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DESIGN OF A DOGLEG BUNCH COMPRESSOR WITH TUNABLE FIRST-ORDER LONGITUDINAL DISPERSION

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Abstract

A nonlinear bunch compressor has been designed for the proposed NSRRC VUV FEL facility. It is a double dog-leg configuration that provides a first order longitudinal dispersion function (i.e. R_{56}) with a sign opposite to that of a conventional four-dipole chicane. A large variation in the bunch length or the peak current for various operation conditions can be done by tuning R_{56}. This can be realized by changing the longitudinal positions of the outside dipoles and adjusting the quadrupoles and sextupoles settings for desired bunch compression. Residual energy chirp left after bunch compression as revealed from ELEGANT simulation can be corrected by a capacitive dechirper structure when the bunch is slightly over-compressed.

INTRODUCTION

A high brightness S-band injector system equipped with a laser-driven photocathode rf gun has been developed in house at NSRRC [1]. This system has been operated regularly in the Accelerator Test Area (ATA) for light source R&D. Recently, the possibility of establishing a free electron laser facility which delivers high intensity tunable coherent VUV radiation in the range of 66.5-200 nm is being investigated. The baseline design is a 4$^{\text{th}}$ harmonic high gain harmonic generation (HGHG) FEL driven by a 325 MeV driver linac system [2]. By making maximum use of existing hardware, a driver linac system has been designed [3]. One unique part of this design is that the bunch compressor is a single-stage double dogleg, which allows a control of nonlinear beam dynamics for efficient bunch compression. In this report, the analysis of nonlinear bunch compressors is recalled and the design this dogleg compressor for the 325 MeV high brightness linac system is studied. Tunability of bunch length and peak current by controlling R_{56} of this compressor is also discussed.

NONLINEAR BEAM DYNAMICS IN BUNCH COMPRESSORS

Consider an electron moving in the traveling-wave field of a constant-gradient linac structure. The energy gain of this electron is

$$\Delta E = eV_0 \cos\left(\omega t - kz + \varphi_0\right), \tag{1}$$

where V_0, ω, k, ϕ_0 are the peak voltage, frequency, wave vector and initial phase of the wave which is propagating in the $+z$ direction with phase velocity of $V_p = \omega / k = c$ respectively. The electron is also moving in the $+z$ direction with velocity $v_e = \beta c$.

When an electron enters the linac structure at $\phi_0 = 0$, acceleration of electron is maximized as it rides on the crest of the wave. It is worth noting that if an electron in a bunch passes a fixed location in space earlier (later) than all other electrons in time, it must be at the very front (end) of this bunch and it defines the location of bunch head (tail). For a bunch of electrons moving with the traveling wave in a linac along the direction of the $+z$ axis, the bunch head always has a positive value with respect to the bunch center.

Nonlinear Energy Chirps

Generally speaking, in a split photo-injector configuration, the associated rf linac structure is operated at a phase (i.e. the rf crest) to minimize beam energy spread and a subsequent chirper linac is used to produce the required energy chirp for the bunch compression in the dispersive section located downstream. Therefore, it is reasonable to assume the correlated energy spread of the electron beam at the entrance of the chirper linac is small and the energy deviation of an electron from the designed value at chirper linac exit (i.e. $\delta(z) = (E_f(z)\text{-}E_{f0})/E_{f0}$ can be expressed by means of Taylor series expansion as

$$\delta\left(z\right) = a\delta_i + h_1 z + h_2 z^2 + h_3 z^3 + \cdots \tag{2}$$

where $E_f(z)$ is the central beam energy at the entrance of chirper linac, δ_i the deviation of electron energy from the designed value with initial uncorrelated energy spread, z the particle's initial longitudinal coordinate relative to the bunch center. E_{f0} is the central beam energy after the chirper linac, $a = Ei_0/E_{f0}$ is the damping factor and

$$\begin{cases} h_1 = \dfrac{keV_0}{E_{f0}} \sin\varphi_0, \\ h_2 = -\dfrac{k^2 eV_0}{2E_{f0}} \cos\varphi_0, \\ h_3 = -\dfrac{k^3 eV_0}{6E_{f0}} \sin\varphi_0, \end{cases} \tag{3}$$

are the first, second and third order energy chirps respectively. It is clear that the signs of the 1st order and the 3rd

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energy chirp depends on the linac phase. The 2nd-order energy chirp, however, is always negative if the linac is operated for electron acceleration (i.e. $-\pi/2 < \phi_0 < \pi/2$).

Bunch Compression

If δ is kept unchanged after passing through a dispersive section, the longitudinal position of an electron at the exit of the section z_f can be expressed as

$$z_f = z_i + R_{56}\delta + T_{566}\delta^2 + U_{5666}\delta^3 + \cdots \quad (4)$$

where z_i is the initial longitudinal position before entering the dispersive section, R_{56}, T_{566} and U_{5666} are the first, second and third order longitudinal dispersion functions of the dispersive beamline respectively. Neglecting the initial uncorrelated energy spread in the high order terms of the right hand side of Eq. (2) and combining Eq. (2) and Eq. (4), the longitudinal position of an electron after regrouping is given as

$$z_f\left(z_i\right) = C_0 + z_i/C_1 + z_i^2/C_2 + z_i^3/C_3 + \cdots, \quad (5)$$

where C_0, C_1, C_2, C_3, … are the corresponding coefficients defined as

$$\begin{cases} C_0 = aR_{56}\delta_i, \\ C_1 = \left(1 + h_1 R_{56}\right)^{-1}, \\ C_2 = \left(h_2 R_{56} + h_1^2 T_{566}\right)^{-1}, \\ C_3 = \left(h_3 R_{56} + 2h_1 h_2 T_{566} + h_1^3 U_{5666}\right)^{-1}. \end{cases} \quad (6)$$

Since the rms electron bunch length is defined as the expectation value of electron longitudinal position in a given distribution. Assuming that the electron bunch preserves a Gaussian distribution after passing through the dispersive beamline, we can therefore neglect the odd order terms in the expansion of the square of longitudinal position and we have

$$z_f^2 = C_0^2 + C_1^{-2} z_i^2 + \left[C_2^{-2} + 2\left(C_1 C_3\right)^{-1}\right] z_i^4 + \cdots \quad (7)$$

As implied by the first term on the R.H.S. of Eq. (7), the compressed bunch length is obviously limited by the initial uncorrelated energy spread of the beam. If we ignore the initial energy spread, C_1 can be interpreted as the linear compression factor. The compressor system can be designed by targeting the linear compressor factor and bunch length according to Eq. (7) and minimizing the quadratic term when the coefficient of the first order term is small. If we neglect the third order term in Eq. (5), the design of a nonlinear bunch compressor involves the design of a beamline with R_{56} and T_{566} such that

$$\begin{cases} R_{56} = -1/h_1, \\ T_{566} = -h_2 R_{56}/h_1^2. \end{cases} \quad (8)$$

In order to have large linear bunch compression factor, h_1 and R_{56} should have opposite signs. Once h_1, h_2 and R_{56} have been determined, the value of T_{566} is known. The signs of R_{56} and T_{566} should be the same as each other so that the second order term in Eq. (5) is minimized. It is well known that R_{56} for a conventional four-dipole chicane is always positive. That is, higher-energy electrons take shorter path while crossing the chicane. It is obvious to let lower-energy electrons at the bunch head of a chirped beam by setting the chirper linac phase. The second order longitudinal dispersion of a four-dipole chicane ($T_{566} = -1.5R_{56}$) is, however, always negative. Therefore, it does not match the requirements as stated in Eq. (8). One method to resolve this problem is to add a higher harmonic rf section operating at decelerating phase to flip the sign of h_2 [4].

DOGLEG COMPRESSOR FOR THE NSRRC VUV FEL DRIVER LINAC

An alternative method is to flip the sign of R_{56} so that both T_{566} and R_{56} have the same sign [5,6]. However, in this case, the chirper linac phase has to be set for positive h_1. By introduction of quadrupole and sextupole magnets into the compressor, the longitudinal dispersion function can be adjusted by controlling the transverse dispersion functions according to the following relations:

$$R_{56} = -\int \frac{R_{16}}{\rho} ds,$$

$$T_{566} = -\int \left[\frac{T_{166}}{\rho} + \frac{1}{2} R_{26}^2 + \frac{1}{2}\left(\frac{R_{16}}{\rho}\right)^2\right] ds. \quad (9)$$

Since the dominant (second and third) terms in the integrand of the second expression of Eq. (9) are always positive, T_{566} will be negative in most cases. This forces us to consider a compressor with negative R_{56}. As implied in the first expression of Eq. (9), R_{56} is the path integral of the product of transverse dispersion function R_{16} and beam curvature ρ^{-1}, one can design a beamline with negative R_{56} by placing the horizontal quadrupoles in the region where transverse dispersion function is nonzero. And the quads help to focus the beam to the point of anti-symmetry of the dogleg.

Our goal is to design a 325-MeV high-brightness sub-100-fsec electron beam at the end of the driver linac system. However, the design is limited by availability of space as well as the existing and affordable hardware. This is the main reason to employ nonlinear magnet compressor and avoid using higher harmonic rf linac and its corresponding pulsed klystron system. In order to fit the whole facility into the 38-m ATA tunnel, the compressor

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under consideration is a single-stage, 130-MeV design at about 5 m in length. Although the beam energy is not too high, deterioration of beam quality due to CSR is considered to be severe. In order to reduce this effect, we considered employing the double dog-leg scheme as illustrated in Figure 1.

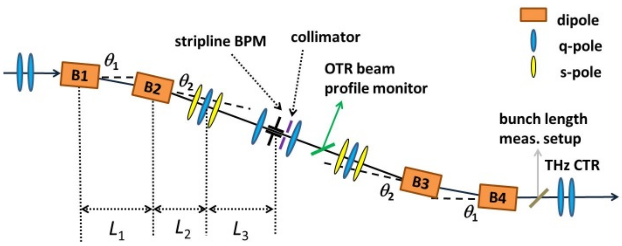

Figure 1: Layout of the double dogleg bunch compressor for the NSRRC VUV FEL driver linac system.

Tunability of R_{56}

A large variation in the bunch length or the peak current for various operation conditions can be done by the tuning of R_{56}. This can be realized by changing the longitudinal positions of the outside dipoles, B1 and B4, and adjust the quadrupoles and sextupoles settings for appropriate bunch compression. Since our nominal C_1 is about 50 when the electron distribution is almost upstood in longitudinal phase space, a small tuning of the R_{56} (in this case, –55 mm) is able to provide a large variation in the bunch length or the peak current.

For example, over-compressing the bunch slightly by changing R_{56} from –55 mm to –56 mm is accomplished simply by translating B1 and B4 longitudinally by approximately 10 cm in the opposite direction will. However, unlike a four-dipole chicane, which requires only simple tuning of the dipole field strength, the dogleg compressor will need retuning of each element from B1 to B4.

Beam Dynamics in the Driver Linac

In simulation study, the electron beam from cathode surface to exit of the photoinjector system is tracked by GPT with 3D space charge effects included. The output beam data at the photoinjector exit (E~100 MeV) is then transferred to ELEGANT for particle tracking so that the effects of wake fields in the linacs and CSR can be included. We assumed the gun field is 70 MV/m and charge from cathode surface is 100 pC. The beam is accelerated near rf crest by the photoinjector.

When the chirper is operated at $\phi_0 = 45^\circ$ with accelerating gradient of 18 MV/m, h_1 and h_2 according to Eq. (3) are 18 m^{-1} and -569 m^{-2} respectively. To compress the electron bunch with $C_1 > 20$ in one stage, R_{56} of -55 mm is required for an upstood bunch. The horizontal dispersion functions are matched to zero at both ends of compressor to avoid the emittance growth. The sign of the first order longitudinal dispersion function has been flipped to have the same sign as second order dispersion, and the required value T_{566} is -258.6 mm. Beam optics of the compressor has been verified with the MAD.

Electron distribution in transverse phase space has been adjusted carefully to an orientation such that the contribution of CSR kicks to emittance growth is minimized [7]. We have considered operating the compressor in the slightly under compression regime to preserve good quality beam. In this case, a compressed bunch with rms bunch length of σ_t ~ 120 fs in a near-Gaussian current profile can be obtained at the compressor exit.

With consideration of wake fields in the main rf linac, a 319 MeV, ~97 fs beam with sliced rms energy spread of ~98 keV and the peak current of 1.1 kA is obtained at the exit of the linac system (Fig. 2). The normalized horizontal and vertical slice emittances in this case are 0.62 and 0.48 mm-mrad respectively.

It may be desirable to operate the dogleg for a slightly over-compressed bunch to reduce energy spread, there is still a residual energy chirp which causes shorten FEL pulses. Since the wakefield in the main linac is not strong enough to reduce this energy chirp, a dechirper is needed. Furthermore, since the dog-leg compressor has a negative R_{56}, the higher energy electron will take a longer path in the compressor. In other words, the electrons in the bunch head will have higher energy for an under-compressed bunch. The capacitive LCLS-type dechirper [8], however, will enhance the energy chirp. Therefore, if we use a LCLS-type dechirper (capacitive), we will have to run the electron bunch in the over-compression mode.

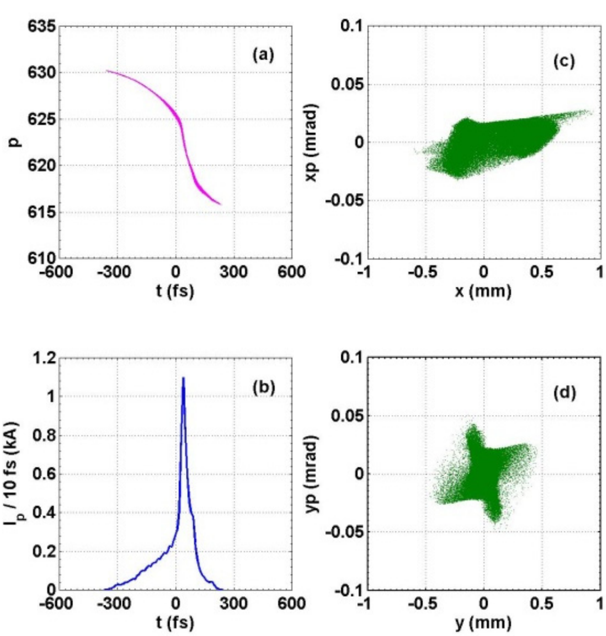

Figure 2: (a) electron distribution in longitudinal phase space, (b) current profile, electron distributions in (c) x-x' phase space and (d) y-y' phase space at the main linac exit.

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CONCLUSION

Beam dynamics in this linac system has been studied by particle tracking simulation including collective effects such as space charge, wake fields and coherent synchrotron radiation. We demonstrated a 319 MeV high brightness electron beam can be generated from the linac for the proposed 4th harmonic HGHG FEL operation. R_{56} of the dogleg is tunable by changing the longitudinal positions of the outside dipoles in opposite directions and adjust the quadrupoles and sextupoles settings for appropriate bunch compression. Further study includes other tuning schemes and the tolerances of parameter variations of this compressor.

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