Electron-bunch compression using a dynamical nonlinearity correction for a compact x-ray free-electron laser

Kazuaki Togawa,^{*} Toru Hara, and Hitoshi Tanaka

XFEL Project Head Office, RIKEN, 1-1-1 Kouto, Sayo, Hyogo 679-5148, Japan[†]

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We propose a novel method to achieve a highly brilliant electron bunch with a peak current of several kA in an x-ray free-electron laser (XFEL) by efficiently correcting nonlinearity of the bunch-compression system. In this method, a second-order positive energy chirp is imprinted to the electron bunch by a correction cavity installed at the beginning of the system, namely the nonlinearity is initially *over-corrected*. The imprinted chirp is enhanced in a compression process at a bunch compressor due to electron bunch rotation in longitudinal phase space, and then continuously corrects the second-order nonlinearity induced in the following sections. Since the frequency and field amplitude of the correction cavity can be significantly lowered to the available technology level, this method enables the use of a high-frequency accelerator, i.e., a high-gradient accelerator, which is indispensable to realize a compact XFEL facility.

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I. INTRODUCTION

A coherent and ultrashort pulsed x-ray light source has been desired from a variety of scientific fields, such as life science, material science, environmental science, and medical science. An x-ray free-electron laser (XFEL) based on the process of self-amplified spontaneous emission (SASE) is one of the most promising candidates to satisfy these demands [1,2]. However, since the facility size of the XFELs reaches a few-km due to the required electron-beam energy as high as 20 GeV [3,4], the total number of such large-scale facilities will be quite limited in the world. In order to spread practical XFELs widely, like as synchrotron radiation rings, and to satisfy the needs of large amounts of scientists, the realization of a compact XFEL is very important [5].

To make the XFEL facility compact, the beam energy should be reduced by using a short-period undulator. At the same time, it is essential to use a high-frequency linac, in which the accelerating field gradient increases with the frequency. According to this scenario, a compact XFEL facility has been proposed at SPring-8 in 2000 [6,7]. Although the use of the high-frequency linac drastically reduces the length of the accelerator section, the attainable peak current is limited to be less than 1 kA due to the nonlinearity of the accelerator system. In a conventional bunch-compression method, the nonlinearity is corrected in a higher-harmonic cavity, but it does not work in a compact XFEL using a high-frequency linac due to the technological difficulty of fabricating a correction cavity

system with much higher frequency than that of the linac. In this paper, we propose a new scheme to efficiently compress the electron bunch by more than 2 orders of magnitude, which is indispensable for compact XFELs.

II. DYNAMICAL CORRECTION OF ENERGY CHIRP NONLINEARITY

A. Overcorrection method

A chicane-type bunch compressor (BC) composed of four bending magnets is widely used for bunch compression from a picosecond to femtosecond range [8]. When a negative energy chirp is supplied by a sinusoidal rf field of the linac, the energy of the electrons at the head of the bunch becomes lower and the energy of the tail becomes higher. Then, in the BC, the head electrons take a longer path and those at the tail take a shorter path, and consequently the longitudinal bunch length is compressed. In the XFEL, several BCs are generally used to accomplish a high compression factor of ~ 100 . However, when such high compression is attained, the beam is easily overbunched in the energy-time phase space due to nonlinearity of the rf field and the BC, resulting in a limitation of the beam intensity and the emittance growth.

The main term of the nonlinearity is a second order of time (or longitudinal position). Since the second-order nonlinear terms of the rf accelerating field and the BC have the same negative sign, an additional device is necessary to linearize the compression system. The correction cavity operated in a deceleration rf phase can cancel out these second-order terms; however, it must be operated at a higher-harmonic frequency of the linac, otherwise the beam cannot gain energy. The required correction field to

^{*}togawa@spring8.or.jp

[†]URL: <http://www.riken.jp/XFEL/>

cancel out the second-order term of the linac is given by

$$\begin{aligned} V_{\text{cor}} \cos \phi_{\text{cor}} &= -\left(\frac{f_{\text{acc}}}{f_{\text{cor}}}\right)^2 V_{\text{acc}} \cos \phi_{\text{acc}} \\ &= -\frac{1}{n^2} V_{\text{acc}} \cos \phi_{\text{acc}}, \end{aligned} \quad (1)$$

where V , f , and ϕ are the rf voltage amplitude, the rf frequency, and the phase of the reference particle, respectively. In this article, the rf voltage is defined as $V(z, t) = V \cos(2\pi f t - kz + \phi)$, where k is the rf wave number, and z of the reference particle is assumed to be zero at $t = 0$. The subscripts acc and cor denote the linac and the correction cavity, and n is a harmonic number, namely $f_{\text{cor}} = n f_{\text{acc}}$. Since $V_{\text{acc}} \cos \phi_{\text{acc}}$ in Eq. (1) expresses the positive energy gain in the linac, the rf field of the correction cavity, $V_{\text{cor}} \cos \phi_{\text{cor}}$, should be negative, and the beam is decelerated in the cavity. From Eq. (1), a large harmonic number n has an advantage to reduce the energy loss in the correction cavity.

In the case of the Linac Coherent Light Source in the U.S., the fourth harmonic of an S-band linac (2.9 GHz), that is X-band (11.4 GHz), is used for a correction cavity [3,9], and the European XFEL in Germany employs the third harmonic (3.9 GHz) of an L-band linac (1.3 GHz) [4,10,11]. Since the high rf frequency, C-band (5.7 GHz), is already used for the linac of the Japanese compact XFEL at SPring-8 (XFEL/SPring-8) [7], a conventional scheme requiring the frequency higher than 17 GHz cannot be adopted.

In order to overcome this, we have devised a new method to efficiently linearize the bunch-compression system using a single correction cavity operated at the same frequency as the linac. A simple configuration composed of a single BC and two linac sections shown in Fig. 1 is considered to explain the principle of the method. By installing the correction cavity before the BC, where the bunch length is still long, a second-order positive energy chirp is imprinted to the electron bunch; namely, the non-linear chirp is initially *overcorrected*. To provide the overcorrection condition, a low-frequency subharmonic linac is located upstream the correction cavity. The overcorrected

chirp is enhanced in the compression process at the BC where the electron bunch rotates in the longitudinal phase space. As described in Sec. II B, we found that the effective frequency of the correction field is up-converted after the BC by a factor of the compression ratio. The amplitude and phase of the correction cavity can be determined so that the second-order nonlinearity is canceled out at the end of the C-band linac in Fig. 1. The overcorrection method allows not only the use of an efficient high-frequency linac to realize a compact XFEL, but also it minimizes the energy loss necessary for the conventional linearization scheme using a harmonic cavity.

B. Analysis using a second-order polynomial approximation

In the following analytical formulation, the nonlinearity of the energy chirp that comes from the accelerating rf fields and the BC is taken into account up to the second-order using a polynomial approximation. The relative longitudinal positions of the electron with respect to the reference center particle are expressed to be Δz_0 and Δz_1 before and after the BC, respectively. Using a first-order momentum compaction factor, R_{56} , and a second-order T_{566} , the relation between Δz_0 and Δz_1 is approximately given by

$$\Delta z_1 \simeq \frac{1}{C_B} \Delta z_0 - \left[T_{566} \left(\frac{E'}{E} \right)^2 + \frac{R_{56}}{2} \frac{E''}{E} \right] \Delta z_0^2, \quad (2)$$

where E is the energy of the reference particle and a single prime denotes d/dz . C_B is the first-order bunch-compression factor, defined as $C_B = (1 - R_{56} E'/E)^{-1}$. From Eq. (2), Δz_0 can be written as

$$\Delta z_0 = C_B \Delta z_1 + C_B^3 \left[T_{566} \left(\frac{E'}{E} \right)^2 + \frac{R_{56}}{2} \frac{E''}{E} \right] \Delta z_1^2 + o(\Delta z_1^3). \quad (3)$$

The energy chirp before the BC ($E_{\text{before BC}}$) given by the L-band linac and the C-band correction cavity is expressed as

FIG. 1. (Color) Schematic diagram of the overcorrection method. A simple configuration composed of a single BC and two linac sections is assumed to explain the principle. In this case, the energy chirp is linearized at the entrance of the next BC.

$$E_{\text{before BC}}(\Delta z_0) = E_L(\Delta z_0) + E_{CC}(\Delta z_0) \\ = E + E'\Delta z_0 + \frac{1}{2}E''\Delta z_0^2 + o(\Delta z_0^3), \quad (4)$$

$$E = eV_0 + eV_L \cos\phi_L + eV_{CC} \cos\phi_{CC}, \\ E' = k_L eV_L \sin\phi_L + k_{CC} eV_{CC} \sin\phi_{CC}, \\ E'' = -k_L^2 eV_L \cos\phi_L - k_{CC}^2 eV_{CC} \cos\phi_{CC}.$$

The subscripts 0, L , and CC , respectively, denote the initial condition, the L-band (1.4 GHz) linac, and the C-band (5.7 GHz) correction cavity. To simplify the model, the initial energy chirp is ignored and the electron velocity is assumed to be the light velocity. Substituting Eq. (3) into Eq. (4), the energy distribution after the BC ($E_{\text{after BC}}$) can be obtained. By adding the energy gain in the following C-band linac (E_C), the final energy distribution ($E_{\text{after C}}$) is expressed as

$$E_{\text{after C}}(\Delta z_1) = E_{\text{after BC}}(\Delta z_1) + E_C(\Delta z_1) \\ = E + eV_C \cos\phi_C + (C_B E' + k_C eV_C \sin\phi_C) \\ \times \Delta z_1 + \frac{1}{2} \left[C_B^2 E'' + 2C_B^3 \left[T_{566} \left(\frac{E'}{E} \right)^2 \right. \right. \\ \left. \left. + \frac{R_{56}}{2} \frac{E''}{E} \right] E' - k_C^2 eV_C \cos\phi_C \right] \Delta z_1^2 \\ + o(\Delta z_1^3), \quad (5)$$

where subscript C denotes the C-band linac.

In order to linearize the energy chirp at the end of the C-band linac, the coefficient of the second-order term, Δz_1^2 in Eq. (5), should be zero. Assuming the correction cavity phase $\phi_{CC} = -180^\circ$, the required rf voltage of the correction cavity can be written as

$$V_{CC} = \left(\frac{k_L}{k_C} \right)^2 V_L \cos\phi_L + \frac{1}{C_B^2} V_C \cos\phi_C \\ - 2C_B T_{566} k_L \left(\frac{k_L}{k_C} \right)^2 \\ \times \left(\frac{V_L \sin\phi_L}{V_0 + V_L \cos\phi_L - V_{CC}} \right)^2 V_L \sin\phi_L \\ + C_B R_{56} k_L \frac{\left(\frac{k_L}{k_C} \right)^2 V_L \cos\phi_L - V_{CC}}{V_0 + V_L \cos\phi_L - V_{CC}} V_L \sin\phi_L. \quad (6)$$

The rf voltage of the correction cavity satisfying Eq. (6) is plotted in Fig. 2 as a function of the compression factor, together with the variation of each term on the right side of Eq. (6). The accelerator parameters used for the plots are indicated in Fig. 1. The first term in Eq. (6) is the correction voltage for the L-band linac. Since it is located before the BC, the voltage does not depend on the compression factor. The second term is the required voltage for a correction of the C-band linac. The voltage reduces inversely proportional to C_B^2 ; that is, the effective frequency of the correction cavity is up-converted in the BC. It has the same effect

FIG. 2. (Color) Required rf voltage of the correction cavity as a function of the compression factor.

as a harmonic number in Eq. (1), and this is the advantage of the overcorrection method. The third and fourth terms correspond to the second-order nonlinearity of the BC and that of the electron bunch. Since the energy chirp of the electron bunch is overcorrected in the correction cavity, the third and fourth terms have opposite signs. As shown in Fig. 2, the required voltage of the C-band correction cavity decreases with increasing the compression factor. It can be reduced to as low as 5 MV for $C_B > 6$.

Other sources of the second-order nonlinear chirp, such as longitudinal wakefields, can be included in the model to cancel out, if necessary.

C. Validity of the second-order approximation

In order to check the validity of the second-order approximation, the previously obtained result is compared with an exact one-dimensional (1D) particle tracking simulation without any truncation of higher-order terms. A 1D model includes, (i) sinusoidal traveling wave accelerator ($E = eV \cos\phi$) with a slippage effect, and (ii) exact 1D path lengths of the particles inside the BC (L_{BC}) as a function of the energy deviation ($\delta = \Delta E/E$). L_{BC} is expressed as

$$L_{BC}(\delta) = 4\rho(\delta)\theta(\delta) + \frac{2\Delta L}{\cos\theta(\delta)} + L_C \\ = 4\rho\sqrt{\frac{(1+\delta)^2 - \gamma^{-2}}{1 - \gamma^{-2}}} \\ \times \arcsin\left(\sin\theta\sqrt{\frac{1 - \gamma^{-2}}{(1+\delta)^2 - \gamma^{-2}}}\right) \\ + \frac{2\Delta L}{\cos[\arcsin(\sin\theta\sqrt{\frac{1 - \gamma^{-2}}{(1+\delta)^2 - \gamma^{-2}}})]} + L_C, \quad (7)$$

FIG. 3. Layout of the bunch compressor composed of four rectangular bending magnets.

FIG. 4. (Color) Comparison of the correction cavity rf voltage obtained from the analytical expression and the simulation.

where $\rho (= \beta E / (ecB))$ and $\theta (= \arcsin(L_B / \rho))$ are the bending radius and angle of the reference trajectory in the magnet (Fig. 3). It is assumed that the magnetic field B is constant in the gap and has no fringe fields. β and γ are the velocity normalized by light velocity and the relativistic mass factor of the reference particle, respectively.

Space-charge effects, coherent synchrotron radiation (CSR) effects, and longitudinal wakefields are not considered in this 1D model.

The initial electron bunch in the simulation has a uniform distribution that is 20-ps long. The compression factor is defined as the ratio of the standard deviation of the bunch distribution with respect to its initial value. Figure 4 compares the analytical expression in Eq. (6) and the result of the simulation as a function of the compression factor. The required rf voltage of the correction cavity decreases for large compression factors also in the simulation, and it agrees well with the analytical prediction, except for a little discrepancy at the low compression factor that is caused by the truncation of the higher-order terms in the polynomial approximation. This result confirms the advantage of the overcorrection method to linearize the bunch-compression system.

III. APPLICATION TO MULTISTAGE BUNCH COMPRESSION IN THE XFEL/SPRING-8

A. Extension of the second-order approximation to multistage bunch compression

Cancellation of rf and BC's nonlinearity has been evaluated by the DESY group [11]. They dealt with nonlinearity of longitudinal position transformation at the first BC up to third order. As mentioned in Ref. [11], it seems to be difficult to extend the third-order analysis to a multistage bunch-compression system. On the other hand, nonlinearity of a longitudinal phase space distribution is treated up to second order in this article, as described in Sec. II B. This procedure is easily extensible to a multistage bunch-compression system in a cascaded manner. Using Eq. (5), the energy distribution at the end of the i th linac can be derived as Eq. (8). Parameters of the i th bunch compressor and the following accelerating linac are indicated with a subscript i :

$$\begin{aligned}
 E_{\text{after linac},i}(\Delta z_i) &= E_{\text{after BC},i}(\Delta z_i) + E_{\text{linac},i}(\Delta z_i) \\
 &= E_{i-1} + eV_i \cos \phi_i + (C_{B,i} E'_{i-1} + k_i eV_i \sin \phi_i) \Delta z_i \\
 &\quad + \frac{1}{2} \left\{ C_{B,i}^2 E''_{i-1} + 2C_{B,i}^3 \left[T_{566,i} \left(\frac{E'_{i-1}}{E_{i-1}} \right)^2 + \frac{R_{56,i}}{2} \frac{E''_{i-1}}{E_{i-1}} \right] E'_{i-1} - k_i^2 eV_i \cos \phi_i \right\} \Delta z_i^2 + o(\Delta z_i^3) \\
 &= E_i + E'_i \Delta z_i + \frac{1}{2} E''_i \Delta z_i^2 + o(\Delta z_i^3).
 \end{aligned} \tag{8}$$

In Eq. (8), E_{i-1} , E'_{i-1} , and E''_{i-1} are the initial coefficient of the energy distribution at the exit of the $(i-1)$ th linac, namely the entrance of the i th BC. The newly defined coefficients E_i , E'_i , and E''_i become initial coefficients for the $(i+1)$ th BC. The rf parameters of the correction cavity for a multistage BC can be determined by numerically solving Eq. (8) so that the second-order term equals to

zero at the end of the whole accelerator, namely the energy chirp is linearized there.

In the design of the three-stage bunch compression at the XFEL/SPRING-8, the cascaded formula of the second-order approximation gives a good parameter basis for the three-dimensional (3D) simulation described in the next section. In the 3D simulation, slight adjustments of the rf param-

FIG. 5. (Color) Schematic layout of the XFEL/SPRING-8. The dashed line is not a real beam line.

ters are added to cancel out the CSR and wakefield effects on the energy chirp.

B. Three-dimensional simulation of the XFEL/SPRING-8

The overcorrection method is adopted in the XFEL/SPRING-8, which is a compact x-ray SASE-FEL source [7,12]. By using short-period in-vacuum undulators, coherent x rays with a wavelength down to 0.06 nm can be generated with 8-GeV electron beams. In the XFEL/SPRING-8, the high-gradient C-band linac with 35 MeV/m is employed, and the length of the accelerator section is only 400 m. The electron beam emitted from a 500-keV thermionic gun is first compressed in the injector by velocity bunching [13,14]. Three BCs are installed downstream to obtain a 3-kA peak current at the end of

the accelerator, as shown in Fig. 5. The rf frequencies of the accelerator are gradually increased from low frequency (L-band) to high frequency (C-band) as the bunch length becomes short. The compression factors of the three BCs are about 3, 10, and 6, respectively. In order to linearize the bunch-compression system, a C-band correction cavity installed before the first BC overcorrects the electron beam so that the second-order nonlinearity is canceled out at the end of the accelerator.

To check the validity of the overcorrection method in a practical configuration a 3D simulation is performed for the XFEL/SPRING-8 using PARMELA [15] and ELEGANT [16], in which other possible nonlinear sources are included; space-charge effects of the bunched electron beam, CSR effects in the bending magnets, and wakefields

FIG. 6. (Color) Bunch distributions in the energy-time phase space and the current profiles along the XFEL/SPRING-8 accelerator. (a) Entrance of the C-band correction cavity. (b) Injector end. (c) Exit of the first BC. (d) Exit of the second BC. (e) Exit of the third BC. (f) End of the C-band main linac. These places are indicated in Fig. 5

FIG. 7. (Color) Normalized slice emittance in the bunch along the XFEL/SPring-8 accelerator. Filled circles (red) and open squares (blue) indicate horizontal and vertical emittances, respectively. The evaluation points in the accelerator are the same as Fig. 6.

in the accelerating structures. Particle tracking of the injector is carried out by PARMELA with the space-charge effects, and ELEGANT is used for the rest of the accelerator, including the CSR effects and the wakefields [17]. Figure 6 shows the bunch distributions in the energy-time phase space together with the longitudinal current profiles along the accelerator. The second-order nonlinearity of the energy distribution at the end of the L-band linac is overcorrected by the correction cavity [Fig. 6(b)] in order to linearize the energy chirp at the exit of the final BC [Fig. 6(e)]. After passing the three-stage BC, the electron bunch is successfully compressed to a peak current more than 3 kA without overbunching. As shown in Fig. 6(f), it is possible to make a flat distribution in the core part by canceling the wakefield effects in the C-band main linac. As a result of avoiding overbunching in the all compression processes, the initial normalized emittance of 0.6π mm mrad at the CeB₆ gun is barely degraded through the acceleration up to 8 GeV and bunch compression down to less than 100 fs. Obtained normalized slice emittance of the bunch is shown in Fig. 7.

These results of the simulation confirm that the overcorrection method enables operation of the correction cavity at the same rf frequency as the main linac. The beam energy loss in the correction cavity is only 5.3 MeV, which is negligibly small compared to the final beam energy of 8 GeV.

IV. SUMMARY

In summary, we introduced an overcorrection method to linearize the bunch-compression system, which is indis-

pensable for a compact XFEL using a high rf frequency linac. Since the method lowers the required rf frequency of the correction cavity, it removes the technological difficulty and significantly simplifies the rf system. The effectiveness of the method was confirmed by both an analytical consideration and simulations. The overcorrection method will be employed in the compact XFEL facility of SPring-8.

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