

# DESIGN STUDY OF NONLINEAR ENERGY CHIRP CORRECTION USING SEXTUPOLE MAGNETS AT THE SOFT X-RAY FREE-ELECTRON LASER BEAMLINE OF SACLA

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## Abstract

At the x-ray free-electron laser (FEL) facility, SACLA, a soft x-ray FEL beamline is driven by a dedicated 800-MeV electron accelerator (SCSS+) and being operated in parallel with two hard x-ray FEL beamlines. Responding to the demands of short laser pulses from users, a nonlinearity correction system using sextupole magnets is proposed to obtain shorter electron bunches. Since the frequency of the SCSS+ injector linac is S-band, the nonlinearity correction of a bunch compression process using a harmonic correction cavity is not so efficient as the SACLA injector [1], whose frequency of the linac is L-band. Instead of a complex and costly correction cavity system, the sextupole magnets are simply installed in a dispersive section of the first bunch compressor chicane. In this paper, we report the basic design concept and some detail studies of the nonlinear correction.

## INTRODUCTION

Nowadays, short-wavelength free-electron lasers (FELs) are indispensable tools for various science fields, e.g., fundamental physics, atomic, molecular, and optical physics, chemistry, biology, and material science.

In the SPring-8 site, the SCSS test accelerator that generated extreme-ultraviolet FEL lights was constructed as a prototype machine for the x-ray FEL facility, SACLA, in 2005 [2]. This accelerator was relocated in the SACLA undulator hall and upgraded to generate soft x-ray FEL lights in the wavelength range from 8 nm to 60 nm [3]. This upgraded accelerator was named as SCSS+. The electron charge of 0.3 nC is accelerated to 800 MeV (max.) at a repetition rate of 60 Hz (max.).

The SCSS+ has two bunch compressor (BC) chicane: one is located at the injector exit to compress the bunch from a few ps to 1 ps at 50 MeV, and the other at the middle of the C-band main linac to compress it to a final state of sub-ps at 500 MeV. Since the injector does not have a harmonic rf cavity that corrects the nonlinear energy chirp, the final bunch length and peak current are restricted to 0.5 ps and 300 A respectively. Although the FEL pulse energy of 100 μJ with a pulse width of ≤100 fs at a photon energy of 100 eV is obtained at the moment, higher peak power and shorter pulse width are demanded from experimental users.

Since the SCSS+ injector uses an S-band linac to accelerate the bunch and to provide an energy chirp to it, an X-band correction cavity is needed to linearize the energy chirp effectively. X-band rf technologies are already established, however, it is a hard task to introduce one more frequency to the accelerator system, and the cost is not inex-

pensive. Therefore, we proposed the nonlinear correction using sextupole magnets at the bunch compressor chicane, as shown in Figure 1.

Since the head and tail energies of the bunch are lower than that of the linear component due to the rf nonlinearity, these parts travel long distance in the chicane and delay at the BC exit, then the bunch is over-compressed, if without correction. The sextupole magnets located in the dispersive section kick the head and tail to the same direction and they travel along short cut courses, then the bunch is linearized if the magnets are properly tuned.

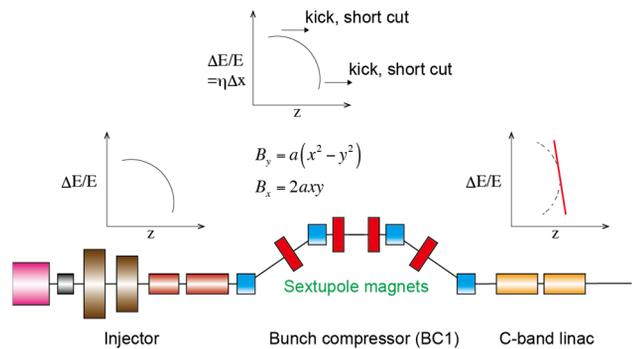


Figure 1: Concept of the nonlinear energy chirp correction using sextupole magnets.

In this paper, we report the design study of the nonlinear energy chirp correction using sextupole magnets at the soft x-ray FEL beamline of SACLA.

## BASIC THEORY

The transformation of longitudinal coordinate via a BC chicane is expressed as

$$z = \frac{1}{C_B} \bar{z} - \left[ \frac{R_{56}}{2} \frac{\bar{E}''}{\bar{E}} + T_{566} \left( \frac{\bar{E}'}{\bar{E}} \right)^2 \right] \bar{z}^2 + o(\bar{z}^3) \approx \frac{1}{C_B} \bar{z} - \frac{1}{2} \alpha \bar{z}^2, \quad (1)$$

where  $z$  and  $\bar{z}$  are longitudinal positions at the BC exit and entrance,  $C_B$  is a linear compression factor,  $R_{56}$  and  $T_{566}$  are 1st- and 2nd- order momentum compaction factors,  $\bar{E}$  is an energy of a reference particle,  $\bar{E}'$  and  $\bar{E}''$  are 1st- and 2nd- derivatives of  $\bar{E}$  with  $z$ , respectively [4]. In the condition of  $\alpha = 0$ , the bunch size is reduced uniformly without over bunching at any compression rate. Since the  $T_{566}$  of a standard chicane using rectangular magnets is approximated to be  $-3R_{56}/2$ , positive  $\bar{E}''$  is required to satisfy this condition, which is accomplished using a higher harmonic rf cavity. Another solution is controlling  $T_{566}$  independently of  $R_{56}$  to be negative by perturbate the path length using four sextupole magnets.

By a perturbative calculation, the  $T_{566}$  can be expressed as

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$$T_{566} = 3\theta^2 \left[ \frac{2}{3}L + \Delta L + \frac{2}{3}K_1\theta \left( \frac{L}{2} + k\Delta L \right)^2 (1-k)\Delta L \right], \quad (2)$$

where  $K_1$  is the sextupole K-value located at the oblique line [5]. From the mirror symmetry condition,  $K_4$  ( $K_3$ ) equals to  $K_1$  ( $K_2$ ). The  $T_{566}$  includes the effect of the 4th sextupole. If the  $K_1$  is negative and the absolute value is enough large, the  $T_{566}$  can be negative. From this  $T_{566}$ , we can obtain the following condition which satisfies  $\alpha = 0$ ,

$$\theta = \frac{2(2L+3\Delta L)(\bar{E}\bar{E}''/\bar{E}'^2-3)}{3K_1(L+2k\Delta L)^2(1-k)\Delta L}, \quad (3)$$

where the geometrical parameters are defined in Figure 2. One more condition is obtained from the definition of the linear compression factor,

$$\theta = \sqrt{\frac{(1/C_B-1)\bar{E}/\bar{E}'}{2(2/3\cdot L+\Delta L)}}. \quad (4)$$

Using these two relations, layout of the bunch compressor and sextupole strengths can be determined.

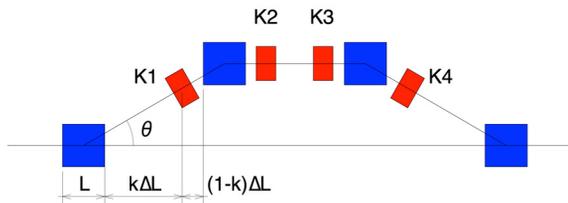


Figure 2: Layout of the bunch compressor chicane with sextupole magnets.

## PARAMETER OPTIMIZATION

The various parameters are optimized within the length of the present BC (11m) because the beta function needs to be kept in a proper scale. We also use the other present parameters: the initial beam energy ( $\bar{E}_0$ : 1 MeV), the frequency ( $k_s$ : S-band) and the rf amplitude ( $eV_s$ : 50 MeV) of the injector linac, and the length of the bending magnets ( $L$ : 0.3 m). The 1st BC's compression factor is chosen to be standard value of  $C_B = 5$  for the multi-stage bunch compression scheme.

### Rf Phase

Before determining the sextupole strengths, the optimum rf phase that gives the minimum second-order nonlinearity of bunch compression process is introduced. If the beam energy at the BC is fixed to be constant, the  $\alpha$  is written as

$$\begin{aligned} \alpha &= \left( \frac{1}{C_B-1} \right) k_s \left[ 3 \frac{(\bar{E}-\bar{E}_0)\tan\phi}{\bar{E}} + \frac{1}{\tan\phi} \right] \\ &\equiv -3 \left( \frac{1}{C_B-1} \right) k_s f(\phi). \end{aligned} \quad (5)$$

The  $f(\phi)$  as a function of  $\phi$  is shown in Figure 3. This function becomes minimum at the following phase,

$$\phi = -\tan^{-1} \sqrt{\frac{\bar{E}}{3(\bar{E}-\bar{E}_0)}}. \quad (6)$$

In the case that the initial energy is small enough to be ignored, the  $\phi$  is exactly  $-30^\circ$ .

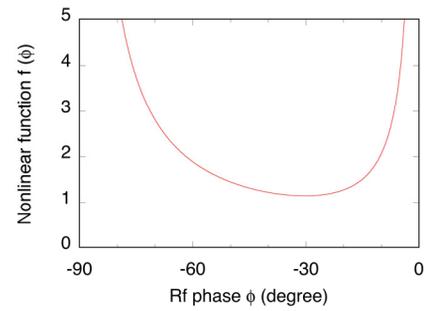


Figure 3: 2nd order nonlinear function  $f(\phi)$ .

### Sextupole Position

From the equation (3), the optimum position factor  $k$  that minimizes the sextupole strength can be introduced. The  $K_1$  takes minimum at  $k = \frac{2}{3} + \frac{L}{6\Delta L}$  as shown in Figure 4. In the case that the length of the bending magnet is short enough to be ignored against the oblique section length  $\Delta L$ , the  $k$  is exactly  $2/3$ . It means that the kick angle given by the sextupole becomes high at a large dispersive point, that is, at large  $k$ , while the pathlengths from the 1st (3rd) to the 2nd (4th) sextupole that contribute the nonlinear correction become short at large  $k$ . Since the  $k$  dependence of  $K_1$  has a flat-bottom, we choose a convenient value of  $k = 0.7$ .

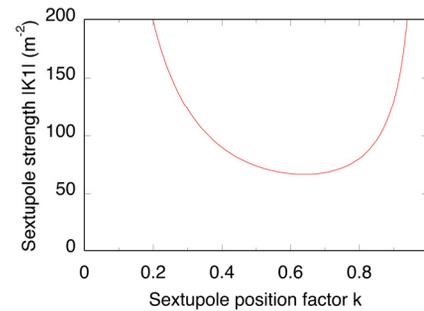


Figure 4: Sextupole strength as a function of the position factor  $k$ .

### Oblique Length, Kick Angle, and Sextupole Strengths

We need to determine the geometrical parameters of BC and the sextupole strengths. Figure 5 shows the conditional equation (3) and (4) for various  $K_1$ . Since long  $\Delta L$  is preferable to make  $K_1$  small, we choose  $\Delta L = 1.9$  m that can be secured in the present BC area. From equation (4), the bending angle of  $\theta = 0.075$  rad is obtained. Then,  $K_1 = -68$  m<sup>-2</sup> is also determined from the equation (3).

The strength of the 2nd sextupole is determined from the condition that the dispersion  $\eta$  and the derivative  $\eta'$  close at the exit of the BC [5].

$$K_2 = -\frac{K_1}{4} \left( \frac{L+2k\Delta L}{L+\Delta L} \right)^2 \quad (7)$$

### Parameter Tunability

Since the bending angle can't be changed so much in the fixed chamber, it is very important to investigate tunability of the nonlinear correction by an S-band rf phase. Figure 6

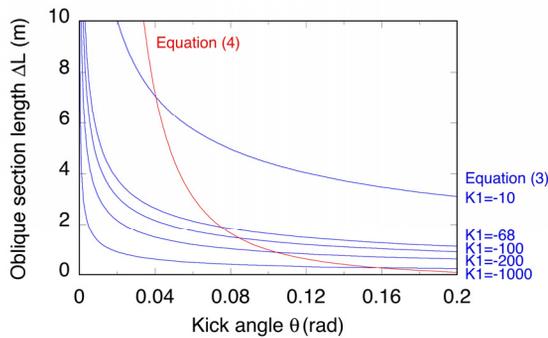


Figure 5: Chicane parameter conditions for various sextupole strengths.

shows the linear bunch compression factor and the sextupole strength that correct the 2nd order nonlinearity as a function of the S-band phase  $\phi_s$ . The compression factor can be tuned from 3 to  $\infty$  in the tunable range from  $-26^\circ$  to  $-36^\circ$ . The sextupole strength does not exceed  $200 \text{ m}^{-2}$ .

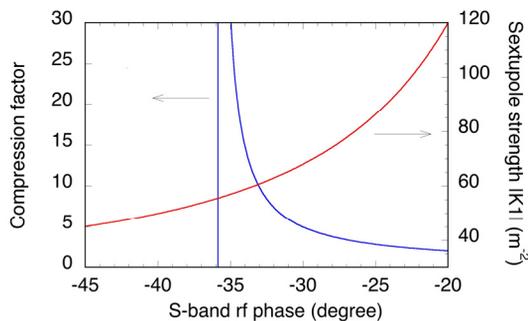


Figure 6: Parameter tunability by the injector S-band phase.

### Particle Tracking Simulation

Finally, particle tracking simulation by means of the code ELEGANT has been done to confirm the nonlinearity correction effect of the sextupole magnets [6]. The beam energy profile at the first BC's entrance was assumed to be a sine-curve, as  $\vec{E} = \vec{E}_0 + eV_s \cos \phi$  ( $\vec{E}_0$ : 1 MeV,  $eV_s$ : 50 MeV, center phase:  $-30^\circ$ ). The bunch profile was uniform with a 10 ps width and the peak current was 25 A. The normalized emittances were 0.6 mm mrad for both directions. The corrective effects: space charge, coherent synchrotron radiation, and wakefield were ignored. The C-band phase from the BC1 (50 MeV) to the BC2 (500 MeV) was  $0^\circ$  and the  $R_{56}$  of the 2nd BC was -37 mm.

Figure 7 shows the energy-time phase plot at the BC2 exit. The sextupole strength  $K_1$  was tuned to be  $-100 \text{ m}^{-2}$  to maximize the bunch compression (Figure 8). Since the nonlinear effects by the C-band linac and the 2nd BC was also corrected by the BC1's sextupole magnets, the strengths became larger than the theoretical values discussed above.

Since the other nonlinearity of the corrective effects can be expressed by polynomial expansion, their 2nd order

nonlinearity can be also corrected by the sextupole magnets. Generally, the nonlinear kick by the multi-pole magnet at the dispersive section causes the growth of the statistical rms emittance. However, the electron density in the core part of phase space should be high enough to increase the FEL pulse energy [7].

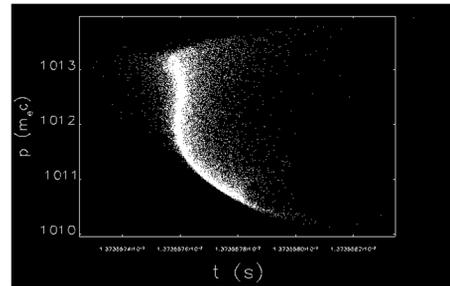


Figure 7: Simulated energy-time phase space plot at the BC2 exit of the SACLA-BL1.

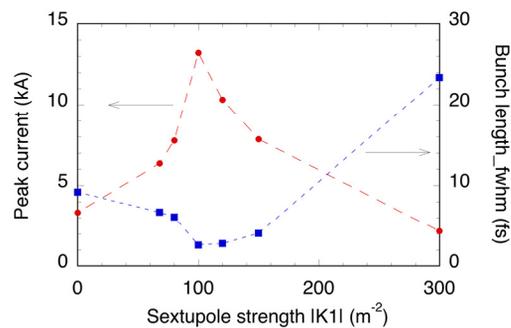


Figure 8: Simulated bunch profile tuning by the sextupole magnets.

### SUMMARY

In summary, we have proposed the nonlinear energy chirp correction by means of the sextupole magnets located at the dispersive section of the bunch compressor chicane of the SACLA-BL1. By optimizing the various accelerator parameters, prospects to increase the bunch peak current and to shorten the bunch length have been obtained. The hardware construction is scheduled in this year.

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