SINGLE-STAGE BUNCH COMPRESSION FOR THE WISCONSIN FEL*

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Abstract

The microbunching gain of the driver for the Wisconsin FEL (WiFEL) is reduced by more than an order of magnitude by using a single-stage bunch compressor rather than a two-stage design. This allows compression of a bunch with lower energy spread for improved FEL performance.

INTRODUCTION

A preliminary design of the WiFEL driver uses a two-stage compression and acceleration system to transform a 4-MeV bunch with peak current of 50 A into a 1.7-GeV bunch with peak current of 1 kA [1, 2]. The compressed bunch is distributed to an FEL beam line and collimated by passing through a three-stage beam spreader [3]. To prevent large current or energy modulations in the compressed bunch at the FEL, the microbunching gain of the driver and beam spreader should be small. With two-stage compression, low gain may require heating of the uncompressed bunch with a laser heater [3, 4].

Analytic estimates and simulations show that the microbunching gain is reduced by more than an order of magnitude if single-stage compression is employed, so that a laser heater is not required. Thus, a single-stage compressor can compress a bunch with lower energy spread for improved FEL performance.

FEL DRIVER

We accelerate and compress a bunch that has normalized transverse emittances of $1\,\mu\text{m-rad}$, charge of 200 pC, peak current of 50 A, Gaussian energy spread of 3 keV and a parabolic longitudinal distribution with rms length of 0.4 mm. A preliminary two-stage compressor design has been previously described [1, 2]. Here, we study a single stage design followed by a beam spreader.

Figure 1 shows the compressor design. The rf parameters compress a parabolic bunch that experiences geometric wakes of the linacs and harmonic cavities, coherent-radiation wakes of the chicane and spreader, and resistive-wall wakes in the spreader vacuum chambers. The bunch is accelerated to 445 MeV in the injector linac. Then, ten third-harmonic cavities modify the nonlinear chirp. After compression at 400 MeV in a chicane with $R_{56} = -100\,\mu\text{m}$, the bunch is accelerated to 1.7 GeV.

BEAM SPREADER

The WiFEL beam spreader separates the compressed bunches for different FELS in three stages, and then collimates the beam. Each separator stage has RF separation amplified by a defocusing quadrupole magnet, followed by dipole bending magnets. In our first spreader design, the R_{56} value of the entire spreader (including the collimator) is $950\,\mu\text{m}$. To reduce the microbunching gain, we created a new design with $R_{56} = 38.5\,\mu\text{m}$ [3].

Figure 2 shows the longitudinal phase space and current histogram at the exit of the low-R_{56} spreader, according to tracking with the ELEGANT code [5] that includes wakes of coherent radiation, geometric wakes of the rf cavities and resistive-wall wakes for the spreader vacuum chambers. Since power limitations of the input couplers may require the use of 30 harmonic cavities for the planned average current of 1 mA, we have verified that a similar phase space and current profile is produced with the wakes of 30 harmonic cavities by using a modified injector linac phase. The central portion of the bunch, which has nearly constant current and energy, will be seeded to produce the FEL output.

To estimate the microbunching gain through the spreader, we model each of the spreader stages and the collimator with a matrix for a compression stage with nonzero R_{56} followed by longitudinal space charge (LSC) impedance, as described in Ref. [3]. In Fig. 3, curves show the estimated microbunching gain. Circles show the gain in ELEGANT simulations of 4 million particles in a 200-pC parabolic bunch with rms length of 0.4 mm, Gaussian energy spread of 3 keV, and peak current of 50 A. The simulations, which utilize noise-

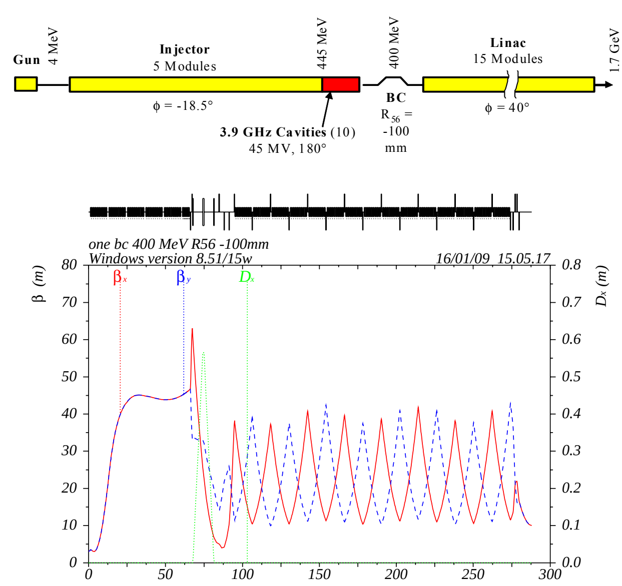

Figure 1: Schematic diagram and lattice functions of the single-stage bunch compressor.

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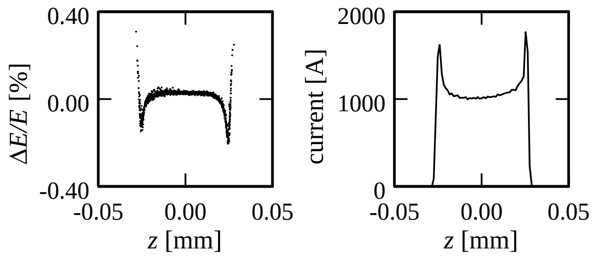

Figure 2: Longitudinal phase space and current distribution after bunch compression, acceleration to 1.7 GeV, and passage through a 3-stage beam spreader with a low value of R_{56} . The tail is on the right.

reduction techniques [2], include a 1D model of LSC, a 1D model of coherent radiation in magnets and drift regions, geometric wakes of the linacs and resistive-wall wakes for the spreader vacuum chambers.

Figure 3(a) describes our first spreader design, in which the R_{56} value of the entire spreader is $950\,\mu\text{m}$. Figure 3(b) shows the reduced gain with a new spreader design whose R_{56} value is $38.5\,\mu\text{m}$. The simulations and analytic estimate are in approximate agreement. The first spreader design increases the peak microbunching gain by more than an order of magnitude, while the low-R_{56} spreader has little effect on the gain.

For current and energy modulations at the entrance of the chicane that are less than 0.5 A and 100 eV, Fig. 3 indicates that the relative modulations at the exit of the low-R_{56} spreader will be smaller than the maximum allowable values of 10% and 3×10^{-4} [2].

SHOT NOISE

We estimate the modulations at the spreader exit from amplified shot noise, for a 200-pC parabolic bunch with normalized transverse emittances of $1\,\mu\text{m}$, 3-keV Gaussian energy spread and peak current of 50 A. For each initial wavelength, we assume the initial rms shot noise from the electron gun obeys $\Delta I / I_{\text{in}} = 1/\sqrt{N_b}$ [6], where $N_b = 1.25\times10^9$ is the number of electrons in the 200-pC bunch. The energy modulation at the entrance of the chicane is calculated for a current modulation that is frozen while the bunch is accelerated at a constant rate from 4 MeV to 400 MeV in the injector linac of length 67.6 m, while experiencing the 1D LSC impedance calculated for $<\beta_x> \approx <\beta_y> \approx 25$ m. Using the analytic gain curves of Fig. 3, we calculate in Fig. 4 the linear amplification of the modulations entering the chicane. With the low-R_{56} spreader, the relative current and energy modulations at all wavelengths are much smaller than the allowed values of 10% and 3×10^{-4} [2].

To provide a simulated overestimate of shot nose, an 8-million particle bunch with randomly populated phase space was tracked with ELEGANT from the electron gun at 4 MeV through the isochronous spreader tree. The tracking includes a 1D model of LSC, a 1D model of coherent radiation in magnets and drift regions, geometric wakes of the rf cavities and resistive-wall wakes for the spreader vacuum chambers. Upstream of the chicane, the effective drift lengths for LSC were reduced by the factor $(1.25\times10^9 / 8\times10^6)^{1/2} = 12.5$, so that the random energy modulations entering the chicane represent a bunch with 1.25×10^9 electrons while the random current modulations are those of a bunch with 8×10^6 particles. In tracking with several random-number seeds, the overestimated relative current and energy modulations at the spreader exit are ~2% and $\sim1\times10^{-4}$, smaller than the maximum allowable values, as shown in Fig. 5.

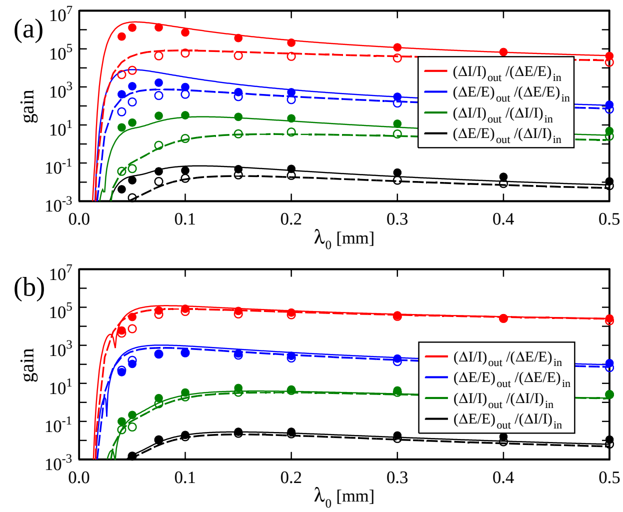

Figure 3: Solid curves show the analytic microbunching gain between the entrance of the chicane and the exit of the spreader tree versus initial wavelength λ_0. Dashed curves show the analytic gain between the entrance of the chicane and the entrance of the spreader tree. Filled circles show the gain from the entrance of the chicane through the exit of the spreader tree from tracking simulations, while open circles show the simulated gain from the entrance of the chicane to the entrance of the spreader tree. (a) First spreader design. (b) Low-R_{56} design.

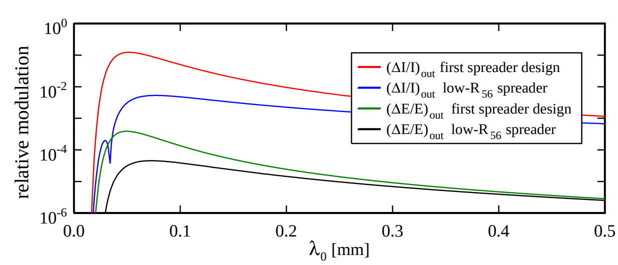

Figure 4: Relative current and energy modulations at the exit of the spreader tree from amplified shot noise, versus initial wavelength λ_0. Analytic calculations for linear amplification are shown for the first spreader design and the low-R_{56} design.

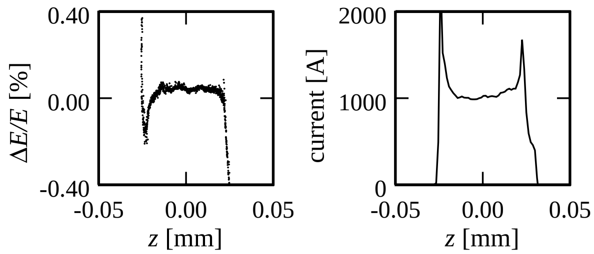

Figure 5: Longitudinal phase space and current distribution after bunch compression, acceleration to 1.7 GeV, and passage through the low-R_{56} beam spreader, with overestimated shot noise.

MINIMUM INITIAL BUNCH LENGTH

We estimate macroscopic wake effects with resistive impedances before and after compression, $R_0 = Z_0$ and $R_1 = 2Z_0$, where $Z_0 = 377\ \Omega$ [2]. For a bunch that enters the chicane with a deviation from linear chirp $\Delta E(z)$, the longitudinal coordinates before and after compression $z = ct$ and $z_1 = ct_1$ (where c is the speed of light; z and z_1 increase towards the bunch tail) obey [2]

$$z_1(z) = z / C_1 + (R_{56} / E_1)[\Delta E(z) - eR_0 I(z)] \qquad (1)$$

Here, C_1 and E_1 are the compression factor and beam energy in the chicane, R_{56} is the chicane's negative energy-to-position matrix element, $e > 0$ is the magnitude of the electron charge, and $I(z)$ is the magnitude of the bunch's initial current profile.

When $dz_1(z)/dz = 0$, a portion of the compressed bunch is upright in phase space. For a linear chirp [$\Delta E(z) \equiv 0$], this occurs when $I'(z) \equiv dI / dz$ equals

$$I'_{\text{crit}} = E_1 / (C_1 R_{56} e R_0) \qquad (2)$$

For the single-stage compressor, $I'_{\text{crit}} = -5.3\times10^5$ A/m, which is five times as large as the value for the preliminary two-stage compressor [2]. For a bunch with peak current of 50 A and a Gaussian or parabolic current profile, the minimum initial rms bunch length that can be compressed with linear chirp, without producing an upright tail in phase space, is $57\ \mu\text{m}$ or $84\ \mu\text{m}$, respectively. For idealized perfect wake compensation with $\Delta E(z) = eR_0 I(z)$, an arbitrarily short initial bunch length can be compressed according to eq. (1).

JITTER

The partial derivative of eq. (1) with respect to $I(z)$ gives the arrival time jitter δt from bunch-to-bunch variation in the current profile δI at the chicane entrance

$$c\delta t = | R_{56} e R_0 / E_1 | \, \delta I\ . \qquad (3)$$

The partial derivative of eq. (1) with respect to $\Delta E(z)$ gives the jitter from bunch-to-bunch variation of the energy at the chicane entrance δE

$$c\delta t = | R_{56} / E_1 | \, \delta E \qquad (4)$$

Equations (3) and (4) agree with ELEGANT tracking. To achieve rms jitter less than 15 fs requires $\delta I < 48$ A and $\delta E / E_1 < 4.5\times10^{-5}$ at the chicane entrance [2].

For a bunch-to-bunch current variation δI from the electron gun, the energy at the chicane entrance varies from bunch to bunch because of the wakes of the injector linac and harmonic cavities. For a current variation from the electron gun, ELEGANT tracking indicates that jitter less than 15 fs requires $\delta I < 2.5$ A.

The injector linac consists of five 8-cavity cryomodules. Under the assumption of uncorrelated errors in the injector linac cavities, the allowable amplitude and phase variations of a cavity (so that $\delta E / E_1 < 4.5\times10^{-5}$) are 0.02% and 0.035°. These variations are at the current state of the art [7].

The two-stage design also requires $\delta E / E_1 < 4.5\times10^{-5}$ to achieve rms jitter less than 15 fs, but its injector linac consists of three 8-cavity cryomodules. Because of the different number of cryomodules, the timing jitter in the one-stage design is 23% less than that of the two-stage design for a given level of uncorrelated cavity errors [2].

SUMMARY

We have studied a single-stage compression system for WiFEL. In comparison with two-stage compression, the microbunching gain is reduced by more than an order of magnitude. If the bunches are distributed to the different FELs by a beam spreader with a low value of R_{56}, it should be feasible to operate the FEL driver without a laser heater. Since the lower microbunching gain allows the compression of bunches with a lower energy spread, the single stage compressor is expected to provide higher quality compressed bunches for the FEL.

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