Compensating effect of the coherent synchrotron radiation in bunch compressors

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Typical bunch compression for a high-gain free-electron laser (FEL) requires a large compression ratio. Frequently, this compression is distributed in multiple stages along the beam transport line. However, for a high-gain FEL driven by an energy recovery linac (ERL), compression must be accomplished in a single strong compressor located at the beam line's end; otherwise the electron beam would be affected severely by coherent synchrotron radiation (CSR) in the ERL's arcs. In such a scheme, the CSR originating from the strong compressors could greatly degrade the quality of the electron beam. In this paper, we present our design for a bunch compressor that will limit the effect of CSR on the e-beam's quality. We discuss our findings from a study of such a compressor, and detail its potential for an FEL driven by a multipass ERL developed for the electron-Relativistic Heavy Ion Collider.

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I. INTRODUCTION

Self-amplified stimulated emission (SASE) x-ray free-electron lasers (FELs) are fast becoming prime sources for cutting edge research in photon sciences [1]. Their peak brightness exceeds by about 10 orders of magnitude that of traditional storage ring-based light sources. However, SASE FELs are currently driven by accelerators with a low repetition rate. Using energy recovery linacs (ERLs) to drive such FELs [2–6] will bring this repetition rate up to tens and hundreds of MHz, and correspondingly, increase their average brightness by 4 to 5 orders of magnitude. A single-pass or multipass ERL can assure a high quality electron beam. In contrast to storage rings, in an ERL, which is similar to a simple linac, the electron beam is generated at the photocathode and propagates only once through the accelerator. Hence, it does not accumulate any significant emittance or energy spread growth due to the synchrotron radiation and microwave instabilities, both of which are typical for storage rings. At the same time, the majority of the beam's power is recycled before the beam goes to the dump. These features support the feasibility of a high-repetition-rate operation of the electron beam. Hence, an ERL could be the perfect candidate for driving next generation FELs.

Both soft and hard x rays are of great interest for many applications in photon sciences, spanning the range from biology to material sciences. X-ray FELs require a multi-GeV electron beam with high peak current and low emittance. Several such facilities presently are in operation, and many more are either proposed or under contraction [7–10]. The future electron-Relativistic Heavy Ion Collider

(eRHIC) ERL [11,12] can prove an excellent platform for providing such high quality electron beam. Although the major usage of the electron beam in eRHIC is intended for electron-hadron collisions, a dedicated FEL operational mode could be incorporated. Therein, a low emittance/low energy spread electron beam would be generated in a dedicated cw photoinjector and accelerated to desired energy in eRHIC's ERL. The quality of the beam, as we demonstrate further in this paper, will be preserved through the ERL beam transport. An array of x-ray FELs could be installed downstream of the ERL to share the high-repetition-rate beam.

High-gain FELs usually are comprised of a low peak current electron beam for acceleration and a strong bunch compressor to compress such a low peak current to a kA-level peak current for the FELs. In linac based SASE FELs, this compression usually is distributed in multiple stages along the beam transport at different energies of the beam. The linacs between two stages, in addition, could be used to accelerate the electron beam to higher energy and to prepare the electron beam for the next stages of compression. In such a way, each buncher's compression factor could be reduced (e.g. via a partial rotation in longitudinal phase space) so resulting in an overall lowering of emittance growth. Furthermore, the phase and strengths between different stages could be tuned for optimal performance. However, in ERL-driven FELs, the entire compression must be completed at the end of the circular passes. Otherwise, in the arcs even a partially compressed beam with peak current of a few hundred amps would experience severe emittance growth caused by coherent synchrotron radiation (CSR) [13–15]. In such a scheme, the CSR originating from the strong compressors could greatly degrade the quality of the e-beam [16–18].

In this paper, we present our design for a bunch compressor that will limit the effect of CSR on the e-beam's quality. We discuss our findings from a study of such a

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compressor, and detail its potential for an FEL driven by a multipass ERL developed for the electron-ion collider, eRHIC.

II. LAYOUT OF THE BUNCH COMPRESSING SYSTEM

As we stated in the previous section, eRHIC is a multipass ERL whose layout is shown in Fig. 1. During the normal operations of the collider, the electron beam is accelerated in six passes to reach to its top energy at 30 GeV before colliding with the hadron beam. Thereafter, the 180° phase difference translates the acceleration into deceleration. The electron beam's energy is recovered in the same linacs before the beam is dumped at about 10 MeV. eRHIC has six straight sections that can serve as linacs (one located at 2 o'clock and the other at 10 o'clock) and interaction regions for nuclear physic experiments [12].

X-ray FEL operation does not require a 30 GeV electron beam and therefore only some of the eRHIC ERL passes will be used to accelerate electrons from 1.8 to 10 GeV. In the FEL mode, a low normalized emittance ($0.2\text{--}0.6\ \mu\text{m}$) and low energy spread (few tens to hundreds of keV) electron beam will be injected from a dedicated gun. The electron beam will be accelerated to the desired energy and extracted on its first or second pass. Table I lists the beam parameters for hard and soft x-ray FEL modes. In this paper, we will focus on the more demanding case of hard x rays, using this both as an example and as demonstration

FIG. 1. eRHIC layout with a six pass ERL (beam travels counterclockwise). Electron beam is generated and preaccelerated to 0.6 GeV before entering eRHIC's main linacs located at 2 o'clock and 10 o'clock. The e-beam gains 2.45 GeV of beam energy in each linac (as labeled) and reaches to its top energy at 30 GeV in six passes. For FEL operation, the bunch compressor will be located at 12 o'clock.

TABLE I. eRHIC beam parameters for FEL operation.

Name	Soft x ray	Hard x ray
Energy (GeV)	1.8	10
Bunch charge (nC)	0.2	0.2
Rms bunch length (ps)	1	1
Rms energy spread (keV)	50–200	500
Rms normalized emittance (μm)	0.6	0.2
Undulator period (cm)	1.85	3
Fundamental wavelength (nm)	1	0.1

of our CSR suppression scheme. The same technique can be implemented for the soft x-ray case; examples are given elsewhere [19].

To preserve the beam quality along eRHIC arcs, we start with bunch charge of 0.2 nC and maintain a low peak beam current (at ~ 40 A level). We generated 20 000 000 macroparticles in ELEGANT [20] and tracked them through the arcs. Dipole magnets were sliced into 600 bins to realize a fine synchrotron radiation and higher order component calculation. Both coherent and incoherent synchrotron radiation are included.

As Fig. 2 illustrates, we could preserve the emittance of the circulating beam while the e-beam propagates through

FIG. 2. The evolution of e-beam emittance in the eRHIC arcs for both soft (top) and hard (bottom) x-ray setup. A bunch charge of 0.2 nC is used to minimized the growth of emittance caused by the CSR effect.

TABLE II. Radio-frequency system parameters for bunch compression simulations (90° on crest).

Name	Value
$E_{\text{tot},2}$ (MV)	2445
$E_{\text{rf},2}$ (MV/m)	12.5
$\phi_{i,2}$ (deg)	77.8
$E_{\text{tot},10}$ (MV)	2499
$E_{\text{rf},10}$ (MV/m)	12.5
$\phi_{i,10}$ (deg)	90.5

the arcs and linacs. A strong bunching system is needed to compress such a low-initial-peak current to a kA-level peak current required for the FELs. In the eRHICs ERL, we will install this bunch compressor in a bypass at 12 o'clock into which the 7.55 GeV electron beam will be guided on its second pass through the ERL. Bunches will pass the 2 o'clock superconducting linac off crest to obtain an energy chirp needed for bunch compression. Table II lists the rf system's parameters for this machine configuration.

As we detail below, using a traditional chicane for a single-stage compressor would blow the e-beam emittance many fold. In the following sections, we also detail our solutions to compensate for, and suppress the CSR effect in the compression process.

III. TRADITIONAL C-SHAPE CHICANE

A traditional approach to e-beam compression is to use a C-shape compensated chicane, i.e., an achromatic chicane with $R_{16}(s_1, s_2) = 0$ and $R_{26}(s_1, s_2) = 0$ with 6D vector $(x, x', y, y', z, \delta)$, comprised of four dipole magnets. In such a chicane, the paths' lengths, as well as the transit time through the chicane, depend on the particles energy. In combination with the correlated energy spread (chirp), this entails a rotation in longitudinal phase space. Ideally, the ratio between the uncorrelated and correlated energy spreads determines the maximum bunch compression. However, in reality, the deterioration of phase space caused by CSR effects can result from a full rotation. Partial rotation, and under some situations, with an asymmetric compressor layout [21,22], assures better performance in reducing emittance growth induced by the CSR effect, and thus results in a beam with a slightly better quality.

In our single C-shape chicane design, we chose a symmetric layout wherein the magnet strengths in four dipoles are equal. Because of the lack of downstream energy spread compensation, energy spread is kept to a small value (less than relative energy spread of 2×10^{-4} rms) throughout the bunching system. Thus, the strong compression ratio requires a large value of R_{56} . The dipole

FIG. 3. The evolution of e-beam emittance in the bunch compressor using a single chicane. The blowup of emittance is caused by the CSR effect.

strengths were selected to assure compression with peak current of 1.2 kA. The optics lattice functions are controlled by quadrupoles outside the chicane.

We used the same simulation setup and tracked 20 000 000 macroparticles in ELEGANT. We implemented Stupakov's model [23,24] to simulate coherent synchrotron radiation in dipoles and near-by drift spaces.

Figure 3 plots the results of the evolution of e-beam emittance along the C-compressor beam line. As expected, the strong CSR wakefields blow up the beam's emittance by about fivefold. The emittance growth originates mostly from the third and fourth magnets, where the beam is already compressed and the peak current is high. This growth in transverse emittance reflects the fact that the CSR wake depends both on longitudinal position within the bunch, as well as on the azimuth along the beam line. The head of the bunch gains energy while the tail part loses energy [25]. Figure 4 illustrates a typical CSR wake potential. Furthermore, the location-dependent energy variation $\delta E(z, s)$ induced by CSR

FIG. 4. A typical CSR wakefield induces energy variation along a 1 ps electron bunch. The head and tail of the bunch, respectively, gain and lose energy.

FIG. 5. Phase-space distribution before (top) and after (bottom) the bunch compressor. The longitudinal energy variation induced by CSR wakes is coupled to the coordinate and angular displacements through R_{16} and R_{26} induced in the chicane. This results in smearing of the transverse phase space.

wakes engender transverse coordinate and angular displacements via nonzero $R_{16}(s, s_2)$ and $R_{26}(s, s_2)$ induced in the chicane. At the end of the chicane, the transverse displacement and the angle deviation will be

$$\delta x(s_2, z) = \frac{1}{E_0} \int_{s_1}^{s_2} \frac{d[\delta E(z, s)] R_{16}(s, s_2)}{ds} ds \neq 0; \quad (1)$$

$$\delta x'(s_2, z) = \frac{1}{E_0} \int_{s_1}^{s_2} \frac{d[\delta E(z, s)] R_{26}(s, s_2)}{ds} ds \neq 0. \quad (2)$$

The coordinate and the angular displacement that depend on longitudinal position of the particle result in a smearing in the transverse phase space, and also in the growth of the projected emittance. Figure 5 illustrates this smearing effect, comparing the plots

of the transverse phase space before and after the chicane.

IV. ZIGZAG CHICANE WITH CSR COMPENSATION

As a remedy for the above problem, i.e., the displacement in the transverse plane due to the longitudinal energy variation induced by CSR wakes, we propose to use two consequent chicanes with reversed bending directions, i.e., a zigzag-type compressor [26]. The opposite signs of the dispersion functions should allow us to decouple the longitudinal and transverse degrees of freedom. This technique is similar to that proposed to compensate the emittance growth in ERL mergers caused by the longitudinal space-charge forces [27]. We expect that in our scheme the transverse phase-space displacement caused by CSR in the 1st chicane could be, at least, partially reversed in 2nd chicane. By controlling optics between the two reversing chicanes, we can suppress the correlated emittance growth due to photon emission along the dispersive path [28]. Thus, the resulting emittance growth due to CSR effects could be greatly reduced. Since bunch length is shorter, correspondingly CSR wake is stronger in the second chicane, and the energy change also is larger. The cancellation of the CSR effect naturally requires a weaker second chicane compared to the first one. Figure 6 is a sketch of the energy variation caused by CSR wake in a zigzag chicane. In addition, we could better align the transverse phase-space displacements originating from two chicanes by adjusting phase advance between them. We now employ quadrupoles located between two chicanes for this purpose, using them to minimize the resulting projected emittance. For optimization, we adopted the same simulation setup in ELEGANT and the same total R56 for the case of a single chicane (described in the previous section). A recurrent process of optimizing the compensation scheme is done in scanning the dipoles angles, the distances between dipoles, the phase advance

FIG. 6. A sketch of expected energy variation along the two-chicane compressor. Because of the higher peak current, the CSR wakes in the second chicane are stronger and a larger energy change is expected.

FIG. 7. Horizontal projected normalized emittance as function of the bending angles of the chicane (listed in the box in the right-upper corner of the graph) and the betatron phase advance between chicane. The vertical axis is the resulting projected normalized emittance after the bunch compressor. The horizontal axis is the phase advance between two chicane. The initial normalized emittance before compression is $0.2 \mu\text{m}$ and the baseline single chicane scheme with a growth factor of 5 is also shown.

between two chicane and the beam optics at the entrance of both chicane. We show selected results in Figs. 7 and 8.

As we expected, the compensation of CSR effect is very sensitive to the relative strengths, or R_{56} (as is listed in Table III), of the two chicane and the betatron phase advance between them. When the strength of the 2nd chicane approaches zero, the overall emittance gradually rises up to that of the case of the single chicane, where a near fivefold emittance growth is observed. When the compression ratio between two chicane was tuned to be 4 to 1, i.e., the second chicane has an R_{56} 4 times lower than that of the first chicane, the emittance growth falls to about 1.5-fold (e.g., a 50% growth). Furthermore, by changing the shape of the ellipse in transverse phase space at the entrance of the compressor (in other words, by changing the beam optics) we could further lower the emittance growth to a few tens of a percent.

To optimize the CSR-compensation scheme, we conducted a full parameter scan in the 10D parametric space using a self-developed external object oriented code. A constant global perturbation was employed to avoid the result to converge into a local optimum. A global optimal working point was found in a few iterations for the parameter set listed in Table III. Figure 9 depicts the evolution of beam emittance along this optimized zigzag bunch compressor and Fig. 10 shows the final current

FIG. 8. A complete scan of the optical functions shows the optimal working point at the entrance of the second chicane is attained when $\beta_x = 22.5$ m and $\alpha_x = -0.85$.

distribution along the bunch. Our optimization of a single-stage 30-fold bunch compressor (from 40 to 1200 A) reduced the resulting emittance growth to 27%, compared with fivefold increase without such optimization. By calculating the particle invariant along the beam line [18], we acquire the theoretical estimation of CSR-induced emittance growth for the zigzag chicane lattice to be 24.3%, which is in excellent agreement with the simulation results.

TABLE III. Parameters of the zigzag-type bunch compressor.

Name	1st chicane	2nd chicane
Dipole angle (rad)	0.225	0.1
Dipole length (m)	1.0	1.0
Drift between dipole 2 and 3 (m)	0.8	0.8
Drift between dipole 1 and 2 (m)	3.5	4.0
β function at entrance (m)	15.2	22.5
α function at entrance	-0.54	-0.85
R_{56} at the end of chicane (mm)	568.24	704.37

FIG. 9. The emittance growth in the first chicane is largely compensated in the second chicane with careful tuning of all parameters.

FIG. 10. The current distribution along the bunch at the end of zigzag bunch compressor.

For a 15-fold compressor such as is needed to achieve 600 A peak current to drive a soft x-ray FEL, a similar optimization reduces the emittance growth to 13%. The beam parameters for the latter bunch compressor are listed in Table IV.

TABLE IV. Beam parameters for eRHIC FEL after the bunch compressor.

Name	Soft x ray	Hard x ray
Energy (GeV)	1.8	10
Peak current (amp)	600	1200
Projected rms energy spread	1.88×10^{-4}	1.77×10^{-4}
Rms normalized emittance (μm)	0.678	0.253
R_{56} (m)	-0.394	-0.692

V. FEL PERFORMANCE WITH E-BEAM FROM THE CSR-MATCHED COMPRESSOR

To thoroughly study the FEL performance we would need to include a very larger number of macroparticles in the ELEGANT simulations. An estimate of the number needed in the initial ELEGANT tracking could be done in the following way. The final bunch length after bunch compression is about 1×10^{-5} m, while to calculate the time-resolved growth in FEL power and the radiation spectrum, we need to slice the beam with step size of radiation wavelength at 1 Å. Thus, we would need 100 000 slices along the bunch for a complete study. Each slice should have a sufficiently large number of macroparticles for proper FEL statistics. In reality, such a complete simulation is very time consuming and, is, in fact, unnecessary because our bunch has a near-Gaussian distribution and its core part has much higher current and much larger FEL gain. This is why we selected the ± 1 rms bunch length and kept only the 30 000 core slices for the FEL simulation. We tracked 20 000 000 particles in ELEGANT and transferred the slice information into GENESIS 2.0 [29] to simulate the FEL process. We simulated the FEL power saturation using both time-resolved and time-independent modes in GENESIS. The latter is much faster and so we used it to match the optics and maximize the FEL gain. For demonstration purposes, we selected a Linac Coherent Light Source (LCLS) type of high-gain FEL undulator with 3 cm of period, and the undulator parameter $K_w = 1.85$.

As shown in Fig. 11, the x-ray FEL saturation is reached in the 100 m wiggler with peak power of 5 GW. The fitted 3D gain length is 3.1 m. The radiation spectrum, shown in Fig. 12, with peak at 1 Å has a narrow bandwidth of 4×10^{-4} rms, resulting in 1×10^{-3} FWHM, comparable to what was achieved in an SASE based FEL facility, such as LCLS.

FIG. 11. Power growth and saturation in 1 Å x-ray FEL predicted by GENESIS.

FIG. 12. Radiation spectrum shows peak at desired hard x-ray wavelength of 1 Å (top) and bandwidth drops to 4×10^{-4} rms at 100 m (bottom).

VI. CONCLUSIONS

In this paper, we describe our systematic studies of a bunch compressor comprised of zigzag-type chicane to suppress CSR-induced emittance growth. We discuss the origin of the emittance growth induced by CSR in a standard C-type chicane, e.g., one wherein the longitudinal energy variation induced by CSR wake is coupled to the transverse plane through nonzero local dispersions in the chicane.

As a remedy for such a mechanism, we propose to use two consequent chicane with reversed bending directions, a zigzag-type compressor. We expect the opposite sign of the dispersion function in them to cancel each other out and to decouple the longitudinal and transverse degrees of freedom.

By carefully tuning the relative strengths of the chicane, the betatron phase advance between them and by optimizing the optics functions, we demonstrate that we could reduce CSR-induced emittance growth below 30%, which has an excellent agreement with theoretical estimation. Our start-to-end simulation verified that the resulting beam is well suited for driving high-performance hard x-ray FELs.

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