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20 MEV S-BAND STANDING WAVEGUIDE

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Summary

A description of the design and performance of a 20 MeV, side-coupled, S-Band Standing Waveguide for electron acceleration is given. Performance data pertinent to the application of this accelerator to cancer therapy is given and discussed.

General Description

The MeV 20 Standing Waveguide was designed for X-ray energies of 12 or 15 MeV and electron energies from 3 to 20 MeV. The guide is a single 1.6 m long LASL-type structure operated in the $\pi/2$ mode at 2856 MHz. It uses a 3.5 cavity buncher of constant phase velocity .90c to capture and bunch the injected beam prior to the velocity of light section.

Table I gives a summary of the guide parameters. Figure 1 shows a photograph of the braze assembly.

Energy range is obtained by varying RF power and injection voltage except for the lowest electron energy which is obtained by tuning to an adjacent resonant mode in the accelerator. Spectral width is minimized over the range of energies required for high beam current, 12 to 15 MeV, by optimizing the buncher, and analysing slits are placed in the vacuum envelope in the bending magnet to prevent out-of-tolerance spectral contribution from contributing to the beam used in treatment.

Figure 4 shows the experimental load lines obtained by varying power and injection voltage.

Examples of parameters used for several operating points is given in Table 2.

The electron gun has a triode structure with a dispenser cathode .25 inches in diameter. The gun develops up to one ampere of beam current over the voltage range 5 to 15 Kv. The spot size the gun optics produce at the waist is .020 to .040 inch at a position about .1 inch beyond the anode structure.

Table I - Standing Waveguide Characteristics

Length	1.6 m
Frequency	2856 MHz
Power	4.5 Mw
Load Line	20 - 60 I_b MeV (I_b in amperes)
Coupling	1.15 over coupled
Shunt Impedance	70 MΩ/m
Injection Voltage	5 - 15 Kv
Q_o	16500
Q_L	7600
Group Velocity	.04 C
Coupling, K	.03

Phase Orbits

The buncher was designed as a compromise between high energy and the need for a good spectrum at X-ray energies; 12 and 15 MeV. The choice was to optimize the spectrum sharpness at 16 MeV.

Phase orbits were calculated using single-orbit phase and energy gain versus distance equations and doing stepwise integration.

The electric field configuration was taken from bead drop data and stored in an array in the computer program. Electric field as a function of position is then obtained by interpolation. For short structures such as this the assumption is made that the average electric field intensity is the same throughout the length of the waveguide.

Note in Figures 2 and 3 the phase convention uses -90° as the phase of maximum acceleration. Also note Z is distance down the guide in meters and that on each orbit is tabulated the injection phase and computed energy.

The no-load phase orbits are shown in Figure 2 for the case of 10 Kv injection voltage and 4.5 Mw of RF power. Electrons injected over the range -80° to +10° are accepted and bunched into the asymptotic range -62° to -116° with energies from 18.4 to 21.3 MeV. Electrons injected at more positive angles than +10° are rejected. The orbit for -90° develops 10.8 MeV.

Figure 3 shows the phase orbits for 90-100 ma of beam at 10 Kv injection voltage and 4.5 Mw of RF power. Electrons injected over the range from -60° to +20° have output phase positions from -127° to -90° and energies of 13.7 to 16.1 MeV. Electrons injected at more positive angle than +20° are rejected, as are those injected at more negative angles than -80°. The orbit or -70° develops 8.5 MeV and comprises part of the spectral tail. The experimental spectrum for this energy is shown in Figure 5.

Phase orbits for the adjacent mode operation were not calculated.

Table 2 - Operating Parameters for Several Energies

Parameter	X-Ray Mode		Electron Mode			
Energy	12	15	6	12	20	MeV
Injection Voltage	9	7	15	12.5	5	Kv
Injected Current	.7	.8	1.0	.45	.25	A
Peak Power	3.0	4.5	1.5	2.3	5	Mw
Beam Current	65	70	8	12	12	Ma

Cold Test

The internal configuration of these cavities was based on the 2998 MHz cavities developed earlier.[6] To offset loss of shunt impedance by frequency reduction, the cavities were made more re-entrant. Total shunt impedance measurements taken using the sapphire rod technique give on axis a total R_T = 164 MΩ/m and at the I.D. of the drift tube 172 MΩ/m.

The coupler was designed for overcoupling of 1.15 at zero beam loading to favor coupling to the high energy case. With a Q_o of 16500 the resulting Q_L is 7600. This gives a rise time of $2\ Q_L/w$ of .54 μs.

The cavity to cavity coupling was set by opening the coupling apertures to the point that the frequency of the π mode and 0 mode differed by 3% of the center frequency. Beyond this degree of coupling it was found that shunt impedance started to decrease.

Tuning

Waveguide tuning is accomplished by isolating each cavity electrically, then measuring, and adjusting the resonant frequency.[5] The resonant frequency is a function of the boundary conditions created by the isolating elements, so that each cavity-type is adjusted to a frequency offset slightly from other cavity types to compensate for the variation in short conditions.

Centerline cavities are isolated by shorting the two adjacent side cavities and inserting probes from the two ends of the waveguides into the drift tube sections adjacent to the cavity in question. These probes serve to short-out adjacent centerline cavities as well as transmit r-f. The probe diameter must be close to the drift-tube diameter to prevent coaxial modes from coupling power to other cavities. The state of the adjacent side cavities affect this measurement slightly, so the tuning is iterated. Different phase-velocity cavities have different diameters and slightly different coupling, so that frequency offsets differ. These are determined in prior measurements using sets of identical cavities. The end cells have reflecting planes near their midplane. This boundary creates a frequency offset of several megacycles which must be compensated for in tuning.

Side cavities are isolated and measured by inserting two loops mounted in a long shorting tube. One loop transmits from one centerline cavity, the other picks up from the adjacent centerline cavity and the resonance measured is indication of the frequency of the side cavity, although influenced by the state of the centerline cavities and the quality of the isolation of other cavities.

The resulting stop band is 5-150 KHz. The stop band for this waveguide was $<$10 KHz.

Mechanical Description

The 31 cells of this waveguide are divided into three regions: 3.5 buncher cells, one coupler cell, and 26.5 standard cells, where a cell is two half-cavities and the attached side cavity. The end plates for the structure are OFHC copper pads brazed into 304L stainless steel flanges. The final assembly of the waveguide includes electron gun with silastic potting, r-f window, 5 l/s vacion pump, vacuum envelope for beam transport through the bending magnet, support tubing, and a focussing solenoid near the buncher end.

Both input and output end of this waveguide are terminated in half-cavities. One reason is to provide boundaries at a reflection plane. The input end is also so terminated to allow for low voltage injection. These boundaries do not form true reflection planes, however, the side cavity cutouts normally alternate from one side of each cavity to the other. With the end plate in place, the side cavity cutouts are on the same side. The result is a frequency shift between this cavity and others so that the cavity must be compensated in diameter to account for the effect.

The r-f input coupler was placed in the center of the waveguide for symmetry and to allow focussing lenses to be placed over the buncher area without mechanical interference. Location of the coupler in this position had the effect of suppressing the modes immediately adjacent to the $\pi/2$ mode.

The RF window is a chip-ceramic of the SLAC type. It is titanium coated on the vacuum side with 50-70 A of titanium to prevent single-surface multipactor and charge build-up from cracking the ceramic.

The structure is designed to be baked-out; however, several bakeable flanges are used: Gun, RF Window, Pinch-off, Vacuum Envelope, Vacion Pump. The guide is baked-out and pinched-off initially. If a failure occurs in a component in place, the component can be replaced easily.

The tolerances in this structure vary from area to area, the closest tolerances being maintained on the contoured surfaces of the main cavities. These are constructed using ground templates and diamond tools on a high speed tracer lathe. The resulting uniformity can be expressed in terms of frequency uniformity: $\pm$1.5 MHz. Other internal tolerances are held $\pm$.001 to $\pm$.003 inches.

Internal surface finish is important in this structure for the reason that r-f-induced field emission can produce dark current. In the X-ray modes this is not important for beam current is 50-100 ma peak, but in the electron mode where beam currents are 1-3 ma peak, dark current can produce a significant percentage of the required field. For this reason, critical parts are electropolished to a mirror finish.

Electron Depth Dose

The application of electrons for treatment of cancer is a complex subject and only the briefest comments are made here. The electron beam developed in the accelerator must be processed carefully to obtain the following characteristics:

1. Energy homogeneity.
2. Minimum penumbra.
3. Variable field size.
4. Uniformity of intensity across the field.
5. Useable, controlled dose rate.
6. Low X-ray contamination.
7. Low leakage outside treatment area.

The characteristic of electrons that make them useful for medical application is the depth dose they exhibit. In Figure 5 is displayed the depth dose from this waveguide beam for three energies: 6, 12 and 20 MeV. The energy was determined with the use of a 30° spectrum analysing magnet using 1% slits. The beam was taken from the analyser port and subjected to minimum scatter prior to striking the depth dose tank 100 cm from the exit window. The 1.9 cm line on the figure is the inside wall of the tank. The surface dose measurements have not been made at the time of this paper.

In the machine, spectrum analysis is not available and a number of other measurement techniques are used; a common one being extrapolated range. $R_p = .52T - .3$ cm H_2O, $5 < T < 50$, where T is the kinetic energy in MeV and R_p is the range extrapolated by continuing the downslope of the depth dose curve to the baseline.[4]

The shape of the depth dose curve is affected by the spectral width of the beam with a wide spectrum causing a more gradual fall-off. For this reason energy defining slits are placed in the achromatic magnet system to obtain ±8% maximum spectral width to be transmitted.

Penumbra is avoided by collimation down to the surface of the patient with low Z applicators. Field size is varied with the use of a set of different applicators or by one that is variable. Intensity uniformity is obtained typically by scatter from a foil or by magnetic scanning.

Dose rate is set and controlled typically by sensing and servoing the output. Accurate and carefully interlocked dosimetry is one of the most important aspects of the use of electrons. X-ray contamination is minimized by use of minimum amount of scattering material.

Leakage is minimized by maintaining all collimation devices greater than one electron range thick for the highest energy. X-rays produced in the applicators are quite low in intensity.

Note the convex shape of the electron depth dose as compared with the X-ray. This can often be used in multiple port treatments for enhancing tumor dose relative to skin dose.

X-Ray Depth Dose

The demands on the X-ray field used for therapy are similar to those for electrons, but with some differences.

Intensity uniformity or field flatness is obtained by field shaping with an appropriate absorber. Useable intensity is a few hundred Rads/minute at 1 m. At 12 MeV this requires 20-30 μa average beam current. The ionizing capability of electrons at this energy is approximately 1000 times greater than X-rays and as a result the amount of beam current is considerably less, depending on the method of application.

Penumbra is minimized by having a small spot size, a short spot length, and accurate beam defining collimators.

Low electron contamination is obtained either by using an absorber or a sweeping field.

Low leakage is obtained with adequate shielding around the target and beam collimators.

X-rays in the MeV range are considerably more penetrating than electrons. Figure 5 shows the depth dose for a 12 MeV beam. The definition of X-ray energy used here is to identify it with the incident electron beam energy. The equivalent photon energy is approximately one third this number.

In the measurement shown in Figure 5 the electron spectrum was taken with a 30° spectrum analyser through 1% slits. After the energy was established by the analyser the beam was brought through a 261° achromatic bending magnet used in the medical system to a water-cooled platinum target. The beam was then collimated by a set of tungsten jaws set for 10 x 10 cm field size 100 cm from the target. The depth dose tank was set 100 cm from the target and a scanner carrying a Victoreen 555 probe (.1) was used to record intensity versus depth. The data obtained compares favorably with published values.

References

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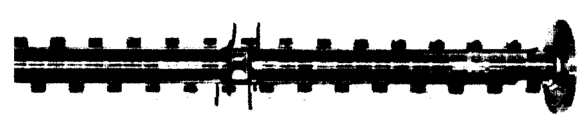

Figure 1.

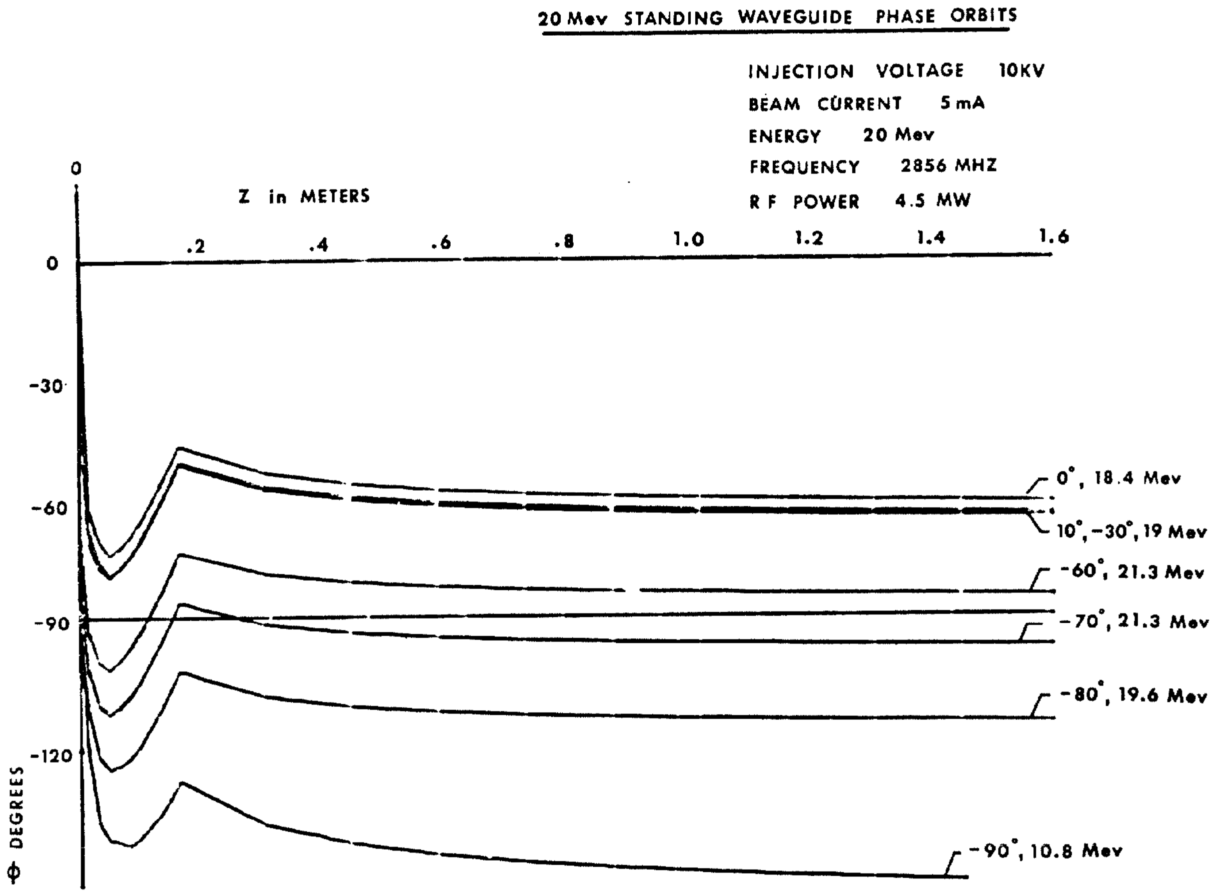

Figure 2.

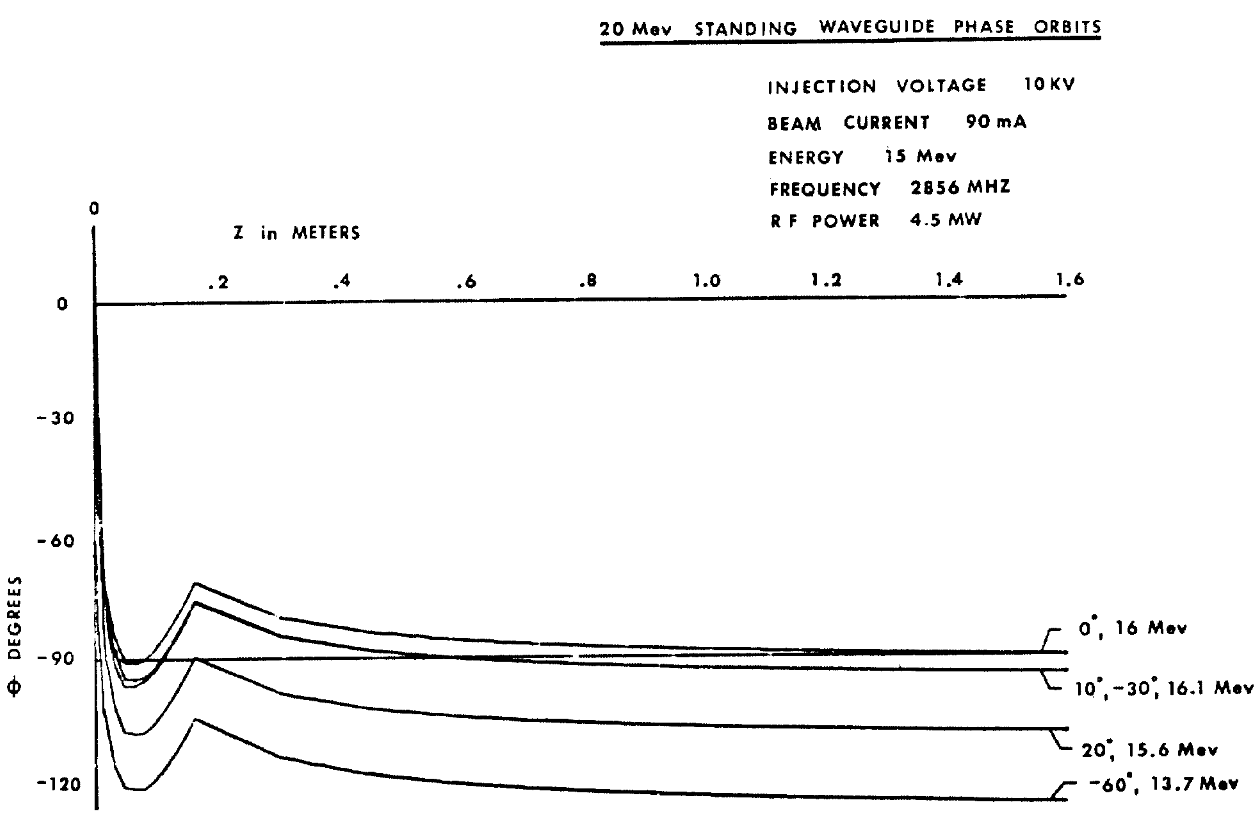

Figure 3.

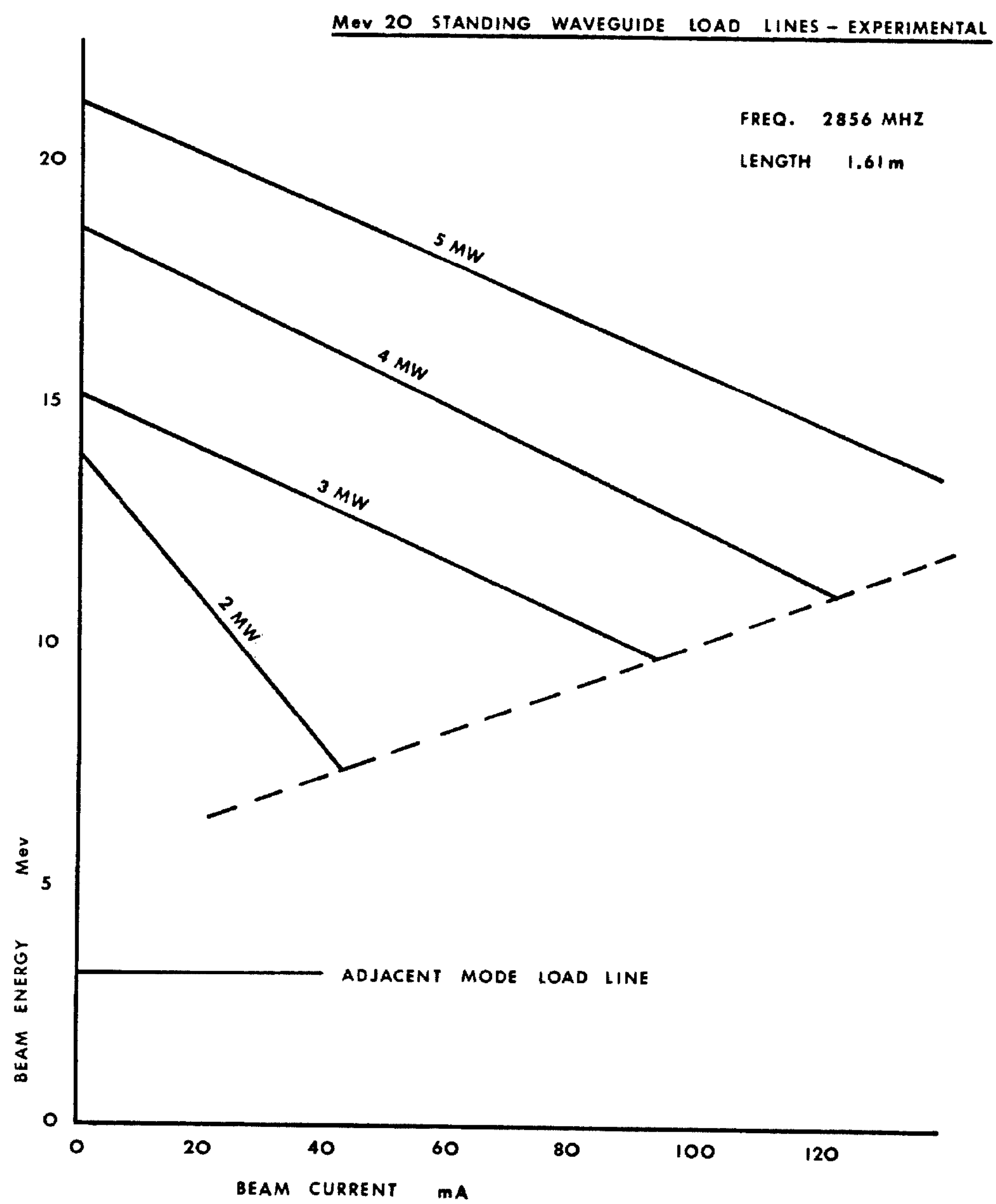
Mev 20 STANDING WAVEGUIDE LOAD LINES - EXPERIMENTAL
FREQ. 2856 MHZ
LENGTH 1.61 m
5 MW
4 MW
3 MW
2 MW
ADJACENT MODE LOAD LINE
BEAM ENERGY Mev
0
5
10
15
20
0
20
40
60
80
100
120
BEAM CURRENT mA

Figure 4.

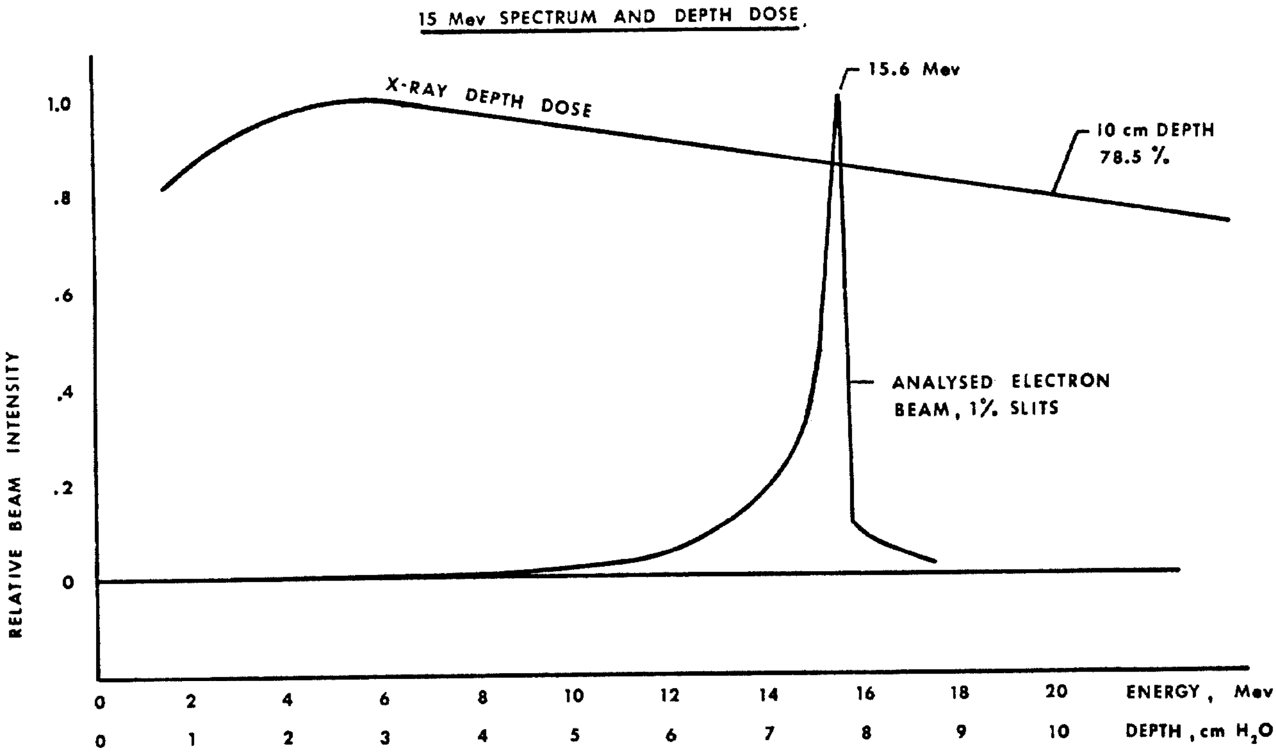

Figure 5.

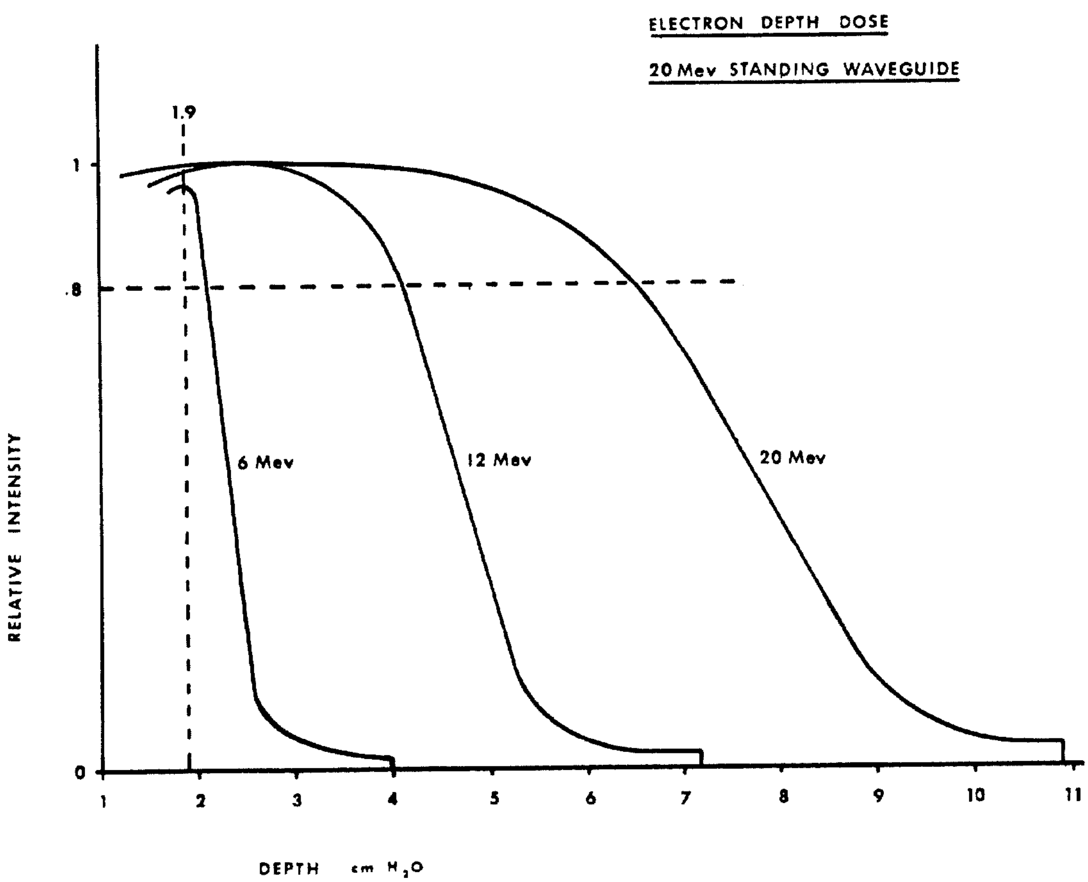

Figure 6.