HARMONIC GENERATION FOR A HARD XRAY FEL*

Q. Marksteiner#, K. Bishofberger, B. Carlsten, L. Duffy, and N. Yampolsky
Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.

Abstract

We present a harmonic generation scheme that is applicable for preseeding a hard x-ray FEL with longitudinally coherent microbunches. In this regime, lasers do not exist even at large subharmonics of the desired bunching, and ISR limits the use of strong magnetic chicanes. Our design uses a combined HGHG-EEHG scheme to convert 1 nm microbunches, which are assumed to be generated when the electrons are at a lower energy, to ¼ Å microbunches. Here we describe the reasoning behind this design, and show the relevant design parameters and simulation results.

INTRODUCTION

The MaRIE XFEL will produce ¼ Å radiation with a 20 GeV electron beam. Our baseline design will use a 100 pC electron beam with an emittance of 0.3 µm, and operate in the SASE mode. We are also considering an advanced design, where we use emittance partitioning [1] to reduce the transverse emittances to 0.15 µm, and prebunch the beam so that it is longitudinally coherent.

In order to prebunch the beam, we will first generate coherent microbunching at ~ 1 nm, the 40th subharmonic of our final FEL. We are considering several methods for generating these electron bunches, including laser driven EEHG [2, 3] (Echo-enabled Harmonic Generation), using an Emittance Exchanger (EEX) with a material mask [4], or using two EEXs as a bunch compressor for Compressed Harmonic Generation [5]. All of these techniques involve using very large chicanes, which would introduce ISR that destroys the prebunching at 20 GeV [6]. To mitigate this, we will pre-bunch the beam at 1 nm when the electrons have only been accelerated to 1 GeV, and then accelerate the bunched beam to 20 GeV.

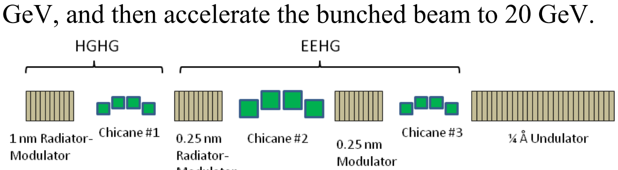

Figure 1: Layout of the scheme described in this paper.

After the beam is accelerated to 20 GeV, the 1 nm bunches must be stepped down to 0.25 Å. A multistage HGHG (High Gain Harmonic Generation) [7] approach would increase the energy spread at every stage resulting in an unacceptably large energy spread at the 0.25 Å undulator. We would like to use EEHG [2], which can generate higher harmonics with a smaller increase in energy spread. Because conventional lasers do not exist below ~200 nm, we must use the radiation generated from the bunched beam traveling through the first undulator to modulate the beam in the second undulator. Unfortunately, slippage between the radiation and the electron beam will result in part of the electron beam not getting bunched at the higher harmonic, and limits our ability to use EEHG. In order to compensate for the shortcomings of HGHG and EEHG, we will first use an HGHG stage to go from 1 nm to 0.25 nm, then use an EEHG section to step the harmonic current to 0.25 Å. A sketch of this scheme is shown in Fig. 1.

BUNCH PRESERVATION

The electrons are initially microbunched to 1 nm at low energy, to avoid the effects of ISR. This bunching must be preserved through the long accelerator section, where the electrons are accelerated from 1 GeV to 20 GeV. If we are not careful, the bunching can disappear through velocity debunching or nonlinear debunching [7].

Velocity Debunching

The energy spread of the electron beam leads to an axial velocity variation among the particles, which can debunch the beam. The initial energy spread of the beam will be amplified when the beam is compressed, and high order cavity harmonics in the accelerator sections will increase the energy spread. We assume the energy spread at 20 GeV is at $\Delta\gamma/\gamma = 5\times10^{-5}$, with a total $\Delta\gamma = 2$. An energy spread of the beam leads to a velocity spread of

$$\Delta\beta = \frac{\Delta\gamma}{\beta\gamma}$$

Pessimistically assuming that the final energy spread exists even at 1 GeV, we can integrate to estimate the total velocity debunching [8]:

$$\delta z = \int_{z_0}^{z_f} \left(\frac{1}{\beta\gamma^2}\right)\left(\frac{\Delta\gamma}{\gamma}\right) \mathrm{d}z = \frac{\Delta\gamma}{2\gamma'}\left(\frac{1}{\gamma_0^2} - \frac{1}{\gamma_f^2}\right)$$

For an accelerating gradient of 50 MV/m, this gives a position shift of ~1 nm when accelerating from 1 GeV to 20 GeV, which is enough to cause significant debunching of the 1 nm bunched beam. One way to overcome this problem is by using negative dispersion sections [7].

Nonlinear Debunching

The RMS particle debunching from an accelerator section, assuming a round beam and constant acceleration will be given by [8]:

$$\delta z = \int_{s_0}^{s_f} \left[\frac{\varepsilon_n^2}{(\gamma_0 + \gamma' s)^2 X^2} + (X')^2\right] \mathrm{d}s \qquad (1)$$

Here γ' is the acceleration gradient, s denotes the length along the accelerator section, $\boldsymbol{X}$ is the RMS beam size in one transverse direction, and ε_n is the normalized emittance in one transverse direction. There is a trade-off

*Work supported by the US DOE LDRD program.
#qrm@lanl.gov

ISBN 978-3-95450-117-5

between the debunching caused by emittance, and the debunching caused by geometric effects of changing the beam size. In addition, the beam must become small enough at the final undulator so that the FEL will work properly. Using the calculus of variations, the minimized debunching along the accelerator will happen when the beam size follows a path given by:

$$\boldsymbol{X}'' = \frac{-\varepsilon_n^2}{(\gamma_0 + \gamma' s)^2 \boldsymbol{X}^3} \quad (2)$$

Given an acceleration gradient, an acceleration length, and a desired initial and final transverse beam size, there is a unique optimized solution. As long as a focusing lattice can be designed which approximates the optimal path given by eqn. [2], the RMS displacement along the accelerator is much less than 1 nm, and should not significantly debunch the beam [7].

LIMITS TO EEHG

After the electron beam is accelerated to 20 GeV, harmonic generation must be used to generate ¼ Å microbunches from the 1 nm microbunches. Because EEHG produces a smaller amount of energy modulation, it would be preferable over HGHG. However, there are limitations that come from the fact that EEHG uses a relatively large chicane to break the modulated beam into energy bands. In this section, we will derive a simple expression for the size of the chicane, and discuss how the size of the chicane can limit EEHG performance.

Estimation of Chicane R_{56}

The bunching factor from EEHG, according to analytical theory [3], is given by:

$$b_m = J_m\left[(m-1)A_2B_2\right] \times J_1\left\{A_1\left[B_1 - (m-1)B_2\right]\right\} \times \exp\left\{-\left(\frac{1}{2}\right)\left[B_1 - (m-1)B_2\right]^2\right\}$$

Here $B_1 = R_{56}^1 k_1 \sigma_E / E_0$, with R_{56}^1 denoting the energy dispersion in the first chicane, k_1 the wavenumber of the fundamental, σ_E the random energy spread in the electron beam, E_0 the energy of the beam, and $A_1=\Delta E_1/E_0$ denoting the normalized energy modulation in the first modulator. Using

$$\xi = B_1 - (m-1)B_2 \quad (3)$$

the value of ξ can be found which optimizes $J_1(A\xi)e^{-\xi^2/2}$ [3]. In order to prevent the exponential term from dominating, this optimization results in $\xi \leq 1$. The second chicane must also be optimized according to [3]:

$$B_2 = \frac{1}{A_2}\frac{m + 0.81m^{1/3}}{m-1} \quad (4)$$

For large harmonics, Eq. 4 gives $B_2 \approx 1/A_2$. The energy modulation in the second undulator is kept small, so that $A_2 \approx 1$, which then makes $B_2 \approx 1$. Then, for large m, the value of ξ must be small compared to the other two terms of Eq. 3. This gives:

$$B_1 \approx (m-1)B_2$$

This yields an estimation of the value of the large chicane in EEHG:

$$R_{56}^1 \approx \frac{\lambda_1 E_0}{2\pi\Delta E_2}(m + 0.81m^{1/3}) \quad (5)$$

Given that our final wavelength is fixed at ¼ Å, it is informative to recast Eq. 5 in terms of the final harmonic wavelength, $\lambda_m = \lambda_1/m$. This gives

$$R_{56}^1 \approx \frac{m^2\lambda_m E_0}{2\pi\Delta E_2} \quad (6)$$

the value of a large chicane in an EEHG system is approximately proportional to m^2. Furthermore, Eq. 5 tells us that the size of the large chicane does not depend on the initial energy modulation, σ_E.

Slippage in the Large Chicane

The EEHG scheme we propose here is different from other EEHG schemes, in that the electron beam is modulated using radiation that is generated from the microbunches in the first 0.25 nm undulator. In the second 0.25 nm undulator, the microbunching will be gone, so the radiation from the first undulator must be used to modulate the electron beam.

Because the large chicane bends the electrons on a curved path, the electron beam will slip behind the x-rays. This slippage will cause the back end of the electron bunch to have no interaction with the x-rays in the second 0.25 nm undulator, and hence not develop any microbunching at 0.25 Å. Because our final, 0.25 Å undulator is much shorter than an undulator for a SASE FEL, this part of the bunch will never develop significant 0.25 Å x-ray power, so that less total photons are produced for a given electron bunch charge. For this hard x-ray EEHG scheme to work efficiently, the total slippage must be small compared to the duration of the pulse itself.

The velocity dispersion of a chicane is given by [9]:

$$R_{56} = \frac{2D\cos\alpha\sin\alpha + L_1\sin^3\alpha - 2D\cos^2\alpha}{\sin\alpha\cos^2\alpha} \quad (7)$$

Here the relationship between the bending angle α, the magnetic field, the the magnet length D is given by

$$\rho = \frac{D}{\sin\alpha} = \frac{\gamma m_e \beta c \sin\alpha}{eD}$$

where γ is the mean electron energy in terms of the relativistic factor, m_e is the electron mass, βc is the electron velocity, e is the electron charge, and the length L_1 describes the distance between the doglegs. The value of R_{56} describes the velocity dispersion in terms of $\Delta z/(\Delta\gamma/\gamma)$, the change in axial position per unit relative energy deviation.

The total path difference between a design electron through a four magnet chicane and an x-ray beam is given by:

$$\Delta S = 4\left[\rho\sin^{-1}\left(\frac{D}{\rho}\right) - D\right] + 2L_1(\sec\alpha - 1)$$

Taylor expanding the $\sin^{-1}(D/\rho)$ and the $\sec\alpha$ terms gives an expression for ΔS that will not lead to floating point errors for small α:

ISBN 978-3-95450-117-5

$$\Delta S = 4\rho\left[\frac{1}{6}\left(\frac{D}{\rho}\right)^3 + \cdots\right] + 2L_1\left[\frac{1}{2}\alpha^2 + \cdots\right]$$

To quickly calculate chicane parameters, a program was written that numerically finds the correct value of α, for a given R_{56}, D and L_1. Using this program, we found that the slippage length ΔS is constant for a given R_{56}, regardless of what you set D and L_1 to. Our electron bunch length is ~100 fs, so a realistic maximum R_{56} that we can use is 8 μm, which will result in a slippage of 13.3 fs.

According to Eq. 6, with this upper limit to the value of R_{56} we can only generate up to about the 10^{th} harmonic. We must include an HGHG stage to first bring the harmonic current to the fourth harmonic, from 1 nm to 0.25 nm. The HGHG section must come first, otherwise the large chicane would still require an R_{56} that is four times larger. The subharmonic modulation that the HGHG section introduces will act like an additional random energy spread, which will hurt the FEL gain in the final undulator, but will not increase the amount of R_{56} that is needed in the EEHG section.

Our large chicane in the EEHG section deflects the electron beam by a total of 2.4 mm, which is enough space to insert a material object (or a mirror) that can properly slow down the x-ray so that it does not slip in front of the electron bunch. This needs to be investigated in the future.

ISR and Nonlinearity in EEHG

The effective drift length in a chicane is given by [9]

$$L = \frac{4D\cos\alpha + 2L_1}{\cos^2\alpha}$$

In the limit of the small bending angles that we will use, this becomes $L \approx 4D + 2L_1$, the total length of the chicane in the z direction. Using Eq. 3, we can estimate the total nonlinear debunching in a drift of length L to be:

$$\delta z = \frac{L\varepsilon_n^2}{\gamma_0^2 \boldsymbol{X}^2}$$

For $\boldsymbol{X}$ = 6 μm, this leads to only a 0.02 Å shift in particle positions, which will not lead to significant debunching. Thus we can assume that the chicanes are linear.

ISR will cause an energy diffusion that is given by [5]:

$$\frac{\delta\gamma}{\gamma} = \sqrt{\frac{55}{24\sqrt{3}}}\sqrt{\frac{he^5B^3}{8\pi^2\varepsilon_0 m^5c^6}}\gamma s^{1/2}$$

Here s is the total path length inside the magnet. Because ISR scales with $B^{3/2}$, but with $s^{1/2}$, we can always lower the effect of ISR by building a longer set of magnets in our chicane, or by including spaces between the doglegs (L_1). A limit on the size of the chicane is given by diffraction of the x-ray beam; if the chicane becomes too long, the x-rays generated in the first 0.25 nm undulator will diffract too much, and will not have enough power when they reach the second 0.25 nm modulator. (Some spreading out of the xray beam between the two 0.25 nm undulators is good, because it ensures that all electrons will get modulated the same way in the final undulator [3]). Since our electron beam has an RMS radius of ~10 μm, the Rayleigh length of 0.25 nm radiation is 5 m, which is also a good estimate for the maximum length of our large chicane.

Our code that calculates chicane parameters shows that the most efficient way to reduce ISR for a given R_{56} and total chicane length L is to set L_1=0. The large chicane we will use is 4 m long, has a magnetic field of 0.164 T, and will introduce $\Delta\gamma = 0.1$ of energy spread from ISR. This is much smaller than the energy bands (see next section), so it will not be a significant effect. In addition, an analytical expression for the total attenuation of bunching from ISR [5] predicts that the effects of ISR will be small in our EEHG system.

THE DESIGN

We simulate the interactions in the four undulators with the GENESIS FEL code [10]. For these simulations, we model a single 1 nm slice of particles throughout the line, and assume this slice is periodic. The electron beam is focused with a FODO lattice, with quad strengths that were chosen to maximize saturation power in the ¼ Å undulator. The transverse size of the electron beam is ~10 μm. We assume a normalized emittance of 0.15 μm in each transverse direction, and an initial uncorrelated energy spread of $\Delta\gamma/\gamma = 5\times10^{-5}$. The three chicanes are modelled by applying an ideal R_{56} to the particle distribution. Our 20 GeV beam initially contains 1 nm microbunching with a bunching factor of 0.1.

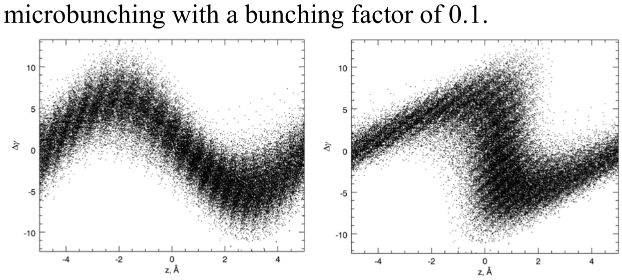

Figure 2: Phase space plots of the electrons in the HGHG section, showing $\Delta\gamma = \gamma - \gamma_0$ vs z. (left) Phase space at the end of the 1 nm undulator (right) Phase space after chicane #1. The electrons enter the 1 nm undulator with 10% 1 nm microbunching, and a random energy spread of $\Delta\gamma/\gamma = 5\times10^{-5}$.

The HGHG Section

The first step is to use an HGHG section to bring the microbunching from 1 nm to 0.25 nm. The 1 nm undulator has a_w = 4.48, and a period of λ_w=14.46 cm, with 26 wiggler periods. The undulator creates coherent 1 nm x-rays from the microbunched electron beam, which in turn creates a 1 nm energy modulation. The 1 nm energy modulation is $\Delta\gamma = 5.3$, which creates a total RMS energy spread of $\Delta\gamma_{tot}$ = 4.4. An R_{56} = 100 nm chicane produces ¼ nm microbunching with a bunching factor of 9.2%. Plots of the particles after the 1 nm undulator and after chicane #1 are shown in Fig. 2.

ISBN 978-3-95450-117-5

The EEHG Section

After this, we use EEHG to bring the microbunching from 0.25 nm to 0.25 Å. The first 0.25 nm undulator has a_w = 2.58, and a period of λ_w =10 cm, and 53 total wiggler periods. In this undulator, the total energy spread grows to $\Delta\gamma_{tot}$ = 8. A total of 1.7 GW of ¼ nm radiation exits the undulator. The ¼ nm modulated beam at the end of the first ¼ nm undulator is shown in Fig. 3 (left).

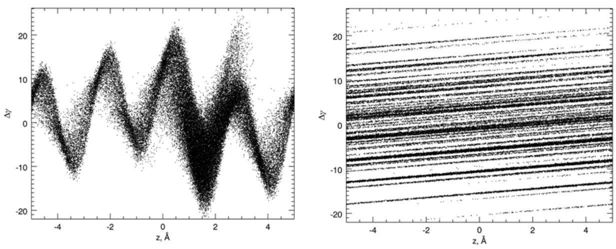

Figure 3: Phase space plots of the electrons in the first part of the EEHG section, showing $\Delta\gamma = \gamma - \gamma_0$ vs. z. (left) Phase space at the end of the first 0.25 nm undulator (right) Phase space after chicane #2.

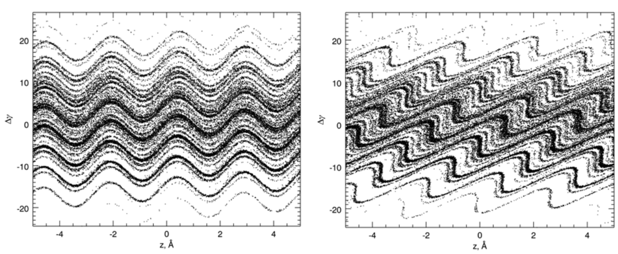

Figure 4: Phase space plots of the electrons in the first part of the EEHG section, showing $\Delta\gamma = \gamma - \gamma_0$ vs. z. (left) Phase space at the end of the second 0.25 nm undulator (right) Phase space after chicane #3.

The large chicane then applies 8 µm of R_{56} to the electron beam. This converts the modulated beam into energy bands, which are shown in Fig. 3 (right). In the 4 m chicane, the 0.25 nm x-rays from the first undulator double in size, from 20 µm to 40 µm. We simulate the 4 m diffraction of the x-ray beam by allowing a 4 m drift before the undulator starts in the GENESIS simulation of the second 0.25 nm undulator.

GENESIS simulations showed that the second 0.25 nm undulator must have low magnetic field, to prevent ISR in the undulator from destroying the energy bands. Because of this, we use an undulator with a_w=1.686, and a period of λ_w = 20 cm. The final undulator has 32 periods, and does not increase the total energy spread by a significant amount. The final energy spread is $\Delta\gamma/\gamma$ =2.1×10^{-4}. The final chicane has R_{56}=767 nm, and produces ¼ Å microbunching with a bunching factor of 8.8%. Figure 4 shows the particles after the second ¼ nm undulator, and after the final chicane.

The ¼ Å Undulator

Figure 5 shows the evolution of power in the final undulator. The saturation power is 37.8 GW, and the saturation length is 27.5 m. Since a SASE FEL at this emittance would take ~65 m to reach saturation, the SASE power does not have time to build up in this shorter distance, and the signal should remain highly coherent.

CONCLUSION

We have demonstrated a feasible design for stepping up the harmonic by a factor of 40, from 1 nm to ¼ Å. In this regime, ISR plays a significant role, because the electrons are at 20 GeV. In addition, there are no lasers at 1 nm, so the microbunched electron beam must be used to generate radiation, which then modulates the beam. The coherent 1 nm microbunching will be generated at lower energies, where there is less ISR so that large chicanes can be used. Analytical estimates indicate that this microbunching can be preserved through a long accelerator section, where the electrons are accelerated up to 20 GeV.

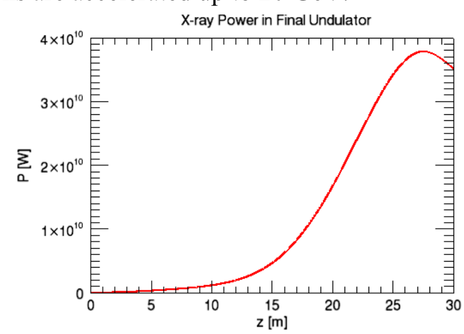

Figure 5: Evolution of ¼ Å power in the final undulator, using particles that were seeded with the combined HGHG-EEHG described in this paper.

REFERENCES

[1] B. Carlsten, K. Bishofberger, L. Duffy, S. Russell, R. Ryne, N. Yampolsky, A. Dragt, *Phys. Rev. ST Accel. Beams* 14, 050706 (2011).

[2] G. Stupakov, *Phys. Rev. Lett. 102*, 074801, (2009).

[3] D. Xiang and G. Stupakov, Phys. Rev. ST Accel. Beams 12, 030702 (2009).

[4] Y.E. Sun, P.Piot, A. Johnson, A.H. Lumpkin, T.J. Maxwell, J. Ruan and R. Thurman-Keup, Phys. Rev. Lett. 105, 234801 (2010).

[5] D. Ratner, A. Chao, Z.Huang, Phys. Rev. ST Accel. Beams 14, 020701 (2011).

[6] N. A. Yampolsky and B.E. Carlsten, "Smearing of harmonic current due to ISR-induced energy diffusion," to be submitted to Phys. Rev. ST-AB.

[6] L. Wu, Phys. Rev. A 44, 5178 (1991).

[7] B. Carlsten *et. al.*, (2011): *New X-ray free electron laser architecture for generating high fluxes of longitudinally coherent 50 keV photons*, J. Mod. Optics, DOI:10.1080/09500340.2011.604733.

[8] Q. Marksteiner, K. Bishofberger, B. Carlsten, L. Duffy, N. Yampolsky, THP162, Proceedings of the 2011 PAC conference, New York, NY.

[9] P. Piot, Y.-E Sun, J.E. Power, and M. Rihaoui, Phys. Rev. ST –AB 14, 022801 (2011).

[10] S. Reiche, Nucl. Instum. Methods Phys.Res. Sect. A, 429, 243 (1999).

ISBN 978-3-95450-117-5