SUPPRESSION OF THE FUNDAMENTAL FREQUENCY FOR A SUCCESSFUL HARMONIC LASING IN SASE FELS

E.A. Schneidmiller, M.V. Yurkov, DESY, Hamburg, Germany

Abstract

Harmonic lasing in X-ray FELs has recently attracted a significant attention and is now seriously considered as a potential method for generation of brilliant photon beams at short wavelengths. It is clear, however, that for a successful harmonic lasing one has to suppress the fundamental. In this paper we discuss different methods for such a suppression: phase shifters, intraundulator spectral filtering, and switching between the 3rd and the 5th harmonics.

INTRODUCTION

Harmonic lasing in single-pass high-gain FELs [1–7] is the radiative instability at an odd harmonic of the planar undulator developing independently from lasing at the fundamental. Contrary to nonlinear harmonic generation (which is driven by the fundamental in the vicinity of saturation), harmonic lasing can provide much more intense, stable, and narrow-band FEL beam if the fundamental is suppressed. The most attractive feature of saturated harmonic lasing is that the brilliance of a harmonic is comparable to that of the fundamental. Indeed, a good estimate for the saturation efficiency is $\lambda_{\mathrm{w}}/(hL_{\mathrm{sat}})$, where λ_{w} is the undulator period, L_{sat} is the saturation length, and h is harmonic number. At the same time, the relative rms bandwidth has the same scaling. If we consider lasing at the same wavelength on the fundamental and on a harmonic (with the retuned undulator parameter K), transverse coherence properties are about the same since they are mainly defined by emittance-to-wavelength ratio. Thus, also the brilliance is about the same in both cases. In many cases, however, the saturation length for harmonics is significantly shorter than that of the fundamental at the same wavelength. As a consequence, for a given undulator length one can reach saturation on harmonics at a shorter wavelength. It was shown in a recent study [6] that the 3rd and even the 5th harmonic lasing in X-ray FELs is much more robust than usually thought, and can be widely used at the present level of accelerator and FEL technology.

For a successful harmonic lasing the fundamental mode must be suppressed. Otherwise it saturates earlier and spoils the longitudinal phase space of the electron beam thus preventing further exponential growth of harmonics. In this paper we discuss and compare different methods of suppression.

PHASE SHIFTERS

An elegant method to disrupt the fundamental without affecting the third harmonic lasing was suggested in [4]: one can use phase shifters between undulator modules. If phase shifters are tuned such that the phase delay is $2\pi/3$ (or $4\pi/3$) for the fundamental, then its amplification is disrupted. At the same time the phase shift is equal to 2π for the third harmonic, i.e. it continues to get amplified without being affected by phase shifters. We define phase shift in the same way as it was done in [4] in order to make our results compatible with the previous studies. For example, the shift $2\pi/3$ corresponds to the advance of a modulated electron beam with respect to electromagnetic field by $\lambda/3$.

Table 1: Parameters of Electron Beam and Undulator

Electron beam	Value
Energy	1.25 GeV
Charge	150 pC
Peak current	2.5 kA
Rms normalized slice emittance	0.5 µm
Rms slice energy spread	250 keV
Rms pulse duration	24 fs

Undulator	Value
Fundamental wavelength	3.9 nm
Period	2.3 cm
K_{rms}	1
Beta-function	7 m
Net magnetic length	25 m

Since there are two possible phase shifts, one can consider different ways of their distributions along the undulator. Here we compare four strategies studied in the literature [4–6, 8] by performing simulations with the code FAST [9]. For the sake of comparison we take a set of parameters from a proposal for FLASH upgrade for harmonic lasing up to 1 keV [7]. The parameters of the beam and the undulator are summarized in Table 1. The undulator is supposed to be made of 3 m long segments with integrated phase shifters (in addition to phase shifters between the segments) such that the distance between the phase shifters is 0.5 m.

In the following we present the results of simulations with four different ways of distribution of phase shifters.

Consecutive Use of the Same Phase Shifts

This variation of the phase shifters method was considered in [4]. The simulations in [4] were done for the case of a monochromatic seed, and the results cannot be applied for a SASE FEL. The reason is that in the latter case the amplified frequencies are defined self-consistently, i.e. there is frequency shift (red or blue) depending on positions and magnitudes of phase kicks. This leads to a significantly weaker suppression effect. We illustrate this for the SASE FEL with the parameters from Table 1.

ISBN 978-3-95450-133-5

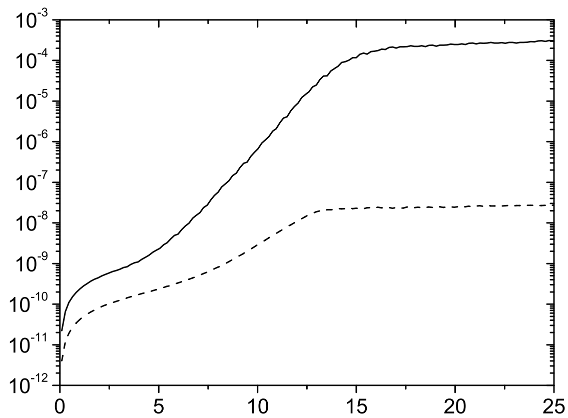

Figure 1: Pulse energy versus magnetic length of the undulator for the fundamental (solid) and the 3rd harmonic (dash). Electron beam and undulator parameters are given in Table 1. Phase shifters are located after every 0.5 m long section of the undulator. All the phase shifts are set to $2\pi/3$.

In Fig. 1 we present the gain curve for the case of using only $2\pi/3$ phase shifters (the case of only $4\pi/3$ phase shifters look similar). One can see that the method is inefficient. The saturation of the fundamental is delayed by about 20%, which is not sufficient for letting the third harmonic reach saturation. Instead, at the position $z \simeq 13$ m in the undulator the fundamental enters nonlinear regime and spoils the longitudinal phase space such that the exponential growth of the third harmonic is stopped. It is interesting to notice that there is no nonlinear harmonic generation which is usually expected to result in emission of radiation on the 3rd harmonic at the level of 1% of the fundamental. This effect is explained in [7].

We can conclude that the version of the phase shifter method, considered in [4], is inefficient in suppression of the fundamental in the case of SASE FELs (although ii works well in the case of a monochromatic seed, see [4]) even if the number of phase shifters is very large.

Alternation of Phase Shifts $2\pi/3$ and $4\pi/3$

The second version of the phase shifter method was proposed in [5]: one should use an alternation of $2\pi/3$ and $4\pi/3$ phase shifters. In this case two frequency bands are generated at the fundamental, and the gain is reduced. We have simulated this configuration with the same parameters of the beam and the undulator. The results are shown in Fig. 2. One can see that this modification of the method works better, i.e. the saturation of the fundamental is delayed more significantly. However, this is still not sufficient to provide the 3rd harmonic lasing up to its saturation in the considered case.

Piecewise Use of Phase Shifts $2\pi/3$ and $4\pi/3$

In [6] we proposed another modification of phase shifters method that works better in the case of a SASE FEL. In the following we assume that a distance between phase shifters is shorter than the gain length of the fundamental harmonic.

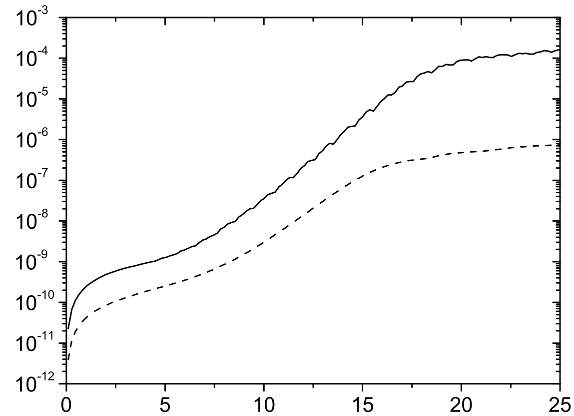

Figure 2: Pulse energy versus magnetic length of the undulator for the fundamental (solid) and the 3rd harmonic (dash). Electron beam and undulator parameters are given in Table 1. Phase shifters are located after every 0.5 m long section of the undulator, the phase shifts are $2\pi/3$ for the even phase shifters, and $4\pi/3$ for the odd ones.

Our method of disrupting the fundamental mode can be defined as a piecewise use of phase shifters with the strength $2\pi/3$ and $4\pi/3$. For example, in the first part of the undulator (consisting of several segments with phase shifters between them) we introduce phase shifts $4\pi/3$. A red-shifted (with respect to a nominal case without phase shifters) frequency band is amplified starting up from shot noise. In the following second part of the undulator we use $2\pi/3$ phase shifts, so that the frequency band, amplified in the first part, is practically excluded from the amplification process. In a realistic 3D case, the radiation is diffracted out of the electron beam, and the density and energy modulations within this frequency band are partially suppressed due to emittance and energy spread while the beam is passing the second part of the undulator (although the suppression effect is often not strong). Instead, a blue-shifted frequency band is amplified in the second part of the undulator, starting up from shot noise. Then, in the third part we change to no phase shifts case, then again to $4\pi/3$ in the fourth part, etc. A more complicated optimization can include using one or two $2\pi/3$ shifts in the first part with $4\pi/3$ phase shifters, and so on. The efficiency of the method strongly depends on the ratio of the distance between phase shifters and the gain length of the undisturbed fundamental mode. The smaller this ratio, the stronger suppression can be achieved after optimization of phase shifts distribution.

In Fig. 3 we present the results of simulations with the parameters from Table 1 and optimized distribution of phase shifts. One can see that the piecewise method works well in the considered case, i.e. it allows to suppress the fundamental such that the third harmonic reaches saturation while the fundamental is still well below its saturation.

We can simply generalize the method to the 5th harmonic lasing. One can introduce a piecewise combination of some of the phase shifts $2\pi/5$, $4\pi/5$, $6\pi/5$, or $8\pi/5$ (for the fundamental frequency). In this case also the third harmonic will

ISBN 978-3-95450-133-5

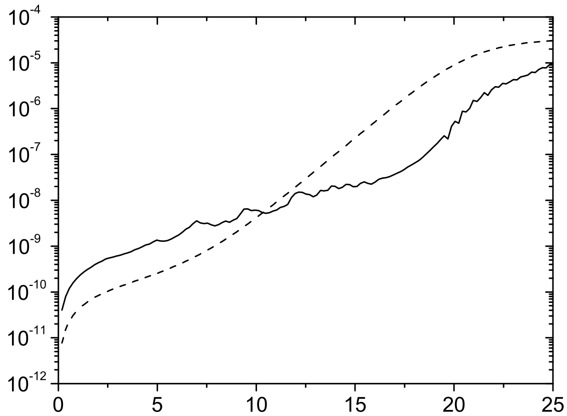

Figure 3: Pulse energy versus magnetic length of the undulator for the fundamental (solid) and the 3rd harmonic (dash). Electron beam and undulator parameters are given in Table 1. Phase shifters are located after every 0.5 m long section of the undulator. The phase shift is $4\pi/3$ after sections 1-4, 6-9, 11-13, 18, 23, 39-49, and $2\pi/3$ after sections 5, 10, 14-17, 19-22, 24-27.

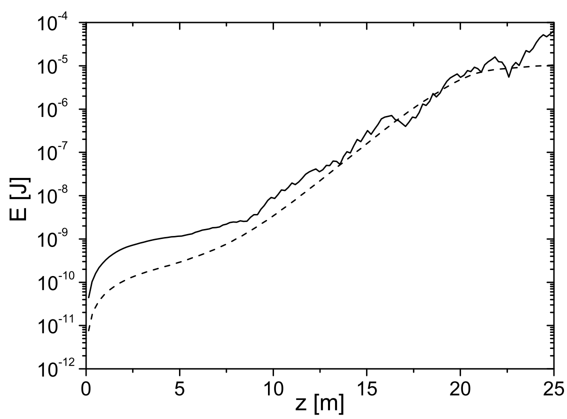

Figure 4: Pulse energy versus magnetic length of the undulator for the fundamental (solid) and the 3rd harmonic (dash). Electron beam and undulator parameters are given in Table 1. Phase shifters are located after every 0.5 m long section of the undulator. A choice between phase shifts $2\pi/3$ and $4\pi/3$ is randomly generated.

see the disrupting shifts, while the fifth harmonic will not be affected. If the number of phase shifters is sufficient, the fundamental mode and the third harmonic can be strongly suppressed.

Random Distribution of Shifts $2\pi/3$ and $4\pi/3$

This variation of phase shifters method is proposed in [8]. We simulated this method using the parameters from Table 1 again. We tried 5 different random realizations of phase shifts, the best result is shown in Fig. 4. One can notice that the approach with random distributions promises better suppression than the first two approaches using regular distributions. However, it looks somewhat less effective than the optimized piecewise distribution.

At the end of our studies of the phase shifters method, we can conclude that the method works but one needs a lot of phase shifters and a fancy way of their distribution.

INTRAUNDULATOR SPECTRAL FILTERING

The method was proposed in [6], its idea is simple: at a position in the undulator where the fundamental harmonic is in the high-gain linear regime (well below saturation), the electron beam trajectory deviates from a straight line, and a filter is inserted that strongly suppresses the fundamental mode but only weakly affects the third harmonic. As a simple bending system one can use, for example, a chicane that substitutes one of the undulator segments as it is done at LCLS [10] for operation of the self-seeding scheme [11]. A possible alternative is to make a closed bump with the help of moving quadrupoles of the undulator focusing system (quadrupoles are usually placed after each undulator segment, so that in this case two segments are excluded from lasing). Although the main purpose of the bending system is to provide an offset for insertion of a filter, it has to satisfy two other requirements: on the one hand a delay of the bunch with respect to a radiation pulse must be smaller than the bunch length; on the other hand, the R_{56} (equal to the double delay) should be sufficient for smearing of energy and density modulations at the fundamental wavelength: $2\pi\sigma_\gamma R_{56}/(\gamma\lambda_1) \gg 1$. Both conditions can be easily satisfied simultaneously in most cases. The active length of the first part of the undulator is chosen such that, on the one hand, the highest possible gain is achieved; on the other hand, energy modulations, induced by the FEL interaction at the fundamental wavelength (and converted to uncorrelated energy spread through the chicane), should be sufficiently small to avoid a significant increase of gain length of the third harmonic in the second part of the undulator.

We present here a numerical example for third harmonic lasing at LCLS at the photon energy of 25 keV with a significant power and a relatively narrow intrinsic bandwidth. LCLS undulator consists of 33 identical 3.4-m-long segments, undulator period is 3 cm, and the peak undulator parameter is 3.5 (rms value of K is 2.5). The 16th segment is replaced with a chicane (hard X-ray self-seeding, or HXRSS chicane) for operation of the self-seeding scheme [11]. As a possible realization of the filter we propose here a silicon crystal that is not supposed to spoil phase front of the third harmonic radiation while attenuating the fundamental harmonic by orders of magnitude. A thickness of the crystal is defined by a required attenuation factor and an expected photon energy range. As an example we consider here the thickness of 600 µm and third harmonic lasing at 25 keV. Attenuation length at 8.3 keV is $\mu^{-1} = 73\ \mu$m, and at 25 keV it is $\mu^{-1} = 1.85$ mm [12], so that the corresponding transmission factors are 2.7×10^{-4} and 0.72. With a given thickness of the crystal the scheme would work well in the range 20-30 keV, and for lower photon energies of the third harmonic a thinner crystal would be needed.

ISBN 978-3-95450-133-5

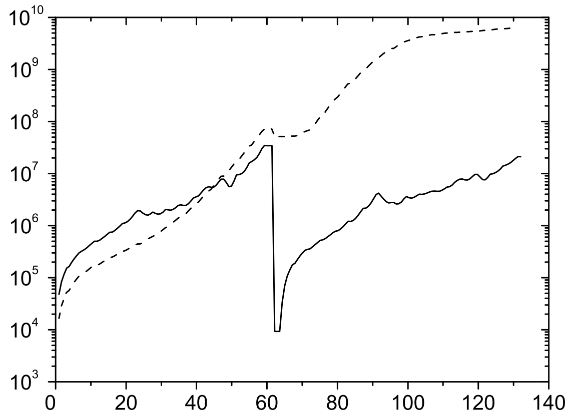

Figure 5: Averaged peak power for the fundamental harmonic (solid) and the third harmonic (dash) versus geometrical length of the LCLS undulator (including breaks). The wavelength of the third harmonic is 0.5 Å (photon energy 25 keV). Beam and undulator parameters are in the text. The fundamental is disrupted with the help of the spectral filter (see the text) and of the phase shifters. The phase shifts are $4\pi/3$ after segments 1-5 and 17-22, and $2\pi/3$ after segments 6-10 and 23-28. Simulations were performed with the code FAST.

In the considered parameter range the spectral filtering method alone is not sufficient, therefore we suggest to combine it with the phase shifters method. We propose to install phase shifters with the shift $4\pi/3$ after undulator segments 1-5 and 17-22, and with the shift $2\pi/3$ after segments 6-10 and 23-28. Let us consider a specific parameter set for third harmonic lasing at 0.5 Å (photon energy 25 keV). The electron beam parameters are as follows: energy is 13.6 GeV (the fundamental wavelength is 1.5 Å), peak current is 3 kA, normalized slice emittance is 0.3 µm, uncorrelated energy spread is 1.4 MeV. The beta-function in the undulator is 30 m. In our simulations we do not consider a specific bunch length, so that our result is the peak power of the third harmonic radiation in the part of the pulse that overlapped with the electron beam after the chicane. We performed simulations with the code FAST [9], the results are presented in Fig. 5. The averaged peak power of the third harmonic radiation is 6 GW, and an intrinsic bandwidth is 3×10^{-4} (FWHM). The power incident on the crystal is in the range of tens of megawatts, and should not be problematic from the point of view of peak and average power load.

It was suggested [13] to perform a test experiment at 18 keV with the filter installed in the soft X-ray self-seeding (SXRSS) chicane and without phase shifters (using only HXRSS chicane as a phase shifter). If this experiment will be successful, one can think of installation of an additional filter in HXRSS chicane and/or phase shifters.

SWITCHING BETWEEN THE 3RD AND THE 5TH HARMONICS

This method was proposed at DESY [14] and independently by SLAC/LBNL group [8]. The method is based on the observation that in some practical cases the gain lengths of the 3rd and the 5th harmonics are close to each other [14]. Thus, the following trick is possible. Imagine, we aim at lasing at 1 Å. We tune the first part of the undulator to the resonance with 5 Å, so that we are interested in the 5th harmonic lasing. The fundamental and the third harmonic are suppressed by the piecewise combination of (some of the) phase shifters $2\pi/5$, $4\pi/5$, $6\pi/5$, and $8\pi/5$ such that they stay well below saturation in the first part of the undulator. Then, in the second part we reduce parameter K such that the resonance at 3 Å is achieved. Now the fifth harmonic from the first part continues to get amplified as the third harmonic (while the first and the third ones are off resonance). The fundamental in the second part is suppressed with the help of piecewise distribution of phase shifters $2\pi/3$ and $4\pi/3$. If necessary, one can later switch back to a resonance with 5 Å, and so on. Also, a use of many pieces with 5th and 3rd harmonic lasing without phase shifters might be possible. Moreover, the scheme can be generalized to the case of even higher harmonics.

CONCLUSION

There exist different methods for suppression of the fundamental to provide conditions for harmonic lasing. There is also a hope that more methods will be invented as soon as the interest to this mode of operation will grow.

REFERENCES

[1] J.B. Murphy, C. Pellegrini and R. Bonifacio, Opt. Commun. **53**(1985)197

[2] R. Bonifacio, L. De Salvo, and P. Pierini, Nucl. Instr. Meth. A293(1990)627.

[3] Z. Huang and K. Kim, Phys. Rev. E, 62(2000)7295.

[4] B.W.J. McNeil et al., Phy. Rev. Lett. 96, 084801 (2006)

[5] G. Parisi et al., Proc. of the FEL2005 Conference, Stanford, California, USA, p. 187, [http://www.jacow.org]

[6] E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST-AB **15**(2012)080702

[7] E.A. Schneidmiller and M.V. Yurkov, Nucl. Instr. Meth. A717(2013)37.

[8] G. Marcus, Z. Huang, T. Raubenheimer, and G. Penn, "Harmonic Lasing Options for LCLS-II", presented at this Conference, MOP054, Proc. of the FEL2014 Conference, Basel, Switzerland.

[9] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Nucl. Instrum. and Methods **A 429**(1999)233

[10] P. Emma et al., Nature Photonics **4**(2010)641

[11] G. Geloni, V. Kocharyan and E. Saldin, preprint DESY-10-133, August 2010

[12] `www.csrri.iit.edu/mucal.html`

[13] D. Ratner et al., Proc. of the FEL2013 Conference, New York, USA, p. 623, [http://www.jacow.org]

[14] R. Brinkmann, E.A. Schneidmiller, J. Sekutowicz and M.V. Yurkov, preprint DESY-14-025, March 2014; arXiv:1403.0465

ISBN 978-3-95450-133-5