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Electron Beam Phase Bunching Mechanism in the Gyroklystron Amplifier

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ABSTRACT

In this paper, nonlinear single mode analysis of the gyroklystron amplifier for the fundamental mode operation has been carried out to study the electron beam phase bunching mechanism. Typical processes of the electron energy modulation and phase bunching taking place during the electron beam and RF wave interaction process have been studied by observing the evolution of electrons momentum and phases along the interaction length for different operating conditions. The conditions for optimum bunching have been obtained using these plots to get the necessary conditions for optimum efficiency operation of a gyroklystron amplifier. Moreover, the results obtained here have been generalized by expressing different operating conditions in a single graph in terms of the efficiency contours. Therefore, results obtained here can be applied for optimizing the design parameters and performance of the gyroklystron amplifier of any desired frequency and power.

Key words: Microwave tubes, fast-wave device, millimeter wave amplifier, gyroklystron, beam-wave interaction.

1. INTRODUCTION

In recent years, considerable research and development interest has aroused in the area of gyro-devices including gyroklystrons. Gyroklystron capability to provide high gain and moderate bandwidth are making them attractive as high-power millimeter and sub-millimeter wave amplifier. These amplifiers have application for millimeter-wave radars, particle accelerators, RF plasma heating systems, etc [1]-[2]. Gyroklystron is a fast wave amplifier and its resonant cavity system is similar to that in a conventional klystron except that instead of reentrant cavities overmoded cylindrical cavities are used here. Electron beam and RF wave interaction mechanism in the gyroklystron is based on cyclotron resonance maser (CRM) instability similar to that in gyrotrons, instead of Weibel instability as in conventional klystrons. In such type of device, the radiation frequency is determined by the background magnetic field rather than by the size of the interaction structure [3]-[4]. This helps gyroklystron to be operated at higher frequencies with increased transverse dimensions which in turn increase their power handling capability at millimeter and sub-millimeter wave frequencies.

In the present paper, a generalized analysis of gyroklystron based on the nonlinear approach for fundamental mode operation under single mode condition [5] has been extended to study the evolution of electron phase bunching in the device along its interaction length. The processes of electrons energy modulation and phase bunching during the beam-wave interaction process have been explicitly shown through electrons momentum and phase variation diagrams along the device length. Using these diagrams, the electron bunching mechanism in a gyroklystron has been studied for different operating conditions. The necessary conditions for optimum efficiency operation of the device have been also obtained by getting the optimum bunching conditions for strong beam wave interaction process. Moreover, the results obtained in this paper have been made generalized by obtaining the efficiency contours corresponding to different operating conditions. These contours help in the preliminary design of the gyroklystron amplifier. The possible operating region can be chosen from these contours by taking suitable normalized parameters, i.e., normalized field amplitude, beam current, interaction length, bunching parameter and detuning parameter. These normalized parameters provide the complete specification of the beam parameter as well as structure parameter. These efficiency contours are generalized and hence can be applied for any operating frequency, and output power owing to the various constraints.

2. ANALYSIS

The coupled equations used for the qualitative study of electron bunching process in a gyroklystron are known as the equation of motion in slow time variable scale and obtained after formulating motion of each particle corresponding to individual eigenmode in the cavity. For weakly relativistic electrons and single mode fundamental mode interaction, equations of momentum (p), phase (θ) and axial position (ς) in normalized form can be written as[5]-[6]:

$$\left.\begin{aligned} \frac{dp}{d\varsigma} &= -Ff(\varsigma)\sin\theta \\ \frac{d\theta}{d\varsigma} &= -(\Delta + p^2 - 1) - Ff(\varsigma)p^{-1}\cos\theta \end{aligned}\right\} \quad (1)$$

where $p=\gamma\beta_{\perp}/\gamma_0\beta_{\perp 0}$, $\theta=\varphi-\omega t_0+\pi/2$, and $\varsigma=\pi\beta_{\perp 0}^2 z/\beta_{\|0}\lambda$. Here $\beta_{\perp}=v_{\perp}/c$ and $\beta_{\|}=v_{\|}/c$, where $v_{\perp}$ and $v_{\|}$ are transverse and axial velocity of the electrons, respectively. Here, φ is the fast time scale phase angle of the electron, t_0 is the time when the electrons enter the interaction region, γ is the relativistic factor, and subscript 0 denotes the initial value of quantity.

The field amplitude *F*, length of the output cavity μ and frequency detuning parameter Δ, are the normalized device parameters and defined as [5]-[6]:

$$\left.\begin{aligned} F&=\frac{E_0\beta_{\perp 0}^{n-4}}{B_0 c}\left(\frac{n^{n-1}}{2^{n-1}n!}\right)J_{m\pm n}\left(k_{\perp}r_b\right)\\ \mu&=\frac{\pi\beta_{\perp 0}^2 L}{\beta_{\|0}\lambda},\quad \Delta=\frac{2}{\beta_{\perp 0}^2}\left(1-\frac{n\omega_{c0}}{\omega}\right)\end{aligned}\right\} \qquad (2)$$

In the analysis, axial field profile is assumed to be Gaussian in nature which is found suitable in the resonant cavities, which are used as the RF interaction structure in gyroklystrons and can be written as $f(\varsigma)=e^{-(2\varsigma/\mu)^2}$. It has been also noticed that the electrons after traveling through the prebuncher assembly of the device which consists of one or more RF cavities along with the drift tubes gets azimuthally bunched due to CRM instability process, the motion of these phase bunched electrons can be represented in terms of momentum and azimuthal phase parameters in a multicavity gyroklystron. Therefore, this bunched electron beam can be modeled in terms of the momentum and phase parameters at the input end of the output RF cavity with initial conditions described as $p_{in}=1$ (assuming no space charge and velocity spread) and $\theta_{in}=\theta_c+q\sin\theta_c-\psi$. Here, p_{in} is initial value of the normalized momentum and θ_c is the initial phase of the electrons, uniformly distributed over the azimuthal space $(0,2\pi)$. q is bunching parameter, and ψ is phase at the input of the output RF cavity. In output RF cavity, the range of integration is taken as the normalized axial position of the cavity, $-\sqrt{3}\mu/2\le\varsigma_{in}\le\sqrt{3}\mu/2$. Equation (1) can now be solved for different values of the gyroklystron parameters *F*, μ, Δ, *q* and ψ . The momentum of the electrons versus axial distance has been plotted for different values of device parameters to study the evolution of electron phase bunching on orbital efficiency $\eta_{\perp}$ [7], which is defined as the average electron energy loss of the electrons from their initial transverse energy.

3. RESULTS AND DISCUSSION

The numerical appreciation of the beam wave interaction process and parametric analysis of the gyroklystron have been performed. For this purpose, 25 macro particles with equal azimuthal distribution in the interval between $[0, 2\pi]$ are considered in the interaction space of the device. In Figure 1(a), the momentum of electrons have been plotted against the axial position of the output RF cavity for a set of gyroklystron parameters corresponding to optimum bunching condition,

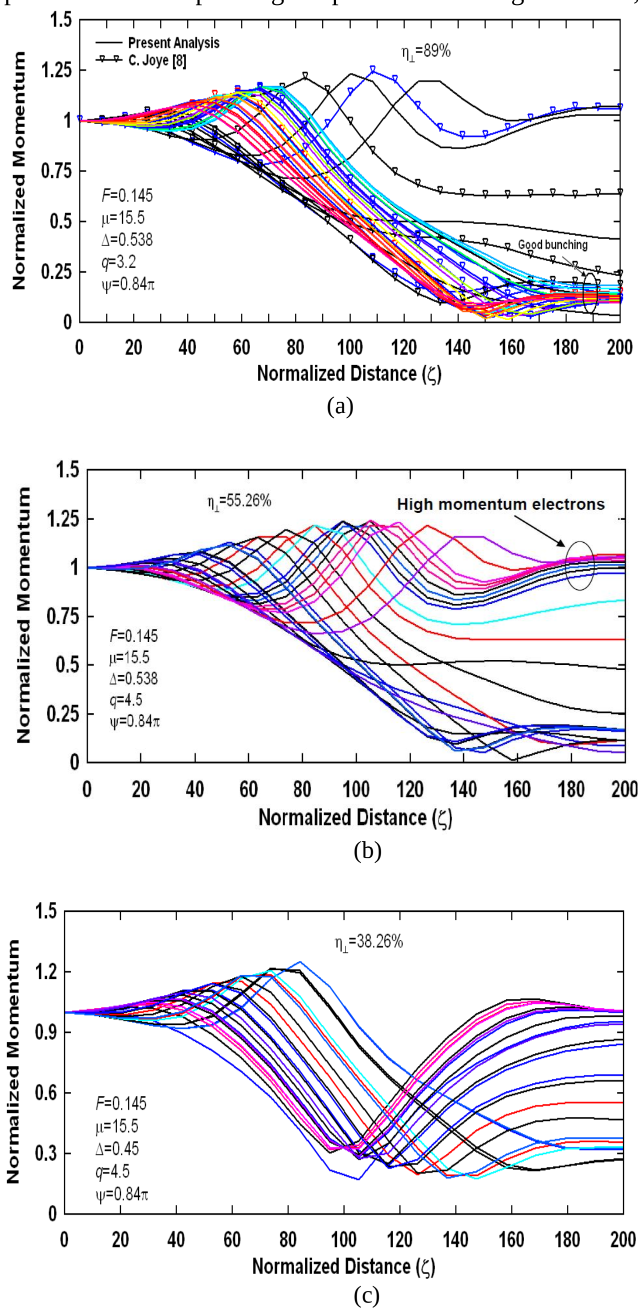

Figure 1: Normalized distance versus normalized momentum plots for a set of gyroklystron parameters (a) under optimum bunching condition. (b) over bunching condition (c) variation in detuning parameter from optimal bunching.

i.e., field amplitude (*F*) = 0.145, length (μ) = 15.5, detuning parameter (Δ) = 0.538, bunching parameter (*q*) = 3.17, and RF phase ψ = 0.84π, necessary for maximum efficiency. Under this optimum condition the phase bunched electrons transfer their maximum energy to the RF field. It can be seen from Figure 1(a), that towards the output end of the interaction length a large number of electrons are in lower momentum state and only few of them are in higher momentum side. The result of Figure 1(a) has been validated with Joye [8]. The Figure 1(b) has been plotted for the same optimized parameters, only the bunching parameter q value has been increased to 4.5 in order to see the effect of over bunching. This results in degradation of the efficiency from 89% to 55% due to the presence of more electrons in the higher momentum side at the output end as shown in the Figure 1(b). The efficiency further decreases, when we decrease the frequency detuning parameter Δ from its optimized value as shown in Figure 1(c). This happens due to the presence of most of the electrons in higher momentum side, resulting in poor bunching and hence less efficiency as the electrons energy is very less perturbed by the RF from their initial value due to weak beam wave interaction process.

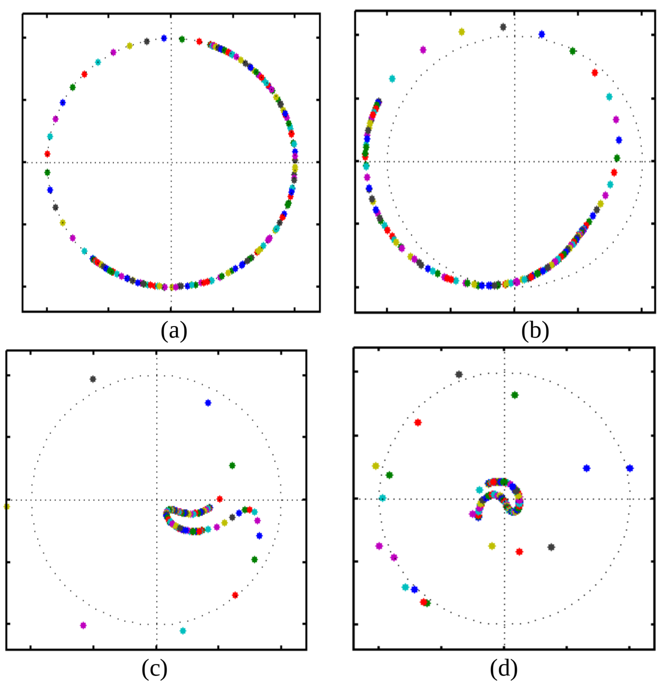

Figure 2: Electrons phase bunching plots for a set of optimum bunching parameters i.e F= 0.14, μ=15.5, Δ=0.538, q=3.17, and ψ=0.84π at different positions (a) inlet of the output cavity (b) one third length of the output cavity, (c) two third length of the output cavity, and (d) outlet of the output cavity.

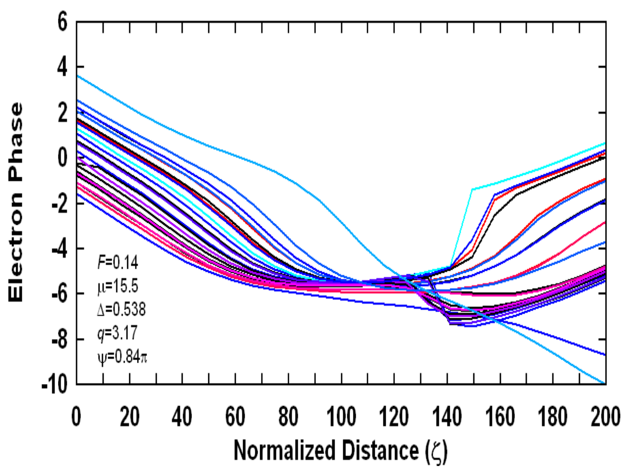

Figure 3: Electrons phase bunching along the axial direction.

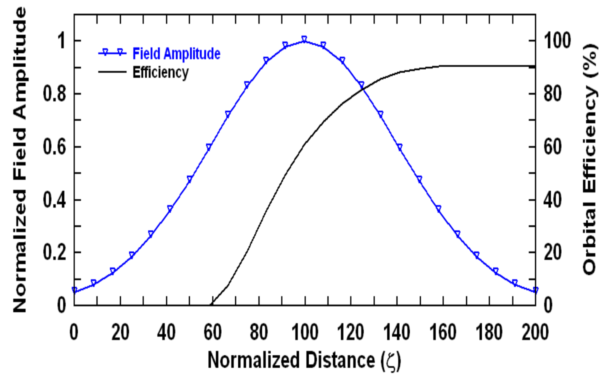

Figure 4: Normalized field amplitude and orbital efficiency as a function of normalized distance.

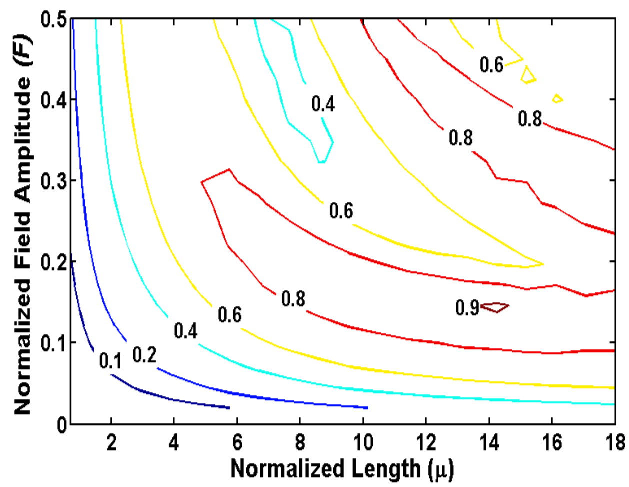

Figure 5: Contour plot of orbital efficiency as a function of normalized field amplitude (F) and normalized length (μ).

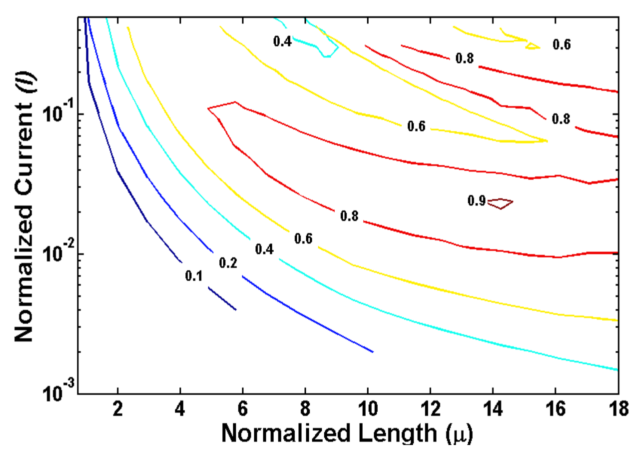

Figure 6: Contour plot of orbital efficiency as a function of normalized current (I) and normalized length (μ).

Figure 2 shows the phase bunching of electrons at different positions of output cavity for the optimized gyroklystron parameters corresponding to optimal bunching condition. It can be seen from Figure 2(a) a center of bunch is formed at the inlet of output cavity. These bunched electrons lose their energy to the RF and disperse in the phase space with reduced Larmor radii indicating loss in energy towards the outlet of the output cavity as shown in Figures from 2(b), 2(c), and 2(d). The phase bunching of the electrons in axial direction is shown in Figure 3. The maximum axial phase bunching occurs nearly at the middle of the output cavity where RF field is maximum in the cavity as shown in Figure 4. This shows that a strong beam wave interaction process takes place at the center of the output cavity. In Figure 4 the RF axial field profile along with the orbital efficiency is plotted as a function of axial position. The orbital efficiency of the gyroklystron could be defined in terms of the average electron energy loss to their initial transverse energy. The evaluation of the orbital efficiency of a gyroklystron is a two step procedure. Firstly, the momentum and phase of all the electrons taken into consideration is calculated at the output end of the RF interaction length by solving equation (1). Here, Runga-Kutta method is used to solve the equation (1). After this, the average of all the electrons momentum obtained through solving equation (1) is taken over the initial phase angle of the electrons for calculating the orbital efficiency. The maximum orbital efficiency calculated for the optimized parameters is around 90% (Figure 4) for field amplitude (F) = 0.14, length (μ) = 15.5, detuning parameter (Δ) = 0.538, bunching parameter (q) = 3.17, and RF phase (ψ) = 0.84π. In order to make the present study more useful, the orbital efficiency of the gyroklystron have been calculated for different set of parameters which corresponds to different operating conditions and the obtained results have been made generalized by expressing the results obtained for different operating conditions in a single graph in terms of efficiency contours. The contour plots of orbital efficiency as a function of field amplitude (F) and length (μ) thus obtained is shown in Figure 5. As it can be seen from Figure 5 the maximum orbital efficiency is ~ 90% at F = 0.14 and μ = 15.5. Figure 5 provides qualitative information about the performance of the gyroklystron amplifier in terms of the work done on the phase bunched electron beam with the variation of normalized RF field amplitude (F) and normalized interaction length (μ). At the lower value of F and μ the orbital efficiency value is small which predicts a weak beam wave interaction process as little work done on the electron beam by RF field. The increase in value of these two parameters leads to increase in efficiency value and at a certain point it reaches to its maximum. Further increasing the value of F and μ, the efficiency value is reduced which means that electron beam starts gaining the energy from the RF field. The contour plots of the efficiency in I-μ space corresponding to F-μ space is shown in Figure 6, which is obtained using energy balance equation $(F^2 = \eta_\perp I)$. The $\eta_\perp(I,\mu)$ contour plot is helpful in deciding the value of the beam current for the optimum efficiency. In this plot, several high efficiency regions are obtained but the gyroklystron design is prefer in the lower value of I and μ to prevent self oscillations in the device which occurs due to operation of the device at currents near to start oscillation current. It must be noticed that these plots are quite general and can be applied to design the gyroklystron amplifier of any value of frequency and output power.

4. CONCLUSION

Study of electron phase bunching mechanism in a fundamental mode operating gyroklystron amplifier has been carried out using time independent nonlinear single mode theory. Typical plots of electrons energy modulation and phase bunching have been explicitly shown for the gyroklystron amplifier for different operating conditions. The conditions for obtaining optimum efficiency using optimum bunching condition in terms of generalized parameters have been obtained. The effects of over bunching and detuning on electron phase bunching process have been clearly shown through the curves of evolution of electrons momentum along the interaction length. Further, the results obtained from the present analysis for different operating conditions are expressed in terms of efficiency contours. These efficiency contours are generalized in nature and can be easily used for the performance evaluation and preliminary design of a gyroklystron of any desired frequency and power. Since, the generalized parameters used here can be easily converted to actual device parameters through standard calculations. Hence, it can be concluded that the present analysis will be helpful for initial design and performance evaluation of the gyroklystron amplifiers.

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