Production of a sub-10 fs electron beam with 10^7 electrons

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(Received 22 November 2010; published 5 May 2011)

We study the possibility to produce a 1.6 pC electron beam (10^7 electrons) with a bunch length of less than 10 fs and a beam energy of a few MeV. Such a short, relativistic beam will be useful for an electron diffraction experiment with a 10 fs time resolution. An electron beam with 10^7 electrons will allow a single-shot experiment with a laser pulse pump and an electron beam probe. In this design, an S-band photocathode gun is used for generating and accelerating a beam and a buncher consisting of two S-band four-cell cavities is used for temporally compressing the beam. Focusing solenoids control the beam transverse divergence and size at the sample. Numerical optimization is carried out to achieve a beam with a 4 fs full-width-at-half-maximum length, a 26 microradian root-mean-square divergence, and a 2 nm transverse coherence length at a 3.24 MeV beam energy. When state-of-the-art rf stability is considered, beam arrival time jitter at the sample is calculated to be about 10 fs.

DOI: 10.1103/PhysRevSTAB.14.050101

PACS numbers: 29.25.Bx, 41.75.Ht, 61.05.J-

I. INTRODUCTION

Atomic motion during the transition processes of physical structures can be observed with femtosecond electron diffraction [1–3]. When an electron bunch of femtosecond range is available and the number of electrons in the bunch is large enough for a single-shot diffraction, “molecular movies” [2,3] with a femtosecond shutter speed will be realized. Recently constructed free-electron lasers [4,5] allow similar experiments with x rays. These large machines can produce strong x rays with a femtosecond pulse length and have opened up new possibilities for experiments in many physical and biological science areas. Compared to the kilometers long x-ray machines, a femtosecond electron experiment setup can be built with much smaller size and cost. Ultrashort electron beam generation setups with a radio-frequency (rf) gun have been built at a few labs for single-shot diffraction experiments [6–9]. The electron pulse length is still limited to about 100 fs. Within the 100 fs time frame, many important atomic processes can be studied. However, when the electron bunch duration reaches the 10 fs range, faster atomic motion, for instance the O-H bond vibration of water molecules, can be observed [3].

When a femtosecond bunch with a high number of electrons is launched at the cathode, space charge force expands the beam immediately if the charge density of the beam is high. This effect mainly takes place near the cathode where the beam energy is nearly zero. To achieve a bunch length below 10 fs by using an rf gun only, the

number of electrons per bunch is limited to be about 10 000 which is insufficient for a single-shot experiment. The peak accelerating field at the cathode should be as high as 100 MV/m or more in order to suppress beam quality degradation from the space charge effect. When the gun field is so high, dark current may be emitted from the cathode and the gun cavity wall. Since the bunch charge for a diffraction experiment is in the order of 1 pC, dark current may impair experiments with background noise. The sample may be damaged by dark current with a few MeV energy as well.

An alternative method to achieve a short bunch is to generate a relatively long bunch (> 1 ps) at the cathode and compress after the gun where the beam obtains a relativistic energy and the space charge effect is reduced. Such a long bunch is less influenced by space charge during the acceleration at the gun so that the beam quality can be preserved. A buncher placed immediately after the gun compresses the beam by using the velocity difference between the head and tail of the bunch. The beam size and divergence are controlled to be focused at the sample by using the solenoids placed around the gun and also after the buncher. In this way, the gun peak field can be reduced to 80 MV/m and a bunch length below 10 fs at a 1.6 pC bunch charge (10^7 electrons) can be achieved. This large number of electrons per pulse will allow obtaining acceptable diffraction patterns with a single-shot [1]. Dark current emission will be minimized thanks to the low gun field.

The layout of the relativistic ultrashort electron beam generation setup is introduced in Sec. II. In Sec. III we review some aspect of the electron beam dynamics at the gun and buncher. The beam performance optimization is carried out with ASTRA [10] in Sec. IV. In Sec. V we investigate beam arrival time and beam parameter fluctuation caused by gun and buncher rf jitter.

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II. SYSTEM LAYOUT

The setup consists of an S-band photocathode gun, an S-band buncher, focusing solenoids, and a sample. The distance between the cathode and sample is 1.6 m. The layout is shown in Fig. 1.

The gun is a standing-wave $1/2 + 1$ cell cavity and operates with the π mode at 2.998 GHz. This gun has been designed for a high repetition rate operation and improved beam parameters [11] compared with the S-band guns utilized in Refs. [6–9]. When operating at a 100 MV/m peak accelerating field at the cathode, this gun can operate at a 1 kHz repetition rate thanks to the coaxial rf input coupler as well as the improved water-cooling channel design. The coaxial coupler has been designed to be long enough to make enough space for the main solenoid installation (see Fig. 1). In this femtosecond beam generation setup, the gun operates at 80 MV/m in order to reduce dark current emission from the cathode and the cavity inner surface. The dark current emission I_{DC} increases with the applied rf field strength as $I_{DC} \sim E^{2.5} \exp(-C/E)$ [12], where E is the peak rf field strength and C is a constant. A 3.6 MW rf peak power is required for this gun field.

The gun main solenoid is placed around the second cell of the gun for an optimum beam transverse emittance control. The bucking solenoid sitting behind the gun compensates the magnetic field tail at the cathode in order to eliminate the beam angular momentum.

The rf buncher is placed immediately after the gun. The buncher is divided into two cavities, which decreases the jitter contribution from buncher rf phase to beam arrival time at the sample. As will be discussed later, beam arrival time variation caused by rf phase jitter in each buncher cavity is comparable to the full-width-at-half-maximum (FWHM) bunch length even when state-of-the-art rf stability is considered. When the rf phase of each buncher cavity is controlled independently, arrival time jitter is reduced by $1/\sqrt{2}$. The cavities are conventional traveling-wave

structures with the rf input coupler connected to a side of the first cell and with the output coupler to a side of the last cell. The cavities consist of four cells and operate with the $2\pi/3$ mode at 2.998 GHz.

After the buncher, another solenoid is placed for the control of the beam transverse divergence and beam size at the sample. This (2nd) solenoid has the same physical dimension as the gun main (1st) solenoid.

The initial bunch profile of an electron beam is controlled with the drive laser pulse shape. Because the buncher cavities should be placed immediately after the gun for minimizing beam arrival time fluctuation from gun jitter, the mirror reflecting a drive laser pulse to the cathode should be placed at about 1.2 m from the cathode. The mirror holder in the vacuum should be designed to be symmetric so that an electron beam does not get a transverse kick by the wakefield.

The beam diagnostic system is not discussed in this paper. However, bunch charge, beam transverse profile, beam arrival time, and bunch length should be monitored during experiments. Beam arrival time monitor and bunch length monitor with a femtosecond resolution are challenging components.

III. BEAM DYNAMICS

An electron beam is emitted from the cathode by a drive laser pulse and the initial beam shape is determined by the laser pulse shape. However, the detailed beam shape after the emission changes from that of the laser pulse because of the space charge effect as well as the rf and solenoid fields during the emission. When the space charge effect is strong, the beam expands during and immediately after the beam emission. The bunch length may be stretched or compressed by the rf field, depending on the beam launch phase, the rf phase when the beam is launched. The solenoid field focuses the beam against the transverse beam expansion by space charge. The photoemission

FIG. 1. Layout of the beam generation setup for relativistic femtosecond electron diffraction experiments. The setup consists of an S-band photocathode gun, an S-band buncher, focusing solenoids, and a drive laser. A sample is placed at 1.6 m from the cathode. A detector for electrons diffracted from the sample should be a few meters downstream of the sample (not shown here).

response time for a metal cathode is far shorter than one femtosecond [13]. Therefore, the photoemission process does not affect the temporal shape of the initial beam with a picosecond pulse length, which means there is no unwanted long tail at the rear part of the beam. In this design, the laser pulse is assumed to be uniform transversely and Gaussian temporally. A root-mean-square (rms) pulse length of 1.2 ps was chosen after beam parameter optimization.

The beam brightness $B = 2I/\pi^2\epsilon_x\epsilon_y$ [14] is the figure of merit of the quality of a beam, where I is the beam current and ϵ_x and ϵ_y are the emittance in the horizontal and vertical directions. In general, a high beam brightness is aimed in the design of an accelerator. However, a high brightness beam at low energy suffers from the space charge effect and the quality is immediately degraded. The influence of the space charge force is scaled by a factor $1/\gamma^2\beta$ [15], where γ is the relativistic Lorentz factor and β the velocity of the beam. Therefore, the bunch length should be kept to be long enough during the emission in order to minimize the beam quality degradation. Once accelerated to a higher energy, the beam can be compressed with less impact from space charge.

The longitudinal component of the rf accelerating field on the beam axis at the gun is shown in Fig. 2. If an electron beam is launched at a positive phase in the gun cavity (see Fig. 3), the beam can be captured by the rf accelerating field. If a beam is launched around 90° , when the rf field is maximal at the cathode, the beam cannot attain energy optimally through the gun because the rf field direction is reversed at the last part of

FIG. 2. The longitudinal component of the rf accelerating field on the beam axis at the gun. The field has two maxima: one at the cathode on the rear plane of the first cell and the other at the center of the second cell. When a beam passes from the first to the second cell, the field direction in the second cell is changed so that the beam can be accelerated by the field. The cathode is at $z = 0$.

FIG. 3. Beam energy at the exit of the gun and longitudinal electric field strength at the cathode as a function of launch phase when an electron beam is emitted from the cathode. Since the field strength is a sine function, the field is maximal at 90° . However, the beam energy is maximal when a beam is launched at 37° .

the second cell before the beam goes out of the gun. This phenomena happens because the beam velocity at the first cell is far lower than the speed of light and therefore the beam cannot catch up the phase change of the rf accelerating field. The launch phase providing a maximal beam energy is somewhere between the 0-crossing phase and 90° , depending on the gun geometry and the rf field strength in the gun [16,17]. In this gun design, the launch phase for maximal beam energy is 37° at a 80 MV/m rf peak field at the cathode. When a higher field is applied at the gun, the launch phase for maximal beam energy gain is shifted toward 90° .

The rf field distribution at the buncher is different from at the gun because the buncher cavities operate with the traveling-wave $2\pi/3$ mode. However, the rf field strength change with rf phase is similar as at the gun. The buncher operates around the 0-crossing phase to apply the velocity bunching, where the beam head gets deceleration but the tail gets acceleration so that the beam becomes compressed during the propagation to the sample.

IV. FEMTOSECOND BEAM GENERATION

As discussed already, the space charge effect is very strong during and immediately after the beam emission at the cathode because the beam energy is close to zero. In order to minimize the space charge effect, the beam size must be large or the bunch length must be long. If the beam size is large at the cathode, the intrinsic (or thermal) emittance is also large because the intrinsic emittance increases linearly with the initial beam size at the cathode. The intrinsic emittance limits the ultimately achievable

beam size and divergence at the sample. Therefore, the initial beam size should be as small as possible. An initial beam length of 1.2 ps rms with Gaussian shape and a beam radius of 0.16 mm with uniform distribution are chosen in this study. The intrinsic emittance is then 0.065 mm mrad when the kinetic energy of emitted electrons is assumed to be 0.6 eV. The intrinsic emittance per initial beam size assumed in this study is higher than the experimentally measured value in Ref. [18], which should give a conservative margin for simulations of beam parameters.

When a high rf accelerating field is applied at the cathode, the space charge effect can be minimized and a better beam quality can be expected. On the other hand, such a strong field generates dark current; therefore the rf field should not be too high. With a high accelerating field at the gun, the beam energy is also high and therefore a stronger bunching force at the buncher is required. For a stronger bunching, a high buncher amplitude or a more negative phase offset from the 0-crossing is required. Electron beam arrival time jitter caused by buncher rf fluctuation becomes bigger when the bunching strength is higher. In this design, the peak field at the cathode has been chosen to be 80 MV/m to keep dark current low and to minimize beam arrival time sensitivity to rf jitter in the buncher. Because the initial bunch length is relatively long (1.2 ps rms), a 80 MV/m peak field is sufficient to keep the beam quality. If the gun field is decreased further, the beam quality at the gun is hardly preserved against the space charge effect. More importantly, the velocity of a beam becomes far lower than the speed of light and, as a result, beam arrival time fluctuation becomes notably sensitive to gun rf amplitude and phase jitter.

When a 1.6 pC electron beam is emitted with an initial length of 1.2 ps rms, the beam is compressed immediately after the emission by the velocity bunching because the launch phase is 22° from the 0-crossing and the space charge effect is weak. At that launch phase, the rf field rises during the beam emission and therefore the beam head has a lower velocity than the tail. The rms bunch length becomes shorter by about 30% within a few millimeters from the cathode (see Fig. 4). The energy difference between the head and tail of the bunch is small, but the beam energy is also small enough (< 100 keV) that strong bunching can be achieved. When the beam is further accelerated through the gun, the beam acquires a higher energy of 3.3 MeV and the energy chirp of a few tens keV is not sufficient for a strong compression [Fig. 5(a)]. However, the beam continues to be gently compressed until the beam arrives at the buncher.

By the buncher, the energy chirp has increased [Fig. 5(b)] so that the beam becomes strongly compressed again during the propagation downstream to the sample. The maximal peak current is achieved at 1.6 m, the sample location, where the central slices are aligned vertically in the longitudinal phase space [Fig. 5(c)]. At this location, the peak

FIG. 4. Beam energy and rms bunch length evolution from the cathode ($z = 0$ m) to the sample ($z = 1.6$ m). A beam is generated and accelerated to be 3.30 MeV at the gun. The beam is compressed by more than 30% immediately after the emission at the cathode and then continues being compressed lightly until arriving at the buncher. Then, the beam is decelerated weakly through the buncher to be 3.24 MeV. The beam is compressed by the buncher by a factor of over 10 in the rms length and over 100 in the FWHM (see Fig. 6). The FWHM bunch length is minimal at 1.6 m but the rms length becomes minimal just before this point.

current reaches 200 A and the FWHM bunch length is 4 fs (Fig. 6).

The peak in the temporal distribution of a bunch is very sharp but the spreads at the head and tail are wide. In the time duration of 10 fs around the peak, there are 5.5×10^6 electrons (55% of the bunch charge). Even though quite a large number of electrons are in the head and tail, the contrast between the peak and head/tail is large. Therefore, the head/tail part will make a small contribution compared to the diffraction pattern produced by the main part around the peak. Furthermore, the electrons at the widely spread head and tail have large energy spreads compared with the electrons at the central peak [Fig. 5(c)].

For a MeV electron beam, the diffraction angle is very small and therefore a screen, where the diffraction pattern is taken, should be placed a few meters downstream of the sample. If the beam divergence is large, the diffraction patterns overlap each other and an informative image cannot be obtained. The beam divergence should be below $50 \mu\text{rad}$ for a few MeV beam [19]. Here, the rms divergence is $26 \mu\text{rad}$ at the sample location (Fig. 7). The divergence can be further reduced by increasing the beam size at the sample. The manipulation of the transverse phase space is carried out by using the second solenoid after the buncher. The transverse phase space at the sample is shown in Fig. 8. The beam divergence is largest for the outermost electrons and can be reduced by a collimator of 2 mm aperture.

FIG. 5. Beam longitudinal phase space at three locations. At the exit of the gun (a), the beam head has a lower energy than the tail and the length becomes gradually shorter by weak velocity bunching. When the beam passes through the buncher (b), the energy chirp is increased so that the beam can be strongly velocity compressed. The maximum peak current is achieved at 1.6 m (c) where the central slices are aligned vertically.

Considering the three phase spaces in Figs. 5(c), 9, and 10, we can find the head and tail parts in the temporal distribution have not only large energy spread but also have large transverse divergence. Therefore, the effect

FIG. 6. Temporal distribution of a 1.6 pC beam at the sample. The peak current is 200 A and the FWHM bunch length is 4 fs. In a time duration of 10 fs around the peak, there is 55% of the bunch charge.

FIG. 7. Evolution of rms beam size and divergence. The beam size and divergence are controlled with the focusing solenoids around the gun and after the buncher. At the sample, the rms beam size is 0.67 mm and the rms divergence is 26 μ rad.

of the head and tail parts to the diffraction pattern produced by the main part of the beam will be further weakened.

Another important measure of the beam quality for diffraction experiments is the transverse coherence length L_c , which is defined as the ratio of the De Broglie wavelength λ and rms divergence σ_θ , $L_c = \lambda/2\pi\sigma_\theta$ [20]. The coherence length defines the limit of the observable structure size of the sample. The structure size may range from a few angstroms to a few tens nanometers depending on samples. In this design, the De Broglie wavelength, $\lambda = h/p$, is 0.00034 nm, where h is the Plank's constant and p beam momentum. The transverse

FIG. 8. Transverse phase space consisting of electron position (x) and angle (x') of a beam at the sample location.

FIG. 10. Phase space consisting of time (t) and transverse angle (x') of a beam at the sample location. The head and tail parts have relatively large transverse divergence compared to the main part around the peak.

FIG. 9. Phase space consisting of transverse angle (x') and longitudinal momentum (p_z) of a beam at the sample location. The beam head with a higher energy and the beam tail with a lower beam energy [see Fig. 5(c)] have larger transverse beam divergence.

FIG. 11. Normalized rms slice emittance. At the central slices where most of electrons are populated, the slice emittance is about 0.1 mm mrad.

coherence length is then 2.1 nm for the 26 μ rad divergence beam.

When the beam is sliced temporally, the emittance is 0.1 mm mrad at the central slices where most of the electrons are concentrated (Fig. 11). Since the slices are aligned vertically in the longitudinal phase space, the rms energy spread increases up to 40 keV, that is 1.2% of the beam energy. When only the central peak, where 55% of electrons are populated, is taken account, the energy spread is 30 keV. The slice energy spread at the central slices is about 17 keV (Fig. 12).

If the beam launch phase is shifted toward the 0-crossing phase, the peak current of a beam is unchanged while the

transverse beam parameters, beam size and divergence, become worse. When the beam launch phase is shifted toward 90° , the transverse beam parameters are improved but the peak current becomes lower. A buncher peak field of 16 MV/m was chosen and the phases were adjusted to make the beam be focused temporally at the sample, -1° and -2.8° at the 1st and 2nd cavities, respectively. The simulation input parameters and the optimized result of the beam parameters are summarized in Table I. The conditions listed in the Table make the beam be focused at the sample position in both the longitudinal and transverse directions and also minimize beam

FIG. 12. Rms slice energy spread. The slice energy spread at the central slices is about 17 keV.

arrival time variation from rf jitter which is important for a pump-probe experiment. The effect on the beam parameters and arrival time from rf jitter is discussed in the next section.

V. EFFECT OF RF JITTER

The last section presented the nominal performance of the system; here we examine the effect of rf amplitude and phase jitter at the gun and buncher on beam arrival time and beam parameters, such as bunch length and divergence, at the sample.

A. Beam arrival time jitter

For a femtosecond electron beam to be useful for a pump-probe electron diffraction experiment with femtosecond resolution, the beam arrival time at the sample should be stabilized to the same order as the electron bunch length at least. To simulate arrival time fluctuation, we use state-of-the-art stability of the rf parameters, 0.013% rms in rf amplitude jitter and 0.014° rms in rf phase jitter, as reported in [21], for electron beam tracking simulations with the ASTRA code.

To simulate femtosecond arrival time fluctuation, an electron beam should be numerically tracked with femtosecond time steps. However, it would be a very time consuming job to repeat such a tracking several times for

TABLE I. Simulation input parameters of laser, gun, and buncher and the simulation result of the beam parameters with ASTRA at 1.6 m.

Parameters		Values
Laser	Pulse length (rms)	1.2 ps
	Full radius	0.16 mm
	E_{kin} of emitted electrons	0.6 eV
	Thermal emittance	0.065 mm mrad
Gun	Peak field at cathode	80 MV/m
	Phase from 0-crossing	22°
Buncher cavity 1	Starting position from cathode	0.45 m
	Peak field	16 MV/m
	Phase from 0-crossing	-1°
Buncher cavity 2	Peak field	16 MV/m
	Phase from 0-crossing	-2.8°
Main gun solenoid	Center position from cathode	0.11 m
	Peak field	0.205 T
2nd solenoid	Center position from cathode	1.0 m
	Peak field	0.205 T
2nd solenoid	Center position from cathode	1.0 m
	Peak field	0.0856 T
Beam at 1.6 m	Number of electrons	10^7
	Bunch length (FWHM)	4 fs
	Peak current	200 A
	Divergence (rms)	$26 \mu\text{rad}$
	Beam size (rms)	0.665 mm
	Normalized projected emittance	0.129 mm mrad
	Central slice emittance	0.105 mm mrad
	Mean energy	3.24 MeV
	Energy spread (rms)	40.2 keV
	Transverse coherence length	2.1 nm

various conditions. In this study, artificially larger rf jitter was assumed for beam arrival time jitter simulation and a bigger time step of 20 fs was used. When arrival time fluctuation at 0.45 m caused by gun accelerating field jitter was studied, a beam was tracked with 20 fs steps from the cathode to 0.45 m, where the entrance of the buncher is placed, for nine different gun amplitudes within a $\pm 1\%$ range of 80 MV/m and then a linear fit was made to allow the results to be scaled to the nominal rf amplitude jitter, 0.013%. The beam arrival time variation to the rf amplitude change was linear over that range. When arrival time fluctuation from rf phase jitter was studied, nine different rf phases within $\pm 0.8^\circ$ range of the nominal phase were used and a beam was tracked with 20 fs time steps. Then, a linear fit was made for the nominal phase jitter, 0.014° .

When an electron beam is accelerated through the gun, the beam energy becomes about 3 MeV. Since the beam is not fully relativistic yet, even though very close to, beam arrival time is sensitive to gun rf amplitude jitter. The arrival time jitter sensitivity to rf amplitude jitter depends on the gun phase where the beam is launched by a drive laser pulse (Fig. 13). The jitter sensitivity decreases as the gun phase increases. Beam arrival time fluctuation caused by gun amplitude jitter is only partially compensated by the buncher and remains to the sample location as will be discussed later in this section.

Beam arrival time dependence on the gun phase (Fig. 14) results from the phase slippage between the beam and the rf field in the gun [15]. Up to 54° launch phase, the arrival time at 0.45 m becomes earlier with increasing phase because the beam experiences a higher rf accelerating field when it is emitted from the cathode. However, when the launch phase increases further the

FIG. 13. Beam arrival time sensitivity at 0.45 m to 0.013% gun rf amplitude jitter at the gun phase when the beam is launched. Arrival time fluctuation to rf amplitude jitter becomes smaller as the launch phase increases. This arrival time fluctuation is partially compensated by the rf buncher (see Fig. 16 and the discussion in the text).

FIG. 14. Beam arrival time at 0.45 m depending on the launch phase (blue nonfilled circle) and arrival time fluctuation caused by 0.014° gun phase jitter (red filled circle). The sensitivity becomes smaller as launch phase increases until about 54° and then becomes larger again. At about 54° , the sensitivity is zero. This arrival time fluctuation from gun rf phase is also partially compensated by the rf buncher (see Fig. 16 and the discussion in the text).

phase slippage becomes larger and the beam experiences a decelerating field at the last part of the second cell of the gun, where the field direction is reversed before the beam goes out of the gun cavity.

According to the result on beam arrival time fluctuation to gun rf amplitude and phase jitter, a gun rf phase between 52° and 57° may be preferred to minimize beam arrival time jitter at 0.45 m when the beam parameter dependence on the gun rf phase is ignored. Actually, bunch length at the sample becomes much longer when a beam is launched at these phases. Furthermore, beam arrival time fluctuation from gun rf jitter is only a partial contribution to the total beam arrival time jitter, and bigger contributions come from buncher rf jitter as will be discussed below.

After the gun, the rf buncher rotates the beam clockwise in longitudinal phase space to attain velocity bunching. When the beam is configured such that the head slice has a lower energy, a smaller rotation in the phase space, by smaller rf amplitude or rf phase offset from the on-crest phase, is required. This means that jitter contribution from the buncher is reduced. Figure 15 shows the longitudinal phase spaces for various beam launch phases at the cathode. With launch phases smaller than 37° we can get a preferred beam distribution in phase space so as to reduce the bunching force required at the buncher. When the rf amplitude at the buncher is low or the rf phase is close to the on-crest phase, beam arrival time fluctuations caused by buncher rf jitter are also reduced. In Table II, the rf amplitudes required at the buncher in order to align the beam vertically at the sample in the longitudinal phase space are listed for various beam launch phases.

FIG. 15. Beam longitudinal phase space at 0.45 m for various beam launch phases. If a beam is launched at 37° (maximum beam energy gain phase), the beam becomes almost flat in the longitudinal phase space. If the launch phase is shifted toward 90° , the beam is configured such that the beam head has a higher energy than the beam tail. If the phase is toward the 0-crossing, the beam head has a lower energy than the tail. The beam is compressed by using velocity bunching at the buncher afterward. Buncher rf jitter greatly affects beam arrival time variation at the sample. When the beam is configured such that the head has a lower energy before the buncher, a smaller bunching strength is required and therefore beam arrival time jitter from buncher rf error can be minimized.

As expected from Fig. 15, higher buncher amplitudes are necessary for higher gun phases. Higher buncher amplitudes result in bigger beam arrival time jitter from buncher rf errors. Alternatively, the bunching force can be increased by changing the buncher rf phase toward -90° while keeping the rf amplitude fixed. In this case, jitter contribution of the buncher to beam arrival is almost the same as the former case.

TABLE II. The rf amplitude required at the buncher for longitudinal focusing at the sample for various beam launch phases at the cathode. The rf phases are set to be the same as the nominal phases, -1° and -2.8° from the 0-crossing phase at the first and second buncher cavities, respectively. When rf amplitude at the buncher is higher, beam arrival time variation produced by rf jitter at the buncher becomes bigger.

Beam launch phase	Buncher amplitude
17°	14.9 MV/m
22°	16.0 MV/m
27°	17.2 MV/m
32°	18.6 MV/m
37°	19.6 MV/m
42°	20.5 MV/m
47°	21.2 MV/m
52°	21.6 MV/m

When the beam propagates further through the buncher to the sample location (1.6 m), arrival time variation caused by gun phase jitter is partially compensated by the phase of the buncher (Fig. 16). When a beam is launched at a gun phase shifted to the positive direction by 0.014° from the nominal gun phase, the beam has a higher beam energy by 85 eV (red nonfilled circle in Fig. 16) and the arrival time at the buncher is earlier by 6.5 fs (red filled circle). Because of the earlier arrival at the buncher, the beam experiences a buncher phase shifted to the negative direction. The beam then gets stronger deceleration within the buncher. After the buncher, the beam energy becomes lower by 293 eV than a standard beam starting from the cathode at the nominal gun phase. When the beam arrives at the sample, arrival time jitter reduces to 2.1 fs. For the case of a beam starting with a negative gun phase shift, the opposite is true.

Arrival time variation caused by gun amplitude jitter is only weakly compensated by the buncher. The beam energy difference is compensated partly by the buncher because a beam with a higher beam energy arrives earlier at the buncher; however, the arrival time variation caused by the beam energy difference at the gun remains. If the gun amplitude is higher by 0.013% from the nominal amplitude, 80 MV/m, the beam has a higher energy as much as 431 eV (blue nonfilled square) and arrives at the buncher

FIG. 16. Beam arrival time and beam energy variation caused by gun phase and amplitude error. An rf error, 0.014° phase or 0.013% amplitude, was assumed to take place at the gun. The buncher was assumed to operate at the nominal phase and amplitude condition without jitter. At the nominal launch phase, 37° , beam arrival time variation at 0.45 m to rf phase error (red filled circle) comes with beam energy variation (red nonfilled circle). When the beam passes through the buncher, the beam energy variation is reversed and the beam arrival time variation is compensated by about 50%. On the contrary, arrival time variation to rf amplitude error (blue filled square) is less compensated by the buncher because the beam energy change (blue nonfilled square) in the buncher is not sufficient. See the text for more discussion.

TABLE III. Beam arrival time fluctuation at the sample produced by rf jitter, 0.013% amplitude and 0.014° phase, at the gun and buncher. Total arrival time jitter was estimated by adding each jitter contribution quadratically.

Jitter sources		Arrival time fluctuation
Gun	0.013% amplitude	6.4 fs
	0.014° phase	2.1 fs
Buncher cavity 1	0.013% amplitude	0.0 fs
	0.014° phase	5.9 fs
Buncher cavity 2	0.013% amplitude	0.0 fs
	0.014° phase	5.2 fs
Total		10.4 fs

earlier by 7.6 fs (blue filled square). Through the buncher the beam loses more energy than a standard beam and the energy decreases further by 89 eV compared to the nominal beam energy. However, the energy loss occurring through the buncher is not sufficient to fully compensate the arrival time variation produced before the buncher. When the beam arrives at the sample, the arrival time is still earlier than the standard beam by 6.4 fs.

Adding quadratically all jitter contributions discussed above, the estimated arrival time jitter is 10.4 fs rms at the nominal operating condition. The beam arrival time variations at the sample for various jitter sources are summarized in Table III.

Timing jitter between the laser pulse and the rf system might be another contribution to beam arrival time jitter. A beam tracking simulation was carried out to study this issue and it was found that a beam arrival time change of 0.92 fs per 1 fs timing mismatch between the laser and rf systems could be produced. An rms relative timing jitter of 2.4 fs and an rms timing drift of 0.84 fs over 8 hours between a laser pulse and an extracted rf signal were reported in Ref. [22]. This timing jitter then produces a beam arrival time fluctuation of 2.3 fs, which will be a minor contribution to the total time resolution when added quadratically.

B. Beam parameter jitter

By using the same method for estimating beam arrival time fluctuation to gun and buncher rf jitter, beam parameter fluctuation caused by rf jitter, 0.013% amplitude and 0.014° phase, was studied. The variations of the beam energy, peak current, and beam transverse divergence at the sample location caused by rf error are listed in Table IV.

The beam energy and transverse divergence were not visibly sensitive to rf error. Especially, rf amplitude error contributes to beam parameter variation much less than rf phase error. Even if rf error increases by a factor of 10, the effect on the beam energy and transverse divergence will be invisible.

Peak current variation was relatively large because the high peak current in this design was a consequence of the

TABLE IV. Beam energy (E), peak current (I_{peak}), and beam transverse divergence ($\sigma_{x'}$) variations at the sample caused by rf error, 0.013% amplitude and 0.014° phase from the nominal conditions, at the gun and buncher. The variations are shown as percentages to the nominal beam parameters shown in Table I.

Error sources		E	I_{peak}	$\sigma_{x'}$
Gun	Amplitude	0.00%	0.37%	0.00%
	Phase	0.01%	0.30%	0.06%
Buncher cavity 1	Amplitude	0.00%	0.27%	0.00%
	Phase	0.01%	0.95%	0.05%
Buncher cavity 2	Amplitude	0.00%	0.24%	0.00%
	Phase	0.01%	0.98%	0.11%

perfect vertical alignment of the beam in the longitudinal phase space. When operating rf parameters are perturbed from the nominal values, the beam is not vertically aligned in the longitudinal phase space any longer and the peak current decreases. In this case, rf amplitude error makes a comparable contribution to peak current variation as rf phase error. However, the variation is still less than 1% for each jitter contribution and about 1.5% for all jitter contributions added quadratically. For a factor of 10 higher rf jitter, the peak current will decrease by about 15%.

VI. DISCUSSION

An electron gun setup was designed, which consists of an S-band photocathode gun with 80 MV/m peak field at the cathode and an S-band buncher with two four-cell $2\pi/3$ mode cavities operating at 16 MV/m peak field. A beam dynamics simulation was carried out with ASTRA and a 4 fs beam at 1.6 pC was obtained. The peak current reached 200 A. The rms beam divergence and rms beam size at 1.6 m were 26 μrad and 0.665 mm. These beam parameters will allow a single-shot electron diffraction experiment with femtosecond time resolution.

When state-of-the-art rf stability, 0.013% amplitude and 0.014° phase, is assumed for beam jitter simulation, rms beam arrival time jitter was simulated to be 10.4 fs, which is larger than the FWHM electron bunch length. In order to have a 10 fs resolution for a pump-probe electron diffraction experiment, total beam arrival time jitter should be 8 fs or less. To satisfy such a tolerance, rf amplitude and phase jitter should be as good as 0.01% and 0.01°, respectively. Beam energy, peak current, and beam transverse divergence variations to rf amplitude and phase jitter were numerically studied. It was found that there were negligible changes in the beam parameters when state-of-the-art rf stability was considered.

In order to scan the time delay between a pump laser pulse and a probe electron beam when a dynamic process is studied, a high repetition rate operation of the experiment system would be required. High repetition rate operation will increase the signal-to-noise ratio of the experiment as well. By using the gun designed for a high repetition rate

operation [11], this ultrashort beam generation system should be capable of running with a 1.5 kHz repetition rate.

ACKNOWLEDGMENTS

The author would like to thank R. P. Walker for encouraging this study and valuable comments. Very helpful discussions with K. Flöttmann at DESY and R. J. D. Miller at CFEL/DESY are appreciated. I. P. S. Martin and R. P. Walker kindly proofread the manuscript.

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