HV INJECTION PHASE ORBIT CHARACTERISTICS FOR SUB-PICOSECOND BUNCH OPERATION WITH A HIGH GRADIENT 17 GHz LINAC[*]

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The results of phase orbit computations are presented showing typical cutoff and acceptance characteristics for high voltage electrons injected into a 60 MV/m, 17 GHz traveling wave (TW) disc loaded structure. The RF fringing fields at beam entry to the TW structure and the presence of a standing wave domain at the input cavity have a dominating influence on the capture and bunching process and on the asymptotic bunch location of the accelerated beam. The effects of beam loading and of different injection energies and input RF power levels are investigated; and injection operating parameters with RF chopped and prebunched beams to ensure high resolution, sub-picosecond bunch performance with the 17 GHz linac, are presented.

I. INTRODUCTION

For conventional gradient S-band linacs, it has been shown [1] that (a) the presence of RF fringe fields at the beam entry port of a traveling wave (TW) accelerator, side coupled, input cavity, (b) the existence of a standing wave domain in the immediate entry region of such a cavity, and (c) the influence of space harmonics (especially in the first few cavities), all play critical roles in the initial bunching and capturing process and in the subsequent asymptotic phase location of the accelerated bunch. It can be expected that these field interactions will have an even greater influence on beam performance for structures designed to operate at high gradients and short wavelengths. Neglecting to carefully analyze these critical effects can result in an incorrect choice of the electron gun operating potential, poor bunching and a substantial reduction in the energy gain of a synchronously operated accelerator waveguide section.

The multi-orbit, time domain, TW linac simulation code HRC-ELOR, [1,2] especially developed to analyze the above effects was used to study the initial bunching and subsequent acceleration through five different configuration, nonuniform impedance, 17 GHz TW structures (refer Table I). The structures were designed to have a 200 mA loaded beam energy of 25 MeV with an input RF power of 20 MW [3]. The phase orbit studies were conducted in parallel with the structure design work to ensure convergence of parameters so that the impedance required to ensure correct field conditions for electron capture and bunching also satisfied the group velocity and impedance requirements for the desired quasi-constant gradient conditions. By iteration, it was possible to establish a suitable set of parameters for the initial uniform impedance segment of the structure so that near optimum injection conditions and asymptotic bunch location could be achieved without having to adopt tapered, reduced phase velocity circuit techniques [1,4]. The phase orbit investigations were directed mainly at studying two different injection energy regimes, namely, 400 to 600 keV and approximately 2 MeV, so that beam injection using either pulsed HV or RF electron guns could be evaluated.

Table I. Comparison of 17 GHz Structure Designs

Design Type	Gradient Type and Total Number of Cavities	Number of Different Cavities in Structure	Iris Diameter 2a (cm) Input	Iris Diameter 2a (cm) Output	Attenuation Parameter τ (Np)
A	Constant n=90	90	0.5758	0.4130	0.550
B	Quasi-C. n=90	15	0.5842	0.4242	0.540
C	Quasi-C. n=90	15	0.5690	0.4318	0.522
D	Quasi-C. n=90	15	0.5690	0.4318	0.564
D(94) (final)	Quasi-C. n=94	15	0.5690	0.4318	0.590

II. PHASE ORBIT CHARACTERISTICS

Initial phase orbit calculations for the constant gradient (Design A) structure, performed under simplified conditions of zero beam loading, are shown in the Figure 1 plots of injected particle entry phase (ϕ_O) at the input coupler fringe field versus electron energy (V_a) at emergence from the accelerator structure. These initial computations, based on an input coupler peak field of 67 MV/m, and an initial average accelerating field strength ($\hat{E}_O$) of 52 MV/m, provided important early information on acceptance, asymptotic phase location, etc., and presented guidelines for establishing the final design parameters of the 17 GHz quasi-constant gradient accelerator structure shown listed in Table II [Design D(94)].

The classical injection characteristic of decreasing phase acceptance with reduced injection energy is clearly illustrated in Figure 1, with a 260° acceptance at 2 MeV and approximately 190° at 400 to 600 keV. An unexpected and important finding during this 17 GHz high gradient accelerator investigation was the strong rejection of particles at injection energies of 100 to 200 keV, i.e., at the energy levels commonly used by the majority of existing high power research linacs (operating at lower frequencies and gradients). It can be noted that even at an electron gun voltage of 250 kV, there are no injection phase angles that allow the maximum available energy to be achieved under synchronous operating

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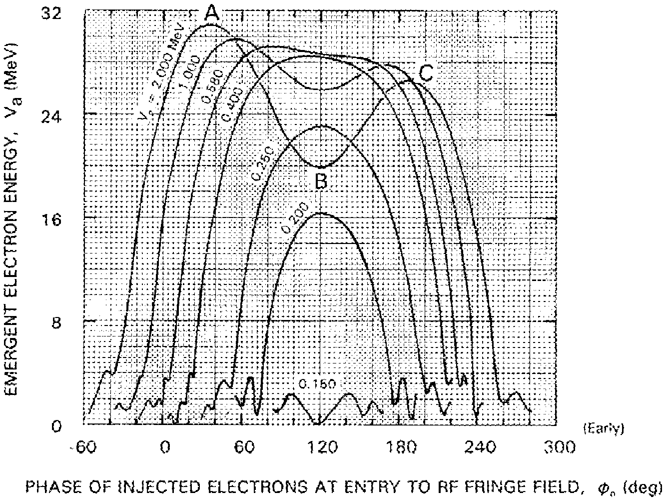

Figure 1: Phase Orbit Plots Showing Cut-off and Acceptance Characteristics of an Unloaded 17.136 GHz, v_p=c, Constant Gradient TW Linac Structure (Design A) for a Range of Injection Energies (V_O).

conditions, because the electrons are asymptotically phased well behind the crest of the wave. [Higher injection energies, especially with narrow RF bunches (≈π/10), assist considerably in achieving beams of low emittance [4] because of the beam formation advantages and because the use of v_p<c capture structures can be totally avoided.]

The 17.136 GHz structure binding field conditions were chosen to provide near optimum acceptance and asymptotic phase location for injection energies in the 400 to 600 keV range, by ensuring that for a specified given spread of entry phase angles, the emergent energy remained essentially constant and close to the maximum available value. For example, at 400 keV, because of the flat-top characteristic shown in Figure 1, it can be seen that a narrow bunch injected in the vicinity of ϕ_O = 120° will produce an emergent beam having a sharp spectrum and a mean energy that is relatively insensitive to small variations of entry phase. Although it is necessary to also evaluate the emergent bunch phase characteristics before deciding on the best mode of linac operation, as discussed below, the Figure 1 V_O=2 MeV curve shows $\partial V_a/\partial\phi_O \rightarrow 0$ at three locations, A, B and C, where narrow bunch injection will result in sharp spectra operation but at different absolute values of emergent beam energy.

The phase orbit characteristics of the Design D(94) structure, taking into account the effects of space charge, changing bunch geometry, reactive phase distortion and power transfer to the beam and circuit are shown plotted in Figure 2 for an injected bunch width of 20° at two different entry phase intervals and for zero and 200 mA beam loading at a 580 keV injection energy. The curves indicate that for an injection phase interval between 105° and 125°, the bunch advances only 1° due to beam loading and emerges with narrow spectra and a longitudinal phase space of <2°, i.e., a bunch width of less than 1/3 of a picosecond. An indication of the versatility of the linac system is given by the results of phase orbit computations using the same injection conditions as in Figure 2 (ϕ_O= 105 to 125°) but with the input RF power lowered from 20 to 10 MW. For these conditions, the emergent phase (δ_a) is delayed 28° (from -88° to -116°), the 200 mA loaded beam energy is reduced from 25.7 to 17.1 MeV, and the bunch width is increased by only 20%, to 1.2°. (Increasing the operating frequency by 1080 kHz will re-advance δ_a, causing V_a to be increased by 3% and the bunch width to be reduced by 4%.)

Table II. 17 GHz Linac Structure Design D(94) Parameters

Operating Frequency in Vacuo at 22°C	17.136 GHz
Total Voltage Attenuation	0.59 Np
Input Group Velocity	0.0474c
Output Group Velocity	0.0196c
Harmonic Mean Group Velocity	0.0316c
Filling Time	57.8 ns
Shunt Impedance Range	100.3 → 124.1 MΩ/m
Output Phase/Frequency Sensitivity	20.8 deg/MHz
Output Phase/Frequency Sensitivity	5.9 deg/°C
Steady-State Beam Loading Derivative	13.3 MeV/A
Accelerating Gradient at Zero Beam Loading —	
Maximum in Cavity No. 76.	$14\sqrt{P_O(MW)}$ MV/m
Maximum Surface Electric Field	$30.5\sqrt{P_O(MW)}$ MV/m

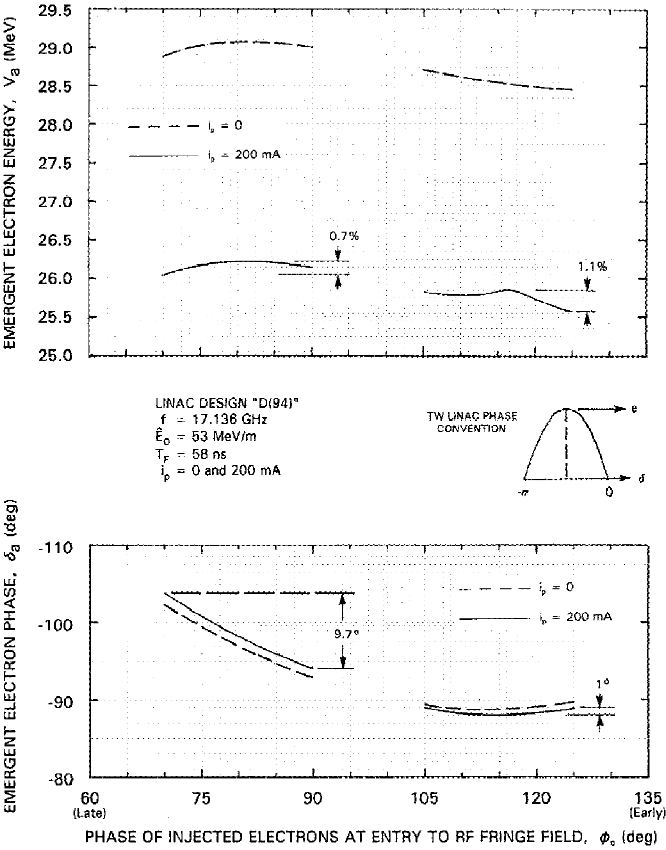

Figure 2: Phase Orbit Characteristics of a 17.136 GHz, v_p=c, Quasi-Constant Gradient TW Linac Structure [Design D(94)] for an Injection Energy of V_O= 580 keV at i_p=0, and at a Steady-State Beam Loading of i_p=200 mA, for an Entry Beam Diameter of 2 mm.

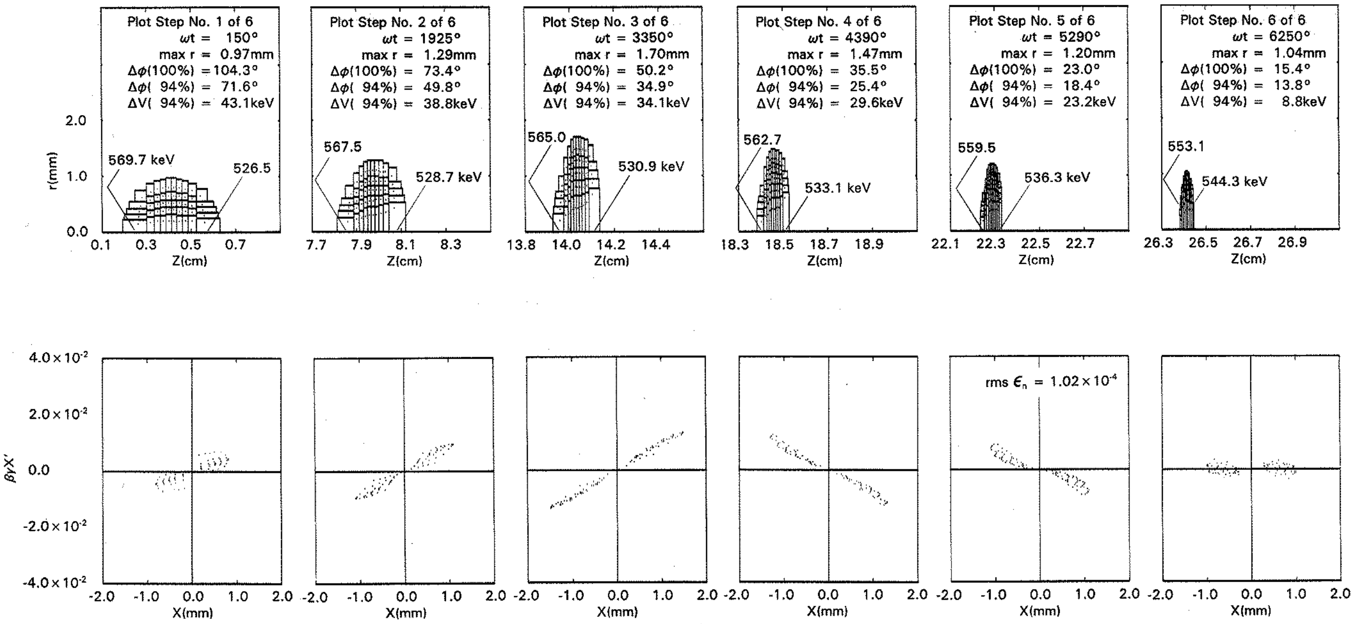

Figure 3: HRC-PRELOR Plots of the 550 kV Chopper-Prebuncher System Showing Progressive Bunch Compression and the Transverse Phase Space during Beam Traversal of the Final Drift Space Prior to Injection into the 17 GHz Accelerator Structure. (Prebuncher Drift = 30 cm, Thin Lens Peak Field = 2400 gauss, i_p = 320 mA, Beam Waist at Injection = 2.1 mm.)

III. 17 GHz CHOPPER-PREBUNCHER

A 550 kV electron gun, chopper-prebuncher, three lens injection system has been designed to satisfy the stringent beam specifications at entry to the linac, [$\beta\gamma\varepsilon \approx 5\pi$ mm-mradians, $\Delta\beta_O < 0.3\%$ (±5 keV) and $\Delta\phi_O < 20°$ (including 5° of phase modulation due to gun voltage variations)]. A biased, RF magnetic field chopping system [2] will be used to produce fully gated bunches at 17.136 GHz so that electrons are injected into the linac only during periods when the RF deflection is passing through a reversal, i.e., when $\partial V_{RF}/\partial\omega t$, $p_\perp$ and $\partial p_\perp/\partial\omega t \rightarrow 0$. A high field prebuncher cavity with a short drift space and final focusing lens has been designed to give 10:1 charge compression, with the initially introduced 50 keV energy spread being reduced to <10 keV by the beam focusing and bunching space charge forces, prior to injection into the linac. Figure 3 shows a simulation of the space charge influenced energy and charge distributions within the compressing bunch as it diverges from the chopper collimator through the final drift space lens and is re-converged to a waist at entry to the accelerator waveguide. These i_p= 320 mA beam bunching computations, based on an initial multi-annular model having a prolate spheroidal geometry with nonuniform longitudinal and radial charge distributions, indicate that >90% of the charge will be injected into the linac with an energy spread of 8.8 keV and a longitudinal phase space of less than 15° (in the absence of phase modulation due to gun voltage variations). The linac phase orbit characteristics, based on the Figure 3 injected electron energy and charge distributions, are shown in Table III and confirm the high probability of demonstrating a 20 MeV beam with 160 femtosecond bunches and a bunch current of 100 A.

Table III. Phase Orbit Performance of the Design D(94) 17 GHz Linac Structure Based on the Figure 3 Injected Bunch Characteristics (i_p = 320 mA, P_O = 20 MW).

Input Orbits		Exit Orbits		
V_O (MeV)	ϕ_O (deg)	V_a (MeV)	δ_a (deg)	$\Delta\delta_a$ (deg)
0.544	121.00	24.270	-91.01	0.93
0.545	118.28	24.219	-91.08	
0.546	115.57	24.172	-91.22	
0.548	113.39	24.137	-91.29	
0.550	109.86	24.106	-91.74	
0.553	107.19	24.092	-91.94	

IV. REFERENCES

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