Harmonic Content in the Beam Current in a Traveling-Wave Tube

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***Abstract*— In a klystron, charge overtaking of electrons leads to an infinity of ac current on the electron beam. This paper extends the klystron theory of orbital bunching to a traveling-wave tube (TWT). We calculate the harmonic content of the beam current in a TWT that results from an input signal of a single frequency. We assume that the electron orbits are governed by Pierce's classical three-wave, linear theory. The crowding of these linear orbits may lead to charge overtaking and, therefore, harmonic generation on the beam current, as in a klystron. We analytically calculate the buildup of harmonic content as a function of tube length from the input, and compare the results with the CHRISTINE code. Good agreement is found. Also found is the surprisingly high level of harmonic contents in the electron beam current, even when the TWT operates in the small signal regime. A dimensionless bunching parameter for a TWT, $X = (2P_{\text{in}}/(P_bC))^{1/2}$, is identified, which characterizes the harmonic content in the ac beam current, where P_{in} is the input power of the signal, P_b is the dc beam power, and C is Pierce's gain parameter.**

***Index Terms*— Current modulation, frequency multiplier, harmonic generation, traveling-wave tube (TWT).**

I. Introduction

IN A traveling-wave tube (TWT), it is recognized that the linear theory of Pierce provides an adequate description of the electron-circuit interaction over approximately 85 % of the tube length, even when the TWT is driven to saturation [1]. Because Pierce's theory is in the linear (small signal) regime, we are not aware of any analytic formulation that calculates the harmonic content in the ac current that would buildup over this 85% of tube length. This paper provides such a formulation.

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The generation of harmonics in the small signal regime seems contradictory at first sight. Our experience with klystron theory [2], however, demonstrates that harmonic generation does indeed occur in the small signal regime [3], [4], and that the amplitudes and phases of the harmonic currents can be calculated accurately [4], [5]. Consider a klystron operating in the low current, small signal, and ballistic regime driven by an input signal of frequency, ω_0. An electron, A, leaves the input gap with velocity v_A at time t_A. Another electron, B, leaves the input gap with velocity v_B at a later time t_B. If $v_B > v_A$, electron B will catch up with electron A at some downstream location and at some later time. At that particular position, and at that instant of time, the ac current is infinite, because charge overtaking occurs [2]. This means that the ac current necessarily contains an infinite number of harmonic frequencies in its Fourier representation, despite the fact that electrons A and B are initially subjected to a small signal velocity modulation (and zero electric field within the drift tube if one ignores the space charge effect as in the ballistic regime) [2]. This charge overtaking, and the resultant harmonic content at $\omega = n\omega_0$, $n = 1, 2, 3, \ldots$, can be calculated exactly and analytically. The key to this success is that, once the (1-D) electron orbit is known, the nonlinear current that results from the crowding of the electron orbits can be calculated exactly using charge conservation [5]. In effect, we solve the linearized force law to obtain the electron motion, but solve the nonlinear continuity equation exactly for the density and current that results from the crowding of these orbits. If we include ac space charge effects within the drift tube, electrons A and B will be acted upon by the small signal ac electric field associated with the fast and slow space charge wave. Again, we solve the linearized force law to obtain the electron motion, but solve the nonlinear continuity equation exactly for the density and current that results. This procedure was verified to be valid [3] by comparing the analytic theory with particle simulation at the fundamental frequency, from the highly nonlinear, ballistic regime to the linear, space-charge dominated regime in a klystron. The fact that all harmonic contents are correctly accounted for in such a formulation, even when charge overtaking occurs, is demonstrated explicitly with examples [5].

Returning to the buildup of harmonic ac current in a TWT, we adopt the analogous treatment as in the klystron. We assume that the electron orbit can be described by Pierce's classical three-wave theory of TWT [1]. These three waves are the forward propagating circuit wave and the fast and slow space charge wave. They are waves in the small signal regime, therefore, containing only the fundamental frequency, ω_0, of the input signal. These three waves in the TWT are entirely analogous to the two waves (fast and slow space charge waves) in the klystron drift tube. Despite the spatial amplification of one of the three waves in the TWT, we assume that a linear description of these three waves suffices. From the linearized electron orbits constructed from these three waves, we solve the nonlinear continuity equation (charge conservation law) exactly. This gives the harmonic content in the beam current that can build up kinematically, which we find to be quite significant even in the small signal regime.

For the TWT model, we consider a nonrelativistic, monoenergetic electron beam. It is subjected to an ac electric field, $E_{10}e^{j\omega_0 t}$, at the input. At $\omega = \omega_0$, we assume that Pierce's dimensionless parameters [1], C, b, QC, and d, are known constants. The launching loss is accounted for in the evolution of the three waves [1], [2]. We express the electron orbits as a linear combination of these three linear waves. We then calculate the current modulation that results from the crowding in such orbits, using the Lagrangian description. If charge overtaking occurs among these orbits, our formulation automatically and completely accounts for it [5]. The results from our analytic formulation are compared with those obtained from the 1-D large signal TWT simulation code, CHRISTINE [6], for a high perveance, C-band TWT example. Excellent agreement is found for two values of input power.

II. Formulation

Consider a monoenergetic, nonrelativistic electron beam of drift velocity v_0, carrying a dc beam current I_0 and confined by an infinite axial magnetic field. The beam interacts with a TWT slow-wave structure. To calculate the current modulation including the harmonic content that results from an input signal, we follow the conventional klystron theory and consider an electron that arrives at the input (located at $z = 0$) at time $t = t_0$. The unperturbed trajectory of this electron, in the absence of an input signal, is given by

$$z = z_0(t, t_0) = v_0(t - t_0). \tag{1}$$

In the presence of a finite input signal at frequency ω_0, we write $z = z_0(t, t_0) + z_1(t, t_0)$, where the perturbation displacement z_1 may be written as

$$z_1(t, t_0) = \mathrm{Re}[Z_1(t, t_0)] \tag{2}$$

whose complex amplitude Z_1 evolves according to Pierce's three-wave small signal theory [7]

$$\frac{d^3 Z_1}{dt^3} + j\omega_0 C(b - jd)\frac{d^2 Z_1}{dt^2} + 4\mathrm{QC}^3\omega_0^2\frac{dZ_1}{dt} + j\omega_0^3 C^3[4\mathrm{QC}(b - jd) + (1 + Cb)^2]Z_1 = 0. \tag{3}$$

In (3), C, b, Q, and d are, respectively, Pierce's dimensionless parameters [1] that characterize the TWT gain, detuning, space charge effect, and cold-tube circuit loss, respectively. The initial conditions to (3) are

$$Z_1(t = t_0) = 0 \tag{4a}$$
$$\dot{Z}_1(t = t_0) = 0 \tag{4b}$$
$$\ddot{Z}_1(t = t_0) = -\frac{e}{m}E_{10}e^{j\omega_0 t_0}. \tag{4c}$$

Equations (4a) and (4b) state that there is no initial displacement or initial velocity perturbation of this electron when it departs the input at $z = 0$ at time $t = t_0$. Equation (4c) states that the electron is acted upon by the ac input electric field of amplitude E_{10} and frequency ω_0, and e is the magnitude of the electron charge. Equations (1)–(4) are written in the Lagrangian variables (t, t_0). In the following, we transform the solution to the Eulerian variables (z, t) to recover Pierce's classical three-wave solution that includes the launching loss.

The solution to the third-order ordinary differential equation (3) subject to the initial condition (4) is

$$Z_1(t, t_0) = -\frac{eE_{10}}{m\omega_0^2 C^2}e^{j\omega_0 t_0} \times [\alpha_1 e^{C\omega_0\delta_1(t - t_0)} + \alpha_2 e^{C\omega_0\delta_2(t - t_0)} + \alpha_3 e^{C\omega_0\delta_3(t - t_0)}] \tag{5}$$

where δ_1, δ_2, and δ_3 are the three complex roots to the cubic characteristic equation

$$\delta^3 + j(b - jd)\delta^2 + 4\mathrm{QC}\delta + j[4\mathrm{QC}(b - jd) + (1 + Cb)^2] = 0 \tag{6a}$$

or

$$(\delta^2 + 4\mathrm{QC})(\delta + jb + d) = -j(1 + Cb)^2 \tag{6b}$$

and the mode amplitudes α_1, α_2, and α_3 are obtained from the solution to

$$\alpha_1 + \alpha_2 + \alpha_3 = 0 \tag{7a}$$
$$\alpha_1\delta_1 + \alpha_2\delta_2 + \alpha_3\delta_3 = 0 \tag{7b}$$
$$\alpha_1\delta_1^2 + \alpha_2\delta_2^2 + \alpha_3\delta_3^2 = 1. \tag{7c}$$

Note that (6b) is simply Pierce's TWT dispersion relation [1]. One may verify that $v_1(z, t)$, the linearized electron velocity perturbation in the Eulerian description in Pierce's three-wave theory, is given by $\partial Z_1(t, t_0)/\partial t$, evaluated at $t_0 = t - z/v_0$. Note further that, from (7), α_1, α_2, and α_3 depend only on δ_1, δ_2, and δ_3, which depend only on the dimensionless Pierce parameters C, b, Q, and d according to (6). The solution (5) accounts for the launching loss for the amplifying wave [1], [2], since the input wave is shared by the three (3) waves, as in Pierce's theory [see (7)].

The electron arrives at the downstream position $z = L$ at time t, given by $L = v_0(t - t_0) + z_1(t, t_0)$, which yields the following implicit relationship between the departure time (t_0) and the arrival time (t):

$$\omega_0(t - t_0) = \frac{\omega_0 L}{v_0} - \frac{\omega_0 z_1(t, t_0)}{v_0} \equiv \frac{\omega_0 L}{v_0} + X\mathrm{Re}[e^{j\omega_0 t_0}R(t - t_0)] \tag{8}$$

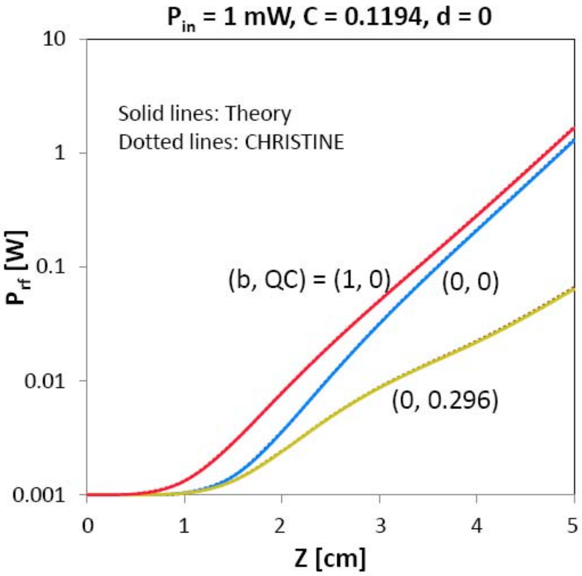


Fig. 1. Evolution of RF power on the circuit wave for 1-mW drive with $C = 0.1194$ and $d = 0$. The three curves assume, from top to bottom, $(b, \mathrm{QC}) = (1, 0)$, $(0, 0)$, and $(0, 0.296)$. Excellent agreement between the analytic theory and CHRISTINE results is found.

where

$$X = \frac{eE_{10}}{m\omega_0 v_0 C^2} \tag{9}$$

$$R(t - t_0) = \alpha_1 e^{C\omega_0\delta_1(t-t_0)} + \alpha_2 e^{C\omega_0\delta_2(t-t_0)} + \alpha_3 e^{C\omega_0\delta_3(t-t_0)}. \tag{10}$$

In deriving (8), we have used (2) and (5). Note that X is the dimensionless bunching parameter which measures the strength of the input electric field. It may be expressed in terms of the input power, P_{in}, and the dc beam power, $P_b = I_0 V_b = I_0(mv_0^2/2e)$, upon using Pierce's coupling impedance K, and its relation to C^3

$$K = \frac{E_{10}^2}{2P_{\mathrm{in}}k^2} = \frac{E_{10}^2}{2P_{\mathrm{in}}(\omega_0/v_0)^2} \tag{11}$$

$$C^3 = \frac{KI_0}{4V_b}. \tag{12}$$

Equation (9) then yields the bunching parameter X in various forms

$$X = \frac{eE_{10}}{m\omega_0 v_0 C^2} = \frac{1}{C^2}\left(\frac{v_w}{v_0}\right) = \sqrt{\frac{2}{C}\left(\frac{P_{\mathrm{in}}}{P_b}\right)} \tag{13}$$

where $v_w = eE_{10}/m\omega_0$ is the characteristic electron wiggling velocity associated with the ac electric field at the input. The last form of (13) is particularly convenient.

The arrival time t may be explicitly solved in terms of the departure time t_0 to any desired order of accuracy [4], in a power series in X. To the zeroth (lowest) order, we have, from (8)

$$\omega_0(t^{(0)} - t_0) = \frac{\omega_0 L}{v_0}. \tag{14}$$

To the kth order, we have [4]

$$\omega_0(t^{(k)} - t_0) = \frac{\omega_0 L}{v_0} + X\mathrm{Re}[e^{j\omega_0 t_0} R(t^{(k-1)} - t_0)] \quad k = 1, 2, 3, \ldots \tag{15}$$

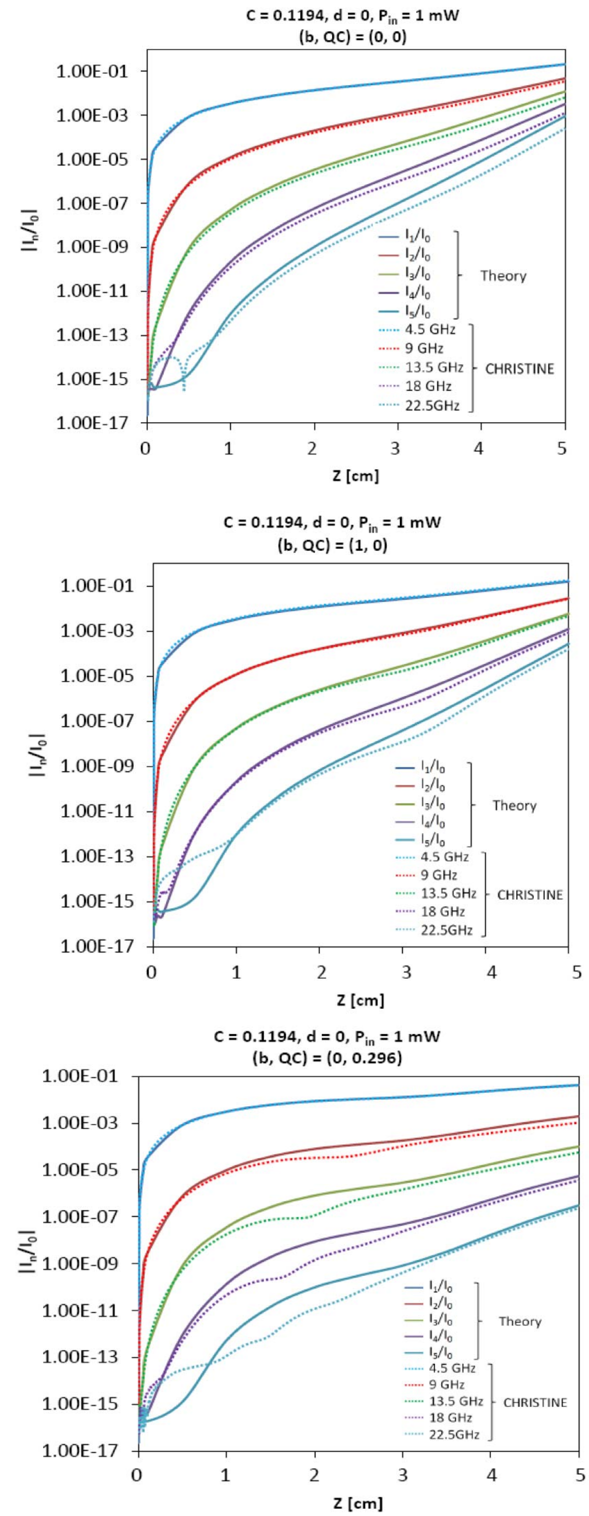


Fig. 2. Harmonic content as a function of z, in log scale, for 1-mW drive. From top to bottom: $(b, \mathrm{QC}) = (0, 0)$, $(1, 0)$, and $(0, 0.296)$.

We found that taking $k = 4$ suffices in all of our numerical computation. Henceforth, we assume that the arrival time, t, is an explicit function of the departure time, t_0. Note from (15) that $(t - t_0)$ is a periodic function of t_0 with period $2\pi/\omega_0$, irrespective of the order k.

Having obtained the arrival time t (at $z = L$) of an electron, whose departure time (at $z = 0$) is t_0, we may

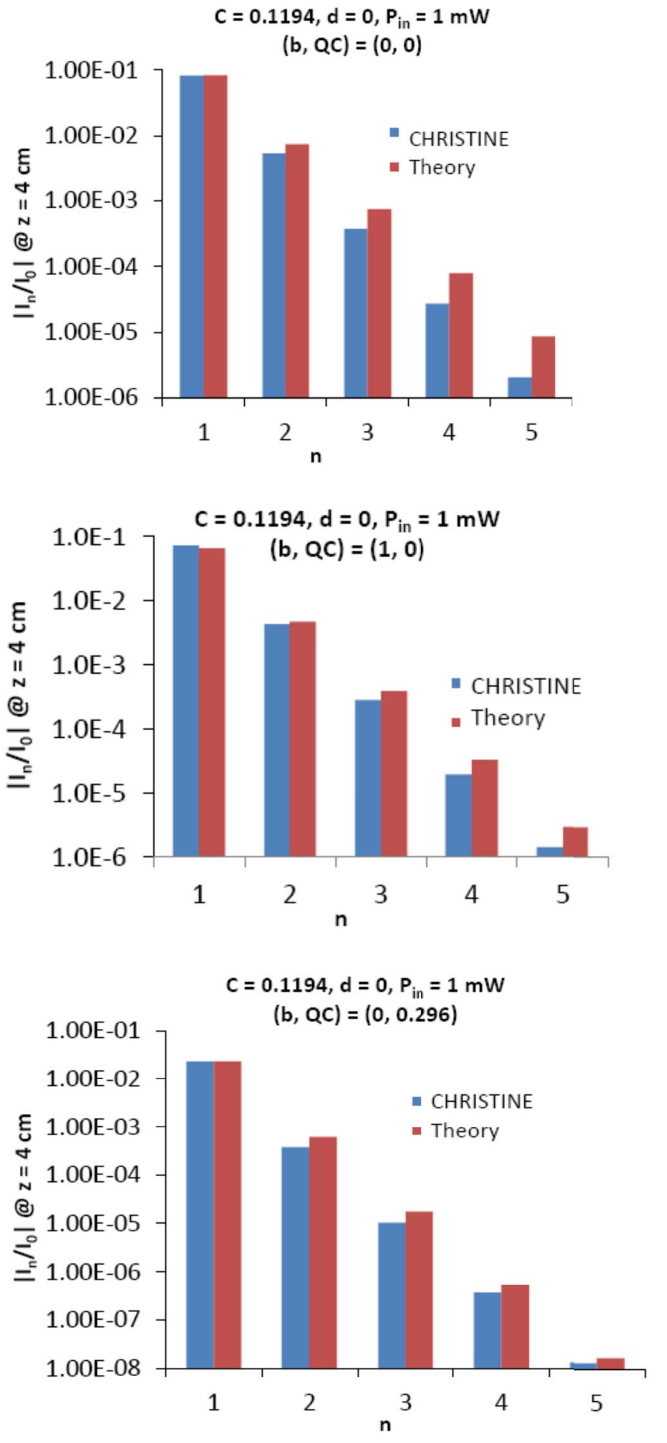


Fig. 3. Harmonic content at $z = 4$ cm for 1-mW drive. From top to bottom: $(b, \mathrm{QC}) = (0, 0)$, $(1, 0)$, and $(0, 0.296)$.

calculate total current at $z = L$, denoted as $I_L(t)$, by charge conservation [2], [5]

$$I_L(t)dt = I_0 dt_0. \tag{16}$$

Since $I_L(t)$ is a periodic function of t of period $2\pi/\omega_0$, we may also represent it in terms of a Fourier series

$$I_L(t) = \sum_{n=-\infty}^{\infty} \tilde{I}_n e^{jn\omega_0 t}. \tag{17}$$

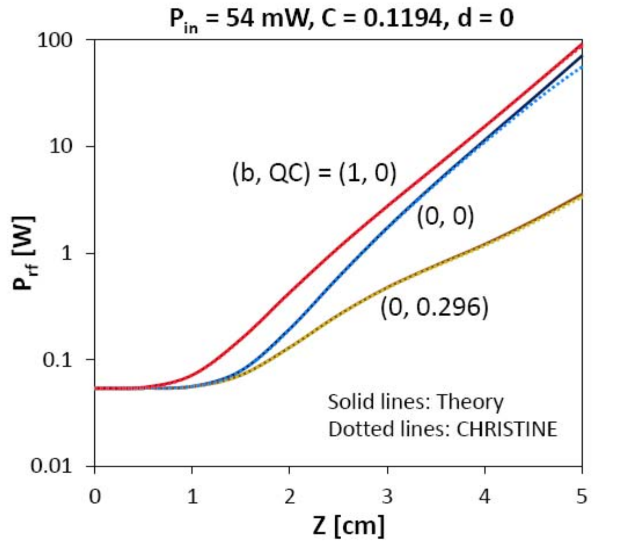


Fig. 4. Evolution of RF power on the circuit wave for 54-mW drive with $C = 0.1194$ and $d = 0$. The three curves assume, from top to bottom, $(b, \mathrm{QC}) = (1, 0)$, $(0, 0)$, and $(0, 0.296)$. Excellent agreement between the analytic theory and the CHRISTINE results is found.

The ac current at the nth harmonic is then given by, upon using (16) and (17)

$$\begin{aligned}\tilde{I}_n &= \frac{\omega_0}{2\pi}\int_0^{2\pi/\omega_0} dt\, I_L(t) e^{-jn\omega_0 t} \\ &= \frac{I_0}{2\pi}\int_0^{2\pi} d(\omega_0 t_0) e^{-jn\omega_0 t_0 - jn\omega_0(t-t_0)}\end{aligned} \tag{18}$$

in which $\omega_0(t - t_0)$ in the last expression may be calculated from (15) to any desired order k ($k = 4$ in our numerical calculations) [4], [5]. It is easy to show from (18) that $\tilde{I}_{-n} = \tilde{I}_n^*$ for all integer n, where the asterisk denotes the complex conjugate. Equation (17) then gives the total current at $z = L$ at time t

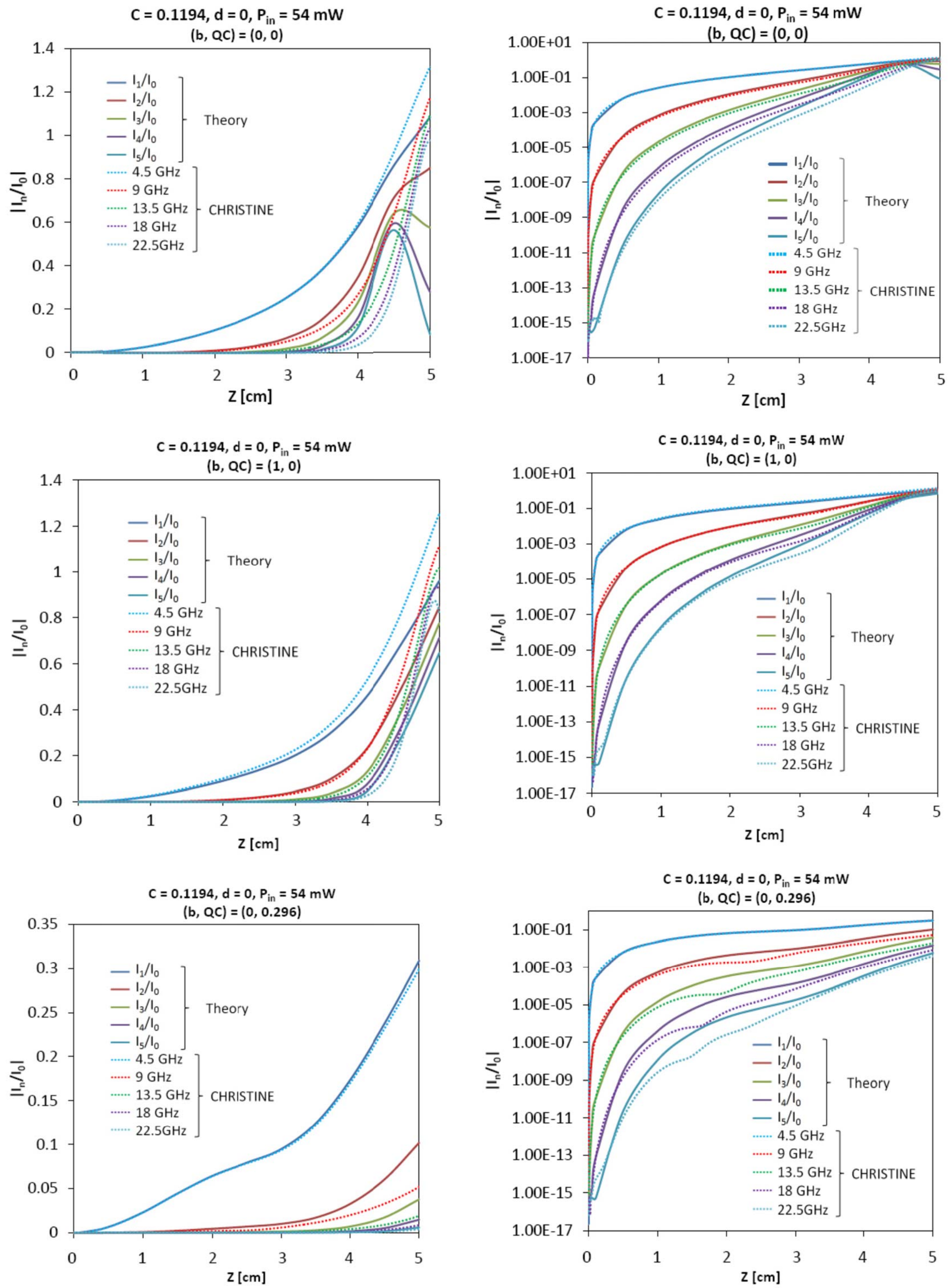
$$I_L(t) \equiv I(L, t) = I_0 + \mathrm{Re}\sum_{n=1}^{\infty} I_n e^{jn\omega_0 t} \tag{19}$$

where $I_n = 2\tilde{I}_n$ is the complex amplitude of the ac current at the nth harmonic, and $\tilde{I}_n$ is given by (18).

Finally, the evolution of the small signal electric field, $E_1(z, t)$, on the circuit may be deduced from the linearized force law, written in accordance with Pierce's theory of TWT [7]

$$\frac{d^2 Z_1}{dt^2} + \omega_0^2 4\mathrm{QC}^3 Z_1 = -\frac{e}{m}E_1(z, t) \tag{20}$$

where the right-hand side (RHS) represents the force on the electron by the operating circuit mode, and the middle term (proportional to Q) represents the force due to all residual modes. This term, proportional to Q, is said to represent the ac space charge effect in the TWT literature [1], [2]. Since $E_1(0, t) = E_{10}e^{j\omega_0 t}$, we obtain from (20), upon



(a) (b)

Fig. 5. (a) Harmonic content as a function of z, in linear scale, for 54-mW drive. From top to bottom: $(b, \mathrm{QC}) = (0, 0)$, $(1, 0)$, and $(0, 0.296)$. (b) Harmonic content as a function of z, in logarithmic scale, for 54-mW drive. From top to bottom: $(b, \mathrm{QC}) = (0, 0)$, $(1, 0)$, and $(0, 0.296)$.

using (5) and (14)

$$\left|\frac{E_1(z,t)}{E_1(0,t)}\right|^2 = \left|\sum_{i=1}^{3}\alpha_i\delta_i^2 e^{C\delta_i(\omega_0 z/v_0)} + 4\mathrm{QC}\sum_{i=1}^{3}\alpha_i e^{C\delta_i(\omega_0 z/v_0)}\right|^2 \tag{21}$$

which expresses the RF power gain of the circuit wave as it propagates along the tube, according to the small signal theory.

III. Example

Consider a C-band TWT operating at $\omega_0 = 2\pi \times 4.5$ GHz, $V_b = 2.776$ kV, $I_0 = 0.17$ A, $C = 0.1194$, $K = 111.2$ ohm,

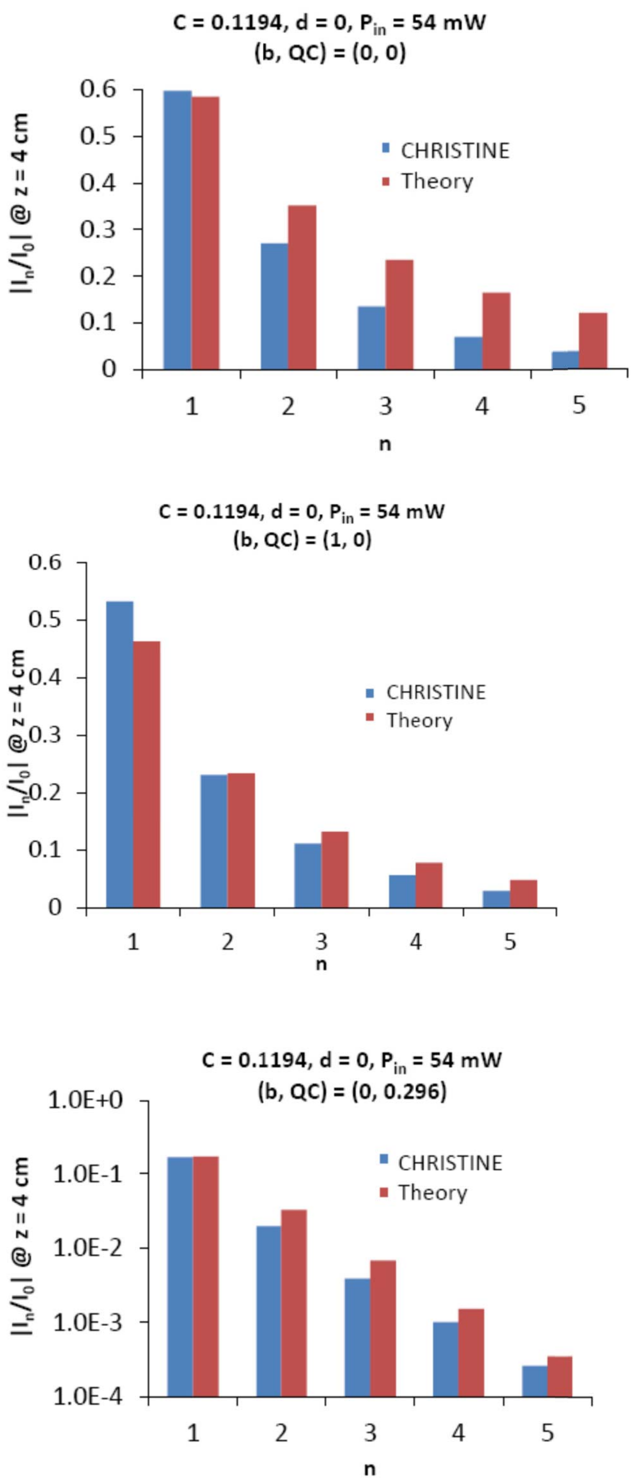


Fig. 6. Harmonic content at $z = 4$ cm for 54-mW drive. From top to bottom: $(b, \text{QC}) = (0, 0)$, $(1, 0)$, and $(0, 0.296)$.

$v_0 = 5.93 \times 10^7$ m/s, $P_b = V_b\ I_0 = 417.9$ W, and $I_0/V_b^{3/2} = 1.16$ microperveance. Note that this value of $C = 0.1194$ is very high. We consider the evolution of the current modulation and of the RF electric field up to $z = L = 5$ cm. We assume that there is no cold-tube loss, so that $d = 0$. The remaining parameters are b, QC, and the input power P_{in}. We shall consider two values of input power: 1) $P_{\text{in}} = 1$ mW and 2) $P_{\text{in}} = 54$ mW, corresponding to $X = 0.006331$ and 0.04652, respectively. The tube is operating entirely ($0 < z < L$) in the small signal regime for $P_{\text{in}} = 1$ mW. $P_{\text{in}} = 54$ mW is the value of input power that produces a 1 dB compression (reduction) of the gain in the case QC $= 0$, and so the TWT may be considered to be operating in the slightly nonlinear regime at $z = L$ in this case.

A. $P_{in} = 1$ mW

In this case, (13) gives $X = 0.006331$. The tube operates in the strictly linear regime for $z < 5$ cm. The evolution of the RF power for $(b, \text{QC}) = (0, 0)$, $(1, 0)$, and $(0, 0.296)$ according to (21) is shown in Fig. 1 (solid lines). For comparison, the CHRISTINE [6] results are shown by the dotted lines. Excellent agreement between the analytic theory and the CHRISTINE is found for all z up to 5 cm. The evolution of the harmonic contents for these three cases of (b, QC) is shown in Fig. 2. Fig. 3 shows negligible harmonic content, $|I_n/I_0|$ at $z = 4$ cm, for this very low drive case, as expected. The detailed agreement shown in Figs. 2 and 3, even for very low levels of harmonic ac current, may be considered as validation of both the analytic theory and the CHRISTINE code.

B. $P_{in} = 54$ mW

In this case, $X = 0.04652$. The evolution of the RF power for $(b, \text{QC}) = (0, 0)$, $(1, 0)$, and $(0, 0.296)$ according to (21) is shown in Fig. 4 (solid lines). For comparison, the CHRISTINE simulation results are shown by the dotted lines. Excellent agreement between (21) and CHRISTINE is noted. Since CHRISTINE is a nonlinear code, Fig. 4 suggested that the linear theory applies up to $z = 4.5$ cm. The evolution of the harmonic contents for these three cases of (b, QC) is shown in Fig. 5(a) in linear scale, and in Fig. 5(b) in logarithmic scale. It is seen that the harmonic content in the ac current is quite significant even when the TWT operates in the linear regime. These harmonic ac currents are only due to kinematic bunching (i.e., orbital crowding) in the electron orbits, and is predicted reasonably well by the analytic theory for z up to 4 cm. The harmonic content relative to the dc current, $|I_n/I_0|$ at $z = 4$ cm, is shown in Fig. 6. Fig. 6 clearly demonstrates that even when the linear theory applies, the harmonic content is quite sizable, and that it can be fairly predicted by our analytic theory.

IV. Concluding Remarks

By considering the crowding of the linearized electron orbits, we compute the harmonic content in the ac current that accompanies these orbits, as a result of charge conservation. Therefore, only the kinematic bunching is considered. Surprisingly high levels of harmonic ac current on the electron beam were found, even when the tube operates in the small signal regime. The theory is applicable even if charge overtaking has occurred. The approach is entirely analogous to that established for electron bunching in the klystron theory. Our results reduce to Pierce's classical three-wave theory, including the effects of the launching loss, for the fundamental frequency component. The harmonic content evaluated from our analytic theory is in good agreement with the CHRISTINE simulation results.

In our theory, we only calculated the generation of harmonic ac currents on the electron beam. All harmonic components in the ac current are due only to the input wave of a single frequency, ω_0. These harmonic ac currents do not have any intrinsic gain mechanism. This is not necessarily true in a wideband TWT, where the second harmonic, $\omega = 2\omega_0$, may also be within the amplification band. Should this be the case, the harmonic ac current calculated here may then be considered as a seed to the second harmonic generation (without any $2\omega_0$ input). Note that the amplitude and phase of this $2\omega_0$ output are completely controlled by the input signal, which is at the fundamental frequency ω_0. This second harmonic may also be suppressed by injecting a $2\omega_0$ signal with an appropriate amplitude and phase [8]. The new insight, together with higher harmonic generation, will be explored in future study.

Our formulation has been restricted to a nonrelativistic electron beam. For a relativistic or even mildly relativistic beam, care must be exercised in the formulation of the linearized force law, in the construction of Pierce's parameters, C and QC, and in the relation between the coupling impedance K and C^3.

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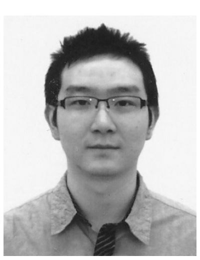

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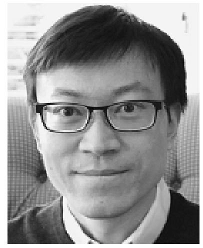

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