field, the synchronous phase, and the gap (g) to cell length (L) ratio. For grid focusing g/L must not be much greater than 1/4 in order that ions of all allowable phases are focussed. With e/m = 0.15, g/L tapering from 0.24 to 0.26, and 2 Mv/ft peak gap field, the cavity length is 14.93 ft, and 36 drift tubes are required. The average voltage gradient, E_0, is 0.5 Mv/ft.

The cylindrical part of the 124.1-in. i.d. vacuum tank is made of copper-clad steel. The steel is 0.45 in. thick, and the copper lining is 0.05 in. thick. The end walls of the tank are made of 4-1/2-in.-thick steel, copper-plated on the inside. The vacuum welds are in the steel, and are covered by copper welds on the inside. In this way the vacuum tank also serves as the rf cavity resonator. The operating vacuum of 1 to 5×10^{-6} mm Hg is produced by one 32-in. mercury diffusion pump. Access to the tank is provided by a 32-in.-diam. port in the tank wall.

In 1954, when the accelerator was designed, no operating experience existed with a strong-focusing linac other than a test made on the 40-ft machine at Berkeley.[18] It was thought that a bore diameter as large as 2 in. might be necessary to accomodate the radial oscillations characteristic of a strong-focusing system. If the radial motion is to remain stable in the prestripper for ions at all allowable phases,[24] the maximum value of the number of quadrupole lenses between polarity alternations, N, is two, i.e. (NNSS). With a bore diameter of 2 in. and N = 2, the required magnetic field at the pole tips of the quadrupole magnet in the first drift tube would be 22,000 gauss. If electrostatic quadrupole lenses were used, the voltage required on the electrodes would be 110,000 v. As it did not appear practical to produce either of these fields inside a drift tube 1-5/8 in. long, grid focusing was used in the prestripper linac. The 3/4-in. bore diameter and the grid design adopted was identical to that used on the 40-ft linac and the Bevatron injector at Berkeley. With random orientation of the grids, 80% of the aperture is obscured. Subsequent experiments at Yale with grids of different designs have not resulted in a significant change in the transmission of the prestripper.

More recently, considerations based on operating experience with the poststripper section, which uses strong-focusing, indicate that a bore diameter considerably smaller than 2 in. could have been used without appreciable loss in beam. In fact, the present 3/4-in. bore might be large enough and would reduce the magnetic field required at the pole tips of the quadrupole magnet in the first drift tube to 8000 gauss. This value would make strong focusing practical in the prestripper and would, ideally, increase the beam by a factor six. However, the forces between drift tubes due to the magnetic leakage fields might be a serious problem, and other difficulties could arise in a detailed design study.

The drift tubes are cylindrical with flat faces and 3/8-in. corner radii. They vary in length from 1.685 in. to 5.594 inches. They are supported from above by cylindrical stems as shown in Fig. 3. To simplify construction, groups of drift tubes are made with the same diameter. The individual rf cells within a group are tuned to the same frequency by varying g/L. The limits on g/L made it necessary to use three groups of drift-tube diameters. The g/L ratio and diameter of the drift tubes is shown in Fig. 8. These parameters were determined by resonance measurements with a 1/8-scale precision model of half an rf cell.

The drift-tube stems are suspended in the tank from a gimballed hanger which allows for the necessary translation and rotations for accurate drift tube alignment. In the alignment procedure the focal axis of a telescope was made coincident with the desired beam axis. The drift-tube position was then adjusted until cross hairs, previously installed in each drift tube, intersected the focal axis. The drift tube position along the beam axis was adjusted at the same time by means of accurately ruled steel tapes, dial indicators and other measuring aids. The alignment was complicated by the lack of parallelism of the drift-tube faces and required averaging methods to overcome this difficulty.

STRIPPER

At the output of the prestripper, the ions are passed through a thin layer of matter to increase their charge and thus improve the electrical efficiency of the poststripper accelerator. To establish equilibrium between capture and loss of electrons, 3 to 5$\mu g/cm^2$ of matter are required.[26-28] This is thin enough so that multiple scattering and energy loss are not significant. For the velocity $\beta = 0.045$ (1.0 Mev/A) of the ions at the stripper, the peak of the equilibrium charge-state distribution is at a value of e/m higher than 0.3 for any ion below aluminum.[28, 29] The stripped beam is distributed over several charge states, but for the lighter ions more than half of the particles are in a single charge state. The alternating-gradient focusing system used in the poststripper section of the linac allows simultaneous acceleration of ions in several charge states at different synchronous phases. However, tuning of the accelerator (i. e. rf level, quadrupole-lens strengths, etc.) for the best beam is slightly different for the different charge states. In experiments where focusing requirements are severe, only one charge can be used, and the stripper introduces a loss in beam intensity of about a factor of three.

The stripper at Yale is a thin foil of aluminum oxide about 40 $\mu g/cm^2$ thick.[30] The foils survive about two weeks and may be changed quickly. At

Berkeley a supersonic jet of mercury vapor is used similar to the one developed by Beringer and Rall.[31] The mercury is condensed and fed back into a boiler as in a diffusion pump. Figure 9 is a diagram of the mercury-jet stripper. The surface density of the mercury stream through which the beam passes is about 10/μg/cm^2. The liquid-nitrogen traps along the beam axis keep the partial pressure of mercury vapor leaking from the stripper into the linac tanks below 10^{-8} mm Hg. Stripping can also be done with thin carbon foils[32, 33] or with a permanent gas in a differential pumping system.[26, 34] However, the latter is impractical for this accelerator because of the large beam aperture and short length available between the prestripper and poststripper tanks. This length is limited by phase debunching of the beam.

POSTSTRIPPER ACCELERATOR

In the poststripper cavity the ions are accelerated from $\beta = 0.045$ (1 Mev/A) to the final velocity of $\beta = 0.148$ (10.4 Mev/A). Since the use of strong-focusing provides radial stability for large values of g/L, all the drift tubes in the poststripper could be made the same diameter and the cavity tuned by varying g/L from 0.248 to 0.334 (See Fig. 10). This tapering of g/L would increase the sparking problem in the shorter gaps if a constant value of the average axial electric field, E_0, were used throughout the poststripper cavity, and for this reason the poststripper cavity was designed for a linear increase in E_0 from 0.44 Mv/ft at the input end of 0.58 Mv/ft at the output end. With this scheme the electric field is the same in all gaps.

The cavity is constructed with copper-clad steel cylindrical sections and 4-in.-thick copper-plated steel end walls. Steel stiffening rings are spaced at 10-ft intervals along the length and a steel rib along the top positions the drift-tube nozzles and further stiffens the structure. Three 32-in.-diam.

access ports allow installation of the drift tube assemblies and other attachments, and numerous other ports are provided for rf loops, pumps, measuring equipment, and other accessories. The cavity is supported at four points by legs attached to hangers welded to the second stiffening ring from either end.

The inside length of the cavity is 89.68 ft. The inside diameter of 108.2 in. is smaller than the diameter of the prestripper because the diameter of the drift tubes is larger in order to accommodate the quadrupole-focusing magnets.

In the Yale poststripper, the polarity of the quadrupole-focusing magnet inside each drift tube is reversed in each succeeding drift tube (N = 1 or NSNS connection). At Berkeley the magnet polarity is reversed after every second drift tube (N = 2 or NNSS connection). The conditions for radial stability have been derived by Smith and Gluckstern for the case where the effective axial length of the focusing magnets is one-half the length of a unit cell of the linac.[24] The magnets were designed for a constant value[35] of the quantity $\theta_0 = \omega_{sf}/\nu$, where $m\omega^2_{sf}$ is the effective spring constant of the focusing magnetic fields and ν is the frequency of the rf accelerating field. For the NSNS mode of operation, the design value of θ^2_0 is 1.74, and for the NNSS mode it is 1.04. In practice, satisfactory operation of the Berkeley linac can be obtained with θ^2_0 as low as 0.72. Recently, the Yale linac was converted to NNSS operation in an attempt to improve beam quality by reducing the radial-oscillation trajectory angles, but no significant change was noted.

The required magnetic field gradient is given by the relation $dH/dx = \theta^2_0 \nu^2 m/(e\beta)$. Figure 10 shows the actual values used which incorporate corrections for the ratio of the axial length of a magnet to the length of a unit cell. At Yale, each magnet has its own power supply, while at Berkeley groups of essentially identical magnets are connected to common power supplies. In either case the magnet currents are adjusted from the control room and are varied empirically for optimum beam.

To allow for the radial oscillations produced when the beam from the prestripper enters the strong-focusing system, the bore diameter of the first drift tube is 2.17. According to the calculations of Smith and Gluckstern,[24] random errors in the positions and strengths of the quadrupole magnets cause the amplitude to increase as the square root of the number of magnets. Therefore, as shown in Fig. 10, the bore diameter increases approximately as the square root of the drift-tube number to 3.5 in. at the output end of the machine. This amount of bore increase was designed to allow a random error of 0.35 in. in the position of each end of the magnet axis and for a 1/2-deg random error in the alignment of the transverse axes of the magnets, without loss of beam due to trajectories striking the drift-tube bores.

The 67 poststripper drift tubes are cylinders of 19.8-in.-diam. with flat faces except for a 1-in. radius at the outer edge and at the bore. These shells are formed from two deep-drawn cups of 3/16-in. oxygen-free, high-conductivity copper joined together with a single circumferential joint and joints at each end of the 1/4-in.-wall bore tube. Thus each drift-tube shell encloses its magnet in a vacuum-tight envelope. The drift-tube shells are supported from the magnets which in turn are supported by 4-in.-diam. stems of copper-plated steel tubing. The water-cooled magnet leads, water-cooling lines for the shells, and the vacuum connection to the inside of the shells all pass through the inside of these stem tubes. Twelve set screws mounted on the outside of the tank provide the six degrees of freedom necessary in aligning the drift tubes. The set screws bear on the upper end of the drift tube stem and the clamp bracket as shown in Fig. 11. The vacuum and rf seal between the drift-tube stem and the tank is made with a copper bellows inside the cavity.

The shell interiors are pumped separately from the tank vacuum to avoid distortion of the drift-tube faces and to avoid contamination of the main vacuum by the magnet-insulating material. To prevent the disastrous occurrence of pressure difference between the two systems and permanent distortion of the shells, the two systems are connected together by a large valve which is automatically opened if the pressure in either system rises above a safe value. Figure 4 shows the drift tubes mounted inside the poststripper cavity.

Figure 5 is a photograph of one of the focusing magnets mounted on a drift tube stem. When the connection is NSNS, the required magnetic fields at the input end of the poststripper are high enough to require tapering of the poles to reduce the saturation of the iron. Saturation becomes unimportant near the output end, and the magnets from No. 26 on were made with straight poles. To simplify machining operations, a radius of curvature of 1.1 times the bore radius was used for the pole tips, rather than the ideal hyperbolic shape. To make room for the coils, the width of the circular part of the pole tip is limited to 1.3 times the bore radius. The deviations from pure quadrupole fields resulting mainly from the limited pole width were shown by orbit calculations to be unimportant.

The coils are made of 1/4-in.-square conductor with a 1/8-in. hole for water cooling. Two layers are used, and the coils are insulated with fiberglas impregnated with epoxy resin. The resin is also used to bond the coils to the poles.

The dc power for the magnets is supplied by transformers and six-phase germanium rectifiers mounted on top of the poststripper cavity. The power required at the design values of the magnetic fields is 280 kw for the NSNS connection and 80 kw for the NNSS connection. Actual operation of the Berkeley machine with the NNSS connection and $\theta_0^2 = 0.72$ requires 40 kw.

POSTSTRIPPER ALIGNMENT

The rf fields in the accelerator gaps of a long drift-tube accelerator are sensitive to small perturbations in the dimensions of the cavity.[18] To obtain some particular set of fields, e.g. fields of the same magnitude in each gap (flat-field distribution), the drift-tube lengths and gaps must be precisely measured and positioned, or auxiliary tuning devices must be introduced at various points along the cavity. In a strong-focusing linear accelerator the magnets must also be located with precision; in the poststripper where the magnets and drift tubes are single units, this places a second set of conditions on the drift-tube locations.

To a considerable extent these two types of alignment are separable. The magnets must be aligned with their centers on the axis and oriented at the correct angle in a transverse plane but their longitudinal position is not very important, whereas the flatness of the rf field is most sensitive to the drift-tube lengths and gaps -- i.e. longitudinal dimensions. By a series of auxiliary measurements and controls during manufacture, both of these conditions can be met with the required precision.

Before being enclosed with its shell, each drift-tube magnet underwent a series of measurements. The most important of these were the location of its central axis -- the zero field line, and the orientation of its transverse magnetic axes -- the planes of purely radial and purely azimuthal field. By careful machining and shimming, the central axis could be placed at the center of a circle touching the four pole tips. This was checked to an rms accuracy of 0.004 in. for the 67 magnets by using a small rotating-coil gaussmeter giving zero signal when placed on the axis. In the high-field magnets at the input end of the cavity it was found that the holes in the yoke which passed the various tubes distorted the central axis and extra iron was added to the yoke in this region.

The orientation of the transverse magnetic axes was measured with search coils whose planes were known relative to an external divided circle and which were positioned for null readings when the magnet was pulsed off or on. These located each of the eight planes of each magnet to a few minutes of arc. In the same series of measurements, the stem axis was accurately set in relation to these axes for reference use in the final alignment of the drift tubes. The maximum misalignment of any plane was 10 min. of arc. The rms error in the angle between the eight transverse planes and the stem of any magnet was less than 5 min. In the same series of magnetic measurements, the axial fringing fields were measured and integrated to give the effective magnet lengths, and the dH/dx gradients vs magnet current were determined.

The drift-tube shells were positioned axially by internal stops screwed into the magnet yokes (see Fig. 5) and the two shell halves were clamped rigidly against these stops during the welding and soldering. Some distortion and up to 0.030-in. lack of flatness of the drift-tube faces resulted. The average lengths of the drift tubes were measured, and where they were shorter than the design values by more than 0.005 in. they were elongated by high-pressure air introduced inside. The average lengths were determined to about 0.002 in.

After the drift tubes had been hung in the tank and roughly aligned, they were accurately positioned by using (a) a telescope line-of-sight to position the magnet-center axes (b) a bubble-level fixed at right angles to the stem to position the orientation of the magnetic axes, and (c) length measurements of the gaps and drift tube locations to position the drift tubes longitudinally. The main complication in this procedure was the changing shape of the tank due to temperature gradients -- a 1.0° C/ft vertical gradient lowers the tank ends 0.15 in.

relative to the center, and since the alignment extended over several weeks this would, if uncorrected, introduce large errors in the telescope alignment. At Berkeley, a servo system of sensing thermocouples and heaters on the tank skin was used to control the temperature gradient to 0.002°C/ft or better. At Yale, the tank was allowed to bend; its instantaneous shape relative to the telescope axis was determined by a three-point fit and the drift tubes were positioned on this curve in space. It should be emphasized that gradual curvature of the accelerator axis introduces no deterioration in beam quality such as that associated with random misalignments of successive drift tubes.

The other stages of alignment differed in detail at the two laboratories. At Berkeley an autocollimating mirror target was used to position and align the magnet-center axis, and the longitudinal position of the drift tubes was determined with multiple dial-gauge measurements in the gaps. At Yale the center-axis was aligned with a wire cross-hair target at each end of the axis of a given drift tube, and the longitudinal position of the drift tube was set relative to a precision steel tape stretched along the cavity. Both laboratories achieved the same precision, ± 0.005 in. rms for the magnet-center axis alignment, ± 0.005 in. rms for the gap settings, and about ± 5 min. of arc for orientation of the transverse magnet axes. Each of these errors was smaller than the design values by about a factor of six and lead us to believe that somewhat smaller magnet bore diameters would have been quite feasible.

When the poststripper tank was resonated it was found to be "flat" (pure lowest mode) to about 10% which is about the limit of error in determining the gap fields from H_ϕ at the tank walls. Fifteen equally spaced loops are provided for measuring this quantity. Measurements of the gap fields were made at Berkeley with "glo-balls" [36] to check the relation between the gap electric fields and H_ϕ at the tank walls. The glo-ball measurments showed that the fluctuations in the fields from gap to gap are less than 2%. The linear variation of average voltage gradient with tank length is produced by moving the end half drift tubes. For the design taper (0.44 Mv/ft to 0.58 Mv/ft) the first gap is increased by 0.13 in. and the last gap decreased by 0.14 in. relative to their values for a "flat" tank.

RADIO FREQUENCY SYSTEM

The rf power required to produce the accelerating electric field in the cavities was calculated from the azimuthal magnetic field, H_ϕ, in the cell and at the various walls. The values of H_ϕ used were obtained from measurements with an analogue network[37] and from calculations by the method of Walkinshaw, Sabel, and Outram.[38] The two methods give shunt impedances that agree to within 6%. In cavities of this type previously built, the measured shunt impedance was always about 25% lower than that calculated from H_ϕ and the accepted value for the dc conductivity of copper. Using this correction, the power required to achieve an average gradient of 0.5 Mv/ft is 0.4 Mw for the prestripper and 2.6 Mw for the poststripper. Measurements made on the completed prestripper cavity at Berkeley are in good agreement with the calculated loss. The calculated values for the losses occurring in the various parts of the cavities are given in Table II. Other quantities of importance to the rf system are given in Table III.

The length of the rf pulses is 3 msec. At 15 pulses per second (pps), the average power dissipated in the walls of the cavities is 75 kw. Originally the cavities were to be cooled by natural air convection; at Berkeley, water cooling has been added to allow a repetition rate of 15 pps at the maximum voltage gradient. In both machines, the shells and stems of the drift tubes are water-cooled.

Radio-Frequency Amplifiers

The 3 Mw of peak rf power is supplied by four amplifiers each using an RCA A2332 LFC shielded-grid triode.[39] At Yale, one amplifier is used to power the prestripper and the others are used on the poststripper. At Berkeley all four amplifiers supply the poststripper cavity, and a transmission line is used to couple power from the poststripper into the prestripper. A fifth amplifier is being added to the Berkeley machine and will be used to power the prestripper cavity. Figure 12 is a drawing of the tuned rf amplifiers used. As shown in the equivalent circuit of Fig. 13, the grid and plate tank circuits each consist of a π network, approximately half of which consists of the tube electrodes themselves. Half-wave lines are used to connect the grid and plate resonators to rotatable loops which couple with the azimuthal magnetic field in the cavity. The grid line is used to neutralize the amplifier. Each amplifier is capable of delivering from 600 kw to 1 Mw peak to the cavity depending on the particular tube being used. The tubes are operated in class C with plate efficiency of about 60%. The peak power input to each amplifier is about 1.5 Mw, and the average power at 15 pps is about 60 kw which is limited by the capability of the present power supplies.

Each main amplifier is driven by a pulsed, grounded-grid amplifier which uses an Eimac 3W5000A3 tube. All the 3W5000A3 driver amplifiers on the poststripper cavity are driven by a single, pulsed amplifier stage which follows several continuous-wave stages of amplifications. At Yale, a similar but separate drive system is used for the prestripper. The drivers for both the prestripper and poststripper are fed from a single, variable-frequency master oscillator. The Yale drive system is shown in the block diagram of Fig. 14.

The operating frequency is the natural resonant frequency of the poststripper cavity. A servo system is used to tune the master oscillator to the frequency of the poststripper. Another servo tunes the prestripper cavity to the same frequency by rotating one of its tuner loops. At Yale, the phase difference between the rf in the prestripper and the poststripper is adjusted manually with a line stretcher in the low-level drive to the prestripper. At Berkeley the rf in the two cavities is locked in phase by the coupling line because of its high standing-wave ratio, and the phase of the ions entering the poststripper is adjusted by moving the prestripper cavity. No beam instabilities attributable to uncontrolled phase shifts are found in operation of the accelerators.

Power Supplies

The 20-kv plate voltage for the main amplifiers is supplied by individual 3-msec pulse lines, each of which stores 8000 joules. Each pulse line is charged to a maximum of 40 kv by a 4-amp, 6-phase rectifier using General Electric type-Gl-562 emission-limited rectifiers.[40] The pulse lines are switched by three Westinghouse type-WX3977 ignitrons[41] in series. The ignitrons are extinguished at the end of the rf pulse by applying a negative pulse to the amplifier grid, which reduces the plate current to zero.

The plate voltage for all pulsed stages of the driver systems is supplied by a 200-μf capacitor bank and a hard-tube modulator. The capacitors are charged to 10 kv with a rectifier similar to those used with the pulse lines of the main amplifiers.

Build-Up of Radio-Frequency Power in the Cavities

At certain rf voltage levels, multipactoring occurs in the cavities.[42] If the rate-of-rise of rf voltage is too slow, the multipactor discharges load the amplifiers to a point where they are not able to increase the cavity voltage. The lowest multipactoring level in the poststripper accelerator is observed to occur at E_0 = 0.5 kv/ft (peak rf power - 5 w) and the highest one occurs at E_0 = 0.25 Mv/ft. It is found that if the initial rate-of-rise doubles E_0 in less than five rf cycles, the multipactor discharges do not cause trouble. The discharges were most intense when the cavities were new. After a few hours of operation at high power levels, the cavity surfaces become conditioned and the rate-of-rise is not as critical, but when the tanks are filled with air for several days the discharges return.

To prevent multipactoring from being started by rf power feeding into the cavity from the cw stages of the driver, the first pulsed stage of the driver is cut off between pulses with a negative voltage on the screen, and carefully neutralized to prevent capacitive feedthrough. To secure the desired rate-of-rise of E_0, the pulsed drive power supplied to the grid circuit of the main amplifiers must produce the full value of rf grid voltage in 10 μsec. This grid-drive pulse is delayed until the dc plate pulse is at full voltage.

One msec is required to reach full rf power in the poststripper cavity, and 300 μsec is required for the prestripper if driven separately. Since rate-of-rise is so important in drift-tube accelerators, it is suggested that future accelerators be provided with rf power in considerable excess of that required to merely produce the correct steady-state acceleration fields. Alternatively, a coupling system between amplifiers and cavity might conceivably be devised that will allow the full rf power to be applied over the build-up time.

The end sections of the pulse lines are adjusted to give a flat top to the 2-msec pulse. During this interval the ion beam is accelerated.

Tube Protection

If the energy (8000 joules) stored in one of the pulse lines is allowed to discharge into a spark in a main rf amplifier, it will seriously damage the tube. To prevent this damage, a triggered spark gap is connected from the output of the pulse line to ground. A current transformer in the plate lead of the tube triggers the spark gap when an overcurrent occurs, and the energy is dissipated in the spark gap. This protection is not entirely satisfactory; when a spark occurs in a tube, an appreciable fraction of the 520 joules of rf energy stored in the cavity can flow back into the tube. It is believed that tubes have been damaged in this way. To prevent this damage, a triggered discharge is also used to dissipate the cavity energy. This rf discharge is initiated by a 100-kv pulse applied to a probe located in one end wall of the cavity. The discharge dissapates the stored energy in the cavity in 20 μsec.

Prestripper Tuning

The modeling and the manufacturing tolerances were not sufficiently accurate to insure that the two cavities would resonate at the same frequency. Since the frequency of the prestripper could be raised more easily, its diameter was purposely chosen to give resonance at a frequency below that of the poststripper. After alignment of the drift tubes in the two cavities, coarse adjustment of the prestripper frequency was made by attaching a radial copper fin along the full length of the side wall of the cavity. The fin tuner raised the prestripper frequency 250 kc.

The fine tuning of the prestripper is done with two tuners of the type shown in Fig. 15.[43] The tuners project through the side wall of the cavity. Each tuner is a loop and capacitance adjusted to resonate at 85 mc/sec. When the tuner is rotated so that the loop is coupled to the magnetic field in the cavity, the resonant frequency of the coupled system is lower than the frequency of the cavity by itself. When the loop is rotated so that it does not couple with the magnetic flux in the cavity, it acts like a conventional slug tuner and raises the frequency of the cavity. Each tuner will shift the cavity frequency by about 90 kc, and with correct design, the frequency shift can be centered at the resonant frequency of the cavity.

VACUUM SYSTEM

Experience with high-rf electric fields in vacuum indicates that sparking occurs more readily if there are thin layers of organic materials on the electrodes. To reduce the amount of organic vapor in the linac cavities, mercury diffusion pumps are used, vacuum gaskets are lightly lubricated, and cold traps are employed on the mechanical pumps used for rough-pumping the cavities and backing the diffusion pumps.

The cavities are pumped with 32-in. mercury diffusion pumps. One pump is attached to the prestripper. At Berkeley, two pumps are attached to the poststripper, and at Yale, three. Backstreaming of mercury from each of the 32-in. diffusion pumps is reduced by two refrigerated baffles in series and by chilling the upper part of the barrels and the jet structures of the pumps. The major part of the backstreaming mercury vapor is caught on a -35°C baffle which fits over the upper jet. The mercury caught on this baffle drips back into the pump. The mercury vapor which gets through the -35°C baffle is trapped by a =115°C chevron-type baffle. The mercury caught by this baffle is frozen and remains until the baffle is warmed, but is not enough to cause any appreciable loss of mercury from the pump. Both baffles are cooled by mechanical refrigeration.[44] When the cavities have been let up to air and opened for inspection, the partial pressure of mercury vapor inside has always been well below the allowable concentration (0.1 mg/m^3) for safe occupancy by personnel, and there is no evidence of mercuric corrosion in the cavities.

A block diagram of the vacuum system is shown in Fig. 16. From atmospheric pressure the tanks can be rough pumped to 200 μ Hg in about an hour. After the diffusion pumps are opened to the tanks, the pressure is reduced to 10^{-5} mm Hg in a few minutes. The pumping time required to achieve reliable rf operation varies from 2 hr to a day depending on the amount of water vapor in the tanks, the baffle temperature, and the length of time the tanks have been exposed to air. Reliable operation usually occurs for pressures below 5×10^{-6} mm Hg. Operating pressures are normally in the range 1 to 5×10^{-6} mm Hg.

PERFORMANCE

Energy

The energy calculated from the dimensions of the cavities and the operating frequency is 10.4 Mev/A. Measurements of the energy agree quite closely with this value but show the existence of components of discrete energy.

At Berkeley, the energy of several ions has been determined from the range-energy measurements, in emulsions, of Heckman, Perkins, Smith, and Barkas.[45] In addition, a magnetic spectrometer was used to measure the energy of carbon ions. These measurements showed that the beam energy varied from time to time, independently of the ion from 10.1 to 10.6 Mev/A. An average of eleven measurements yields 10.4 Mev/A.

At Yale, L. C. Northcliffe has observed the detailed energy spectra of various beams in a magnetic spectrometer. Using various beams directly from the machine, he always found several discrete energies in the region of 10 Mev/nucleon, spaced by about 0.3 Mev/nucleon. There were frequently as many as six of these components, each sharp to perhaps 0.1 Mev/nucleon. The relative intensities of the components varied markedly from run to run, but the measurements seemed to suggest that the energies themselves were the same for all runs. In addition, there were other discrete components, usually of low intensity, at various energies down to about 5 Mev/nucleon. It is known that the populations of these energy components depend in detail on all of the operating parameters of the accelerator in a very complex way, but the explanation for the components is not known. Since the addition of a magnetic analysis system,[47] Northcliffe has found that the beam from this system contains only one component except for certain rare coincidences with one of the low-energy components in a lower charge state. With the analysis system, the accelerator is tuned to maximize the momentum-analyzed beam, which is sharp to about 0.1 Mev/nucleon but whose absolute energy can be chosen over a range from about 10.2 to 10.6 Mev/nucleon.

Several energy groups have also been seen at Berkeley when the rf field distribution in the poststripper cavity differs from the design value. However, with the design values of the rf gradient, only one high-energy component has been observed. The full width of the energy distribution at half maximum is about 2%.

The ability of the poststripper to accelerate simultaneously ions of several charge states was mentioned. This feature can lead to ion beams of dubious purity. Even magnetic analysis is insufficient on occasion to insure a pure monoenergetic beam. Lower-energy components in a lower charge state can have the same value of Hρ as the primary beam. For example, in the case of a Li^6 beam, the singly charged ions from the prestripper have been found to pass through the poststripper without gaining energy and emerge with the same Hρ value as the triply charged full-energy beam. The combined use of absorbers and magnetic analysis is required to remove this contaminant. A similar problem exists in the case of argon beams. Here the contaminant is the neon which is present in commercial-grade argon gas. Although the neon content is very low, the relative efficiency for the production of Ne^{3+} as compared to A^{6+} added to the greater stripping efficiency for Ne^{6+} as compared to A^{12+} results in a considerable contamination of the argon beam. Fortunately, this can be avoided by using the A^{13+} ions which are present with only a slightly lower intensity.

Beam Current and Quality

The beam currents available at various points in the accelerator vary from ion to ion. Table IV shows typical results. The maximum beams obtained are about double these typical ones.

The beam intensity available for a given experiment depends on the collimating system. For example, at Berkeley about half the total beam available can be focused through a 1/8-in.-diam aperture. A collimating system of two 1/8-in.-diam apertures spaced 3 ft apart will only transmit about one-tenth of the total beam available. In order to focus the beam through small-diameter collimating systems, the quadrupole magnets in the drift tubes as well as external quadrupole magnets must be tuned carefully. For maximum beam through small collimators some of the drift tube magnets must be set as much as 30% off the design currents. The best magnet settings vary a few percent from day to day for the same collimating system but change radically from one collimator to another.

At Yale, the beam is always used after passing through a magnetic analysis system,[46] and the focal properties of this system partly determine the size and shape of the final image. Typically, about half the output beam current is carried through the system to the experiment. As at Berkeley, it is found that for experiments requiring small collimators, the beam output from the system is strongly dependent on all of the accelerator parameters.

ACKNOWLEDGMENTS

The construction of these machines was made possible by the interest and support of G. Breit and W. W. Watson at Yale University and G. T. Seaborg and A. Ghiorso at the University of California.

The major design features of the machines were determined by a joint group from Yale and Berkeley. They benefited from the experience with the 32-Mev proton linear accelerator and the Bevatron injector at Berkeley and the high-current linear accelerator at Livermore.

A large number of men made important contributions to the design and construction of the machines. F. N. Holmquist performed many of the orbit calculations. Important mechanical engineering was done by W. O. Brunk, F. F. Fletcher, P. B. Kennedy, L. R. Lucas, E. F. McLaughlin, D. T. Scalise, M. J. Schwager, S. K. Yee, and R. W. Young at Lawrence Radiation Laboratory and by L. Baron, W. J. Harlow, F. G. Timberley, and C. B. White at Yale. Major electronics-design work was done by W. L. Dexter, L. E. Brown, E. C. Hartwig, and K. Stern. Assistance in measuring the Berkeley drift-tube magnets was given by C. G. Dols, J. H. Dorst, and L. G. Ratner. Important contributions to the assembly and preliminary operation of the Berkeley machine were made by R. Bollaert, W. S. Burgess,

R. J. Davis, B. F. Gavin, F. S. Grobelch, R. Grazier, V. B. Jones, S. J. Knoll, A. W. Stahl, and J. F. Steinhaus. W. Rall and R. V. Vallera provided valuable assistance at Yale.

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Table I. Accelerator parameters for various ions.

Ion	Injector voltage (kv)	Injector and prestripper: Charge state	Injector and prestripper: e/m	Prestripper rf (kv/ft)	Poststripper: Charge state	Poststripper: e/m	Poststripper: rf (kv/ft)	Final energy (Mev)
He^{4}	280	1	0.250	300	2	0.500	300	40
B^{11}	389	2	0.182	412	4	0.364	412	114
C^{12}	425	2	0.167	450	4	0.333	450	124
N^{14}	331	3	0.214	351	5	0.357	420	145
O^{16}	379	3	0.187	401	6	0.375	400	166
Ne^{20}	472	3	0.150	500	6	0.300	500	207
A^{40}	472	6	0.150	500	12	0.300	500	414

Table II. Percentage of rf power lost in various parts of the cavities.

Surface	Prestripper	Poststripper
Cylindrical cavity walls	56	58
Cavity end walls	12	4
Drift tubes	14	20
Drift-tube stems	18	18

Table III. Parameters for cavities.

Parameter	Prestripper	Poststripper
Shunt impedance (megohm)	100	400
Q	135,000	85,000
Stored energy (joules)	115	520
PEAK Power loss at 0.5 Mv/ft (Mw)	0.4	2.6

Table IV. Typical beam currents.[a]

Ion	Gas used	Injector Charge	Injector Current (meter μa)	Prestripper Charge	Prestripper Current (meter μa)	Poststripper Charge	Poststripper Current (meter μa)
		A. At Yale[b]					
He^4	He	1+	5,000	1+	60	2+	13
Li^6	Metal cathodes	1+	3,000	1+	20	3+	5
B^{10}	BF_3	2+	300	2+	3	4+	0.6
B^{11}	BF_3	2+	1,500	2+	15	4+	3
C^{12}	CO_2	2+	3,000	2+	60	5+	20
N^{14}	N_2	3+	2,000	3+	35	6+	10
O^{16}	O_2	3+	3,000	3+	40	6+	18
F^{19}	CF_4	3+	1,200	3+	10	6+	1.2
Ne^{20}	Ne	3+	1,000	3+	6	6+	2
Cl^{35}	CCl_4 or Cl_2	6+	500	6+	3.5	12+	0.5
A^{40}	A	6+	300	6+	2.0	12+	0.05
		B. At Berkeley					
He^4	He	+1	2,000	+1	90	+2	80
B^{11}	BF_3	+2	700	+2	80	+4	30
C^{12}	CO_2	+2	1,400	+2	90	+5	80
N^{14}	N_2	+3	600	+3	40	+5	20
O^{16}	O_2	+3	800	+3	60	+6	70
Ne^{20}	Ne	+3	500	+3	40	+7	20
A^{40}	A	+6	40	+6	2	+13	1

[a] Beam currents quoted are peak currents during a pulse. Average beam currents at the normal pulse rate of 15 pps are a factor of 30 lower. For multiply charged ions, the beam currents in meter μa must be divided by the charge on the ion in order to obtain the current in units that represent the same number of particles per second as a μa of protons.

[b] Poststripper beam-currents at Yale are measured after the energy-analysis system.

FIGURE LEGENDS

Fig. 1. Perspective drawing of the heavy-ion linear accelerator at Yale.

Fig. 2. Photograph of the Berkeley Hilac during construction.

Fig. 3. Photograph of the interior of the Berkeley prestripper cavity. The ion beam passes from right to left. The access port is seen in the upper left.

Fig. 4. Photograph of the Berkeley poststripper cavity looking toward the high-energy end. Radio-frequency anode loops and grid loops (smaller) are seen on the left. The grilled apertures beyond them are pumping ports. One of the three access ports is seen in the upper right.

Fig. 5. Photograph of a quadrupole magnet taken during assembly. The drift-tube stem is shown attached at upper right. Two of the four screw stops for locating the shell half are shown on the front face of the magnet yoke.

Fig. 6. Layout of ion source and lens system at Berkeley. The magnetic field is normal to the paper.

Fig. 7. Drawing of the buncher.

Fig. 8. Design data for prestripper drift tubes. Here g is the length of gap between drift-tube faces, L is the length of the rf cell in the linac, and β is the velocity of ions in units of the velocity of light.

Fig. 9. Top view of the mercury-jet stripper in the Berkeley accelerator.

Fig. 10. Design data for quadrupole focusing magnets in the poststripper drift tubes.

Fig. 11. Arrangement of set screws used to align the drift tubes.

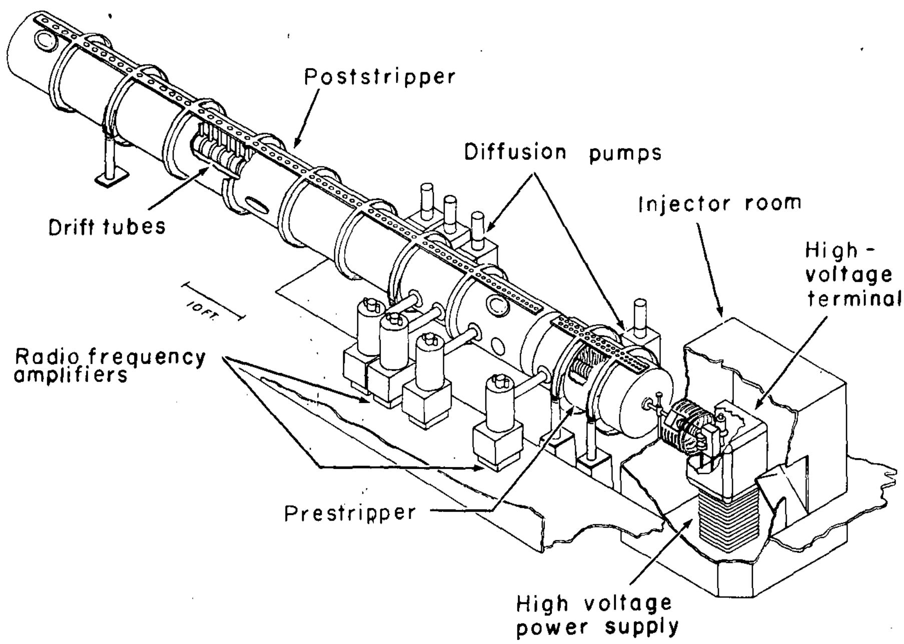
Fig. 12. Cut-away side view of main rf amplifier.

Fig. 13. Equivalent circuit of main rf amplifier.

Fig. 14. Block diagram of the Yale rf system.

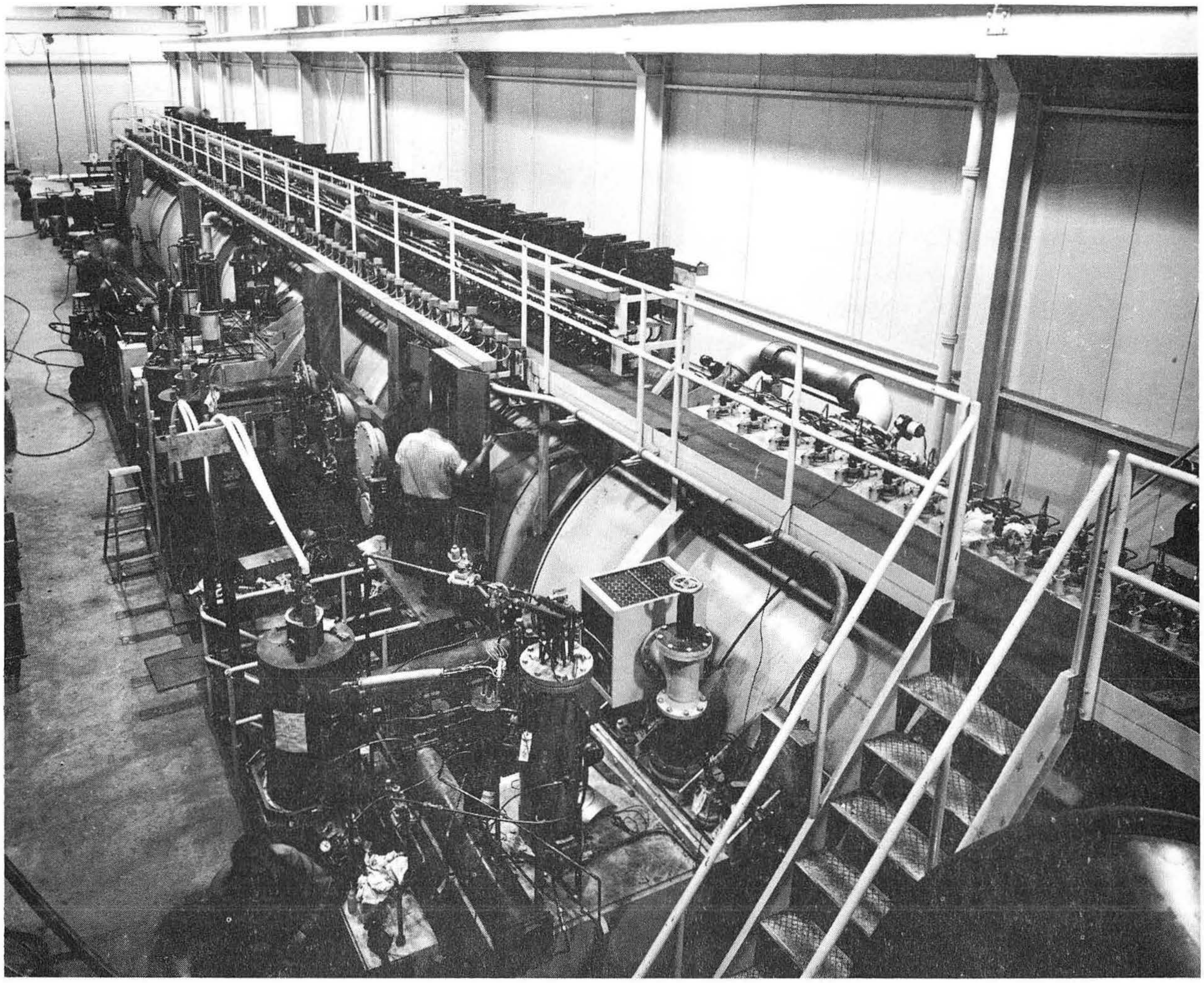
Fig. 15. Tuner for rf cavities.

Fig. 16. Block diagram of Yale vacuum system.



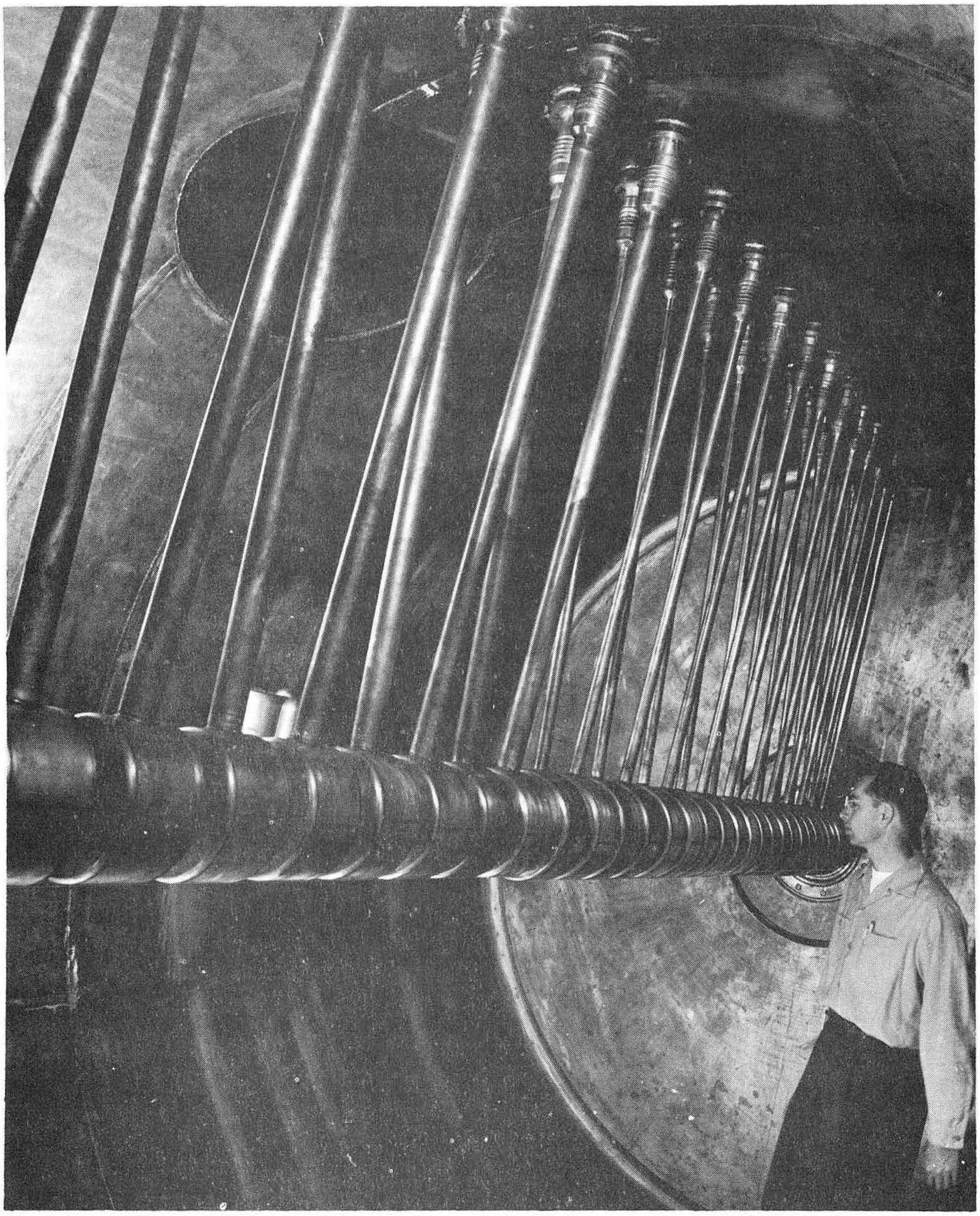
MU-22152-A

Figure 1



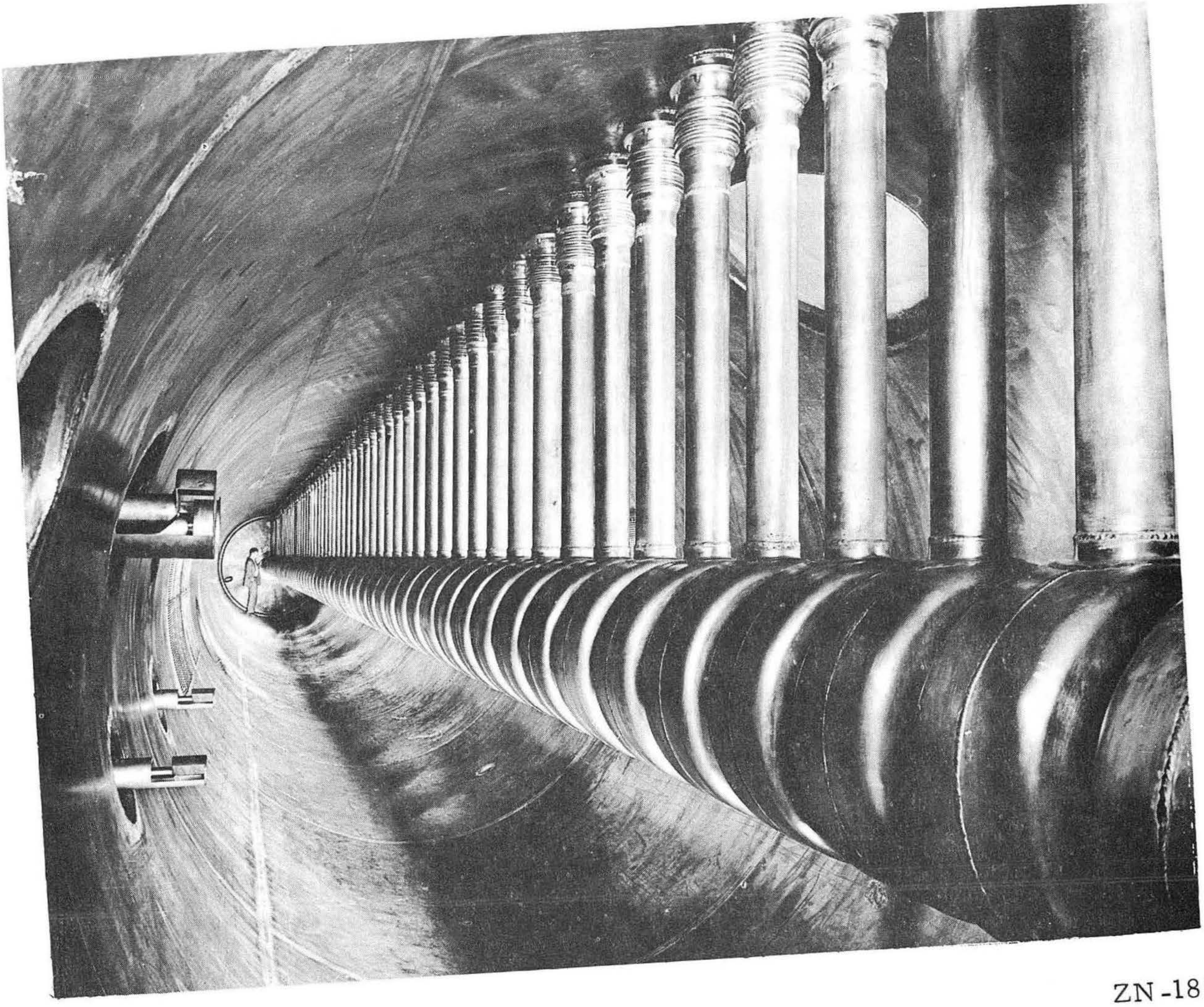
ZN-2634

Figure 2



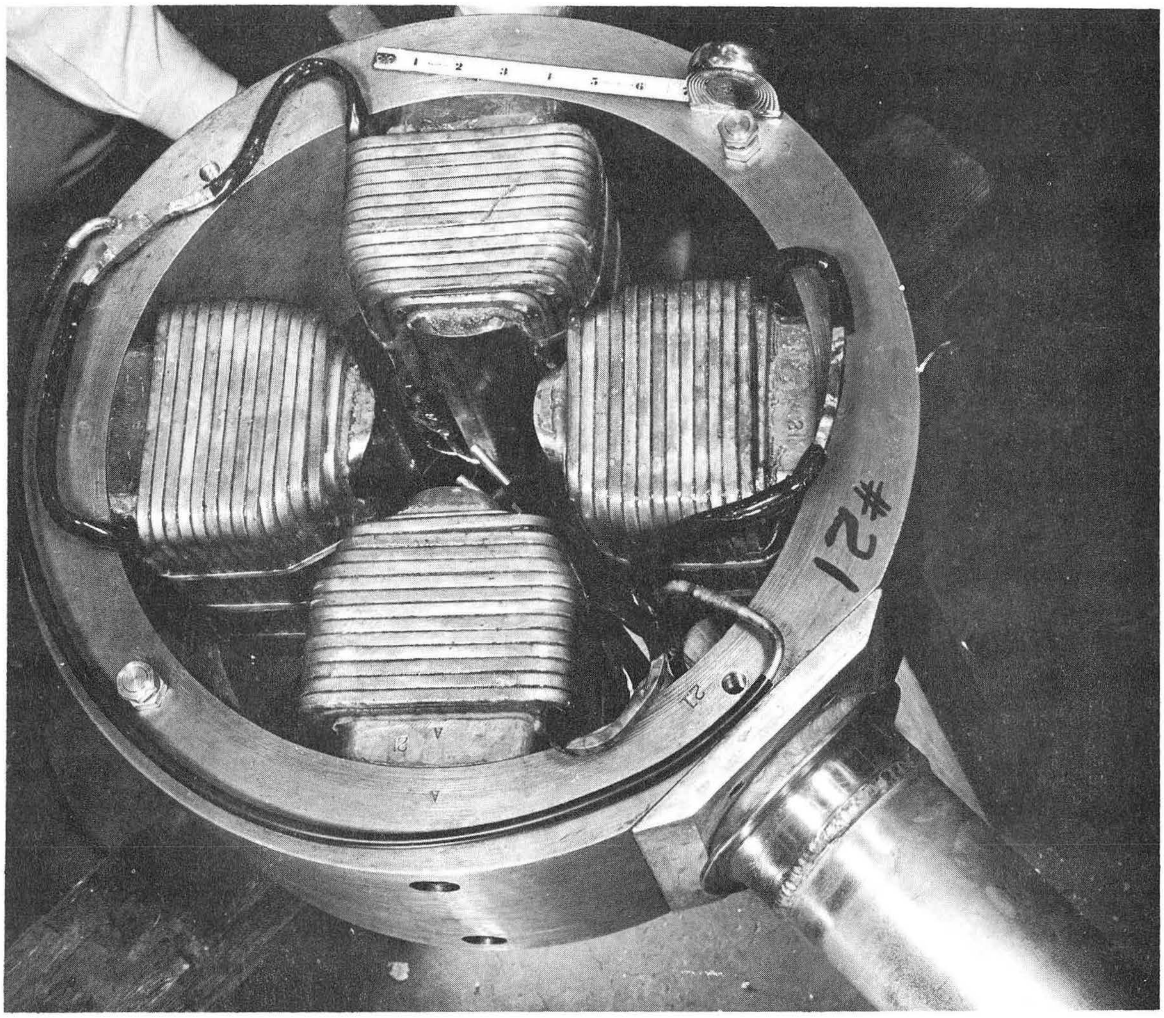
ZN-2635

Figure 3



ZN-1852

Figure 4



ZN-2636

Figure 5

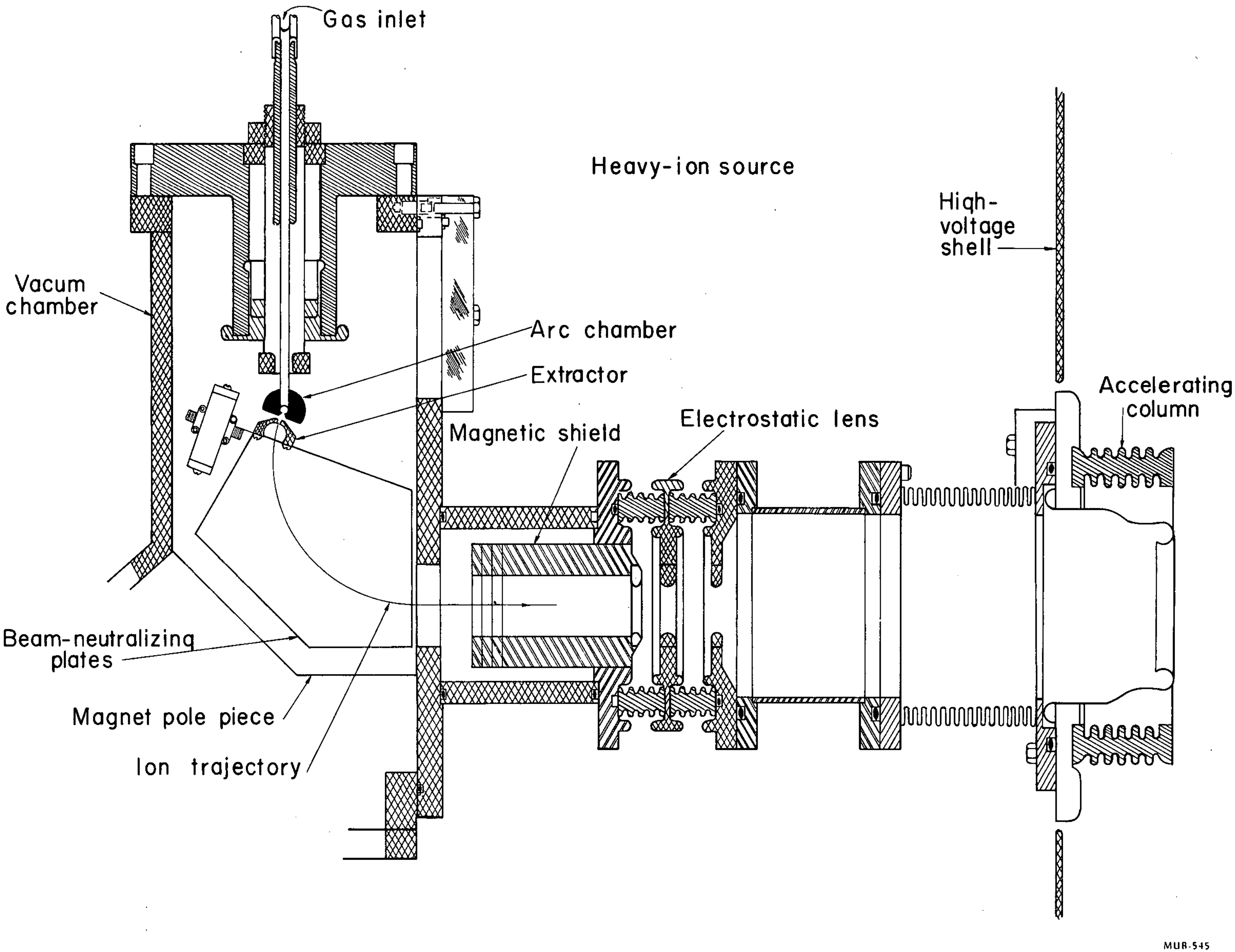
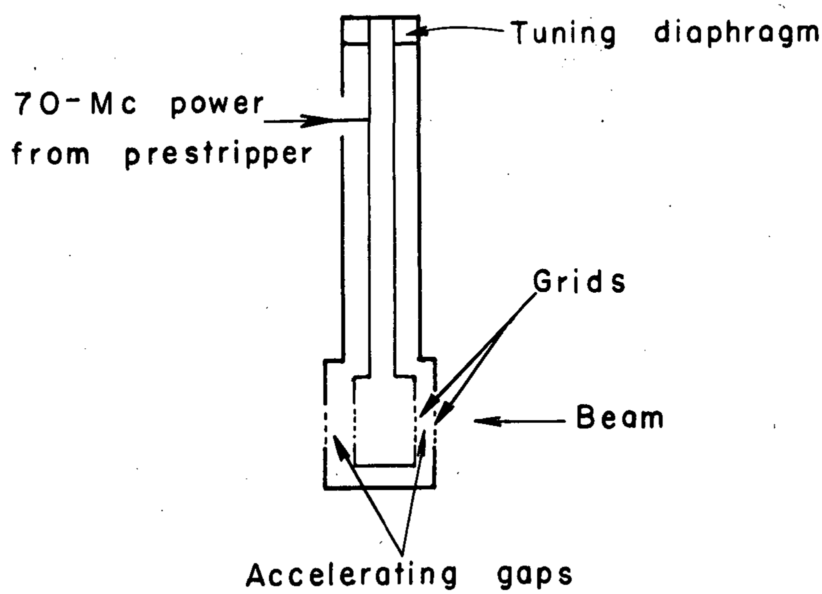
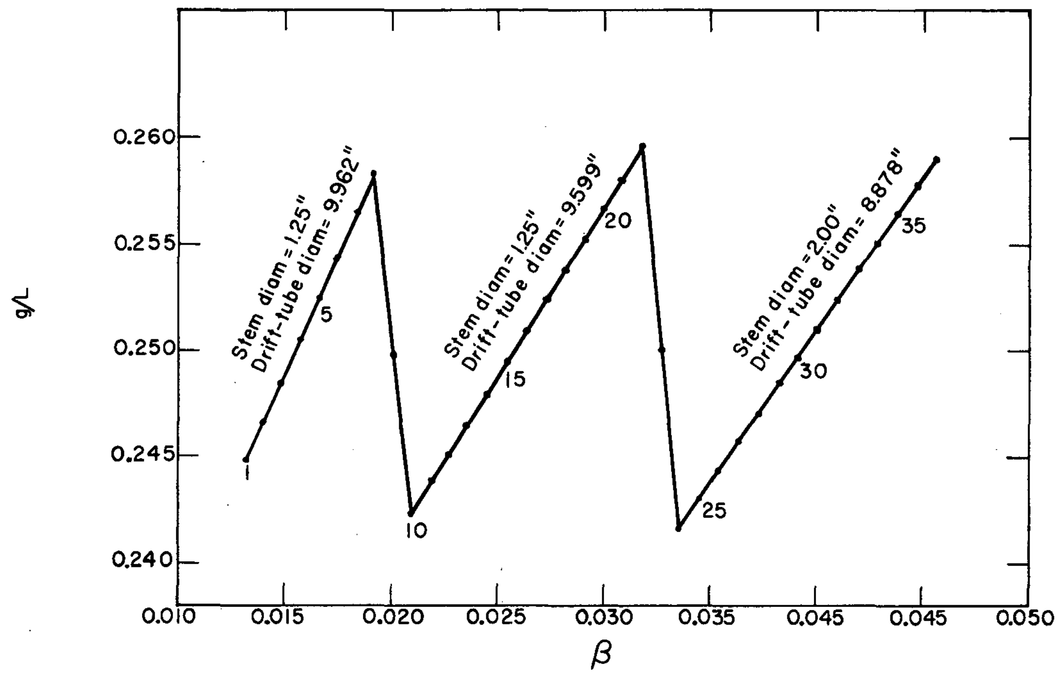

Gas inlet
Heavy-ion source
High-voltage shell
Vacum chamber
Arc chamber
Extractor
Accelerating column
Electrostatic lens
Magnetic shield
Beam-neutralizing plates
Magnet pole piece
Ion trajectory
MUB-545

Figure 6



MU-22418

Figure 7



MU-22419

Figure 8

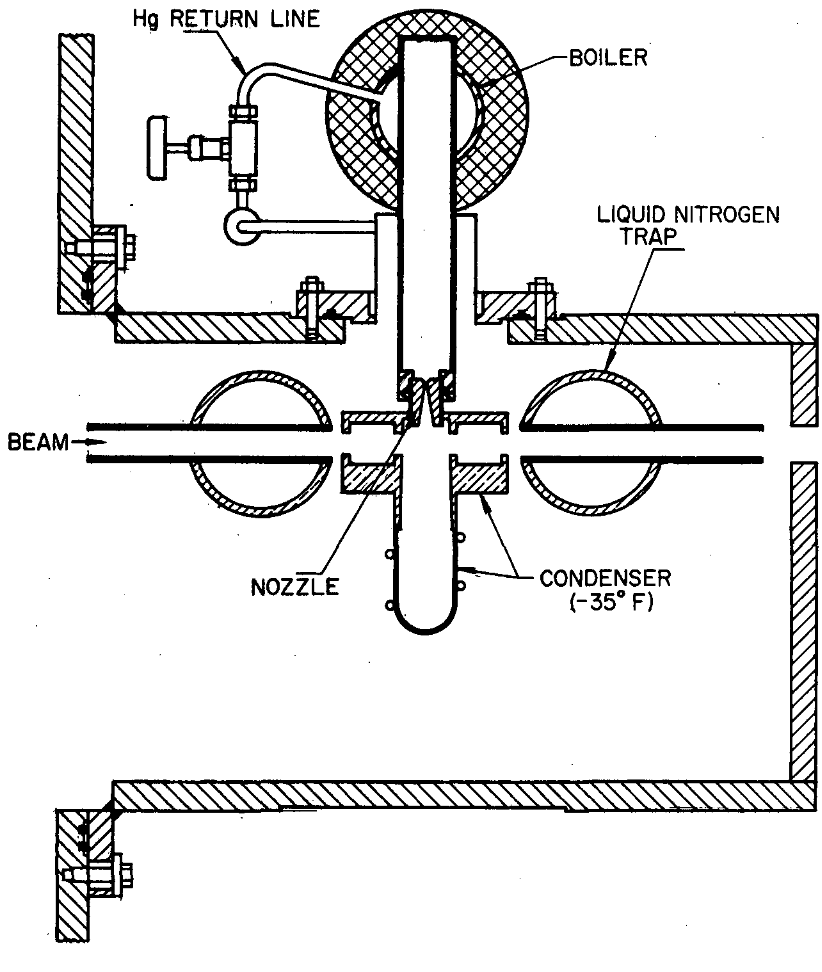

Hg RETURN LINE
BOILER
LIQUID NITROGEN TRAP
BEAM
NOZZLE
CONDENSER (-35° F)
MU-13465

Figure 9

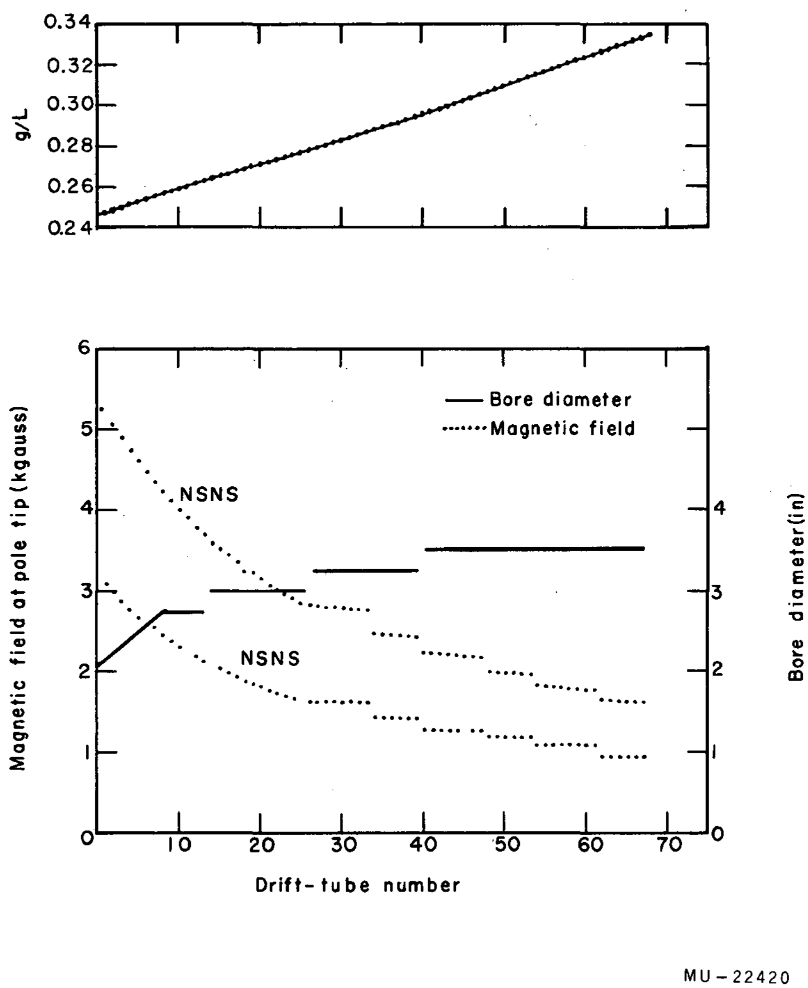

0.34
0.32
0.30
0.28
0.26
0.24
g/L
6
5
4
3
2
1
0
Magnetic field at pole tip (kgauss)
Bore diameter
Magnetic field
NSNS
NSNS
10
20
30
40
50
60
70
Drift-tube number
4
3
2
1
0
Bore diameter (in)
MU-22420

Figure 10

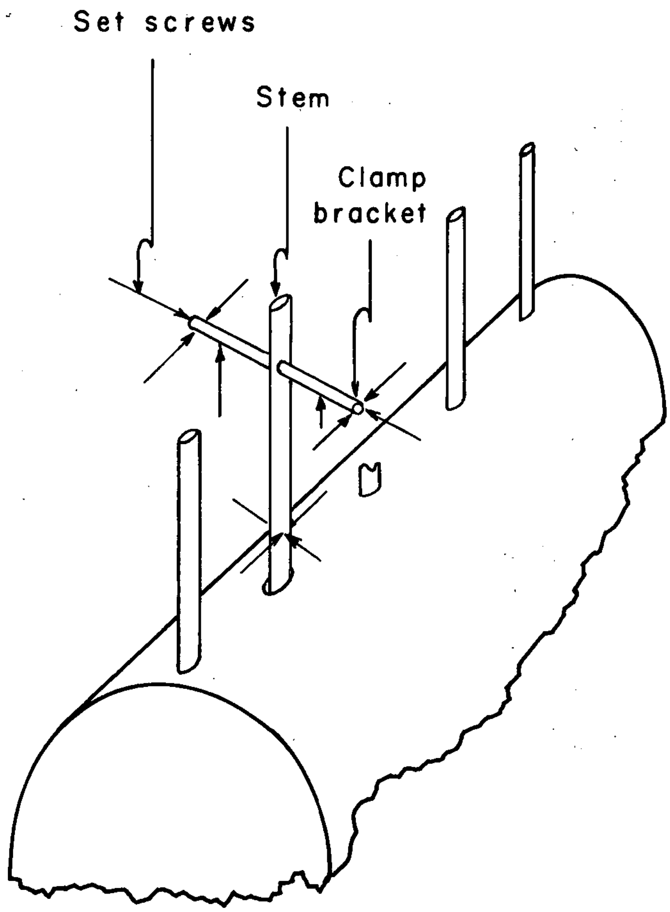
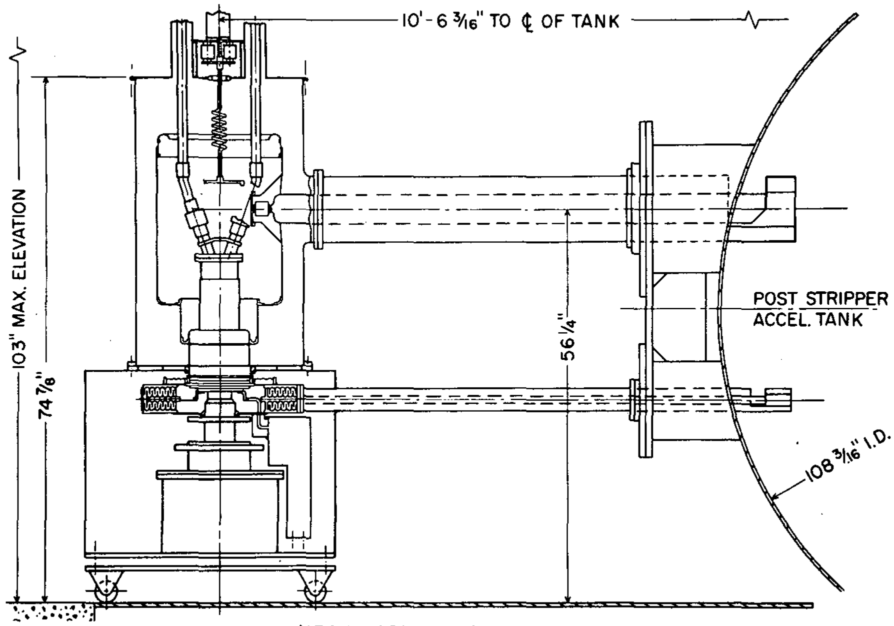


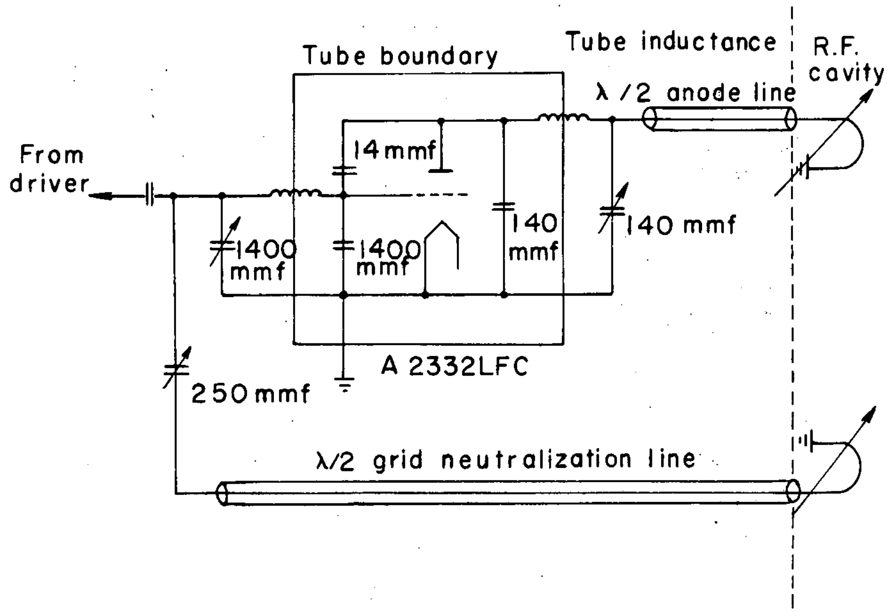
Figure 11



HEAVY ION ACCELERATOR
CUT-AWAY VIEW OF A2332LFC AMPLIFIER ASSEMBLY

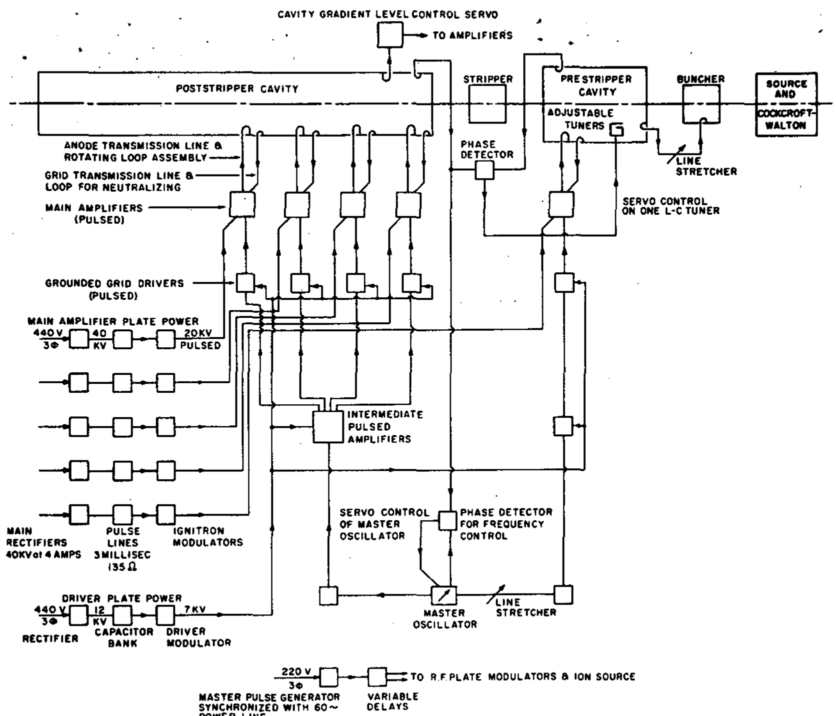
MU-9063-A

Figure 12



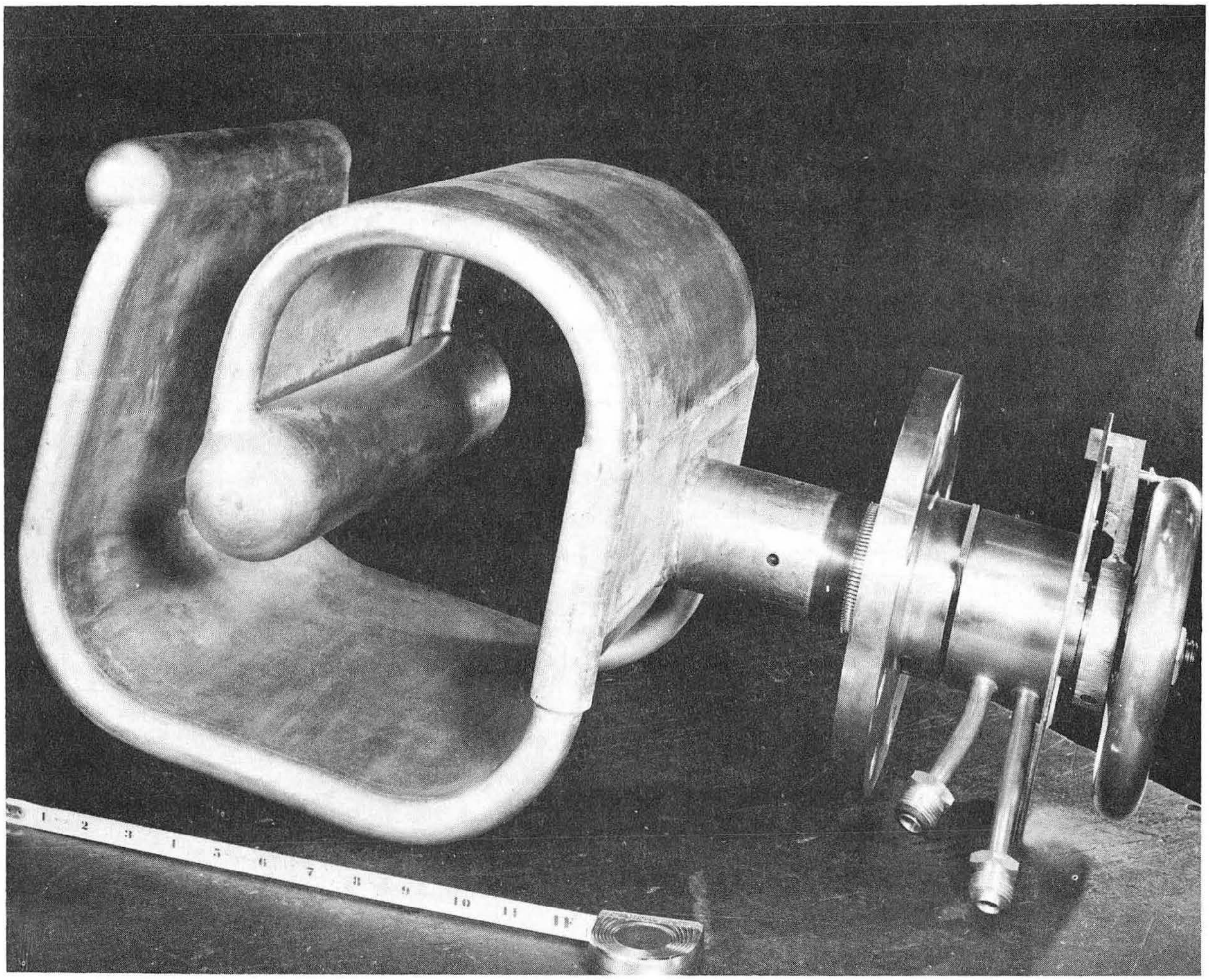
MU-22422

Figure 13



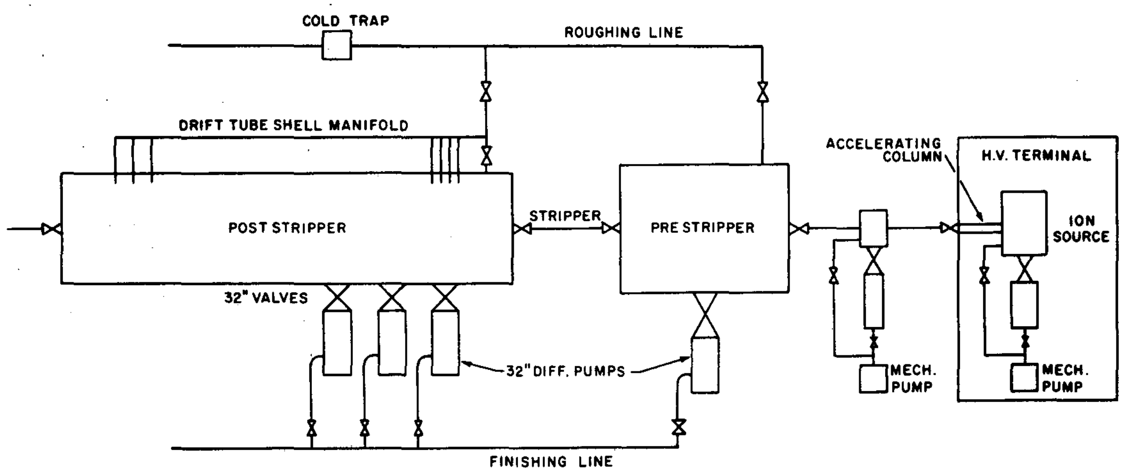
MU-22423

Figure 14



ZN-2637

Figure 15



MU-22424

Figure 16