ELECTRON BUNCH COMPRESSION WITH DYNAMICAL NON-LINEARLITY CORRECTION FOR A COMPACT FEL

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Abstract

To realize a compact FEL facility, a high-frequency high-gradient accelerator is indispensable to shorten the accelerator length. Then a high-harmonic correction cavity conventionally used for nonlinearity compensation in bunch compression encounters a technological difficulty of an extremely high-frequency rf system. In order to overcome this difficulty, we propose to directly use a frequency up-conversion effect obtained in a bunch compressor. In this scheme, a correction cavity and a sub-harmonic accelerator section are installed before the first bunch compressor. Since the effective frequency of the energy chirp given by the correction cavity is increased as the electron bunch length compressed, the same rf frequency as a main accelerator can be used for the correction cavity. In this paper, we derive analytical expressions of the nonlinearity correction scheme, then its application to the XFEL/SPring-8 project is described.

INTRODUCTION

Intense coherent x-ray beams generated by x-ray free-electron lasers (XFELs) are expected to bring innovation to many scientific fields. The first success of an XFEL has been achieved by LCLS (Linac Coherent Light Source) in the United States in 2009, and XFEL/SPring-8 and the European XFEL (Euro-XFEL) will follow in the upcoming years [1-3]. In the current configuration of XFELs, a linear accelerator (linac) is used to produce high-brightness electron beams required for FEL operation. Since the beam emittance reduces as increasing the beam energy in a linac, the facility scale of LCLS and Euro-XFEL reaches several kilometers to accelerate the electron beam more than 10 GeV.

When synchrotron radiation sources entered the third-generation, three large facilities, ESRF, APS and SPring-8, had been planned and constructed in 1990s as tri-polar bases of Europe, the United States and Asia [4-6]. Since the sizes of these facilities are too large for a single country, scale reduction was an important issue for the widespread distribution of the light sources. After in-vacuum undulators becoming popularly used at synchrotron radiation facilities around 2000, low-emittance medium-size facilities, such as SLS, SOLEIL and DIAMOND, have been come into operation [7-9]. Although the beam energies of these medium-size facilities are lower, they can produce competitively bright radiation in x-rays by using short-period in-vacuum undulators [10]. The advent of these medium size facilities has proved the usability of the synchrotron radiation and accelerates its applications.

In analogy, reduction of a facility size is also an essential issue for XFELs. In order to reduce the beam energy and facility scale, XFEL/SPring-8 has been designed based on a compact FEL concept [11]. XFEL/SPring8 employs short-period in-vacuum undulators together with a low-emittance injector [12]. The use of C-band high-gradient linacs helps to reduce further the facility length within 700 m. In general, the gradient of an accelerator is inversely proportional to its rf frequency, therefore a higher frequency has an advantage to achieve a higher acceleration gradient. For that reason, X-band and C-band accelerators had been developed for the linear collider project [13].

The technology of the C-band accelerator has been well developed for a practical use. The SCSS EUV FEL facility uses four C-band acceleration tubes of 5.7 GHz and proves its long-term stable operation at 37 MV/m [14,15]. The C-band linacs employed in XFEL/SPring-8 can accelerate the electron beam to 8 GeV only with 250 m.

High-frequency accelerators can increase a field gradient, however, it raises a problem in bunch compression. Since XFELs require high-brightness electron beams with a typical peak current of several kA, longitudinal bunch compression is indispensable. In the bunch compression process, nonlinearity of the system limits the attainable compression factor and peak current. In a conventional bunch compression scheme, nonlinearity is compensated by a correction cavity operated at a high-harmonic of a main linac [16,17]. However in a compact FEL using a high-frequency main linac, the correction scheme imposes a technological difficulty of an extremely high-frequency rf system. Here we propose a method to overcome this difficulty by utilizing dynamical evolution of the electron bunch length through a bunch compression process [18].

NONLINEARITY CORRECTION USING A HIGH-HARMONIC CAVITY

A chicane composed of four bending magnets is widely used as a bunch compressor (BC) [19]. When an electron bunch having a coherent energy chirp passes a chicane, the bunch length changes according to the path-length dependence on the beam energy. The energy chirp is normally given by an rf field by accelerating the electron bunch at an off-crest phase. In order to compress the bunch, a negative energy chirp with respect to the longitudinal z-axis is given and the energy of the bunch head becomes lower than the tail. Then in the BC, the tail electrons take a shorter path and they catch up the head

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electrons. Generally, several BCs are used to obtain sub-ps electron bunches in XFELs.

Within a linear framework, the bunch length can be compressed to zero (Fig. 1 (a)), but nonlinearity actually limits the attainable minimum length (Fig. 1 (b)). In XFELs, a peak current of several kA corresponding to a compression factor of 100~3000 is generally required. When nonlinearity remains in this extreme compression, the electron bunch is easily over-bunched in a longitudinal phase space before reaching the desired beam current as shown in Fig. 1 (b). Since over-bunching results in an emittance growth, it should be avoided.

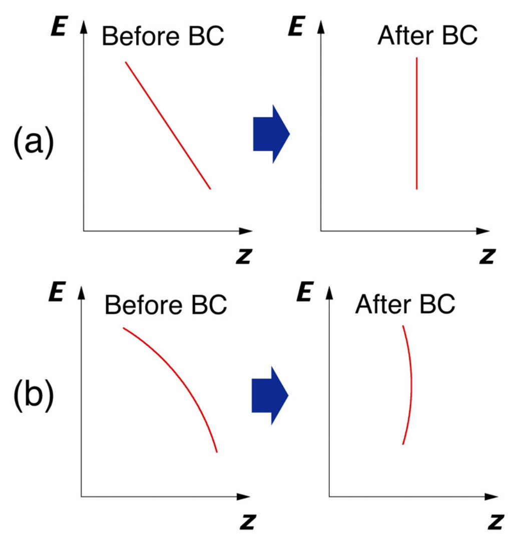

Figure 1: Bunch compression in a longitudinal phase space, (a) linear framework and (b) with nonlinearity. Positive z-axis shows the direction of bunch movement.

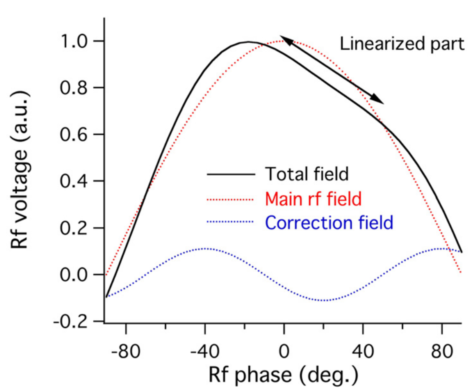

Figure 2: Linearization of rf field. The frequency of the correction cavity is the third-harmonic.

While wake fields and coherent synchrotron radiation (CSR) also adds a nonlinear chirp on the electron bunch, the main sources of nonlinearity are sinusoidal rf field curvatures and high-order momentum compaction factors of the BCs. Since the second-order nonlinear terms of the rf acceleration field and the BC have the same negative sign, an additional device is necessary for linearization. A correction cavity is generally used for this purpose. Since the correction cavity is operated in a deceleration phase for nonlinearity compensation, its frequency should be higher than that of the rf acceleration field. Otherwise the electron beam can not gain energy. To synchronize with the acceleration field, the frequency of the correction cavity is chosen at a high-harmonic of the main rf field as shown in Fig. 2 [16,17].

To compensate the second-order term of the main rf field, the required correction field can be easily obtained as

$$V_{cc}\cos\phi_{cc} = -\left(\frac{f_{acc}}{f_{cc}}\right)^2 V_{acc}\cos\phi_{acc} \quad (1),$$

where V, f and ϕ are the rf voltage, frequency and the phase of a reference electron in the bunch. Subscripts *cc* and *acc* denote the correction cavity and the main rf field respectively. From Eq. 1, it is noticed that the correction cavity should be operated in a deceleration phase and a higher frequency of the correction cavity minimizes the required correction field, thus the energy loss.

At LCLS, the fourth-harmonic of a S-band linac (2.9 GHz), that is X-band (11.4 GHz), is used for the correction cavity [20,21]. In case of Euro-XFEL, the third-harmonic (3.9 GHz) of an L-band linac is planned to be used as a correction field [22,23].

NONLINEARITY CORRECTION USING DYNAMICAL EVOLUTION OF A BUNCH LENGTH

In a compact FEL, a high-frequency rf linac is already used for beam acceleration. Therefore, the operation of a correction cavity at even higher frequency encounters a technological difficulty. For example, XFEL/SPring-8, which employs C-band (5.7 GHz) for a main linac, requires the frequency of a correction cavity higher than 17 GHz in a conventional correction scheme.

In order to overcome this problem, we can use bunch compression to increase the effective frequency of a correction cavity. When a correction cavity is installed before the first BC, the nonlinear energy chirp is given to the bunch at the frequency of the correction cavity. Then the frequency of this nonlinear chirp is increased after the BC, since the bunch length is compressed.

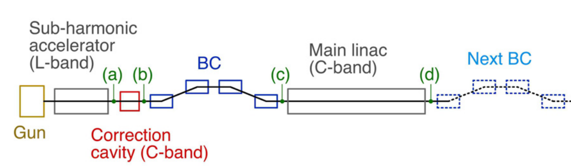

Figure 3: Simple model for nonlinearity correction with a sub-harmonic accelerator.

Figure 3 is a simple configuration of the nonlinearity correction scheme using the frequency up-conversion due to the bunch compression. The correction cavity is installed before the first BC and operated at the same frequency as the main linac. Since the electron beam loses energy in the correction cavity, an accelerator is necessary upstream of the correction cavity. This first accelerator is operated at a sub-harmonic frequency of the correction cavity and the main linac, thus the nonlinearity of this first accelerator section can be compensated by the correction cavity. Also the energy chirp required for the bunch compression in the first BC is given by this sub-harmonic accelerator.

Once the electron beam passes through the BC, the frequency of the nonlinear energy chirp given by the correction cavity is effectively increased by a factor of the compression factor. Thus the correction cavity can cancel out the nonlinearity of the main linac located downstream of the first BC.

SECOND-ORDER ANALYTICAL EXPRESSION

In this section, we estimate the parameter of the correction cavity using second-order analytical formulae [18]. We take a simple accelerator configuration of Fig. 3 as an example. In the following, we take into account the second-order nonlinerities of the rf fields and the BC, but wake fields, CSR and space charge effects will not be included in the formulae. The frequency of the main linac and the correction cavity is chosen to be C-band (5.7 GHz), and that of the first sub-harmonic accelerator to be L-band (1.4 GHz). A reference electron having a reference beam energy is defined in the electron bunch, and a relative longitudinal position of each electron inside the bunch is expressed as Δz with respect to the reference electron. In this example, a single-stage BC is first considered and we derive the condition required to linearize the energy chirp at the end of the main linac. Then the formulae will be extended to a multi-stage BC case.

Before the BC, the electron energy chirp can be written as

$$E_{beforeBC}(\Delta z_0) = E_0 + E_0'\Delta z_0 + \frac{1}{2}E_0''\Delta z_0^2 \quad (2),$$

where a subscript 0 means the parameters before the BC. E_0 is the energy of the reference electron, and single and double primes denote first and second derivatives with respect to the longitudinal coordinate z.

In the accelerator configuration of Fig. 3, the energy of the reference electron and its derivatives before the BC are given by

$$E_0 = eV_0 + eV_L\cos\phi_L + eV_{cc}\cos\phi_{cc},$$
$$E_0' = k_L eV_L\sin\phi_L + k_{cc}eV_{cc}\sin\phi_{cc},$$
$$E_0'' = -k_L^2 eV_L\cos\phi_L - k_{cc}^2 eV_{cc}\cos\phi_{cc}.$$

e is the charge of an electron and subscripts L and cc mean the parameters of the L-band accelerator and the correction cavity. In this article, we express the rf field as $V\cos(2\pi ft - kz + \phi)$, where k is a wave number of the field.

By using R_{56} and T_{566} of the BC, the electron position after the BC, Δz_1, can be obtained as

$$\Delta z_1 = \frac{1}{C_B}\Delta z_0 - \left[\frac{R_{56}}{2}\frac{E_0''}{E_0} + T_{566}\left(\frac{E_0'}{E_0}\right)^2\right]\Delta z_0^2 \quad (3).$$

In Eq. 3, the first-order bunch compression factor C_B is defined by

$$C_B = \left(1 - R_{56}\frac{E_0'}{E_0}\right)^{-1} \quad (4).$$

From Eq. 3, we have

$$\Delta z_0 = C_B\Delta z_1 + C_B^3\left[\frac{R_{56}}{2}\frac{E_0''}{E_0} + T_{566}\left(\frac{E_0'}{E_0}\right)^2\right]\Delta z_1^2 \quad (5).$$

By adding the energy gain in the C-band main linac, $E_C(\Delta z_1)$, to Eq. 2, the final energy chirp at the end of the main linac can be written as

$$\begin{aligned} E_{afterC}(\Delta z_1) &= E_{beforeBC}(\Delta z_0) + E_C(\Delta z_1) \\ &= E_{afterBC}(\Delta z_1) + E_C(\Delta z_1) \end{aligned} \quad (6).$$

Substituting Eqs. 2 and 5 into Eq. 6, the energy chirp after the main linac can be derived as

$$E_{afterC}(\Delta z_1) = E_0 + eV_C\cos\phi_C + \left(C_B E_0' + k_C eV_C\sin\phi_C\right)\Delta z_1$$
$$+\frac{1}{2}\left\{C_B^2 E_0'' + 2C_B^3\left[\frac{R_{56}}{2}\frac{E_0''}{E_0} + T_{566}\left(\frac{E_0'}{E_0}\right)^2\right]E_0' - k_C^2 eV_C\cos\phi_C\right\}\Delta z_1^2 \quad (7).$$

In order to compensate the second-order nonlinearity, the coefficient of Δz_1^2 in Eq. 7 should be zero. This condition is satisfied for the correction cavity voltages plotted in Fig. 4 as a function of the compression factor C_B. In Fig. 4, we assume the parameters listed in Table 1, and the rf phase of the correction cavity is fixed at -180 deg. The compression factor is changed by varying R_{56} of the BC, so the energy chirp in Eq. 4 is constant.

As we expected, the correction cavity voltage decreases for large compression factors. It means that the effective frequency of the correction cavity is up-converted and the required voltage to compensate the nonlinearity of the C-band main linac reduces according to Eq. 1. Since the second-order correction for the L-band and the BC does not benefit from the frequency up-conversion, there remains a residual voltage to cancel them out in Fig. 4.

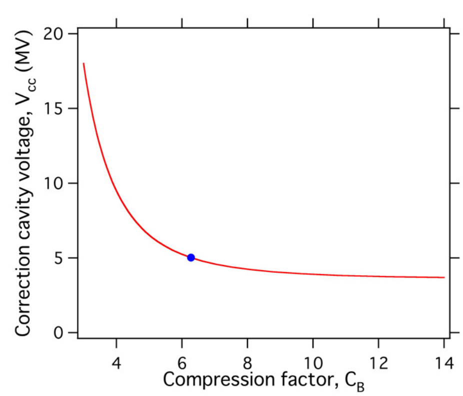

Figure 4: Required correction cavity voltage for second-order compensation as a function of the compression factor. Blue point shows the condition of Fig. 5.

Table 1: Parameters used to obtain Fig. 4

Initial energy, V_0	1 MV
L-band phase, ϕ_L	-23 deg.
L-band amplitude, V_L	40 MV
Correction cavity phase, ϕ_{cc}	-180 deg.
C-band amplitude, V_C	400 MV
C-band phase, ϕ_C	-17 deg.

The evolution of the energy chirp along the accelerator is shown in Fig. 5 for the condition of a compression factor 6.3 and a correction cavity voltage 5 MV (blue point in Fig. 4). The nonlinear sinusoidal curvature of the L-band rf field is slightly convex upward as shown in Fig. 5 (a). This curvature is over corrected in the correction cavity in order to compensate the nonlinearities of downstream components (Fig. 5 (b)). In the BC, the curvature is enhanced due to the frequency up-conversion (Fig. 5 (c)). Although the final energy chirp has slight third-order nonlinearity, which is not considered in the formulae, the energy chirp is linearized at the exit of the C-band main linac (Fig. 5 (d)).

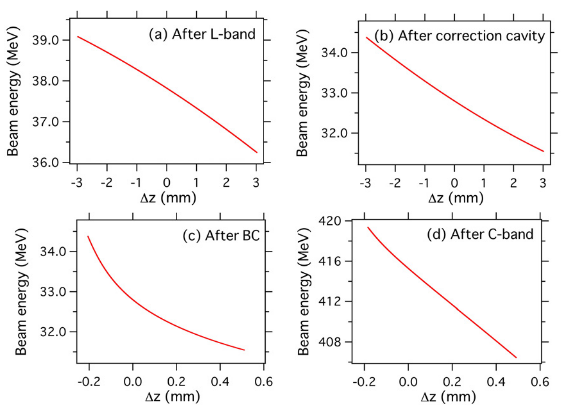

Figure 5: Evolution of the energy chirp along the accelerator, at the exits of (a) L-band accelerator, (b) correction cavity, (c) BC and (d) C-band respectively. (a)~(d) correspond to the locations indicated in Fig. 3. A correction cavity voltage of 5 MV and a compression factor 6.3 are assumed (blue point in Fig. 4). Positive Δz corresponds to the bunch head.

Eq. 7 is the formula for a single-stage BC, but it can be easily extended to a multi-stage BC system in a cascaded manner. By representing the parameters of the *i*-th BC and linac with a subscript *i*, the energy chirp at the end of the *i*-th linac is given as follows.

$$E_{afterlinac,i}(\Delta z_i) = E_{afterBC,i}(\Delta z_i) + E_i(\Delta z_i)$$
$$= E_{i-1} + eV_i\cos\phi_i + \left(C_{B,i}E'_{i-1} + k_i eV_i \sin\phi_i\right)\Delta z_i$$
$$+\frac{1}{2}\left\{C_{B,i}^2 E''_{i-1} + 2C_{B,i}^3\left[\frac{R_{56,i}}{2}\frac{E''_{i-1}}{E_{i-1}} + T_{566,i}\left(\frac{E'_{i-1}}{E_{i-1}}\right)^2\right]E'_{i-1} - k_i^2 eV_i\cos\phi_i\right\}\Delta z_i^2 \quad (8)$$

In Eq. 8, E_{i-1}, E'_{i-1} and E''_{i-1} are the initial coefficients of the energy chirp for the *i*-th BC obtained at the end of the (*i-1*)-th linac. The parameters of the correction cavity can be numerically solved using Eq. 8 so that the second-order term of Eq. 8 becomes zero.

APPLICATION TO XFEL/SPRING-8

The XFEL/SPring-8 is a compact x-ray SASE source currently under construction and the beam commissioning will be started in 2011 [2]. By using short-period in-vacuum undulators of an 18 mm period, coherent x-rays of the wavelengths down to 0.06 nm can be generated with 8 GeV electron beams. In order to accelerate the beam, high-gradient C-band linacs with 35 MV/m are employed, but a correction cavity for the bunch compression had been a serious issue. Installation of an X-band cavity was first discussed in the original design, however, the X-band rf system turned out to be costly and require development of rf components. Finally we decided to adopt a C-band correction cavity operated with the frequency up-conversion scheme in the BCs as described in the previous sections.

A schematic configuration of XFEL/SPring-8 is shown in Fig. 6. A thermionic pulsed DC gun is used in the injector for its stability and reliability. The initial beam emitted from the cathode has a 0.5 MeV beam energy with a current of 1 A. A fast chopper slices out 1 ns bunches from the cathode emission. Then a low frequency 238 MHz buncher gives an energy chirp, and the electron bunch is compressed by velocity bunching in the injector. In order to compensate the nonlinearity of the velocity bunching, an L-band correction cavity is installed right behind a 476 MHz cavity, where the bunch length is still long. This L-band correction cavity also uses the frequency up-conversion effect for nonlinearity compensation.

After the velocity bunching terminated inside the L-band linac, the electron bunch is further compressed in three BCs to obtain a 3 kA peak current. The compression factors of these three BCs are chosen to be 3, 10 and 6 respectively. The rf frequency of the accelerator is gradually increased according to the bunch length compression. In Fig. 6, there are two more chicanes at 3 GeV and before the BL3 undulator, which are used for the elimination of dark currents from the linacs. For the linearization of the three-stage BC, a C-band correction cavity is installed upstream of the first BC. Main parameters of the rf fields and the BCs are given in Table 2.

In the design of the three-stage bunch compression, the previously derived analytical formulae are used to determine basic parameters. Since it is difficult to analytically treat the effects of space charge, CSR and wake fields, which all depend on an electron bunch distribution, a particle tracking and parameter optimization are necessary to compensate these effects. In the particle tracking, the low energy injector is simulated by PARMELA with space charge effects, and ELEGANT is used for the rest of the accelerator including CSR effects and wake fields [24,25].

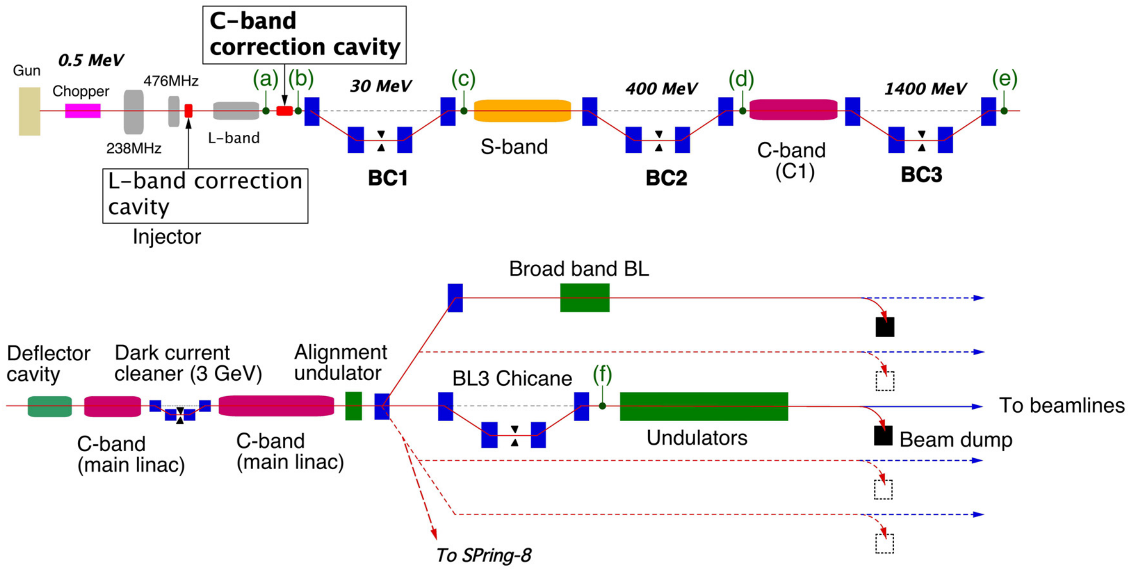

Figure 6: Schematic layout of XFEL/SPring-8. (a)~(f) correspond to the locations of Fig. 7.

Table 2: Main rf and BC parameters of XFEL/SPring-8

L-band amplitude	38 MV (14 MV/m)
L-band phase	-25 deg.
C-band correction cavity amplitude	5.3 MV (12 MV/m)
C-band correction cavity phase	-193 deg.
S-band amplitude	400 MV (17 MV/m)
S-band phase	-20 deg.
C-band (C1) amplitude	1400 MV (32 MV/m)
C-band (C1) phase	-43 deg.
C-band (main) amplitude	6600 MV (35 MV/m)
C-band (main) phase	0 deg.
R_{56} of BC1	-41 mm
R_{56} of BC2	-37 mm
R_{56} of BC3	-7.6 mm

Figure 7 shows the evolution of the bunch distribution in the longitudinal phase space along the accelerator. The nonlinearity of the energy chirp at the end of the L-band linac (Fig. 7 (a)) is over-corrected by the C-band correction cavity (Fig. 7 (b)) in order to obtain a linear energy chirp at the end of the third BC (Fig. 7 (e)). The electron bunch is successfully compressed without over-bunching and a peak current more than 3 kA is obtained at the undulator section (Fig. 7 (f)).

Figure 8 shows the final slice emittance of the electron beam at the undulator section ((f) in Fig. 6). As a result of avoiding over-bunching in the compression process, the initial emittance at the gun (0.6 πmm-mrad) is almost preserved after the bunch compression and acceleration.

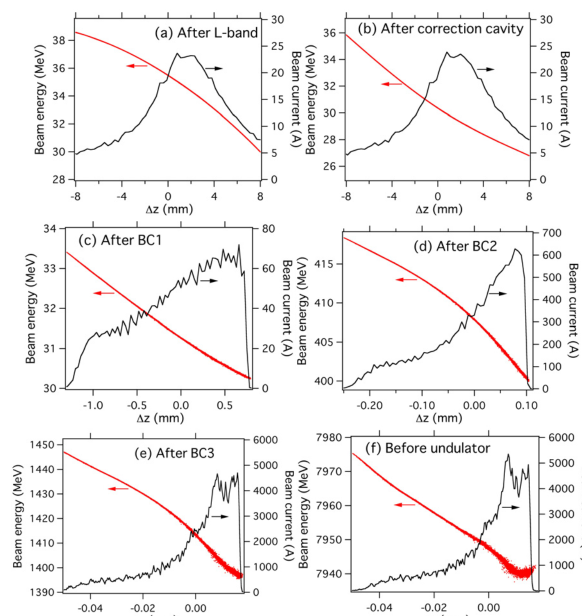

Figure 7: Evolution of the energy chirp in XFEL/SPring-8 (red dots). (a)~(f) correspond to the locations along the accelerator indicated in Fig. 6. A slit is installed in the BC1 chicane to remove energy tails of the bunch, and the distributions of the bunch core are shown in (a) and (b). Black lines are the beam current distributions. Positive Δz corresponds to the bunch head.

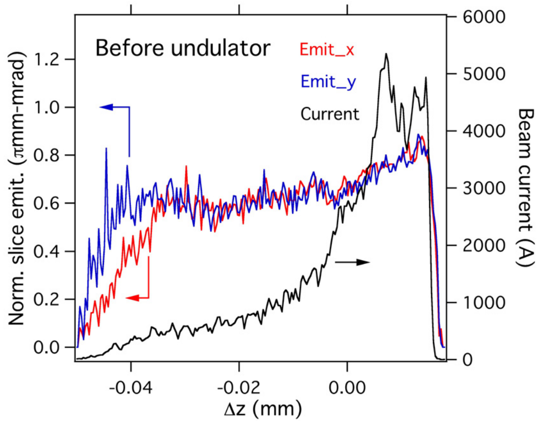

Figure 8: Slice emittance of the 8 GeV electron bunch at the entrance of the undulator ((f) in Fig. 6). Positive Δz corresponds to the bunch head.

SUMMARY

By directly using a frequency up-conversion effect due to the dynamical evolution of a bunch length, it is possible to correct the nonlinearity of a bunch compression system without using a high-harmonic correction cavity. In this correction scheme, a correction cavity and a sub-harmonic accelerator section are installed before the first BC. Then the correction cavity operated at the same frequency of the main linac over-corrects the nonlinearity to obtain a linear energy chirp at the end of the final BC or the accelerator. Elimination of a high-harmonic cavity is an important issue for a compact FEL.

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