SLAC-PUB-219
October 1966

INITIAL OPERATING EXPERIENCE AND PERFORMANCE OF THE SLAC ACCELERATOR*

R. B. Neal
Stanford Linear Accelerator Center, Stanford University, Stanford, California

Introduction

At the date of this report somewhat more than four years have passed since the initial ground-breaking occurred at the SLAC site (July 9, 1962). From the viewpoint of construction, the overall results achieved are probably best observed in an air view of the site (Fig. 1) showing the principal buildings, shops, laboratories, the accelerator housings, and the research area facilities. The entire site comprises 480 acres located about two miles west of the main Stanford campus.

Buildings and structures having a total floor area of approximately 870,000 square feet have been constructed and are listed in Table I. Also given are the date of start of construction and the date of completion of each structure and its cost (to the nearest dollar) per square foot. The variation in unit cost results from the differing functional requirements of these structures and to a lesser extent to the state of the national economy at the time competitive bids were received in each instance. The costs given here include in each case the building and its standard facilities (heating, lighting, plumbing, ventilation, etc.) but not the cost of specialized equipment housed in the building. The total cost of the structures listed is $22.9 million. Other miscellaneous small buildings add about $2 million to this total. It is perhaps interesting to note that the average cost of all the listed space is $26 per square foot.

In September 1961, Congress appropriated $114 million for the construction of the two-mile accelerator. The integrated overall project construction costs and costs plus commitments versus time are shown in Fig. 2. These are in the form of the classical "lazy S" curves applicable to most construction projects. These curves represent the sum of SLAC and ABA (Aetron-Blume-Atkinson, the joint venture of three firms handling the architect-engineering-management work for SLAC) cost experiences. Considering the relatively small amount of construction remaining at this date, it now appears that the entire construction effort will be accomplished within the appropriated amount.

During the summer of this year, an electron beam was successfully accelerated through the two-mile machine and a maximum energy of 18.4 GeV was obtained. Extensive testing has shown that the accelerator meets specifications in almost all respects. The only notable exception to this statement is the failure to attain rated beam current due to the onset of "beam break-up" phenomena. A detailed account of these phenomena and of steps being taken to overcome them is being presented in a separate report[1] to this conference.

Description

The evolution of the design of the two-mile accelerator is given in several earlier reports.[2-6] A brief review of the final design configuration of the accelerator and some of its principal components will be given here.

General Plan

A schematic diagram depicting the entire two-mile accelerator is shown in Fig. 3. The first item of interest starting at the west end of the accelerator is the main injector. A beam analyzing station (No. 1) is located about 40 feet downstream from the injector to permit easy set-up and analysis of the injected beam. An instrumentation section is located in a 9-foot drift space at the end of each 333-foot sector to provide information on beam current, intensity, and profile. This region also contains the quadrupoles used for focusing the beam. A branch in the accelerator housing at the one-third point is provided for the future construction of a reduced energy research facility at this point. Just downstream from the beam take-off point is a facility to house a future injector. Next in line is the positron source, which has assumed increasing importance as the research program planning has evolved. Beam Analyzing Station No. 2, located in Sector 20, permits beam operation and analysis during periods when the beam cannot be run into the beam switchyard or research area. At the two-thirds point, another branch in the accelerator housing occurs to provide for a second future intermediate research facility. It is at this point that the proposed positron-electron storage ring[7] will be located if its construction is authorized by Congress. The beam switchyard at the east end of the accelerator contains the magnets, collimators, energy-defining slits, and other special beam handling and monitoring instrumentation required to determine the characteristics of the beam and to direct it into any of the three experimental areas. Two separate control rooms have been constructed. One of these, called the Central Control Room, contains all of the instrumentation and control equipment required for monitoring and controlling the components and systems of the two-mile accelerator. The other control room, known as the Data Assembly Building, contains similar equipment relating to monitoring and controlling the components and systems of the Beam Switchyard. Numerous control and data links extend between the two control rooms. Some data links also extend to the research area from the Data Assembly Building.

Accelerator Housing And Klystron Gallery

A cross section of the accelerator housing and the klystron gallery is shown in Fig. 4. Penetration tubes, 27 inches in diameter and spaced 20 feet apart, carry the waveguides, vacuum manifolds, water cooling pipes and instrumentation cables between the two housings. A personnel accessway is provided once per sector (333 feet).

Accelerator Structure and Support Girder

A complete 10-foot accelerator section[8] is shown in Fig. 5. This structure is fabricated by a special brazing technique from separately machined copper disks and rings. The dimensions of the separate parts vary over the 10-foot length to result in a constant

*Work supported by the US. Atomic Energy Commission.

(Presented at 1966 Linear Accelerator Conference, Los Alamos, October 1966.)

gradient design, i.e., the axial electric field which accelerates the electrons is constant over the entire section. Four 10-foot sections are mounted on a 40-foot aluminum girder which serves not only as a support for the sections but also as a portion of a continuous "light pipe" through which a laser beam from a source located at the east end of the accelerator is transmitted for alignment purposes[9] through a distance of two miles to a detector located at the west end. A retractable Fresnel target located in one end of each 40-foot girder, as shown in Fig. 6, serves to focus the laser beam on the detector. Deviations of the accelerator from correct alignment are indicated by the displacement of the laser image at the detector. Realignment is accomplished by adjustment of the jacks supporting the girders.

High Power Klystrons

A total of 245 klystrons is required to fill all the sockets along the two-mile accelerator. These tubes are rated at 21 megawatts peak and 21 kilowatts average power output. They have a design capability somewhat higher than these ratings. In view of the importance and criticalness of these tubes to the entire accelerator program and the large number required to fill the accelerator sockets and the repair cycle "pipe-line," several parallel procurements have been undertaken. A basic tube design with permanent magnet focusing was first developed at SLAC. Later four outside companies fabricated tubes meeting the same basic specifications but not identical to the SLAC tube in mechanical and electrical design details. However, all of these tubes are electrically and mechanically interchangeable in the SLAC sockets. These developments led to three outside procurements, as noted in Table II. These procurements did not all start at the same time. Klystron models manufactured by SLAC and the four commercial companies are shown in Fig. 7. These tubes are all designed to be repairable. After repair they are put through the same acceptance tests as new tubes and must meet original specifications. As discussed in more detail later, operating results and failure rates have been sufficiently favorable that we have been able to negotiate an extended warranty agreement with one of the outside suppliers wherein, after initial purchase of a tube, SLAC pays a fixed hourly rate for the first 1500 hours of operation of the tube and a decreased rate thereafter. Under this arrangement, the manufacturer agrees to replace a failed tube with a tube meeting original specifications at no additional cost to SLAC.

Installation of klystrons in the gallery is shown in Fig. 8. Also shown in the same figure are the modulators and the ion-getter pumps and manifolds which evacuate the waveguides and accelerator.

The power output from each klystron is divided into four equal parts and feeds four successive 10-foot accelerator sections. The general arrangement is illustrated in Fig. 9. Waveguide feeds to adjacent sections are from opposite sides to compensate for residual coupler asymmetries. The provision of a waveguide valve just above each klystron allows the klystron to be replaced without affecting the accelerator vacuum or interfering with beam operation.

Other Components and Systems of the Accelerator

Time limitations permit only a brief review of the few more accelerator components and systems. The main injector system is illustrated in Fig. 10. The 80-kV, 2-ampere gun is followed by a pre-bunching cavity, a disk-loaded $v_p = 0.75 \cdot c$ buncher, and a 10-foot accelerator section. For phase coherence, all of these are fed by a single high power klystron. Electron bunching within 5 electrical degrees (0.15 cm) is achieved. Other devices are provided to focus, steer and collimate the beam, and to measure its intensity, transverse position, phase spread and profile. The injector is capable of providing three independent time-interlaced beams, each adjustable in intensity and pulse length.

At the end of each 333-foot sector there is an instrument section, as shown in Fig. 11, containing devices for measuring the beam characteristics (intensity, position, and profile) and for steering and focusing the beam. The position monitors are of the microwave type utilizing two rectangular cavities which are excited in the TM_{120} mode by an off-axis beam. Two types of intensity monitors are used. One is a cylindrical microwave cavity operating in the TM_{010} mode which provides, with the aid of appropriate electronic circuitry, an output proportional to the logarithm of the charge contained in the beam pulse. The other intensity monitor, utilizing a toroid with a ferrite core, provides an output directly proportional to the charge in the beam pulse. Both of these devices, as well as the position monitors, can sense independent pulses and therefore are capable of measuring the characteristics of several time-interlaced beams. Focusing is provided by means of three quadrupoles whose coils are connected in series and whose polarities are such that they constitute a quadrupole triplet. In order to strengthen the overall focusing along the accelerator for the purpose of increasing the beam break-up threshold,[1] the quadrupole triplets will shortly be rearranged in the form of doublets with the shorter quadrupoles located in the early sectors and the longer quadrupoles in the later sectors. Larger power supplies will be provided for the downstream doublets.

The positron source located at the one-third point along the accelerator includes equipment located on three separate girders having a total length of 40 feet. This equipment is shown in Fig. 12. The positron sources proper are located on the first girder. There are two sources each consisting of one layer of gold, two of silver, and eight of copper, with cooling water passages between. Each layer is approximately 1/8 inch thick. The total material in each source constitutes about 3.5 radiation lengths. One of the sources (the "wand" radiator) is used to give an intermittent source of positrons. It consists of a small target about 0.5 inch wide which is driven across the beam path on command in a time equivalent to about nine machine pulses (at 360 pps). The center pulse of this group results in a positron pulse; the other eight are eliminated by gating of the main injector. All the remaining pulses (up to 351) may be electrons if desired. If a continuous low intensity positron beam is desired, the wand can be caused to remain stationary in the incident beam. The "wand" source and its associated hardware (still incomplete) is shown in Fig. 13. The second source, shown in Fig. 14, is in the form of a water-cooled wheel which is caused to undergo a nutating motion by a crank mechanism and an external motor drive system. With an incident electron beam of 100 kW on the wheel radiator, it is predicted that a positron average current of approximately 1.5 μA can be accelerated in an energy band of about 1% and a transverse phase space of approximately 0.3 mc-cm. A magnetic lens system is used to improve the match between the source emittance and the accelerator phase space acceptance. The radiator is located in a 20-kilogauss axial magnetic field which decreases rapidly to 2.4 kilogauss about 2 feet downstream from the radiator and then remains constant for the next 25 feet. Acceleration begins 2.5 feet downstream from the radiator and the positron energy at 25 feet is about 75 MeV, at which point the solenoidal focusing is replaced by a series of 13 quadrupole triplets whose spacing increases with energy until this focusing system merges with the regular machine triplet system located at the end of each sector. A pulsed rf deflector located downstream from the converter is used to produce an angular deflection of the positron and electron beams. Since the beams are 180 degrees apart in phase, they are both deflected by the same angle; a pulsed steering magnet is then used to restore the direction of whichever beam is desired to the axis while the other unwanted beam is deflected even farther from the axis. The second and third of the positron source girders are shown in Fig. 15 as they appeared in the assembly area just prior to installation in the accelerator housing.

The Beam Switchyard

A diagram of the Beam Switchyard indicating the location of the various pulsed and dc magnets, steering devices, quadrupoles, collimators, slits, and other beam handling equipment is shown in Fig. 16. Also shown is the cross section of the switchyard housing at various locations along its approximately 1000-foot length. The beam path is in the lower level of the two-level structure and is separated from the upper level by means of removable concrete shielding blocks. The upper level contains utility and instrumentation runs, tracks for maintenance cars, and three overhead cranes.

The problems of operation and maintenance in the switchyard are severe because of the high-level radiation environment. Provisions for remote handling of components in case repair or replacement is necessary have been essential. These factors have imposed design requirements which make the achievement of a vacuum as low as that of the accelerator ($< 10^{-7}$ torr) very unlikely. Fortunately, a much poorer vacuum (10^{-3} to 10^{-4} torr) is adequate in this area. At these pressures and with the large volume to be pumped, diffusion pumps are the most feasible and economic solution. The entire siwtchyard is pumped by eight stations located at ground level about 40 feet above the top of the switchyard. Each pumping station utilizes a 6-inch oil diffusion pump and a refrigerated trap. Connection of each pumping station to the switchyard is accomplished by means of a 20-inch-diameter stainless steel manifold. The beam switchyard vacuum system is effectively isolated from the accelerator vacuum system by means of a differential pumping system, which includes a special 10-foot accelerator section refrigerated to -30°C to trap migrating oil molecules.[10]

An artist's conception of the exterior of the beam switchyard and its surroundings is shown in Fig. 17.

The high average power (≈ 1 MW) carried by the electron beam requires the use of large and complicated beam handling devices. Typical of such devices is the adjustable energy-defining slit[11] shown in Fig. 18. This unit is 16 feet long. Two such devices, with one rotated 90 degrees about the beam axis with respect to the other, are utilized as an adjustable collimator to define the size and position of the beam as it enters the beam switchyard.

Beam Switchyard Instrumentation

Instrumentation is provided in the beam switchyard to measure the beam characteristics (intensity, pulse shape, energy, energy spectrum, transverse position, and profile). Other instruments are used to protect various sensitive devices from being damaged by high temperatures or radiation effects due to excessive beam interception. A typical instrumentation grouping is shown in Fig. 19. All of the instruments illustrated can be installed, aligned, or removed by personnel located in the upper level using remote operation tools.

A general impression of some of the individual instruments in the beam switchyard can be gained from Figs. 20-26.

Figure 20 shows a 3-inch-aperture beam current monitor which incorporates two ferrite toroids. One of the toroids is used in the current monitoring system and the other in a precision integrating system. These devices have a sensitivity of 2 mV/mA and an effective rise time of 30 nsec.

The microwave-type beam position monitor shown in Fig. 21 is similar to that used along the accelerator except that the aperture has been increased to 2 inches. To prevent unwanted coupling between the x and y cavities, it was found necessary to separate them by about 4 inches by means of a 2-inch-aperture pipe. The sensitivity of these monitors is $0.17\ \mathrm{mW/(mA\ mm)^2}$.

Three different techniques for viewing the beam profile are employed in the devices shown in Figs. 22, 23, and 24. A synchrotron light pick-up station is shown in Fig. 22. Light radiated by the electron beam as it is deflected in the first dc magnet of the beam transport system is transmitted by means of metal mirrors to a television camera located in an enclosure on top of the beam switchyard. Using a vidicon camera, this monitor can view beams having a current of 1 μA or higher. The lower limit can be extended to about 10^{-2} μA by using a more sensitive orthocon camera. An advantage of this type of monitor is that it does not intercept the beam. However, it is somewhat less sensitive than the monitors to be described next and requires a suitable magnetic field in the near vicinity of the position where the profile is viewed. A "carrousel" type of zinc sulphide screen profile monitor is shown in Fig. 23. Since the individual screens lose luminescence after exposure to an integrated beam current of about 10 μA hr/cm^2, the carrousel device containing 48 independent screens has been designed. The carrousel can be rotated and the individual screens can be raised or lowered by remote control. Other types of zinc sulphide screen monitors in the forms of individual flaps and film rolls have also been developed. The third type of profile monitor, utilizing Cerenkov light, is shown in Fig. 24. A cell filled with argon or helium at a pressure slightly above atmospheric can be moved into the beam by a remotely controlled pivoting action. The gas cell has 3-mil-thick aluminum entrance and exit windows. The Cerenkov light cone is reflected vertically by a 1-mil-thick aluminum mirror located inside the cell at an angle of 45 degrees to the beam. The beam image is observed by means of a television camera looking at one part of the radiated cone. The Cerenkov monitor has a sensitivity of about 10^{-3} $\mu A/cm^2$ (with helium) or 3×10^{-4} $\mu A/cm^2$ (with argon).

Secondary emission monitors (SEM) are used in the beam switchyard for spectrum analysis, monitoring of beam interception by the jaws of the slits and collimators, to provide beam centering information at the high power beam dumps, and to provide signals for the equipment protection system. Aluminum foils having a secondary emission coefficient of about 4% are used in all of these applications. The spectrum analyzer used just upstream from the main energy-defining slits is shown in Fig. 25. Two foil holders each carrying 6 foils made of 1-mil aluminum can be moved into or out of the beam by a remotely controlled pivoting action. The foils vary in width from 6 mm (0.1% resolution) for those nearest to the beam axis to 48 mm(0.8% resolution) for those farthest from the axis.

To prevent thermal or radiation damage to components accidentally struck by the high power electron beam, an equipment protection system consisting of more than 20 protection collimators along with associated ionization chambers and thermometers is used in the beam switchyard. An out-of-limit signal from any of these sensing devices will either shut off the beam or give a warning signal to the operator. A typical water-cooled protection collimator and its two associated ion chambers are shown in Fig. 26. The size and shape of the aperture of each protection collimator depends upon the corresponding beam configuration at the point where the protective action takes place.

The Research Area

A general view of the research area is shown in Fig. 27. The beam line to End Station A has been completed and the beam line to End Station B is scheduled to be completed by November 1, 1966. A central (C) beam line has been designed and will be completed by June, 1967. End Station A will be used primarily for elastic and inelastic scattering of electrons and positrons and for photoproduction experiments. Three large spectrometers capable of analyzing scattered particles with maximum energies of 1.8, 8, and 20 GeV, respectively, are nearing completion. A two-meter streamer chamber and associated magnet will be located just downstream from End Station A. This device is on rails and can be moved into or out of the beam as desired. After passing through the A experimental area, the electron beam will be transported in an evacuated pipe covered by concrete shielding to a high power dump ("Beam Dump East"). End Station B is the center of experiments involving secondary particles. Initially, three secondary beams of μ mesons, monochromatic photons, and K mesons, respectively, are being constructed. A one-meter bubble chamber and a large spark chamber, both under construction at SLAC, will be used in conjunction with the secondary particle experiments on the B side. An 82-inch bubble chamber is now undergoing modification at Berkeley and will be moved to SLAC around July, 1967. It will be used in conjunction with the C-Beam experimental program.

Operating Results

Starting in January, 1965, when a 1.5-GeV beam was accelerated through the first two sectors (666 feet), the two-mile machine has been activated in a series of steps. Some of the more significant events and dates are shown in Table III. The most recent advance noted was the transmission on September 20, 1966, of a beam through the accelerator, the beam switchyard, and End Station A to the farthest point the beam can reach, Beam Dump East.

The performance of the accelerator in its operation to date is summarized in Table IV. Comparison of the experimental results with design parameters shows that, with the exception of peak beam current which has been limited by beam break-up phenomena to about 40% of the design level, all design parameters have been met or bettered.

Typical energy spectra are shown in Fig. 28. The spectrum of higher energy was obtained for light beam loading (2.3-mA peak beam current). A higher beam current (15-mA) results in the lower energy spectrum having 0.44 GeV less energy than the first. Note that the lower energy spectrum contains some electrons having energies as high as the lightly loaded spectrum. These are the electrons which pass through the accelerator during the earliest part of the pulse before a significant amount of stored rf energy has been absorbed by the beam. The spectrum width at half maximum is 1.33%, of which about 0.9% is attributable to the resolution of the measurement devices.

Compensation of the beam loading exhibited in Fig. 28 can be achieved by delaying the trigger to one or more of the accelerator sectors. In this case, the first electrons accelerated during the beam pulse pass through some sectors which are only partly filled with rf energy and therefore they gain less energy than they would if the sectors were completely filled. The compensation achievable with this technique is demonstrated in Fig. 29, where the dashed line shows the uncompensated spectrum and the solid line shows the compensated spectrum resulting from trigger delay to one sector by approximately 0.5 μsec.

The energy spectra shown in Figs. 28 and 29 represent the output of one foil of the spectrum analyzers described earlier as the deflecting magnet current is swept through a range corresponding to the energy spread of the electrons in the beam. The simultaneous output of all of the foils gives an instantaneous representation of the energy spectrum as shown in Fig. 30.

Beam transmission through the accelerator has been found to be quite good. About 90% of the current measured close to the input end of the machine, say at the beam analyzing station No. 1 located 40 feet from the injector, is preserved through the entire two-mile length. This favorable result arises from the effective performance of the beam position and intensity monitors, the steering and focusing systems, and the long ion chamber. The microwave position monitors have been able to indicate the transverse position of the beam with respect to the accelerator axis within ± 0.5 mm. The long ion chamber, which is an argon plus CO_2-filled 1-5/8-inch coaxial line installed alongside the accelerator, enables the operator to detect beam losses and from the times of arrival of the ionization signals to resolve their location within one or two hundred feet. The oscilloscope presentation of the long ion chamber signal is shown in Fig. 31, where the ordinate is the ion chamber reading proportional to beam interception and the abscissa is the sector number where the beam loss occurs. The solid-line curve shows the original ion chamber reading and the other curves show the ion chamber reading as the steering and focusing is improved in successive steps by the operator.

Tests to date have demonstrated the feasibility of accelerating at least three beams of different energies in a time-interlaced manner. The pulse length and intensity of each of these beams can be independently controlled. Spectra of three beams having energies of 1.17, 1.79, and 2.42 GeV are shown in Fig. 32. These relatively low energy beams were measured at beam analyzing station No. 2 located at Sector 20. The irregular base line is due to scattered low energy electrons at the analyzing station. Figure 33 shows the presentation observed by the operator on the "Linear Q" oscilloscope when two interlaced beams having energies of 11 and 5.65 GeV, respectively, are accelerated. The heights of the dots above the base line are proportional to the beam current measured at the end of each sector. These measurements are made by means of the toroid-type beam current monitors described earlier.

The beam break-up phenomena which presently limit the maximum current achievable with the two-mile accelerator are discussed in detail in a separate report[1] being presented to this conference and will not be treated comprehensively here. Various means of curing or mitigating the beam break-up problem are under investigation. These include microwave suppression and feed-back schemes, the addition of sextupole or octupole devices, and improved quadrupole focusing along the machine. The latter measure is the only one which so far has been found to be definitely efficacious. As discussed earlier steps are now underway to increase the effective quadrupole focusing strength along the two-mile accelerator and it is expected that these measures will lead to a significant increase in the beam break-up current threshold.

During the past several months an endurance run involving 14 sectors of the accelerator was conducted. In order to gain information as to the performance and life of accelerator components (especially klystrons) as a function of the operating level, seven different levels were maintained as indicated in Table V. The variables were the pulse repetitition rate which ranged from 60 to 360 pulses per second and the klystron beam voltage ranging from 200 to 245 kV. The corresponding peak power outputs and the equivalent electron beam energies (assuming 230 klystrons in operation) are also shown in the table. Experimental results are the total failures under each condition in approximately 1200 hours of operation and the average number of klystron station faults per minute (extrapolated to 230 stations). The number of failures for the various conditions ranged from 0 to 6 and the fault rate from 0.2 to 2.0 per minute. The larger number in each instance occurred for the operating condition resulting in maximum peak and average power output from the klystrons. Another indication arising from the experimental results is the fraction of the time the klystrons will, on the average, be available under each operating condition. These latter results are shown in Fig. 34. These results, while preliminary, would seem to suggest that an attempt to achieve energies higher than about 20 GeV (at the maximum repetition rate) by increasing the klystron power output will meet with diminishing returns due to decreasing klystron availability.

Tests of the accelerator and beam switchyard are continuing on a 10-shift-per-week basis. Installation in the B side of the beam switchyard and in the research area takes place regularly during the day shift so that beam operation into these areas can now occur only during the two night shifts. However, accelerator beam tests up to Beam Analyzing Station No. 2 in Sector 20 are regularly conducted during the day shift without interference with other work. During the last two weeks, runs have started for preliminary checkout of equipment in End Station A. The actual research program in both End Stations A and B will start around December, 1966.

References

1. E. V. Farinholt, Z. D. Farkas, W. B. Hermannsfeldt, H. A. Hogg, R. F. Koontz, C. J. Kruse, G. A. Loew, and R. H. Miller, "Beam Break-Up Experiments at SLAC," 1966 Linac Conference (Los Alamos).
2. R. B. Neal and W.K.H. Panofsky, Proceedings of the International Conference on High Energy Accelerators, (CERN, Geneva, 1956), Vol. I, p. 530.
3. R. B. Neal, Proceedings of the International Conference on High Energy Accelerators, (CERN, Geneva, 1959), p. 349.
4. K. L. Brown, A. L. Eldredge, R. H. Helm, J. H. Jasberg, J. V. Lebacqz, G. A. Loew, R. F. Mozley, R. B. Neal, W.K.H. Panofsky, T. F. Turner, Proceedings of the International Conference on High Energy Accelerators, (Brookhaven, 1961), p. 79.
5. W.K.H. Panofsky, Proceedings of the International Conference on High Energy Accelerators, (Dubna, 1963), p. 407.
6. J. Ballam, G. A. Loew, R. B. Neal, Proceedings of the Fifth International Conference on High Energy Accelerators (to be published), (Frascati, 1965).
7. S. Berman et al., "Proposal for a High-Energy Electron-Positron Colliding-Beam Storage Ring at the Stanford Linear Accelerator Center" (June, 1965).
8. R. P. Borghi, A. L. Eldredge, G. A. Loew, and R. B. Neal, "Design and Fabrication of the Accelerating Structure for the Stanford Two-mile Accelerator," to be published in Advances in Microwaves, Vol. I, (Academic Press, New York, N.Y.)

9. W. B. Herrmannsfeldt, The First National Particle Accelerator Conference, (Washington, D.C., 1965), IEEE Transactions on Nuclear Science, Vol. NS-12, No. 3, p. 929. Also: W.B. Hermannsfeldt, "SLAC Alignment System," 1966 Linac Conference, (Los Alamos).
10. E. L. Hoyt and E. L. Garwin, The First National Particle Accelerator Conference, (Washington, D.C., 1965), IEEE Transactions on Nuclear Science, Vol. NS-12, No. 3, p. 740.
11. D. R. Walz, J. Jurow, and E. L. Garwin, The First National Particle Accelerator Conference, (Washington, D.C., 1965), IEEE Transactions on Nuclear Science, Vol. NS-12, No. 3, p. 867.

TABLE I

PRINCIPAL SLAC BUILDINGS AND STRUCTURES

Name	Date Construction Started	Date Of Completion	Gross Area ($Ft.^2$)	Cost ($\$/Ft.^2$)
Test Laboratory	7/62	6/63	39,500	23
Administration-Engineering Bldg.	9/62	9/63	43,640	18
Construction Office Bldg.	12/62	6/63	15,000	13
Electronics Bldg.	2/63	11/63	26,500	13
Fabrication Bldg.	2/63	12/63	31,855	24
Accelerator Housing	6/63	10/64	122,000	39
Klystron Gallery	10/63	6/65	343,000	11
Central Laboratory	12/63	4/65	57,855	27
Heavy Assembly Bldg.	12/63	10/64	32,000	24
Control Bldg.	6/64	3/65	12,850	22
Beam Switchyard	9/64	3/66	50,000	85
Cafeteria	1/65	8/65	3,975	33
Auditorium	1/65	8/65	5,750	32
End Station A	3/65	7/66	30,360	83
End Station B	3/65	7/66	17,000	57
Cryogenics Bldg.	8/65	5/66	8,060	37
Fire Station	12/66	7/67	2,500	36(est.)
General Services Bldg.	3/67	11/67	28,000	19 (est.)

TABLE II

KLYSTRON PROCUREMENT CONTRACTS

Supplier	Total Contract	Accepted to Date (9/1/66)
RCA	216	130
Sperry	144	80
Litton	144	67
SLAC	36	36
TOTAL	540	313

245 Klystrons are required to fill all accelerator sockets.

TABLE III

Key Dates

April, 1957	Proposal for 2-Mile Accelerator
September, 1961	Authorization by Congress
April, 1962	Contract with AEC
January, 1965	1.5 GeV Beam Through 2 Sectors
April 21, 1966	Beam to 2/3 Point (Sector 20)
May 21, 1966	Beam Through 30 Sectors to Beam Switchyard
June 2, 1966	18.4 GeV Beam in Beam Switchyard (Tune-up Dump)
September 16, 1966	Beam to A Beam Dump in Beam Switchyard
September 20, 1966	Beam to Research Area A and Beam Dump East

TABLE IV

COMPARISON OF SIGNIFICANT
SLAC DESIGN PARAMETERS AND PERFORMANCE (September 1966)

	Specified	Actual
Energy contribution per klystron $E_{MeV} = K\sqrt{P_{MW}}$	$K_{max} = 20.6$	$K_{obtained} = 20$ average
Effective[a] number of installed klystrons	242	242
Peak klystron power at 360 pps and 2.5-μsec pulse length	22 MW	22 MW
Conservative[b] klystron peak power at 360 pps		16-18 MW
Maximum beam energy for above conservative level		~ 20 GeV
Maximum peak beam current at 1.6-μsec pulse length	50 mA	20 mA (beam break-up limited)
Corresponding number of e^-/pulse	5×10^{11}	2×10^{11}
Average beam current at 360 pps and 1.6-μsec pulse	~ 30 μA	~12 μA
Beam loading derivative in GeV/amp	35	35
No. of simultaneous beams at different energies, pulse lengths and repetition rates	3	3
Typical energy spectrum width at half maximum	1%	0.6 - 1.3% depending on total current
Accuracy of automatic phasing system[c]	$\pm 5^\circ$	$\pm 5^\circ$ or better
Electron bunch width at 40-foot point	$<5^\circ$	$<5^\circ$
Klystron phase stability (within pulse and pulse to pulse)	5°	5°
Beam phase space: Injector emittance ($\pi r \times p_r$)	0.05	0.025 mc-cm
Accelerator emittance	0.10	0.05 mc-cm
Accelerator vacuum (torr)	$< 10^{-5}$	$\sim 10^{-7}$
Shift in accelerator alignment - horizontal (April - August 1966)		0.5 mm (max)
- vertical		1 mm (max)

a This number had been adjusted to take into account non-standard accelerator girders.

b Based on 90% availability of klystrons.

c Improvements are still required to make the system more reliable.

TABLE V

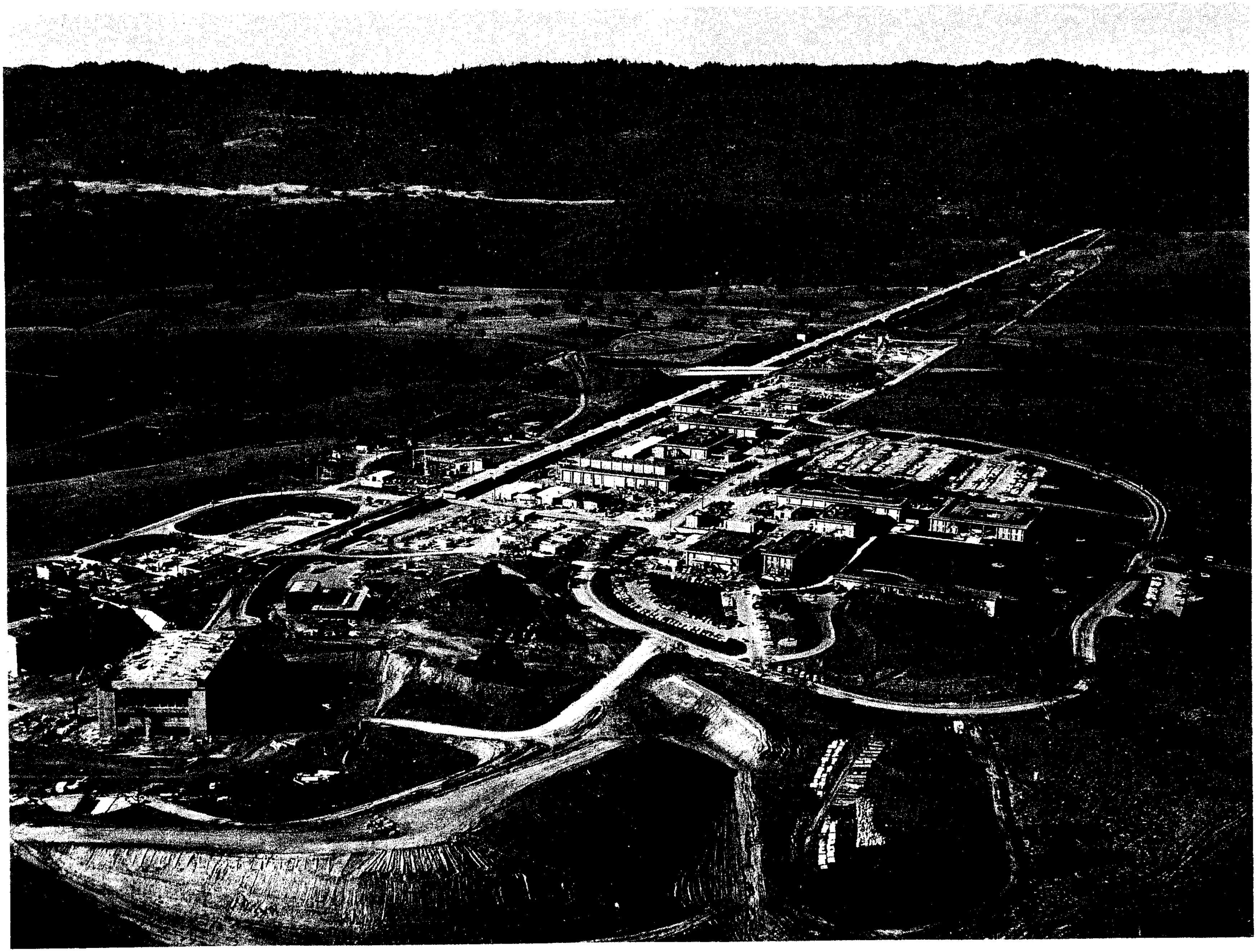
ENDURANCE RUN

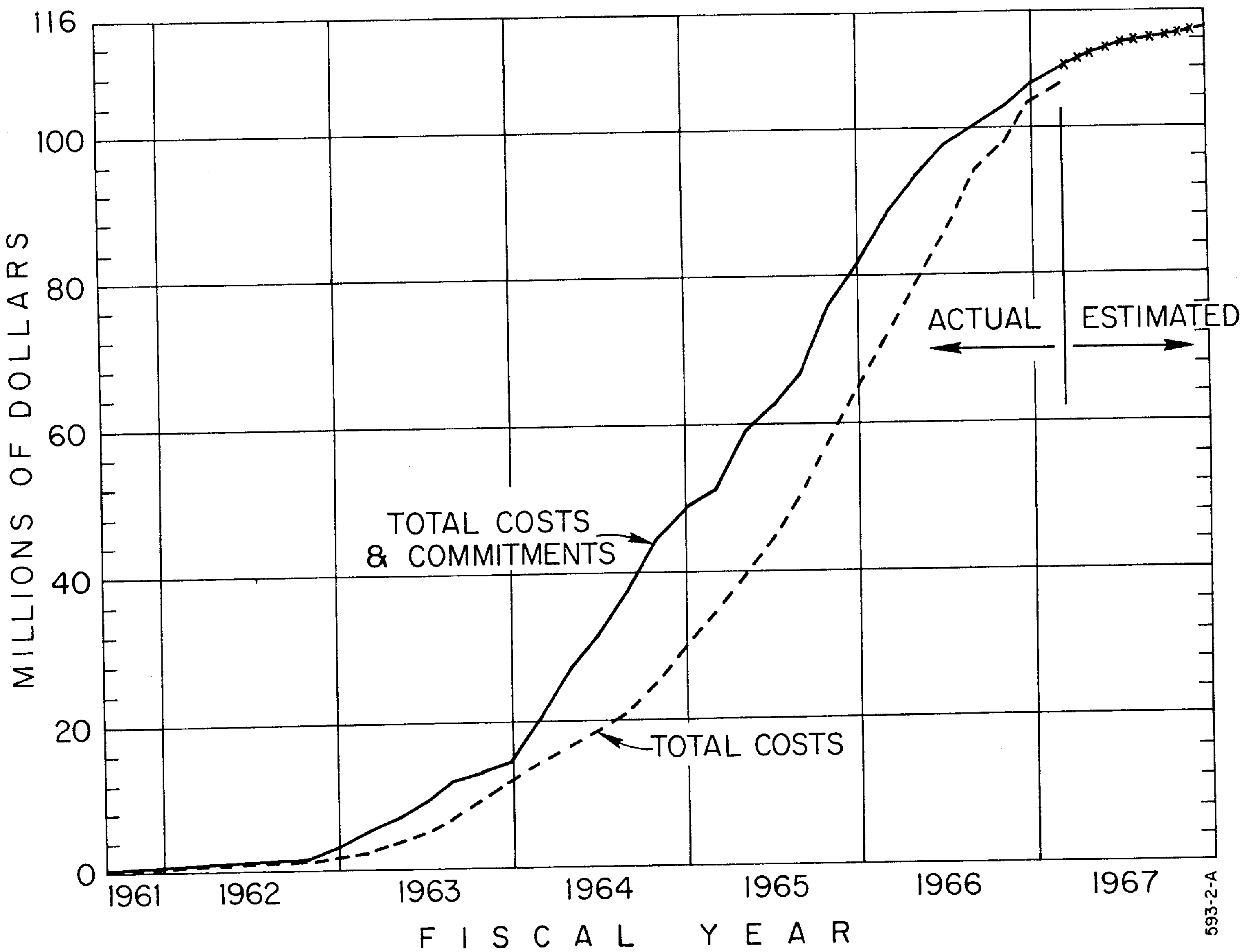
SECTOR PAIR	OPERATING LEVEL V_k (kV)	P_{out} (MW)	V_o (GeV)	PRR (pps)	ACCUMULATED HRS. (AVG. OF 16 STATIONS)	TOTAL KLYSTRON FAILURES	FAULTS PER MINUTE (Extrapolated to 230 Stations)
3 & 4	245	21	21	60	1175	1	0.4
5 & 6	245	21	21	360	1050	6	2.0
7 & 8	230	17.5	19	60	1200		0.2
9 & 10	230	17.5	19	180	1140		0.2
13 & 14	230	17.5	19	360	1135	2	0.6
15 & 16	200	12	16	60	1200	1	0.2
17 & 18	200	12	16	360	1190		0.4

P_{out} = EXPECTED AVERAGE POWER OUTPUT AT KLYSTRON BEAM VOLTAGE V_k

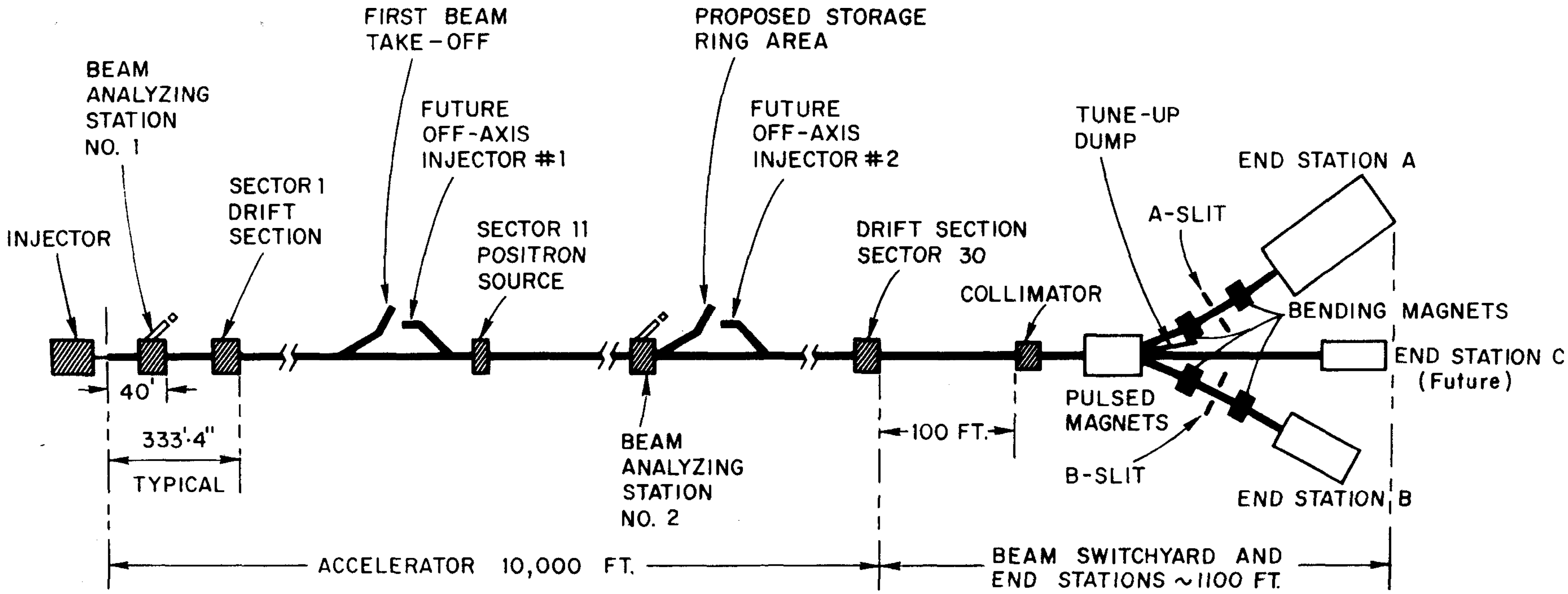
V_o = COMPUTED NO-LOAD ELECTRON BEAM ENERGY FOR 230 STATIONS OPERATING AT V_k $\left(V_o = 4.6\sqrt{P_{out}}\right)$

List of Figures

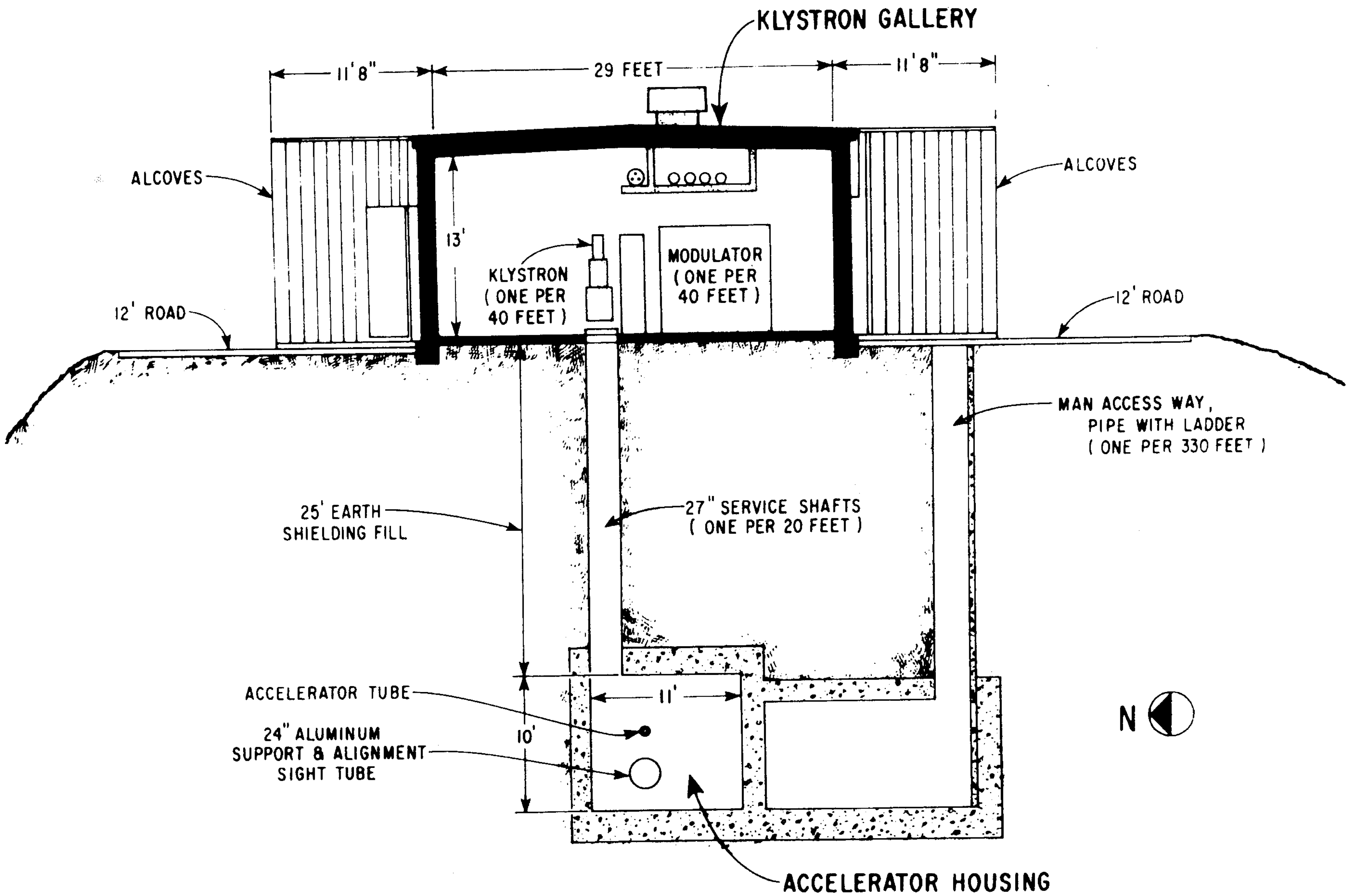


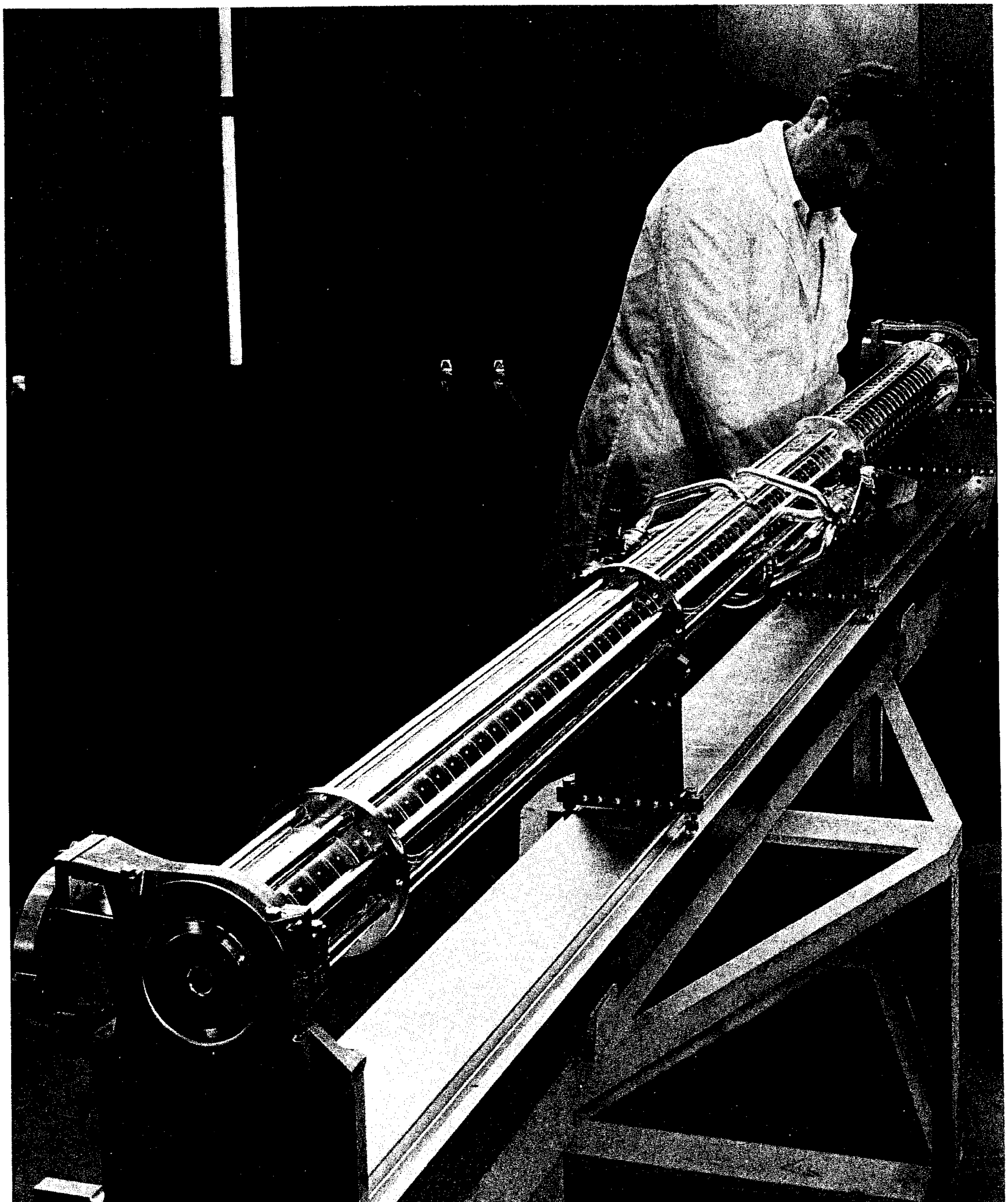


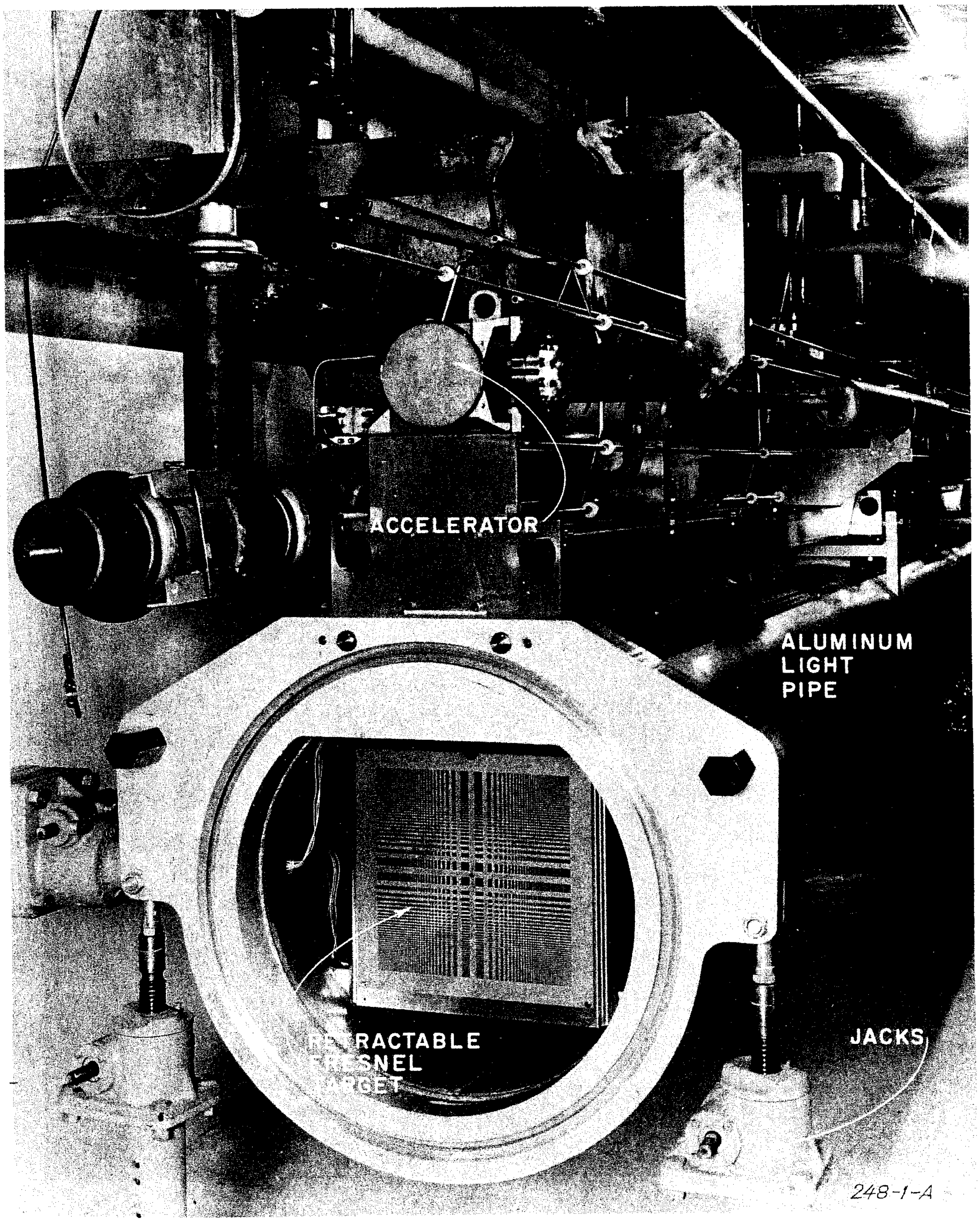
MILLIONS OF DOLLARS
116
100
80
60
40
20
0
1961
1962
1963
1964
1965
1966
1967
FISCAL YEAR
TOTAL COSTS & COMMITMENTS
TOTAL COSTS
ACTUAL
ESTIMATED
593-2-A


FIRST BEAM TAKE-OFF
PROPOSED STORAGE RING AREA
BEAM ANALYZING STATION NO. 1
FUTURE OFF-AXIS INJECTOR #1
FUTURE OFF-AXIS INJECTOR #2
TUNE-UP DUMP
END STATION A
SECTOR 1 DRIFT SECTION
A-SLIT
INJECTOR
SECTOR 11 POSITRON SOURCE
DRIFT SECTION SECTOR 30
COLLIMATOR
BENDING MAGNETS
END STATION C (Future)
40'
PULSED MAGNETS
333'-4"
TYPICAL
100 FT.
BEAM ANALYZING STATION NO. 2
B-SLIT
END STATION B
ACCELERATOR 10,000 FT.
BEAM SWITCHYARD AND END STATIONS ~1100 FT.

585-1-A

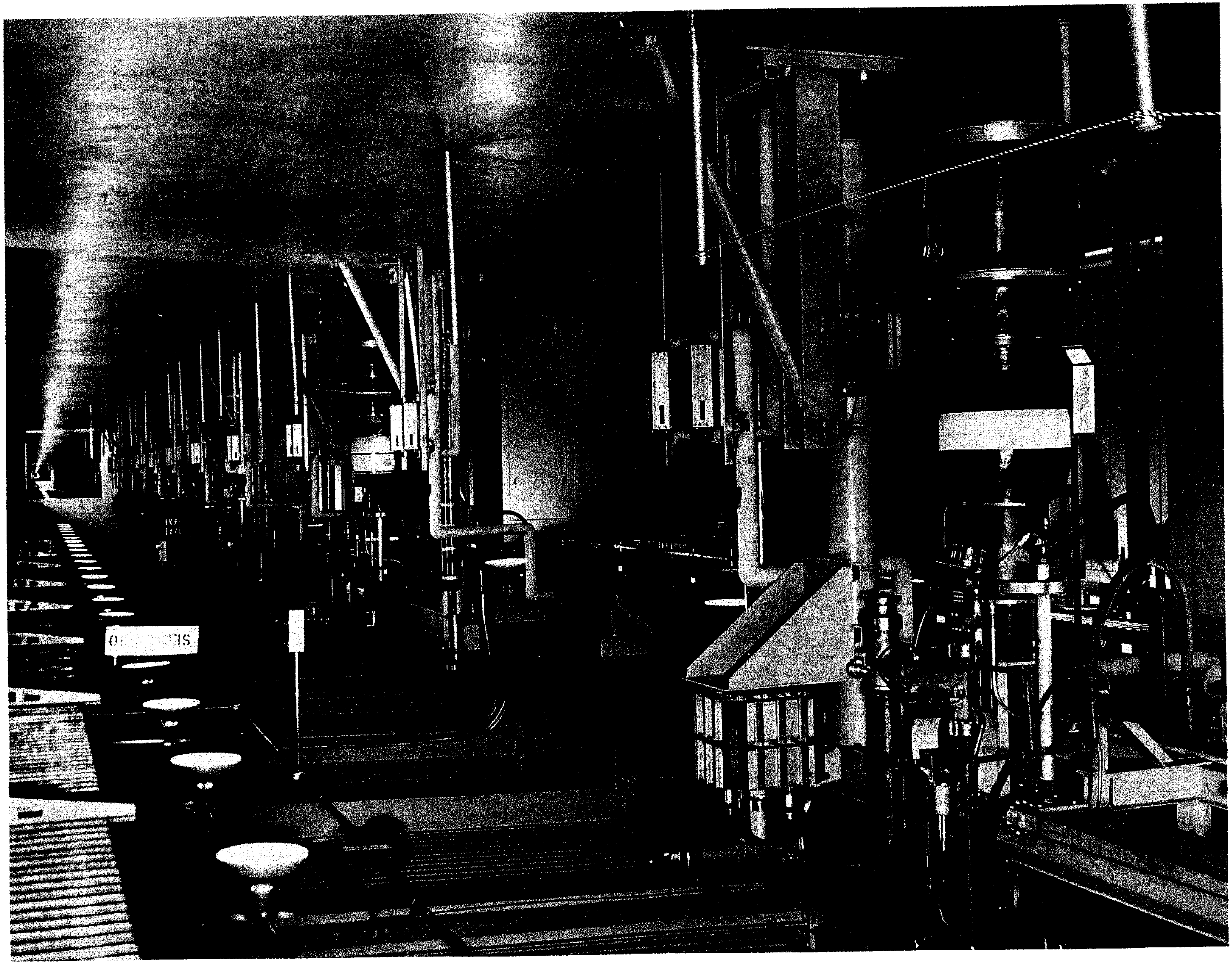

KLYSTRON GALLERY
11'8"
29 FEET
11'8"
ALCOVES
ALCOVES
13'
KLYSTRON
(ONE PER
40 FEET)
MODULATOR
(ONE PER
40 FEET)
12' ROAD
12' ROAD
MAN ACCESS WAY,
PIPE WITH LADDER
(ONE PER 330 FEET)
25' EARTH
SHIELDING FILL
27" SERVICE SHAFTS
(ONE PER 20 FEET)
ACCELERATOR TUBE
11'
24" ALUMINUM
SUPPORT & ALIGNMENT
SIGHT TUBE
10'
N
ACCELERATOR HOUSING

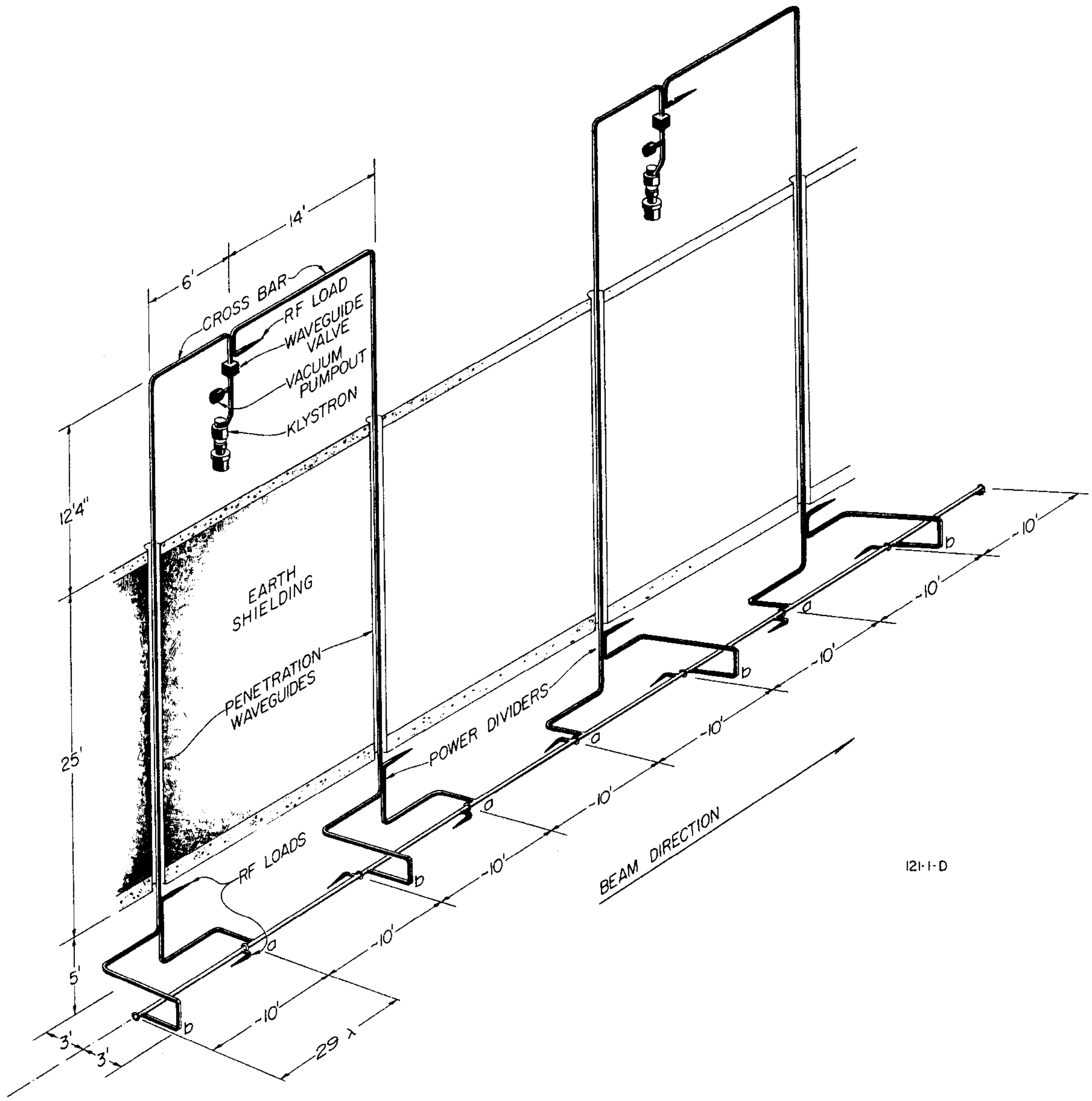



ACCELERATOR
ALUMINUM
LIGHT
PIPE
JACKS
248-1-A

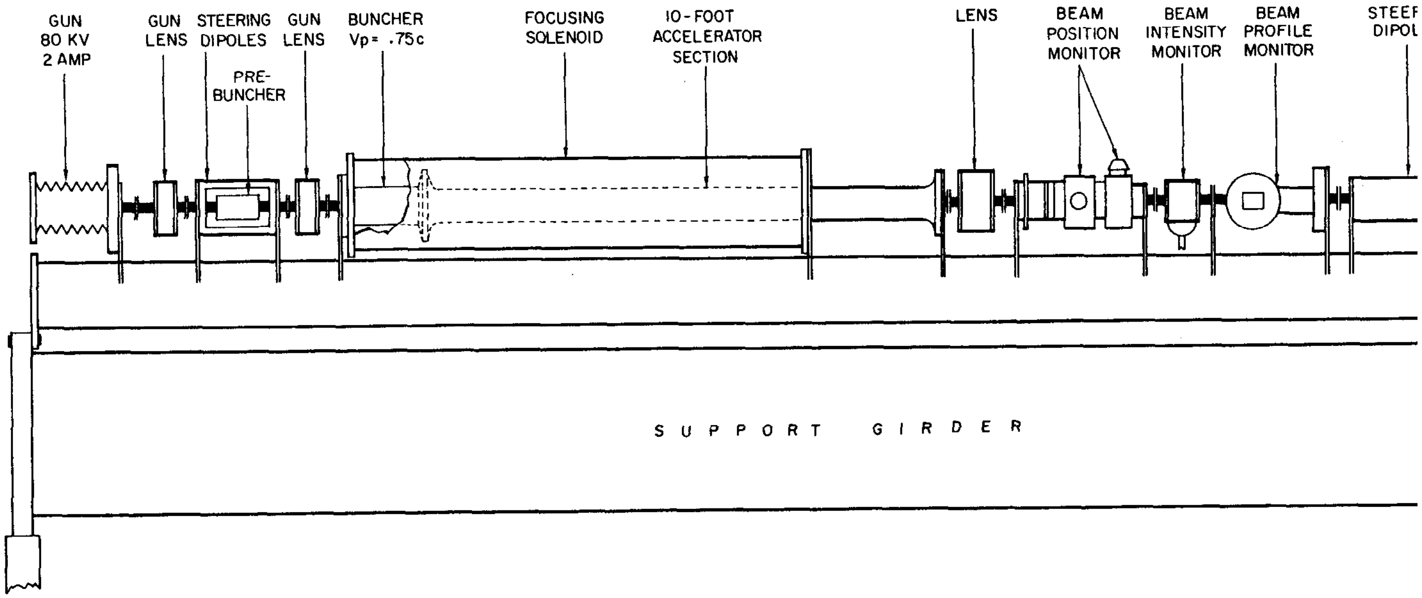
EIMAC SPERRY LITTON SLAC RCA

353-5-A

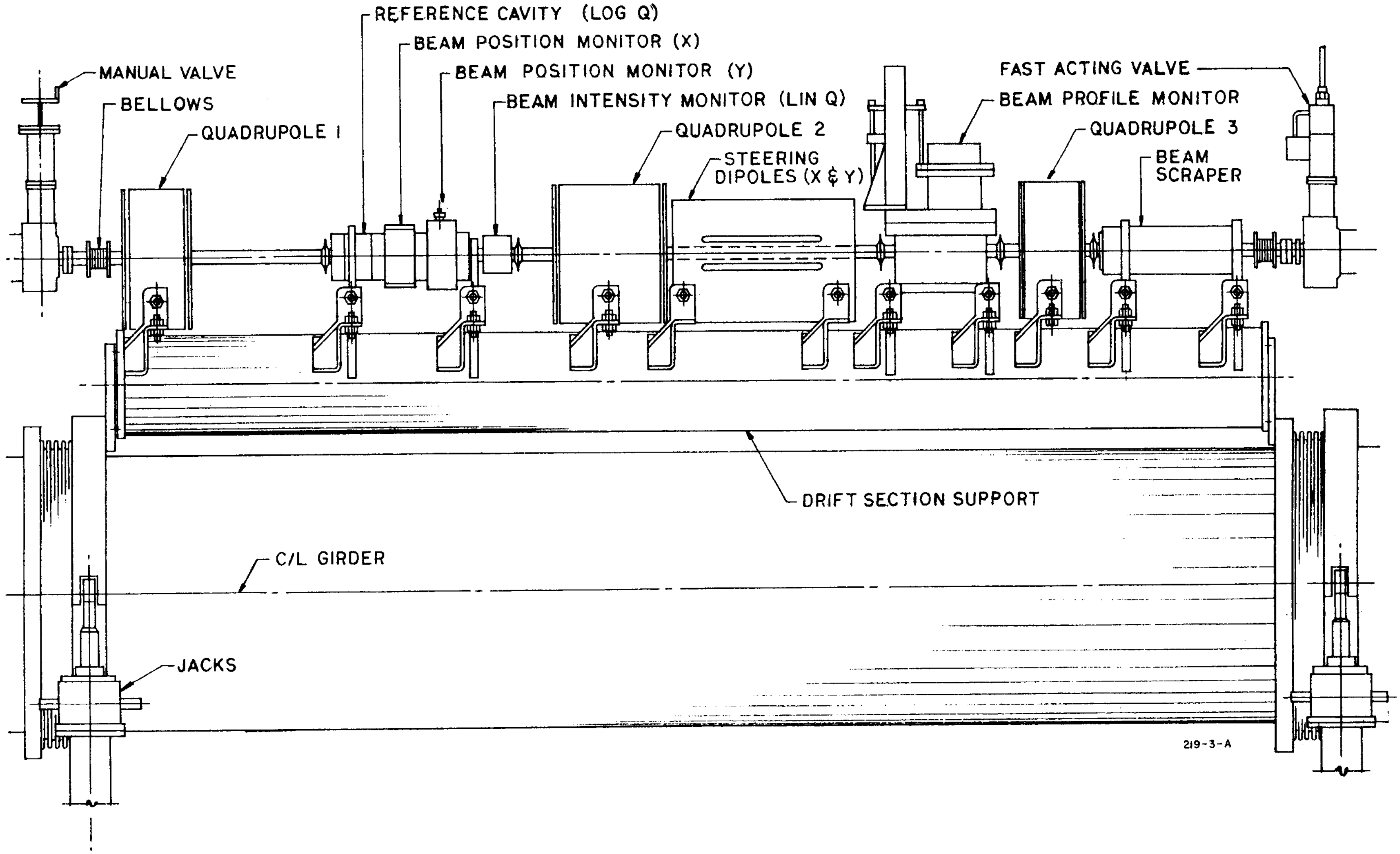


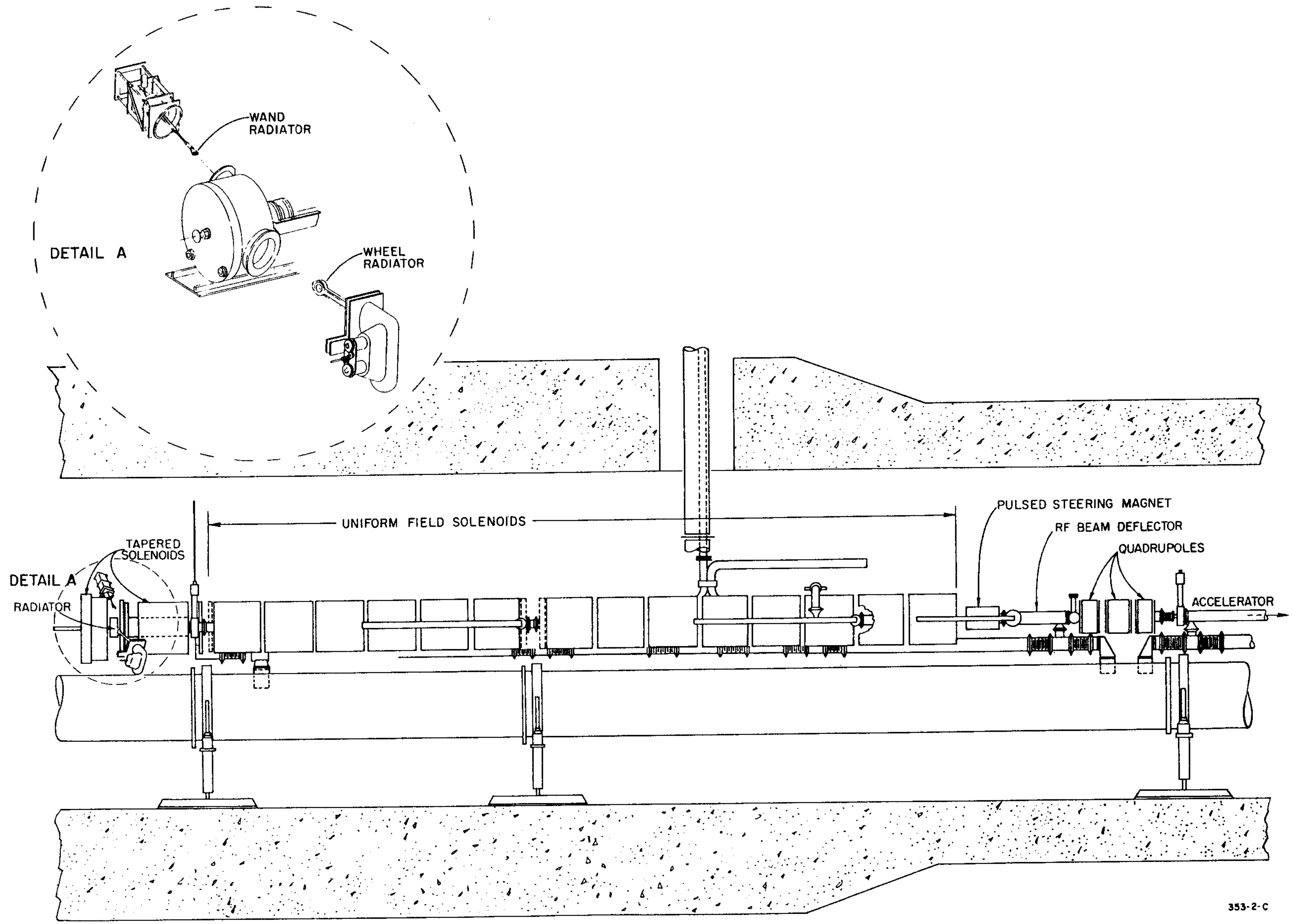

14'
6'
CROSS BAR
RF LOAD
WAVEGUIDE
VALVE
VACUUM
PUMPOUT
KLYSTRON
12'4"
EARTH
SHIELDING
PENETRATION
WAVEGUIDES
25'
POWER DIVIDERS
RF LOADS
5'
3'
3'
29 λ
-10'
a
b
BEAM DIRECTION

121-1-D

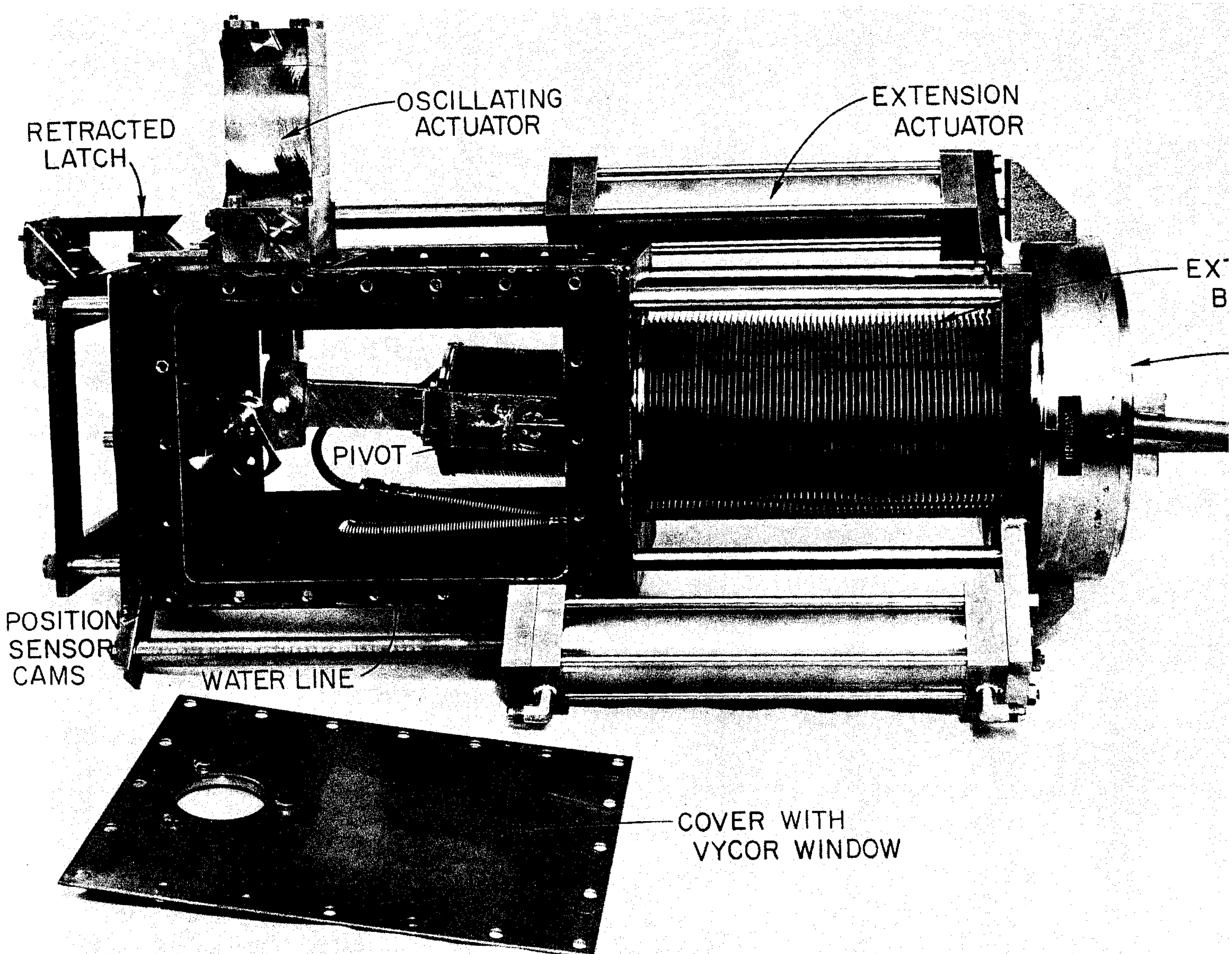


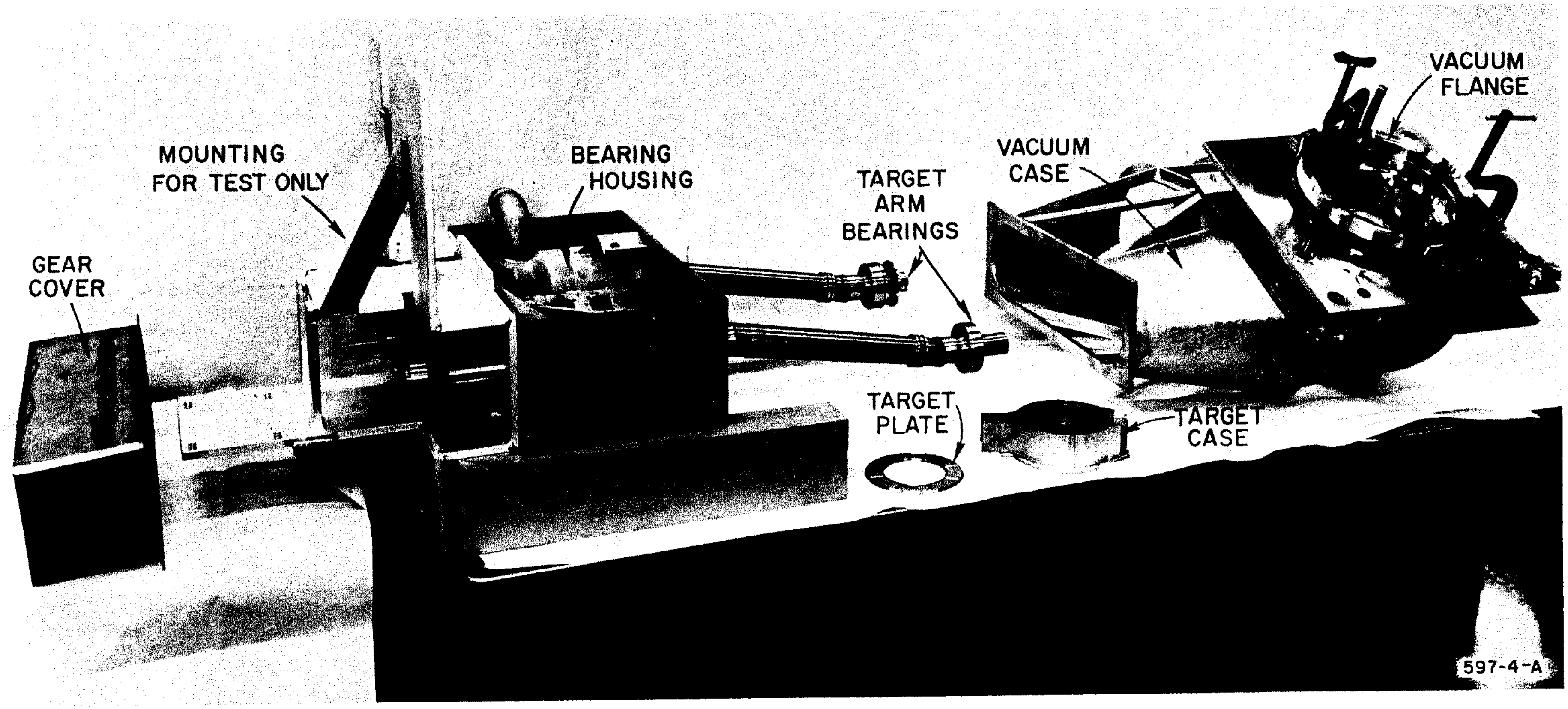
GUN
80 KV
2 AMP
GUN
LENS
STEERING
DIPOLES
PRE-
BUNCHER
GUN
LENS
BUNCHER
Vp= .75c
FOCUSING
SOLENOID
10-FOOT
ACCELERATOR
SECTION
LENS
BEAM
POSITION
MONITOR
BEAM
INTENSITY
MONITOR
BEAM
PROFILE
MONITOR
SUPPORT GIRDER


REFERENCE CAVITY (LOG Q)
BEAM POSITION MONITOR (X)
BEAM POSITION MONITOR (Y)
BEAM INTENSITY MONITOR (LIN Q)
MANUAL VALVE
BELLOWS
QUADRUPOLE 1
QUADRUPOLE 2
STEERING DIPOLES (X & Y)
FAST ACTING VALVE
BEAM PROFILE MONITOR
QUADRUPOLE 3
BEAM SCRAPER
DRIFT SECTION SUPPORT
C/L GIRDER
JACKS
219-3-A

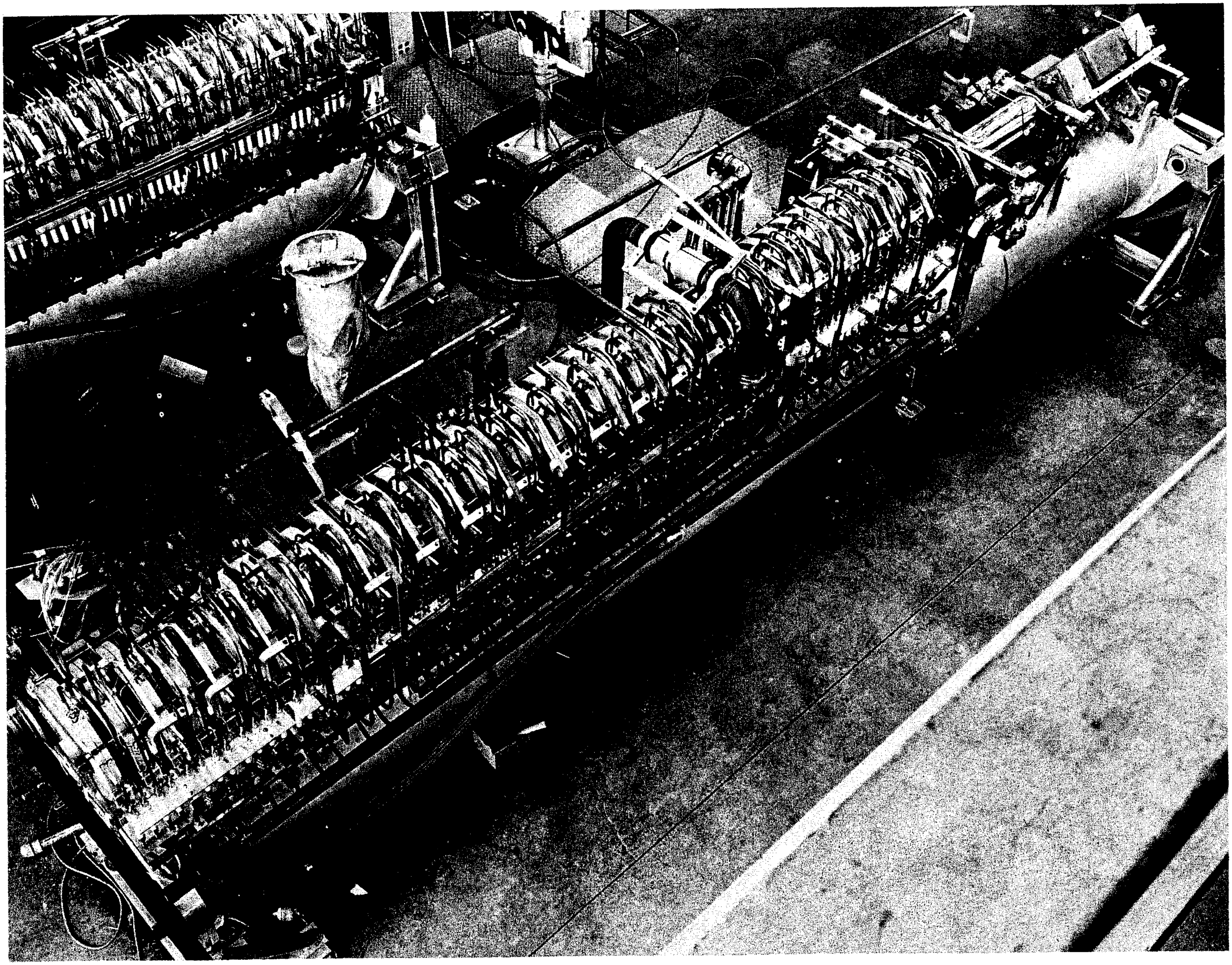


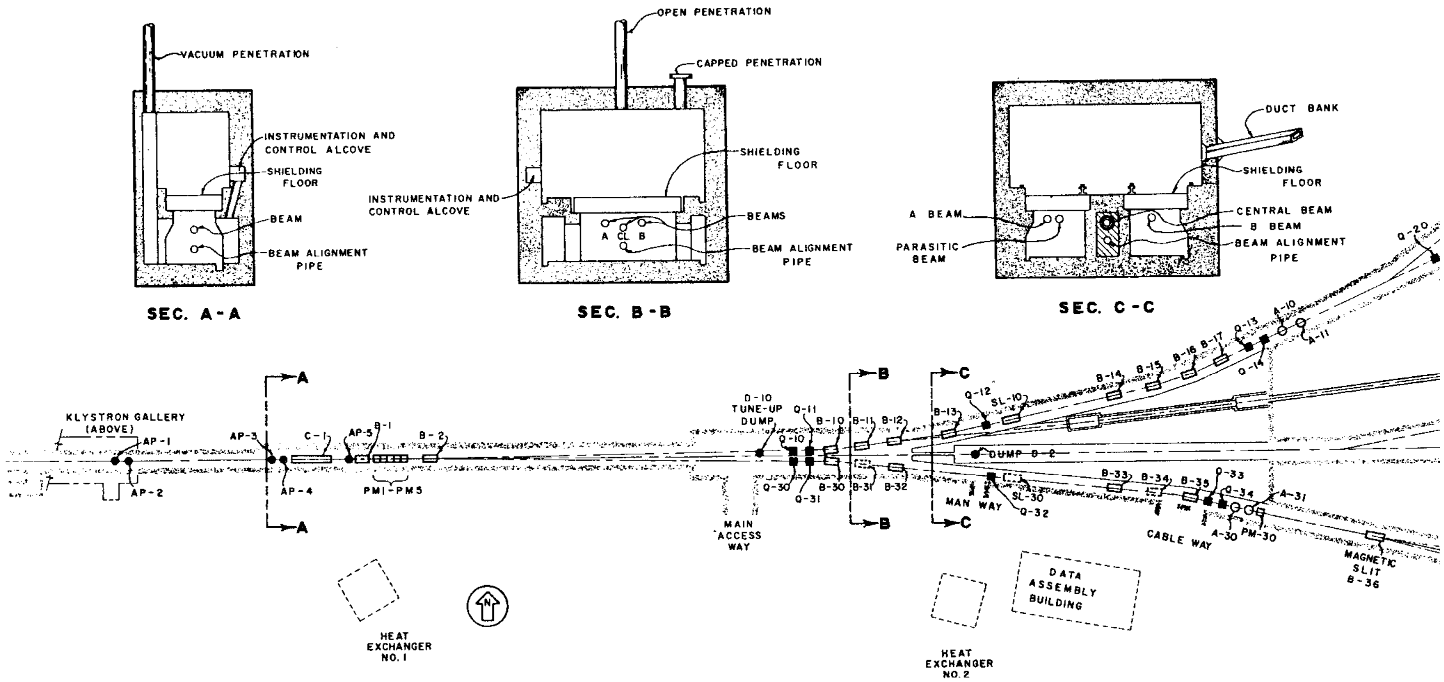
WAND
RADIATOR
DETAIL A
WHEEL
RADIATOR
UNIFORM FIELD SOLENOIDS
PULSED STEERING MAGNET
RF BEAM DEFLECTOR
QUADRUPOLES
TAPERED
SOLENOIDS
DETAIL A
RADIATOR
ACCELERATOR
353-2-C


OSCILLATING ACTUATOR
EXTENSION ACTUATOR
RETRACTED LATCH
EX
B
PIVOT
POSITION SENSOR CAMS
WATER LINE
COVER WITH VYCOR WINDOW



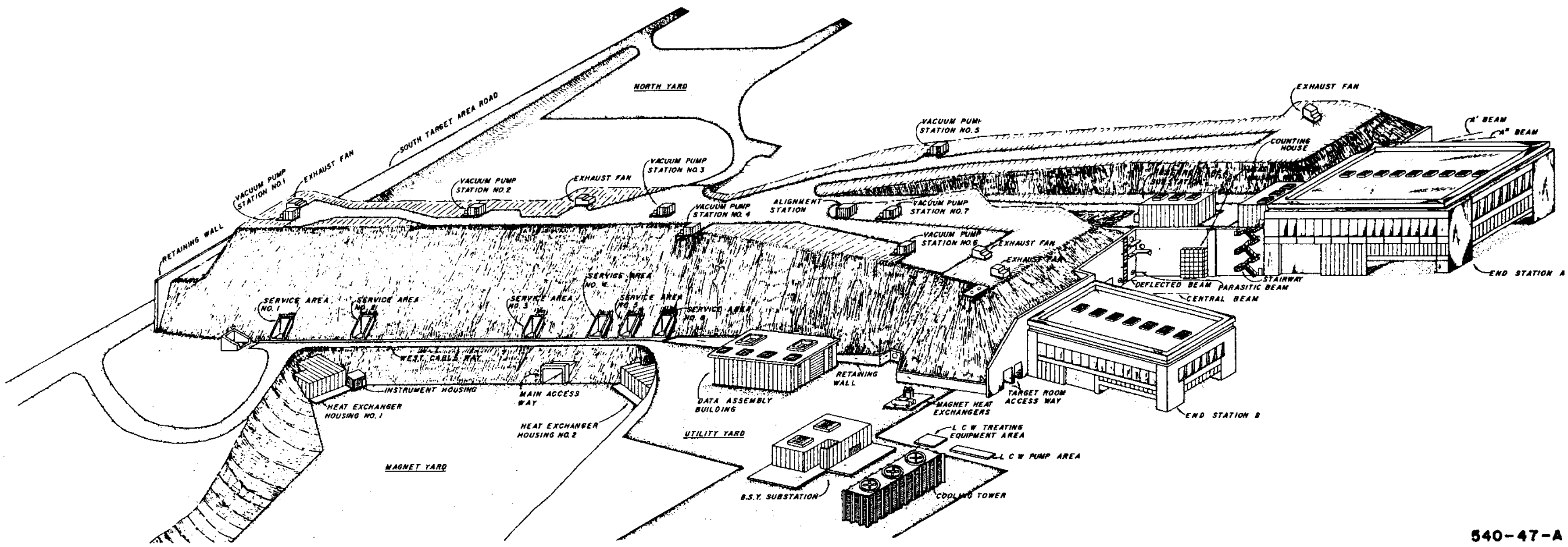
VACUUM
FLANGE
VACUUM
CASE
MOUNTING
FOR TEST ONLY
BEARING
HOUSING
TARGET
ARM
BEARINGS
GEAR
COVER
TARGET
PLATE
TARGET
CASE
597-4-A



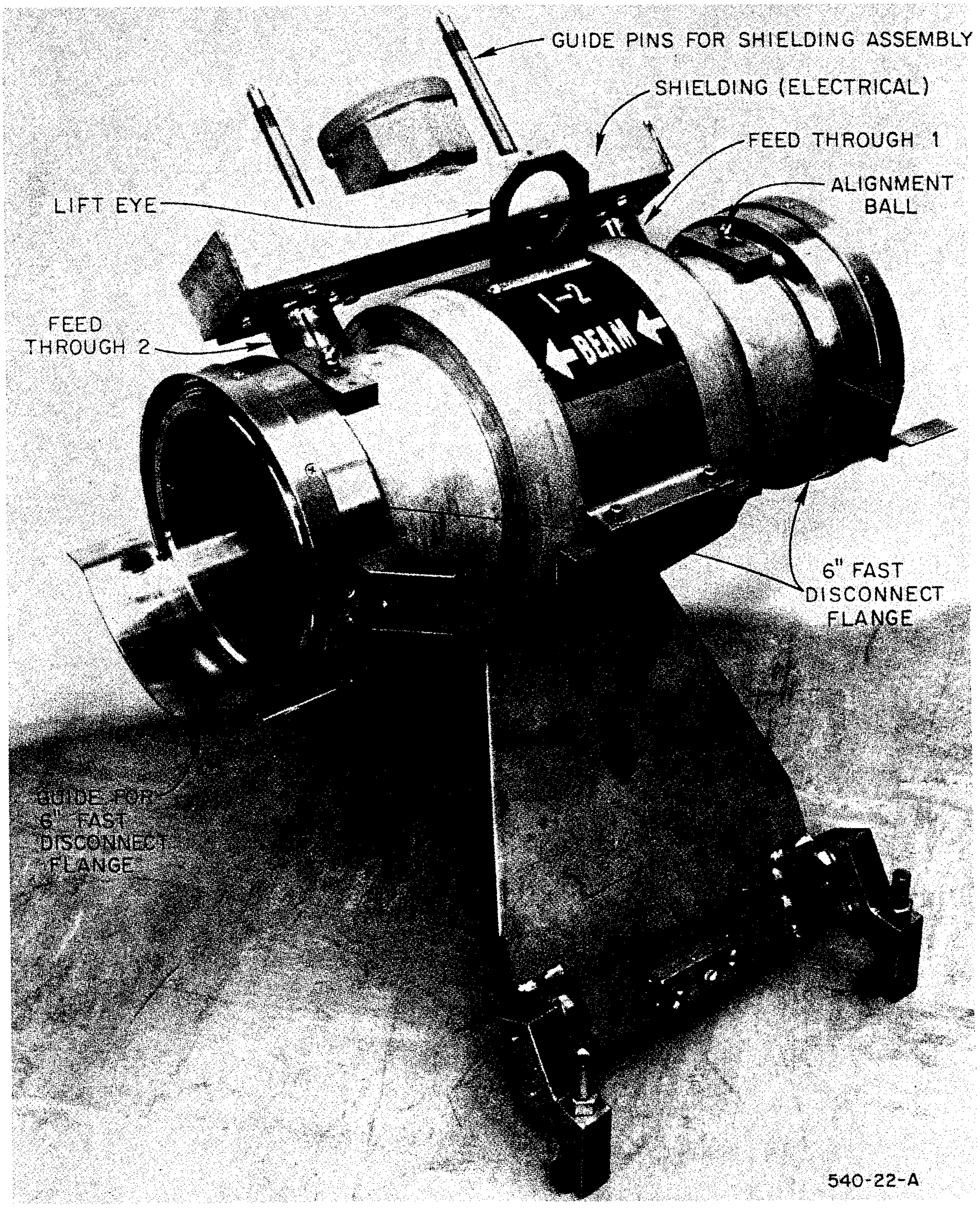


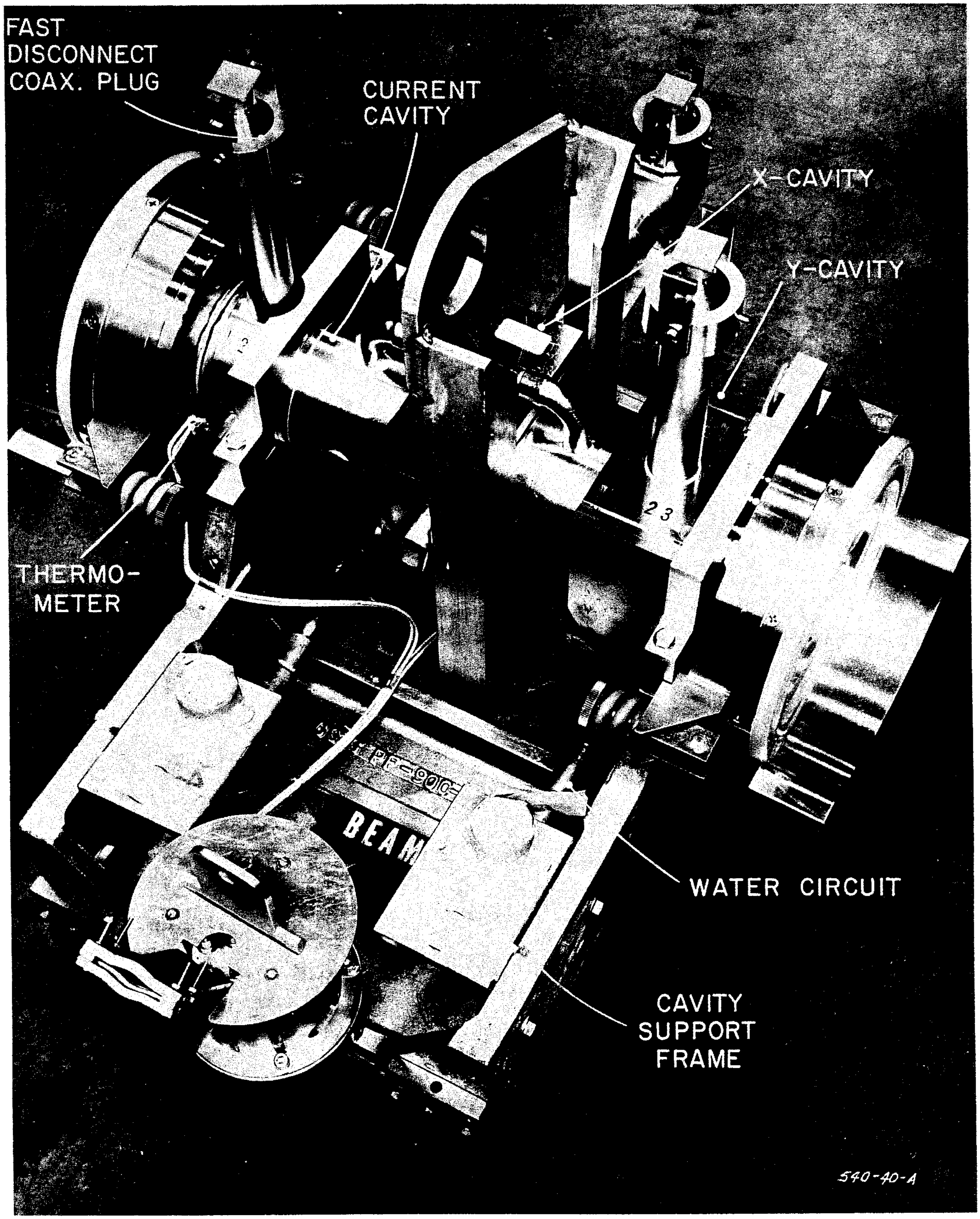
AP - Pulsed Steering Magnet
C - Collimator
B - Bending Magnet
PM - Pulsed Magnet

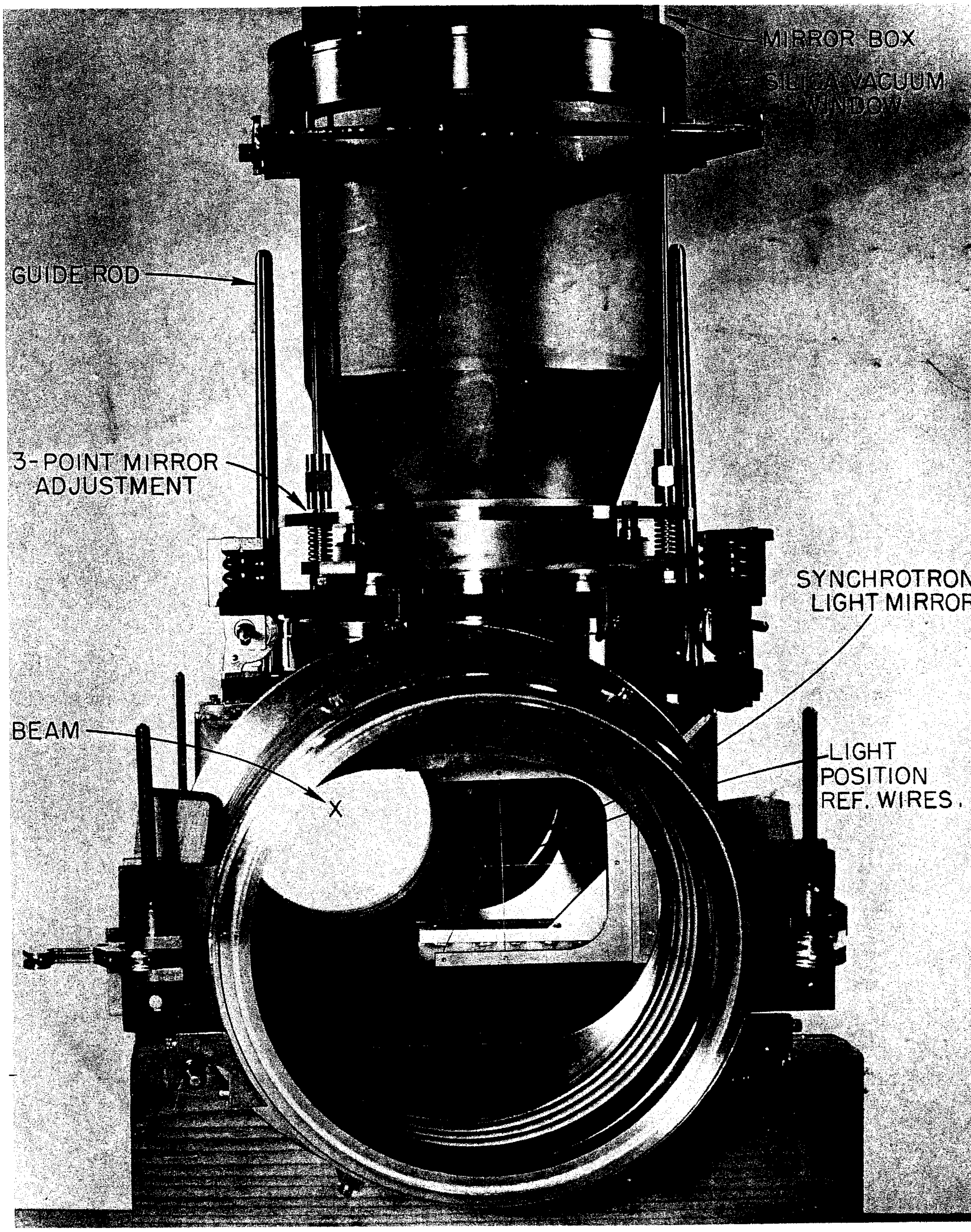
D - Beam Dump
Q - Quadrupole
SL - Energy Defining Slit
A - dc Steering Magnet

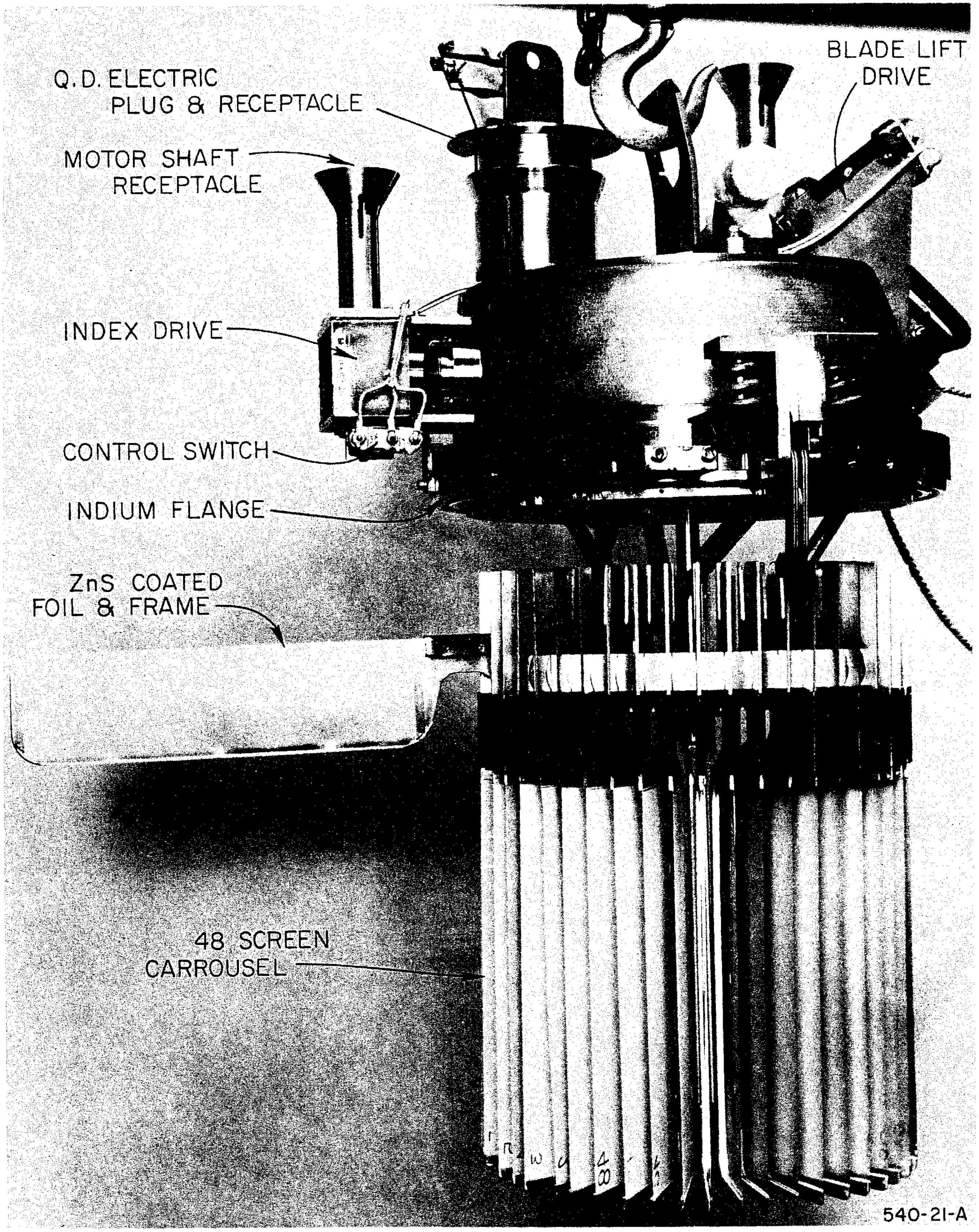

NORTH YARD
SOUTH TARGET AREA ROAD
RETAINING WALL
VACUUM PUMP STATION NO.1
EXHAUST FAN
VACUUM PUMP STATION NO.2
EXHAUST FAN
VACUUM PUMP STATION NO.3
VACUUM PUMP STATION NO.4
ALIGNMENT STATION
VACUUM PUMP STATION NO.5
VACUUM PUMP STATION NO.7
VACUUM PUMP STATION NO.6
EXHAUST FAN
EXHAUST FAN
COUNTING HOUSE
A' BEAM
A" BEAM
SERVICE AREA NO.1
SERVICE AREA NO.2
SERVICE AREA NO.3
SERVICE AREA NO.4
SERVICE AREA NO.5
SERVICE AREA NO.6
WEST CABLE WAY
INSTRUMENT HOUSING
HEAT EXCHANGER HOUSING NO.1
MAIN ACCESS WAY
HEAT EXCHANGER HOUSING NO.2
MAGNET YARD
DATA ASSEMBLY BUILDING
UTILITY YARD
RETAINING WALL
MAGNET HEAT EXCHANGERS
TARGET ROOM ACCESS WAY
DEFLECTED BEAM
CENTRAL BEAM
PARASITIC BEAM
STAIRWAY
END STATION A
END STATION B
L C W TREATING EQUIPMENT AREA
L C W PUMP AREA
B.S.Y. SUBSTATION
COOLING TOWER

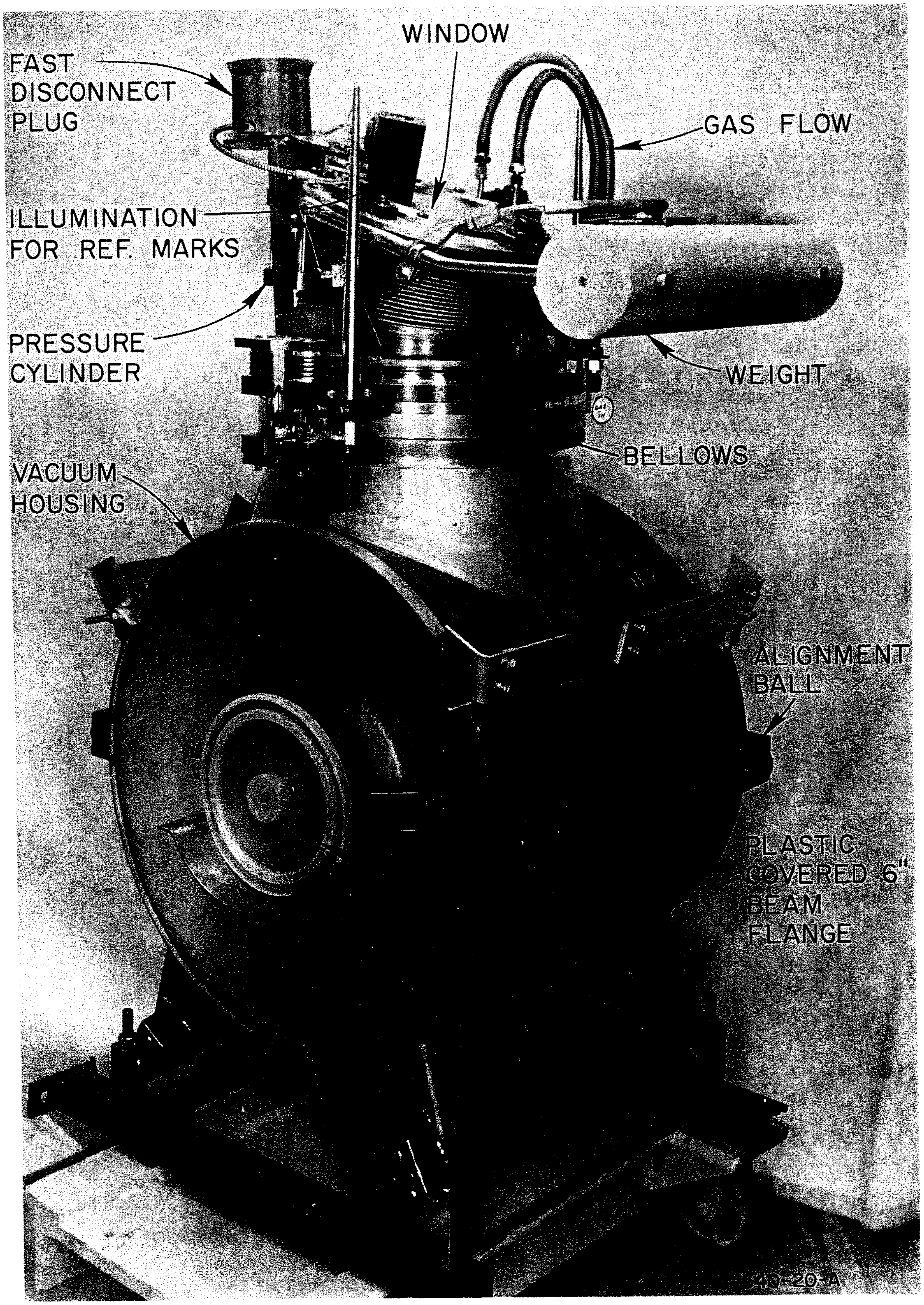
540-47-A

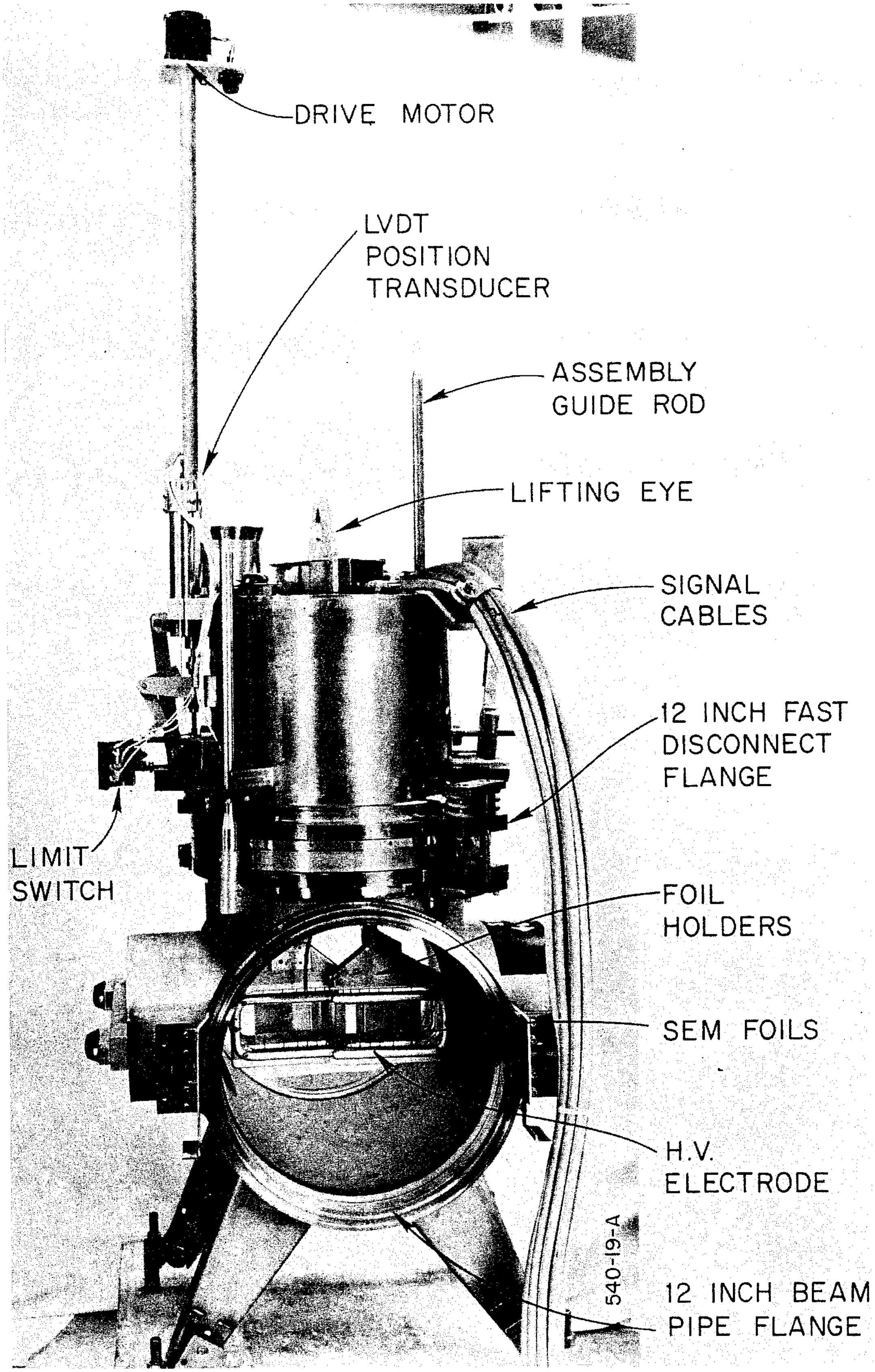

GUIDE PINS FOR SHIELDING ASSEMBLY
SHIELDING (ELECTRICAL)
FEED THROUGH 1
ALIGNMENT BALL
LIFT EYE
FEED THROUGH 2
1-2
BEAM
6" FAST DISCONNECT FLANGE
GUIDE FOR 6" FAST DISCONNECT FLANGE
540-22-A

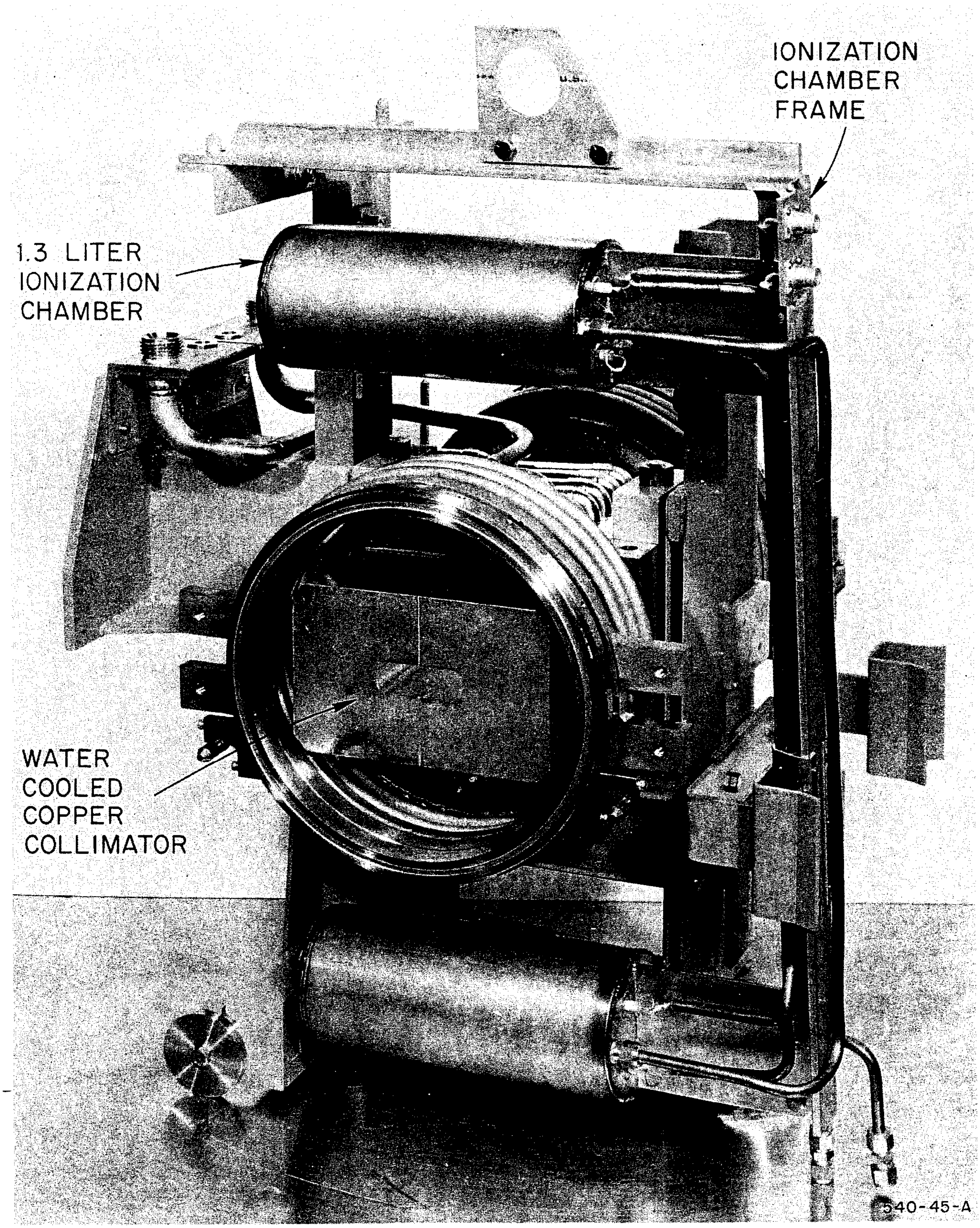

FAST
DISCONNECT
COAX. PLUG
CURRENT
CAVITY
X-CAVITY
Y-CAVITY
THERMO-
METER
BEAM
WATER CIRCUIT
CAVITY
SUPPORT
FRAME
540-40-A


MIRROR BOX
SILICA VACUUM WINDOW
GUIDE ROD
3-POINT MIRROR ADJUSTMENT
SYNCHROTRON LIGHT MIRROR
BEAM
X
LIGHT POSITION REF. WIRES.

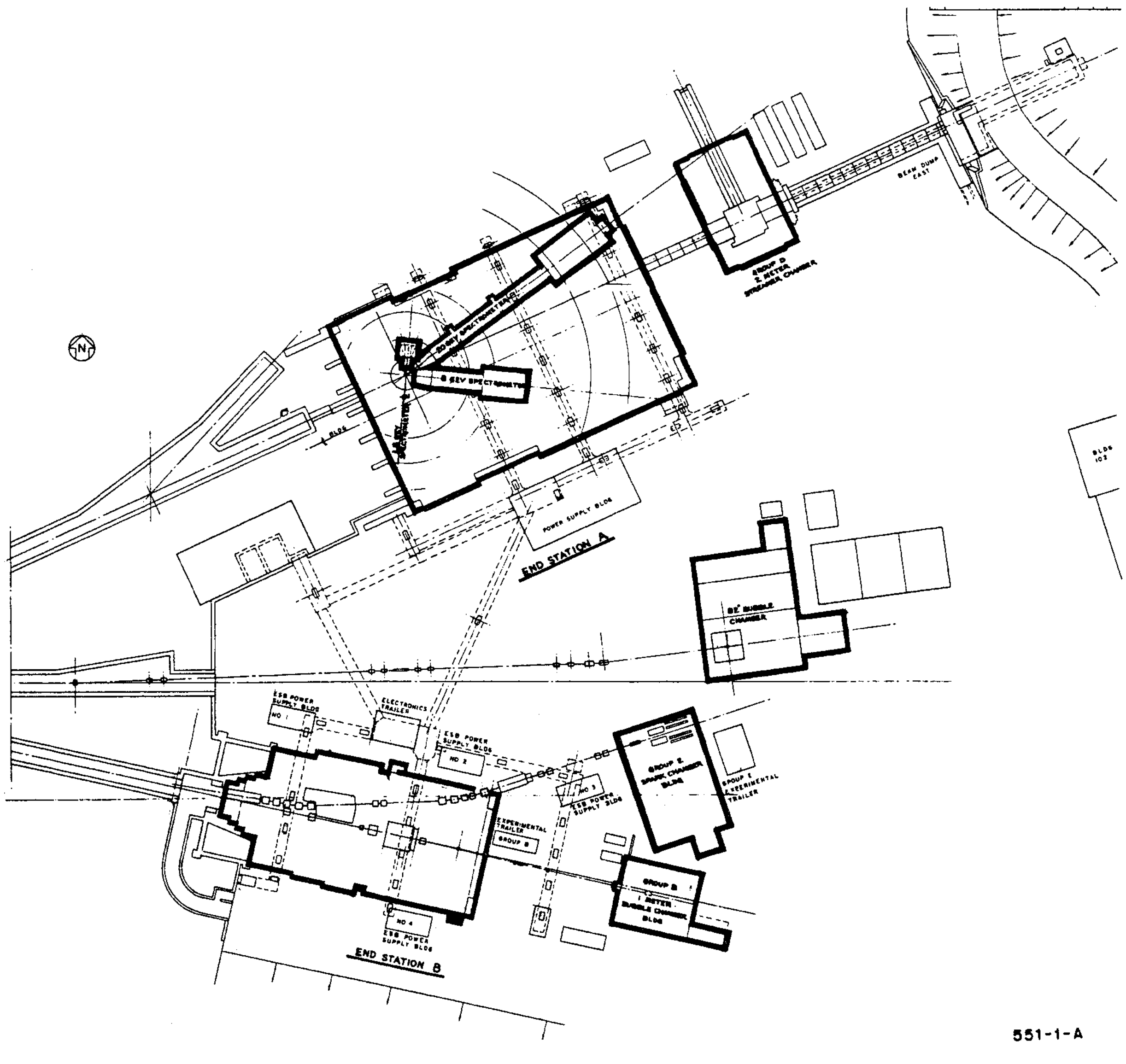

Q.D. ELECTRIC
PLUG & RECEPTACLE
MOTOR SHAFT
RECEPTACLE
BLADE LIFT
DRIVE
INDEX DRIVE
CONTROL SWITCH
INDIUM FLANGE
ZnS COATED
FOIL & FRAME
48 SCREEN
CARROUSEL
540-21-A


WINDOW
FAST DISCONNECT PLUG
GAS FLOW
ILLUMINATION FOR REF. MARKS
PRESSURE CYLINDER
WEIGHT
BELLOWS
VACUUM HOUSING
ALIGNMENT BALL
PLASTIC COVERED 6" BEAM FLANGE
45-20-A

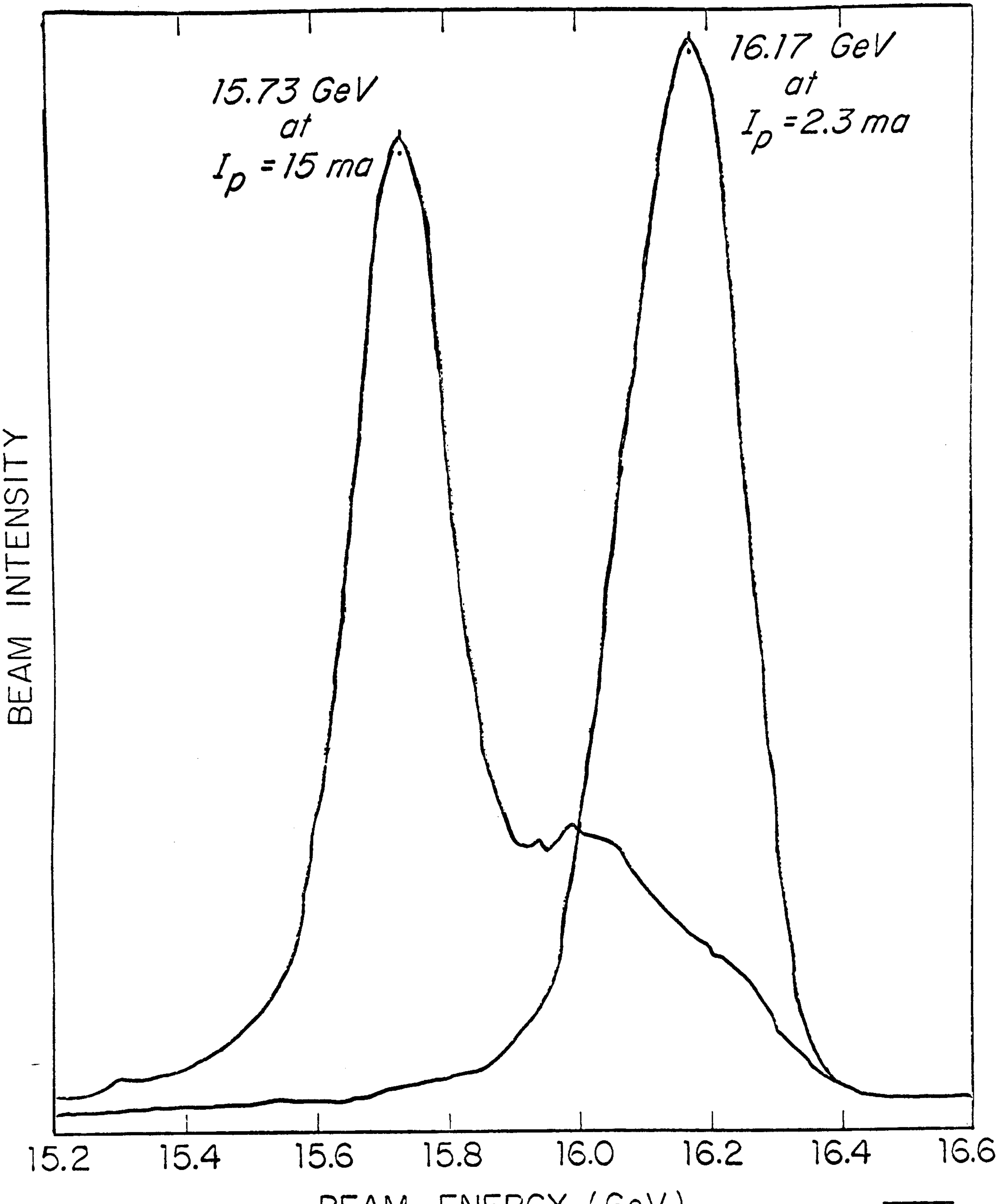

DRIVE MOTOR
LVDT POSITION TRANSDUCER
ASSEMBLY GUIDE ROD
LIFTING EYE
SIGNAL CABLES
12 INCH FAST DISCONNECT FLANGE
LIMIT SWITCH
FOIL HOLDERS
SEM FOILS
H.V. ELECTRODE
12 INCH BEAM PIPE FLANGE
540-19-A



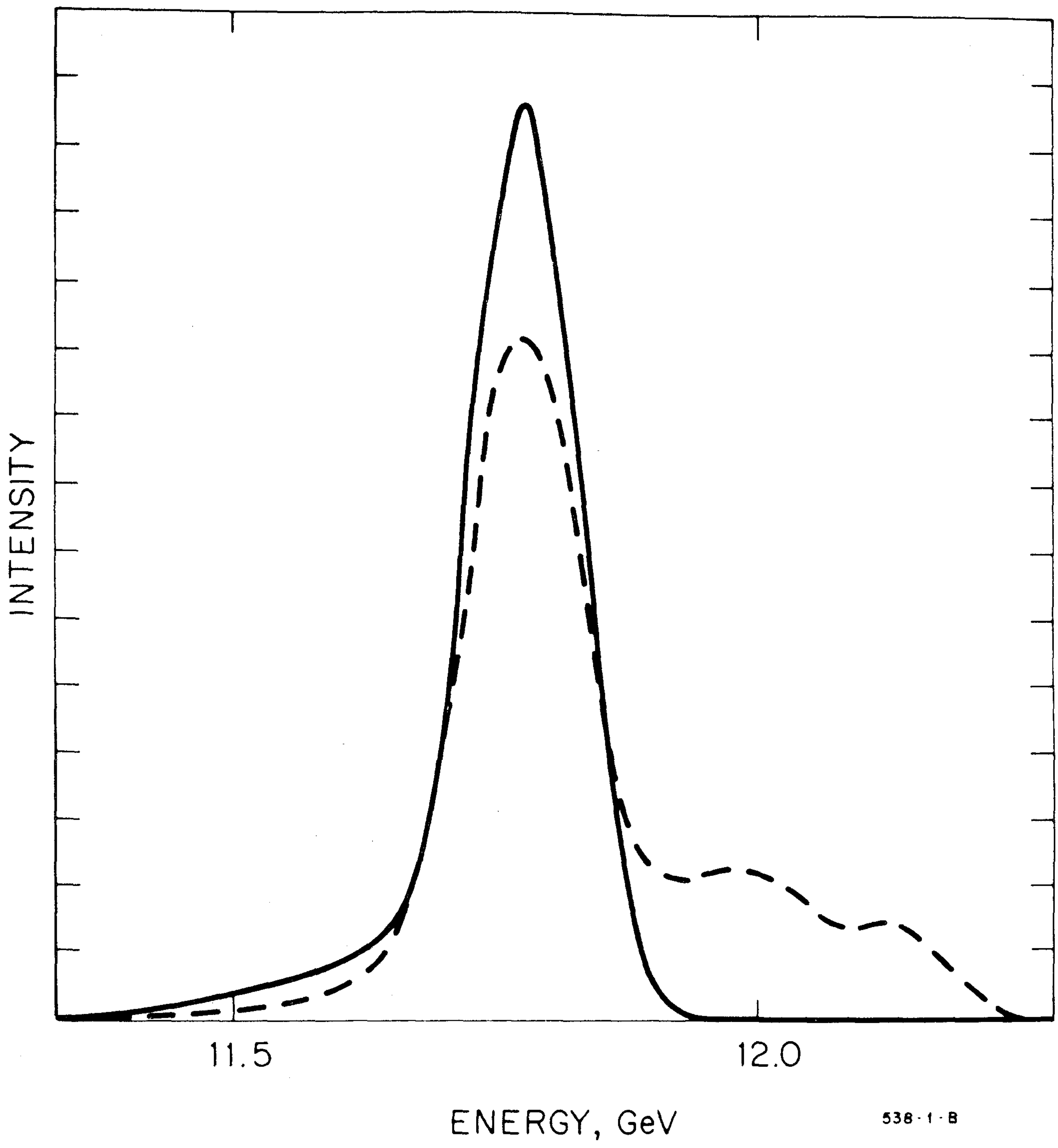
IONIZATION
CHAMBER
FRAME
1.3 LITER
IONIZATION
CHAMBER
WATER
COOLED
COPPER
COLLIMATOR
540-45-A


END STATION A
POWER SUPPLY BLDG
8 GEV SPECTROMETER
BEAM DUMP EAST
82" BUBBLE CHAMBER
ESB POWER SUPPLY BLDG
NO 1
ELECTRONICS TRAILER
NO 2
NO 3
NO 4
GROUP E SPARK CHAMBER BLDG
GROUP B 1 METER BUBBLE CHAMBER BLDG
EXPERIMENTAL TRAILER GROUP B
END STATION B

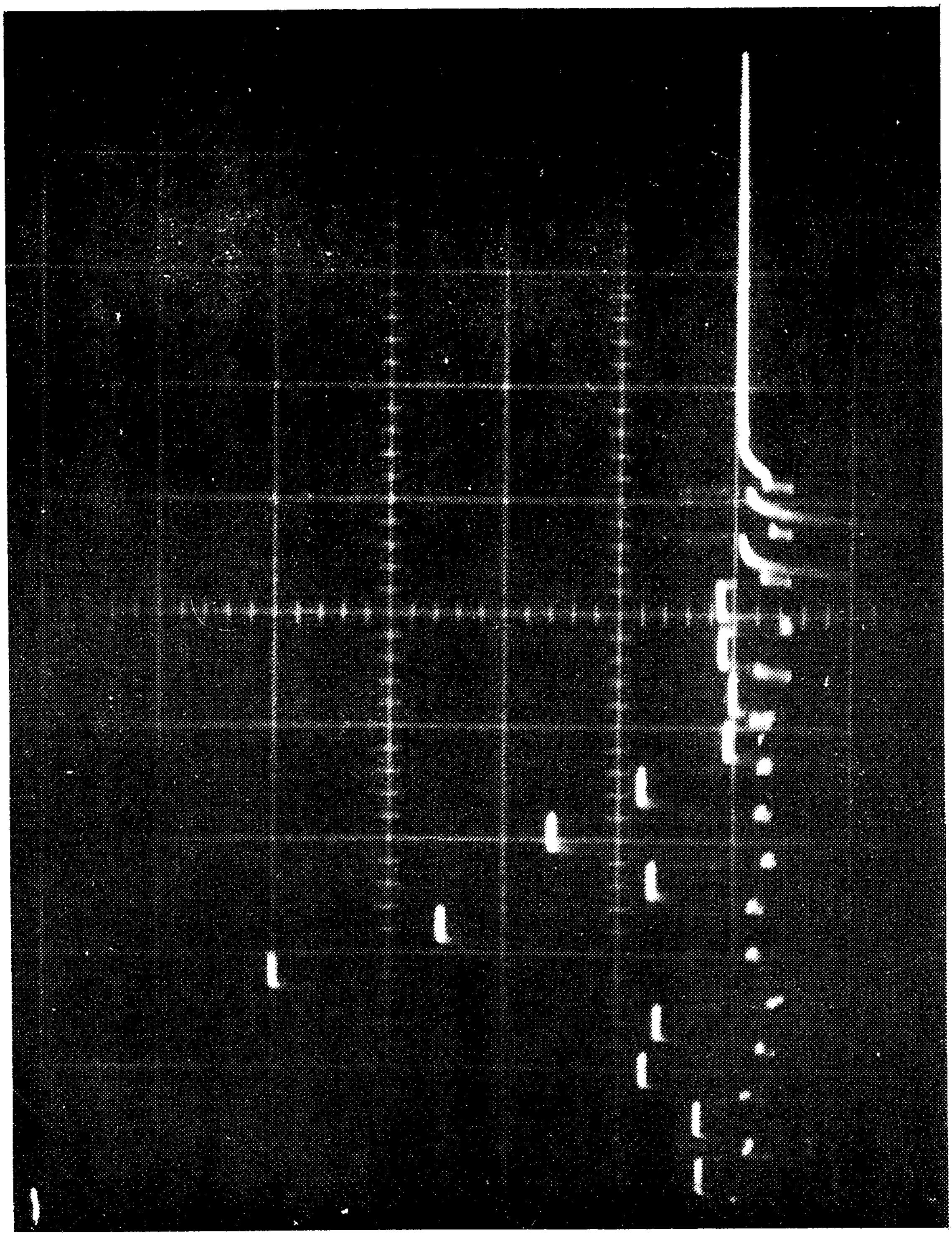
551-1-A

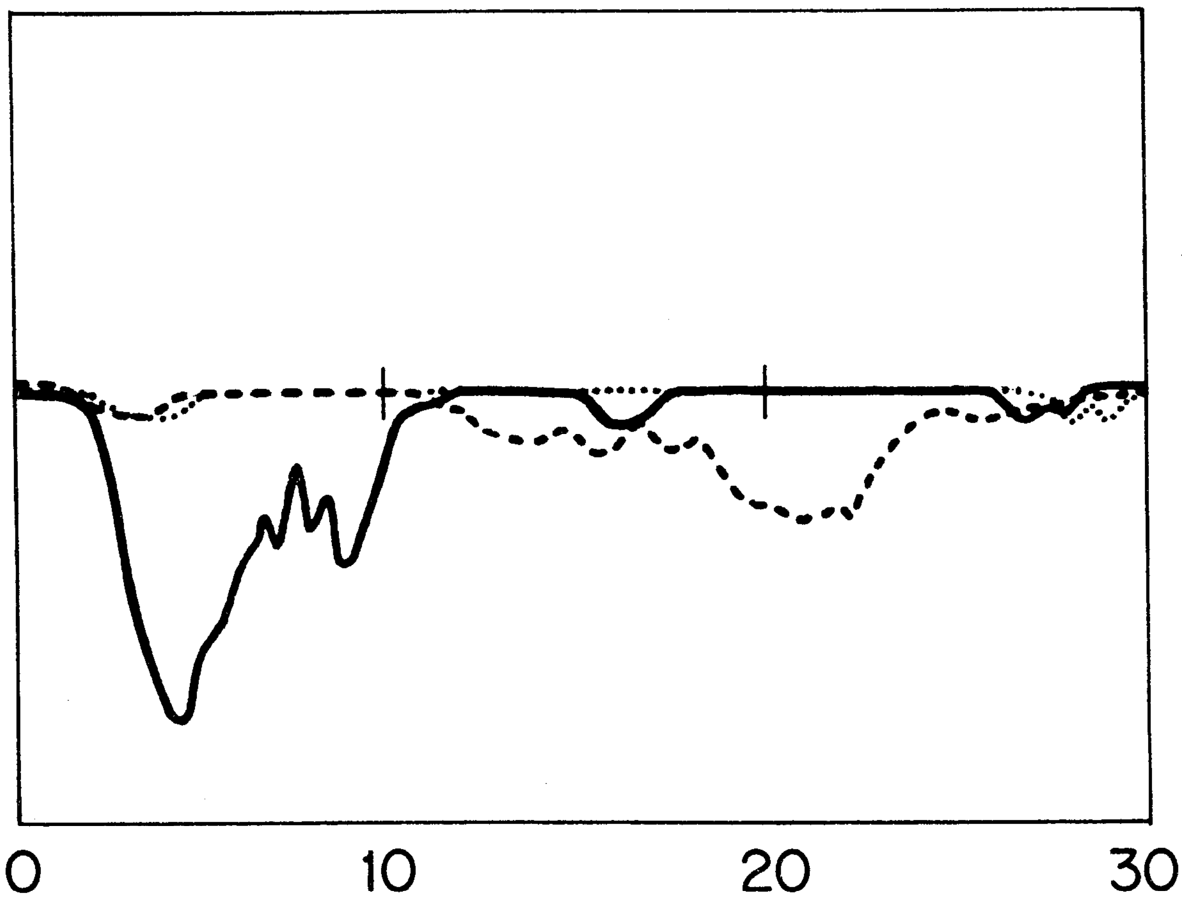

15.73 GeV
at
I_p = 15 ma
16.17 GeV
at
I_p = 2.3 ma
BEAM INTENSITY
15.2
15.4
15.6
15.8
16.0
16.2
16.4
16.6
BEAM ENERGY (GeV)

537-2-A

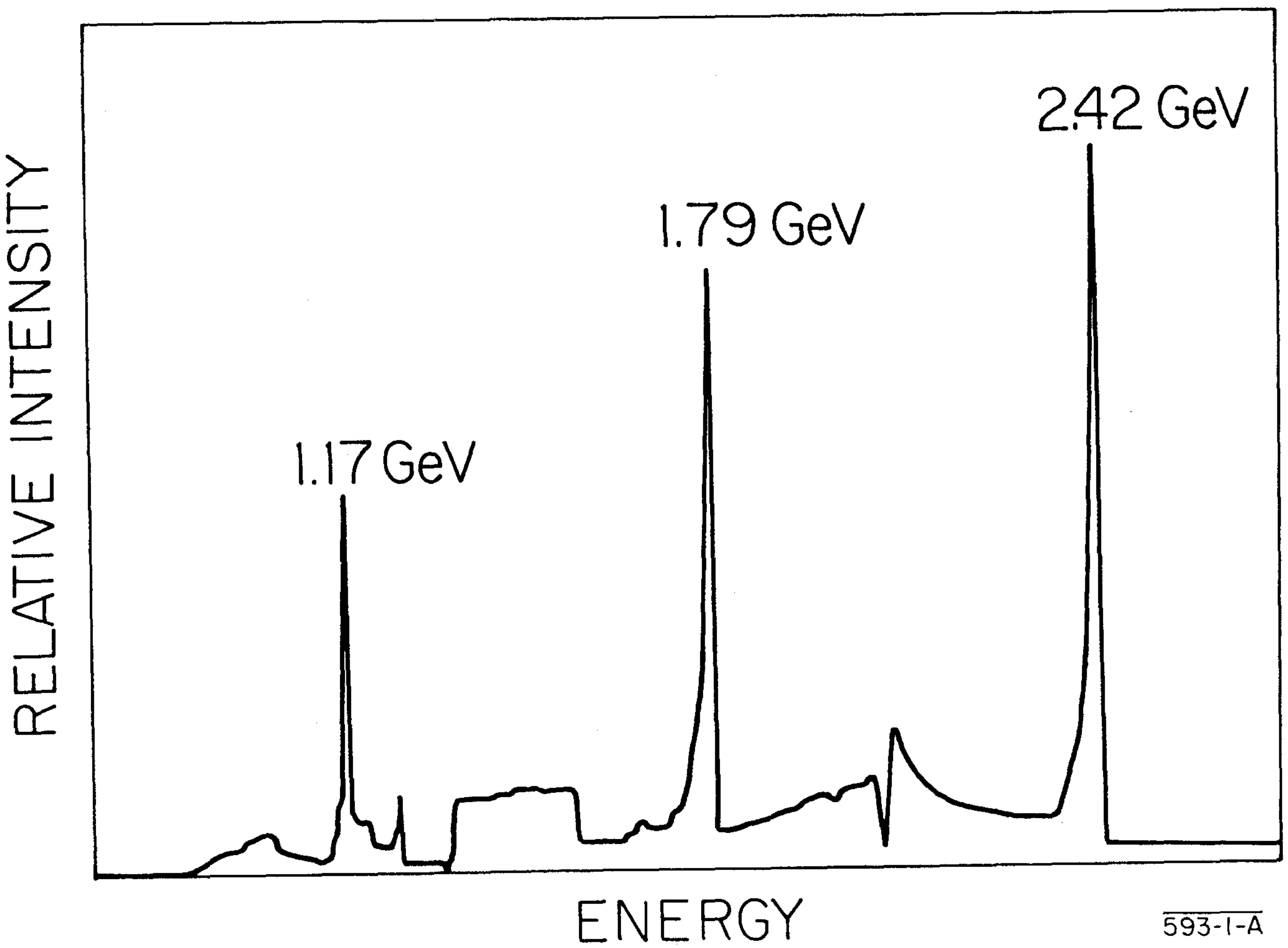


INTENSITY
11.5
12.0
ENERGY, GeV
538-1-B





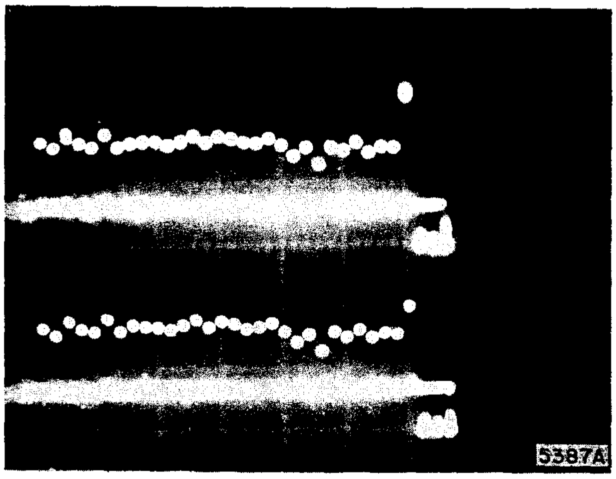
538-8-A

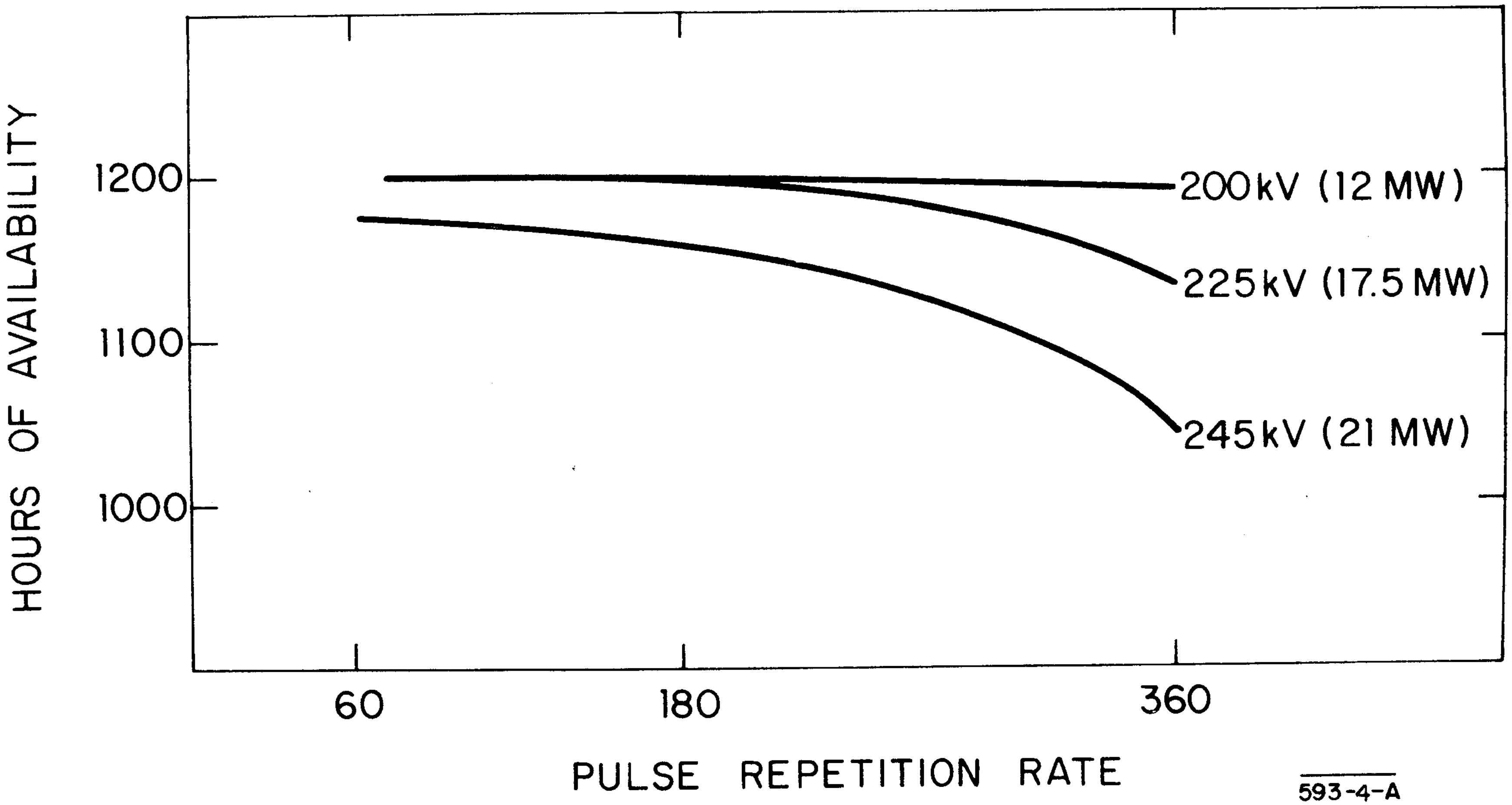


RELATIVE INTENSITY
2.42 GeV
1.79 GeV
1.17 GeV
ENERGY
593-1-A

11 GeV
4 ma

5.65 GeV
4 ma





HOURS OF AVAILABILITY
1200
1100
1000
200 kV (12 MW)
225 kV (17.5 MW)
245 kV (21 MW)
60
180
360
PULSE REPETITION RATE

593-4-A