A POSSIBLE UPGRADE OF FLASH FOR HARMONIC LASING DOWN TO 1.3 nm

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Abstract

We propose the 3rd harmonic lasing in a new FLASH undulator as a way to produce intense, narrow-band, and stable SASE radiation down to 1.3 nm with the present accelerator energy of 1.25 GeV. To provide optimal conditions for harmonic lasing, we suggest to suppress the fundamental with the help of a special set of phase shifters. We rely on the standard technology of gap-tunable planar hybrid undulators; total length of the undulator system is 34.5 m. With the help of numerical simulations we demonstrate that the 3rd harmonic lasing at 1.3 nm provides peak power at a gigawatt level and the narrow intrinsic bandwidth, 0.1% (FWHM). Pulse duration can be controlled in the range of a few tens of femtoseconds, and the peak brilliance reaches the value of 10^{31} photons/($\mathrm{s\ mrad^2\ mm^2\ 0.1\%\ BW}$). With the given undulator design, a standard option of lasing at the fundamental wavelength to saturation is possible through the entire water window and at longer wavelengths.

INTRODUCTION

FLASH (Free electron LASer in Hamburg) is the first VUV and soft X-ray FEL user facility [1]. Presently, the facility is operated for users with the accelerator energy up to 1.25 GeV and the shortest wavelength of 4.1 nm, i.e. the photon energy is slightly above Carbon K-edge. This makes it possible to perform first experiments in the so-called water window. However, even shorter wavelengths are requested by the FLASH user community. In particular, lasing through the entire water window (i.e. down to 2.34 nm) would be interesting for some experiments. Moreover, resonant magnetic scattering studies would strongly profit from lasing down to 1.3 nm. In this case the L-edges of the most interesting materials would be covered. One of the possible ways to extend wavelength range would be an upgrade of FLASH beyond 2 GeV. However, such an extensive energy upgrade is not possible in the next few years. In this paper we propose an alternative way, namely using the present accelerator energy of 1.25 GeV and the 3rd harmonic lasing in a new undulator.

Harmonic lasing in single-pass high-gain FELs [2–7] is the radiative instability at an odd harmonic of the planar undulator developing independently from lasing at the fundamental wavelength. 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 which is easier to handle due to the suppressed fundamental. The most attractive feature of saturated harmonic lasing is that the brilliance of a harmonic is comparable to (or even larger than) that of the fundamental. In our recent study [7] we came to the conclusion that the 3rd 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.

In this paper we show that the saturation of 3rd harmonic lasing at 1.3 nm can be achieved within 25 m (net magnetic length) of the optimized undulator at FLASH if we assume that slice parameters of the electron beam are close to those taken from start-to-end simulations [9]. In the same undulator one can lase to saturation at the fundamental wavelength through the entire water window. More details can be found in [8] where we have also considered such additional options as polarization control, bandwidth reduction, self-seeding, X-ray pulse compression, and two-color operation.

MAIN PARAMETERS

A possibility of FLASH operation in the considered wavelength range (down to 1.3 nm) is supported by recent achievements in production of low-emittance electron beams. Start-to-end simulations [9] for FLASH and the European XFEL have shown that low emittances can be preserved during bunch compression and transport of electron beams to the undulator. In Table 1 we present parameters of the electron beam that were used in our FEL simula-

Table 1: Electron Beam and Undulator Parameters

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**
Period	2.3 cm
Minimum gap	9 mm
K_{rms} (at minimum gap)	1
Beta-function	7 m
Net magnetic length	25 m
Total length	34.5 m

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tions (the results are shown below in this paper). We used the model of Gaussian bunch with the charge of 150 pC and slice parameters close to those obtained in start-to-end simulations [9] in this range of charges.

Parameters of the new undulator are also presented in Table 1. Several gap-tunable hybrid undulators with the period of 2.3 cm are in operation at the Advanced Photon Source, and for the gap of 9 mm the rms value of K (which is equal to peak value divided by $\sqrt{2}$) in the Table 1 is very safe and conservative. As it was already mentioned, an unusual feature of the proposed undulator is a big number of phase shifters that are necessary for a sure suppression of the fundamental. We propose to build a 3 m long undulator module consisting of 0.5 m long sections with a phase shifter behind each section, see Fig. 1. Phase shifters for this parameter range can be made compact: either permanent magnet or electromagnetic phase shifters can easily fit in 10 cm space between sections. We assume that the gap between two modules, shown schematically in Fig. 1, is 0.5 m long (for quadrupoles, BPMs etc.), so that with 10 modules the total length of the undulator system is 34.5 m, and the net magnetic length is 25 m. The tunability range for this undulator length was calculated with the help of formulas from [7] and is presented in Fig. 2.

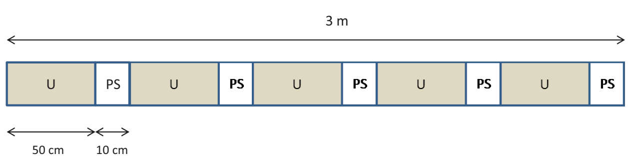

Figure 1: Schematic view of an undulator module, consisting of undulator sections (U) and phase shifters (PS).

If we want the third harmonic to lase to its saturation, we have to suppress the fundamental. A method to disrupt the fundamental (while keeping the lasing at the third harmonic undisturbed) was proposed in [5]. In case of gap-tunable undulators, phase shifters are foreseen between the undulator segments. 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. However, the simulations in [5] 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. In particular, a consecutive use of phase shifters with the same phase kicks $2\pi/3$ (or $4\pi/3$) is inefficient, i.e. it does not lead to a sufficiently strong suppression of the fundamental wavelength. The method was generalized in [6], where the alternation of the shifts

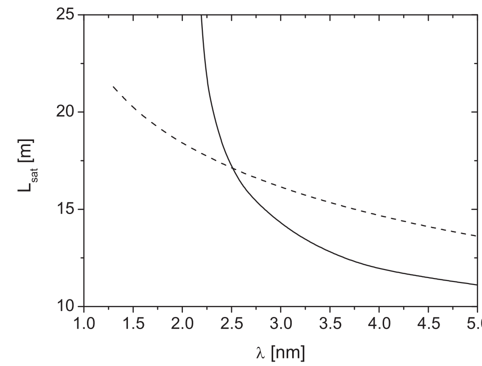

Figure 2: Saturation length of the fundamental (solid) and of the 3rd harmonic (dash) versus wavelength. In the case of the 3rd harmonic the tuning of wavelength is done by changing beam energy for a fixed gap with $K_{\rm rms} = 1$. In the case of the fundamental the tuning is achieved by changing $K_{\rm rms}$ at fixed beam energy of 1.25 GeV for wavelengths shorter than 3.9 nm, and by changing beam energy at $K_{\rm rms} = 1$ for longer wavelengths. In all cases the beam energy does not exceed 1.25 GeV. Other parameters are given in Table 1.

$2\pi/3$ and $4\pi/3$ was considered. This improves the situation, but still does not provide a sure suppression of the fundamental in realistic situations. In [7] we proposed another modification of phase shifters method that works better in the case of a SASE FEL. Our method of disrupting the fundamental mode can be defined as a piecewise use of phase shifters with the strength $2\pi/3$ and $4\pi/3$. A compar-

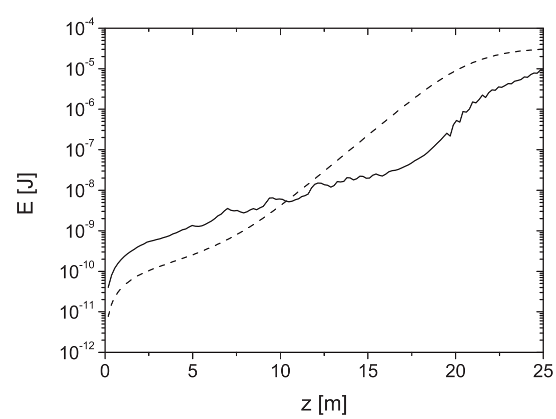

Figure 3: Pulse energy versus magnetic length of the undulator for the fundamental (solid) and the 3rd harmonic (dash). Electron beam and undulator parameters are given in Table 1. Phase shifters are located after every 0.5 m long section of the undulator. The phase shift is $4\pi/3$ after sections 1-4,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

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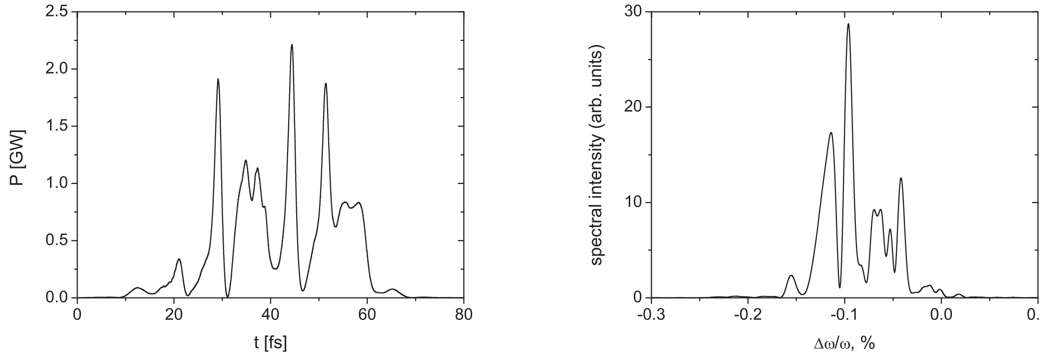

Figure 4: Single shot radiation power (left plot) of the 3rd harmonic at saturation and the corresponding spectrum (right plot). Radiation wavelength is 1.3 nm. Electron beam and undulator parameters are given in Table 1.

ison between the three modifications of the phase shifter method can be found in Appendix A. Below we present an example on the optimized distribution of phase shifters. The result of our studies is that in the considered parameter range we need a distance about 0.5 m between phase shifters.

THIRD HARMONIC LASING IN A NEW UNDULATOR

Third harmonic lasing to saturation at 1.3 nm is possible in the undulator described in Section 2. We performed numerical simulations with the code FAST [10] recently adapted for harmonic lasing. In the simulations we used the parameters presented in Table 1. In order to disrupt the fundamental harmonic with the help of phase shifters, we used the approach described in Section 2. The phase shifters are positioned after every 0.5 m long section of the undulator, and the distribution of the phase shifts is specified in the caption to Fig. 3. One can see from this Figure that the fundamental is sufficiently suppressed, and the 3rd harmonic can reach saturation without being disturbed by the fundamental. Note that if the power of the fundamental (about 30% of the 3rd harmonic power in Fig. 3) would hamper an experiment, it could easily be filtered out by, for example, Aluminum filter.

In Fig. 4 we present radiation power of the third harmonic at saturation (single shot), and the corresponding spectrum. One can see that the third harmonic lasing reaches gigawatt level of power, and also provides a narrow bandwidth, about 0.1% (FWHM).

Ensemble-averaged parameters of the radiation are summarized in Table 2. Note that pulse duration and pulse energy can be varied within some range by changing, for example, bunch charge, while keeping slice parameters at the values close to those from Table 1. Analyzing Table 2, we come to the conclusion that the third harmonic lasing to saturation produces a very bright photon beam. In particular, peak brilliance, a figure-of-merit of an X-ray FEL performance, may reach the record value for FLASH. Parameters from Table 2 can satisfy many user experiments, in particular, resonant magnetic scattering experiments.

Table 2: Radiation Parameters for Saturated 3rd Harmonic Lasing

Parameter	Value
Wavelength	1.3 nm
Averaged peak power	1 GW
Pulse energy	30 μJ
Shot-to-shot fluctuations	$<$ 10 %
Pulse duration (FWHM)	30 fs
Bandwidth (FWHM)	0.1 %
Angular divergence (FWHM)	10 μrad
Peak brilliance	10^{31}

APPENDIX A: THIRD HARMONIC PERFORMANCE FOR DIFFERENT DISTRIBUTIONS OF PHASE SHIFTS

We would like to compare different versions of the phase shifter method for suppression of the fundamental originally proposed in [5]. We use beam and udulator parameters from Table 1 and aim at the third harmonic lasing at 1.3 nm, i.e. the fundamental at 3.9 nm must be disrupted.

The first version of the method is the consecutive use of the same phase shifts, as proposed in [5]. In Fig. 5 we present the gain curves for the case of using only $2\pi/3$ phase shifters (left plot) or only $4\pi/3$ phase shifters (right plot). One can see that in both cases the method is inefficient, and also that there is only a minor difference between the two cases. 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.

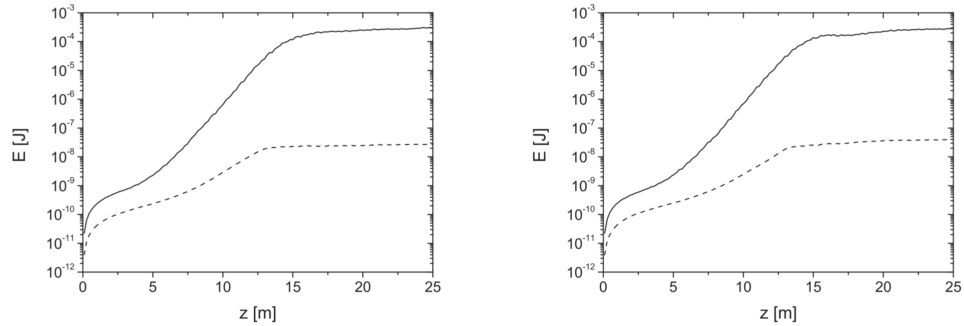

Figure 5: Pulse energy versus magnetic length of the undulator for the fundamental (solid) and the 3rd harmonic (dash). Electron beam and undulator parameters are given in Table 1. Phase shifters are located after every 0.5 m long section of the undulator. The phase shifts are $2\pi/3$ for the left plot, and $4\pi/3$ for the right plot.

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 can be explained as follows. As we already mentioned in this paper (and discussed in detail in [7]), there is a frequency shift $\Delta\omega$ of the fundamental that depends on a number and a magnitude of phase shifts. When the fundamental saturates (at frequencies around $\omega_1 + \Delta\omega$, where ω_1 is the resonant frequency of the undulator), the density bunching contains higher harmonics at frequencies $h(\omega_1 + \Delta\omega)$, h being harmonic number. Normally, the odd harmonics of the bunching would produce coherent radiation at frequencies around $h\omega_1$ in a planar undulator, but in the case under consideration a significant frequency offset $h\Delta\omega$ does not let them do it. Thus, as a by-product of our studies we can propose a method for suppression of nonlinear harmonic generation which can be useful for operation of X-ray FEL user facilities. We should note that an idea of using phase shifters for this purpose was proposed in [11] but in a different way, namely to use disruptive phase shifts for harmonics (i.e., π/h to disrupt the nonlinear growth of the h-th harmonic). The authors of [11] have found out, however, that the method is not very efficient (and they proposed undulator tapering as a better solution). In our case, paradoxically, an application of phase shifters, that are transparent for the 3rd harmonic, resulted in its strong suppression.

Coming back to the main topic of this Appendix, we can state that the version of the phase shifter method, proposed in [5], is inefficient in suppression of the fundamental in the case of SASE FELs (although is works well in the case of a monochromatic seed, see [5] for the details) even if the number of phase shifters is very large. The second version of the phase shifter method was proposed in [6]: one should use an alternation of $2\pi/3$ and $4\pi/3$ phase shifters. We have simulated this configuration with the same parameters of the beam and the undulator. The results are shown in Fig. 6. 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.

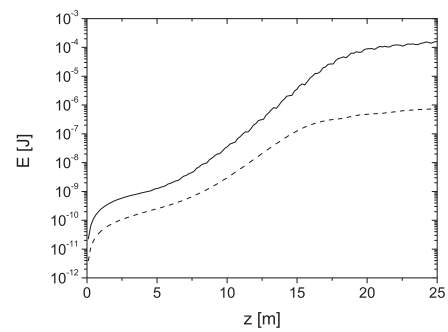

Figure 6: Pulse energy versus magnetic length of the undulator for the fundamental (solid) and the 3rd harmonic (dash). Electron beam and undulator parameters are given in Table 1. Phase shifters are located after every 0.5 m long section of the undulator, the phase shifts are $2\pi/3$ for the even phase shifters, and $4\pi/3$ for the odd ones.

Finally, we note that the third version [7] of the phase shifter method (also described in Section 2 of this paper) constitutes a further improvement of the method and allows to solve the problem under consideration (see Fig. 3). Generally speaking, this is only possible if the number of phase shifters is large. In other cases the application of intraundulator spectral filtering [7] might have to be considered.

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