Azimuthal-Current-Prebunching Effects on Electron-Wave Interactions

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(Received August 31, 1970)

Abstract

In the case where $b = 0$, $d = 0$, $Q = 0$, $\beta_e \approx 20$ and $C \approx 0.05$ and the azimuthal current variation was applied at the input, the expressions for the small-signal forward-wave output and the equivalent resistance were given. The power output is due to growing-and decreasing-waves and the effect of characteristic ripple is negligible.

Contents

1. Introduction

Recently, analyses of the centrifugal electrostatic focusing or CEF-type devices, in which the centrifugal force of electrons in the interaction region is balanced by an equal and opposite radial electric field, have been presented by Nunn and Rowe[1),2)]. More recently, Sakuraba and Rowe[3),4),5)] have shown that certain types of photodemodulators may make an effective use of a CEF-type electron beam. Furthermore, Sakuraba has proposed a microwave electron prism, where microwave frequency modulation of an optical signal can be converted into spatial modulation by passing the light through a prism and radial current waves can be amplified and coupled out of the elecron prism by interactions common in the CEF-type devices[6),7)]. A review of the literature reveals that the prebunching effects in CEF-type systems have received relatively little analytical attention[8),9)].

This paper deals with the azimuthal-current-prebunching effect on electron-wave interactions in CEF-type forward-wave devices. The derivation will be based on Sakuraba and Rowe's analysis for forward- and backward-wave CEF-type devices, which treats the electron-wave interaction problem from a viewpoint of the equivalent circuit analysis. The equivalent resistance of demodulating output will be expressed in terms of the growing wave, the decreasing wave and the characteristic rippling.

2. The Demodulating Output Power and the Equivalent Resistance

The equations of motion for an electron revolving about the center of CEF-type forward-wave device from the Lagrange function for a single particle

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$$\ddot{r}-r\dot{\theta}^2 = -\eta[E_r+E_r(r)], \quad (1)$$
$$2\dot{r}\dot{\theta}+r\ddot{\theta} = -\eta E_\theta, \quad (2)$$

where

E_r = radial r-f electric field intensity,
$E(r)$ = static radial electric field intensity which balances the centrifugal force of the electron at radius r,
E_θ = azimuthal r-f electric field intensity,
η = magnitude of the electron's charge-to-mass ratio.

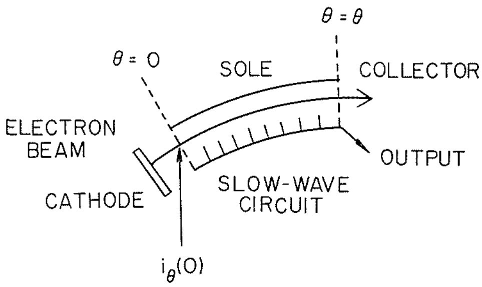

Fig. 1. Model for analysis of CEF-type forward-wave devices.

The dots appearing above the quantities in the foregoing equations signify the total time derivation of those terms. The azimuthal velocity and radial dependence can be expressed in terms of their unperturbed values by means of the relations

$$r = r_0+r_1, \quad (3)$$
$$\dot{\theta} = \Omega_0+\Omega_1, \quad (4)$$

where

r_0 = radius of the center-of-the beam radius,
r_1 = radial perturbation function,
Ω_0 = unperturbed spatial angular velocity of an electron at radius r,
Ω_1 = azimuthal velocity perturbation function.

It is important to observe that r_1 and Ω_1 depend on the spatial angle and on the time, both of those functions must be independent of radial variations. This condition follows in the wake of Eulerian fluid hypothesis and prohibits the crossing electron trajectories. The requirement of zero rate of change of Ω_1 with respect to r results from the Brillouin flow assumption which asserts that the spatial angular velocity of all particles in the electron stream must remain invariant. The quantity $E(r)$ results from the condition in which the radial electric force at r just balances the centrifugal force of the electron at the same radius, so that the particle possess a stable motion in the interaction space. This condition may be described mathematically as

$$-\eta E(r) = \frac{-\eta(V_C-V_S)}{r\ln(r_S/r_C)} = -\frac{(r_0\Omega_0)^2}{r_0+r_1}, \quad (5)$$

where

V_C = potential of the circuit measured relative to the cathode,
V_S = potential of the sole electrode measured relative to the cathode,
r_C = radius of the circuit,
r_S = radius of the sole.

The azimuthal current equation has the form

$$I_\theta = (\tau_0+\tau_1)(r_0+r_1)(\Omega_0+\Omega_1) = -I_0+i_\theta \quad (6)$$

where

$$-I_0 = \Omega_0 r_0\tau_0, \quad (7)$$
$$i_\theta = \Omega_0\tau_0 r_1+r_0\tau_0\Omega_1+\Omega_0 r_0\tau_1+\tau_0 r_1\Omega_1+\Omega_0 r_1\tau_1+r_0\Omega_1\tau_1+r_1\Omega_1\tau_1, \quad (8)$$

where

τ_0 = d-c component of ring charge density due to the steady motion of the beam,

τ_1 = a-c component of ring charge density due to the space-charge bunching. The ring charge density of the beam may be expressed as

$$\tau = \rho h \sigma \tag{9}$$

where

ρ = volume charge density of the beam,
h = height of the beam parallel to the z-axis,
σ = radial width of the beam.

The radial current equation is given by

$$i_r = (\tau_0+\tau_1)\frac{d}{dt}(r_0+r_1) = jr_1(\omega\tau_0-\beta\Omega_0\tau_0-\beta\tau_0\Omega_1+\omega\tau_1-\beta\Omega_0\tau_1-\beta\Omega_1\tau_1), \tag{10}$$

The continuity equation has the well-known form

$$\nabla\cdot(\bar{l}_r i_r+\bar{l}_\theta I_\theta) = -\frac{\partial}{\partial t}(\tau_0+\tau_1), \tag{11}$$

where

$\bar{l}_r$ = unit radial vector,
$\bar{l}_\theta$ = unit azimuthal vector.

While the above expressions satisfy the Brillouin flow and the Eulerian fluid hypothesis described earlier, they must be simlified further in order to keep the mathematical development within reasonable bounds of complexity. This is accomplished through the use of the small-signal assumption which imposes the condition that all r-f quantities are small in proportion to the d-c or steady quantities, and that squares and products of perturbation functions may be neglected in comparison to the first power of these terms. Within the scope of these limitations the ring charge density may be explicitly written in the terms of the r-f fields

$$\tau_1 = \frac{\eta\tau_0}{\Omega_0^2 r_0(\beta_e-\beta)}\left[\frac{-\beta_e E_r+jE_\theta((\beta_e-\beta)\beta+2)}{(\beta_e-\beta)^2-2}\right], \tag{12}$$

where $\beta_e = \omega/\Omega_0$, which may be considered as the circular propagation constant of a disturbance traveling with the same azimuthal velocity as the electron stream.

The general equation for a lossless anisotropic transmission line in the case of a sheet beam passing parallel to the face of a biperiodic structure has been treated by Rowe[10]. The approximation for E_r/E_θ, evaluated at the radius of the center-of-the-beam electron, is replaced by $-j\,1.0$, according to the Nunn and Rowe discussion[1),2)]. Therefore the general circuit equation applicable to forward-wave devices may be written

$$E_\theta = +\frac{j\beta\beta_0\omega K}{\beta_0^2-\beta^2}\tau_1, \tag{13}$$

where the magnitude of the effective interaction impedance K at the center-of-the-beam radius r_0 was definea as

$$K = \left|\frac{k_G^2 r_G Z_{0,0}}{r_0}\right|, \tag{14}$$

where

k_G = coupling factor between the ribbon beam and the biperiodic circuit,
$Z_{0,0}$ = azimuthal component of the circuit impedance at the surface of the slow-wave structure,
β_0 = cold-circuit circular propagation constant.

The quantities τ_1, E_θ and E_r can be eliminated from Eqs. (12) and (13) so as to obtain the secular equation

$$\frac{C^3\beta^2\beta_0\beta_e}{(\beta_0^2-\beta^2)(\beta_e-\beta)}\left[\frac{\beta(\beta_e-\beta)+\beta_e+2}{\beta(\beta_e-\beta)^2-2\beta}\right] = 1, \tag{15}$$

where the quantity C is the gain parameter whose mathematical definition is

$$C^3 \equiv \frac{-\eta\tau_0 K}{\Omega_0 r_0} = \frac{KI_0}{2V_0}. \tag{16}$$

It is appropriate at this point to introduce the incremental propagation constant following the usual method. Thus, the expression for the circular propagation constans in the presence and in the absence of the electron beam are defined as

$$\beta = \beta_e(1+jC\delta), \qquad \beta_0 = \beta_e, \tag{17}$$

where

$$\delta = x+jy, \tag{18}$$

and it was assumed that the spatial angular velocities of the circuit wave and the elecron beam at radius r_0 are in synchronism and the loss and the space-charge parameters are zero. The expression for the circular propagation constant, given by Eqs. (17) and (18), may now be substituted into Eq. (14) to obtain

$$(1+jC\delta)[(-j\beta_e^2C^3)\delta^5+(-2\beta_e^2C^2)\delta^4+jC(\beta_e^2C^3-2)\delta^3 \\ +2(\beta_e^2C^3-2)\delta^2+jC^2(-\beta_e^2+\beta_e+2)\delta+C(\beta_e+2)] = 0. \tag{19}$$

This is the general determinantal equation for CEF-type traveling-wave devices in the case where the circuit wave and the electron beam at radius r_0 are in synchronism and the space-charge and loss effects are zero.

An extremely wide range of digital computer results given by Nunn and Rowe[1),2)] have shown that, under all circumstances applicable to both forward- and backward-wave devices, the two incremental propagation constants are accurately given by

$$\delta_6 = j2/C, \tag{20}$$

$$\delta_5 = j/C. \tag{21}$$

Equation (20) shows that the wave, which arises on the r-f circuit from the charge-induction fields of the electron beam, is identified as the backward traveling wave. Equation (21) imples the wave possesses no azimuthally-oriented propagation and is thus constrained to exhibt only radial motion, if any. Althogh Eq. (19) is the general expression for the small-signal equation, its significance can be more readily appreciated through the introduction of approximate simplifications. In particular, it will be assumed that $\beta_e \approx 20$ and $C \approx 0.05$. Upon making the assumption the expressions for incremental propagation constant take the appropriate form

$$\delta_{1,2} \approx \pm\frac{1}{2}\sqrt{\beta_e C}-j\frac{3}{4\beta_e^2 C}, \tag{22}$$

$$\delta_{3,4} \approx j\left(\frac{\sqrt{2}}{\beta_e C}\mp\frac{3}{4\beta_e^2 C}\right). \tag{23}$$

The real part of the incremental propagation constant x_1, which is greater than zero, is associated with the wave that exponentially increases with increasing spatial angle, while x_2 is associated with the exponentially decreasing wave. The imaginary parts of the incremental propagation constant y_1 and y_2 possess the same value and these are slow space-charge waves. By the same reasoning, y_3 is a fast and y_4 is a slow space-charge wave. The δ_1 and δ_2 waves are due to the interaction between a synchronous space-charge wave and a forward wave. The δ_3 and δ_4 waves are due to the characteristic ripple in the CEF-type focusing system.

In order to investigate the demodulating characteristics of the CEF-type devices it is necessary to determine the initial wave amplitude set up at the input boundaıy. Since the solution of the determinantal equation involves six roots, each of which may posses real and imaginary parts, a total of six waves are excited by an energy-carrying electron beam. Only four of those waves are found to be important, however, as a careful examination of the results of incremental propagation constants indicates.

It is thereforc essential to prescribe only four independent conditions which must be satisfied at the input. These are:

1. The total circuit voltage applied is zero at the input.
2. The azimuthal r-f convection current applied at the input of the electron beam is equal to the sum of the azimuthal r-f convection currents associated with the individual waves propagation on the beam.
3. The radial current is zero at the input.
4. The azimuthal velocity variation of the electron beam is zero at the input.

These boundary conditions at $\theta=0$ and $r=r_0$ can be expressed using coefficients in the compact form of matrix algebra

$$\begin{Vmatrix} 0 \\ A_\theta i_\theta(0) \\ 0 \\ 0 \end{Vmatrix} = \begin{Vmatrix} 1 & 1 & 1 & 1 \\ C_{\theta 1} & C_{\theta 2} & C_{\theta 3} & C_{\theta 4} \\ C_{r1} & C_{r2} & C_{r3} & C_{r4} \\ C_{\Omega 1} & C_{\Omega 2} & C_{\Omega 3} & C_{\Omega 4} \end{Vmatrix} \cdot \begin{Vmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{Vmatrix}, \tag{24}$$

where

$$A_\theta = -r_0\Omega_0/\eta\tau_0 k_C\beta_e \tag{25}$$

V_n = the amplitude of the circuit voltage of the wave at $\theta=0$,

$i_\theta(0)$ = the azimuthal r-f convectin current applied to the electron beam at $r=r_0$ and $\theta=0$,

$$C_{\theta n}V_n = i_{\theta n}A_\theta, \tag{26}$$

$$C_{rn}V_n = i_{rn}(jr_0\Omega_0/\eta\tau_0 k_C\beta_e^2), \tag{27}$$

$$C_{\Omega n}V_n = \Omega_{1n}(-r_0^2\Omega_0/\eta k_C\beta_e^2) \tag{28}$$

The inverse of the C-matrix leads to the desired set of initiail wave amplitude. Thus

$$\begin{Vmatrix} V_1/A_\theta i_\theta(0) \\ V_2/A_\theta i_\theta(0) \\ V_3/A_\theta i_\theta(0) \\ V_4/A_\theta i_\theta(0) \end{Vmatrix} = \begin{Vmatrix} D_{11} & D_{12} & D_{13} & D_{14} \\ D_{21} & D_{22} & D_{23} & D_{24} \\ D_{31} & D_{32} & D_{33} & D_{34} \\ D_{41} & D_{42} & D_{43} & D_{44} \end{Vmatrix} \cdot \begin{Vmatrix} 0 \\ 1 \\ 0 \\ 0 \end{Vmatrix} = \begin{Vmatrix} D_{12} \\ D_{22} \\ D_{32} \\ D_{42} \end{Vmatrix} \tag{29}$$

The D-matrix is the symbolic form of the desired inverse of the C-matrix, while the elements D_{12}, D_{22}, D_{32} and D_{42} are the initial wave amplitudes appropriated to the stipulated boundary conditions.

The total voltage of r-f circuit becomes at $\theta=0$

$$V_R(\theta) = \sum_{n=1}^{4} V_n e^{-j\beta_n\theta}, \tag{30}$$

where

$$V_n = A_\theta D_{n2} i_\theta(0), \qquad n = 1, 2, 3, 4. \tag{31}$$

Upon substituting Eq. (30) into Eq. (31) it follows that

$$V_R(\theta) = A_\theta\Big(\sum_{n=1}^{4} D_{n2} e^{\phi\delta_n}\Big) i_\theta(0) e^{-j2\pi N}, \tag{32}$$

where

$$\phi = \beta_e C\theta = 2\pi CN. \tag{33}$$

Finally, the r-f voltage of the circuit at $\theta=\theta$ may be used to obtain the demodulating output of the CEF-type devices by means of formura

$$P(\theta) = \frac{1}{2K}|V_R(\theta)|^2 = \frac{1}{2}R_{eq\theta}|i_\theta(0)|^2, \tag{34}$$

where $R_{eq\theta}$ is the equivalent resistance which is defined as

$$R_{eq\theta} = \frac{K}{k_C^2\beta_e^2C^4}\left|\sum_{n=1}^{4}D_{n2}e^{\phi\delta_n}\right|^2, \tag{35}$$

and the resistance depends on the circuit characteritics of the CEF-type device and its output connections.

3. Discussions

In the reference condition where $\beta_e \approx 20$, $C \approx 0.05$ and $k_C = 0.8$, the equivalent resistance can be written

$$R_{eq\theta} = \frac{K}{k_C^2\beta_e^2C^4}\left|\left[-\frac{3}{\beta_e^2}\cosh(\sqrt{\beta_e C}\,\phi/2) + j\frac{8\beta_e C^2}{(8+\beta_e^3C^3)\sqrt{\beta_e C}}\sinh(\sqrt{\beta_e C}\,\phi/2)\right]\right.$$
$$\left. + \left[\frac{3}{\beta_e^2}\cos(\sqrt{2}\,\phi/\beta_e C) + j\left(\frac{9}{2\sqrt{2}\,\beta_e^3} - \frac{3}{\sqrt{2}\,\beta_e^2} - \frac{3\beta_e C^3}{\sqrt{2}(8+\beta_e^3C^3)}\right)\sin(\sqrt{2}\,\phi/\beta_e C)\right]\right|^2. \tag{36}$$

The terms of $\cosh(\pi CN)$ and $\sinh(\pi CN)$ are due to the growing and decreasing waves in the device and the terms of $\cos(2\sqrt{2}\pi CN)$ and $\sin(2\sqrt{2}\pi CN)$ are due to the characteristic ripple in the CEF-type focusing system. The quantity $R_{eq\theta}/K$ vs. CN in this case is given in Fig. 2. A study of Fig. 2 shows that the equivalent resistance possesses a dependency on the waves associated with incremental propagation constants δ_1 and δ_2 and the effect of δ_3 and δ_4 waves is negligible. Relative amounts of the four wave components of circuit voltage, azimuthal current, radial current and azimuthal velocity at various distances down the device are shown in Table 1. Each component of the circuit voltage, the azimuthal current, the radial current or the azimuthal velocity is modified by the factor exp $[\beta_e C\theta x - j\beta_e\theta(1 - Cy)]$ as it progresses down the interaction region. The actual field or current is the sum of four waves. The total circuit voltage must be zero at $\theta = 0$ and $r = r_0$ where the d-c beam enters. On the other hand, the total azimuthal current applied at

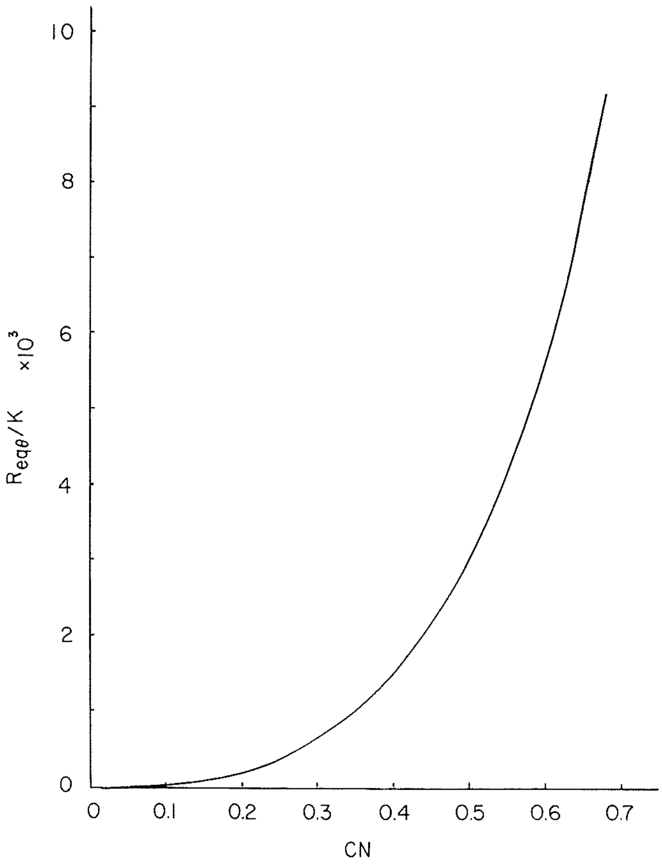

Fig. 2. $R_{eq\theta}/K$ vs. CN in the case where $b=0$, $d=0$, $Q=0$, $k=0.8$, $\beta_e \approx 20$ and $C \approx 0.05$

Table 1 Relative amounts of the four wave components of circuit voltage, azimuthal current, radial current and azimuthal velocity at various distances down the device.

CN	0	0.25	0.50	0.75
$V_1/A_\theta i_\theta(0)$	$-0.00375+j\,0.02220$	$-0.00535+j\,0.04910$	$-0.00538+j\,0.10830$	$0.00221+j\,0.22700$
$V_2/A_\theta i_\theta(0)$	$-0.00375-j\,0.02220$	$-0.00231-j\,0.01004$	$-0.00132-j\,0.00451$	$-0.00072-j\,0.00202$
$V_3/A_\theta i_\theta(0)$	0.00100	$-0.00056+j\,0.00083$	$-0.00039-j\,0.00092$	$0.00098+j\,0.00019$
$V_4/A_\theta i_\theta(0)$	0.00649	$-0.00422-j\,0.00493$	$-0.00102+j\,0.00641$	$0.00556-j\,0.00335$
$i_{\theta 1}/i_\theta(0)$	$0.444-j\,0.222$	$0.944-j\,0.543$	$1.997-j\,1.265$	$4.190-j\,3.130$
$i_{\theta 2}/i_\theta(0)$	$0.444+j\,0.222$	$0.209+j\,0.089$	$0.095+j\,0.033$	$0.045+j\,0.013$
$i_{\theta 3}/i_\theta(0)$	-0.364	$0.202-j\,0.303$	$0.125+j\,0.335$	$-0.357-j\,0.069$
$i_{\theta 4}/i_\theta(0)$	0.364	$-0.230-j\,0.269$	$-0.054+j\,0.349$	$0.303-j\,0.182$
$i_{r1}/j\beta_e i_\theta(0)$	$0.00028+j\,0.00111$	$0.00076+j\,0.00239$	$0.00196+j\,0.00516$	$0.00494+j\,0.01100$
$i_{r2}/j\beta_e i_\theta(0)$	$0.00028-j\,0.00111$	$0.00009-j\,0.00051$	$0.00003-j\,0.00024$	$0.00001-j\,0.00010$
$i_{r3}/j\beta_e i_\theta(0)$	0.00177	$-0.00098+j\,0.00146$	$-0.00069+j\,0.00163$	$0.00173+j\,0.00034$
$i_{r4}/j\beta_e i_\theta(0)$	-0.00167	$0.00115+j\,0.00134$	$0.00027-j\,0.00175$	$-0.00152+j\,0.00091$
$\Omega_1/(\beta_e/r_0\tau_0)i_\theta(0)$	$0.00222-j\,0.00111$	$0.00463-j\,0.00271$	$0.01000-j\,0.00657$	$0.21000-j\,0.01566$
$\Omega_2/(\beta_e/\;{}_0\tau_0)i_\theta(0)$	$0.00222+j\,0.00111$	$0.00104+j\,0.00045$	$0.00049+j\,0.00018$	$0.00023+j\,0.00007$
$\Omega_3/(\beta_e/r_0\tau_0)i_\theta(0)$	-0.00250	$0.00139-j\,0.00208$	$0.00098+j\,0.00230$	$-0.00245-j\,0.00048$
$\Omega_4/(\beta_e/r_0\tau_0)i_\theta(0)$	-0.00250	$0.00162+j\,0.00190$	$0.00039-j\,0.00247$	$-0.00214+j\,0.00129$

the input is equal to the azimuthal current associated with each wave.

4. Conclusions

The expression for the demodulating power output and the equivalent resistance was given in the CEF-type device in a special case where $b=0$, $d=0$, $Q=0$, $\beta_e \approx 20$, $C \approx 0.05$ and the azimuthal current variation was applid at the input. The equivalent resistances is due to growing and decreasing waves and the characteristic ripple effect is negligible.

The authors are grateful to Professor M. Suzuki for his helpful suggestions and critical reading of the manuscript. The authors also wish to express their appreciation to Professor J. E. Rowe, whose excellent book "Nonlinear Electron-Wave Interaction Phenomena" has been a helpful guide throughout this work. Finally, the authors wish to thank Mr. K. Koyanagi, Mr. T. Haga, and Mr. K. Iwasaki for their valuable discussions.

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