FIRST OPTICAL MEASUREMENT OF A BUNCHED BEAM PRODUCED BY A 35 GHZ FREE ELECTRON LASER

J.Gardelle, J.Labrouche and J.L.Rullier*, CEA/CESTA, BP 2, 33114 Le Barp, France

Abstract

We present the first direct observation of electron beam bunching produced by a high gain Free Electron Laser (FEL). This work is performed to study the feasibility of producing the drive beam of a two beam accelerator. The FEL amplifier uses an induction linac which delivers a 1 kA, 2.2 MeV electron beam. The beam interacts in a helical wiggler with a 35 GHz input wave which is amplified to power levels of the order of 10 MW. Optical measurements clearly show beam bunching which occurs at the FEL frequency. The evolution of bunches as a function of experimental parameters is discussed. In particular we study debunching along the beam propagation axis.

The next generation of electron-positron linear colliders with energy in the TeV range will require high gradient acceleration (20-100 MeV/m). Different approaches seeking to achieve such gradients are being actively pursued throughout the world [1]. Among them, the Two Beam Accelerator (TBA) concept appears promising [2,3,4]. In a TBA the first accelerator transports an intense low-energy drive beam which, thanks to 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 generation of the drive beam is a major challenge which could be solved by using the bunching which occurs in the Free Electron Laser (FEL) interaction.

In a FEL [5], an electron moves in the ponderomotive potential created by the wiggler and the EM field. For high gain FELs, most of the electrons are bunched every EM period, during the exponential gain regime. The bunching parameter [6], describing an average over the electrons in the phase space, is defined by $b = \left|\left\langle e^{i\theta} \right\rangle\right|$, with $\theta = (k+k_w)z - \omega t$ defining the phase. Here $k_w = 2\pi/\lambda_w$ where k_W, ω and λ_w denote the EM wavenumber, EM frequency and wiggler period, respectively. Calculations show that maximum bunching should occur just before FEL saturation [7]. Consequently, the wiggler's length must be carefully adjusted to optimise 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 high energy. However, a direct measurement is required to evaluate the potential of a FEL as a reliable source of bunched relativistic electrons. In this paper we present the first experimental measurement of a bunched beam produced by a 35 GHz high gain FEL [8].

A schematic of the experiment is shown in Fig. 1. The components of the device are the pulse-forming line which is a magnetic compression system (MAG), the induction linac, the axial guiding magnetic field coils, the bifilar wiggler, the magnetron and the various measuring devices. 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.

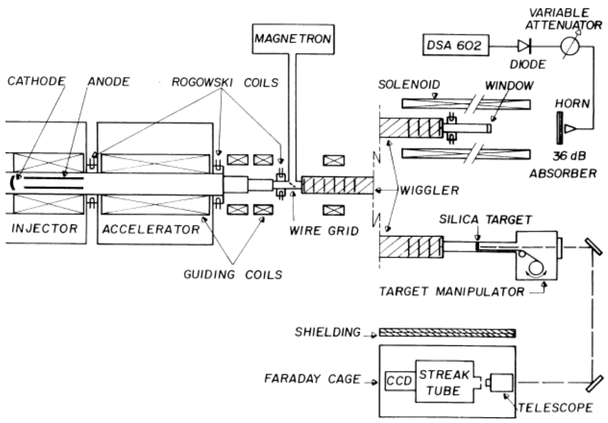

Figure: 1 Free Electron Laser (upper) and bunching measurement (lower) set-ups

The MAG is a high-voltage generator which delivers a 80 ns FWHM, 100 kV pulse to each cell in the 10-cell injector and the 12-cell accelerating module which constitute our induction linac, called LELIA [9]. The injector generates a 1 MV potential across a Anode-Cathode gap, producing a low-emittance electron beam from a thermionic cathode. The beam then passes through the induction accelerator module 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 130 π mm mrad. 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 placed between the accelerator and the FEL were used to match the electron beam into the wiggler section. Nevertheless, because of transport issues, 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 B_w of up to 3 kG on its axis. An adiabatic entrance, 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 down-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 3-D code ELECTRA [10].

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 Ka-band rectangular waveguide, and is then converted to a circular waveguide, 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 in the correct TE_{11} mode at the FEL's entrance. The output power from the FEL is transmitted through a microwave window which maintains the vacuum. After attenuation caused by spreading in the air and losses in a 36 dB absorber, a small fraction of the radiation is collected by a rectangular horn (Ka-band). Then a variable attenuator (0-40 dB) reduces the power to the desired level for the diode detector whose response on the oscilloscope (Tektronix DSA-602) determines the power level. The entire system is calibrated using the known input power of the magnetron.

To obtain amplification at 35 GHz with the 2.2 MeV electron beam, the basic theory of the FEL indicates that the appropriate wiggler field is approximately 1.1 kG [11]. The experimental variation around this nominal value illustrates the sharpness of the FEL resonance. A relatively small change in B_w produces a substantial power reduction, in agreement with the simulation results given by the 3-D FEL code called SOLITUDE [10].

The FWHM signal duration is about 25 ns, which is roughly half the duration of the useful part of the current pulse. If we compare this result with the one obtained in a previous experiment [12] performed with a pulsed-line generator, the FEL power lasts in this experiment 3-times longer. The electrical power carried by the electron beam of 450 A and 2.2 MeV is 0.99 GW. Consequently, 15 MW of FEL power corresponds to an efficiency of 1.5 %. As mentioned above, the quality of the bunches is strongly dependent on the FEL power. The behavior of the output power as a function of the FEL interaction length for the nominal B_w value has been investigated. The experimental results were obtained with a kicker magnet, which was used to deflect the electron beam into the wall at any desired longitudinal position. Experimentally, we observe saturation at period 20, with 15 MW of peak power, whereas the numerical prediction for perfect beam (zero emittance and zero energy spread) suggests earlier saturation at a power level roughly ten times as great. Nevertheless, both experiment and calculation exhibit a gain of 33 dB for the exponential regime. Consequently, the wiggler was truncated at period 20 in order to maximise beam bunching. The addition of 4 adiabatically decreasing exit periods allows satisfactory beam extraction.

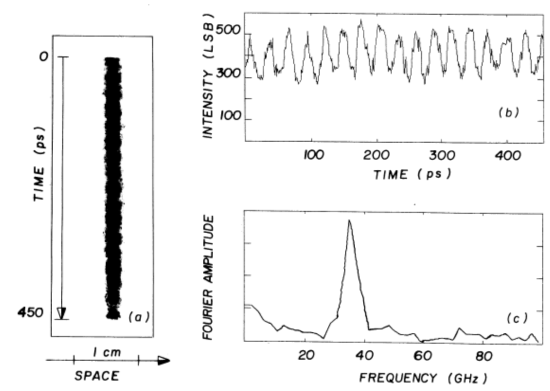

Figure 2 : Example of optical bunching measurement for a sweep speed of 25 ps/mm at a position 27.5 cm after the wiggler exit: (a) streak camera recording; (b) digitized intensity of (a) plotted vs time; (c) frequency spectrum of (b).

Given these FEL results, it was considered feasible to perform a direct measurement of beam bunching. The bunches are optically measured by analyzing the Cerenkov emission in a 5 mm thick target of silica glass, which is metalized on its upstream face so as to avoid charging the target. We first used a gated camera to determine the position and size of the beam at the point where it strikes the target. The Cerenkov light produced is then detected with a Photonetics-ARP (Application de la Recherche en Photonique) 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. 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 450 ps of time interval shown corresponds to 35.6 ± 0.8 GHz, which is consistent with the input frequency of the magnetron. We clearly see the temporal variation of the Cerenkov light intensity, which is proportional to the beam current. The image shown is in fact a 512 x 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 a modulation of 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 the FEL frequency.

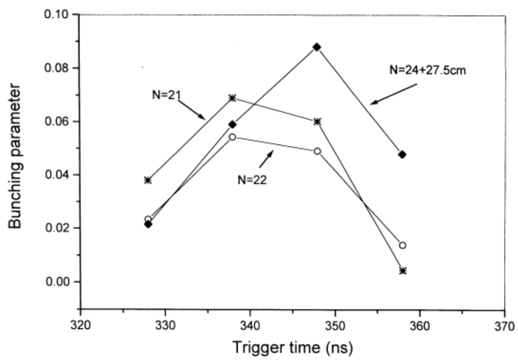

Figure 3 : Experimental bunching parameter at different time slices within the electron beam for three axial positions

Two tests have been performed to verify that the bunching is produced by the FEL interaction. First, if we turn-off the magnetron, the FEL operates in the super-radiant regime at low power, and no bunching is observed. Second, upon slightly changing the wiggler magnetic field from its optimal value, the bunching disappears rapidly, in accord with the FEL power reduction.

We have investigated whether the bunching we observe persists throughout the entire pulse. To do this, we triggered the camera at various different times throughout the pulse, and determined the corresponding bunching. The timing of the trigger was based on a start signal provided by the high-voltage pulse, which permitted us to achieve an overall precision of 2 ns. The results of these measurements are illustrated in Fig. 3, which displays the bunching parameter b for different time slices inside the FEL pulse. The bunches are present throughout the 25 ns-long FEL pulse for the three different longitudinal positions where this measurement was accomplished.

The total apparatus could be moved so as to scan the beam in the vertical direction. 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. While some of the debunching may be attributed to longitudinal space charge effects, we find that there is some dependence on the value of the solenoidal magnetic field used to extract the beam. The greater the field, the more rapidly the beam debunches.

The principal result of this experiment was the demonstration of the production of a time and space modulated relativistic electron beam together with the 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. Earlier works with similar FELs have obtained efficiencies up to 35 % [13], which leaves considerable room for improvement of the present experiment.We thank G. Marchese for providing invaluable technical assistance. We would like also to acknowledge fruitful discussions with J. T. Donohue, D. Gogny, and D. Villate. The support of the LELIA group and the diagnostics team is greatly appreciated.

* Supported by CERN

REFERENCES

[1] J. S. Wurtele, Physics Today, July 1994, page 33.

[2] A. M. Sessler, D. H. Whittum, J. S. Wurtele, W. M. Sharp and M. A. Makowski, Nucl. Instrum. Methods, A **306**, 592 (1991).

[3] A. M. Sessler and S. S. Yu, Phys. Rev. Lett. **58**, 2439 (1987).

[4] K. Hübner, CERN/PS 92-43, CLIC note N° 176.

[5] W. B. Colson and A. M. Sessler, Annu. Rev. Nucl. Part. Sci. **35**, 25 (1985).

[6] H. D. Shay, R. A. Jong, R. D. Ryne, S. S. Yu and E. T. Scharlemann, Nucl. Instrum. Methods, A **304**, 262 (1991).

[7] W. Barletta et. al., Nucl. Instrum. Methods,.A **329**, 348 (1993).

[8] J. Gardelle, J. Labrouche and J. L. Rullier, to appear in Phys. Rev. Lett.

[9] J. Launspach et al., Nucl. Instrum. Methods, A **304**, 368 (1991)

[10] J. Gardelle, J. Labrouche, P. Le Taillandier and P. Gouard, Phys. Rev. E **50**, 4973 (1994)..

[11] T. C. Marshall, *Free Electron Lasers*, ed. Macmillan 1985.

[12] J. L. Rullier, A. Devin, J. Gardelle, J. Labrouche , P. Le Taillandier and J. T. Donohue, Phys. Rev. E **53**, 2787 (1996).[13] T. J. Orzechowski et al., Phys. Rev. Lett. **57**, 17 (1986).