Direct Observation of Beam Bunching Produced by a High Power Microwave Free-Electron Laser

J. Gardelle, J. Labrouche, and J. L. Rullier*
CEA/CESTA, BP 2, 33114 Le Barp, France
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In this Letter we present a direct measurement of beam bunching by a high power free-electron laser (FEL). An induction linac delivered a 1 kA, 2.2 MeV electron beam to a FEL in which a 35 GHz input signal was amplified to power levels of the order of 10 MW. Measurements using both electronic and optical techniques were performed at the wiggler exit, and have clearly demonstrated beam bunching. The behavior of bunches as a function of experimental parameters is discussed. [S0031-9007(96)00320-1]

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Designs for the next generation of electron-positron linear colliders with energies in the 0.5–1.5 TeV range have high gradient acceleration (20–100 MeV/m) [1]. Among the different means proposed to obtain such gradients, the two beam accelerator (TBA) concept appears promising [2–5]. In a TBA the first accelerator transports an intense low-energy drive beam which, because of its spatially bunched structure, generates high-frequency electromagnetic (EM) power that is transferred to the accelerating cavities of the main high-energy accelerator. The latter accelerates the low average current main beam into the TeV range. The proposed Compact Linear Collider (CLIC) at CERN [6,7] is a TBA where the drive beam consists of trains of dense electron bunches (about 40 nC) spaced at 10 mm intervals. The generation of such a high-intensity drive beam is a challenge which could be solved by using the bunching which occurs in a free-electron laser (FEL).

In a FEL [8], an electron moves in the ponderomotive potential created by the wiggler field and the EM field with a phase $\theta = (k + k_w)z - \omega t$. Here $k_w = 2\pi/\lambda_w$, where λ_w is the wiggler period, and k and ω denote the EM wave number and frequency, respectively. As predicted by the Kroll-Morton-Rosenbluth equations [9] for high gain FELs, most of the electrons in one EM period are bunched about $\theta = 0$ during the exponential gain regime. One may define the bunching parameter by $b = |\langle e^{i\theta}\rangle|$, which represents an average over the electrons in the phase space $\lambda - \theta$, where γ is the Lorentz factor. Calculations show that maximum bunching should occur just before FEL saturation [10]. Consequently, the wiggler's length must be carefully adjusted to optimize bunching. The observation of high output power from the FEL indicates that some bunching has taken place, since coherent radiation of the electrons is needed to produce the energy. However, a direct measurement is required to evaluate the potential of FEL as a reliable source of bunched relativistic electrons.

Induction linacs are well suited for producing the electron beam, since they can generate kA currents whose pulse duration is typically a few tens of nanoseconds, compatible with the CLIC main-linac filling time. Furthermore, they have been proved capable of generating electron pulses with a repetition rate in the kHz range [11]. The primary aim of the present experiment is to evaluate the potential of using a FEL for producing the drive beam for CLIC. Prior work on bunching of electrons in a FEL has been carried out by Wurtele and collaborators at MIT [12], who studied prebunching in the first half of a wiggler. Recently, Marshall and Cecere have performed an experiment to study the feasibility of using the strong space-charge field produced by the bunches in a FEL to accelerate electrons to high energy [13].

We present a direct observation of the beam bunching which is predicted to occur in the FEL interaction. This work has been performed at CESTA (Centre d'Etudes Scientifiques et Techniques d'Aquitaine) where we operate a 35 GHz FEL amplifier driven by our induction linac called LELIA. We have obtained reproducible output power of 15 MW, which indicates that bunching has occurred. Furthermore, two independent methods were used to observe it. After the adiabatic wiggler exit, the beam was fed through a thin foil into an empty wave guide, where its passage generated EM power, provided that the beam was bunched. This simple method provides only a crude indication of the bunching, but it has the advantage that, simply by moving the foil, one may see how the beam debunches as a function of distance from the wiggler exit. In the second method the beam is totally absorbed by a 5 mm thick target of fused silica. It has been shown that electrons stopping in the target emit mainly Cherenkov light [14], which is then photographed with a streak camera. The variation of intensity with time in the image indicates the bunching. Since the image is obtained with a charge-coupled device (CCD), a numerical treatment has been performed to obtain a quantitative estimate of the bunching.

The main components of the experiment are schematized in Fig. 1. The right-hand side of the figure shows the two distinct terminations of the apparatus: The upper is used to measure the FEL output power, while the lower is designed to observe the bunching by optical means with

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the streak camera. The LELIA accelerator is an induction linac composed of a 10-cell injector plus a 12-cell accelerating module [15]. A high-voltage generator delivers a 80 ns FWHM, 100 kV pulse to the cells. The ten cells in the injector generate a 1 MV potential across a narrow *A*-*K* gap, producing a low-emittance electron beam from a thermionic cathode. The beam then passes through the induction accelerator cells where it is brought to 2.2 MeV. Each induction cell includes a solenoid to focus the beam and steering magnets to correct alignment errors. This ensures that all the current, as measured by Rogowsky coils, is transmitted through the accelerator. The measured unnormalized edge emittance at the end of the injector is 130π mm mrad. Magnet current adjustments are computed by a code which solves the envelope equation and predicts the beam radius as a function of distance along the axis [16]. We measure the beam radius by analyzing the Cherenkov emission which occurs when the beam hits a 5 mm thick fused silica target. This target can be moved along the axis owing to a mechanical system which permits translation under vacuum. We observe the emitted light with a gated camera which gives an integrated image (of duration 10, 20, or 50 ns) of a transverse section of the beam. Generally, the predicted envelope results are in very good agreement with measurements. This is important for the experiment, since we must know the beam's position precisely in order to inject it properly into the wiggler. Inside LELIA, the beam tube radius is 75 mm, whereas the wave guide radius in the wiggler is only 19.5 mm. In addition, two solenoids between the accelerator and the FEL were used to match the electron beam into the wiggler section. Because of transport issues during these series of experiments, only about 500 A of beam current was transported through the FEL region.

In our experiment we use a 2.88 m long wiggler with a 12 cm period. This pulsed helical wiggler provides a circularly polarized magnetic field of up to 3 kG on its axis. An adiabatic entry, made by strapping the first six periods, allows the beam to be correctly injected and gradually increases the transverse momentum of the electrons. A solenoid magnet was placed around this region in order to compensate transverse defocusing forces. Near the end of the wiggler, the wiggler field was adiabatically tapered over four periods, so that the electron beam was extracted on axis. Two Rogowski coils were used to measure beam current at the wiggler entrance and exit, respectively. To compute the electronic trajectories throughout the experiment (i.e., formed by the accelerator, the transport section, and the wiggler) we have used the 3D code ELECTRA [17].

The FEL runs in the amplifier mode, with the input power provided by a 100 kW magnetron which delivers a linearly polarized 500 ns pulse at 35 GHz. The initial TE_{10} mode propagates through a standard K_a-band rectangular wave guide, and is then converted to a circular wave guide, which transmits only the fundamental TE_{11} mode at the operating frequency. Its radius is adiabatically increased to the radius of the drift tube. A tungsten-wire grid then launches the EM wave into the interaction region, of which 50% has the correct circular polarization to interact with the electron beam. We have measured that 10 kW of drive power can be injected into the correct TE_{11} mode at the FEL's entrance. The output power from the FEL is transmitted through a microwave window to a radiative horn operating at room atmosphere. Standard techniques were used to measure the output power, and the known power of the magnetron allowed us to calibrate the detection system.

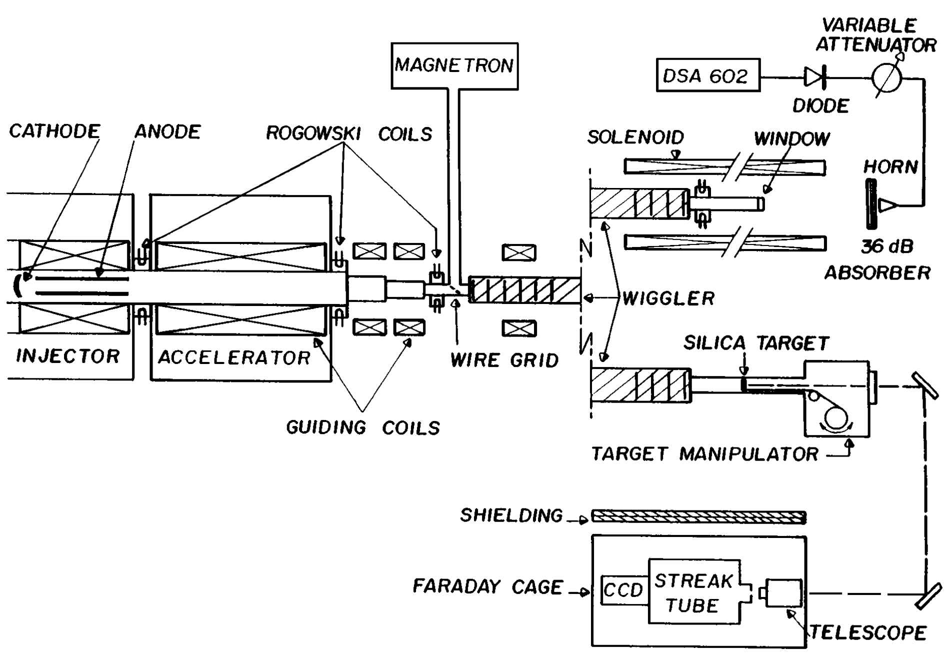

FIG. 1. Free-electron laser (upper) and bunching measurement (lower) setups.

The frequency f of the radiation being amplified may be written as

$$f = \frac{k_w v_z - \omega_p/\gamma_z \gamma^{1/2}}{2\pi(1 - v_z/c)},$$

where ω_p, v_z, γ_z, and c denote, respectively, the plasma frequency, electron axial velocity in the wiggler, axial Lorentz factor, and speed of light. The axial velocity v_z is given by $v_z = \sqrt{v_0^2 - v_\perp^2}$ where v_0 is the initial electron velocity and $v_\perp$ is the perpendicular electron velocity due to the wiggler field. For a helical wiggler in a one-dimensional model, $v_\perp = Kc/\gamma$, where $K = 93.4\lambda_w B_w$ is the dimensionless wiggler parameter (λ_w is in meters and B_w in tesla). For amplification at 35 GHz with our 2.2 MeV electron beam, the appropriate wiggler field is approximately 1.1 kG. The frequency of the output signal was measured by mixing with the output of a variable frequency local oscillator. Both the magnetron and the FEL signals were observed to have the same frequency, 35.02 $\pm$ 0.02 GHz.

The FEL gain and saturation length were computed with the 3D FEL code SOLITUDE [17]. The calculation predicts that saturation occurs at the seventeenth period. Our measurements, using a kicker magnet to defect the electron beam into the wall at different longitudinal positions, show fair agreement with the code, although the power level attained is somewhat less. Experimentally, saturation is reached near the nineteenth period where the peak power is 15 MW. Beyond this period we enter the nonlinear regime of FEL operation, where computations suggest that the quality of bunches will decrease. Since the bunching parameter b is predicted to reach its maximum value just before saturation, the wiggler was truncated at period 20. The addition of four adiabatically decreasing exit periods allows satisfactory beam extraction.

Given these promising FEL results, it was considered feasible to perform a direct measurement of bunching. First, we demonstrated that bunching occurs by carrying out a simple EM measurement. At a distance of 7 cm downstream from the wiggler exit, a 120 μm titanium foil was placed at a 45° angle across the beam tube. This foil completely deflects the incident microwave power, and the electron beam, upon passing through the foil, enters a region of the wave guide where no radiation field exists from the FEL interaction. A bunched beam will then create a new low-power EM wave whose power and frequency can be measured using the same diagnostic techniques as explained before. In a preliminary exploration of bunching carried out with a pulse-line diode to power the FEL, we had measured the frequency of this signal to be 35 GHz [18]. This method, by virtue of its simplicity, was extensively used both to optimize the extraction of the bunched beam by varying the position and field of the solenoid magnet, and to study the variation of bunching as a function of axial distance. For the latter, we placed a tungsten grid 30 cm behind the titanium foil in order to reflect the signal emitted by the beam between the titanium foil and the grid. Upon passing through the grid, the beam regenerates radiation whose power is measured. A reduction of about 80% of radiated power was observed, indicating an important debunching. We attribute this to the space-charge effects, which debunch the beam linearly with distance.

Although this method is simple, it is not sufficiently quantitative to characterize the bunched beam. Therefore we have performed an optical measurement of the bunching as well. We first used the gated camera to determine the position and size of the beam at the point

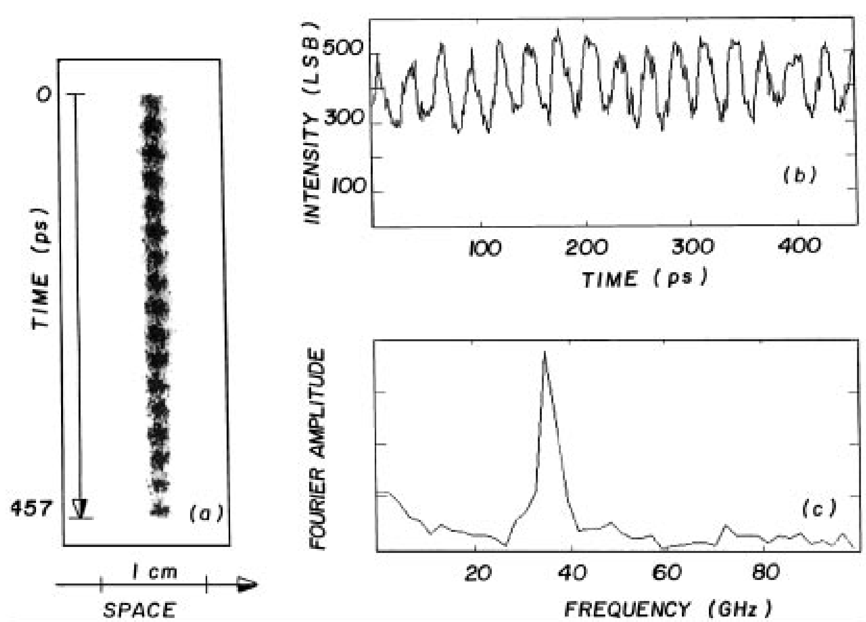

FIG. 2. Example of optical bunching measurement for a sweep speed of 25 ps/mm at a position 27.5 cm after the wiggler exit: (a) streak camera recording; (b) digitized intensity of (a) plotted vs time, and (c) frequency spectrum of (b).

where it strikes the target. The Cherenkov light produced in the target is then detected with an Application de la Recherche en Photonique (ARP) picosecond streak camera, as indicated in Fig. 1. The camera gathers light which falls on a narrow rectangular slit 10 mm wide and 0.3 mm high. The image of this slit is then displaced in time to provide a photographic record of the light intensity. The apparatus could be moved so as to scan the beam in the vertical direction, and the camera could be triggered at any instant within the time interval of the beam pulse. A series of measurements was executed by placing the target at different axial positions inside the wiggler, starting with the nineteenth period. A typical picture taken by the streak camera is displayed in Fig. 2(a), where the horizontal direction represents the distance along the slit, and the vertical axis indicates time. For this image the target was located 27.5 cm beyond the wiggler exit. The sweep speed was 25 ps/mm, and the time interval shown corresponds to 457 ps $\pm$ 5%. We clearly see the temporal variation of the Cherenkov light intensity, which is proportional to the beam current. The bunches are quite distinct, and their number in the time interval is consistent with the FEL frequency. The image shown is in fact a 512×512 pixel matrix which has been treated numerically. The light intensity integrated over a 4 mm wide strip in the horizontal direction is plotted vs time in Fig. 2(b), and one may estimate that the Fourier component at 35 GHz is 30% of the dc beam current. The Fourier transform of this signal is shown in Fig. 2(c), where a significant peak is visible at a frequency which is compatible, within errors, with 35 GHz. This constitutes clear evidence that the electrons are indeed bunched after extraction from the wiggler.

A number of tests have been performed to verify that the bunching is produced by the FEL interaction. If we turn off the magnetron, the FEL operates in the superradiant regime at low power, and no bunching occurs. Upon slightly changing the wiggler magnetic field from its optimal value, we observe that the bunching disappears rapidly, in accordance with the FEL power reduction. By the displacement in time of the observation window, we have verified that the bunches are present throughout the 25 ns FEL signal. Inside the wiggler, the vertical scan of the beam shows it to be bunched over its 5 mm diameter. As we proceed downstream from the wiggler exit, we find that debunching takes place. That portion of the beam which displays bunching is reduced to a spot of 0.5 mm diameter at a distance of 80 cm from the wiggler exit.

The bunching of the Cherenkov light generated in the silica target must inevitably be less sharp than the true bunching of the electrons striking the radiator, and the optical system has a finite time resolution as well. The simulations we have performed suggest that the combined resolution could be as large as 5 ps, which means that the electrons would be somewhat more bunched than our measurements indicate. In addition, while we expect the Cherenkov light to be proportional to the beam current, the optical detection system may have some modest nonlinearity, which would make our observed signal not strictly proportional to the beam intensity.

The principal result of this experiment was the demonstration of the production of a time and space modulated relativistic electron beam together with extraction of a bunched beam from an FEL. The measured rf current was estimated at 30% of the total current, or about 150 A. The electron bunching would presumably be enhanced by increased FEL efficiency, which was only 1% in this experiment. For untapered-wiggler FELs like ours, calculations indicate that the bunching parameter increases roughly linearly with FEL output power up to efficiencies of order 7%. In order to obtain very high FEL efficiency, such as the 35% obtained by Orzechowski *et al.* [19], a tapered wiggler is needed, and then it is not obvious that the bunching increases with higher power.

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