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PARTICLE ACCELERATION BY THE INVERSE AXIAL-FREE-ELECTRON LASER INTERACTION*

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We describe an acceleration mechanism that is based on the inverse axial-free-electron laser interaction. Like Smith-Purcell acceleration and inverse Cherenkov acceleration this mechanism uses the axial electric field of a copropagating rf or light pulse; however, this mechanism is based on a fast-wave instead of a slow-wave interaction with the particles. Synchronism between the axial field and the particles is established by letting the light slip by the particles and shifting the transverse location of the mode back and forth. We provide a simple analysis demonstrating that the beam emittance dilution from this mechanism is small and the average accelerating gradient is insensitive to beam size and exact beam location. The physical dimensions of such a device is on the order of millimeters. A 1.5-GW, 350-μm laser could produce accelerating gradients of 0.25 GV/m, and a single 1 μsec laser pulse can in principle be used to accelerate 1 nC of electrons to 1 TeV over several kilometers of distance.

KEY WORDS: Electromagnetic field calculations, free-electron lasers, laser-beam accelerators, linear accelerators, particle dynamics

1 INTRODUCTION

Various schemes have been proposed to accelerate electrons in the high electric fields possible with lasers, such as the Smith-Purcell accelerator,[1,2] the inverse Cherenkov accelerator,[3,4] and the inverse free-electron laser (FEL) accelerator.[5,6] The Smith-Purcell accelerator uses a grating to produce a wave with a phase velocity matching the electrons' velocity, and the inverse Cherenkov accelerator uses a medium to reduce the phase velocity of the rf. The inverse FEL uses a fast-wave interaction instead of a slow-wave interaction and needs a transverse wiggler to provide the synchronism between the fast wave and the electrons. All of these mechanisms have serious technical issues to resolve. The slow-wave mechanisms require complex structures that are comparable in size to the wavelength of the light and that must sustain high electric fields, or use mediums that scatter the light and the electrons and which may breakdown. The inverse FEL interaction, on the other hand,

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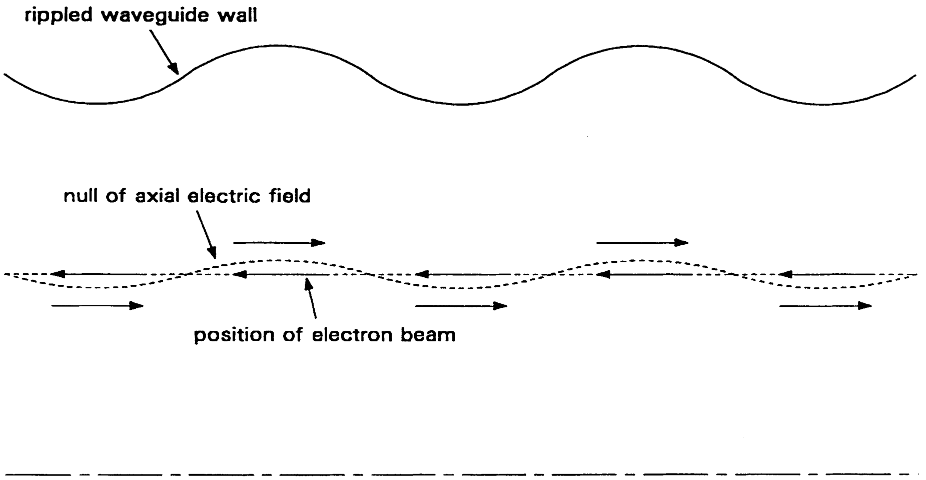


FIGURE 1: Axial electric field orientations for a synchronous particle in an axial FEL amplifier when the particle reaches the centers of the ripples in $r-z$ geometry.

has dimensions far exceeding the wavelength of the light, but as the electrons become ultrarelativistic it is hard to provide sufficient transverse motion for a significant interaction strength.

Recently, an axial FEL interaction was proposed for the generation of gigawatt microwave radiation.[7] In this device, an annular electron beam interacts with the axial electric field of a TM_{03} mode in a circular waveguide. The radius of this waveguide is periodically rippled which causes the mode to radially expand and contract. The ripple amplitude is only a few percent of the average radius, and the mode is able to adiabatically conform to the gradual change in the waveguide radius. The axial FEL interaction for a synchronous particle is shown in Figure 1. The annulus is located at a zero of the axial electric field when the mode is in a waveguide with a radius equaling the mean radius of the rippled waveguide. When an electron is at the axial position of the smallest waveguide radius the axial electric field at the location of the electron opposes the electron's motion. As the electron travels to the region of larger radius the rf slips by the electron. When the electron is at the location of the maximum waveguide radius one half of a rf wavelength has slipped by, resulting in a sign change in the mode's fields. Additionally, the electron is experiencing the electric field at a radius larger than the axial field zero instead of a radius smaller. This switch from one side of the null of the axial electric field to the other provides another sign change in the axial field at the location of the electron, and the electric field is again opposing the electron's motion. This interaction is equivalent to the interaction of a transverse-coupling FEL except the rf field is wiggled instead of the electrons to provide synchronism. It is important to realize that this interaction is with the fast wave, and is not a slow-wave interaction. In Figure 2 we see a typical dispersion curve for a periodically rippled waveguide. A slow-wave interaction takes place if the phase velocity of the wave is less than the speed of light, e.g. point A

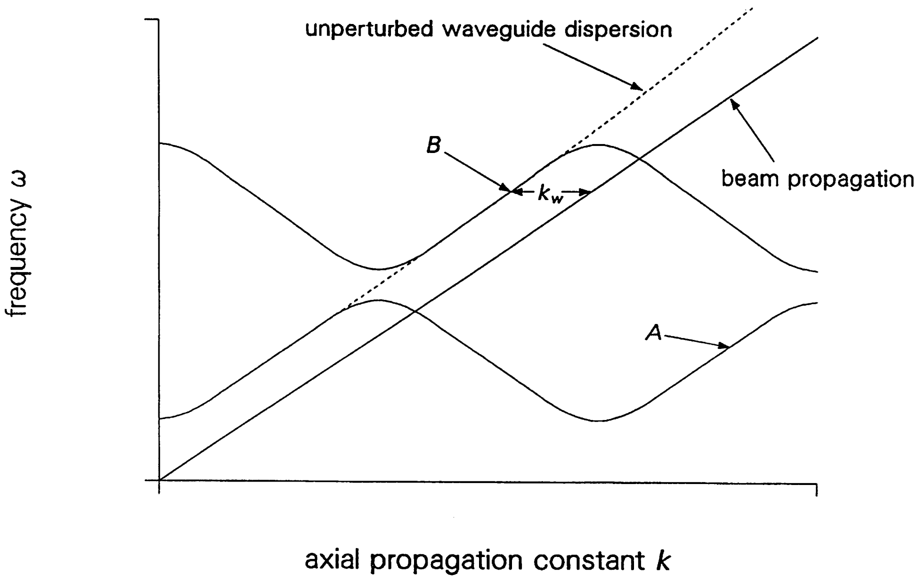


FIGURE 2: Dispersion relation for a typical periodic waveguide with small perturbations for the axial FEL amplifier.

in the figure. This interaction takes place at the point B where the phase velocity of the mode is faster than the propagation of the electrons. The wiggler wavenumber $k_w = 2\pi/\lambda_w$, where λ_w is the ripple period, provides synchronism between the mode wavenumber and the beam's wavenumber.

The axial FEL interaction can be used to accelerate a short electron bunch by operating at the phase where the electric field accelerates the particles. This was first proposed in 1986 by J. Nation[8] who described an interaction between a TM_{0m} mode in a cylindrical waveguide and the electron bunch. However, this interaction mostly cancels and requires a large ripple amplitude (on the order of 60% of the beam pipe radius) to generate significant accelerating gradients. The large ripple amplitude in turn causes a large emittance growth in the bunch and effects the mode's propagation. As a result this approach was not pursued. An alternative method to establish the inverse axial FEL interaction is to use a pencil beam in a rectangular waveguide TM_{nm} mode where either n or m is odd and the other is even. The waveguide is sinusoidally offset in the horizontal direction, eliminating any first order transverse focusing and establishing the axial FEL interaction. We will be examining this scenario in this paper.

Note that this interaction can also be established in a rectangular waveguide if the waveguide is straight and the beam is periodically transversely offset. This configuration is not as desirable as when the beam motion is purely axial because of emittance growth considerations. A magnetic chicane could be used to offset the beam but the acceleration between chicane dipoles would destroy the chicane's achromaticity.

2 MODE ANALYSIS

Let us consider the case that we have a TM_{nm} mode in a rectangular waveguide with horizontal dimension a and vertical dimension b. The electric and magnetic fields are given by Ref. 9

$$\begin{aligned} E_z &= E_o \sin\left(\frac{n\pi x}{a}\right) \sin\left(\frac{m\pi y}{b}\right) \\ E_x &= -jE_o\frac{\beta_{nm} n\pi}{ak_c^2} \cos\left(\frac{n\pi x}{a}\right) \sin\left(\frac{m\pi y}{b}\right) \\ E_y &= -jE_o\frac{\beta_{nm} n\pi}{ak_c^2} \sin\left(\frac{n\pi x}{a}\right) \cos\left(\frac{m\pi y}{b}\right) \\ H_x &= -E_y/Z \\ H_y &= E_y/Z \end{aligned} \tag{1}$$

where we have assumed an $\exp(j\omega t - j\beta_{nm}z)$ dependence, the origin is at the lower left corner of the waveguide, and

$$\begin{aligned} Z &= \left(\frac{\mu}{\varepsilon}\right)^{1/2} \sqrt{1 - \frac{\omega_c^2}{\omega^2}} \\ k_c &= \left(\left(\frac{n\pi}{a}\right)^2 + \left(\frac{m\pi}{b}\right)^2\right)^{1/2} \\ \omega_c &= ck_c \\ \beta_{nm} &= \left(\frac{\omega^2}{c^2} - k_c^2\right)^{1/2}. \end{aligned} \tag{2}$$

For the case where both n and m are nonzero (which must hold if there is an axial electric field) the power within the waveguide is

$$P = \frac{E_o^2 ab}{2\sqrt{\mu/\varepsilon}} \frac{\omega^2}{\omega_c^2} \sqrt{1 - \frac{\omega_c^2}{\omega^2}}. \tag{3}$$

The transverse forces on a particle with an axial velocity β_z are

$$\begin{aligned} F_x &= eE_x \left(1 - \beta_z \left(1 - \frac{\omega_c^2}{\omega}\right)^{-1/2}\right) \\ F_y &= eE_y \left(1 - \beta_z \left(1 - \frac{\omega_c^2}{\omega}\right)^{-1/2}\right) \end{aligned} \tag{4}$$

which tend to vanish as the particle energy is increased for modes far from cutoff. For an ultrarelativistic particle ($\beta_z = 1$) the synchronism equation is

$$k_w = \frac{\omega}{c}\left(1 - \sqrt{1 - \frac{\omega_c^2}{\omega^2}}\right). \tag{5}$$

Now let us specifically consider the case for the TM_{21} mode. The electric field components at a position horizontally displaced δ_x and vertically displaced δ_y from the center of the waveguide (note the change of origin from the equations in Equation (1)) are

$$\begin{aligned} E_z &= E_o\left(\frac{2\pi\delta_x}{a}\right)\left(1 - \frac{1}{2}\left(\frac{\pi\delta_y}{b}\right)^2\right) \\ E_x &= jE_o\frac{2\pi\left(1 - \omega_c^2/\omega^2\right)^{1/2}}{\sqrt{(2\pi)^2 + (\pi a/b)^2}}\frac{\omega}{\omega_c}\left(1 - \frac{1}{2}\left(\frac{2\pi\delta_x}{a}\right)^2\right)\left(1 - \frac{1}{2}\left(\frac{\pi\delta_y}{b}\right)^2\right) \\ E_y &= -jE_o\frac{\pi\left(1 - \omega_c^2/\omega^2\right)^{1/2}}{\sqrt{(\pi)^2 + (2\pi b/a)^2}}\frac{\omega}{\omega_c}\left(\frac{2\pi\delta_x}{a}\right)\left(\frac{\pi\delta_y}{b}\right). \end{aligned} \tag{6}$$

Note that at cutoff the transverse electric field vanishes, and as the mode becomes optical ($\omega \gg \omega_c$) the transverse fields dominate. Also note that the transverse forces are out of phase with the axial force.

Ignoring the small second order terms, the average accelerating gradient for an electron in a waveguide that sinusoidally shifts horizontally with a maximum amplitude of Δ (Figure 3) is

$$E_{z,\text{ave}} = E_o\frac{\pi}{a}\Delta. \tag{7}$$

Because the field is approximately linear with horizontal displacements the average accelerating gradient is not sensitive to small transverse displacements either in the horizontal or vertical directions. Thus the entire cross-section of a small beam will be accelerated with a rms energy spread of

$$\frac{\Delta\gamma}{\gamma} = \frac{1}{2}\left(\frac{\pi\sigma_y}{b}\right)^2 \tag{8}$$

where σ_y is the rms vertical beam size. This energy spread can be kept below 1% by focusing the beam to less than a vertical rms size 5% of the vertical waveguide dimension.

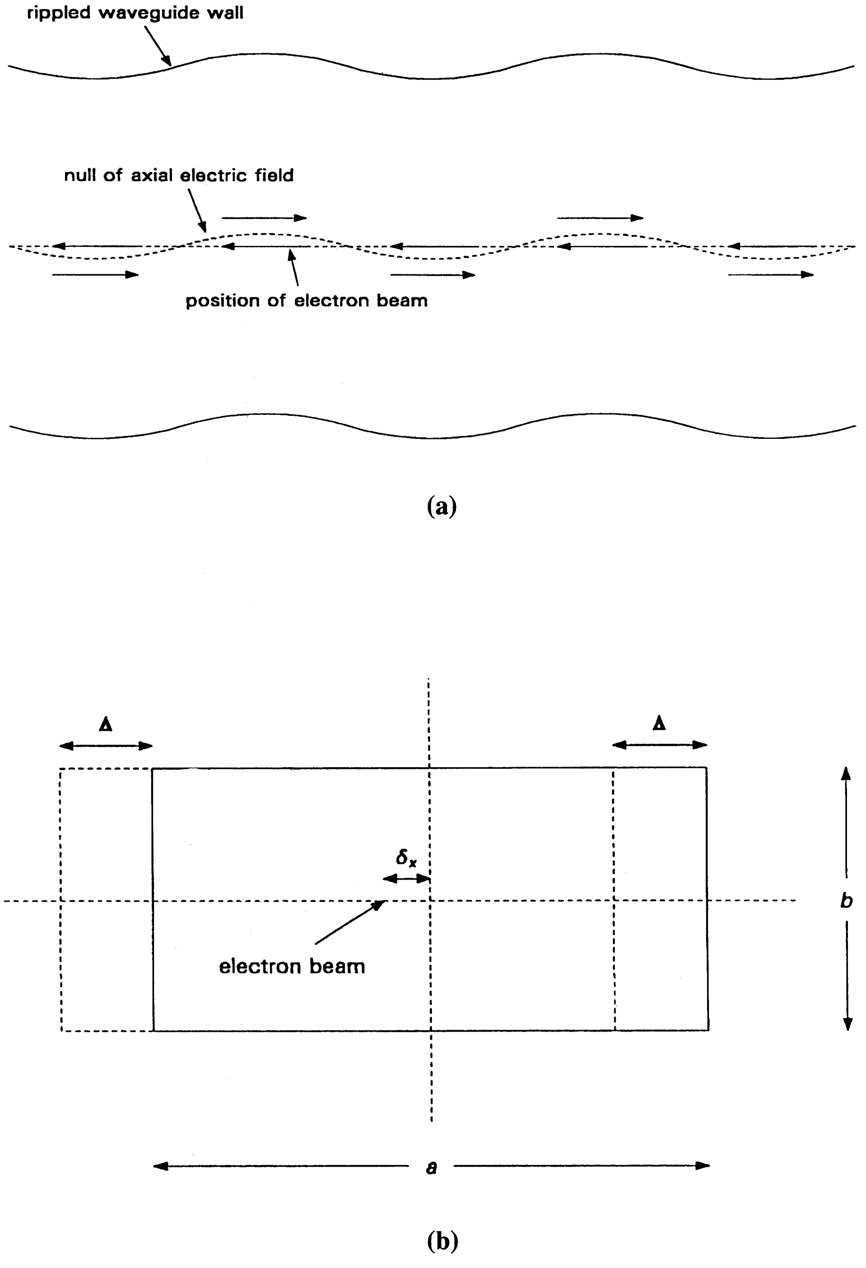


FIGURE 3: Waveguide geometry for an inverse axial FEL accelerator. (a) Top view showing the sinusoidal waveguide offset. (b) Transverse cut in waveguide. At the peak of the waveguide ripples the beam offset $\delta_x = \Delta/2$.

Note also that the horizontal force is an even function of both the horizontal and vertical displacements, and the vertical force is an odd function of the displacements. The net transverse forces less the dipole terms are:

$$\begin{aligned} F_x &= -jeE_o \frac{2\pi\left(1-\omega_c^2/\omega^2\right)^{1/2}}{\sqrt{(2\pi)^2+(\pi a/b)^2}} \frac{\omega}{\omega_c} \left(1-\left(1-\frac{\omega_c^2}{\omega^2}\right)^{-1/2}\right) \frac{\pi^2}{b^2}\left(\chi\delta_x+\zeta\delta_y\right) \\ F_y &= jeE_o \frac{\pi\left(1-\omega_c^2/\omega^2\right)^{1/2}}{\sqrt{(\pi)^2+(2\pi b/a)^2}} \frac{\omega}{\omega_c} \left(1-\left(1-\frac{\omega_c^2}{\omega^2}\right)^{-1/2}\right) \frac{2\pi^2}{ab}\left(\chi\delta_y+\zeta\delta_x\right) \end{aligned} \tag{9}$$

where χ and ζ are the horizontal and vertical positions relative to the bunch centroid, and now δ_x and δ_y are the displacements of the beam centroid from the waveguide center. The emittance growth from these forces can be made small by a number of techniques. For sufficiently small beam transverse dimensions and operation far above cutoff these forces are adequately small. Betatron focusing can be used to average each individual electron's transverse coordinates within the bunch to zero, making the overall emittance growth vanish too. For an electron phased to gain the most energy these forces will cancel over a single ripple period. By rippling the waveguide vertically in addition to horizontally, the terms with ζ can be made to vanish, leaving only linear forces. The only emittance growth from these forces arises from the fact that the bunch is not infinitely thin and different parts of the bunch experience transverse forces at different phases of the rf. The normalized emittance growth in this case is on the order of

$$\varepsilon_n \sim \frac{zeE_o}{2\sqrt{2}mc^2} \frac{\omega_c}{\omega} \frac{\pi^2}{b^2} \sigma_x^2 \phi \Delta \tag{10}$$

where z is the distance over which the bunch is accelerated, σ_x is the rms beam size and ϕ is the rms bunch length in degrees of the rf. Any net force resulting from not having the beam centered in the waveguide can be compensated for by external focusing.

3 DESIGN RELATIONSHIPS

By manipulating the mode equations we can derive various design equations relating the ripple wavelength to the rf wavelength, the surface electric field to the average accelerating gradient, and other important parameters to each other.

Using the synchronism relation (Equation (5)) we find

$$\lambda_w = \frac{\lambda_g\sqrt{1-\omega_c^2/\omega^2}}{1-\omega_c^2/\omega^2} \tag{11}$$

where λ_g is the guide wavelength of the rf. To allow the mode to adiabatically conform to the waveguide ripples we require multiple guide wavelengths per ripple period. If we let

$\omega = 2\omega_c$ then the radical expression is about 0.866 and there are 6.5 guide wavelengths per ripple period.

If the transverse dimensions a and b are related by

$$\frac{a}{n} = \frac{b}{m} \tag{12}$$

then the maximum surface transverse field for the TM_{21} mode is equal in both transverse directions and is given by (using Equation (7))

$$E_{\perp} = \frac{E_{z,\text{ave}}}{\pi\sqrt{2}} \frac{\omega}{\omega_c} \frac{a}{\Delta} \sqrt{1 - \omega_c^2/\omega^2}. \tag{13}$$

For the case the operating frequency is twice the cutoff frequency we find that the transverse field is $0.39\frac{a}{\Delta}$ times the average accelerating gradient. If the ripple amplitude is 10% of the waveguide width the transverse field is about four times the average accelerating gradient.

For the case where Equation (12) is satisfied, the power flow in the waveguide, Equation (3), becomes

$$P = \frac{E_{z,\text{ave}}^2 ab}{2\pi^2\sqrt{\mu/\varepsilon}} \left(\frac{a}{\Delta}\right)^2 \frac{\omega^2}{\omega_c^2} \sqrt{1 - \omega_c^2/\omega^2}. \tag{14}$$

The rf group velocity is $c\sqrt{1 - \omega_c^2/\omega^2}$. An rf pulse of length l will slip by the electrons in a length L of acceleration, where L is given by

$$L = \frac{l}{1 - \sqrt{1 - \omega_c^2/\omega^2}}. \tag{15}$$

A final consideration is that the electrons in a bunch can only extract the energy present in the part of the rf wave slipping by the electrons. By comparing the bunch's energy gain in a wiggler period to the power in the rf that is slipping by the electrons we find that the energy balance is satisfied if

$$E_{z,\text{ave}} ab \left(\frac{a}{\Delta}\right)^2 > 2ne\pi^2 c\sqrt{\mu/\varepsilon}\, \frac{\omega_c^2}{\omega^2} \frac{\sqrt{1 - \omega_c^2/\omega^2}}{1 - \sqrt{1 - \omega_c^2/\omega^2}}, \tag{16}$$

where n is the number of electrons in a bunch. This expression is easily verified by considering the case where the bunch is accelerated over a distance L, slipping by an rf pulse of length l. The energy gain of the bunch ($LneE_{z,\text{ave}}$) cannot exceed the total energy of the rf pulse ($Pl/c\sqrt{1 - \omega_c^2/\omega^2}$). For the case where the operating frequency is twice the cutoff frequency this requires that the left hand side of Equation (16) is greater than $n5.7710^{-7}$ Vm, or 3600 Vm per nanoCoulomb of charge. Note that for a given geometry the power balance can be satisfied either by decreasing the ripple amplitude or by increasing the accelerating gradient (because the power in the rf scales as the gradient squared).

4 EXAMPLES OF INVERSE AXIAL FEL ACCELERATION

In this section we will pick some possible dimensions and laser wavelengths and evaluate the inverse axial FEL acceleration mechanism. The main limitations to this acceleration mechanism arise from surface breakdown issues and from attenuation of the rf mode in the waveguide.

The first important limitation on this type of device results from the maximum possible field on the waveguide surface. If a suitable open boundary waveguide can be found, both the average accelerating gradient and the ripple period can be increased, and the ripple amplitude can be decreased. As an example, let us consider a 1.5 THz mode in a waveguide with dimensions $a = 1$ mm and $b = 0.5$ mm and a convenient ripple period of 2.0 cm. With a ratio of ripple amplitude to horizontal waveguide dimension $\Delta/a = 0.015$ we find that a 13 TW rf field would produce an average accelerating gradient of 1 GV/m, but with a surface gradient of 44 GV/m. It should be noted that this power is about two orders of magnitude lower than laser power proposed for some Smith-Purcell acceleration schemes.[10]

In order to escape this limitation, let us consider a lower rf frequency in this waveguide, such that $\sqrt{1 - \omega_c^2/\omega^2} = 0.866$. As before the cutoff frequency is $f_c = 424$ GHz, but now the operating frequency is 848 GHz (the free-space wavelength is 354 μm). From the synchronism equation the periodicity of the waveguide is 2.65 mm. Let us additionally assume that the ripple amplitude is 10%, and that the maximum allowable transverse gradient on the waveguide surface is 1 GV/m.

These conditions lead to an accelerating gradient of 0.25 GV/m with a required rf power of 1.46 GW at the operating frequency. This gradient and ripple amplitude satisfies the energy balance equation, Equation (16). Accelerating one nanoCoulomb of charge to 1 TeV requires 1 kJ of energy. A 1 μsec long rf pulse at this power has 1.46 kJ, enough for the electron bunch acceleration. This rf pulse is 260 m long, and the electron bunch, using Equation (15), takes about 2000 m to pass through the entire rf pulse. Thus a 1 TeV accelerator could be constructed in two continuous segments of waveguide separated by a dispersive section that delays the electron bunch 1 μsec to reestablish synchronism between the electron bunch and the rf pulse. Because the waveguide dimension is small, small-bore magnets can be used to provide an axial guide field for the electrons and to help provide magnetic insulation against breakdown. Quadrupoles, dipoles, and other focusing and steering elements could also be outside the waveguide and would not require additional beamline space where there is no acceleration. Thus an entire TeV accelerator could be built in a distance less than 10 km.

The required power generation at this frequency is within current technology capabilities. Gigawatt power levels at microwave frequencies has been demonstrated with FELs,[11] although at shorter pulse lengths. The advantage of this scheme, over using a slow-wave structure, is that the ripple dimension is about an order of magnitude larger than the dimension of the rf wavelength whereas the dimensions of a slow-wave structure must be comparable to the rf wavelength.

The normalized emittance growth estimate (Equation (10)) for either case is about 0.1 πmm mrad if the beam size is 100 μm and the bunch length is 5° of phase long.

The second main limitation of this acceleration concept is from rf losses in the waveguide. For a standard copper waveguide the mode attenuation rate would be too high at these frequencies. The mode decays exponentially as $e^{-\alpha z}$, where

$$\alpha = \frac{3}{2} \frac{R_s}{b\sqrt{\mu/\varepsilon}\sqrt{1 - \omega_c^2/\omega^2}} \tag{17}$$

and where the surface resistivity for normal copper is $R_s = 2.6110^{-7}\sqrt{f}$ in ohms if the frequency is specified in Hertz. For the 848 GHz case discussed above the fields would drop to one half their amplitude in about 3/4 meter. A layered metal/dielectric structure, in common use for low-loss transmission lines,[12] could be used to reduce the attentuation significantly, as could materials with lower resistivity than room-temperature copper. Additionally, the attentuation of the mode's fields due to reflections from the ripples would have to be minimized. The power reflected per ripple period scales as the square of the ripple amplitude, whereas the power gain per unit distance is proportional to the ripple amplitude. Thus the attenuation due to reflections for a distance corresponding to a fixed energy gain will scale proportional to the ripple amplitude, which can always be reduced to bring the attenuation to an acceptable value. Note that if the transverse electric field can be increased the device can be operated further away from cutoff which elongates the ripple period, decreases the number of ripple periods per unit energy gain, and decreases the total power reflected per unit energy gain. Alternatively, the rf source can emit multiple shorter pulses which are independently directed to different sections of the accelerator, each of which copropagates a much shorter distance with the electron bunch. Note that if multiple shorter rf pulses are used they can be transported to the accelerator in a circular TE_{0m} mode, which has negligible attenuation at high frequency.

Other important issues include the frequency stability of the rf, wakefield effects, and the angular rotation of the rf fields.

If the rf source has too large a bandwidth the phase of the rf will become incoherent after many wiggler periods. Using the synchronism equation the phase shift per wiggler period is

$$\Delta\phi = -\frac{\delta k}{k} \frac{2\pi}{\sqrt{1 - \omega_c^2/\omega^2}} \tag{18}$$

where δk is the shift in the wavenumber. For the above case we are considering about a million wiggler periods — this would require a source frequency stability on the order one part in a million, or, lacking that, multiple rf sources.

The wakefield produced in the accelerating structure will drive all the waveguide modes, some of which may have a phase velocity that leads to a resonant interaction with the electron beam. These beam-breakup modes can be eliminated by periodically changing the waveguide width and ripple period slightly while maintaining synchronism with the inverse axial-free-electron laser interaction. These periodic shifts will make it extremely unlikely that any beam-breakup mode can copropagate with the beam over any appreciable distance. The wakefield will also decrease the amplitude of the fundamental mode in a manner consistent with the mode losing energy to the electron bunch. This feature could lead to an accelerating gradient slew across the bunch (up to 14% for the 848 GHz case discussed above). However, the electron bunch can be phased such that the back of the bunch is closer to the phase where a single particle would gain the most energy. Thus the effect of the decrease in the mode's amplitude is offset by the increasing interaction strength with the rf. This is a common technique used to control the effect of wakefields in standing-wave accelerating structures[13] and typically leads to smaller energy spreads than possible without the wakefields.[14] However this may lead to a somewhat lower effective accelerating gradient and may require a relatively long bunch length.

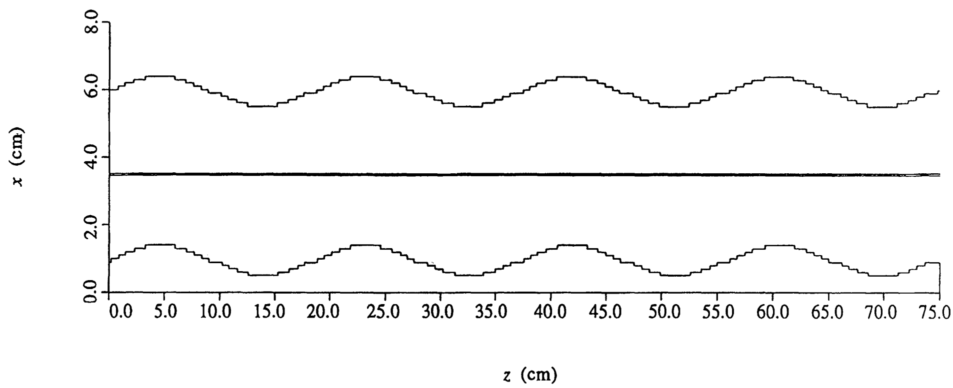
Another potential issue is the angular rotation of the axial electric field as the waveguide changes direction. For the ripple amplitude and dimensions described in the first case this angular change is less than 80 mrad. For an electron phased for maximum energy gain the net transverse force cancels over a ripple period and is negligible for small phase offsets. Also, the effect of the ripples on the rf mode's phase and group velocity are negligible. An 80 mrad angle would introduce about a 0.3% change in the longitudinal mode propagation velocity which is almost two orders of magnitude less than the difference between the bunch's velocity and the rf group velocity for the condition that $\sqrt{1-\omega_c^2/\omega^2}=0.866$.

Now let us consider a lower frequency application, for example a 17 GHz pulse in a waveguide of dimensions 5 cm by 2.5 cm. At this frequency a 5 degree bunch is just under 1 ps long. We now find that we have a 10 MV/m average accelerating gradient in a 1.3 GW rf field for a ripple amplitude of 10%. This power is comparable to that in the first case but because of the power flow scaling with the transverse waveguide size it now leads to an unremarkable gradient. However, this combination of frequency, power, and electron bunch length conveniently matches existing or emerging accelerator technologies.[9,15–17] An experiment to demonstrate this interaction mechanism could be easily performed at this frequency and allow an evaluation of the interaction's effect on the electron beam quality as a function of the ripple amplitude, beam size, and other relevant parameters. Using Equation (17) we find that the mode attenuates a factor of two in standard copper waveguide after 250 meters, sufficiently low for a demonstration experiment. In addition, an accelerator with an average accelerating gradient of 100 MV/m could be built at this frequency if a 130 GW source can be developed.

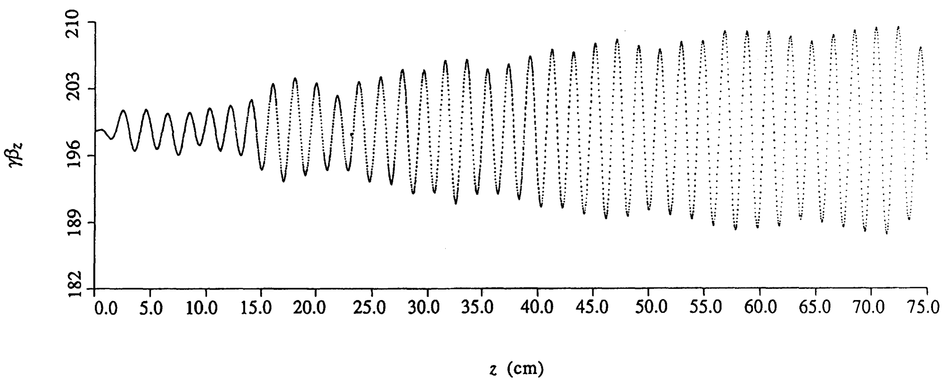
In Figure 4, we demonstrate the inverse axial-free-electron laser mechanism for the lower frequency application using the particle-in-cell code ISIS[18] for an injection energy of 100 MeV. A DC electron beam was used in the simulation to demonstrate the energy gain or loss for all injection phases as the beam travels down the device. The x–z geometry is shown in Figure 4(a). The energy gain or loss should depend on the injection phase, as we see in Figure 4(b). The slight oscillation in the growing energy envelope results from a minor mismatch in the phase velocity of the incoming electromagnetic wave in the simulation which introduces other waveguide modes and is not inherent in the acceleration mechanism.

5 CONCLUSION

We have presented an analysis of the inverse axial FEL acceleration mechanism and have shown that exceptionally high gradients are possible using as rf-sources free-electron lasers that are technically achievable. In addition, good beam quality can be preserved with this form of acceleration due to the linear nature of the fields near the axial electric field null. The acceleration mechanism additionally provides for long copropagation, and a single rf pulse can be used to accelerate the electron bunch to high energy.



(a)



(b)

FIGURE 4: (a) Geometry showing thin beam in a rippled waveguide for PIC simulation. (b) Buildup in the axial momentum for all injection phases as a function of position along the accelerator.

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