Operation of a Compact Free-Electron Laser in the Millimeter-Wave Region with a Bunched Electron Beam

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The waveguide operation of a compact free-electron laser driven by a 2.3-MeV S-band microtron is reported. Power up to 1 kW in 4-μs pulses has been generated at wavelengths in the range between 2.1 and 2.6 mm. Novel tuning features and temporal characteristics of the emitted radiation, related to the bunched nature of the electron beam and to the dispersive effect of the waveguide, have been observed.

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In recent work [1–3] the waveguide operation of a free electron laser (FEL) has been discussed, pointing out new kinematic and dynamic features that affect the tuning capability, the mode selectivity, and the short pulse operation at long wavelengths. Waveguide effects have been extensively investigated in the so-called Ubitrons [4] and Raman FELs [5] which utilize a continuous beam of nonrelativistic electrons produced by an electrostatic gun. In this paper we report novel characteristics of a waveguide FEL that appear in the operation, in the Compton regime, with a bunched electron beam such as that produced by radio-frequency (rf) accelerators (linacs or microtrons). Because of their high energy gradient these devices can be employed to build compact FELs for a wide spectral region, which extends from millimeter waves to the far-infrared.

Several issues arise in a long wavelength FEL driven by an rf accelerator as a result of the short electron bunch duration. When the bunch length is comparable to the operating wavelength λ, a considerable amount of coherent emission is expected even with no feedback in the resonator [6]. On the other hand, the buildup of the FEL pulse is strongly affected by the "slippage" [7], i.e., the lack of overlapping between the wave packet and the electron bunch due to their different velocities. In free space the slippage length at the end of the interaction region is $\delta = N\lambda$, where N is the number of undulator periods; in the millimeter-wave region it can be quite large compared to the electron bunch length and may preclude the onset of oscillation. In a waveguide it is possible to control the group velocity of the excited mode by a proper choice of the waveguide transverse dimension and therefore reduce the slippage. A particular condition is found when $\lambda_u \approx 2\gamma_z b(1-0.8/2N)$ for the fundamental mode in a planar waveguide, where λ_u is the undulator period, γ_z is the relativistic factor of the electron associated with the drift motion along the undulator with velocity β_z, and b is the waveguide gap. In this condition a broad band gain curve with a relative bandwidth $\Delta\lambda/\lambda \approx 1/\sqrt{N}$ is obtained [2] around a central frequency having a group velocity equal to the electron velocity; it is therefore called "zero-slippage" condition.

To test the features of the waveguide FEL, and in particular the operation at zero slippage, an experiment has been designed [8] and performed at the ENEA submillimeter FEL facility in Frascati. A 5-MeV microtron, previously employed in a Cherenkov FEL experiment [9], was modified to extract the electron beam (e beam) at a total energy of 2.3 MeV. The microtron delivers short electron bunches with 15-ps duration spaced at the frequency of 3 GHz. The bunches form a train (macropulse) with duration up to 4 μs, which is repeated at a maximum frequency of 40 Hz. The peak current in the bunch is $I_p = 6$ A. The e-beam emittance has been measured to be 21π mm mrad and 14π mm mrad in the radial and vertical plane, respectively. The energy spread is estimated to be $\approx 1\%$.

The layout of the FEL facility, the e-beam transport system and the optical diagnostics have been described in detail in Ref. [9]. The undulator and resonator assembly is shown in Fig. 1. The compactness of this waveguide FEL has been obtained by using a linearly polarized permanent magnet undulator with a period $\lambda_u = 2.5$ cm and a length of 22.5 cm. It provides a peak magnetic field of 6.1 kG on axis at a 0.63-cm gap between its poles, corresponding to a value of the undulator parameter $K = 1$.

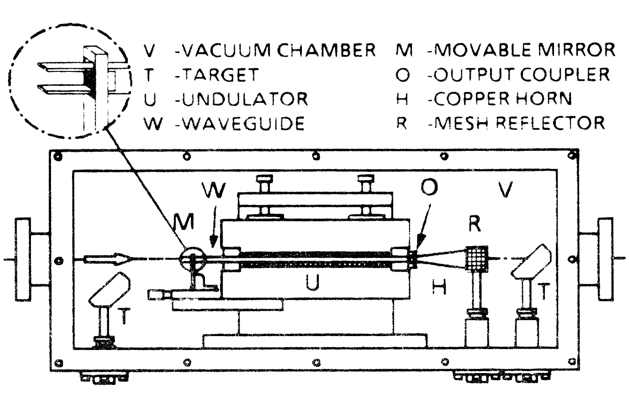

FIG. 1. A view of the undulator and resonator assembly.

The two assemblies of the undulator poles are directly clamped on a straight section of WR42 rectangular copper waveguide which has a length of about 30 cm and internal dimensions $a=1.067$ cm and $b=0.432$ cm.

With this set of fixed parameters the electron energy can be varied over a 10% range around 2.3 MeV by adjusting the microtron magnetic field; in this way the zero-slippage condition can be explored. In the approximation of weak coupling between the electron motion and the modes of the empty waveguide, the excitation of a single transverse mode ($TE_{0,1}$) is predicted with the electric field perpendicular to the plane of the undulator axis and magnetic field. A wide gain curve is expected for the $TE_{0,1}$ mode, covering the frequency range from 90 to 140 GHz (see Fig. 2). According to the analytical model reported in Ref. [2] a maximum gain per pass $G \approx 25\%$ is calculated at a wavelength of 2.5 mm (120 GHz) for 4 A of transported beam current.

Since the emitted radiation is linearly polarized, wire grids made of 10-μm-diam gold-coated tungsten wire with pitches in the range 80–200 μm are used as electron-transparent mirrors (ETM) [10] at both ends of the waveguide to provide feedback and output coupling. An 80-μm wire spacing is used for the upstream mirror, resulting in a reflectivity $>99\%$ at wavelengths longer than 2 mm. This mirror intercepts the e beam with a transparency of 90%. The scattering of the residual 10% of the beam due to the presence of the wires does not significantly affect the e-beam quality and the expected performance of the laser due to the long operating wavelength [10]. Wider wire spacing is used for the output coupler placed at the downstream end of the undulator and provides up to 10% transmission. The passive losses in the resonator are mainly due to attenuation of the $TE_{0,1}$ mode along the oversized waveguide and are estimated to be 5% per round-trip. Immediately after the output coupler a pyramidal horn, matched to the waveguide cross section, and a 45° copper-mesh reflector launch the excited wave into a copper circular light pipe with 2.5 cm clear aperture. The spent e beam passes through the mesh reflector and is sent to a beam dump. At the end of the 3-m-long light pipe the radiation is analyzed by means of a wire-grid Fabry-Pérot interferometer (FPI) and a pyroelectric detector (Molectron P4-32), which can be used as an energy detector or as a power detector depending on the choice of its electrical time constant.

Spontaneous emission measurements were carried out without mirrors in the resonator and reported elsewhere [11]. About 20 W of power was generated in a composite broad-band emission covering the spectral range from 1.5 mm to 4 mm, showing the coherent excitation of discrete frequencies which are harmonics of the 3 GHz radio frequency due to the bunched structure of the e beam.

The first oscillation of the laser was observed in a narrow band at a wavelength of 2.43 mm (123 GHz) with a fixed resonator length of 29.34 cm and a 2% output coupler. The spectral characteristics of the emitted radiation were analyzed by means of the FPI. The finesse of the instrument is calculated to be $F=20$. The FPI was placed at the output of the light pipe and a $f/4$ condenser cone was used after the FPI to focus the light onto the pyroelectric detector. The interferogram relative to a 4-mm scan of the FPI taken at 10-μm step intervals is shown in Fig. 3. The position of the peaks is extremely close to a frequency corresponding to the 41st harmonic of the 3 GHz rf. The measured linewidth is $<1.5\%$ and is limited by the instrument finesse. Comparative measurements of the linewidth at different interferometric orders have allowed us to determine the instrument contribution and to estimate a natural width of the line of $\approx 0.6\%$. An output power in the range between 5 and 10 W was measured depending on the adjustment of the current profile in the macropulse. The measured power level and the narrow linewidth observed are well explained by the growth and saturation mechanism described in Ref. [11] for a coherent signal at a single harmonic of the 3 GHz which is stored in the resonator and gains energy from the electron bunches that synchronously enter the undulator. The narrow linewidth of the emitted radiation indicates that many bunches contribute to

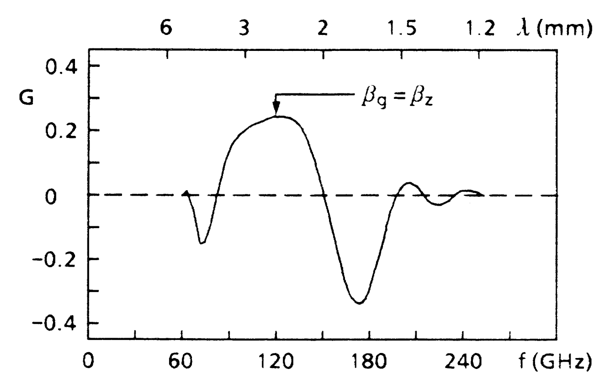

FIG. 2. FEL gain per pass vs frequency and wavelengths calculated with the parameters reported in the text.

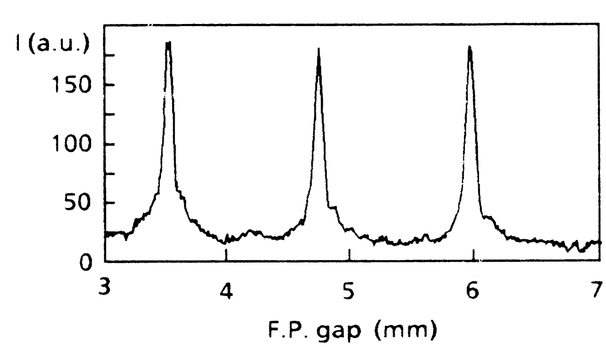

FIG. 3. Fabry-Pérot interferogram of the FEL output at $L_c=29.34$ cm.

the buildup of the oscillation, which occurs over a time duration much longer than the electron bunch and the bunch spacing itself. When the radiation is generated inside a cavity, the harmonic components of the electron beam current modulation have to drive resonant modes of the cavity within the FEL resonance band. Matching between the driving frequencies and the natural frequencies is therefore required. The bandwidth and the time behavior of the optical pulse are then linked to the number of harmonics of the radio frequency that is sustained in the cavity.

In order to form a short optical pulse, a large number of harmonics of the 3 GHz close to the FEL resonant frequency must be excited. To make this possible the round-trip time of a wave packet in the resonator has to be tightly synchronized to the time distance between bunches entering the undulator. This condition is expressed by

$$L_c = \tfrac{1}{2} c\beta_g n T_{\mathrm{rf}} + \delta L_c \,, \qquad (1)$$

where L_c is the resonator length, β_g is the group velocity of the wave normalized to the light velocity c, n is an integer, and T_{rf} is the period of the rf. δL_c is the so-called "cavity mismatch" due to the FEL lethargy [7] which is an increasing function of gain and is proportional to the slippage length in the guide. Since the group velocity in a waveguide is a function of frequency, Eq. (1) shows the possibility of tuning the laser by varying the resonator length. Once Eq. (1) is satisfied, the optimum overlapping between wave packet and electron bunch is achieved when $\beta_g = \beta_z$ ($\delta L_c = 0$) as mentioned before. With our set of experimental parameters $\beta_z = 0.952 \pm 0.001$ which at zero slippage, gives a resonator length $L_c = 28.56 \pm 0.03$ cm for $n = 6$.

To test the resonator length tuning, the upstream end of the waveguide has been modified by cutting the side walls of the guide to allow the wire-grid mirror to be moved along the resonator axis as shown in Fig. 1. Since the $TE_{0,1}$ mode is essentially confined by the "bottom and top" walls of the guide, which are parallel to the undulator poles, a small reflection loss is expected for this configuration. The holder of the wire-grid mirror is mounted on a translational stage driven by a stepper motor and a micrometric screw with a resolution of 2.5 μm and a total travel of 14 mm. The resonator length can be scanned in this way from 28.50 to 29.90 cm. A detail of such a scan (from 28.55 to 28.65 cm) is shown in Fig. 4. An asymmetrical intensity profile is observed, with maximum power generated at a resonator length corresponding to the zero-slippage condition. The generation of short pulses with a large bandwidth is expected at this position. A FP interferogram taken at this point (filled arrow in Fig. 4) shows the excitation of the 37th to 40th harmonics of the 3 GHz rf with a FWHM bandwidth of $\approx 5\%$ [see Fig. 5(a)]. The Fourier transform of such a signal gives a pulse duration of ≈ 100 ps. This pulse duration is longer than the electron bunch and can be ascribed to the spread of the pulse due to the dispersion of the guide and to the frequency selectivity of the resonator. A time-resolved measurement and display of single pulses is not at present feasible at such long wavelengths. There is, however, experimental evidence of emission of coherent radiation at frequencies corresponding to harmonics of the fundamental rf. The fields generated at these harmonics do have a precise phase relationship and an optical pulse is formed from their superposition, as it has been discussed in Ref. [11].

It is interesting to compare this result with another

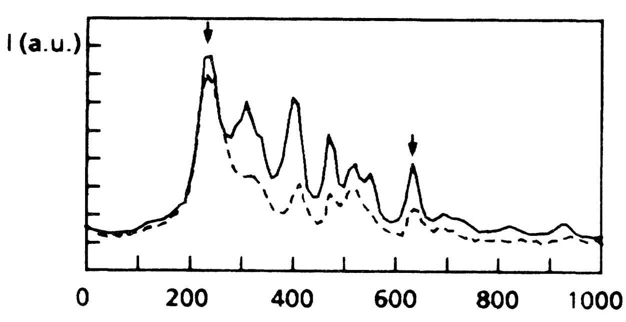

FIG. 4. FEL intensity vs resonator-length variation: solid line, 1% output coupling; dashed line, 3.5% output coupling. The intensity profiles are normalized to the maximum value and are slightly displaced vertically for greater clarity.

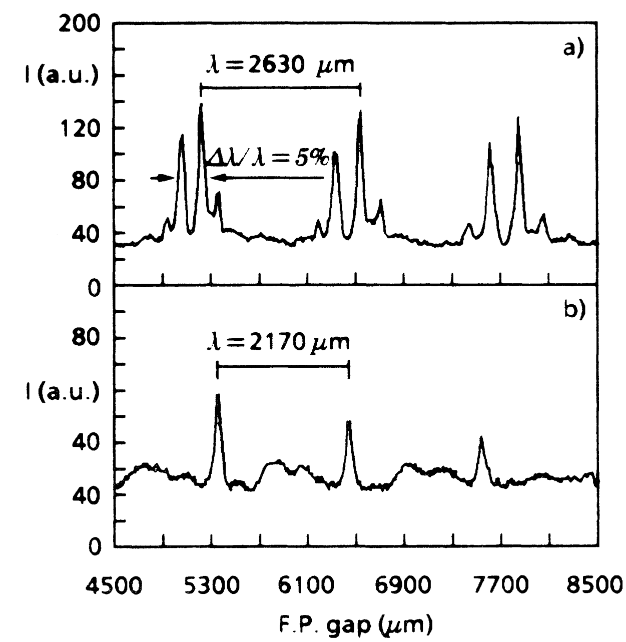

FIG. 5. FP interferograms for (a) $L_c = 28.57$ cm (filled arrow in Fig. 4), (b) $L_c = 28.61$ cm (empty arrow in Fig. 4).

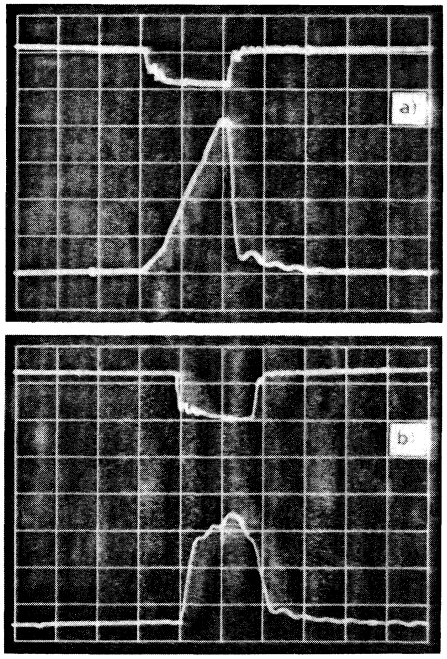

FIG. 6. FEL pulse profile for (a) 6% output coupling, (b) 3.5% output coupling. Upper trace, electron beam current. Lower trace, pyroelectric detector signal with 300-ns response time. Time base, 2 μs/div.

spectral measurement taken toward the tail of the resonator length tuning profile at $L_c = 28.61$ cm (empty arrow in Fig. 4). The corresponding FP interferogram in Fig. 5(b) shows the emission of radiation in a narrow band ($\Delta\lambda/\lambda \approx 1\%$) around a wavelength of 2.17 mm (46th harmonic of 3 GHz). Synchronism is satisfied at a shorter wavelength due to the dispersion of the guide and the presence of slippage at this resonator length causes a lengthening of the pulse during amplification; therefore a narrowing of the line is observed experimentally. The tuning range of the resonator length decreases with increasing output coupling as shown in Fig. 4, since the gain bandwidth is correspondingly reduced.

Absolute power measurements have been carried out at the output of the light pipe by using an optoacoustic microwave energy meter and have been compared to the pyroelectric detector measurements. The dependence of the emitted power on the amount of output coupling has also been investigated. A maximum power of about 300 W was obtained with 6% output coupling. This does not correspond to the maximum energy in the pulse due to the different build-up time of the oscillation [see Figs. 6(a) and 6(b)]. As can be seen from the graphs, at 6% output coupling the net gain is not sufficient to saturate the radiated power during the macropulse duration. At 3.5% output coupling the FEL output builds up in less than 1 μs. The power at the resonator output, before the light collecting system, is estimated to be close to 1 kW.

Operation of a waveguide FEL driven by an rf accelerator has been proven for the first time with this experiment. The tuning characteristics have been investigated showing new interesting features in the dependence of frequency and bandwidth on the resonator length. A theoretical model for the FEL pulse evolution in a waveguide which takes into account the different slippage properties with respect to the free-space case has to be developed to fully explain the experimental results.

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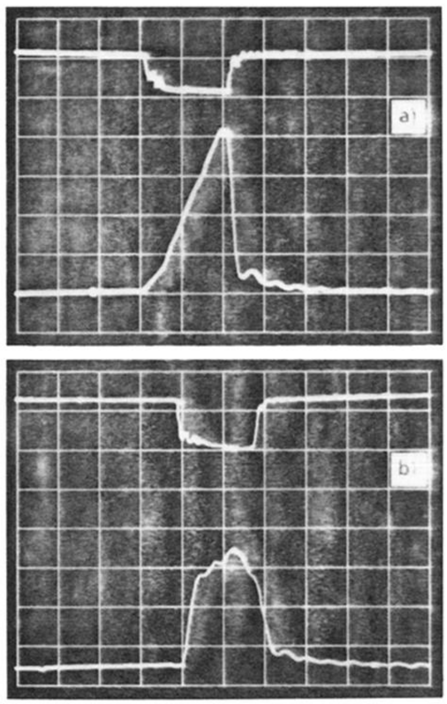

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