ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-WEP074

SIMULATIONS OF THE DEPENDENCE OF HARMONIC RADIATION ON UNDULATOR PARAMETERS*

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Abstract

The flux and bandwidth of radiation produced at harmonics of the fundamental are very sensitive to the undulator parameter, and thus the beam energy or undulator period. We look at high-energy XFELs with parameters relevant to the MaRIE FEL design. Both SASE and seeded FELs are considered.

INTRODUCTION

One method to extend the photon energy reach of free electron lasers (FELs) is to radiate at harmonics of the resonant wavelength. There are two main versions of this technique. Nonlinear harmonic gain [1, 2] occurs as the fundamental radiation enters saturation; the microbunching becomes sufficiently strong to include a significant component at harmonics of the fundamental. This is most prominent for planar FELs, which can couple to the microbunching at odd harmonics to produce strong, forward-directed radiation. There is also linear harmonic gain, where radiation at wavelengths shorter than resonance self-amplifies. In this case the amplification process almost requires a planar undulator and use of an odd harmonic. Strong radiation at the fundamental wavelength tends to interfere with linear harmonic gain, but there are methods to overcome this [3] and, for an FEL seeded at a harmonic, that harmonic can reach saturation well before the fundamental.

Linear harmonic gain can reach much higher power than nonlinear harmonic gain. However, it is imposes greater demands on the electron beam and other systems. This paper will mostly focus on nonlinear harmonics.

IMPORTANCE OF THE UNDULATOR PARAMETER

For nonlinear harmonic generation in a planar undulator, ignoring transverse effects such as the angular and energy spread of the electrons, the ratio of the third harmonic radiation to the fundamental near saturation has been calculated as [2]:

$$\frac{P_3}{P_1} \simeq 0.094\,\frac{J_1(3\xi) - J_2(3\xi)}{J_0(\xi) - J_1(\xi)}\,, \tag{1}$$

where the J_i are Bessel functions, $\xi \equiv 0.5\,a_u^2/(1 + a_u^2)$, and a_u is the rms undulator parameter. For undulator parameters close to unity, there is a strong improvement in this ratio as a_u is increased. As the undulator parameters becomes $\gg 1$, the ideal ratio saturates close to 2.1%. The power of the fundamental also improves with the undulator parameter, but the term defined above varies more rapidly. The scaling with undulator parameter is shown in Fig. 1.

This effect is multiplied by the "3D" effects corresponding to beam emittance and energy spread. The third harmonic can only tolerate roughly 1/3rd of the energy spread or emittance, and so it can be strongly suppressed by changes which only slightly affect the fundamental.

For undulators tuned to a fundamental photon energy of 14 keV, the undulator parameter $a_u \geq 2$, and the harmonic is not sensitive to small changes in the undulator parameter.

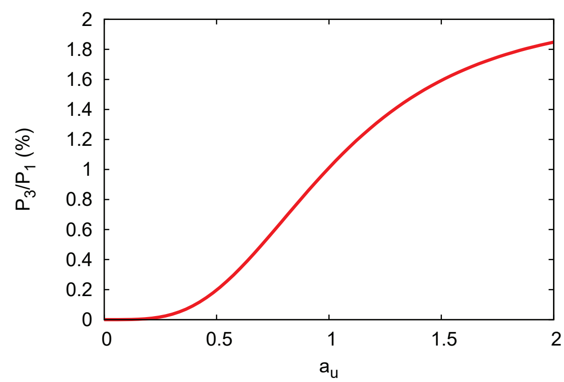

Figure 1: Scaling of the ratio of nonlinear third harmonic to fundamental radiation near saturation, for ideal beams.

BEAM PARAMETERS AND CONFIGURATION

The beamline parameters are modeled loosely after those of the MaRIE X-FEL [4] as summarized in Table 1. A self-seeding stage uses undulators tuned to 14 keV to produce not only strong SASE radiation at the fundamental but also a significant 3rd harmonic component. This harmonic component is then put through a monochromator. At this point, there can be a fresh-slice [5] or multi-bunch stage to allow for unperturbed electrons to interact with the narrow-bandwidth 40-keV radiation. This radiation is then amplified and can be used to produce third harmonic radiation in turn.

The undulator sections used for the final stage are taken to each be 3.6 m in length. Breaks in between sections are either 0.9 m or 1.26 m in length. Undulator periods in the range of 15 mm to 20 mm have been considered, corresponding to undulator parameters of 1.10 to 0.81. The corresponding ideal ratio P_3/P_1 ranges from to 1.16% to 0.69%. Superconducting undulators with a 15-mm period are consistent with a beam pipe diameter of roughly 9 mm, if a large tuning range is not required. PPM undulators with an 18-mm period are consistent with a beam pipe diameter of roughly 5 mm. Advanced designs such as superconducting

* This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
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or in-vacuum undulators would be helpful in improving the performance, allowing for more beam clearance, and reducing wake fields.

Table 1: Beam Parameters

Energy	12 GeV
Energy spread	1.2 MeV
Peak current	3 kA
Emittance	0.2 µm
Beta function	15 m
Radiation wavelength	0.01, 0.03, 0.09 nm
Undulator period	15 — 20 mm
Undulator section	3.6 m

SIMULATION RESULTS

The self-seeding stage to yield 40-keV photons is not simulated; instead, the beam is assumed to be unperturbed, possibly using the fresh-slice or multi-bunch technique, and the radiation is taken to be monochromatic with a peak power of 100 kW. The precise value of this power is mostly important in determining the length of the amplification stage, although for realistic beams the bandwidth will tend to grow as variations in the slice energy lead to phase shifts. The seeded power must also be well above noise levels. From there, nonlinear harmonic generation of the third harmonic is simulated using the GENESIS simulation code [6].

Although linear amplification of the 40-keV photons in undulators tuned to 14 keV is a possibility, the gain length using this method is close to and slightly longer than the gain length for undulators tuned to a fundamental of 40 keV. Furthermore, the saturated power is significantly lower. As there is no advantage to using this scheme, results for this case are not shown. For different electron beam parameters the ratio of gain lengths could be more promising. Similarly, linear amplification of the third harmonic in undulators tuned to 40 keV is suppressed by the beam emittance and energy spread. Thus, the focus is on direct amplification of 40 keV radiation, and the production of 120-keV photons by nonlinear harmonic generation.

The undulator strength was not tapered from section to section, which could improve performance. However, the average energy loss due to incoherent synchrotron radiation was removed, which has the effect of a fixed linear undulator taper.

The results are shown in Figs. 2 and 3 for the power radiated at the 40-keV fundamental and the third harmonic, respectively. For the fundamental, there is a modest improvement in power near saturation both as the undulator period is made shorter and as the breaks between undulator sections are made shorter. The third harmonic shows almost an order of magnitude improvement with shorter undulator period (and thus larger undulator parameter), while the impact of reducing the break between undulators is mostly to reduce the distance required to reach saturation. The third harmonic continues to grow past saturation, even without undulator taper. The impact of tapering should be explored.

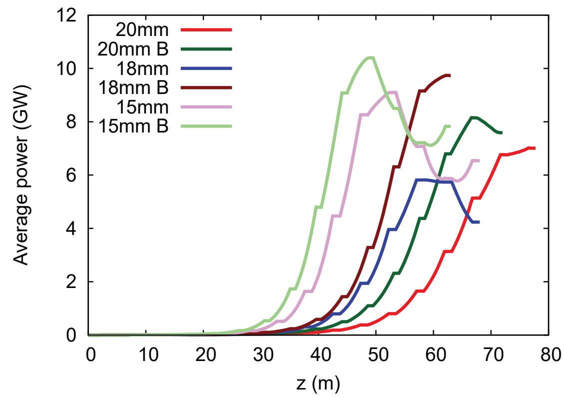

Figure 2: Radiation at the fundamental tuned to 40 keV starting with a seed having peak power of 100 kW, for various undulator choices. Curves marked with a "B" have a smaller break between undulator sections.

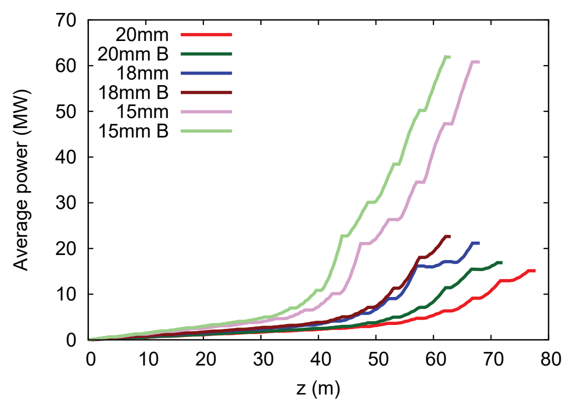

Figure 3: Radiation at the third harmonic for undulators tuned to a fundamental of 40 keV, starting with a seed having peak power of 100 kW, for various undulator choices. Curves marked with a "B" have a smaller break between undulator sections.

The radiated power at the third harmonic is mostly produced in the final undulators after the fundamental has reached saturation. Thus, it should be possible initially to use longer period undulators, and only switch to shorter period undulators near the end of the undulator line. In Fig. 4, the power at the third harmonic is shown for the case of larger breaks between undulators, where the initial undulator period is 18 mm and is then switched to undulators with a 15-mm period after either 49 m or 58 m. The cases of uniform undulator lines with periods of 15, 18, or 20 mm are shown for comparison. By changing over after 49 m, the power produced after 80 m almost matches that of the case where all undulators have a 15-mm period. Waiting until after 58 m to switch undulators yields a final power that is roughly in the middle of the output from undulators that are all 15-mm or all 18-mm period.

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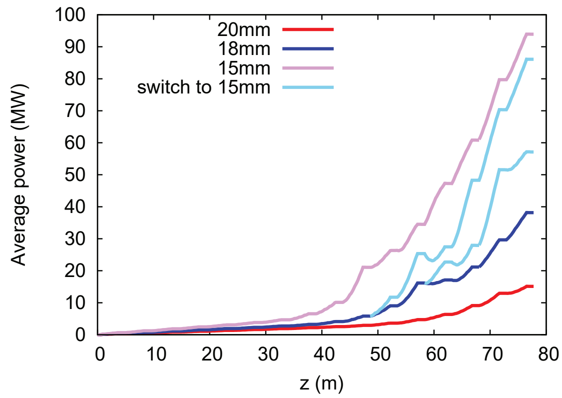

Figure 4: Radiation at the third harmonic for undulators tuned to a fundamental of 40 keV, ending around 80 m after the self-seeding monochromator. Various undulator periods are considered, including switching from 18-mm to 15-mm period for the final sections.

CONCLUSION

For generating harmonics through nonlinear harmonic gain, the undulator parameter is an important quantity to optimize. Besides changing the undulator period, the undulator parameter can be increased by going to higher electron energy. For example, changing the beam energy to 14 GeV will raise the resonant a_u for an 18-mm period undulator from 0.92 to 1.23. The "fill fraction", or percentage of the undulator line that is taken up by active undulators instead of drift sections, does not seem to have as strong an effect, although the fill fraction was only varied from 74% to 80%.

Another important impact on radiation at harmonics is the electron beam energy spread. A fresh-slice or fresh-bunch stage before reaching saturation of the fundamental could increase the final power radiated at the third harmonic. If the fresh-slice technique is used for the self-seeding, and the unperturbed part of the bunch could be made twice as long as the initial radiating part, a simple delay line could move the seeded portion of the radiation to a reasonably unperturbed part of the bunch. To maintain good spectral quality, microbunching and wake fields need to be minimized. The use of energy spread heating to control microbunching will be limited by tight tolerances on the energy spread to allow for good coupling to the third harmonic.

REFERENCES

[1] R. Bonifacio, L. De Salvo and P. Pierini, "Large harmonic bunching in a high-gain free-electron laser," *Nucl. Instr. Meth. A*, 293:627–629, 1990. doi:10.1016/0168-9002(90)90334-3.

[2] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, "Properties of the third harmonic of the radiation from self-amplified spontaneous emission free electron laser," *Phys. Rev. ST Accel. Beams*, 9:030702, 2006. doi: 10.1103/PhysRevSTAB.9.030702.

[3] E.A. Schneidmiller and M.V. Yurkov, "Harmonic lasing in x-ray free electron lasers," *Phys. Rev. ST Accel. Beams*, 15:080702, 2012. doi: 10.1103/PhysRevSTAB.15.080702.

[4] J.W. Lewellen, K.A. Bishofberger, B.E. Carlsten, *et al.*, "Status of the MaRIE X-FEL accelerator design," in *Proc. 6th Int. Particle Accelerator Conf.,* Richmond, VA, USA, 2015. TUPMA026.

[5] A.A. Lutman, T.J. Maxwell, J.P. MacArthur, M.W. Guetg *et al.*, "Fresh-slice multicolour X-ray free-electron lasers," *Nature Photonics*, 10:745–750, 2016. doi:10.1038/NPHOTON.2016.201.

[6] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code." *Nucl. Instr. Meth. A*, 429:243–248, 1999. doi:10.1016/S0168-9002(99)00114-X.