MICROBUNCHING FROM SHOT NOISE SIMULATED WITH FEWER PARTICLES THAN THE BUNCH*

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Abstract

In high-current magnetic bunch compression, shot-noise-induced energy and current fluctuations at the chicane entrance may cause microbunching. For the case where the energy fluctuations are the primary cause of microbunching, we perform approximate simulations with fewer particles than the bunch population by using a reduced value of the space-charge impedance upstream of the chicane. This method is applied to bunch-compressor designs for the Wisconsin Free Electron Laser (WiFEL).

INTRODUCTION

The microbunching induced by shot noise can disrupt magnetic bunch compression [1]. Since the relative shot noise is proportional to $1/\sqrt{N_b}$, where N_b is the bunch population [1–3], a straightforward simulation with a smaller number of particles N_s will overestimate the effect. In the linear regime, the shot noise and microbunching are overestimated by the factor $\sqrt{N_b / N_s}$.

Typically, two assumptions are satisfied in high-current magnetic compression [4]: (1) The bunch's longitudinal profile is quickly frozen after the bunch exits the electron gun. (2) The microbunching is mostly caused by energy fluctuations at the entrance of the first (or only) chicane, given by the product of the frozen current fluctuations and the upstream longitudinal space-charge (LSC) impedance.

Under these assumptions, the shot-noise-induced microbunching of N_b electrons may be approximately simulated with N_s particles, where $N_s < N_b$, by reducing the LSC impedance upstream of the first chicane by the factor $\sqrt{N_b / N_s}$. The current fluctuations at the chicane entrance are $\sqrt{N_b / N_s}$ times their value for N_b electrons. With the reduced LSC impedance, the energy fluctuations at the entrance of the first chicane describe N_b electrons. If sufficiently many particles are simulated, so that the simulation's microbunching is mostly caused by the energy fluctuations, this method approximates the microbunching of N_b electrons.

COMPRESSION SCHEMES

The WiFEL driver uses acceleration in superconducting linacs and magnetic compression to transform a 4-MeV bunch with peak current of 50 A into a 1.7-GeV bunch with peak current of 1 kA [5]. We accelerate and compress a bunch that has normalized transverse emittance of 1 μm-rad, charge of 200 pC (i.e., $N_b = 1.25\times10^9$ electrons), peak current of 50 A, Gaussian energy spread of 3 keV rms and a parabolic longitudinal distribution with rms length of 0.4 mm. The compressed bunch is distributed to an FEL beam line and collimated by passing through a three-stage beam spreader [6]. We will consider two beam-spreader designs: our original design whose R_{56} matrix element is 950 μm and an improved design with a low R_{56} value of 38.5 μm.

Figure 1 shows schematic diagrams for single-stage and two-stage compressors [5–7] that compress by a factor of 20. In the two-stage design, the first chicane compresses by a factor of 8 while the second chicane compresses by a factor of 2.5. The rf phases give a compressed, dechirped bunch at the exit of the beam spreader.

The bunch is longitudinally frozen after it travels 3 m and its energy reaches 6.4 MeV [8]. This satisfies our first assumption for simulating shot noise with $N_s < N_b$.

To characterize the bunch after acceleration, compression and passage through a beam spreader, we perform tracking simulations with the ELEGANT code [9]. To model a bunch from the electron gun, we track a 200-pC, 4-MeV bunch containing 8 million randomly distributed particles with a 3-keV Gaussian energy spread. To model a bunch that is heated by a matched laser heater, we track an initial semicircular energy distribution with 10-keV rms energy spread [5, 10]. The tracking includes wakes of LSC and coherent radiation, geometric wakes of the rf cavities and resistive-wall wakes for the spreader vacuum chamber. The cutoff frequency for simulated wakes is well above the frequency range of microbunching gain [5–7].

In shot-noise simulations with $N_s < N_b$, we reduce the LSC wake upstream of the first chicane by changing the effective lengths for LSC. We do not reduce the

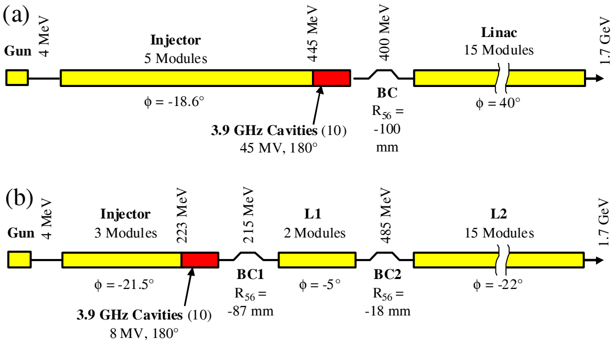

Figure 1: Schematic diagrams for two bunch compressors. (a) Single-stage compressor. (b) Two-stage compressor.

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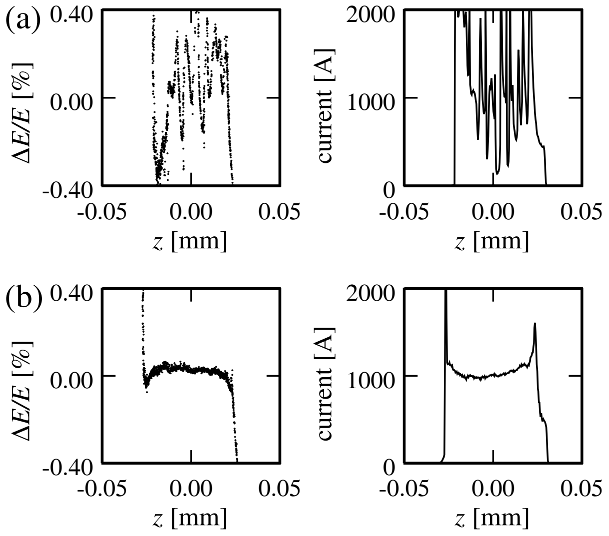

Figure 2: Longitudinal phase space and current profile after single-stage bunch compression, acceleration to 1.7 GeV, and passage through a 3-stage beam spreader with a low value of R_{56}. The bunch tail is on the right. Simulations are performed for 8 million particles with initial energy of 4 MeV and 3-keV rms Gaussian energy spread. (a) LSC wakes included throughout the design. (b) No LSC wake upstream of the chicane.

geometric wake of rf cavities, whose long-wavelength impedance affects the macroscopic bunch profile [5]. Since the bunch chirp at the first chicane entrance is affected by LSC, we maintain 1-kA output current by adjusting the phase of the upstream rf cavities by a few tenths of a degree.

SINGLE STAGE COMPRESSION

We first consider single-stage compression and the low-R_{56} beam spreader. For initial 3-keV rms Gaussian energy spread, Fig. 2(a) shows the longitudinal phase space and 200-bin current histogram when LSC wakes are modeled. The shot noise of 8 million particles causes a high level of microbunching. In Fig. 2(b), a simulation without the LSC wake upstream of the chicane is quiet, showing that the microbunching in Fig. 2(a) is mostly caused by energy fluctuations at the chicane entrance due to the upstream LSC wake. This satisfies our second assumption for simulation of shot noise with fewer particles than the bunch population. We expect that 8-million-particle simulations can model the microbunching from shot noise when it exceeds the level of Fig. 2(b).

In Fig. 3(a), the LSC wake upstream of the chicane is reduced by a factor of 3.125 to model microbunching from shot noise for a bunch population of $(3.125)^2(8\times10^9) = 7.8\times10^{10}$. In Fig. 3(b), the upstream LSC wake is reduced by 6.25 to model a population of $(6.25)^2(8\times10^9) = 3.13\times10^{11}$. With increasing bunch population, the microbunching decreases.

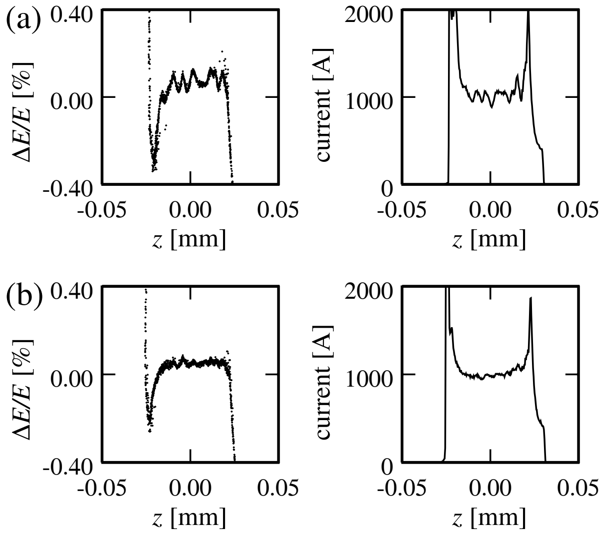

Figure 3: Longitudinal phase space and current profile after single-stage compression and the low-R_{56} beam spreader, for 8 million particles with a 3-keV rms Gaussian energy spread. (a) The LSC wake upstream of the chicane is reduced by 3.125 to model 78 million particles. (b) The LSC wake upstream of the chicane is reduced by 6.25 to model 313 million particles.

To simulate microbunching from shot noise for the real bunch population of $N_b = 1.25\times10^9$ electrons, Fig. 4(a) shows tracking of 8 million particles with the LSC impedance upstream of the chicane reduced by a factor of $[(1.25\times10^9)/(8\times10^6)]^{1/2} = 12.5$. The simulated microbunching is larger than modeling with no upstream LSC wake [shown in Fig. 2(b)], and much smaller than

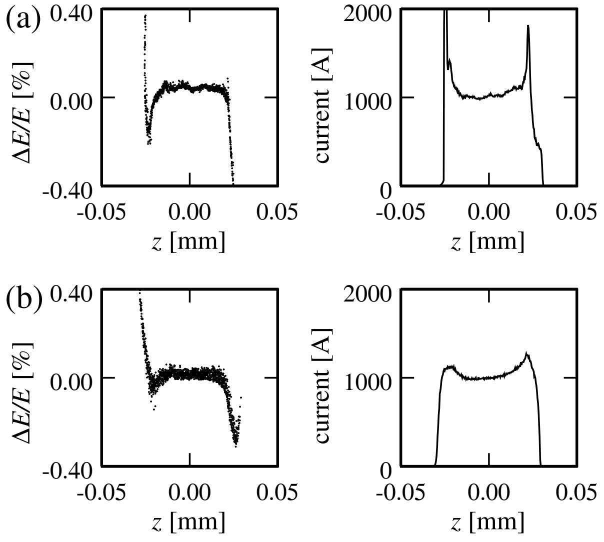

Figure 4: Longitudinal phase space and current profile after single-stage compression and the low-R_{56} beam spreader. The microbunching of 1.25×10^9 electrons in a 200-pC bunch is simulated with 8 million particles by reducing the LSC impedance upstream of the chicane by the factor 12.5. (a) Initial 3-keV rms Gaussian energy spread. (b) Initial 10-keV rms semi-circular energy spread from a matched laser heater.

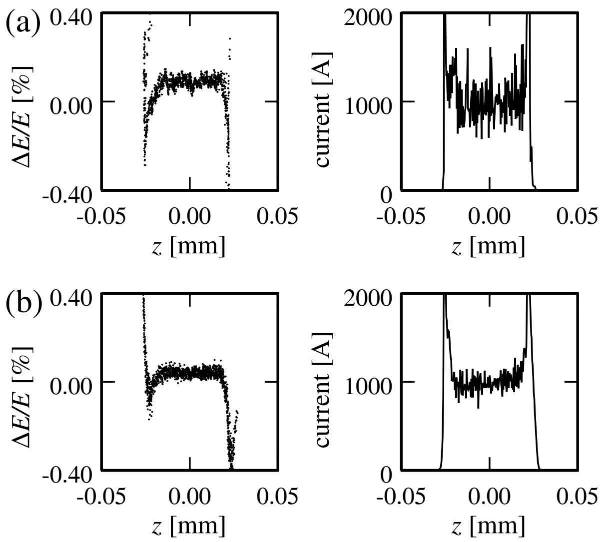

Figure 5: Longitudinal phase space and current profile after single-stage compression and passage through the original beam spreader design with R_{56} = 950 µm. The microbunching of a 200-pC bunch is simulated with 8 million particles by reducing the LSC impedance upstream of the chicane by the factor 12.5. (a) Initial 3-keV rms Gaussian energy spread. (b) Initial 10-keV rms semicircular energy spread from a matched laser heater.

modeling with twice as much upstream LSC wake [shown in Fig. 3(b)], so we expect that Fig. 4(a) gives a reasonable estimate of microbunching from shot noise. The small modulations on the compressed bunch satisfy the FEL requirement for current modulations less than 10% and relative energy modulations less than 3×10^{-4}.

For operation with a matched laser heater, Fig. 4(b) shows a simulation for an initial semicircular energy distribution [5, 10] with 10-keV rms energy spread. Microbunching from shot noise is not evident.

We now display additional 8-million-particle simulations in which the LSC wake upstream of the first chicane is reduced by a factor of 12.5. The observable modulations exceed those of simulations with no upstream LSC wake, and are much smaller than those of simulations with twice as much upstream LSC wake. This suggests that the displayed simulations give a reasonable estimate of microbunching from shot noise for a 200-pC bunch containing 1.25×10^{9} electrons.

ORIGINAL BEAM SPREADER DESIGN

According to analytic estimates and simulations of modulated bunches, our original beam spreader design (with R_{56} = 950 µm) causes an order-of-magnitude increase in microbunching gain for initial wavelengths around 50 µm [6, 7]. This corresponds to wavelengths around 2.5 µm in the compressed bunch. Figure 5 displays simulations for single-stage compression with the original spreader design; confirming that microbunching from shot noise is greatly increased with the original spreader design. For an initial 3-keV energy spread, the microbunching violates the FEL requirement that current modulations be less than 10%, so that a laser heater is needed to satisfy the FEL requirements.

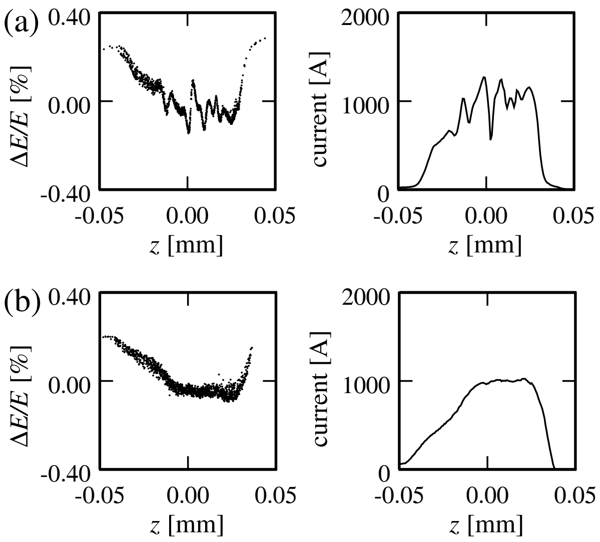

Figure 6: Longitudinal phase space and current profile after two-stage bunch compression and the low-R_{56} beam spreader. The microbunching of a 200-pC bunch is simulated with 8 million particles by reducing the LSC impedance upstream of the first chicane by the factor 12.5. (a) Initial 3-keV rms Gaussian energy spread. (b) Initial 10-keV rms semicircular energy spread from a matched laser heater.

TWO-STAGE COMPRESSION

According to analytic estimates and simulations, two-stage compression has much larger microbunching gain for initial wavelengths of 50–300 µm [6, 7], which corresponds to wavelengths of 2.5–15 µm in the compressed bunch. Figure 6 shows the increased microbunching from shot noise in simulations for two-stage compression and passage through the low-R_{56} beam spreader. A laser heater is needed to satisfy the FEL requirements.

Figure 7 shows that microbunching from shot noise is further increased when the original beam spreader design is used with two-stage compression.

SUMMARY

By performing simulations with reduced LSC impedance upstream of the first chicane, we have approximated microbunching from shot noise with fewer particles than the bunch population. We reduce this LSC impedance by the square root of the ratio of the bunch population to the number of simulation particles. A reasonable approximation is expected when a simulation has enough particles so that its microbunching is mostly caused by LSC-induced energy fluctuations at the entrance of the first chicane.

For studying shot-noise-induced microbunching, our method is complementary to analytic gain calculations [1,

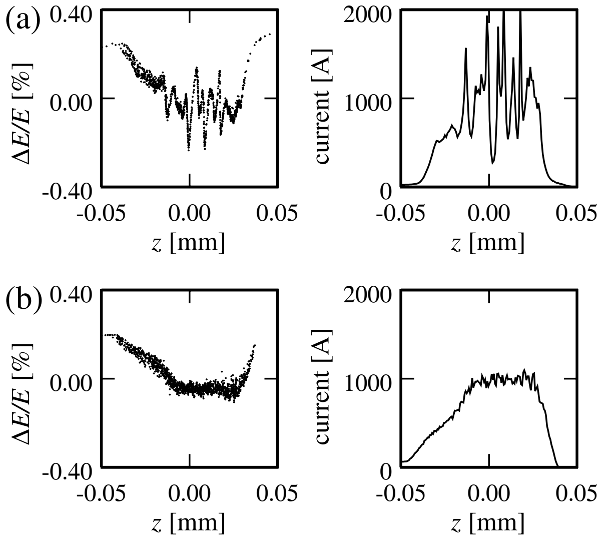

Figure 7: Longitudinal phase space and current profile after two-stage compression and passage through the original beam spreader design with R_{56} = 950 µm. The microbunching of a 200-pC bunch is simulated with 8 million particles by reducing the LSC impedance upstream of the first chicane by a factor of 12.5. (a) Initial 3-keV rms Gaussian energy spread. (b) Initial 10-keV rms semicircular energy spread from a matched laser heater.

4–7, 10], use of a Vlasov solver [1], and parallel-processing simulations of all electrons in a bunch [11].

We used our method to study designs for the WiFEL bunch compressor and beam spreader. As expected from analytic modeling and simulations of modulated bunches [6, 7], the microbunching from shot noise is small when a single-stage compressor is used with a beam spreader that has a low R_{56} value of 38.5 µm. In this case, FEL requirements are satisfied by compressing a bunch with 3-keV Gaussian energy spread from the electron gun.

As expected from previous modeling [6, 7], a much higher level of microbunching occurs with our two-stage compressor design. The microbunching is also greatly increased with our original beam spreader design whose R_{56} value is 950 µm. For these cases, the use of a laser heater can suppress the shot-noise-induced microbunching so that FEL requirements are satisfied.

With single-stage compression and the low-R_{56} beam spreader, the microbunching from shot noise is sufficiently small that FEL requirements are satisfied without using a laser heater. By compressing a bunch with low energy spread, a high quality compressed bunch with low energy spread is provided for the FEL.

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