High-Power Operation and Strong Bunching at 3 GHz Produced by a 35-GHz Free-Electron-Laser Amplifier

J. Gardelle, T. Lefevre, G. Marchese, and J. L. Rullier*
CEA/Centre d'Etudes Scientifiques et Techniques d'Aquitaine, B.P. 2, 33114 Le Barp, France

J. T. Donohue
Centre d'Etude Nucléaires de Bordeaux-Gradignan, B.P. 120, 33175 Gradignan, France

(Received 26 March 1997)

Pronounced electron-beam bunching and high-power emission at 3 GHz have been observed in the 35-GHz free-electron-laser (FEL) experiment at CEA/CESTA. It corresponds to the low-frequency resonance of the FEL which appears in addition to the high-frequency resonance when a waveguide is used. The dependence of the bunching on length (in the wiggler) and time (in the pulse) shows that the spontaneously generated low-frequency mode comes to dominate the high-frequency injected mode at long distances and late times. [S0031-9007(97)04542-0]

PACS numbers: 41.60.Cr

An interesting utilization of high-power microwave free electron lasers (FEL) is to furnish an intense bunched electron beam which could serve as the drive beam in a two beam accelerator [1]. We are examining this possibility both for the CLIC project at CERN [2] and the RK-TBA project at LBNL [3]. Results which showed a bunched beam of 150 A above a steady current of 450 A were obtained, and have been reported [4,5]. The beam energy was 2.2 MeV, and the bunching was at the FEL frequency $f_+ = 35$ GHz. In a continuing effort to improve the performance of our experiment we have redesigned certain features. With our new setup, a greatly increased current with better beam bunching has been observed. In the course of this round of experiments, we observed a remarkable phenomenon: the existence of extremely strong bunching at the lower resonant FEL frequency $f_- = 2.95$ GHz.

Our experiment is similar to several other microwave FELs, which operate in the frequency range (10–250 GHz) [6,7]. They generally use intense electron beams (0.1 to 1 kA) of moderate energy (from 0.5 to a few MeV) to amplify either an external electromagnetic (EM) signal (i.e., amplifier mode) or the shot noise from spontaneous emission in the so-called self-amplified-spontaneous-emission (SASE) mode [8]. In the microwave regime a waveguide is needed to contain the EM wave being amplified. The waveguide is also the vacuum tube in which the beam propagates and its geometry depends on the wiggler type, rectangular for planar wigglers or cylindrical for helical ones. When a waveguide is present the FEL resonance occurs at the intersections of two dispersion curves. The first is the waveguide mode given by

$$\omega^2 = k^2c^2 + \omega_{\rm co}^2\,,$$

which relates the pulsation ω and wave number k of the EM wave, c is the speed of light, and $\omega_{\rm co}$ is the cutoff frequency of the corresponding mode. The second expresses the resonance condition between the wave and the beam,

$$\omega = c(k + k_w)\beta_z\,,$$

where $k_w = 2\pi/\lambda_w$ is the wiggler wave number, λ_w is the wiggler period, and $\beta_z = v_z/c$ is the normalized axial velocity of the electron beam. We have neglected plasma frequency effects for simplicity. These curves are shown in Fig. 1. The solutions are given by

$$\omega_\pm = \beta_z c k_w \gamma_z^2 \left\{1 \pm \beta_z \left[1 - \left(\frac{\omega_{\rm co}}{ck_w\beta_z\gamma_z}\right)^2\right]^{1/2}\right\}.$$

When the two roots are equal one speaks of grazing incidence (case 1 in Fig. 1), and some experiments have been performed at this limit [9]. Most experiments have been designed so that the frequencies ω_+ and ω_- were

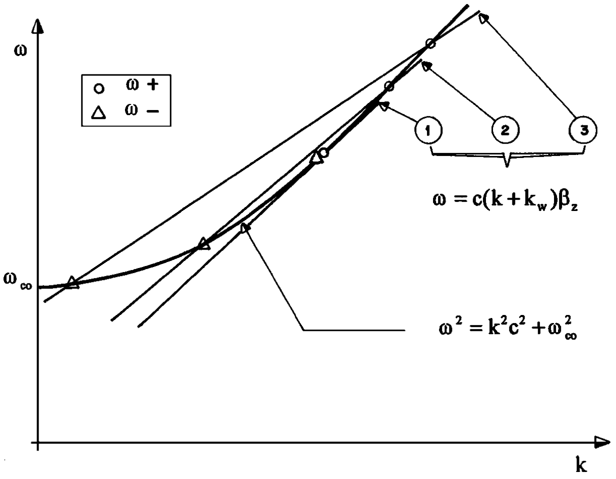

FIG. 1. Illustration of operating frequencies for a FEL in a waveguide assuming a single mode of cutoff frequency $\omega_{\rm co}$. Corresponding to different choices of the FEL parameters, three different possibilities are drawn: (1) grazing incidence $\omega_+ = \omega_-$, (2) both frequencies well above cutoff, (3) our situation with $\omega_- \approx \omega_{\rm co}$.

0031-9007/97/79(20)/3905(4)$10.00

distinct with both well above cutoff (case 2 in Fig. 1) and usually the operating frequency was chosen to be ω_+ [10–14]. A notable exception is the well-known reversed field amplifier experiment of Conde and Bekefi at MIT, who injected at $f_- = 33.4$ GHz, compared to a cutoff of 17.2 GHz [15]. As an illustration of case 3, with the lower frequency close to cutoff, one may cite the superradiant experiment performed by Fajans *et al.* [16]. Our experimental parameters also correspond to case 3, with an injected frequency of $f_+ = 35$ GHz and where f_- is very near 2.85 GHz, which is the cutoff of the fundamental TE_{11} mode. This mode propagates in the forward direction. We present in this Letter results obtained in an amplifier configuration, in which high power is generated at the injected frequency, and still more power at the lower frequency. In addition to the expected beam bunching at high frequency, we observe even greater bunching at the lower. While the parasitic excitation of the second FEL frequency has been observed previously [14,16,17], to the best of our knowledge, the size of the effects we observe has not been anticipated in the literature.

A schematic of our experiment is shown in Fig. 2. Our induction linac LELIA delivers a 1 kA electron beam of energy 2.2 MeV. This beam is injected into a 12-cm–period helical wiggler fed by a capacitor discharge. Three solenoidal magnets are used to transport the beam from the accelerator to the wiggler, and the last of these of length 25 cm and a maximum field of 0.08 T is placed 6 cm downstream from the entrance to the wiggler. No axial guide field is employed, since the wiggler field provides sufficient focusing to maintain the beam. The beam adiabatically gains transverse momentum in passing through the first six periods of the 312-cm-long wiggler, where the magnetic field B_w increases from zero to its desired value. Inside the wiggler the beam amplifies a 35 GHz EM wave propagating in the TE_{11} mode of the cylindrical waveguide. The signal is generated by a magnetron which injects up to 10 kW into the waveguide. The high-frequency FEL power is measured as usual by microwave lines that were calibrated using the well-known magnetron output signal. One major difference with our previous experiment [5] is an increase of the radius of the beam pipe from 1.95 to 3.05 cm. We also modified the adjustments of the last guiding coils of the transport line, with the aim of increasing the current entering the FEL. Consequently, the current propagating through the wiggler has increased to 800 A compared to the 450 A we had before. With the parameters listed above, the resonance of the FEL at 35 GHz occurs at $B_w = 1100$ G. The maximum FEL power we measure is 80 MW, and the corresponding energy extraction efficiency is 4.5%, which is 4 times that of our previous experiment. The frequencies of both the FEL output and the input signal delivered by the magnetron have been measured, and they have the same value 35.04 GHz.

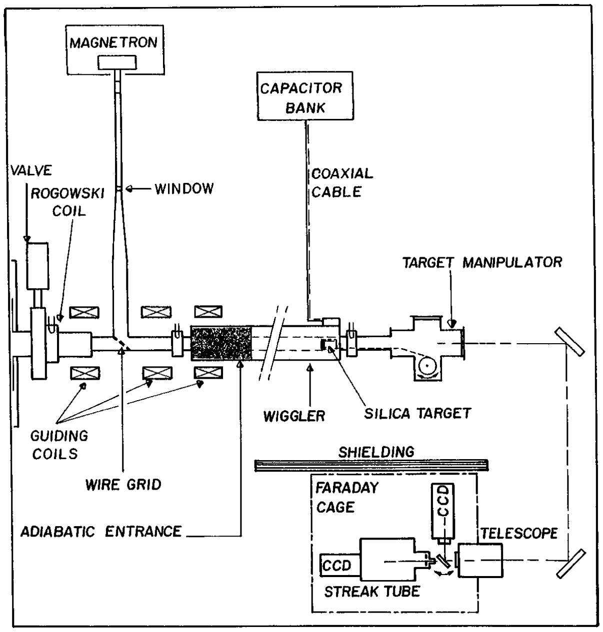

FIG. 2. Free electron laser and setup for bunching measurement. The induction accelerator is off image at left.

The bunching of the electrons was observed by causing the beam to strike a 2-mm-thick fused silica target, producing thereby Cerenkov radiation at visible wavelengths. The target could be moved under vacuum, thereby allowing us to observe the bunching at any desired position along the axis. The optical setup consists of a telescope that collects the Cerenkov light, and focuses it either onto a beam position camera or onto a high-resolution streak camera, as shown in Fig. 2. The sweep speed of the streak camera could be chosen among a set of nominal values in the interval 10 to 1000 ps/mm, although we typically used 25 and 50 ps/mm. The width of the camera slit was chosen to be 0.2 mm in order to optimize the resolution at these latter sweep speeds. By varying the trigger delay of the camera, we could study the bunching as a function of the time in the beam pulse. In this way we are able to scan the beam throughout the whole FEL pulse, using a series of shots to get a complete picture. We thus have the capacity to observe the bunching as a function of both distance along the wiggler axis and time.

Optical measurements of bunching are displayed in Fig. 3. At the top are the direct streak camera images, whereas the curves beneath each picture show the corresponding beam current profile as a function of time. They represent a digitized representation of the images, after averaging in the transverse direction, and subtracting the off-beam background. We see in Fig. 3(a) (period 19) the bunching at 35 GHz, as expected. Here, the sweep speed of the streak tube is 25 ps/mm so that we are analyzing a 419-ps-long slice at the beginning of the 40-ns-long electron beam. If one defines the radio-frequency current I_{rf} to be the ratio of the Fourier coefficient at 35 GHz divided by the value of the average we find $I_{\rm rf} = 0.5$. This value is 3 times higher than in our previous experiment [5]. While studying this 35 GHz bunching as a function of both position and time, we discovered the low frequency FEL mode at approximately 3 GHz in competition with the main high-frequency mode. Both frequencies are clearly visible in Fig. 3(b) (period 22), that has been obtained using a nominal sweep speed of 50 ps/mm corresponding to a 920 ps time interval. This photograph was taken about 15 ns later in the beam pulse than the preceeding one. The competition only appears towards the end of the FEL interaction region where the FEL power at 35 GHz has nearly reached its maximum value. The bunching at 3 GHz increases in relative importance both as a function of time in the pulse and as a function of distance in the wiggler. Indeed, we found that at the end of the wiggler and near the end of the beam pulse, the bunching occurs only at 3 GHz. It is remarkably sharp, as may be seen in Fig. 3(c) (period 23), taken approximately 15 ns later than Fig. 3(b). The Fourier spectrum of the corresponding beam profile has a very rich harmonic content, extending clearly to the tenth harmonic. Therefore, we prefer to use a compression factor to quantitatively characterize this bunching. It is defined as the ratio of the maximum intensity divided by the average value, and for well-chosen positions and times, compression factors between 5 and 8 were obtained. It means that we have obtained narrow bunches, typically 50 ps, with a peak current of approximately 5 kA (250 nC).

Using the current $I_{\rm rf}$ to characterize the bunching at 35 GHz, and the compression factor to measure the bunching at 3 GHz, we have made two rough contour maps in the two dimension space of axial position (as represented by the wiggler period number) and time in the pulse. These maps are displayed in Figs. 4(a) and 4(b), respectively. The former clearly shows that the high-frequency bunching is greatest between wiggler periods 19 and 20. Beyond these periods, a zone of competition appears with the upper frequency losing importance as time in the pulse increases. This competition ends with the dominance of the bunching at the lower frequency around period 23 and the disappearance at the higher frequency at the end of the pulse, as is evident in Fig. 3(c) and Fig. 4(b).

In order to check whether this strong bunching corresponds to appreciable microwave emission at 3 GHz, we have performed additional measurements using *S*-band hardware suited to this frequency. We thereby measured 300 ± 100 MW of FEL power. The large error on the power measurement is caused by our not disposing of a well-calibrated source like our 35 GHz magnetron. However, the frequency is determined with fair precision by a heterodyne method to be 2.95 ± 0.05 GHz. This is consistent with the frequency obtained by a fast fourier transform analysis of the bunching measurements.

Among the results of this experiment, we note the substantial improvement of the FEL output power (from 10 to 80 MW) and the bunching at 35 GHz ($I_{\rm rf}$ increased from 0.18 to 0.5), compared to our earlier results. Much of this is undoubtedly due to the increased current and improved beam transport, the latter being facilitated by our larger beam-tube radius. In terms of our primary aim, the study of a FEL as a source for an intense bunched electron beam, our results represent genuine progress. The next step, currently under preparation, is to inject our bunched beam at 35 GHz into a suitable resonant cavity, in order to study the power generated.

The major result of this experiment is the observation of quite pronounced bunching at the lower resonant FEL frequency f_-. To the best of our knowledge, this is the first time behavior of such magnitude has been seen. We note that in our previous experiment no evidence for bunching at the lower frequency was visible. In that experiment, the smaller waveguide radius corresponds to a cutoff frequency of 4.6 GHz. Upon reexamining our data we see no bunching near that frequency. We note two major differences between our present and earlier experiments. In the latter the beam current was only

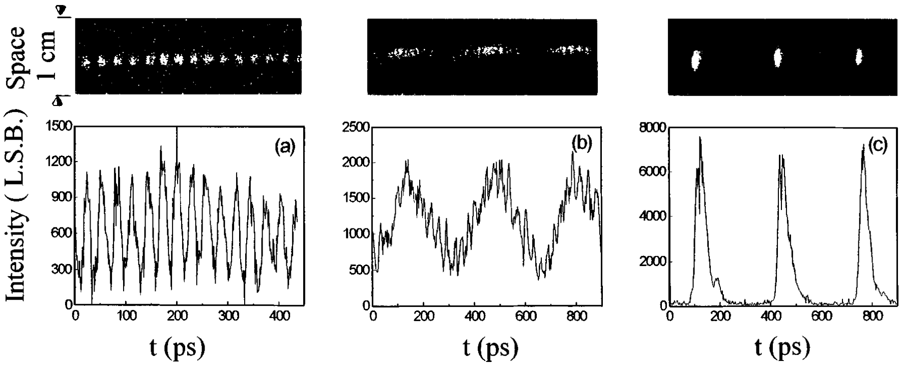

FIG. 3. Streak camera images of bunched electron beam and the corresponding digitized representations at different positions in space and time. Bunching appears first at the upper frequency of 35 GHz in (a), then at both upper and lower frequencies (b), and, finally, strong bunching is seen only at the lower frequency 3 GHz.

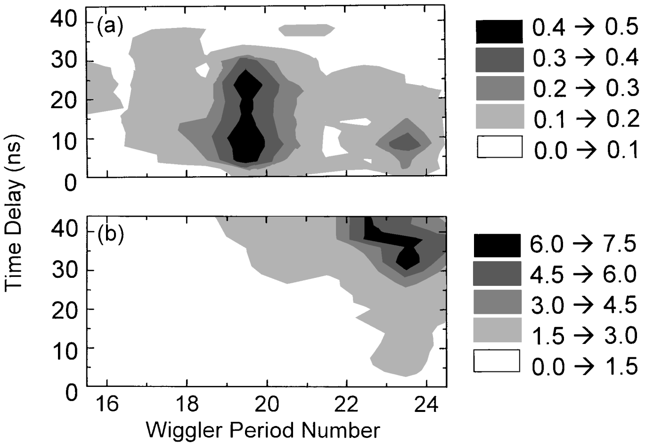

FIG. 4. Intensity of bunching as a function of interaction length and of time in beam pulse. (a) The current I_{rf} at 35 GHz. (b) The compression factor (defined in text) for the bunching at 3 GHz.

half that of our present version, and the output power was much less. One may imagine that some sort of threshold effect is involved, depending either on the beam current or the output power at 35 GHz, or both. Two possibilities come to mind, a SASE effect which is sensitive only to the beam current, or, conversely, as cooperative effect in which energy is transferred from the beam bunched at 35 GHz to the EM wave at 3 GHz. One may also conjecture that a particular ratio of the frequencies might favor the appearance of high output power and strong bunching at the lower frequency. More experimental work is needed to provide understanding of this remarkable effect. In conclusion, we point out that the bunching we observe at the lower FEL frequency is much sharper that at the upper frequency, despite the fact that the microwave power levels are of similar magnitude.

The authors acknowledge fruitful discussions with D. Gogny, J. Labrouche, and D. Villate. We thank M. Lavergne and M. O. Lelion for providing invaluable technical assistance.

---

*Supported by CERN.

[1] H. D. Shay *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **304**, 262 (1991).
[2] W. Schnell, Report No. CERN SL/92-51 and CLIC Report No. 97 (unpublished).
[3] G. Westenskow *et al.*, in *Proceedings of the Particle Accelerator Conference* (IEEE, Dallas, 1995), p. 737.
[4] J. Gardelle, J. Labrouche, and J. L. Rullier, Phys. Rev. Lett. **76**, 4532 (1996).
[5] J. Gardelle *et al.*, Phys. Plasmas **3**, 4197 (1996).
[6] H. P. Freund and T. M. Antonsen, Jr., in *Principles of Free-electron Lasers* (Chapman & Hall, London, 1996), 2nd ed.
[7] J. A. Pasour and S. H. Gold, IEEE J. Quantum Electron. **QE-21**, No. 7, 845 (1985).
[8] K. J. Kim, Phys. Rev. Lett. **57**, 1871 (1986).
[9] S. H. Gold *et al.*, Phys. Rev. Lett. **52**, 1218 (1984).
[10] C. W. Roberson *et al.*, Infrared Millim. Waves **10**, 361 (1983).
[11] R. K. Parker *et al.*, Phys. Rev. Lett. **48**, 238 (1982).
[12] L. Y. Lin and T. C. Marshall, Phys. Rev. Lett. **70**, 2403 (1993).
[13] D. A. Kirkpatrick *et al.*, Phys. Fluids B **1**, 1511 (1989).
[14] J. Fajans and G. Bekefi, Phys. Fluids **29**, 3461 (1986).
[15] M. E. Conde and G. Bekefi, Phys. Rev. Lett. **67**, 3082 (1991).
[16] J. Fajans *et al.*, Phys. Rev. Lett. **53**, 246 (1984).
[17] J. A. Pasour *et al.*, Phys. Rev. Lett. **53**, 1728 (1984).