

# ON DISRUPTION OF THE FUNDAMENTAL HARMONIC IN SASE FEL WITH PHASE SHIFTERS

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## Abstract

A method to disrupt the fundamental harmonic with phase shifters installed between undulator modules (while keeping the lasing at the third harmonic undisturbed) was proposed in [1]. 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  $2\pi$  for the third harmonic, i.e. it continues to get amplified without being affected by phase shifters. We note that simulations in [1] 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, we found out that a consecutive use of phase shifters with the same phase kicks  $2\pi/3$  (as proposed in [1] is inefficient, i.e. it does not lead to a sufficiently strong suppression of the fundamental wavelength. In the present report we propose a modification of phase shifters method that can work in the case of a SASE FEL.

## INTRODUCTION

When the saturation is achieved at the fundamental frequency, the nonlinear harmonic generation occurs, i.e. the radiation of the bunched beam at odd harmonics of the undulator [2–7]. This radiation has a relatively low power (for the 3rd harmonic it is on the order of a per cent of the saturated power of the fundamental wavelength), and its relative bandwidth is about the same as that of the fundamental [8]. Intensity of harmonics is subjected to much stronger fluctuations than that of the fundamental frequency [4,8,9]. Linear amplification of a harmonic does not proceed due to a strong impact of the saturation at the fundamental mode on the longitudinal phase space of the electron beam.

If, however, we disrupt the lasing at the fundamental frequency such that it stays well below saturation, then the third harmonic lasing proceeds up to saturation resulting in a significant intensity (about 30 % of the saturated power of the fundamental mode in 1D limit), narrow relative bandwidth (also about 30 % of that at the fundamental in 1D case). In other words, the brilliance can be by two orders of magnitude higher than in the case of nonlinear harmonic generation (for the 5th harmonic the improvement can reach three orders of magnitude). Intensity fluctuations of a harmonic are about the same as those at the funda-

mental wavelength of a SASE FEL since statistics is the same. Moreover, if the fundamental harmonic is strongly suppressed in the undulator, the users of X-ray facilities do not need filters which are in most cases required if one uses nonlinear harmonic generation. Note that the filters suppress the fundamental wavelength but may also partially suppress harmonics. Thus, harmonic lasing up to its saturation has decisive advantages over nonlinear harmonic generation, so one should have good methods to disrupt the fundamental mode.

## DESCRIPTION OF THE METHOD

A method to disrupt the fundamental harmonic (while keeping the lasing at the third harmonic undisturbed) was proposed in [1]. The undulators for X-ray FELs consist of many segments. In case of gap-tunable undulators, phase shifters are foreseen between the 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  $2\pi$  for the third harmonic, i.e. it continues to get amplified without being affected by phase shifters. However, the simulations in [1] 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, we found out that a consecutive use of phase shifters with the same phase kicks  $2\pi/3$  (as proposed in [1]) is inefficient, i.e. it does not lead to a sufficiently strong suppression of the fundamental wavelength. 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 small). We propose here a modification of phase shifters method that can work in the case of a SASE FEL. We define phase shift in the same way as it was done in [1] in order to make our results compatible with the previous studies. For example, the shift  $2\pi/3$  corresponds to the advance<sup>1</sup> of a modulated electron beam with respect to elec-

<sup>1</sup>In a phase shifter (like a small magnetic chicane) the beam is, obviously, delayed with respect to electromagnetic field. One can, however, always add or subtract  $2\pi$ , so that the shift is kept between 0 and  $2\pi$ . Therefore, a delay in the phase shifter by  $2\pi/3$  corresponds to the phase

romagnetic field by  $\lambda_1/3$ . In the following we assume that a distance between phase shifters is shorter than the field gain length of the fundamental harmonic. 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<sup>2</sup>. 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.

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 back to  $4\pi/3$  phase shifters, having the residual modulations in the electron beam and diffracted radiation from the first part as initial conditions for the red-shifted frequency band. Then one can change to the fourth part with  $2\pi/3$  phase shifts, and so on. A more thorough optimization can also include a part (or parts) of the undulator with zero phase shifts. As a result of these manipulations, the bandwidth of the FEL radiation strongly increases, while the saturation is significantly delayed. The efficiency of the method strongly depends on the ratio of the distance between phase shifters and the field gain length of the undisturbed fundamental mode. The smaller this ratio, the stronger suppression can be achieved after optimization of phase shifts distribution. For example, when the ratio is about 0.5, one can relatively easily increase the "effective" gain length by a factor of 2.

## PHASE SHIFTERS METHOD IN 1D MODEL

It was suggested in [1] that the fundamental mode can be disrupted by introducing consecutive phase shifts  $2\pi/3$  while the third harmonic is amplified without interruptions up to saturation. However, the simulations in [1] were done for the case of a monochromatic seed. We would like to check if this method also works in the case of a SASE FEL, using the same 1D model as in [1], and similar normalization procedure. For example, the reduced longitudinal coordinate  $\hat{z}$  in our notations [10] corresponds to  $\bar{z}$  in [1].

We define phase shift in the same way as it was done in [1] to make the results compatible. For example, the shift  $2\pi/3$  corresponds to the advance of a modulated electron beam w.r.t. electromagnetic field by  $\lambda_1/3$ . In Fig. 1 we present the simulation of SASE FEL with the set of phase shifters considered in [1]: phase shifts are equal to  $2\pi/3$  at the positions  $\hat{z} = 4, 5, 6, \dots$ . One can see that this set does not provide a sufficient disruption of the fundamental

shift of  $4\pi/3$  according to the definition in [1], and vice versa.

<sup>2</sup>A magnitude of the red shift is defined by the condition that the phase shift,  $-2\pi/3$  in the considered case, is compensated by the following phase advance in the undulator section between the phase shifters. Also sidebands (with a smaller gain) can be amplified for which an additional phase shift in the undulator section is  $2\pi$  or a multiple of it.

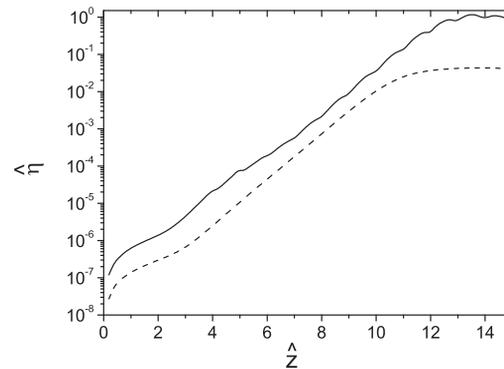


Figure 1: Normalized power of the fundamental harmonic (solid) and of the third harmonic (dash) versus normalized undulator length for a SASE FEL. Phase shifts are equal to  $2\pi/3$  at the positions  $\hat{z} = 4, 5, 6, \dots, 14$ , as suggested in [1]. The undulator parameter is large,  $K \gg 1$ . Definitions of the normalized parameters can be found in [10].

mode so that it reaches saturation not allowing the third harmonic to achieve high intensity level (although it is somewhat larger than that in the case without phase shifters). Note that starting with phase shifts earlier, at  $\hat{z} = 1$ , or using them more often does not bring a significant improvement of the situation. Better results are achieved if one uses  $4\pi/3$  shifts, but this is also not sufficient for a sure suppression of the fundamental harmonic and obtaining an ultimate performance of the third harmonic. The main difference of a SASE FEL with a seeded FEL amplifier is that in the former case the amplified frequency band is defined self-consistently, i.e. the mean frequency is shifted depending on magnitude and positions of phase shifts.

One can try to use a sequence of phase shifters  $2\pi/3, 4\pi/3, 2\pi/3, 4\pi/3 \dots$  [11] but this is a less efficient method than the one described in Section 4.1, namely a piecewise use of phase shifts  $2\pi/3, 4\pi/3$ , and 0. In the latter case we can achieve a desirable situation as one can see from Fig. 2. Indeed, the third harmonic saturates while the fundamental mode stays well below saturation.

If, however, we apply a modified method described in Section 4.1, namely a piecewise use of phase shifts  $2\pi/3$  and  $4\pi/3$ , we can achieve a desirable situation as one can see from Fig. 2. In this case the third harmonic saturates while the fundamental mode stays well below saturation.

## DISCUSSION

We can simply generalize the method to the 5th harmonic lasing (higher harmonic numbers we do not discuss in this paper). 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 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

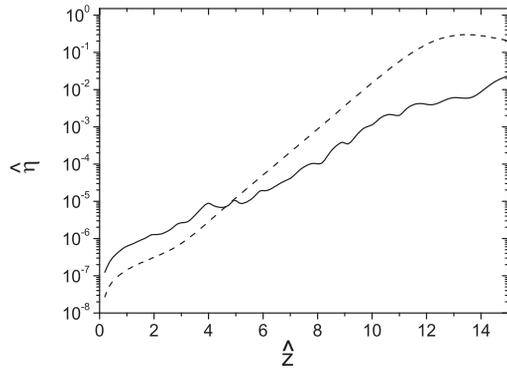


Figure 2: Normalized power of the fundamental harmonic (solid) and of the third harmonic (dash) versus normalized undulator length. Phase shifts are equal to  $4\pi/3$  at the positions  $\hat{z} = 1, 2, 3, 8, 9$  and  $2\pi/3$  at the positions  $\hat{z} = 4, 5, 6, 7, 10, 11$ . The undulator parameter is large,  $K \gg 1$ .

can be strongly suppressed so that the fifth harmonic can reach saturation.

We have considered the case when a distance between phase shifters is shorter than the field gain length of the fundamental frequency. If the distance is essentially larger, the phase shifts can still be used to delay the saturation of the fundamental but typically the suppression effect is not sufficiently strong. However, a combination of these rare phase shifts with intra-undulator spectral filtering can be efficient enough.

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