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FIRST-PRINCIPLE SIMULATIONS OF A LASER-ASSISTED BUNCH COMPRESSION SCHEME*

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Abstract

Bright electron beams with high peak current are critical for reducing the size of X-ray free-electron lasers (XFELs). A promising approach to generating bright electron bunches involves combining low-emittance bunches produced by high-frequency photo-injectors with a laser-assisted bunch compression scheme. This compression method uses an infrared laser to modulate the electron beam's energy in a planar undulator and a low R_{56} chicane to map these energy modulations into density modulation and produce a micro-bunched beam. We present first-principle simulations of this compression process, including the impact of coherent synchrotron radiation (CSR) on beam dynamics. These simulations were performed using the large-scale self-consistent LW3D code for two compression configurations under study for compact XFEL designs.

INTRODUCTION

X-ray free-electron lasers (XFELs) are extremely important research tools in a broad range of disciplines as they can provide ultrafast coherent X-ray pulses [1]. With femtosecond pulses at Angstrom-wavelengths, XFELs enable the exploration of structures and dynamical processes at the Å-fs space and time scales. However, XFEL facilities require large infrastructure typically available only in national laboratories, thus limiting the number of facilities accessible to users worldwide. Therefore, new approaches to develop compact and cheaper XFELs have been proposed in an effort to further disseminate XFEL capabilities beyond national laboratories. One of these innovative approaches is the ultra-compact XFEL (UC-XFEL), proposed and currently under study by a team at the University of California, Los Angeles (UCLA) [2]. The UC-XFEL concept integrates two beam physics frontiers: advanced high-gradient acceleration and radiation generation (XFELs).

An important aspect of the UC-XFEL scheme is the generation of 6D ultra-bright electron beam. This is achieved by a combination of an ultra-low transverse-emittance beams generated in a high-gradient radio-frequency (RF) photo-injector and a laser-assisted bunch compression (LABC) technique [2]. The high-field RF photo-injector can produce a significantly high 4D brightness with a low normalized transverse emittance down to 50 nm, and the LABC technique enhances the beam current to multi-kA. The LABC was first proposed by Zholents [3] as part of the Enhanced Self-Amplified Spontaneous Emission (ESASE). The main components of LABC are the modulator and a magnetic chicane. In the modulator, an infrared laser propagates co-linearly with the electron beam in a planar undulator where the beam energy is modulated and the current spikes are established. The beam is accelerated to high energies and then compressed by a low R_{56} magnetic chicane producing a high current micro-bunched beam.

The LABC allows to reduce the length of the XFEL system by using a several-mm-period, small gap undulator. It can also reduce the impact of the coherent synchrotron radiation (CSR) on the beam brightness at high energy by using a mm-scale R_{56} chicane which requires significantly less bending. A relatively large R_{56} corresponds to more bending and thus increases the CSR impact, especially as the bunch/micro-bunch length decreases through the chicane.

During bunch compression, the primary concern is the potential degradation of beam brightness due to CSR interaction, leading to increased transverse emittance and energy spread. Therefore, the UC-XFEL team investigated the CSR effect in the compression chicane using both a 1D model in `elegant` [4] and a 3D model in GPT [5]. Their findings revealed that the final slice emittance remained around 70 nm within the current spike, while the final slice relative energy spread stayed below 10^{-3} [2, 6, 7]. These simulations indicate a marginal dilution of the beam brightness due to CSR.

In this work, we employ first-principle simulations using the self-consistent LW3D code to study the 3D CSR impact on the beam brightness in the LABC for the UC-XFEL at UCLA. Our simulations are performed for both the modulator and the chicane assuming free space propagation (no shielding effects).

SIMULATION METHOD

The LW3D code, developed by Ryne [8], functions as a large-scale parallel program designed to compute 3D electromagnetic fields directly from the Liénard-Wiechert potential. Its first-principle implementation enables the algorithm to calculate CSR fields on a 3D grid at any time step. In the self-consistent mode of LW3D, these fields are applied to the particles by interpolating the computed CSR fields on the 3D grid points at each particle's position. This approach enables LW3D to calculate radiative effects and their influ-

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ence on beam dynamics in the presence of arbitrary external electric and magnetic fields, not limited to dipole magnets.

SIMULATIONS OF THE MODULATOR

In the modulator, an infrared laser co-linearly propagates with the electron beam through a planer undulator. The laser wavelength λ_L must satisfy the resonance condition with the electron beam inside the undulator with peak field B_0

$$\lambda_L = \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_u^2}{2}\right),$$

where $K_u \equiv \frac{eB_0}{k_u m_e c}$ is the undulator parameter ($k_u \equiv 2\pi/\lambda_u$, and m_e is the electron's rest mass), γ_0 is the electron Lorentz factor. Due to the inverse dependence of λ_L on γ_0^2, it is preferable to modulate at a relatively moderate energy and subsequently accelerate the beam to the desired high energy.

In our implementation, we model the undulator field as a series of horizontally-bending dipole magnets with alternating polarity and a peak magnetic field amplitude of B_0. The laser is simulated as a horizontally-polarized travelling optical pulse with field [9]

$$E_x = E_0 \frac{w_0}{w(z)} \cos\left(k_L z - \arctan\left(\frac{z}{z_R}\right) + \frac{k_L r^2}{2R(z)} - \omega_L t\right)$$
$$\cdot \exp\left(-\frac{r^2}{w(z)^2}\right) \exp\left(-\frac{(z-ct)^2}{2\sigma_z^2}\right), \quad B_y = E_x/c,$$

where $w(z) = w_0\sqrt{1 + \left(\frac{z}{z_R}\right)^2}$ and $R(z) = z\left[1 + \left(\frac{z_R}{z}\right)^2\right]$. Here, $w(z)$ is the laser waist along z, $z_R = \pi w_0^2/\lambda_L$ is the laser Rayleigh range, $R(z)$ is the radius of curvature of the beam's wavefronts, and σ_z^2 is the laser pulse length. The parameters used in our simulations of both the modulator and the initial electron beam are described in Table 1.

Table 1: Modulator and Electron Beam Parameters in the Simulations

Parameter	Value	Unit
Undulator period λ_u	15	cm
Number of periods	10	
Undulator peak field B_0	0.87	T
Laser pulse length σ_z	9	µm
Laser waist w_0	3.7	mm
Laser wavelength λ_L	9.2	µm
Laser peak electric field E_0	600	MV/m
Laser peak power	10.3	mJ
Bunch charge	100	pC
Bunch energy	400	MeV
Bunch full length	73.5	µm
Bunch energy spread $\Delta\gamma$	34	keV
Bunch current	400	A
Bunch normalized emittance ε_x	55	nm

The laser's peak power is selected to induce an energy modulation amplitude significantly larger than the uncorrelated energy spread. This sizable modulation leads to a pronounced energy chirp of the micro-bunches, facilitating the reduction of R_{56} in the subsequent magnetic chicane. We have tailored the laser parameters to ensure a substantial energy modulation amplitude, necessitating a low R_{56} chicane for compression. Commencing with a uniform current distribution of the electron beam, we co-propagate it with the laser through the undulator using LW3D simulations in self-consistent mode (CSR effects included).

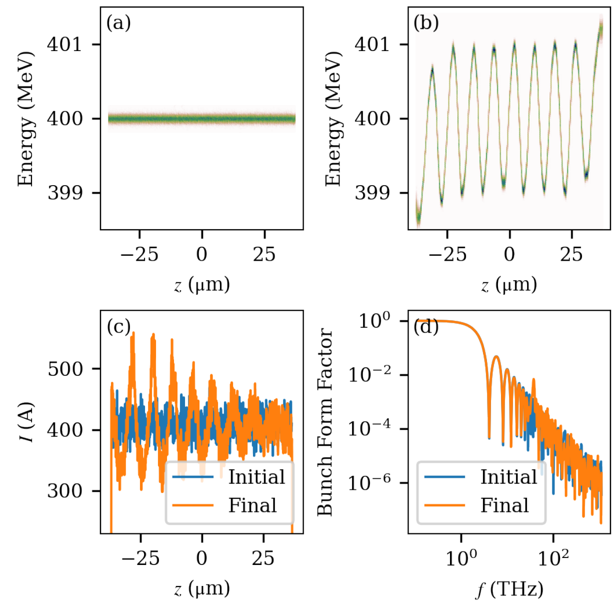

Figure 1: LPS distributions upstream ("initial") (a) and downstream ("final") (b) of the energy modulator with associated current distributions (c) and bunch form factors (d).

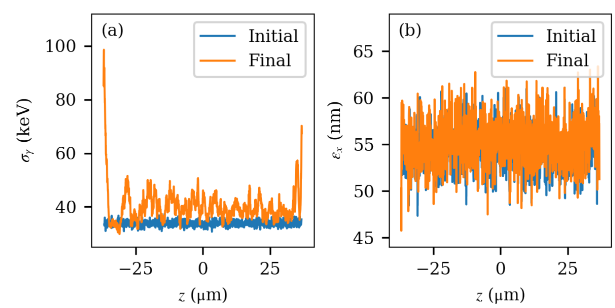

Figure 2: Comparison of slice energy spread (a) and the slice horizontal (bending-plane) emittance (b) before (blue traces) and after (orange traces) the energy modulator.

In Fig. 1(a,b), the initial and final longitudinal phase spaces (LPSs) of the electron beam reveals prominent energy modulations. Additionally, inspection of the initial and final current distributions indicate the presence of density modulations with the bunch form factor (BFF) confirming the density modulation appears at the resonant frequency; see Fig. 1(c,d). Figure 2 presents the slice energy spread and slice emittance, showcasing a slight increase in energy spread while the transverse emittance remains unaffected by

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CSR. This energy spread increment primarily stems from the intense laser field rather than CSR effects.

SIMULATIONS OF THE CHICANE

After the beam's energy has been modulated and the current micro-bunches has been established, the beam is accelerated to 1 GeV. This acceleration does not affect the modulations because of the ultra-relativistic energy. Then, the bunch goes through a standard chicane to compress the micro-bunches and enhance the current. We scanned the R_{56} values by varying the dipoles' bending angle until we achieved the best compression. The chicane parameters are included in Table 2.

Table 2: Parameters of the Four-Dipole Magnetic Chicane Used in the Simulations

Parameter	Value	Unit
Dipole bending angle	± 1.43	°
Dipole length	10	cm
Drift between dipoles	1	m
Chicane R_{56}	1.25	mm

In our LW3D simulations, including CSR effects, the longitudinal bunch configuration before and after the chicane is depicted in Fig.3. This illustration highlights noticeable

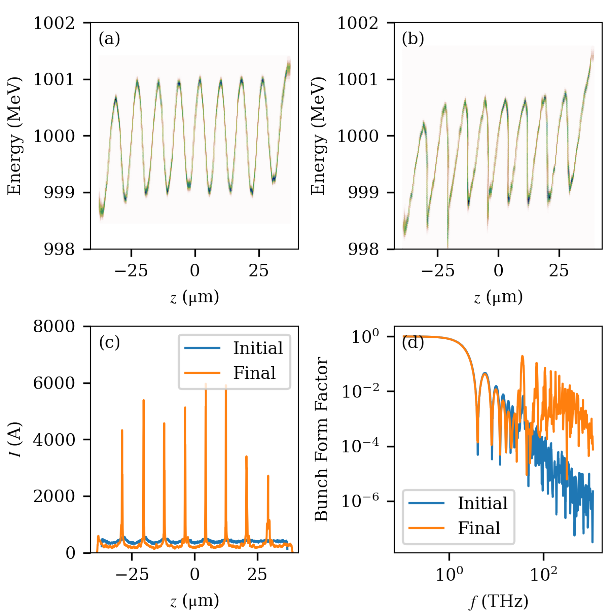

Figure 3: LPS distributions upstream ("initial") (a) and downstream ("final") (b) of the magnetic chicane with associated current distributions (c) and bunch form factors (d).

energy loss along the bunch, a substantial increase in current to over 5 kA, and the generation of high harmonics as inferred from the higher value of BFF for spectral range above the resonant frequency; see Fig. 3(d). Figure 4 displays the slice emittance and slice energy spread of the four middle current spikes. Within these spikes, the slice emittance has increased to around 120 nm (less than a threefold increase), while the slice energy spread remained below 10^{-3}. Despite minor CSR effects such as energy loss and transverse emittance dilution, the overall impact on the LABC performance is negligible and still enable the formation of micro-bunches with adequate brightness to drive a soft X-ray compact FEL.

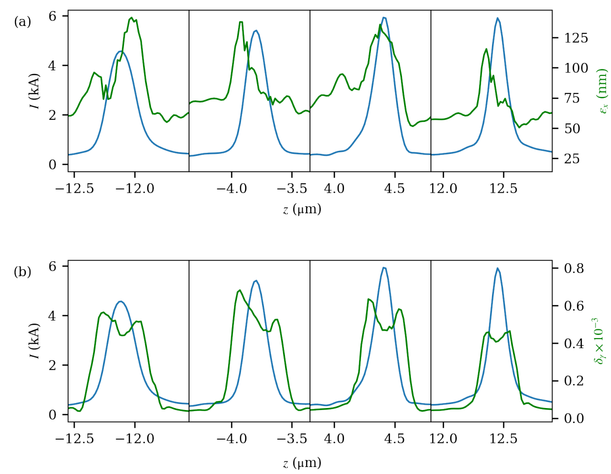

Figure 4: Close up of the slice horizontal emittance (a) and the slice relative energy spread (b) for the four central current spikes shown in Fig. 3.

CONCLUSION

We conducted first-principle CSR simulations for the LABC at UC-XFEL, UCLA, investigating CSR's impact on beam brightness. Our simulations achieved a peak current of approximately 5 kA, while maintaining a relative energy spread below 10^{-3}. The CSR influence was minimal, resulting in slight energy loss and less than a threefold increase in slice transverse emittance within the current spike. While our study yields a slightly lower final beam brightness than discussed in [6], the phase-space dilution remains minimal, posing insignificant alterations to the FEL process. Encouraged by these results, we aim to further explore this LABC technique and apply it to a compact FEL project currently under investigation at Argonne National Lab. This project is based on a high-gradient electron source and linac powered via a two-beam-accelerator [10, 11].

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