Demonstration of a Two-Stage Backward-Wave-Oscillator Free-Electron Laser

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An experimental study of a two-stage millimeter-wave source in which the same intense relativistic electron beam first produces powerful (500-MW) radiation at 12.5 GHz and then uses that radiation as a "pump" for a free-electron–laser interaction at frequency $f > 140$ GHz is described. Implication for two-stage free-electron–laser experiments with reduced electron energy requirements are discussed.

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Free-electron lasers (FEL's) have the potential of providing very high-power, continuously tunable, coherent radiation over an extensive range of wavelengths, and are currently the subject of an intensive research effort. In the usual FEL configuration, a relativistic electron beam is passed through a wiggler magnet producing conditions for coherent amplification of radiation at a wavelength $\lambda \sim l_w/2\gamma^2$, where l_w is the wiggler period and $\gamma = (1 - v^2/c^2)^{-1/2}$ is the relativistic energy factor based on the axial beam velocity, v. With a typical wiggler period of a few centimeters, FEL's have been operated in the infrared[1] with $\gamma \sim 100$ and at millimeter wavelength[2,3] with $\gamma \sim 3$.

At millimeter wavelengths strong resonance effects have been observed[3] and predicted[4-8] when a uniform axial guide magnetic field is applied in addition to the wiggler field. This resonance takes place near values of the axial magnetic field of

$$\overline{B} = 2\pi\gamma v (m/e) l_w^{-1} \tag{1}$$

(rationalized mks units). In the present paper, we report on a millimeter-wave FEL in which a powerful electromagnetic (EM) "pump" wave replaces the usual magnetostatic wiggler. A salient feature used to identify the process was the distinctive FEL resonant behavior which was observed as the magnetic guide field was varied.

An EM wave with transverse electric field E_0 and a phase velocity v_{ph} would be equivalent to an FEL wiggler transverse magnetic field of peak amplitude[9] given by

$$B_w = E_0(1 - v/v_{ph})/v. \tag{2}$$

Thus, to equal the effect of a rather modest wiggler field of a few hundred gauss, an EM wave with power density ~ 10 MW/cm^2 would be required. Because microwave sources producing such power densities are not readily available, there have been few FEL experiments employing EM waves in place of magnetostatic wigglers.

One experiment[10] in which an electromagnetic wave was thought to function in place of a magnetostatic wiggler employed an intense relativistic electron beam to produce ~ 100 MW of 2-cm radiation through the electron cyclotron maser instability. Interpretation of that experiment, however, was complicated by the fact that both the pump as well as the FEL interaction were strongly affected by the guide magnetic field. Another mechanism capable of efficiently (~ 25%) generating hundreds of megawatts of microwave radiation[11] is the backward-wave-oscillator (BWO) mechanism. The wavelength of the BWO radiation is determined by the period of the wall ripple and is unaffected by a guide magnetic field; BWO radiation functions as the pump wave in the present study.

A schematic of the experimental device is shown in Fig. 1. A BWO interaction took place when an intense relativistic electron beam was passed through a waveguide with a rippled wall. A carefully designed diode[12] produced the "cold" 1-kA pencil beam of 900-keV electrons. The beam had 6-mm diameter and axial velocity spread < 1%. Such a beam can support a slow

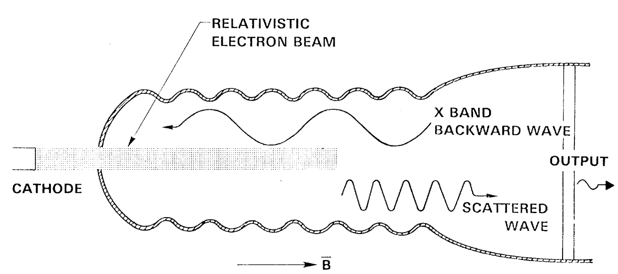

FIG. 1. Schematic of two-stage BWO-FEL experiment. X-band backward wave is produced by BWO mechanism. Scattered wave at millimeter wavelengths is produced by FEL mechanism. Rippled waveguide had corrugation period L =1.6 cm, 5 cm o.d., 4 cm i.d., and 25 cm length.

space-charge wave with the dispersion relation

$$\omega_0/k_0 = v/(1+\omega_p/\gamma\omega_0) \approx v. \qquad (3)$$

In Eq. (3) ω_0 and k_0 are the angular frequency and axial wave number, respectively, of the wave supported by the beam, and ω_p is the frame-invariant reduced plasma frequency ($\omega_p/2\pi = 0.6$ GHz). Equation (3) and the dispersion relation[13] of the corrugated wall structure are plotted in Fig. 2. Only the TM_{02} mode is of interest because the starting current for that mode is by far the lowest.[13] The power in that mode was observed in the present experiment to peak at 500 MW ($f \sim 12.5$ GHz) and is constant over a wide range of magnetic field (14 to 22 kG). Below 10 kG the peak power decreases because the beam current decreases [see Fig. 3(a)]. This powerful wave acts as a self-generated pump to drive the second-state FEL interaction.

The Floquet mode presentation of the BWO wave is given by

$$\bar{E}(x,y,z,t) = \sum_{m=-\infty}^{+\infty} \tfrac{1}{2}\bar{\epsilon}_m(x,y)\exp[-i\omega_0 t + i(k_0 - m2\pi/L)z] + \text{c.c.}, \qquad (4)$$

where $k_0 < 0$. All the spatial harmonics have the same frequency and (negative) group velocity, but different phase velocities. As can be seen from Fig. 2, the dispersion curve of the slow space-charge wave [Eq. (3)] intersects the TM_{02} dispersion curve in the second Brillouin-zone region $\pi < k_0L < 3\pi$. The space-charge wave is thus synchronous with the slow "-1"-order space harmonic whose phase velocity is positive and is given by $\omega_0/[(2\pi/L)+k_0]$.

On the other hand, the fundamental space harmonic ($-\pi < k_0L < \pi$) which usually carries most of the mode power has negative axial wave number and negative phase velocity $v_{ph} = \omega_0/k_0 = -7 \times 10^8$ m/sec. It thus propagates counter to the direction of the electron beam and acts as a pump wave for the FEL interaction which produces the strong high-frequency radiation ($f > 140$ GHz) as shown in Fig. 3(b). (Relatively little radiation was detected between 13 and 140 GHz.)

As in the case of a magnetostatic wiggler,[3] the dependence of the high-frequency emission on $\bar{B}$ (viz., the magnetic signature) is characterized by a doubly peaked curve with the peaks above and below a magnetic resonance which is given by Eq. (1). In this case, l_w in Eq. (1) is the wiggler pe-

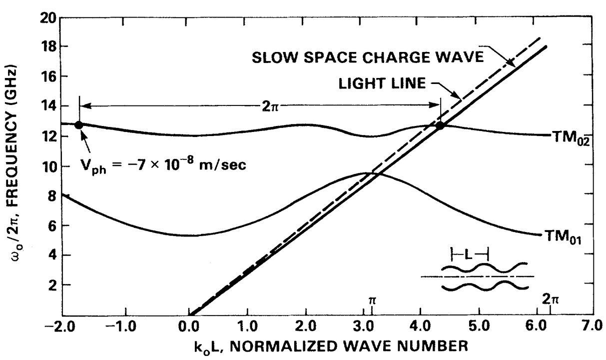

FIG. 2. Dispersion relations for BWO interaction showing coupling of the slow space-charge wave to the TM_{02} mode of the rippled-wave waveguide. The position of the fundamental TM_{02} BWO emission is indicated 2π away from the normalized interaction wave number.

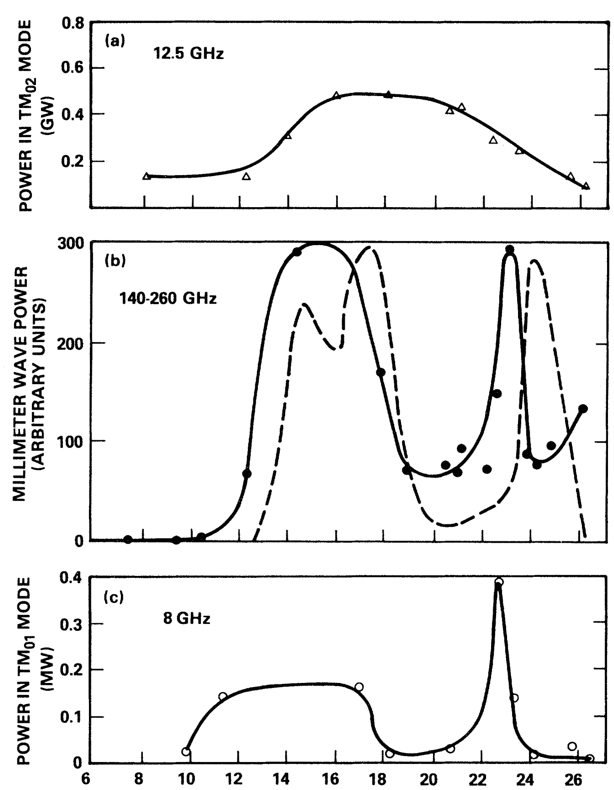

FIG. 3. Magnetic signatures of power emitted at various frequencies from two-stage BWO-FEL experiment. (a) BWO emission (TM_{02}) at 12.5 GHz vs $\bar{B}$. (b) High-frequency FEL emission at $f > 140$ GHz vs $\bar{B}$. Dashed line is magnetic signature of high-frequency emission from an FEL with magnetostatic wiggler. (c) Low-frequency FEL emission (TM_{01}) at 8 GHz vs $\bar{B}$.

riod produced by the transverse electromagnetic (TM_{02}) pump, whose phase velocity is $v_{ph} = -7 \times 10^8$ m/sec. The equivalent electromagnetic wiggler period is[9]

$$l_w = 2\pi c/[\omega_0(1 - v/v_{ph})]. \qquad (5)$$

Substituting the experimental values in Eq. (5) yields an effective wiggler period of $l_w = 1.7$ cm.

In Fig. 3(b), the results of a magnetostatic-wiggler FEL experiment[14] are also plotted against magnetic field. For the sake of comparison, the axial magnetic field values have been adjusted in making this plot to take into account the difference between the magnetostatic wiggler period (3 cm) and the present electromagnetic wiggler period (1.7 cm). The magnetic signature for the magnetostatic-wiggler FEL emission is seen to be strikingly similar to the magnetic signature of the high-frequency emission in the present experiment. The EM pump in the present experiment is equivalent to $B_w = 200$ G [Eq. (2)] while the magnetostatic wiggler strength for the plot in Fig. 3(b) was 350 G.

The magnetic signature of the TM_{01} radiation is plotted in Fig. 3(c) and is also seen to be a doubly peaked curve characteristic of an FEL process. We suggest that the generation of the 8-GHz TM_{01} radiation is generated by a parametric process of Doppler down-conversion stimulated scattering[15] of the TM_{02} pump. The high-frequency millimeter-wave radiation is generated by a parametric process of up-conversion stimulated scattering. In each case the pump wave (ω_0, k_0) is converted into a plasma wave (ω_p) and a scattered electromagnetic wave (ω, k).

For the Doppler up-conversion process

$$\omega - \omega_0 = vk - vk_0 - \omega_p/\gamma \qquad (6a)$$

while for the Doppler down-conversion process

$$\omega - \omega_0 = vk - vk_0 + \omega_p\gamma. \qquad (6b)$$

The change in sign of the ω_p/γ term in going from Eq. (6a) to Eq. (6b) reflects the fact that the interaction is with the negative-energy (slow) space-charge wave in each case. However, since ω_p/γ is in fact small compared to the other terms, we have represented both Eq. (6a) and Eq. (6b) as a single line in Fig. 4.

The intersection of Eq. (6) with the TM_{01} dispersion curve at negative values of k as shown in Fig. 4 involves interaction with a scattered wave propagating opposite to the beam velocity and can therefore give rise to oscillation (absolute instability). The intersection of Eq. (6) with the dispersion curve of millimeter waves propagating near the speed of light at positive values of k corresponds to the Doppler up-conversion process and occurs near 200 GHz in agreement with the experimental observation.

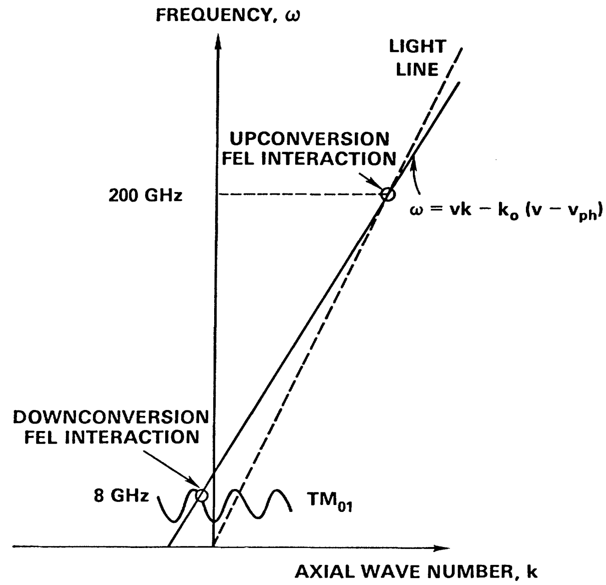

FIG. 4. Dispersion relations for FEL interaction ($k_0 = -1.2 \times 10^2$ m^{-1}, $v_{ph} = -7 \times 10^8$ m/sec).

Other mechanisms for explaining the observed millimeter-wave radiation were considered. These include the following: cyclotron maser high-order harmonic emission[16]; high-order space harmonics of the corrugated wall structure (Smith-Purcell traveling-wave–amplifier effect)[17]; FEL interaction pumped by the longitudinal electric field of the TM_{02} wave,[18] and FEL interaction pumped by the electrostatic field between the electron beam and the corrugated wall.[19] These alternative mechanisms were a less satisfactory explanation than an FEL interaction pumped by the transverse field of the TM_{02} wave because their calculated gain was considerably smaller and/or they could not explain the observed magnetic signature.

The study of a two-stage device in which the same electron beam first produces powerful radiation at relatively long wavelength (2.4 cm) and then uses that radiation as a pump for an FEL interaction is potentially of practical interest. It has been suggested[20,21] that for a given output wavelength, electron energy requirements could be greatly reduced if a two-stage FEL could be constructed. Such an FEL would operate at a wavelength $\lambda \sim l_w/8\gamma^4$. While in the present study of a two-stage process, only the second stage is an FEL, we nevertheless expect the insights gained in this study of an EM pump to be relevant to a better evaluation of the potential for a two-stage FEL.

Last, it is interesting to note that the two mechanisms, the BWO and the FEL, are going on simultaneously, and while the BWO mechanism is powerful (500 MW) and efficient (~20%), no effort has been yet made to optimize the FEL interaction (up-converted power < 0.35 MW). Also, it should be noted from Fig. 3(b) that there is no indication of increasing 200-GHz emission at $\bar{B} > 24$ kG; this may be due to another mechanism and bears further investigation.

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