Contribution to
Advanced Accelerators Workshop
Port Jefferson, NY
June 14-20, 1992

BNL--47616

DE92 016097

POWER EXCITATION BY THE USE OF A RF WIGGLER*

A.G. Ruggiero

Brookhaven National Laboratory
Upton, NY 11973, USA

INTRODUCTION

It is well-known[1] that there are difficulties to obtain rf power sources of significant amount for frequencies larger than 3 GHz. Yet, rf sources in the centimeter/millimeter wavelength range would be very useful to drive, for example, high-gradient accelerating linacs for electron-positron linear colliders.[2] Ordinary conceived methods to produce radiation with short wavelengths is to let a bunch of electrons to travel on a circular orbit by the action of bending magnets[3] or along a magnetic structure with alternating field direction as in *wigglers* or in *undulators*[4]. Application of these devices to generate radiation in the centimeter-to-millimeter wavelength range, has often been proposed, and in a few cases also demonstrated[5-7].

We would like to propose an alternative method to produce such radiation. It makes use of a short electron bunch traveling along the axis of a waveguide which is at the same time excited by a TM propagating electromagnetic wave.[8] It is well known that radiation can be obtained by *wiggling* the motion of the electrons in a direction perpendicular to the main one.[4] The wiggling action can be induced by electromagnetic fields in a fashion similar to the one caused by wiggler magnets. We found that an interesting mode of operation is to drive the waveguide with an excitation frequency very close to the cut off. For such excitation, the corresponding e.m. wave travels with a very large phase velocity which in turn has the effect to increase the wiggling action on the electron bunch.

Our method, to be effective, relies also on the *coherence* of the radiation; that is the bunch length is taken to be considerably shorter than the radiated wavelength.[9,10] In this case, the total power radiated should be proportional to the square of the total number of electrons in the bunch.

The paper concludes with possible modes of operation, a list of performance parameters and a proposed experimental set-up.

* Work performed under the auspices of the U.S. Department of Energy.
Contribution to the Advanced Accelerator Concepts Workshop, Port Jefferson, NY, 14-20 June 1992

FIELD DISTRIBUTION IN A WAVEGUIDE

We shall consider an infinitely long *waveguide*, straight, with rectangular cross-section of width w and height h. We shall introduce a rectangular co-ordinate system x, y and z; where x and y are the transverse distances from the upper left corner of the waveguide (see Fig. 1) and z is the longitudinal coordinate along the axis. In this section we describe the propagation of a TM traveling electromagnetic wave in the waveguide.[11] If we use the Lorentz representation, the fields can be derived from a scalar V and vector potential $\mathbf{A}$ satisfying the following equations

$$\nabla^2 V - \frac{1}{c^2}\frac{\partial^2 V}{\partial t^2} = 0 \tag{1}$$

$$\nabla^2 \mathbf{A} - \frac{1}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} = 0 \tag{2}$$

$$\text{div } \mathbf{A} + \frac{1}{c}\frac{\partial V}{\partial t} = 0 \tag{3}$$

In cartesian coordinates the explicitly form of Eq. (1) is

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 V}{\partial t^2} = 0 \tag{4}$$

A solution of Eq. (4) is

$$V = V_0\,(\sin\alpha_1 x + V_1\cos\alpha_1 x)\,(\sin\alpha_2 y + V_2\cos\alpha_2 y)\,e^{i(kz-\omega t)} \tag{5}$$

The nature of the traveling wave is described by the last factor where ω is the angular frequency and k the wave number which defines the longitudinal propagation mode. Insertion of Eq. (5) into Eq. (4) yields

$$k^2 = \frac{\omega^2}{c^2} - \alpha_1^2 - \alpha_2^2 \tag{6}$$

The horizontal and vertical propagation constants, respectively α_1 and α_2, are to be determined by specifying proper boundary conditions of the electric and magnetic fields at the walls of the waveguide. The same boundary conditions will be used to estimate V_1 and V_2 appearing at the right-hand side of Eq. (5).

According to the conventional waveguide terminology[11], a TM mode is defined as that traveling wave with vanishing magnetic field in the main direction of propagation, that is the z-axis of the waveguide. This mode is associated to solutions of the vector potential $\mathbf{A}$ which actually is completely directed along the z-axis

$$\mathbf{A} \equiv (0, 0, A) \tag{7}$$

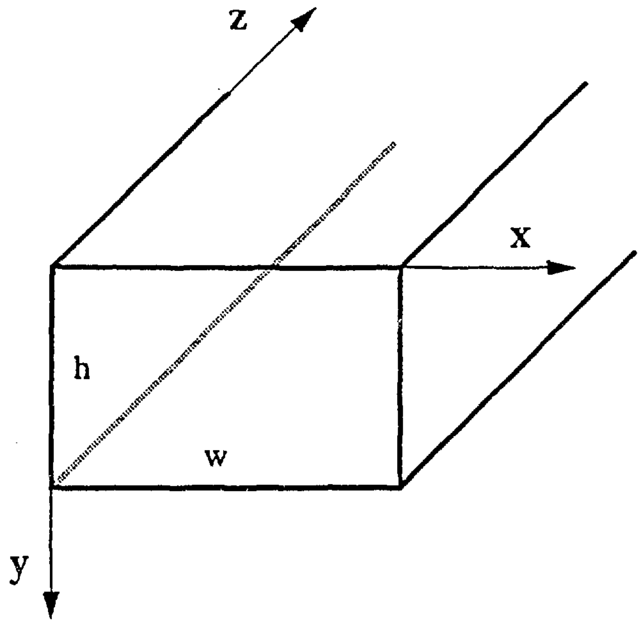

Fig. 1: Waveguide Geometry.

where A satisfies an equation similar to Eq. (4). Moreover, to satisfy the Lorentz condition represented by Eq. (3)

$$A = \beta_w V \tag{8}$$

where

$$\beta_w = \omega / kc \tag{9}$$

is the wave phase velocity, normalized to the speed of light. Thus the vector potential **A** is completely determined from the knowledge of the scalar potential V.

The electric **E** and magnetic **B** fields can be determined from the usual relations

$$\mathbf{E} = -\text{grad } V - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} \tag{10}$$

$$\mathbf{B} = \text{rot } \mathbf{A} \tag{11}$$

We shall take the walls of the waveguide with the most general electromagnetic properties, described by the surface characteristic impedance ξ, a complex function of the angular frequency ω. As shown in ref. [8] we derive easily

$$V_j = -i \frac{\xi \beta_w \alpha_j}{k\,(\beta_w^2 - 1)} \tag{12}$$

where we let $j = 1$ or 2. Letting

$$tg\ \mu_j = \frac{2i\xi\beta_w\alpha_j k\left(\beta_w^2 - 1\right)}{k^2\left(\beta_w^2 - 1\right)^2 + \xi^2\beta_w^2\alpha_j^2} \tag{13}$$

it has been shown[8] that the eigenvalues of α_1 and α_2 are given by

$$\alpha_1 w - \mu_1 = \pi n \tag{14}$$

$$\alpha_2 h - \mu_2 = \pi m \tag{15}$$

with n, m integer real numbers. These equations can be used in conjunction to Eq. (6) to calculate the propagation constant k.

The constant V_0 in Eq. (5) determines the amplitude of the field potential and is related to the power flux in the waveguide. The following relation is obtained[8,11]

$$P = \frac{c\beta_w}{64}\pi V_0^2\left(\frac{k}{w}n^2 + \frac{w}{h}m^2\right) \tag{16}$$

where we have ignored the effect of the wall impedance.

PERFECTLY CONDUCTIVE WAVEGUIDE

A special case is a waveguide with perfectly conductive walls, that is $\xi = 0$. In this case it is easily seen that $V_1 = V_2 = 0$ and $\mu_1 = \mu_2 = 0$; moreover k^2 is real. Solving Eq. (6) gives the following dispersion relation

$$k = \sqrt{\frac{\omega^2}{c^2} - \frac{\omega_c^2}{c^2}} \tag{17}$$

where

$$\omega_c = \pi c\sqrt{\frac{n^2}{w^2} + \frac{m^2}{h^2}} \tag{18}$$

is the angular frequency at *cut-off*. It is convenient to introduce the form factor

$$q = \omega_c/\omega \tag{19}$$

It is seen from Eqs. (6 and 9) that

$$\beta_w = \frac{1}{\sqrt{1 - q^2}} \tag{20}$$

The range of values of the form factor fulfilling the *condition of propagation*, which corresponds to k positive, is

$$0 < q < 1 \tag{21}$$

that is $\omega > \omega_c$. It is then seen that β_w is always real and larger than 1: that is the wave phase velocity is always larger than the speed of light.

An inspection of the dispersion relation shows that below the cut-off, $\omega < \omega_c$, there is no propagation, and k assumes no real values. For large values of ω, k increases about linearly. An interesting plot, shown in Fig. 2, is the display of the wave phase velocity β_w versus the form factor q as given by Eq. (20). Observe that approaching the cut-off from below, $q \to 1$, the phase velocity β_w becomes infinitely large.

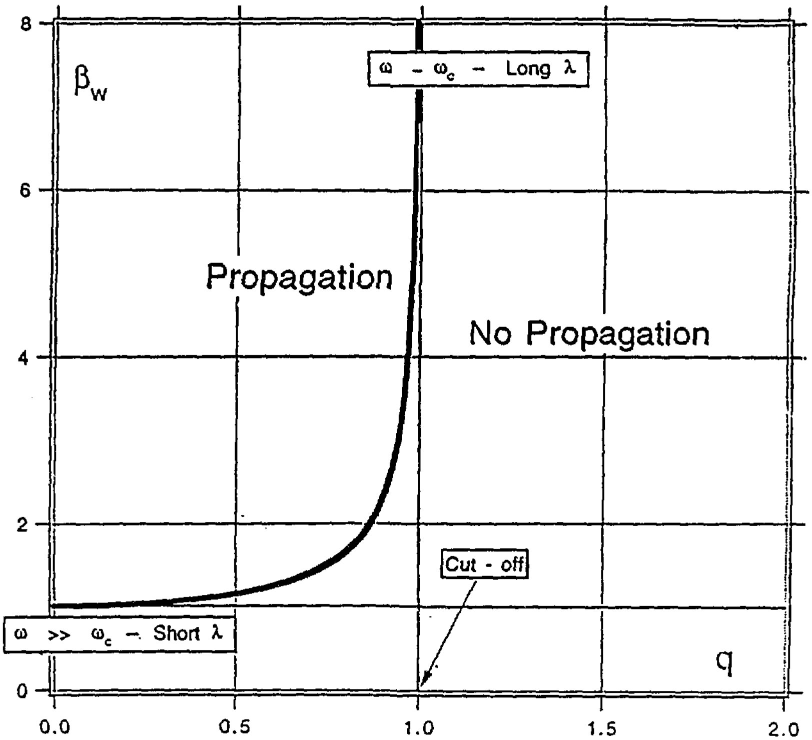

Fig. 2: Phase Velocity vs. Form Factor.

WAVEGUIDE WITH RESISTIVE WALLS

In the following we consider the case of *resistive* walls. For this case the surface characteristic impedance is

$$\begin{aligned}\xi &= (1-i)\sqrt{\frac{\omega\mu}{8\pi\sigma}} \\ &= (1-i)\,\mathcal{R}\end{aligned} \tag{22}$$

where σ is the electric conductivity and μ the magnetic permeability of the wall material. The dispersion relation Eq. (6) can now be written

$$k^2 = \frac{\omega^2}{c^2} - \frac{\omega_c^2}{c^2} - \Delta^2 \tag{23}$$

where

$$\Delta^2 = \frac{\mu_1^2}{w^2} + \frac{\mu_2^2}{h^2} + 2\pi\left(\frac{n\mu_1}{w^2} + \frac{m\mu_2}{h^2}\right) \tag{24}$$

and k, Δ are complex quantities. Let us separate explicitly the real and imaginary parts; that is

$$k = k_r + i\ k_i \tag{25}$$

$$\Delta = \Delta_r + i\ \Delta_i \tag{26}$$

then

$$2k_r^2 = \frac{\omega^2 - \omega_c^2}{c^2} - \Delta_r^2 + \Delta_i^2 + \sqrt{\left(\frac{\omega^2 - \omega_c^2}{c^2} - \Delta_r^2 + \Delta_i^2\right)^2 + 4\Delta_r^2\Delta_i^2} \tag{27}$$

and

$$k_i = -\frac{\Delta_r\Delta_i}{k_r} \tag{28}$$

The last quantity k_i is the measure of the wave propagation attenuation per unit length, whereas k_r is the proper constant of propagation of the wave. The wave phase velocity is then given by

$$\beta_w = \frac{\omega}{ck_r} \tag{29}$$

from which we can derive the following relation to the form factor q

$$\beta_w^2 = \frac{2}{\left(1 - q_0^{-2}q^2\right) + \sqrt{\left(1 - q_0^{-2}q^2\right)^2 + 4c^4\frac{\Delta_r^2\Delta_i^2}{\omega_c^4}q^4}} \tag{30}$$

where

$$q_0^{-2} = 1 + \frac{c^2}{\omega_c^2}\left(\Delta_r^2 - \Delta_i^2\right). \tag{31}$$

Both Δ_r and Δ_i depend on the angular frequency ω and the propagation constant k; nevertheless in the case of a good conductor, for instance copper with $\mu = 1$ and $\sigma = 5 \times 10^{17}\ \mathrm{s}^{-1}$, one can treat the contribution of the surface characteristic impedance $\mathcal{R}$, given by Eq. (22), as a perturbation to the field distribution. In proximity of the cut-off we can then let $\mathcal{R} = \mathcal{R}_c$ where $\mathcal{R}_c$ is $\mathcal{R}$ evaluated for $\omega = \omega_c$. Inspection of Eqs. (30 and 31) shows that β_w^2 is always a positive quantity for any value of q; the maximum occurs for $q = q_0$, which can be interpreted as a shift of the cut-off frequency. At cut-off the maximum is

$$\beta_{w_{\max}}^2 \approx \frac{\omega_c^3}{2\pi^2 c^3 \mathcal{R}_c\left(\frac{n^2}{w^3} + \frac{m^2}{h^3}\right)} \tag{32}$$

COMPARISON OF DIFFERENT METHODS

For an electron moving along the longitudinal direction z, the field distribution in a waveguide is different from that the same electron would experience in the case of a wiggler magnet or a photon beam. To see this, we can operate a transformation of the field distribution in the frame where the electron is at rest. Let β and γ be the relativistic factors respectively for velocity and energy of the particle. Let us first consider the case of a planar electromagnetic wave moving in the z-direction. The electric and magnetic fields are perpendicular to each other and perpendicular to the direction of motion. The components of the fields of the plane wave in the laboratory frame are

$$E_y = E_z = B_x = B_z = 0 \qquad (33)$$

$$E_x = B_y = E_0 \; e^{i(kz-\omega t)} \qquad (34)$$

where E_0 is a constant amplitude, ω the angular frequency and k the propagation constant of the wave. After performing the relativistic transformation, the components of field distribution of the same wave, in the system where the electron is at rest, are

$$E'_y = E'_z = B'_x = B'_z = 0 \qquad (35)$$

$$E'_x = B'_y = \gamma(1+\beta)\, E_0 \; e^{i(k'z'-\omega' t')} \qquad (36)$$

where we have denoted with prime the variables in the frame at rest. We have

$$k' = \gamma\left(k - \omega\frac{\beta}{c}\right) \qquad (37)$$

$$\omega' = \gamma(\omega - \beta kc) \qquad (38)$$

In the vacuum $k = \omega/c$ and the previous relations become

$$\omega' = \gamma(1-\beta)\,\omega \qquad (39)$$

$$k' = \omega'/c \qquad (40)$$

Now let us consider the case of a wiggler magnet, that is a sequence of dipole magnets where the magnetic field is in the y-direction and changes periodically sign from one magnet to the next. Let L be the periodicity of the wiggler. In the laboratory frame the field components are

$$B_x = B_z = 0 \qquad (41)$$

$$E_x = E_y = E_z = 0 \qquad (42)$$

$$B_y = \pm B_w \qquad (43)$$

where B_w is the wiggler field. There is no electric field in a wiggler. After performing the Lorentz transformation where the electron is at rest, one obtains a field distribution similar to that given by Eqs. (35,36) except that

$$E'_x = \beta\gamma B_w \qquad (44)$$

$$B'_y = \gamma\, B_w \qquad (45)$$

To a relativistic electron with $\beta \sim 1$, the wiggler is equivalent to a plane electromagnetic wave with amplitude $E_0 \simeq B_w/2$ and

$$\omega' = c\gamma k_w \tag{46}$$

where $k_w = 2\pi/L$. Thus the interaction of an electron with a planar electromagnetic wave or with a wiggler magnet is the same; if the electron moves against the wave, the consequence is a Compton scattering by which the electron loses energy and the photon field intensity increases.

Let us turn now our attention to the field distribution in the waveguide. After the Lorentz transformation to the frame where the electron is at rest is performed, the new field distribution is given by

$$E'_z = E_z \tag{47}$$
$$E'_x = \gamma(1-\beta\beta_w)\,E_x \tag{48}$$
$$E'_y = \gamma(1-\beta\beta_w)\,E_y \tag{49}$$

$$B'_z = 0 \tag{50}$$
$$B'_x = -\gamma(\beta_w-\beta)\,E_y \tag{51}$$
$$B'_y = \gamma(\beta_w-\beta)\,E_x \tag{52}$$

where k and ω are replaced by k' and ω' also given by Eqs. (37-38). Since ω and k are related to each other by the phase velocity given by Eq. (9), it is

$$k' = \gamma k\,(1-\beta\beta_w) \tag{53}$$
$$\omega' = \gamma k c\,(\beta_w-\beta) \tag{54}$$

from which the phase velocity in the rest frame is

$$\beta'_w = \frac{\omega'}{k'c} = \frac{\beta_w-\beta}{1-\beta\beta_w} \tag{55}$$

If we neglect the longitudinal component E'_z, it is seen that the two vectors $\mathbf{E}'$ and $\mathbf{B}'$ are perpendicular to the main direction of motion and to each other. Also, for a relativistic electron, $\beta \sim 1$ and the two vectors have about the same magnitude. This represents also an electromagnetic wave, but having nonplanar properties. Since $\beta_w > 1$, it is seen from Eq. (55) that in order for the wave to propagate in the positive direction of the z-axis also in the frame at rest, the electron should move in the opposite direction ($\beta < 0$) to start with. This will create an enhancement of the equivalent field as seen by the electron; otherwise, if the wave and the particle would move in the same direction there would be a cancellation, which is the most effective when $\beta_w \sim 1$ that is in the short wavelength regime, with frequencies ω well above the cut-off value ω_c. In the other regime with $\beta_w \gg 1$, in proximity of the cut-off, which corresponds to long wavelengths λ, the cancellation does not apply: a part from a sign, the amplitude of the wave is then proportional to

$\gamma\beta_w$ independently of the direction of motion of the electron with respect to the wave.

A case of interest is the following. The electron and the e.m. wave, as seen in the laboratory frame, are moving in the same direction, which is the positive direction of the z-axis of the waveguide, as shown in Fig. 3. Assume $\beta \sim 1$ and $\beta_w \gg 1$; then, from Eq. (55), $\beta'_w \sim -1$ and, in its own frame at rest, the electron sees a wave moving against its position; the consequence is again a forward Compton scattering. Let us also suppose that initially $x = y = 0$, then the only nonvanishing field components are

$$E'_x = 2\pi \frac{V_0}{w} \gamma \left(\beta\beta_w - 1\right) \cos\phi \tag{56}$$

$$B'_y = -2\pi \frac{V_0}{w} \gamma \left(\beta_w - \beta\right) \cos\phi \tag{57}$$

which have an amplitude

$$\gamma E_w = 2\pi \frac{V_0}{w} \gamma\beta_w \tag{58}$$

that is to be compared to the value γB_w corresponding to a magnetic wiggler. Inspection of Eq. (58) shows that the field amplitude can reach very large values when driving the waveguide in proximity of the cut off.

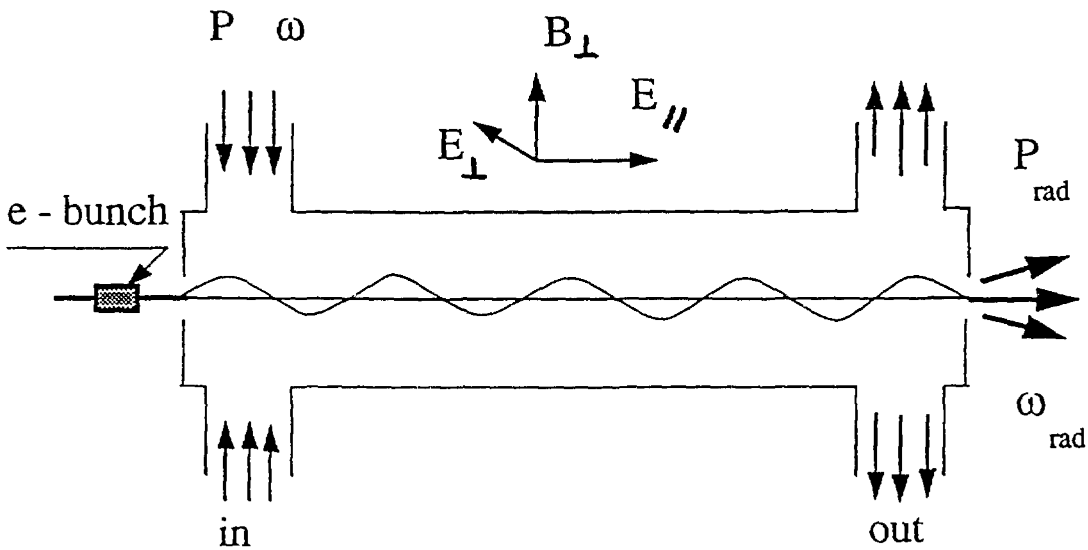

Fig. 3: The rf Wiggler Concept.

THE EQUATIONS OF MOTION

Consider now an electron with mass at rest m and electric charge e moving down the waveguide. The components of the equations of motion are

$$\frac{dp_x}{dt} = -e\left(\frac{\dot{z}}{c}\beta_w - 1\right)E_x \tag{59}$$

$$\frac{dp_y}{dt} = -e\left(\frac{\dot{z}}{c}\beta_w - 1\right)E_y \tag{60}$$

$$\frac{dp_z}{dt} = e\left(\frac{\dot{x}}{c}\beta_w E_x + \frac{\dot{y}}{c}\beta_w E_y + E_z\right) \tag{61}$$

where $\mathbf{p} \equiv (p_x, p_y, p_z)$ is the momentum and $\mathbf{v} \equiv (\dot{x}, \dot{y}, \dot{z})$ the velocity vector.

The equations of motion simplify considerably if we assume that the motion of the electron is confined in proximity of the $y = -h/2$ plane. In this case, if n is even and m is odd, $y = \dot{y} = 0$ is a solution of the equations of motion since $E_y = 0$. Moreover, if also x is very close to the $x = w/2$ axis, then in good approximation the equations of motion are

$$\frac{dp_x}{dt} \approx e\left(\frac{\dot{z}}{c}\beta_w - 1\right)V_0\alpha_1 \cos\phi \tag{62}$$

$$\frac{dp_y}{dt} \approx 0 \tag{63}$$

$$\frac{dp_z}{dt} \approx -e\frac{\dot{x}}{c}\beta_w V_0 \alpha_1 \cos\phi \tag{64}$$

where we have taken the real part of the traveling wave exponential factor and $\phi = kz - \omega t$.

It is seen that the perturbation to the longitudinal motion is of first order in $\dot{x}$ and it can thus be neglected. At the same time

$$\begin{aligned} \frac{d\phi}{dt} &= k\dot{z} - \omega \\ &\approx kv - \omega \\ &\approx ck(\beta - \beta_w) = -\Omega_0 \end{aligned} \tag{65}$$

Since $\beta_w > \beta$ this quantity is always negative. A phase slippage occurs when the particle and the electromagnetic wave are traveling in the same direction. In proximity of the cut-off, the phase slippage $\Omega_0 \approx \omega$. It is reasonable to assume that during the interaction with the electromagnetic wave, the velocity β of the electron does not change considerably and it remains close to unit.

In the approximation that the horizontal displacement remains small, that is $x \ll w/2$, Eq. (62) can be written as

$$\ddot{x} = \Omega^2 w \cos\phi \tag{66}$$

where

$$\Omega^2 = eV_0\alpha_1 \frac{\beta\beta_w - 1}{m_0\gamma w} \tag{67}$$

With a change of variables Eq. (66) becomes

$$\frac{d^2x}{d\phi^2} = \nu^2 w \cos\phi \tag{68}$$

with

$$\nu = \Omega/\Omega_0 \tag{69}$$

The solution of Eq. (68) can be easily derived to be

$$x = -a\cos\phi \tag{70}$$

that is an oscillation at the frequency equal to the phase slippage Ω_0 and amplitude

$$a = w\nu^2 \tag{71}$$

The solution given by Eq. (70) is correct only as long as the amplitude a of the oscillation is small compared to the width w of the waveguide, that is $\nu^2 \ll 1$, which sets a limit on the value of the voltage amplitude V_0.

ENERGY LOSS BY RADIATION

Consider an electron which is moving at relativistic velocity along the z-axis and at the same time is performing small amplitude oscillations at the angular frequency Ω_0. It is well known that the electron will lose energy by radiating electromagnetic waves moving forward in the same direction of the motion of the particle, within an angular aperture of about $1/\gamma$. In the approximation that the oscillatory motion has been occurring for an infinitely long period of time, the spectrum of the radiation is made of only one line at the angular frequency[4]

$$\omega_{\text{rad}} = 2\gamma^2\Omega_0 \tag{72}$$

The radiated power at that frequency by one electron can also be calculated

$$P_0 = \frac{1}{3}\frac{e^2}{c^3}\gamma^4 a^2 \Omega_0^4 \tag{73}$$

where a is the amplitude of the oscillation.

In the extreme case where the beam bunch is much longer than the wavelength of the radiation $2\pi c/\omega_{\text{rad}}$, each electron will radiate independently from the others and the total power radiated is $P_{\text{rad}} = NP_0$ where P_0 is the power from a single electron, given by Eq. (73), and N the total number of electrons in the bunch. On the other hand, when the bunch length is considerably smaller than the radiated wavelength it is conceivable that all the electrons are radiating *coherently* and in this case the total power is[9]

$$P_{\text{rad}} = N^2 P_0 \tag{74}$$

At the same time, though, in order to take advantage of this effect, it is also important that the transverse dimensions of the electron beam are made as small as possible. Indeed, they should not exceed the amplitude of the oscillations given by Eq. (71) and should be smaller than the bunch length itself.

APPLICATIONS

It is convenient to define two parameters that best summarize the interaction between the electron motion and the field in the waveguide. One is the *frequency transformer ratio* $r = \omega_{\mathrm{rad}}/\omega$, that is the ratio of the *radiated* frequency to the *input* frequency to the waveguide. From Eqs. (65 and 72) we derive

$$r = 2\gamma^2 \frac{\beta_w - \beta}{\beta_w} \tag{75}$$

In proximity of the cut-off $\beta_w \gg 1$ and with good approximation $r \sim 2\gamma^2$.

The second parameter is the *power amplification factor* $\eta = P_{\mathrm{rad}}/P$, that is the ratio of the power radiated by the beam bunch to the *input* power to the waveguide. Assuming that the condition of short bunches is satisfied, we derive

$$\eta = \frac{64N^2 r_0^2 \gamma^2 \pi n^2 \left(\beta\beta_w - 1\right)^2}{3hw^3 \left(\frac{n^2}{w^2} + \frac{m^2}{h^2}\right) \beta_w} \tag{76}$$

where $r_0 = 2.82 \times 10^{-15}$ m is the classical electron radius. An optimum case is given by a waveguide with a square cross- section, that is $h = w$, and by the lowest order of propagation, namely $m = 1$ and $n = 2$. In proximity of the cut-off then

$$\eta \simeq \frac{256}{15} \pi N^2 \gamma^2 \frac{r_0^2}{w^2} \beta_w \tag{77}$$

and from Eqs. (18 and 32)

$$\beta_w^2 \approx \frac{w\omega_c}{2c\,\mathcal{R}_c} \tag{78}$$

An application is a *frequency transformer*. In this mode of operation the power radiated by a short electron bunch is at a frequency larger than the one used in input to the waveguide. In this case it is sufficient that the power gain $\eta \sim 1$. An example of frequency transformer is shown in Table 1, where the waveguide material is taken to be warm temperature copper and the waveguide itself is driven in proximity of the cut-off where the phase velocity β_w is the largest.

An experimental demonstration of the method of generating power with the use of the rf wiggler is useful and feasible. It can be executed at the Accelerator Test Facility either at Brookhaven[12] or at Argonne National Laboratory[13]. A proposed experimental set up is shown in Fig. 4. Because of the relatively low energy of the electrons, the rf wiggler is immediately attached to the electron gun. It is followed by a dipole magnet to bend the electron beam out of the way and by a second waveguide properly terminated to trap and absorb the emitted radiation. The measurement and the experiment shall then be conducted as explained in ref. [10] which describes a similar experiment with a conventional wiggler (magnetic).

Table 1: An Example of Frequency Transformer

Kinetic Energy of Electrons	4 MeV
Number of Electrons	6×10^{10}
Bunch Length	1 mm
Input Frequency	1.3 GHz
Radiated Frequency	190 GHz
Frequency Transform Ratio	146
Power Amplification Factor	0.5
Phase Velocity, β_w	350
Cut-off Frequency	1.3 GHz
Waveguide Dimension, w	25.8 cm
Period of Oscillations	24.5 cm

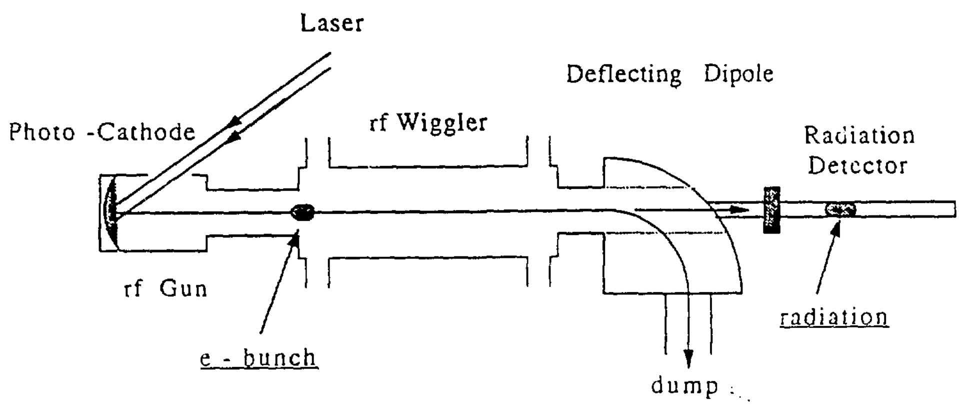

Fig. 4: Experimental Set-Up.

CONCLUSION

We have shown in this paper that it is possible to convert electromagnetic power from one frequency to another with reasonable efficiency by letting a short electron bunch interact with a waveguide driven by an electromagnetic wave in proximity of the cut-off. We have estimated the maximum power gain and the required electron bunch and dimensions; they are within reach of present state of the art of electron sources. Our method to be effective relies on the coherent radiation by which, if the wavelength radiated is larger than the bunch length, the power radiated is proportional to the square of the number of electrons in the bunch.

REFERENCES

1. M.A. Allen, et al., Proceedings of EPAC 90, Nice, France, June 1990, Vol. 1, p. 146.
2. H. Henke, Proceedings of EPAC 90, Nice, France, June 1990, Vol. 1, p. 174.
3. J. Schwinger, Phys. Rev. 75, No. 12 (1949), p. 1912.
4. J.M.J. Madey, J. Appl. Phys. 42, 1906 (1971).
5. R. Bonifacio, Proceedings of EPAC 90, Nice, France, June 1990, Vol. 1, p. 340.
6. A.M. Sessler, Proc. of the Workshop on Laser Acceleration of Particles, Los Alamos, New Mexico, 1982, AIP Conference Proceedings 91, 154 (1982).
7. T.J. Orzechowski, et al., Phys. Rev. Lett. 54, 889 (1985).
8. A.G. Ruggiero, BNL Internal Reports, AD/AP-35 and 41 (1992).
9. F.C. Michel, Phys. Rev. Lett. 48, No. 9, (1982), p. 580.
10. A.G. Ruggiero, contribution on this subject in these conference proceedings.
11. J.D. Jackson, Classical Electrodynamics, Chapter 8, John Wiley & Sons, 2nd Edition.
12. I. Ben-Zvi, 1991 Particle Accelerator Conference, IEEE 91CH3038-7, page 550.
13. P. Schoessow, et al., Proceedings of EPAC 90, Nice, France, June 1990, Vol. 1, p. 606.

DISCLAIMER