TWO-CHICANE COMPRESSED HARMONIC GENERATION OF SOFT X-RAYS *

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Abstract

We propose a simple single-stage scheme to produce fully coherent 3nm radiation. Seeding an electron bunch prior to compression simultaneously shortens the laser wavelength and duration, and increases the modulation amplitude. The final X-ray wavelength is tunable by controlling the compression factor with the RF phase. We propose a two chicane scheme that allows for nearly arbitrary modulation amplitudes, extending the method to photocathode beams. We also show that transportation of fine compressed modulation structure is feasible due to a canceling effect of the second chicane.

INTRODUCTION

A Free Electron Laser (FEL) [1] can theoretically produce fully coherent X-rays, a promising tool for the fields of physics, chemistry and biology. Current X-ray FELs in use or under construction rely on self-amplified spontaneous emission (SASE) [2, 3]. SASE FELs can reach the hard X-ray region, but are saddled by long saturation lengths and poor longitudinal coherence. In contrast, FELs 'seeded' by optical or UV lasers promise full coherence and shorter FEL lengths. At present, the leading seeded FEL scheme is high gain harmonic generation (HGHG) [4, 5]. However, single-stage HGHG suffers from noise during the high-energy modulation, requires high laser power (expensive and degrading to the FEL), and is limited to around 20nm [6]. Multiple-stage HGHG can reach shorter wavelengths, but is expensive and technically challenging.

Seeding the electron beam prior to bunch compression is an alternative approach [7, 8, 9]. Dispersion from the compression smears out longitudinal modulation, but the modulated structure remains imprinted in phase space and can be revived later. Echo Enhanced Harmonic Generation (EEHG) is a promising proposal to manipulate such hidden structure to produce high harmonics [10]. We propose an alternative simple one-stage seeded FEL that exploits this beam memory to recover harmonics down to 3 nm, well within the water window.

Our scheme uses two dispersive sections to first compress and then bunch the modulation. Starting from the gun, an accelerator section brings the beam to energy E_a, while adding a linear chirp, h. A laser then modulates the beam energy by $A_L \cos(k_L z)$. A dispersive section, $R_{56}^{(a)}$, simultaneously compresses the bunch length by a factor of $\alpha = 1/(1 + R_{56}^{(a)} h)$, while also strongly over-bunching the laser modulation. Another accelerator section flattens the beam with a second chirp, $-\alpha h z$, while increasing the energy to $E_b = gE_a$. Finally, a second dispersive section with effective opposite sign, $R_{56}^{(b)} \approx -R_{56}^{(a)} g/\alpha \pm g/(A_L \alpha^2 k_L)$, unwinds the over-bunched laser modulation, recovering a maximally bunched beam at wavevector αk_L while simultaneously suppressing second order effects in the accelerator and first chicane. The entire process, which we will refer to as Compressed Harmonic Generation (CHG), is summarized in Fig. 1.

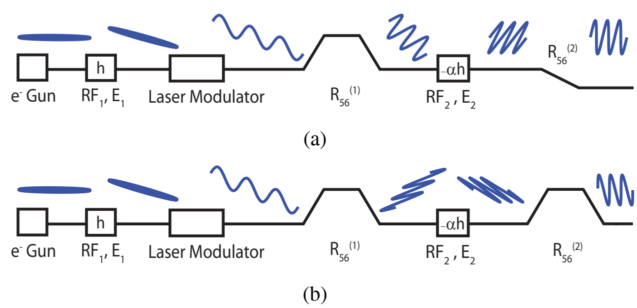

Figure 1: Diagram of CHG scheme. a) The first accelerator section gives a linear chirp, h. After modulating with a laser, the first dispersive section, $R_{56}^{(a)}$, compresses the beam and over-bunches the modulation. A second RF section accelerates and cancels the chirp of the first section. The final dispersive section unwinds the over-bunching. b) Operating $R_{56}^{(a)}$ in over-compression rotates the electron beam head-to-tail, allowing us to use a chicane for $R_{56}^{(b)}$ as well.

CHG ADVANTAGES

CHG offers several advantages over alternative seeding methods. First, the bunch compressor reduces the laser wavelength by a factor of α. Seeding from a 157 nm F_2 laser with $\alpha \approx 10$ gives 3nm radiation at the 5th harmonic (50th harmonic of the original seed laser). Second, the RF phase controls α, so changing the phase tunes the final wavelength. Third, the bunch compressor amplifies the laser modulation by the compression factor, reducing the required laser power by α^2.

CHG also requires relatively few components. The first chicane doubles as the bunch compressor (required to increase current for all FELs), so we need only one additional modulator and chicane, the same as for single-stage

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HGHG. The low power requirement allows seeding by a short-wavelength excimer laser.

An earlier compressed seeding proposal for a thermionic electron gun used a single dispersive section to both compress the beam and bunch the laser modulation [7]. In this scheme the chirp and modulation strengths must be matched, limiting the modulation amplitude to a few tens of eV. This small amplitude is acceptable for the small energy spread of a thermionic gun, but far below the incoherent energy spread for high current, photo-cathode beams. Our proposal allows nearly arbitrary modulation strengths by reviving bunching with a second dispersive section. This separates the compression, carried out by $R_{56}^{(a)}$, and the bunching, determined by the modified sum $R_{56}^{(T)} = R_{56}^{(a)} + \frac{\alpha}{g} R_{56}^{(b)}$. In addition, the second chicane recompresses the beam, reversing second order effects in the first chicane and subsequent accelerator sections.

BUNCHING FACTOR

The seeding can be quantified by the bunching amplitude at the end of the linac,

$$b_f(k) = \int dz_f \int dp_f e^{ikz_f} \Psi(z_f, p_f) \qquad (1)$$

with final longitudinal particle position, z_f, normalized energy, $p_f = (E_f - E_b)/E_b$, and distribution $\Psi(z_f, p_f)$. We can evaluate Eq. 1 analytically if we assume a simple initial distribution, $\Psi(z_i, p_i) = I \exp[-p_i^2/2\sigma_\delta^2]$, with initial coordinates, z_i and $p_i = (E_i - E_a)/E_a$, and energy spread, $\sigma_\delta = \sigma_E/E_a$.

We describe the CHG process as follows: 1. We chirp the beam and modulate with a laser. 2. The first dispersive section compresses the beam. 3. We accelerate again, adding a second chirp. 4. A second dispersive section unwinds the over-bunching.

$$\begin{aligned} z_1 &= z_i, & p_1 &= p_i + A_L \sin(k_L z_i) + h z_i \\ z_2 &= z_1 + R_{56}^{(a)} p_1, & p_2 &= p_1 \\ z_3 &= z_2, & p_3 &= (p_2 - \alpha h z_2)/g \\ z_f &= z_3 + R_{56}^{(b)} p_3, & p_f &= p_3 \end{aligned} \qquad (2)$$

To evaluate Eq. 1, we change to the initial coordinates, $dz_f dp_f \to dz_i dp_i/g$, where we know $\Psi(z_i, p_i)$. Solving for z_f in terms of z_i, we find

$$z_f = z' + R_{56}^{(T)} (p_i + A_L \sin(k_L \alpha z')) \qquad (3)$$

with definitions $z' \equiv z_i/\alpha$ and $R_{56}^{(T)} \equiv R_{56}^{(a)} + R_{56}^{(b)} \alpha/g$. Eq.3 has the same form as for a single modulation, at compressed wavelength αk_L, with effective dispersive section, $R_{56}^{(T)}$, and relative laser modulation amplitude, A_L/σ_δ.

The two terms in $R_{56}^{(T)}$ must have opposite signs to achieve $R_{56}^{(T)} \ll R_{56}^{(a)}, R_{56}^{(b)}$. We may either use opposite sign dispersive sections (e.g. one chicane, one 2-bend dogleg), or negative α (over-compression). We choose negative α so we may use chicanes for both dispersive sections.

We can integrate Eq. 1 to find bunching at the harmonics as in HGHG [4]

$$b_f(m\alpha k_L) \propto e^{-\frac{\left(m\alpha k_L R_{56}^{(T)} \sigma_\delta\right)^2}{2}} J_m(m\alpha k_L R_{56}^{(T)} A_L) \quad (4)$$

with maxima at $\alpha k_L R_{56}^{(T)} A_L \approx \pm 1$. To avoid suppression by the energy spread, we require $|m\alpha k_L R_{56}^{(T)} \sigma_\delta| < 1$, giving significant bunching at the mth harmonic when $A_L > m\sigma_\delta$. A 1D simulation with parameters from Table 1 illustrates the process (Fig. 2).

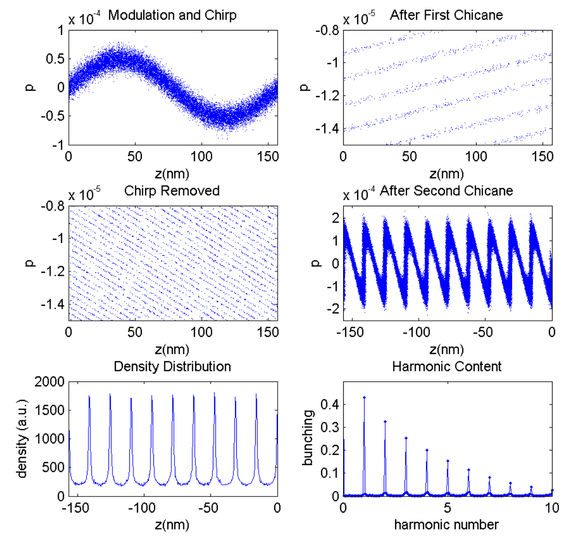

Figure 2: In the first step, we add a chirp and laser modulation. After the first chicane, the modulation is overbunched. A second chirp reverses the first chirp. After more acceleration, the second chicane revives bunching. Note the compression of the wavelength by $\alpha = 10$, and the increase in modulation amplitude by $\alpha/g = 2.5$. We find strong bunching past the 5th harmonic.

Table 1: Simulation Parameters

Laser wavelength (λ_L)	157nm
Laser power	6MW
Laser modulation amplitude (A_L)	5×10^{-5}
Uncorrelated RMS energy spread (σ_δ)	1×10^{-5}
Normalized transverse emittance (ϵ)	1μm
Electron energy (E_a, E_b)	250MeV,1GeV
Chicanes ($R_{56}^{(a)}, R_{56}^{(b)}$)	50mm, 20mm
Compression factor (α)	10

We can now confirm the advantages of our setup. First, radiation is at the harmonics of the compressed wavelength λ_L/α. Second, α, and thus the final wavelength, is tunable by the RF phase. Third, the laser modulation, A_L, is measured relative to the initial energy spread, σ_δ, rather than the post-compression energy spread, $\alpha\sigma_\delta$. Even with the laser focused to a large radius (required for transversely uniform modulation at large β function), we need only 6 MW of seed power. In total, we can reach a tunable wavelength at 3 nm with a fraction of the standard HGHG laser power.

FEASIBILITY

CHG is most sensitive to errors originating between the dispersive sections; errors prior to the first chicane are largely canceled by the second chicane. Here we estimate the effects of incoherent synchrotron radiation (ISR), broadening from 3D effects, and errors in the second chirp strength.

ISR Induced Energy Spread

Incoherent energy spread, $\Delta\delta^{\text{(ISR)}}$, from ISR between the two dispersive sections could destroy the fine phase space structure. To preserve high harmonics, we must limit the longitudinal broadening, $\Delta z^{(\delta)}$, from the total energy spread to less than $\lambda_L/2\pi m\alpha \sim 0.5$ nm. We can estimate

$$\Delta z^{(\delta)} = R_{56}^{(a)}\sigma_\delta + R_{56}^{(b)}\frac{\alpha}{g}\sigma_\delta + R_{56}^{(b)}\Delta\delta^{\text{(ISR)}} \qquad (5)$$

where σ_δ is the initial energy spread of the beam. The first two terms are small by design, so for $R_{56}^{(b)} = 20$ mm, we find $\Delta\delta^{\text{(ISR)}} \sim 10^{-8}$ for each bend, achievable with weak compression chicanes at 1 GeV. Fig. 5 shows bunching including ISR effects. The accelerator lattice is shown in Fig. 4.

Second Order Lattice Effects

The laser modulation must survive transport through two strong chicanes, and approximately 60 m of accelerator. Smearing from second order effects (e.g. emittance and curvature from energy modulation) could broaden the fine 3 nm structure.

The second chirp helps to cancel such effects. An electron with coordinates $X = [x, x', y, y', z, \delta]$ acquires a longitudinal deviation of $\Delta z^{\text{(T)}} = \tilde{X}T_{5ij}X$, with T_{5ij} the second order transport matrix from the modulator to the beginning of the second chirp. The chirp imparts a relative energy modulation of $-\frac{\alpha}{g}h\Delta z^{(\epsilon)}$, so that following the second chicane the particle has a final longitudinal shift of

$$\begin{aligned}\Delta z^{\text{(F)}} &= \Delta z^{\text{(T)}} - R_{56}^{(b)}\frac{\alpha}{g}h\Delta z^{\text{(T)}} \\ &\approx \Delta z^{\text{(T)}}/\alpha \end{aligned} \qquad (6)$$

The smearing between the two chirps is reduced by the compression factor, α, with smearing from within the chirps and second chicane reduced by lesser amounts (Fig. 3). For our lattice (Fig. 4), the transverse components of the T_{5ij} matrix are dominated by the first chicane, where we increase the beta function after the small beam radius of the modulator. The compression from the second chicane is sufficient to maintain bunching, as seen in elegant simulations (Fig. 5).

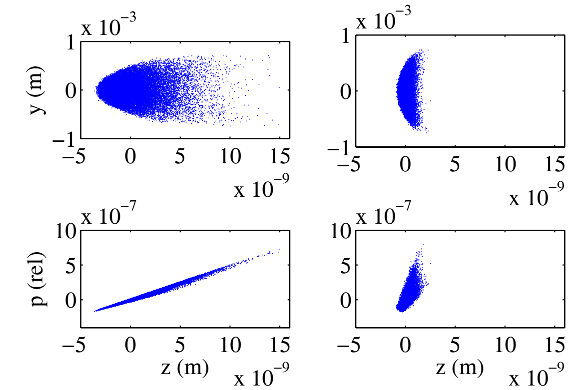

Figure 3: Elegant simulation demonstrating the emittance cancelation effect. Starting from a longitudinal delta slice after the laser modulation, emittance effects increase the beam size before the second chicane (left, before $R_{56}^{(2)}$), but also introduce a chirp to the beam (bottom left). The chicane then recompresses the bunch by α (right, after $R_{56}^{(2)}$). Bunch head is to the left.

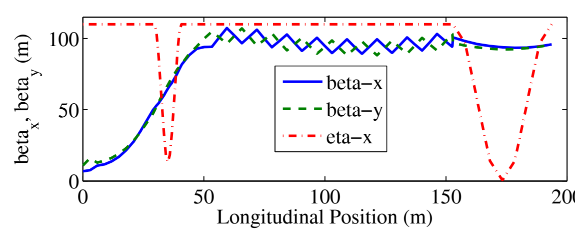

Figure 4: Twiss parameters for 3D elegant simulations. We use L-band structures to decrease wakefield fluctuations, and a weak second chicane to minimize ISR effects.

RF Phase and Wakefield Stability

RF phase errors, wakefields, and RF curvature alter the chirp between dispersive sections and degrade the final bunching. An error in the second, canceling chirp shifts the unwinding process and leaves the beam either under or over-compressed. (The first chirp is less problematic because the two dispersive sections have canceling effects.)

To estimate the sensitivity to a linear chirp error, we repeat the earlier analysis, with the addition of an error, ϵ, in the final chirp. Step three becomes

$$z_3 = z_2 \qquad p_3 = (p_2 - \alpha h z_2 - \epsilon z_2)/g \qquad (7)$$

Again solving for z_f in terms of z_i, we find

$$z_f = z' + (R_{56}^{(T)} - \delta_R)\left(p_i + A_L \sin\left(\frac{\alpha k_L}{1-\delta_k}z'\right)\right) \qquad (8)$$

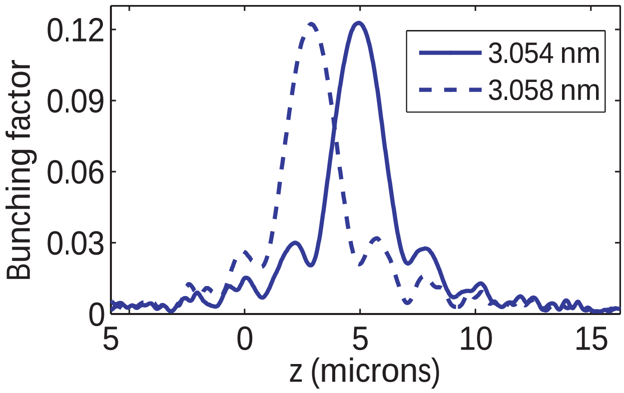

Figure 5: Bunching factor with 0.15% bandwidth from elegant [11] simulation (parameters in table 1). Bunching is lower than for the 1D case because of 2nd order effects (emittance, T_{566}) and finite laser radius.

with definitions $\delta_k \equiv R_{56}^{(b)}\epsilon/g$, $\delta_R \equiv R_{56}^{(a)}R_{56}^{(b)}\epsilon/g$, and $z' \equiv z_i(1-\delta_k)/\alpha$. The error has two effects: the wavevector shifts by factor $1-\delta_k$ and the $R_{56}^{(T)}$ required to unwind the over-compression shifts by δ_R. While the shift in wavevector is small, the second condition implies a tight constraint on the phase stability of the second chirp; if the phase shifts, the final modulation will be either over or under-bunched. To maintain maximal bunching we need chirp error $|\epsilon| \ll gR_{56}^{(T)}/R_{56}^{(a)}R_{56}^{(b)} \approx 0.2/\mathrm{m}$, requiring control of the second chirp to better than 0.1%. The dot-dash curve in Fig. 6 shows bunching decreases to 10% with a $\pm$ 0.1% phase error. With charge fluctuations of $\sim$1%, we can only ignore the wakefield if it contributes less than 10% of the chirp. For this reason we chose superconducting structures for our simulations.

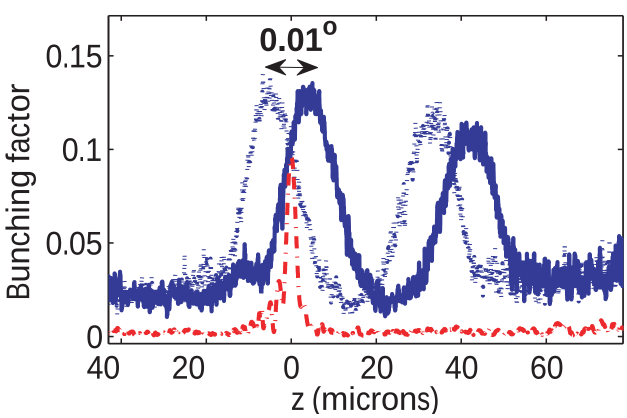

Figure 6: Wide bandwidth bunching for two simulations with a 0.01 degree phase shift. An FEL would pick out a narrow 0.0015% bandwidth, leaving lower bunching (narrow peak). We note the double peak in the wide bandwidth bunching, corresponding to forward and reverse bunching for opposite signs of $R_{56}^{(T)}$.

FEL

At the end of the linac, our parameters give a 1 GeV beam with $\sim$10% bunching at 3 nm. With a Pierce parameter $\rho \approx 7.4 \times 10^{-4}$ [13], we can use the bunched beam itself for an FEL stage. The strong initial bunching requires only 10 m of undulators to reach saturation of nearly 1 GW. CHG also has the potential to produce ultra-short pulses; after compression, a seed pulse of a few femtoseconds produces only a few hundred attoseconds of seeded electron beam. However, an FEL would require a smaller beta function in the undulators, and the additional required focusing could smear out the fine bunching. More study is required here.

ACKNOWLEDGMENTS

We would like to thank Y. Ding, P. Emma, H. Geng, H. Merdji, and G. Stupakov for helpful discussions.

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