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Berkeley, California

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ABSTRACT

The Bevatron requires an intense source of high-energy protons. The machine should accept monoenergetic protons for a duration of approximately 500 microseconds once every 6 seconds. To satisfy the requirements of small loss due to scattering by the gas in the accelerating chamber, a 9.9-Mev linear accelerator has been built and and operated.

A 500 kilovolt Cockcroft-Walton generator is used to inject 2-ma peak proton current into the linear accelerator. Focusing grids intercept approximately half of the injected beam. Additional losses, including radial defocusing and acceptance phase angle, result in a peak accelerated beam of 140 microamperes. The energy spread of the accelerated protons has not been measured, but an upper limit is less than ±30 kev.

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INTRODUCTION

The proton synchrotron design is simplified if high-energy protons are injected into the machine. An injection energy of 9.9 Mev was selected for the 6.2-Bev bevatron because the scattering due to gas molecules is less at high energies. When the Bevatron[1] was designed, gas scattering was considered to be a serious problem.

With high injection energy, the magnetic field at injection is greater, thus the residual magnetic field has a smaller effect on the trajectories during injection. Also, the "n value" or gradient of the magnetic field does not have to be compensated over such a wide range of field, and the required frequency range of the proton synchrotron drift-tube voltage is considerable narrower.

Since modifications in the gas scattering calculations[2] have made lower energy injection appear reasonable for the pressure range in the bevatron of 8×10^{-6} mm of mercury, a lower-energy high-current injector should be quite feasible. Table I is a summary of the estimated losses based on the calculations of Courant.[2]

To obtain an intense source of accelerated protons from the Bevatron, several additional requirements should be satisified. The injector beam should be monoenergetic, because the large electrostatic inflector is such a good energy analyzer. The beam should have a small angular divergence, because the focusing forces of the Bevatron are not very effective until the beam has made many traversals of the magnetic field. The beam should be intense and be injected at the proper time of buildup of the magnetic field, so that it will maintain a stable orbit.

A 9.9-Mev proton linear accelerator has been built to satisfy the above requirements. The system consists of an ion source and Cockcroft-Walton generator (cascade rectifier) arranged to accelerate protons to an energy of 500 kev. These protons are injected along the axis of the 200-megacycle linear accelerator, accelerated to 9.9 Mev, and deflected by the electrostatic inflector. (See Fig. 1a and b). Many of the design parameters were selected to be simple extrapolations of the Berkeley 32-Mev proton linear accelerator,[3, 4]

TABLE I

Bevatron Gas Scattering Losses Assuming a Useful Vertical Aperture 7 in. plus 5 in. Spread Due to Divergence of the Beam

Energy Mev	Loss percent	Pressure mm of Hg	Injection field gauss
0.500	10	4.0×10^{-7}	67
0.500	50	7.3×10^{-7}	
0.500	94	1.4×10^{-6}	
0.500	99.3	2.8×10^{-6}	
3.5	10	3.0×10^{-6}	176
3.5	50	5.1×10^{-6}	
5.0	10	4.3×10^{-6}	210
5.0	50	7.5×10^{-6}	
10.00	10	8.5×10^{-6}	300
10.00	50	1.5×10^{-5}	

THE COCKCROFT-WALTON GENERATOR

General Arrangement

The 500 kv Cockcroft-Walton generator is contained in a rectangular house, 12 feet wide, 15 feet high and 18 feet long, (Fig. 2).

The generator consists of 12 pairs of RCA 8013A air-cooled rectifier tubes arranged on lucite shelves as shown by Fig. 3. The filaments of the rectifier tubes are heated by 60-kilocycle power coupled through ferroxcube-core cascade transformers. The plate voltage is supplied by an 800-cycle motor generator and is coupled through the pyranol condensers, each rated 20 kv. dc, 0.25 microfarads. The 500 kv supply tubes have a rating of 20 ma average.

The ion source and power supplies are located inside a duraluminum shell, 4 feet on a side and 6 feet long. The present source is a cold cathode, axial type,[5] arranged to give 2 ma of protons with 35 kev energy. The various power supplies in the high-voltage shell are made as "plug in" units so they can easily be modified or serviced. The proton beam is accelerated along the horizontal accelerating tube which is 6 feet long and consists of 27 sections. The insulating sections are made of zircon, and the accelerating electrodes are made of spun stainless steel.

Voltage Stabilization

Two methods have been devised for stabilizing the voltage of the 500-kv generator. One method measures the horizontal deflection of the molecular hydrogen after the beam passed through the deflection magnet.[6] The deflected molecular hydrogen beam is detected on either of two plates and the signals are amplified. The differential signal is used to supply a signal to the voltage-regulation feedback system. Voltage regulation of better than ±0.1% can be obtained by this method.

Since without the buncher a range in the injection energy of the protons of ±2% reduces the beam from the linear accelerator by only 5%, a second method of voltage stabilization has been used for initial operation. This method amplifies a signal from a 2,000-megohm resistance type of voltage divider. This signal is used to regulate the field current of the 800-cycle generator, which supplies the plate voltage of the Cockcroft-Walton generator.

Also, a signal can be applied to the grid of a 304TH tube voltage regulator arranged to raise or lower the potential of the entire stack of Cockcroft-Walton coupling condensers. This regulator has a response time of 50 microseconds, thus corrections can be made during the 700-μsec beam pulse. This correction signal will allow a peak current of 30 ma from the 500-kv supply with less than 1,000 volts decrease in potential.

Vacuum System

An attempt was made to keep the vacuum system reasonably free of organic vapors. The components were cleaned by sandblasting. O-ring gaskets were assembled without oil, and a liquid-nitrogen-trapped mercury-vapor pump is used to evacuate the ion source and accelerating tube. The pump has a speed of a few hundred liters per second and a base pressure of 4×10^{-6} mm Hg. During normal operation, the pressure at the exit of the accelerating tube is 1×10^{-5} mm Hg.

Operation

The cold cathode ion source gives a 2-ma peak beam of 500-kev protons at the exit of the Cockcroft-Walton accelerator. The beam can be focused to a diameter of approximately 2 mm at the exit. Typical operating conditions are as follows; arc voltage 500 volts, arc current 2 amps, arc gas pressure 40 microns, exit aperture 1 mm. diam, axial magnetic field 1000 gauss. For maximum accelerated beam, the probe voltage is 12 kv, the focus voltage is 7 kv, and the accelerating voltage is 35 kv. The beam is deflected through an angle of 20° by a double focusing magnet and brought to a focus along the axis of the linear accelerator.

THE LINEAR ACCELERATOR CAVITY

Geometry

The proton linear accelerator has a cylindrical cavity 18.2 feet long and $42\frac{1}{4} \pm \frac{1}{16}$ inches in diameter and operates in the axial electric (0, 1, 0) mode at 202.5 megacycles ($\lambda = 148$ cm). The protons are injected along the axis and are accelerated as they cross the gaps between each of the 42 drift tubes. Fig. 4 (Photograph).

The spacing between drift tube centers is made equal to $\beta\lambda$. The ratio of the velocity of the proton to the velocity of light, β is 0.030 at injection and $\beta \doteq 0.144$ at the exit of the linear accelerator.

To reduce the probability of electrical discharges in the vacuum, the contours of the drift tubes were made of elliptical cross section at the entrance end of the machine. At the exit end, the cylindrical drift tubes have hemispherical end. To reduce the radial component of velocity of the proton beam, focusing grids are used at the entrance of each drift tube. The drift tubes are supported from 5/8-inch diameter copper supports.

The dimensions of the drift tubes were determined by full-scale-model tests. The full-scale-model tests were designed to include the above requirements. A 42 $\frac{3}{8}$ inch inner diameter cylindrical cavity approximately 12 inches long was used to model one, two, or three unit cells, consisting of one, two, or three drift tubes.

Beam Dynamics

Following the method of Panofsky,[4] the dimensions of the drift tubes were then computed by assuming that each gap was the center of a unit cell. The synchronous velocity $\beta_s C$ of the n^{th} cell for this accelerator is related to the repeat length L_n and the free-space wave length λ by the relations

$$\frac{L_n}{\lambda} = \frac{(\beta_{n-1,s} + \beta_{n,s})}{2}$$

The total increase in the relativistic energy W of the synchronous proton due to the axial electric field E_z^o is

$$W_{n,s} - W_{n-1,s} = \int eE_z^o \cos\left(\frac{Wz}{\beta_s C} + \phi_s\right) dz$$

where ϕ_s is the synchronous phase of the accelerated proton of charge e.

The mean effective field is

$$E_o = \frac{\int_{gap} E_z^o dz}{\int_{gap} dz}$$

and the transit time factor is

$$T = \frac{\int E_z^o (z) \cos (2\pi z/L_n) dz}{\int E_z^o (z) dz}$$

Assuming a uniform accelerating field across the gap, and integrating the above expression,

$$T = \frac{\sin(\pi g_n/L_n)}{\pi g_n/L_n}$$

where g_n is the length of the n^{th} gap.

Because the electric field penetrates the exit aperture of the drift tubes, a correction has been made to the calculated transit time. This correction for the radial variations due to a cylindrical exit aperture and a cylindrical entrance aperture of radius A_n is:

$$F_1 = \frac{I_o(2\pi r/L_n)}{I_o(2\pi A_n/L_n)}$$

where I_o is the zeroth order Bessel function of the first kind, with imaginary argument.

For the 9.88-Mev proton linear accelerator with entrance grids, this factor was modified to,

$$F_2 = \frac{1}{2}\left[1 + \frac{I_o(2\pi r/L_n)}{I_o\left(2\pi A_o/L_n\right)}\right],$$

where r is the "effective" radius from the axis of the drift tubes.

The energy gain per unit wave length is, for this accelerator, in units of $M_o C^2$,

$$W_\lambda = \frac{eE_o\, T\, F_2 \lambda}{M_o C^2} \cos \phi_s$$

In this machine, the fractional change in velocity is small for each accelerating gap, thus the increment of momentum at the n^{th} cell is

$$\Delta W_{n,s} = V_{ns}\, \Delta P_{ns},$$

thus $$P_{n,s} - P_{n-1,s} = M_o C W_\lambda$$

or the momentum is a linear function of the number of drift tubes. The momentum of a synchronous particle at the center of the n^{th} cell is then

$$\begin{aligned} P_{n,s} &= M_o C (n+n_o) W_\lambda \\ &= M_o C n' W_\lambda \end{aligned}$$

where n_o is the effective number of gaps corresponding to the velocity at injection, and $n' = n + n_o$.

If the total energy of a synchronous particle at the center of the n^{th} cell is $W_{n,s}$, then

$$\begin{aligned} W_{n,s}^2 &= (T + M_o C^2)^2 \\ &= (Cp)^2 + (M_o C^2)^2 \end{aligned}$$

where T is the kinetic energy of the proton of momentum p.

Combining with the above equation and solving for the kinetic energy,

$$T = M_o C^2 \left(\sqrt{1 + (n')^2 W_\lambda^2} - 1 \right).$$

The calculations of the velocity of the synchronous protons were made assuming an injection energy of 0.450 Mev and a final energy of 9.88 Mev. A length of 18.2 feet was selected, corresponding to a mean electric field gradient of 0.5663 Mev/foot. The ratio of gap length to repeat length was selected as 0.25. Thus

$$T = \frac{\sin \frac{\pi g}{L}}{\frac{\pi g}{L}} = \frac{\sin \frac{\pi}{4}}{\frac{\pi}{4}} = 0.900$$

The length of the entrance tube plus half the accelerating gap (distance to the next drift tube) totals one-half the repeat length. The same is true for the exit tube.

The accelerator was designed to have 42 full drift tubes and 2 half drift tubes. These have an elliptical cross section so that high voltage breakdown will be reduced. Ribbon Grids 1/16-inch wide and 0.002 inch thick were used with their edges in the plane of the proton beam (Fig. 5).

Drift-Tube Dimensions

When the above factors were included, the change in the velocity of a synchronous proton in the n-1 cell is,

$$\Delta\beta_{n-1}^{s} = 0.00275 \left(1-\beta_s^{2}\right)^{\frac{3}{2}} \times \frac{1}{2} \left[1 + \frac{I_o\left(0.3\,\frac{2\pi a_n}{Ln}\right)}{I_o\left(\frac{2\pi a_n}{L_n}\right)}\right]$$

The exit apertures of the first eleven drift tubes have a radius $a_n = \frac{1}{4}$ inch, the remainder of the drift tubes have $a_n = \frac{3}{4}$ inch. The "effective distance" of the trajectory of a proton from the axis of the drift tubes were assumed to be 30 percent of the radius of the aperture in the drift tube.

The synchronous velocity and dimensions of the drift tubes are given by Table II and by UCRL drawing 3N9524.

The diameters of the drift tubes were determined by the results of the full-scale-model test, Figs. 6 and 7.

Electrical Measurements

The 18-foot cavity was first assembled without drift tubes and observed to be a cylinder uniform in diameter to within ± 0.060 inch. The drift tubes with 5/8-inch diameter copper supports were assembled and spaced according to Table II. Cross hairs were inserted in each drift tube and aligned on the axis by means of a telescope. The spacing between drift tubes was adjusted and then measured with a cathetometer to an accuracy of ± 0.020 inches. The entire cavity was then assembled and observed to have a resonant frequency of 202.5 megacycles and an unloaded Q of 90,000. Thus, the final assembled unit agreed with the model tests to within the accuracy of frequency measurements ±20kc, or 1 part in 10^4.

TABLE II

10-Mev Bevatron Linear Accelerator Drift Tube Calculations

8/24/50

M	β_n^s	L_n in.	Tube Length In.	Diam. In.
0	.03312	1.854	.690	5.560
1	.03312	2.004	1.448	5.524
2	.03566	2.153	1.558	5.498
3	.03823	2.303	1.671	5.472
4	.04082	2.455	1.784	5.446
5	.04343	2.607	1.898	5.419
6	.04605	2.760	2.013	5.393
7	.04868	2.914	2.128	5.365
8	.05132	3.068	2.243	5.336
9	.05397	3.222	2.359	5.305
10	.05663	3.378	2.475	5.266
11	.05930	3.533	2.592	5.225
12	.06197	3.687	2.708	5.185
13	.06458	3.840	2.822	5.145
14	.06720	3.993	2.937	5.100
15	.06983	4.145	3.052	5.040
16	.07245	4.298	3.166	4.980
17	.07508	4.452	3.281	4.920
18	.07771	4.605	3.396	4.840
19	.08035	4.759	3.512	4.760
20	.08299	4.913	3.627	4.680
21	.08564	5.068	3.743	4.590
22	.08829	5.222	3.859	4.500
23	.09095	5.377	3.975	4.410
24	.09361	5.532	4.091	4.310
25	.09627	5.688	4.207	4.220
26	.09894	5.843	4.324	4.120
27	.10161	5.998	4.441	4.020
28	.10426	6.153	4.557	3.920
29	.10691	6.307	4.672	3.820

TABLE II

10-Mev Bevatron Linear Accelerator Drift Tube Calculations (cont.)

8/24/50

M	β_n^s	L_n In.	Tube Length In.	Diam. In.
30	.10957	6.462	4.789	3.720
31	.11223	6.617	4.905	3.620
32	.11489	6.772	5.021	3.520
33	.11755	6.927	5.137	3.420
34	.12021	7.082	5.254	3.320
35	.12287	7.237	5.370	3.220
36	.12552	7.392	5.486	3.120
37	.12817	7.546	5.602	3.020
38	.13082	7.700	5.717	2.920
39	.13347	7.855	5.833	2.820
40	.13612	8.009	5.949	2.720
41	.13877	8.164	6.065	2.620
42	.14142	8.317	6.181	2.520
43	.14405		3.148	2.420
	.28547			

METHOD OF CONSTRUCTION

Resonant Cavity

The cylindrical liner is made of rolled copper sheets riveted to U-shaped ribs (Fig. 8). The bottom semicylindrical section is rigid and is the support for the top half of the cavity. The top section is supported on two horizontal dural channels securely fastened to each other at either end by cylindrical dural tubes. The drift tubes are supported from 2-inch-diameter stainless steel tubes which are fixed at each of the 6 arches.

Two support tubes are used so that alternate drift tubes can be rotated as a group to permit installation of grids. Also, when the accelerator was designed, electron multiplication between adjacent drift tubes was considered a problem. This method of construction allows a dc bias potential to be applied between adjacent drift tubes. During operation, however, this bias potential is not required.

The voltage distribution in the cavity is adjusted by moving the centers of the end diaphrams in an axial direction, "oil-canning". By this means the current distribution along the edge of the cavity has been made uniform to ± 3.0 percent; or the ratio of the current distribution at the entrance to the current at the exit can be shifted ± 20 percent.

The cavity is cooled by flowing water through copper tubes soft-soldered to the outside of the copper walls. Provision was made for water cooling of the drift tubes, but cooling is not required for the duty cycle of 2×10^{-3}.

Vacuum Tank

The vacuum tank is 54 inches in diameter and 20 feet long, and is made in two semicylindrical sections joined by a rubber gasket (Fig. 9). The tank is pumped with either of two 20-inch-diameter mercury diffusion pumps. A complete baffle is cooled by circulating dry-ice-refrigerated trichlorethylene. A liquid-nitrogen thimble is inserted in the vacuum manifold.

The system was cleaned by sandblasting, and an attempt was made to keep the amount of organic vapor at a minimum. The usual operating pressure in the tank is 2×10^{-6} mm Hg. The speed of each pump with baffles is 1000 liters per second for air. The second 20-inch pump, appearing in Fig. 9, is a spare.

EXCITATION OF THE CAVITY

Oscillators

The peak power of 500 kw required to excite the cavity is supplied by three EIMAC type 3W 10,000 A3 triode oscillators.[3] These are tightly coupled to the cavity in such a manner that oscillations build up only when a loosely coupled preexciter builds up voltage in the cavity at the proper frequency. Initial operation was obtained with a preexciter that consisted of a modified radar type BC-677 oscillator, but an EIMAC 4W 20,000 tetrode oscillator (Fig. 10) now replaces this. This oscillator is being developed by a group working with Jack Franck.

Power Supplies

The cathode of each oscillator tube is heated by electron bombardment. Since the peak current requirements for this application are considerable less than the tube ratings, the filament and cathode bombardment power are adjusted to approximately 85 percent of the rated value.

The plate and screen voltage for the 4W 20,000 A preexciter is supplied by a 7 section lumped transmission line 120 microseconds long. The condensers have a capacitance of .045 microfarads, the inductors are 3 millihenries, and the characteristic impedance is 266 ohms.

The plate voltage for the main oscillators is supplied by a 11 section lumped transmission line 700 μsec long. The condensers have a capacitance of 0.24 μf, the inductors are 6 mh, and the characteristic impedance is 160 ohms. Resistor loads can be connected in parallel with the oscillator plate load for impedance matching.

The energy from the lumped transmission line is switched by means of a spark gap, operating in one atmosphere of air and triggered by a probe which is pulsed to 40 kv.

Typical operation is to charge the preexciter line to 18 kv, which gives a 9-kv pulse at the plate of the oscillator. When three main oscillators are used, the plate line is charged to 24-kv, which gives a 12-kv pulse at the plate of the oscillator. At this voltage the three oscillators supply approximately 0.5 megawatts peak power, which is the calculated power required for a Q of 90,000. The anodes of the oscillator tubes are water-cooled, the grid and filament structures are forced-air-cooled.

AUXILIARIES

Strong-Focusing Magnets

To reduce the divergence of the proton beam, four magnetic quadrupoles[7] are located at the exit of the linear accelerator. These require a gradient of 700 gauss per inch and a power of 80 watts for maximum beam through the electrostatic deflection plates at the entrance of the Bevatron.

Electrostatic Deflector

The geometry of the bevatron requires that the injected proton beam enter at an angle of greater than 30° to the edge of one of the straight sections. A pair of electrostatic deflection electrodes with a radius of curvature of 18 feet deflects the beam through an angle of 35° in the horizontal direction.

The electrodes are 132 inches long, spaced with a gap of 7/8 inch, and require a potential difference of 78 kv to deflect the 9.9-Mev beam.

The potential for the deflection plates is supplied by 8 stages of cascade 5825 rectifier tubes. The plate and filament power are supplied by separate oscillators, 123 kc and 61 kc respectively. A stable 100-megohm resistance divider is used to supply the regulation signal. The supply is stable to one part in 16,000 for periods of 5 hours or more.

Voltmeters

The current density along the edge of the cavity is measured by inserting loops at approximately 12-inch intervals. A crystal diode is inserted at each loop and the rectified 202-megacyle signal is observed on an oscilloscope. Also, this signal can be coupled into a feedback type of peak volmeter. The Cockcroft-Walton voltmeter is calibrated by measuring the γ-ray yield for protons bombarding lithium. This resonance occurs at 440 kev.

Beam Current-Measuring Probes

To monitor the accelerated protons, faraday cups can be inserted in the beam at the exit of each accelerator and at the entrance and exit of the electrostatic inflector. The probe at the exit of the inflector is divided into five sections so that the distribution of the deflected beam can be measured. The probes are air-driven and controlled by solenoid-operated valves. The beam can be monitored between bevatron pulses, 10 per minute, by inserting these probes. The signals from the various faraday cups are amplified and observed directly on oscilloscopes.

Proton Buncher

A 202.5 megacycle tuned re-entrant cavity has been placed between the 20° deflecting magnet and the entrance to the linear accelerator, Fig. 11. Protons entering along the axis of the cavity gain or lose energy as they cross the gap between the drift tubes and then drift for a distance of 40 inches before entering the linear accelerator. The gap is 3/8 inches and grids are used in both the entrance and exit apertures so that the electric field lines are more nearly parallel.

Power to excite the cavity is obtained by coupling a small amount of energy from the main linear accelerator cavity by means of a variable coupling loop. The phase is adjusted by means of a variable length coaxial transmission line. The cavity has a Q of 2000 and is tuned by means of a tuning plug.

OPERATION

Initial Observations

The 0.5-Mev accelerator was first operated during February, 1953. Since the stored energy of the Cockcroft-Walton generator is so great, 2500 joules, no attempt has been made to spark it to ground. Surge resistors have been installed to limit the discharge current to 80 amperes, but the supply has never sparked directly to ground. On several occasions, the pressure in the accelerating tube has inadvertently been allowed to become great enough so that a glow discharge occurred. The accelerating tube was not damaged and no difficulty has been encountered in holding voltage.

The linear accelerator has been operated sincy May, 1953. Although some initial sparking occurred at high rf level, no difficulty was encountered in building up radiofrequency voltage across the drift tubes. After a few hours' operation at slightly higher than accelerating voltage gradient in the cavity, sparking is very rare, only a few occurrances each day, at the optimum gradient.

During the first few months of operation the accelerator was used as a source of 9.9-Mev protons for proton-proton scattering[8] and proton-alpha scattering experiments.[9] The machines have been very reliable, with approximately 50 hours' operation each week. The vacuum tank and cavity were not opened for the first year after initial operation. Recently the cavity was opened to install new coupling loops for the new preexciter. Some sputtered copper was observed at the first ten drift tubes but cleaning was not required.

Energy and Energy Spread

Measurements show that the optimum injected energy from the Cockcroft-Walton generator is 460 kv, compared to the design value of 450 kv. Without the buncher, if the injection energy differs from the optimum value by ± 10 kv, the accelerated beam current is reduced 5%, and if the injection energy differs from the optimum value by ± 40kv, the accelerated beam is reduced to half value.

Panofsky[7] has calculated the tolerable energy spread at injection for various values of synchronous phase. For this accelerator the velocity at the entrance to the first drift tube corresponds to a drift tube of number $n_o = 11$. Then, assuming a synchronous phase angle of $\phi_s = 25^o$, $\Delta W = \pm 39,000$ volts. This value is in good agreement with the measured value, and is then in agreement with the measured value of the synchronous-phase angle.

The energy of the accelerated protons was measured by scattering from helium through an angle of 30^o. Measurements were made of the amount of aluminum absorber required to stop the scattered protons. A triple-coincidence proportional-counter telescope was used as a detector, with the third counter connected in anticoincidence.[10] The amount of aluminum absorber required to stop the protons in a foil separating the second and third counters was a measure of the energy and the energy spread. The measured energy was 9.88 ±0.1 Mev, and the energy spread was less than 0.1 Mev. Range straggling limited the accuracy of measurement of the energy spread to the above value.

The electrostatic deflection plates make the 35^o inflector a very good energy selector. It is observed that twice as much beam strikes the central 1/4-inch strip of the Faraday cup after the electrostatic deflector as strikes each 1/4-inch-wide strip on either side of the center. Monoenergetic protons have a fixed radius of curvature in this system.

$$\frac{mv^2}{2r} = \frac{eE}{2} ,$$

so the kinetic energy is given by

$$T = \frac{eEr}{2} .$$

Because changing the kinetic energy of the incident protons changes the effective curvature of protons deflected through an angle θ, a factor $\frac{1}{1-\cos\theta}$ is required when the differential energy variation is calculated. And

$$\Delta T = T \frac{\Delta r}{r} \frac{1}{1-\cos\theta}$$

$$= \pm\ 30{,}000 \text{ volts}$$

Assuming a gaussian type of energy distribution, this is then the maximum half-width energy spread of the protons that get through the inflector. Generally, only 75 percent of the incident protons are transmitted by the inflector. The reasons for this loss have not been determined. The strong-focusing magnets double the amount of the transmitted beam, suggesting that divergence of the beam is still a large factor in determining the loss. Also, the finite width of the beam at the entrance to the inflector, approximately 1/4 inch in diameter, increases the apparent energy spread.

Assuming the effective divergence of the proton beam is ± 0.0015 radians, the spread in the beam after traveling 11 feet along the inflector is ± 0.2 inches. If the beam is focused part way along the inflector, the spread is less by a corresponding amount. The strong-focusing magnets do this, but with a considerable amount of astigmatism because of the way they are used. It is concluded that the energy spread is probably somewhat less than ± 30,000 volts.

Magnitude of the Accelerated Beam

During typical operation, the Cockcroft-Walton accelerator will give 2.0 milliamperes peak of accelerated proton. With this injected beam current, and without the buncher, the linear accelerator will accelerate a peak beam current of 40 microamperes. The geometrical transmission of the focusing grids is estimated to be 50 percent. Assuming no losses due to radial defocusing, the acceptance phase angle is then 20°.

Measurements have been made to determine the synchronous phase angle. The crystal diodes described above give a signal that is proportional to the voltage across the drift tubes. If the full energy component of the accelerated beam is selected by means of the strong focusing magnets, or magnets plus electrostatic inflector, the threshold value of radiofrequency voltage is 128 (on a relative scale), the value for maximum accelerated beam is 138, and the high-voltage cutoff is at 153, or ± 8 percent width. This corresponds to a synchronous phase angle of 25°, or an acceptance phase angle of approximately 75°. Thus, an additional loss, probably due to radial defocusing, causes a further loss to approximately one fourth of the expected current.

The acceptance phase angle has been increased by inserting a buncher ahead of the linear accelerator. Assuming a drift distance D, a bunching voltage V_o of frequency $f = C/\lambda$ will cause a change in the injection energy E of an amount ΔE. Then the change in velocity is

$$\Delta v = \frac{\beta\lambda}{4} \times \left(\frac{D}{\beta c}\right)^{-1}$$

or $$C\Delta\beta = \frac{\beta^2 \lambda C}{4D}.$$

but $$\frac{\Delta\beta}{\beta} = \frac{1}{2}\,\frac{\Delta E}{E},$$

so $$\Delta E = \frac{\beta\lambda E}{2D}.$$

If E = 450 kv, $\beta\lambda = 1.9$ inch, and D = 40 inches, then $\Delta E = 10{,}700$ volts. This is a reasonable voltage for a small re-entrant type of resonant cavity.

The tolerance on the voltage stability of the protons injected into the buncher can be estimated by assuming that the bunched protons should not be smeared out more than one-half cycle in the drift distance D. In traveling in groups of length $\beta\lambda = 1.9$ inch, n = 21 groups are included in the drift distance D. Thus, the tolerance on the injection energy is approximately $\frac{\Delta E}{n} = \frac{10{,}700}{21} =$ ± 500 volts or one part in a thousand.

The buncher is now used with approximately the calculated voltage and tolerance on injection energy. The peak beam current at the exit of the linear accelerator with the buncher operating at the optimum voltage and phase is 140 microamperes, or somewhat more than twice the beam current without the buncher.

Background Radiation

Electrons are accelerated along the Cockcroft-Walton accelerating tube and bombard the ion source. After a few hours' operation the maximum radiation due to this source of X-rays at any point outside the high-voltage enclosure is 5 mr/hour. The maximum amount of radiation at the outside of the 20-foot long vacuum tank of the linear accelerator is 10 mr/hour. This is caused by high-energy electrons accelerated between the drift tubes. This radiation level is so low that no shielding is required.

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The machines have been assembled and operated by a group which includes Walter Hartsough, Robert Richter, Warren Chupp, Harry Heard, Emery Zajec, Howard Smith, Ross Nemetz, Robert Gisser, Duward Cagle, and Glenn White, with help from the assembly shop, the accelerator technician group, and Robert Pratt.

The electrical construction has been under the supervision of G. V. Wilson and Felix Caldera. Most of the electrical maintenance has been done by L. C. Eggertz, Robert Carpenter and P. H. Culter.

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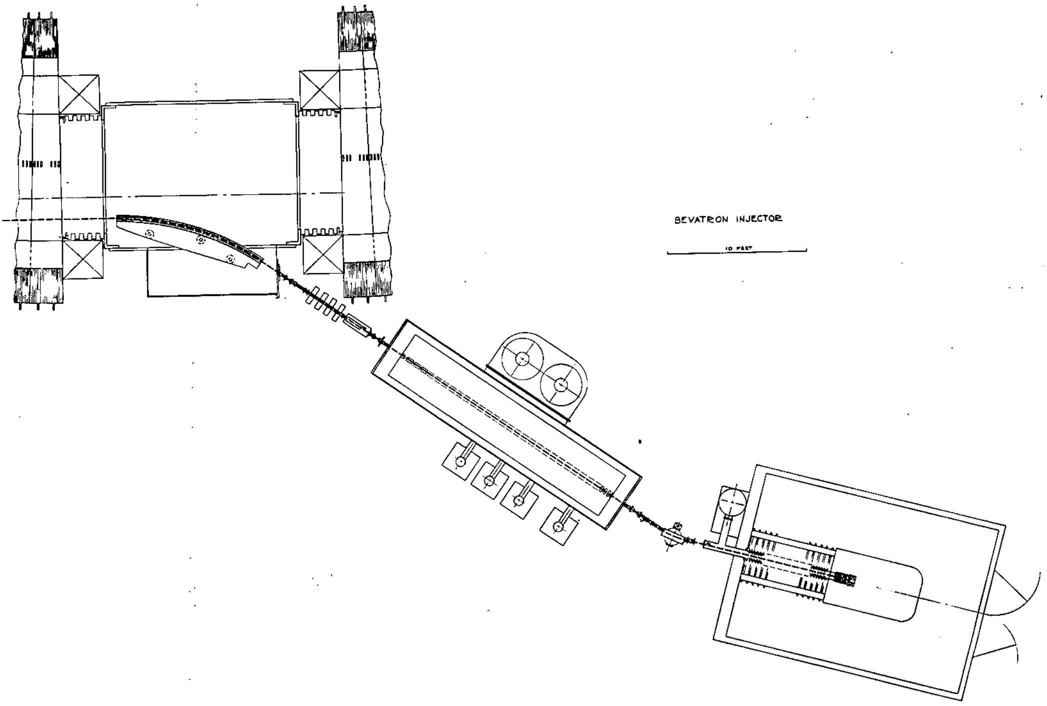
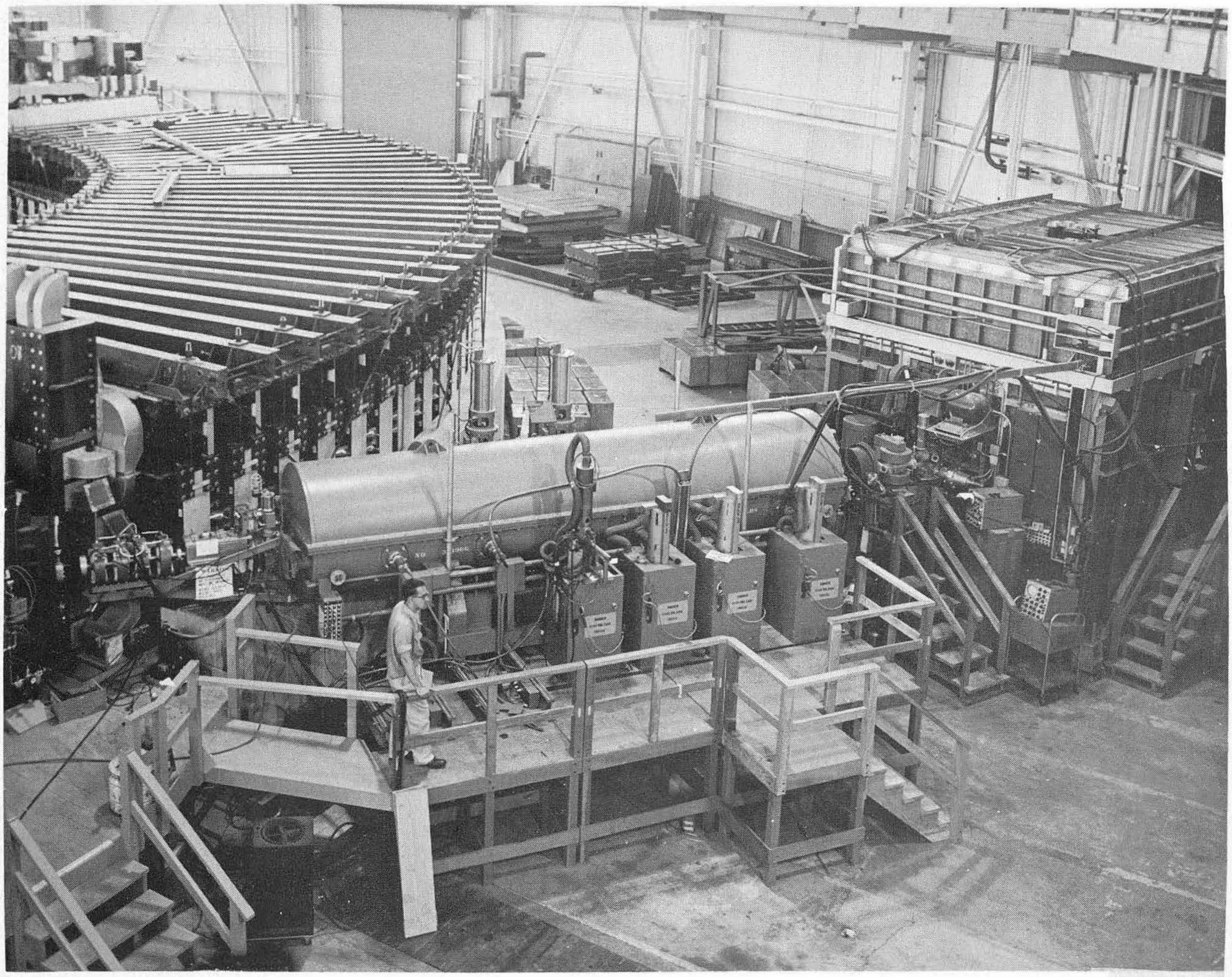
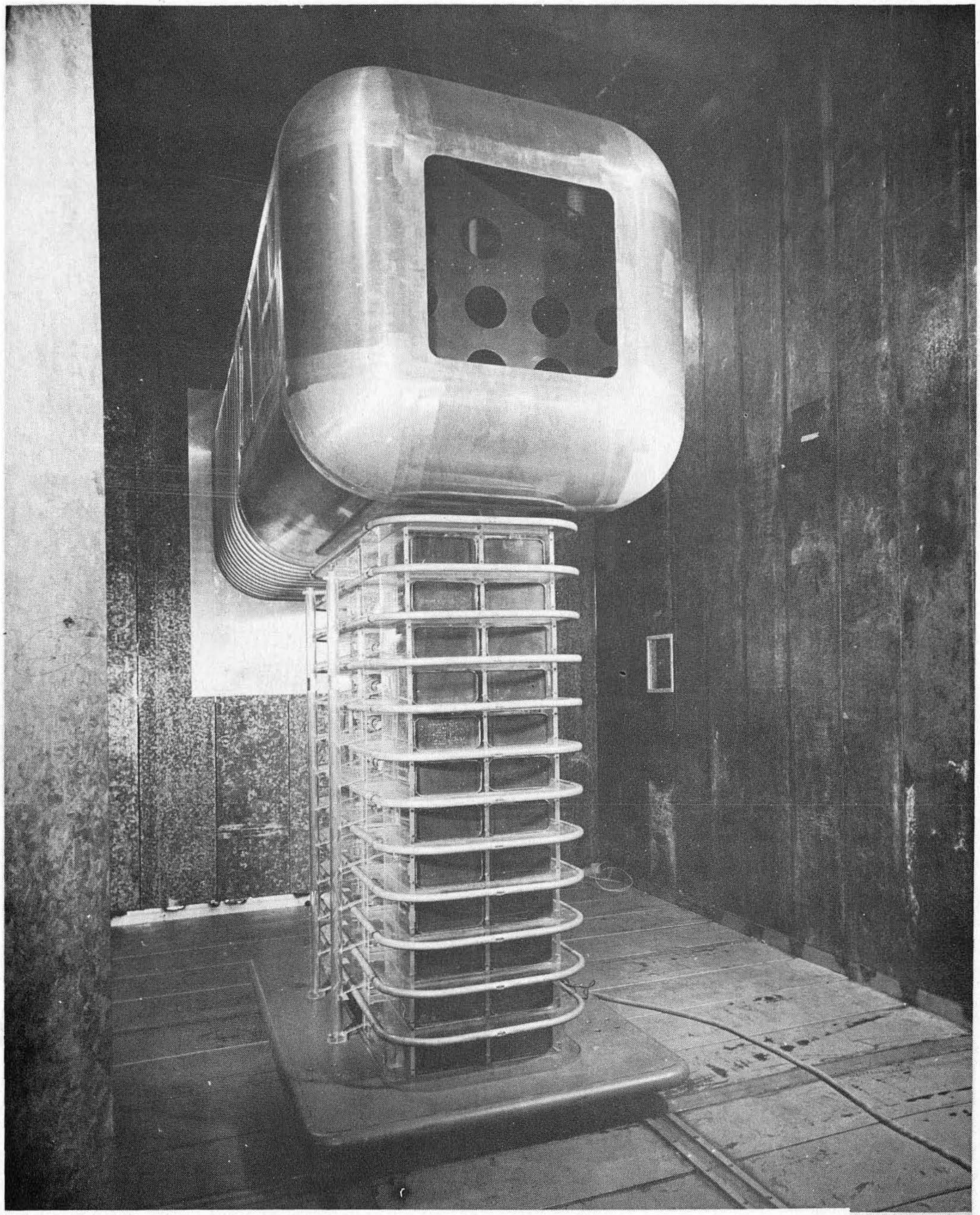


Fig. 1a Bevatron Injection Geometry.



ZN-1021

Fig. 1b. Bevatron Injection Geometry.



ZN-981

Fig. 2 The 500-kv Generator and Enclosure.

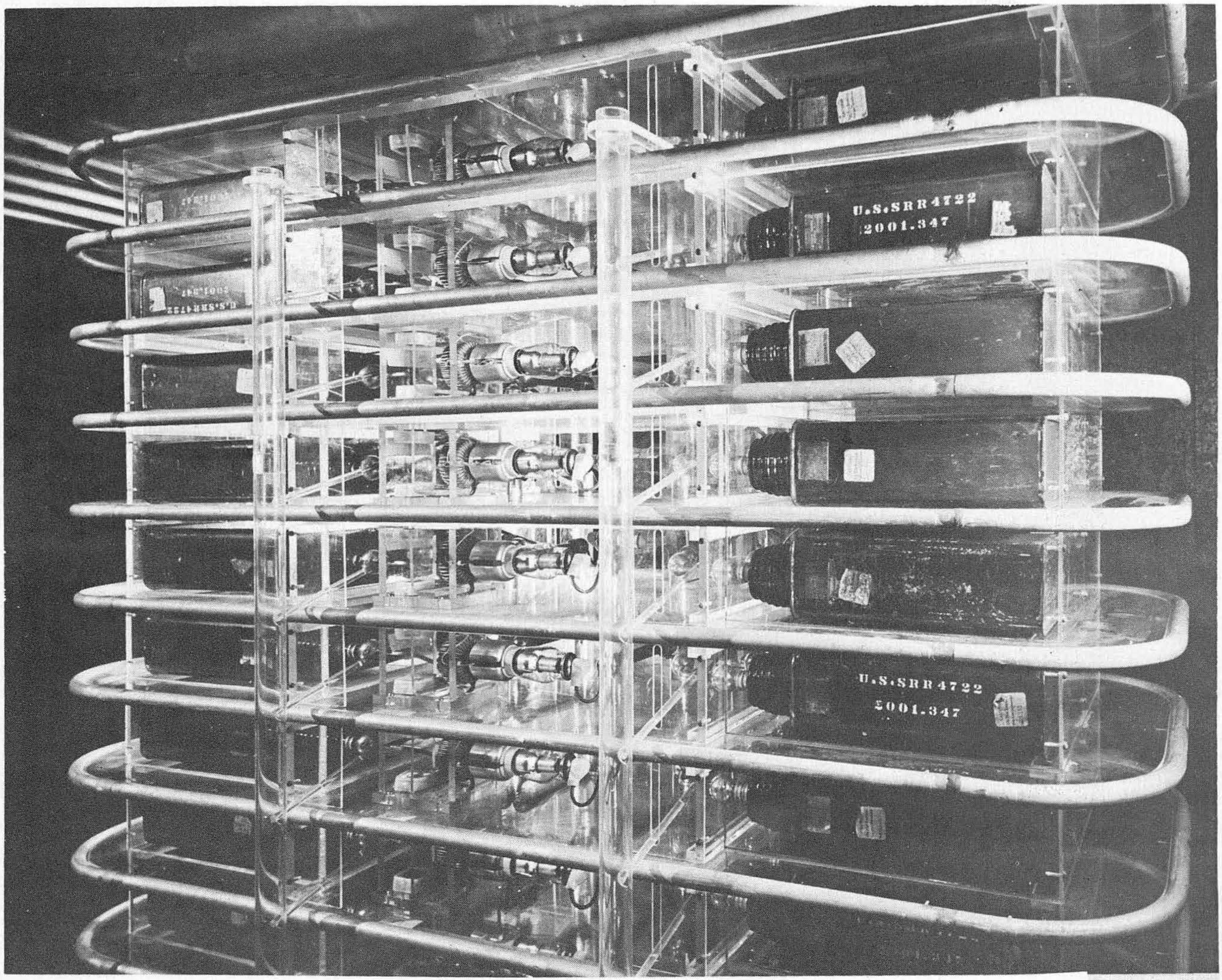


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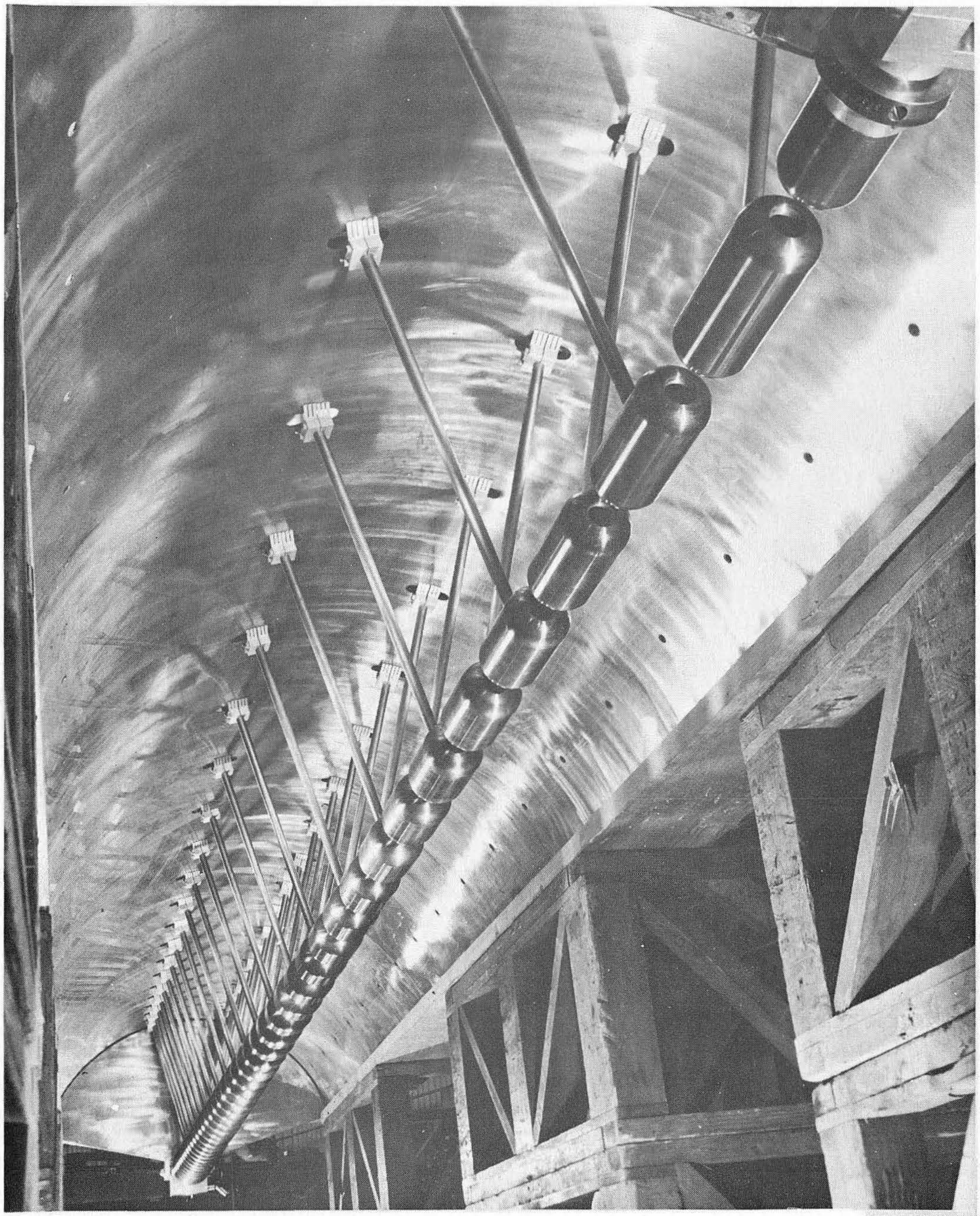
Fig. 3 The 500-kv Cascade Rectifiers.



ZN-983

Fig. 4 The Linear Accelerator Drift Tubes, Looking Toward the Entrance.

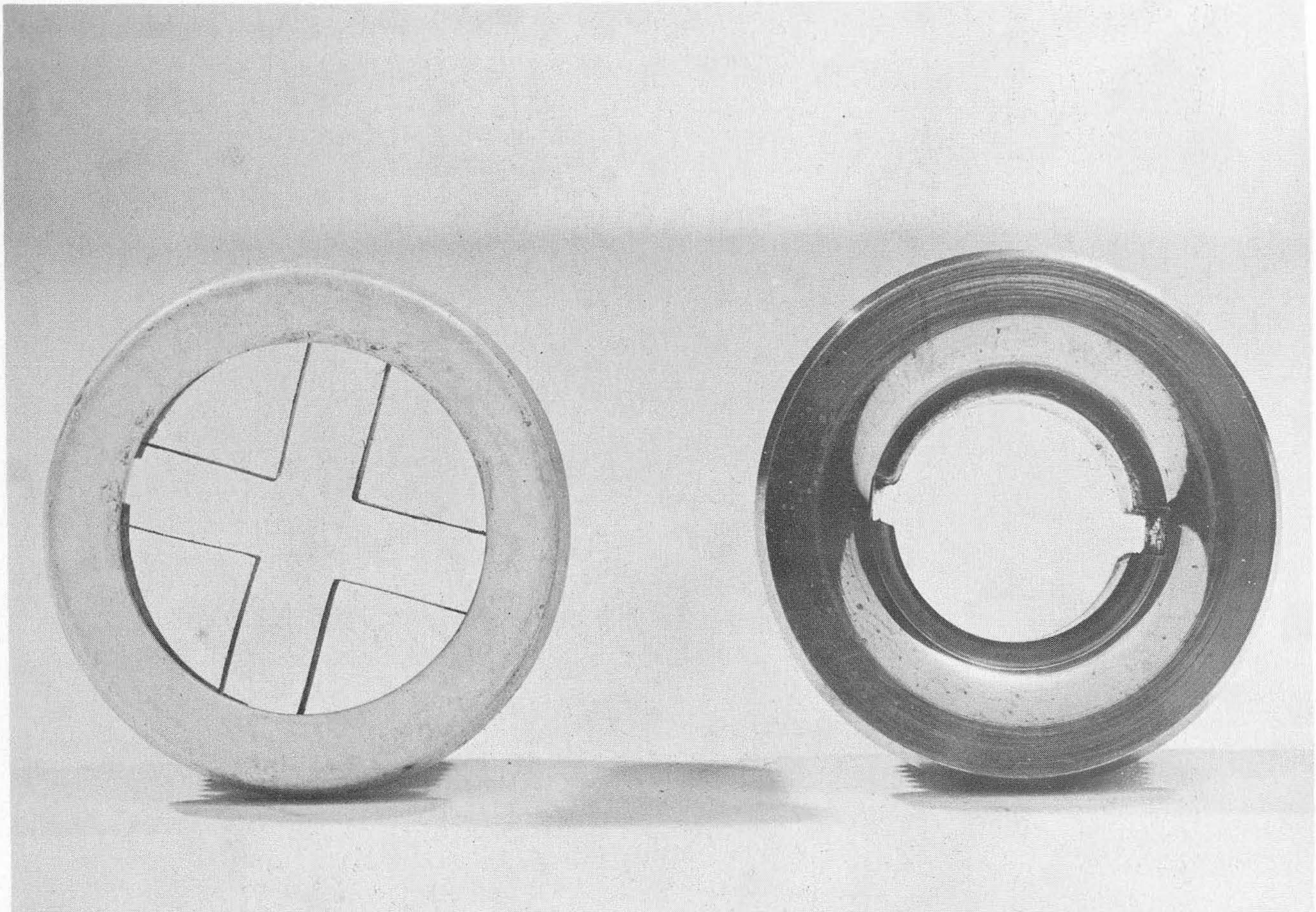


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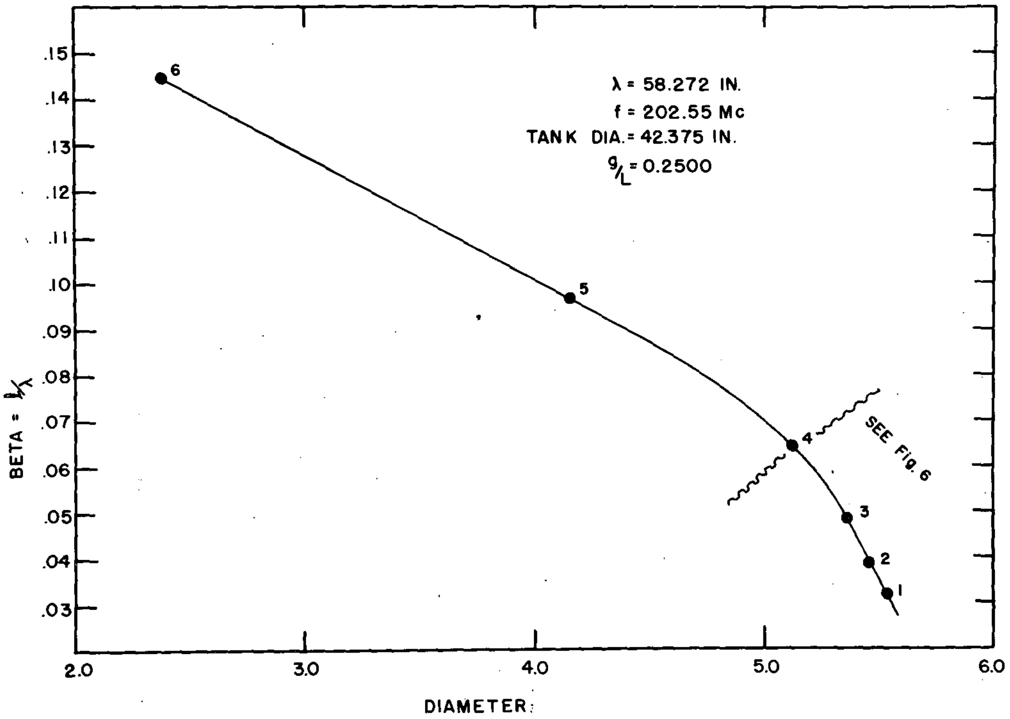
Fig. 5. Ribbon-Type Focusing Grid and Exit Aperture.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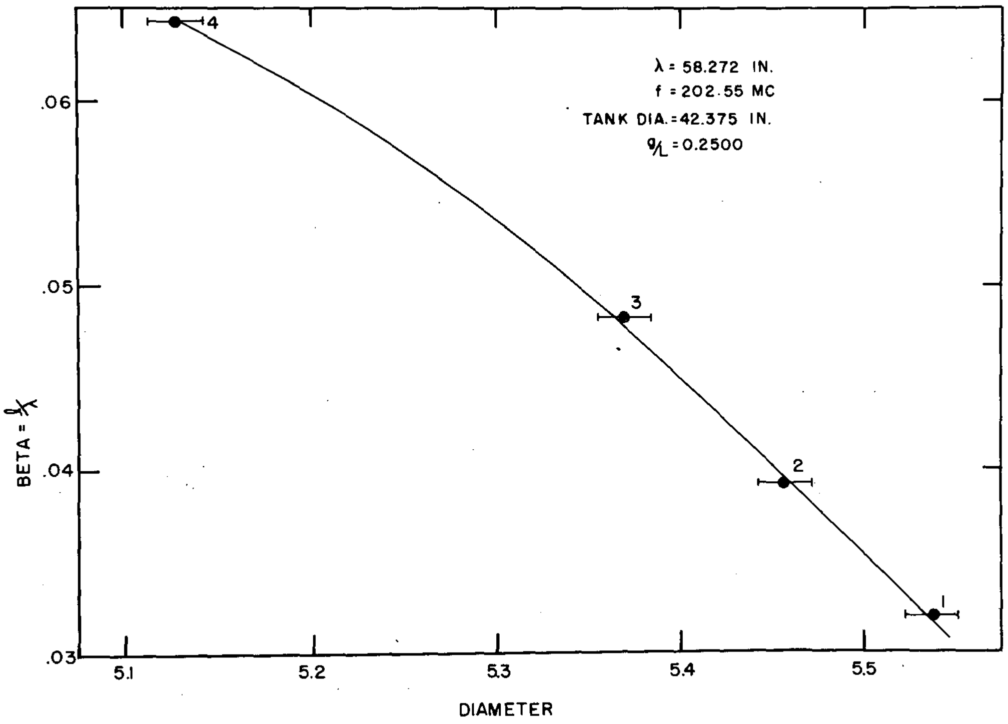
f = 202.55 Mc
TANK DIA. = 42.375 IN.
g/L = 0.2500
SEE Fig. 6
1
2
3
4
5
6
BETA = l/λ
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
2.0
3.0
4.0
5.0
6.0
DIAMETER

Fig. 5

MU-7854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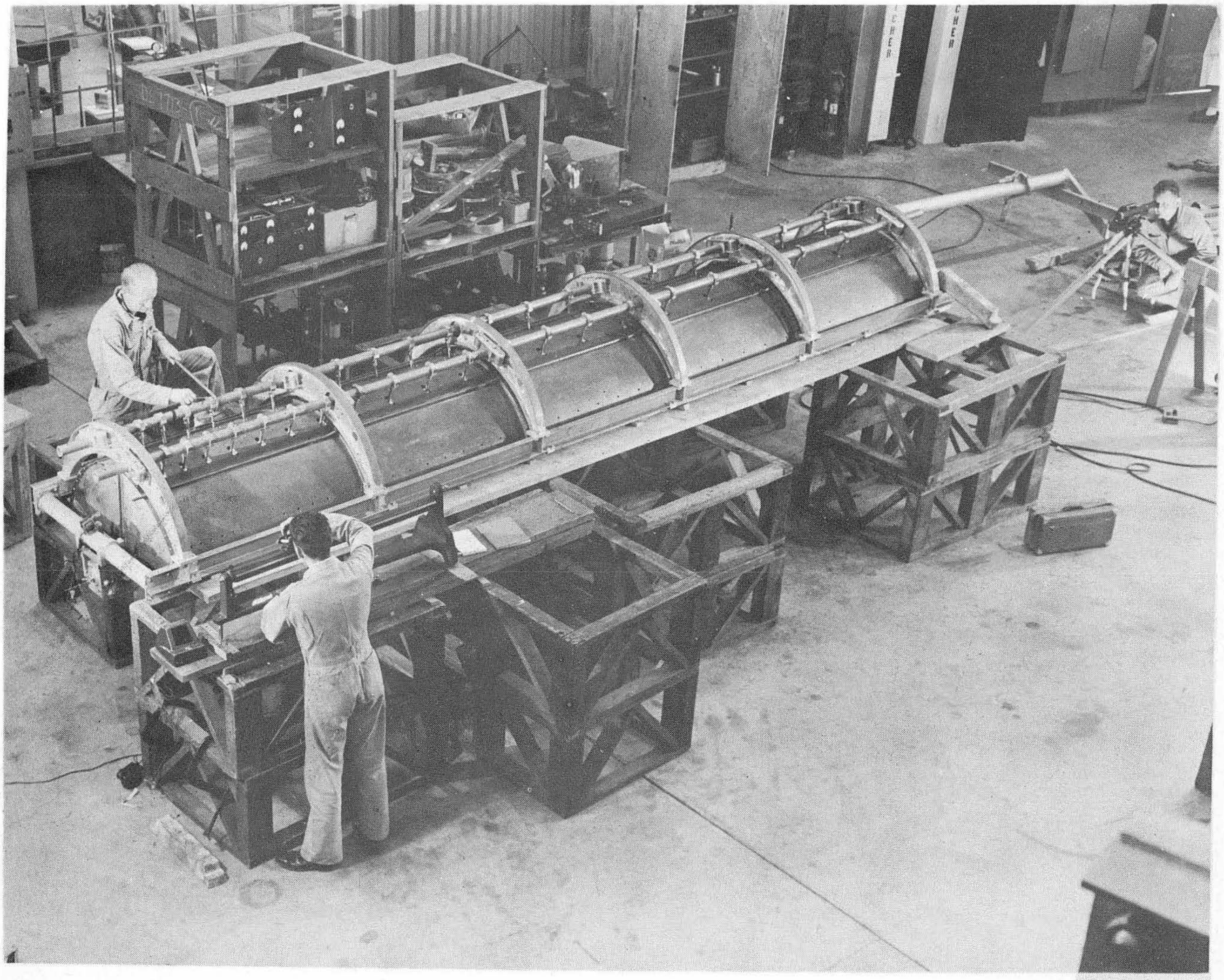
f = 202.55 MC
TANK DIA.=42.375 IN.
g/L = 0.2500
BETA = ℓ/λ
.06
.05
.04
.03
5.1
5.2
5.3
5.4
5.5
DIAMETER
1
2
3
4

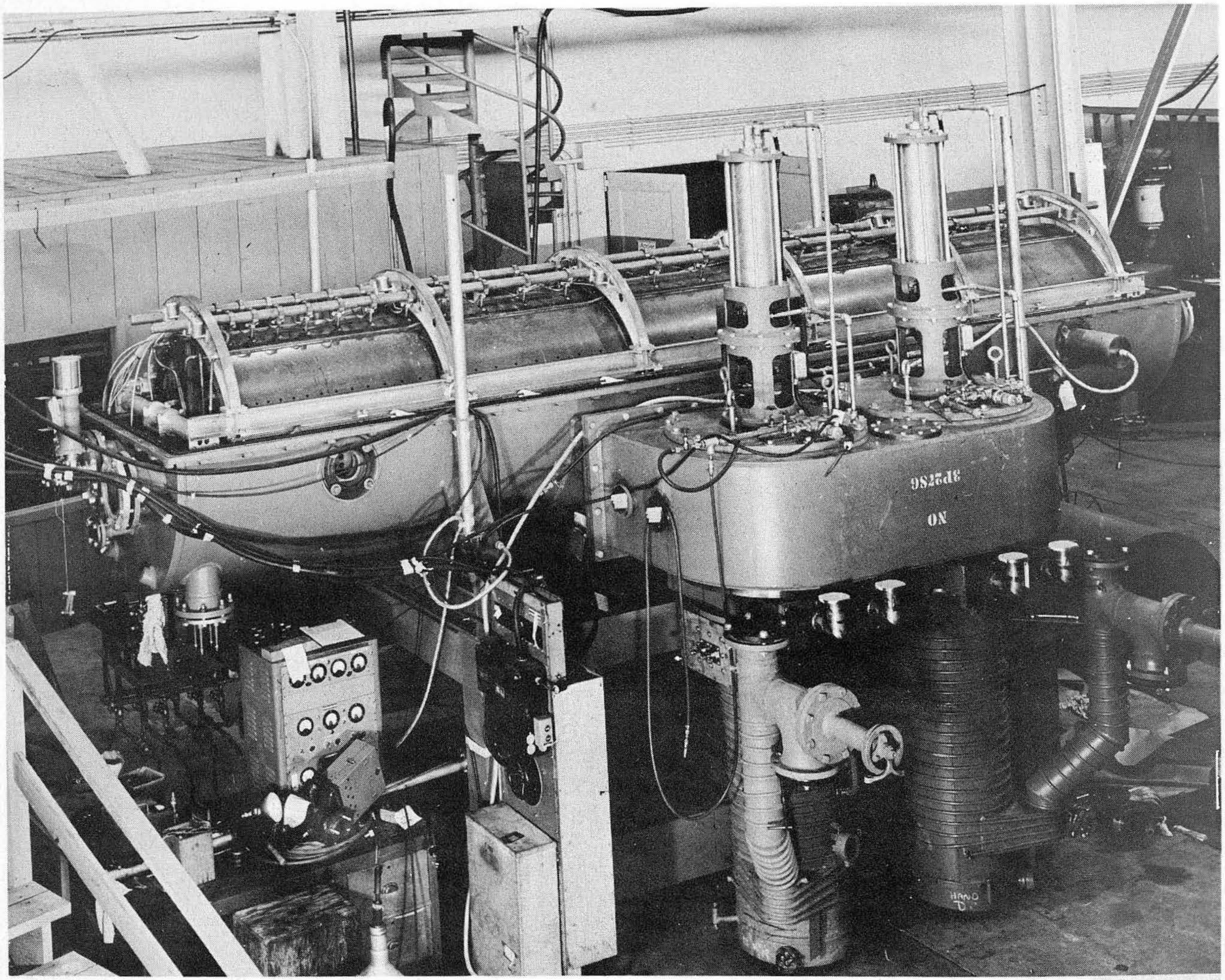
Fig. 6

MU-7855



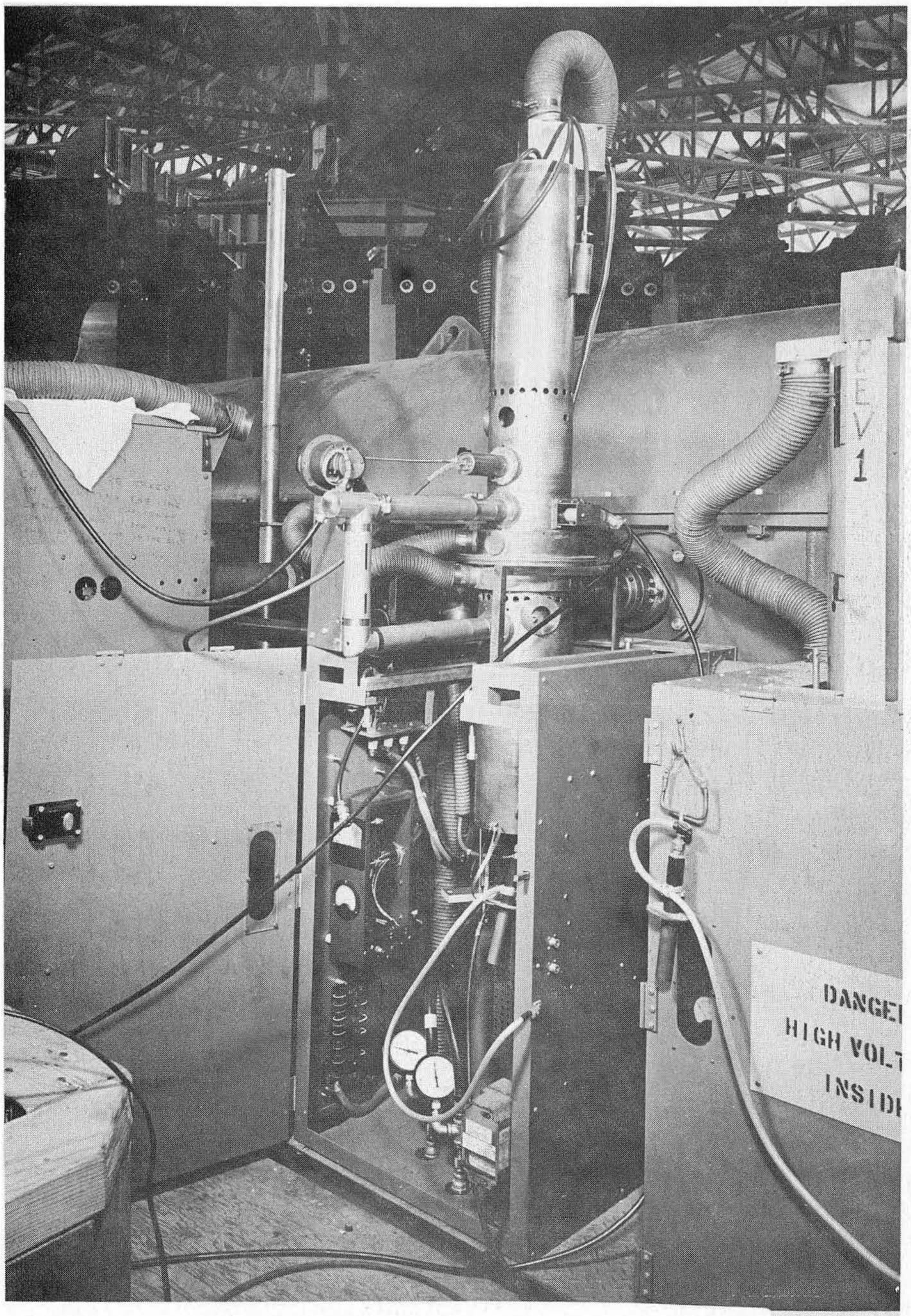
ZN-984

Fig. 8 The Top Section of the 200-Megacycle Cavity with the Drift Tubes Mounted.



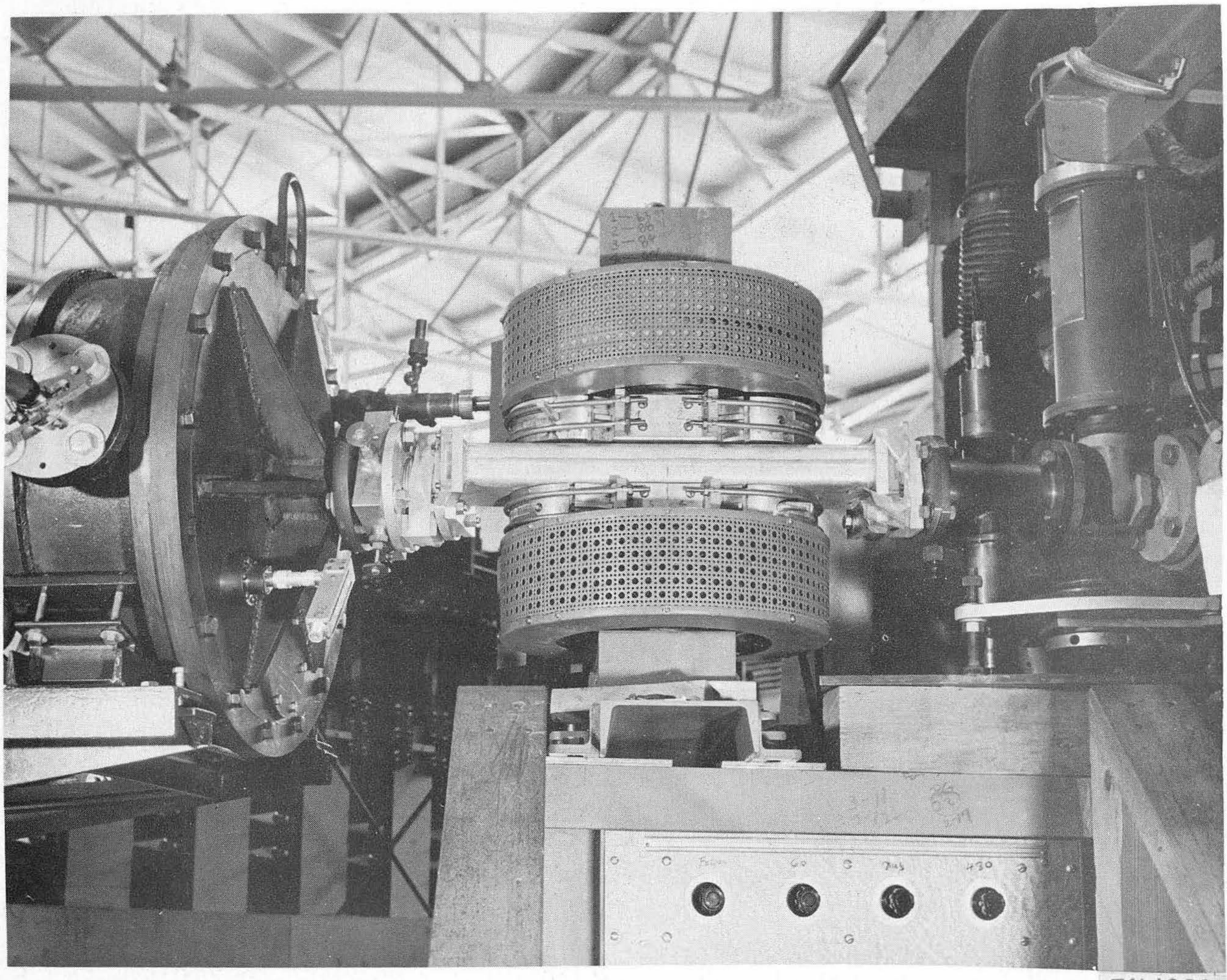
ZN-985

Fig. 9 The Vacuum Tank and Vacuum Pumps.



ZN-986

Fig. 10 The Tetrode Preexciter (center) and the Main Oscillator (right).



ZN-1022

Fig. 11 200 Megacycle Proton Buncher.