International Journal of Scientific Research in Physics and Applied Sciences
Research Paper Vol-3, Issue-4 E-ISSN: 2348–3423

Interaction of the Pulsed Electron Beam with RF Fields of Dielectric Loaded Waveguide

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Received: 11/Oct/2015 Revised: 26/Oct/2015 Accepted: 18/Nov/2015 Published:31/Dec/2015

Abstract- The interaction of the electromagnetic wave and the electron beam is studied. Finite difference method is used to study the interaction of the pulsed electron beam with RF fields of dielectric loaded waveguide. The dielectric loaded waveguide slow down the EM wave. When the velocity of both EM wave and the beam is comparable then a fruitful interaction takes place. It is observed that the strength of interaction depends on the detuning between the wave and beam. If velocity of the beam is greater, than the energy transfer takes place from beam to wave and the wave grows in amplitude.

Keyword: Dielectric loaded waveguide, Beam-wave interaction, Pulsed electron beam

I. Introduction

A monoenergetic electron beam supports two space charge waves. One is a fast space charge wave which propagates faster than the beam and the other is slower space charge wave. The slow space charge wave is a negative energy wave. This wave gains amplitude when energy extracted out of it. This wave is responsible for the transfer of kinetic energy of the streaming electrons to the electromagnetic (EM) waves. However, to have meaningful interaction, the electromagnetic waves must be slowed down. In Cherenkov microwave sources, a slow wave structure(SWS) is used to reduce the axial phase velocity of the normal mode of a waveguide below the vacuum speed of light so that they can exchange energy directly to the beam of the drifting electrons; each electrons feel an accelerating and decelerating force, depending on the local phase of the wave. If the electrons are initially some -what faster than the wave, however, more electrons are decelerated than accelerated, and a net transfer of the energy to the wave occurs in addition to the bunching. The exchange of energy causes the wave to grow in amplitude, and the bunching enforces the coherence of the emitted radiations [1-3]. In the previous paper [1], the interaction is theoretically studied for inertial bunching by solving self consistent coupled equation. However, in this paper another approach i.e. finite difference method is used. The coupling of a slow guided electromagnetic wave and the slow space-charge mode of an electron beam can be a source of coherent, high-power, millimeter-wavelength radiation [4-8]. The structure of this paper is as follows: The model used for the numerical analysis is given in the section 2. Numerical results of the problem and the discussions are shown in section 3. Finally, conclusions are given in the last section.

II. Numerical model

In this paper the following model is considered. An electron beam is injected into a hollow metallic waveguide lined by a dielectric. The dielectric acts as SWS. Interaction of electron beam with an EM wave of the vacuum structure is then studied. The interaction is weak in the sense that, if examined over a region of space of the order of one wavelength in size, the EM field has the temporal and spatial dependences of a wave in the empty structure. The effect of the beam is to cause the EM wave to vary slowly in time and axial distance. Further, the beam induces a relatively small space charge field which is proportional to beam density. In figure1, cylindrical metallic waveguide of radius r_2, lined with dielectric of thickness r_2-r_1 is considered. Vacuum exists in the remaining region.

In absence of beam, the waveguide fields are given as:

$$\vec{E} = \vec{E}_p \cos\phi \qquad (1)$$

$$\vec{B} = \vec{B}_p \cos\phi , \qquad (2)$$

where $\phi = \omega t - kz$

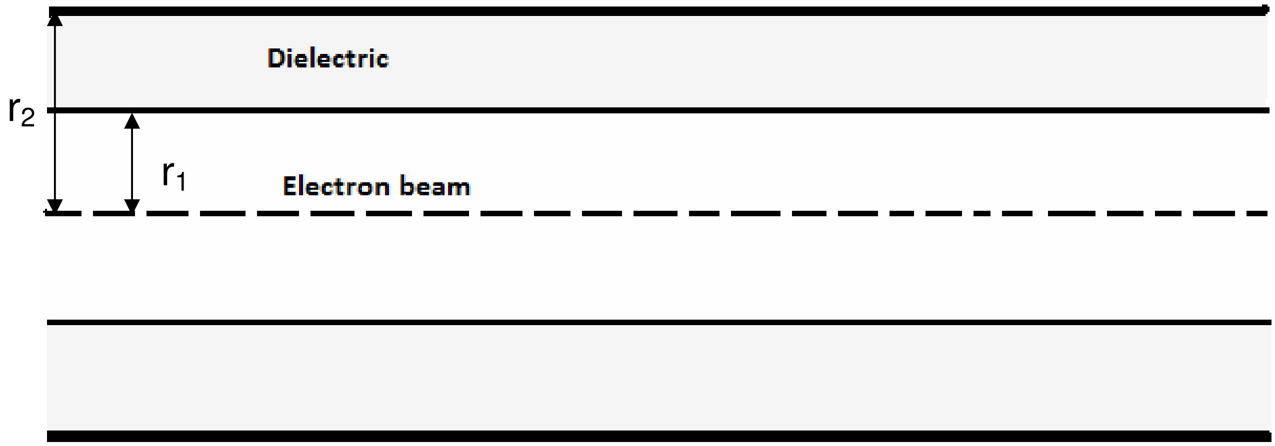

Figure1: The Schematic of dielectric loaded metallic waveguide.

In presence of the electron beam, the fields are

$$\vec{E} = \left(E_p \varepsilon + E_p^{(1)}\right)\cos\phi \quad (3)$$

$$\vec{B} = \left(B_p \varepsilon + B_p^{(1)}\right)\cos\phi \quad (4)$$

where ε is a function of axial position z and time t, and is a slowly varying amplitude of the EM wave, E_p and B_p are the amplitudes of the EM fields which represent the solutions for waves in the empty structure, and $E_p^{(1)}$ and $B_p^{(1)}$ are the small first-order space charge fields which are proportional to the beam density. The fields E_p and B_p satisfy Maxwell equation for waves with frequency ω and Floquet wave number k .

Using these fields (3) and (4) to solve for the Maxwell equations

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \quad (5)$$

$$\vec{\nabla} \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c} j\,, \quad (6)$$

After some manipulations, we get

$$\frac{\partial \varepsilon}{\partial t} + v_g \frac{\partial \varepsilon}{\partial z} = \frac{2}{U}\int \vec{E}_p \cdot j \cos\phi dV \quad (7)$$

$$\gamma^3 \beta\left(\frac{\partial \beta}{\partial t} + v_z \frac{\partial \beta}{\partial z}\right) = \frac{qv}{mc^2}\left[\vec{E}_p \varepsilon \cos\phi\right] \quad (8)$$

where $\beta = \frac{v}{c}$,

$\gamma = \frac{1}{\sqrt{1-\beta^2}}$ is relativistic factor, v_g is group velocity and U is the energy of EM of the wave. j is the current density of the beam. Solving the equations (7) and (8) with the equation of continuity,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot j = 0 \quad (9)$$

where the ρ is the charge density per unit volume.

Normalizing the equations by the time period 'T' and wavelength 'λ'of the wave, we get

$$\frac{\partial \varepsilon}{\partial \tau} + \frac{v_g}{v_{ph}}\frac{\partial \varepsilon}{\partial \xi} = \frac{2\lambda}{U v_{ph}}\int \vec{E}_p \cdot j \cos\phi dV \quad (10)$$

$$\left(\frac{\partial \beta}{\partial \tau} + n_r \beta \frac{\partial \beta}{\partial \xi}\right) = -\frac{2\pi n_r}{\gamma^3}\frac{e}{mc^2 k}\left[\vec{E}_p \varepsilon \cos\phi\right] \quad (11)$$

$$\frac{1}{n_r}\frac{\partial \tilde{n}}{\partial \tau} + \tilde{n}\frac{\partial}{\partial \xi}\beta + \beta \frac{\partial}{\partial \xi}\tilde{n} = 0 \quad (12)$$

where v_{ph} represent the phase velocity of the EM wave,

$n_r = \frac{c}{v_{ph}}$,

$\tilde{n} = \frac{n}{n_0}$,

e, m is charge,mass of the electron, respectively and n_0 is the density of beam per unit volume.

Finite difference technique is used to solve the set of equations (10)-(12).

Discretizing the equations, we get

$$\beta_j^{i+1} = \beta_j^i + h_t\left[-n_r\beta_j^i\frac{\beta_{j+1}^i-\beta_j^i}{h_z} - A\varepsilon_j^i\cos\phi\right] \quad (13)$$

$$\varepsilon_j^{i+1} = \varepsilon_j^i + h_t\left[-\frac{v_g}{v_{ph}}\frac{\varepsilon_{j+1}^i-\varepsilon_j^i}{h_z} - \frac{2\lambda}{Uv_{ph}}\int \vec{E}_p\cdot j\cos\phi dV\right] \quad (14)$$

$$n_j^{i+1} = n_j^i - n_r h_t\left[n_j^i\frac{\beta_{j+1}^i-\beta_j^i}{h_z} + \beta_j^i\frac{n_{j+1}^i-n_j^i}{h_z}\right]$$

where h_t and h_z is the step size is in time and space, respectively. Here

$A = \frac{2\pi n_r}{(\gamma_j^i)^3}\frac{e\vec{E}_p}{mc^2k}$ is constant.

III. Results and Discussions

We use the parameters as follows: The initial conditions taken for analysis are $\varepsilon_j^{i=0}=1$, $\tilde{n}_j^{i=0}=0$ and $\beta_j^{i=0}=0$. The step size in space and time, h_t =0.01and $h_z = h_t/5$. Beam frequency ω_b =5 GHz is used. We consider k= 8.72 cm^{-1}, ω =157 GHz, dielectric constant=3.75, Electric field strength=10^4 V/m, Length of the system=3 λ, r_1 =1 cm and r_2 =2 cm.

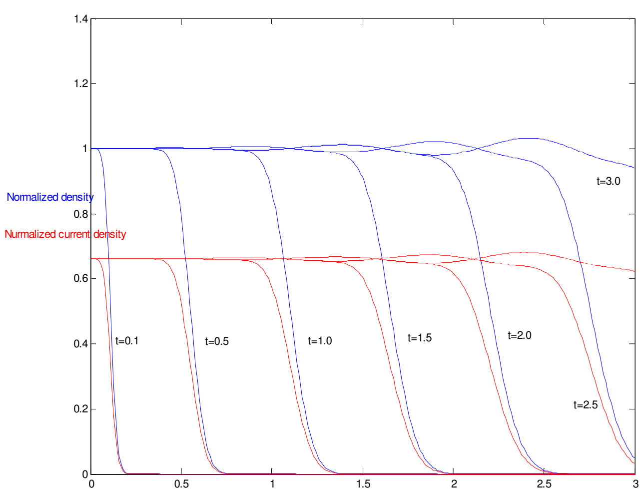

Figure 2: Evolution of density and current density with space for different time.

In figure 2, the density variation in the waveguide with normalized position at different time is shown. The red curve depicts the normalized current density and the blue curve is plotted for normalized density. It can be seen that for a fixed time the density as well as the current density are initially constant and after some distant both decreases. So the spatial variation in the electron beam density shows the typical bunching of the beam electrons due to the interaction with RF fields of the structure.

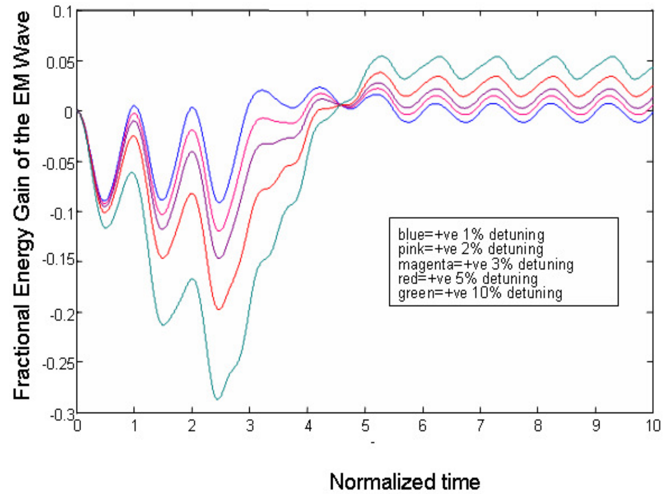

Figure 3: Fractional energy gain of the EM wave with normalized time for different positive detuning.

In figure 3, the fractional gain in energy in EM wave is plotted with normalized time for different values of positive detuning. The detuning is positive in the sense the velocity of electron is greater than the velocity of the EM wave in the medium. The blue, pink, magenta, red and green curves are for the detuning 1%, 2%, 3%, 5%, and 10%, respectively. As the detuning increases the growth of the EM wave increases i.e. more and more energy exchange takes place from electron beam to the EM wave.

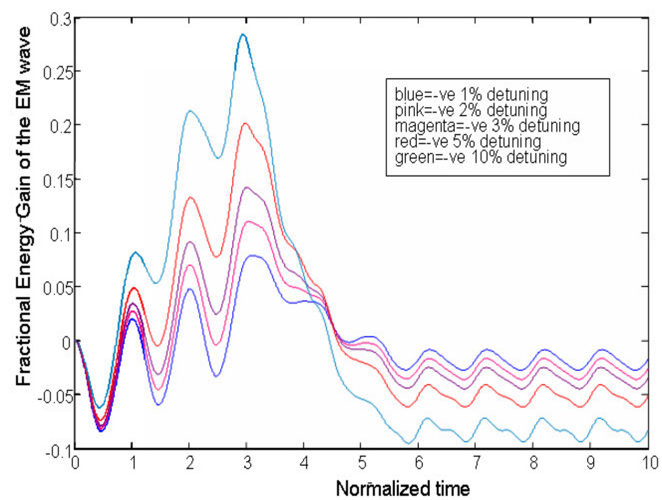

Figure 4: Fractional energy gain of the EM wave with normalized time for different negative detuning.

In figure 4, the fractional gain in energy in EM wave is plotted with normalized time for different values of negative detuning. In this case, the velocity of electron is less than the velocity of the EM wave in the medium. The blue, pink, magenta, red and green curves are for the detuning -1%, -2%, -3%, -5% and -10%, respectively. As the detuning increases the change in energy of the EM wave increases i.e. more energy exchange takes place from EM wave to electron beam.

IV. Conclusions

We have studied the interaction of the pulsed electron beam with RF fields of dielectric loaded waveguide with the help of finite difference method. The interaction takes place only when the velocity of both EM wave and the beam is comparable. Thus for interaction it is necessary to slowdown the EM wave. The strength of interaction depends on the detuning between the wave and beam. As the detuning increases the growth of the EM wave increases i.e. more and more energy exchange takes place from electron beam to the EM wave and the wave grows in amplitude.

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