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THE X-BAND LINEAR COMPRESSION SYSTEM IN DALIAN COHERENT LIGHT SOURCE

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Abstract

Dalian Coherent Light Source (DCLS) is a free-electron laser (FEL) user facility working in the extreme ultraviolet (EUV) wavelength region from 50 to 150 nm. It mainly operates on the High Gain Harmonic Generation (HGHG) mode with the seed laser, although it can also run in the Self Amplified Spontaneous Emission (SASE) mode. The brightness and bandwidth of FEL radiation strongly depends on electron bunch quality, such as normalized transverse emittance, electron bunch energy, energy spread, peak current, etc. The high peak current with uniform longitudinal distribution is especially helpful for high peak power and narrow bandwidth of FEL, although it is not easy to achieve, due to the nonlinearity of sinusoidal accelerating radio frequency (RF) field and the 2nd-order momentum compaction coefficient T_{566} of bunch compressor. An X-band linearizer will be installed before the bunch compressor in order to correct this nonlinearity properly. In this paper, the beam dynamics design of the X-band linear compression system in DCLS is focused, and the simulation results with Elegant are presented and discussed.

INTRODUCTION

As shown in Fig. 1, DCLS is composed of linear accelerator (LINAC) and FEL Amplifier, and its main parameters are listed in Table 1 [1]. The high-quality electron bunch is produced, accelerated and compressed in the LINAC, and then delivered into the FEL Amplifier to generate the desired FEL radiation. In this process, bunch compression plays a vital role in the generation of intense FEL radiation, because the brightness of the radiation is closely related to the peak current and longitudinal distribution of electron bunch. In order to achieve high peak current, the longitudinal phase space of electron bunch is compressed in the bunch compressor. For DCLS, the compression ratio is 3-5 indicating the peak current up to 300 Amperes. Furthermore, the flat longitudinal current distribution is critical to increase the pulse energy of FEL radiation, and the flat longitudinal energy distribution is essential to improve the bandwidth of FEL spectrum when the FEL facility operates on HGHG mode [2]. Hence, the linear compression system is usually a standard configuration for the HGHG-mode FEL facility with narrow bandwidth and high brightness.

Table 1: Main Parameters of DCLS

Parameter	Nominal Value
Electron Bunch	
Energy	300 MeV
Slice Energy Spread	<20 keV
Normalized Emittance	1-2 mm·mrad
Charge	500 pC
Peak Current	≥300 Amp
Repetition Rate	50 Hz
FEL Radiation	
Wavelength	50-150 nm
Pulse Energy@1ps	≥100 μJ
Pulse Duration (FWHM)	130fs / 1ps

The configuration of X-band linear compression system is shown in Fig. 1. L1 provides a positive chirp for the electron bunch, and then the chirped bunch can be compressed in the chicane with negative (1st-order) momentum compaction coefficient R_{56}. In order to eliminate the nonlinear longitudinal part imposed by sinusoidal curve of L1 and 2nd-order momentum compaction coefficient T_{566} of Chicane, an X-band RF structure is employed following L1. The theoretical description of X-band linear compression system has been illustrated in detail by P. Emma [3]. According to the theory, the X-band RF structure works on the maximal decelerating RF phase π, and the linear compression can be achieved when the following condition is satisfied

$$eV_x = \frac{E_0\left\{1+\frac{1}{2\pi^2}\frac{\lambda_s^2 T_{566}}{|R_{56}|^3}(1-\sigma_z/\sigma_{z0})^2\right\}-E_i}{(\lambda_s/\lambda_x)^2-1}, \quad (1)$$

where e is elementary charge, V_x is the desired decelerating voltage of X-band, E_i and E_0 are the electron bunch energy at the exit of L0 and at the exit of Chicane, σ_z and σ_{z0} denote the rms bunch length at the entrance of L1 and at the exit of Chicane, λ_s and λ_x represent the wavelength of S-band and X-band RF field, and $\lambda_s = 4\lambda_x$. For the Chicane of DCLS, the approximate relation $T_{566} = -\frac{3}{2}R_{56}$ can be used.

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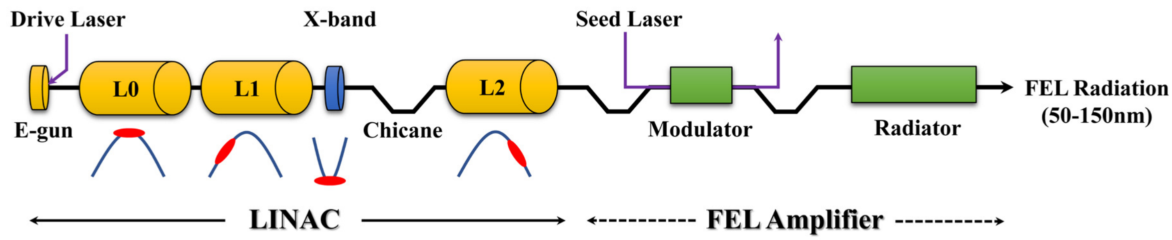

Figure 1: Layout of DCLS. The X-band linear compression system is composed of L1, X-band and Chicane. L0, L1 and L2 are the S-band RF structure. L0 works on the maximum RF acceleration phase. L1 provides a positive chirp which means the head of electron bunch suffers a lower accelerating RF field than the tail (the head is in the left), and then, the electron bunch with positive chirp comes into the negative chicane and is compressed. Because the accelerating field is sinusoidal, the longitudinal energy distribution is not linear actually but with a broad convex curve. However, the X-band RF structure could provide a narrow concave curve which happens to remove the convex curve from L0~L1 and also compensates the 2nd-order momentum compaction coefficient of Chicane. After the linear compression, the electron bunch undergoes a negative chirp to eliminate the positive chirp imprinted by L1. Finally, at the exit of LINAC, the linearly compressed electron bunch is of a high peak current and flat longitudinal distribution. Then it is delivered into the HGHG-mode FEL Amplifier to generate FEL radiation of high intensity and narrow bandwidth.

Table 2: Main Parameters of Linear Compression System in DCLS

Parameter	Nominal Value
Accelerator (S-band, 2856MHz)	
L0 Voltage V_0	50 MV
L0 Phase φ_0 (peak phase)	0°
L1 Voltage V_1	86 MV
L1 Phase φ_1	-23°
L2 Voltage V_2	96 MV
L2 Phase φ_2	26°
Linearizer (X-band, 11.424GHz)	
Voltage V_x	7.8 MV
Phase φ_x	180°
Chicane	
1st-order Momentum Compaction Coefficient R_{56}	-50 mm
2nd-order Momentum Compaction Coefficient T_{566}	75 mm
Electron Bunch Energy	
At the Entrance of L1 E_i	4.5 MeV
At the Exit of Chicane E_0	128 MeV
Before/After Compression	
Peak Current I_p	72 / 305 Amp
Bunch Length (rms) σ_t	2.26 / 0.58 ps
Normalized Equivalent Charge Ratio C_e (with X-band)	0.32 / 0.35
Normalized Equivalent Charge Ratio C_e (without X-band)	0.32 / 0.44

SIMULATION RESULTS

When the X-band RF structure works on the RF phase π, its desired voltage can be calculated via Eq. (1). And using the parameters of accelerator, linearizer and Chicane listed in Table 2, the S2E simulation results via Elegant [4] were obtained, as shown in Fig. 2. The initial current distribution (a2, b2, c2 in Fig. 2) before compression is approximately flat, but after compression without X-band, a large number of electrons move towards the head of electron bunch and the current distribution becomes distorted (Fig. 2-e2). It is the reason that the longitudinal energy distribution at the exit of L1 holds a convex curve (Fig. 2-b1) and the Chicane with negative R_{56} and positive T_{566} will enhance the convexity (Fig. 2-e1). In order to compensate this convex curve imposed by L1 and Chicane, a concave curve is required and the radius of curvature should be larger than that of convex curve to ensure the little energy loss of electron bunch. According to these constrains, the X-band RF structure which is of larger radius of curvature and works on the decelerating RF phase (concave curve) is selected as a linearizer, but not the S-band RF structure. In comparison with the results without X-band RF structure (e1 and e2 in Fig. 2), X-band linearizer makes the electron bunch of much flatter longitudinal energy distribution (Fig. 2-d1) and current distribution (Fig. 2-d2).

DISCUSSION

The simulation results under the nominal peak current 300A have been presented. In addition, more works have been done when the compression ratio σ_z/σ_{z0} is not at the nominal point, and the relationship of the linear compression ratio and the desired voltage of X-band RF structure is shown in Fig. 3. The simulation result was obtained by Elegant tracking (blue star) and was well fitted (orange curve) via Eq. (1). The goodness of fit is 0.999, which indicates that the quadratic relation between V_x and σ_z/σ_{z0} in Eq. (1) is valid.

In order to estimate the flat level of current distribution and linearized level of compression, a parameter is defined as normalized Equivalent Charge Ratio C_e

$$C_e = \frac{I_p \cdot \sigma_t}{Q_0}, \quad (2)$$

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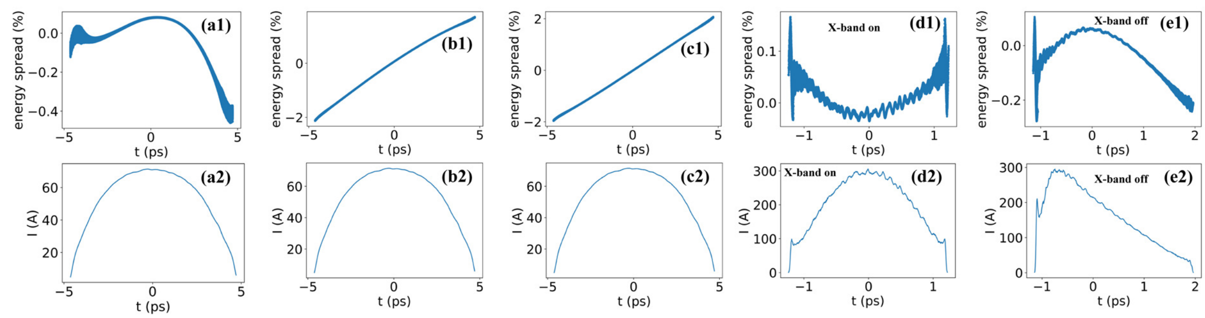

Figure 2: Simulation results of the longitudinal phase space (upper) and current distribution (lower) at the exit of L0 (a1, a2), at the exit of L1 (b1, b2) and X-band (c1, c2), and at the exit of LINAC with X-band on (d1, d2) and off (e1, e2). When the X-band is on, the longitudinal energy distribution (d1) and current distribution (d2) at the exit of LINAC is flatter than that when the X-band is off (e1, e2).

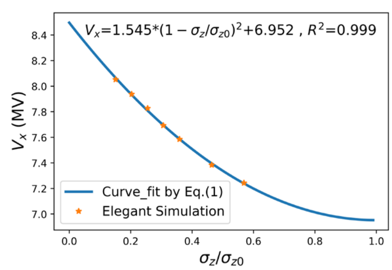

Figure 3: The relationship of the linear compression ratio and the desired voltage of X-band. The blue star represents the results from Elegant simulation. The orange line is the fitting result of the simulation via Eq. (1), and the goodness of fit is 0.999.

where I_p and σ_t are the peak current and the rms bunch length in time scale respectively, and Q_0 is the total charge of electron bunch.

As an illustration, we discuss the Gaussian distribution and uniform distribution (shown in Fig. 4). The former is usually used to describe the current distribution of electron bunch actually and the latter is the ideal current distribution for FEL lasing. The basic Gaussian current distribution can be expressed as

$$I(t) = \frac{Q_0}{\sqrt{2\pi}\sigma_t} e^{-\frac{t^2}{2\sigma_t^2}}, \tag{3}$$

where t is the longitudinal position in electron bunch. According to Eq. (3), it can be derived that $I_{p,G} = \frac{Q_0}{\sqrt{2\pi}\sigma_t}$ and $C_{e,G} = \frac{1}{\sqrt{2\pi}} = 0.399$. On the other hand, uniform current distribution can be expressed as

$$I(t) = \begin{cases} \frac{Q_0}{t_{FWHM}}, & |t| \leq \frac{t_{FWHM}}{2} \\ 0, & |t| > \frac{t_{FWHM}}{2} \end{cases}, \tag{4}$$

where t_{FWHM} is the full width at half maximum and $\sigma_t = \frac{t_{FWHM}}{2\sqrt{3}}$. Similarly, it is shown that $I_{p,u} = Q_0$ and $C_{e,u} = \frac{1}{2\sqrt{3}} = 0.289$. In comparison with these results, it suggests that the smaller of the normalized Equivalent Charge Ratio C_e, the flatter of the current distribution.

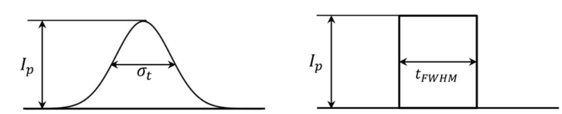

Figure 4: The gaussian distribution (left) and uniform distribution (right).

According to the simulation results of linear compression listed in Table 2, the initial (at the exit of L0) and final (at the exit of LINAC) normalized Equivalent Charge Ratios in DCLS are $C_{e,0} = 0.32$ and $C_{e,w} = 0.35$ respectively. It indicates that the compression is almost linear. In addition, the normalized Equivalent Charge Ratio is $C_{e,wo} = 0.44$ when compression without X-band. It is clear that $C_{e,u} < C_{e,w} < C_{e,G} < C_{e,wo}$, which implies that although both the flat levels of compression with and without X-band are not better than uniform distribution, compression with X-band is better than Gaussian distribution while compression without X-band is worse. In a word, the X-band makes C_e better in the electron bunch compression system.

In contrast to DCLS, the normalized Equivalent Charge Ratio of SXFEL test facility [5] is also calculated at the exit of its LINAC, where I_p =727A, $\sigma_t = 235$fs, $Q_0 = 500$pC, thus $C_e = 0.34$. It can be found easily that the normalized Equivalent Charge Ratio of DCLS ($C_e = 0.35$) and SXFEL test facility ($C_e = 0.34$) is almost same. Although both of them don't reach the C_e value of uniform distribution ($C_{e,u} = 0.289$), they are better than that of Gaussian distribution ($C_{e,G} = 0.399$).

CONLUSION

The X-band linear compression system in DCLS is described in this paper, including the layout and simulation results. The relationship of the linear compression ratio and the desired voltage of X-band is discussed, and the normalized Equivalent Charge Ratio C_e is defined to estimate the flat level of current distribution and linearized level of compression.

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