Free-Electron Laser as a Driver for a Resonant Cavity at 35 GHz

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An intense beam of relativistic electrons (800 A, 6.7 MeV) has been bunched at 35 GHz by a free-electron laser, in which output power levels exceeding 100 MW were obtained. The beam was then extracted and transported through a resonant cavity, which was excited by its passage. Microwave power levels of 10 MW were extracted from the cavity, in reasonable agreement with the simple formula which relates power to known properties of both the beam and the cavity.

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The Two-Beam Accelerator (TBA) has been proposed as a means of obtaining high energy electron beams (TeV) in a linear collider of moderate length [1,2]. In the TBA, a very intense low energy electron beam, called the drive beam, is transported parallel to the low current high energy beam to be accelerated. This bunched drive beam passes through a sequence of resonant output cavities, where some of its energy is deposited. These cavities are thus filled with high power microwave energy, which is then transported to the cavities which accelerate the main beam. Studies of the feasibility of this concept are being pursued at CERN [3] and at Lawrence Berkeley National Laboratory (LBNL) [4]. The frequencies aimed at are 30 GHz in the Compact Linear Collider (CLIC) project at CERN and 11.4 GHz in the LBNL Relativistic Klystron Two-beam Accelerator scheme. Among the technological challenges are the production of a bunched beam at such frequencies, and the extraction of microwave energy in the resonant cavities, of necessarily limited size. Various methods have been proposed to generate the bunched drive beam, in particular, the use of a free-electron laser (FEL) was suggested by Shay and co-workers [5]. With this aim a FEL powered by a high-current (kiloampere) induction accelerator has been investigated at CEA/CESTA over the past few years. Previous results [6,7] indicated that the FEL mechanism was capable of generating an intense beam bunched at the FEL operating frequency of 35 GHz. In this note we report on the production of microwave power obtained by extracting the bunched beam from the FEL, and then focusing and injecting it into a resonant cavity. An experiment designed to test transfer structures in the CLIC scheme has been performed at CERN [8], and traveling-wave cavities were tested at Lawrence Livermore National Laboratory [9]. The cavities we use in the present experiment were designed at LBNL [10] and built by the CLIC collaboration at CERN.

Although the earlier results were obtained with the induction accelerator "LELIA" (2 MeV), the rapid debunching of the beam, which is caused by its space-charge, makes it hard to preserve the bunching during the extraction and focusing of the beam and its transfer into the resonant cavity. For this task the accelerator "PIVAIR" [11], designed for flash x-ray radiography, is better suited. It delivers a single-shot 6.9 MeV, 3 kA electron beam of duration 60 ns FWHM. The normalized edge emittance at the injector exit is 1000π mm mrad, and the energy spread is less than 1% over 60 ns. The extensive instrumentation of PIVAIR permits us to verify in detail the shot-to-shot reproducibility by eliminating those shots where some anomaly occurred.

In Fig 1 the experimental layout is shown, with PIVAIR indicated schematically at left. On the right are shown two alternative ends for the beam line, the upper for measuring the cavity output power, and the lower for beam position and size (with an inclined thin Mylar target), and bunching measurements (with a thick fused silica target) using optical diagnostics which have been described elsewhere [7]. The inset shows the details of the resonant cavities used. The full current from PIVAIR was collimated to 830 ± 30 A at the FEL entrance. The wiggler is a pulsed bifilar helix, with 32 periods of length 20 cm. The input electromagnetic signal of 5 kW at 35 GHz, generated by a magnetron, is then amplified in the wiggler by the electron beam. In order to bring the electron beam onto the ideal helical trajectory, an adiabatic section six periods long is used to increase the wiggler magnetic field from zero to

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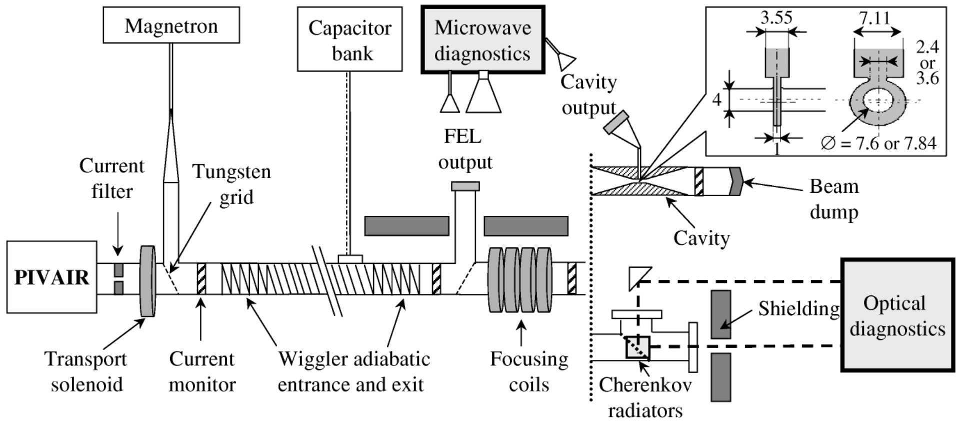

FIG. 1. Experimental setup, showing the accelerator PIVAIR, magnetron, wiggler, focusing system, FEL and cavity output lines, and optical and rf detectors. Two alternative terminations are shown for measuring cavity power and beam characteristics, respectively. The inset shows details of resonant cavities (all dimensions in mm).

its nominal value. Similarly a six-period adiabatic exit is employed to extract the bunched electron beam along the axis at the end of the wiggler. These adiabatic sections are essential components of the beam transport, and they are described in detail in a separate paper [12]. The microwave power produced in the wiggler is deflected out of the beam line by a fine tungsten wire mesh, identical to that used to inject the magnetron signal into the beam tube. Microwave power and frequency measurements are performed using calibrated attenuators, Schottky diodes, horns, and waveguides for both Ka and X frequency bands, respectively. Upon leaving the wiggler the bunched beam is focused by a group composed of four thick coils. The aim is to obtain a centered waist at the position of the cavity, and the coils may be displaced or tilted in order to achieve this.

In this experiment, we used two resonant cavities (one at a time). These cavities, which operate in the TM_{010} mode, differ in their resonant frequencies and Q values. Since wall and beam tube losses are negligible, the Q values depend essentially on the coupling to the output WR28 waveguide. The low-Q cavity, with resonant frequency f_0 tuned closer to the beam modulation ($Q = 60$, $f_0 = 35.18 \pm 0.05$ GHz), will extract more power than the high-Q cavity. The latter, with its resonance inductively detuned from the modulation frequency ($Q = 270$, $f_0 = 35.64 \pm 0.05$ GHz), extracts less power, but induces a head-tail energy correlation over the bunch. This counteracts the effects of debunching due to self-field forces and incoherent energy spread, and leads to stability in the longitudinal dynamics by introducing synchrotron rotations. This is an important dynamics issue in low energy TBA schemes and requires detailed study. The beam, which had been propagating in a tube of 38 mm diameter, must pass through an orifice 4 mm in diameter. This dimension is dictated by the need to be below cutoff for the 35 GHz radiation produced in the cavity.

The experiment consisted of essentially three distinct parts: first, to obtain an adequate power level with the FEL; second, to transport the bunched beam, properly focused, into the cavity and measure the output power; and finally to measure the bunching at the beam waist using a streak camera in the optical detection line.

We show in Fig. 2a the currents at the wiggler entrance and exit as a function of time (the latter has been shifted by the time of flight of electrons between the two current monitors), while in Figs. 2b and 2c we show the FEL power signals vs time for the upper and lower resonant frequencies, f_+ (35 GHz) and f_- (9.5 GHz). Again the time of propagation of these signals to the detectors has been subtracted, to permit comparison with Fig. 2a. One sees that the output power at 35 GHz attains its peak value

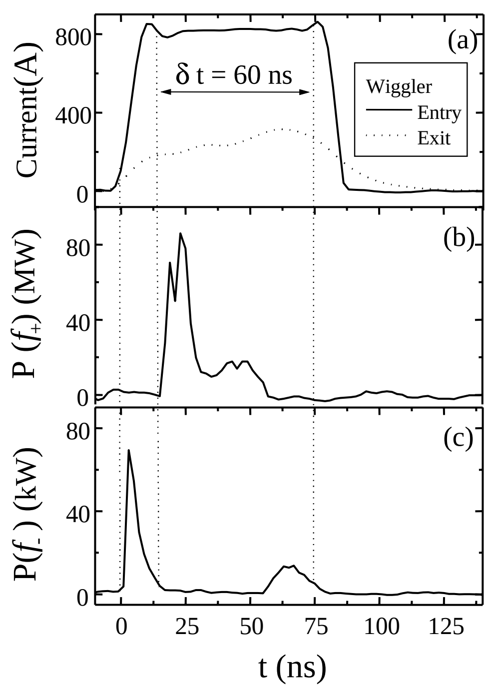

FIG. 2. Temporal current (a) and power signals at both high (b) and low (c) resonant FEL frequencies (corrected for time of flight).

only during the early part of the pulse. In contrast, the low frequency signal, which is not injected, appears to increase towards the end of the pulse, and may be responsible for the decrease in f_+ output [7].

By moving a magnet along the beam line, it was possible to deflect the electrons into the beam tube at any desired position, and thus determine the peak FEL power as a function of axial distance. Such measurements were performed, and are shown in Fig. 3. Also displayed are the predictions of the code "SOLITUDE" [13] for the power and the bunching parameter b. Although the code is stationary and cannot reproduce the time dependence of the output power, it does provide a fair description of the variation of the peak power as a function of distance. The bunching parameter calculated by the code is 0.4 ± 0.05 at the end of the wiggler. In addition, the important loss of current shown in Fig. 2a is reproduced by the simulation.

At this point in the course of the experiment, breakdown problems occurred in the injector, which required that the beam energy, initially 6.9 MeV, be reduced to 6.7 MeV. At this slightly different energy, higher peak FEL power ($>$100 MW) was obtained and all subsequent measurements were made at this energy. Once suitable operation of the FEL was achieved, the optical detection line with a thin Mylar target placed at the beam waist was employed to optimize the beam position and transverse size. At the waist, its diameter was about 8 mm. The cavity was then mounted, and measurements included power levels in both the FEL and cavity detection lines. Current monitors were placed before and after the cavity. The frequencies of both the FEL (f_+) and the cavity radiation were found to be the same as that of the input magnetron. The main results are displayed in Table I. The errors shown are statistical only, based on the number of shots indicated in the last row. We observed some energy variation in the performance of the accelerator, which led us to reject a certain number of shots, thereby limiting our statistics. We note that the current measured at the entrance to the cavities is of the order of 200 A. Since the beam spot size at the cavity position exceeded the aperture of the cavities, only half the entrance current, at best, exits the cavity. We found that a modest (5%) decrease in the wiggler magnetic field led to much better beam transmission through the cavity, without severely reducing the FEL output power. Thus the table has four columns, two for each cavity, corresponding to the different operating fields, 1680 and 1580 G, respectively.

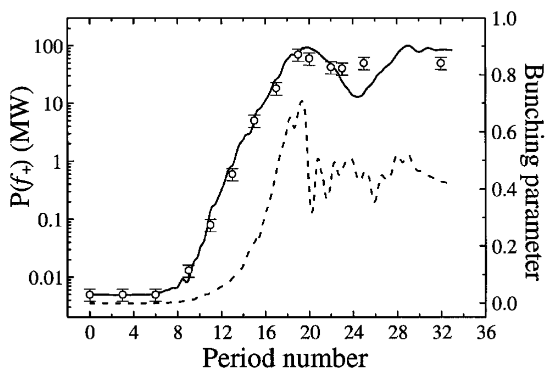

FIG. 3. FEL power output as a function of axial distance, along with predictions of the code SOLITUDE for the power (solid curve, log scale on left) and bunching parameter (dashed curve, linear scale on right).

In Fig. 4 are shown the cavity output current, FEL output power, and cavity output power for two shots, one with the low-Q and the other with the high-Q cavity. Again the time of flight differences have been removed to align these different curves to a common origin. Both the FEL and cavity signals are significantly shorter than the current pulse, but both peaks coincide with the maximum of the output current.

With a current of 200 A, the light output from the Mylar target was not sufficient to allow streak camera photography. Instead, a thick (2 cm) fused silica target was used as a radiator, producing Cherenkov radiation in the forward direction. Since this requires the electrons to stop in the target, straggling is appreciable and background emission is significant. Thus only a noisy optical signal was observed, which indicated bunching at 35 GHz, but did not permit a quantitative measurement. Calculations using GEANT [14] indicate that the FWHM of the light signal from a delta-function electron pulse striking the target is approximately 12 ps. This would make the observed bunching only 50% of the true value. We conclude that this method does not lead to a valid estimation of the bunching parameter b without further experimental work. However, a theoretical approach, which combines the results for the electron phase-space density, as calculated by SOLITUDE, with the code RKS [15] to calculate the transport of the beam from the wiggler exit through the cavity, predicts b as a function of distance. This calculation indicated a substantial increase, from 0.4 to 0.5 at the cavity entrance, followed by a jump to 0.6 just inside the cavity. It also indicates current losses in transport comparable to those we observe. In fact, the transport and the cavity appear to act as filters, accepting preferentially the bunched portion of the beam.

The formula

$$P = \left[\frac{R}{Q}\right] Q (Ib\cos\phi)^2$$

may be used to calculate the output power from a cavity in terms of b, the current I, the Q of the cavity, the factor $[\frac{R}{Q}]$ which characterizes the coupling between beam and cavity, and the phase $\phi = \tan^{-1}[\frac{Q(f_0^2 - f^2)}{ff_0}]$, where f denotes the frequency of the bunched beam [15]. This formula supposes that the beam lasts several cavity-filling times, and that the bunching is stable in time. The calculated filling time is approximately 0.5 ns, while the bunching certainly varies with time over a period of 15 ns. Nevertheless, if one applies the formula, one finds, assuming $I = 100$ A, $b = 0.6$, and $[\frac{R}{Q}] = 45$, output power of 8 MW for the low-Q and 520 kW for the high-Q cavity. While we

TABLE I. Summary of results.

Cavity	Low-Q		High-Q	
Wiggler magnetic field (G)	1680 ± 40	1580 ± 40	1680 ± 40	1580 ± 40
FEL power (MW)	150 ± 30	110 ± 20	150 ± 20	110 ± 40
Cavity input current (A)	210 ± 10	210 ± 20	190 ± 30	210 ± 10
Cavity output current (A)	25 ± 5	100 ± 30	50 ± 15	110 ± 20
Cavity rf power (MW)	0.28 ± 0.04	10 ± 3	0.06 ± 0.03	0.7 ± 0.5
Reproducibility (number of slots)	15	15	10	3

observe somewhat higher power levels than these, the order of magnitude is reasonable. These numbers are comparable to the power levels shown in Fig. 4. In addition, the large variation in output power seen for our two choices of wiggler field can be explained by the large difference in current transmission and a modest variation in the bunching parameter.

While this experiment has demonstrated power generation by a FEL bunched beam, improvements are needed to demonstrate that the FEL could be used as a drive beam source. To do this, it is necessary to produce cavity output power of at least 100 MW over a pulse ≥ 30 ns, and to measure bunching both at the entrance and the exit of the cavity. These goals could be reached by transmitting 400 A through the cavity, which could be achieved with a better design of the wiggler and beam transport, and by suppressing the growth of the lower FEL frequency f_-, which would extend the pulse length. With the increased current, reliable bunching measurements using the thin Mylar radiator would become feasible, avoiding the difficulty of using the thick silica target. On the basis of our present experience, we think such improvements can be made.

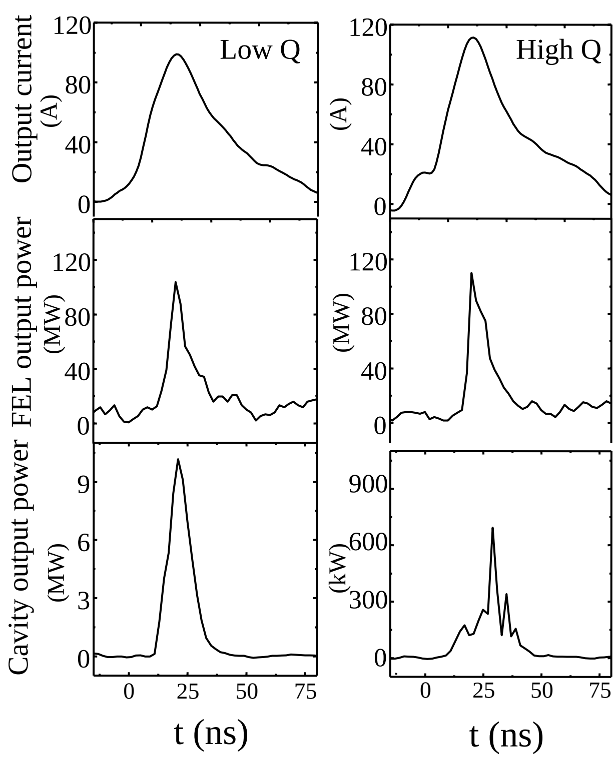

FIG. 4. Current exiting cavity (top), FEL power (middle), and cavity output signals (bottom) as functions of time for low-Q (left) and high-Q (right) cavities.

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[1] A. M. Sessler and S. S. Yu, Phys. Rev. Lett. **58**, 2439 (1987).
[2] K. Hübner, Report No. CERN/PS 92-43, CLIC note No. 176 (unpublished).
[3] J. P. Delahaye *et al.*, in *Proceedings of the 1999 Particle Accelerator Conference, New York* (IEEE, Piscataway, NJ, 1999), p. 250.
[4] G. Westenskow *et al.*, in *Proceedings of the 1995 Particle Accelerator Conference, Dallas, Texas* (IEEE, Piscataway, NJ, 1995), p. 737.
[5] H. D. Shay *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **304**, 262 (1991).
[6] J. Gardelle, J. Labrouche, and J. L. Rullier, Phys. Rev. Lett. **76**, 4532 (1996).
[7] J. Gardelle *et al.*, Phys. Rev. Lett. **79**, 3905 (1997).
[8] R. Bossart *et al.*, in *Proceedings of the XIX International Linac Conference, Chicago, 1998* (Argonne National Laboratory, Argonne, IL, 1999), p. 85.
[9] G. A. Westenskow and T. L. Houck, IEEE Trans. Plasma Sci. **22**, 750 (1994).
[10] S. M. Lidia *et al.*, in *Proceedings of the XIX International Linear Accelerator Conference, Chicago, 1998* (Ref. [8]), p. 97
[11] P. Anthouard *et al.*, in *Proceedings of the 1997 Particle Accelerator Conference, Vancouver, Canada* (IEEE, Piscataway, NJ, 1997), p. 1254.
[12] Y. Meurdesoif *et al.* (to be published).
[13] J. Gardelle, J. Labrouche, P. Le Taillandier and P. Gouard, Phys. Rev. E **50**, 4973 (1994).
[14] F. Carminati *et al.*, *The GEANT Manual* (CERN, Geneva, 1996).
[15] S. M. Lidia, in *Proceedings of the 1999 Particle Accelerator Conference, New York* (Ref. [3]), p. 2870.