national accelerator laboratory

TM-442
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A. DESCRIPTION OF LINAC BEAM EXTRACTION AND TRANSPORT FOR A MEDICAL FACILITY

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October 2, 1973

I. Linac Description

Design details and early performance data for the 200-MeV Alvarez linac have appeared in several reports[1-4]. Figure 1 is a simplified layout of the machine installation. There are nine cavities coming after a short 750-keV transport line from the Cockcroft-Walton preaccelerator. The accumulated length of the linac is 144.8 meters. Each cavity is energized by a radio-frequency power amplifier located in an equipment bay adjacent to the linac tunnel. Each rf power amplifier, an RCA 7835 triode, is capable of providing about 6 MW of power at 201 MHz. The rf pulse is variable in length up to 400 μsec at a repetition rate of 15 pulses per second.

The typical 200-MeV operating beam current has been 80 mA for several months. Most of the time during the past year, the linac has operated at values of 70 to 100 mA. The basic linac design permits pulses up to 100 μsec at 15 pulses per second.

Beam-diagnostic equipment includes several beam-current toroids, motor-driven emittance probes and wire scanners, multi-wire beam-profile monitors, and a spectrometer magnet. Monitoring with these devices occurs on a routine basis during regular operation. They show the 80-mA beam emittance area to be approximately 1π cm mrad in both planes at 200 MeV and the relative momentum spread to be approximately 2.5×10^{-3}. These values become somewhat smaller at lower beam currents.

The control and monitoring system[5-7] is developed around an XDS Sigma 2 computer, an alphanumeric scope and a storage scope for making displays. The computer assembles information from the various components as commanded by various programs and prepares displays of the assembled information for the operator. An example of such a display is the beam-emittance display shown in Figure 2.

Great flexibility in linac operation and beam handling is possible through the computer control. Energies in the range of 40 to 150 MeV may be needed frequently for medical purposes. It has been demonstrated[4] that all beam energies from 203 MeV down to 37 MeV can be reached. A program which shifts the rf excitation off beam time for one or more of the cavities beginning at the high-energy end and which adjusts the rf phase of the last operating cavity can select any specified energy. Beam intensity likewise can be computer controlled through adjustment of ion source and linac parameters. For reasons of inherent safety and reliability, however, one may choose to combine linac parameter adjustment with use of beam collimators and energy degrading absorbers.

In typical operation of the complete NAL accelerator, the main-ring cycle is variable from roughly three to six seconds. At the beginning of each cycle, the linac is called upon to deliver up to 12 consecutive beam pulses at a 15-Hz repetition rate to the booster synchrotron and thus to the main ring. During the remainder of the main accelerator cycle, the linac, which is still in operation, could deliver beam into a separate beam line and to a patient-treatment facility. The two modes of operation could be compatible with no restrictions placed on the primary accelerator operation.

II. Beam Extraction to the Medical Facility

The proton beam from the linac enters the 200-MeV diagnostic area where the energy, momentum spread, profiles and emittance of the beam can be measured routinely. For injection into the booster an electrostatic chopper is pulsed to deflect a portion of the beam pulse into the field of a septum magnet for further deflection into the transport line to the booster.

It is possible, and has been recommended for booster injection, to move the chopper and septum magnet downstream slightly and to increase the deflection angle with a rebuilt septum magnet. This maneuver opens a space approximately six feet long immediately following the linac. In this space can be inserted a 5.7-kilogauss pulsed magnet as shown in Figure 3 to deflect the beam into a transport line leading to the medical facility. A horizontal beam deflection of 18° at this point is followed by a second horizontal deflection of about 12° to give a net angle of 30° for clearing the linac enclosure wall and the momentum beam dump. The 12° bend is achieved with the magnet which is made surplus to the booster line upon relocation of the septum magnet. Added quadrupole magnets make the bends achromatic and control the beam size. The first portion of the medical transport line as shown depends on adjustment of the last few pulsed quadrupoles in the last linac cavity for matching the beam to the line. An alternative is addition of more quadrupoles in the line.

III. The Beam Transport Line

Following the exit from the linac enclosure the beam line is dropped in elevation by 7 feet to a level approximately 12 feet below grade.[8] The depth provides shielding against potential radiation from losses in the line, which will carry proton intensities of 10^{14} protons/sec or more at energies between 50 and 200 MeV. The vertical displacement of the beam requires two vertical bend magnets of approximately 7.5° each plus quadrupole magnets to make the bends achromatic and to focus the beam through the bend magnet apertures.

Plans call for the beam switching point of the treatment facility to be at a distance of approximately 811 feet (247 meters) from the linac building or about 222 meters from the last vertical bend magnet. Whether or not additional horizontal bend magnets are required depends on the exact location of the treatment building. The design of the transport line is strongly influenced by the decision to do neutron therapy, which requires high proton beam current. Both the depth below ground and number of focusing magnets required are substantially increased over what are necessary for proton therapy alone.

In an effort to minimize the tunnel cost, one can treat the line as a buried pipe with manholes at appropriate intervals for placement of magnets, pumps and beam diagnostic gear. The larger the vacuum pipe, the larger can be the spacing of the manholes, although the larger also the vacuum pumps and the bore of the quadrupoles required. Because of the manhole type of structure and the quite modest gradient required for the magnets, one can place a doublet in each manhole and ask what the maximum spacing might be. An approximate expression for this spacing, L, when the only consideration is emittance of the beam is:

$$L = \frac{\pi a^2}{E}$$

where a is the maximum half-width of the beam in the doublet and E is the beam emittance, assumed to be an ellipse. The emittance for 90% of our 80-mA beam at 200 MeV is approximately 1π cm mrad. If one doubles this value to exclude little beam in the tails of the distribution and then permits the beam to fill two-thirds of the quadrupole bore, one doublet with 8-inch bore is adequate for the long straight section of the transport line. Likewise, four 4-inch bore doublets will serve under the same conditions. The emittance for an 80-mA beam at 50 MeV is twice as large, however, so that the same limitations on beam size require two 8-inch bore doublets or eight 4-inch bore doublets.

There are other considerations in determining the manhole spacing. Chromatic aberration due to momentum spread of the beam and gas scattering for a pressure of 10^{-4} Torr do not contribute significantly. The earth's magnetic field or stray fields along the line must be shielded out, however. Otherwise a field of 0.75 gauss deflects the beam by 10 cm in 50 meters.

For high current beams, an important determinant of manhole spacing can be spreading of the beam because of space charge forces. To a first approximation, the change in radius, r, of an initially parallel beam of uniform current density while traveling a distance d is:

$$S = \frac{e}{m}\frac{I}{r} \quad \frac{d^2B}{v^3\gamma^2}$$

where I is total beam current, v is the velocity and B is the bunching factor defined as the bunch spacing over the bunch length. The bunching factor can be written approximately as:

$$\frac{1}{B} \cong \left[\left(\frac{\Delta\phi}{2\pi}\right)^2 + \left(\frac{(\Delta v)}{v}\frac{df}{v}\right)^2 \right]^{\frac{1}{2}}$$

where $\Delta\phi$ is the phase spread of the proton bunch when the beam reaches final energy, d is the drift distance following acceleration, Δv is the velocity spread and f is the linac rf frequency. Some additional debunching caused by longitudinal space charge forces is neglected here. The bunching factor is less severe for reduced beam energy, but, overall, the beam spreading is worse for lower energies and a small fixed distance d.

At 200 MeV, with $\Delta\phi \approx 20°$ and momentum spread $\Delta p/p = 0.25\%$, the bunching factor is 18 at the end of the linac and decreases to ≈13 at the beginning of the long line 25 meters from the linac. If the first of eight manholes is located at this point with a spacing of 30 meters, the space-charge spreading in a 4-inch diameter line over 15 meters (the beam waist is at the midpoint between manholes) is about 0.28 cm on the radius for a radius of 2 cm. This spreading becomes somewhat smaller further along in the line because of further debunching of the beam. Partial space-charge neutralization of the beam would help to reduce the spreading.

At 50 MeV, $\Delta\phi$ becomes approximately 35° and $\frac{\Delta p}{p} \approx 0.54\%$. These values give a bunching factor of $B \approx 3.6$. The corresponding spread in radius of the beam becomes 0.43 cm in 15 meters. If one takes into account the extra drift distance of 101 meters within the linac following tank #3 (since the rf power in all the other tanks must be off or out of time to give 50 MeV), the beam almost completely debunches, giving a radial spread of ≈ 0.12 cm, less than for the bunched 200-MeV beam. This statement assumes negligible beam-cavity interaction in the unexcited tanks.

At an intermediate energy of 100 MeV, the corresponding spread in 15 meters becomes 0.35 cm. With additional drift distance of 67 meters within the linac, the spread becomes ≈ 0.11 cm.

It thus appears that, when the additional drift distances for debunching of the lower energy beams are included, the radial space-charge spreading of the beam is less severe for lower energy than for 200 MeV. The emittance spreading of the beam is appreciably larger at lower energy, however, and primarily determines the necessary size of the beam line. An 80-mA beam at 50 MeV with an emittance large enough to contain 98-99% of the beam has a beam radius of 3.4 cm (filling two-thirds of a 4-inch line) at the doublets when the doublet spacing is 27 meters. The beam radius at the waist between the doublets is approximately 2.5 cm. A four-inch diameter beam line with manhole spacing of 25-30 meters, therefore, appears adequate to transport beams of all energies at a beam intensity of about 100 mA. A beam pulse of 100 mA for 10 μsec 15 times per second gives 10^{14} protons/sec. If space-charge spreading were a problem, the beam current could be lowered and the pulse lengthened accordingly to give the same proton yield.

Each manhole will include a quadrupole doublet, an ion pump and perhaps a roughing pump, a steering magnet, a beam-current transformer and a beam-position monitor, preferably a multi-wire profile monitor. Each quad may be about 16-inches long. The separation of quads is not critical and can be very small. The field gradient required is only a few hundred gauss/cm. The appearance of the equipment layout in a typical manhole is shown in Figure 4. Dimensions of 12 feet long by 7 feet wide by 7 feet deep give comfortable accommodation of equipment and working space. The first manhole layout near the linac building showing the last vertical bend is shown in Figure 5. Figure 6 shows in plan view the line of manholes joining the linac and medical facility buildings. Figure 7 shows the spacing of the manholes in more detail. The spacing of the first few manholes has been reduced from the 30 meters assumed in the above calculation and allowed to increase gradually from 18 to 30 meters.

The average pressure in the beam pipe is given by:

$$P_{Av} = P_o \left(1 + \frac{S}{6C}\right)$$

where P_o is the pressure at the pump, S is the speed of the pump in each manhole and C is the conductance of half the line segment between manholes. The required pump speed for the total line length of 247 meters is approximately 1600 liters/sec at a P_0 of 5×10^{-6} Torr and an assumed outgassing rate of 10^{-8} Torr liters/sec. The average pressure becomes 2.1×10^{-5} Torr. This conservative outgassing rate can be expected to improve with time. The ion pump in each manhole will have an approximate speed of 200 liters/sec.

Because of expected shifting of a beam pipe between manholes when covered with earth, it is desirable to run a four-inch vacuum pipe through a much larger (12-inch) pipe, which is in contact with the earth. The vacuum pipe can be made adjustable in position at its end supports in the manholes. Additional supports at perhaps two intermediate points will be required to prevent sag. These can be positioned after ground settling is complete or they can be made adjustable at the end of long rods. A second adjacent pipe can be used as an electrical cable conduit to bring leads to the magnets, pumps and beam diagnostic gear in the manholes. Most power supplies are to be located in the linac building and the medical building at either end of the transport line.

IV. Handling of the Proton Beam at the Treatment Building

The proton beam enters a magnet room at the treatment building at the end of the transport line. Here the beam can be switched for delivery to one of three treatment rooms. A horizontal-bend magnet deflects the beam 15° either right or left to send it to a neutron producing target at one of two neutron treatment rooms.[9] A neutron collimator delivers a beam of forward going neutrons to the patient. The usual full-intensity proton beam up to or exceeding 10^{14} proton/sec is required for neutron production.

The third treatment room is for use of protons on the patient. Since it is subject to precision control, several additional elements for this purpose are shown in Figure 8. The proton beam intensity required for proton therapy is three or four orders of magnitude less than that required for neutron therapy; therefore, the beam intensity must be reduced drastically. This can be done at low energy before acceleration through the linac or after acceleration. From the standpoint of reliability and safety from overdose, it may be preferable to run the linac in a mode of near maximum beam intensity and to reduce the intensity at high energy by severe collimation in the transport line or by splitting off only a small fraction of the beam to the proton treatment room channel. Any discarded beam must be dumped in a well-shielded region because of the high level of radiation produced. The devices for reduction of beam intensity are not shown in Figure 8, except for the final step of reduction by collimation in the beam channel leading to the proton treatment room. The beam into the channel shown has been reduced to an intensity of order 1 mA and is focused to a waist approximately 5 cm in diameter at the position of the first collimator slit. Collimation to a few millimeters in beam size, taken from the center of the beam, gives a quite uniform density across the pencil of beam, which also has a very small angular divergence. This parallel beam can now be spread to a larger size both horizontally and vertically by two small bore quadrupole magnets arranged as a doublet followed by a suitable drift distance. Small dipole magnets following the quads steer the beam to the patient and can be used for scanning if desired.

As a numerical example[3], one may assume a 1.3 mA beam with an emittance area of 0.5 cm mrad obtained by collimation of an 80-mA beam. Let the beam be collimated further as in Figure 6 to a square beam 4 mm on a side and to about one percent in intensity. If each beam-spreading quad is 50 cm long, a field at the edge of the beam of 1.1 kilogauss (or a gradient of 5.5 kilogauss/cm) will spread the beam to a width of 35 cm on the target. The dipoles with a field strength of 12 kilogauss can deflect the beam up or down a distance of 15 cm. An area 35 cm square can be irradiated on each pulse. By using an average of 50 pulses at each proton energy and 60 energy steps to give a transformed Bragg peak of ionization in the target, five minutes of irradiation give a total dose of 4×10^{-7} coulombs or approximately 250 rads. Variation in beam shape on the target can be achieved by magnet adjustment or by pattern collimators.

ACKNOWLEDGEMENTS

Several persons contributed to the thoughts expressed in this report. There were discussions with D. Young on the general layout of the transport line. M. Shea suggested the beam extraction modification. B. Prichard assisted with the vacuum calculations. C. Owen contributed to linac operation and vacuum considerations. M. Awschalom determined the radiation shielding requirements. In addition he has been in charge of neutron yield calculations and has worked with George Doddy of DUSAF on treatment room and other building arrangements. R. Peters and J. Sauer have been doing computer calculations on the beam line using the TRANSPORT program. This work will continue until a final beam line design is confirmed.

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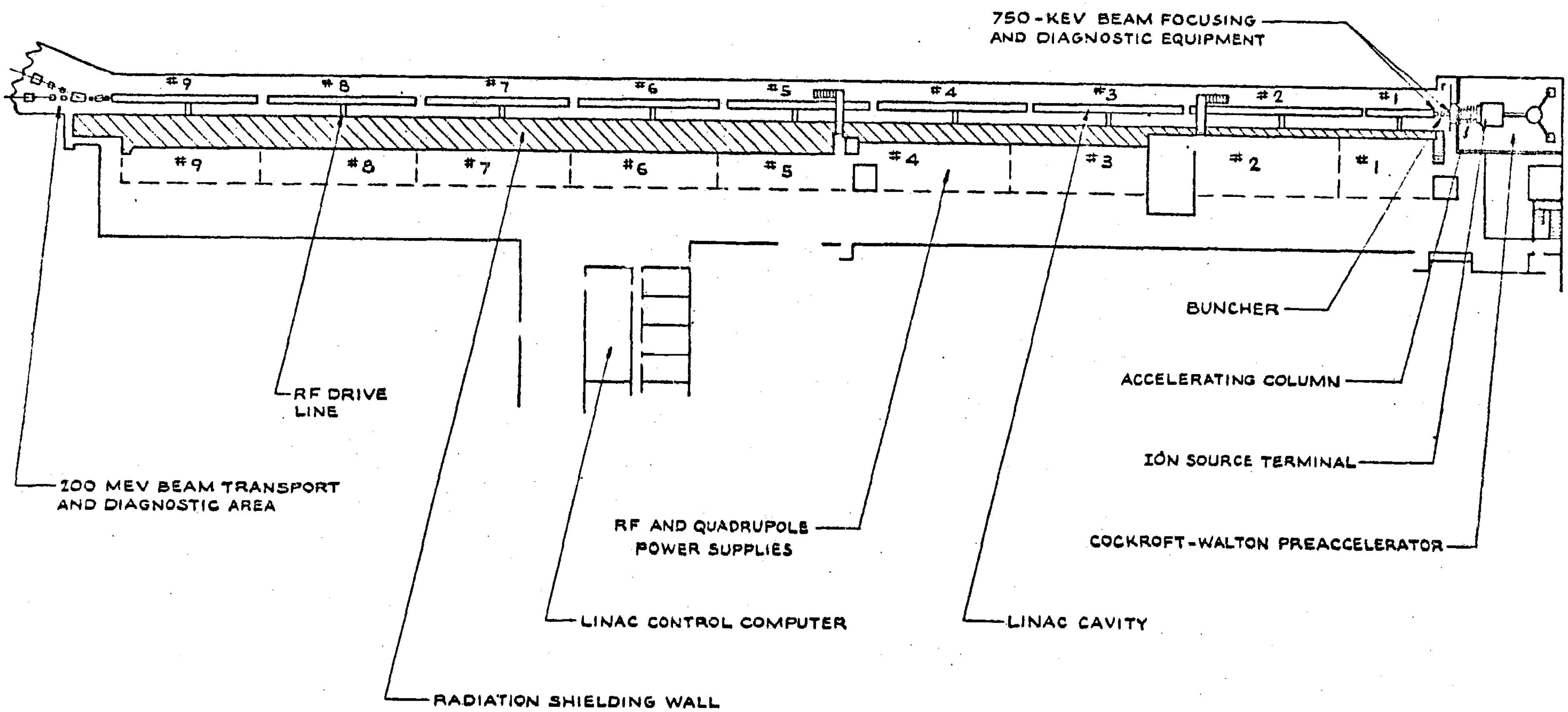


Fig. 1. Simplified plan view of linac.

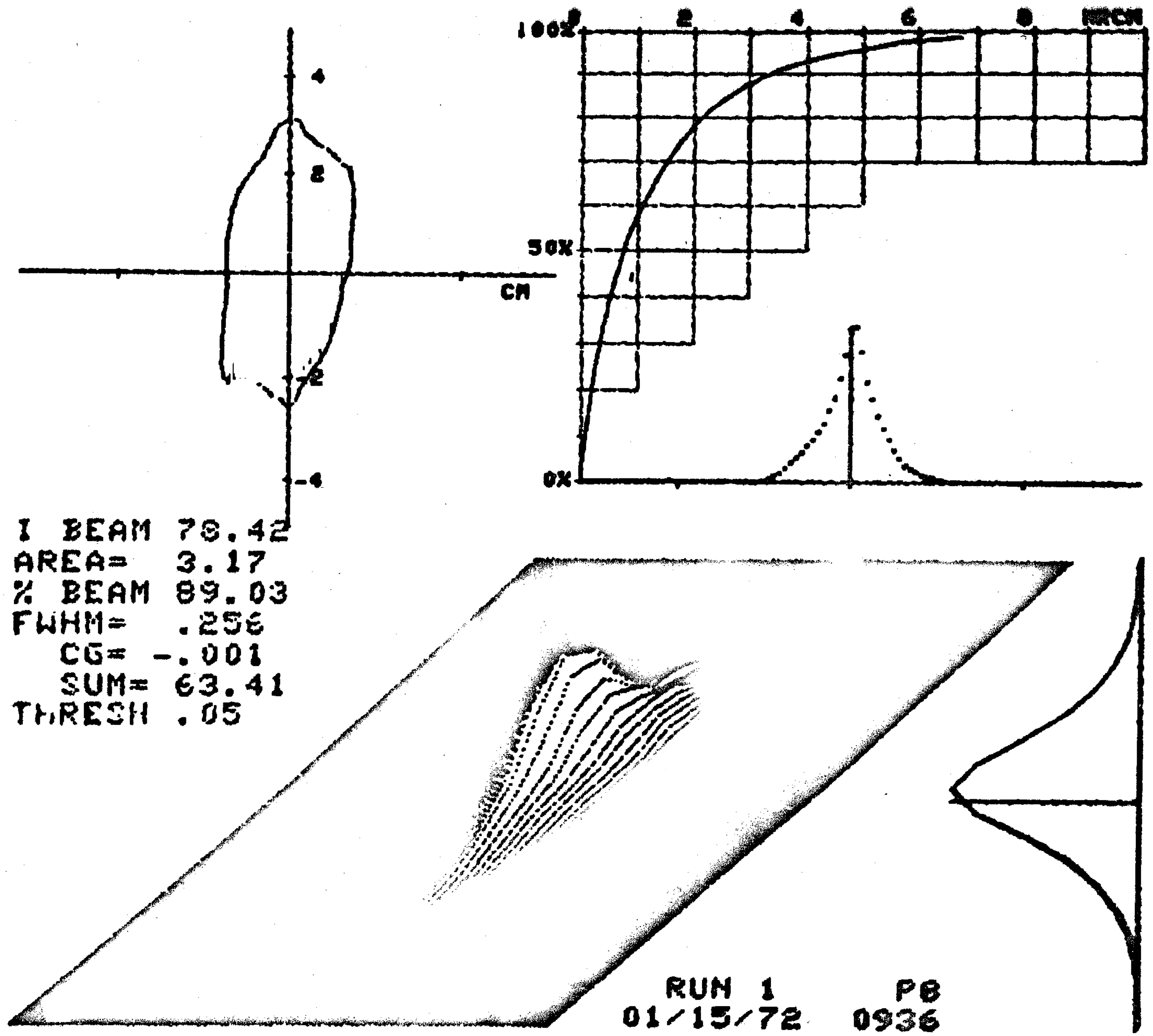


Fig. 2. Beam Emittance at 200 MeV in the Vertical Plane

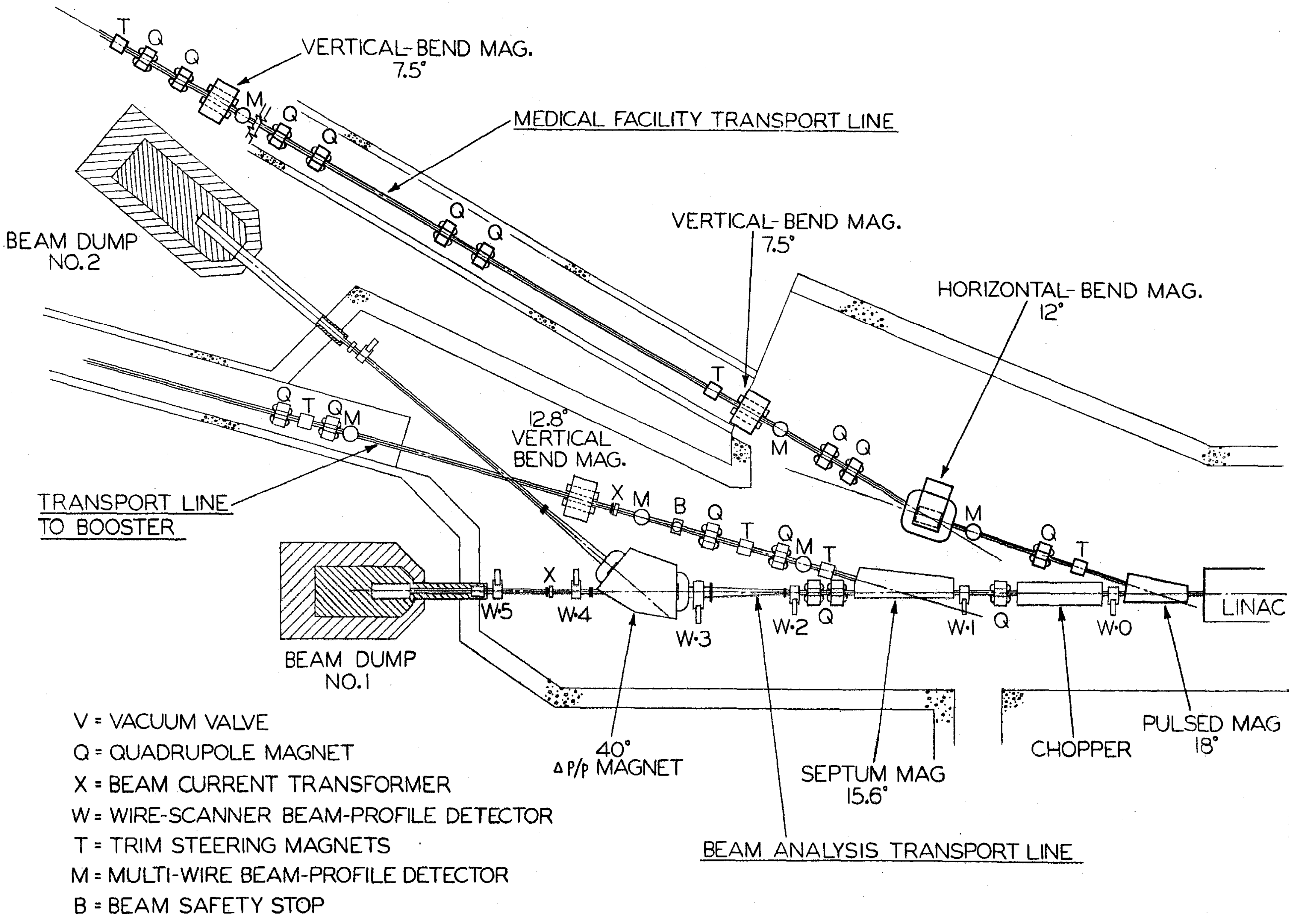


Fig. 3. Beam Switchyard at 200 MeV

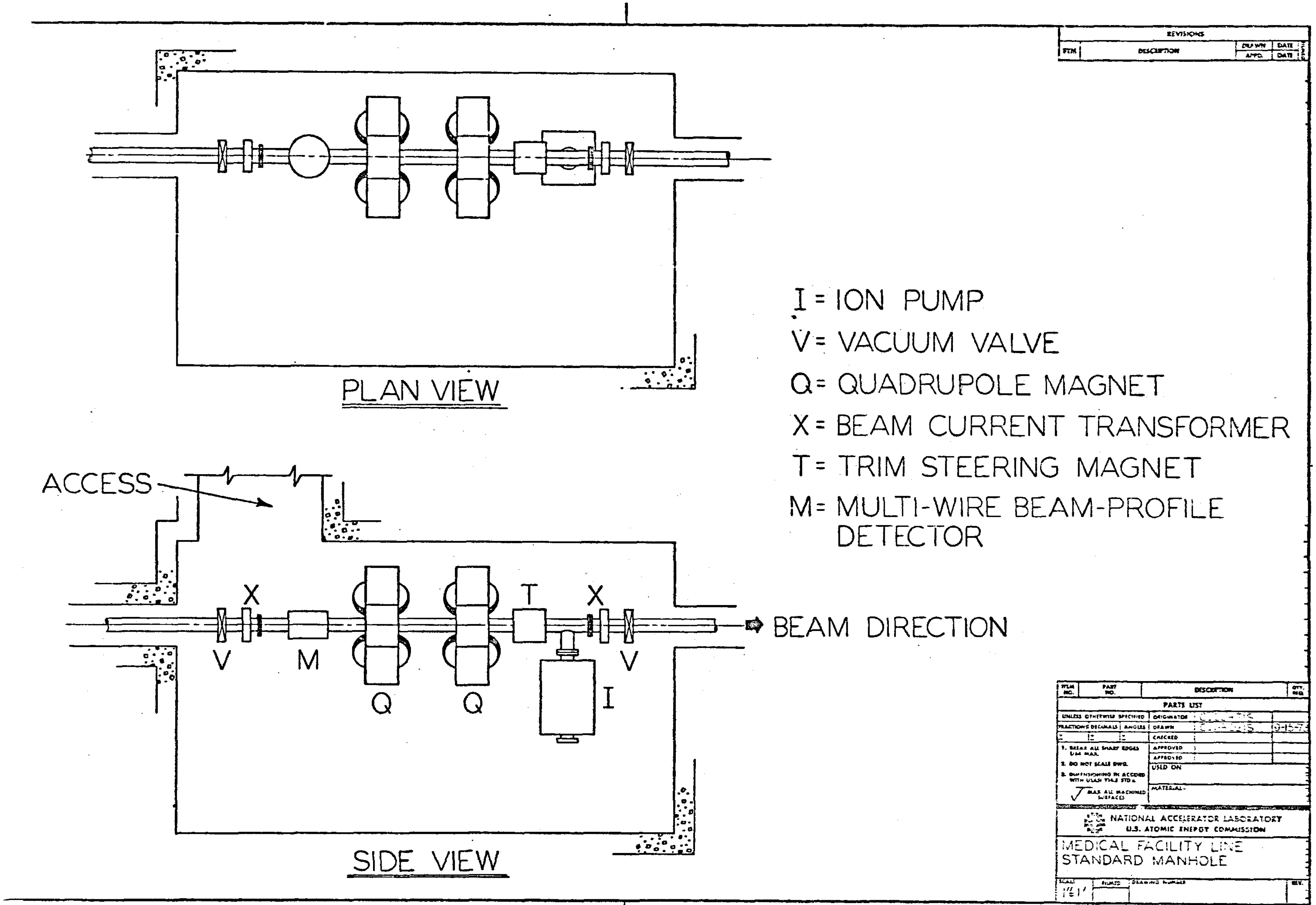
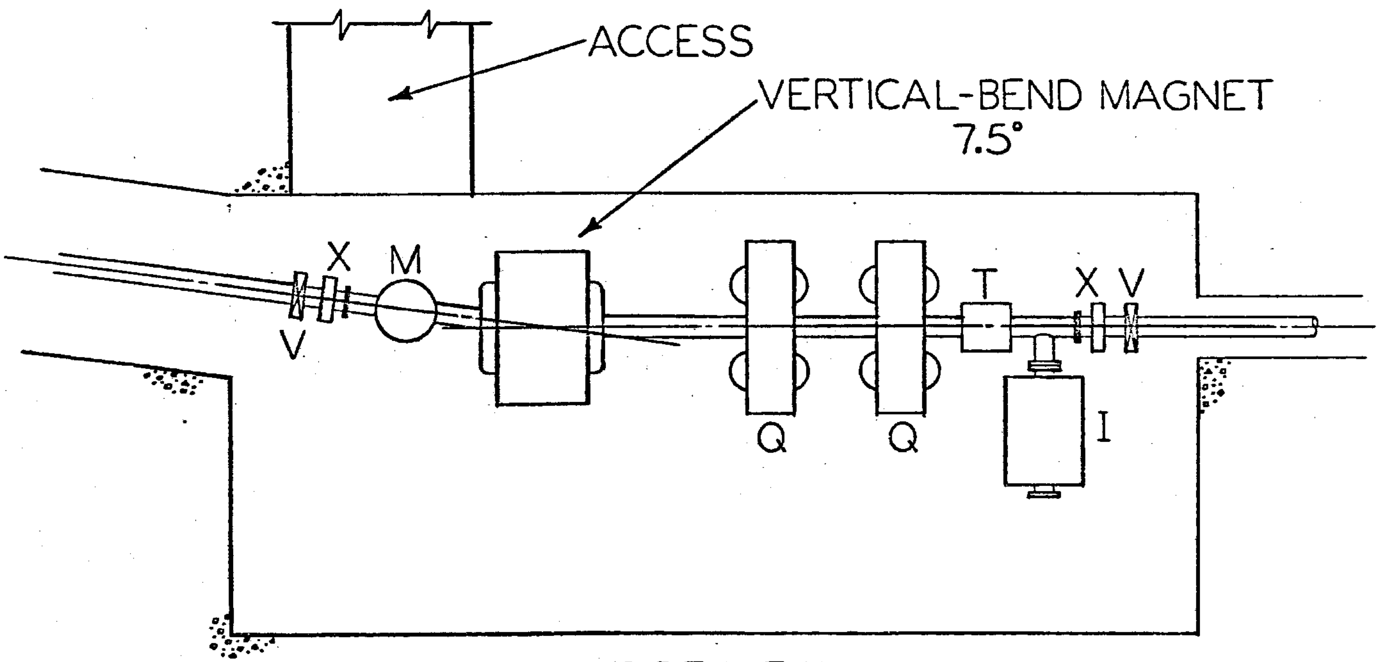

PLAN VIEW
I = ION PUMP
V = VACUUM VALVE
Q = QUADRUPOLE MAGNET
X = BEAM CURRENT TRANSFORMER
T = TRIM STEERING MAGNET
M = MULTI-WIRE BEAM-PROFILE DETECTOR
ACCESS
X
T
X
V
M
Q
Q
I
V
BEAM DIRECTION
SIDE VIEW
REVISIONS
PARTS LIST
NATIONAL ACCELERATOR LABORATORY
U.S. ATOMIC ENERGY COMMISSION
MEDICAL FACILITY LINE
STANDARD MANHOLE

Fig. 4



SIDE VIEW

I = ION PUMP
V = VACUUM VALVE
Q = QUADRUPOLE MAGNET
X = BEAM CURRENT TRANSFORMER
T = TRIM STEERING MAGNET
M = MULTI-WIRE BEAM-PROFILE DETECTOR

NATIONAL ACCELERATOR LABORATORY
U.S. ATOMIC ENERGY COMMISSION

MEDICAL FACILITY LINE
BENDING MAGNET MANHOLE

Fig. 5

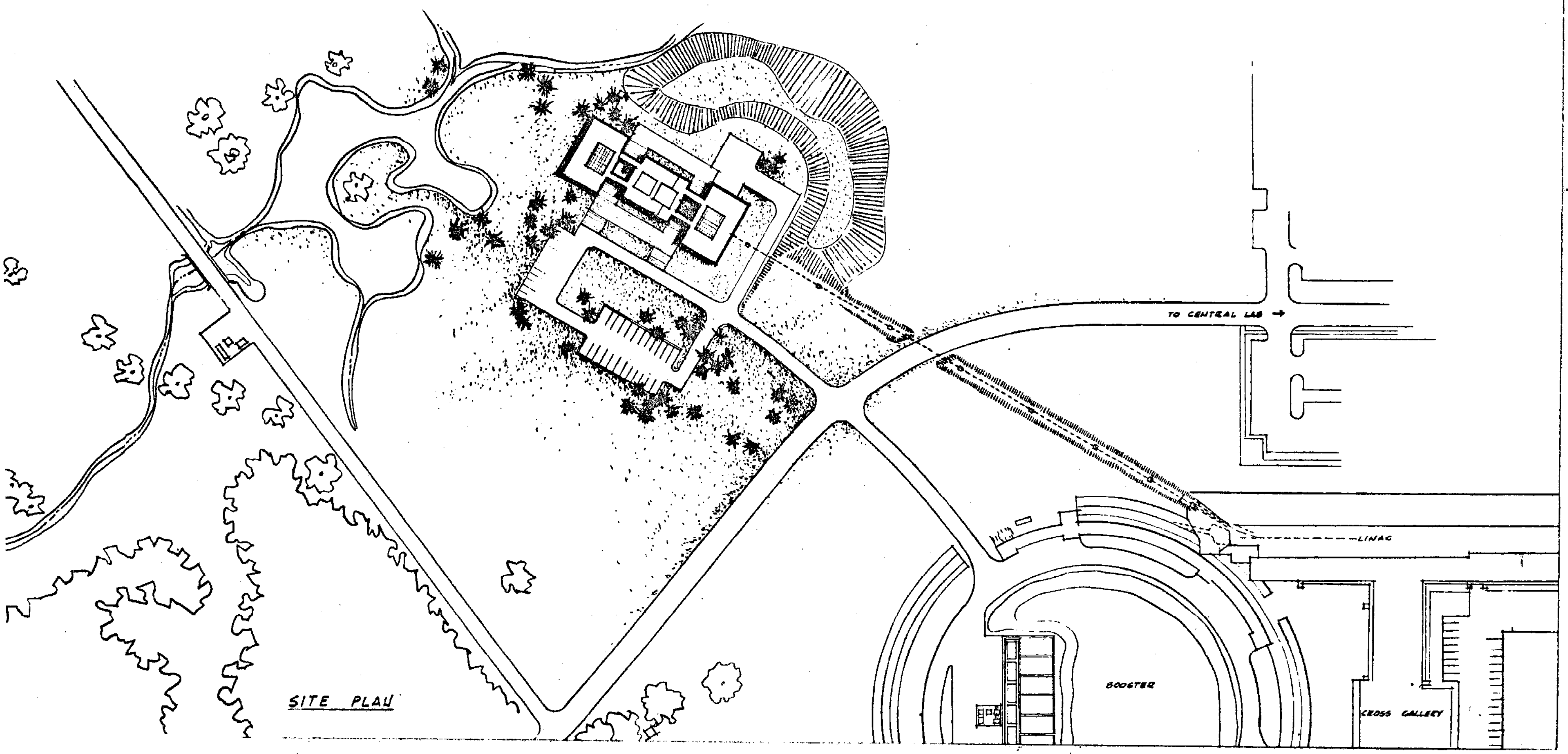


Fig. 6. Beam Transport Line Connecting Linac and Medical Facility Buildings

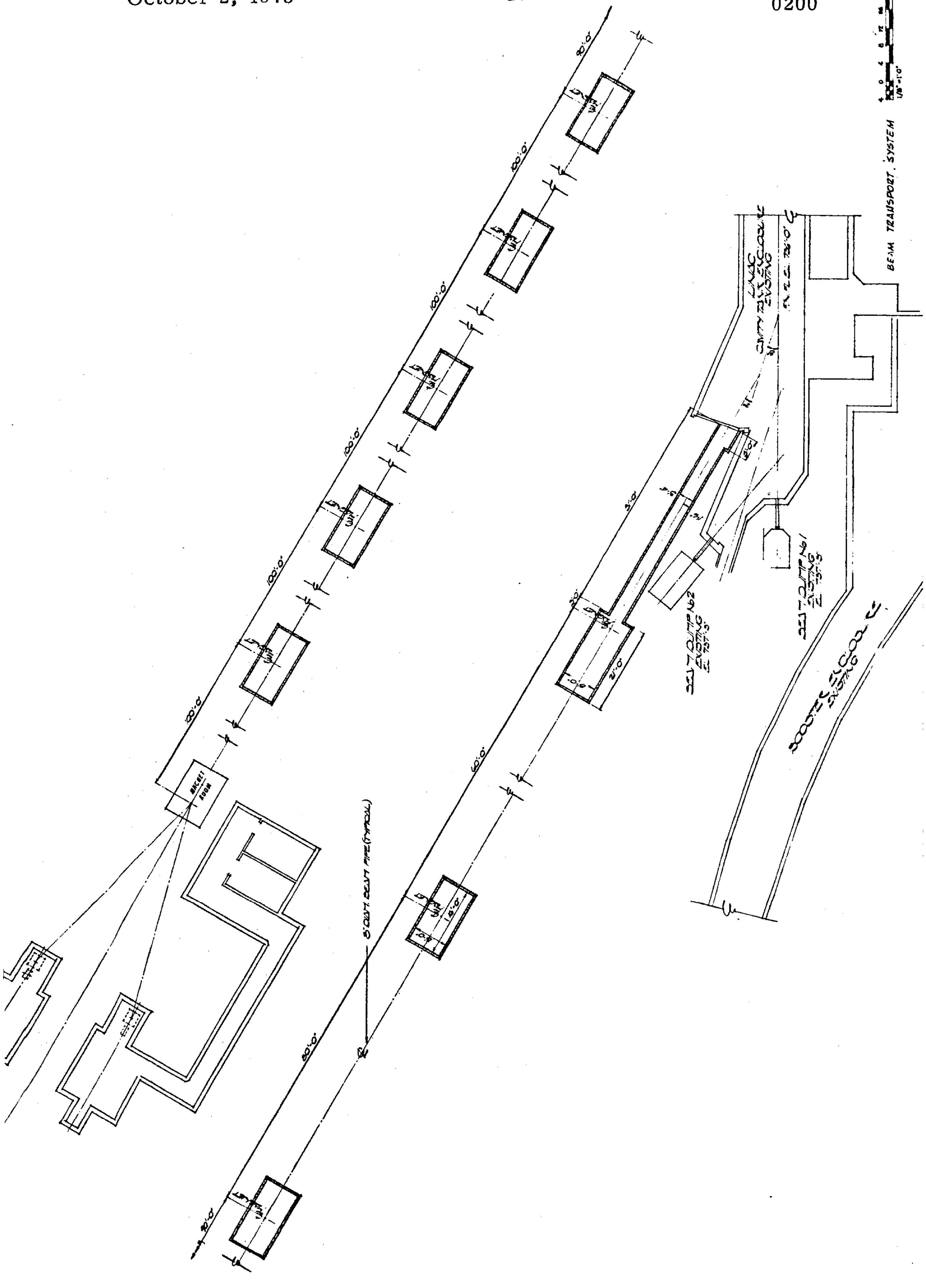


Fig. 7. Manhole Spacing in the Beam Transport Line

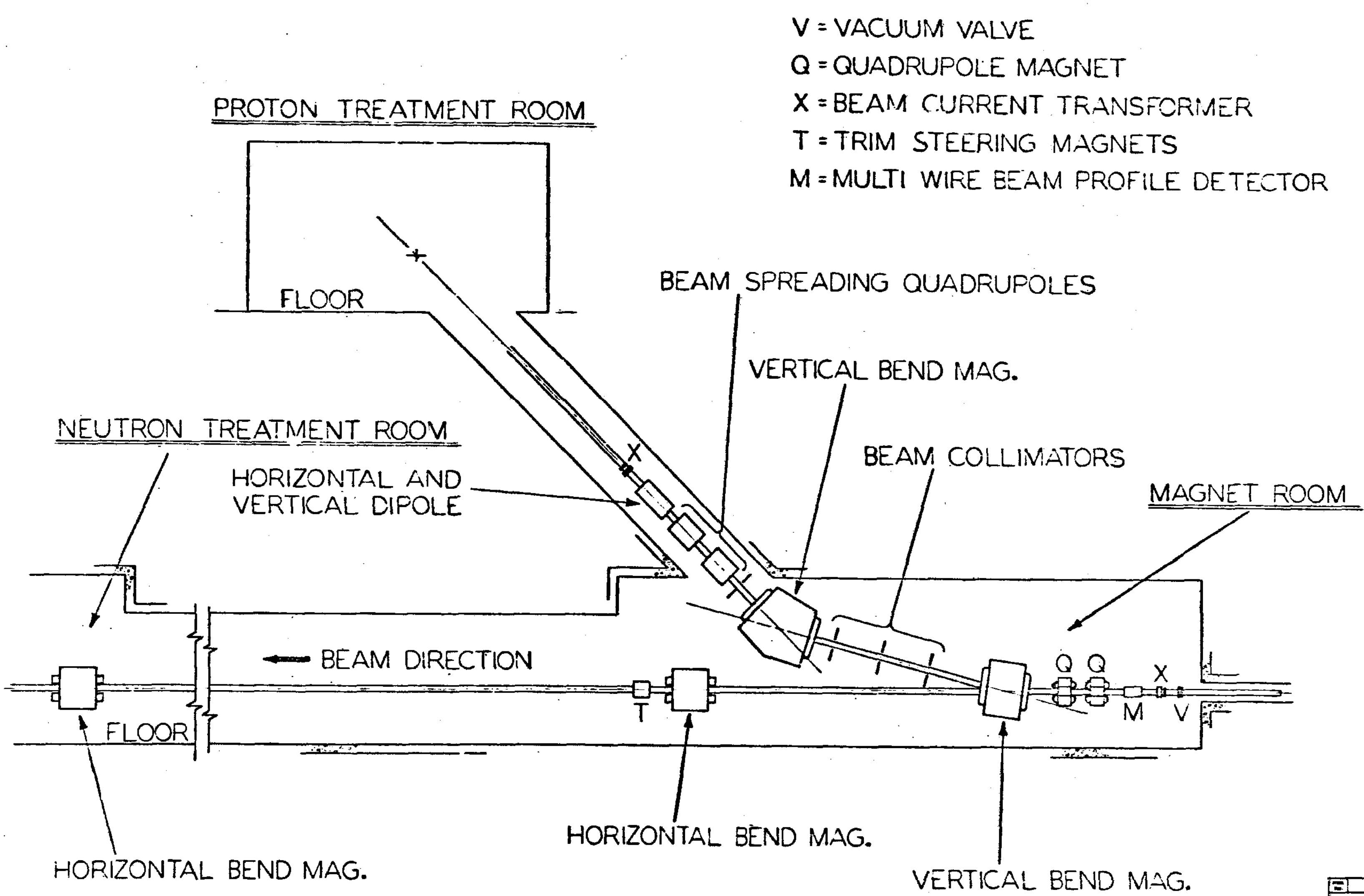

V = VACUUM VALVE
Q = QUADRUPOLE MAGNET
X = BEAM CURRENT TRANSFORMER
T = TRIM STEERING MAGNETS
M = MULTI WIRE BEAM PROFILE DETECTOR
PROTON TREATMENT ROOM
FLOOR
BEAM SPREADING QUADRUPOLES
VERTICAL BEND MAG.
NEUTRON TREATMENT ROOM
HORIZONTAL AND
VERTICAL DIPOLE
X
BEAM COLLIMATORS
MAGNET ROOM
BEAM DIRECTION
Q Q
X
T
M
V
FLOOR
HORIZONTAL BEND MAG.
HORIZONTAL BEND MAG.
VERTICAL BEND MAG.

Fig. 8