

Formation of nanosecond multibunch structure in thermionic electron beams and generation of multibunch x-ray free-electron laser pulses

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The x-ray free-electron laser (XFEL) facility SACLA uses a thermionic pulsed electron gun and a beam chopper to produce a low-emittance, short-bunch beam. Recently, a new type of fast pulse generator, which utilized wideband rf amplifiers and a new chopper chamber with high-impedance strip-line electrodes, was developed to reliably and accurately cut out a short bunch from the long-pulsed beam emitted from a single-crystal CeB₆ hot cathode. Using these apparatuses, we succeeded in forming nanosecond multibunch structure in the thermionic electron beam and generating a double-bunch XFEL pulse with a total pulse energy of 1 mJ at 10 keV. The results will provide new possibilities for XFEL beams: higher intensity, higher coherence, and higher pulse repetition rate.

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I. INTRODUCTION

Since the success of the first lasing of x-ray free-electron laser (XFEL) light at Linac Coherent Light Source (LCLS) in 2009 [1,2], several XFEL facilities have been constructed around the world and have been playing indispensable roles for atomic and molecular, material, and biological sciences [3–6]. In the past decade, the requirements for XFEL light characteristics have expanded to include not only pulse stability and reliability but also pulse duration, temporal coherence, repetition rate, and other characteristics. Nowadays, almost all XFEL facilities can deliver temporally coherent XFEL light using seeding techniques [7–9]. The pulse repetition rates of the XFELs are constantly increasing in both the superconducting and normal-conducting linear accelerators [10–12].

Bunch structure is also an important characteristic for the application of XFELs. Multibunch trains with inter-bunch separation of the order of nanoseconds have been developed at the LCLS for an x-ray laser oscillator, experiments on matter under extreme conditions, and so on [13–16]. Recently, the European XFEL group succeeded in generating fully coherent XFEL light in the cavity-based XFEL using a multibunch beam [17]. These XFELs use photocathode electron guns. In such guns, a

multipulse structure is first formed in the excitation laser light using a split-and-delay line in the laser system. Then, the multibunch electron beam is extracted directly from the photocathode.

The Japanese XFEL facility SPring-8 Angstrom Compact free-electron Laser (SACLA) uses a thermionic pulsed electron gun to produce low-emittance beams [18–20]. The gun voltage, the peak beam current, the pulse width, and the pulse repetition rate are 500 kV, 1 A, 3 μ s, 60 Hz, respectively. A beam chopper system is used to form a one-nanosecond-long bunch by chopping it out from the microsecond-long pulsed beam extracted from a single-crystal CeB₆ hot emitter. Specifically, a dc magnetic field deflects the whole beam transversely except for a nanosecond-long fraction that stays on course and passes through a collimating aperture thanks to a compensating 2-ns flattop 3 kV pulse from an avalanche-type high-voltage pulse generator. This type of pulse generator is quite compact and easy to operate. However, it inevitably causes instabilities in pulse timing and height due to the switching process's inherent mechanism. In contrast, solid-state linear amplifiers operate very stably, and their reliability has been verified in various scientific and technological fields. Hence, to make the beam chopper system more stable, we have developed and deployed a new type of fast pulse generator which utilizes wideband rf amplifiers (WBA) [21].

Another advantage of the new pulser is that a multibunch structure in the electron beam can be formed relatively easily by preparing a low-level input signal with the target bunch structure. Although the production of the multibunch high-voltage pulses by means of the above method was succeeded in 2022 [21], the multibunch beam production has not been demonstrated yet. First, we upgraded the WBA power to generate a voltage high

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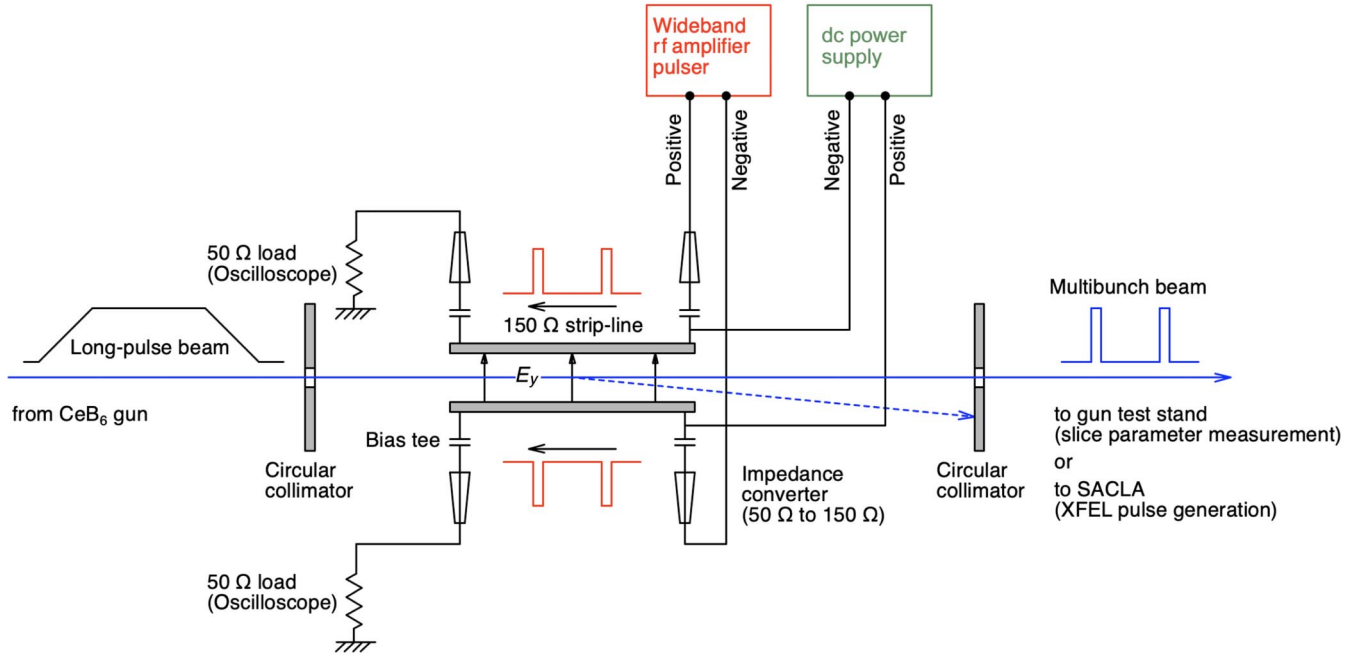


FIG. 1. Schematic of the multibunch structure generator in the SACLA electron injector.

enough to deflect the 500-keV beam. A new chopper chamber with high-impedance strip-line electrodes was also developed to reduce the WBA's power to a usable 10 kW. The new chopper system was initially tested at the gun test stand before being installed in the SACLA injector. Finally, we succeeded in generating double-bunch XFEL pulses at SACLA.

In this paper, we describe the details of the WBA upgrade and the new chopper chamber. The experimental results on producing low-emittance multibunch electron beams and investigating their slice parameters at the gun test stand are reported. The first experiment to generate multibunch XFEL beams at SACLA is briefly described. Finally, future perspectives of multibunch operation in XFELs are also discussed.

II. MULTIBUNCH GENERATOR

The generator of a multibunch beam structure in the SACLA injector is schematically shown in Fig. 1. The μ s collimated beam from the gun (not shown) passes through a strip-line composed of two circular conductors. A dc bias voltage applied to the conductors deflects the beam transversely (dashed line) such that the deflected beam is blocked by a collimator located downstream. A nanosecond-pulsed rf field compensates the dc deflection field and allows for a nanosecond fraction of the beam to be transmitted through the collimator for further compression and acceleration.

Note that in the original chopper system, a horizontal magnetic field was used to deflect the long-pulse beam downward continuously. Lorentz forces from the

dc magnetic field and the short-pulsed electric field from the pulser cancel each other in the strip-line chamber; only a short-pulse portion passes through a circular collimator located downstream of the strip-line electrodes. To avoid degrading the low emittance, the Lorentz forces need to be completely canceled out; however, it is not easy to achieve the same spatial distribution of the magnetic field as that of the short-gap strip-line electric field. To completely cancel out the forces, the magnetic deflection was replaced by electric one via dc voltages applied to the strip-line electrodes shown schematically in Fig. 1.

In this section, the upgraded wideband rf amplifier and the newly developed high-impedance chopper chamber are described.

A. Wideband rf-amplifier pulser

Generally, the group velocity and amplitude of an electromagnetic wave in a medium are functions of frequency. In the processes of power amplification, power combining, and power division of a pulse signal comprising a wide frequency range, the pulse shape is distorted in the circuit owing to the dependence of the group velocity and gain on frequency. To correct pulse-shape distortion, we proposed and demonstrated a frequency-segmented power-amplification method [21]. The circuit diagram of the WBA is shown in Fig. 2. The seed pulse generated by a signal generator is amplified by a preamplifier and then divided into six subpulses. Each subpulse is sent to an individual control line comprising a low-pass filter (LPF) or bandpass filter (BPF), a variable delay line (DELAY), a variable power attenuator (ATT), and an rf power

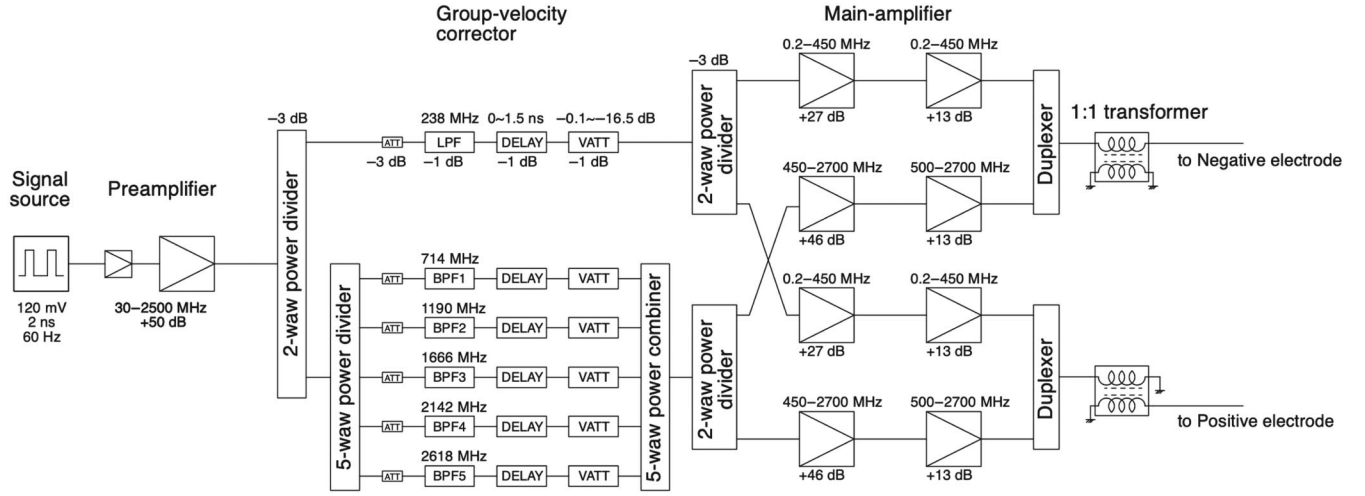


FIG. 2. Circuit diagram of the wideband rf amplifier pulser.

amplifier. The LPF and BPFs selectively pass particular frequencies. The DELAY compensates for the temporal differences between the frequency bands. ATT was used to adjust the rf amplitude to an optimal level. After amplifying the rf power of each channel, all rf waves were combined and sent to the application load.

Because the power of the prototype WBA was not enough to deflect the 500-keV beam extracted from the CeB₆ gun, the output peak power of the WBA was upgraded from 3 to 8.5 kW. Here, the output power is defined as the peak power in the rectangular pulse. The waveforms of the WBA pulser measured by an 8-GHz, 50-Ω oscilloscope are shown in Fig. 3. The blue line shows the pulse signal for the upper strip-line electrode, and the green one shows the inverted signal for the lower electrode. The red line stands for a numerical sum of the above

two signals, which is proportional to the deflection angle of the electron beam. The peak voltage, the bunch width, and the bunch separation are 0.65 kV in 50 Ω, 1.9 ns (full width at half maximum), and 33.6 ns, respectively.

Waveform adjustment was performed manually using the following steps. (1) The timing of each subpulse was individually tuned to roughly the same timing. (2) The flattop region was made as wide as possible using the lower three frequencies while observing an oscilloscope signal. (3) The remaining modulation was suppressed as small as possible by tuning the higher three frequencies and the lower three as needed.

Because only the electrons with the maximum rf deflection angle can pass through the collimator hole, the rf signal ringing around the ground level in the WBA output pulse does not affect the performance of the beam chopping. However, the ringing gives signal offsets to the trailing bunches. The offsets cannot be ignored in cases where the bunch separations are not long enough to dump the ringing, because the offsets cause orbit difference. These offsets can be compensated for by bunch-by-bunch amplitude tuning of the input seed bunches.

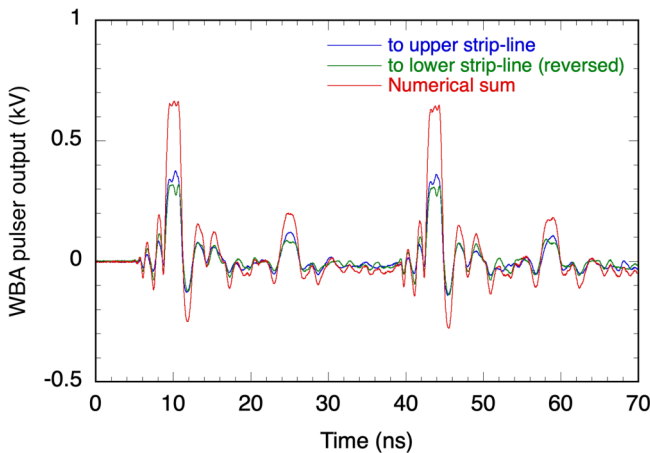


FIG. 3. Example of the WBA pulser waveforms. The blue line shows the pulse signal for the upper strip-line electrode, and the green one shows the inverted signal for the lower electrode. The red line is a numerical sum of the above two, which is proportional to the deflection angle of the electron beam.

B. High-impedance chopper chamber

To generate high-peak voltages with rf amplifiers requires substantial power. Hence, the chopper chamber was redesigned using the following power-reduction strategy. (1) The applied voltage between the strip-line electrodes was divided in half. The half-voltage pulse with positive polarity was applied to the upper electrode, and that with negative polarity to the lower electrode. Because the power is proportional to the square of voltage ($P = V^2/R$), the required total rf power can be reduced by half. (2) The characteristic impedance of the electrode was chosen to be 150 Ω, which is 3 times higher than that of standard 50 Ω impedance. The rf power can be reduced

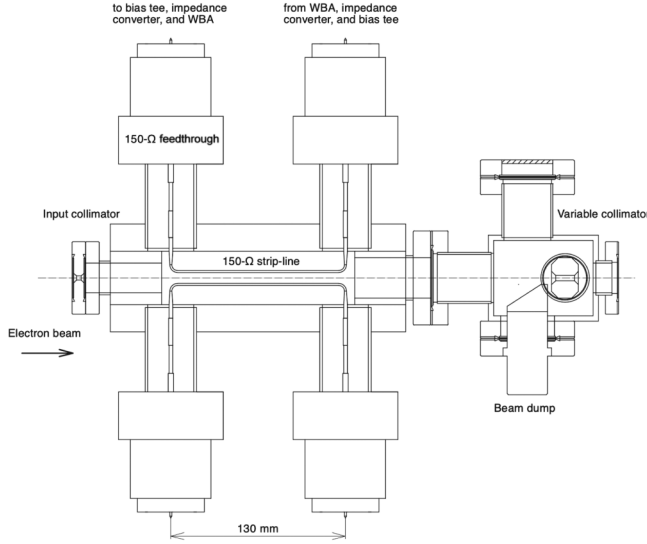


FIG. 4. Mechanical drawing of the high-impedance chopper chamber (side view).

to one-third. (3) The deflection angle of the electrons by the electric field of the traveling wave heading along the strip-line is expressed as

$$\frac{dy}{dz} = -\frac{e(1+\beta)}{\gamma m_e c^2 \beta^2} \int E_y dz,$$

where e is the elementary charge, m_e is the electron mass, c is the light velocity, β is v_z/c , γ is the relativistic mass factor, and E_y is the transverse electric field. The voltage can be further reduced by narrowing the electrode gap to the minimum value at which the deflected electron beam does not strike the lower electrode. By adopting the three modifications above, the rf power can be reduced by one order of magnitude, from 180 to 10 kW.

In the new chopper design, dc “deflection” voltages are applied to the strip-line electrodes through bias tees as shown in Fig. 1. Figures 4 and 5 show a mechanical drawing of the new chopper chamber and the electric equipotential line distribution in a plane perpendicular to the beam axis, respectively. The longitudinal length of the strip-line electrodes, the electrode gap, and the dc vertical electric field on the z axis are 13 cm, 0.81 cm, and 1.6 kV/cm, respectively.

To keep the rectangular pulse shape in the high-impedance chopper chamber, four main components—impedance converters, bias tees, vacuum feedthroughs, and strip-lines—are designed and fabricated to have a high transmission ratio of wideband frequency from 0.2 to 3 GHz. Figure 6 shows the waveforms at the entrance and the exit of the chopper chamber measured by the oscilloscope. The flat-top of the input pulse was well tuned by the group-velocity corrector of the WBA, in accordance with the method described above. The amplitude drop and

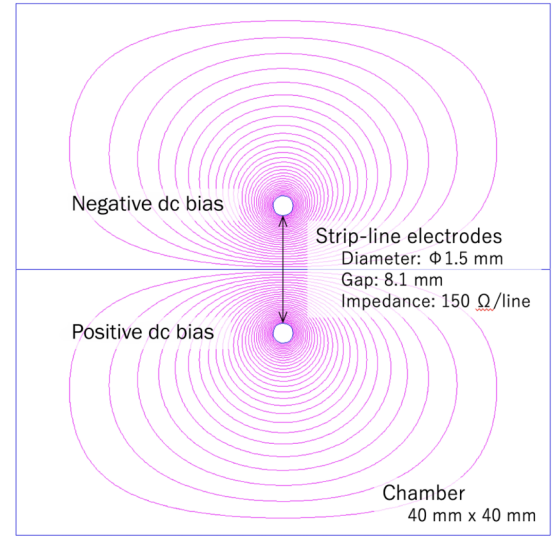


FIG. 5. Electric equipotential line on a plane perpendicular to the beam axis simulated using POISSON code [22].

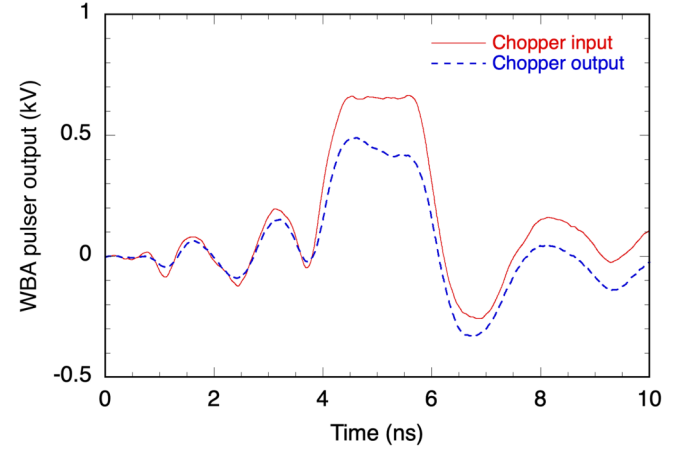


FIG. 6. Waveforms of the WBA pulse at the entrance and the exit of the chopper chamber.

droop of the output pulse were attributed to poor transmission of the low-frequency component at the bias tee. Because the strip-line is located between two bias tees, the real pulse shape is expected to be the average of these pulses. The linear component of the droop can be corrected by tuning the group delay of the fundamental-frequency component (238 MHz). The pulse shape of the fundamental-frequency component is quadratic near the peak region in the form $V(t) = A - Bt^2$. After shifting the timing by Δt , the voltage waveform becomes $V(t) = A - B(\Delta t)^2 - Bt^2 + 2B(\Delta t)t$. The fourth linear term counters the negative slope and compensates for the voltage droop.

C. Multibunch generation

One advantage of using the wideband amplifier is the relatively easy generation of a multibunch structure.

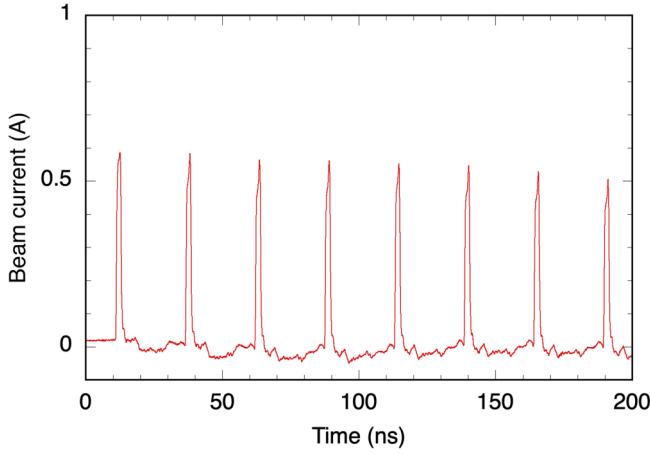


FIG. 7. Example of the multibunch electron beam generation. The current was monitored by the fast wall-current monitor located 1.5 m downstream of the chopper chamber.

Any available arbitrary function generator can be used as a signal source to make a multibunch seed pulse. The WBA amplifies the seed pulses at the same magnification. A demonstration experiment to generate a multibunch electron beam has been performed at the SACLA gun test stand, which was constructed for preparation and maintenance of the operational SACLA gun and for the R&D works toward the future SACLA upgrade [23–26]. Figure 7 shows an example of multibunch beam formation. The energy and the peak current of the original long-pulse beam were 500 keV and 1 A, respectively. Eight bunches with 25.5-ns separation were cut out from the peak region of the original long-pulse beam. The beam waveform was measured by a fast wall-current monitor located 1.5 m downstream of the chopper chamber [23]. Only the bright core of the electron bunch goes through the aperture of the chopping collimator, whereas the outer electrons are removed. Hence, the peak current is reduced by half, see the details below. Adjustment of the peak current levels of the microbunches was carried out in the multibunch XFEL generation experiment, which will be discussed in Sec. IV.

III. SLICE PARAMETER INVESTIGATION OF THE MULTIBUNCH ELECTRON BEAMS

Slice parameter investigation of the multibunch electron beams was conducted at the SACLA gun test stand. The gun voltage, the peak beam current, the pulse width, and the pulse repetition rate were 500 kV, 1 A, 3 μ s, 10 Hz, respectively. Two bunches with 33.6 ns separation were cut out from the original long pulse. The transverse round edge of the beam, in which nonlinear phase space components of the beam exist, was removed by two circular collimators located at the entrance ($\phi 2.5$ mm) and the exit ($\phi 5$ mm) of the chopper chamber. The beam current transmission rate was $\sim 50\%$. Figure 8 shows projected spatial profiles of a

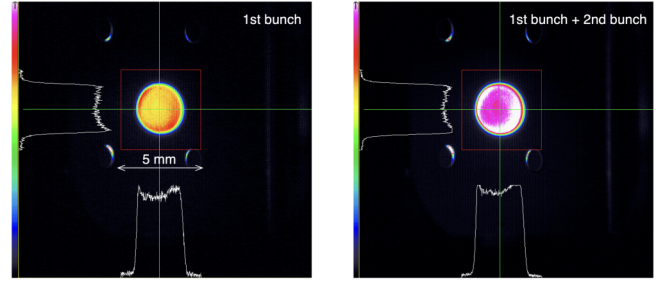


FIG. 8. Projected spatial profiles of a single-bunch beam and a double-bunch beam measured using the Ce:YAG screen monitor. The white lines show horizontal and vertical line intensities.

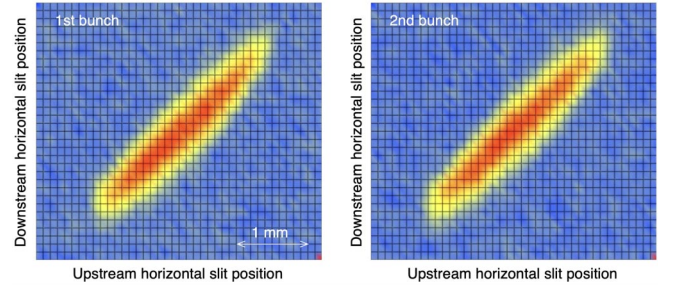


FIG. 9. Sliced phase-space profiles of two bunches. The horizontal (vertical) axis is the horizontal (vertical) center position of the upstream slit. The genuine phase-space profile can be obtained by converting the vertical axis to the horizontal angle.

single-bunch beam and a double-bunch beam measured by a Ce:YAG screen monitor. Uniform current density was observed in the single bunch profile, and no blur was observed in the superimposed profile of the double bunches. These results show that a constant kick was achieved in the single bunch, and equivalent kicks were applied to the two bunches.

Evolution of the slice beam parameters in the double bunches was measured using a slit-grid system [23]. A combination of horizontal and vertical slits was used to measure the spatial beam profiles, while the phase-space profile was measured using two horizontal slits separated by 0.5 m. Beamlet currents corresponding to each slit grid were measured using a fast wall-current monitor and an oscilloscope. Sliced spatial and phase-space profiles were reconstructed from all beamlet current data. Figure 9 shows sliced phase-space profiles of two bunches, whose sliced bin was 3.1 ps. The horizontal axis shows the horizontal center position of the upstream slit x_u , and the vertical axis shows that of the downstream slit x_d . Both opening widths were set to 0.1 mm. The genuine phase-space profile can be obtained by converting the vertical axis to the horizontal angle, which is described as $x' = (x_d - x_u)/L$, where L is the distance between these two slits. The data reconstruction can produce movies of phase-space evolution with a time response of 25 ps [27].

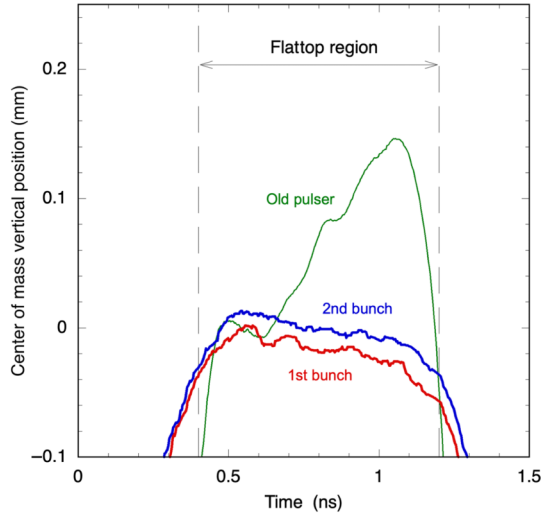


FIG. 10. Evolutions of the center of mass vertical position in the 1-ns bunches. The red (blue) line shows the 1st (2nd) bunch, and the green line shows the data taken with the old pulser.

Almost the same profiles could be observed for these two bunches.

Figure 10 shows the evolution of the center of mass (COM) vertical position in the 1-ns bunches. The COM position is defined as

$$\langle y(t) \rangle \equiv \frac{\sum_{m,n} [y_{m,n}(t) i_{m,n}(t)]}{\sum_{m,n} [i_{m,n}(t)]},$$

where m and n denote the integers of horizontal and vertical slit-grid positions, respectively, and $i_{m,n}(t)$ is the beamlet current. The COM positions of both bunches are almost constant in the flattop region. Compared with the

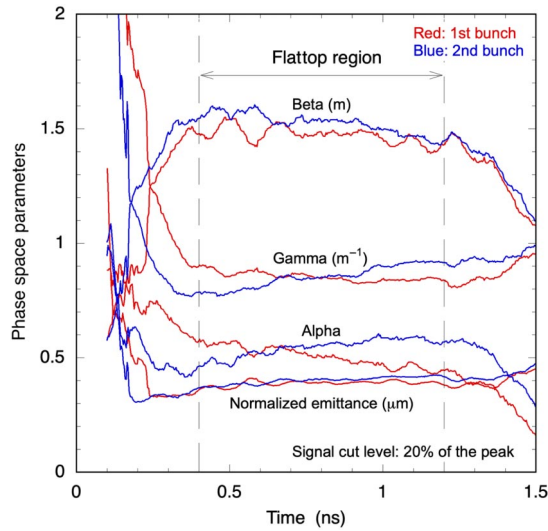


FIG. 11. Evolutions of the normalized emittance and Twiss parameters in the 1-ns bunches. The red (blue) line shows the 1st (2nd) bunch.

old avalanche pulser, the bunch position drift was dramatically reduced. The transverse drift of the COM position in the bunch results in projected emittance growth, which affects XFEL lasing performance. The peak-to-peak drift in the flattop region was reduced to 0.04 mm. It is so small compared with the 2.5 mm beam diameter that the emittance growth is negligible. The difference in vertical position between the two bunches comes from the difference in the kick angle at the chopper chamber. Precise matching of these angles is important to keep the same beam trajectory in the accelerator and the undulator line. The trajectory-matching procedure will be described in the next section.

Figure 11 shows the sliced normalized emittance [$\epsilon_{n,\text{rms}}(t)$] and the Twiss parameters [$\alpha_x(t)$, $\beta_x(t)$, $\gamma_x(t)$] in the two bunches, where they are defined as

$$\epsilon_{n,\text{rms}}(t) = \beta\gamma \sqrt{\langle x^2(t) \rangle \langle x'^2(t) \rangle - \langle x(t)x'(t) \rangle^2},$$

$$\alpha_x(t) = -\frac{\langle x(t)x'(t) \rangle}{\epsilon_{n,\text{rms}}(t)/(\beta\gamma)},$$

$$\beta_x(t) = -\frac{\langle x^2(t) \rangle}{\epsilon_{n,\text{rms}}(t)/(\beta\gamma)},$$

$$\gamma_x(t) = -\frac{\langle x'^2(t) \rangle}{\epsilon_{n,\text{rms}}(t)/(\beta\gamma)}.$$

The signals below 20% of the peak signal in the phase space were cut in the analysis process to reduce the noise influence. These results show that the sliced parameters also remained constant in the flattop region. This feature is important for increasing the XFEL pulse energy by controlling the sliced phase spaces [24,26] and is crucial for achieving multibunch XFEL generation, as described in Sec. IV.

IV. GENERATION OF MULTIBUNCH XFEL PULSES AT SACLA

The SACLA accelerator was constructed based on C-band rf technologies developed for the Japanese electron/positron linear collider project, JLC-1 [28]. The C-band choke-mode accelerating structure was designed to accelerate more than 100 microbunches with a narrow separation of 2.8 ns. The structure damps the wakefield noise, which can disturb the acceleration of the trailing bunches [29,30]. The SACLA's 8-GeV main linac is perfectly suited for the multibunch acceleration.

Recently, an experiment to generate a multibunch XFEL pulse was conducted at SACLA. First, the bunch separation was chosen to the eighth subharmonic of the buncher cavity (33.6 ns), which was suitable for the regeneration experiment [13]. However, the double-bunch XFEL

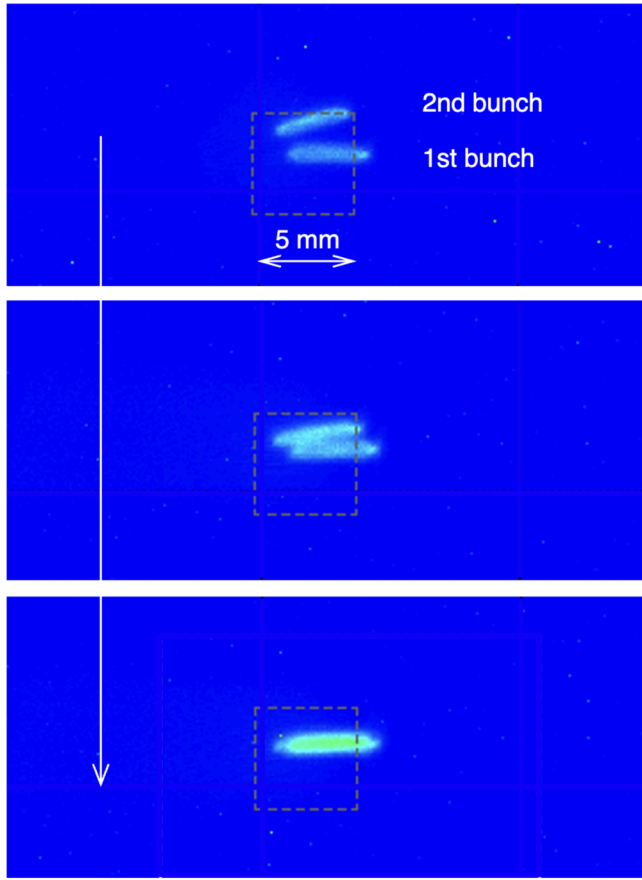


FIG. 12. Beam profiles at the dispersive point in the second bunch compressor. The beam energy was 440 MeV, and the dispersion was 345 mm. Only the amplitude of the second seed pulse of WBA was tuned until these profiles were overlapped.

generation was not successful because of the large energy difference between the two electron bunches. The bunch separation of 33.6 ns is not negligibly short compared with the rf pulse length of the C-band main linac (500 ns). Therefore, the shorter separation of 8.4 ns was chosen to demonstrate the first generation of double-bunch XFEL pulses.

Figure 12 shows the beam profiles at the dispersive point in the second bunch compressor. The horizontal direction shows the beam energy and the vertical direction shows the vertical beam position, demonstrating the fact that these two parameters are identical. The beam energy was 440 MeV, and the dispersion was 345 mm. First, the two bunches were separated vertically, though the energy difference between the two bunches was as low as 0.1%. To overlap these profiles, the kick angle of the second bunch was finely tuned at the chopper chamber located at the uppermost part of the accelerator. Individual tuning of each pulse height can be achieved by generating the corresponding seed signals. The remaining small energy difference is corrected by bunch-by-bunch control of the linac's acceleration phase. The phase of the second bunch

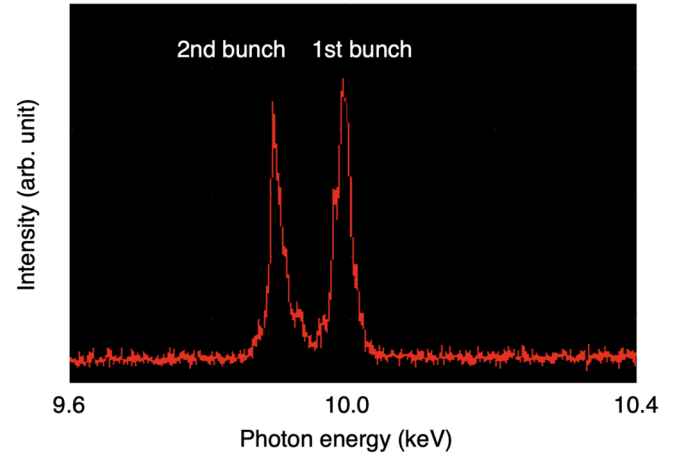


FIG. 13. A single-shot spectrum of the double-bunch XFEL pulse.

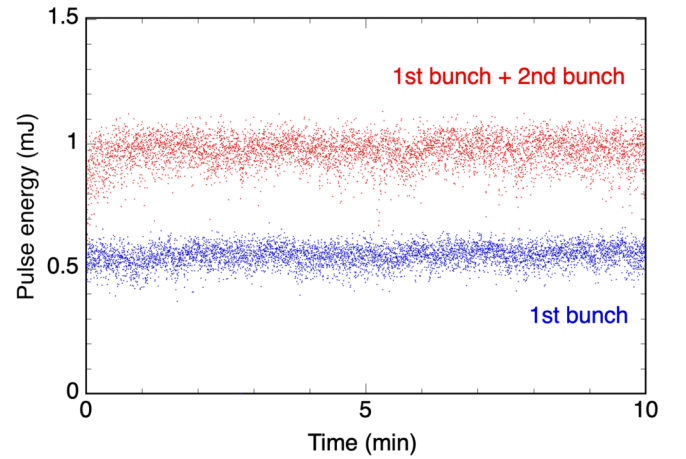


FIG. 14. Trends of the XFEL pulse energies in the cases of single- and double-bunch generation.

can be shifted by changing the time of flight from the gun to the linac; that is, the difference in electron velocity is intentionally introduced by choosing the chopping timing in the long-pulse beam, in which the energy varies along the curve [18].

Figures 13 and 14 are a single-shot spectrum of the double-bunch XFEL pulse and intensity trends of the single and double XFEL pulses, respectively. These results show that the same amount of XFEL output energy (0.5 mJ/bunch) was obtained at around 10 keV, and that the same sliced-beam parameters were achieved in both bunches.

V. DISCUSSION

Several XFEL facilities have begun using multibunch electron beams to improve coherence, such as the cavity-based XFEL. To realize a regenerative cavity-based XFEL at SACLA, an optical cavity with several crystal reflectors

and an undulator in between is required. By utilizing a 5 m long undulator segment and allocating approximately 2.5 m of space both upstream and downstream to separate the electron beam from the x-ray pulses, an optical cavity with a round-trip distance of about 20 m can be constructed, corresponding to the bunch separation of approximately 70 ns. This compact circulation geometry matches the required nanosecond-order bunch separation, making our demonstrated multibunch generation technique highly applicable to this future scheme.

Another possible application is the fast distribution of electron bunches to multiple undulator lines. SACLA is running at a pulse repetition rate of 60 Hz, and the electron bunches are distributed between two undulator lines on a pulse-by-pulse basis. Therefore, the repetition rate per undulator line is halved. If an extremely fast kicker with a rise time of several tens of nanoseconds is developed and installed at the end of the main linac, multiple bunches can be distributed to the undulator lines simultaneously, doubling the pulse repetition rate per undulator line. SwissFEL developed an ultrafast kicker system to distribute double bunches to two beamlines [31]. The resonant kicker, consisting of resonator capacitors and an inductor, operates at 17.85 MHz and delivers more than 160 A of current to kick the second bunch, separated by 28 ns from the first bunch, with 3.3 GeV. Because the beam conditions of the SACLA accelerator are close to those of the SwissFEL, the ultrafast kicker system is a promising technology for achieving double-bunch distribution. Another method is to use bunch-by-bunch position shifts via kicks at the injector or in a low-energy section of the linac. At the end of the linac, a septum magnet located in the undulator splits the trajectories of the multiple bunches.

The bunch-by-bunch control using the WBA can be applied not only to XFELs but also to various linear and circular accelerators. As another application, the WBA can be used for arbitrary modulation of laser light, such as fast polarization switching with a Pockels cell.

VI. SUMMARY

In summary, a new type of fast pulse generator, which utilized wideband rf amplifiers with a group-velocity corrector and a new chopper chamber with high-impedance strip-line electrodes to reduce amplifier power, was developed to cut out the short bunch from the long-pulse beam generated by the CeB₆ thermionic electron gun. Using these apparatuses, we succeeded in forming a nanosecond multibunch structure in the thermionic electron beam, and the beam quality was confirmed by measuring the time-dependent emittance and Twiss parameters with a 25 ps time response at the gun test stand. The multibunch generation system was installed in the SACLA injector, and double-bunch XFEL pulses with a total pulse energy of 1 mJ at 10 keV were first generated at SACLA. The results will enable new applications using multibunch

XFEL beams and contribute to the repetition-rate upgrade of multiple XFEL beam lines. And new applications, not only in accelerator science but also in laser science and so on, are expected.

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DATA AVAILABILITY

The data that support the findings of this article are openly available.

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