ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPJE052

# BUNCH COMPRESSION IN THE DRIVER LINAC FOR THE PROPOSED NSRRC VUV FEL

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*Abstract*

A bunch compressor is designed for the S-band driver linac system of the proposed NSRRC VUV free electron laser (FEL). Instead of using a more conventional rf harmonic linearizer, one main feature of this compressor is to use electron linearization optics to correct the nonlinearity in the energy-time correlation of the electron bunch longitudinal phase space. The strategy of compressor design will be discussed by an analytical calculation and particle tracking simulation. The beam dynamics which include the collective instabilities such as the space charge effects, the wake fields and the coherent synchrotron radiation (CSR) effects are discussed.

## INTRODUCTION

A photocathode rf gun driver linac system for a proposed FEL facility by making maximum use of existing hardware at National Synchrotron Radiation Research Center (NSRRC) is under study [1]. The baseline design is a fourth harmonic high gain harmonic generation (HGHG) FEL seeded by a 266 nm laser to generate VUV radiation at 66.5 nm. The layout of the proposed facility is shown in Fig. 1. The length of the accelerator system from the gun cathode to the exit of the last linac section is about 28 m and the length of the diagnostics and FEL stations is about 8 m. The whole facility tightly fits into the existing $38\text{m}\times5\text{m}$ tunnel.

Generally, the electron beam after the bunch compressor has the profile of a banana shape instead of a single straight line in the longitudinal phase space. The high order dispersion term of the bunch compressor and the high order energy chirp of the accelerating rf wave are the origin of these nonlinearities. These nonlinearities set the limitation of compression in bunch length and lead to undesirable current spikes in the compressed bunch. In order to control this nonlinear effect, usually a higher harmonic rf section is added at the upstream of the compressor. However, such a linac section together with its klystron system requires additional expense. In this study, a magnetic compressor with linearization optics by the introduction of quadrupole and sextupole magnets is applied instead [2, 3]. The setup of this injector system is considered to be much more cost-effective.

## BUNCH COMPRESSOR WITH LINEARIZATION OPTICS

Assume the energy of injected electron is relativistic, there is no relative phase slippage between the rf field and the electron, the energy of an electron after rf acceleration in a traveling wave constant gradient accelerating structure can be expressed as

$$E_f(z) = E_{i0}(1+\delta_i) + eV_0\cos(\phi_0 - kz), \tag{1}$$

where $V_0$, $k$, $\phi_0$ are the accelerating peak voltage, the wave vector and the initial rf phase respectively, $\delta_i$ is the initial uncorrelated energy spread which is induced by rf and space charge effect in the gun, $z$ is the particle's longitudinal position relative to the bunch center. In this report, we define the bunch head as the electron with large relative longitudinal position, i.e. with relative earlier arrival time. The relative energy spread after passing through an rf section is [3]

$$\delta(z) = \frac{E_f(z) - E_{f0}}{E_{f0}} = a\delta_i + h_1 z + h_2 z^2 + h_3 z^3 + \dots, \tag{2}$$

where $a = E_{i0}/E_{f0}$ is the adiabatic damping factor and

$$\begin{cases} h_1 = \dfrac{keV_0}{E_{f0}}\sin\phi_0, & 1^{\text{st}} \text{ order energy chirp} \\ h_2 = -\dfrac{k^2 eV_0}{2E_{f0}}\cos\phi_0, & 2^{\text{nd}} \text{ order chirp} \\ h_3 = -\dfrac{k^3 eV_0}{6E_{f0}}\sin\phi_0, & 3^{\text{rd}} \text{ order chirp} \end{cases}. \tag{3}$$

The signs of the $1^{st}$ order and the $3^{rd}$ energy chirp depend on the operation of initial rf phase. The $2^{nd}$ order energy chirp is always negative if the initial phase is for electron acceleration. A negative first order energy chirp $h_1<0$ means the bunch tail has higher energy than the bunch head. The chirped beam is then sent to a dispersive region for bunch compression. The longitudinal position of an electron traversing the dispersive region is described as

$$z_f = z_i + R_{56}\delta + T_{566}\delta^2 + U_{5666}\delta^3 + \dots, \tag{4}$$

where $R_{56}$, $T_{566}$ and $U_{5666}$ are the first, second and third order longitudinal dispersion. Neglect the initial high order correlations of energy spread, the longitudinal position of an electron can be expressed by combining Eq.2 and Eq.4 as,

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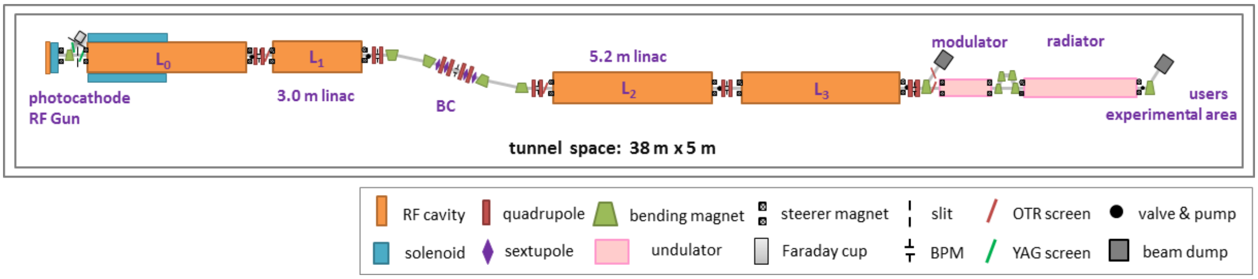


Figure 1: The layout of the proposed FEL facility at NSRRC.

$$z_f\left(z_i\right)=aR_{56}\delta_i+\left(1+h_1R_{56}\right)z_i+\left(h_2R_{56}+h_1^2T_{566}\right)z_i^2 \\ +\left(h_3R_{56}+2h_1h_2T_{566}+h_1^3U_{5666}\right)z_i^3+\ldots \quad (5)$$

If the initial energy spread and the high order dispersion terms are ignored, the rms bunch length can be expressed as $\sigma_z=\sigma_{z,i}/C$ where $C=\left(1+h_1R_{56}\right)^{-1}$ is defined as the linear compression factor. Hence to eliminate the nonlinear distribution in the longitudinal phase space of the compressed bunch, the coefficient of high order term in Eq. 5 has to be minimized.

For a typical chicane compressor, the second order and the first order of dispersion are with opposite signs. It is clear that the coefficient of the second order term in Eq. 5 always exists for the typical compressor. This contribution of high order term limits the possible minimum bunch length even if the linear compression factor is infinitely large. However, the longitudinal dispersion function of compressor can be adjusted by the control of transverse optics. According to this strategy, a set of linearization optics is employed by introducing quadrupole and sextupole magnets. It is possible to minimize the nonlinearity when the system is operated at a proper arrangement of rf condition and dispersion optics.

## BEAM DYNAMICS IN THE INJECTOR

The injector system is operated at 2998 MHz in S-band. Three 5.2-m linac sections are operated at rf crest for full acceleration and a 3-m section is used for providing the required rf chirp for bunch compression. A double dog-leg with linearization optics in the middle section of the dog-leg dipole magnets is used in this scheme. The larger transverse dispersion after two consecutive bending magnets allows it to control the longitudinal dispersion function easier compared to the chicane type compressor in a limited space. On the other hand, the straight line extension after $L_1$ can be considered for another possible application in the future. To save the injector space, a single stage compressor is adopted. Although the shot-to-shot variation of the electron beam lacks the possible compensation scheme by the second compressor, the CSR induced microbunching instability which is generally more severe in the multi-stage compression scheme is reduced. In this design, the condition of compressor was verified with MAD program [4]. The generated beam from the cathode is tracked with 3D space charge effects to $L_0$ exit by GPT [5]. The accelerated beam is then transferred to ELEGANT for particle tracking with the consideration of the CSR effect in the compressor as well as the wake field in the linac [6].

Assume the gun accelerating field is operated at 70 MV/m, the injected beam with charge of 100 pC is considered as the Baseline operation mode. The electron beam is accelerated on rf crest by a linac $L_0$ and the combination of a solenoid cascaded after the gun is used to compensate the induced linear space charge emittance growth in the rf gun. When the linac $L_1$ is operated at the rf phase of $\varphi_0$ = 45° from the crest with accelerating gradient of 18 MV/m, the first and the second order rf chirp ($h_1$ and $h_2$) are 18 m$^{-1}$ and -569 m$^{-1}$ according to Eq. 3. To compress the electron bunch with a compression factor of above 20 in a single stage process, a compressor with the first longitudinal dispersion function $R_{56}$ = -55 mm is required.

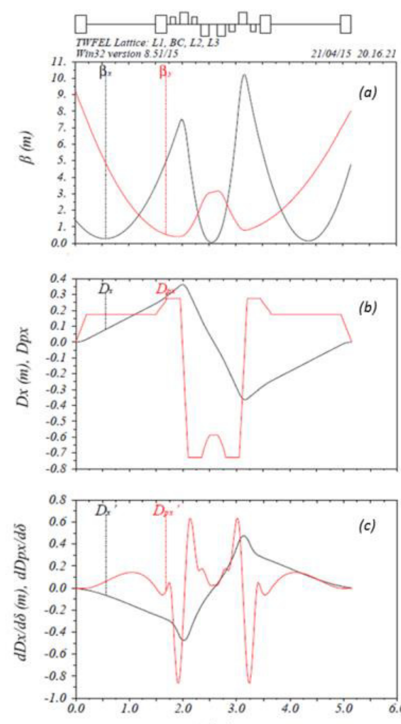


Figure 2: Optics of the bunch compressor: the evolution of the (a) betatron function (b) first order dispersion ($R_{16}$ and $R_{26}$) (c) second order dispersion ($T_{166}$ and $T_{266}$) in the compressor.

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The length of compressor is 5 m in space. The optics of the bunch compressor is shown as Fig. 2. The horizontal dispersion functions are closed at the end of compressor to avoid the emittance growth after the compressor. The sign of the first order longitudinal dispersion function has been flipped to become the same as the sign of the second order one, and the values of $R_{56}$ and $T_{566}$ are -55.0 mm and -258.6 mm respectively. It is well known that the CSR will degrade the electron beam emittance in the compressor especially when the bunch length is shorter than the radiation wavelength. The orientation of transverse phase space of the electron beam has been adjusted carefully to orient the CSR kick for reducing the emittance growth [7]. On the other hand, we have considered operating the compressor in an under-compression regime to meet a good quality beam under the competition between the CSR deterioration and bunch compression. Furthermore, the betatron functions are kept less than 15 m in the compressor to reduce the possible chromatic aberration.

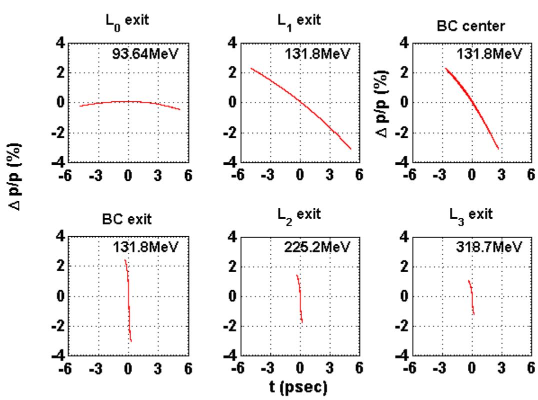


Figure 3: Evolution of longitudinal phase space through the beamline.

Evolution of the beam in the longitudinal phase space through this injector system is shown in Fig. 3. From the fitting polynomial of longitudinal phase space of electron bunch after the $L_1$ exit, the rf chirps $h_1$ and $h_2$ are 17.4 $m^{-1}$ and -1840 $m^{-1}$ respectively. The discrepancy of chirping slope, especially the second order one, comes from the contribution of rf chirp before the $L_1$ section. However, thanks to this additional contribution of rf curvature, the coefficient of the quadratic dependence term of Eq. 5 is smaller than the prediction and a compressed bunch with near-Gaussian current profile is acquired at the compressor exit. With the consideration of wake filed through the subsequent linac acceleration, a 319 MeV beam with slice energy spread of ~ 98 keV and the peak current of ~ 1.1 kA is achievable at the linac exit as shown in Fig. 4. The transverse slice emittance are 0.62 and 0.48 mm-mrad in the horizontal and vertical direction respectively.

Different combinations of the available undulators at NSRRC have been studied. In the HGHG operation, expected VUV radiation with brightness of ~ $10^{28}$ photons/$\mu m^2$/0.1%B.W. and peak power of 200 MW at 66.5 nm is achieved. The specifications of the undulators used for the function of modulator and radiator are listed in Table 1. The combination of EPU56 and CU18 is more efficient. It is preferred to achieve early saturation and stable operation.

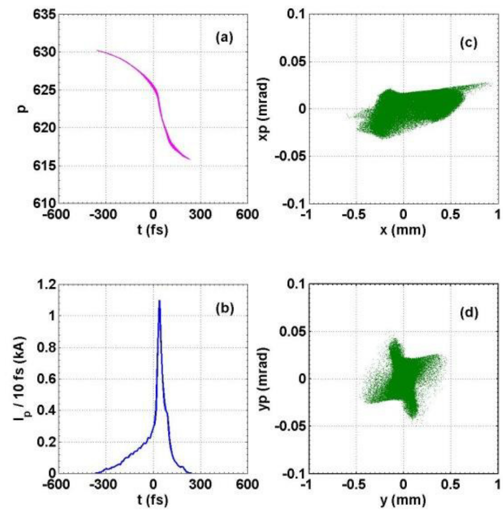


Figure 4: The (a) longitudinal phase space (b) current profile (c), (d) transverse ($x$ and $y$-plane) phase space of electron distribution at the $L_3$ exit.

Table 1: Parameters of the Undulator Candidates

| | Modulator | | Radiator | |
|---|---|---|---|---|
| | EPU56 | U100 | CU18 | IU22 |
| Period (mm) | 56 | 100 | 18 | 22 |
| No. of periods | 16 | 18 | 166 | 140 |

## CONCLUSION

A photocathode rf gun injector which is inclusive of a nonlinear compressor for the high brightness electron beam has been designed and studied by the electron tracking simulation from the start to the end. The error analysis of magnet and the possible shot-to-shot jitter is under study. Installation of the photoinjector system including the beam diagnostics tools and the first linac section is in progress. The commission of the accelerated beam to $L_0$ exit will be achieved before this summer.

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