INJECTOR AND WAVEGUIDE DESIGN PARAMETERS FOR A HIGH ENERGY ELECTRON-POSITRON LINEAR ACCELERATOR

J. Haimson

Varian Associates
Palo Alto, Calif.

Summary

This paper discusses the electron beam optics design of a six klystron, twelve section, 450 Mev electron 350 Mev positron linear accelerator which has been designed as an injector for a storage ring. The beam centerline comprises three zones; namely, the injection system, the high current waveguide sections and the high energy gain sections. The injection system is arranged such that the beam from a pulsed diode source is chopped and prebunched at 2856 Mc to provide well defined tightly focussed short bunches of electrons for injection into the first accelerator section. A nanosecond inflection system, located between the chopper and prebuncher cavities, provides variable short pulse capability as well as 9.5 Mc modulation of the beam to produce a train of short pulses during each gun pulse.

The first four waveguide sections are designed for an unloaded beam energy of 107.5 Mev, and 500 ma peak current at 60 Mev with 10 MW peak r-f power at each input coupler. A positron converter is located at the end of these sections and immediately prior to the high energy gain portion of the machine which comprises eight waveguides each of which is 504 cm in length and designed for an unloaded beam energy of 45.4 Mev with 10 MW peak r-f input power. Details of the microwave design parameters and some electron beam characteristics are presented together with preliminary measurements of actual beam performance.

Specification and Design Parameters

The performance specifications of the accelerator and pertinent design parameters are listed below.

Specifications	
Number of klystrons (Type TV 2014)	6
Peak r-f power per klystron	25 MW
Average r-f power per klystron	24 KW
Number of accelerator sections	12
Unloaded beam energy, sections 1-4	105 Mev
Loaded beam energy at 418 ma, sections 1-4	65 Mev
Unloaded beam energy, sections 5-12	348 Mev
Total loaded electron beam energy at 100 ma	374 Mev
Total positron beam energy	348 Mev
Positron current within 1 percent energy spread	100 μamp
Pulse repetition rate at 3.2 μsec beam pulse	250 pps
Pulse repetition rate at 0.1 μsec beam pulse	700 pps

Injection system capable of producing a beam pulse train of 30 percent ON and 70 percent OFF at 9.5 Mc and single pulse down to 10 nanosecond with 5 nanosecond rise and fall times.

Design Parameters

The following design parameters are based on 10 MW peak r-f power at the input coupler of each waveguide section. The phase orbital behavior of the particles through the variable impedence waveguides were computed from step function solutions of the two simultaneous first-order differential equations relating incremental rate of energy gain and the associated change in phase position.[1]

Accelerator Section No. 1		
Length	1.995	meter
Number of cavities	57	
Total voltage attenuation	0.37	neper
Filling time	0.54	μsec
Unloaded beam energy	22.3	Mev
Loaded beam energy at 418 ma	15.5	Mev
Accelerator Sections 2 through 4		
Length	2.940	meter
Number of cavities	84	
Total voltage attenuation	0.39	neper
Filling time	0.57	μsec
Unloaded beam energy	28.4	Mev
Loaded beam energy at 418 ma	17.8	Mev
Accelerator Sections 5 through 12		
Length	5.040	meter
Number of cavities	144	
Total voltage attenuation	0.82	neper
Filling time	1.19	μsec
Unloaded beam energy	45.4	Mev
Loaded beam energy at 100 ma	37.5	Mev
Unloaded beam energy, sections 1 through 4	107.5	Mev
Unloaded beam energy, sections 5 through 12	363	Mev
Loaded beam energy at 100 ma, sections 1 through 4	98.2	Mev
Loaded beam energy at 418 ma, sections 1 through 4	68.9	Mev
Total loaded electron beam energy at 100 ma	398	Mev

Positron unloaded beam energy (not including the injection energy)	363 Mev
Positron current within 1 percent energy bin and 10^{-3} radian-cm emittance	500 μamp

Injection System

This system has been designed for chopper prebuncher operation to produce clearly defined narrow phase width bunches for injection into the first accelerator waveguide. In practice, single cavity prebuncher operation can result in approximately 70 percent of the current being injected in 50 to 60° bunches. Phase widths of this magnitude however, as well as the current distribution between bunches over the larger phase width corresponding to the waveguide acceptance region ($\simeq$ 180°), cause undesirable broadening of the bunch width emergent from the first section. This inherent feature is a limiting factor in the achievement of minimum energy spread from multi-section machines. (R-f power and frequency fluctuations usually constitute the largest individual contributions to energy spread.)

By suitable selection of bunching parameter and inter-cavity phase relationships, chopper prebuncher systems typically produce 30° clearly isolated bunches at injection, containing 30 percent of the incident current and with negligible inter-bunch current. The advantages of chopper prebuncher operation have been discussed elsewhere[2] and the overall layout of such a system, including an inflector assembly to provide nanosecond pulse operation, is shown in Figure 1.

The source comprises a Pierce type diode electron gun, with a space charge limited cathode emission of 4 amperes at 105 KV, and is separately pulsed from a line type modulator which provides a high stability continuously variable voltage control over the range 90 to 120 KV. The carburized thoriated tungsten cathode is indirectly heated and temperature regulated using a feedback controlled 3 KV bombarder system. The beam, in converging to a minimum of approximately 3 mm diameter 20 cm from the cathode, passes through an r-f chopper cavity (C) and a thin lens assembly (No. 1) positioned adjacent to the anode. The diverging beam is then refocussed through a prebuncher cavity (D) by lens No. 2 such that the beam minimum is imaged at a small aperture located in the water-cooled tungsten assembly (A). After transmission through this aperture the beam is refocussed at the final injection aperture (B), adjacent to the input coupler of the first accelerator waveguide, by the thin lens No. 3.

The focussing magnets and a set of orthogonally positioned steering magnets, located at the gun anode, can be controlled from the main console to satisfy differing gun voltage and beam intensity operational requirements. When the higher current levels obtained from space charge limited emission are not required, for example, the contraction of the beam minimum position due to temperature limited operation of the source may be compensated by adjustment of lens No. 1. This procedure enables the optimum geometry to be maintained by providing symmetric image and object distances either side of lens No. 2.

Chopper Operation

The rectangular chopper cavity (C), designed to operate in the TE_{102} mode, sweeps the beam across the clipping aperture located in the tungsten block assembly (A) at a frequency of 2856 Mc. By using dc magnetic bias at the chopper cavity, the beam scan is offset to one side of the system center line and the fraction of each RF cycle transmitted through the clipping aperture into the accelerator may be controlled by adjustment of the bias level and the chopper cavity drive power (P_{ch}). The focussed beam (second minimum) is arranged to sweep along a water-cooled V-shaped notch which is cut in the incident surface of the tungsten block (A) to reduce the dissipation per unit area and avoid surface erosion. This notch is oriented with respect to the plane of the chopper cavity sweep to allow for beam spiralling of the off-axis rays in passing through the first and second focussing lenses (approximately 6° and 110° respectively at 105 KV). Biased operation using only the chopper cavity enables controllable phase widths of mono-energetic electrons with the least radial momentum to be injected into the accelerator. This mode of operation offers a means of achieving sharp energy spectra from the machine but the high transmission losses for small injection phase widths requires a large initial current level. These losses increase for reduced phase widths and are dependent upon the ratio of aperture (D) to beam diameter (d), the bias level, and the length of the beam scan (X) which is proportional to the square root of the chopper cavity peak r-f drive power.

Computed chopped beam transmission characteristics for the 180° mode of operation, normally used in conjunction with a prebuncher cavity, are shown in Figure 2 (b). These curves are based upon the slightly "skew" current density distribution shown in Figure 2 (a) taken through the beam minimum cross section using a micro-profilometer during injector bench tests under space charge limited conditions and at 105 KV. Data of this nature provides injection current phase distribution information and enables the overall machine performance to be analysed for various D/d ratios, bias and chopper settings, etc.

The computed integrated transmitted

current for 180° chopper operation as a fraction of the incident beam for different (D/d) ratios, a constant bias of $\frac{1}{2}(D+d)$ and increasing chopper scan (X), is shown in Figure 3 (a). Actual beam test data confirming these reduction factors are recorded in Figure 3 (b) for various chopper power levels (P_{ch}) and bias magnet settings. The intercepts of a vertical line through the +30 ma bias setting represents the $\frac{1}{2}(D+d)$ conditions for a D/d ratio of 5/6. It can be noted that the transmitted current is reduced to 25 or 30 percent of the incident current level under these circumstances. For the leverage distance involved with this system, 180° chopper operation is obtained with only 1.5-2.0 KW peak r-f drive to a chopper cavity having an unloaded $Q_o \simeq 3000$.

Chopper Prebuncher Operation

By positioning the prebuncher (D) Figure 1, ahead of the clipping aperture, it was possible to prevent high levels of r-f power being induced in the cavity by the chopped beam and this enabled the gap voltage to be selected by simple adjustment of the drive line attenuation. A major objection in using the chopped beam to drive the prebuncher cavity is that operational requirements for wide variations of beam intensity, and to a lesser extent bunch length, necessitate adjustable high drive levels, a large range detuning mechanism and, under some circumstances, a reduced Q. Furthermore, as discussed in a following section, beam excitation of the prebuncher cavity during short pulse operation (several nanoseconds) would result in an undesirable energy spread due to build-up of the velocity modulating electric field during the pulse.

To facilitate uninterrupted passage through the prebuncher of the transversely oscillating biased beam during chopper cavity operation, the prebuncher cavity was arranged with slotted drift regions on both sides of the gap as shown unshaded in Figure 1. The cavity resonates in the normal TM_{010} mode, is water cooled and constructed of copper and stainless steel with tungsten inserts. The unloaded $Q_o \simeq 2800$ and the coupling was arranged for $\beta = 1.2$.

Drive power for the chopper and prebuncher is obtained through separate remotely controlled phase shifters and direction couplers connected to the high power rectangular waveguide feeding the first accelerator section. Consequently, by simple adjustment of the chopper and prebuncher phase shifters it is possible to arrange for that portion of the chopped beam, per r-f cycle, which is transmitted through the aperture, say 180°, to experience bunch compression by traversing the prebuncher gap during phase reversal of the velocity modulating (bunching) longitudinal electric field. Selection of this chopper prebuncher phase relationship together with a slightly "over-critical" bunching parameter results in all of the transmitted current being contained in clearly separated bunches of approximately 30° phase width at the end of the drift space immediately prior to injection. Adjustment of the above phase relationship with respect to the phase of the accelerator waveguide input coupler electric field ensures injection over the optimum phase width within the acceptance region (See inset sketch Figure 7). A bunch monitoring system, comprising orthogonally oriented chopper cavities phased in quadrature and used to analyze the injector performance has been described in an accompanying paper.[3]

A feature, which has been incorporated in a large number of machines, is the use of a thin focussing lens and a small injection aperture to produce, and assist in maintaining, a small beam cross section along the length of the waveguide. The accurately aligned finite length aperture, combined with the spread of foci of the velocity modulated beam due to the focussing magnet, produces some filtering action as well as ensures radially symmetric injection into the accelerator. By locating the final aperture in what is effectively the pole face of a strong axial magnetic field, it is possible to reduce divergence contributions due to space charge and r-f fields and maintain a small beam cross section during the initial critical bunching period. For peak current levels of approximately 2 amperes and final injection apertures of $2\frac{1}{2}$ - 3 mm diameter, the combined interaction of the No. 3 focussing lens and velocity modulation, when using a slightly over-critical bunching parameter, causes up to 25 percent transmission loss due to strong radial and longitudinal space charge forces. (A 3 mm bunch (sphere) corresponds to 10° at 2856 Mc.)

Short Pulse Operation

Referring again to Figure 1, the two sets of deflection plates, located between the chopper and prebuncher cavities, provide short pulse injection capability in the following manner. One of each pair of plates is grounded and a biasing dc magnetic field (E) is applied perpendicularly across both of the second pair of plates. The ungrounded plates of each set can then be coaxially driven (up to 10 Kv) by separately triggered pulse amplifiers to provide independent fast start and stop injection control by sweeping the beam on and off the clipping aperture located in assembly (A), i.e. the same tungsten V-notch and collimating system is used for both chopper and inflector operation. Orientation of the plates to allow for beam spiralling, as discussed in an earlier section, has been omitted from Figure 1 for simplicity.

When the linear accelerator is operating into the storage ring, the injection system inflector will receive a 9.5 Mc triggering signal, synchronised to the storage ring r-f system, to provide a 30 percent ON 70 percent OFF, train of short pulses during each main pulse. Figure 4 shows the preliminary beam wave shapes that were obtained during initial tests on this injection system while operating at 9.5 Mc with the above mentioned duty cycle and a transmitted beam current of 500 ma.

Accelerator Waveguides

All of the waveguides are of non-uniform impedance design, $2\pi/3$ mode and phase velocity equal to the speed of light. A schematic arrangement of the beam centerline is shown in Figure 5 together with the unloaded electric field distributions for the three basic waveguide designs used in this twelve section machine. The values are based on 10 MW peak r-f input power and the corresponding design beam loading characteristics and attenuation parameters are recorded in the introductory section.

The high initial electric field strength in the first accelerator section was chosen to provide tight bunching and correct asymptotic phase positioning for electrons injected at energies over the range 90 to 120 KV. In general, the remainder of the beam centerline operates at field strengths below 100 KV/cm. The first four waveguide sections were designed for a maximum conversion efficiency current i_m=580 ma and a higher attenuation parameter was chosen for the five meter sections to provide high energy gain rather than power conversion. These longer sections have a total voltage attenuation of 0.82 neper and i_m=290 ma.

Some typical microwave parameters used in the design of $2\pi/3$ mode, 2856 Mc waveguides are shown plotted against iris aperture (2a) in Figure 6. This information was obtained from a series of cold stack measurements and the indicated space harmonic corrected values of $(r/Q)_e$ have been reduced by 4 percent in the interests of design conservatism especially when considering the use of large a/λ ratios. Symmetric field iris couplers were used on all waveguide sections to reduce beam dispersion effects and the corresponding values of group velocity and frequency passband are indicated on Figure 6.

A positron converter is located between the fourth and fifth waveguide sections and positrons within a given solid angle and energy spread are confined by a strong magnetic field which is arranged for optimum collection[4] and which directs the positron beam through the high energy sections. A description of this system together with photographs of the accelerator are presented in an accompanying paper.[5] The problem of excessive beam induced electric fields in this machine, due to the combination of high conversion efficiency waveguides and high energy gain variable impedence sections, and the possibility of back-phasing when reverting from positron to electron operation has been discussed elsewhere;[6] and it has been shown that under certain circumstances field strengths sufficient to cause voltage breakdown can be encountered.

Waveguide Section No.1 Beam Characteristics

Figure 7 shows the No. 1 section emergent energy and phase angle (δ_A) versus injection phase angle (δ_o) for injection voltages of 90, 105 and 120 KV. The analysis is based on 10 MW peak r-f input power and a beam loading of 100 ma. Although the energy spread is less than 300 Kev over a 40° injection phase width, a minimum contribution to energy spread during traversal of subsequent sections depends on minimizing the emergent bunch width. It can be noted that this bunch width increases rapidly for increasing injection phase angle and velocity modulation content.

A desirable compromise is obtained with chopper prebuncher operation as indicated by the typical injected bunch intensity distribution shown in Figure 7. Electron phase and energy distributions of this nature are used in a Monte Carlo program to predict the effect on energy spectra due to small random (and known) fluctuations of various system parameters.

Test Measurements

At the time of preparing this presentation, preliminary tests had been completed on the injection system, the first four waveguide sections had been operated at full peak power, preliminary positron tests using one high energy section had been performed and some energy spread measurements had been obtained.

(a) The injection system demonstrated satisfactory chopper prebuncher operation with 1.5 KW on the chopper and 0.7 KW on the prebuncher. The inflection system demonstrated 9.5 Mc operation as indicated in Figure 4. Minimum rise times of 3 nanoseconds were achieved during preliminary short pulse inflection tests.

(b) The performance of the first four waveguide sections is listed below and confirms previously established good agreement with theory.

	Design	Guarantee	Achieved*
V_o	107.5	105	106
V at 100 ma	98.2	95	96.2
V at 420 ma	68.9	65	66

*R-f power measurements at the klystrons during these tests were, P_1=9.8 MW, P_2=7.3 MW, P_3=9.4 MW and P_4=10.2 MW. (Allow approximately 5 percent loss for the rectangular waveguide runs between the klystrons and the input couplers.)
(c) A beam cross section of approximately 5 mm was measured at the end of the fourth section.
(d) Positron test measurements are reported in an accompanying paper.[5]
(e) Preliminary energy spread measurements were obtained with ±0.25 percent klystron cathode voltage ripple, ±0.5 percent gun voltage ripple and ±0.1°C temperature control (information on frequency stability was not available). Initial chopper prebuncher injection operation with 100 ma peak straight ahead current at 115 Mev resulted in 75 percent of the current contained within half intensity points when analysed through 1 percent slits. It is anticipated that these figures will be improved with further optimisation of the injector operational parameters and r-f system stability.

References

1. Varian Associates Report RDRI, March 29, 1963.
2. J. Haimson, IRE, Trans.Nucl.Sci.9, 32, April 1962.
3. J. Haimson, Paper J2, Particle Accelerator Conference, Washington, March 1965.
4. Varian Associates Technical Proposal VATP-R63, April 24, 1963.
5. C. S. Nunan, Paper E6, Particle Accelerator Conference, Washington, March 1965.
6. J. Haimson, Nucl. Inst. Meth., 33, 93, March 1965.

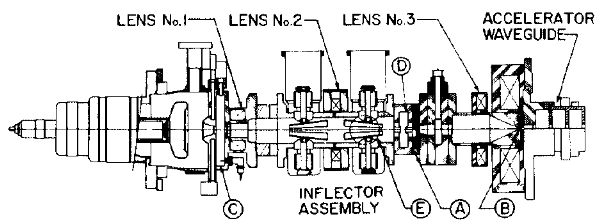


Fig. 1. Cross-sectional view of injection system.

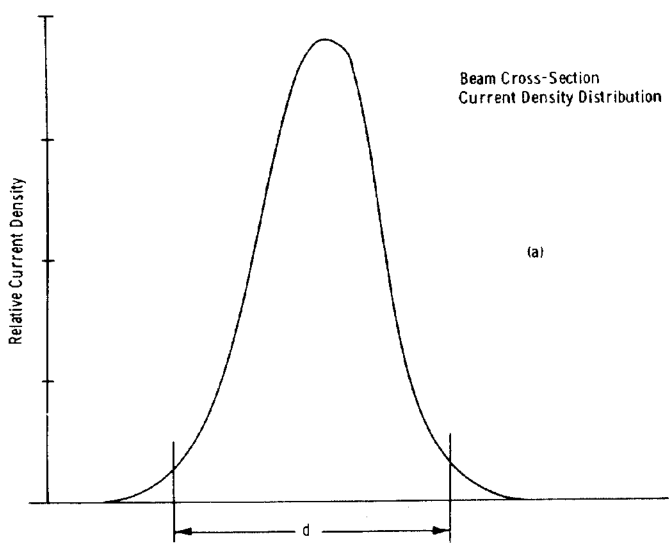


Fig. 2(a). Typical current density distribution through the beam cross section at the beam minimum position.

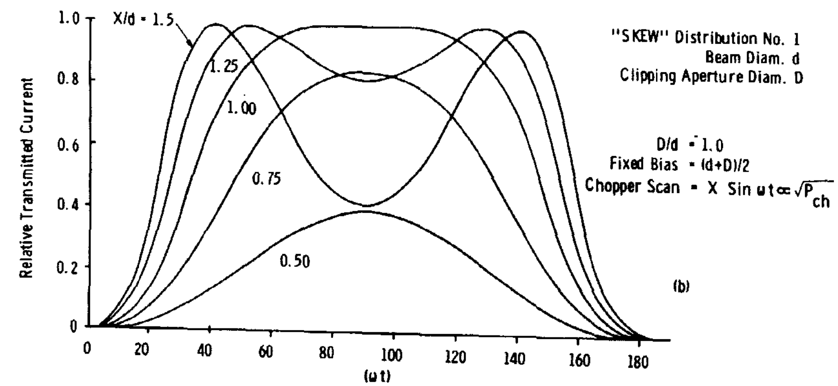


Fig. 2(b). Computed relative transmitted currents for fixed bias operation (180° chop) and increasing chopper sweep amplitude.

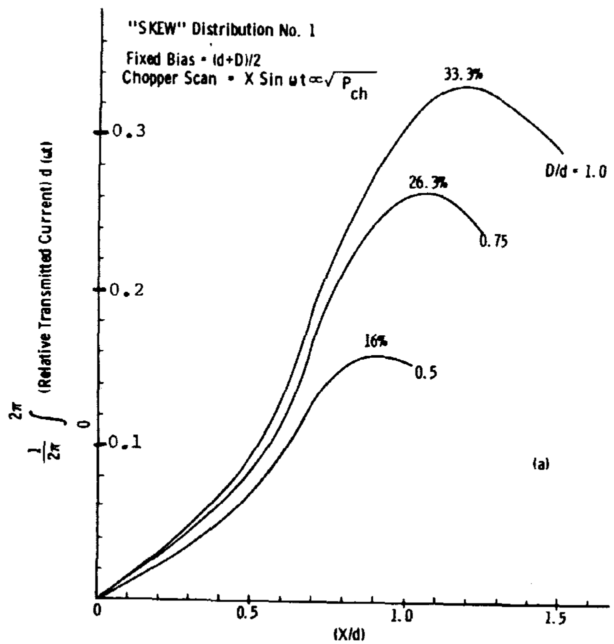


Fig. 3(a). Computed fraction of incident beam transmitted during chopper operation for various aperture to beam diameter ratios and increasing chopper sweep amplitude.

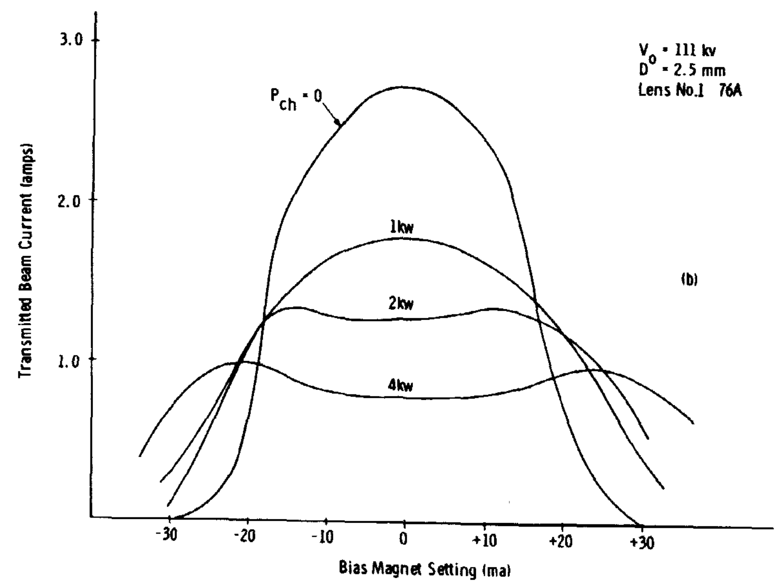
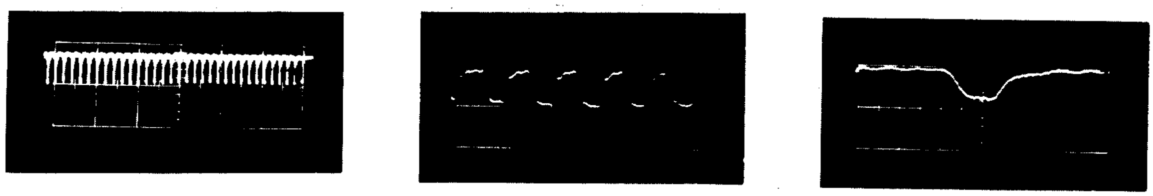


Fig. 3(b). Beam test measurements of transmitted current for various chopper drive levels and bias magnet settings.



500 ns/cm 100 ns/cm 20 ns/cm

INFLECTOR SYSTEM OPERATING AT 9.5 Mc, i = 500 ma.

Fig. 4. Preliminary beam wave shapes during initial injector tests showing inflector operation at 9.5 Mc and i = 500 ma.

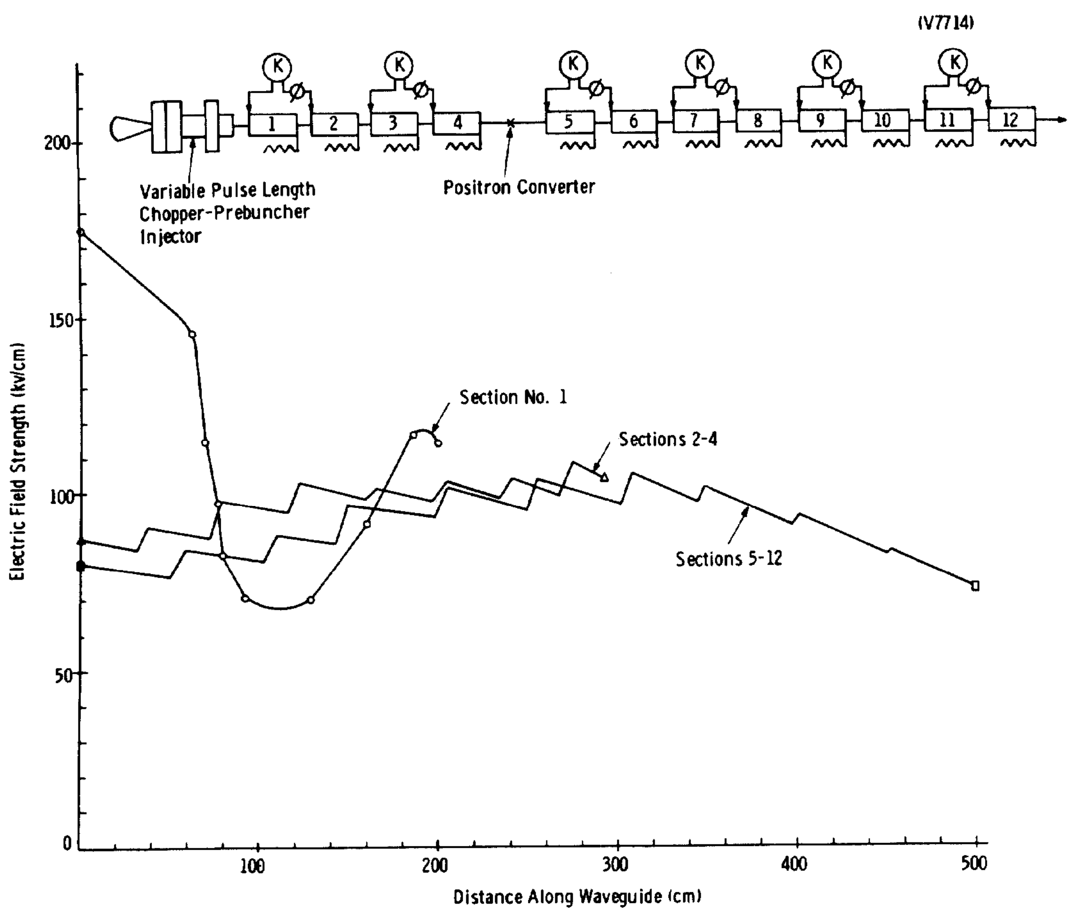


Fig. 5. Accelerator waveguide electric field strength distributions at i = 0 and 10 MW peak r-f input power.

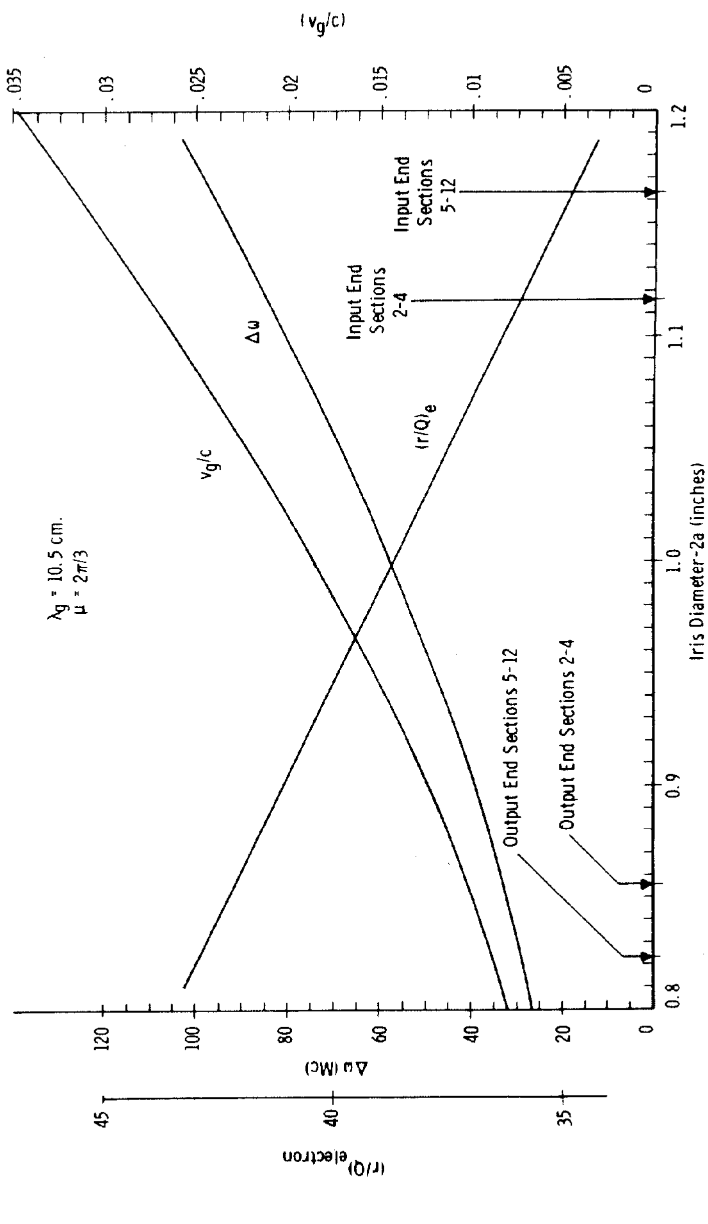


Fig. 6. Accelerator waveguide typical design parameters versus iris aperture dimension (2a).

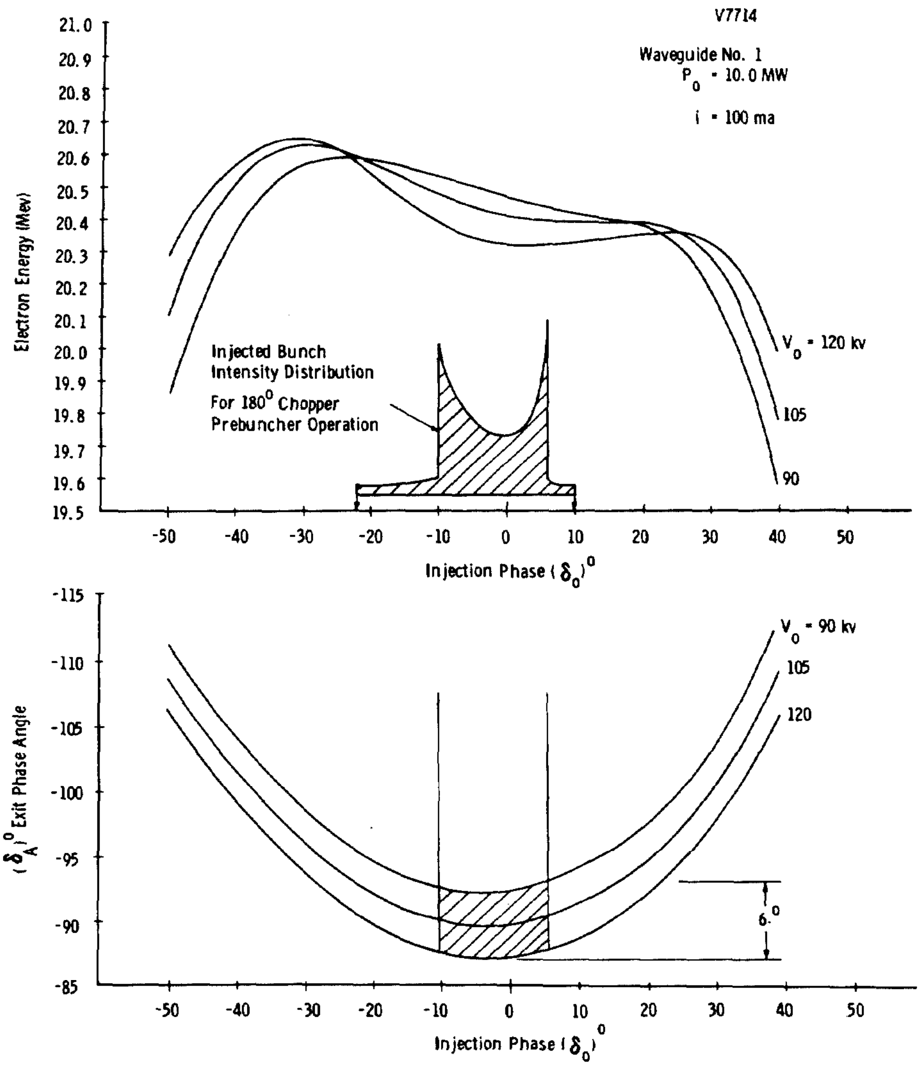


Fig. 7. Accelerator waveguide No. 1, emergent bunch phase and electron energy versus injection energy and phase angle for i = 100 ma.