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Energy gain by an electron in the fundamental mode of a rectangular waveguide by microwave radiation

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Abstract. Energy gain by an electron during its motion in the fields of the fundamental TE_{10} mode excited by microwave radiation in a rectangular waveguide is analysed. Expressions have been obtained for the fields of the mode, the angle of deflection and the acceleration gradient of the electron when it is injected along the direction of mode propagation. An electron of energy 25 keV gains 120.44 keV when a microwave of intensity 10^{10} W m^{-2} at frequency 6 GHz is employed to excite the mode in a waveguide of width 0.03 m and height 0.02 m. The effects of the microwave frequency and the width of the waveguide are to decrease the electron energy gain for fixed microwave intensity. However, higher acceleration gradients are obtained when the electron is injected with greater initial energy.

1. Introduction

The acceleration of charged particles to high energies is a subject of recent interest for experimental as well as theoretical research. Plasma-based acceleration schemes, namely the plasma wakefield accelerator, the plasma beatwave accelerator and the laser wakefield accelerator have been successful in achieving large acceleration gradients for electrons and protons (Esarey et al. 1996). Also in microwave plasma interaction experiments, electron acceleration has been realized via a $\mathbf{v}_p \times \mathbf{B}$ process (Nishida et al. 1985; Nishida and Sato 1987) and that of resonance absorption during wave–particle interaction (Nishida and Shinozaki 1990). Pantell and Smith (1982) have attempted to provide the electron acceleration by the interaction of laser and microwave fields. Bakhtiari et al. (2000) have studied proton acceleration by the transverse field of the wake associated with a high-intensity laser. Neglecting the effect of the longitudinal field of a laser pulse in direct acceleration scheme, McKinstrie and Startsev (1996) have proposed that a pre-accelerated electron can be accelerated significantly. Lu et al. (1998) have studied electron motion in the electromagnetic field of a short-pulse high-intensity laser in vacuum for electron acceleration. Taking the effects of longitudinal and transverse laser fields, Du and Xu (2000) have studied the direct acceleration of a positron using a laser and significant acceleration has been noted even when the particle was initially at rest.

It can be noted that most of the investigations, including the direct acceleration scheme, make use of short-pulse high-intensity lasers. However, it would be of significant interest to use microwaves in place of such high-intensity lasers. Therefore,

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in the present paper, we make an attempt to accelerate an electron in a rectangular waveguide, when the electron is injected along the direction of propagation of the TE_{10} mode excited by the microwave. It is revealed from the present analysis that the electron in the waveguide gains significant energy over a distance equal to $\lambda_g/4$, where λ_g is the wavelength in the waveguide.

2. Fundamental mode and electron trajectory

We consider an evacuated rectangular waveguide of width s along the x-axis and height h along the y-axis and a microwave is used to excite the TE mode along the z-axis. Using Maxwell's equations, we obtain the following equations for the fields $\mathbf{E}$ and $\mathbf{B}$ with a time dependence of $\exp(-i\omega t)$:

$$c^2\nabla^2\mathbf{E} + \omega^2\mathbf{E} = 0, \qquad c^2\nabla^2\mathbf{H} + \omega^2\mathbf{H} = 0, \tag{1}$$

where $\omega = 2\pi f$ is the microwave frequency and c is the speed of light. Equation (1) is solved for the field components of the TE_{mn} mode, where $E_z = 0$, considering the waveguide of a perfectly conducting material so that no tangential components of the $\mathbf{E}$ field and normal components of the $\mathbf{H}$ field exist at the walls of the waveguide. Under such boundary conditions, all the field components can be determined from the axial magnetic field H_z as

$$\begin{aligned} E_x &= \left(i\omega\mu_0/k_c^2\right)\partial H_z/\partial y, \qquad E_y = -\left(i\omega\mu_0/k_c^2\right)\partial H_z/\partial x, \\ H_x &= \left(ik_g/k_c^2\right)\partial H_z/\partial x, \qquad H_y = \left(ik_g/k_c^2\right)\partial H_z/\partial y, \end{aligned} \tag{2}$$

where $H_z = A\cos(m\pi x/s)\cos(n\pi y/h)\exp(ik_g z)$. In the above relations, k_c is the wave number corresponding to the cutoff condition given by $k_c^2 = m^2\pi^2/s^2 + n^2\pi^2/h^2$, k_g is the propagation constant given by $k_g^2 = \omega^2/c^2 - m^2\pi^2/s^2 - n^2\pi^2/h^2$ and A is the amplitude constant associated with the TE_{mn} mode. The dispersion relation for this mode in the waveguide is obtained as

$$\omega^2 = c^2\left[k_g^2 + m^2\pi^2/s^2 + n^2\pi^2/h^2\right]. \tag{3}$$

The following cutoff frequency f_{cmn} is obtained for the propagation of the present mode

$$f_{cmn} = c[m^2/s^2 + n^2/h^2]^{1/2}/2. \tag{4}$$

For the propagation of the dominant TE_{10} mode, the frequency f of the microwave should satisfy $f_{c10} < f < f_{c01}$ for the waveguide with $s > h$. Therefore, the following useful frequency band for the propagation of the TE_{10} mode is obtained from the above equation, which shows the dependence on the dimensions of the waveguide:

$$c/2s < f < c/2h. \tag{5}$$

Now we can obtain the field components of the TE_{10} mode from (2) as

$$\begin{aligned} E_y = (i\omega\mu_0 sA/\pi)\sin(\pi x/s)\exp(ik_g z), \qquad H_x = -(ik_g sA/\pi)\sin(\pi x/s)\exp(ik_g z), \\ H_z = A\cos(\pi x/s)\exp(ik_g z). \end{aligned} \tag{6}$$

It can be seen from (5) that the microwave frequency f for the propagation of the dominant TE_{10} mode in a rectangular waveguide of width $s = 0.03\,\mathrm{m}$ and height

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$h = 0.02\,\mathrm{m}$ should be $5 < f < 7.5$ GHz. For a microwave of frequency 6 GHz and intensity $10^{10}\,\mathrm{W\,m^{-2}}$, the field components of the TE_{10} mode at the front opening ($x = s/2$, $z = 0$) of the waveguide are $E_y \sim 10^6\,\mathrm{V\,m^{-1}}$ and $H_x \sim 10^3\,\mathrm{A\,m^{-1}}$, if there is no loss of power in excitation of the mode. In the present mechanism, this electric field is used for the electron acceleration when the electron is injected along the direction of mode propagation in the waveguide. As Palmer (1972) discussed, the trajectory of the charged particle in the presence of sinusoidally varying fields with a fixed direction is sinusoidal, here the electron will execute a sinusoidal path along the direction of propagation of the mode (z-axis) under the action of mode fields. In the present case the electron motion under the influence of the force $-eE_y$ will make an angle with the z-axis and the forces due to the magnetic field components will also act on it at the same time. This angle θ by which the electron becomes deflected from the z-axis can be calculated from the electron equation of momentum $d\mathbf{p}/dt = -e[\mathbf{E} + \mu_0 \mathbf{v} \times \mathbf{H}]$, from which we obtain

$$dp_y/dz = -e[E_y - \mu_0 v_x H_z + \mu_0 v_z H_x]/v_z. \tag{7}$$

Since the electron is injected along the z-axis, the second term on the right-hand side of the above equation can be neglected and then the integration yields the following expression for the angle of deflection:

$$\theta = \tan^{-1}(p_y/p_z) = \tan^{-1}\left\{\left[-eE_0(\omega - v_z k_g)/\omega m_e v_z^2 k_g\right] \sin(\pi x/s)\cos(2\pi z/\lambda_g)\right\}. \tag{8}$$

It can be noted from (8) that the deflection (angle θ) of the electron from the z-axis is maximum when $z = 0$ (at the opening of the waveguide) and it becomes smaller as the electron travels a finite distance along the z-axis. Finally, when the electron completes a distance $\lambda_g/4$, its direction of motion is parallel to the z-axis ($\theta = 0°$) and after that it gets deflected in the opposite direction, i.e. the electron executes sinusoidal oscillation along the z-axis. In addition, the electron injected at higher velocity and/or at $x <$ (or $>$) $s/2$ becomes deflected by a relatively smaller amount. It will be seen in the next section that the electron gains energy up to a distance of $\lambda_g/4$, i.e. its velocity increases with distance up to $\lambda_g/4$. Therefore, the deflection becomes smaller and smaller over this distance according to (8).

3. Electron energy gain in TE_{10} mode fields

In this section, we obtain the expression for the electron energy gain (acceleration gradient) using the following momentum and energy equations with electron rest mass m_e and velocity $\mathbf{v}$:

$$d(m_e\gamma\mathbf{v})/dt = -e[\mathbf{E} + \mu_0 \mathbf{v} \times \mathbf{H}], \tag{9a}$$

$$dU/dt = -e\mathbf{v} \cdot \mathbf{E}, \tag{9b}$$

where the energy $U = \gamma m_e c^2$. It can be noticed that the first term on the right-hand side of (9a) is the accelerating term and the second one is a decelerating (gyratory) term. Therefore, the electron should gain energy until the first term is dominant over the second one. This gives rise to the following condition:

$$(\omega + k_g v_z)\tan^2(\pi x/s) > \pi^2 v_z/k_g s^2. \tag{10}$$

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It is apparent from the above condition that the decelerating effects become dominant near the walls at $x \sim 0,\ s$. If we assume that the position of the electron is solely specified in the z-direction and transform the coordinates to $\zeta = v_g t - z$, we find

$$v_y = [m_e(v_g - v_z)/e\mu_0 H_x](\gamma v_z)_\zeta, \qquad (\gamma v_x)_\zeta + (H_z/H_x)(\gamma v_z)_\zeta = 0,$$
$$\gamma_\zeta = -ev_y E_y/(v_g - v_z)m_e c^2. \tag{11}$$

In the above equations, the subscript ζ denotes differentiation. The last equation of (11) will provide an expression for the energy gradient of the electron, if v_y is calculated in terms of the dominant component v_z. We integrate the second equation under the boundary condition that the field components vanish at large distances from the mode as $|\zeta| \to \infty$ and solve the y-component of the momentum equation, eliminating highly nonlinear terms in order to obtain γ_ζ in terms of v_z. This procedure gives

$$(\gamma v_z)_\zeta = -\big(E_y H_x + \mu_0 v_z H_z^2 + \mu_0 v_z H_x^2\big)\big[e^2\mu_0/m_e^2 v_g(v_g - v_z)\big]/\gamma_\zeta. \tag{12}$$

The use of the first equation of (11) in conjunction with (12) in the last equation of (11) yields the following expression for the change in γ per unit distance:

$$\Delta\gamma/\Delta z = eE_0\big[(\omega/k_g)\sin^2(\pi x/s) + \big(\pi^2 v_z/s^2 k_g^2\big)\cos^2(\pi x/s)\big]^{1/2}\sin(2\pi z/\lambda_g)/m_e c^2(v_g - v_z)^{1/2}. \tag{13}$$

It is clear from the above equation that the rate of change of γ is positive. If we multiply $\Delta\gamma/\Delta z$ by the rest energy $m_e c^2$ of the electron, we find the rate of energy gain (acceleration gradient) in eV m^{-1} as

$$(\Delta U/\Delta z)_{\mathrm{eV}} = E_0\big[(\omega/k_g)\sin^2(\pi x/s) + \big(\pi^2 v_z/s^2 k_g^2\big)\cos^2(\pi x/s)\big]^{1/2} \times \sin(2\pi z/\lambda_g)/(v_g - v_z)^{1/2}. \tag{14}$$

The factor $[(\omega/k_g)\sin^2(\pi x/s) + (\pi^2 v_z/s^2 k_g^2)\cos^2(\pi x/s)]^{1/2}$ in the above expression has a maximum at $x = s/2$ and minima at $x = 0,\ s$. Therefore, the electron gains maximum energy when injected at $x = s/2$. The condition (10) holds good for a wider range of x in addition to $x = s/2$, e.g. if the electron is injected in the region $s/4 < x < 3s/4$. However, the energy gain under such condition will not be as great as in the case of $x = s/2$, since E_y is maximum at $x = s/2$. Therefore, the following handy formula for the maximum acceleration gradient in eV m^{-1} along the z-axis is obtained

$$(\Delta U/\Delta z)_{\max} = E_0[\omega/k_g(v_g - v_z)]^{1/2}\sin(2\pi z/\lambda_g). \tag{15}$$

It can be noted from (15) that the maximum energy gain is achieved when the electron travels a distance (or an odd multiple of) $\lambda_g/4$, as $\sin(2\pi z/\lambda_g)$ attains maximum values at $z = (2p+1)\lambda_g/4$, where $p = 0,\ 1,\ 2$, etc. Moreover, it is evident that the electron decelerates to its initial energy over a distance of $\lambda_g/4$ to $\lambda_g/2$ and then again gains energy in the opposite direction. Therefore, the acceleration mechanism in the present case is similar to those of McMillan (1950) and Chan (1971), who used the electromagnetic wave field as the possible origin of cosmic rays and laser radiation for acceleration of particles, respectively. In the present case, since the electric field of the mode is perpendicular to the initial direction of

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motion of the electron, the initial acceleration is also in the perpendicular direction, which deflects the electron at a finite angle with respect to the direction of mode propagation and thus the electron is accelerated along its direction of motion as well. After a finite distance $\lambda_g/4$, the electron sees the reverse field and starts to decelerate to its initial energy and then again gains energy in the opposite direction. Therefore, it is required that the electron should be collected at a distance of $\lambda_g/4$ or at one of its odd multiples. In addition, the electron should be injected at the centre of the waveguide in order to achieve maximum energy gain.

4. Extraction of an accelerated electron

It would be interesting to extract the accelerated electron from the waveguide. In this regard, it is evident from the above discussion that the electron should be collected when it completes a distance equal to $\lambda_g/4$ or one of its odd multiples, in an ideal situation. Moreover, at such positions the electron motion is directed along the $+z$-axis and it nearly reaches either upper wall at $\lambda_g/4$, $5\lambda_g/4$, etc. or the lower wall at $3\lambda_g/4$, $7\lambda_g/4$, etc., as suggested by (8). Therefore, a static magnetic field of moderate strength (< 0.1 T for the present case) applied instantly for a small region near $z = \lambda_g/4$ or its odd multiples in the $-x$ ($+x$) direction will suffice to deflect the accelerated electron upward (downward) when it is near the upper (lower) wall, and can be collected through a judiciously placed hole in the wall, which must be made available at that time only. Recently, a static magnetic field (5 T) has been successfully employed for the extraction of accelerated electrons captured in a tightly focused laser beam of intensity $\sim 10^{24}$ W m^{-2} (Salamin and Keitel 2002).

Since the accelerated electron nearly reaches either upper or lower wall at odd multiples of $\lambda_g/4$ ($= p\lambda_g/4$ with $p = 1$, 3, 5, etc.), the length of the waveguide can be set equal to $p\lambda_g/4$ (ideally) and another dielectric filled waveguide of smaller height and width can be coupled with the first waveguide (0.03×0.02 m^2) in order to match the wave impedance of the TE_{10} mode (Fig. 1). In this situation, the mode will continue to propagate through the dielectric-filled waveguide and the accelerated electron can be collected through a prudently placed hole (h1 or h2 as per (8)) in the upper or lower side of the front end of the accelerating waveguide. For such a configuration, a plastic-filled (dielectric constant = 2) waveguide of height ~ 0.01 m and width 0.019 m (cutoff frequency 5.5 GHz) can be used to match the wave impedance for the present case, where a microwave of frequency 6 GHz is employed. For this purpose, an evacuated waveguide of the same width as that of the first one but with a smaller height can also be coupled, since the wave impedance in both waveguides will be the same. Alternatively, a parabolic mirror may be used at $z = p\lambda_g/4$ to diffract the mode away from the z-axis (through a glass window) and the accelerated electron can be collected through a hole made immediately available in the mirror. Such a type of scheme has been proposed for the extraction of an accelerated electron beam in a laser-driven electron cyclotron autoresonance accelerator (Hirshfield and Wang 2000).

It would be worth mentioning here that if the accelerated electron, which is collected using the above methods, could be directly injected into another waveguide for further acceleration, the present mechanism may be used in multiple stages and finally a huge amount of energy gain can be achieved by the electron; as the energy gain with the present mechanism is higher for an electron injected with a larger initial energy.

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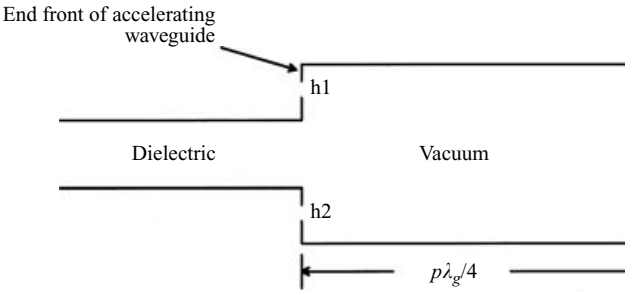


Figure 1. Vertical cross-sectional view of coupled waveguides. The right-hand waveguide, with length equal to an odd multiple of $\lambda_g/4$ ($= p\lambda_g/4$), is used for electron acceleration and the accelerated electron is collected through a prudently placed hole, h1 or h2, depending upon its position as per (8). A dielectric-filled waveguide is used to match the wave impedance of the TE_{10} mode.

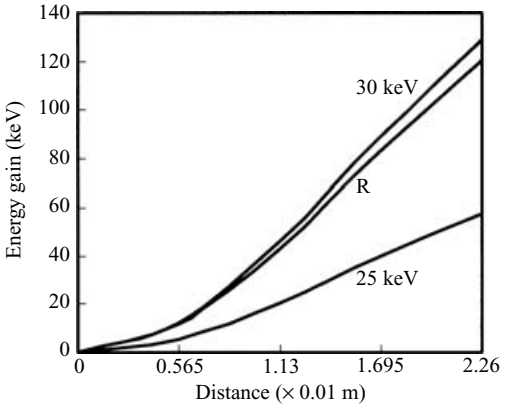


Figure 2. Energy gain ΔU by an electron along the z-axis in a rectangular waveguide of width 0.03 m and height 0.02 m for a microwave intensity of 10^{10} W m^{-2}. Curve R (30 keV) represents the energy gain when the initial electron energy is 25 keV (30 keV) and the microwave frequency is 6 GHz. The 25 keV curve is plotted at a microwave frequency of 7 GHz for the 25 keV electron.

5. Graphical presentation of the results

By giving typical values to the waveguide dimensions, the microwave frequency and the intensity, we analyse the results graphically in this section. In addition, using (8) we optimize the microwave frequency, which should be greater (lower) than the lower (upper) cutoff frequency f_{c10} (f_{c01}) so that the maximum amplitude of the electron oscillation is always less than half of the height of the waveguide. Furthermore, in view of the discussion made in Sec. 3, the numerical calculations are kept limited to a distance of $\lambda_g/4$ to analyse the effect of microwave frequency, waveguide width, etc. on the amplitude of oscillation, energy gain and the acceleration gradient.

Figure 2 shows the energy gain (ΔU) by the electron along the z-axis in a rectangular waveguide of width 0.03 m and height 0.02 m for different initial electron energies. Here the microwave intensity is taken as 10^{10} W m^{-2}. Curve R (30 keV) represents the energy gain when the initial electron energy is 25 keV (30 keV) and

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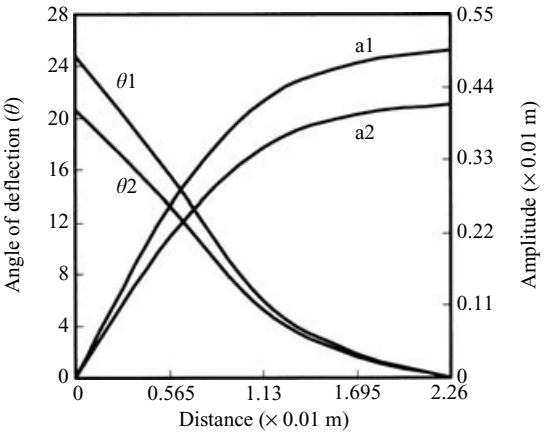


Figure 3. Change in angle of deflection θ and the amplitude of oscillation of electron along the z-axis, when the electron is injected in the waveguide with an energy of 25 keV (for graphs $\theta 1$ and a1) and 30 keV (for graphs $\theta 2$ and a2) for a microwave frequency of 6 GHz. Other parameters are the same as in Fig. 2.

the microwave frequency is 6 GHz. The curve 25 keV is plotted at a microwave frequency of 7 GHz for a 25 keV electron. It is apparent from the figure that the energy gain increases with the distance travelled by the electron along the z-axis. Furthermore, it can be seen that an electron injected with an energy of 30 keV gains more energy in comparison with one of energy 25 keV at the same microwave frequency and intensity (compare curves R and 30 keV). However, the effect of the microwave frequency is to decrease the energy gain, which is clear from curves R and 25 keV. This can be explained on the basis of (15), which says that the propagation constant k_g should be lower and the group velocity of the mode $v_g \approx v_z$ in order to achieve higher energy gain. However, k_g and v_g increase for higher microwave frequencies and hence lower energy gains are obtained.

Changes in the angle of deflection θ and the amplitude of oscillation of the electron along the z-axis are portrayed in Fig. 3. The initial electron energy is 25 keV for graphs $\theta 1$ (which represents the change in deflection angle) and a1 (which represents the change in amplitude) and 30 keV for graphs $\theta 2$ and a2. The microwave frequency is taken as 6 GHz and the other parameters are the same as in Fig. 2. It is clear from Fig. 3 that while the angle of deflection gets smaller, the amplitude increases with distance along the z-axis up to $\lambda_g/4$ (= 0.0226 m in the present case). It is also apparent here that a smaller deflection angle and a lower amplitude are realized when the electron is injected with larger energy.

The dependence of the acceleration gradient and the lower cutoff frequency on the width of the waveguide is shown in Fig. 4 for a microwave intensity of 10^{10} W m^{-2}. Curve AG represents the change in acceleration gradient and the cutoff frequency is shown by curve CF for increasing waveguide width. It can easily be seen that the acceleration gradient as well as the cutoff frequency decrease for larger waveguide widths. This is because of the increased k_g and v_g for larger waveguide widths (15). It is also implied from the figure that higher acceleration gradients can be achieved when the lower cutoff frequency is maintained at a higher level. However, one would have to reduce the width of the waveguide to achieve such a configuration.

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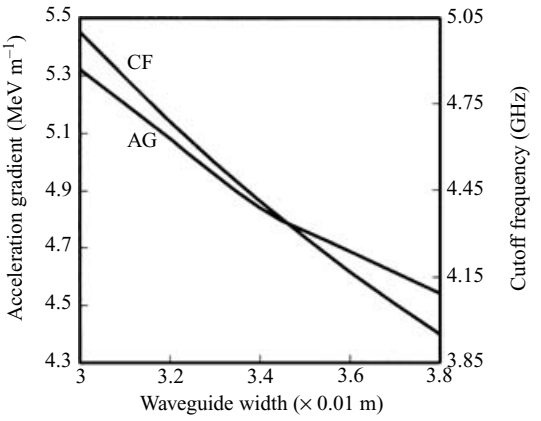


Figure 4. Dependence of the acceleration gradient (marked as AG) and the lower cutoff frequency (marked as CF) on the width of the waveguide for a microwave intensity of 10^{10} W m^{-2} and an arbitrary microwave frequency in view of (5), (8) and (10).

It may be noticed here that although we have analysed the energy gain and the acceleration gradient achieved by electron for the fixed microwave intensity (field), higher gradients and the larger energy gains are expected with higher microwave fields according to (15).

6. Conclusions

We have examined the acceleration of electrons in a rectangular waveguide via the fundamental TE_{10} mode excited by a high-intensity microwave. The effects of microwave frequency, intensity and the width of the waveguide on the energy gain, angle of deflection, amplitude of oscillation and the acceleration gradient of the electron have been studied. The energy gain, acceleration gradient and the amplitude of oscillation of the electron increase with the distance along the z-axis up to $\lambda_g/4$, but the angle of deflection becomes smaller. The electrons injected with larger energy attain higher acceleration gradients and a lower oscillation amplitude. However, lower acceleration gradients are obtained with waveguides of larger width and higher microwave frequencies.

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