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OSCILLATOR EXPERIMENT

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Subharmonic Buncher for the Los Alamos
Free-Electron Laser Oscillator Experiment*

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Abstract

A high efficiency free-electron laser oscillator experiment is being constructed at Los Alamos National Laboratory. A buncher system has been designed to deliver 30-ps, 5-nC electron bunches to a 20-MeV standing-wave linac at the 60th subharmonic of the 1300-MHz accelerator frequency. The first 108.3-MHz buncher cavity accepts a 5-ns, 5-A peak current pulse from a triode gun. Following a 120-cm drift space, a second 108.3-MHz cavity is used, primarily to enhance the bunching of the trailing half of the bunch. A 1300-MHz cavity with 20-cm drift spaces at the each end completes the beamline components. The bunching process continues into the linac's first three accelerating cells. Two thin iron-shielded lenses and several large-diameter solenoids provide axial magnetic fields for radial focusing.

Introduction

The experimental conditions of the free electron laser oscillator experiment at Los Alamos require a single optical bunch in the 7-m-long resonator. Therefore, the repetition rate of the electron beam bunches must be ~30 ps long and contain at least 3 nC per bunch to the linac.

A Litton triode gun with a grid pulser and a postaccelerator was designed to deliver a peak current of over 5 A at 80 keV, with a base width of 5 ns. The computed normalized transverse emittance¹ is ~25 mm·mrad. Tapered OFHC copper apertures are provided to spatially filter the gun emittance, if necessary, to achieve the required emittance of 1 mm·mrad at 20 MeV in the wiggler.

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Choice of Subharmonic Frequency

The length ℓ of the optical cavity is constrained for various reasons to lie between 4 and 8 m and is related to the gun-pulse frequency f_{gun} by $\ell = 150 f_{\text{gun}}^{-1}$, where ℓ is in meters and f is in megahertz. The gun-pulse width must be shorter than a half-period of the first subharmonic buncher-cavity field; therefore, $f_{\text{shb}}^{-1} > 2$ times the gun-pulse width. Finally, the gun-pulse frequency and the subharmonic buncher frequency must be harmonically related to the linac frequency, 1300 MHz, and to each other. Hence, $f_{\text{shb}} = 1300/n$, $f_{\text{gun}} = 1300/m$, and $m/n = k$, where k , m , and n are integers. A lower limit on f_{shb} is imposed to minimize the size of the buncher cavities, which are located within the central boreholes of several solenoid magnets.

The chosen parameters are $n = 12$, $m = 60$, and $\ell = 6.92$ m. For $n < 12$, the rf period is too short; for $n < 13$, the cavities are too large; and for $m > 60$, the optical cavity is too large. Therefore, $f_{\text{gun}} = 21.67$ MHz and $f_{\text{shb}} = 108.33$ MHz.

Design Calculations

A one-dimensional ring code² was used as a guide in selecting the number and location of the buncher cavities and to select field amplitudes and phases in the cavities. This code is the most recent in a long line of computer simulations derived from the large-signal theory of traveling-wave tube amplifiers.³ The ring radius is assumed to remain constant, while the current's effective value increases as the bunching proceeds.

As a complementary approach, integration of the Pierce paraxial envelope equation⁴ was used to determine the axial magnetic field required to maintain Brillouin flow or constant equilibrium beam radius. The Pierce equation ignores beam emittance but this is acceptable for the

present case in which space charge forces dominate the beam behaviour throughout the injector.⁵

The axial magnetic field produced by a trial set of collinear solenoids was calculated for use in the paraxial envelope code. The beam current's effective value was assumed to increase linearly from 5 A at the first buncher to 100 A at the end of the bunching region.

The chosen design, based on the foregoing calculations, consists of two subharmonic-frequency buncher cavities and one buncher cavity at the linac frequency. The ring-model calculation shows clearly that under the given input conditions, the initial bunching must be gentle, with a long drift space. A second subharmonic buncher cavity is required to correct a nonlinear bunching that is an unavoidable relativistic effect. Equal and opposite energy changes imposed in the two halves of the sinusoidal buncher field result in different values of fractional velocity change, hence different bunching. The second buncher is phased to enhance the bunching of the trailing half of the bunch. Finally, the third cavity is required to compress the bunch sufficiently so as to minimize the energy spread in the high field gradients of the first three accelerator cells, where further bunching occurs.

The bunching voltages, phases, frequencies, and drift distances following each buncher gap are given in Table 1.

The charge and energy distributions after passing through the third graded- β linac cell are shown in Fig. 1. The total charge injected into the first subharmonic buncher was 20 nC. In Fig. 1, the total charge in the central peak, 34 ps wide, is 13 nC. In the energy spectrum, the peak, which is 160 keV wide, contains 9 nC.

The results of integrating the paraxial envelope equation with the chosen solenoid parameters are shown in Fig. 2. Brillouin flow was not achieved with the assumed conditions, but the scalloping is small enough to allow the beam to be transported within the available apertures.

TABLE I
BUNCHER VOLTAGES, PHASES, FREQUENCIES,
AND DRIFT DISTANCES

<u>Cavity No.</u>	<u>Frequency (MHz)</u>	<u>Peak Voltage (kV)</u>	<u>Phase (degrees with respect to reference ring)</u>	<u>Drift (cm)</u>
1	108.33	30	0	120
2	108.33	18	-30	20
3	1300	20	-10	20

Buncher Cavity Design

The three buncher cavities are of the coaxial resonator type. In the 108.33-MHz cavities, the over-all dimensions were reduced by placing disks on the ends of the inner members of the coaxial structure to provide capacitive loading. Details of the design were established with the aid of the SUPERFISH code. The measured Qs were 7900 and 8400 for the 108.33- and 1300-MHz cavities, respectively. The computed power dissipations to achieve the required peak voltages given in Table I are 1100, 400 and 400 watts respectively.

The cavities are provided with tuning plungers mounted on micrometer actuators with bellows vacuum seals. The tuning ranges available are 0.7 and 0.6% for the 108.33- and 1300-MHz cavities, respectively. Each buncher cavity is provided with a water-cooling coil to stabilize the cavity temperature.

The Injector Assembly

An elevation view of the complete injector assembly is shown in Fig. 3. The beam from the electron gun first passes through two thin lenses of the electromagnet type. Steering coils and a pumping channel are located between the thin lenses.

As the beam approaches the first subharmonic buncher cavity, it enters a ramped axial magnetic field (Fig. 2).

A second set of steering coils, a valve, and a retractable fluorescent screen are located between the two subharmonic-frequency cavities. Three broad-band wall-current monitors of the type used in the injector for the proposed SLAC Linear Collider are located in the injector beam line.

A graded set of three beam-limiting apertures is provided in the space between the two thin lenses. The apertures are tapered with a 10° half-angle in a 5-cm-thick block of OFHC copper. Tapered apertures located near dispenser cathodes have been shown⁶ to eliminate poisoning of the cathodes caused by metal atoms sputtered upon impact of negative oxygen ions emitted from the cathode.⁷ The aperture diameters are 4, 6, and 8 mm; a fourth position of the aperture frame presents no obstruction to the beam.

Cavity excitation by the beam

A bunched beam will radiate energy into a cavity as it passes through. In an accelerating cavity, the energy acquired from the bunch will normally be much smaller than the energy stored in the cavity from the rf generator. In a buncher cavity, however, the stored energy is relatively small. Consequently, the excitation of a buncher cavity by a pre-bunched beam cannot be ignored. Furthermore, when a train of beam bunches passes through the cavity at a repetition frequency which is a subharmonic of the cavity resonant frequency, the stored energy accumulates up to an equilibrium level governed by the bunch charge, the bunch repetition rate and the loaded Q value of the cavity.

The beam-induced voltage in the buncher gap will be 180° out of phase with the bunch phase. The net buncher gap voltage will usually be required to reach its peak value 90° from the bunch phase hence the beam will induce a phase shift as well as an amplitude change in the net cavity voltage. For a train of 5 nC bunches at a repetition rate of 21.67 MHz in a 108.3 MHz cavity with a loaded Q of 4000, the equilibrium beam-induced voltage is approximately 34 kV. Since the net cavity voltage (in buncher number one) is required to be 30 kV, the rf generator voltage must be varied by a factor of 1.5 and its phase shifted by 49° from the zero beam to full beam condition.

Figure 4 shows the rf envelope in buncher number one. The initial rise is the natural filling of the cavity. The dip in the middle of the envelope is due to the resonant build-up of the beam-induced voltage, the relative phases of the rf generator and beam being such as to result in a net decrease of the cavity voltage. Figure 5 shows the result on the cavity voltage of activating the phase and amplitude control loops. The initial filling of the cavity is now much more rapid and only small transients remain at the beginning and end of the beam pulse train.

Bunching Measurements

The initial tuning of the triple buncher system was done with the aid of broadband wall current monitors. These are located 12 cm upstream from the first buncher, between the first and second bunchers and 7 cm downstream from the third. The monitor signals were observed through 50 m of corrugated-jacket, foam-dielectric cable on a Tektronix 7104 oscilloscope. Figure 6 shows a typical pulse at the third wall-current monitor with the three bunchers operating. The minimum pulse width observed, about 300 ps FWHM, was undoubtedly limited by the system response. The bunching factor over the gun pulse width of 4 ns FWHM is in excess of 13 and bunch width is small enough to match the phase acceptance of the linac (equivalent to 350 ps). Further measurements on the buncher performance await the installation of longitudinal and transverse emittance diagnostics in the linac output beam line.

Acknowledgments

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Figure Captions

- Fig. 1 Linac input phase and energy distribution from the ring-model calculation.
- Fig. 2. Beam radius, R , from the integration of the Pierce paraxial envelope equation. The axial magnetic field, B_z , is produced by the set of lenses and solenoids indicated at the top of the figure. The current, I , is assumed. The circles are equilibrium radii from Ref. 5. Buncher beam pipe and linac apertures are indicated.
- Fig. 3. The injector assembly for the Los Alamos free electron laser oscillator experiment.
- Fig. 4. RF envelope in buncher number one showing the resonant buildup of the beam-induced field starting 100 μ s from the start of the sweep. Scale: 50 μ s/div.
- Fig. 5. RF envelope as in Fig. 4 but with phase and amplitude control loops operating.
- Fig. 6. Bunched beam as observed at a wall-current monitor after the third buncher. Scale: 1 ns/div.

(1)

(2)

(3)