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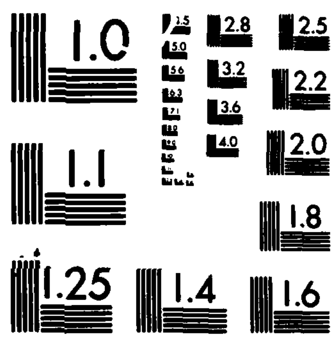

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Uniform Magnetic-Field-Induced Free-Electron Laser in a Waveguide

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We discuss how a uniform focusing magnetic field can affect the performance of a microwave source such as a backward-wave oscillator. It is argued that the uniform magnetic field can cause the existence of a free-electron laser within the waveguide; the Doppler up-and/or down-shifted cyclotron radiation can undergo amplification (or absorption) due to interaction of electrons (in helical orbits) with electromagnetic radiation.

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CONTENTS

1. INTRODUCTION

Some time ago V. S. Ivanov et al[1] observed experimentally that the output radiation power in their Cerenkov self-generator (a corrugated waveguide) can depend rather strongly on the magnitude of the focusing magnetic field. More recently, a similar phenomenon was observed at the backward-wave oscillator (BWO) experiment performed cooperatively by the Harry Diamond Laboratories (HDL) and the University of Maryland (UMD).

In this short report we wish to argue that the dependence of output radiation on the magnitude of the uniform magnetic field most likely comes from the free-electron laser (FEL)-like action within the waveguide. This FEL is due to the Doppler-shifted cyclotron radiation which can either be amplified or absorbed when the electrons (in helical orbits) interact with electromagnetic radiation (waveguide modes).

In section 2, the outline of the idea of the FEL due to the uniform magnetic field is given. Section 3 is devoted to numerical discussion and the conclusion. Our system of units is such that $\hbar = c = 1$.

2. OUTLINE OF FEL IN A WAVEGUIDE

When an electron beam is guided by a uniform magnetic field along a waveguide, it will encounter a propagating electromagnetic wave. Hence an electron from such a beam can interact simultaneously with the uniform magnetic field and the electromagnetic wave.

Now in order to see how the FEL can get established in a waveguide, let us suppose that the electron interacts first with the uniform magnetic field and then with electromagnetic radiation. Let us take the uniform magnetic field to point in the positive z-direction:

$$\vec{B} = \hat{z}B \quad . \tag{1}$$

If an electron starts interacting at, say, $t = 0$, then from the Lorentz force equation we deduce that its velocity and position can be expressed as

$$\vec{v} = \vec{v}_\perp + \vec{v}_\parallel \quad , \tag{2a}$$

$$\vec{v}_\parallel = \hat{z}v_0 \quad , \tag{2b}$$

$$\vec{v}_\perp = v_\perp^0 \left\{-\hat{x} \sin(\omega_c t + \phi) + \hat{y} \cos(\omega_c t + \phi)\right\} \quad , \tag{2c}$$

$$\vec{r} = \vec{r}_\perp + \vec{r}_\parallel \quad , \tag{3a}$$

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[1] *V. S. Ivanov, S. I. Krementsov, V. A. Kutsenko, M. D. Raizer, A. A. Rukhadze, and A. V. Fedotov, Sov. Phys. Tech. Phys.* <u>*26*</u> *No. 5 (1981), 580.*

$$\vec{r}_{\parallel} = \hat{z}(v_0 t + z_0) \quad , \tag{3b}$$

$$\vec{r}_{\perp} = \frac{v_{\perp}^0}{\omega_c} \{\hat{x} \cos(\omega_c t + \phi) + \hat{y} \sin(\omega_c t + \phi)\} + \vec{r}_{\perp}^0 \quad ,$$

$$\vec{r}_{\perp}^0 = x_0 \hat{x} + y_0 \hat{y} \quad . \tag{3c}$$

In the expressions (1), (2a-c), and (3a-c), B denotes the magnitude of the uniform magnetic field; t denotes the time; $\hat{x}$, $\hat{y}$, and $\hat{z}$ are unit vectors in x, y, and z directions, respectively; the vectors $\vec{r}$ and $\vec{v}$ denote the electron position and velocity, respectively (the parallel and perpendicular components of any vector with respect to $\hat{z}$ carry subscripts $\parallel$ and $\perp$, respectively); ϕ and all quantities that carry subscript or superscript 0 are constants of motion; while the cyclotron angular frequency, ω_c, is given in terms of the electron gyrofrequency, ω_B, as

$$\omega_c = \frac{\omega_B}{\gamma} \; , \; \omega_B = \frac{|e|B}{M} \quad , \tag{4}$$

where M is the electron mass and γ is defined as usual, $\gamma^2 = (1 - \vec{v}^2)^{-1}$, $\vec{v}^2 = v_0^2 + (v_{\perp}^0)^2$. The third component of the electron angular momentum is given as

$$\hat{z}L_3 = (\vec{r}_{\perp} - \vec{r}_{\perp}^0) \times M\gamma\vec{v}_{\perp}$$

$$= \hat{z} \frac{(v_{\perp}^0)^2 M\gamma}{\omega_c} \quad .$$

Clearly, since $L_3/[L_3] = 1$, the electron executes the right-handed helical motion. Since the quantities v_0, $v_{\perp}^0$, ϕ, and $\vec{r}_{\perp}^0$ are all constants of motion, so are γ and L_3.

One immediately sees that regardless of what the radial position of the electron guiding center is (given by x_0 and y_0), the electron will execute helical motion only if $v_{\perp}^0 \neq 0$; i.e., when the electron beam is not completely cold. Of course, $v_{\perp}^0$, the magnitude of the perpendicular velocity, and other constants of motion have to be given beforehand. From equation (2c) we see that the phase ϕ determines the direction of $\vec{v}_{\perp}$ at t = 0. However, different electrons in a beam may have different ϕ's. In fact, except for this phase dependence of $\vec{v}_{\perp}$, equation (2c), and $\vec{r}_{\perp}$, equation (3c), the electron helical motion here is very similar to the electron helical motions for the free-electron Cerenkov laser (FECL)[2] and the free-electron laser (FEL).[3] (For FEL and FECL, it is the wiggler magnet that causes the electron helical motion.)

[2] *J. Šoln, J. Appl. Phys.* 52 *(1981), 6882.*
[3] *S. K. Ride and W. B. Colson, Appl. Phys.* 20 *(1979), 41.*

Hence, in the analogy to the FECL,[2] we can immediately write down the current density that is relevant for the FEL in the waveguide:

$$\vec{j}(\vec{x},t_x) = e\vec{v}_\perp(t_x)\delta[\vec{x} - \vec{r}_\parallel(t_x)] \quad . \tag{5}$$

The Fourier transform of equation (5) is[2] (written separately for each component)

$$j_1(\vec{k},\omega;t) = -iev_\perp^0 e^{-i(k_3 z_0+\phi)} \frac{\sin[\delta\omega(\theta)t/2]}{\delta\omega(\theta)} \quad ,$$

$$j_2(\vec{k},\omega;t) = ij_1(\vec{k},\omega;t) \quad , \text{ and} \tag{6}$$

$$j_3(\vec{k},\omega;t) = 0 \quad ,$$

where t is the interaction time interval of the electron, given in terms of the length of the waveguide, L, as

$$t \simeq L/v_0 \quad . \tag{7}$$

In equation (6), the off-resonance ($\delta\omega$) and the resonance ($\bar{\omega}$) frequencies are given as

$$\delta\omega(\theta) = \left(1 - v_0 \cos\theta\right)[\omega - \bar{\omega}(\theta)] \quad ,$$

$$\bar{\omega}(\theta) = \omega_c/\left(1 - v_0 \cos\theta\right) \quad , \tag{8}$$

$$\theta = 0, \pi \quad .$$

Here it is implied that, because the current interacts with the radiation, ω in equation (8) corresponds to the frequency of the electromagnetic wave, which is either propagating in the positive ($\theta = 0$) or negative ($\theta = \pi$) z-direction.[2] This interpretation is equally valid for the free-like radiation and the waveguide TE and TM modes.[4] (In BWO's, the modes of interest are mostly TM_{01} and TM_{02} modes.[1])

[1] *V. S. Ivanov, S. I. Krementsov, V. A. Kutsenko, M. D. Raizer, A. A. Rukhadze, and A. V. Fedotov, Sov. Phys. Tech. Phys.* <u>26</u>*, No. 5 (1981), 580.*
[2] *J. Šoln, J. Appl. Phys.* <u>52</u> *(1981), 6882.*
[4] *A. Fruchtman, J. Appl. Phys.* <u>54</u> *(1983), 4289.*

In fact, in analogy to the FECL,[2] we can calculate that when there was initially no radiation present, the probability distribution function for spontaneously generating m free-like photons of any polarization and travelling in either positive or negative z-direction is simply the Poisson distribution function:

$$P_m = \frac{b^m(\vec{k},\omega;t)}{m!} \exp[-b(\vec{k},\omega;t)] \quad ,$$

$$b(\vec{k},\omega;t) = \frac{\left(ev_\perp^0\right)^2 \sin^2[\delta\omega(\theta)t/2]}{V\omega[\delta\omega(\theta)]^2} \quad , \tag{9}$$

$$\theta = 0,\ \pi \quad .$$

Here, V is the volume occupied by the electron beam, and t is given by equation (7). Now, as soon as a considerable radiation is established within interaction volume V (which may be due to spontaneous and/or other background sources), we have not only spontaneous but also stimulated radiation. In other words, an FEL has been established in the waveguide. Basically the same kind of reasoning leads to an FEL if instead of free-like radiation we talk about TE or TM waveguide modes.[4]

3. DISCUSSION AND CONCLUSION

Depending on the direction of radiation propagation, a waveguide FEL can generate (or absorb) radiation whose frequency is either a Doppler up-shifted or a Doppler down-shifted cyclotron frequency. (For simplicity, we restrict our discussion to just free-like radiation.)

From relation (8) we see that the radiation frequency, ν, and the resonant frequency, $\bar{\nu}$, are related as

$$\nu = \bar{\nu}(B;\theta) + \Delta\nu(B;\theta) \quad ,$$

$$\Delta\nu(B;\theta) = \frac{v_0[\delta\omega(\theta)t]}{2\pi L\left(1 - v_0 \cos\theta\right)} \quad , \tag{10}$$

[2] *J. Šoln, J. Appl. Phys.* *52 (1981), 6882.*
[4] *A. Fruchtman, J. Appl. Phys.* *54 (1983), 4289.*

where, in general, the gain is expected to be significantly different from zero when[2-4]

$$-10 < \delta\omega(\theta)t < 10 \quad . \tag{11}$$

The parameters that are representative of both the Ivanov et at[1] and the HDL-UMD* experiments are

$$\gamma \simeq 2.4 \quad , \quad L \simeq 20 \text{ cm} \quad ,$$

$$B \simeq 0.6 \text{ to } 1.6 \text{ T} \quad . \tag{12}$$

With these parameters we obtain for $\Delta\nu$'s

$$\Delta\nu(0) \simeq 3.7 \times [\delta\omega(0)t] \text{ GHz} \quad , \tag{13}$$

$$\Delta\nu(\pi) \simeq 0.1 \times [\delta\omega(\pi)t] \text{ GHz} \quad . \tag{14}$$

Similarly we obtain for the resonant frequencies

$$\bar{\nu}(0.6T;0) \simeq 87 \text{ GHz} \quad , \quad \bar{\nu}(1T;0) \simeq 144 \text{ GHz} \quad ,$$

$$\bar{\nu}(1.6T;0) \simeq 232 \text{ GHz} \quad , \tag{15}$$

$$\bar{\nu}(0.6T;\pi) \simeq 3.5 \text{ GHz} \quad , \quad \bar{\nu}(1T;\pi) \simeq 5.6 \text{ GHz} \quad ,$$

$$\bar{\nu}(1.6T;\pi) \simeq 9.4 \text{ GHz} \quad . \tag{16}$$

From relations (10), (11), (13), and (15), we see that the range of frequencies that can be associated with waveguide FEL in the forward direction, $\theta = 0$, is

$$\theta = 0: \nu \simeq 50 \text{ to } 270 \text{ GHz} \quad . \tag{17}$$

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[1] *V. S. Ivanov, S. I. Krementsov, V. A. Kutsenko, M. D. Raizer, A. A. Rukhadze, and A. V. Fedotov, Sov. Phys. Tech. Phys. 26, No. 5 (1981), 580.*

[2] *J. Šoln, J. Appl. Phys. 52 (1981), 6882.*

[3] *S. K. Ride and W. B. Colson, Appl. Phys. 20 (1979), 41.*

[4] *A. Fruchtman, J. Appl. Phys. 54 (1983), 4289.*

**S. Graybill, private communication, 1983.*

Similarly, from relations (10), (11), (14), and (16), we find that the range of frequencies that can be associated with waveguide FEL in the backward direction, $\theta = \pi$, is

$$\theta = \pi : \nu \simeq 2.5 \text{ to } 10.4 \text{ GHz} \quad . \tag{18}$$

Now, the slow-wave (ripple) structure of the BWO is such that it supports a radiation frequency in the range (mostly in TM_{01} and TM_{02} modes)

$$\nu = 9 \text{ to } 10 \text{ GHz} \quad . \tag{19}$$

Hence, experimentally the effects of waveguide FEL should be observed only in the backward direction (eq (18)). In the case of the BWO, the radiation, generated by the slow-wave structure, itself propagates in the backward direction and as such may contribute to the establishment of the backward waveguide FEL. However, one should keep in mind that for a fixed radiation frequency, the waveguide FEL is possible only for some values of the guiding uniform magnetic field. For example, fixing $\nu = 9$ GHz, from (4a), (4b), (8), (10), and (11), we obtain that, for

$$B \simeq 1.3 \text{ to } 1.7 \text{ T} \quad , \tag{20}$$

waveguide FEL in the backward direction is possible.

Now, how this waveguide FEL operates depends on whether the gain is positive (emission) or negative (absorption). This in turn depends on the off-resonance parameter, $\delta\omega(\pi)t$. This parameter, on the other hand, depends implicitly on parameters γ, v_0, B, and ν. For example, if we just vary B from small to large values, the gain may vary from negative values toward positive values. It appears that this was the case in the experiment of Ivanov et at,[1] where the radiated power at $\nu \simeq 9.4$ GHz increased significantly (to 1 GW) when B reached 1.6 T. No doubt, to see explicitly how a waveguide FEL affects the working of the BWO, an expression for the gain of such an FEL needs to be analyzed.

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[1] *V. S. Ivanov, S. I. Krementsov, V. A. Kutsenko, M. D. Raizer, A. A. Rukhadze, and A. V. Fedotov, Sov. Phys. Tech. Phys. 26, No. 5 (1981), 580.*

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